2024 CHiP Annual Meeting

The New AS GW Laboratory – Status and Plans

Cheng-Han Chan, Kun-Yao Chang, Dong-Yu Chen, **Hsiang-Chieh Hsu**, Hsiang-yu Huang, Yoyo Huang, You-Ru Lee, Feng-Kai Lin, Chien-Yu Lin, Yi-Shong Lin, Miftahul Ma'arif, Avani Patel, Daiki Tanabe, Vivek Kumar, Chun-Huan Wang, Zi-Yu Wang, Dennis Yu

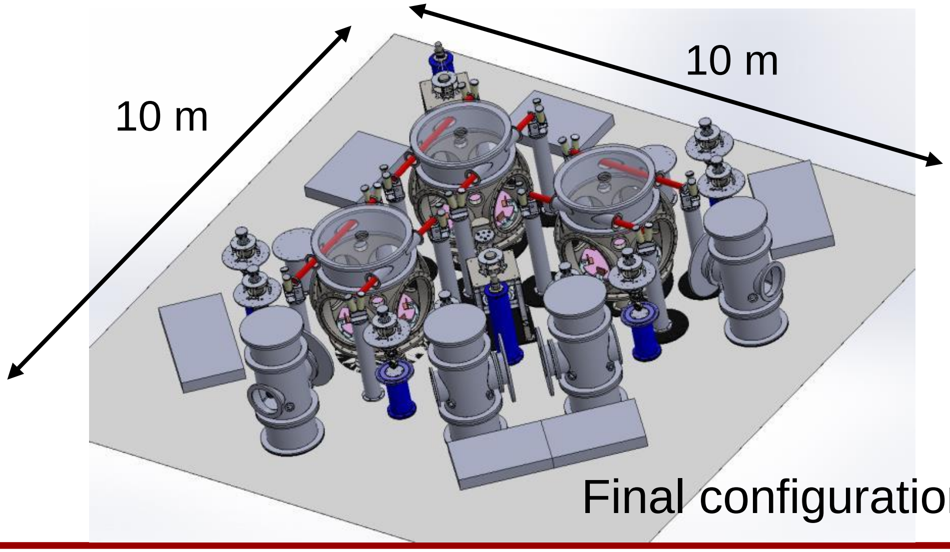
Prof. Henry Tsz-King Wong, Prof. Yuki Inoue, Prof. Shiuh Chao
ASGRAF team
2024/11/20

ASGRAF
ACADEMIA SINICA
GRAVITATIONAL PHYSICS
RESEARCH FACILITY

The New AS GW Laboratory

- **Academia Sinica GRAvitational research Facility (ASGRAF)**
- IOP B1 $10 \times 10\ m^2$, Clean Room Spec @ C-10000
- Menu (plan)
  - GW “System” Test Facility
  - Cryo & Mirror & AVIS Research
  - Move NTHU Lab
  - Future CHRONOS prototype

ACADEMIA SINICA GRAVITATIONAL PHYSICS RESEARCH FACILITY



Final configuration

Clean Room@ C-10000

Group member

- Collaboration team: AS + NCU + NTHU
- Prof. Chao retired after Jul. 2024
  - Move to ASGRAF
- A new gas line was built for LPCVD SiON fabrication in TSRI (Kun-Yao Chang's report).

AS

- **Henry Tsz-King Wong**
- Feng-Kai Lin
- Daiki Tanabe
- Hsiang-Chieh Hsu
- Vivek Kumar

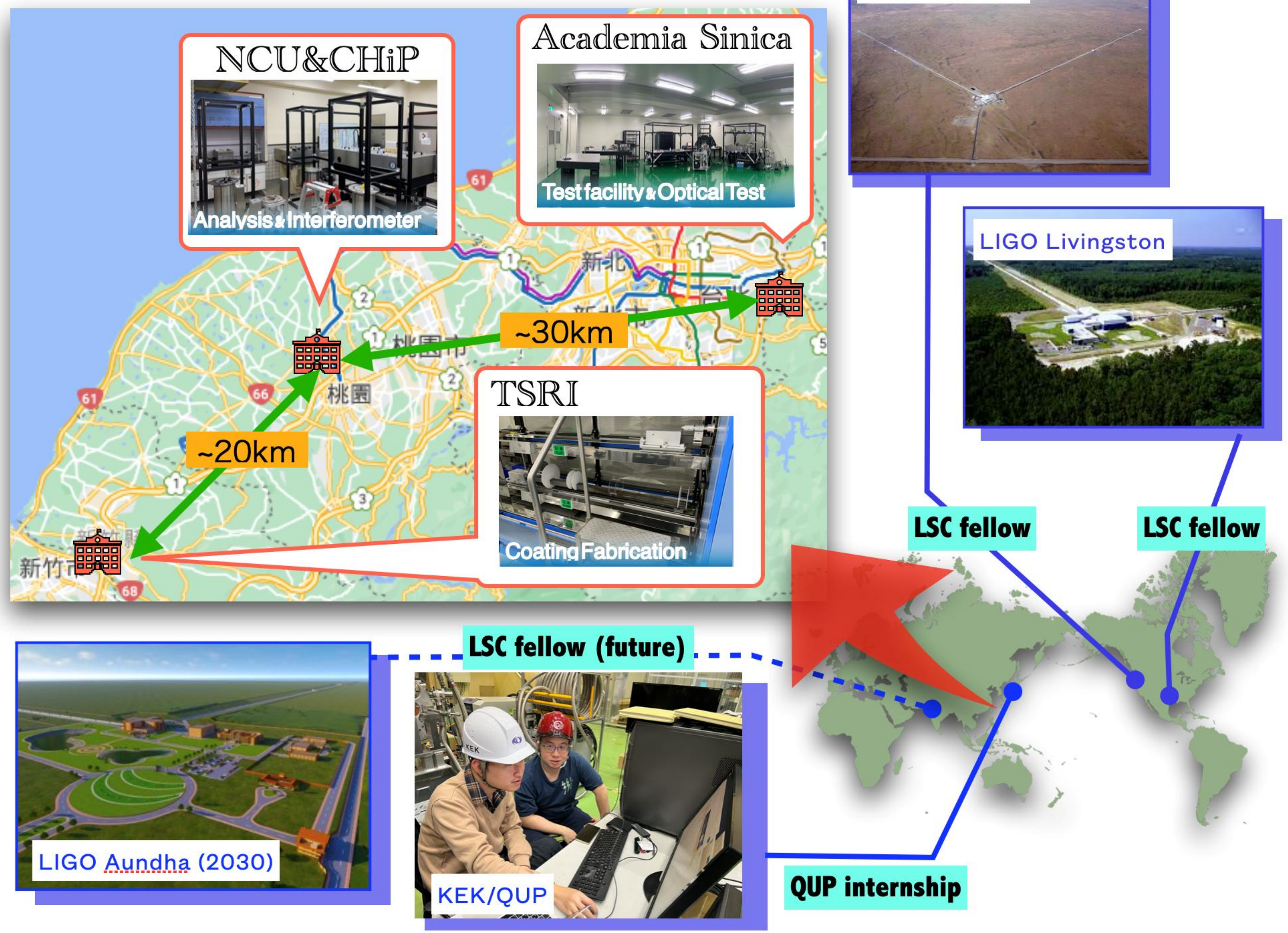
NCU

- **Yuki Inoue**
- Avani Patel
- Hsiang-yu huang
- Miftahul Ma'arif
- You-Ru Lee
- Yi-Shong Lin
- Cheng-Han Chan
- Kun-Yao Chang
- Dennis Yu
- Yoyo Huang

NTHU

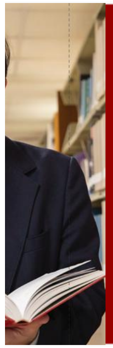
- **Shiuh Chao 趙煦 (Retired)**
- Chien-Yu Lin (Grad.)
- Chun-Huan Wang (Grad.)
- Dong-Yu Chen (Grad.)
- Zi-Yu Wang (Grad.)

Taiwan-LIGO instrumentation group and World



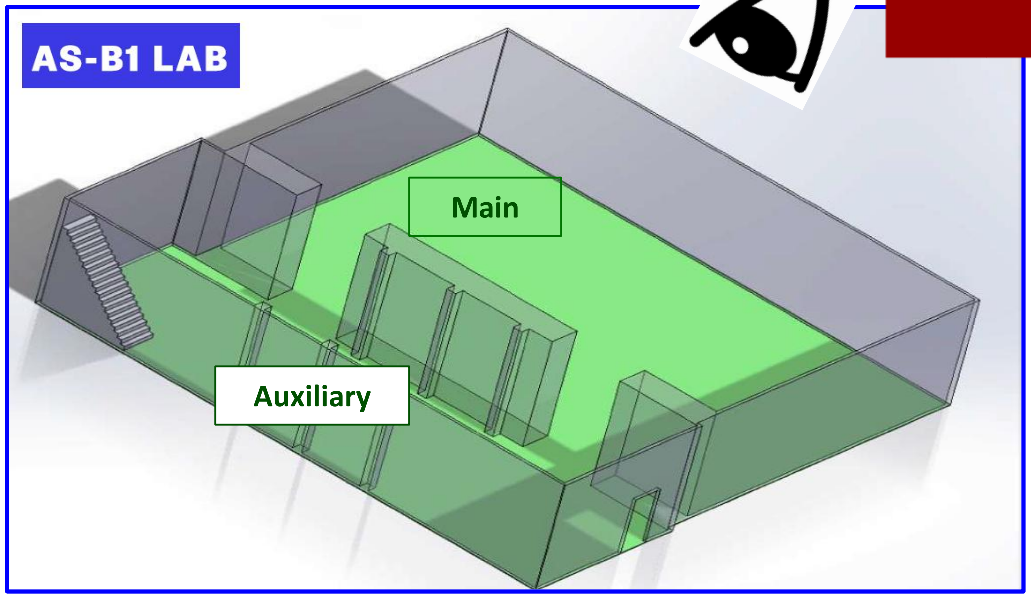
- Collab
- Prof. C
  - Move
- A new fabrica

AS

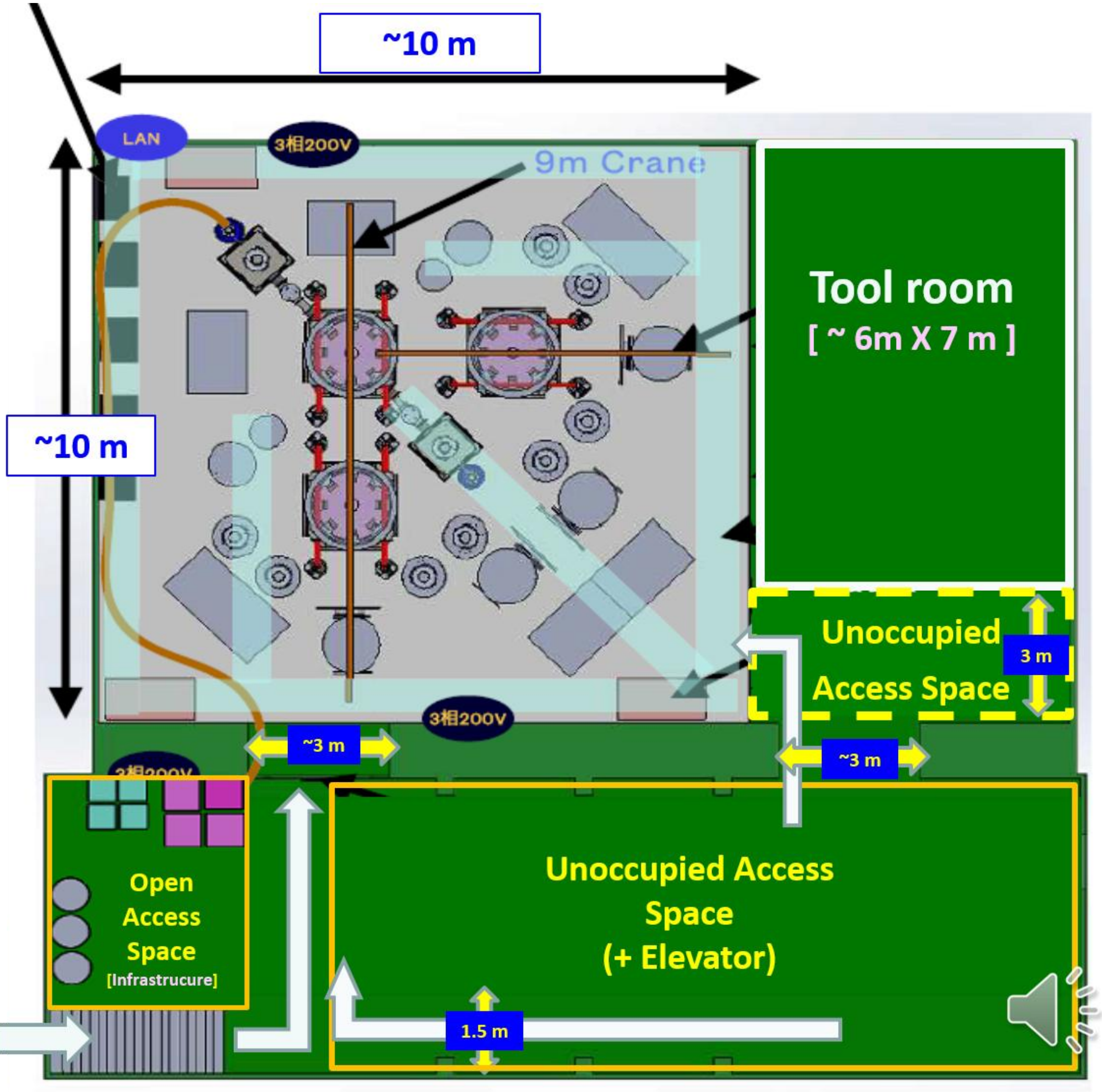


趙煦 (Retired)
n (Grad.)
Wang (Grad.)
hen (Grad.)
(Grad.)

Construction: Lab design schematic



Top View



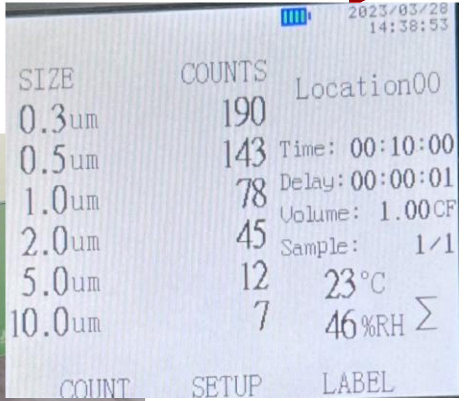
Walk-In Possible with Hand-Held Equipment

TIMELINE

2022/09: Clean old Lab

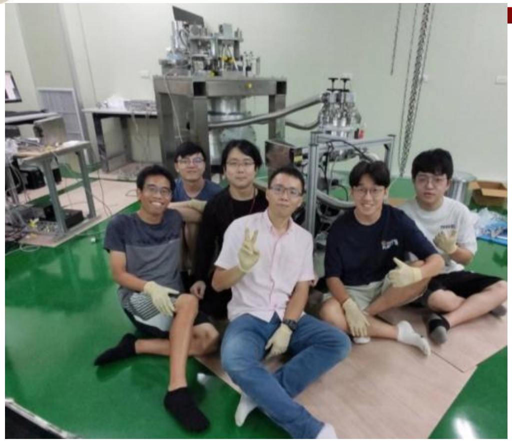
2023/01: construction

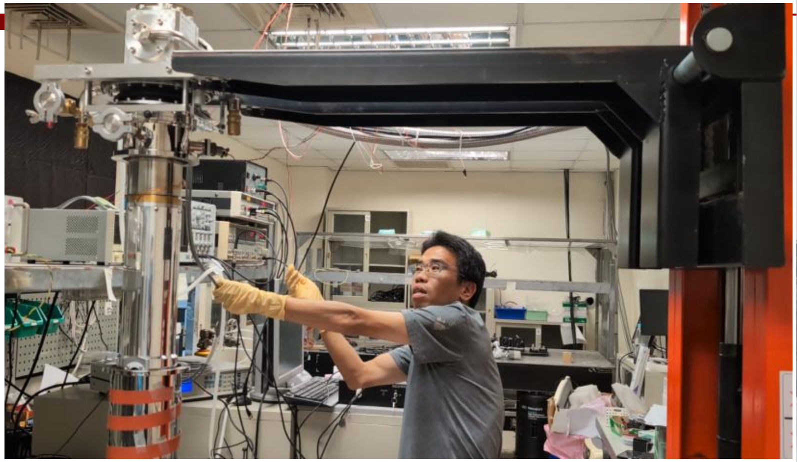
2023/03: clean room finish & testing



Class 10,000: <10,000 particles of 0.5 microns or larger/cubic foot

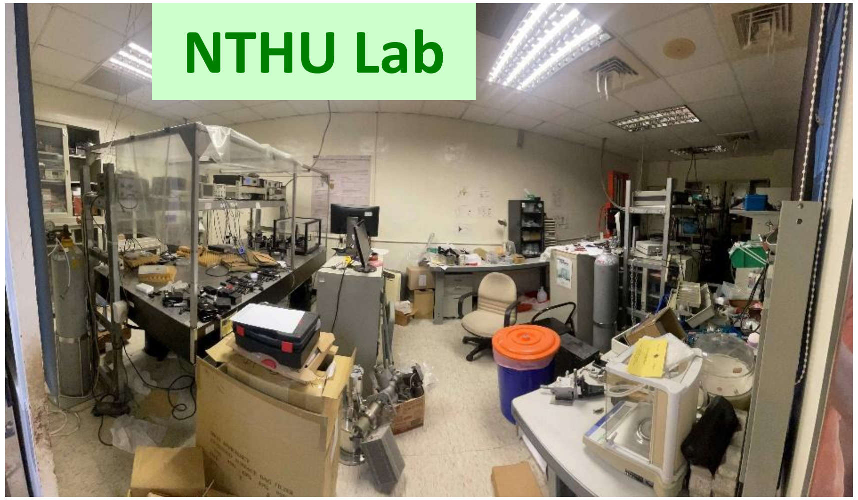
TIMELINE

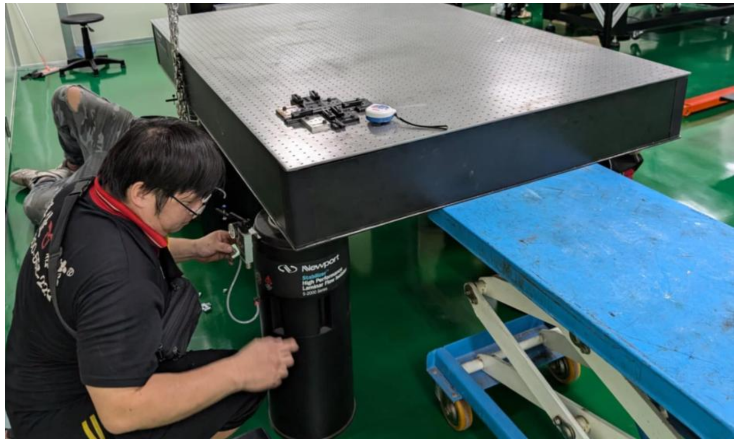




2024/05: moving instrument into Lab

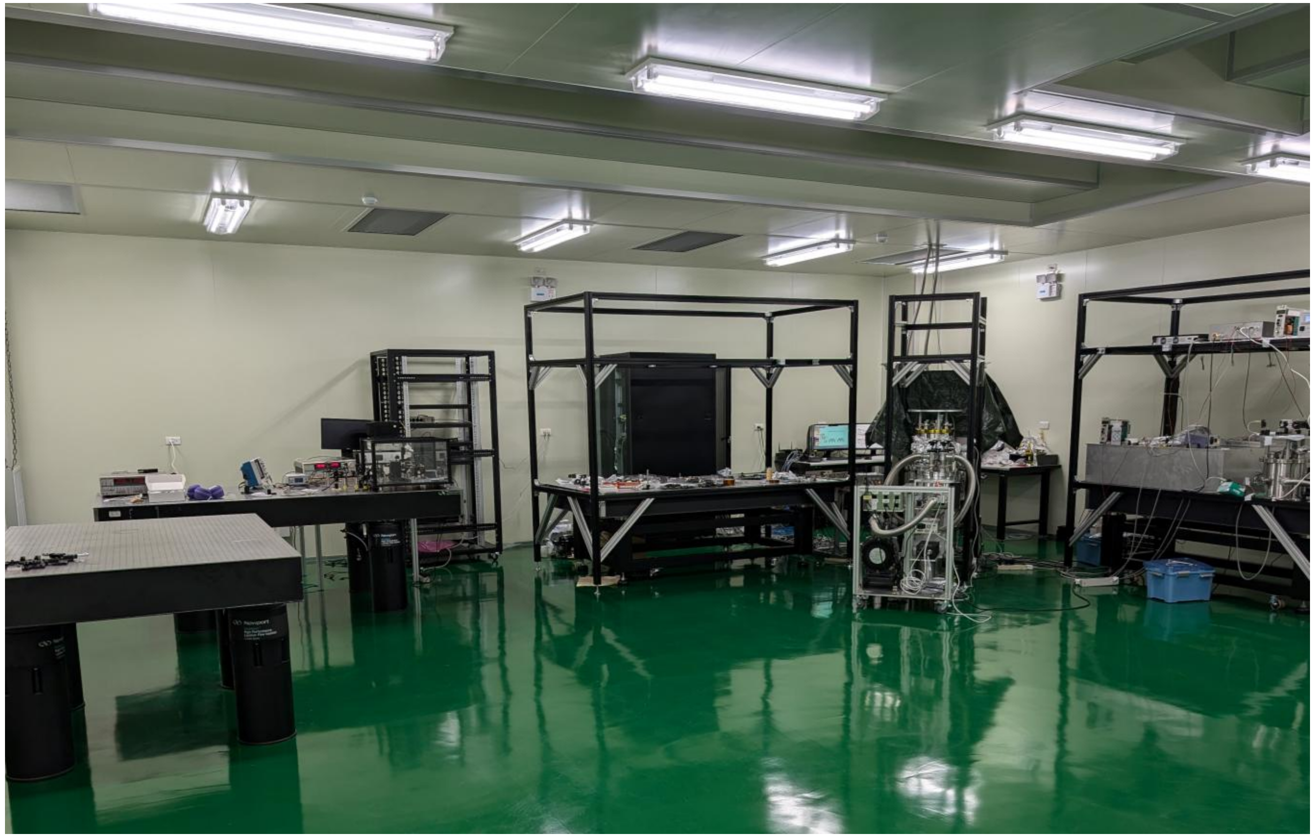
2024/10: moving NTHU Lab





Status now

Before (Sep. 2022)



Now (Nov. 2024)

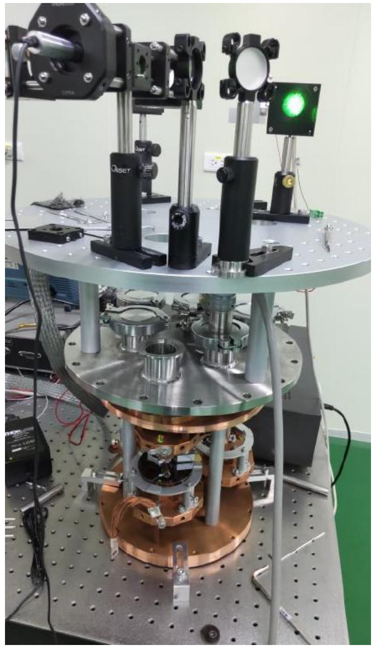
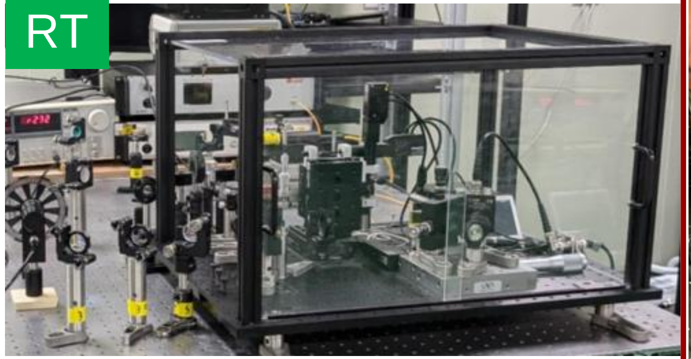
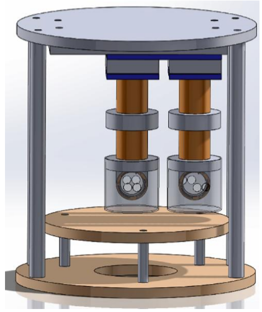
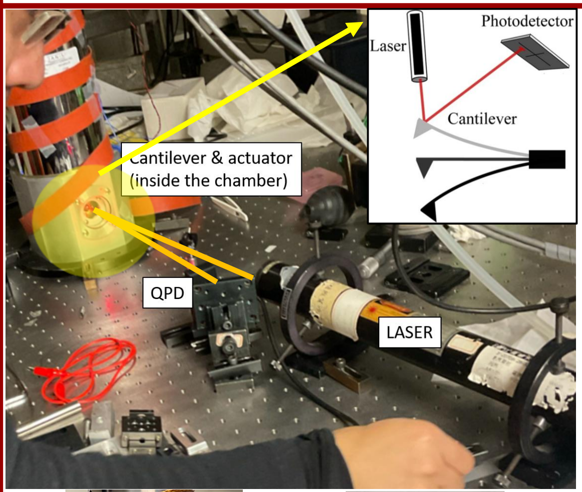
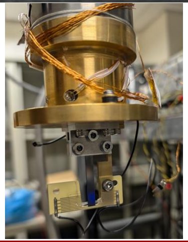
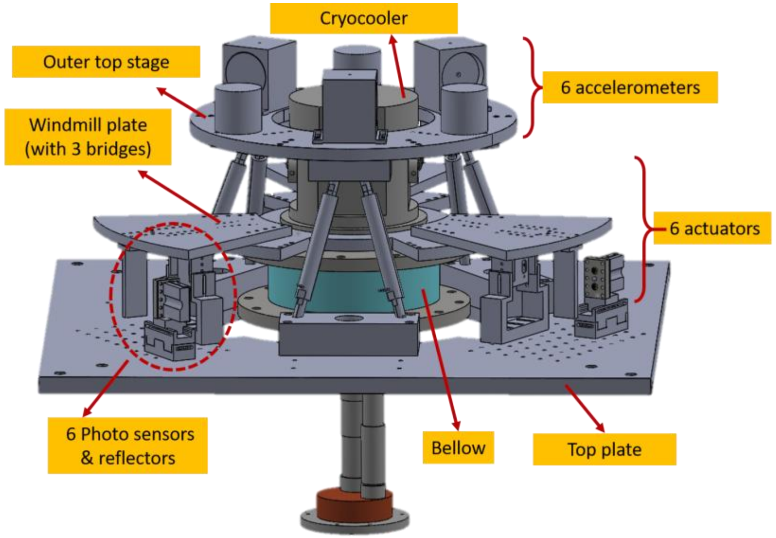
Instruments now

- Loss measurement: 3 Machine (**Cantilever**, **GNS**, **PCI**) * 2 version (RT/Cryo): 6 in total

(**GNS**: **G**entle **N**oodle **S**uspension; **PCI**: **P**hotothermal **C**ommon-path **I**nterferometry)

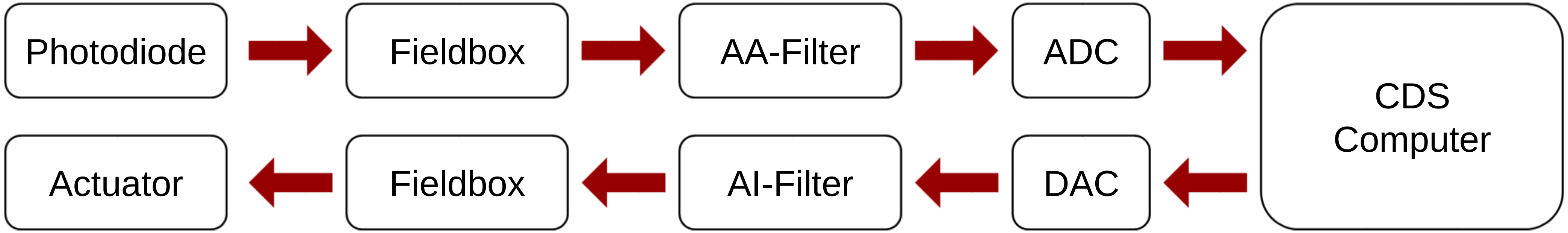
- **A**ctive **V**ibration **I**solation **S**ystem (**AVIS**)

■ : Newly developed system
■ : Legacy system from NTHU

RT/Cryo-GNS	RT/Cryo-PCI	RT/Cryo-Cantilever	AVIS
	RT  Cryo 	  	

Control and Data System

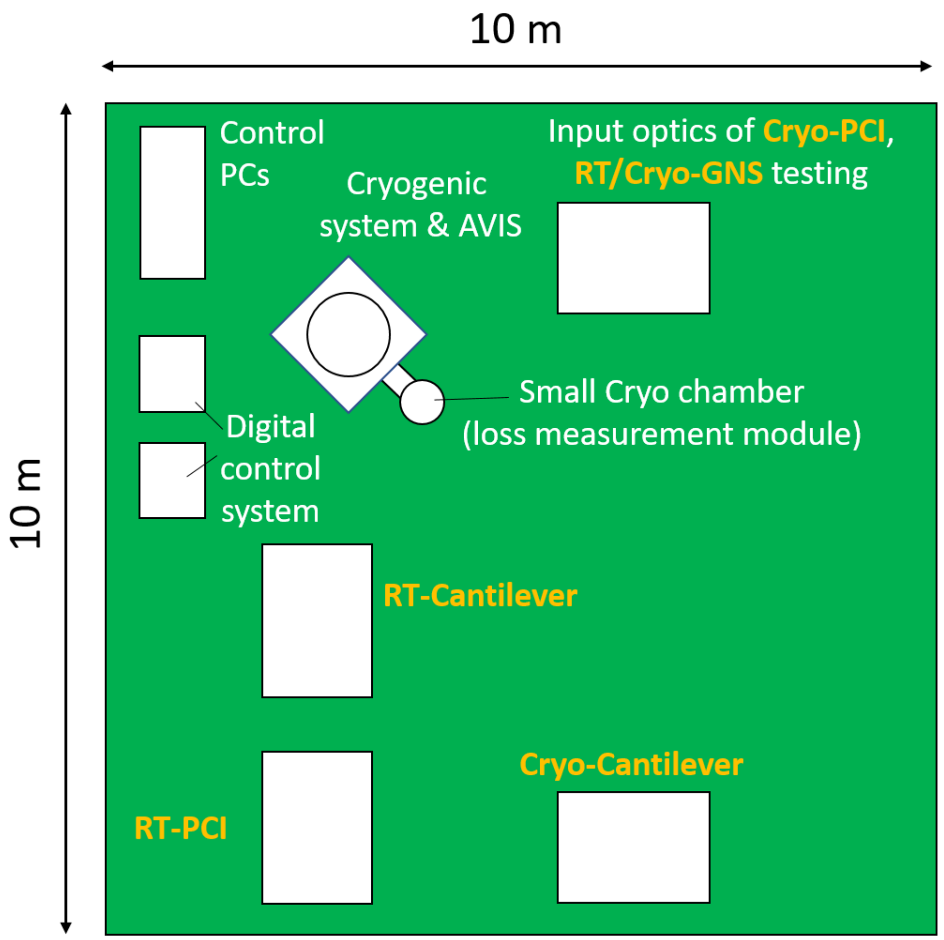
- Many sensors and actuators: **C**ontrol and **D**ata **S**ystem (**CDS**) by LIGO
- **Hardware**: To form multiple-input multiple-output control loops
  - DAC, ADC
  - PCIe extension board, I/O board and timing board connecting with Standalone system
  - AA and AI filters
- **Software**: based on a real-time enabled Linux operating system
  - **E**xperimental **P**hysics and **I**ndustrial **C**ontrol **S**ystem (**EPICS**): operators control screens and channel access
  - Matlab/Simulink tools: workflow for a digital control circuit.
  - Creating a real-time kernel module from this circuit model by Matlab/Simulink, and control the module via EPICS



*Fieldbox: pre-processes the signal.

Status of the lab

- 3 Machine * 2 version + 1: 7 in total



Mechanical Loss

	Room Temperature (RT)	Cryogenic (~4K)
3-inches silicon Wafer	• RT-Gentle Nodal Suspension (RT-GNS) • 3 NTHU Master's Theses	• Cryo-GNS • Cooling down…
Cantilever	• RT-Cantilver • Moved from NTHU: taking data…	• Cryo-Cantilever • Moved from NTHU: under assembly.

Optical Loss

	Room Temperature (RT)	Cryogenic (~4K)
1-Inch Quartz Substrate	• RT- Photothermal Common-path Interferometry (RT-PCI) • Moved from NTHU: under recovery	• Cryo-PCI • Under development, by Mar. 2025

Summary

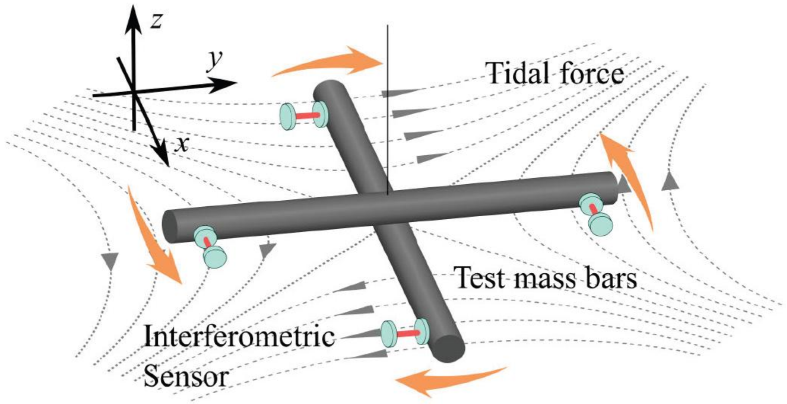
- From 2022 to the present, we have been establishing a lab for GW research and the characterization of cryogenic mirror coatings
- NTHU Lab (Prof. Chou retired in 2024) has already moved to ASGRAF
- AVIS for the cryogenic system is developed
- For loss measurement, we have RT/Cryo-[Cantilever, GNS (Mech.), PCI (optical)], 6 machines in total

	2024 Sep.	2024 Oct.	2024 Dec.	2025 Mar.
RT-Cantilever	Validation	Run		
Cryo-Cantilever		Move	Run	
RT-GNS	Noise study	Run		
Cryo-GNS		Cooling test	Run	
RT-PCI		Move Assembly	Run	
Cryo-PCI		Input optics	cooling test	Run

Backup

ASGRAF

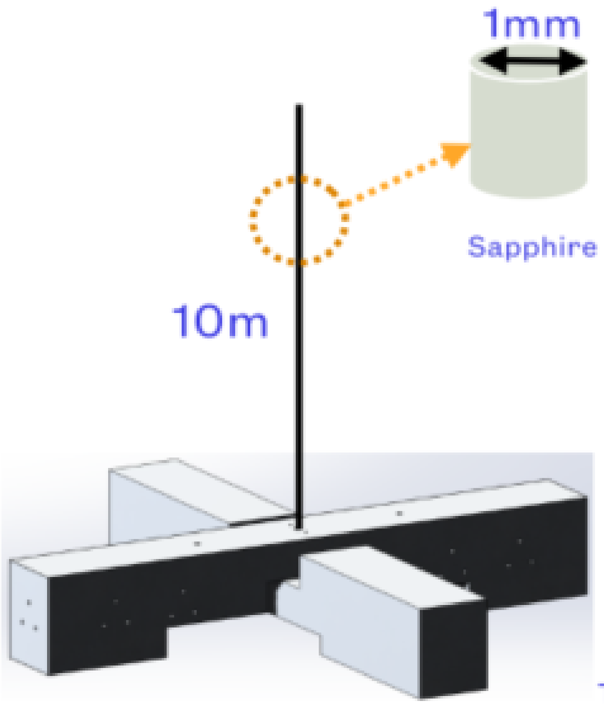
- Academia **S**inica **GRA**vitational physics research **F**acility (**ASGRAF**)
- Laboratory at the basement of ASIoP ($10\text{m} \times 10\text{m}$)
- Target: **Sub-Hz region**
- **3** key **technologies**:
  - Two **cross bar-shape** test masses (torsion bars)
    → System to be measured
  - Speed meter (**sagnac** interferometry)
    → Measuring apparatus
  - **Cryogenic** technology

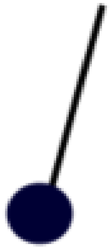
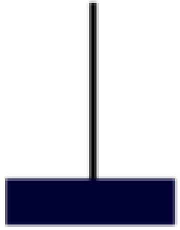


Credit: T. Shimoda, TOBA

Cross-Torsion Bar

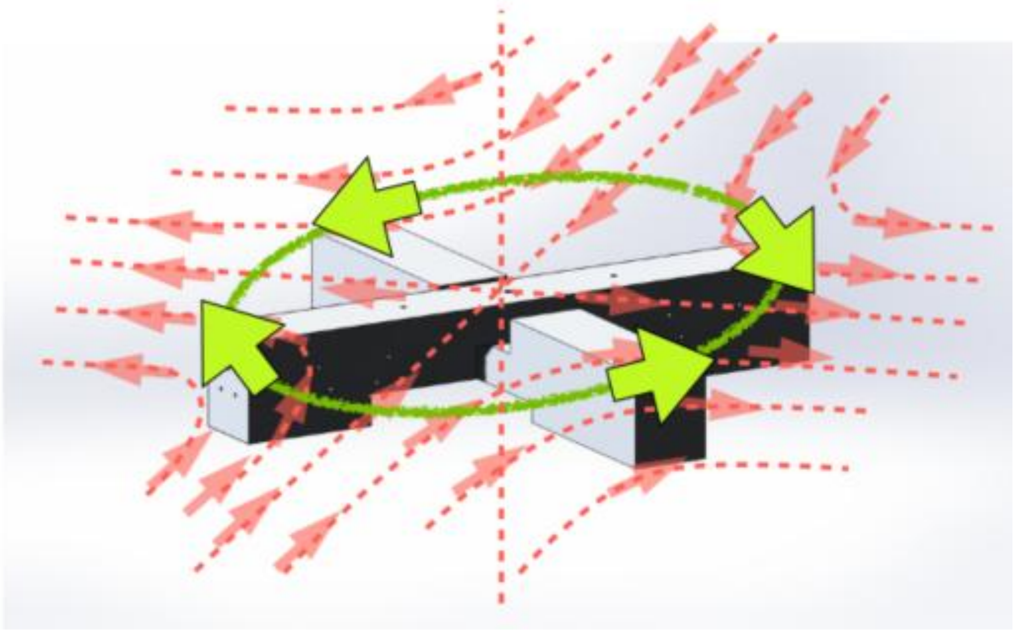
Resonant frequency

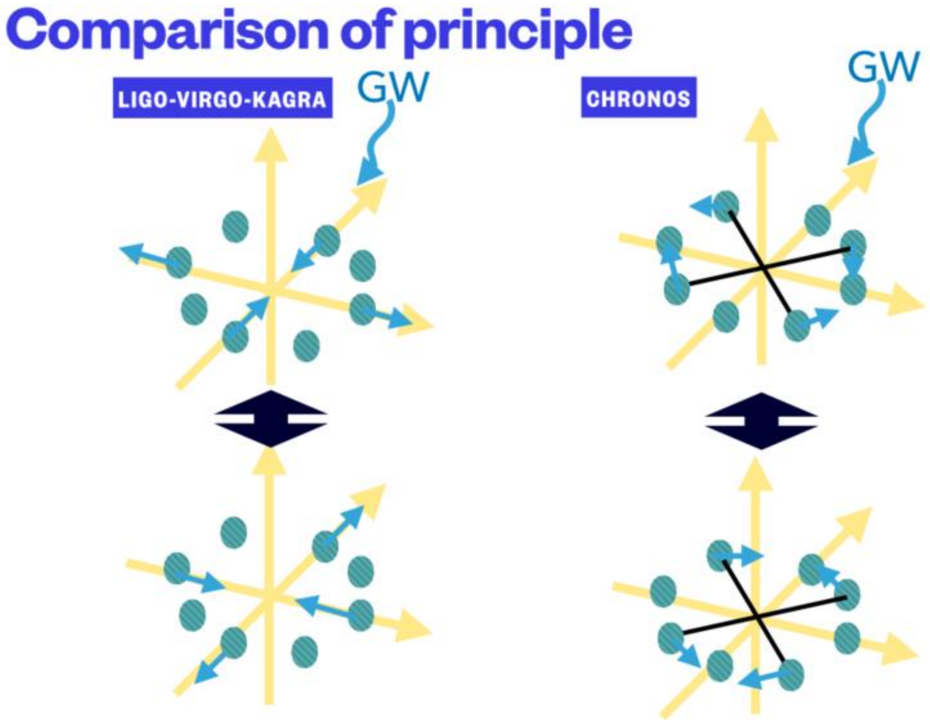


	LVK	CHRONOS
type	 Pendulum	 Torsion bar
EOM	$m\ddot{x} + c\dot{x} + kx = F$	$I\ddot{\theta} + \Gamma\dot{\theta} + \mu\theta = \tau$
Resonant Freq.	$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$	$f = \frac{1}{2\pi}\sqrt{\frac{\mu}{I}}$ $\mu = \frac{\pi G r^4}{2l}$ $G = \frac{E}{2(1+\nu)}$
Typical value (l=10m, d=1mm)	0.15Hz	0.004Hz

We can dramatically reduce resonant frequency

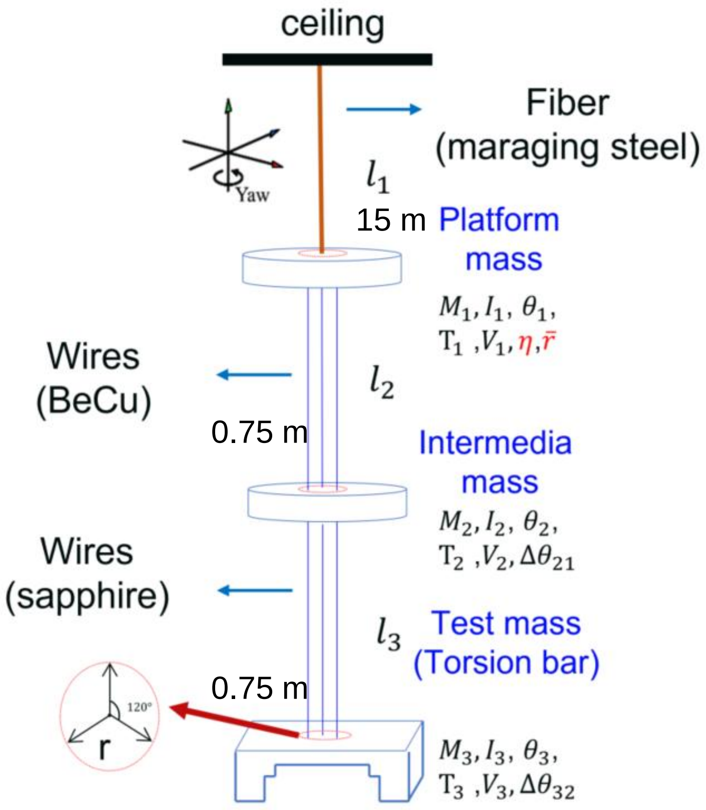
Cross-Torsion Bar





- Metric perturbation (GW) changes the relative angle of cross-bars
- By measuring relative angle, we can reconstruct the gravitational waveform, h(t).

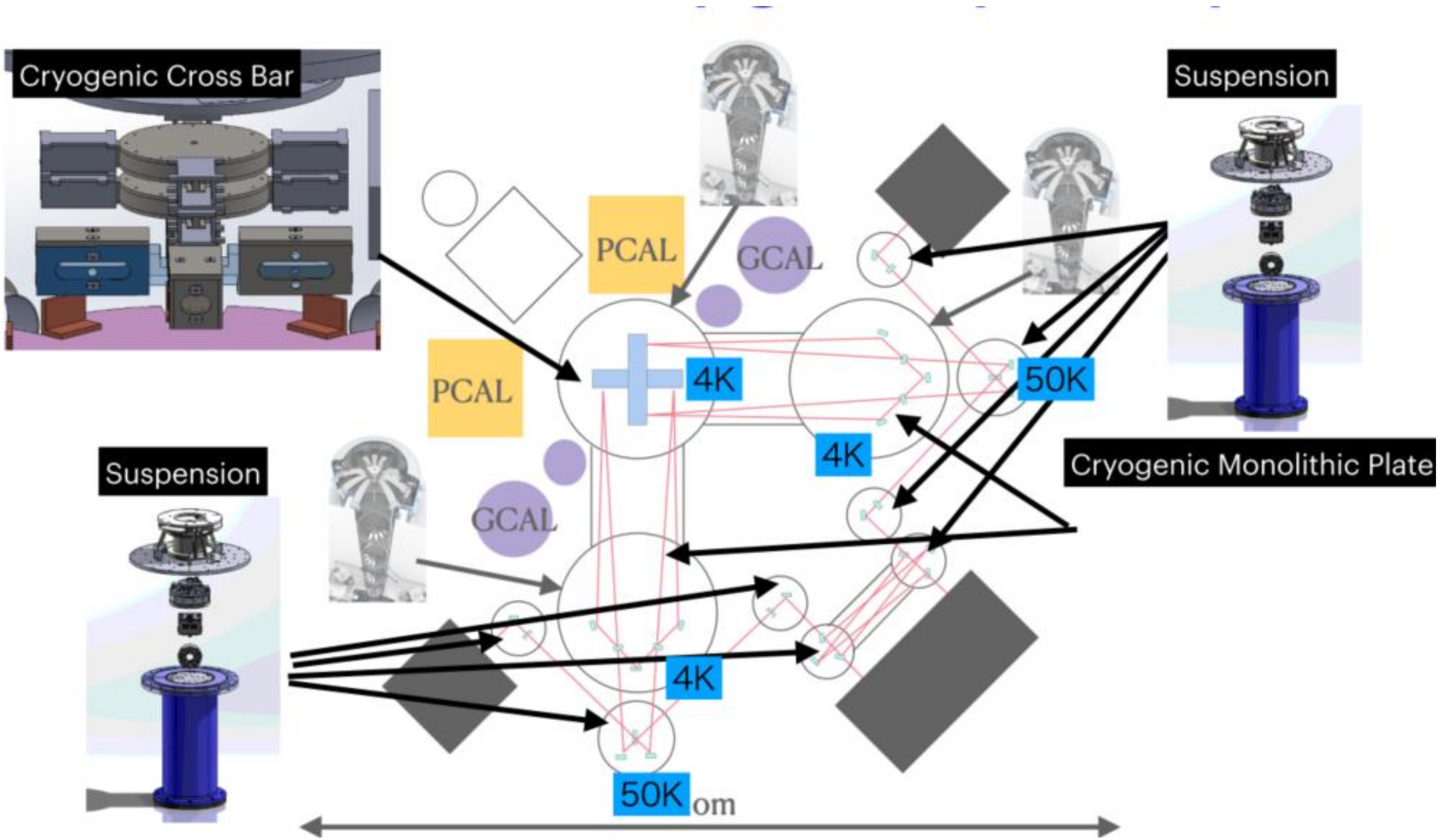
Design parameters



M : Mass
I : Moment of inertia
l : length of wires
θ : Angle of Yaw rotation (w.r.t the ceiling)
T : kinetic energy
V : potential
r : Distance between the center and wires
$\bar{r}$: radius of Fiber
η : Modulus in Torsion (shear modulus)
$\Delta\theta_{21}$: $\theta_2 - \theta_1$
$\Delta\theta_{32}$: $\theta_3 - \theta_2$

- Resonance Freq.
  - $f_1 = 0.004$ Hz
  - $f_2 = 0.107$ Hz
  - $f_3 = 0.047$ Hz
- We focus on the sub-Hz region
  - Bridge LISA (<0.01 Hz) and LIGO (>10 Hz)

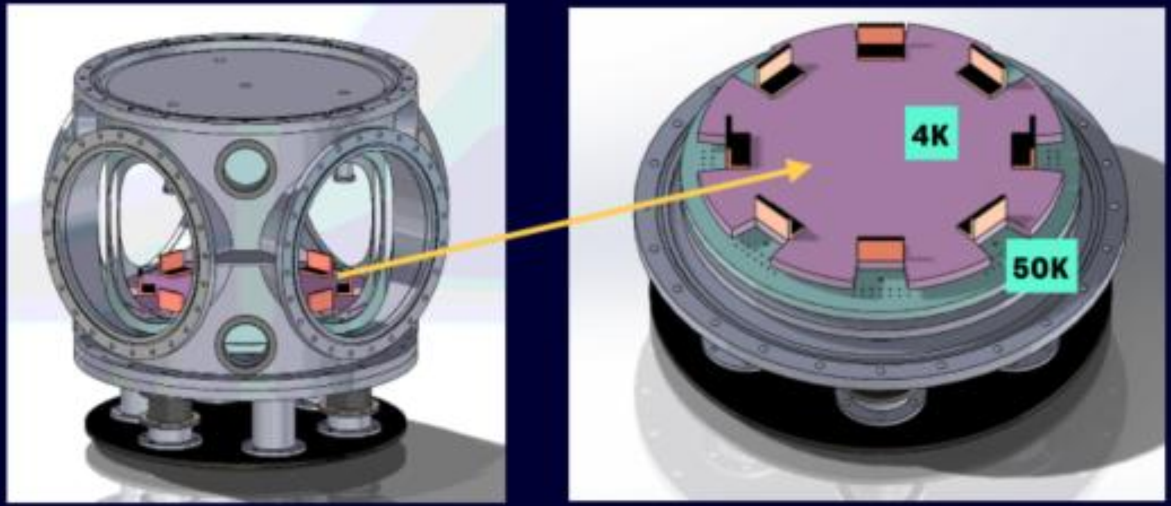
Configuration



Cryogenics for large chamber

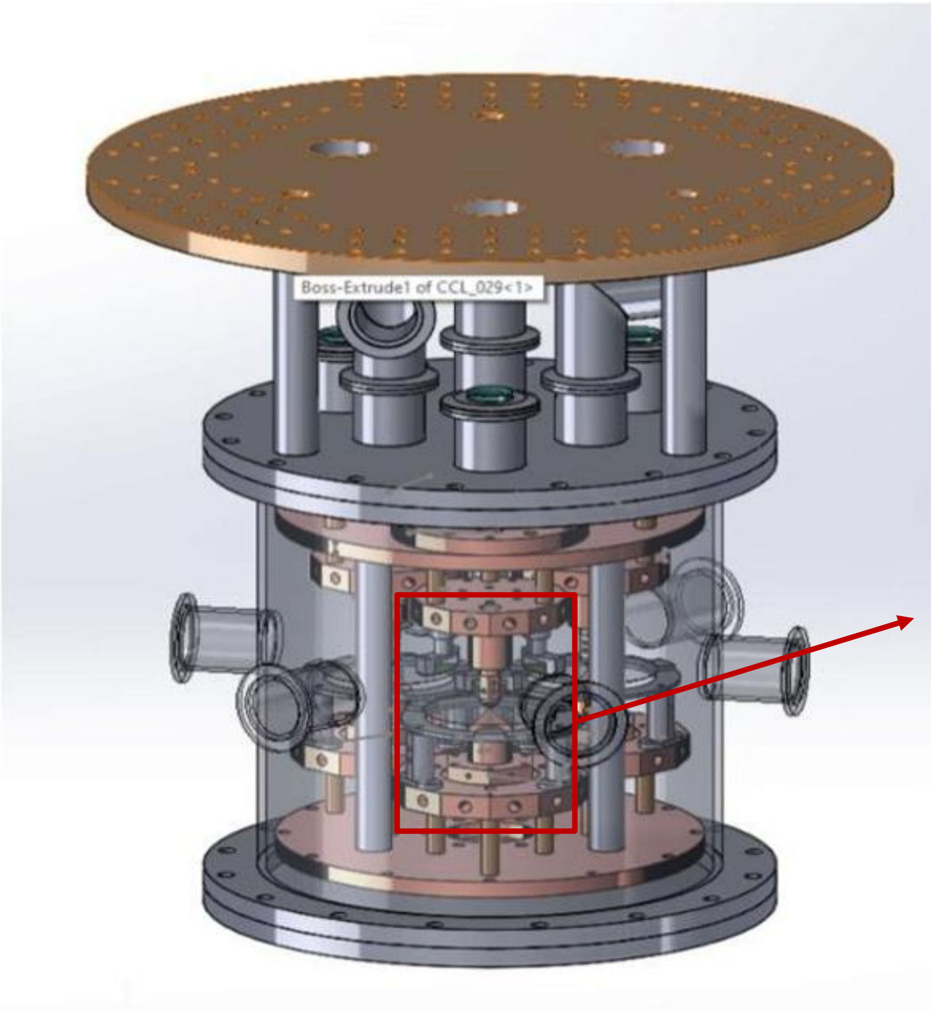
Temperature of large chamber

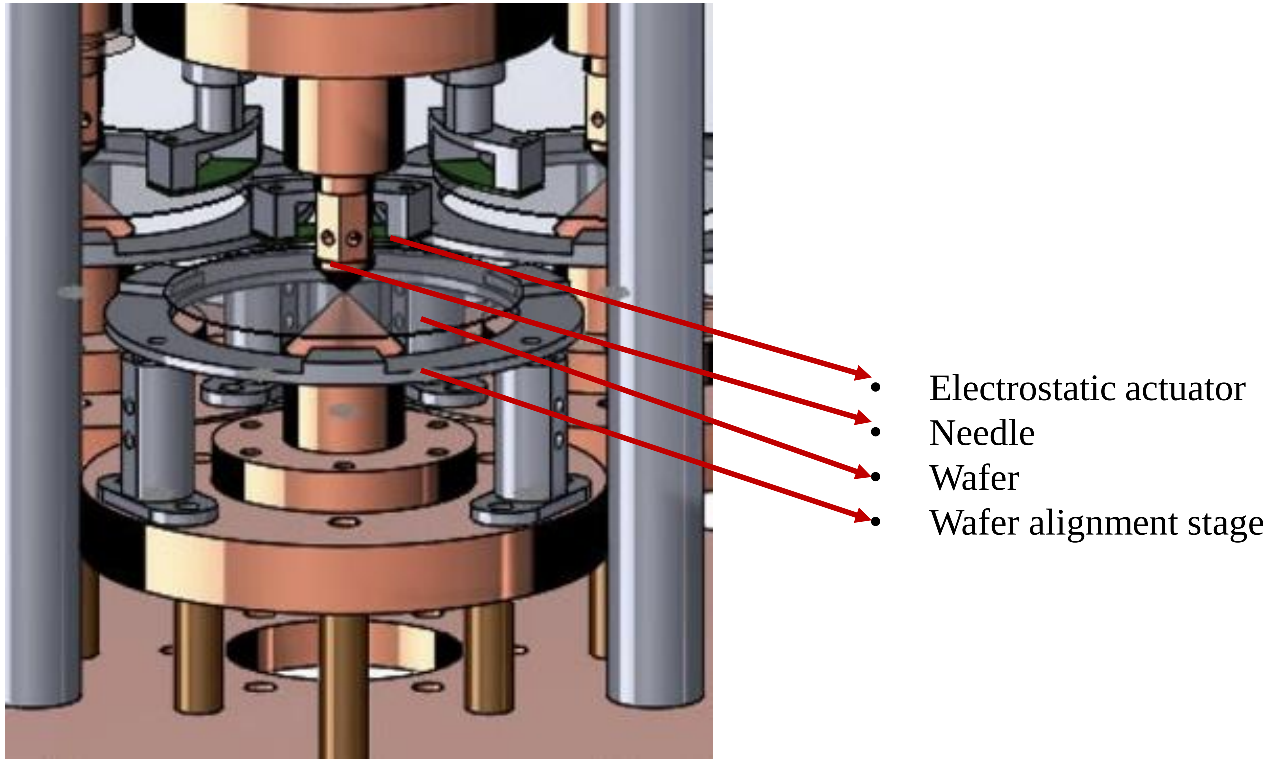
We need to achieve the 4K temperature at main stages. We need to reduce the thermal loading and establish the heatlink technology with pure aluminum wire.



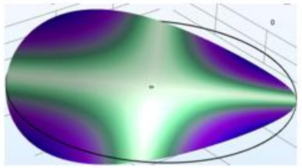
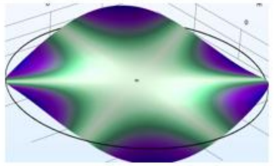
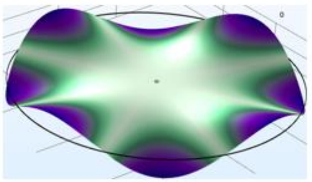
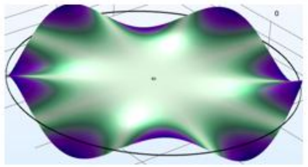
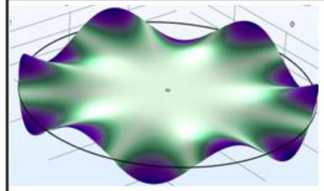
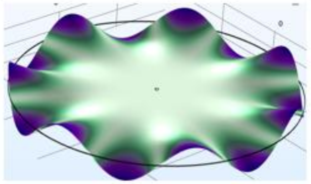
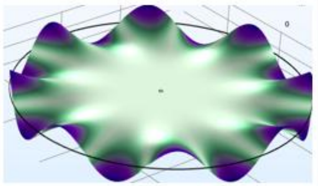
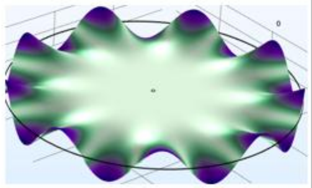
System setup

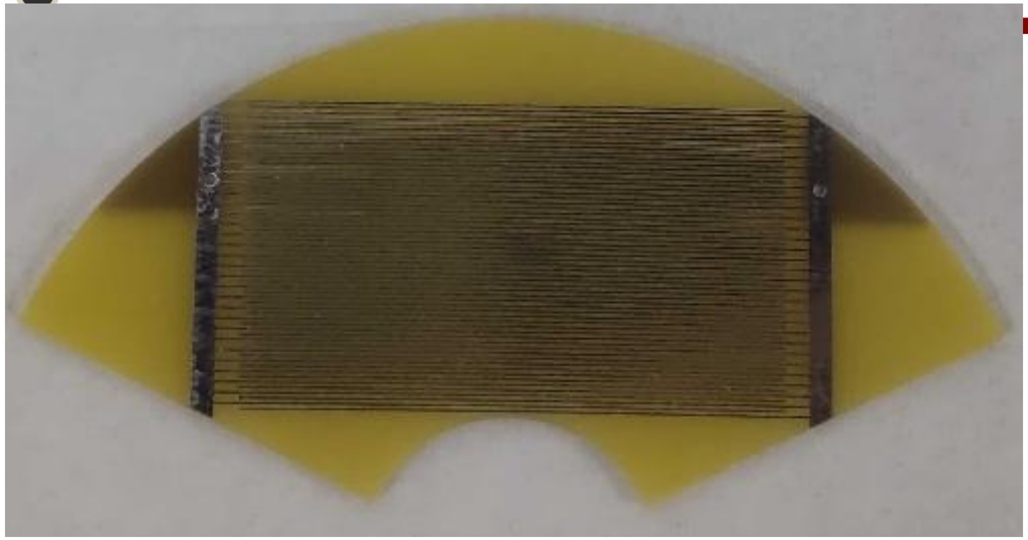
- Design for 3-inch size wafer measurement
- Contains three nodal suspensions, which can perform uncoated wafer measurement, coated wafer measurement, and temperature monitoring at the same time



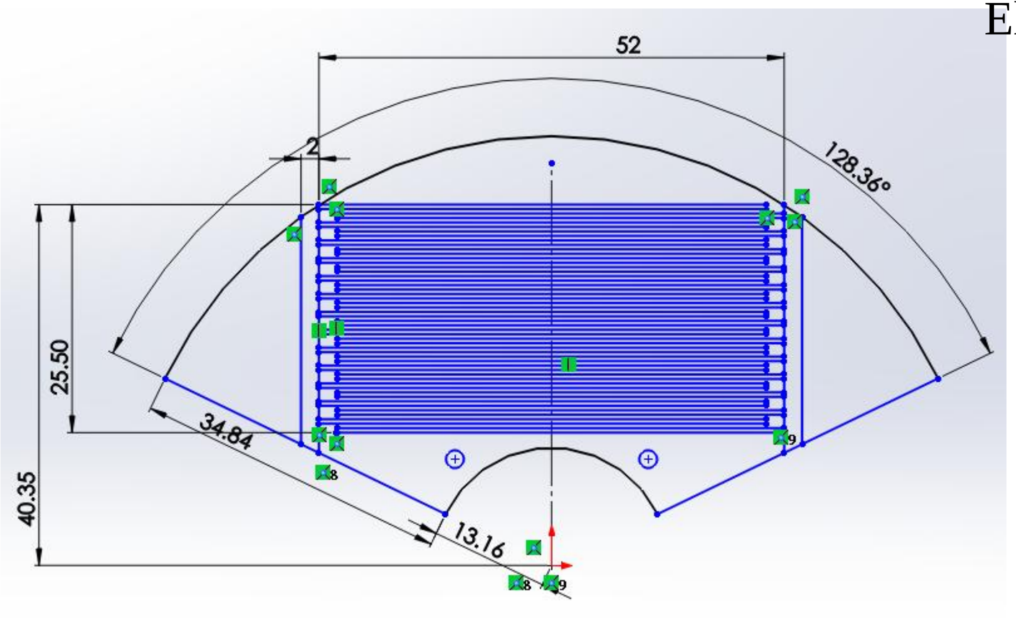


Wafer With $200um$ thickness

305.5Hz	707.5Hz
	
1240.5Hz	1901.5Hz
	
2688.1Hz	3598.7Hz
	
4632.4Hz	5788.2Hz
	



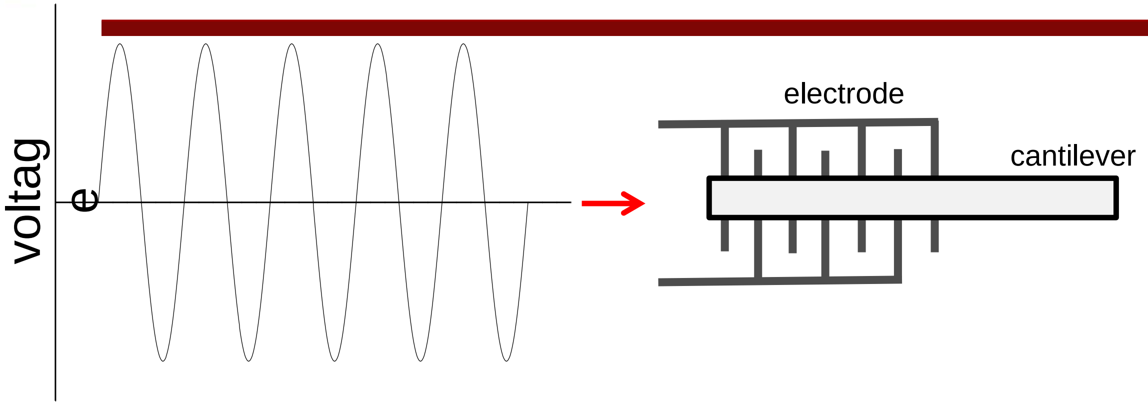
Electrostatic actuator

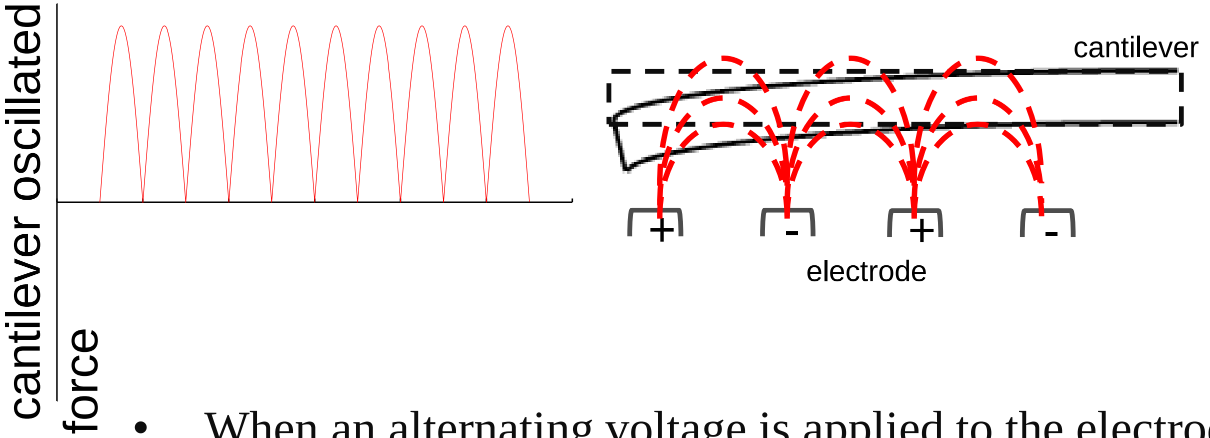


Dimension of Actuator	
1.Comb length (Lc)	50mm
2. Comb Width (Wc)	0.25mm
3. Gap between moving comb and fixed comb (g)	0.1mm
4.Overlapping area (y0)	48mm
5. Thickness of Actuator (t)	30um~35um
6. No. of Moving combs (n)	26

$$C = \frac{2n\varepsilon_0 t y_0}{g}$$
$$= 6.629 \times 10^{-12} (\mathrm{C/V})$$

Electrostatic actuator





The relation between force, capacitance and electric field is given below.

The relationship between electric field and force:

$$F = Q \times E$$

The relationship between capacitance and charge:

$$Q = C \times V$$

The relationship between voltage and electric field:

$$E = V \div d$$

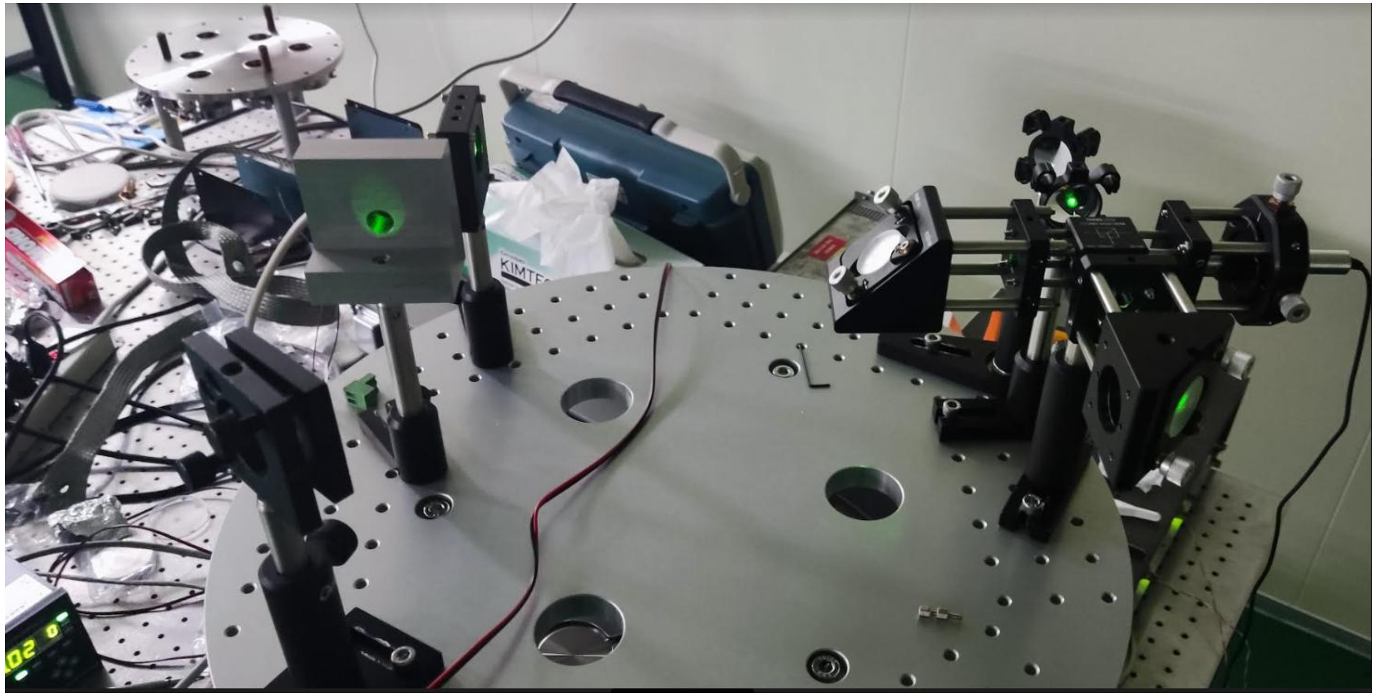
$$\rightarrow F = CV^2/d$$

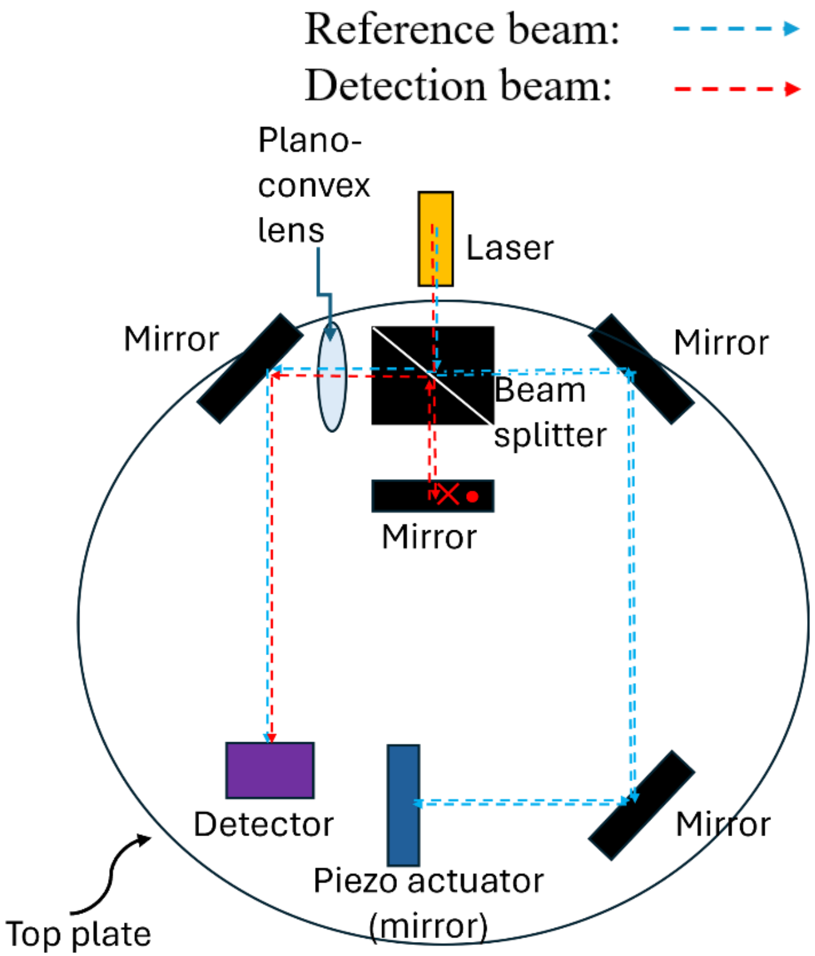
- When an alternating voltage is applied to the electrode plates, an electric field is generated between the electrodes. The cantilever will experience an attractive force due to this electric field, causing it to move towards the electrode plates.

(Dielectric polarization)

Optical measurement system

Use Michelson interferometer to measure the vibration.
Use piezo actuator to lock the system.
Use convex lens to help us find the interference.

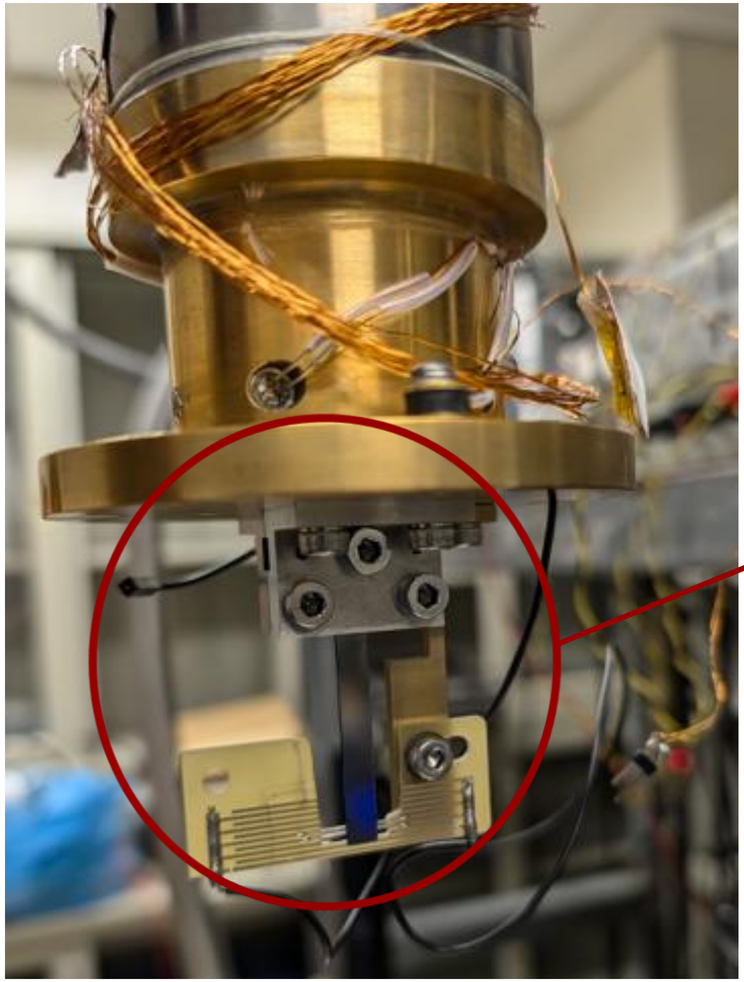


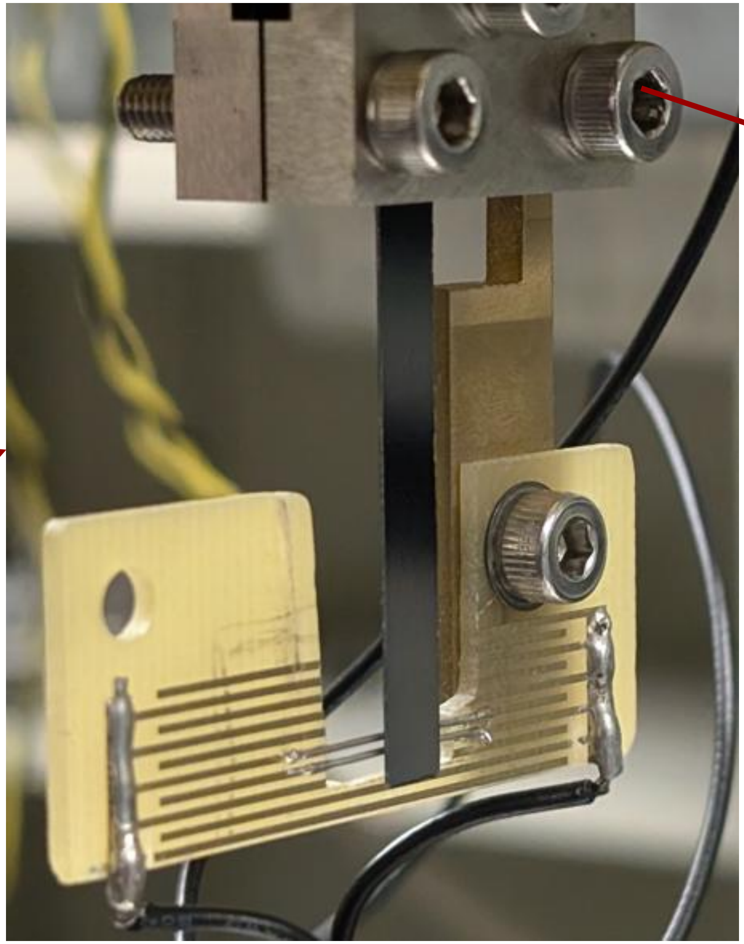


Optical path diagram

Mechanical Loss (Structural Loss)-2

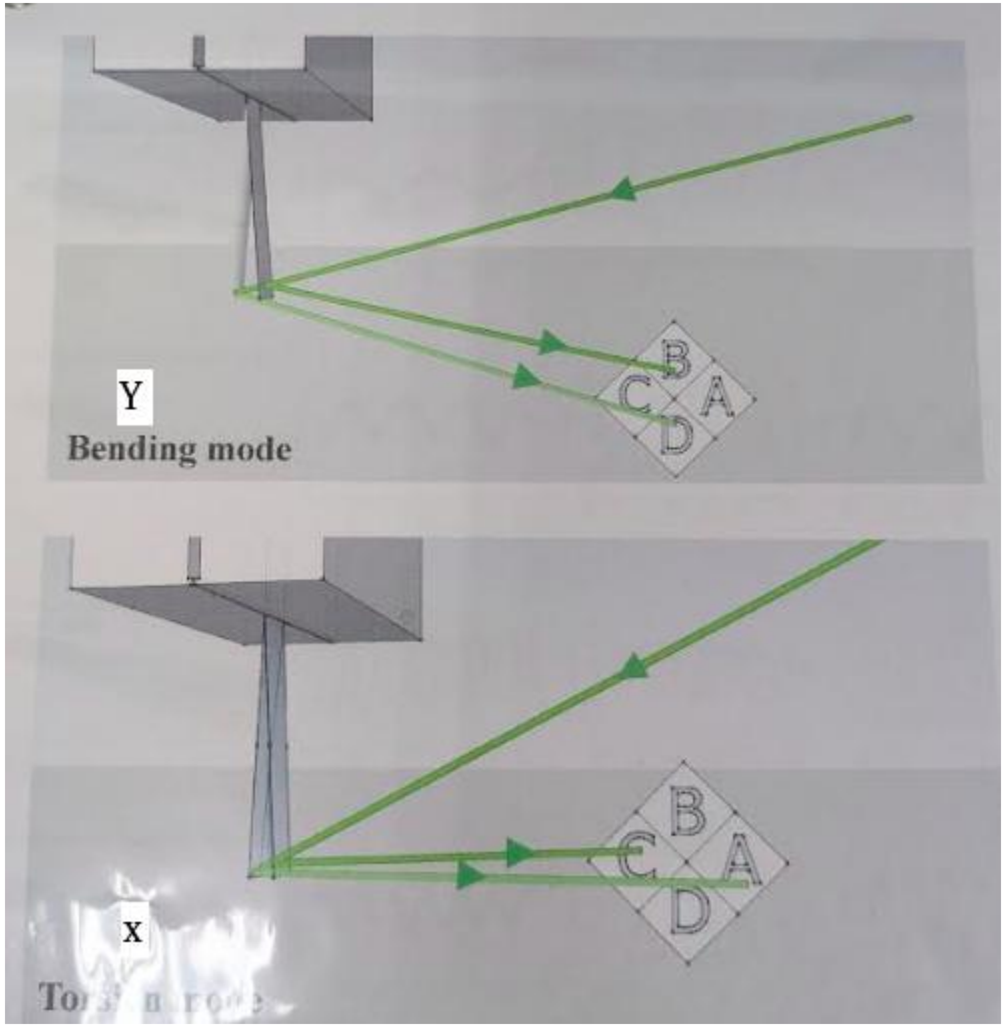
- RT/Cryo - **Cantilever**

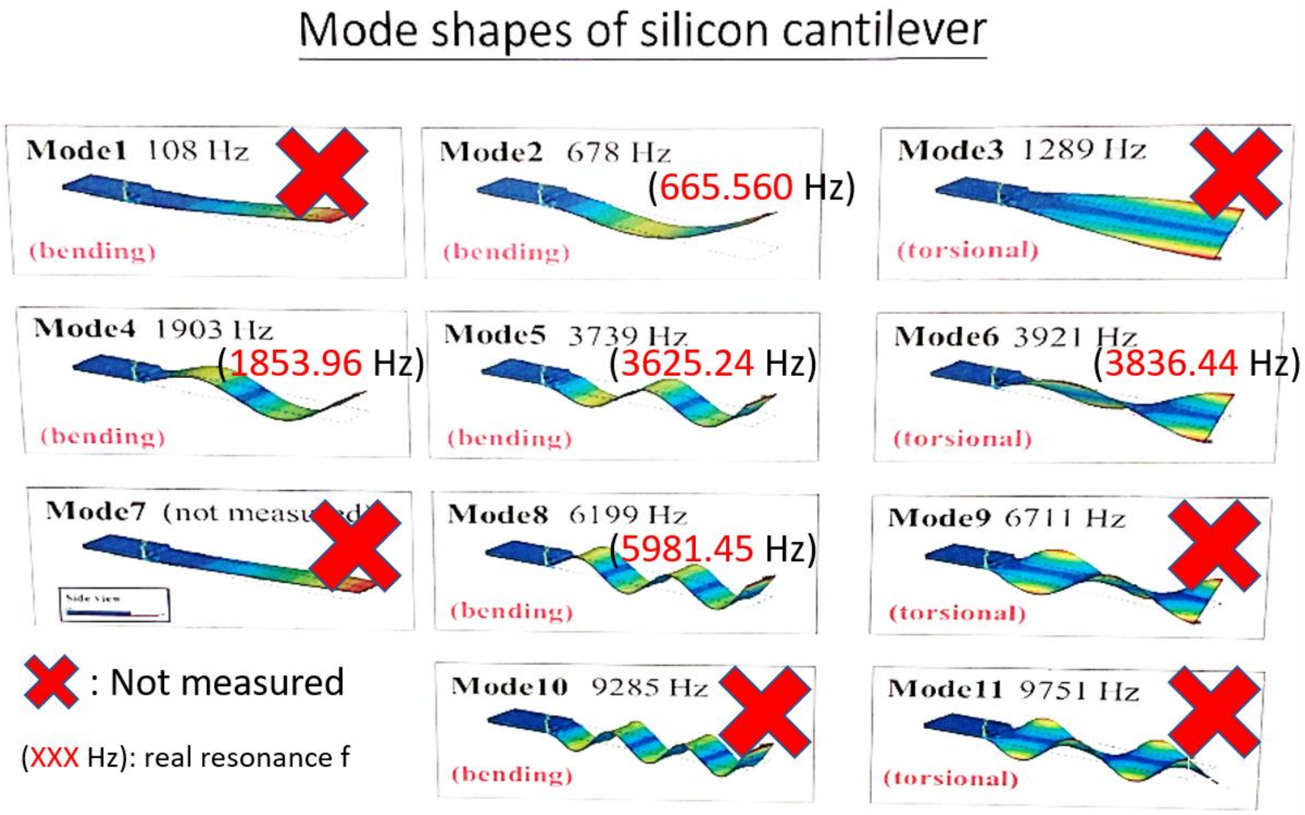




Mechanical Loss (Structural Loss)-2

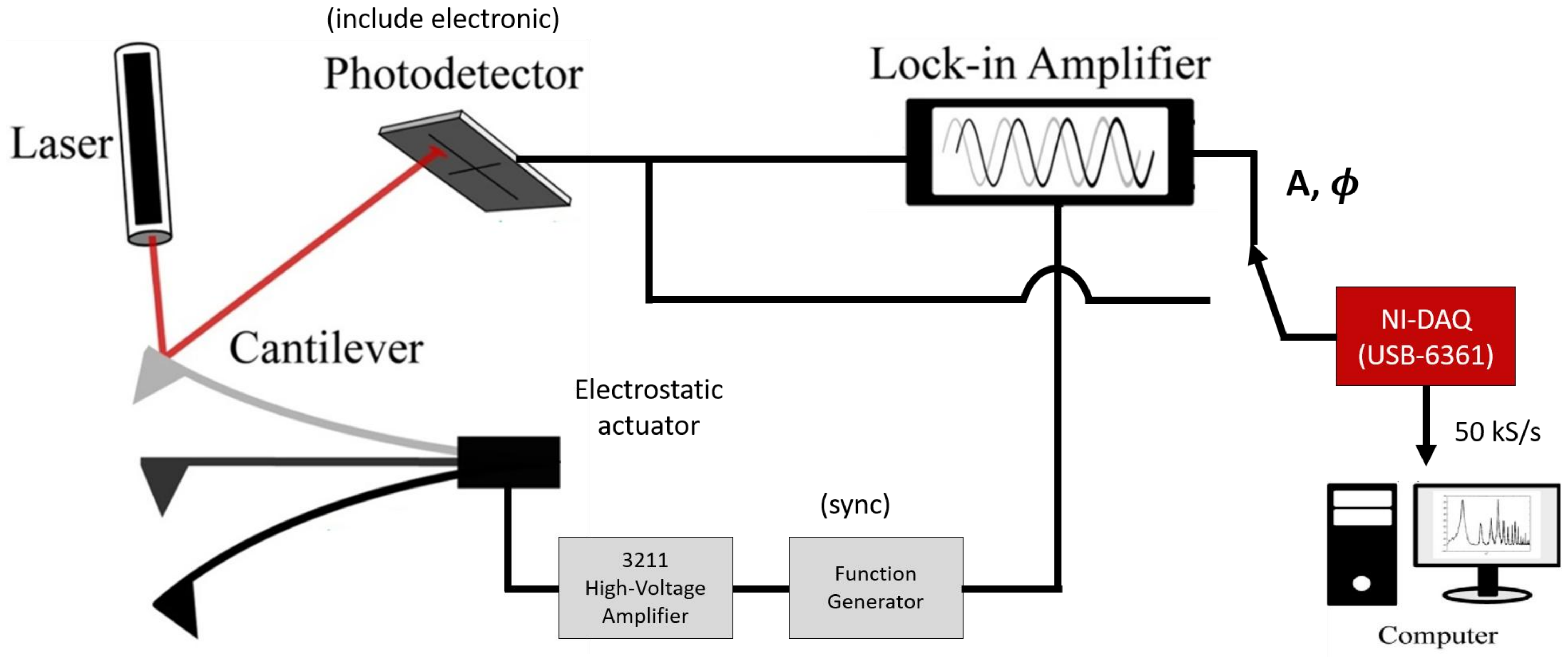
- RT/Cryo - **Cantilever**





Mechanical Loss (Structural Loss)-2

- RT/Cryo - **Cantilever**



Mechanical Loss

Deriving Q(quality factor) from time constant of ringdown.

$$\phi(f_0) = \frac{1}{Q(f_0)} = \frac{1}{2\pi}\frac{E_{dissipated\ per\ cycle}}{E_{stored}} = \frac{1}{\pi f_0 \tau}$$

$$\phi(f_0)_{sub} = \frac{1}{2\pi}\frac{E_{dissipated\ (sub)}}{E_{stored\ (sub)}}$$

$$\phi(f_0)_{film} = \frac{1}{2\pi}\frac{E_{dissipated\ (film)}}{E_{stored\ (film)}}$$

$$\phi(f_0)_{total} = \frac{1}{2\pi}\frac{E_{dissipated\ (sub)} + E_{dissipated\ (film)}}{E_{stored\ (total)}}$$

$$\Rightarrow \phi(f_0)_{total} = \frac{E_{stored\ (sub)}}{E_{stored\ (total)}}\phi(f_0)_{sub} + \frac{E_{stored\ (film)}}{E_{stored\ (total)}}\phi(f_0)_{film}$$

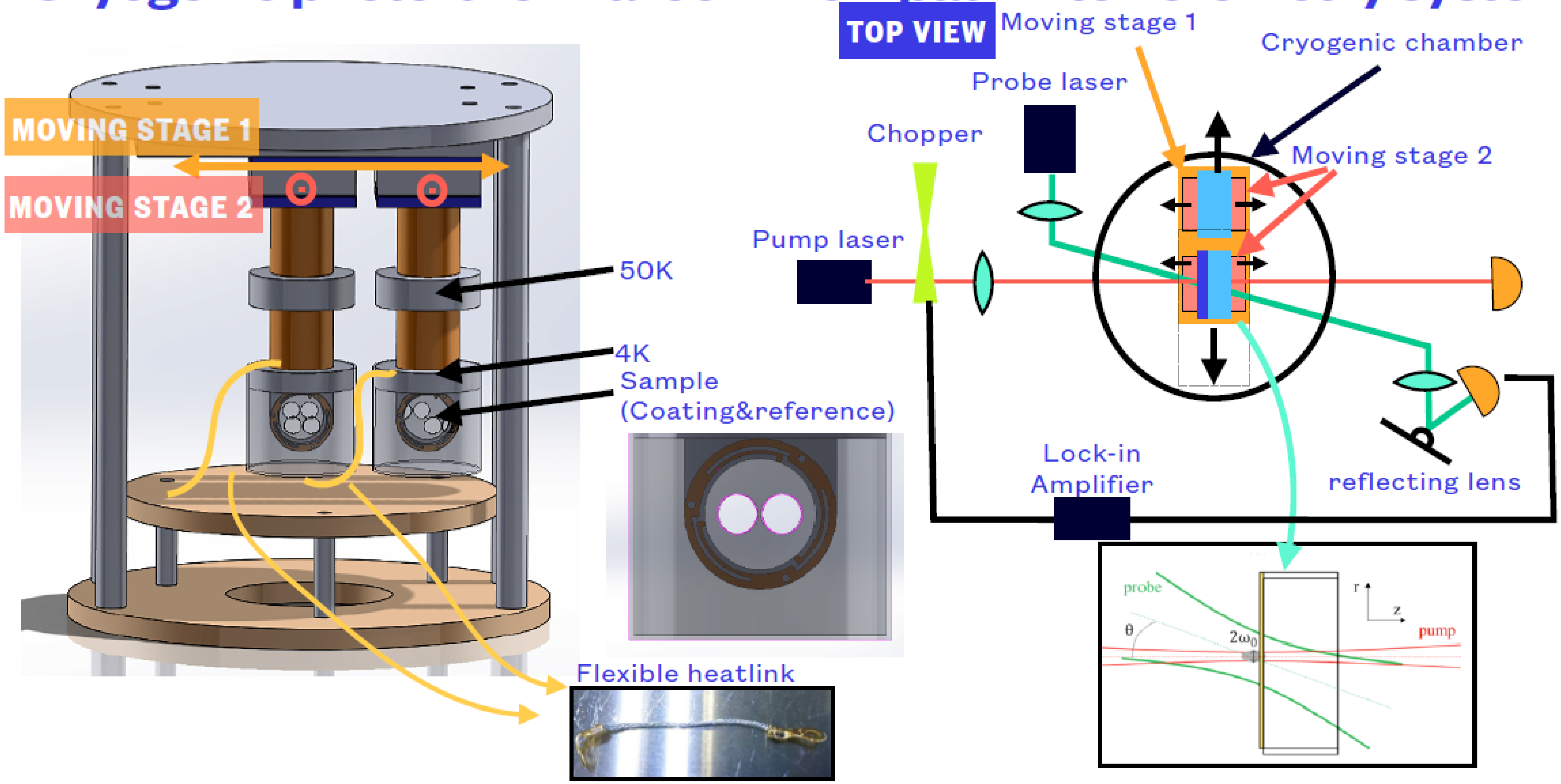
$$E_{stored\ (film)} \ll E_{stored\ (sub)}$$

$$E_{stored\ (total)} \cong E_{stored\ (sub)}$$

$$\phi(f_0)_{film} = \frac{E_{stored\ (sub)}}{E_{stored\ (film)}}\left(\phi(f_0)_{total} - \phi(f_0)_{sub}\right)$$

Cryo-PCI

Cryogenic photo-thermal common-path interferometry system



Moving stage 1: Replace Coating sample and reference sample

Moving stage 2: Alignment of sample position

- We will mount the radiation shield around the sample
- We can replace the mirrors with piezo motor.
- We employ the high purity aluminum wire for moving cryogenic stage.

Demodulator

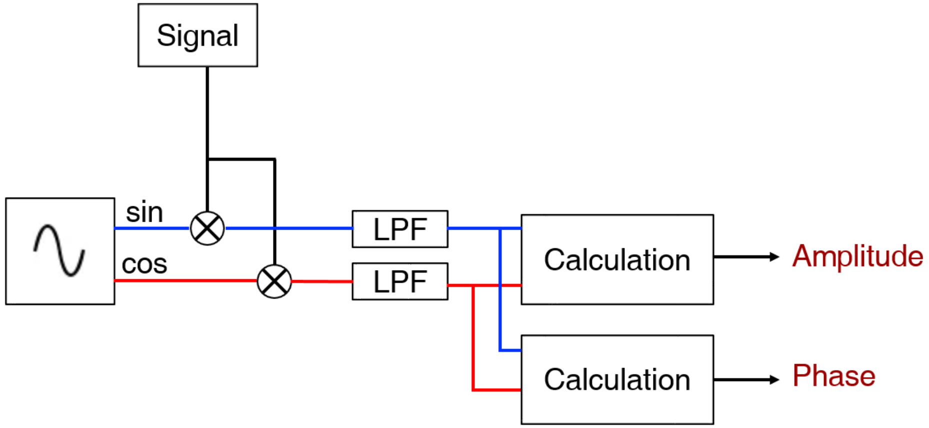
- A method to **know** the **amplitude** and **phase** of signal at a certain frequency in **real-time**

Signal to be measured:

$$s(t) = A(t)\sin(\omega t + \phi) + \text{other frequency component}$$

1.Oscillator

$$s(t)\cdot\sin(\omega' t) = A(t)\cdot\sin(\omega t + \phi)\cdot\sin(\omega' t)$$
$$= \frac{1}{2}A(t)\cos((\omega t + \phi) + \omega' t) - \frac{1}{2}A(t)\cos((\omega t + \phi) - \omega' t).$$
$$s(t)\cdot\cos(\omega' t) = A(t)\cdot\sin(\omega t + \phi)\cdot\cos(\omega' t)$$
$$= \frac{1}{2}A(t)\sin((\omega t + \phi) + \omega' t) + \frac{1}{2}A(t)\sin((\omega t + \phi) - \omega' t)$$



2.Apply Low-Pass Filter

$$\mathrm{LPF}\{s(t)\cdot\sin(\omega' t)\} = -\frac{1}{2}A(t)\cos((\omega t + \phi) - \omega' t)$$
$$\mathrm{LPF}\{s(t)\cdot\cos(\omega' t)\} = \frac{1}{2}A(t)\sin((\omega t + \phi) - \omega' t).$$

Amplitude

$$A(t) = 2\sqrt{(\mathrm{LPF}\{s(t)\cdot\sin(\omega' t)\})^2 + (\mathrm{LPF}\{s(t)\cdot\cos(\omega' t)\})^2}$$

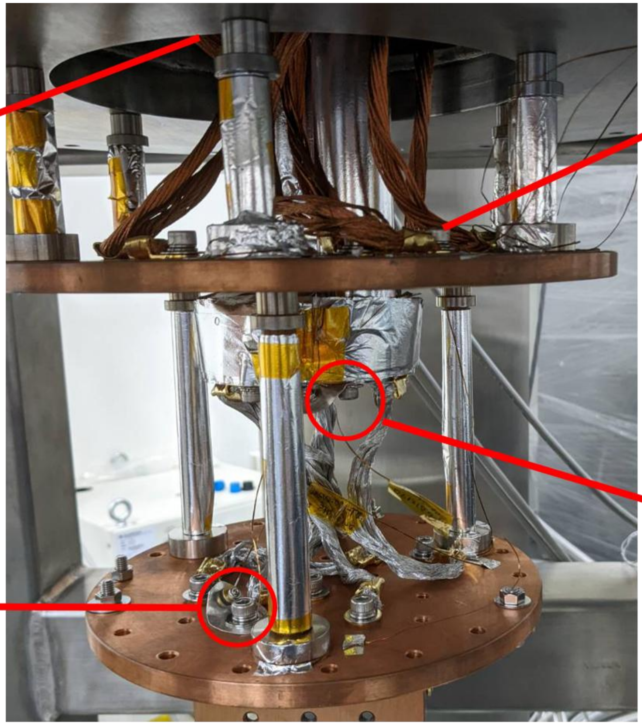
Phase

$$((\omega t + \phi) - \omega' t) = \tan^{-1}\left(-\frac{\mathrm{LPF}\{s(t)\cdot\cos(\omega' t)\}}{\mathrm{LPF}\{s(t)\cdot\sin(\omega' t)\}}\right).$$

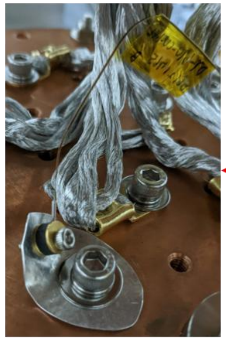
$(\omega - \omega')$ should be **close to 0** for discarding other frequency components

Thermometers installation

C : DT-670B (D6117620)
-> 50K head



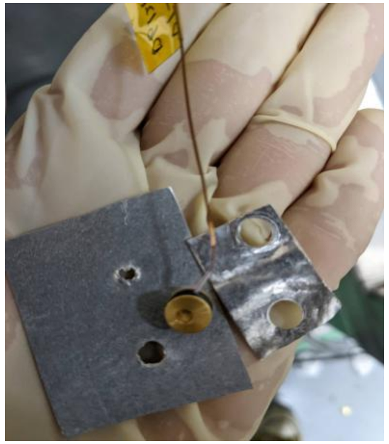
D : DT-670B (D6122524)
-> 50K stage



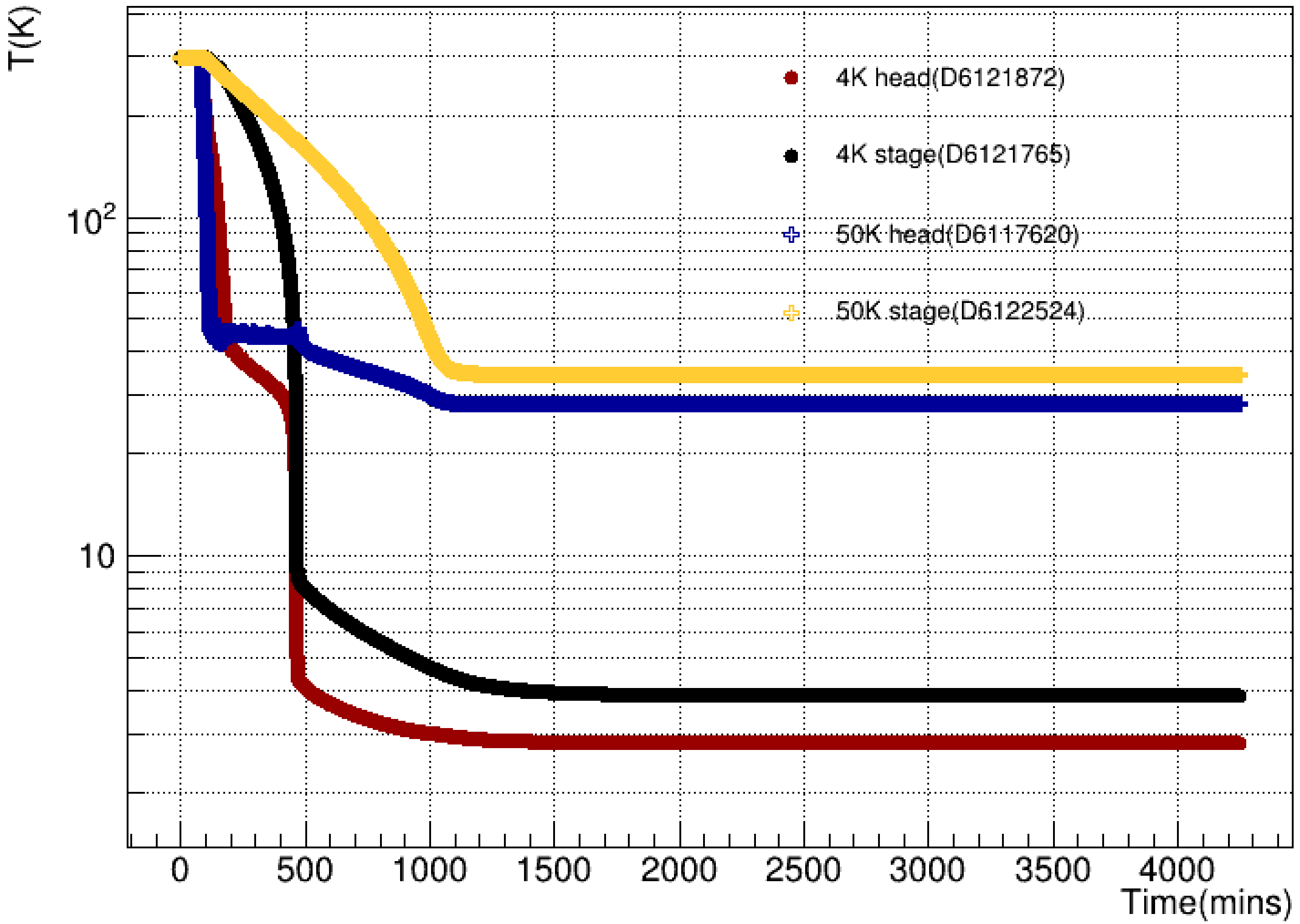
B:DT-670-CU-1.4L (D6121765) -> 4K stage

A : DT-670-CU-1.4L (D6121872)
-> 4K head

Sensor:
Can be mounted to any flat surface
with a 4-40 or M3 screw



Cooling procedure



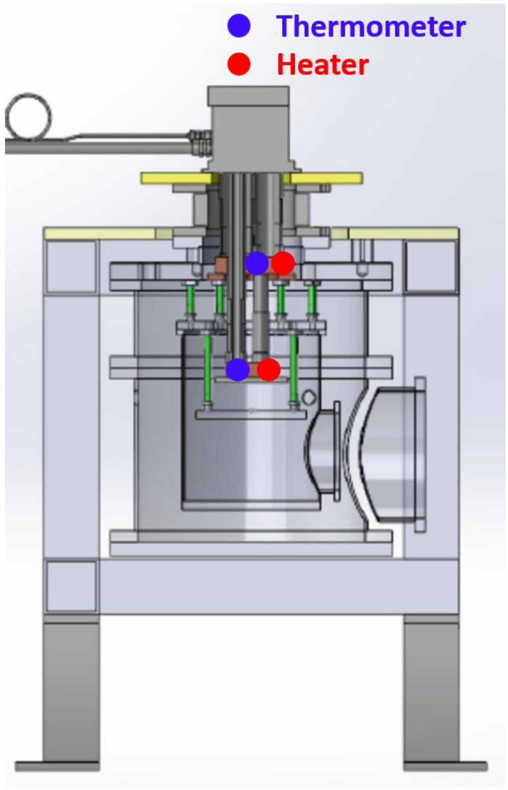
- ~ 25 hours

Final Temperature

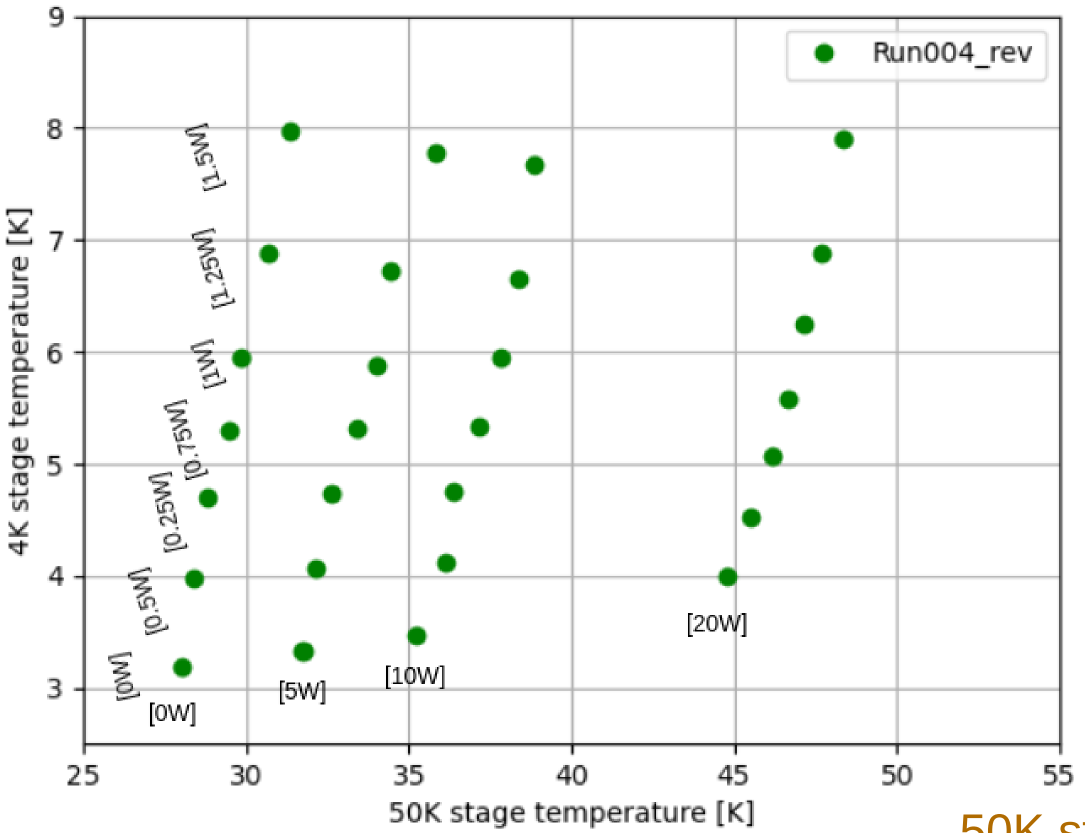
- Upper part:
  - Head: 27.9 K
  - Stage: 34.16 K
- Lower part:
  - Head: 2.80 K
  - Stage: 3.87 K

Working field of cryogenics

- To validate that the target temperatures will be reached, it is crucial to have a load map ("working field") of the used cryocooler.

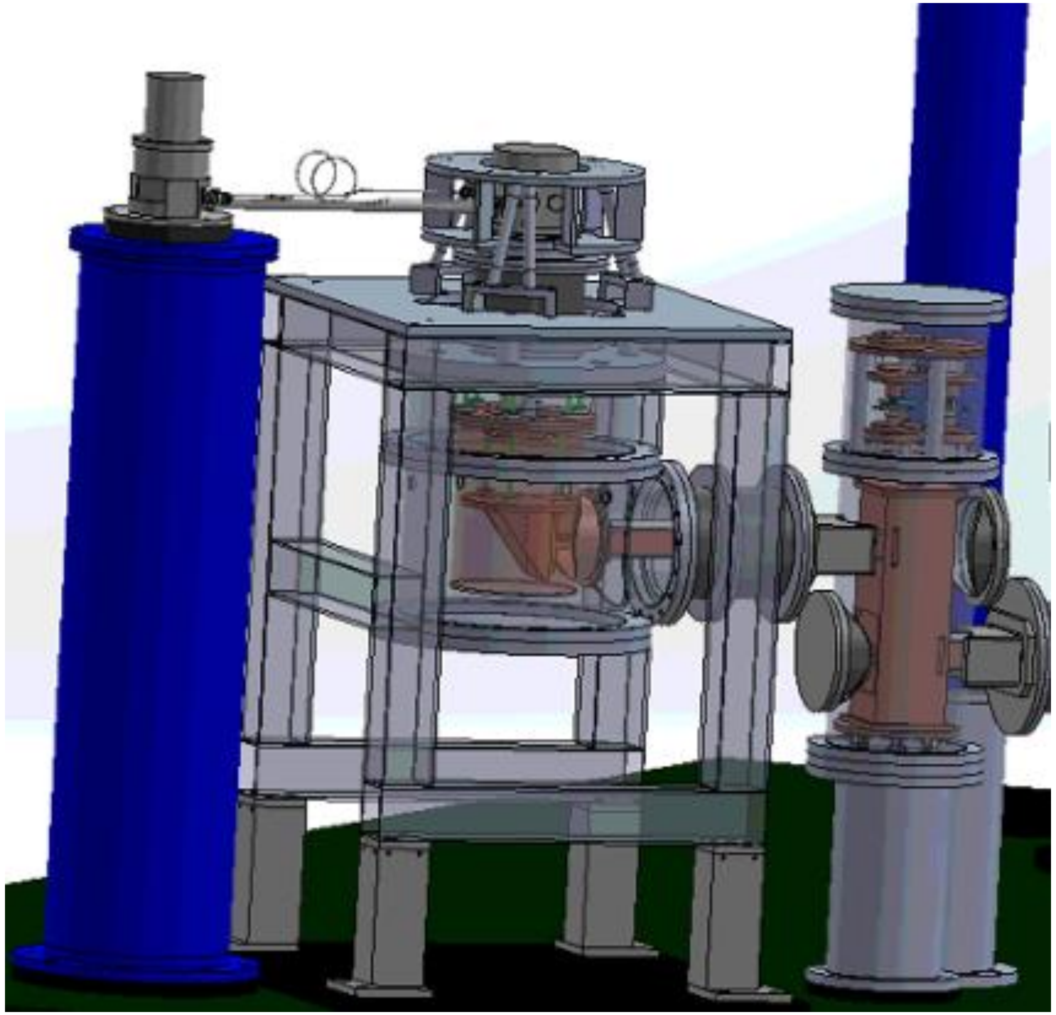


4K stage



50K stage

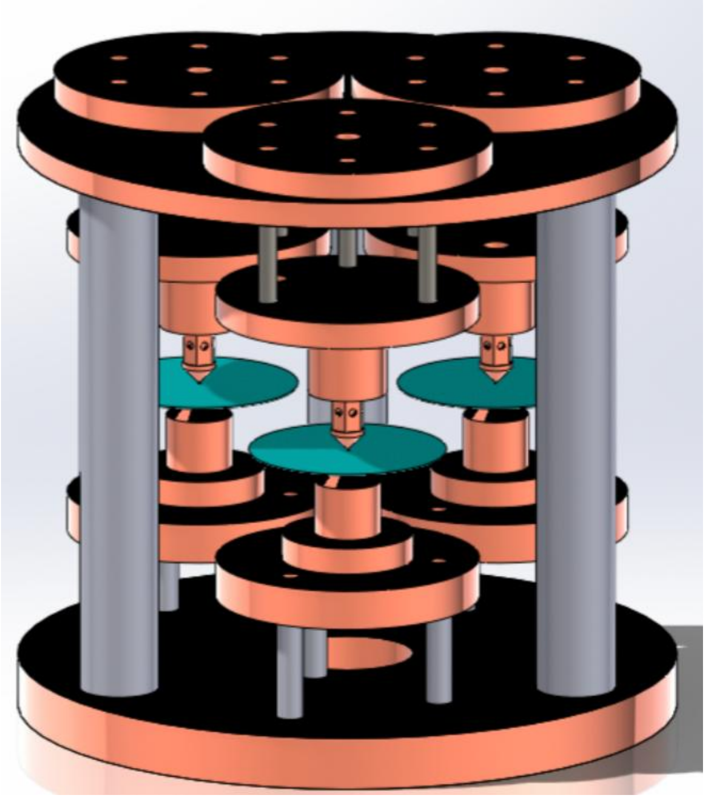
Cryogenic design

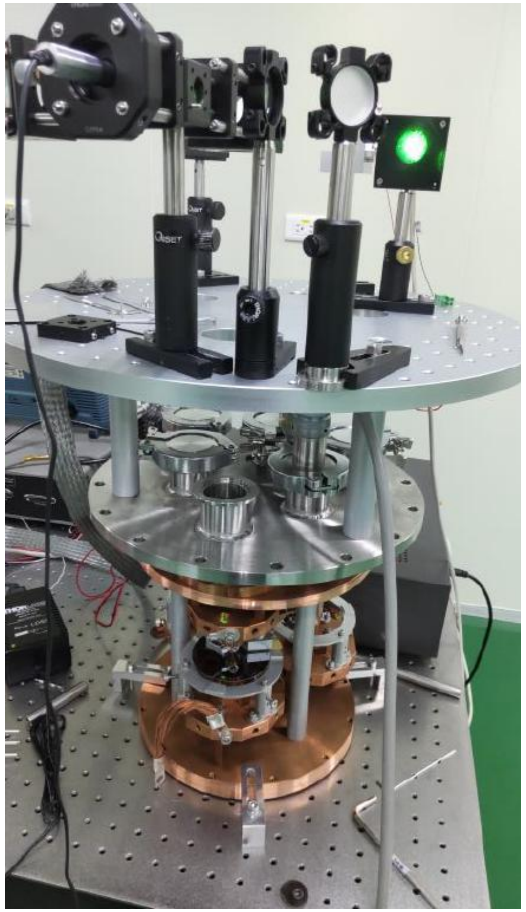


Mechanical Loss (Structural Loss)-1

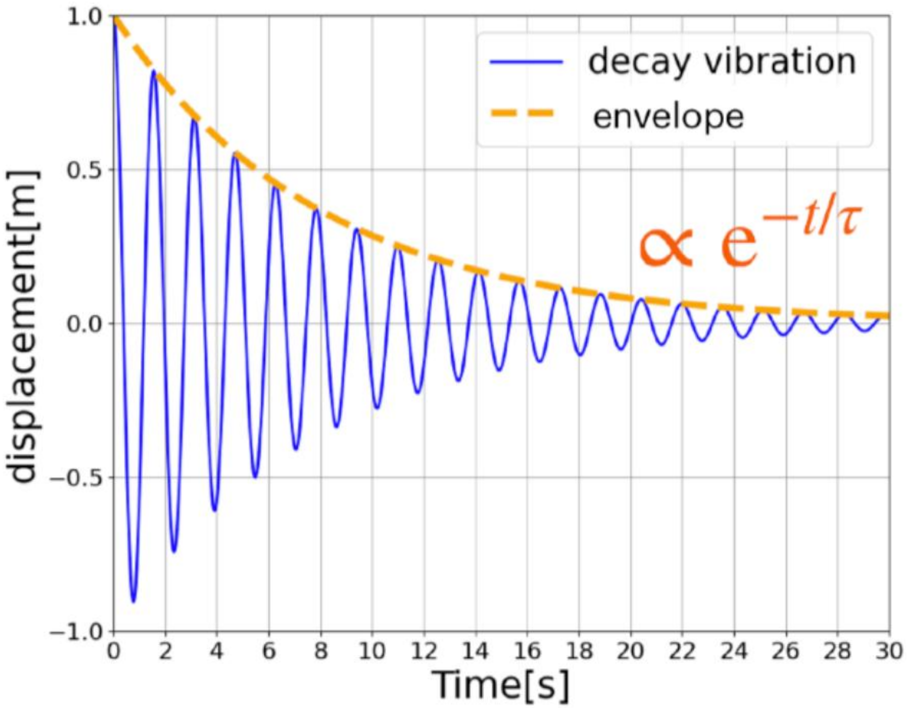
- RT/Cryo - **G**entle **N**odal **S**uspension (**GNS**)

[Newly developed system]



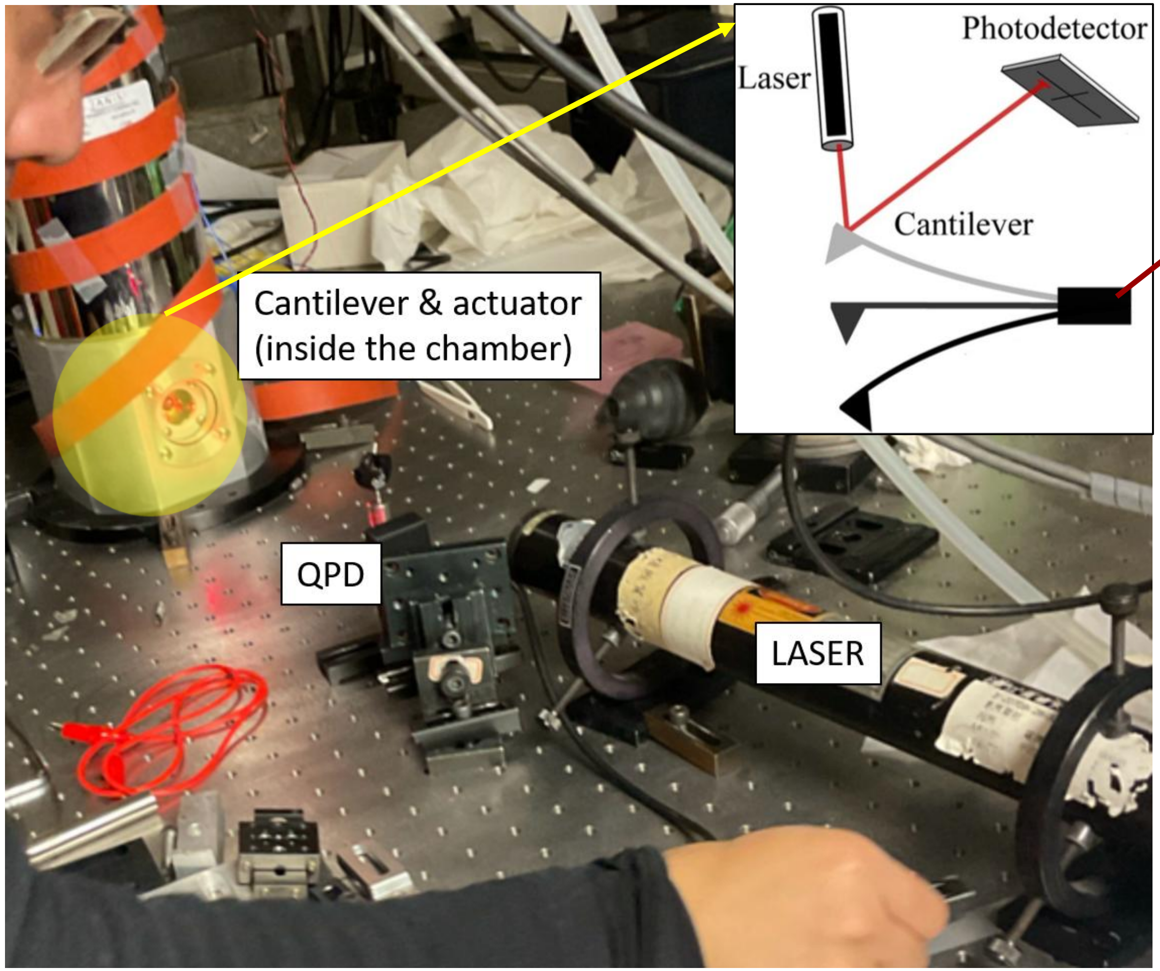


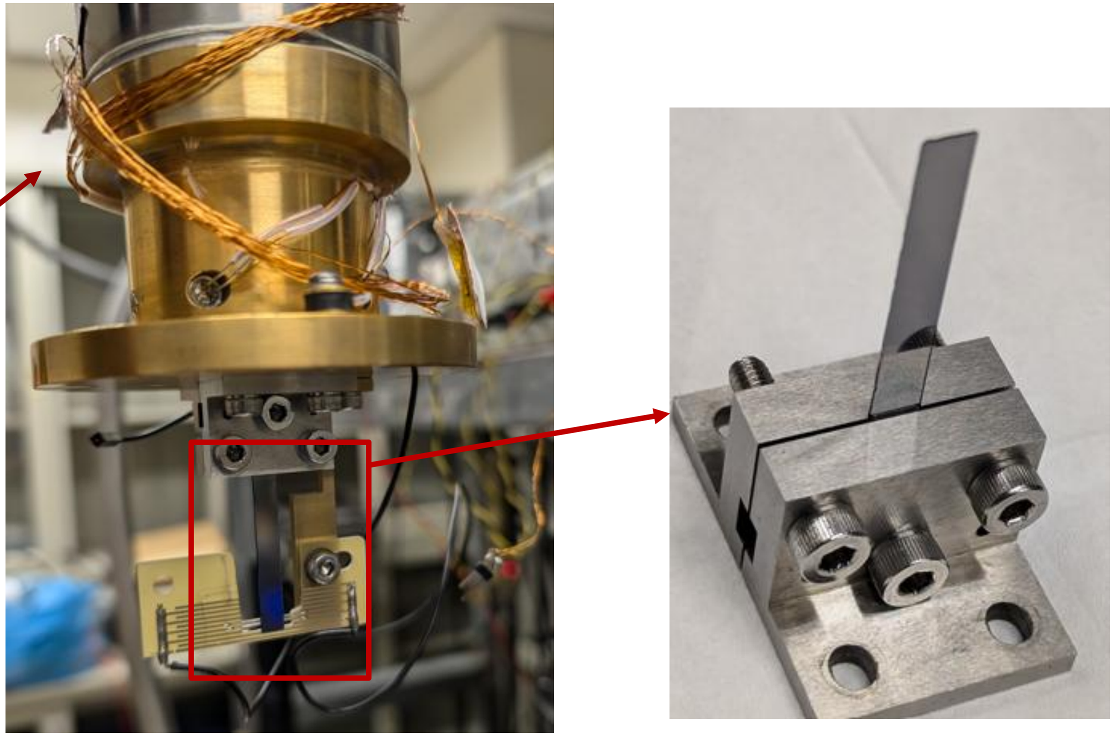
- Excite modes with an electrostatic actuator
- Measure vibration with a Michelson interferometer.



Mechanical Loss (Structural Loss)-2

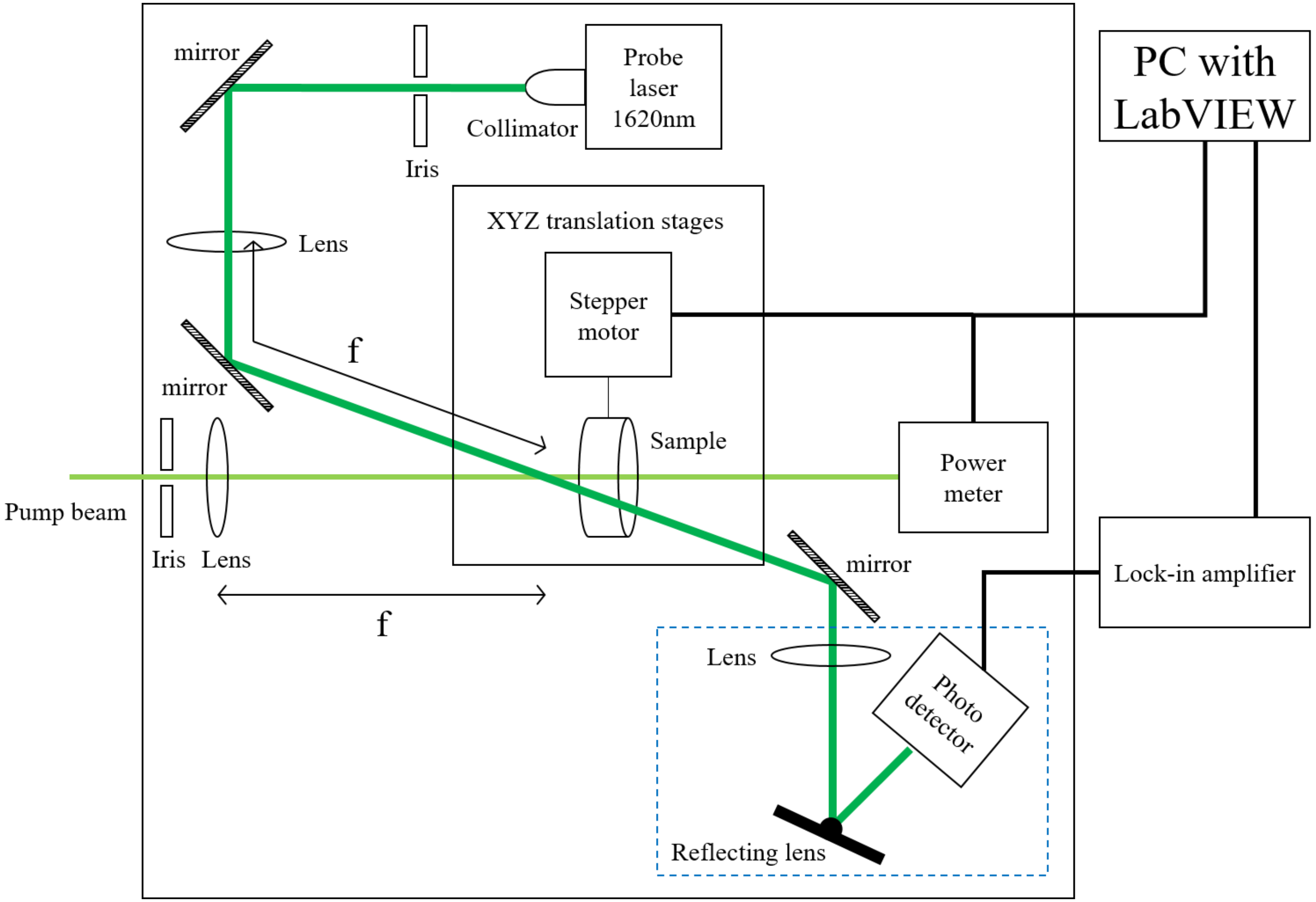
- RT/Cryo - **Cantilever** [Legacy system from NTHU]



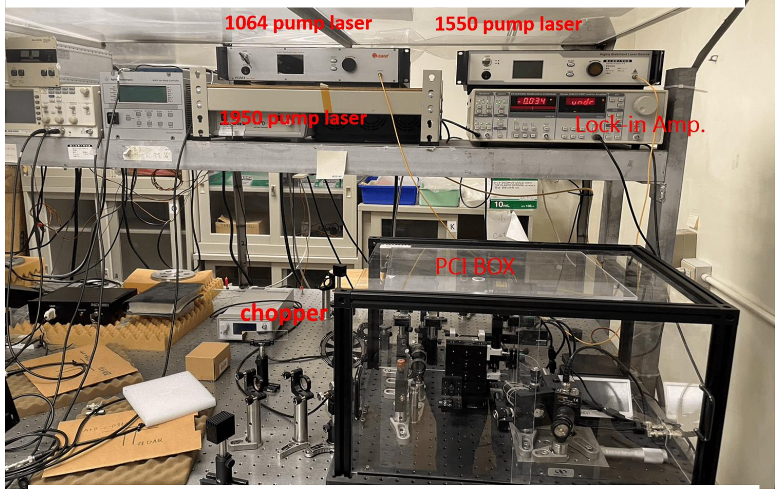


Optical Loss (Absorption-related Thermal Noise)

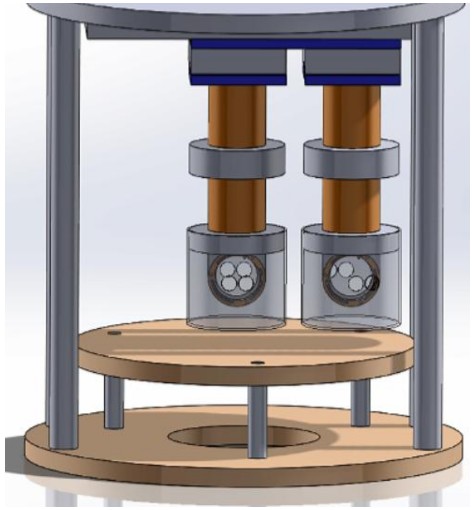
- RT/Cryo-**P**hotothermal **C**ommon-path **I**nterferometry (**PCI**)



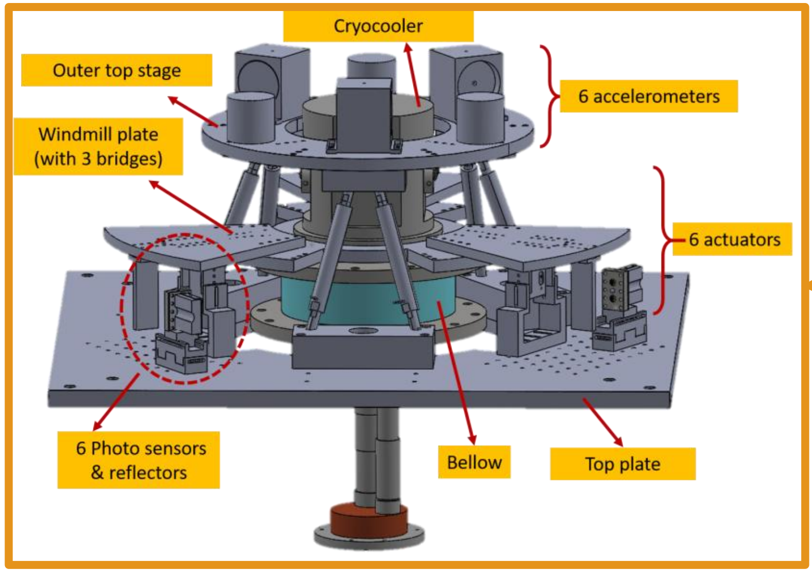
[RT: Legacy system from NTHU]

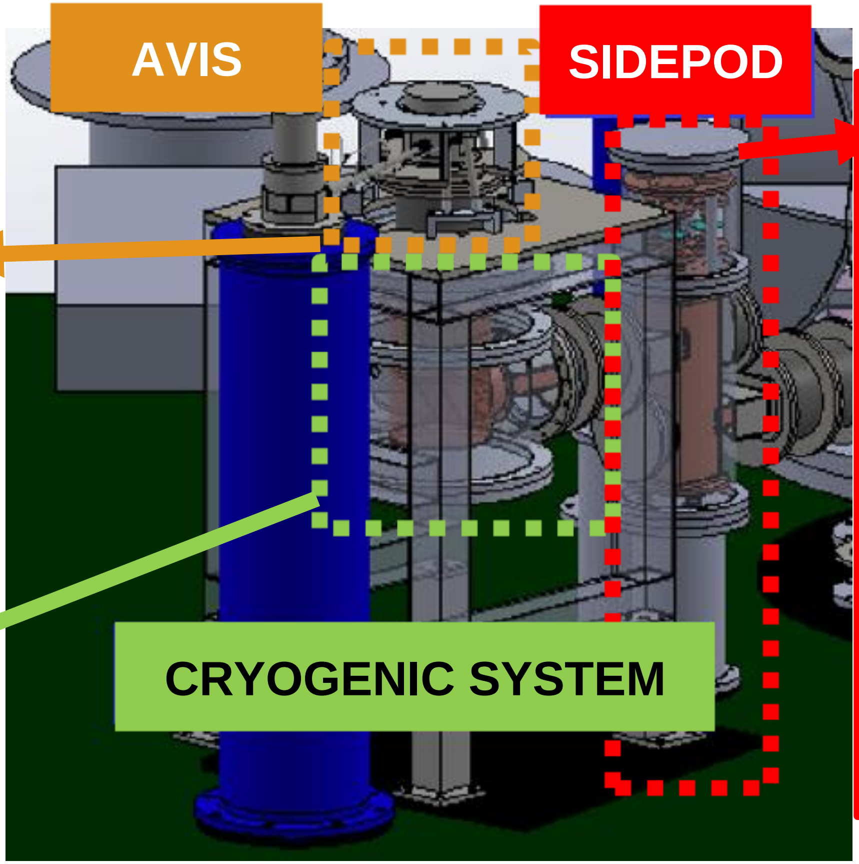


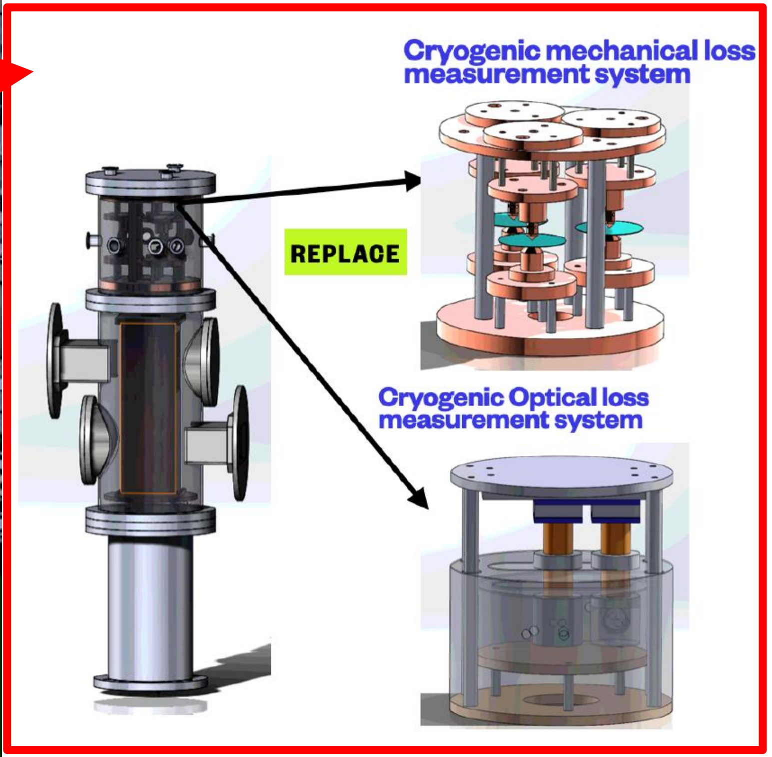
[Cryo: Newly developed system]

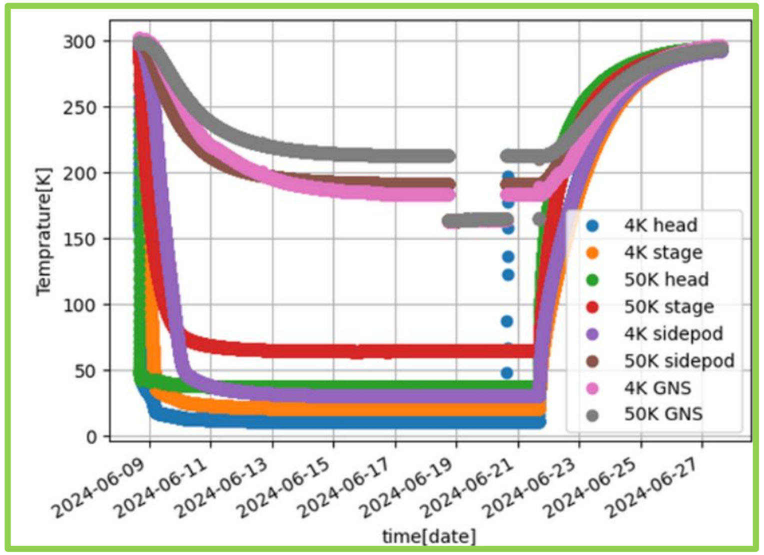


Cryogenic system & AVIS









- Main chamber: 20.4 K
- Sidepod chamber: 30.3 K