Cryogenics and Cyogenic payload in KAGRA

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Contents

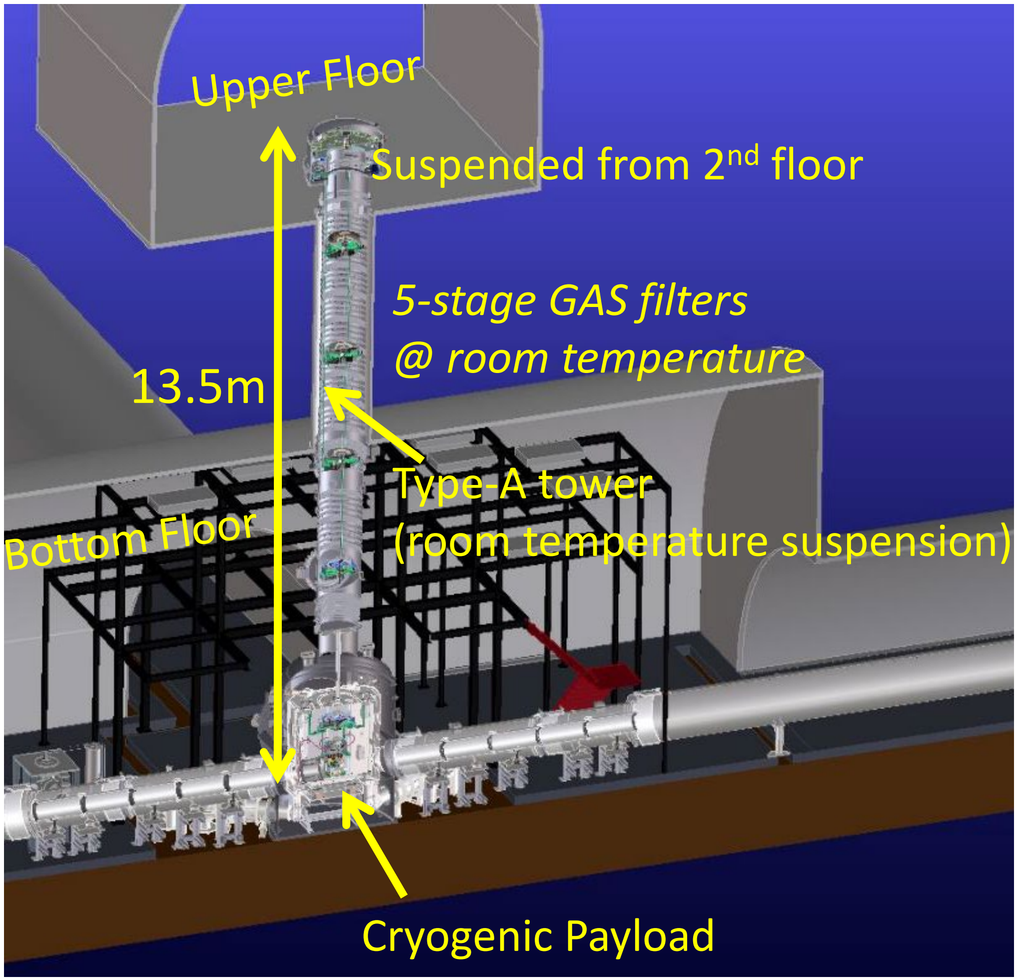
Cryogenic payload

Main mirror suspension (Type-A suspension) in KAGRA

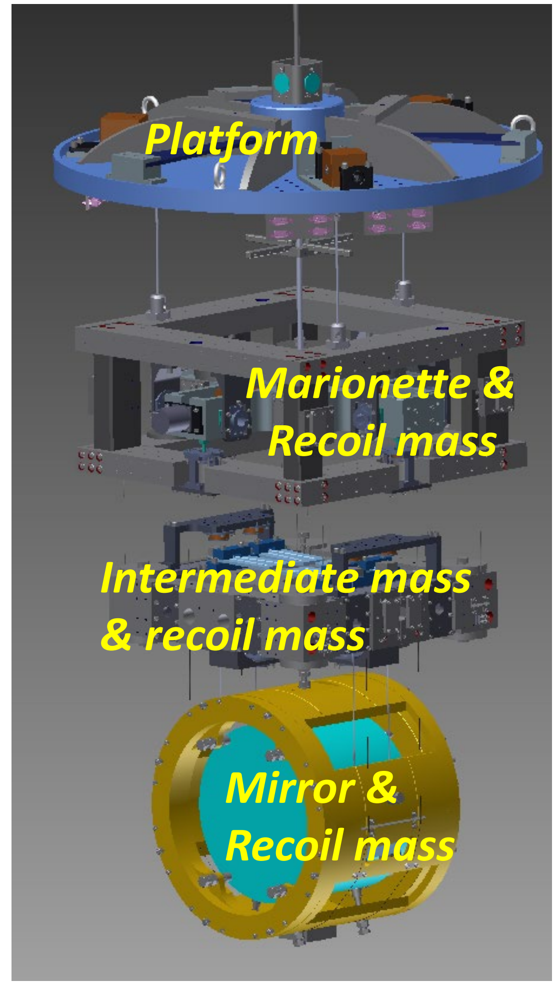
Cryogenic sapphire mirror is one of key features of KAGRA.

The sapphire mirror is suspended by four-stage cryogenic pendulum.

It is suspended from a huge tower called Type-A tower for vibration isolation.



Type-A suspension



Cryogenic payload

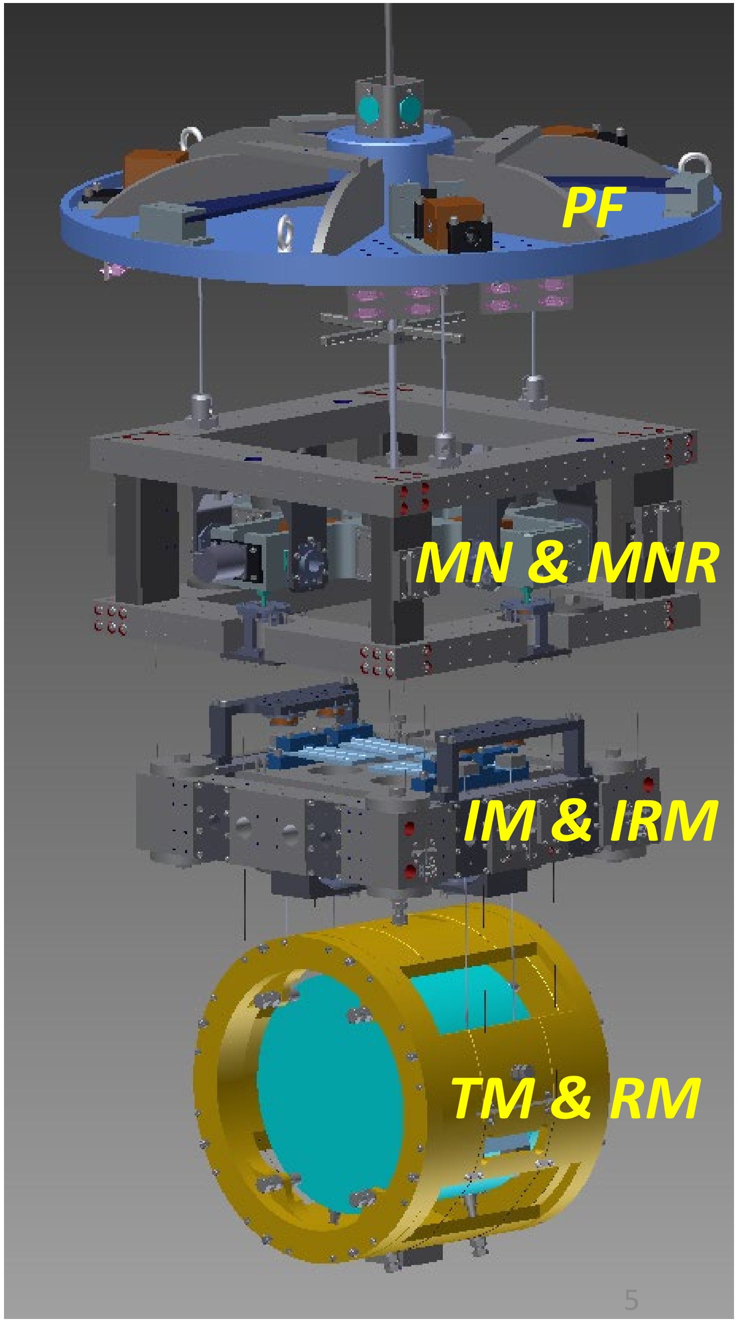
Cryogenic payload

Platform (PF):
- Lateral and vertical vibration isolators

Marionette and its recoil mass (MN and MNR):
- Heat link connection (marionette recoil mass)
- Mirror inclination control
- Damping control of TM chain
- Mass lock of arm cavity at low frequencies

Intermediate mass and its recoil mass (IM and IRM):
- Mass lock of arm cavity at middle frequencies

Test mass and its recoil mass (TM and RM):
- Mass lock of arm cavity at high frequencies



Sensors and actuators on cryogenic payloads

Sensor: blue, actuator: red

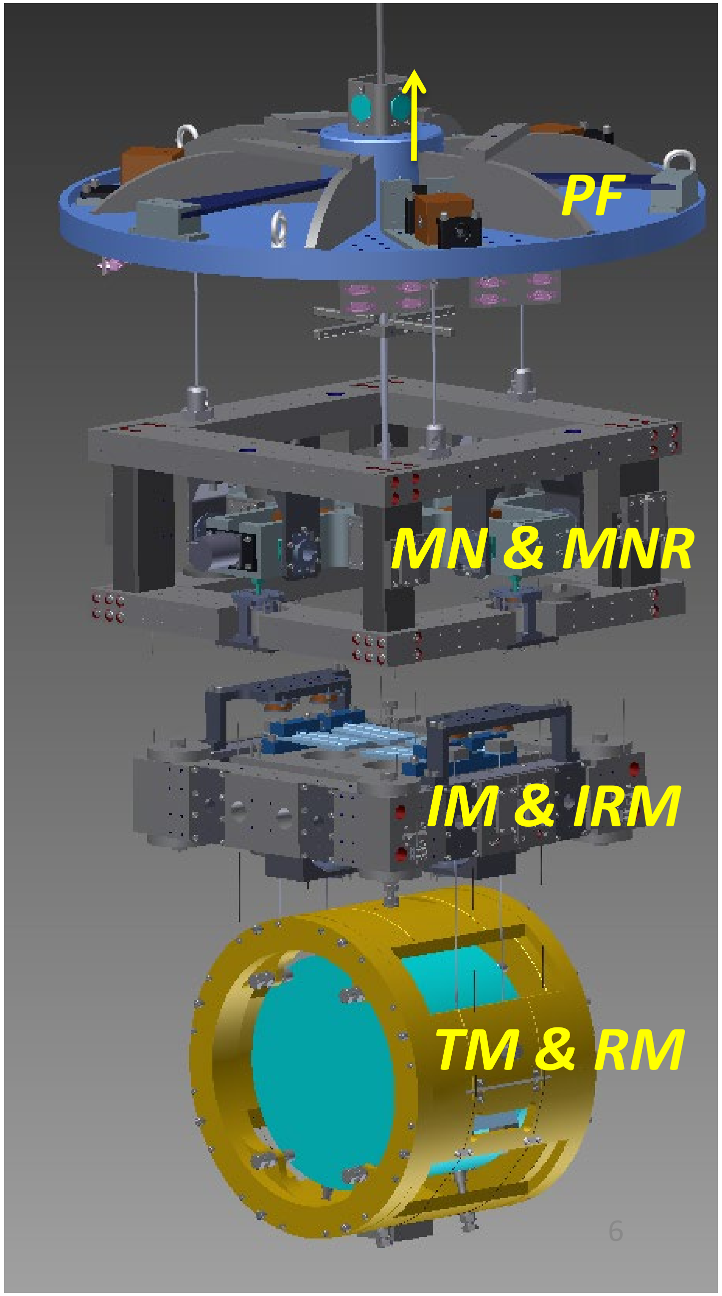
Platform (PF):
- Optical lever (OpLev) and length-sensing OpLev (L, P, Y)

Marionette stage (MN and MNR):
- Reflective photosensors (PS) (L, T, V, R, P, Y)
- OpLevs and length-sensing OpLevs (L, T, V, R, P, Y)

- Moving mass (P, R)
- Coil-magnet actuators (L, T, V, R, P, Y)

Intermediate mass stage (IM and IRM):
- Reflective photo sensors (L, T, V, R, P, Y)
- Coil-magnet actuators (L, T, V, R, P, Y)

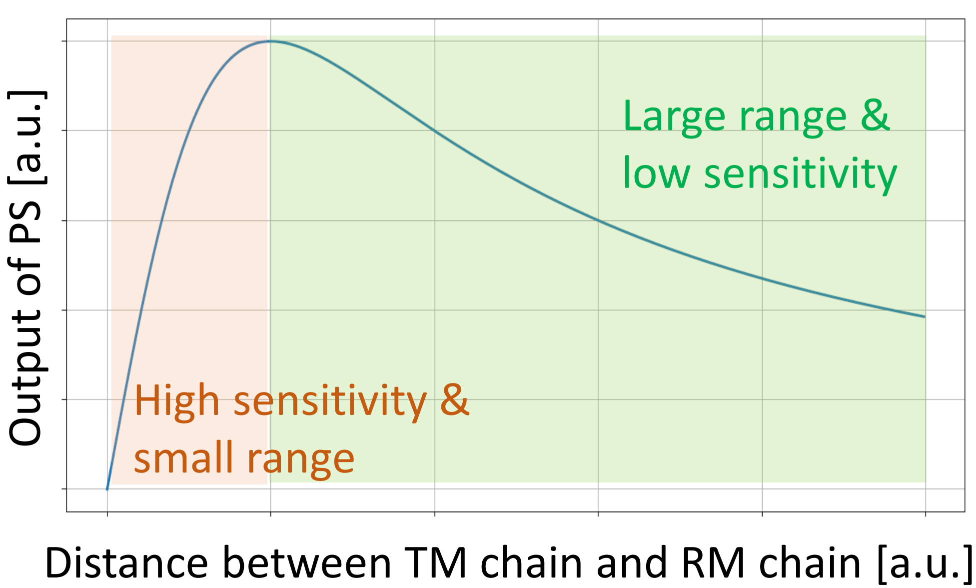
Test mass stage (TM and RM):
- OpLevs and length-sensing OpLevs (L, P, Y)
- Coil-magnet actuators (L, P, Y)



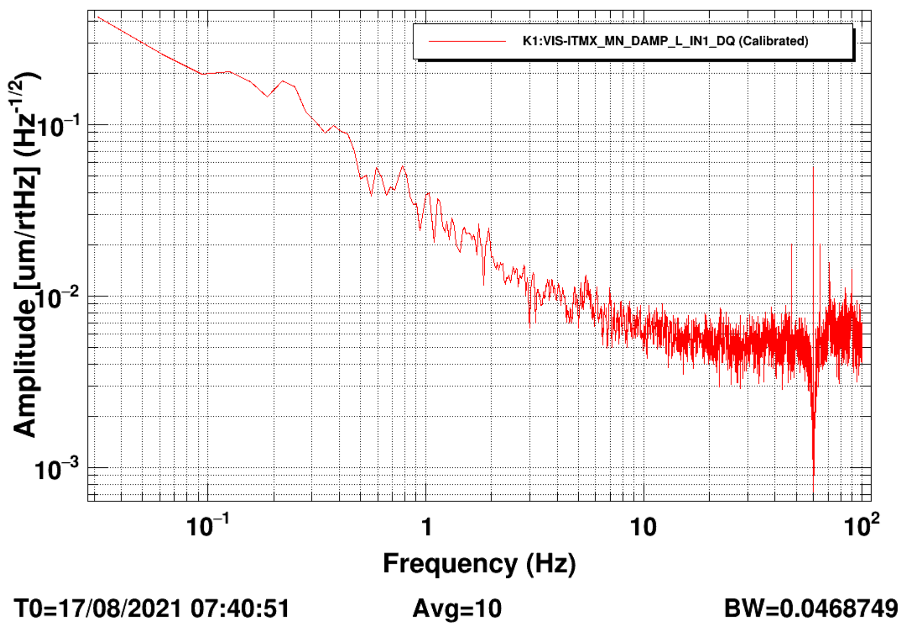
Reflective photosensors

- To monitor the relative motion between the TM chain (TM, IM, and MN) and the RM chain (RM, IRM, MNR), reflective photosensors (PSs) are used.
- PSs consist of one LED and two PD to decrease the anglar-to-lateral coupling.
- Considering cryogenic compatibility, AlGaAs LED and InGaAs PDs are used.
- Since relative displacement of TM chain and RM chain is difficult to be predicted and mitigated, PSs are used at the low-sensitive large-range region.
- In our configuration, the noise spectrum of PSs is about 2×10^{-7} m/rtHz @ 0.1 Hz and 6×10^{-9} m/rtHz @ 10Hz.

PS output vs distance



Typical noise spectrum of PSs

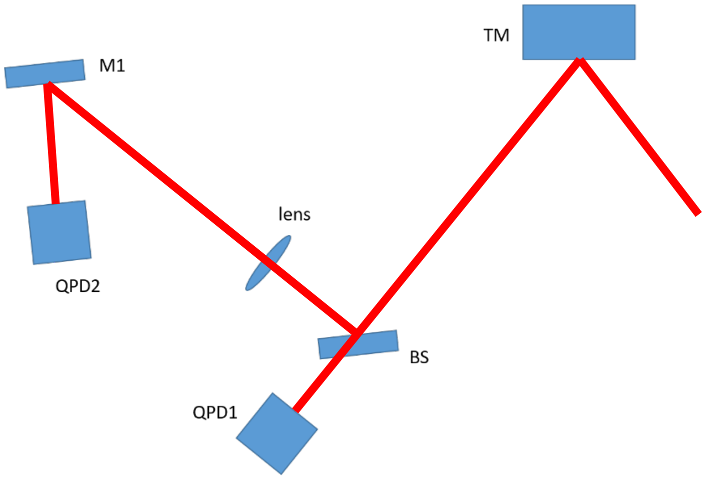


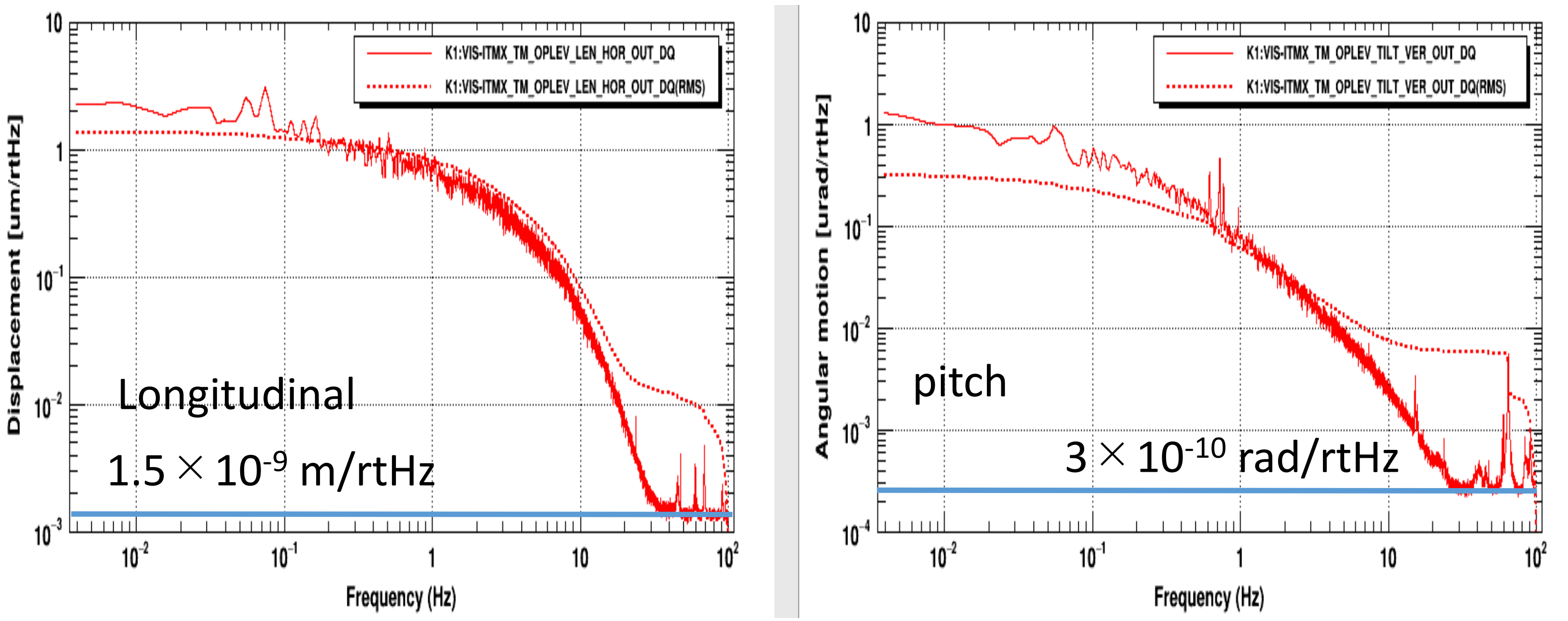
OpLevs and length-sensing OpLevs (LS OpLevs)

OpLevs configure gouy phase telescopes in order to distinguish beam shift and tilt.

→Three degrees of freedom can be detected by one set of OpLevs.

- Even though OpLevs measure the suspension motion with respect to the ground, noise level at high frequency is much better than PSs thanks to the quite environment of the underground site.





Example of spectra (suspension in air)

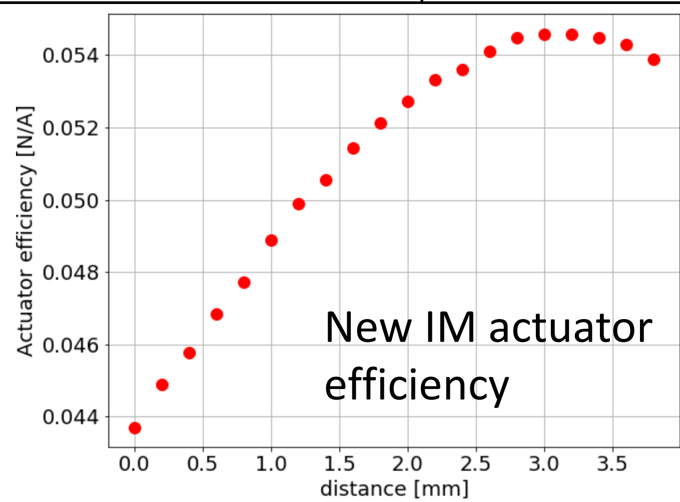
Large noise below 30Hz is due to air disturbances and decreases in the vacuum condition.

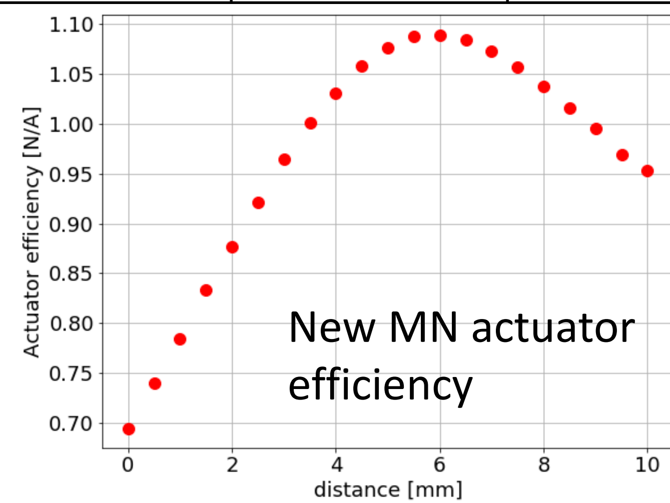
Coil-magnet actuators

- SmCo magnets are used for coil-magnet actuators because they have small temperature dependence of magnetism.
- Magnet size is updated from O3 to increase the actuation range for longitudinal motion at low frequency range (below ~ 10 Hz).
- Since large current generate heat, low current operation with large actuator efficiency is beneficial for cryogenic suspensions.

Red: changed from O3

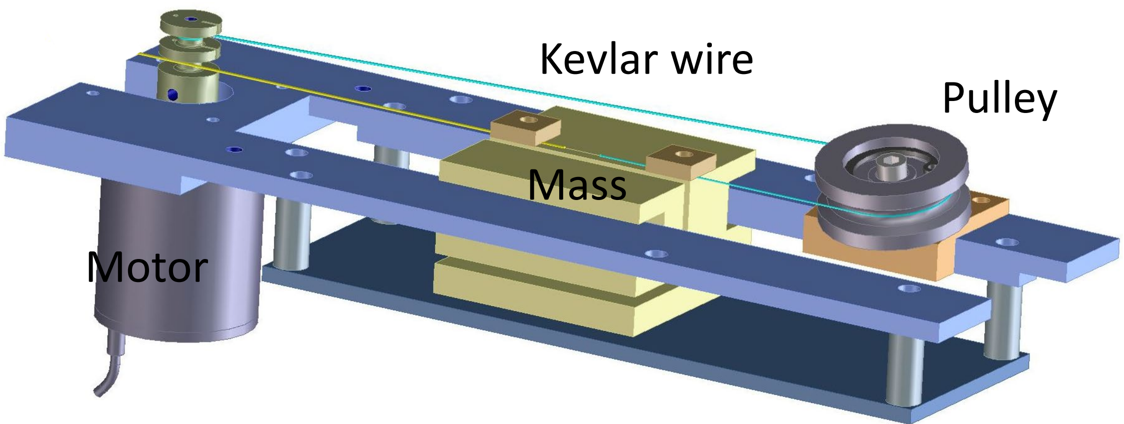
Stage	O3		O4	
	Coil Turns	Magnet size	Turns	Magnet size
MN	600	Φ5×13	600	Φ7×20
IM	600	Φ2×2	600	Φ2.5×4
TM	100	Φ2×2	100	Φ2×2





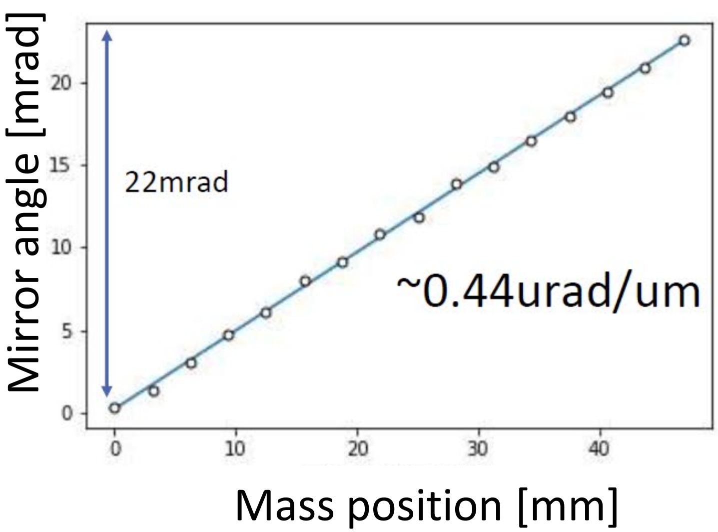
Moving mass

We developed a moving mass so called “ropeway style moving mass” for roughly aligning the mirror inclination.

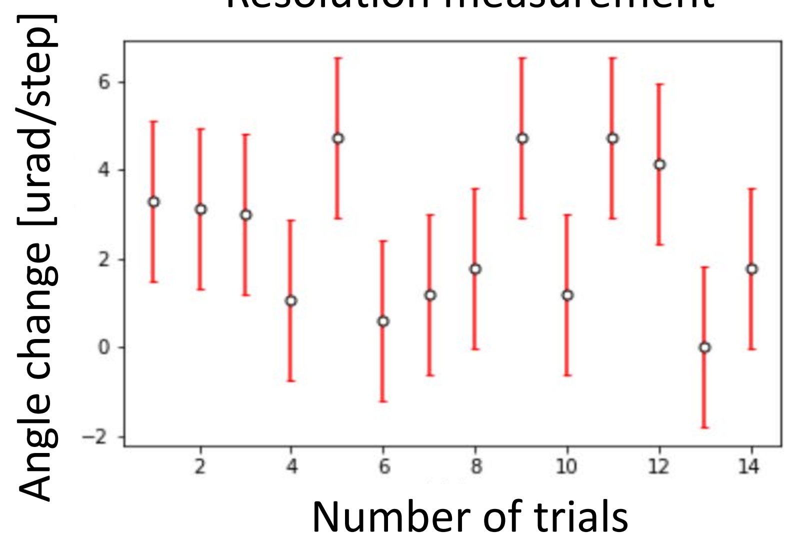


Mass: 300 g
Moving range: 50 mm
Control range: ±11 mrad
Resolution: ~3 urad

Range measurement



Resolution measurement

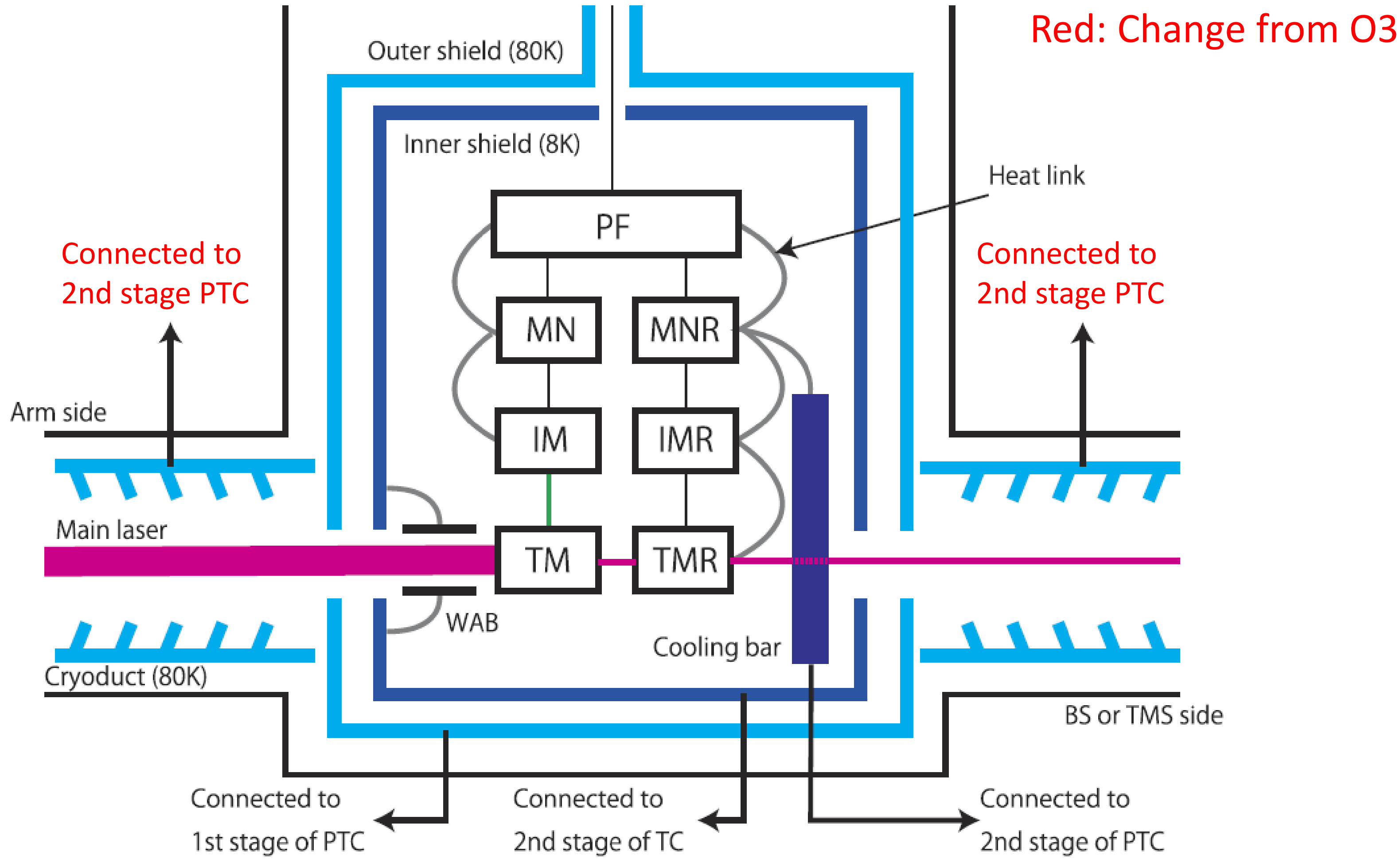


Cryogenic system

Cryogenic system in KAGRA

A cryogenic payload is stored inside the cryostat with two-layer radiation shields (80 K shield and 8 K shield).

Both HR and AR side of a mirror, there are 5-m cryogenic duct shield for reducing the thermal radiation from the beam tubes,

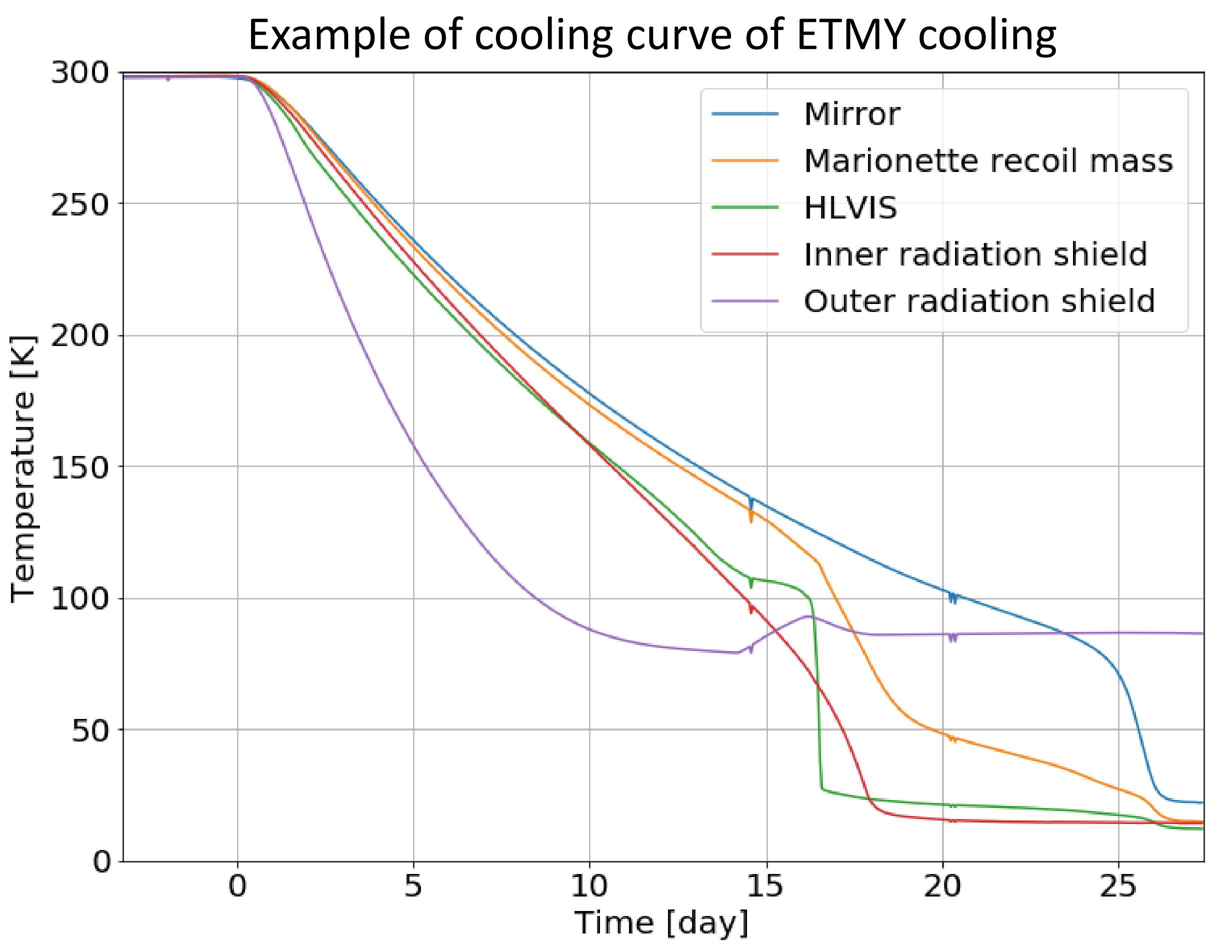


Example of the cooling curve (O3 commissioning)

Above 100 K, thermal radiation is the dominant heat extraction path.

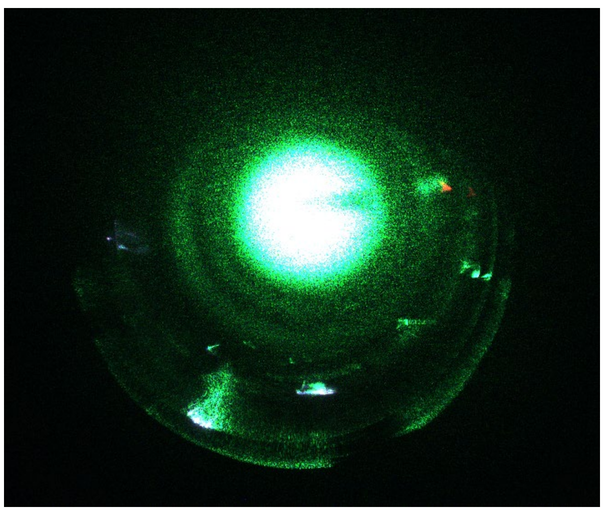
Below 100 K, thermal conduction by heat links (HKs) is the dominant heat extraction path.

It takes one month for cooling the mirror to 20 K.

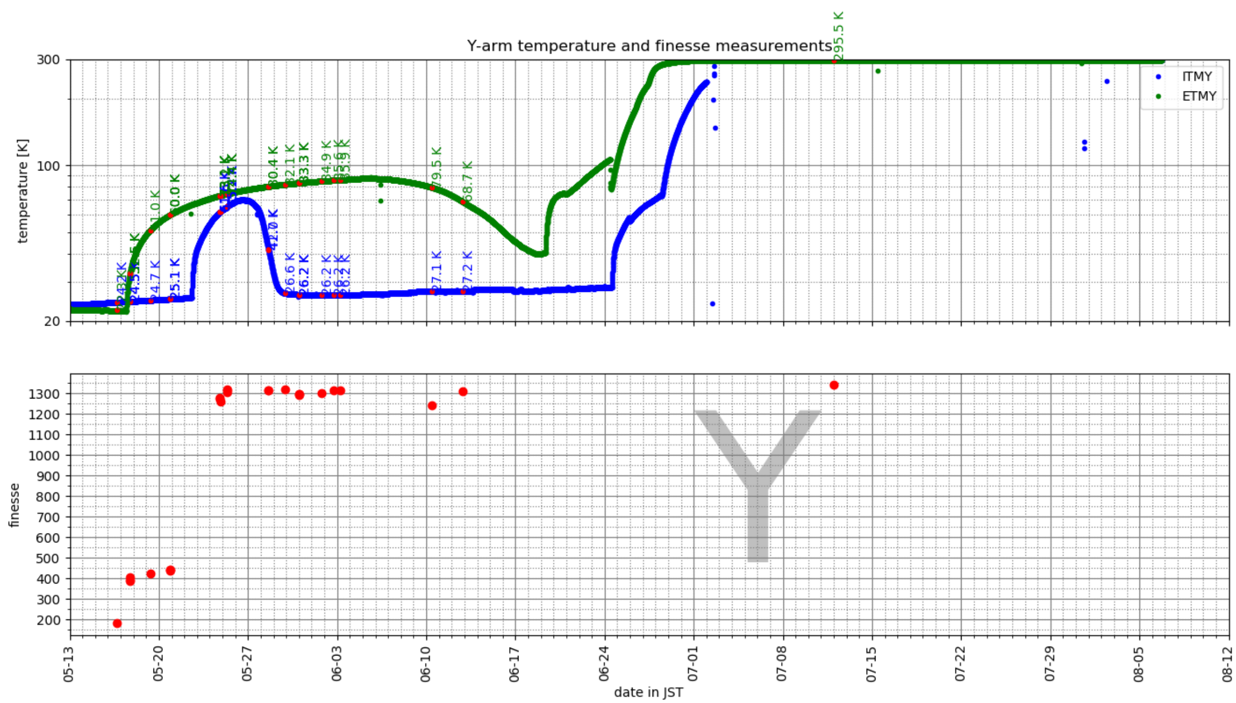


Problem of the cooling (frosting issue)

- During the cooling, thick frost was formed on the mirrors, which causes drastic finesse drop of arm cavities.
- Since a part of finesse drop can be recovered when warming up the mirrors at 70 – 80 K, the main components of the frost seems N_2.



Mirror surface at cryo temp.



Lab scale test of N_2 frosting (and defrosting)

Injecting small amount of pure N2 gas and make frost intentionally.
Then, heating up around the mirror and viewport with heaters.

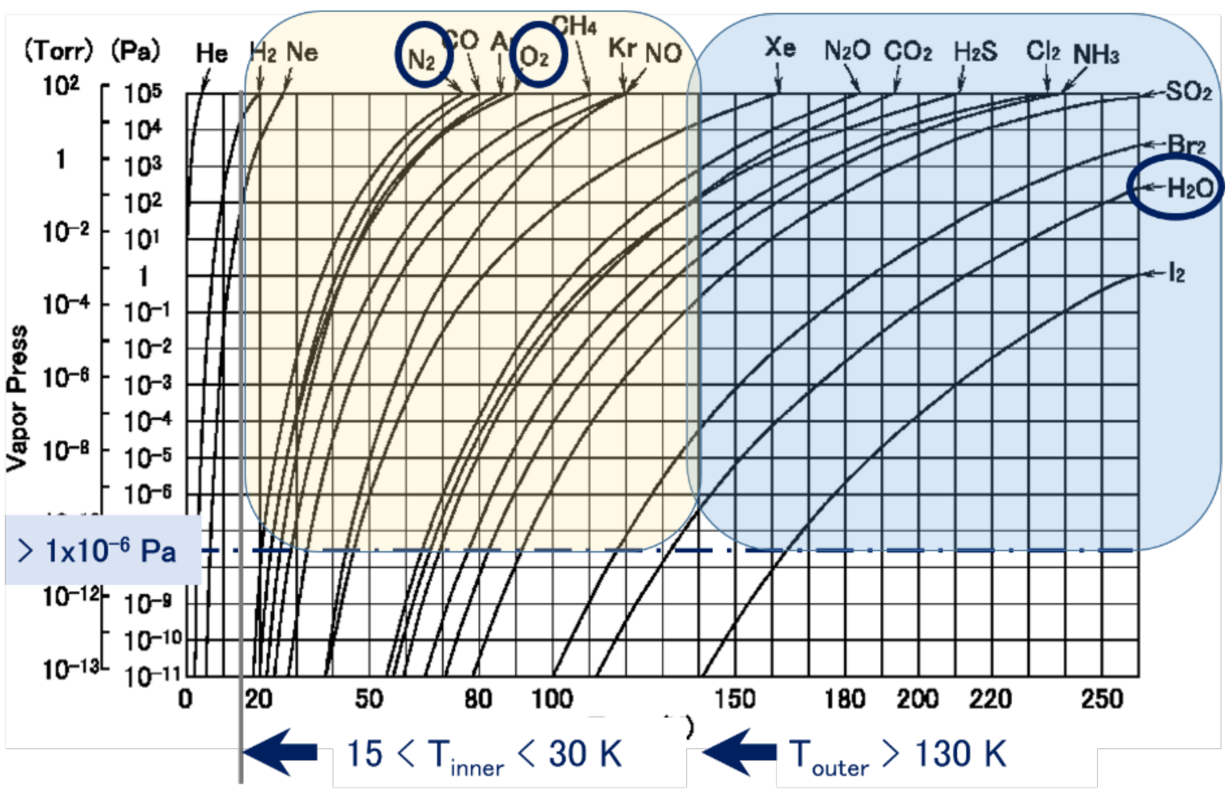
New cooling scheme

Considering the vapor pressure of the several molecules, step by step cooling could be effective for the counter measure of the frosting issue.

New procedure:

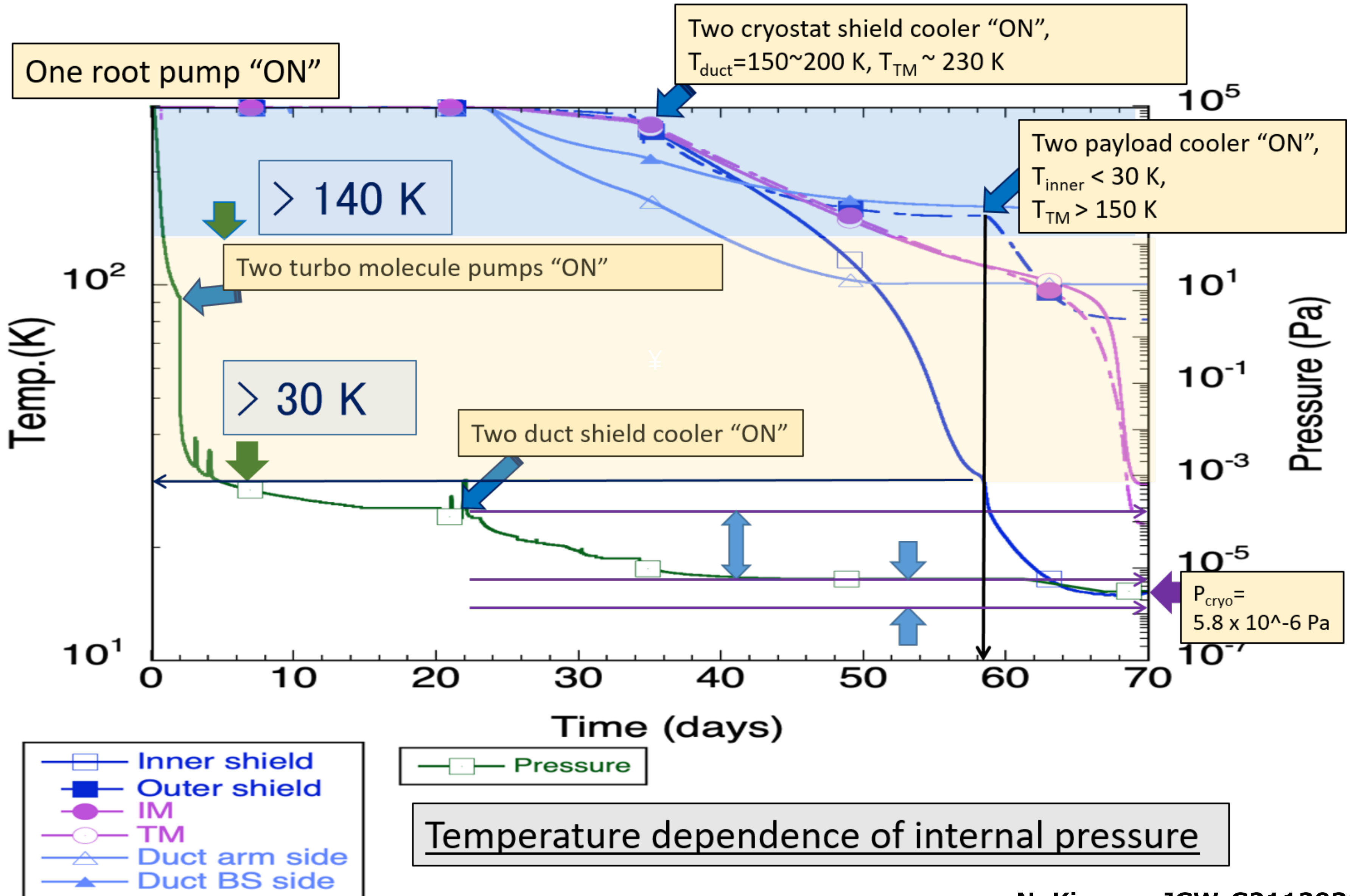
1. Pumping until pressure inside cryostat reaches below 10^{-4} Pa. (3 weeks)
2. Start only duct shield cryocoolers to trap H_2O at the duct shields. (2 - 3 weeks)
3. Start cryocoolers for radiation shields to trap N_2 and O_2 at the radiation shield. (3 - 4 weeks)
4. Start cryocoolers for the payload to cool the mirror at 20 K. (2 - 3 weeks)

→ Total 2.5 - 3 months to complete the cooling.



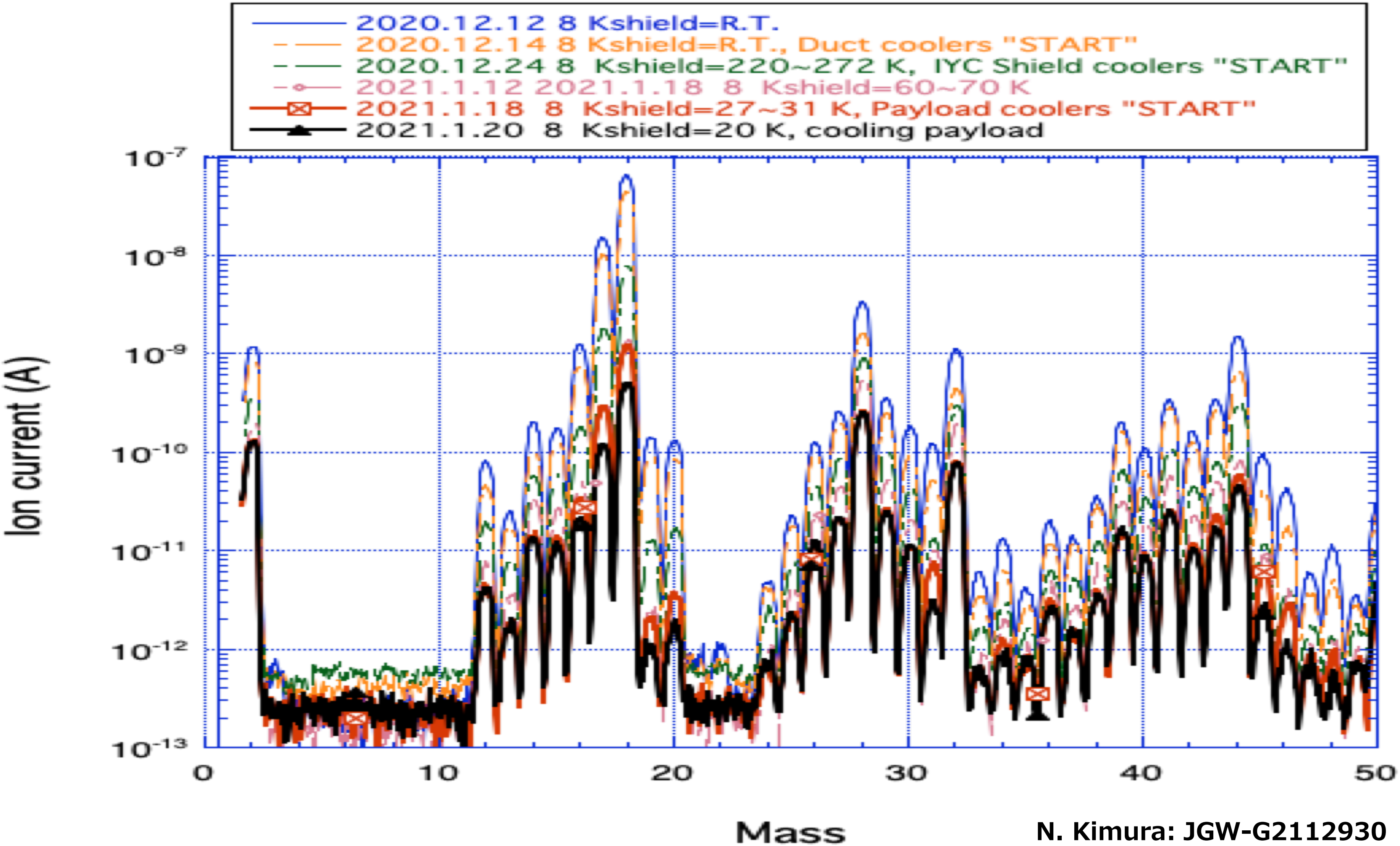
Test of new cooling scheme

New cooling scheme was tested at IYC on Febrary, 2021.



Temperature dependence of internal pressure

Test of new cooling scheme



N. Kimura: JGW-G2112930

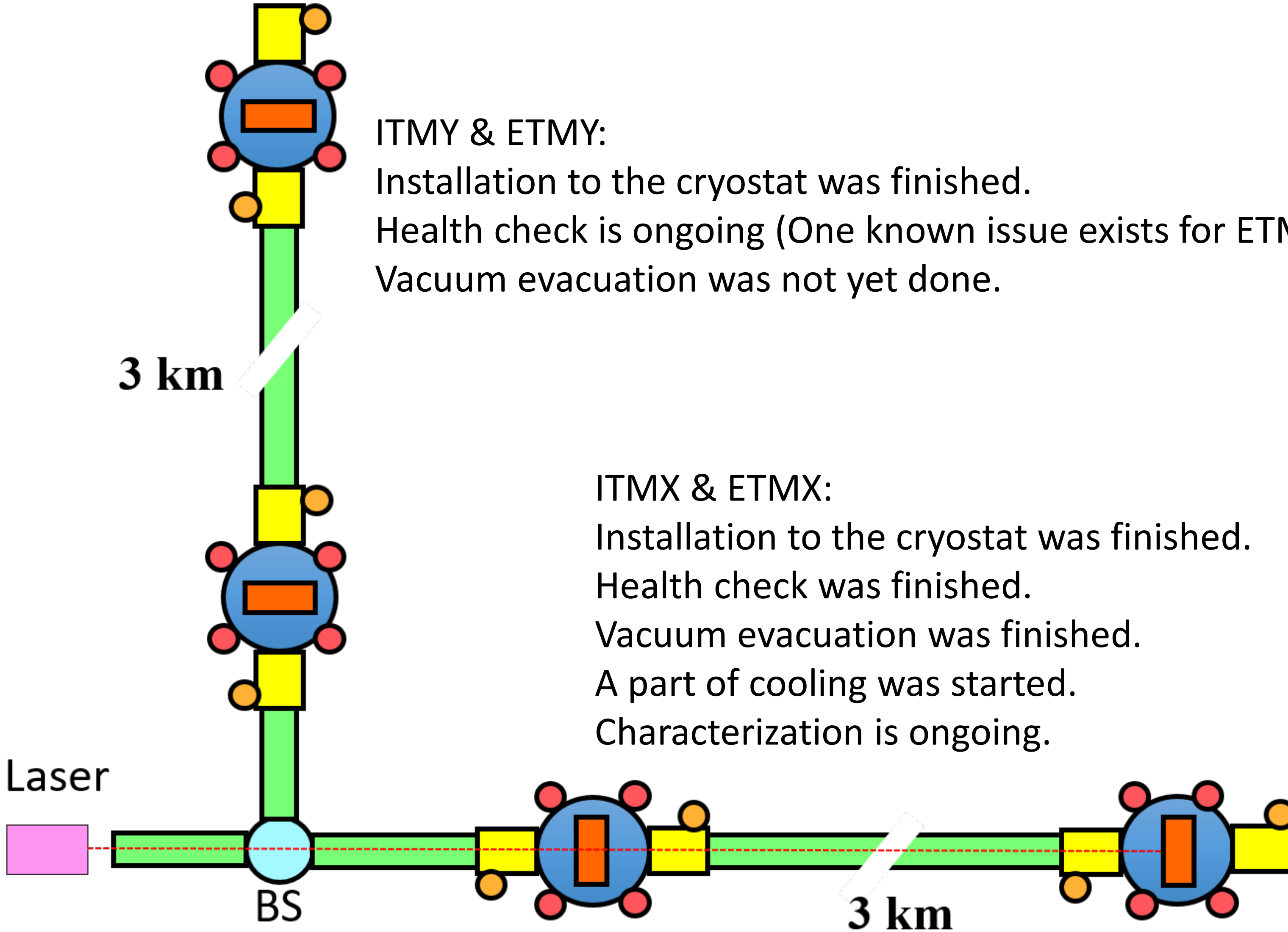
Even after the completion of cooling, a mirror doesn't seem to be covered by frost.
Since finesse could not be measured at this cooling time, we will do it at the next cooling

Preparation status for O4

Current preparation status of the cryogenic payload

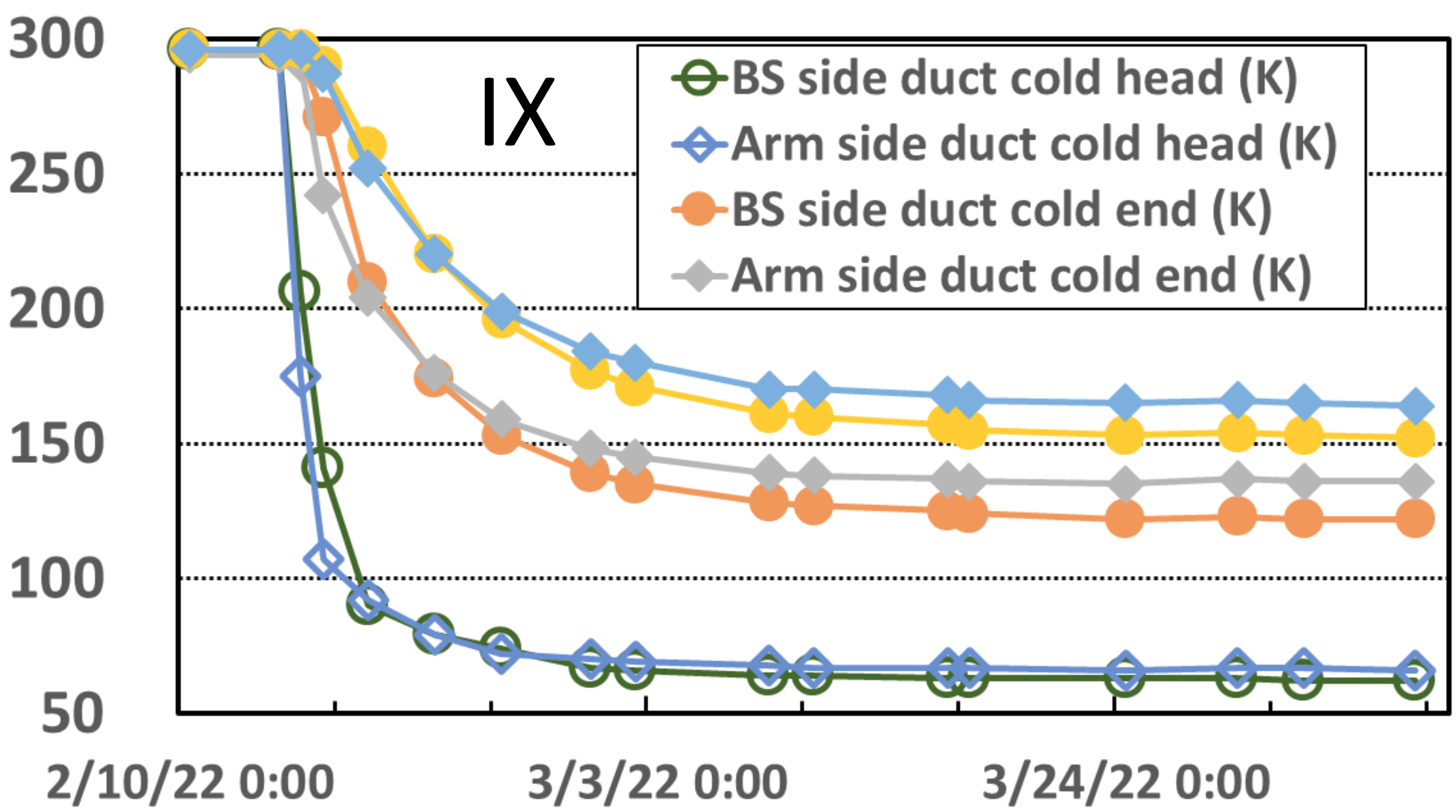
ITMY & ETMY:
Installation to the cryostat was finished.
Health check is ongoing (One known issue exists for ETMY).
Vacuum evacuation was not yet done.

ITMX & ETMX:
Installation to the cryostat was finished.
Health check was finished.
Vacuum evacuation was finished.
A part of cooling was started.
Characterization is ongoing.



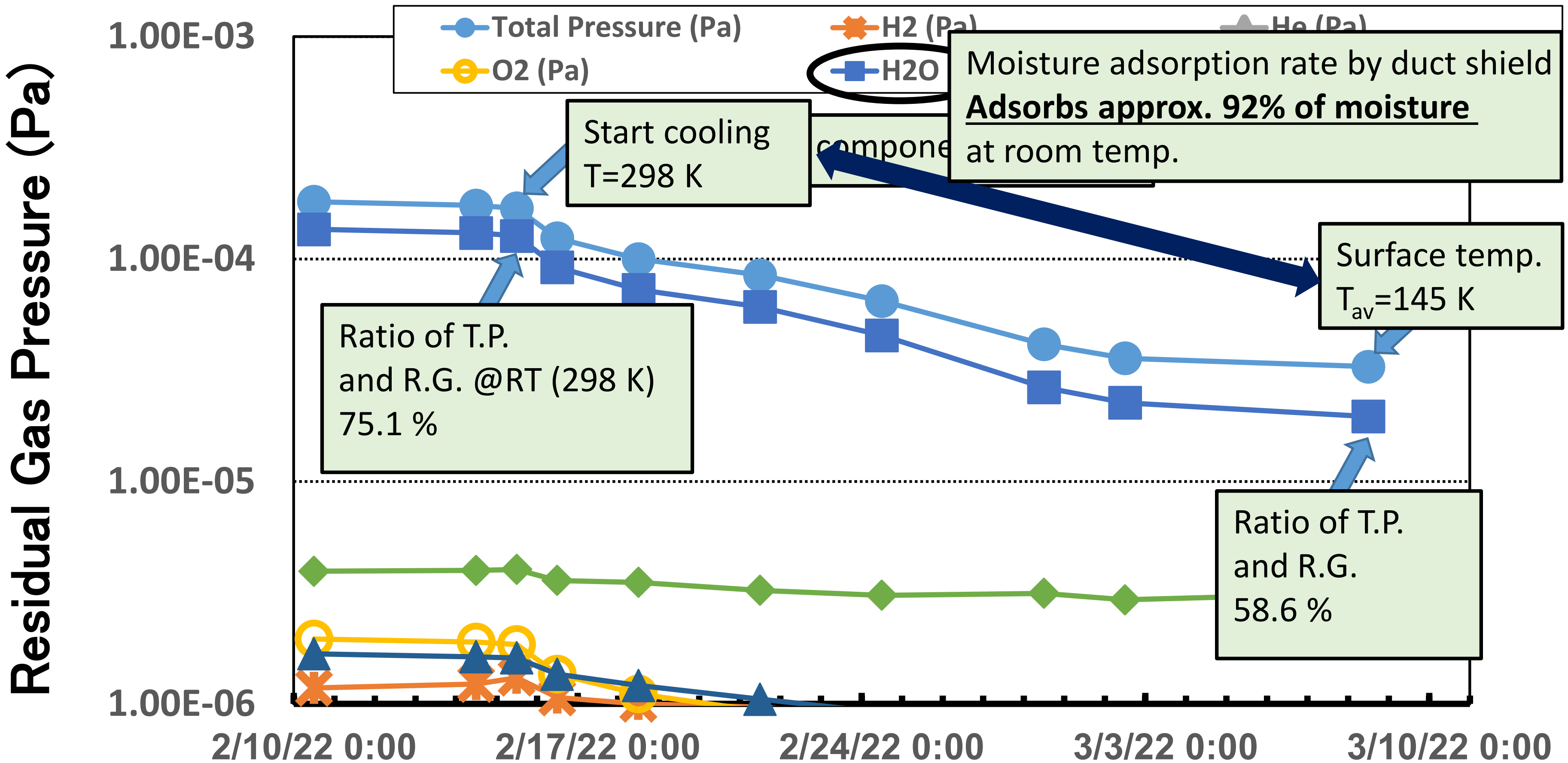
Cooling status toward O4

Vacuum evacuation for ITMX and ETMX was started at the end of the last year.
Cooling of duct shields of ITMX was started from the middle of Febrary.
Cooling of duct shields of ETMX was started from the end of March.
Temperature of duct shields for ITMX reaches steady state.
Temperature of duct shields for ETMX is gradually decreasing now.



Example of the duct shields cooling curve

Vacuum status toward O4

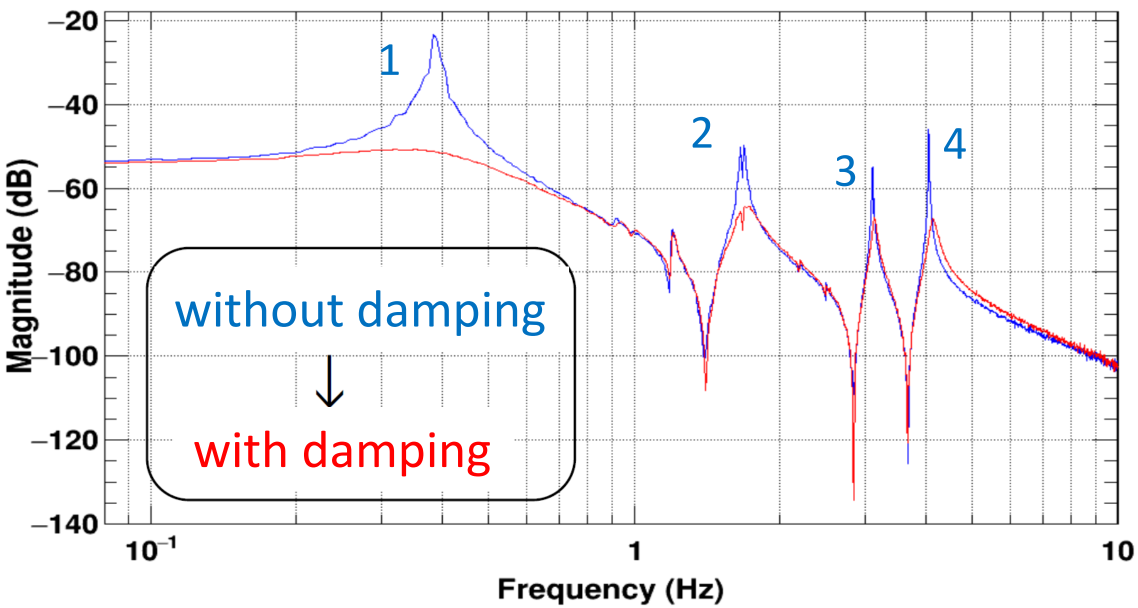


Results of temperature dependence of residual gas pressure in KAGRA cryostat
T.P.; Total Pressure, R.G.; Residual Gas Pressure

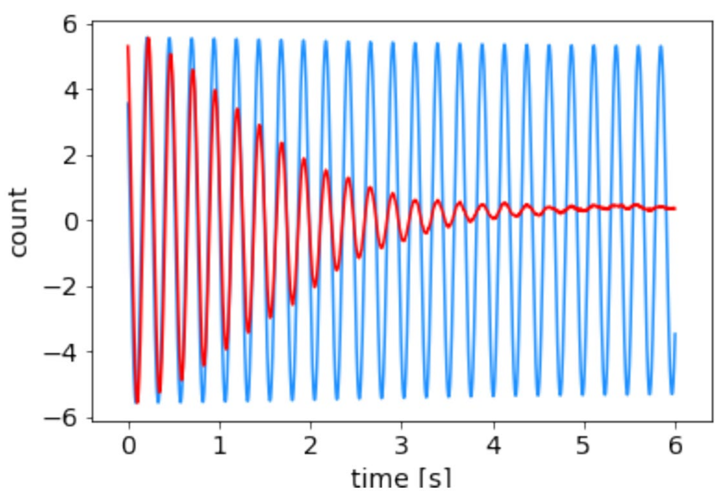
Suspension characterization and damping

- Suspension characterization and damping control implementation is now ongoing.
- Currently, only strong damping for lock acquisition is implemented: noise contribution at observation band is not yet minimized.

Mechanical transfer function from MNY excitation to differential yaw motion of MN stage



Example of ring down measurement (4th mode)



$\tau = 97$ s → $\tau = 2$ s

Summary

- Using cryogenic sapphire mirror for reducing the thermal noise is one of key features of KAGRA.

- Sensors and actuators are designed, considering cryogenic compatibility.
  — Reflective PSs with large sensing range.
  — OpLevs and length-sensing OpLevs.
  — Coil-magnet actuators.
  — “Ropeway style” moving mass

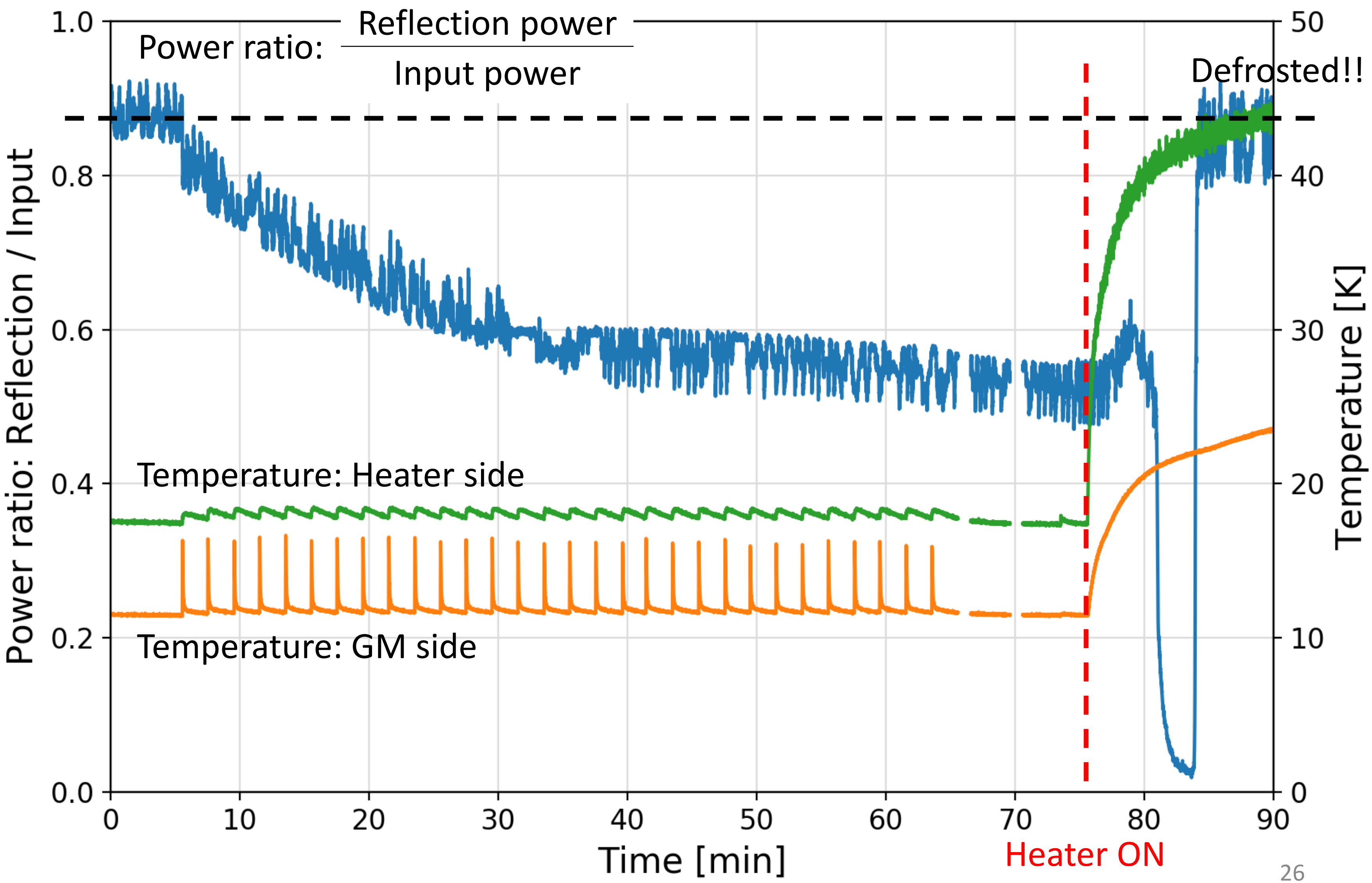
- Cooling mirros can occure the serious problem: frosting on the mirror.
  — Vapor pressure of the molecules needs to be considered.
  —Step by step cooling seems effective.

- Preparation of the payload and a part of cooling is ongoing toward O4.

- We hope our cryogenic experiences can help future gravitational wave detectors such as Einstein telescope.

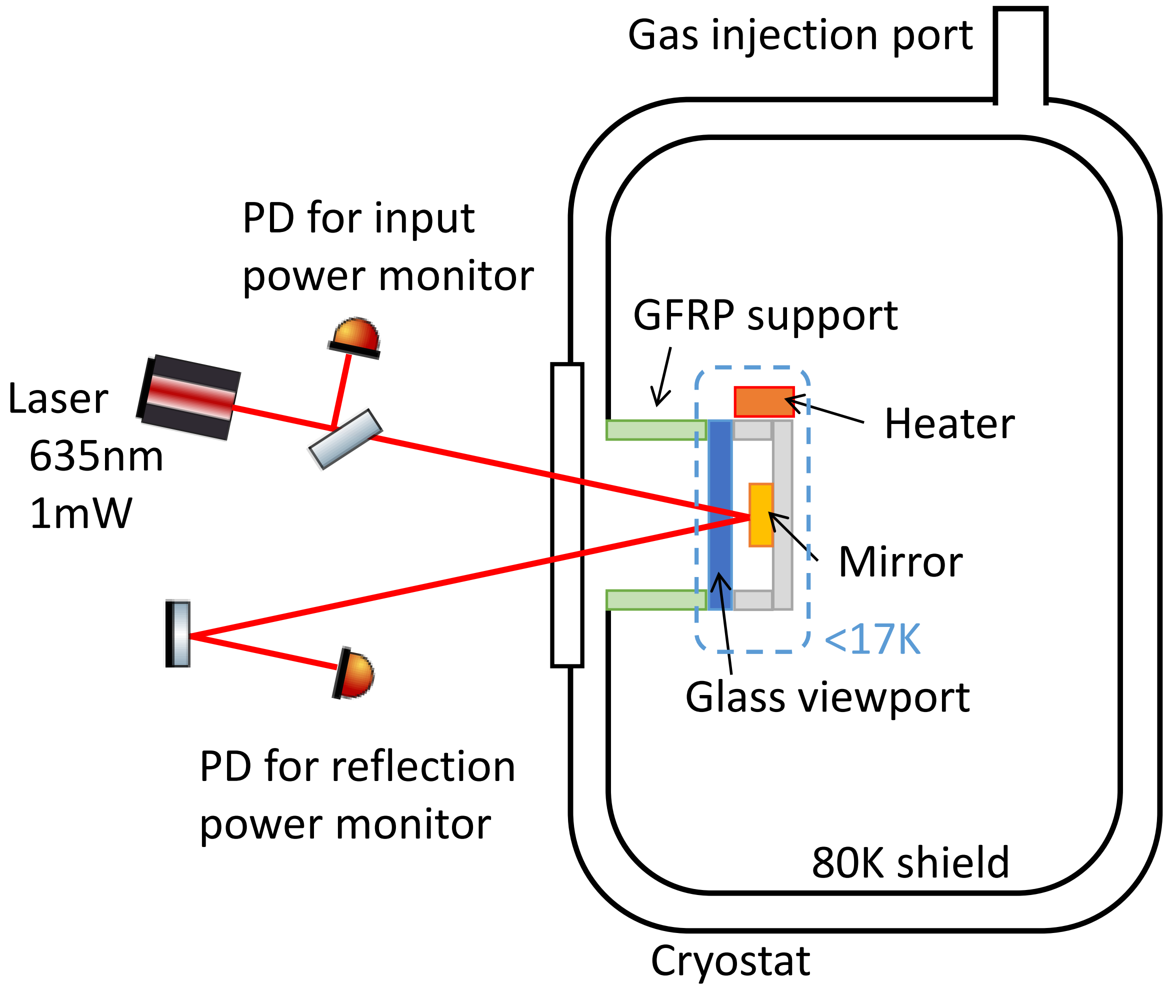
Backup

Result



Power ratio:
Reflection power
Input power
Defrosted!!
Temperature: Heater side
Temperature: GM side
Power ratio: Reflection / Input
Temperature [K]
Time [min]
Heater ON
1.0
0.8
0.6
0.4
0.2
0.0
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90

Demonstration experiment in KEK



With measuring laser power at each PD,

1: inject fixed volume pure N2 gas several times for artificial frosting,

2: warm up a viewport with a heater for defrosting.