Dark Matter Axion Search Experiments Using 18T HTS Magnet at CAPP/IBS in KAIST

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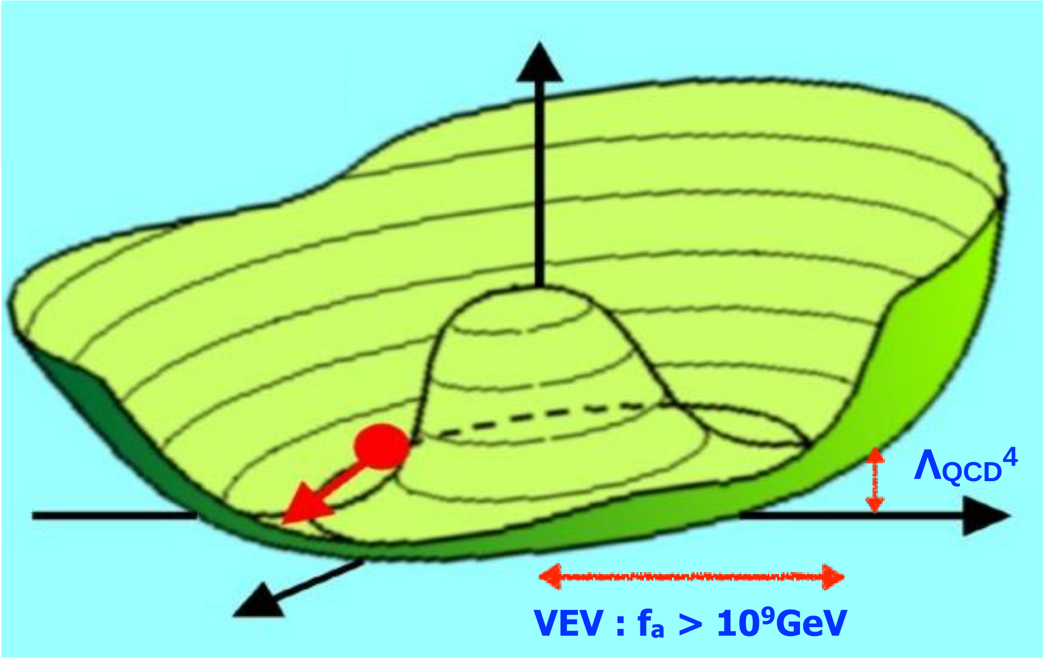
Outline

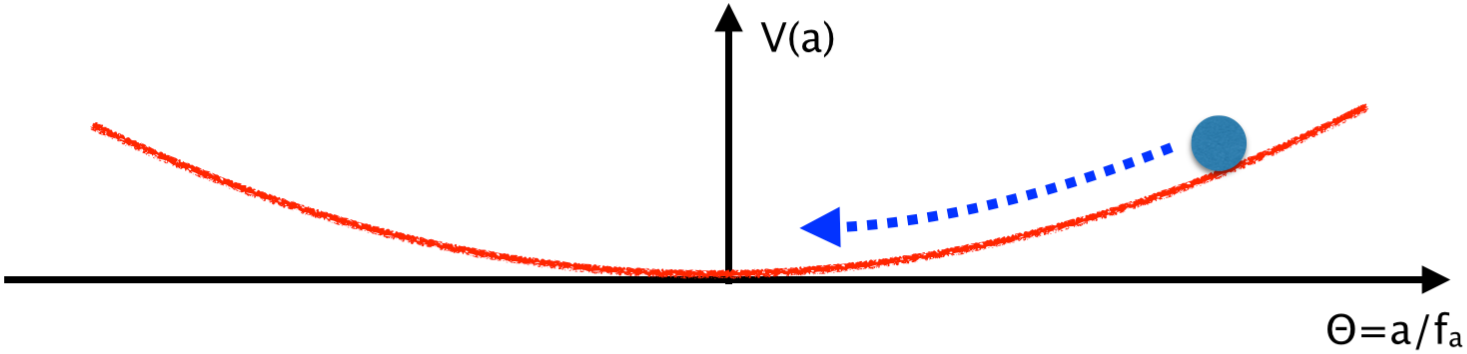
1. Axion as dark matter
2. Important factors for Axion search
   - HTS Magnet (18T)
   - Cryostat (4K)
   - Cavity
   - DAQ system
3. Results from our present setup
4. Factors improvement
   - Dilution refrigerator (~20 mK) with 18 T magnet
   - JPC : First stage amplifier
   - Cancellation magnet
5. Our Project

Invented to solve the strong-CP problem in QCD

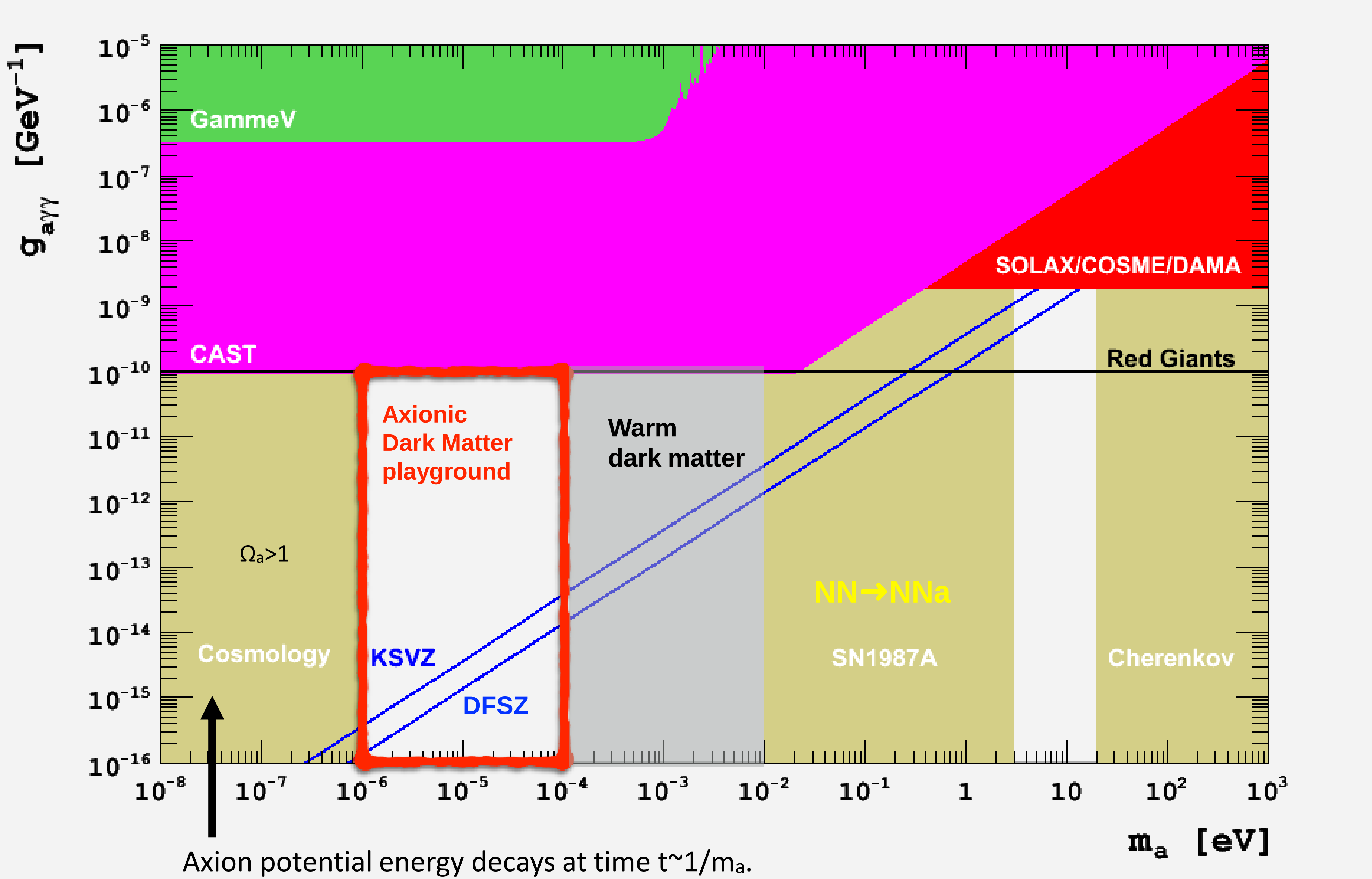


- Non-thermal mechanism of producing axion dark matter in the early Universe
- The initial axial angle Θ determines the potential energy to be released.
- The potential energy density (order of Λ_{QCD}^4) is converted into **cold dark matter**
- Axion dark matter mass is determined by the harmonic oscillator frequency

$m_a \simeq \Lambda_{QCD}^2/f_a < 10^{-3}$ eV !



Axion Dark Matter Search



Axion potential energy decays at time $t \sim 1/m_a$.
If this is too late (too small m_a) in cosmological time
the dark matter can be overproduced relative to the photons

Axion Haloscope

Assume: $m_a \simeq \mu eV$

$$\rho_{DM} = 3 \times 10^8 \text{ eV/cc} = 2.4 \times 10^{-6} \text{eV}^4$$

$$\beta = 10^{-3} \text{ or } < v_a >= 10^{-3} c$$

$$L_{coh} = \frac{1}{p} \simeq 10^9 \text{eV}^{-1} \simeq 200 \text{ m}$$

$$t_{coh} = \frac{1}{E} \simeq 10^{12} \text{eV}^{-1} \simeq \text{msec}$$

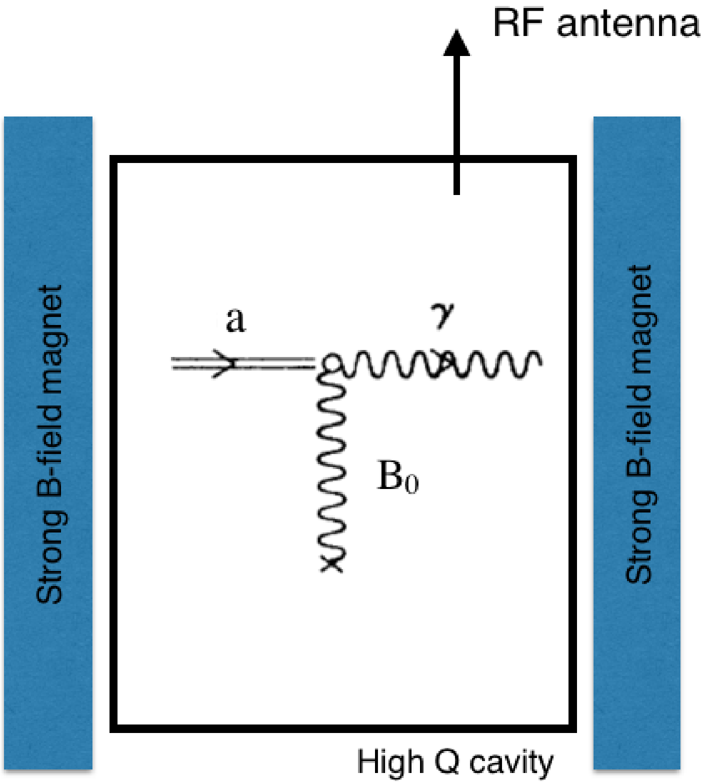
$$\mathcal{L} \equiv -\frac{1}{4} g a F \tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F \tilde{F}$$

$$= g a \vec{E} \cdot \vec{B}$$

$$\frac{\partial(\mathbf{E}^2/2)}{\partial t} - \mathbf{E} \cdot (\nabla \times \mathbf{B}) = g_{a\gamma} \dot{a} (\mathbf{E} \cdot \mathbf{B})$$

Oscillating source current ➔ RF photons

RF photon frequency = axion mass



$$P_a = g^2 \frac{\rho_a}{m_a} B_0^2 V \times \min(Q_{cav}, Q_a)$$

~ 10^{-21}W at m_a=μeV

(assuming B=8T, V=0.2 m^3 magnet and cavity Q =10^5)

CAPP's Dark Matter Axion Search Strategy

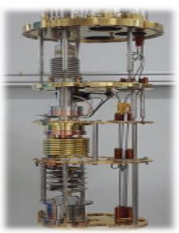
Strong magnetic field (18T)

$$\frac{df}{dt} = \frac{70\,\mathrm{MHz}}{\mathrm{year}}\left(\frac{4}{[s/n]}\right)^2\left(\frac{\mathrm{V}}{10\,l}\right)^2\left(\frac{\mathrm{B}_0}{10\,\mathrm{T}}\right)^4 \times C^4\left(\frac{g_a}{0.36}\right)^4\left(\frac{\rho_a}{0.3\,\mathrm{GeV/cc}}\right)\left(\frac{1\,\mathrm{K}}{\mathrm{T}_n}\right)^2\left(\frac{f}{\mathrm{GHz}}\right)^2\left(\frac{\mathrm{Q}}{\mathrm{Q}_a}\right)$$

Lower the thermal noise temperature of first stage amplifier

High Q cavity ($Q \sim 10^6$)

Cryogenics
<100mK

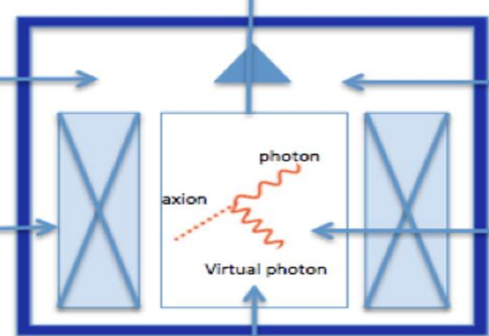


Oxford Kelvinox

High Field SC Magnet

SuNam Co.
2G-HTS
(18 T)

To RF Receiver

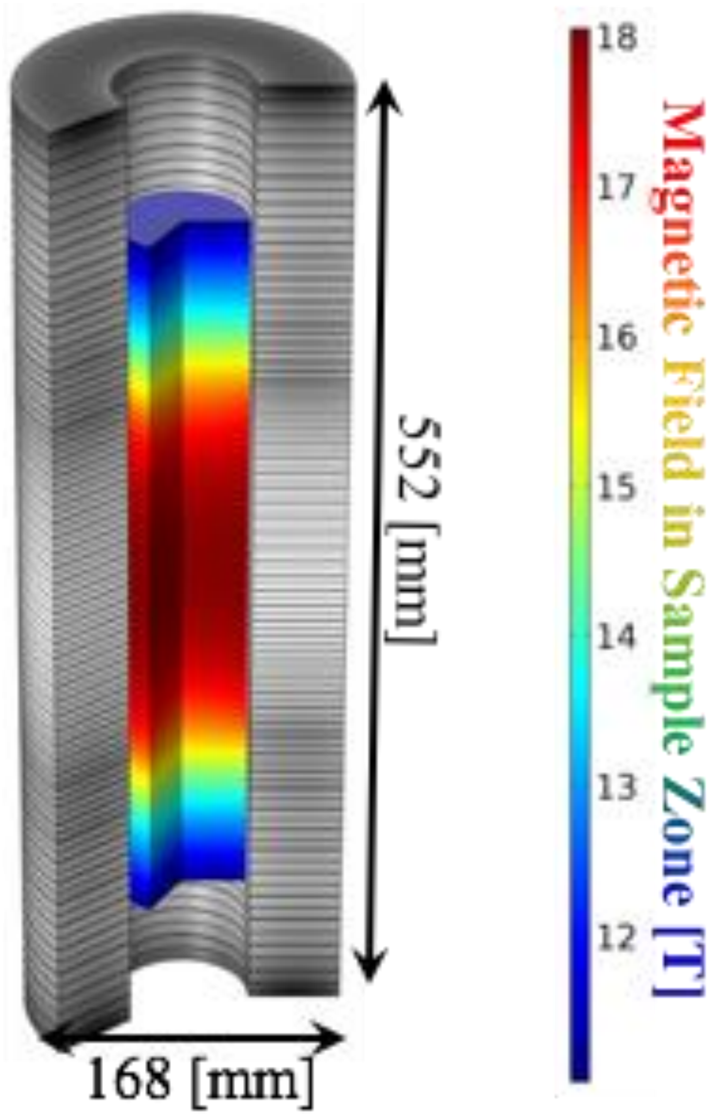


(Reverse) Primakoff Effect

JPC Amplifier

QCI Co.

High Q Tunable Cavity



A strong B-field and large bore HTS magnet can be commercially produced by SuNAM Co. Ltd.

2G HTS Superconducting Magnet
Magnetic field : 18 Tesla
Dimension: 70 mm ID / 168mm OD
200 mm uniform field (>90%)
552 mm length
Quench free design (No-Insulation winding)
Compact and easy to operate

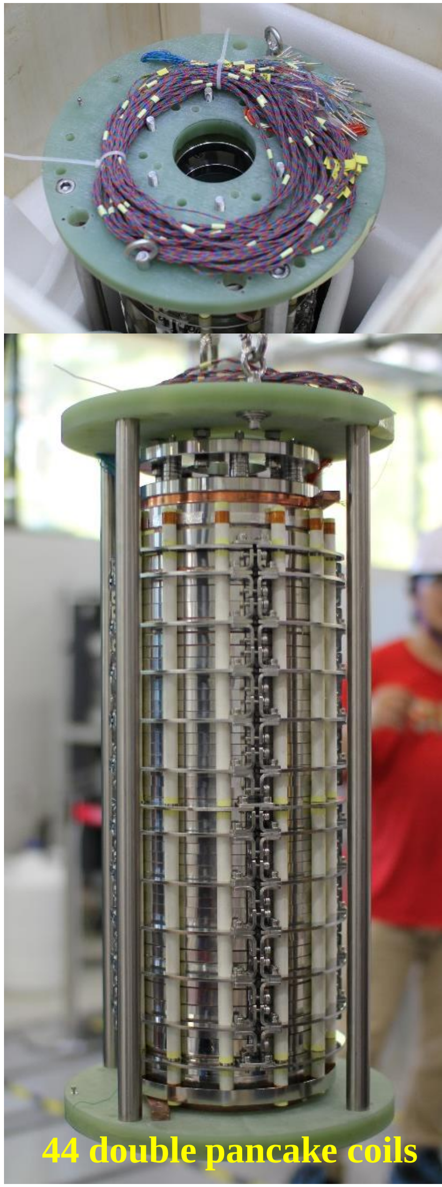
The magnet delivery by summer 2017

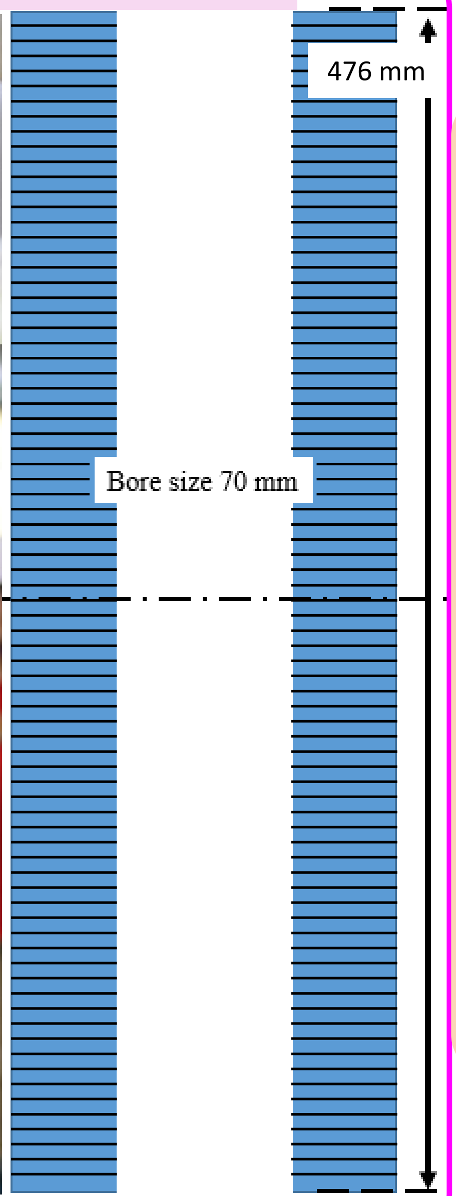
Initial DM axion mass range to probe:
17 to 36 μeV

(Later we will apply multiple cavity method to probe higher mass range search)

18 T no insulation magnet

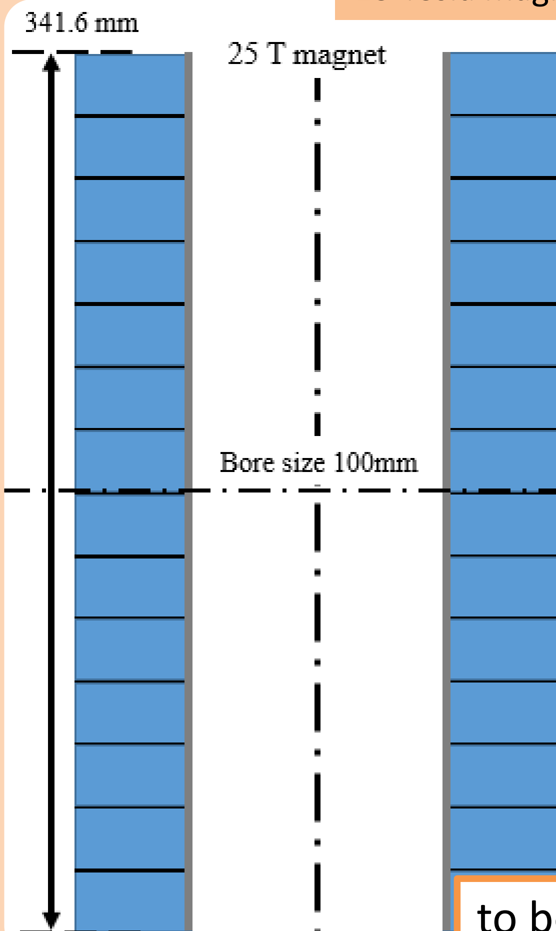
18 Tesla magnet

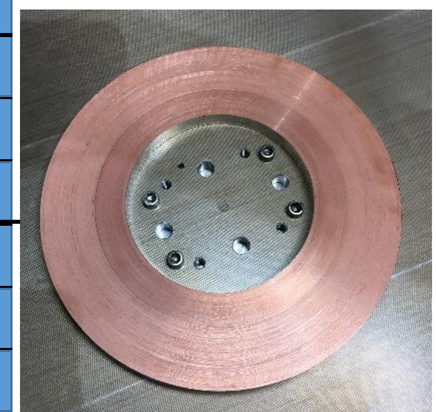




- non insulation type
- No quench in LHe

25 Tesla magnet



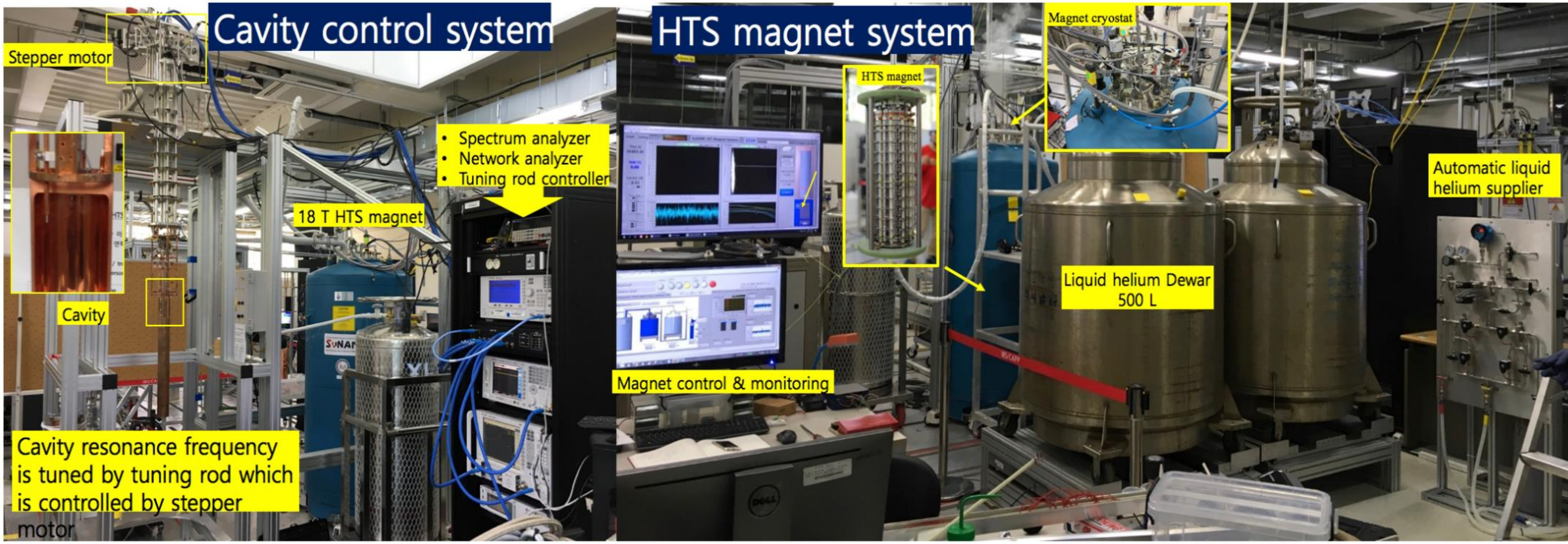


1st coil
for 25 T magnet

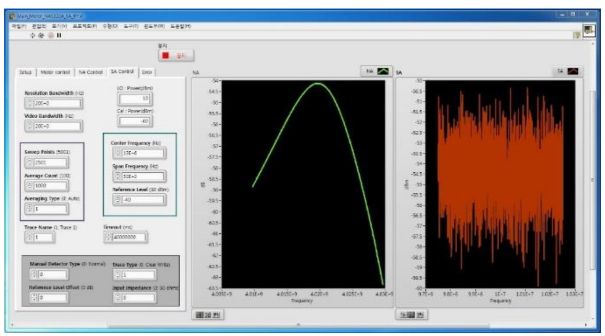
to be delivered in 2020

18 T was delivered in 2017.

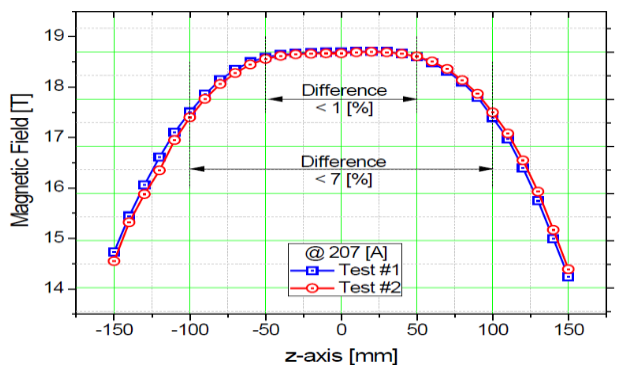
18T HTS Magnet with 4 K Cryostat

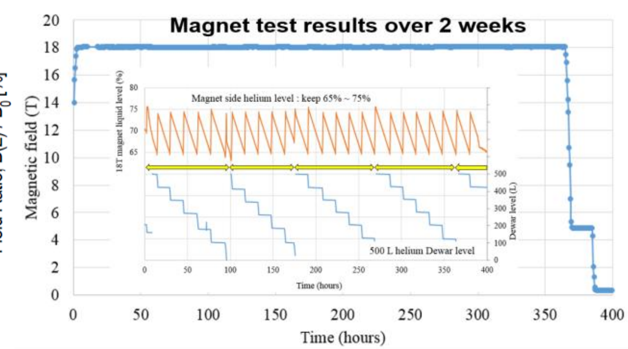


Measurement program



The cavity resonance frequency is tuned by tuning rod which is controlled by stepper motor





- Uniformity: 93%(±100 mm)
- Stability: <0.05% in 2 weeks

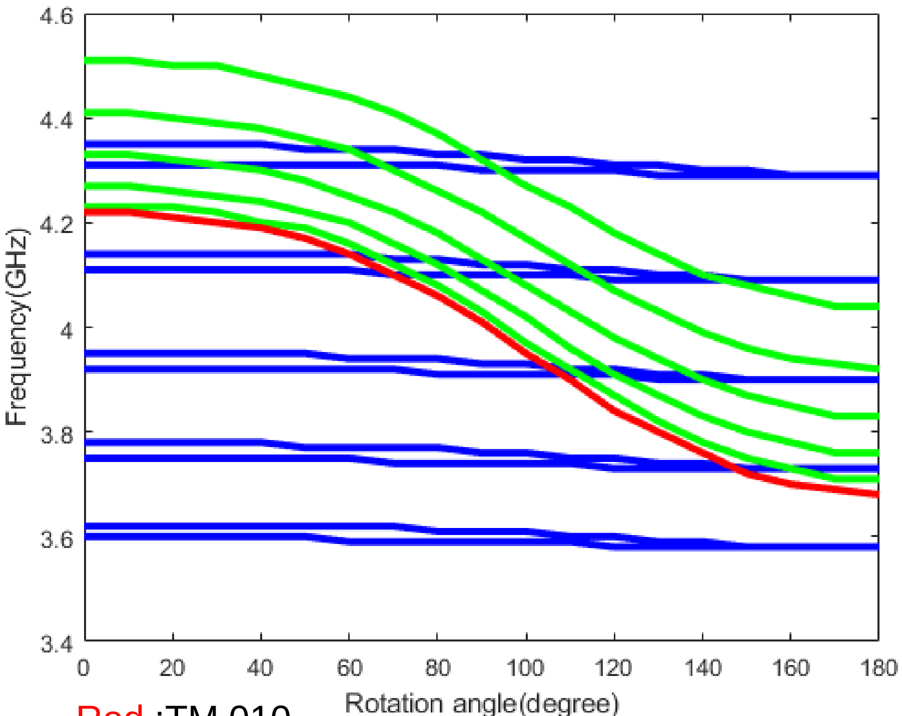
Very high quality of our HTS magnet.

❖ Related Poster : JongKuk Kim(6 July 2018, 18:30)

Simulation of frequency in cavity

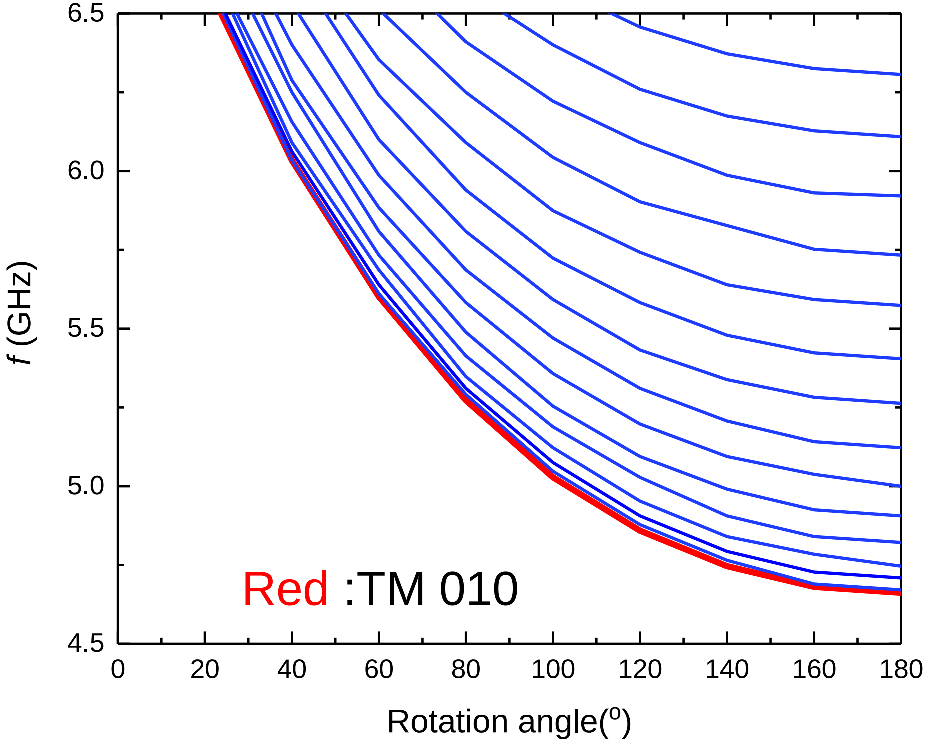
- The third factor for axion search is high Q-value cavity

Dielectric rod



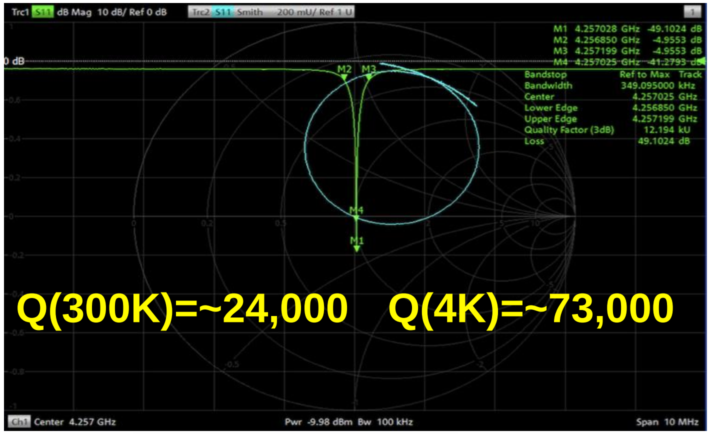
Red :TM 010
Green : TM 01m
Blue : TE11m

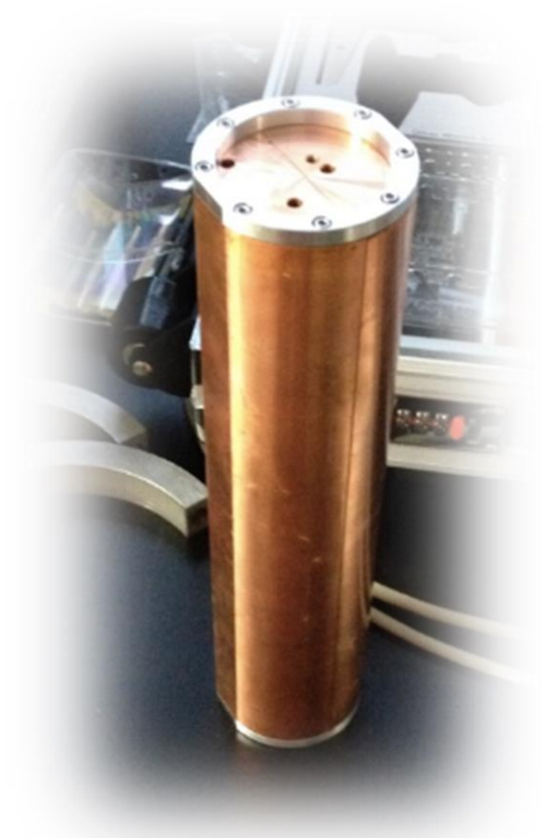
Conducting rod



- The dielectric rod has lower frequency than conducting rod .
- We use the red line (TM010 mode)for axion search.

❖ Related Poster : YoungJae Lee (6 July 2018, 18:30)

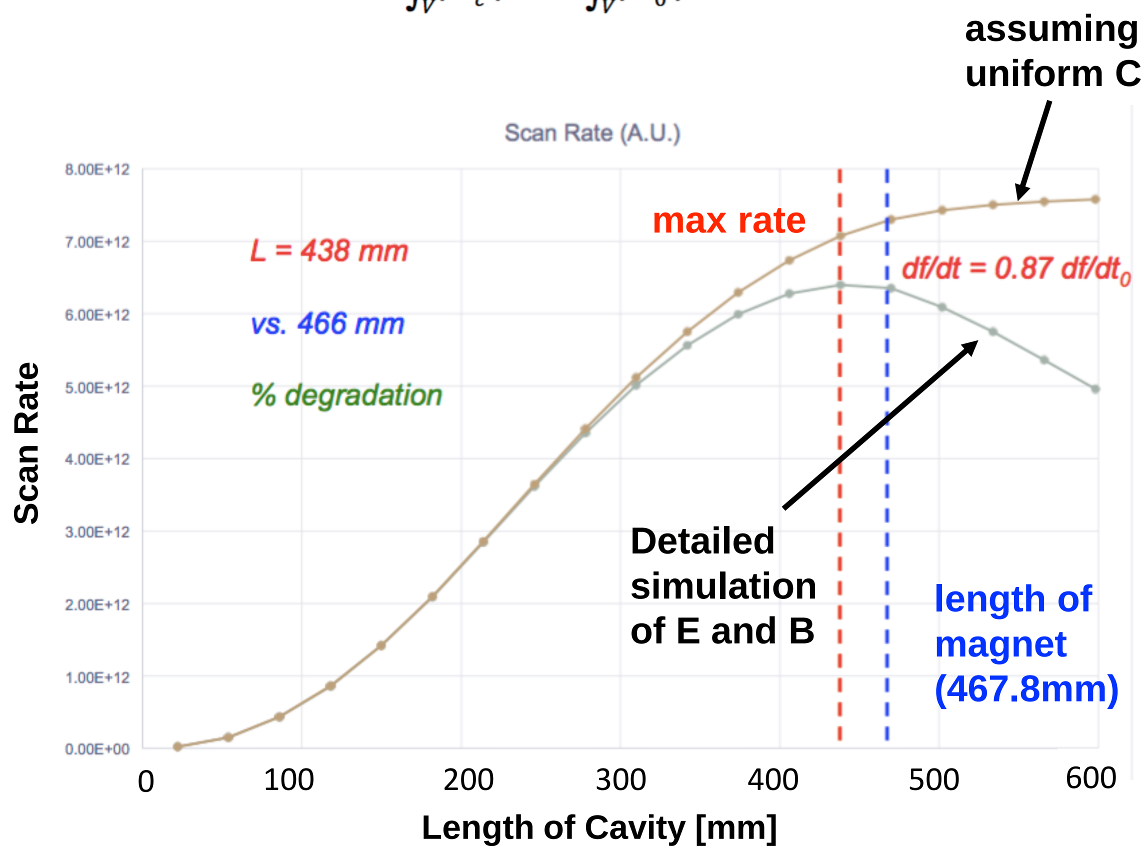




• Scanning Rate vs. Length of Cavity

$$\frac{df}{dt} = \left(\frac{1}{snr}\right)^2 \left(\frac{P_{signal}}{k_B T_{syst}}\right)^2 \frac{Q_a}{Q_L} = g_{a\gamma\gamma}^4 \left(\frac{\rho_a}{m_a}\right)^2 \left(\frac{B^2 VC}{k_B T_{syst}}\right)^2 Q_0 Q_a \frac{\beta^2}{(1+\beta)^3}$$

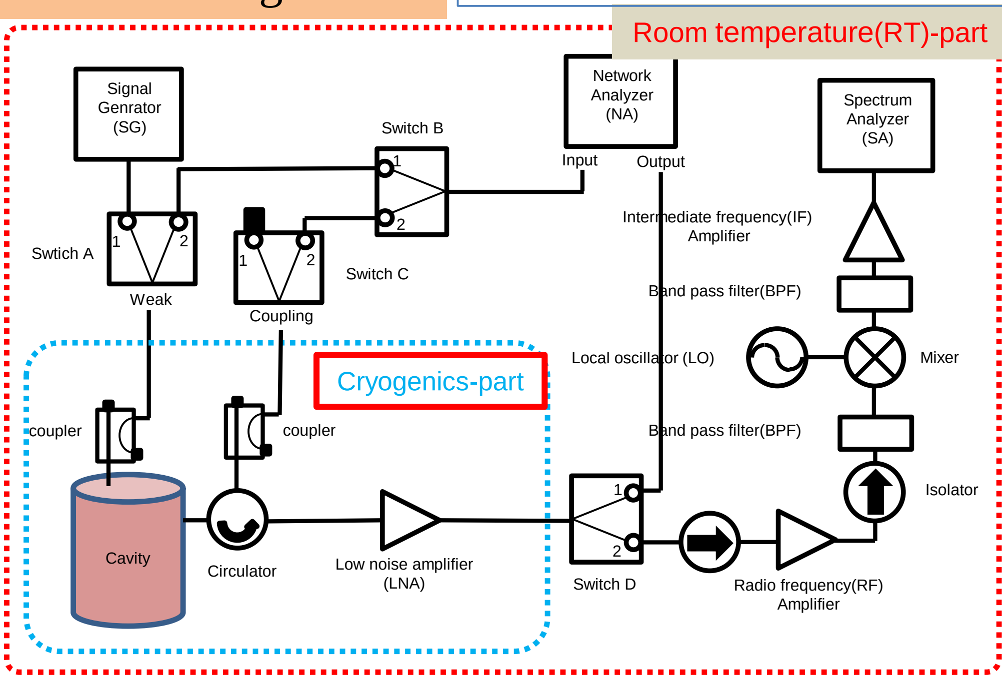
$$C = \frac{\left|\int_V \vec{E}_c \cdot \vec{B}_0 \, dV\right|^2}{\int_V |\vec{E}_c|^2 \, dV \cdot \int_V |\vec{B}_0|^2 \, dV}$$

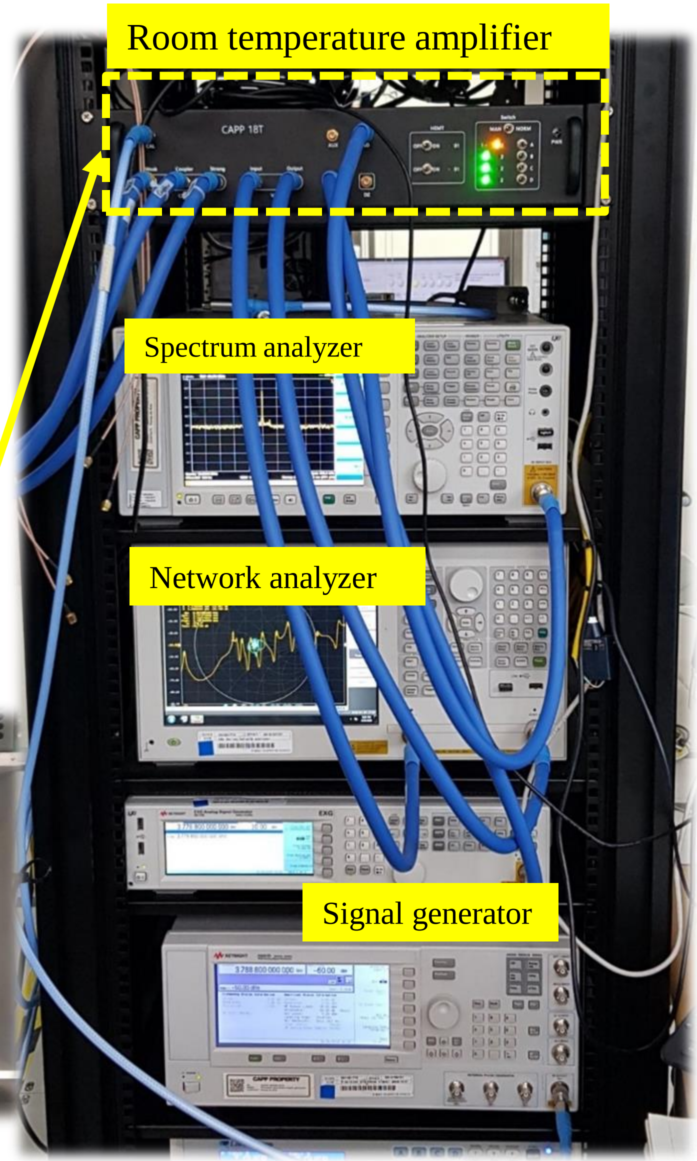


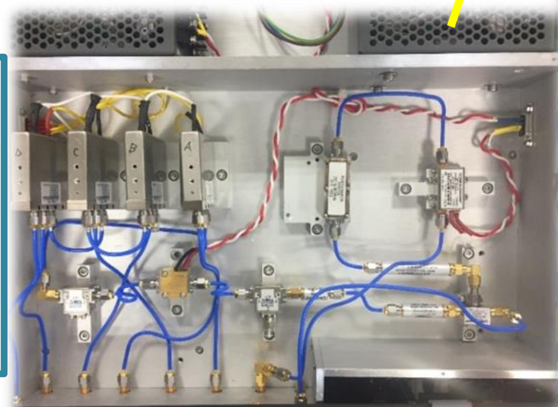
DAQ System

RF chain configuration

Cryo- and room temp. DAQ system





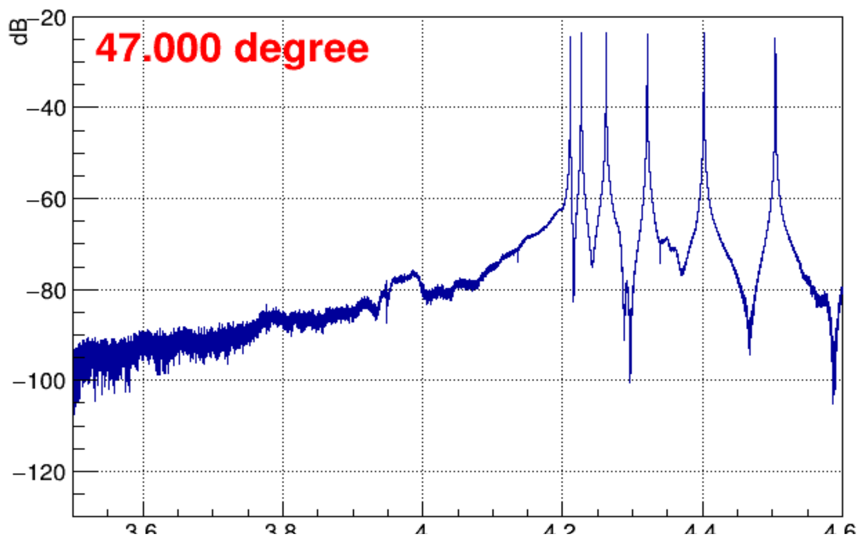


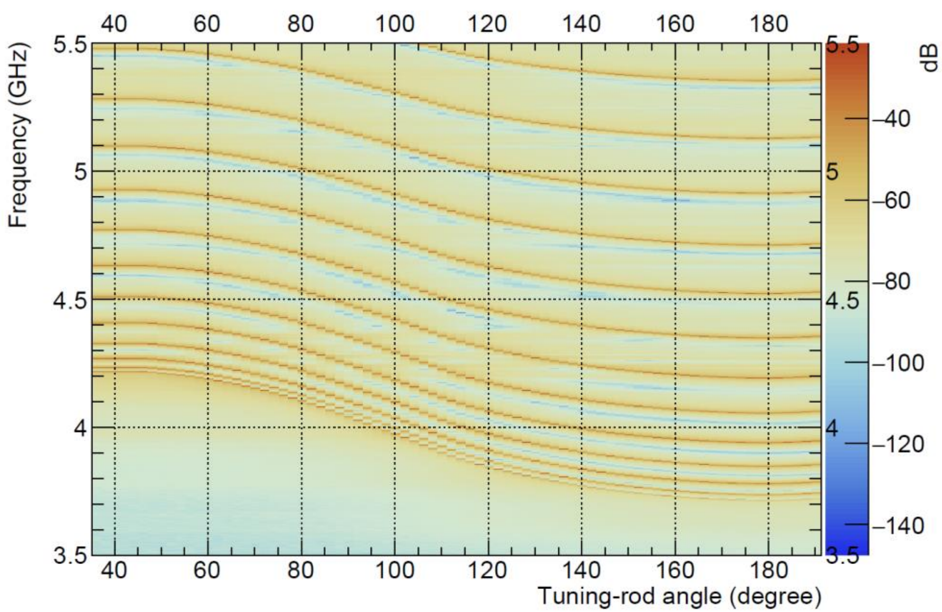
Room T. amp.

- It can be switched with 4 states by program (S11,S21,S22,SA)

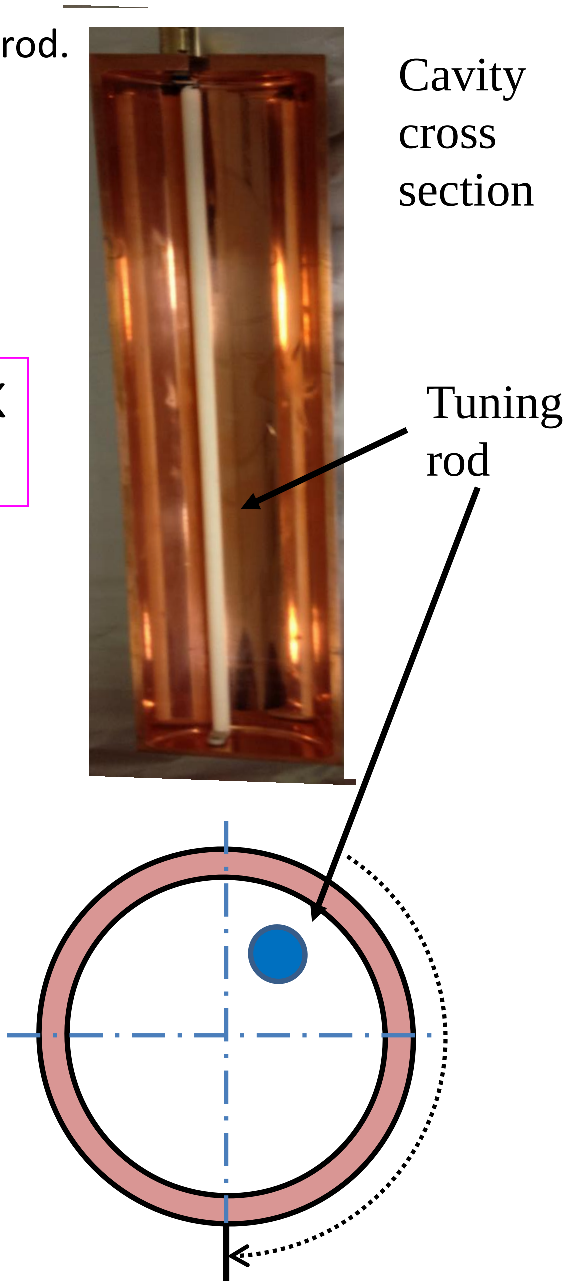
Measurement of the resonant frequency in the copper cavity

We measured the resonant frequency of our cavity with dielectric tuning rod.

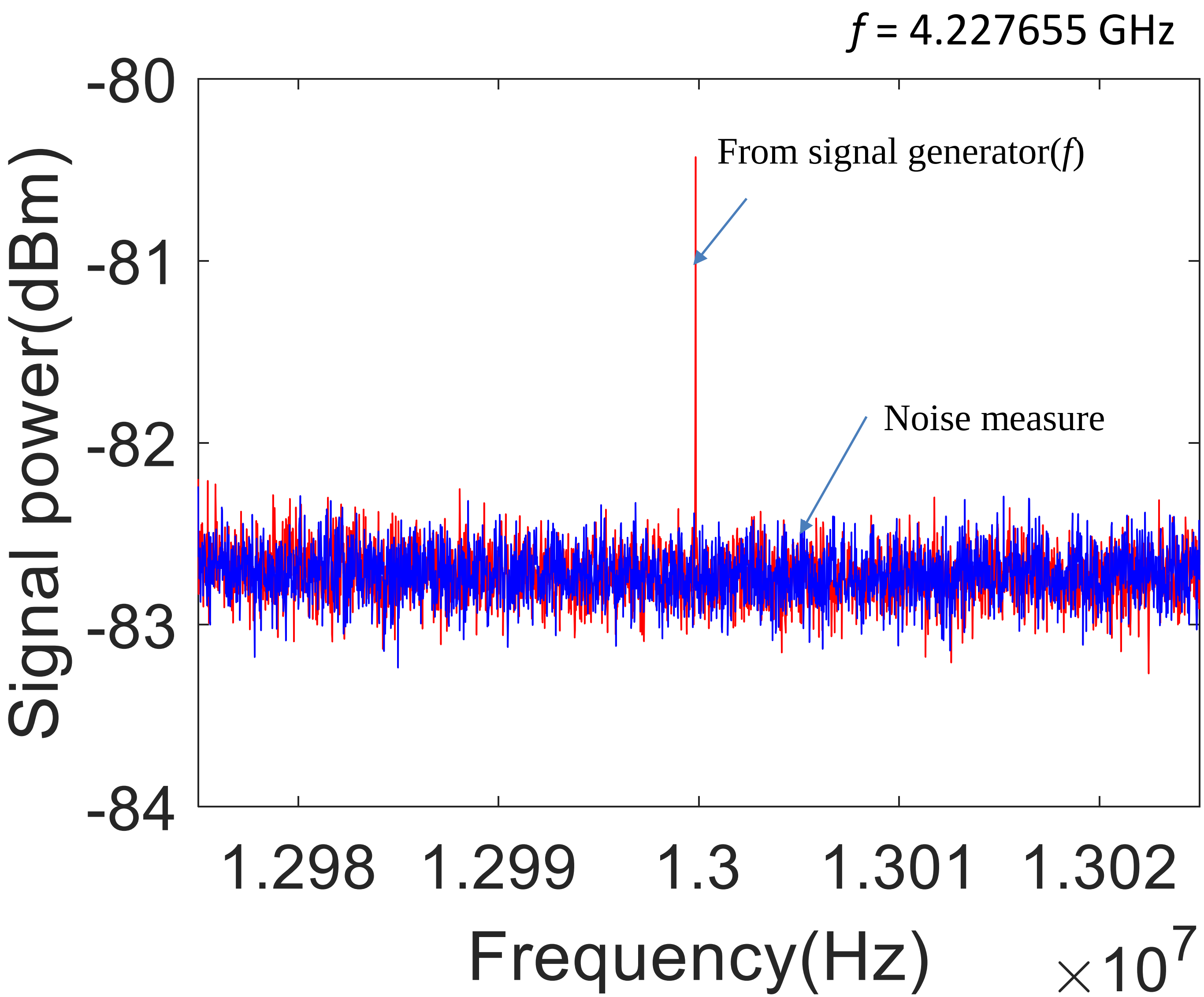




Temp: 4 K
B : 18 T



Background Noise at 4 K (under 18 T)



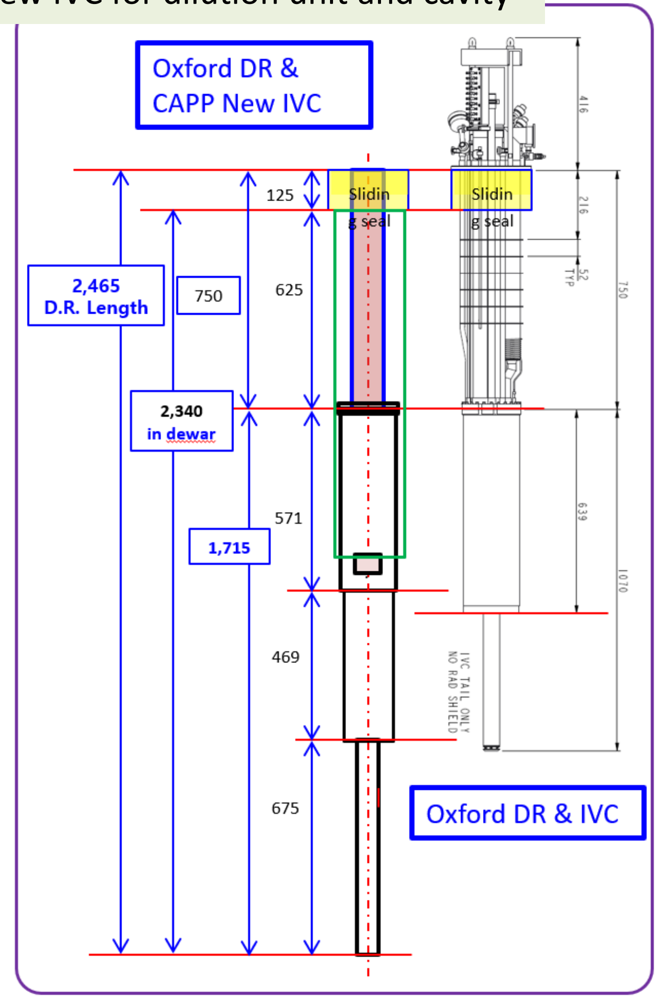
T : 4 K
H : 18 T

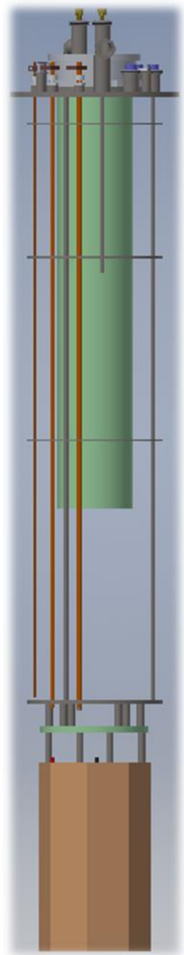
(Down converted IF)

Combination of Dilution refrigerator and 18 T magnet

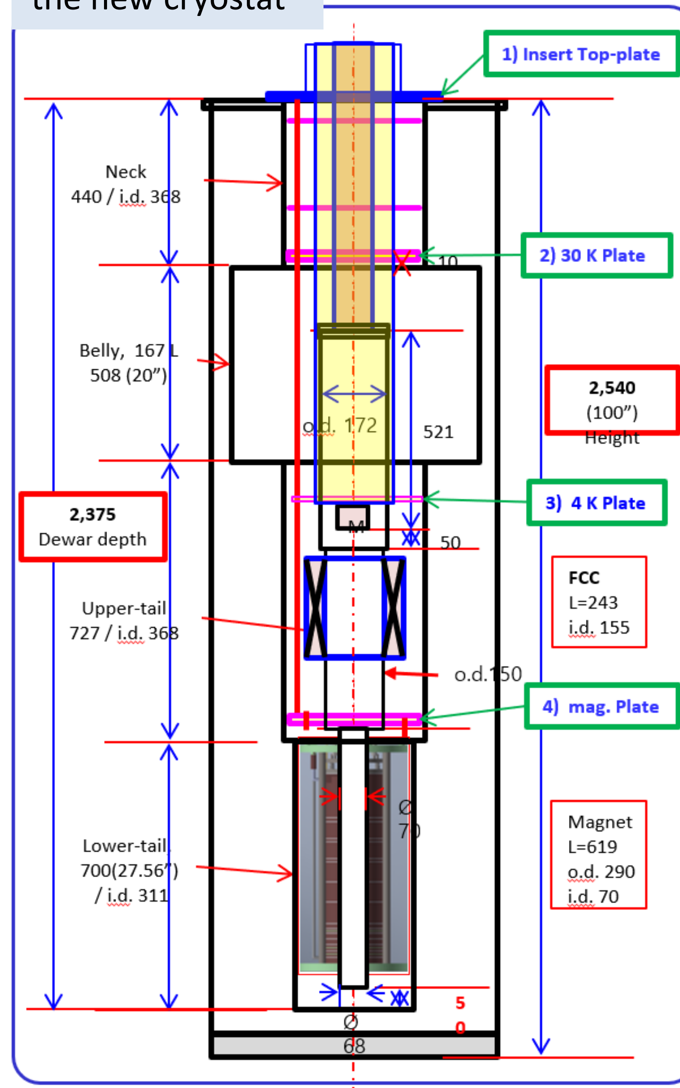
- At present, we are going to improve our experimental setup.

the new IVC for dilution unit and cavity





the new cryostat

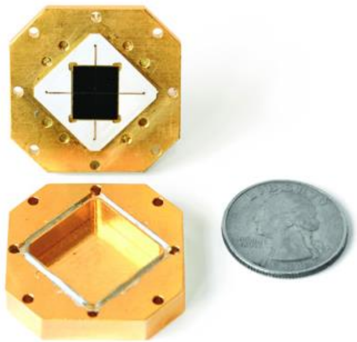


Josephson Parametric Converter (JPC : Quantum Limit Amplifier)

4 K exp. : HEMT amp.(2 K Noise Temp.)

→ Improve the 1st stage amp.

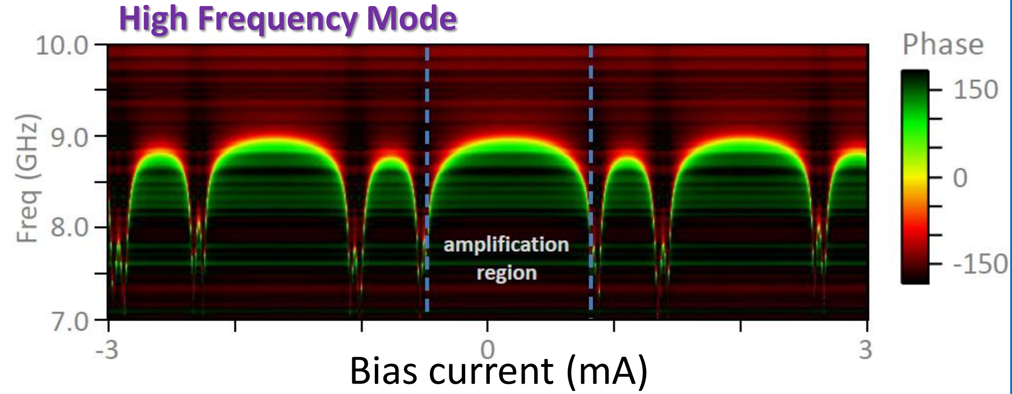
Inside

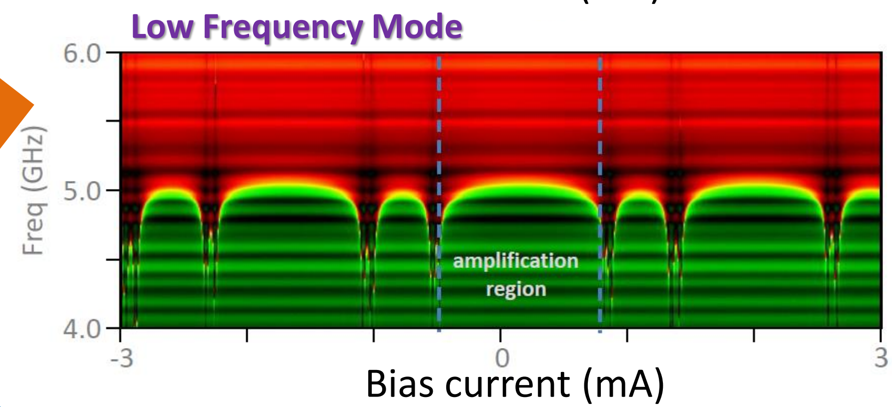


Outside

Flux maps were measured from our JPC.

Flux Maps





From this maps, we find the two frequency range.

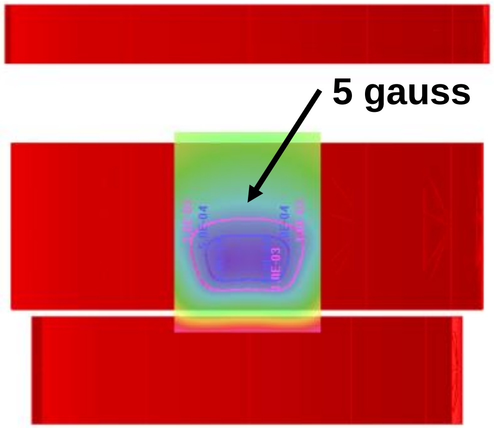
Gain(20 dB min)	F_{min} (GHz)	f_{max} (GHz)
High frequency	7.72	8.802
Low frequency	4.757	5.01

❖ Related Poster : JiYoung Lee

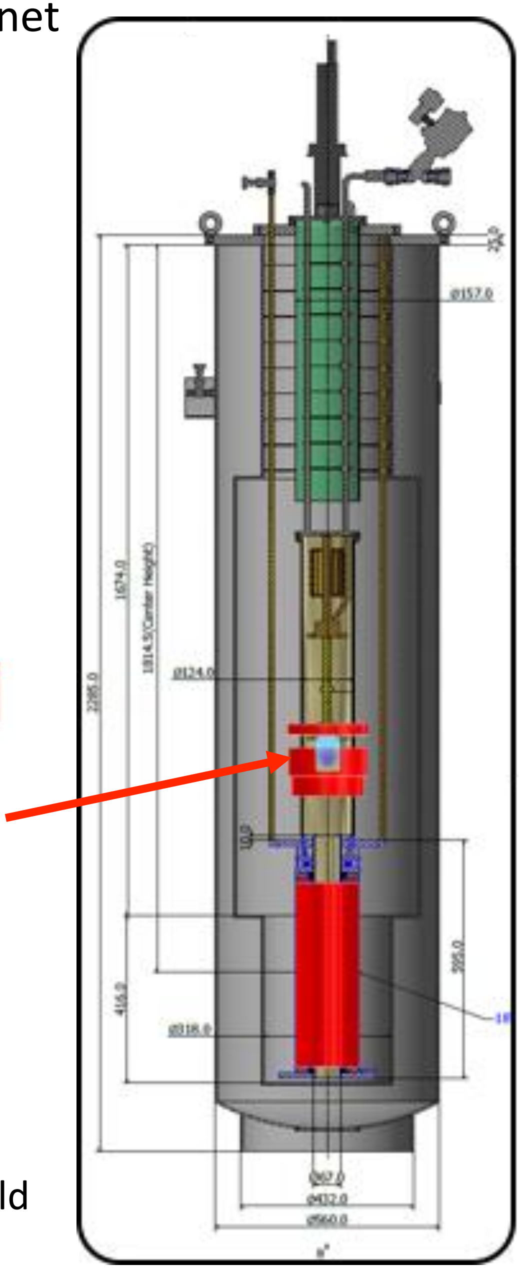
Next plan : Measure the noise temperature of JPC

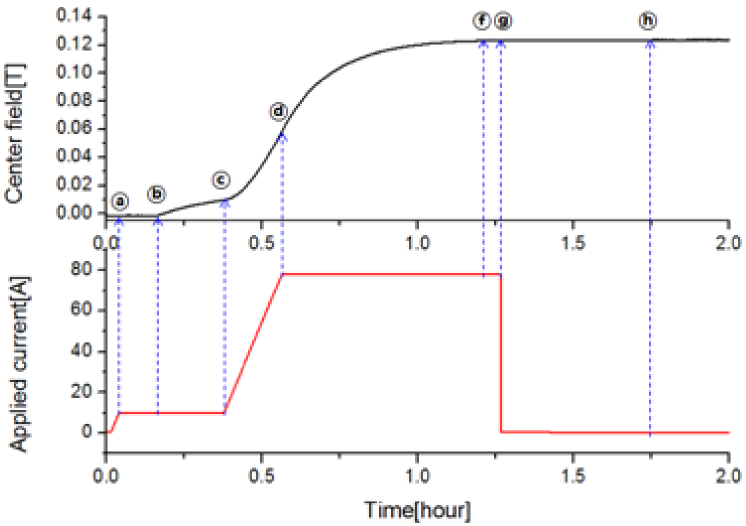
Cancellation Magnet Development

Need the cancellation magnet for JPC operation in 18 T

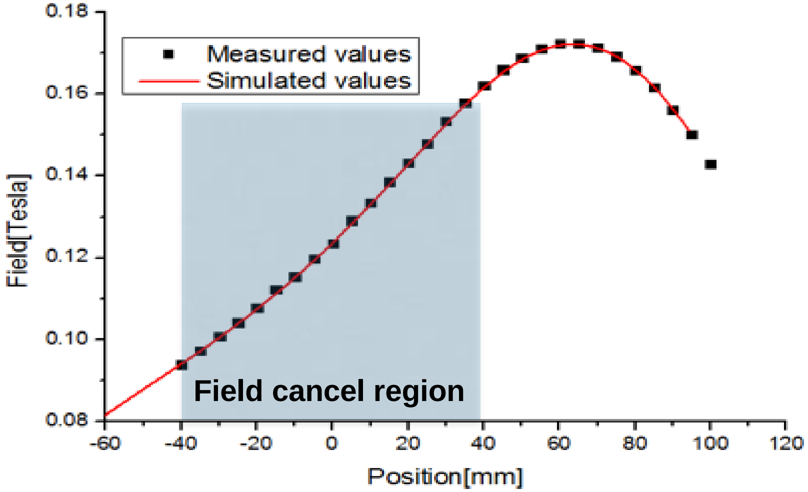


The main purpose of it is cancellation of magnetic field around the JPC



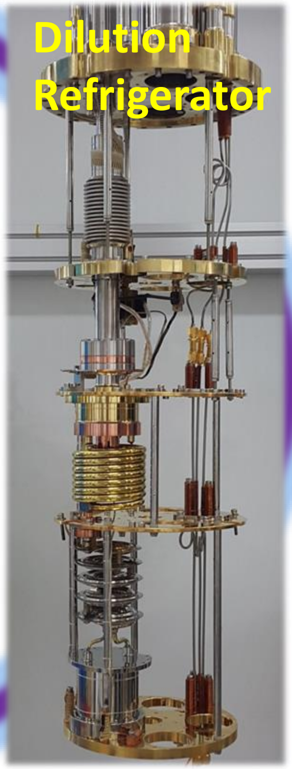


- Cancel out ~kG of stray field to a few G
- Field stability ~25ppm/hr
- Field profile test & quench test passed



Installation of improvement factors for experiment

Our experimental setup will be installed with this condition.



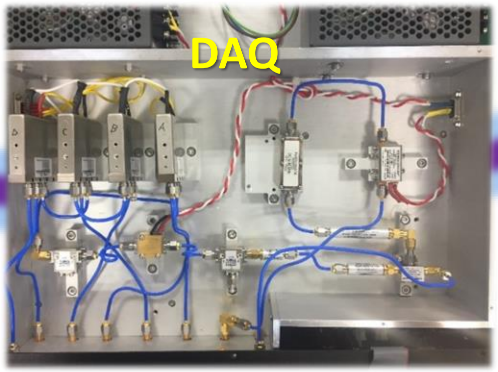
Magnetic field : 18 T

Noise temperature : ~ 500 mK

Q-factor : ~70,000

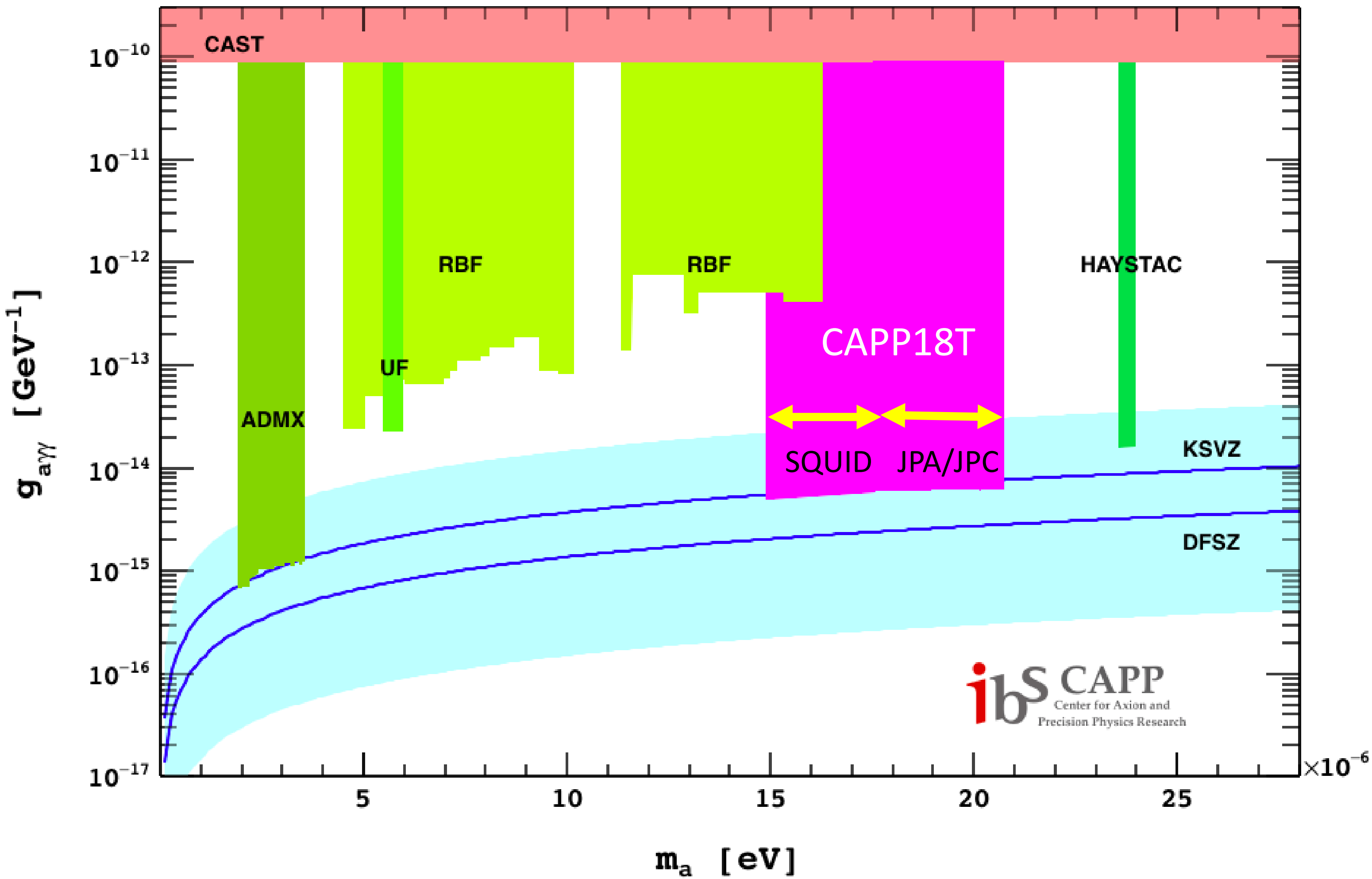
Real time DAQ : ~ 80% (efficiency)

(Physical temperature :~ 20 mK)



Projected Axion Search Goal

We will probe the axion with Dilution and JPC and so on.



Summary

- We use 18 T HTS solenoid magnet for Axion Haloscope research.
- We measured the TM modes in the cavity at 4 K(under 18 T)
- We will install the dilution refrigerator and 18 T magnet in October.
- We will sure probe the dark matter Axion in the range of 17 ~ 36 μeV.
  (f : 3.7 ~ 8.8 GHz)