KAGRA's experience: icing issues and cryogenic suspensions

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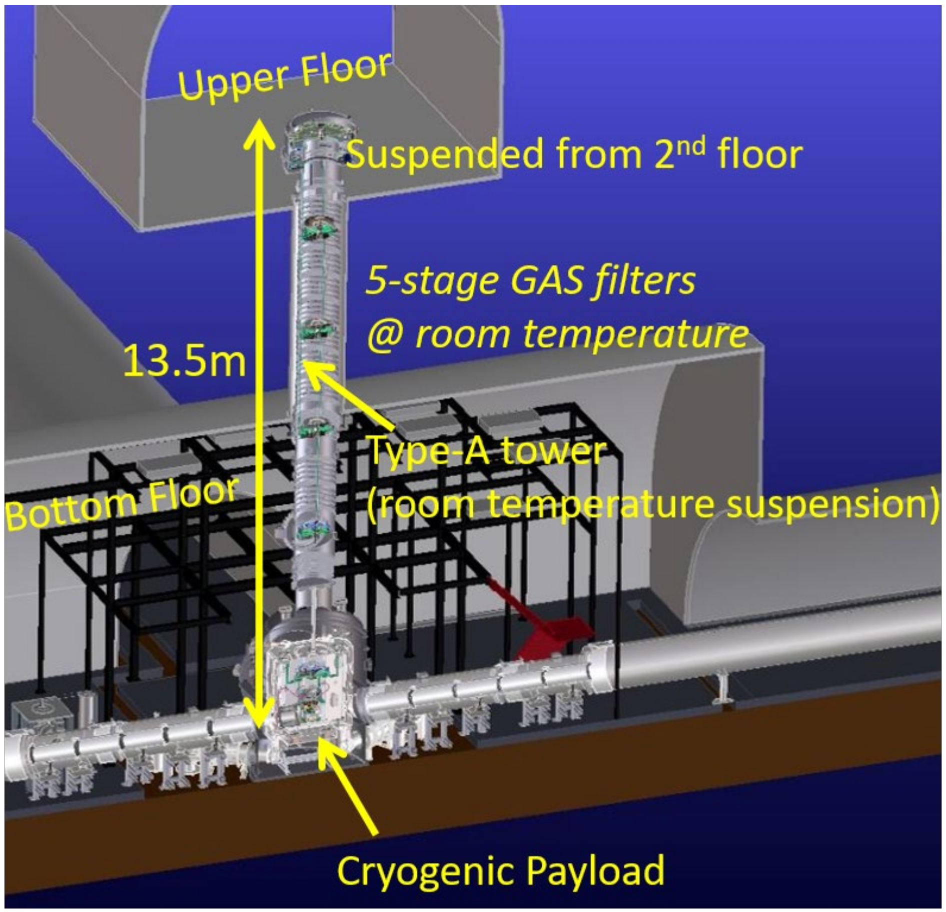
Contents

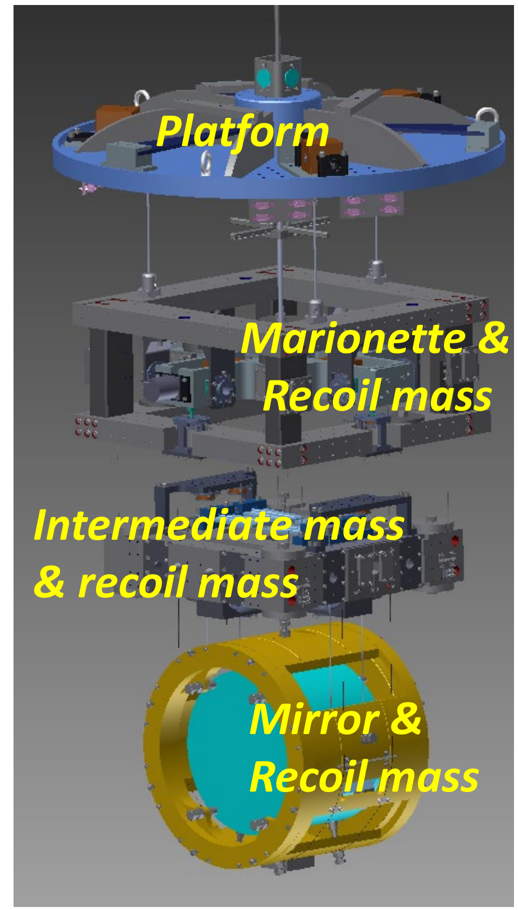
KAGRA Cryogenic payload

Cryogenic payload is bottom four stages of KAGRA mirror suspension, including a sapphire mirror.

To isolate from the ground vibration, it is suspended from huge tower of VIS called Type-A tower

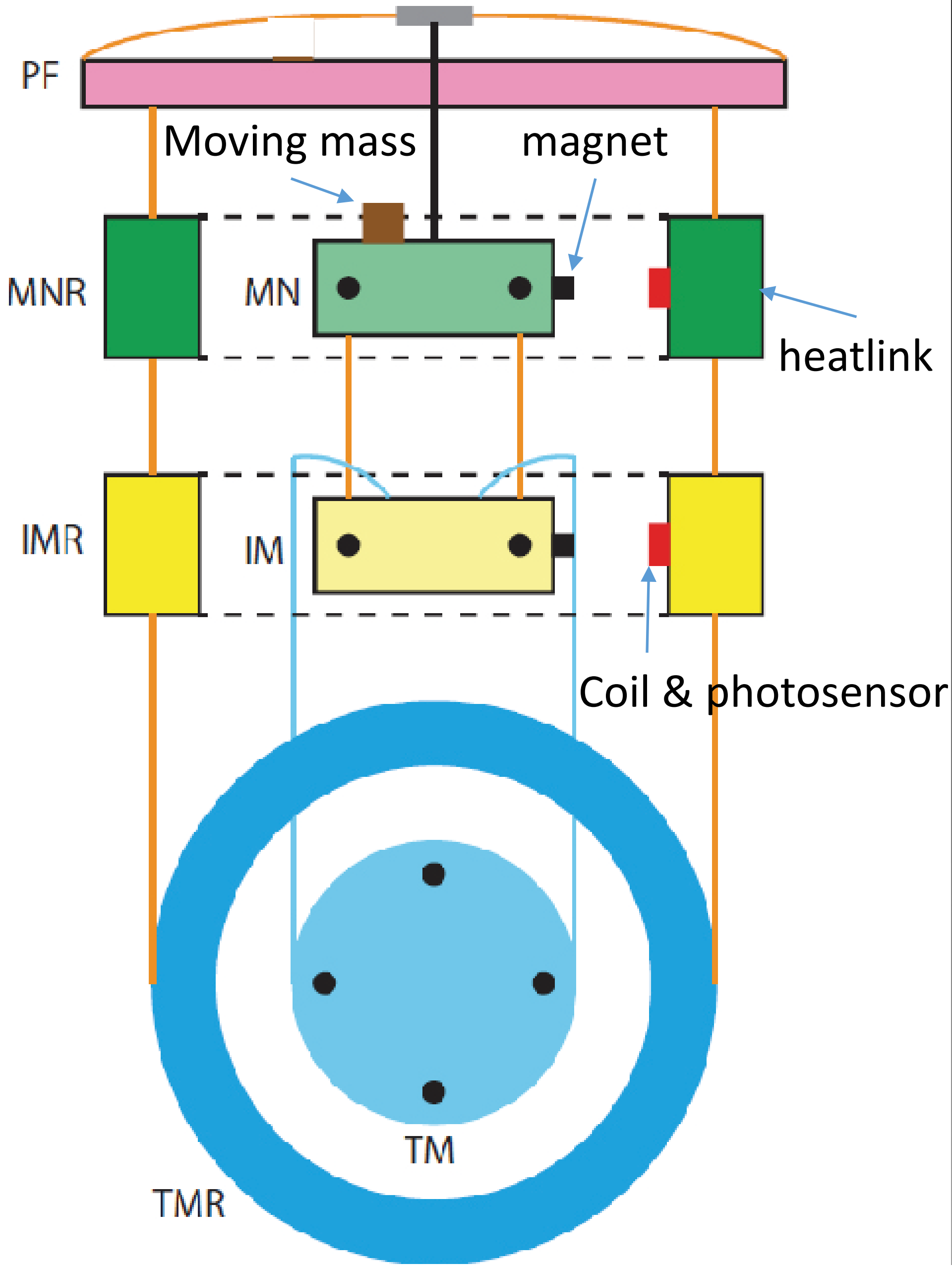


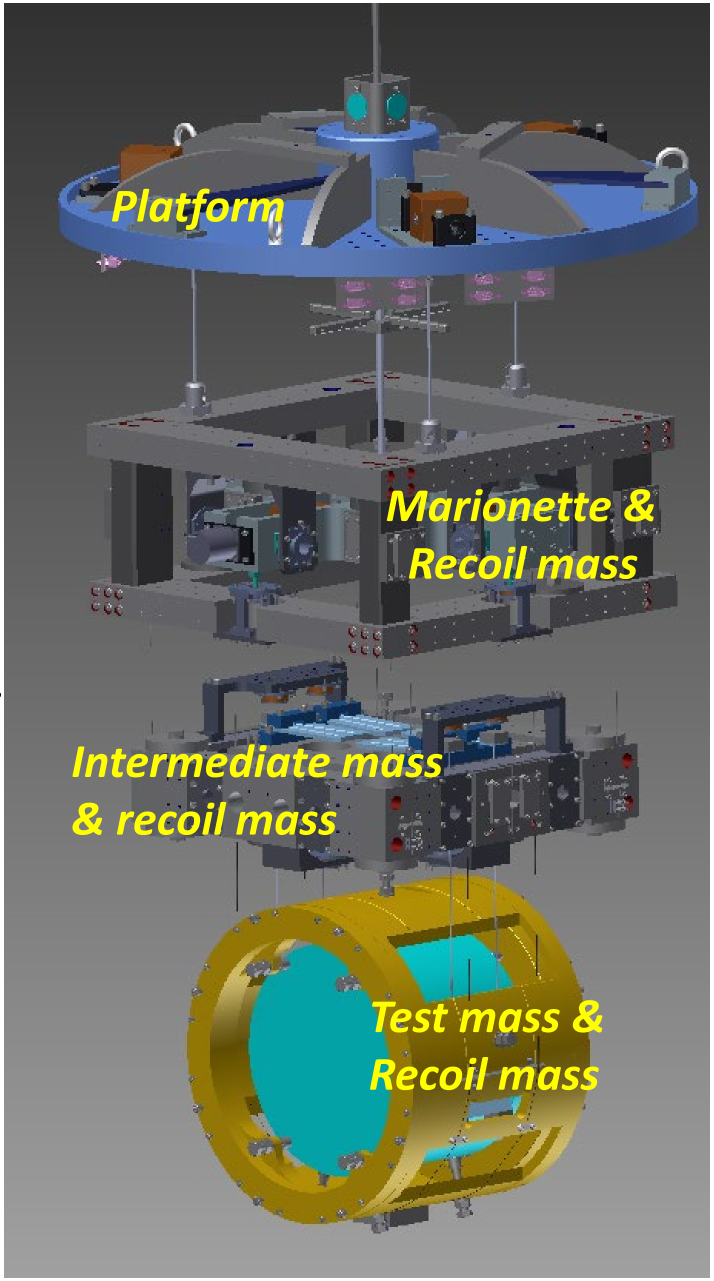
Type-A suspension



Cryogenic payload

Schematic of the payload





Basic concept of the payload

- Platform (PF)：

Isolate the TM chain from vibration via heatlink.
Align RMs to an inner chain (MN, IM, and TM).

- Marionette (MN)：

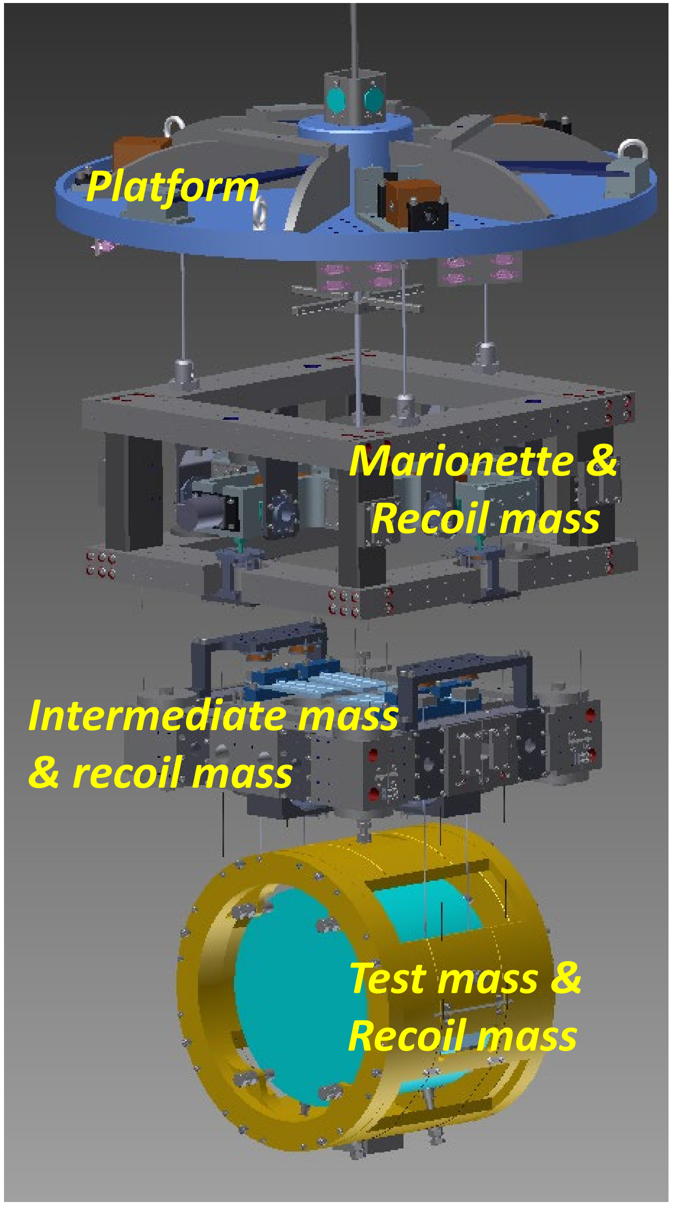
Actuate TM below 1Hz for interferometer locking.
Damp eigenmodes of the cryogenic payload.
Align pitch inclination of TM (moving mass).

- Intermediate mass (IM)：

Actuate TM at 1 - 10Hz for interferometer locking.
Installed a heater for defrosting.

- Test mass (TM)：

Actuate TM above 10Hz for interferometer locking.

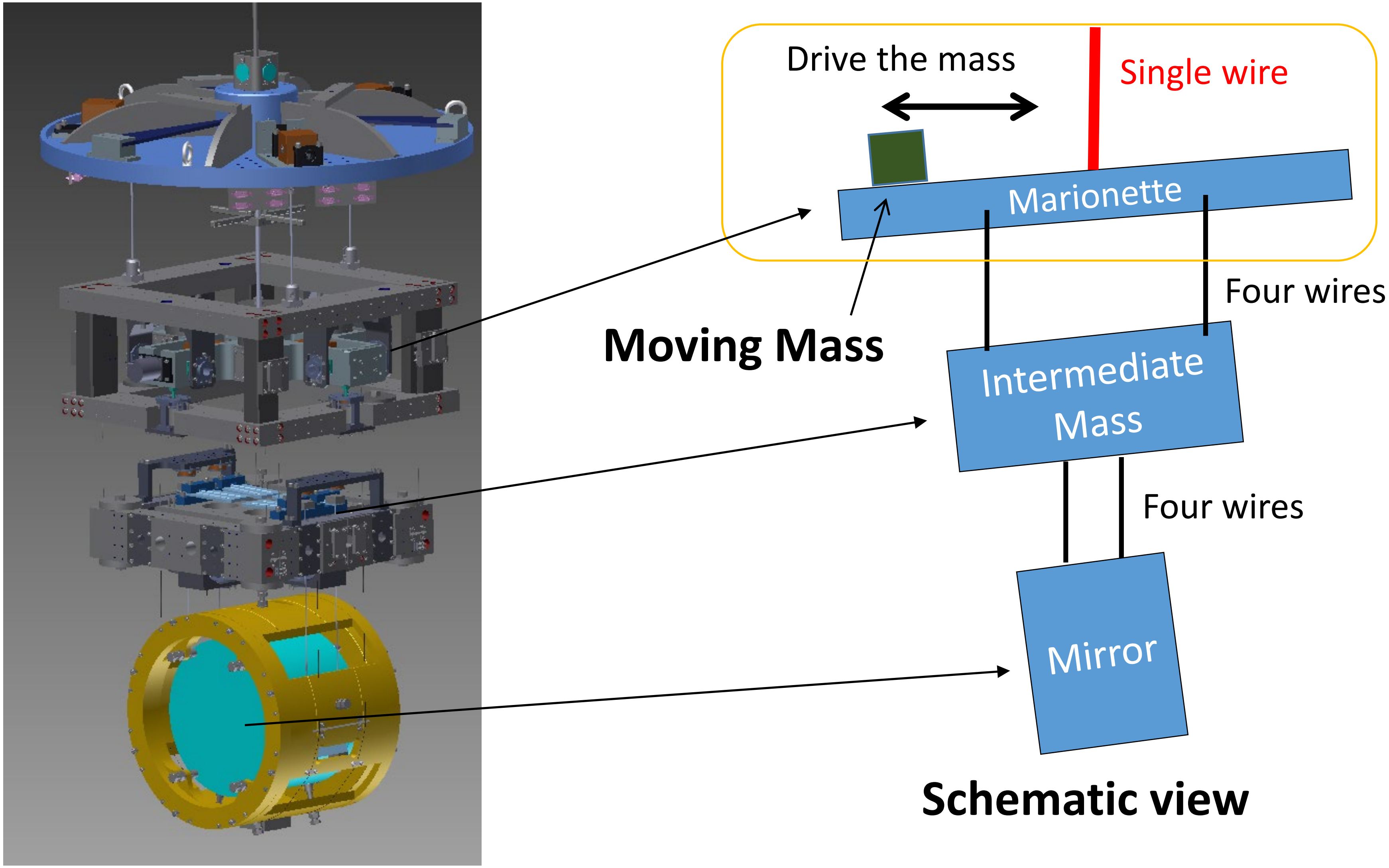


Cryogenic payload

Cryogenic payload

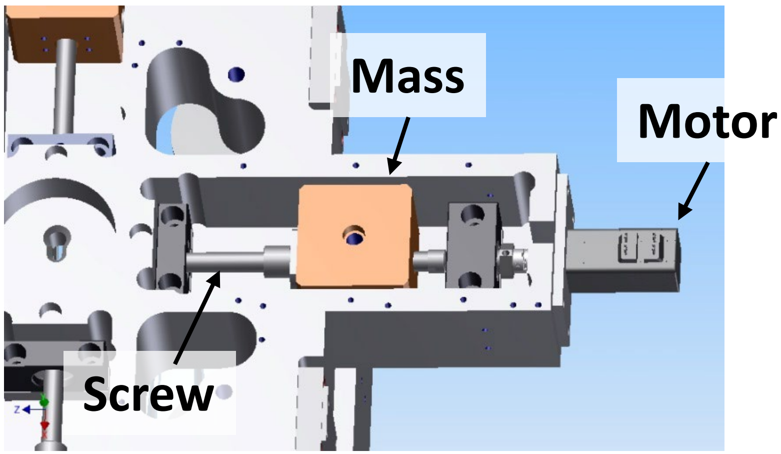
Moving mass

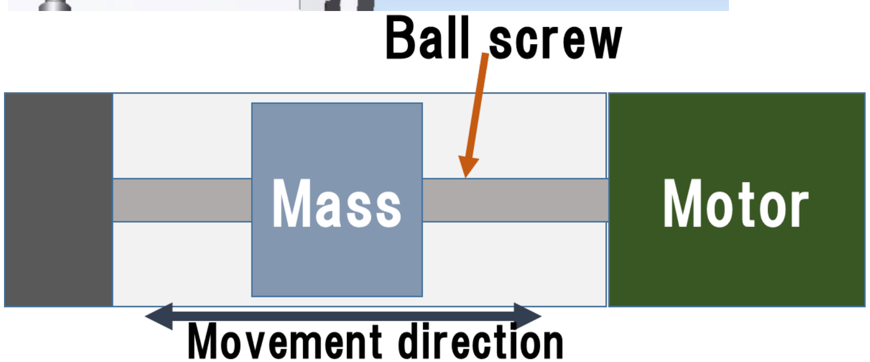
- Since MN is suspended from PF by a single wire, pitch inclination of a mirror need to be adjusted by MN or lower.

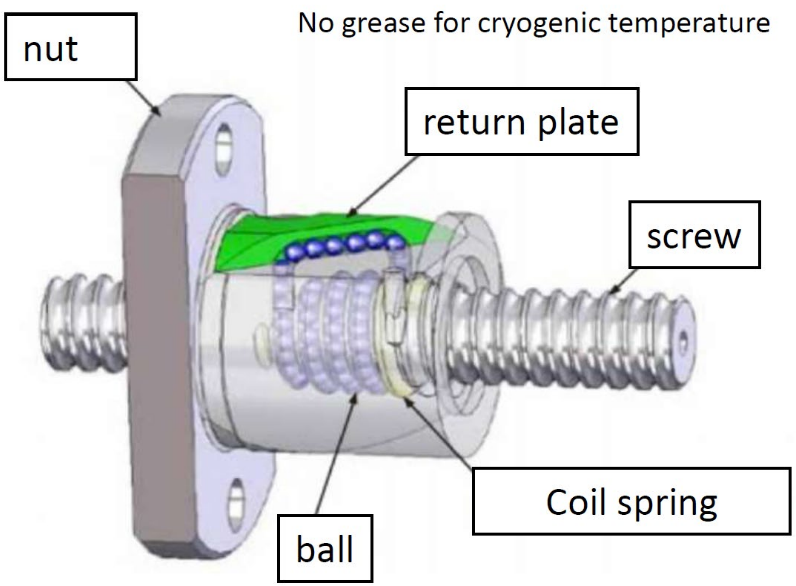


Ball screw type moving mass

- Moving mass which uses ball screw to convert rotation of motors into lateral motion of masses.







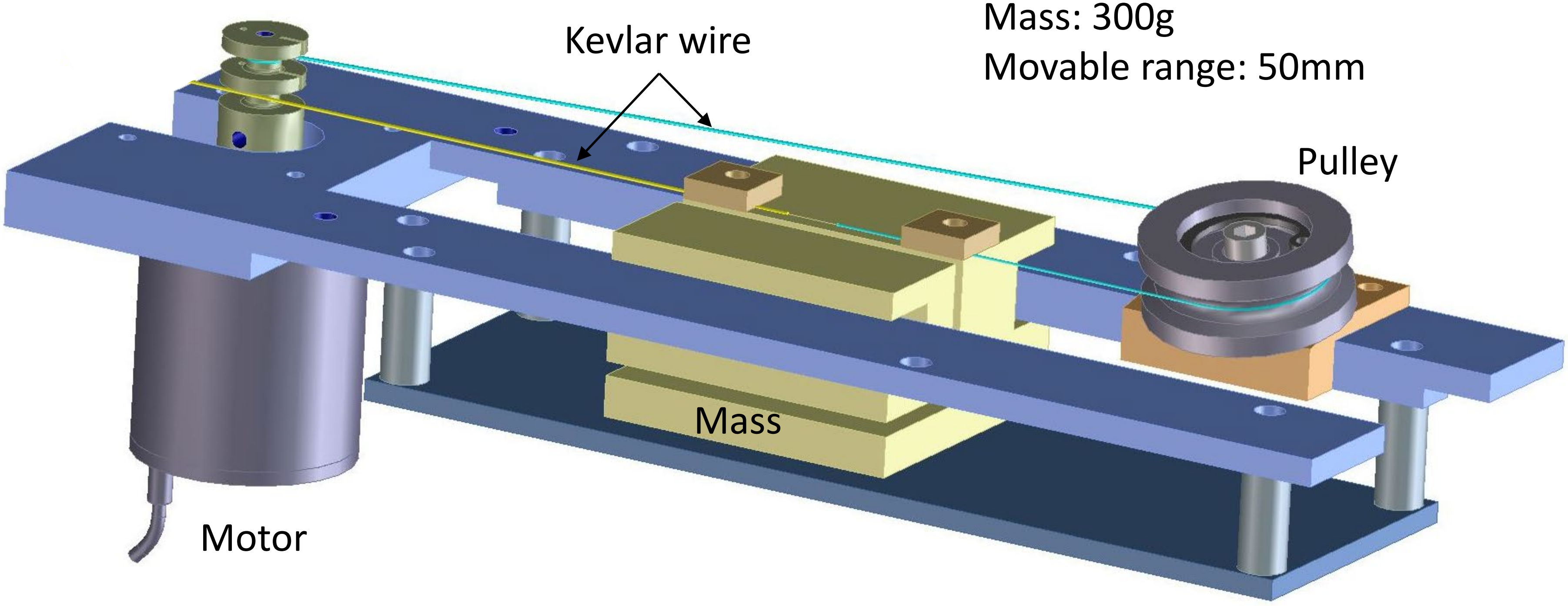
Schematic of ball screw

Due to complex structure of ball screw, nuts are sometimes stuck after moving several times.

New moving mass

To avoid the stuck of moving mass at cryogenic temperature, we designed new moving masses that have simple structure.

Mass: 300g
Movable range: 50mm



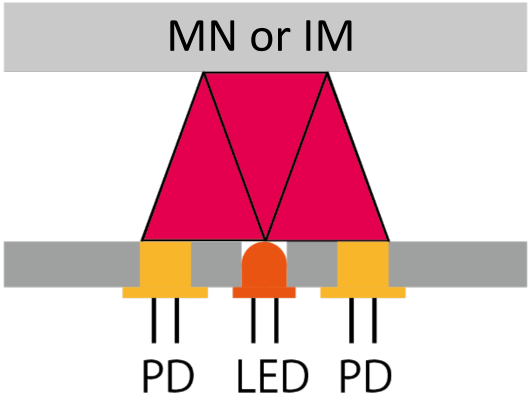
Advantage of the new moving mass:
Less chance to be stuck because of simpler structure.
No need DC current for keeping the position of moving mass.

Whole size is also important for installing without large design change of the payload

Local ensors: Photosensor (PS)

PSs are consist of a set of one LED and two PDs.

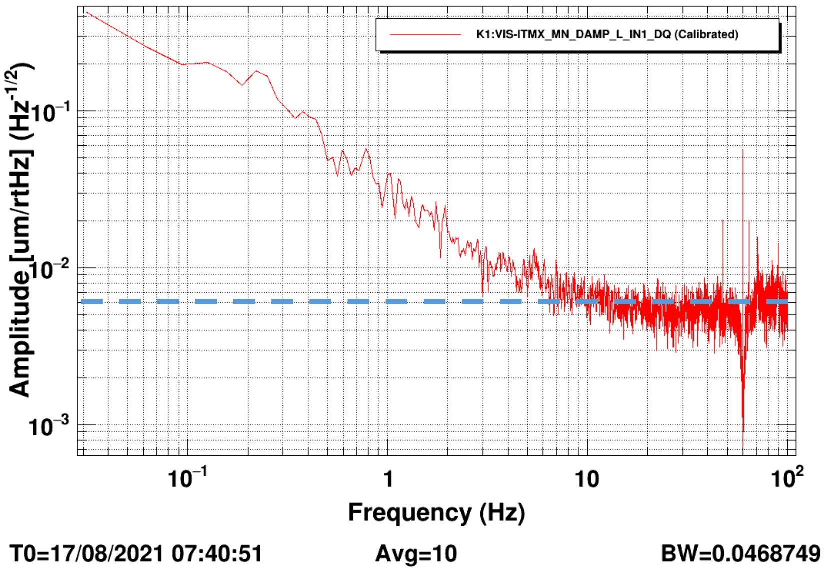
They are mounted on MNR and IRM, and LED lights are reflected at the surfaces of MN and IM.



Since the drift at cryogenic temperature, especially the amount of twist, is difficult to be predicted, the distance between PSs and reflection surfaces are designed as wide range region.

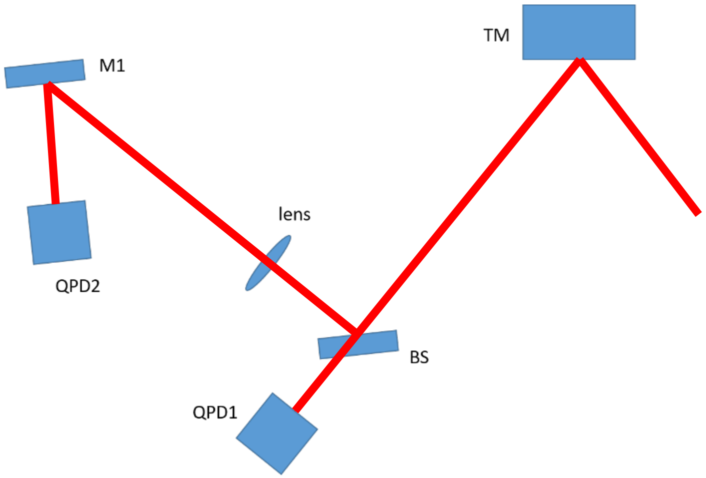
To obtain abut 5-10 mm range, the sensor noise level is not so good compared with OSEM (shadow sensors for RT suspension).

From the experience during the O3GK, the noise level seems 6×10^{-9} m/rtHz above 10Hz.



Local sensors: Optical levers

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

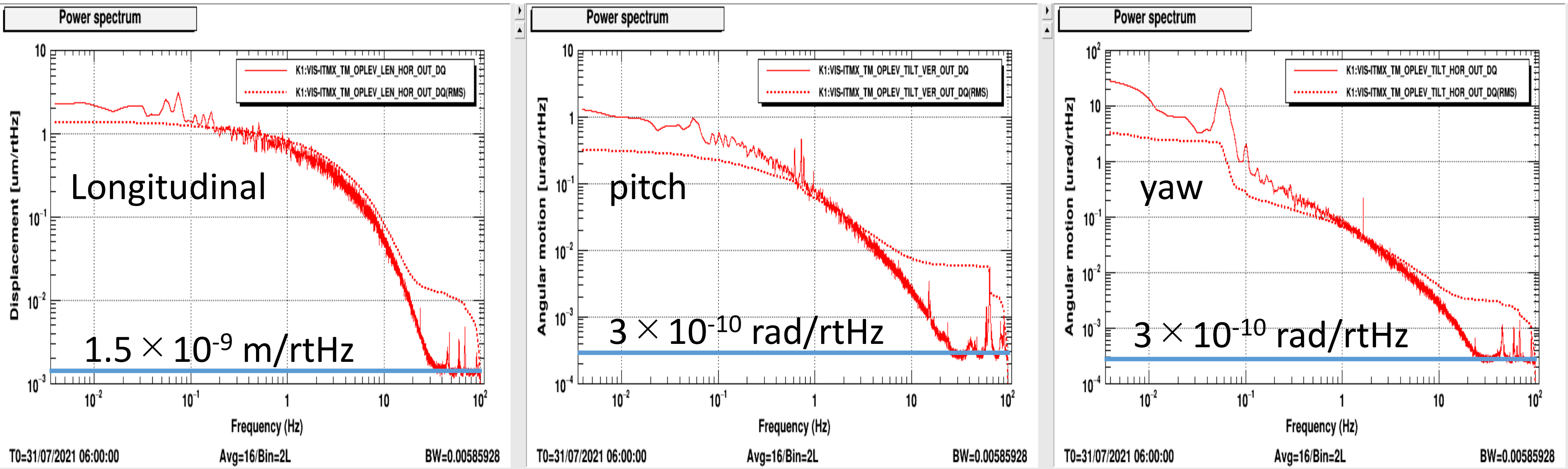


→Three degrees of freedom can be detected by one set of OpLevs.

- Typical OpLev noise above 10 Hz

For tilt motion: 3×10^{-10} μrad/rtHz

For translational motion: 1.5×10^{-9} m/rtHz



Example of spectra (suspension in air)

Rises below 30Hz are due to air disturbance and will be lowered in vacuum condition.

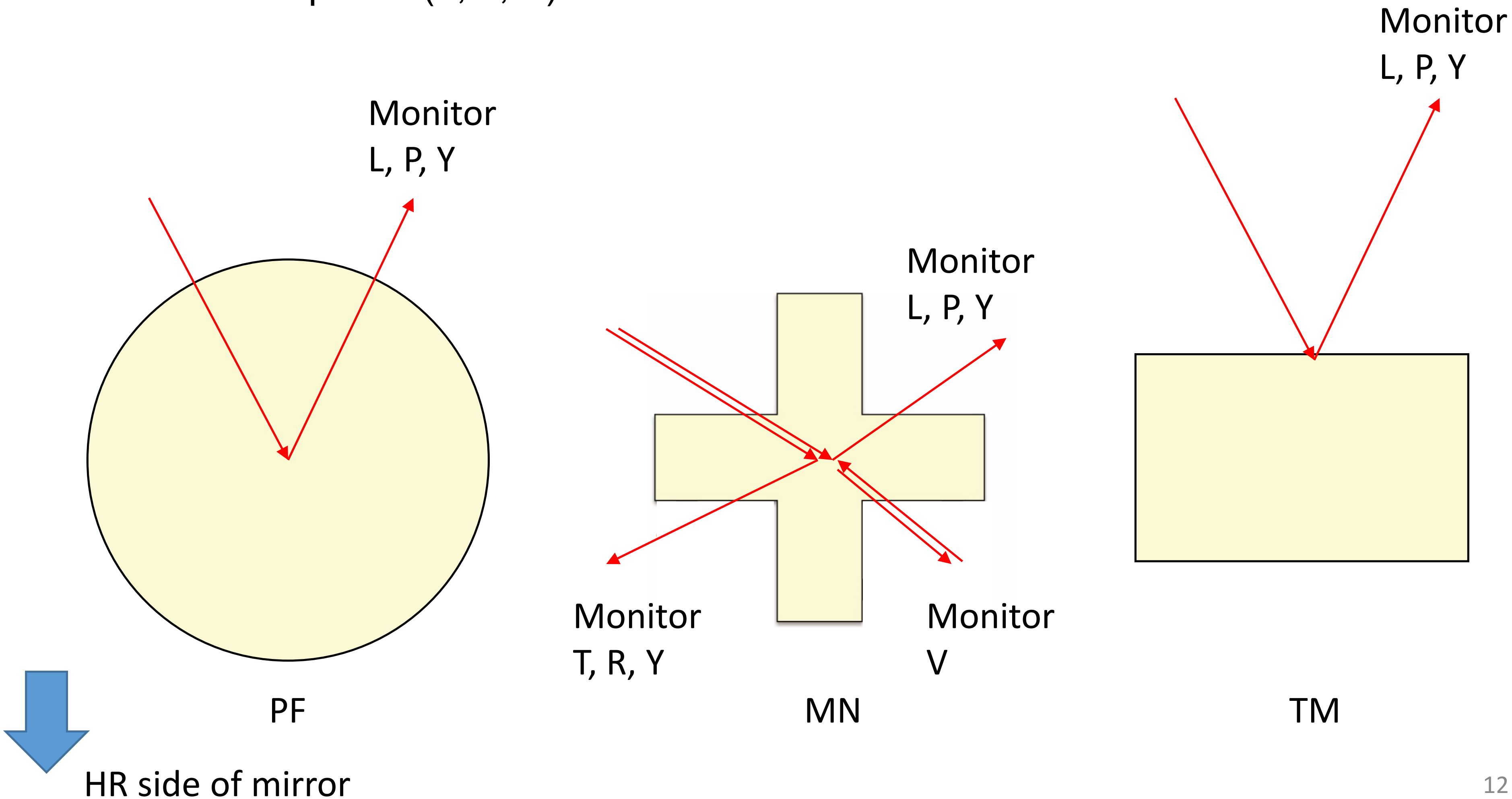
Setup of OpLevs

- In our setup of OpLevs, following degrees of freedom can be sensed.

TM : one set of OpLevs (L, P, Y)

MN : two sets of OpLevs and one vertical monitor with retro reflector (L, T, V, R, P, Y)

PF : one set of OpLevs (L, P, Y)



Icing issues

Icing issues

Residual gas molecules can be trapped on the surface of the cryogenic materials and make thin layers.

→It reduces the performance of cryogenic GW detectors through

- Heat absorption
- Oscillation of reflectance of the mirror
- Cavity optical loss

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Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes

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Optical loss study of the cryogenic molecular layer using a folded cavity for future gravitational-wave detectors

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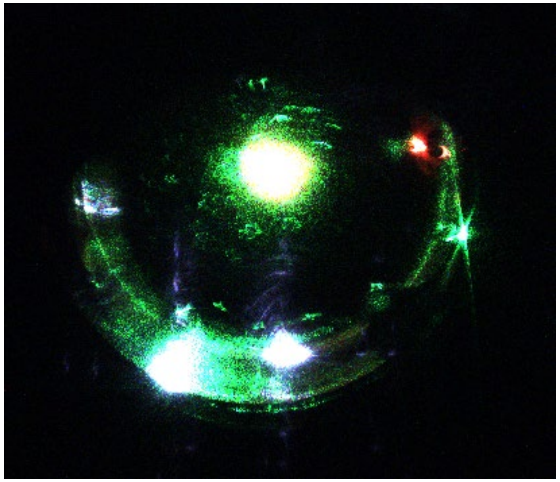
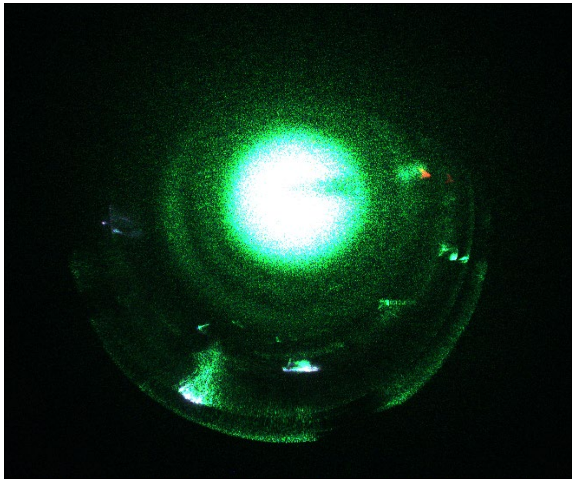
However, the icing on the mirror caused much more severe situation in KAGRA during the commissioning term.

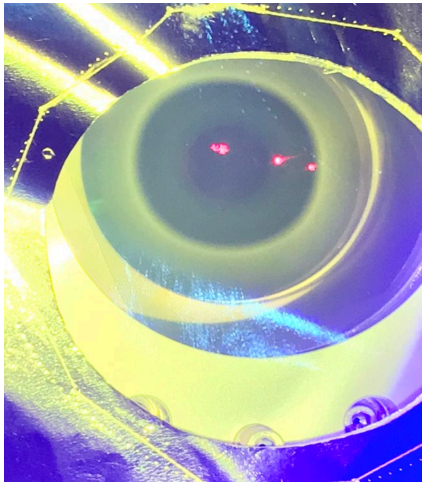
What we faced during the previous commissioning



mirror with green light at room temperature



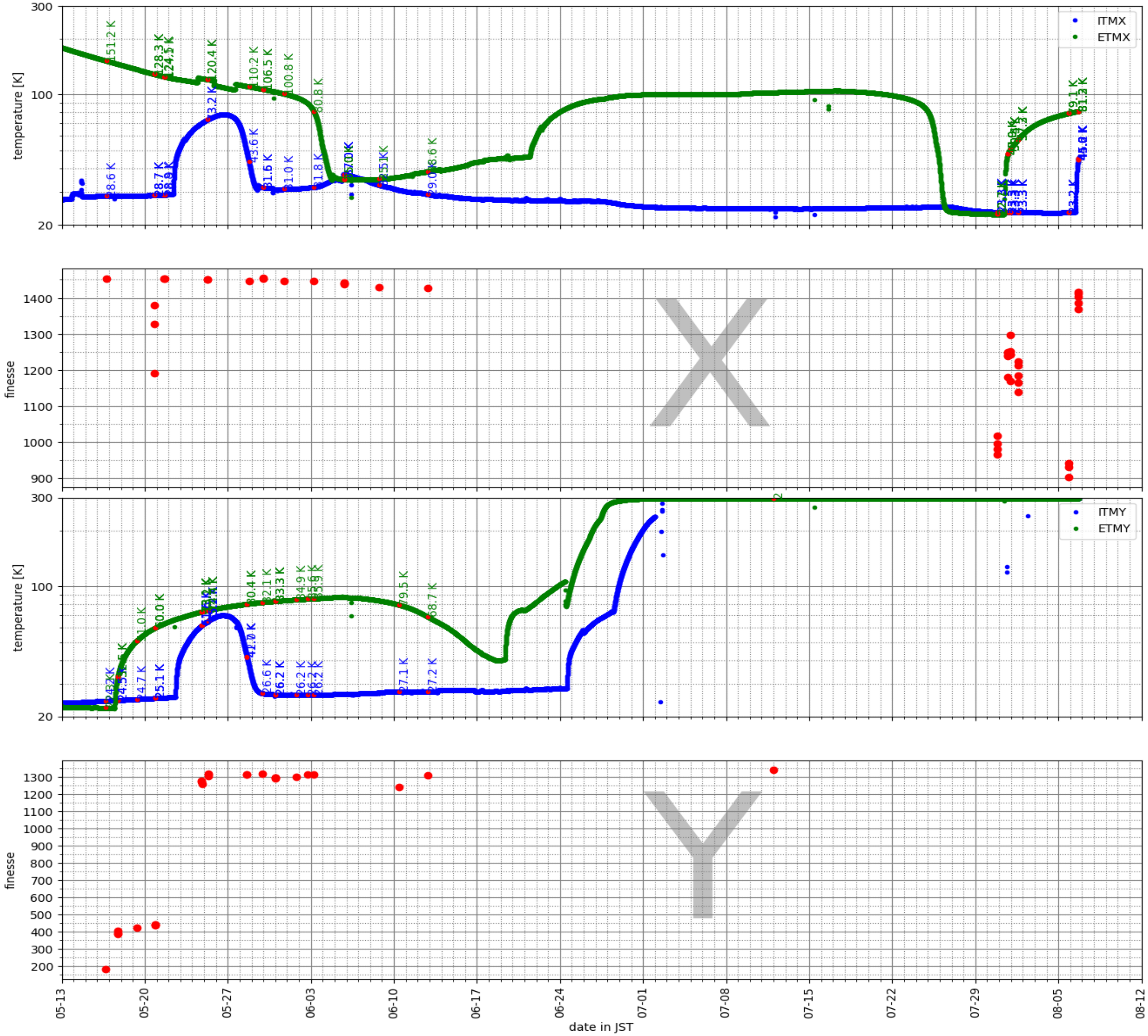
mirror with green light at cryogenic temperature



Viewport for an OpLev

- During cooling, a lot of molecules were trapped on the mirror surface and configured significantly thick layer, which causes a large drop or finesse of the cavity and made it impossible to lock the interferometer.
- We also face the icing of viewports, which used for optical levers, and the ice made it difficult even to engage local damping control of the suspension.

X and Y arm finesse drop during cooling



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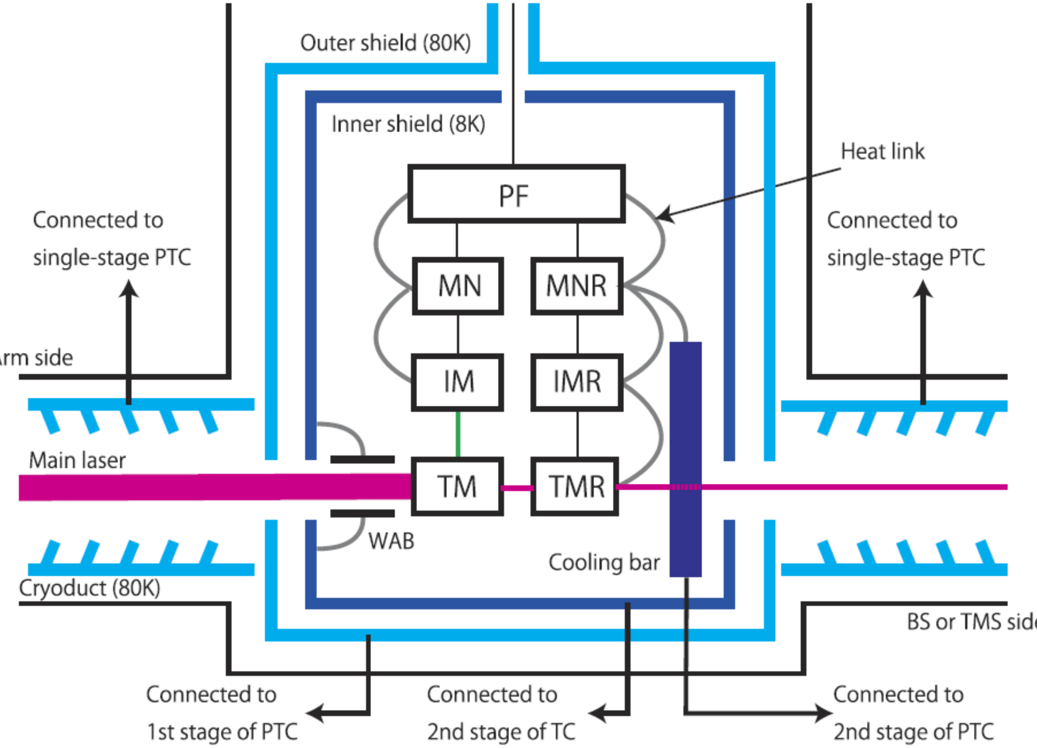
New cooling scheme in KAGRA

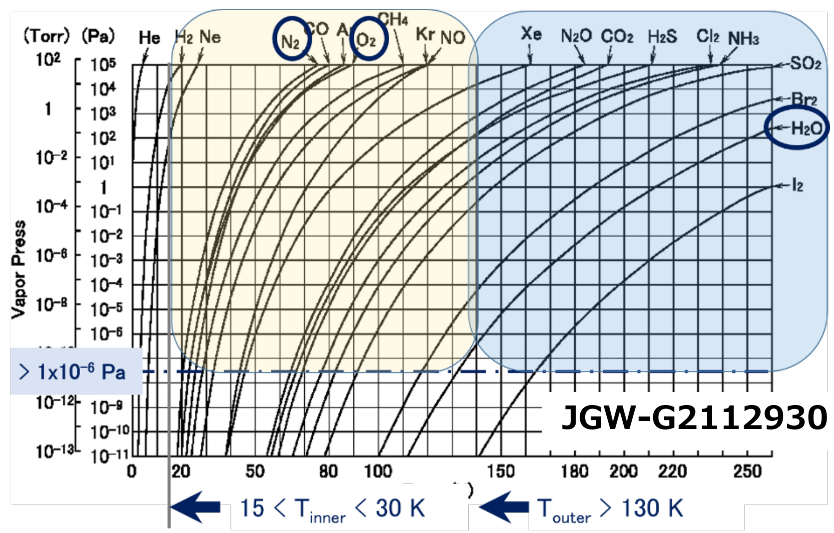


Schematic of cooling system

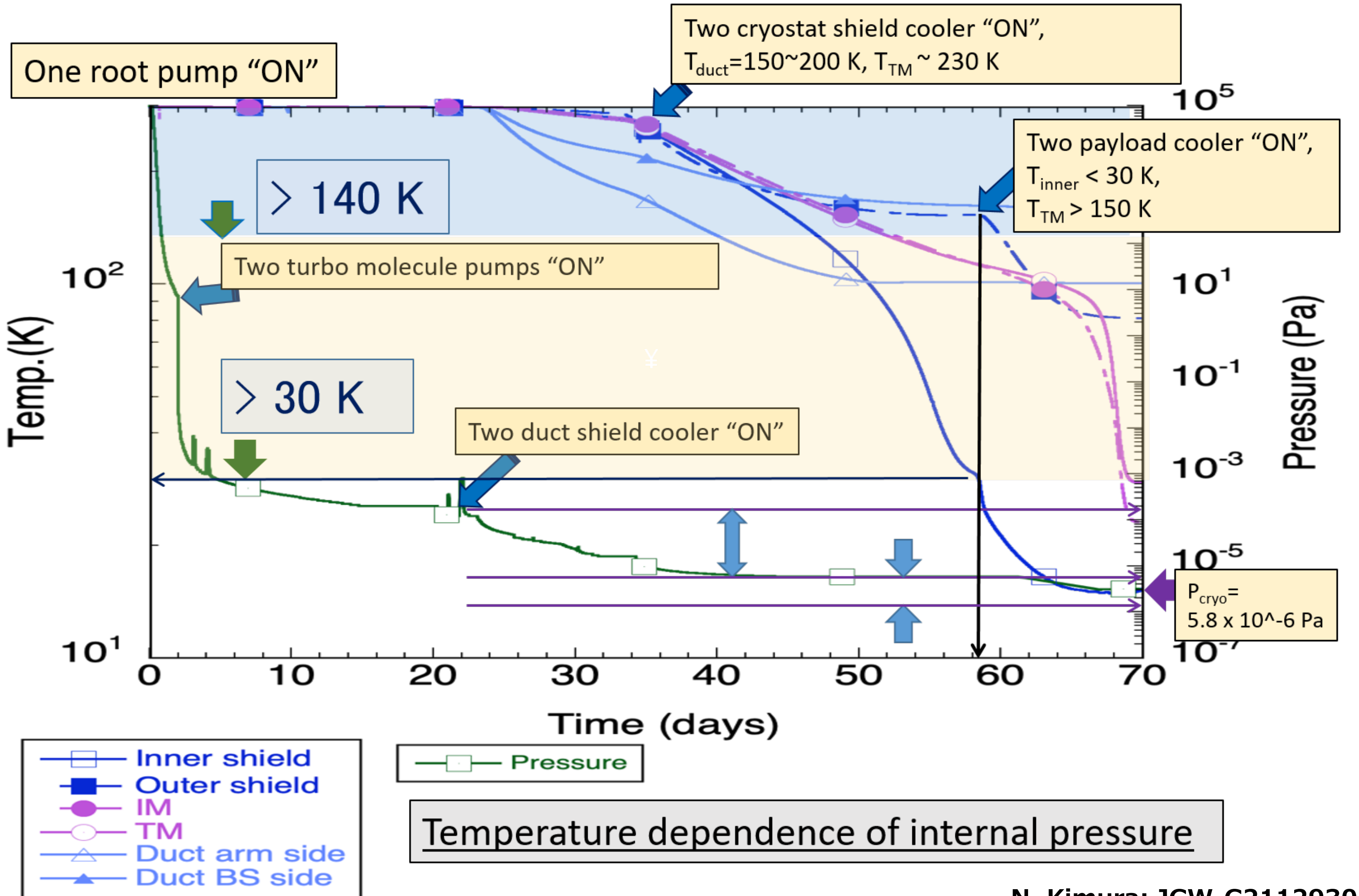
New procedure:

0. Perform leak test seriously and reduce leakage.
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 weeks)
3. Start cryocoolers for radiation shields to trap N_2 and O_2 at the radiation shield. (3.5 weeks)
4. Start cryocoolers for the payload to cool the mirror at 20 K. (1.5 weeks)

→ Total 2.5 months to complete the cooling.



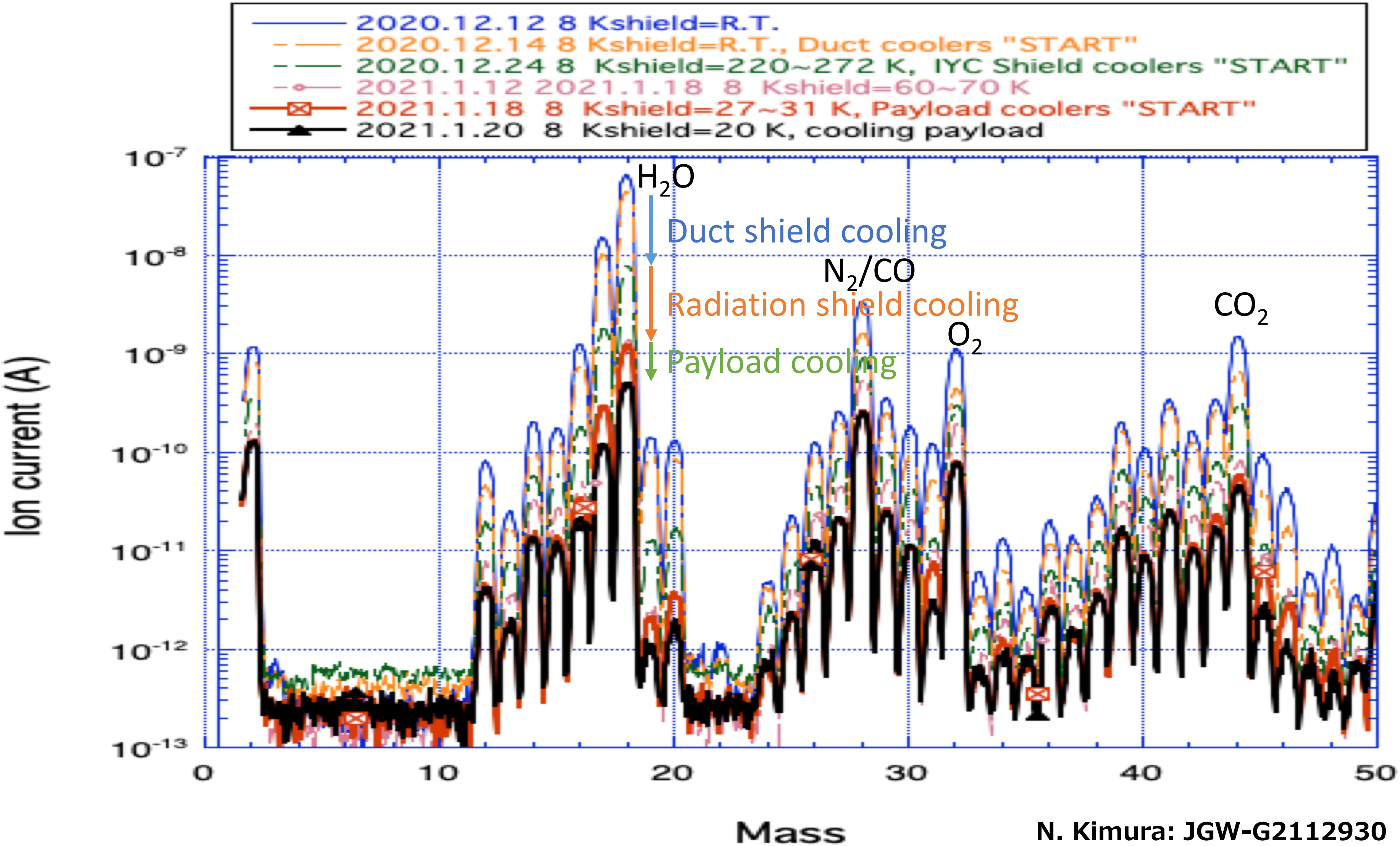
Test of new cooling scheme



Temperature dependence of internal pressure

N. Kimura: JGW-G2112930

Test of new cooling scheme



N. Kimura: JGW-G2112930

Even after the completion of cooling, a mirror and viewports don't seem to be covered by frost.

Lessons we learned

- Icing on the mirrors during initial cooling is very serious problem for operating cryogenic GW detectors.

—Leak test is very important.
—Step by step cooling seem to work well at least visual inspection level.
—Cryogenic pump is very useful for reducing the residual gas molecules, especially water molecules in KAGRA.

- Defrosting system development is needed in case the icing happens.

—Currently, defrosting heater is installed at IM stage in KAGRA.
—CO2 laser is one promising candidate but entire suspension is warmed up.
—Another possibility is to use lasers with the wavelength of water-molecule absorption like 1.4 um, 3 um, and so on but need to be tested.

- To reduce long-term contamination, the long cryogenic duct between cryostat and room-temperature beam duct is very effective.

— Water molecules are trapped by cryogenic duct in KAGRA.
—Two-layer ducts can be more effective for trapping, especially low vapor pressure molecules like nitrogen, oxygen, and so on.

Summary

- Sensor and actuator development is important:

— Moving mass is newly developed for initial alignment. Long-term reliability is much better than old design.

— Cryogenic compatible local sensors are necessary. Reflection-type photosensor was developed but the sensitivity is relatively low compared with the local sensors, which used in the room-temperature suspension.

- Icing is problematic for the cryogenic GW detectors in terms of not only long-term operation but also reliability.

— Cooling system should be well designed for trapping residual gas.

— Cooling strategy is also well considered to reduce the risk of icing.

— Development of defrosting system is important: heaters, CO2 lasers, and so on.