Axion haloscope using an 18 T high temperature superconducting magnet

Moohyun Ahn, Yougjae Lee, Hojin Yoon
Byeongsu Yang Jonghee Yoo

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❖ Axion

➢ Axion

- Axion is a hypothetical particle postulated at first as a solution of the strong CP problem by Peccei and Quinn. (1977)
- Introduce an additional, global chiral U(1) symmetry ($U(1)_{PQ}$)

$$\mathcal{L}_{total} = \mathcal{L}_{SM} + \bar{\Theta}\frac{g^2}{32\pi}G_a^{\mu\nu}\tilde{G}_{a\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{int} + \xi\frac{a}{f_a}\frac{g^2}{32\pi^2}G_{\mu\nu}^a\tilde{G}^{a\mu\nu}$$

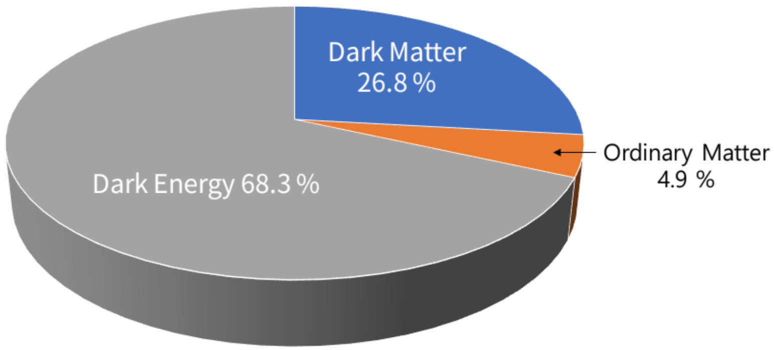
- Coefficient of the CP violating $G\tilde{G}$ term becomes dynamical vanishes for the value $\langle a \rangle = -\bar{\Theta}f_a/\xi$ at which V_{eff} has its minimum.

➢ Invisible Axion

- The original axion model of weak scale was ruled out by experiments.
- f_a need not to be weak scale to solve the strong CP problem.
- If $f_a \gg v_F$, then the axion is very light, very weakly coupled and very long lived, and such axion is called invisible axion.
- **KSVZ** Model (**K**im(1979) and **S**hifman,**V**ainshtein,**Z**akharov(1980)) or Hadronic Model
  - A extra heavy quark Q, and a scalar field Φ carry PQ charge.
- **DFSZ** Model (**D**ine,**F**ischler,**S**rednicki(1981), and **Z**hitnitskii(1980))
  - Two Higgs doublets, and a scalar field Φ, which carry PQ charge.

❖ Dark Matter Axions

➢ Constituents of Our Universe



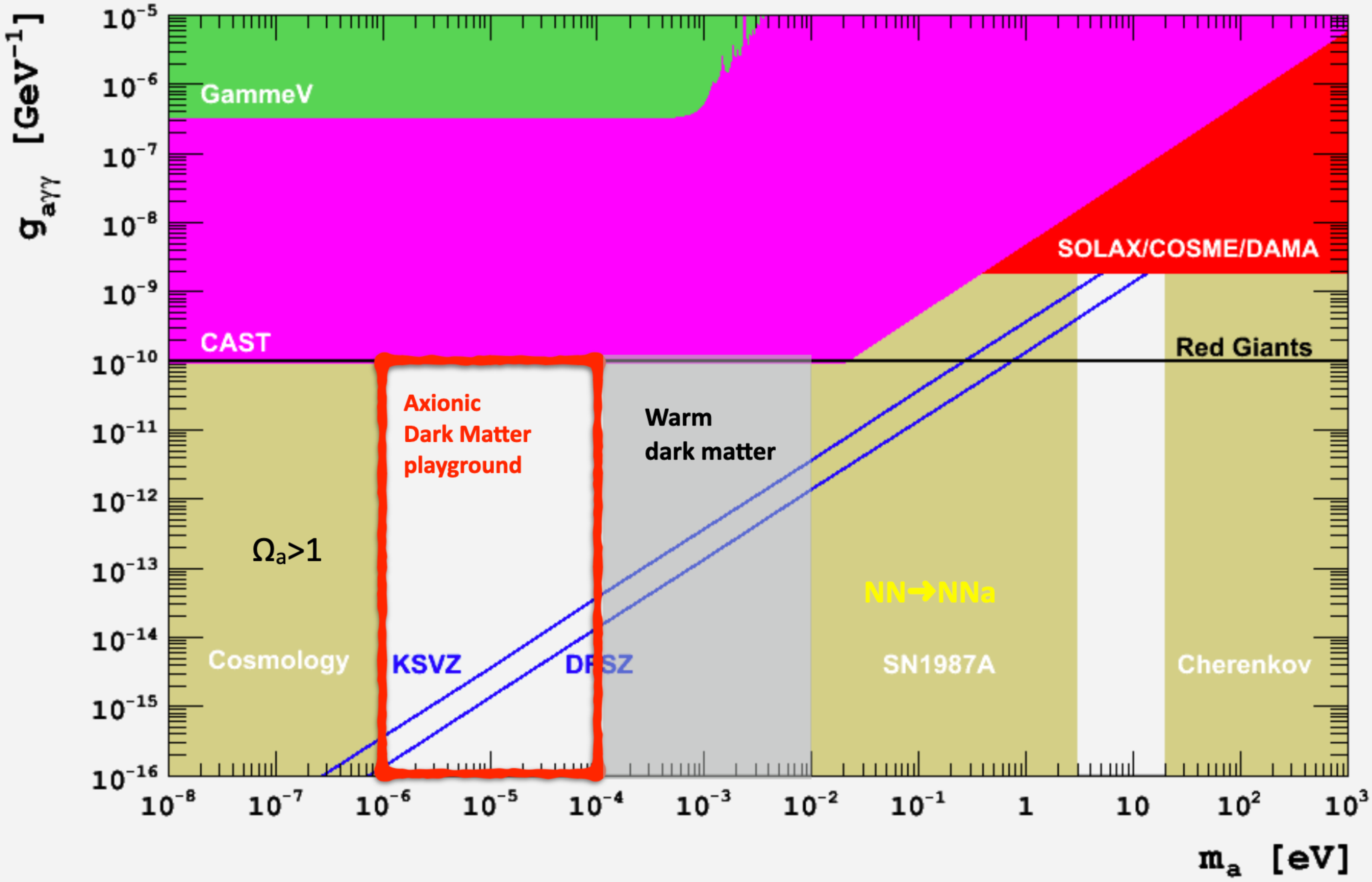
- Dark Matter Properties
  - stable
  - non-baryonic
  - non-relativistic
  - gravitation interacting
- The contents of dark matter ?
  - neutrino
  - WIMP
  - lightest SUSY particle

➢ Axion as a CDM candidate

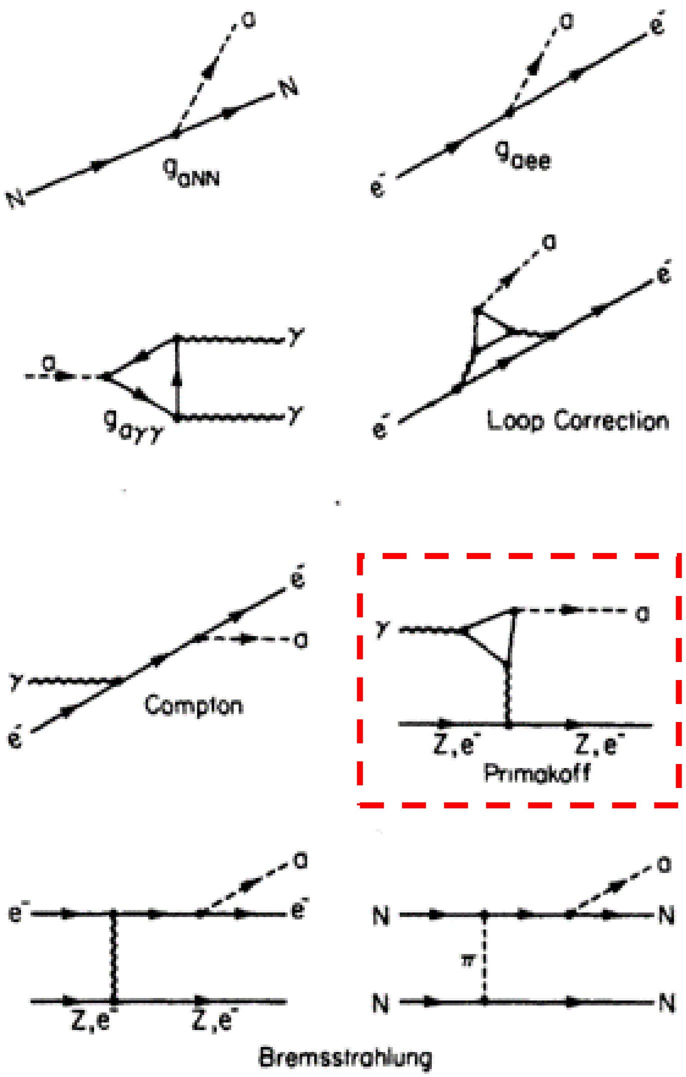
- Non-thermal mechanism of producing axion dark matter in the early Universe
- The potential energy density (order of $\Lambda_{QCD}{}^4$) is converted into cold dark matter
- Axion dark matter mass is determined by the harmonic oscillator frequency

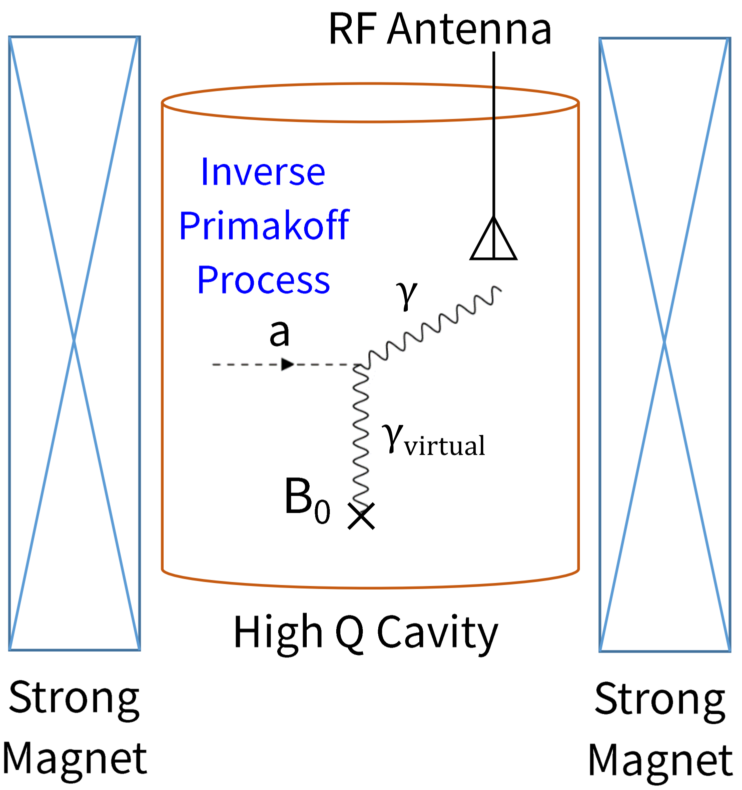
$$m_a \simeq \frac{\Lambda_{QCD}^2}{f_a} < 10^{-3}\mathrm{eV}$$

❖ Axion Mass Range



❖ Axion DM detector : Axion Interactions

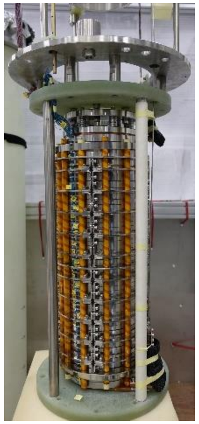




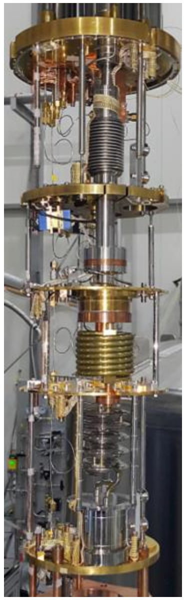
$$P_{sig} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} \frac{\beta}{1+\beta} \omega_0 B_0^2 V C_{nlm} Q_L \frac{1}{1+(2\delta\nu_a/\Delta\nu_c)^2}$$

- Axion are converted into single photon via the Inverse Primakoff process.

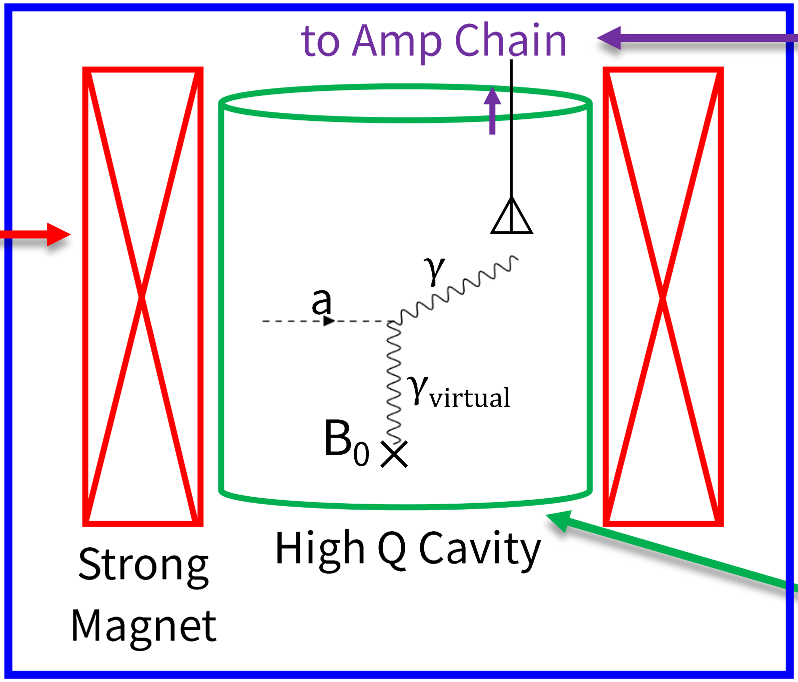
❖ CAPP's Dark matter Axion Search Strategy



High Field
HTS Magnet



Cryogenics



Quantum-limited
Noise Amp

High Q Cavity

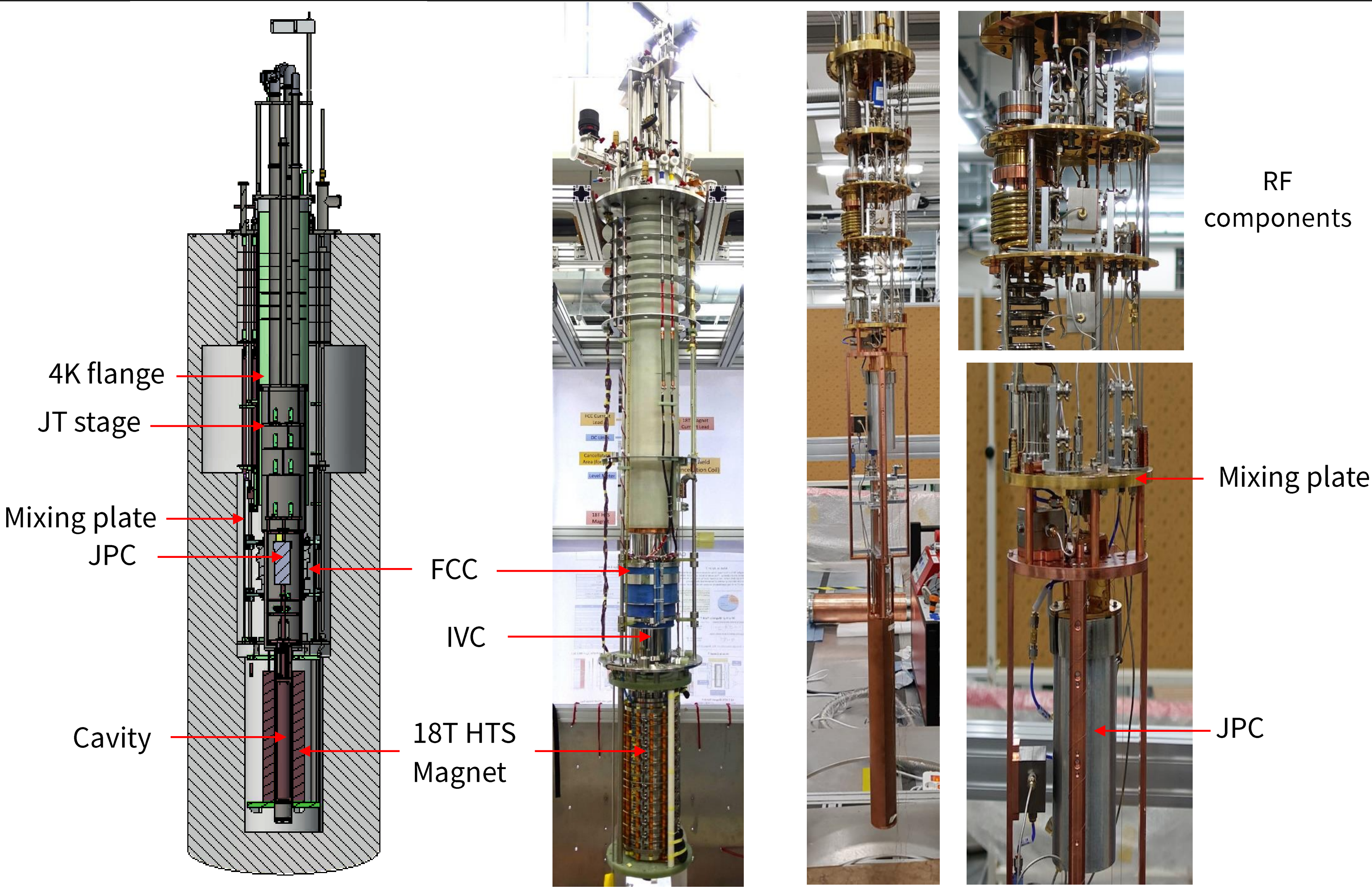
$$SNR = \frac{P_{sig}}{k_B T_{SYS}} \sqrt{\frac{\tau}{\Delta \nu_a}}$$: Dicke Radiometer Equation

$$\frac{df}{dt} \propto \frac{P_{sig}^2}{T_{SYS}^2 SNR^2} \propto g_a^4 \rho_{DM} f_a^2 \frac{V^2 \ \boldsymbol{B_0^4} \ C_{nlm}^2 \ \boldsymbol{Q_L}}{\boldsymbol{T_{SYS}}^2} \frac{\beta^2}{(1+\beta)^3}$$

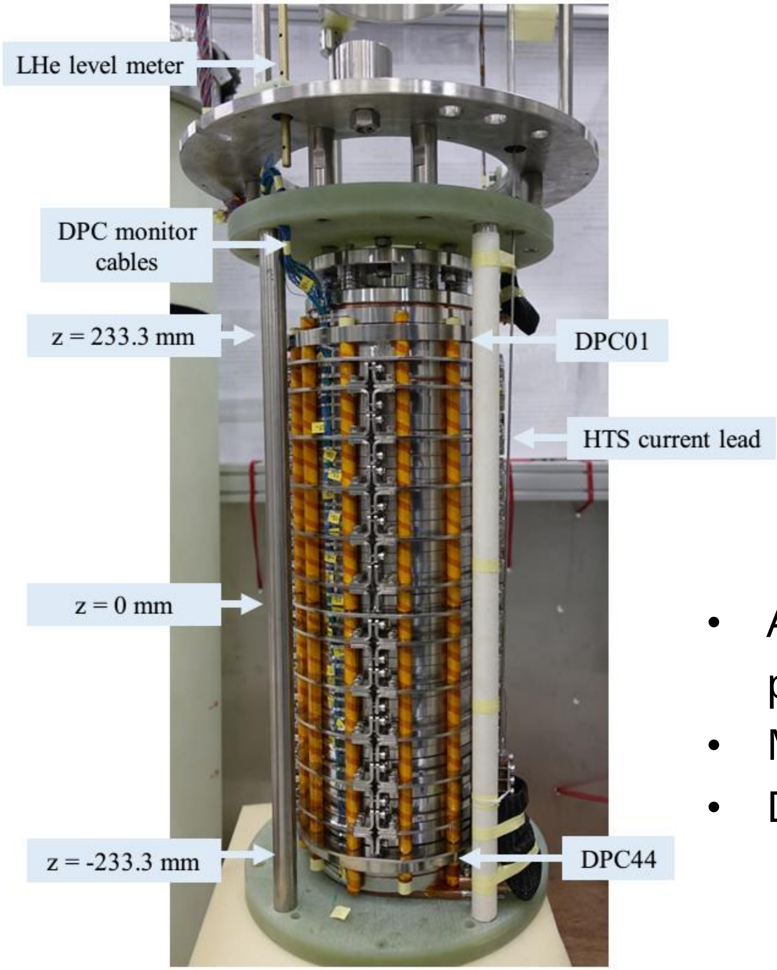
$$T_{SYS} = T_{PHY} + T_{N,amp}$$

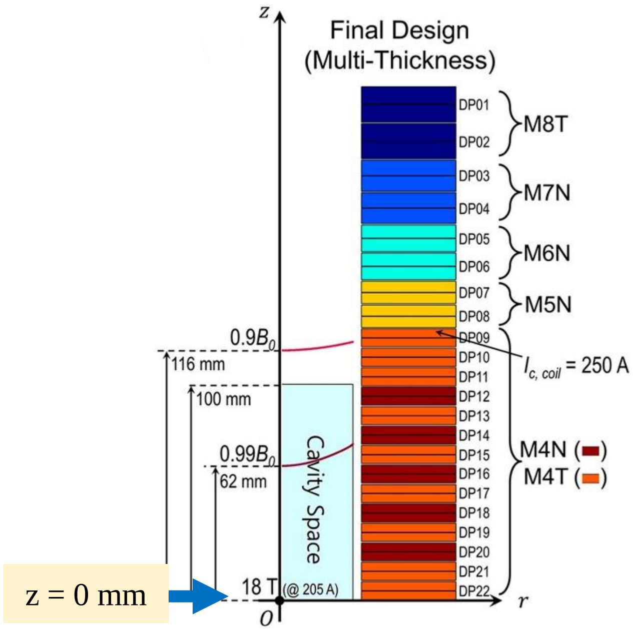
$$\text{where } T_{N,amp} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots$$

❖ CAPP18T: Detector



❖ 18T HTS Magnet





- A strong B-field and large bore HTS magnet is produced by SuNAM Co. Ltd. in Korea
- Magnetic field : 18 Tesla (21T Max. engineering design)
- Dimension
  - 70 mm ID (bore size)
  - 476 mm length
  - 200 mm uniform field (>90%)
- Multi-Thickness design for field uniformity
- Quench safe design (No-Insulation winding)

❖ Cryogenic System – Dilution Refrigerator

4 K Plate (IVC Top)

J.T. Plate

Still Plate

Still

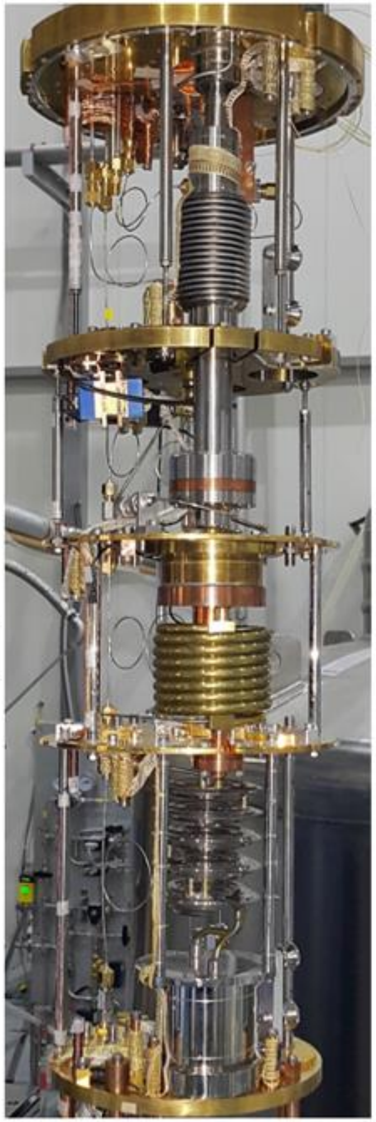
Tube-in-Tube H.Ex.

Cold Plate

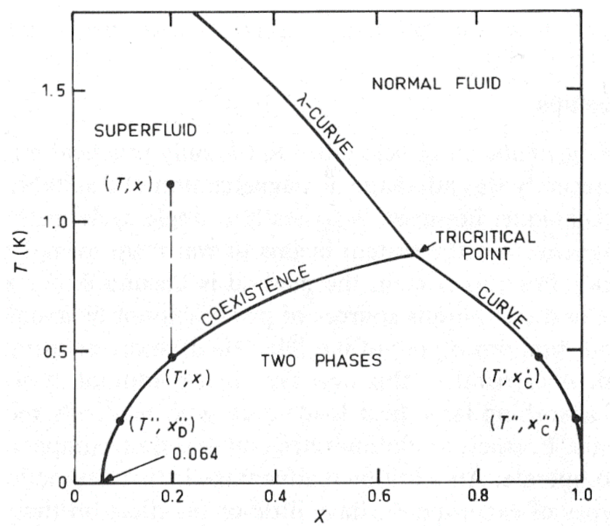
Step H.Ex.

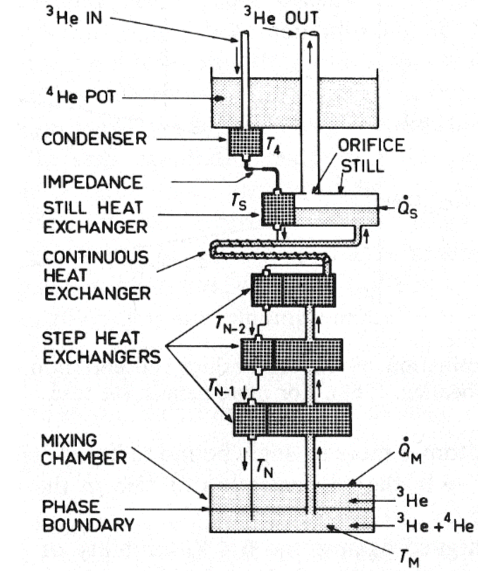
Mixing Chamber

M.C. Plate



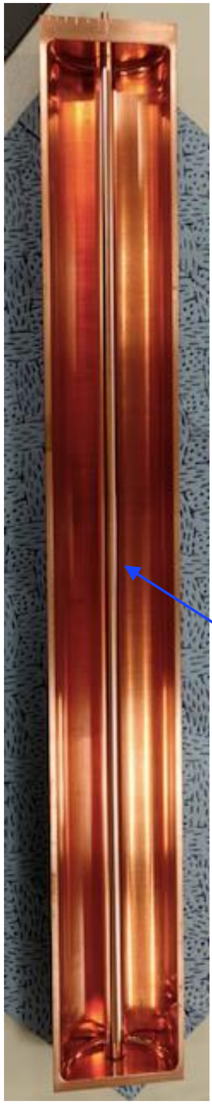
Oxford Kelvinox 400



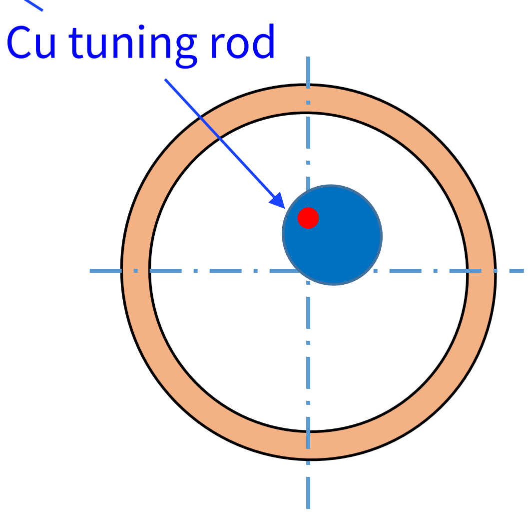


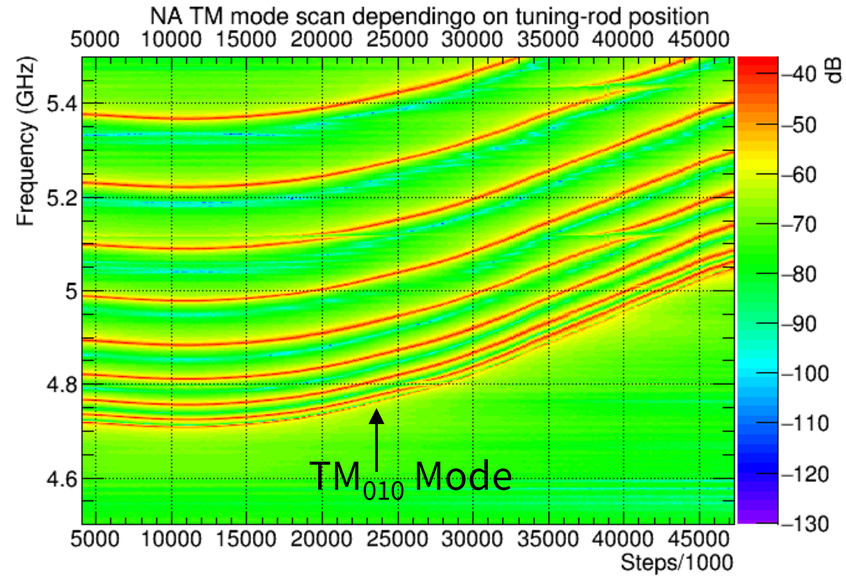
- DR is a cryogenic system can reach under 100 mK and also do a continuous operation.
- DR is suitable to the CAPP18T experiment using JPC, which operated under 1 K.
- Kelvinox 400
    - Cooling Power : > 400 μW at 100 mK
    - Base Temperature : < 30 mK

Cavity Resonance Measurement

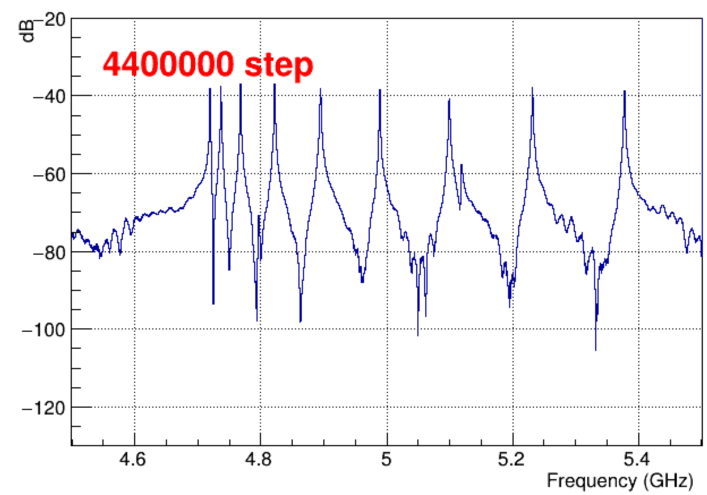


- Rotator is controlled by Kevlar wires connected to the step motors.
- The step motors are controlled by a LabVIEW based program.
- TM010 Mode is used to get large form factor.
- Cu tuning rod position determined by rotation around acentric axis (red dot).

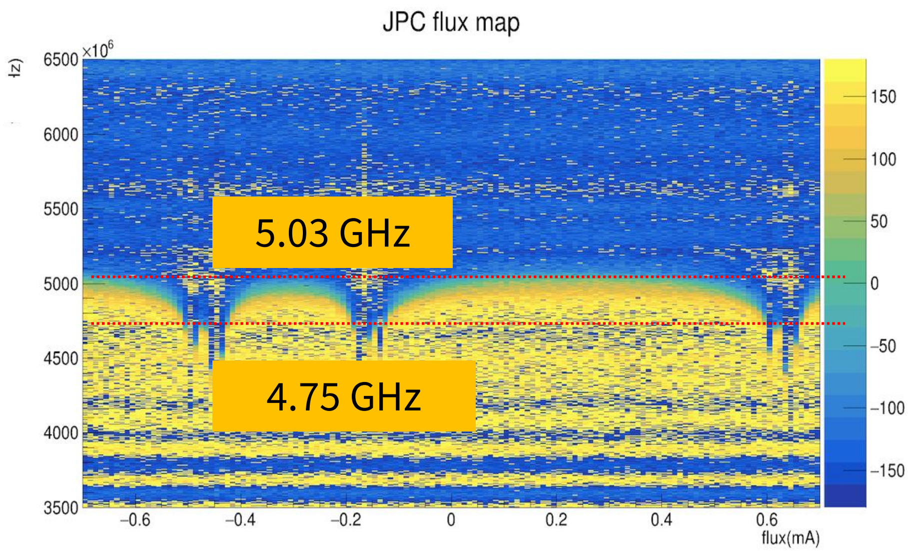


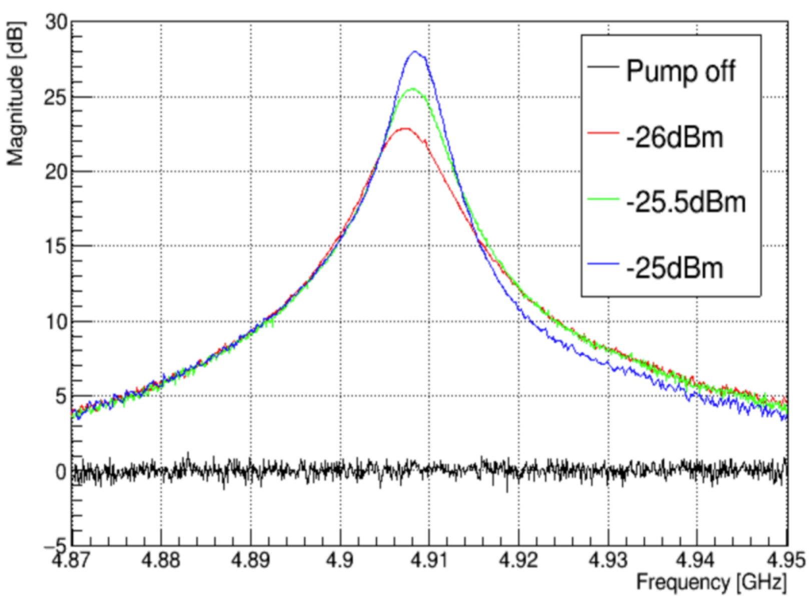


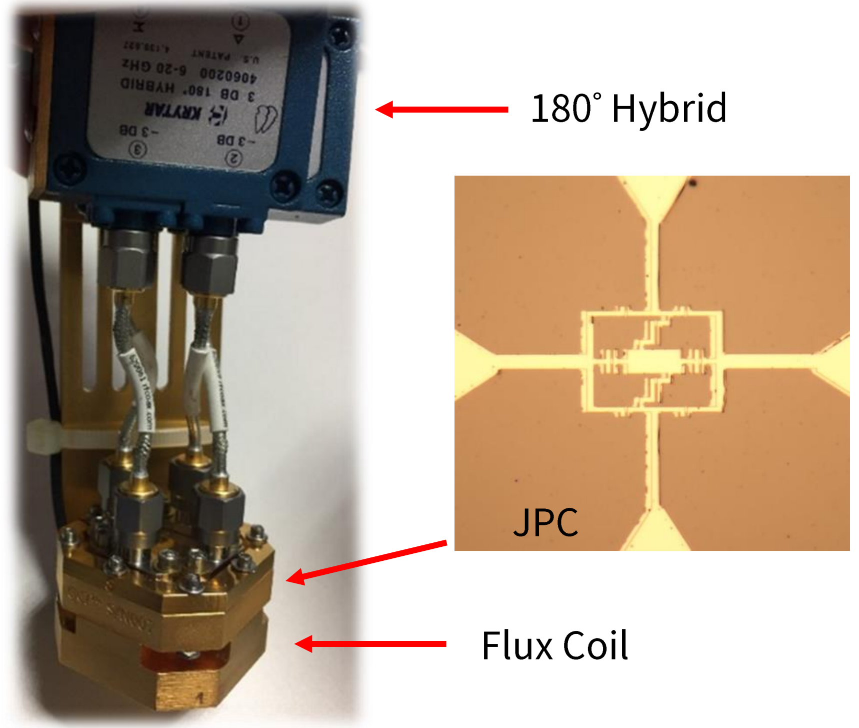
Cavity resonance peak vs. tuning rod position



❖ Josephson Parametric Converter





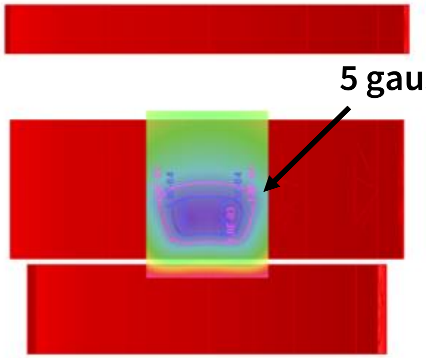


Gain(20 dB min)	f_{min} (GHz)	f_{max} (GHz)
Signal	7.720	8.802
Idler	4.757	5.01

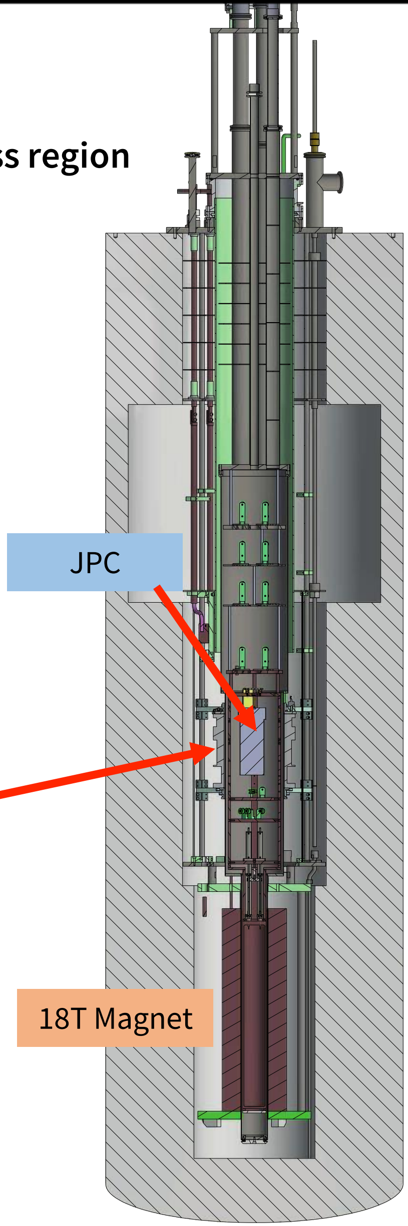
- ~ 25 dB Gain at proper pump power.
- 250 MHz Dynamic Bandwidth

$$T_{N,amp} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots$$

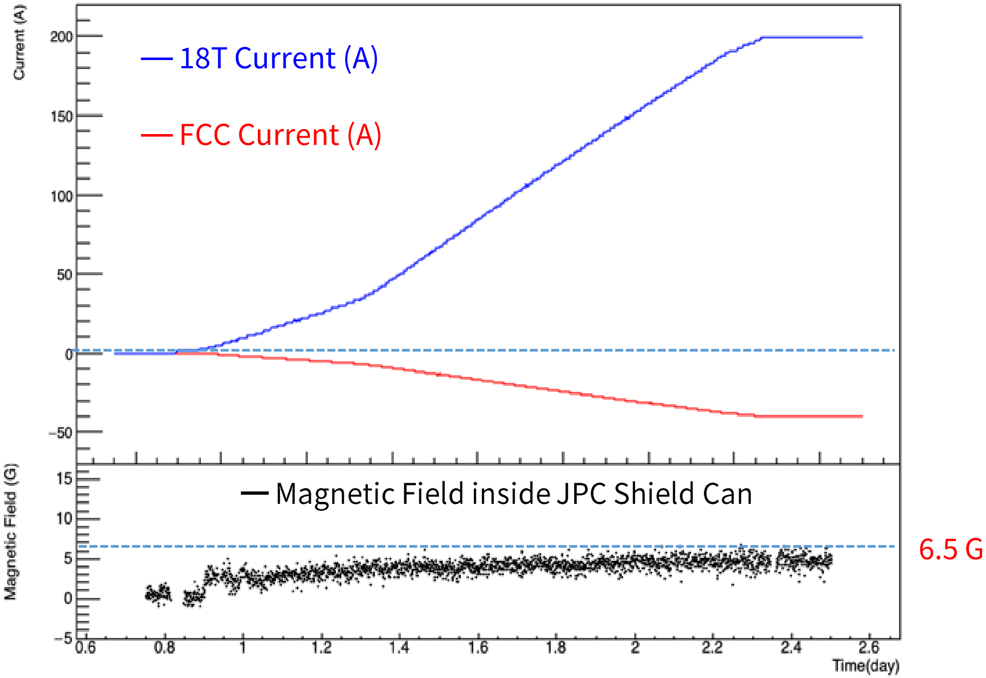
Field Cancellation Coil (FCC)



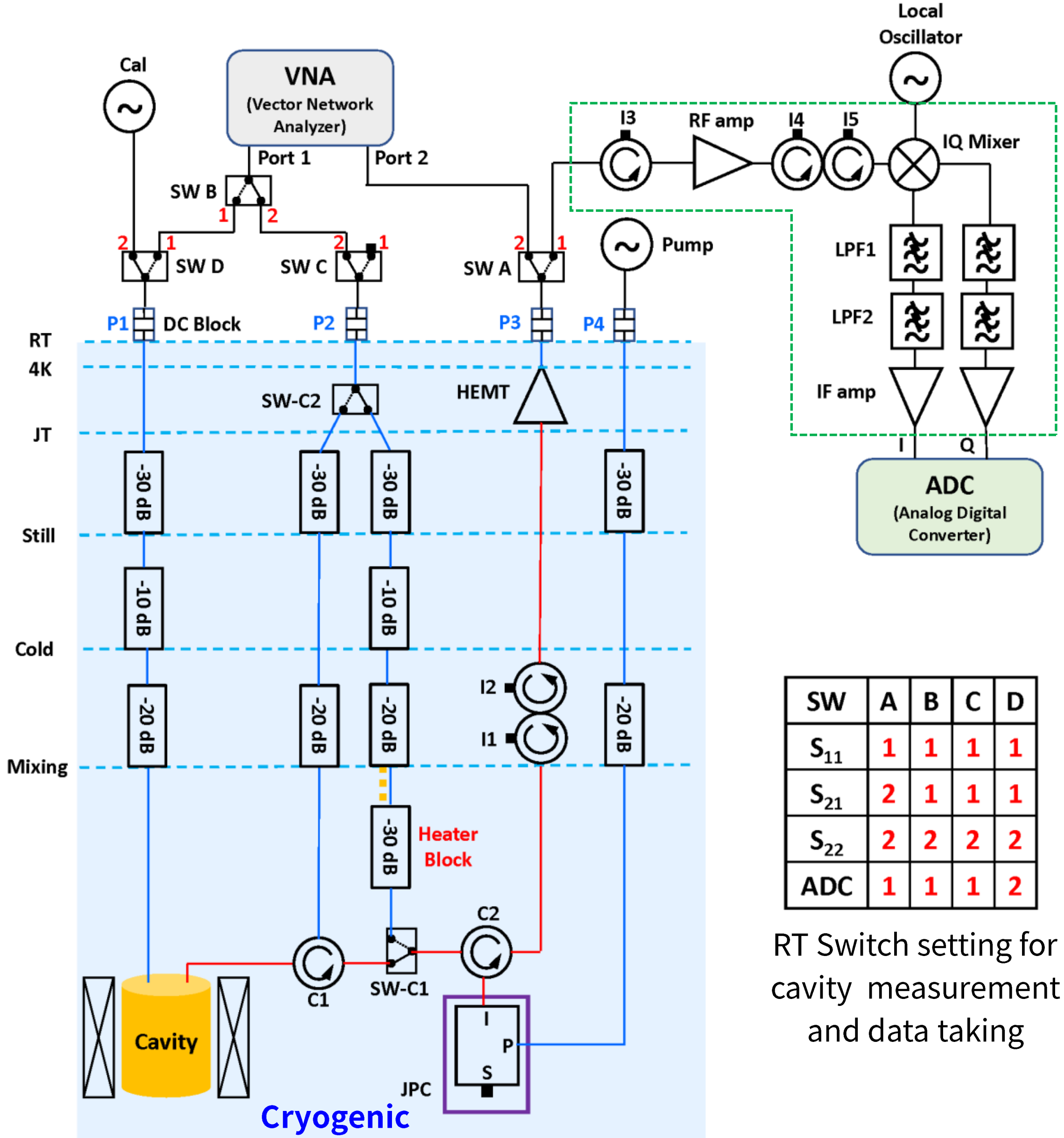
Field Cancellation Coil



- JPC should be worked in near zero field.
- FCC is installed to cancel out 18T magnet stray field at JPC location.
- Stary field cancellation - successful

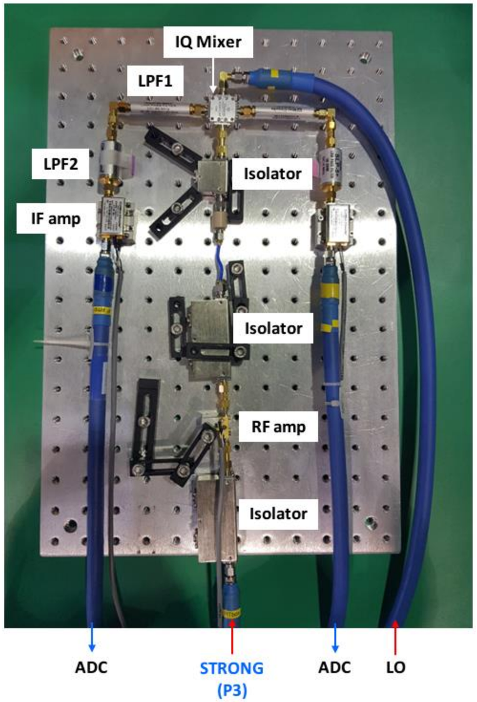


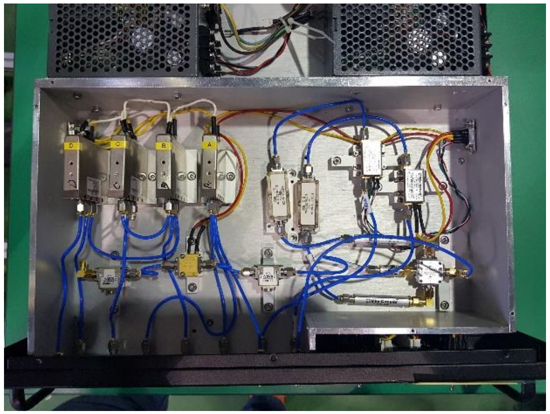
RF Chain



SW	A	B	C	D
S_{11}	1	1	1	1
S_{21}	2	1	1	1
S_{22}	2	2	2	2
ADC	1	1	1	2

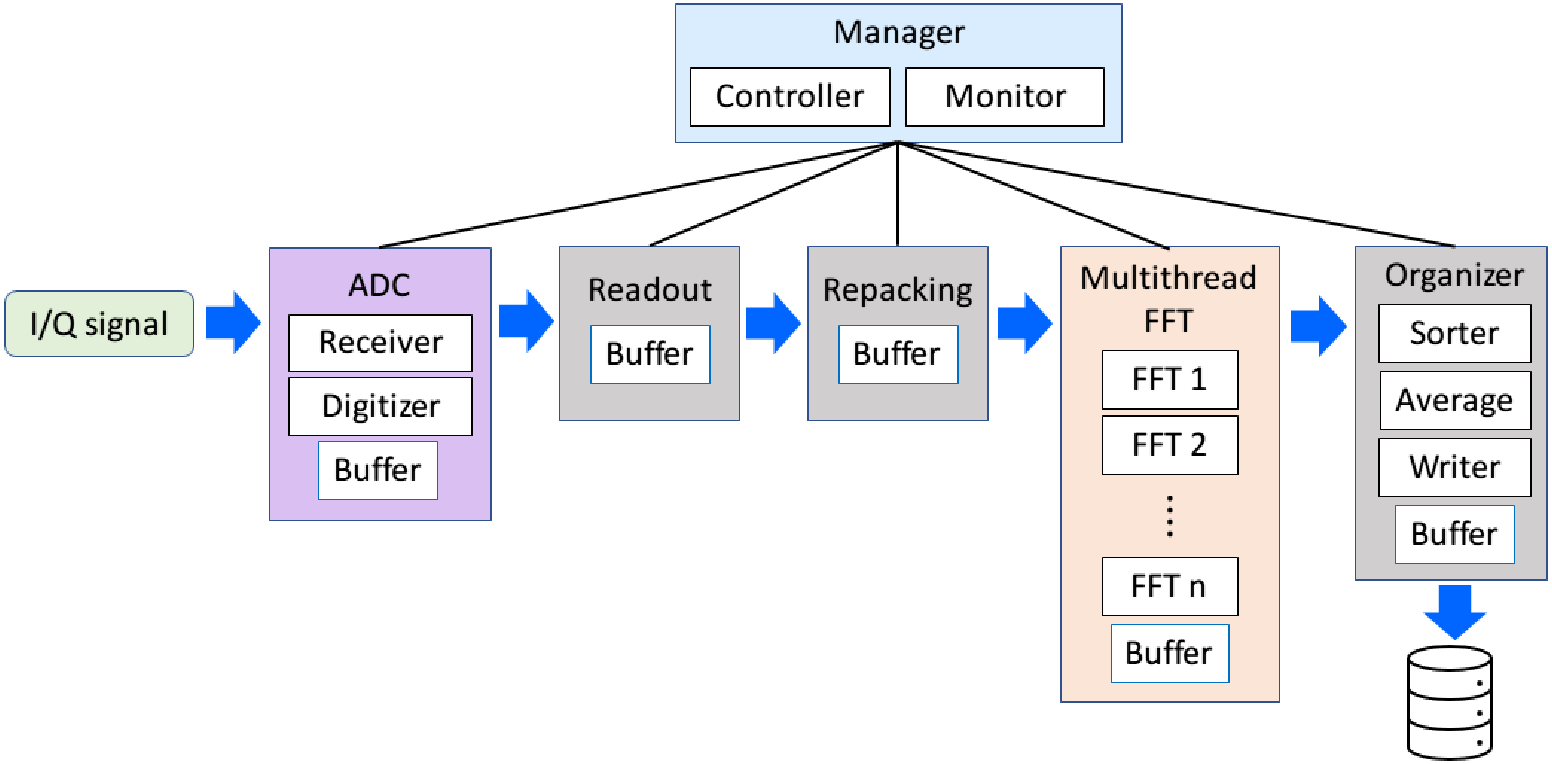
RT Switch setting for cavity measurement and data taking





Switch Box

❖ DAQ system



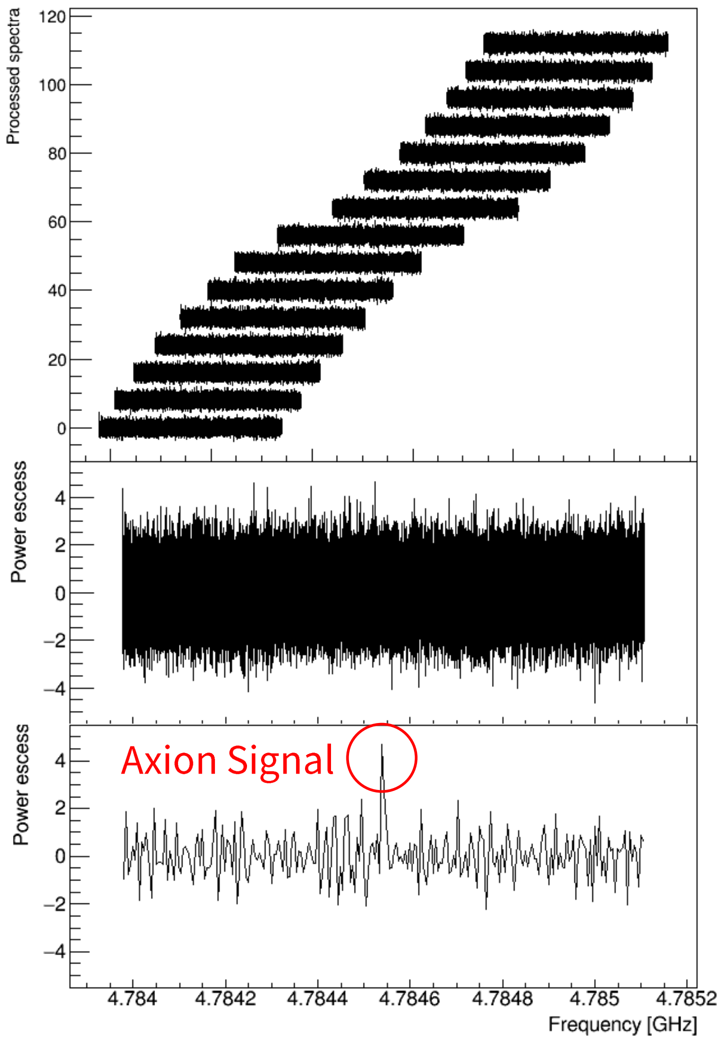
- Data taking using SA is one of the simplest way to get frequency domain data
- However, SA has about 50% of dead time, i.e. it cannot take data for a half of the live time
- We use an ADC board to make dead-time free DAQ system
- The ADC board is 14 bit, dual channel of Max. sampling rate of 400 MS/s
- Digitized time domain data are repacked and converted to the freq. domain data via multithread FFT

❖ Pilot Run & Run-1 – SRF Facility at RAON site

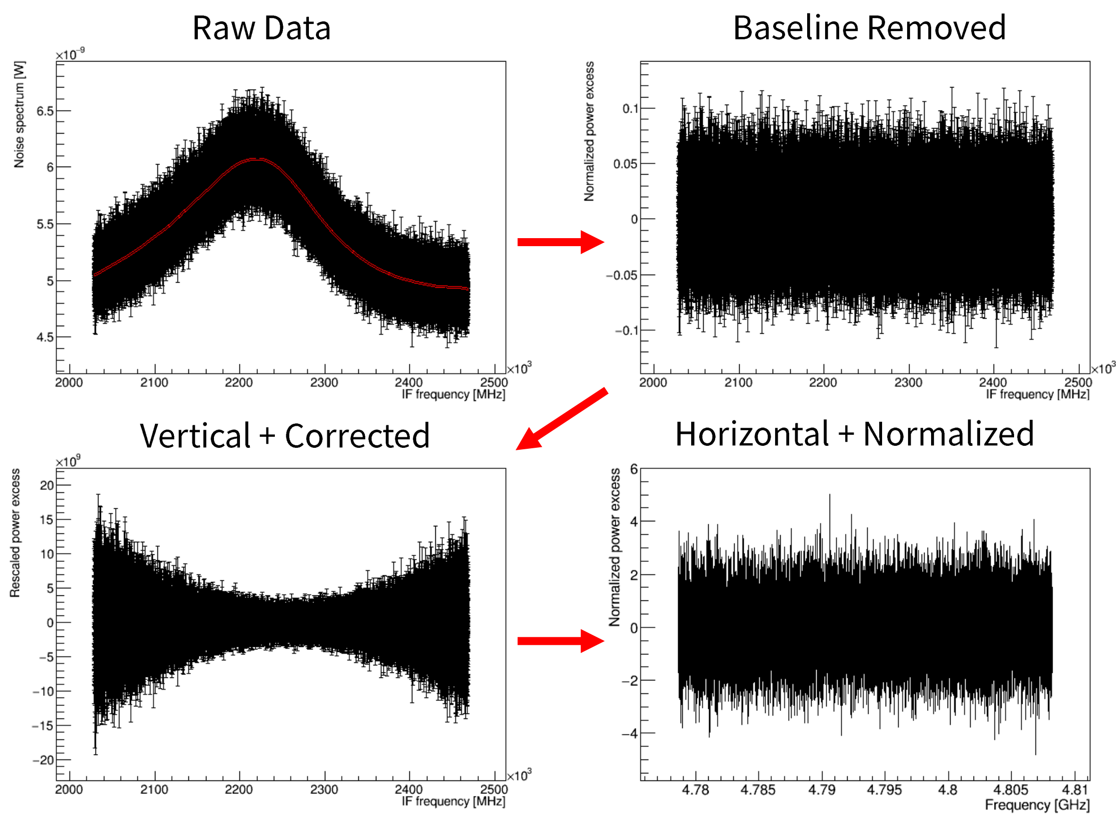
Linde L280 model : maximum condensing rate of 280 L/hour with total 8,000 L of LHe storage

- The pilot run & run-1 were performed at SRF facility in RAON site due to LHe liquefier.
- The cryostat was in the pit at SRF building.
- LHe recovered by the LHe liquefier : Linde L280 (280 L/hour, 8.000 L storage).

Data analysis

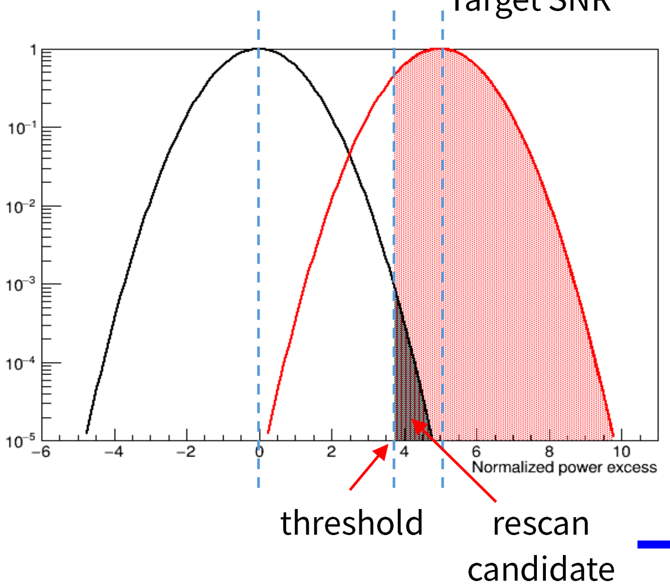


- Baseline removed using SG-filter
- Vertical combine : Weighted sum of spectra of same frequency
- Horizontal combine : Weighted sum of vertically combined spectra

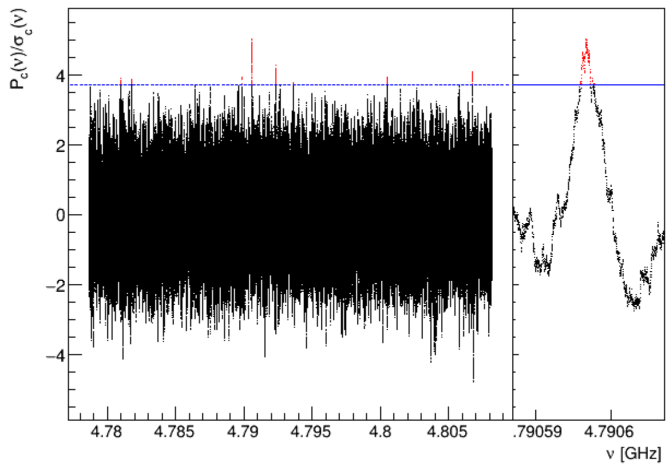


❖ Data Analysis

➢ Frequentist



- Find Axion Signal higher than target SNR
- Gray Shaded Region for Rescan Candidate
- If no axion signal found, set limit by the deviation of the grand power spectrum



➢ Bayesian

$$P(X|Y) = \frac{P(X)P(Y|X)}{P(Y)}$$

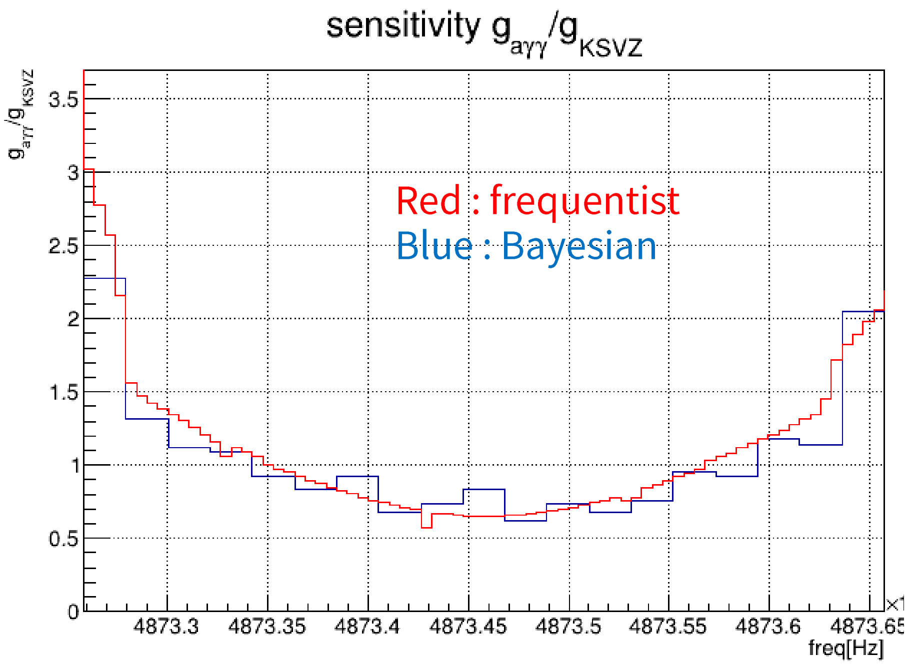
$$\frac{P_{exc}}{P_{KSVZ}} = \frac{g_{exc}^2}{g_{KSVZ}^2}$$

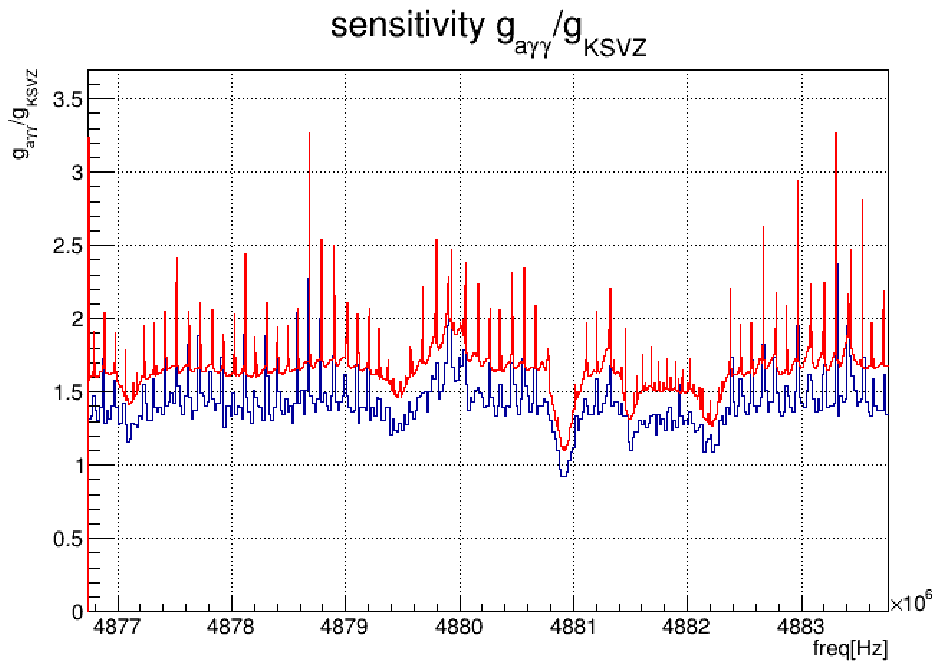
- Set the limit by the probability of rejecting of the existence of the axion
- Getting the updated probability for each data bin
- Set limit using the power excess of the grand power spectrum

❖ Pilot Run

- The Pilot Run to see the performance of CAPP18T System
- 2020-11-07 ~ 2020-11-09
  - 100 ms for each spectrum
- Deep Scan
  - 11-07 9:50 ~ 19:30 (9.76 hours)
  - T_{SYS} : 629 mK
  - Q : ~ 29,000
  - Target RF Freq. : 4.872509 GHz
  - Target IF Freq. : 1.3 MHz
  - Live Time : 6.80 Hours
  - Tuning Rod Fixed – Scan at a single frequency
- Shallow Scan
  - 11-07 22:22 ~ 11-09 21:37 (47.3 hours)
  - Scan with various RF frequency
  - T_{SYS} : 584 mK
  - Q : ~ 30,000 / Frequency Step : 100 kHz
  - Scan time for a frequency : ~ 10 min/step

❖ Result of the Pilot Run



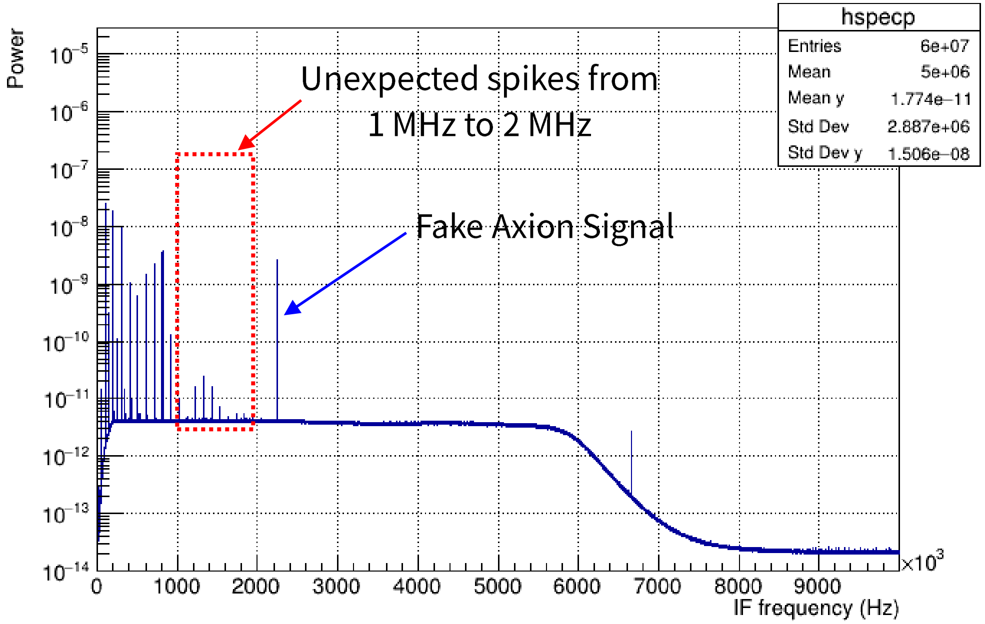


- Deep Scan
  ~ $0.7 \times |g_{KSVZ}|$ limit

- Shallow Scan
  ~ $1.5 \times |g_{KSVZ}|$ (Bayesian)
  ~ $1.7 \times |g_{KSVZ}|$ (Frequentist) limit

- Rescan did not carried out since the purpose of the pilot run is check the full performance of the CAPP18T with Magnet, DR and JPC.

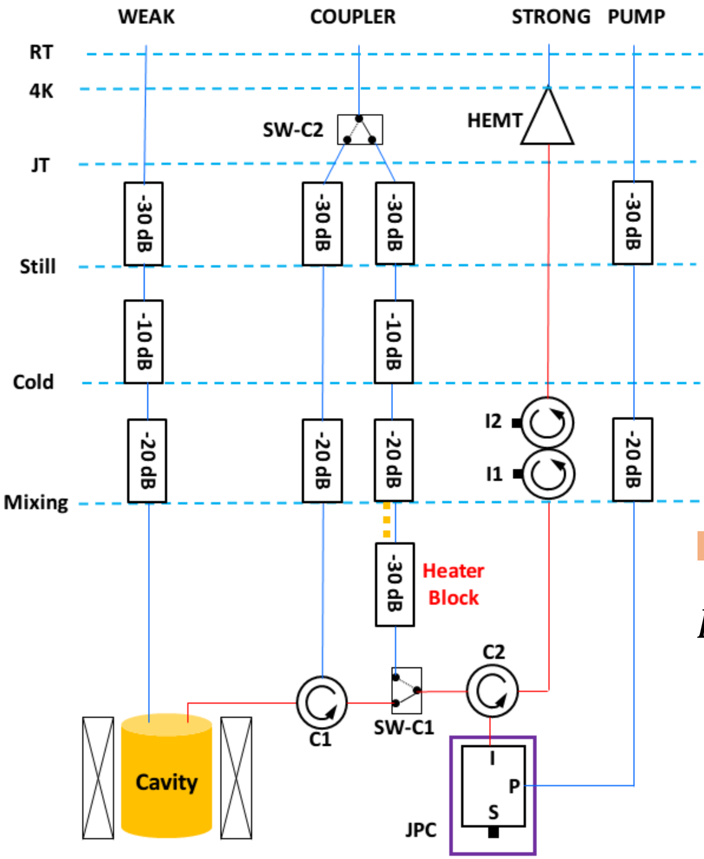
❖ Result – What to learn from the Pilot Run



- The main purpose of the pilot run is to check the scan speed of the fully assembled CAPP18T experiment setup.
- ADC showed unwanted spikes in the range of 1 MHz ~ 2 MHz
  → Target IF frequency changed from 1.3 MHz to 2.25 MHz.

- The noise temperature have to be measured during the run since it changes while data taking.
  → Change of the RF circuit to be able to do the SNRI measurement for system noise temperature.
- We estimate the proper scan time to reach the KSVZ limit for the data taking run
  → 0.7 KSVZ for 6.8 hours and 1.7 KSVZ for 10 min scan
  → Set the scan time as 6 hours for deep scan and 30 min for shallow scan

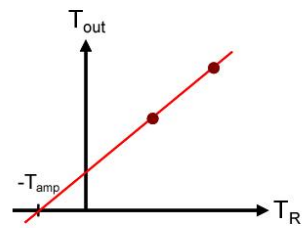
Update – System noise measure during data taking



Pilot Run

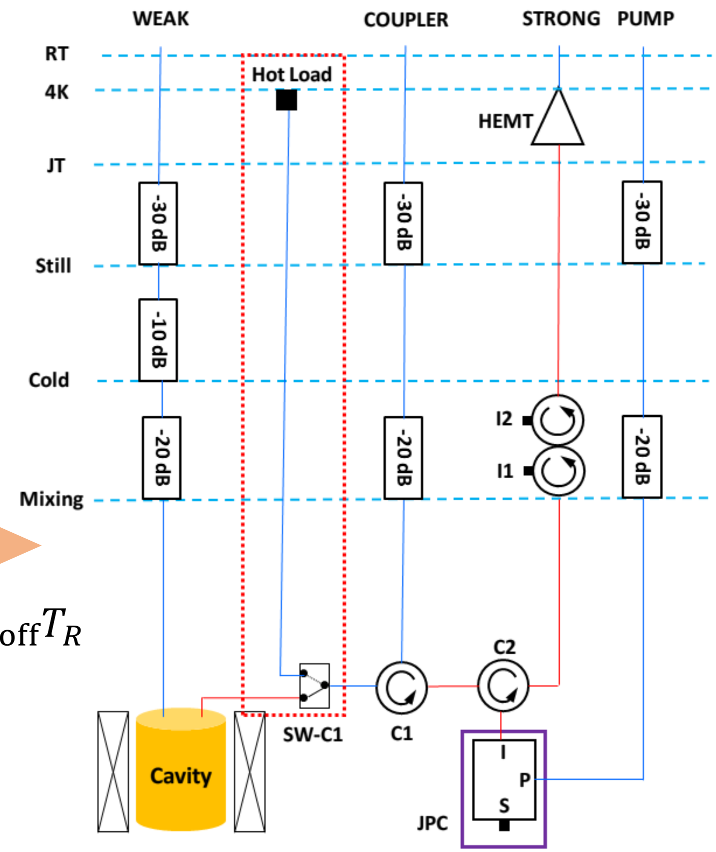
$$Y = \frac{P_H}{P_C} = \frac{T_H + T_A}{T_C + T_A}$$

$$T_A = \frac{T_H - YT_C}{Y - 1}$$



$$P_{\mathrm{on}} \propto G_{\mathrm{on}} T_S \qquad P_{\mathrm{off}} \propto G_{\mathrm{off}} T_R$$

$$T_S = \left[\frac{P_{\mathrm{on}}/G_{\mathrm{on}}}{P_{\mathrm{off}}/G_{\mathrm{off}}}\right] T_R = \frac{T_R}{\mathrm{SNRI}} = \frac{T_C + T_A}{\mathrm{SNRI}}$$



Data Taking Run

- The RF chain was changed to measure the system temperature as if no JPC were installed by Y-factor method, when LHe transfer.
- The Combination of the result of the Y-factor measurement and SNRI measurement of the JPC can give the system temperature.

❖ Data Taking Run – Run 1 / 1st Paper (Frequentist)

PHYSICAL REVIEW LETTERS **128,** 241805 (2022)

Searching for Invisible Axion Dark Matter with an 18 T Magnet Haloscope

Youngjae Lee,[1] Byeongsu Yang,[2] Hojin Yoon,[1] Moohyun Ahn,[3] Heejun Park,[2] Byeonghun Min,[2] DongLak Kim,[2] and Jonghee Yoo[1,2,3]

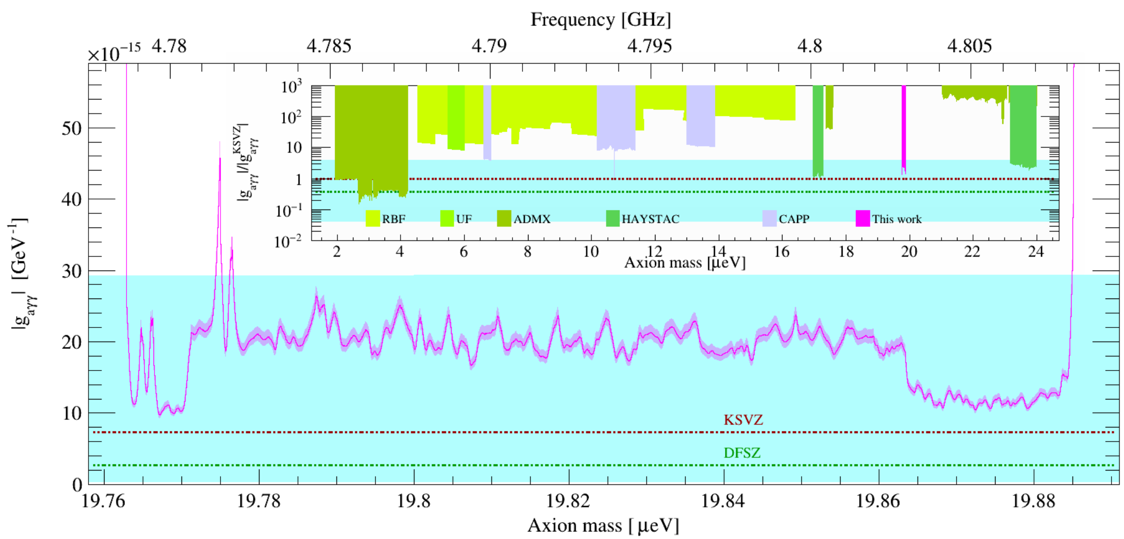
[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea*
[2]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Korea*
[3]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*

(Received 18 August 2021; revised 27 April 2022; accepted 19 May 2022; published 17 June 2022)

We report the first search results for axion dark matter using an 18 T high-temperature superconducting magnet haloscope. The scan frequency ranges from 4.7789 to 4.8094 GHz. No significant signal consistent with the Galactic halo dark matter axion is observed. The results set the best upper bound of axion-photon-photon coupling ($g_{a\gamma\gamma}$) in the mass ranges of 19.764 to 19.771 μeV (19.863 to 19.890 μeV) at $1.5 \times |g_{a\gamma\gamma}^{\mathrm{KSVZ}}|$ ($1.7 \times |g_{a\gamma\gamma}^{\mathrm{KSVZ}}|$), and 19.772 to 19.863 μeV at $2.7 \times |g_{a\gamma\gamma}^{\mathrm{KSVZ}}|$ with 90% confidence level, respectively. This remarkable sensitivity in the high mass region of dark matter axion is achieved by using the strongest magnetic field among the existing haloscope experiments and realizing a low-noise amplification of microwave signals using a Josephson parametric converter.

DOI: 10.1103/PhysRevLett.128.241805

- Run-1 : 2020-11-30 ~ 2020-12-24
- First CAPP18T Axion Search Paper
- Frequentist method applied
  ~ $1.5 \times |g_{KSVZ}|$ (Deep Scan)
  ~ $2.7 \times |g_{KSVZ}|$ (Shallow Scan)



❖ Data Taking Run – Run 1 / 2nd, Long Paper (Bayesian)

PHYSICAL REVIEW D **106**, 092007 (2022)

Axion haloscope using an 18 T high temperature superconducting magnet

Hojin Yoon,[1] Moohyun Ahn,[2] Byeongsu Yang,[2,3,†] Youngjae Lee,[1] DongLak Kim,[3]
Heejun Park,[3] Byeonghun Min,[3] and Jonghee Yoo[2,1,3,*]

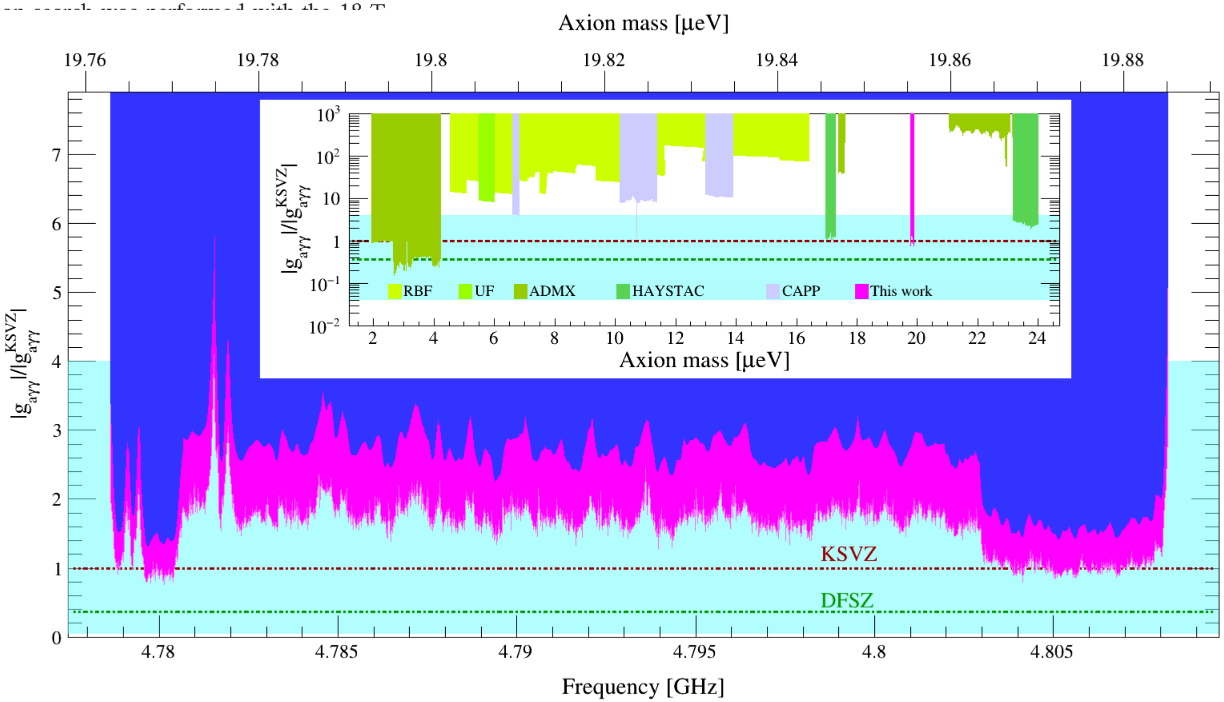
[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea*
[2]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*
[3]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Korea*

(Received 29 June 2022; accepted 17 October 2022; published 29 November 2022)

We report details on the axion dark matter search experiment that uses the new technologies of a high-temperature superconducting (HTS) magnet and a Josephson parametric converter (JPC). An 18 T HTS solenoid magnet is developed for this experiment. The JPC is used as the first stage amplifier to achieve a near quantum-limited low-noise condition. A first dark-matter ax… axion haloscope [Youngjae Lee *et al.*, Phys. Rev. Lett. **128**, 2418… from 4.7789 GHz to 4.8094 GHz (30.5 MHz range). No signific… matter axion is observed. Our results set the best limit of the axi… axion mass range of 19.764–19.890 μeV. Using the Bayesian me… $0.98 \times |g_{a\gamma\gamma}^{KSVZ}|$ ($1.11 \times |g_{a\gamma\gamma}^{KSVZ}|$) in the mass ranges of 19.764–19.… $1.76 \times |g_{a\gamma\gamma}^{KSVZ}|$ in the mass ranges of 19.772–19.863 μeV with … report design, construction, operation, and data analysis of the 1…

DOI: 10.1103/PhysRevD.106.092007

- Detailed Paper on the CAPP18T Axion Search Experiment
- Bayesian method applied
  - ~ $0.98 \times |g_{KSVZ}|$ (Deep Scan)
  - ~ $1.76 \times |g_{KSVZ}|$ (Shallow Scan)

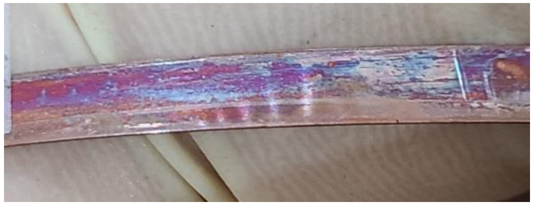


❖ Magnet Quench

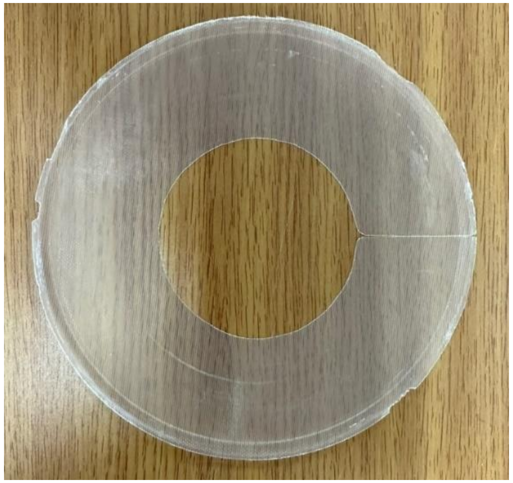
- We experienced the magnet quench just after data taking run-1 during magnet ramp down.

- Damages from magnet Quench
    - Boil off of LHe made severe mechanical vibration
    - Mechanical Vibration caused damages to HTS tapes and G-10 insulators
    - Rapid change of the magnetic field made the cavity bent
    - Magnet was repaired by the manufacturer

- System reassembled after magnet repair
    - Structures under the mixing plate were modified.
    - Thermal Contact was improved
    - Impedance matchings of the RF chain were also improved.



Damaged HTS Tape



Damaged G-10 insulator

Bent Cavity

❖ Data Taking Run – Run 2

Extended Axion Dark Matter Search Using the CAPP18T Haloscope

Hojin Yoon,[1] Byeongsu Yang,[2] Youngjae Lee,[1] Moohyun Ahn,[2] and Jonghee Yoo[2,1,3]
[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon, 34141, Korea*
[2]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*
[3]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon, 34051, Korea*
(Dated: March 9, 2023)

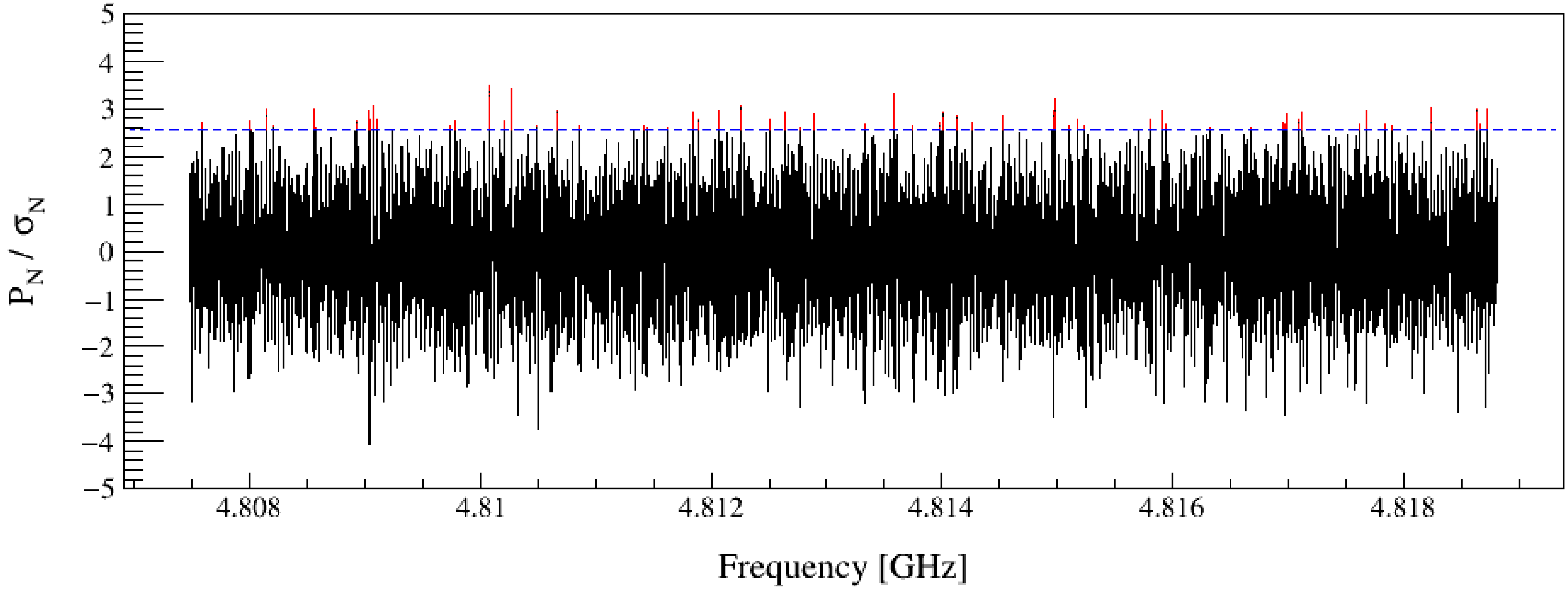
We report an extended search for the axion dark matter using the CAPP18T haloscope. The CAPP18T experiment adopts innovative technologies of a High-Temperature Superconducting (HTS) magnet and a Josephson Parametric Converter. The CAPP18T detector was reconstructed after an unexpected incident of the HTS magnet quenching. The system reconstruction includes rebuilding the magnet, improving the impedance matching in the microwave chain, and mechanically readjusting the tuning rod to the cavity for improved thermal contact. The total system noise temperature is ∼0.6 K. The coupling between the cavity and the strong antenna is maintained at $\beta \simeq 2$ to enhance the axion search scanning speed. The scan frequency range is from 4.8077 to 4.8181 GHz. No significant indication of the axion dark matter signature is observed. The results set the best upper bound of the axion-photon-photon coupling ($g_{a\gamma\gamma}$) in the mass ranges of 19.883 to 19.926 μeV at $\sim 0.7\times|g_{a\gamma\gamma}^{\rm KSVZ}|$ or $\sim 1.9\times|g_{a\gamma\gamma}^{\rm DFSZ}|$ with 90 % confidence level. The results demonstrate that a reliable search of the high-mass dark matter axions can be achieved beyond the benchmark models using the technology adopted in CAPP18T.

Axions are hypothetical particles introduced to solve the Strong CP problem. The axions may have been non-

damaged during the incident, while other detector parts were intact. The haloscope was completely dismantled

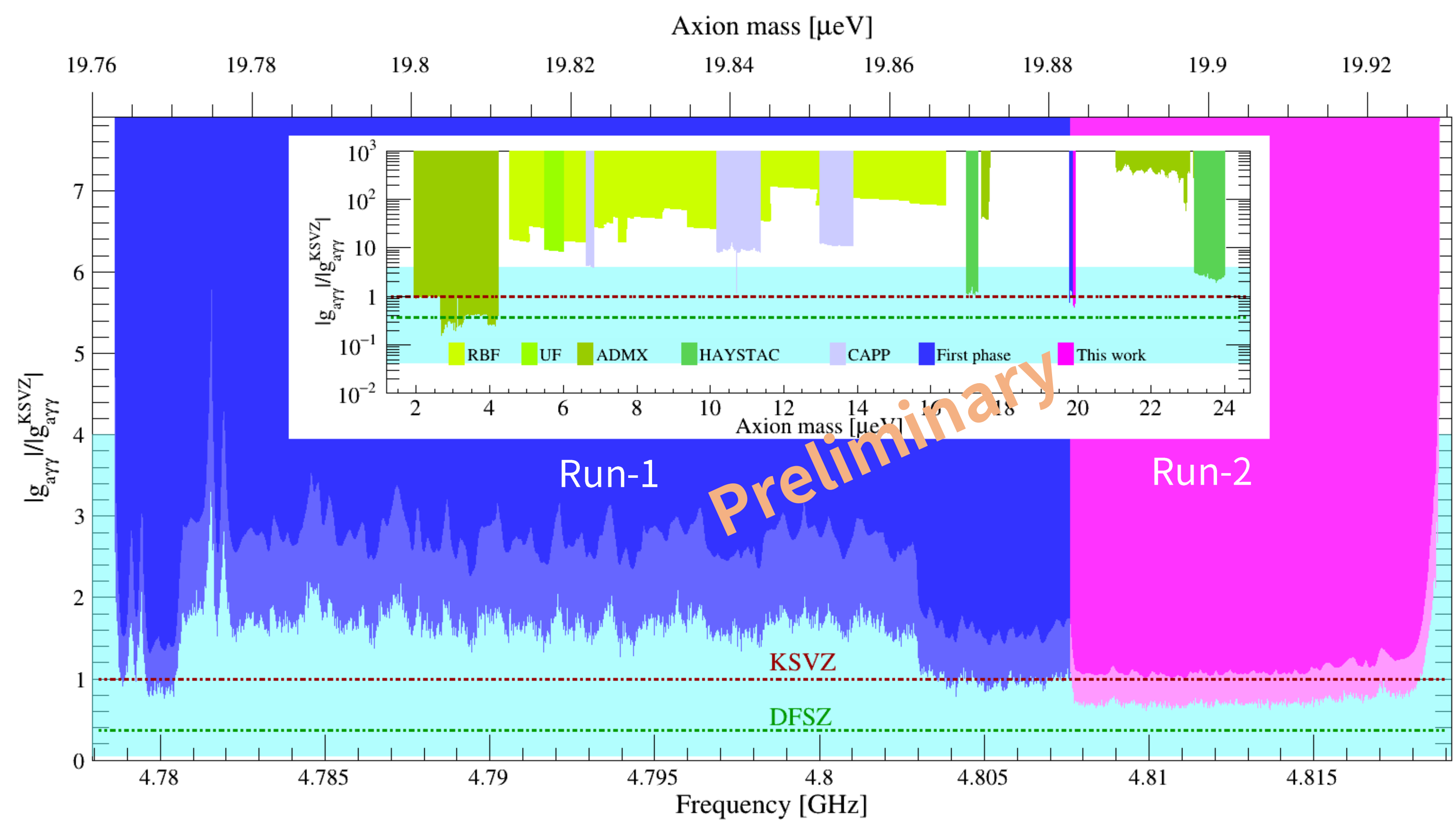
- 2021-06-03 ~ 2021-08-17
  - Target IF freq. : 2.25 MHz
  - Q : ~ 14,300 / Step : 200 kHz
  - Set β =2 to get optimal scan speed
  - Step set to 200 kHz due to lower loaded Q

❖ Data Taking Run – Rescan



- Rescan were performed after the run-2
- Rescan included some rescan candidates of the run-1.
- Rescan threshold set by Bayesian method – The rescan candidates are not different from ones by the frequentist method.
- No Axion Signal was found.

❖ Data Taking Run



- Scan Time for a Step : ~ 12 hours
- T_{SYS} : ~ 540 mK
- Reached at ~ $0.7 \times |g_{KSVZ}|$ limit

❖ Summary

- The pilot run of the CAPP18T axion dark matter was performed.

- The performance of the 18T magnet, FCC, and JPC were tested.

- From data taking runs, problems appeared in the pilot were fixed
  - Change target IF frequency
  - Noise temperature measurement during the runs using SNRI and Y-factor methods
  - Some improvements of thermal contact and impedance matching of RF chain

- CAPP18T experiment is the first axion haloscope using 2G HTS magnet.

Back up

❖ Axion

- U(1)$_A$ problem
  - QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_a^{\mu\nu} G_{a\mu\nu} - \bar{q}_f (i\gamma^\mu D_\mu + m_f) q_f$$

possesses a global symmetry in the limit $m_f \rightarrow 0$ regarding the u and d quarks, the theory shows a symmetry under U(2)$_V$×U(2)$_A$.

  - U(2)$_V$= SU(2) ×U(1) → nucleon doublet and pion triplet in hadron spectrum
  - U(2)$_A$, quark condenation → breaking symmetry to SU(2)$_A$ ×U(1)$_A$
    - Expect 4 Nambu-Goldstone bosons
      → 3 pions, but no 4th, U(1)$_A$ pseudoscalar boson was observed.

U(1)$_A$ problem !

- QCD vacuum as a solution of U(1)$_A$ problem
  - A possible resolution of the U(1)$_A$ problem seems to be provided by the chiral anomaly for axial currents.
  - t'Hooft : QCD vacuum structure is non-trivial → $|\Theta\rangle = \sum_n e^{in\Theta}|n\rangle$
  - The extra added term in QCD Lagrangian

$$\mathcal{L}_{QCD}^{eff} = \mathcal{L}_{QCD} + \bar{\Theta}\frac{g^2}{32\pi} G_a^{\mu\nu}\tilde{G}_{a\mu\nu}$$

violates CP, where $\bar{\Theta} = \Theta + Arg(\det M)$.

❖ Axion

➢ CP violation and Neutron EDM

- Neutron has magnetic moment : μ
- Neutron EDM

$$d_n \simeq \frac{e \cdot m_q}{m_N^2} \overline{\Theta}$$

- Non-zero EDM violate CP invariance. It estimated as

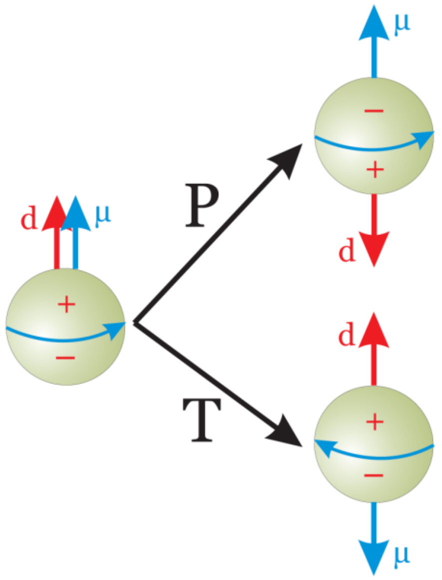
$$d_n \sim 10^{-16} \overline{\Theta} \text{ e cm}$$

- The EDM of neutron has a strong experimental bound

$$|d_n| \leq 10^{-25} \text{ e cm}$$

$$\Rightarrow \overline{\Theta} < 10^{-9}$$

- Extreme fine-tuning of $\overline{\Theta}$ to the value of $Arg(\det M)$



Why the $\overline{\Theta}$ is so small ?

➜ The Strong CP Problem

❖ Peccei-Quinn Model

- Peccei-Quinn Model

  - Introduce an additional, global chiral U(1) symmetry ($U(1)_{PQ}$)

$$\mathcal{L}_{total} = \mathcal{L}_{SM} + \bar{\Theta}\frac{g^2}{32\pi}G_a^{\mu\nu}\tilde{G}_{a\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a + \mathcal{L}_{int} + \xi\frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

  - Broken spontaneously at the PQ scale f_a

  - Corresponding pseudo-Nambu-Goldstone boson is the axion couples to gluons such that the chiral anomaly in the $U(1)_{PQ}$ current is reproduced

$$\partial_\mu J^\mu_{PQ} = \xi\frac{g_s^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

  - Coefficient of the CP violating $G\tilde{G}$ term becomes dynamical vanishes for the value $\langle a\rangle = -\bar{\Theta}f_a/\xi$ at which V_{eff} has its minimum.

Solves the strong CP problem

❖ Invisible Axion

- Invisible Axion
  - The original axion model of weak scale was ruled out by experiments.
  - f_a need not to be weak scale to solve the strong CP problem.
  - If $f_a \gg v_F$, then the axion is very light, very weakly coupled and very long lived, and such axion is called invisible axion.
  - These models introduce field which carry PQ charge but are $\mathrm{SU(2)} \times \mathrm{U(1)}$ singlets.
  - **KSVZ** Model (**K**im(1979) and **S**hifman,**V**ainshtein,**Z**akharov(1980)) or Hadronic Model
    - A extra heavy quark Q, and a scalar field Φ carry PQ charge.
  - **DFSZ** Model (**D**ine,**F**ischler,**S**rednicki(1981), and **Z**hitnitskii(1980))
    - Two Higgs doublets, and a scalar field Φ, which carry PQ charge.

❖ Axion DM detector : Axion Haloscope

Assume: $m_a \simeq \mu eV$

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

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

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

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

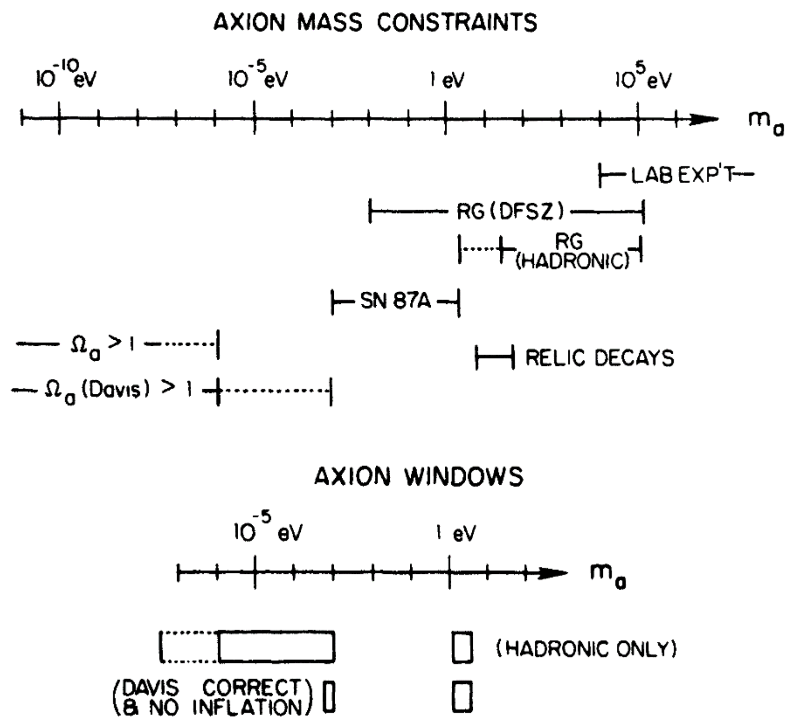
$$\mathcal{L} \equiv -\frac{1}{4} g a F\tilde{F} \approx \frac{\alpha}{8\pi f_{PQ}} a F\tilde{F}$$

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

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

Oscillating source current ➜ RF photons

RF photon frequency = axion mass



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

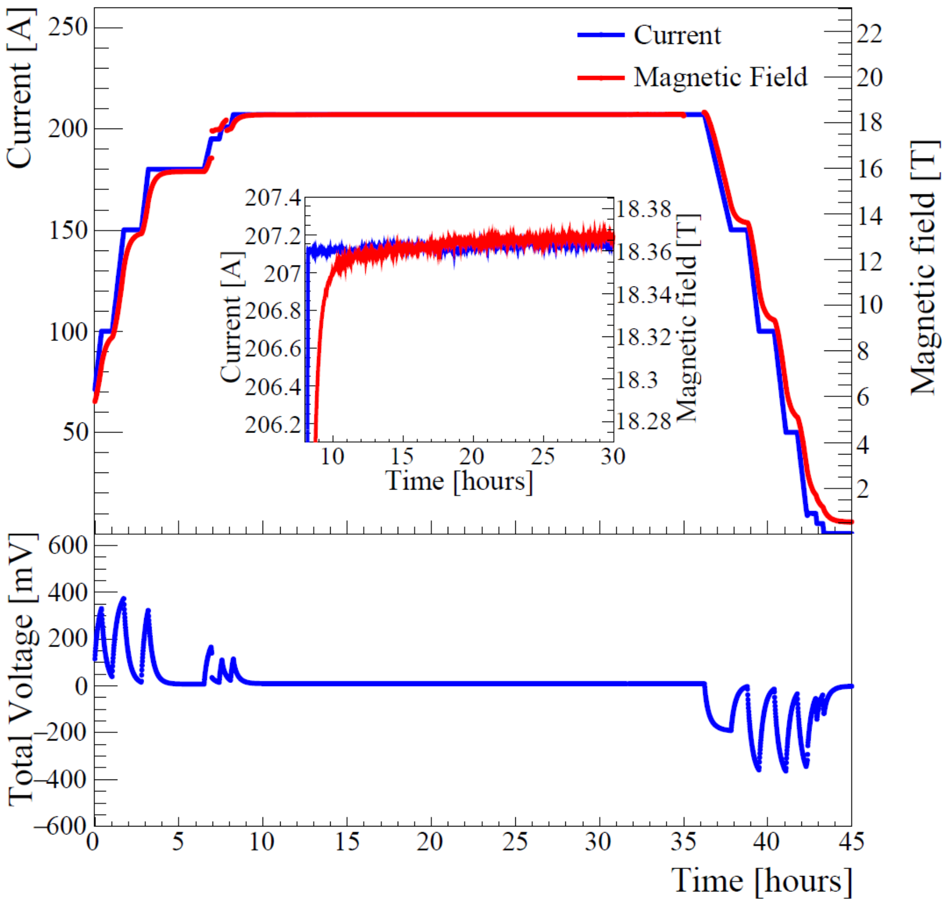
~ 10^{-21}W at m_a=μeV

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

Too low. Very difficult to detect!

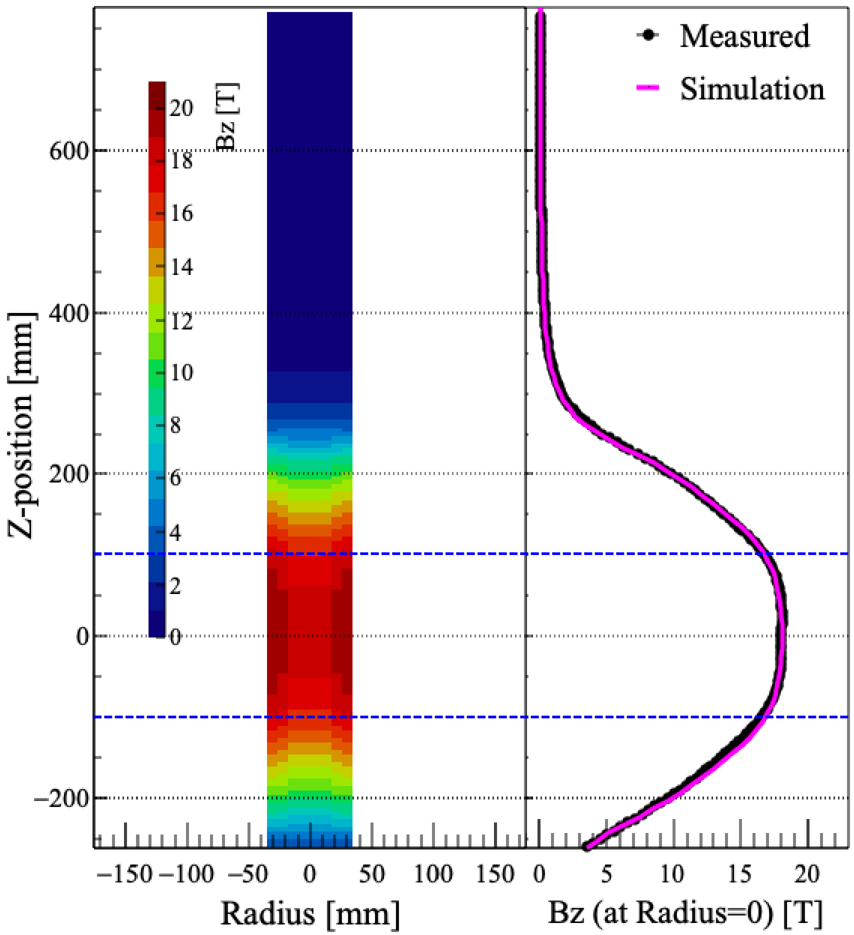
❖ 18T HTS Magnet Performance

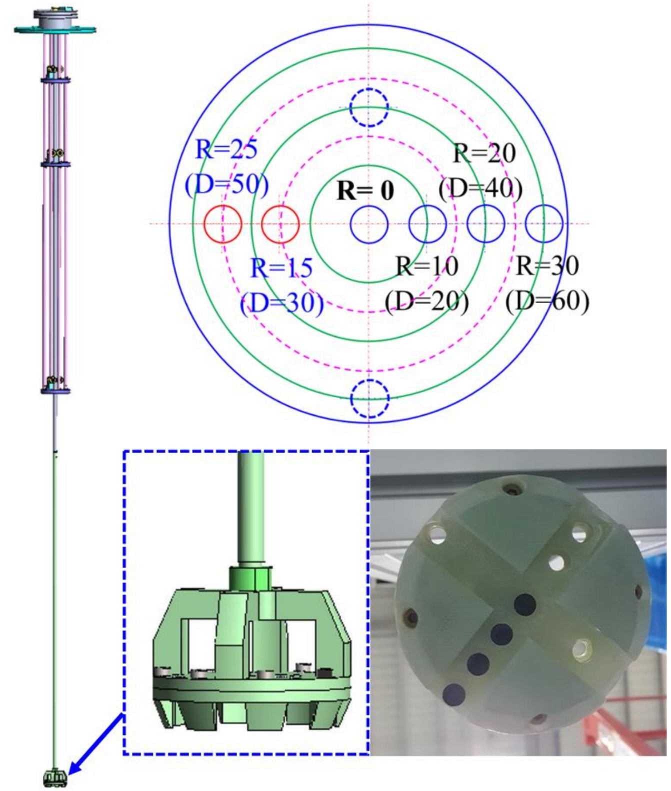
➢ 18T magnet performance



- Show expected performance
- Stable magnetic filed during the test period
- About 2 hours of saturation time to get a target field after current reached at target value does not matter to CAPP18T haloscope experiment.
- LHe consumption rate
  - during the Magnet Charging
    : ~140 L/day
  - during Stable Operation
    : ~120 L/day

18T HTS Magnet Performance





- Field mapping was done to find out the field profile of the 18T magnet.
- The field profile of the 18T magnet was same as expected.
- Field Uniformity as expected. (> 90% for 200 mm)

CAPP18T: DR Insert

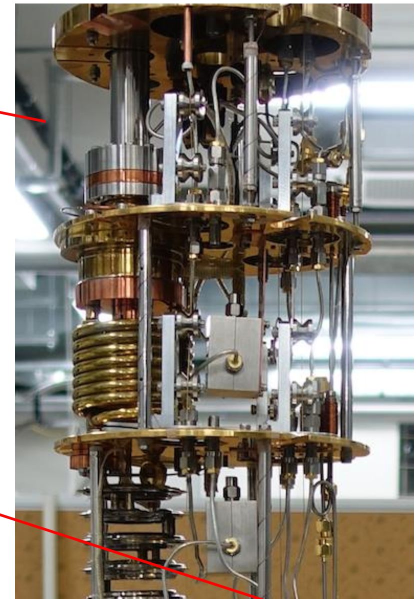
Cavity & rod

Step motors

Tuning-rod and antennas control

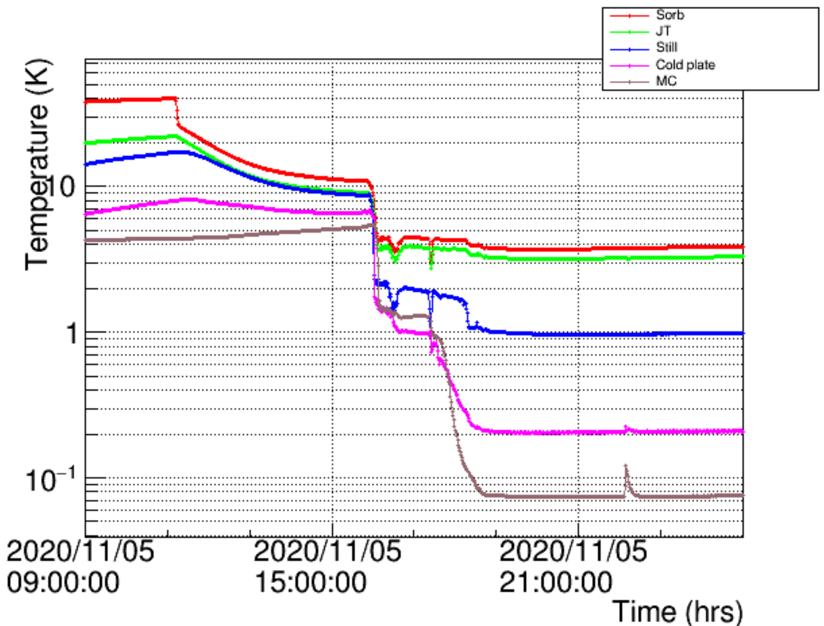
DR insert

RF components

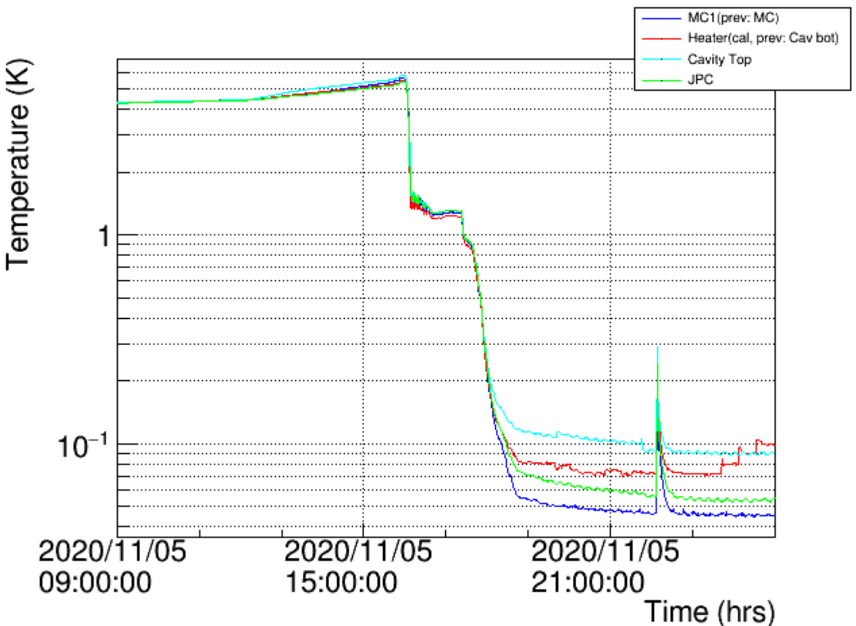


JPC on DR unit

❖ Cryogenic System – Dilution Refrigerator



Temperatures of DR stages



Temperatures of System

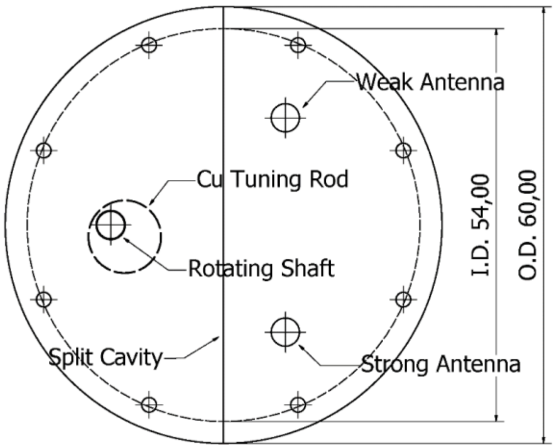
- Our DR system can cool down the system under 100 mK.
- DR is the only cryogenic system to get temperature range to operate the JPC. (< 1 K)
- DR also achieved the low physical temperature

❖ Cavity & Tuning System

Step Motor

Rotator Pulley

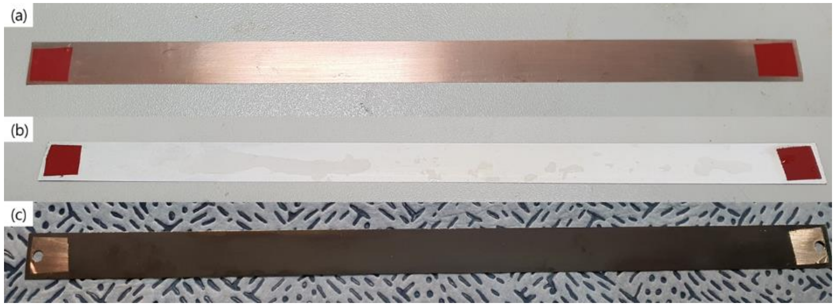
Antenna Control

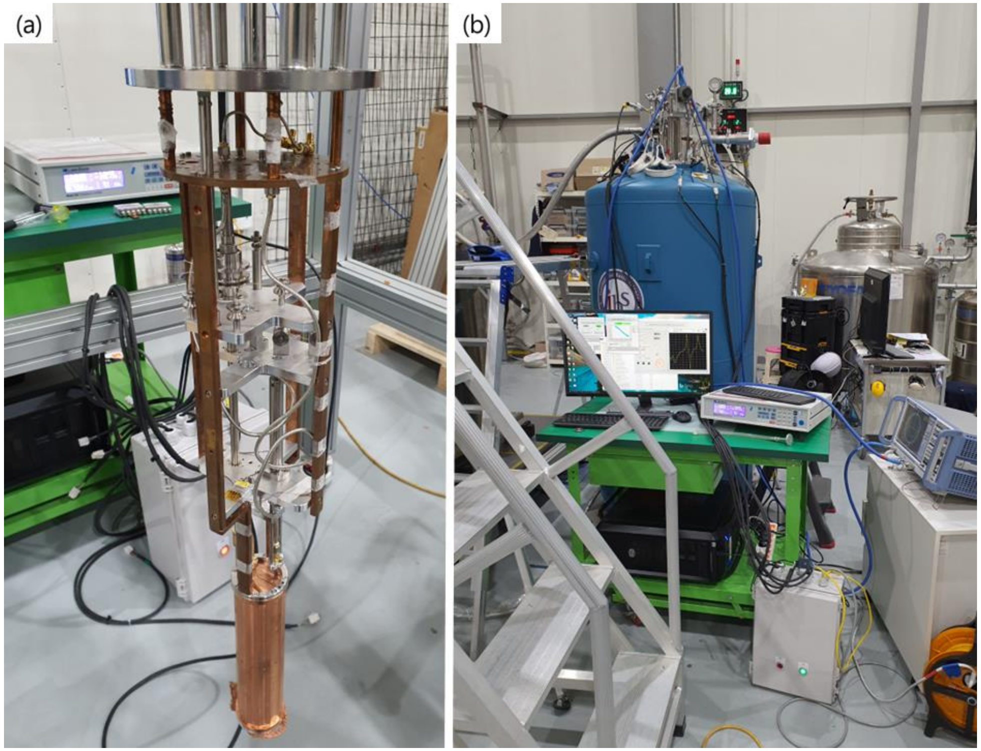


Drawing of Cavity Top

- Cavity was fabricated with OFHC copper to get higher Q-factor as possible.
- Vertical split design to reduce the eddy current when magnet ramp up and to get higher Q-factor
- Length : 466.6 mm (Inside) / 481.6 mm (Outside)
- O.D. : 60 mm / I.D. : 54 mm
- Tuning Rod made of OFHC copper of 10 mm
- Rotating Shaft installed at 2.5 mm off-center from the rod center

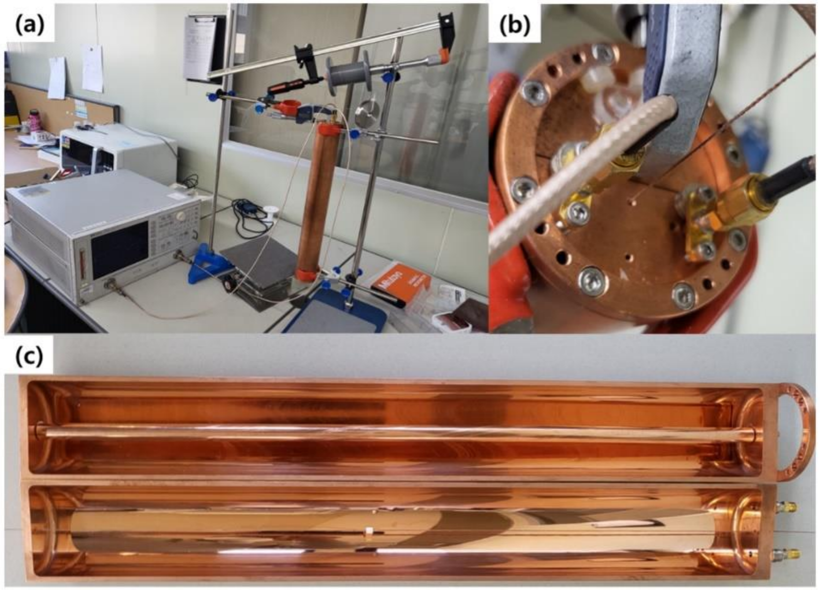
❖ Dodecahedral Superconducting Cavity





- Test to make the superconducting cavity.
- Etch out the protection layers of the HTS tape (GdBCO, same tape of 18T magnet)
- Etched using Nitric acid (Cu), Hydrogen Peroxide + Ammonia (Ag)
- The results are not consistent.

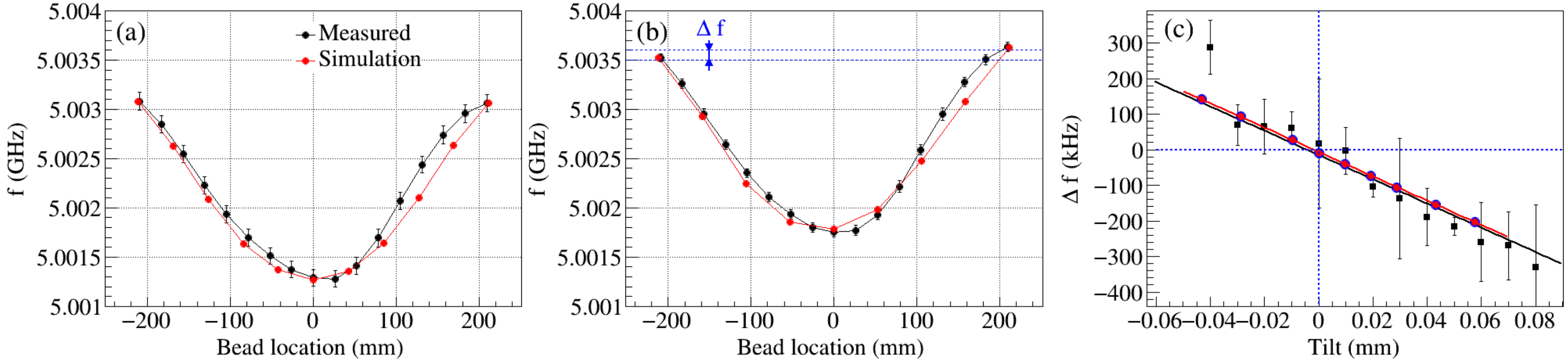
❖ Cavity – Form Factor / Bead Perturbation Test



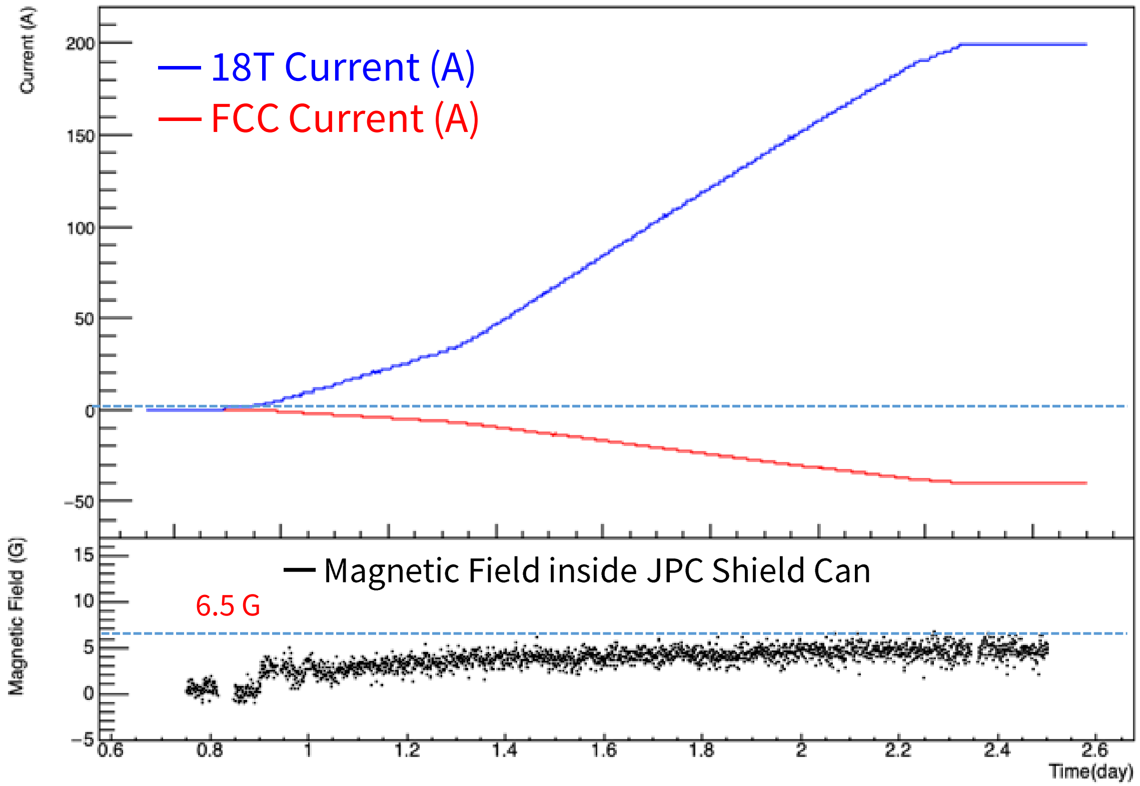
- Form factor

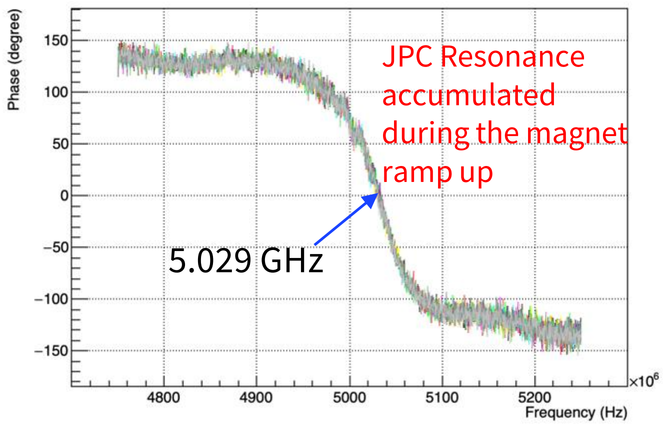
$$C_{nlm} = \frac{\left(\int d^3\mathbf{x}\, \hat{\mathbf{z}} \cdot e^*_{nlm}(\mathbf{x})\right)^2}{V \int d^3\mathbf{x}\, \epsilon(\mathbf{x})\, |e_{nlm}(\mathbf{x})|^2}$$

  - Form factor estimated by simulation
  - Bead perturbation measurement done to check the validity of the simulations.



Dynamic Field Cancellation





JPC phase response during 18T magnet ramp up (16 measurements overlapped)

- To operate JPC, the stray filed should be kept very low level.
- To do this, FCC must be ramped up with 18T magnet ramping up.
- JPC phase checked during the ramp up – almost not chamged

System noise measure

$$P_{noise} = Gk_BT_{SYS}B = G_{JPC}G'\,k_BT_{SYS}B$$

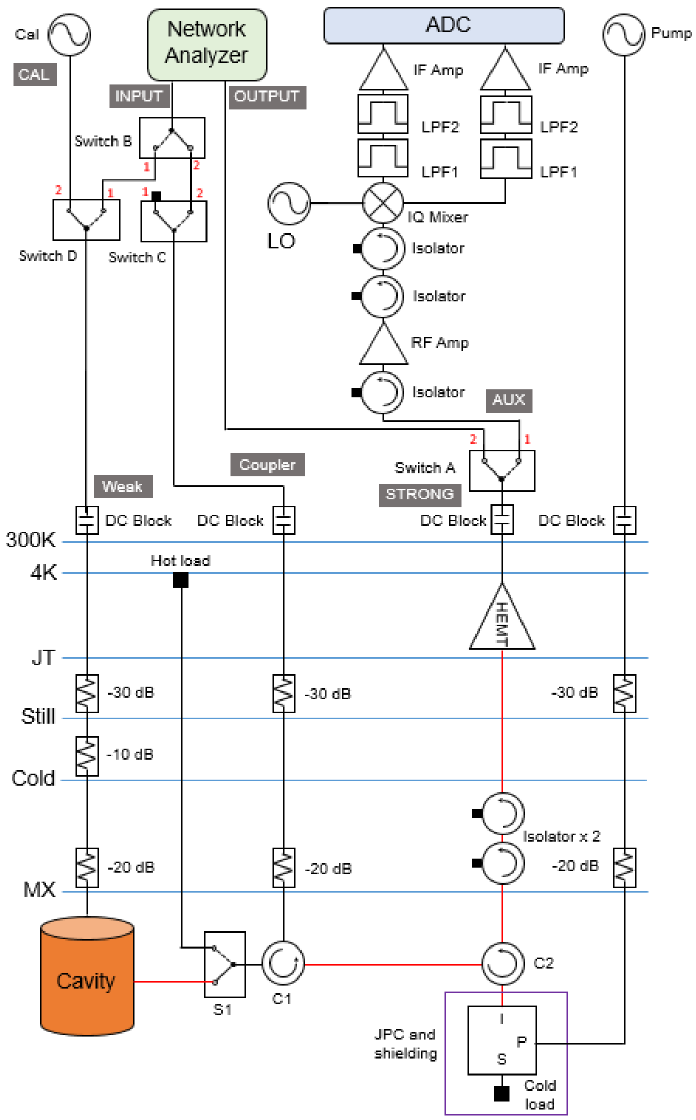
where G': HEMT gain + RT amps gain + Line Attenuations

$$T_{sys} = \frac{P_{noise}}{G_{JPC}}\frac{1}{G'k_BB} = \frac{h\nu}{k_B}\left(\underbrace{\frac{1}{e^{h\nu/k_BT_{PHY}} - 1}}_{\text{Thermal Noise of Physical Temperature}} + \underbrace{\frac{1}{2}}_{\text{Half Photon Noise}} + N_A\right)$$

where N_A : Noise of Amplifier Chain

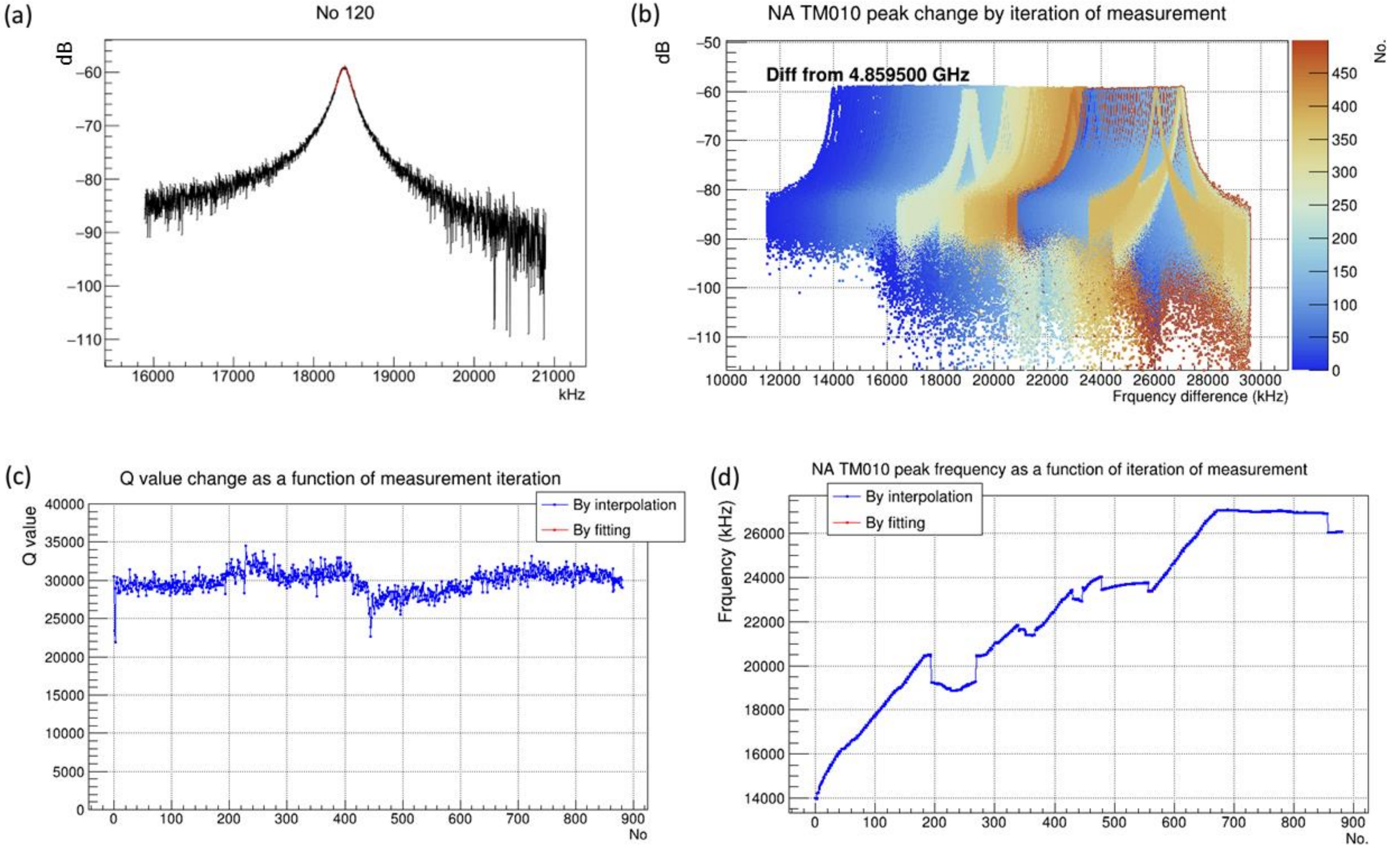
- Estimate the added noise of the amplifier chain to calculate the system noise temperature

❖ Data Taking Run – Overview



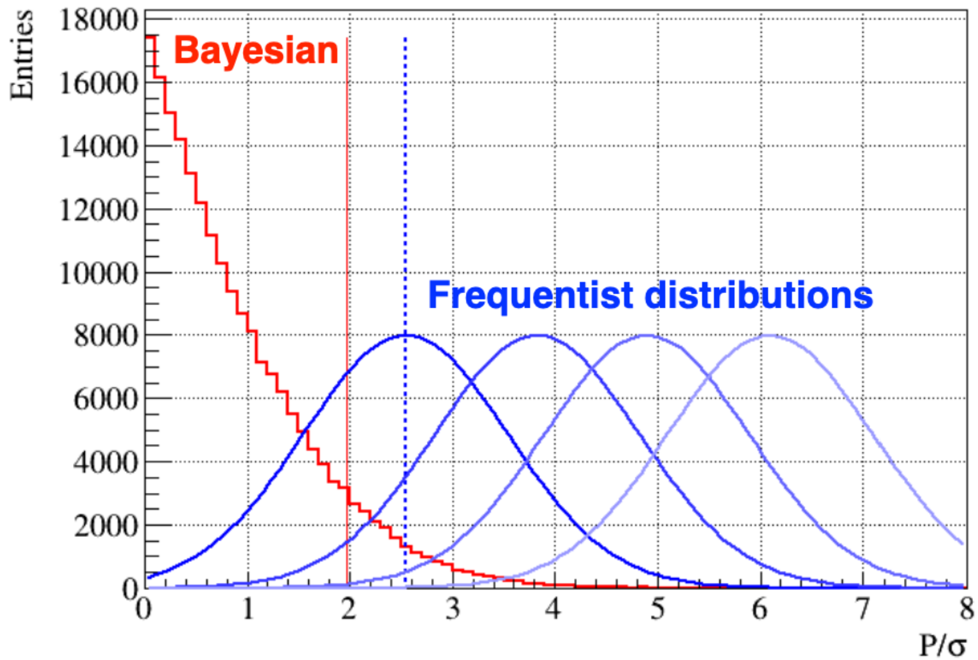
- After the end of the pilot run, data taking run was performed.
- Target IF frequency was changed to 2.25 MHz due to the unwanted spikes around 1.3 MHz
- RF chain was changed to measure the system noise temperature during data takings.
- Run-1 : 2020-11-30 ~ 2020-12-24
  - Target IF freq. : 2.25 MHz
  - β : 1 / Q : ~ 24,400 / Step : 100 kHz
  - Deep Scan
    - Scan Time for a Step : ~ 5 hours
    - T_{SYS} : ~ 1 K
    - Reached at ~ $1.10 \times |g_{KSVZ}|$ limit
  - Shallow Scan
    - Scan Time for a Step : ~ 30 min
    - T_{SYS} : ~ 900 mK
    - Reached at ~ $1.76 \times |g_{KSVZ}|$ limit

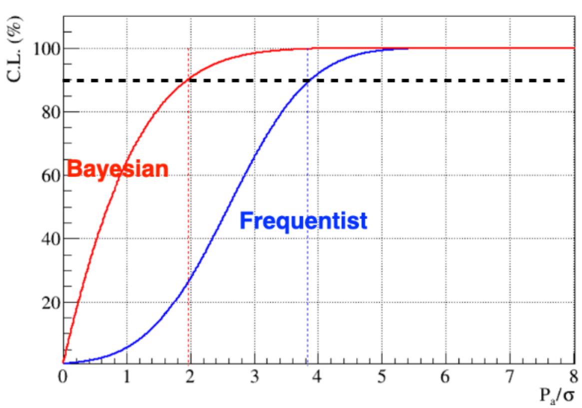
❖ Data Analysis

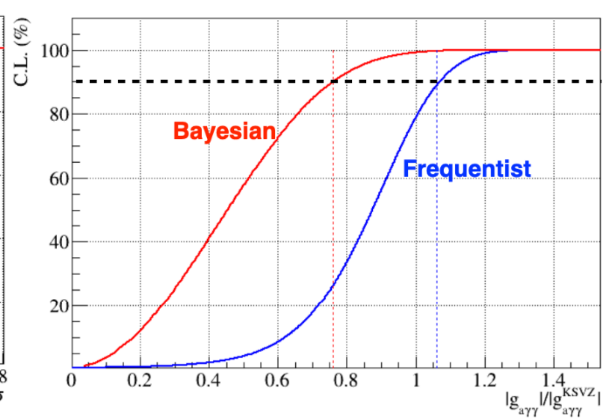


- Power spectra converted to the ROOT files with the other information of the run

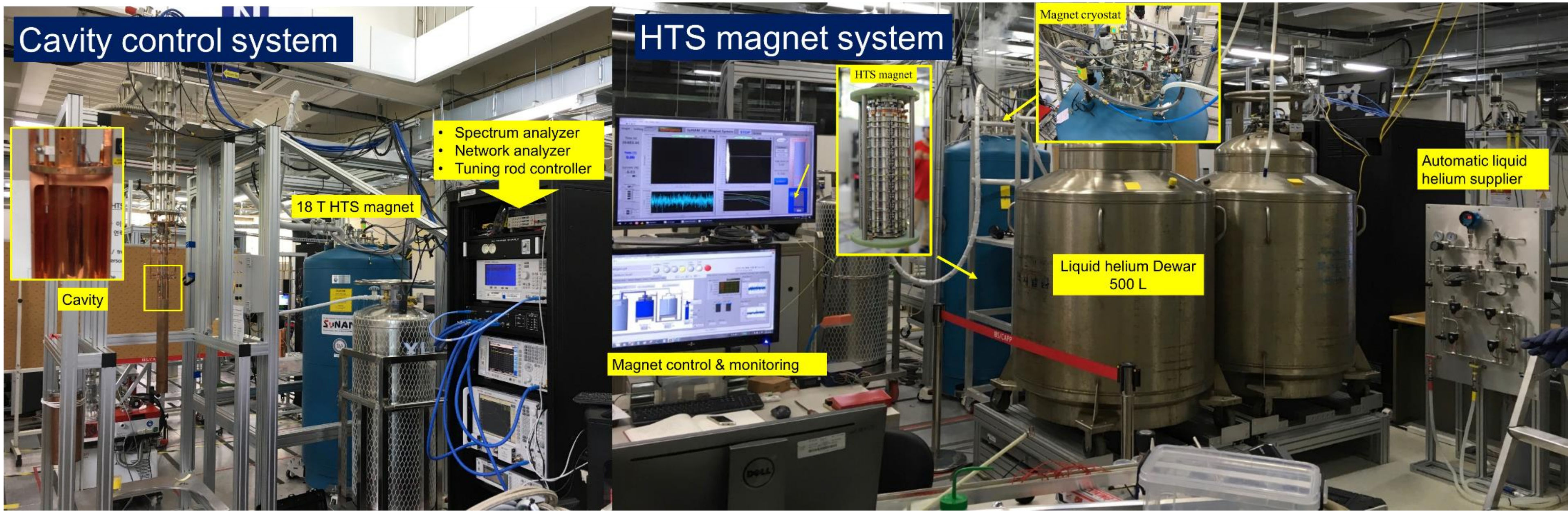
Frequentist vs. Bayesian





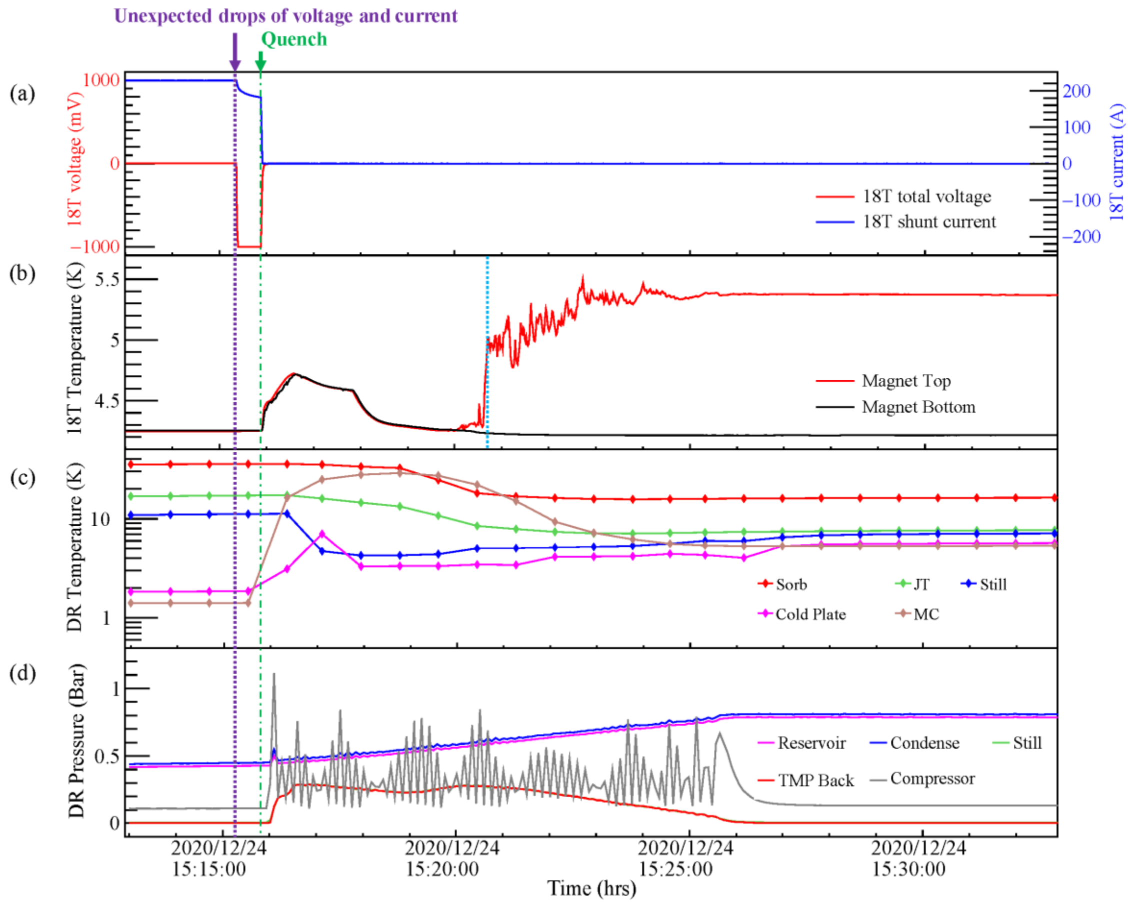


❖ 4K HEMT Run – Test Run



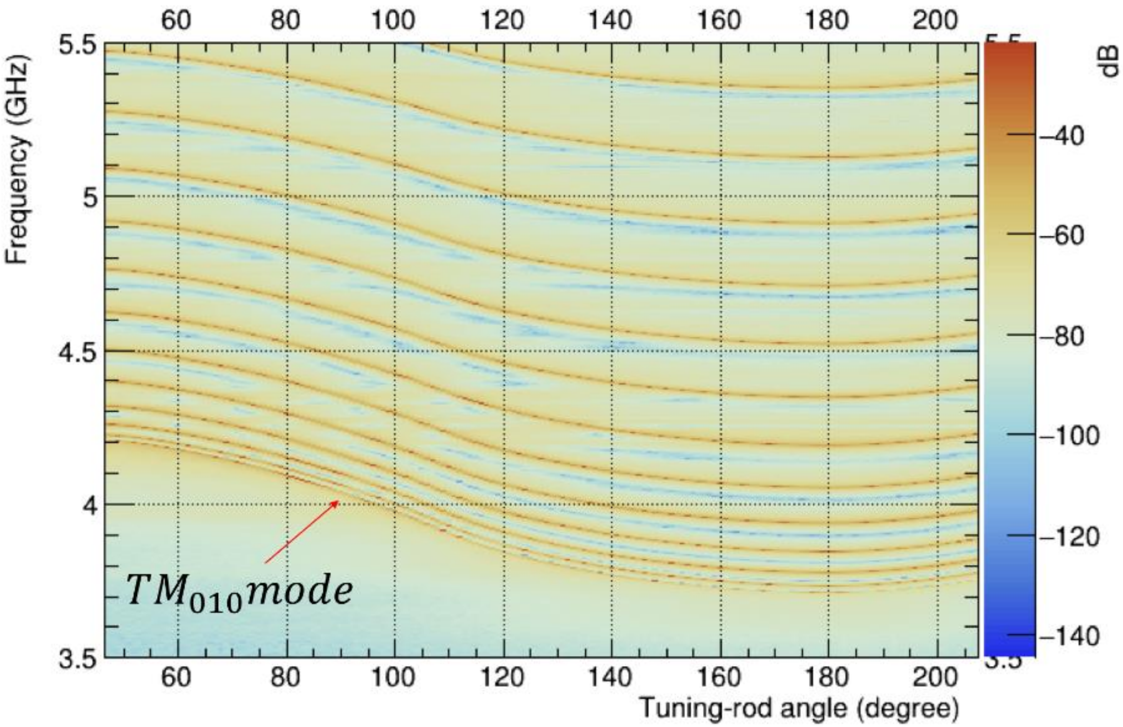
- After the delivery of the 18T magnet, the test run was performed to check the power of the strong magnet to axion dark matter search experiment.
- No Dilution Refrigerator → Test at LHe temperature
- Using low noise HEMT as the first amplifier. (Noise temperature : ~ 2K)
- Superconductive Devices, such as JPA, JPC, were unavailable

❖ Magnar Quench



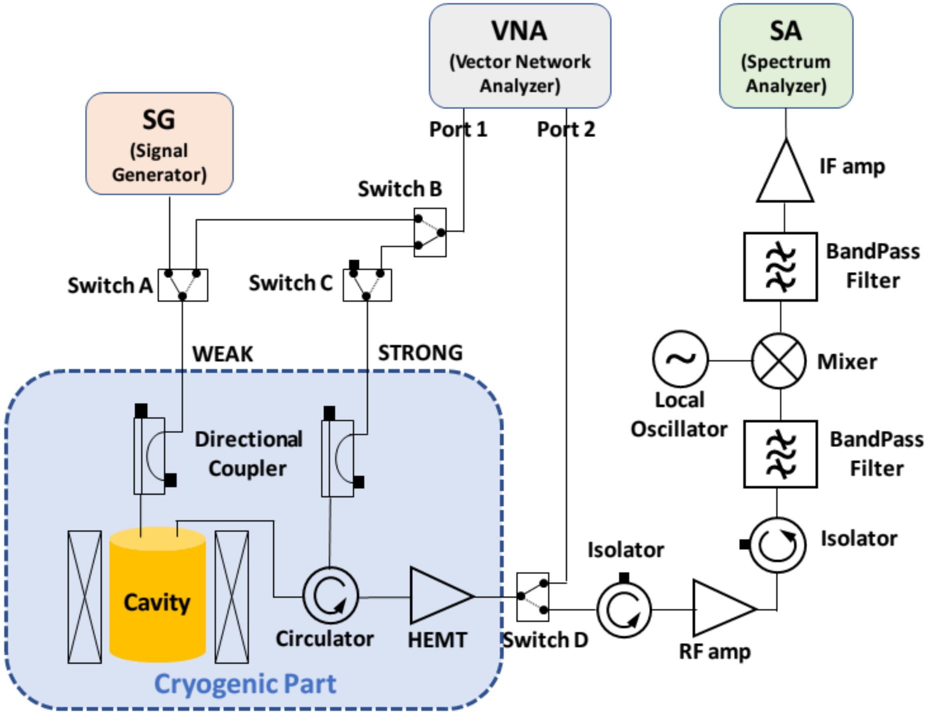
- We experienced the magnet quench just after data taking run-1 during magnet ramp down.
- The cause of the quench was not fully understood, but we guess it was from the problem of Power Supply or Power supplying circuit.

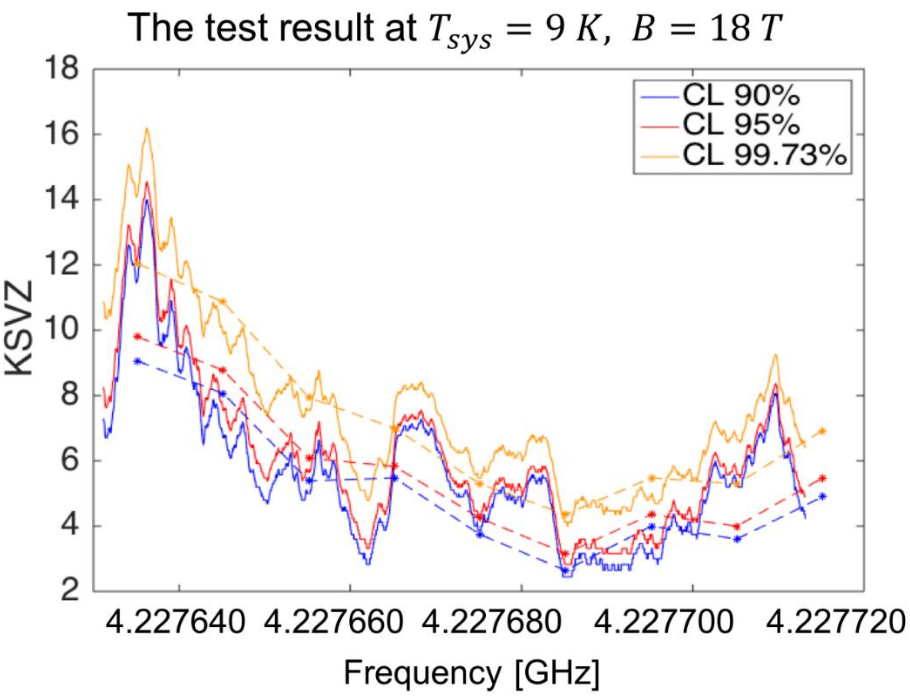
4K HEMT Run – Test Run



- Test at LHe temperature
- Superconductive Devices, such as JPA, JPC, were unavailable.
- Using low noise HEMT as the first amplifier. (Noise temperature : ~ 2K)
- Frequency tuning was done by step motors and Kevlar wires
- Using dielectric tuning rod Lower the resonant frequency

❖ 4K HEMT Run – Test Run



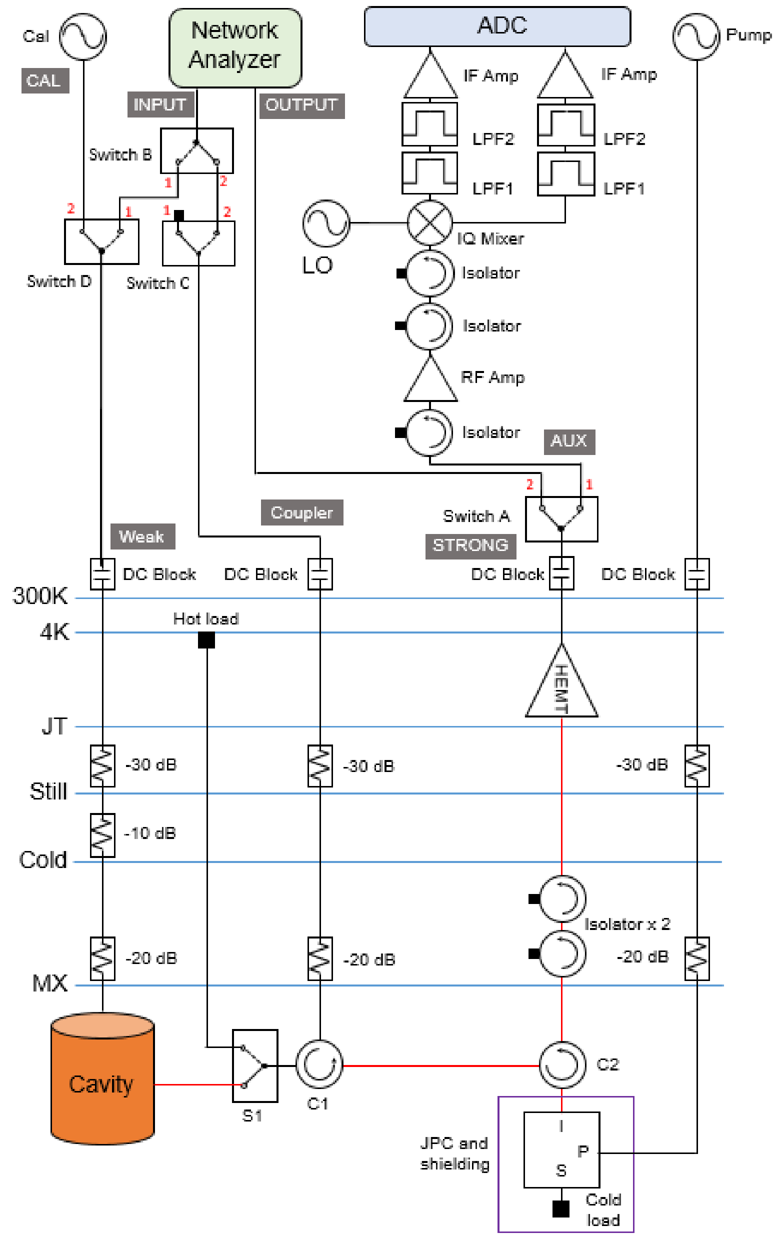


- Frequency tuning was done by step motors and Kevlar wires
- Using dielectric tuning rod Lower the resonant frequency
- Data were taken by a spectrum analyzer.
- 8 hours of data taking time under 18T magnetic field.
- Reached at ~ 5 KSVZ sensitivity limit with 9 K system temperature.
- See the possibility of the tuning system using step motors and Kevlar wire.
- Test run showed the power of the strong magnet to axion haloscope.

❖ Data Analysis Procedure

- The goal of an axion haloscope experiment is to combine a set of overlapping axion sensitive power spectra to produce a single spectrum that optimize the SNR throughout the search range.
- If axion exist → An excess power relative to the noise power in the combined spectrum
- If axion does not exist in the search range → Only Gaussian noise shown in the combines spectrum
- The analysis procedure :
  - 1. Reformat data from binary file to root file, and insert the LO, calibration information, etc.
  - 2. Baseline remove using SG filter, and then correct cavity weights and input attenuations
  - 3. Correction with system temperature, cavity shape, etc.
  - 4. Combining subruns with same rotator position. (Vertical Combine)
  - 5. Combine spectrum throughout the scan range. (Horizontal Combine)
  - 6. Correction with signal shape estimated from the Maxwell-Boltzmann distribution
  - 7.Get the sensitivity limit using Bayesian statistics.

RF Chain



SW	A	B	C	D
S_{11}	1	1	1	1
S_{21}	2	1	1	1
S_{22}	2	2	2	2
ADC	1	1	1	2