Superfluid Frequency Tuning of Superconducting Cavities for Axion Dark Matter Search

18th Patras Workshop on Axions, WIMPs and WISPs
University of Rijeka, Croatia

HeeSu Byun (CAPP-IBS)

- DEVELOPED: SUPERFLUID HELIUM TUNING

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- APPLIED : 10M Q-FACTOR SUPERCONDUCTING CAVITY

- Developed: Superfluid Helium tuning
- Applied: 10M Q-factor superconducting cavity
- Expected: 1 MHz/day, KSVZ, 200mL cavity

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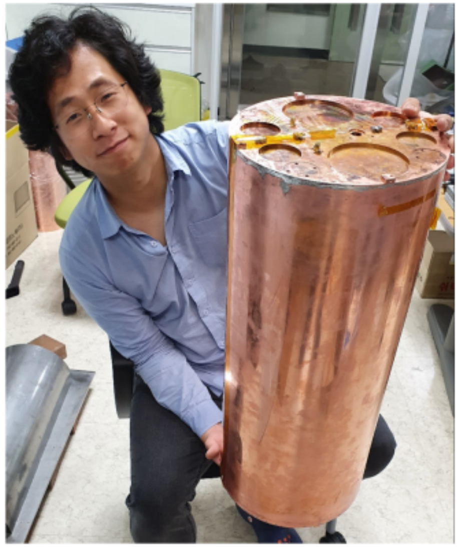
Problems with conventional tuning methods

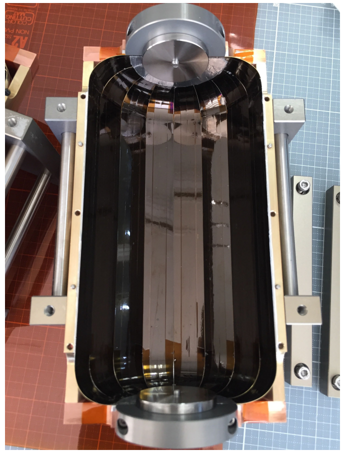
- Q-factor dropping
- Form factor decreasing
- Heating from motion controller
- Hot rod problem

The advantage of the superfluid helium

- **Dielectric constant of Liquid Helium: 1.057**
  - Large enough to shift resonance frequency
  - Small enough not to disturb field inside of cavity
- **Superfluid helium:** Instant permeating thru any geometry
- **The pre-cooled superfluid helium is introduced into the cavity.**
- **Relatively high thermal conductivity:** NO hot rod problems

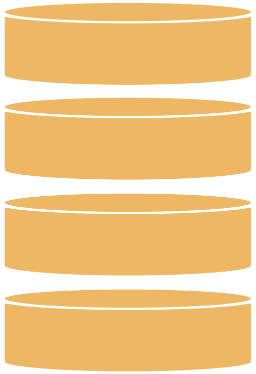


Metamaterials cavity,
OJ Kwon, 2019 Patras

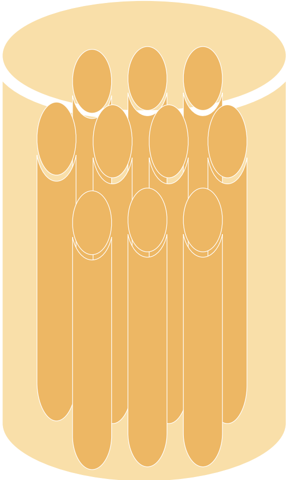


Superconducting cavity
Danho Ahn, 2022

Piza cavity
Junu Jeong, 2023



Stack cavity

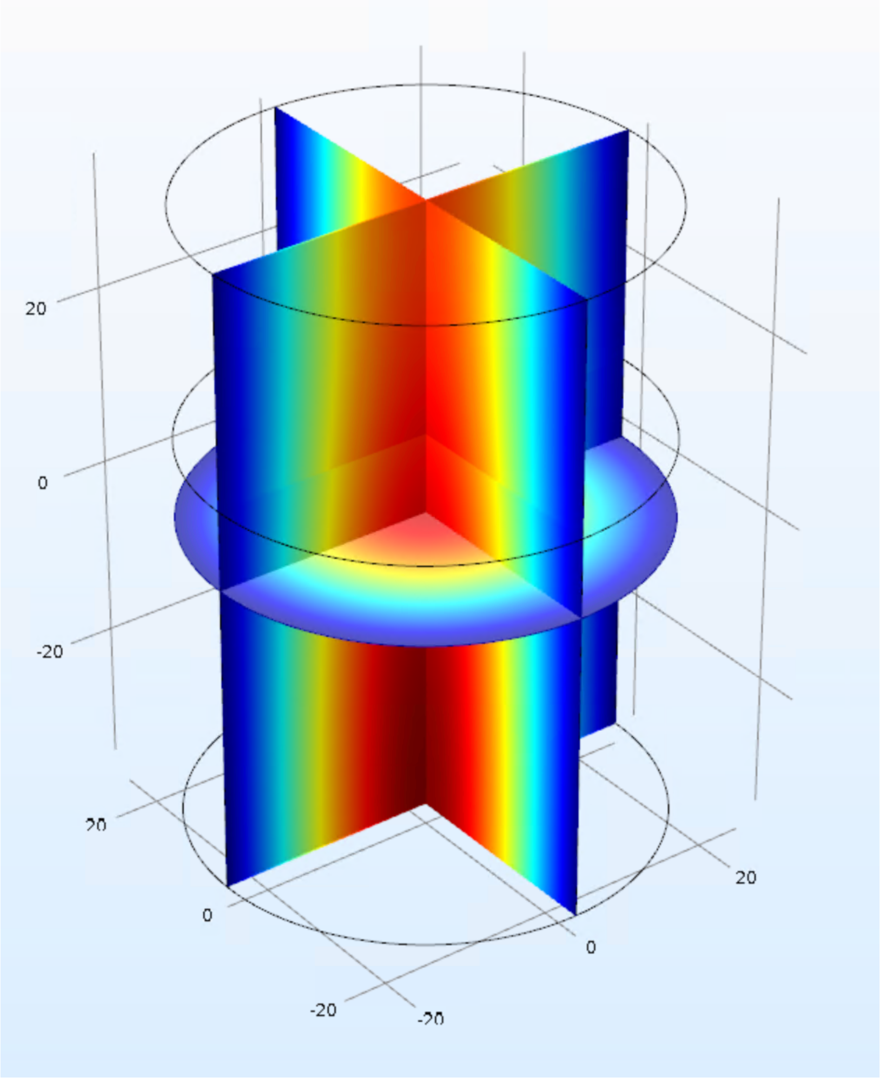


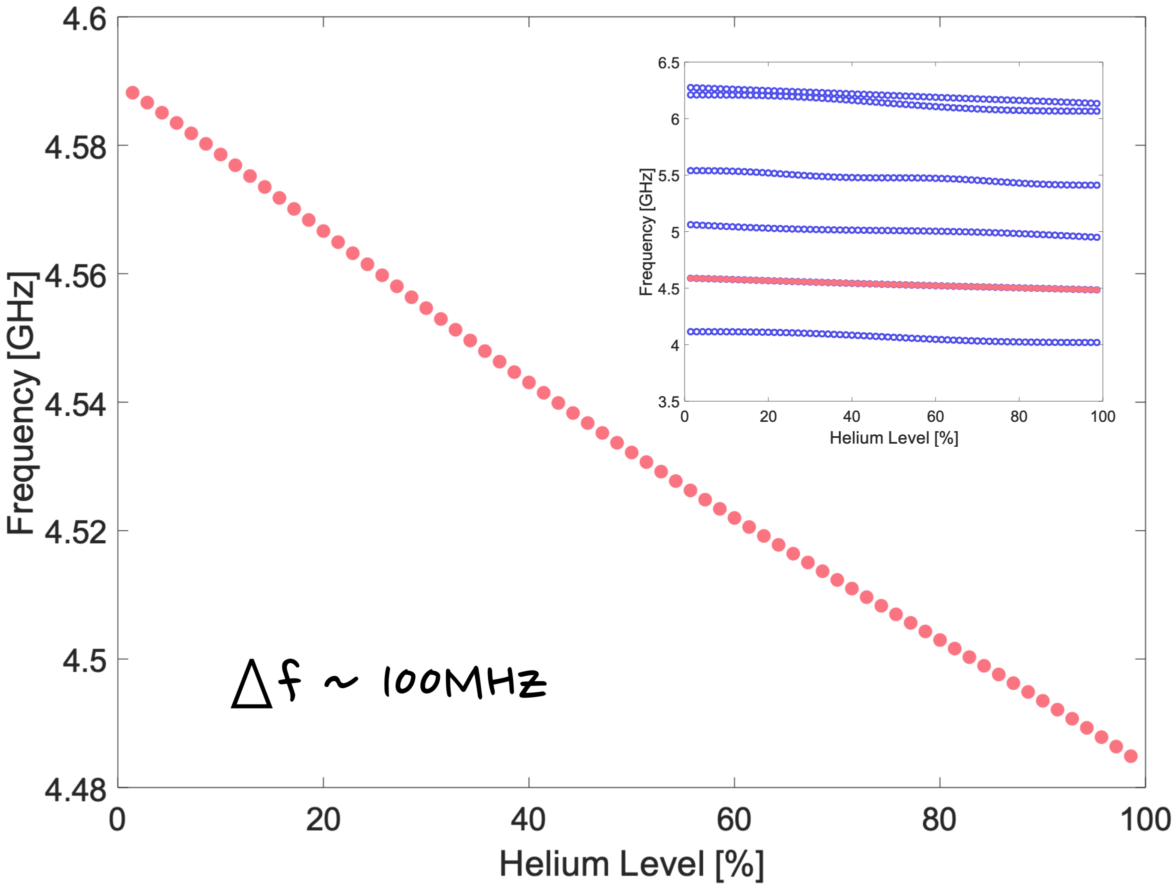
Multi cavity

Contents

- Simulation with superfluid helium in superconducting cavity
- Implementation of Superfluid helium tuning
- Commissioning run and Future work

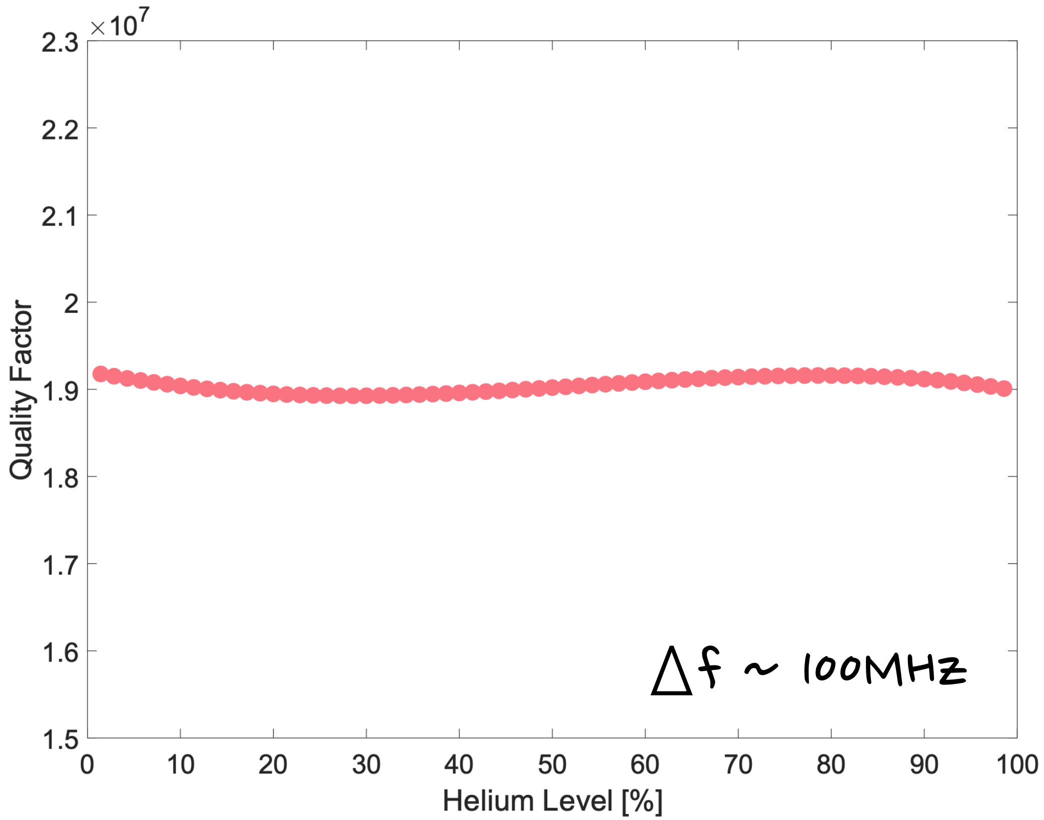
Simulation with superfluid helium in superconducting cavity

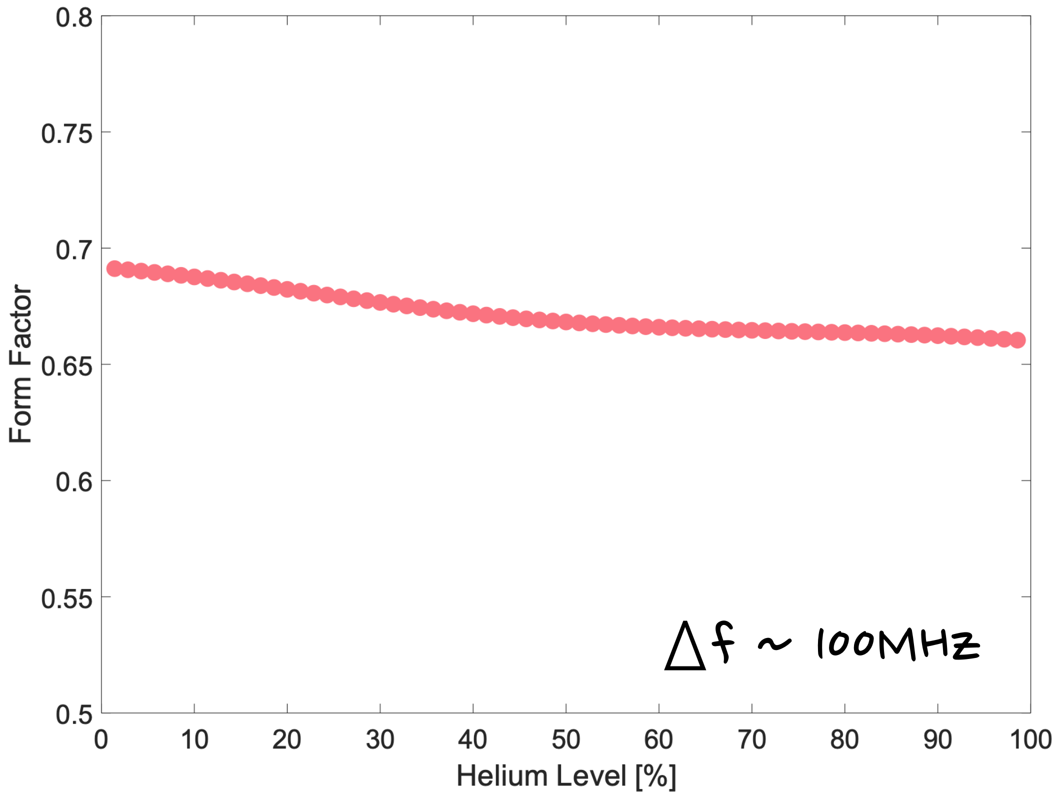




- The tuning range is around 100 MHz
- No mode crossing or mode localization

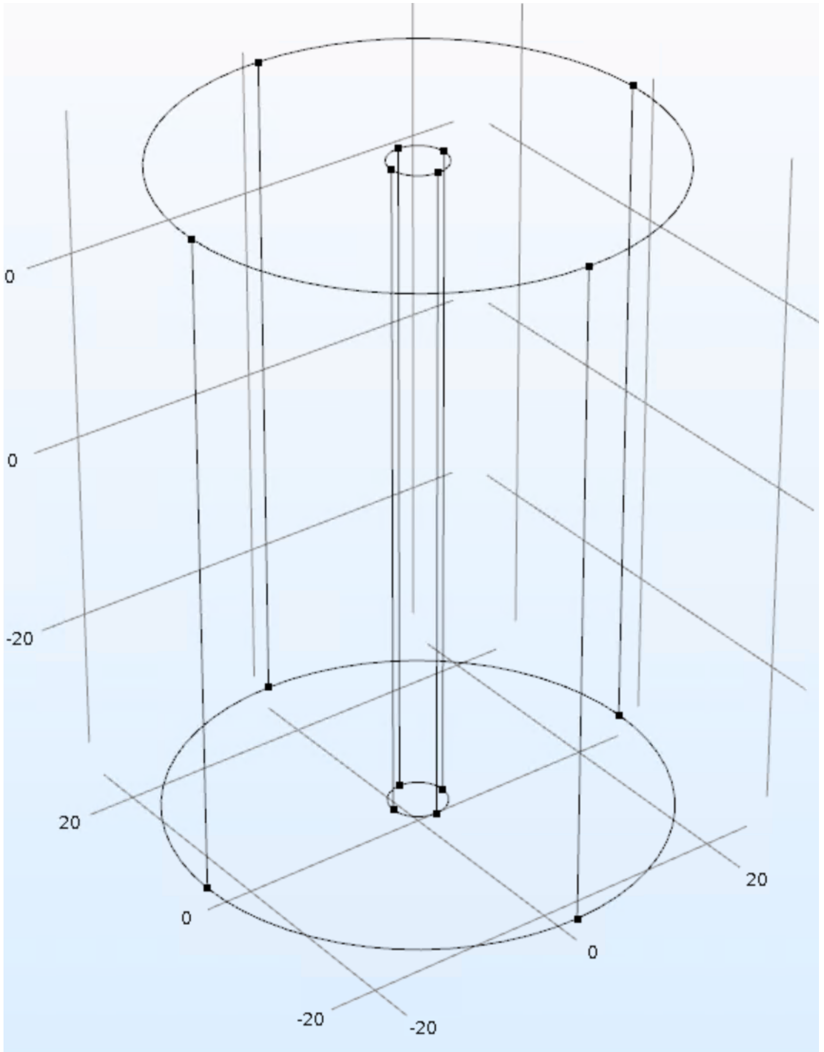
Q-factor and form factor change during the tuning



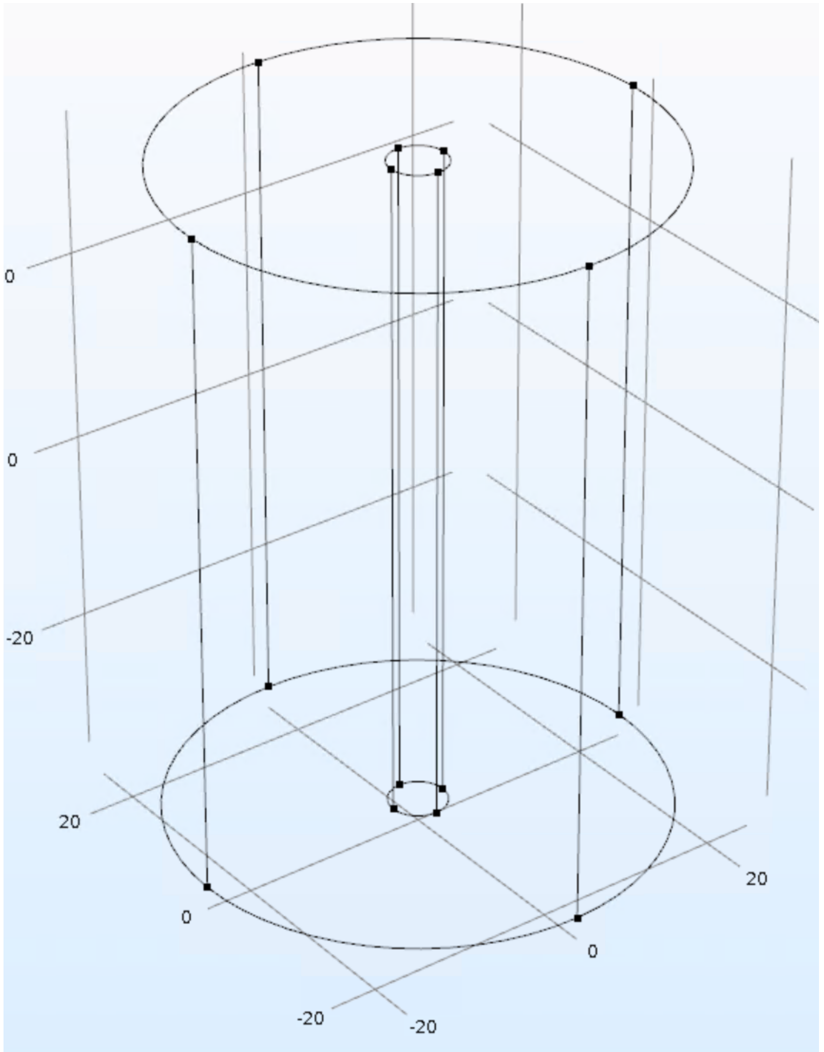


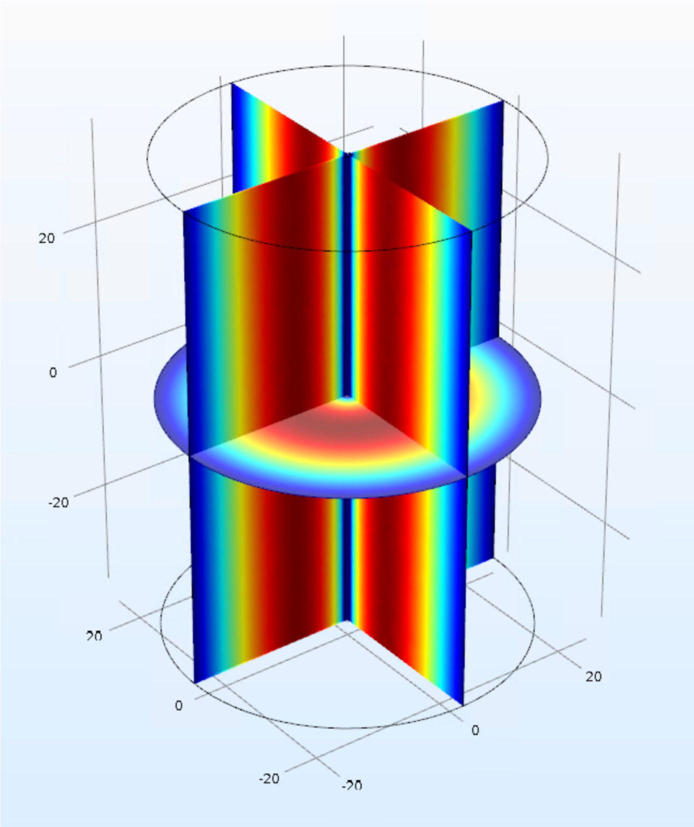
- Stable Q-factor whole range of frequency tuning
- The form factor maintains above 0.65
- Negligible effect on field distribution inside of the cavity

Tuning beyond the limitation of superfluid helium



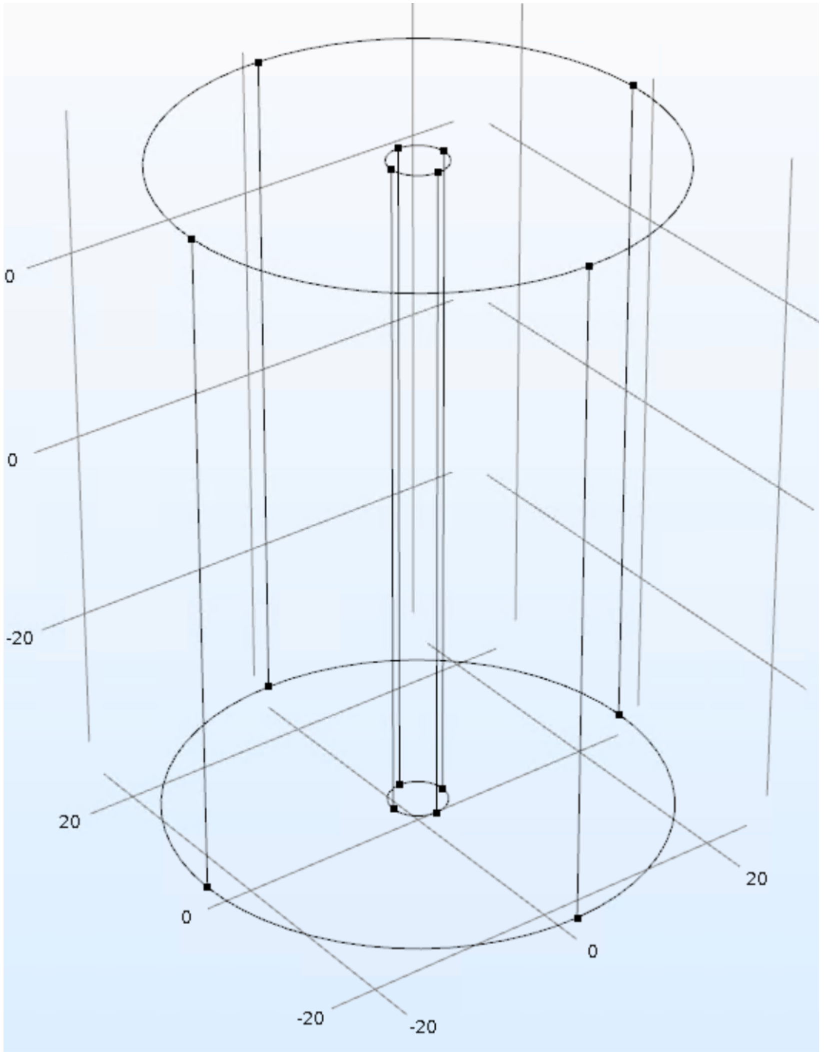
Tuning beyond the limitation of superfluid helium

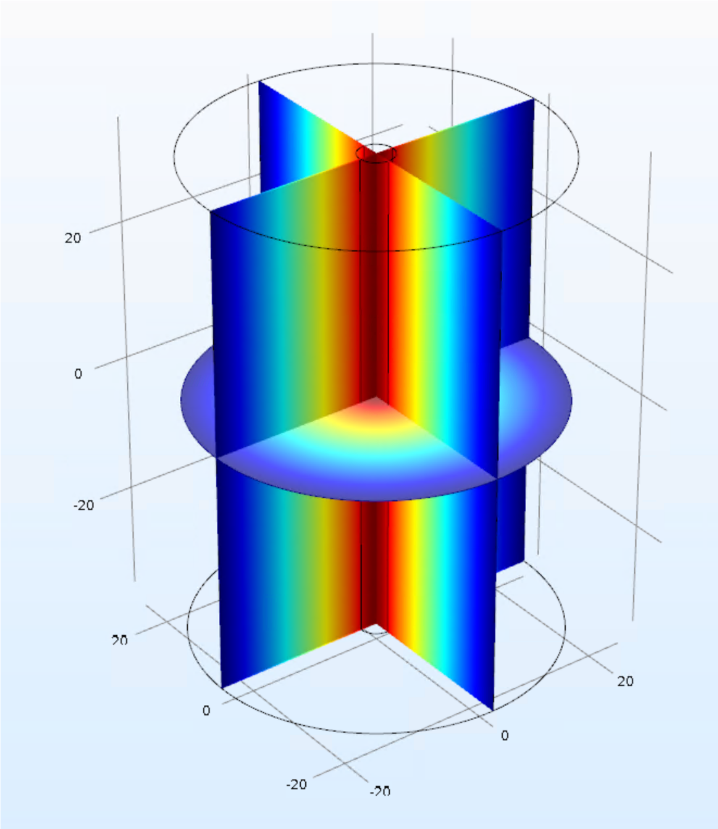




To increase resonance frequency
-Superconducting rod

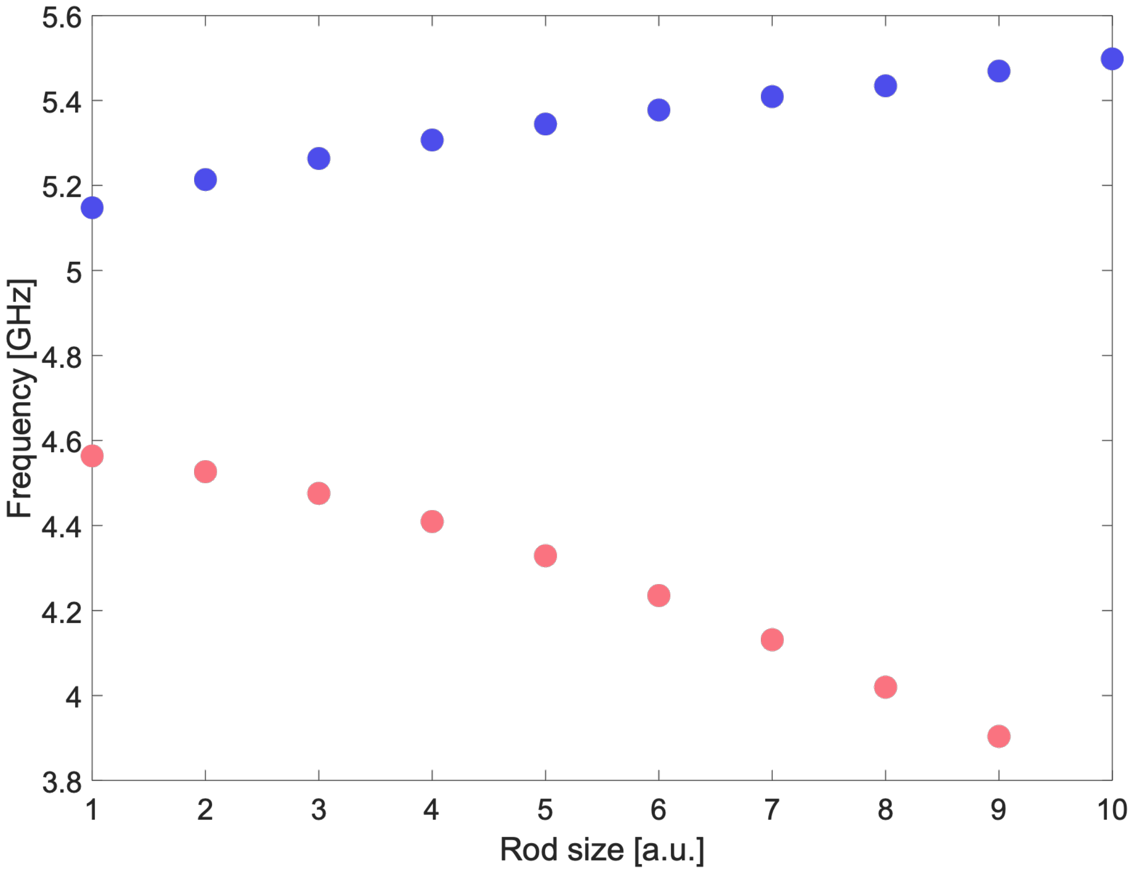
Tuning beyond the limitation of superfluid helium

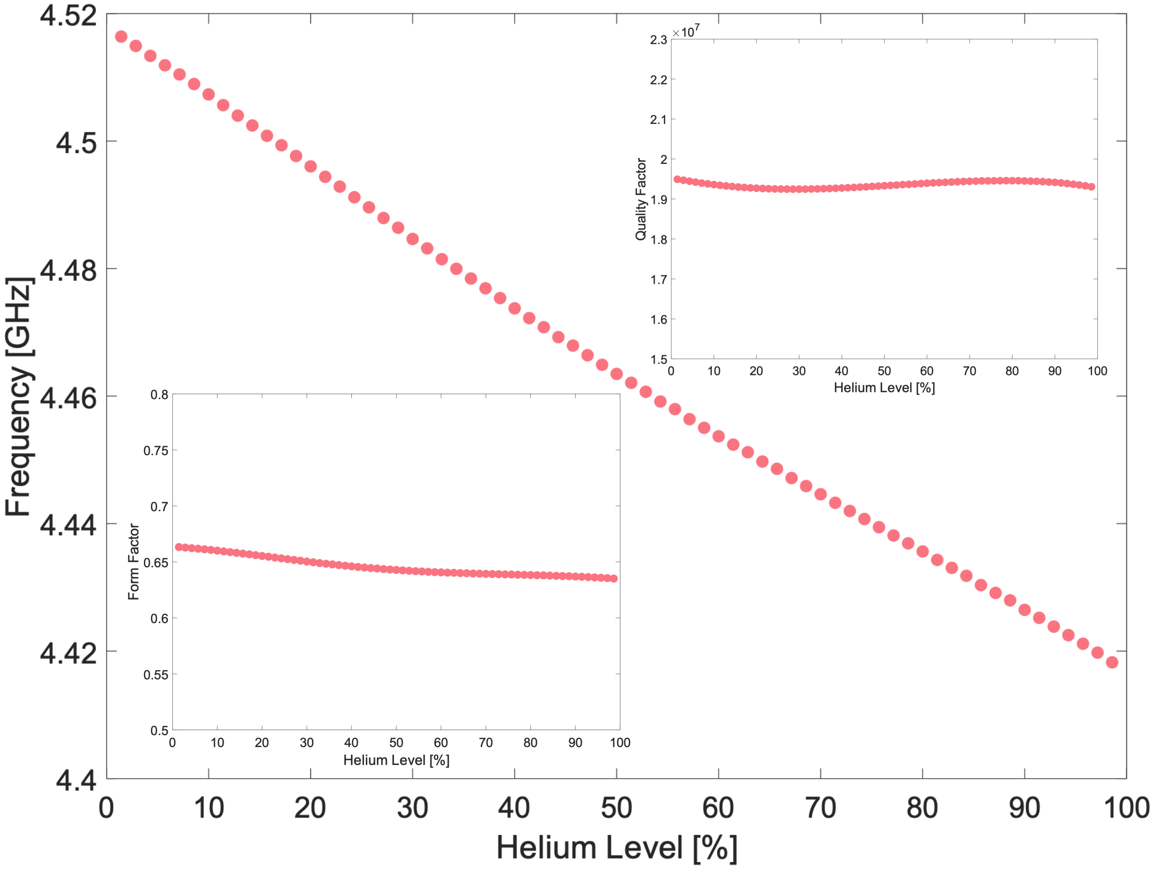




To decrease resonance frequency
-Dielectric rod

Superfluid helium tuning with rod

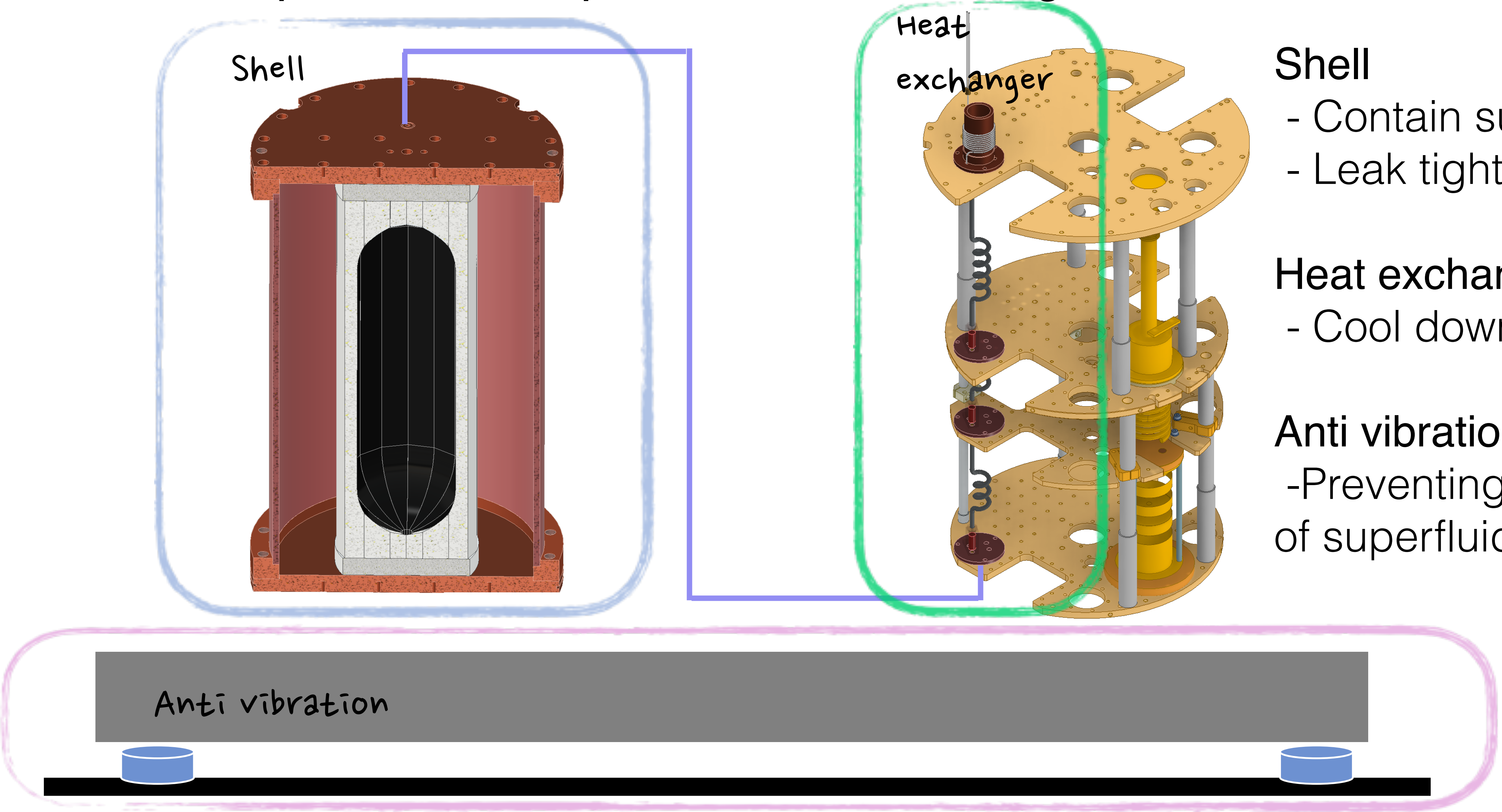




● : Superconducting rod ● : Dielectric rod

-Superfluid helium tuning will cover gap between rod tuning

Three components of superfluid helium tuning



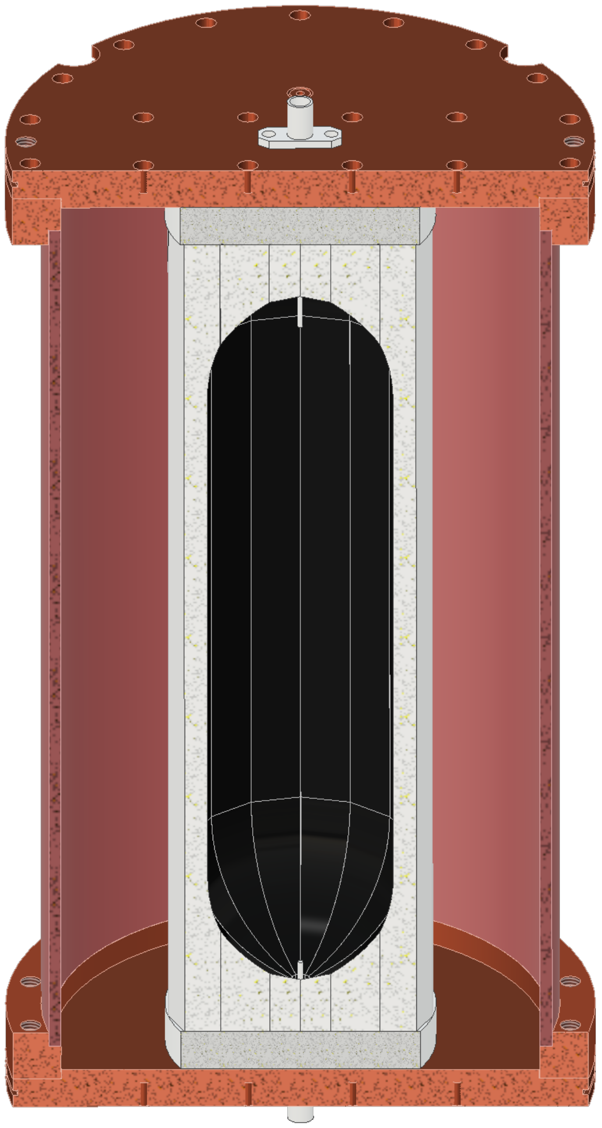
Shell
- Contain superfluid
- Leak tight

Heat exchanger
- Cool down LHe

Anti vibration
-Preventing vibration of superfluid

Shell design

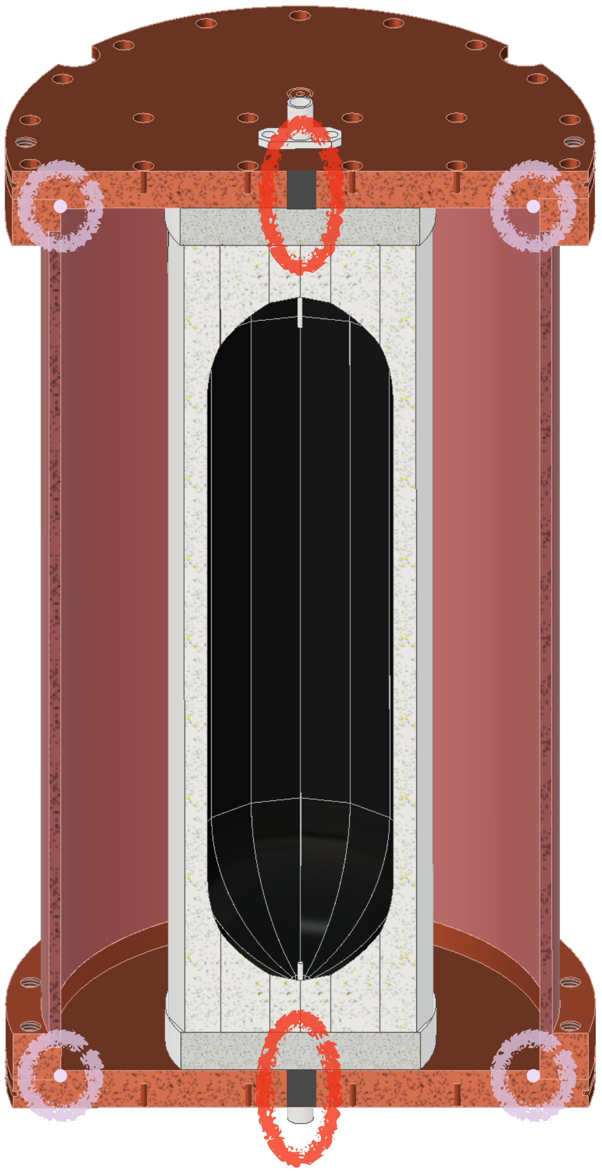
- Should be leak tight
- Easy to open & close
  - Antenna length
  - Rod
- Compatible for various size of cavity
- To maximize volume size



Shell design

- Should be leak tight
- Easy to open & close

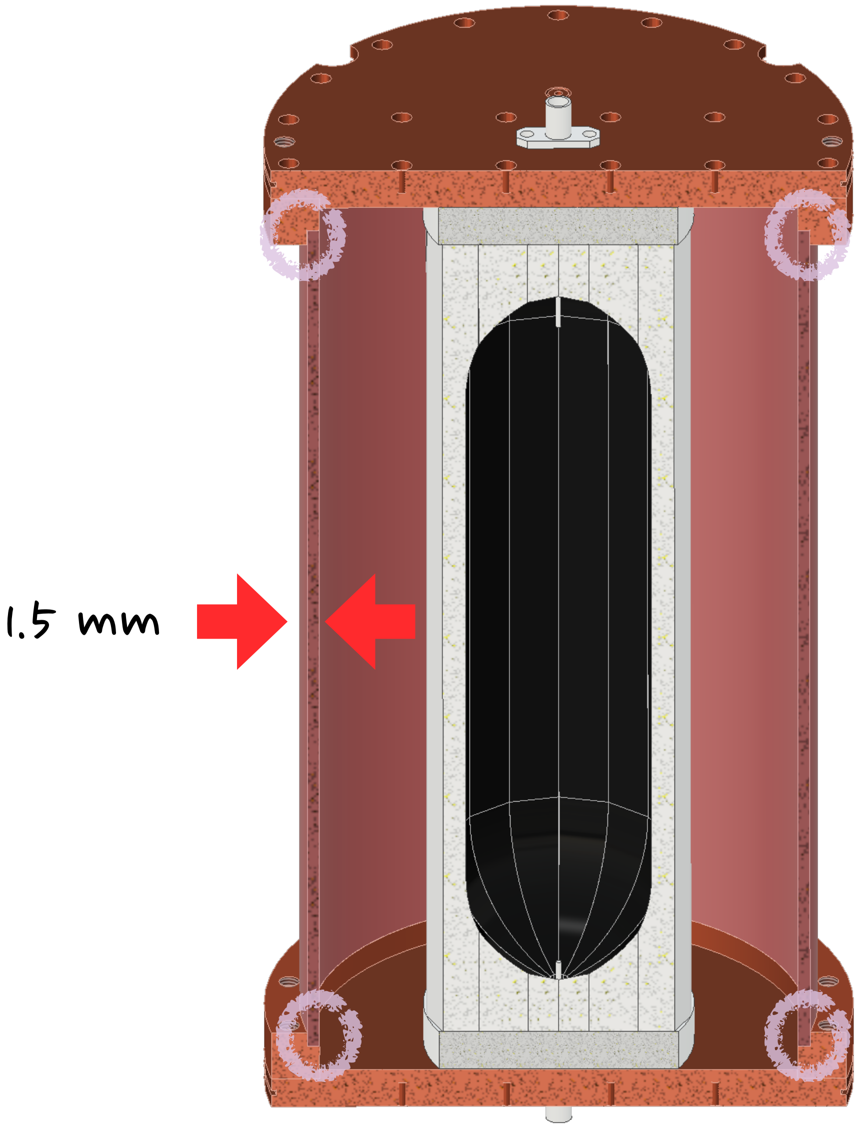
- Indium sealing
- Stycast 2850



Shell design

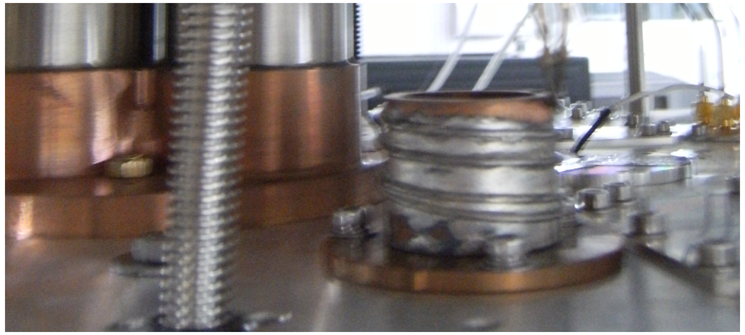
- Should be leak tight
- To maximize volume size

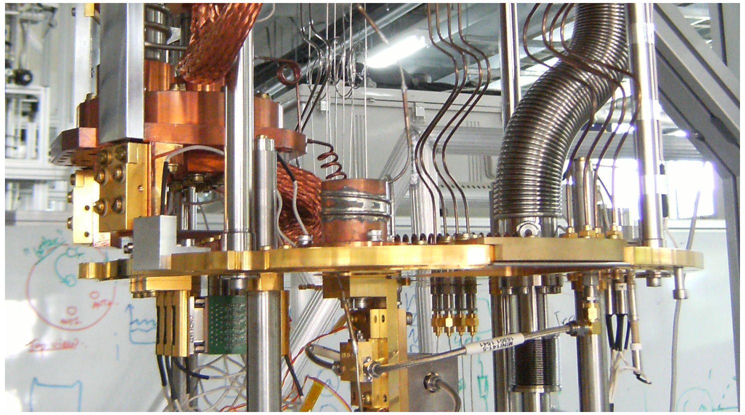
- Brazing copper wall
- 1.5 mm thickness



Two types of heat exchanger

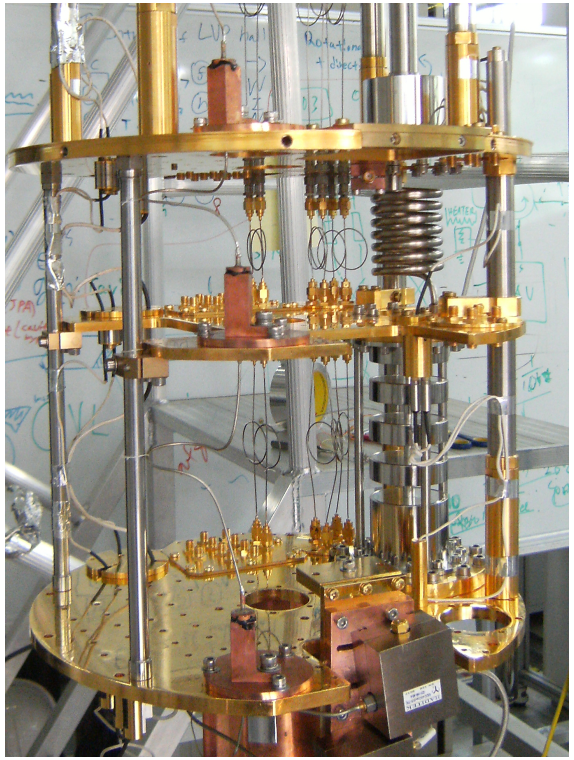
Capillary type





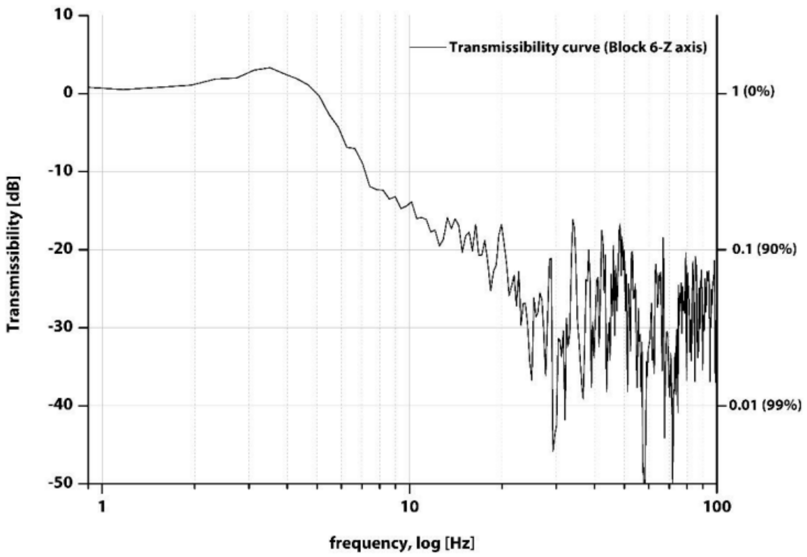
- Low impedance
- Small surface area
- 50K, 4K plate

Powder type



- High impedance
- Large surface area
- Still, cold, and MXC plate

Anti vibration system



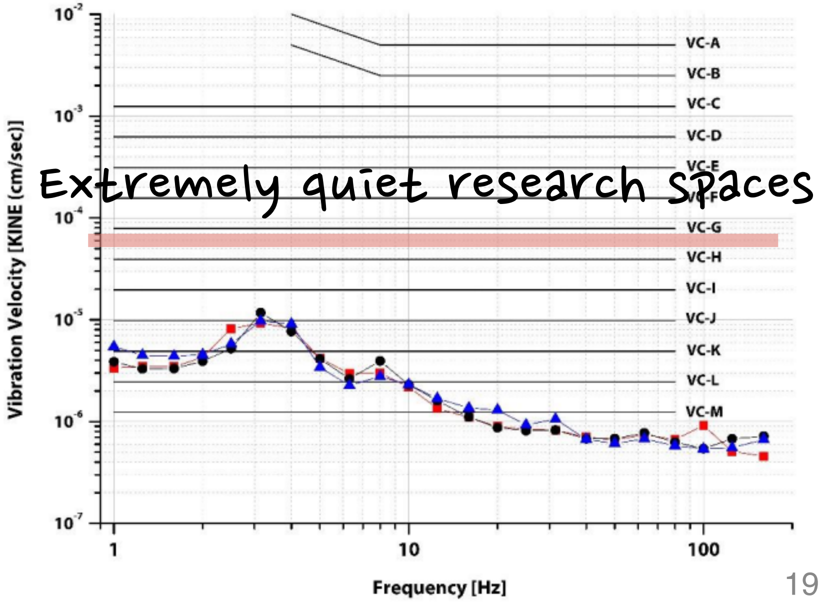
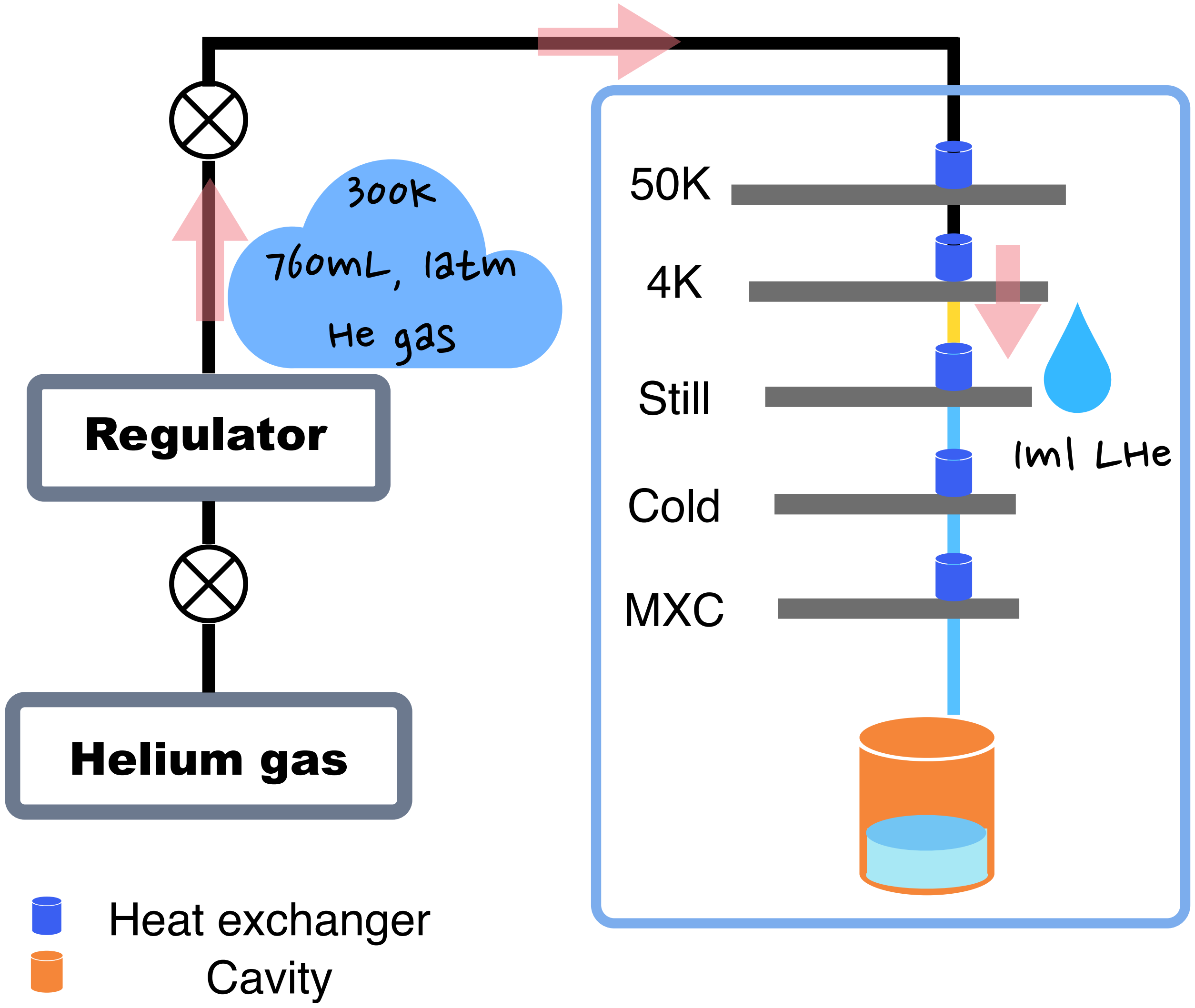
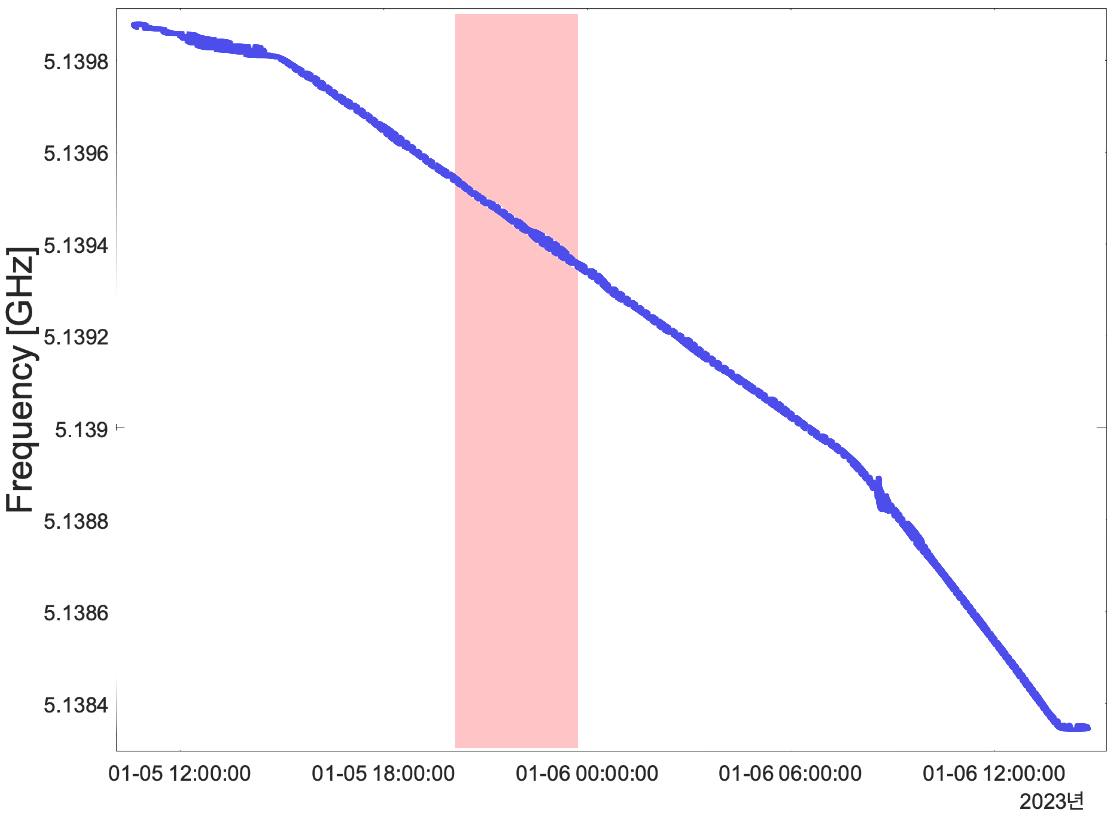
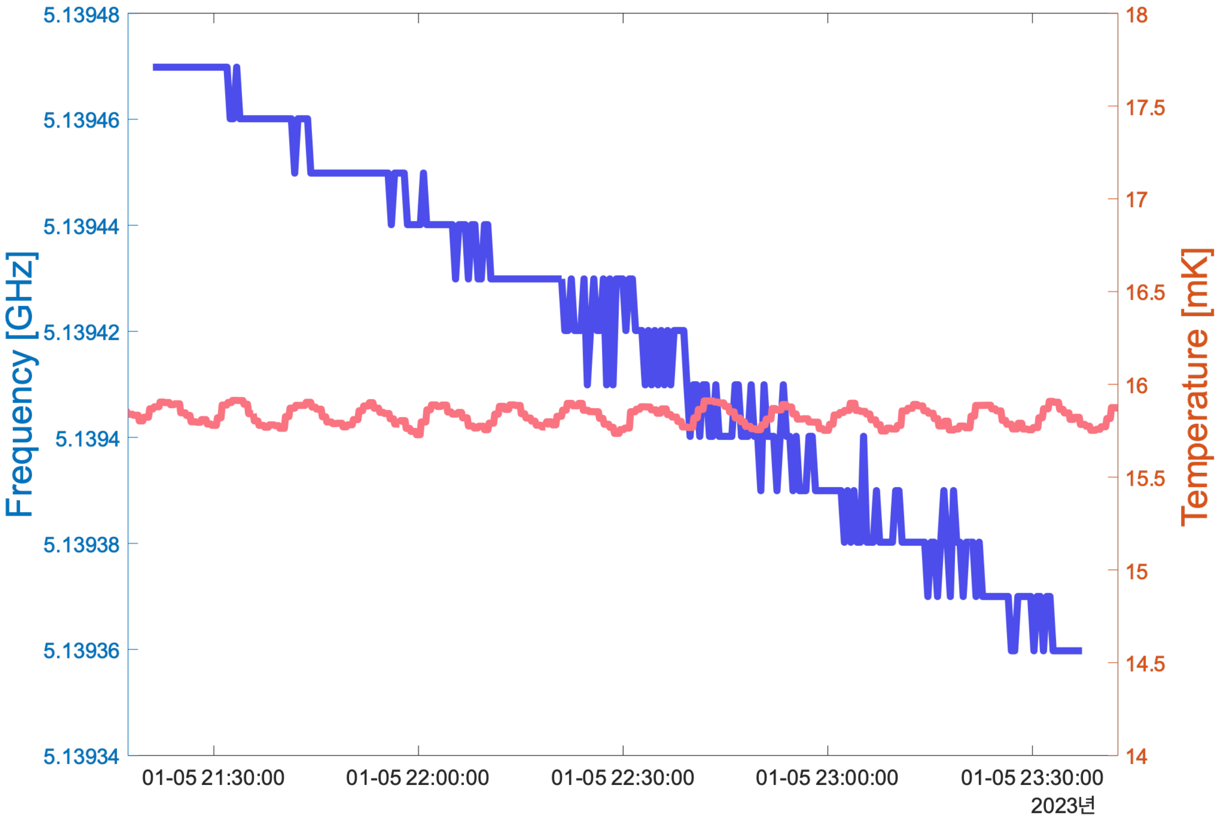


Diagram of helium tuning



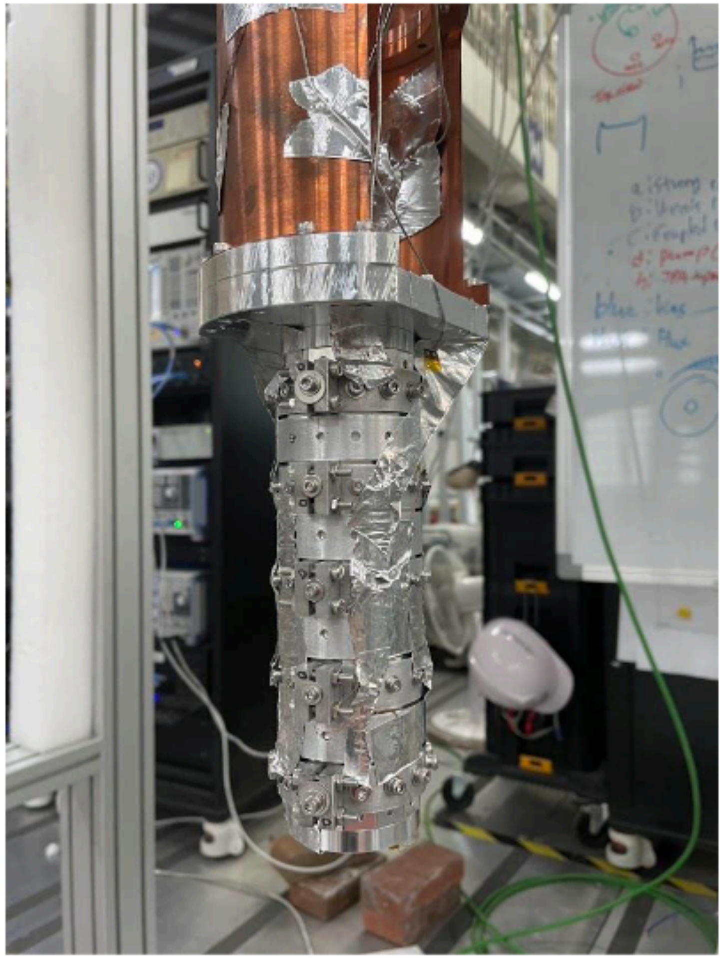
Frequency shift by helium tuning

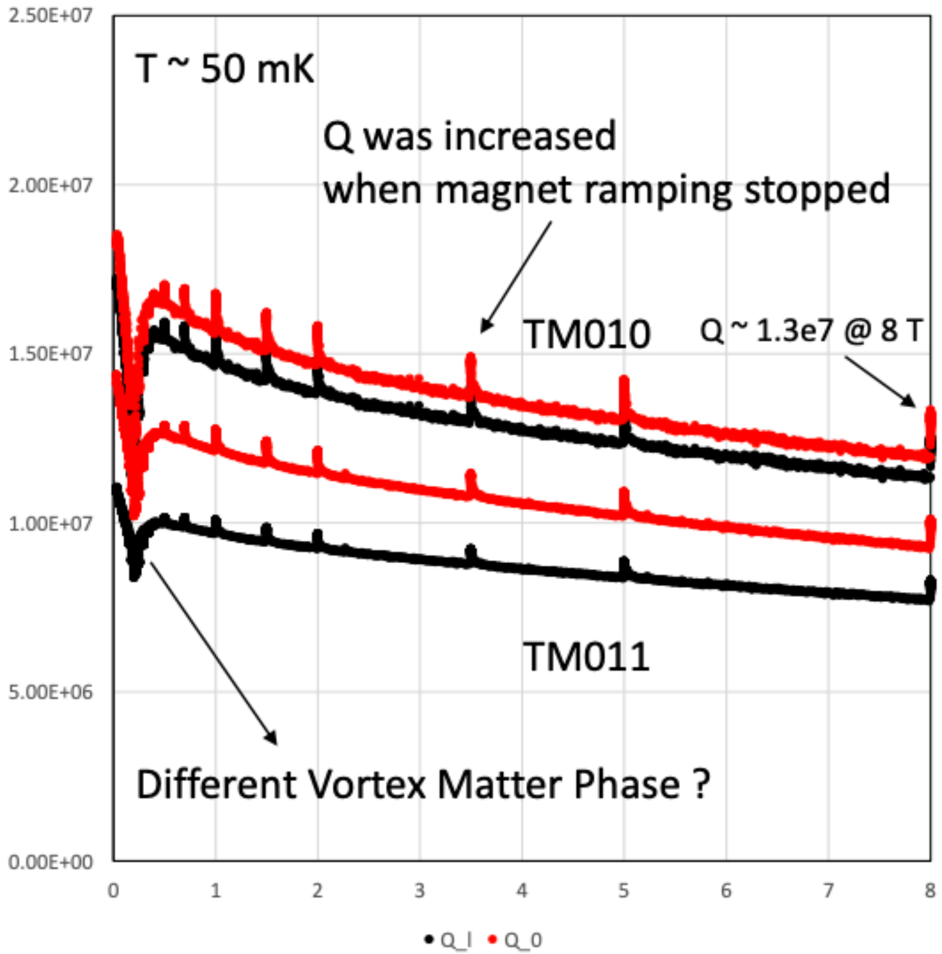




- Tuning step could tune by the pressure
- Observed oscillation in resonance frequency during the tuning
- The MXC temperature is stable during helium tuning

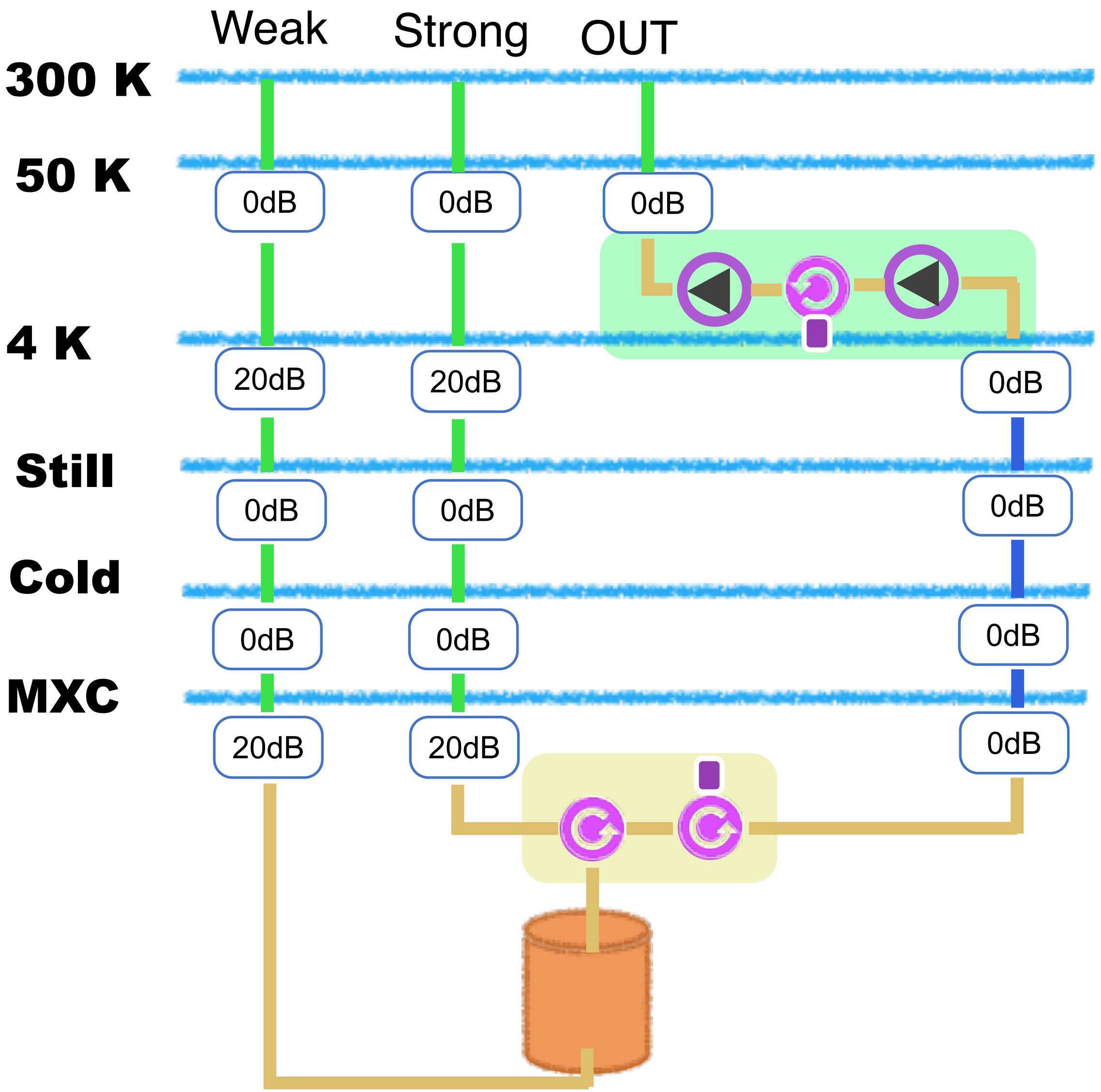
Superconducting cavity and magnetic field test



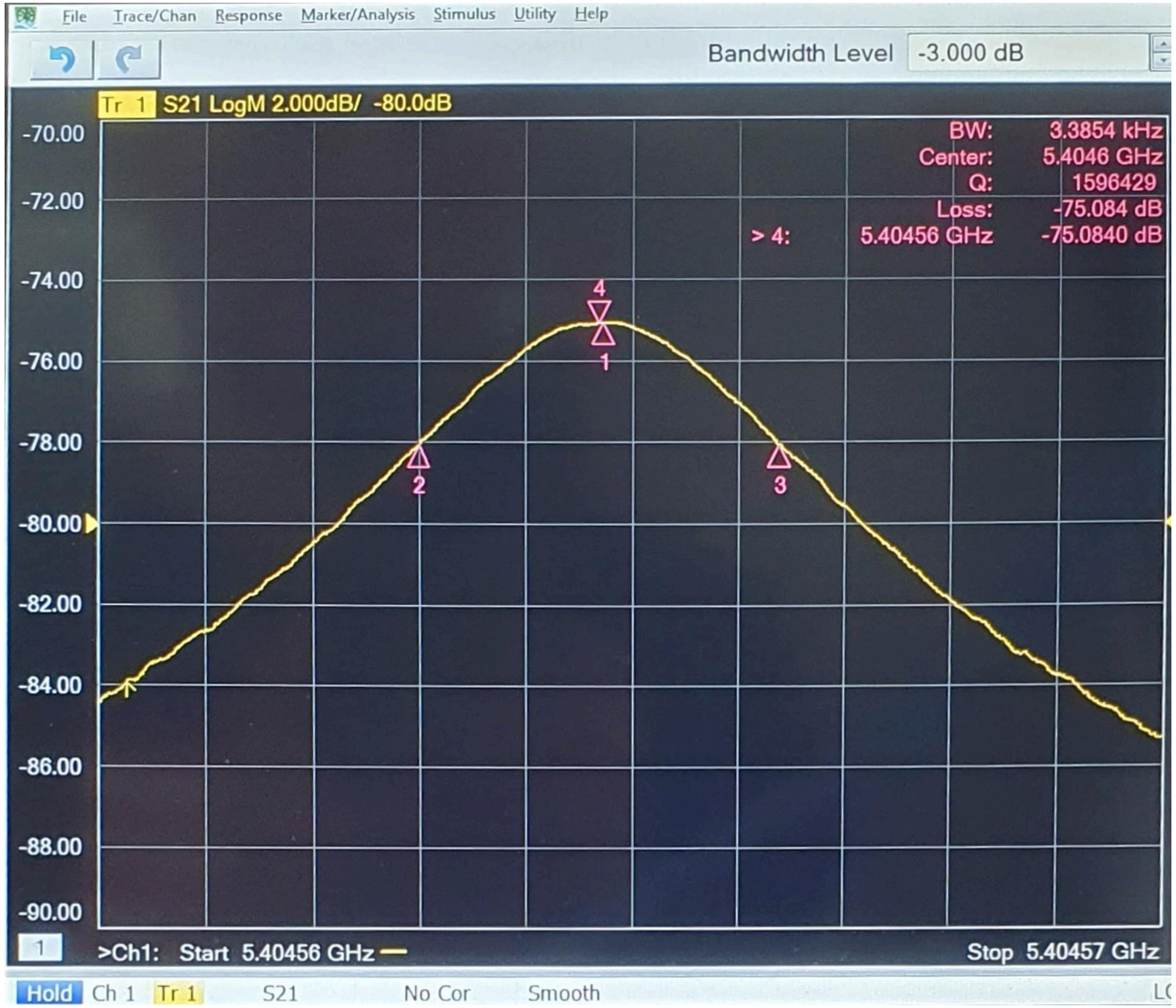


Superconductong cavity, Danho Ahn, 2022 Patras, 2023 Patras

Commissioning run



Expectation of commissioning run



- Commissioning run
- HEMT run
  - Noise: 1.5K
- Loaded quality factor
  - 1.5 M
- Beta : 1.2
- 1 MHz/day @ 3.5 KSVZ

Summary

- Superfluid helium tuning could be applied to various types of cavities
- Superconducting cavity could be tuned by superfluid helium without a sudden drop of quality factor and form factor
- The combination of superfluid helium tuning and additional tuning rod provides a wider tuning range
- The success of helium tuning depends on the proper design of the shell, heat exchanger, and anti-vibration system.

- The Commissioning run is currently in progress

Future work

- JPA implementation to reduce noise temperature
- Cold valve will be applied to reduce the dead time from tuning
- Target scan rate : 1MHz/day @KSVZ

- Superfluid helium tuning could be employed in other experiments such as the superconducting cavity for CAPP-MAX

APPLIED PHYSICS LETTERS **111**, 172601 (2017)

Tuning a 3D microwave cavity via superfluid helium at millikelvin temperatures

F. Souris, H. Christiani, and J. P. Davis[a)]
Department of Physics, University of Alberta, Edmonton, Alberta T6G 2E9, Canada

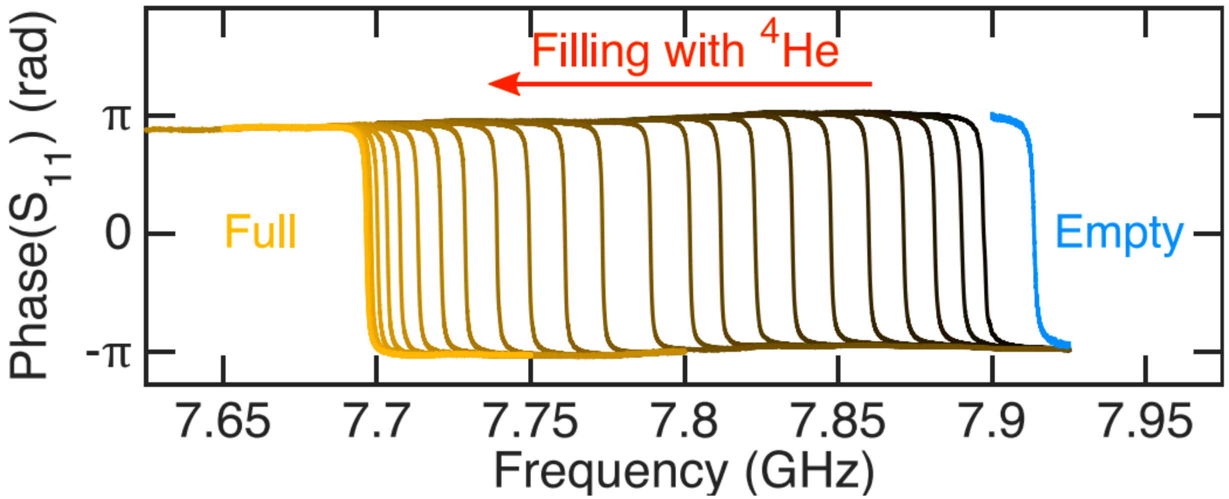


FIG. 2. Evolution of the superconducting 3D microwave cavity resonance as it is filled with liquid helium. Each colored curve corresponds to the phase of the S_{11} signal measured every ~30 s, with the total fill time being about 10 min. While filling, the mixing chamber is maintained below 100 mK. Filling could be stopped at any point, thereby setting the cavity resonance frequency.

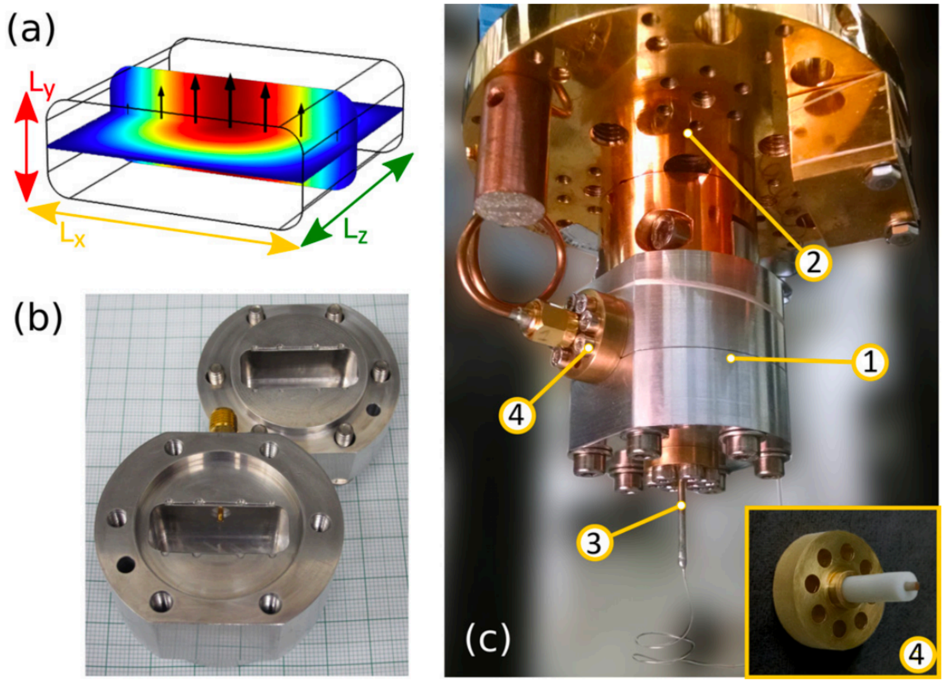


FIG. 1. (a) COMSOL simulation of the electric field component of the TE101 mode of our rectangular 3D microwave cavity. The electric field is oriented along the y-axis and is coupled via an extended SMA waveguide. (b) Photograph of the 3D aluminum cavity, opened to show the internal geometry. (c) Photograph of the assembled 3D cavity (1) mounted to the base plate of the dilution refrigerator (2). Two brass adapters, which allow a filled-line capillary (3) and a hermetic SMA (4) to be soldered in, are sealed to the cavity using indium o-rings. The two halves of the aluminum cavity are also sealed using a standard superfluid-leak-tight indium o-ring. In the inset, we show an extended waveguide added to the helium side of the hermetic SMA connector, necessary to achieve over-coupling.

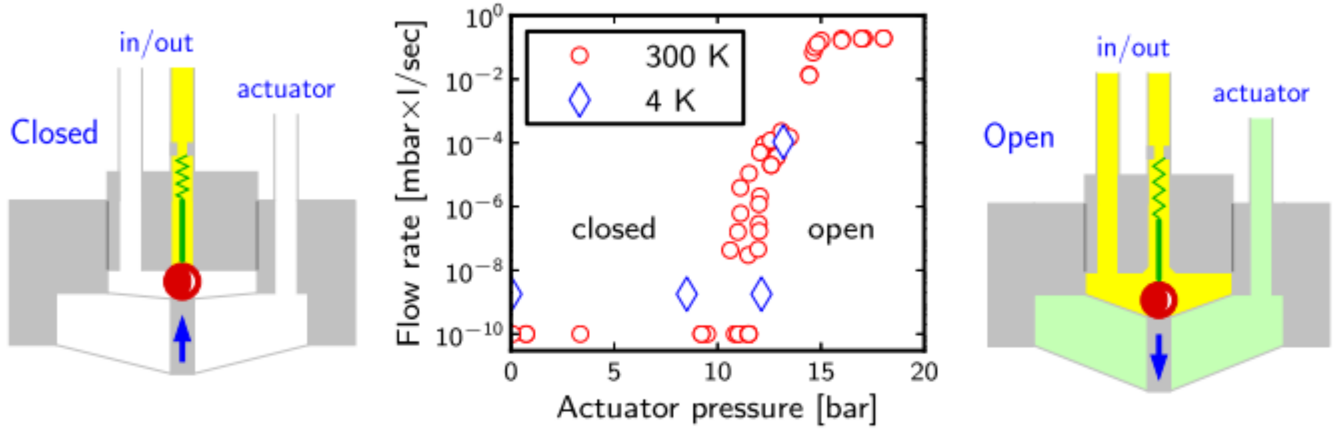


Fig. 7 Superleak-tight cryogenic valve. The seal is between a stainless steel seat and a ruby ball. The actuator with two flexible membranes pushes the ball into the seat, unless pressurised to about 15 bar, where the valve opens. This is a development of the design [48] with a micro spring added to prevent the ball from sticking to the seat. The resolution of the flow measurements was 10^{-10} and 10^{-9} mbar $\times$ l/sec at room temperature and 4 K respectively (Color figure online)

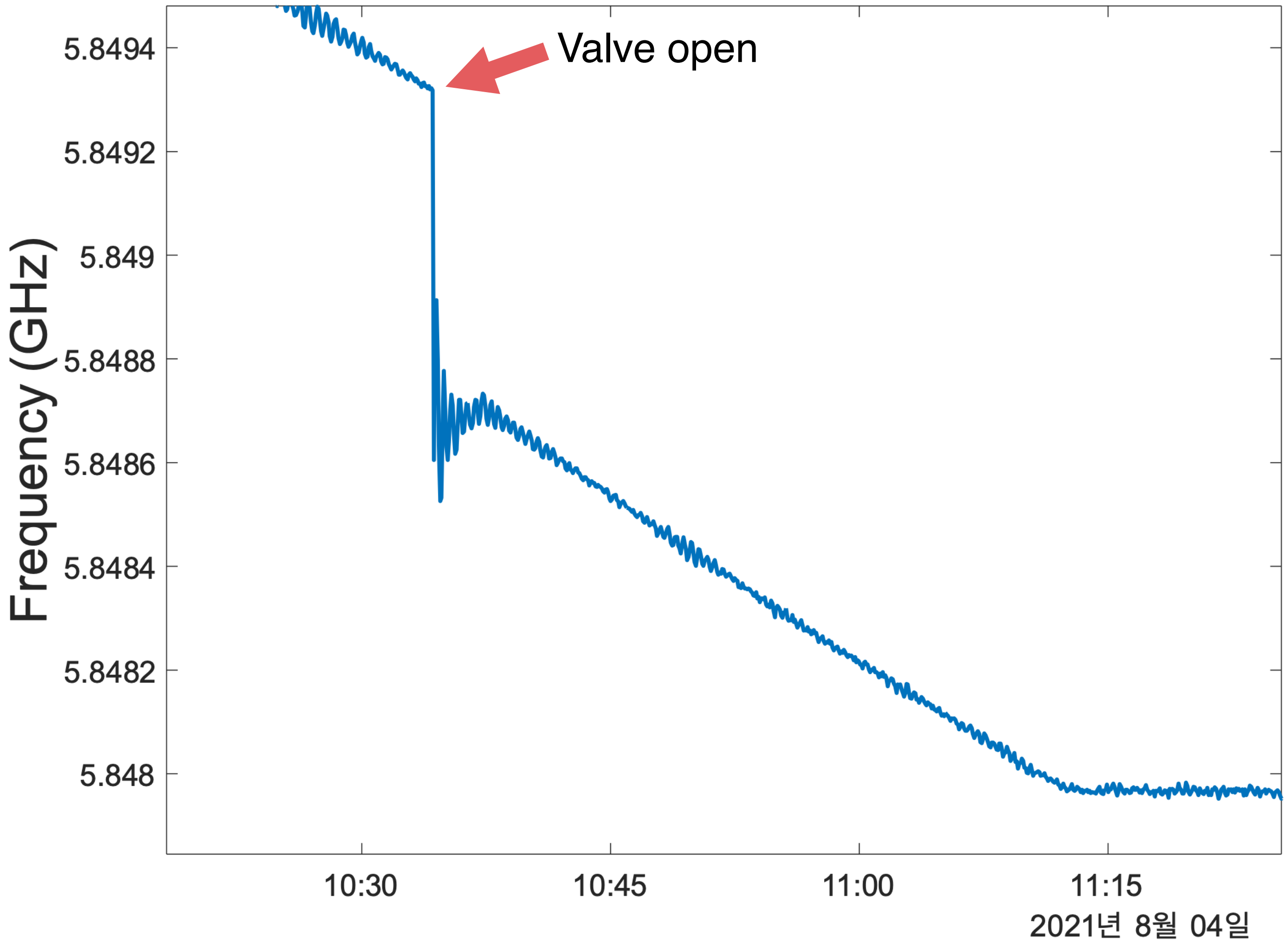
J Low Temp Phys (2014) 175:667–680
DOI 10.1007/s10909-014-1145-1

Study of Superfluid ^{3}He Under Nanoscale Confinement

A New Approach to the Investigation of Superfluid ^{3}He Films

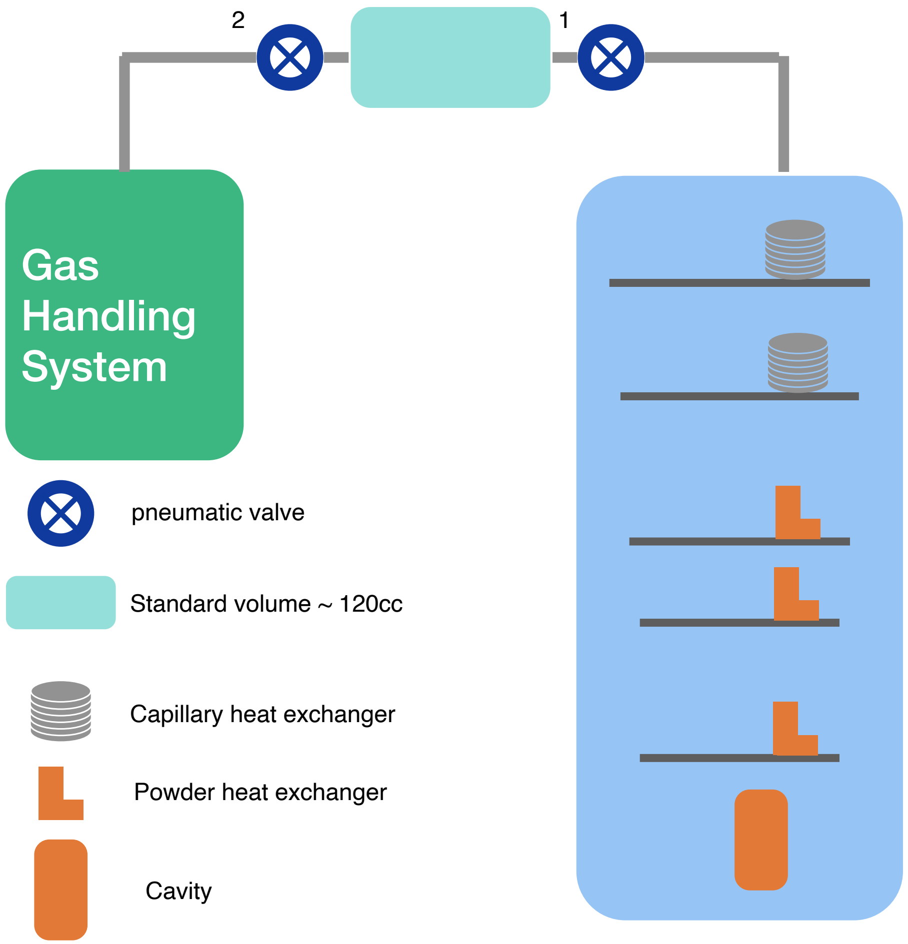
L. V. Levitin · R. G. Bennett · A. Casey · B. Cowan · J. Saunders · D. Drung · Th. Schurig · J. M. Parpia · B. Ilic · N. Zhelev

Helium Tuning : Step



Tuning Cycle

1)Open Valve 2, charge 2 bar to standard volume
2)Close Valve 2
3)Open Valve 1, 5min
4)Close Valve 1



Helium Tuning : Continuous