The KAGRA Vacuum and Cryogenic and its upgrades

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On behalf of KAGRA collaboration

Institute for Cosmic Ray Research/University of Tokyo

The Gravitational Wave Detector Vacuum workshop

Hermitage Hotel in La Biodola, Isola d'Elba, Italy

30 September 2022

Contents

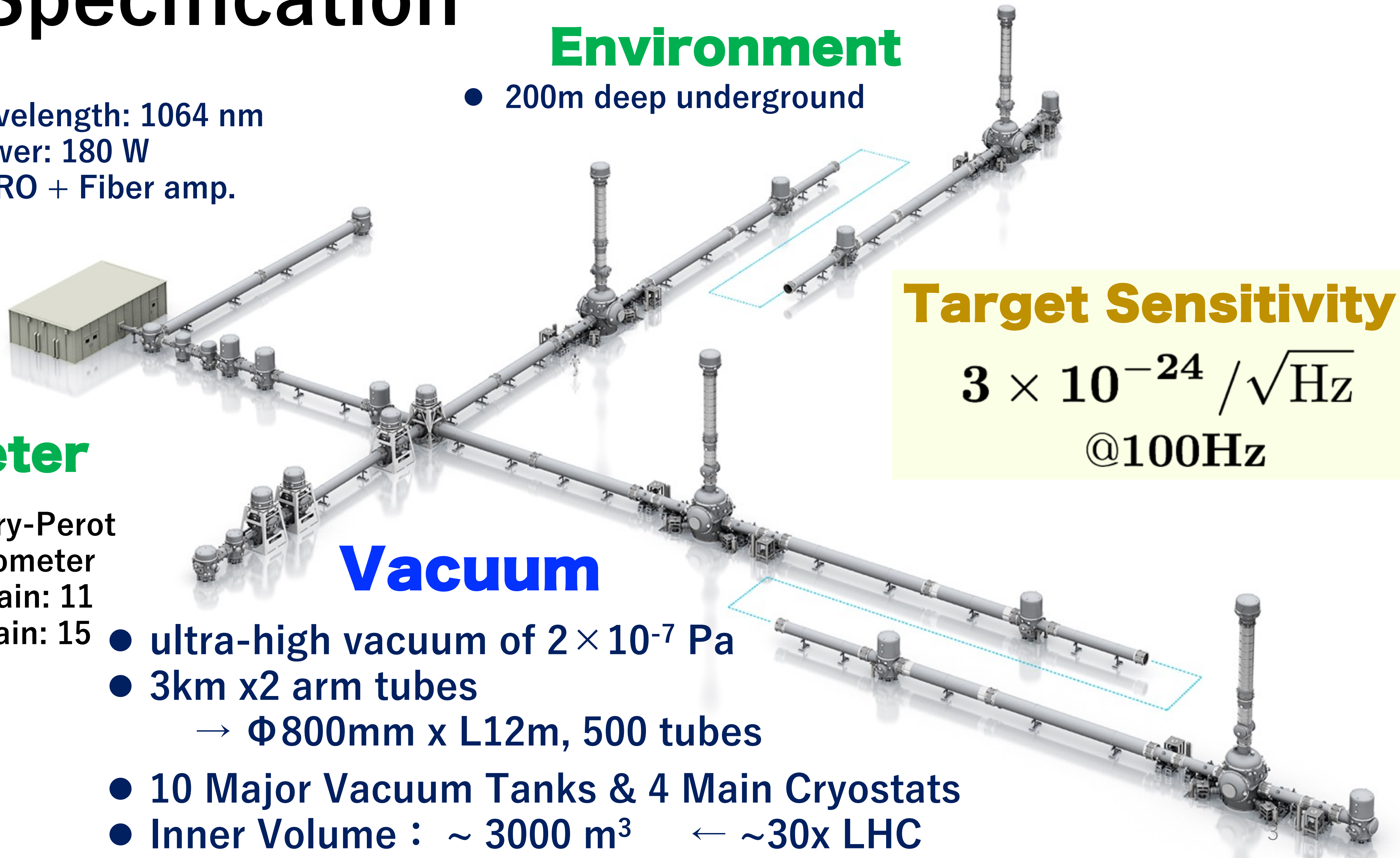
KAGRA Specification

Laser

- Wavelength: 1064 nm
- Power: 180 W
- NPRO + Fiber amp.

Environment

- 200m deep underground



Target Sensitivity

$$3 \times 10^{-24} /\sqrt{\mathrm{Hz}}$$

@100Hz

Interferometer

- Dual Recycled Fabry-Perot Michelson Interferometer
- Power Recycling Gain: 11
- Signal Recycling Gain: 15
- DC readout

Vacuum

- ultra-high vacuum of 2×10^{-7} Pa
- 3km x2 arm tubes
  → Φ800mm x L12m, 500 tubes
- 10 Major Vacuum Tanks & 4 Main Cryostats
- Inner Volume： ~ 3000 m^3 ← ~30x LHC
- Surface Area： ~ 15,000 m^2 ← ~2x LHC
- 50 Vacuum Pump Units (Roots + Turbo + IP) in design

KAGRA

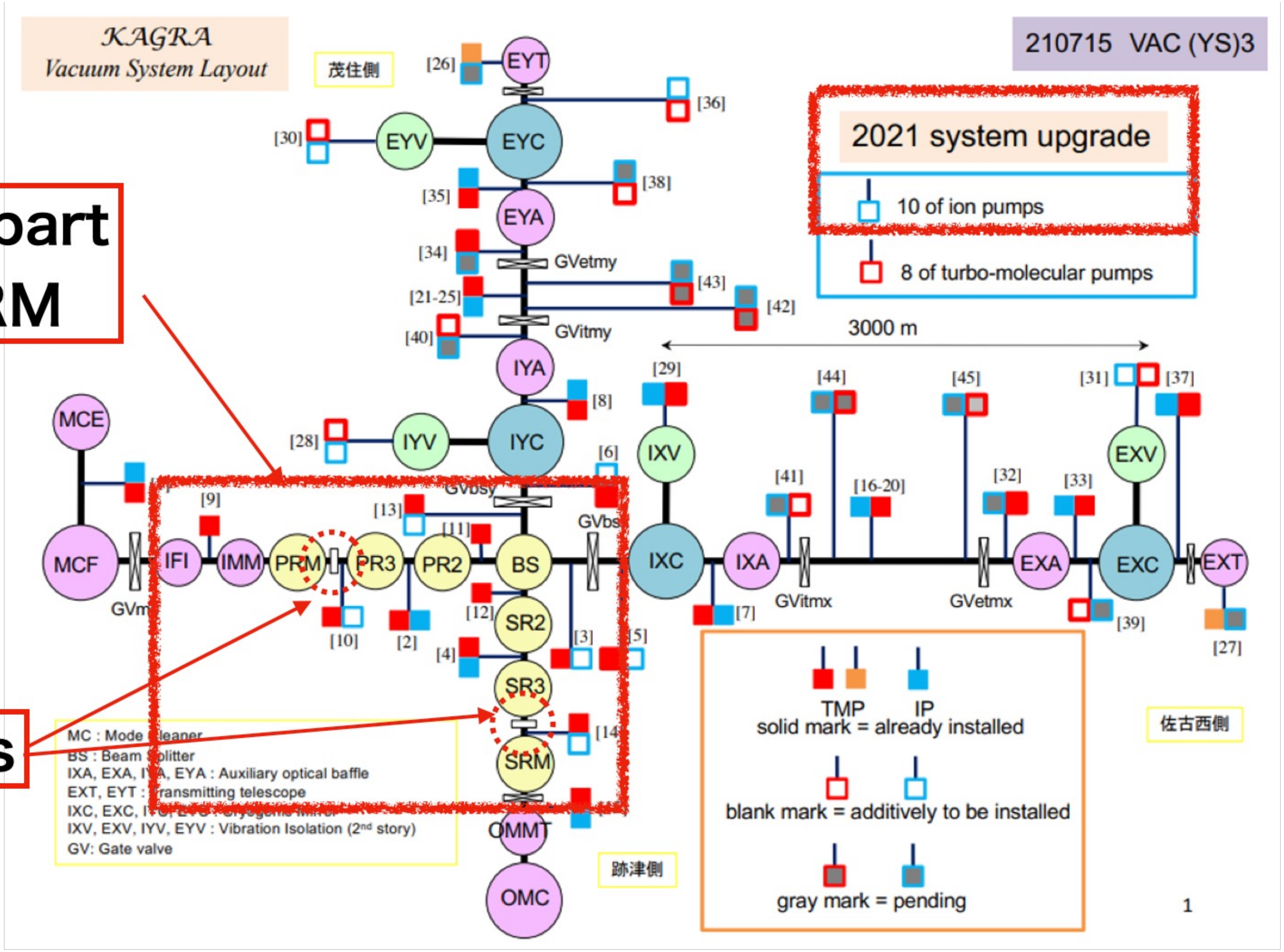
2. Upgrade plan of the KAGRA vacuum system

For the improvements of the vacuum system;

- Increase of ion pumps
  20 sets -> 30 sets
  Keep vacuum pressure better than before quietly
- Insert two GVs in the central part of the KAGRA interferometer
  In the past, all nine vacuum chambers in the central area were in the same vacuum, but if necessary, some parts were kept in a vacuum, and part of them could be opened to work.
- Bellows cover
  Install 482 covers for the KAGRA beam ducts and 240 covers for the beam ducts of the geophysical interferometer
  Protect the bellows from dropping stones from the arm tunnels

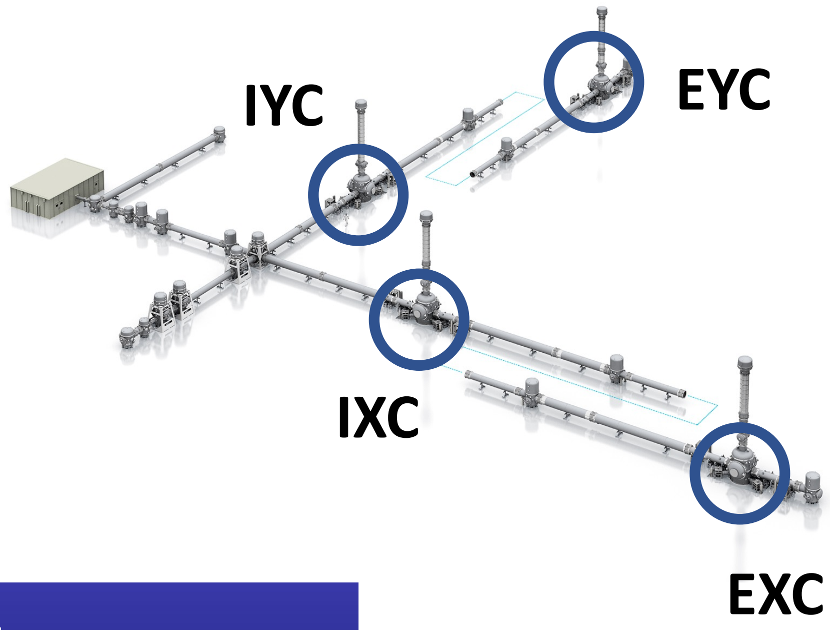
Central part
IFI - SRM

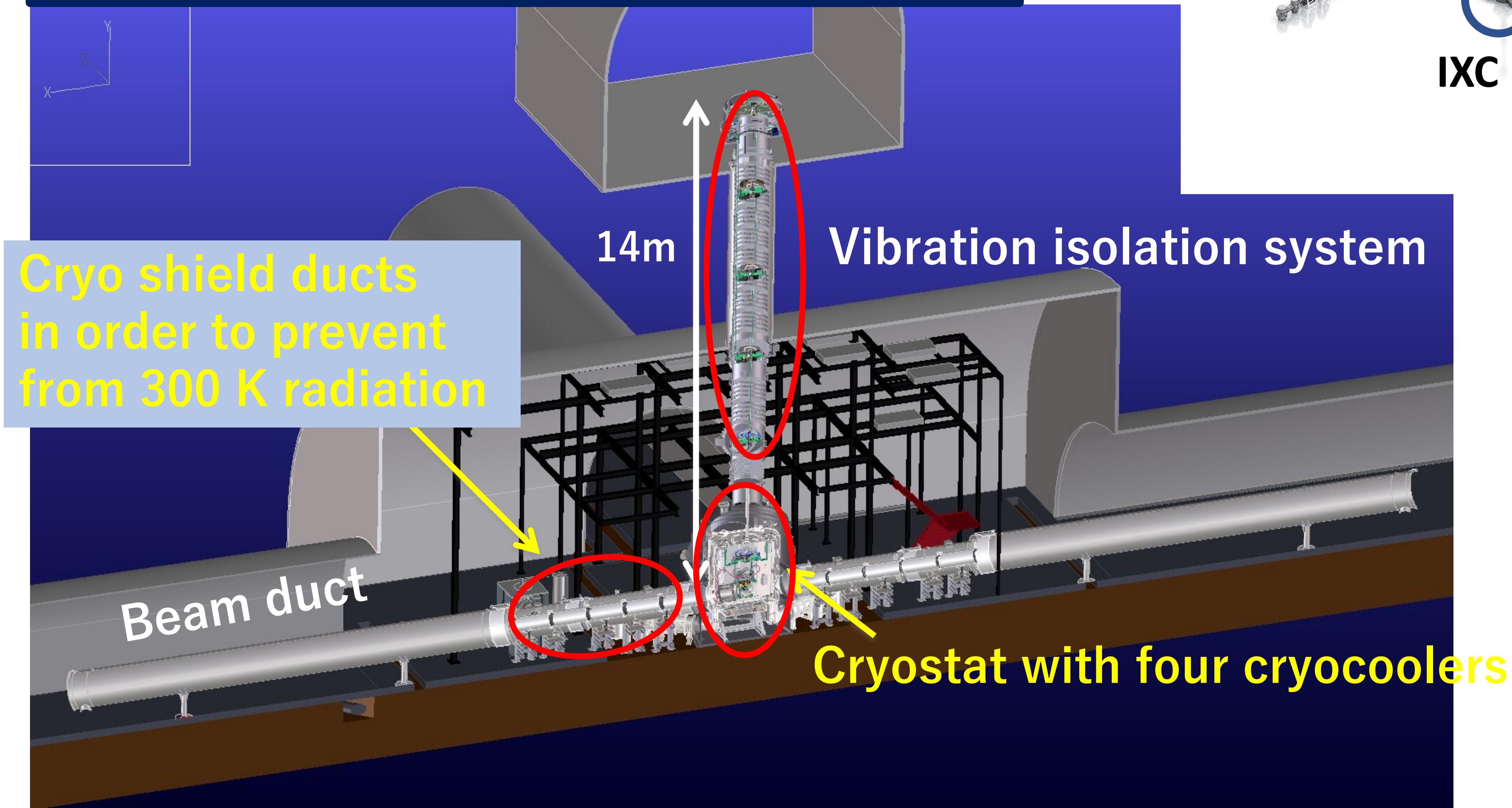
New GVs



3. Status of the KAGRA cryogenic system

Overview of KAGRA Cryogenics system

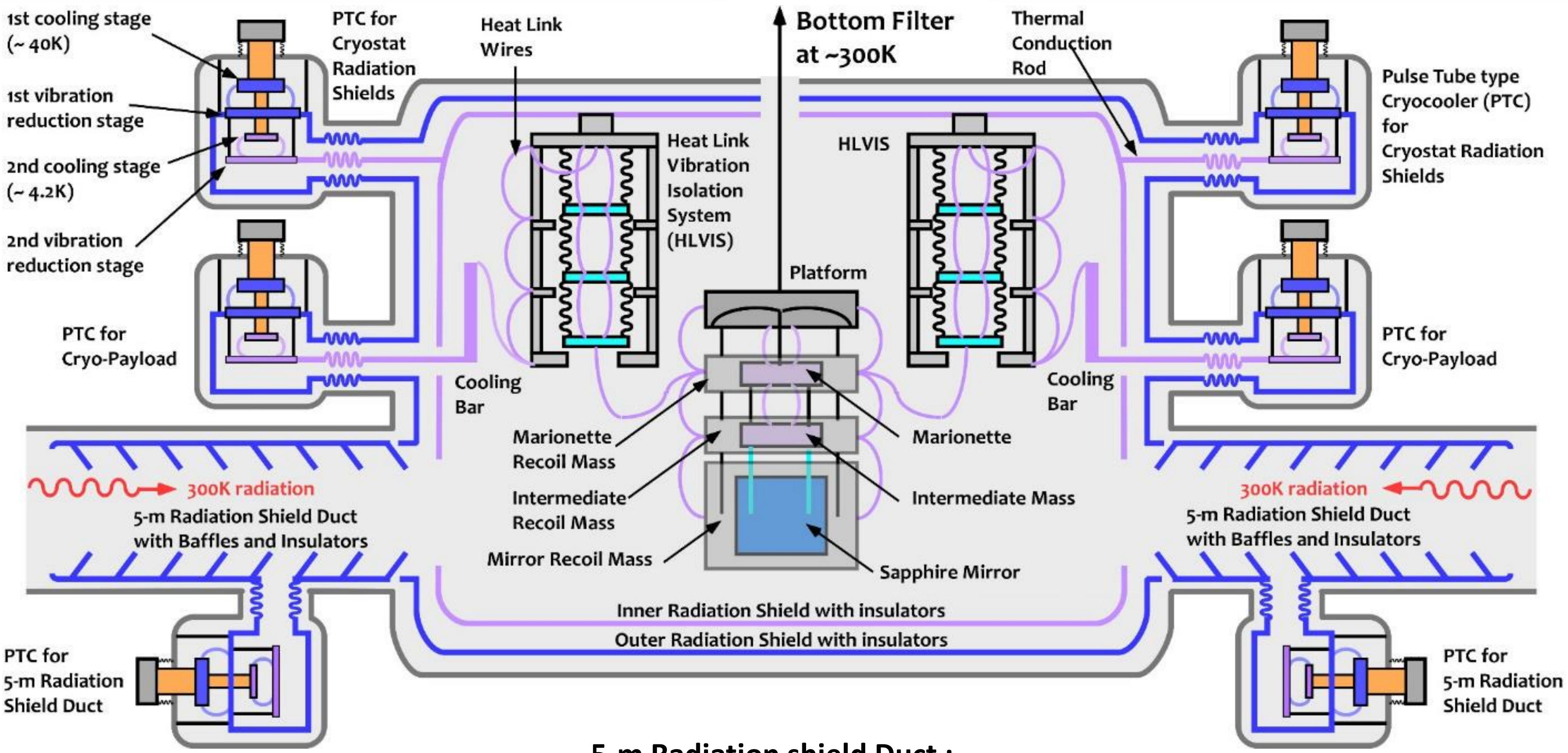




KAGRA Cryogenic System

Cryostat Chamber Dimensions:
Diameter: 2.4 m, Height: ~4.3 m, Mass: ~ 12 ton
I/O shields Mass: 8K: ~455 kg, 80 K: ~590 kg

Cryocoolers: 2 stage Pulse tube type
Cooling power: 0.9 W at 4K (2nd)
36 W at 50K (1st)



Cryogenic payloads:

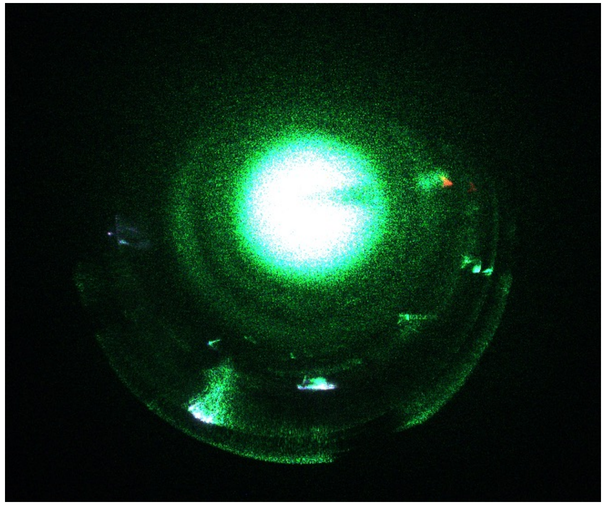
5-m Radiation shield Duct :

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

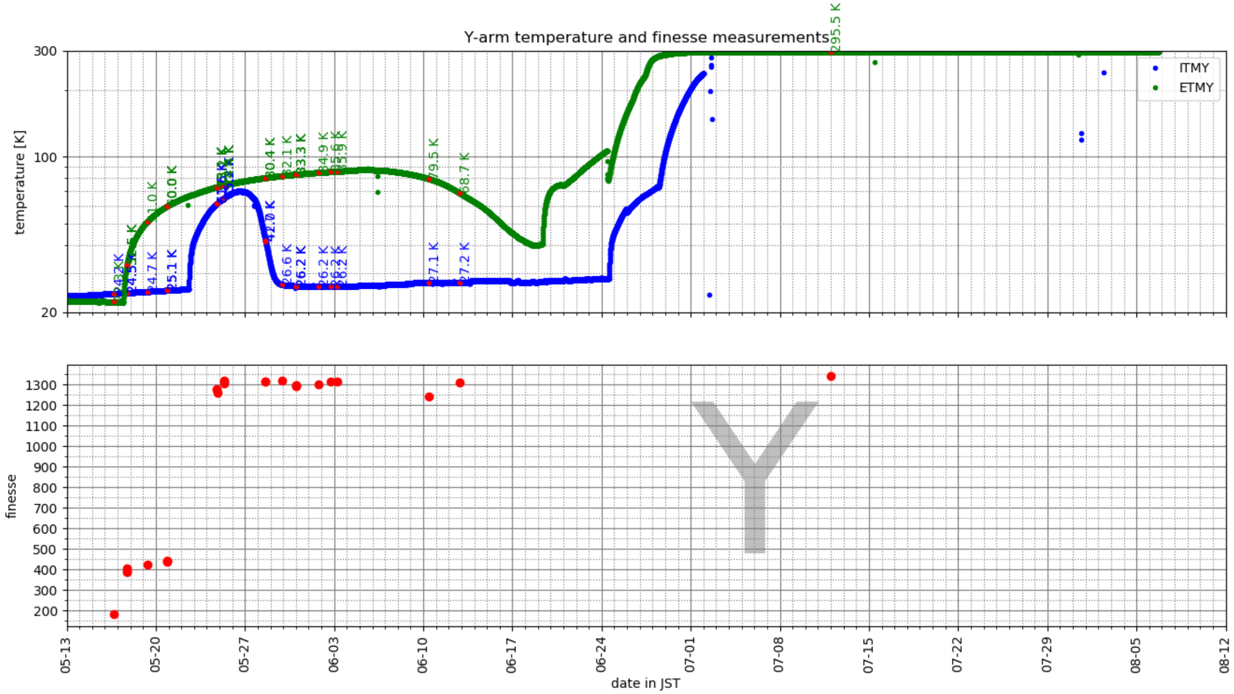
Both HR and AR side of a mirror, there are 5-m cryogenic duct shields for reducing the thermal radiation from the beam tubes.

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.



Background & Our motivations

One of KAGRA's key priorities for O4 is to establish a stable operation of the cryogenic mirrors.

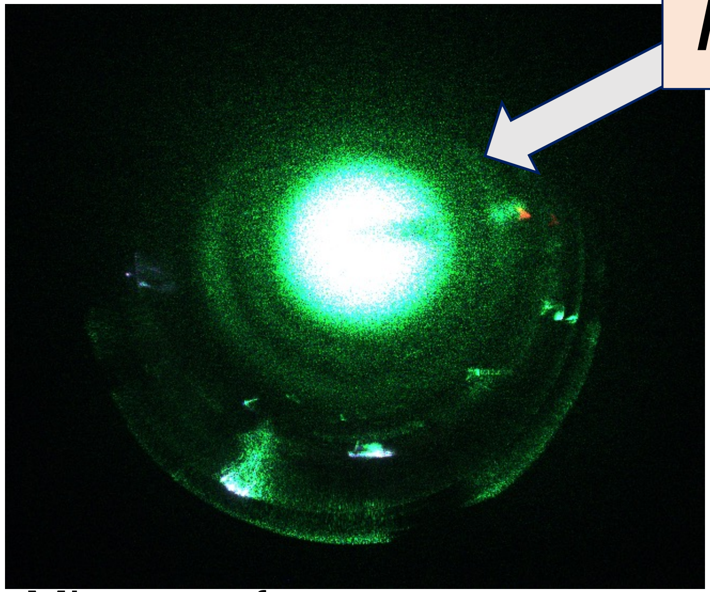
The following items are short history for stable cooling operation of the mirrors in KAGRA:

- *On 3rd/Sep./2018, the first frosting troubles in KAGRA cryostat was reported at KAGRA chief meeting.*
  https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=8952
- *Cryo-system improvement was proposed after O3GK.*
  https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=11705
- *On 17th/Sep./2020, IYC experiment to avoid frosting was proposed.*
  https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=12014
- *From Nov./2020 to Mar./2021, IYC experiment was performed.*
  https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=12704
- *Confirmed cooling scheme avoid frosting was proposed to SEO,*
  and reviewed at "KAGRA External Review" on 19th/July/2021.
  https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=13118

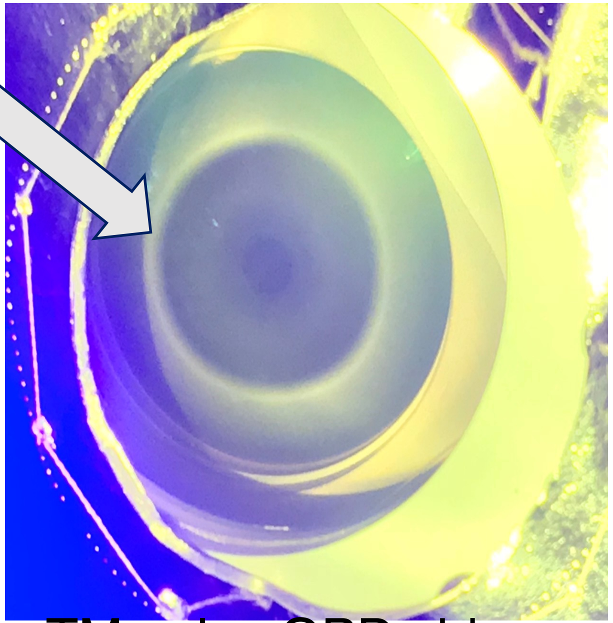
Example of frosted mirror and view port

- In order to find stable operation of cryogenic mirrors down to ~20 K while preventing frosting, KAGRA Cryogenic group have conducted the cooling experiment using IYC cryostat from end of 2020 to beginning of 2021.

Frosting



Mirror surface at cryo temp.



TM oplev QPD side

Photos show examples of the frosting on the surface of view ports with vacuum leak at TM temperature of ~25K. (@EXC 2020/08)
It was assumed that frost was formed by frosting of O_2, N_2 or H_2O.

Confirmed Cooling strategy to avoid frosting

Step 1
- ✓ Vacuum pumping
- ✓ Internal pressure < 10^-4 Pa
- ✓ No leakage > 10^-10 Pam^3/s

→ ~ 21 days

Turn On 2 duct coolers

Step 2
- ✓ Cooling down duct shields.
- ✓ Duct shields Temp. 90 K ~ 150 K
- ✓ Trap H_2O

→ ~ 28 days

Turn On 2 radiation coolers

Step 3
- ✓ Cooling down inner/outer shields
- ✓ Radiation Temp. 20 K ~ 30K
- ✓ Trap O_2 and N_2

→ > 21 days

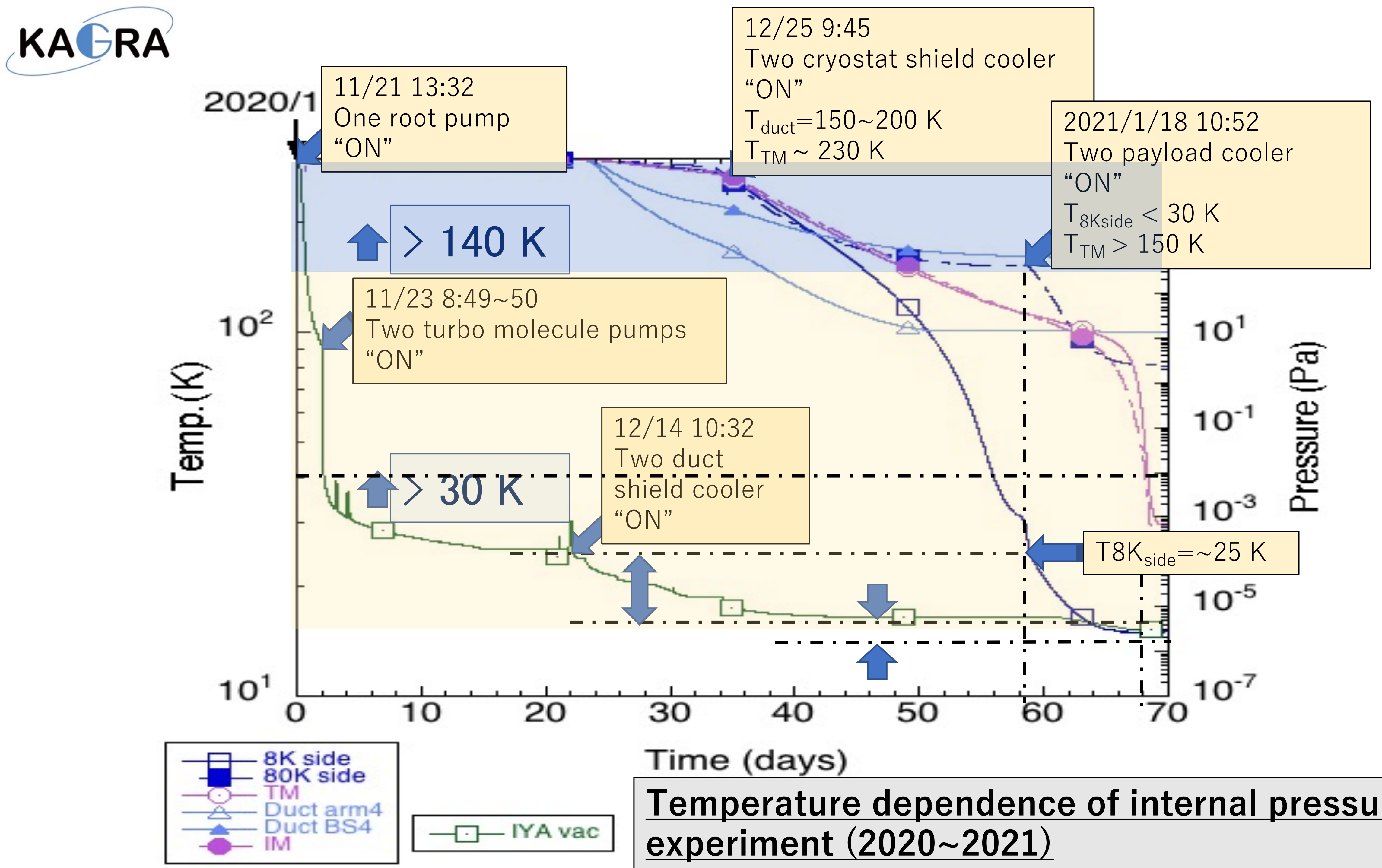
Turn On 2 payload coolers

Final Step
- ✓ Cooling down Test Mass

→ 10 days

76 days

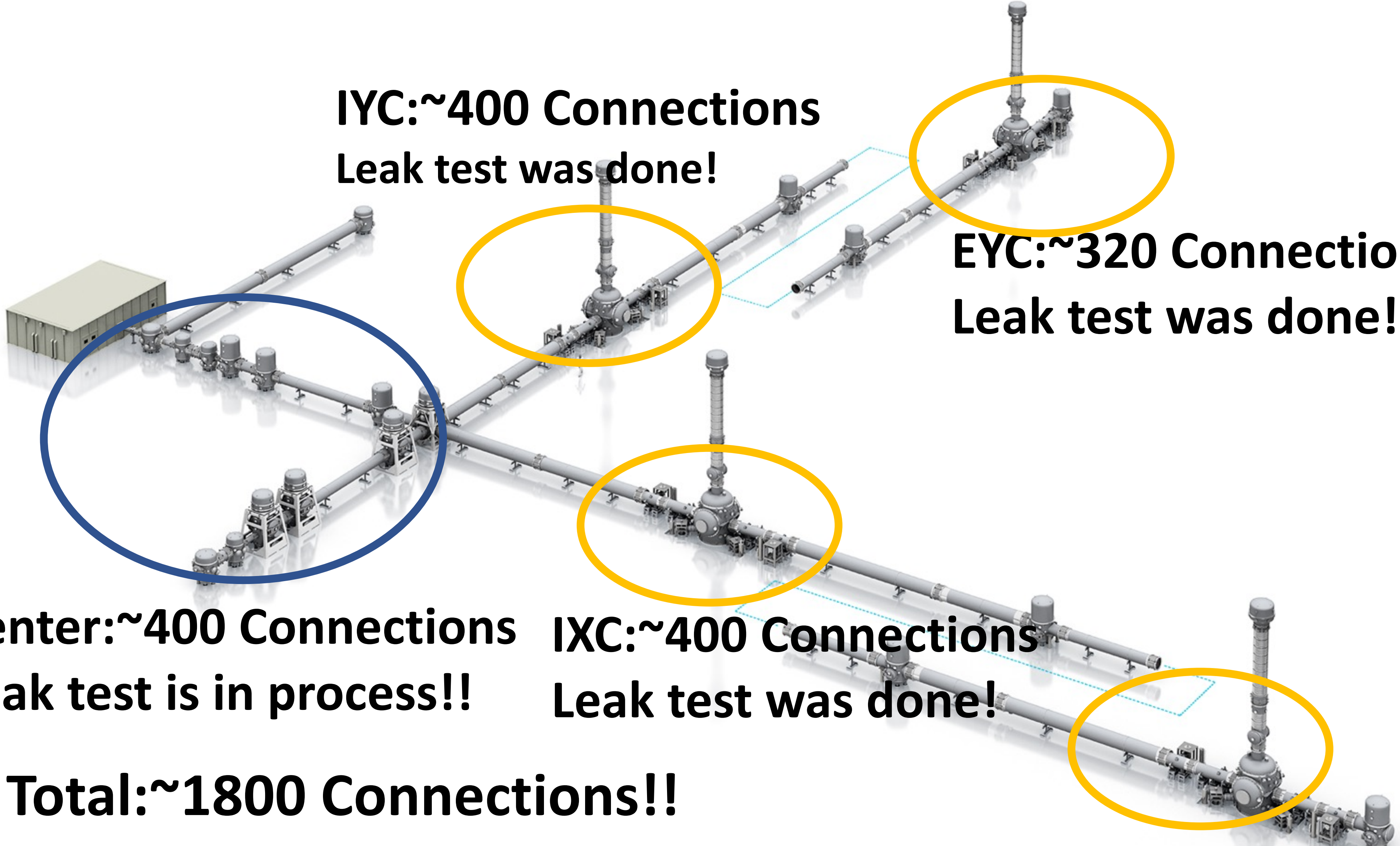
Goal
- ✓ T_{TM}=~20 K



Temperature dependence of internal pressure @ IYC experiment (2020~2021)

Short summaries for IYC experiment

- Frost on the surface of view ports were not appeared during IYC experiment.
- It confirmed ;
  - ✓Frost on the view ports are not appeared by prosed cooling scenario.
  - ✓Calibration heaters on the surface of inner radiation shield well worked as defrost heater for view ports on the surface of inner radiation shield up to ~50 K. It will take **2 days** for defrosting for surface of the view ports.
  - ✓Heater on the IM well worked as defrost heater for mirror on the up to ~70 K. It will take **2 days** for defrosting for surface of mirror.
  - ✓Partial pressure measurement of residual gas at each temperature was performed.



IYC:~400 Connections
Leak test was done!

EYC:~320 Connections
Leak test was done!

Center:~400 Connections
Leak test is in process!!

IXC:~400 Connections
Leak test was done!

EXC:~320 Connections
Leak test was done!

Total:~1800 Connections!!
Leak level of all connections should be
$< 10^{-9}$ Pa m^3/sec to 10^{-10} Pa m^3/sec.

State-of-the-art cooling strategy: a 76-day journey

EY

IX

IY

250K

Turn On
2 coolers

EX

82 K

Step 1 → 21 days → **Step 2** → 11 days → **Step 3** → 24 days → **Final Step** → 10 days → **Goal**

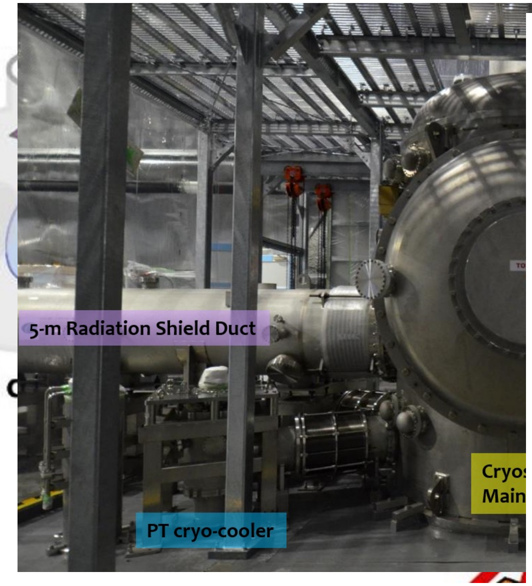
Step 1
- ✓ Vacuum pumping
- ✓ Internal pressure $< 10^{-4}$ Pa
- ✓ No leakage $> 10^{-10}$ Pam^3/s

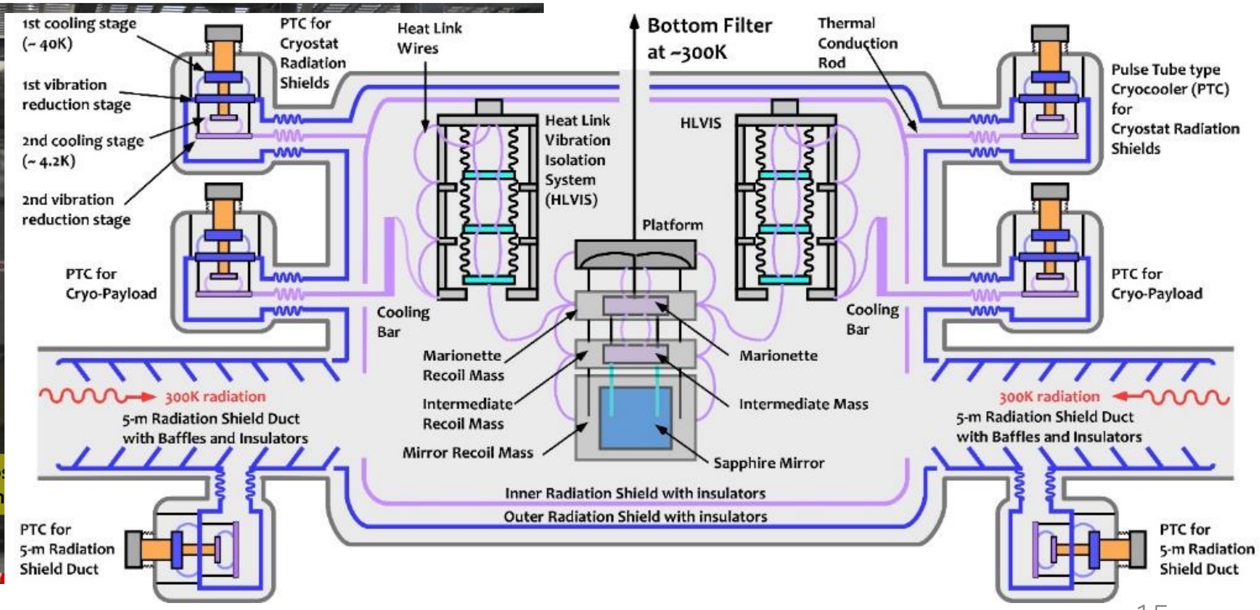
Step 2
- ✓ Cooling down radiation shield ducts
- ✓ Radiation Temp. 90 K ~ 150 K
- ✓ Trap H_2O

Step 3
- ✓ Cooling down inner/outer shields
- ✓ Radiation Temp. 20 K ~ 30K
- ✓ Trap O_2 and N_2

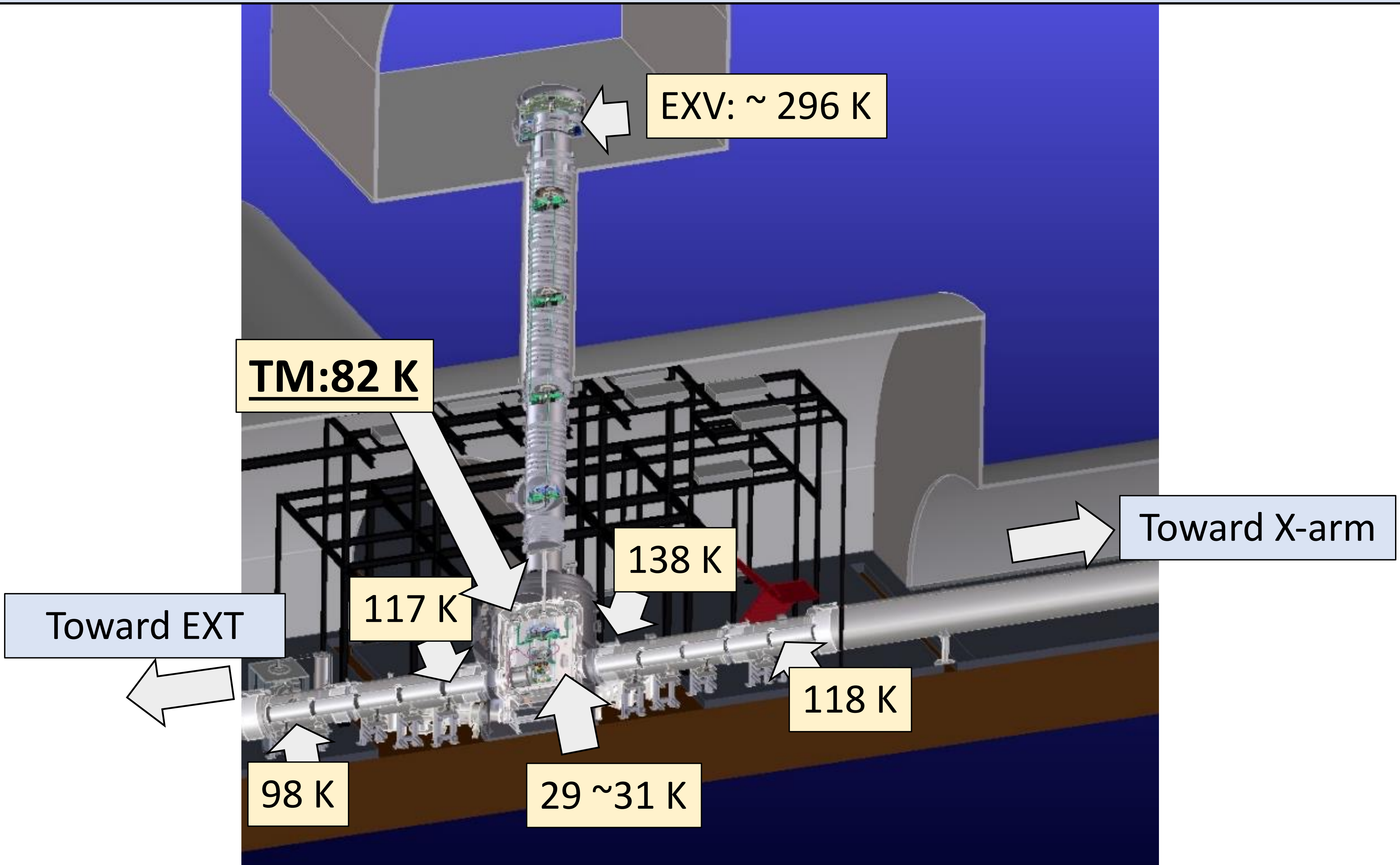
Final Step
- ✓ Cooling down Test Mass

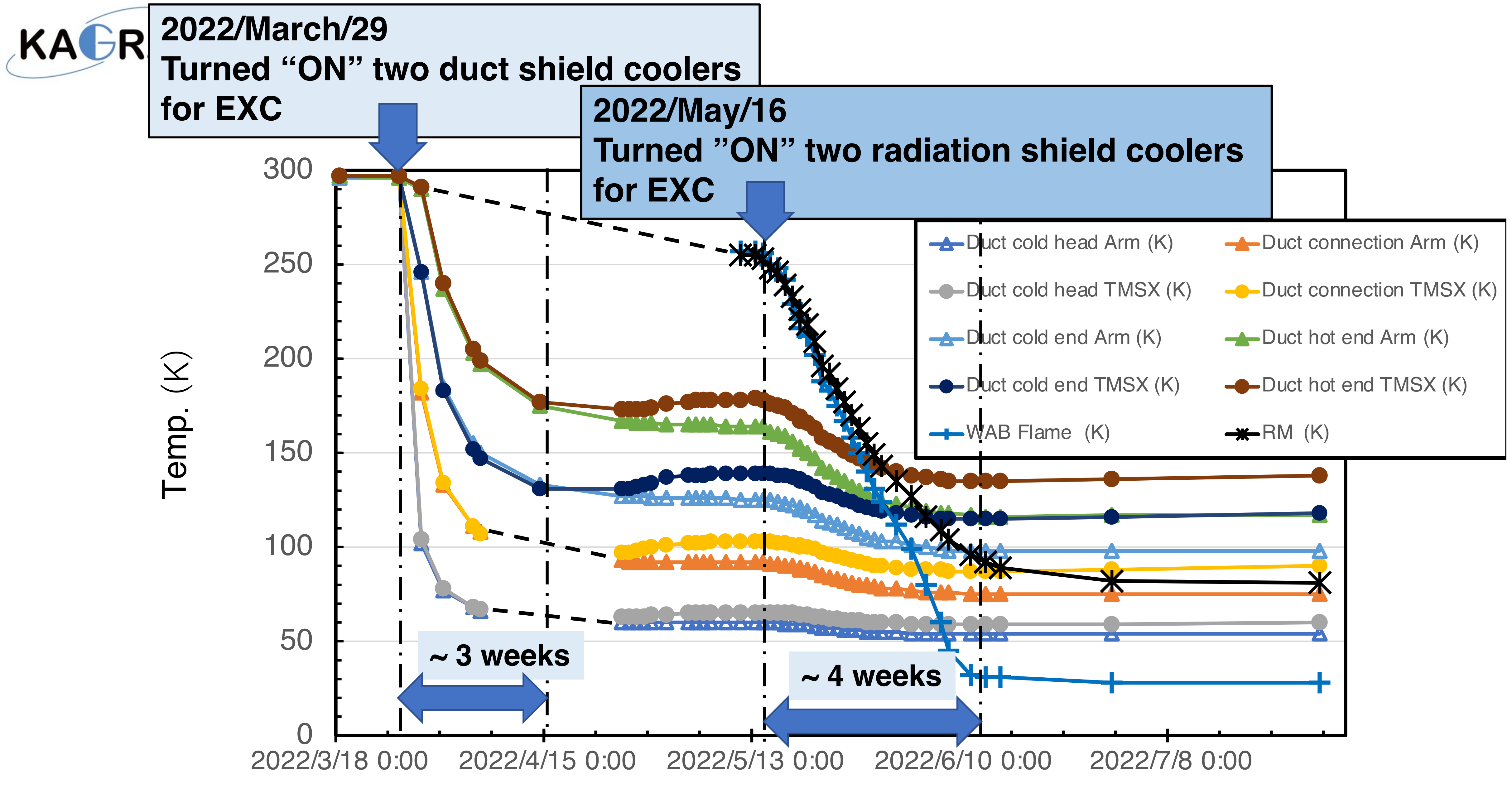
Goal
- ✓ T_{TM}=~20 K





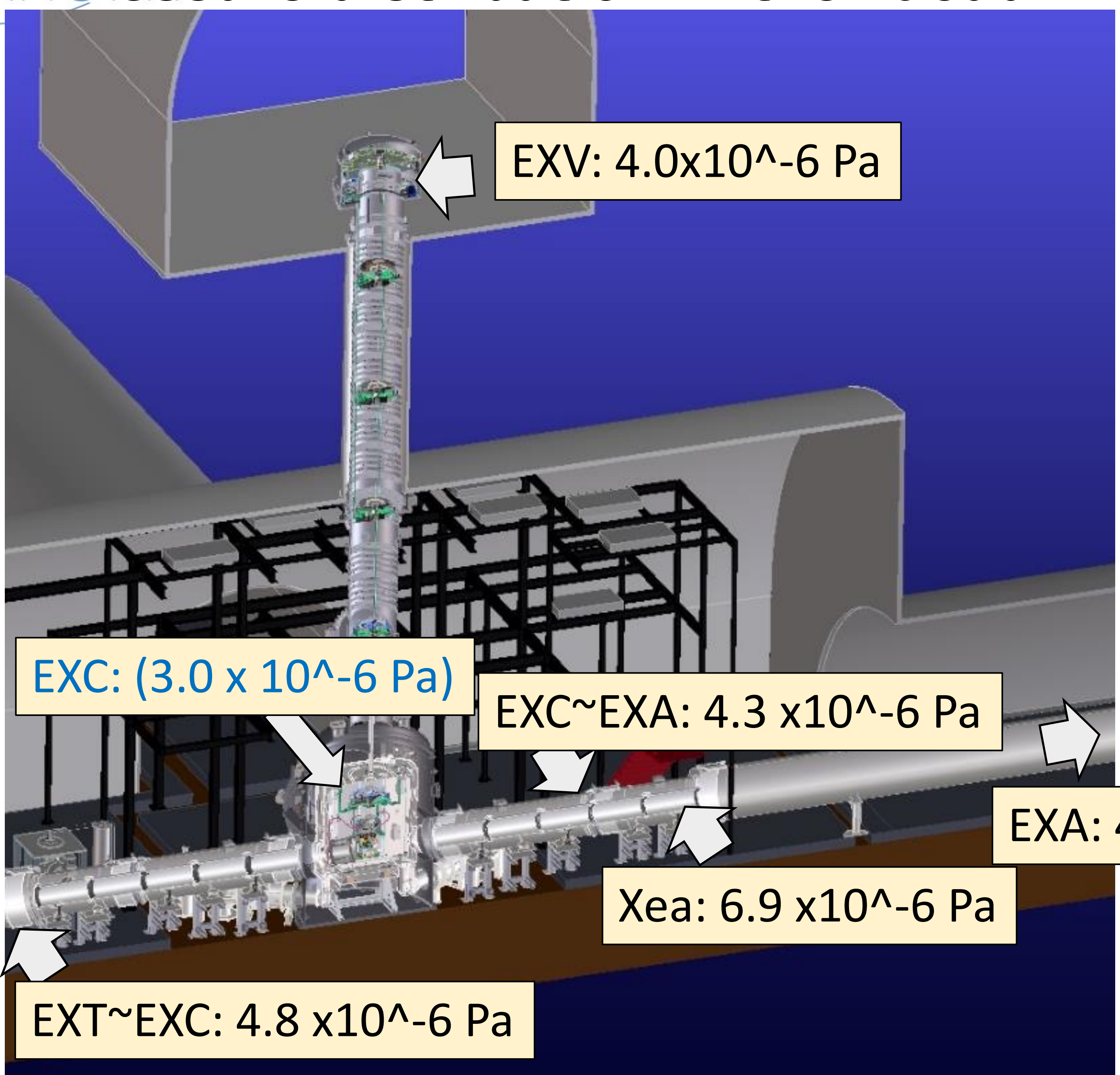
Temperature distribution around the EXC on 28/July/2022



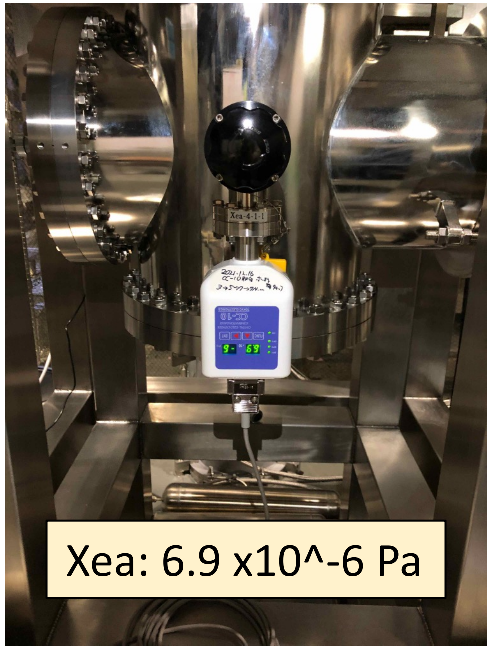


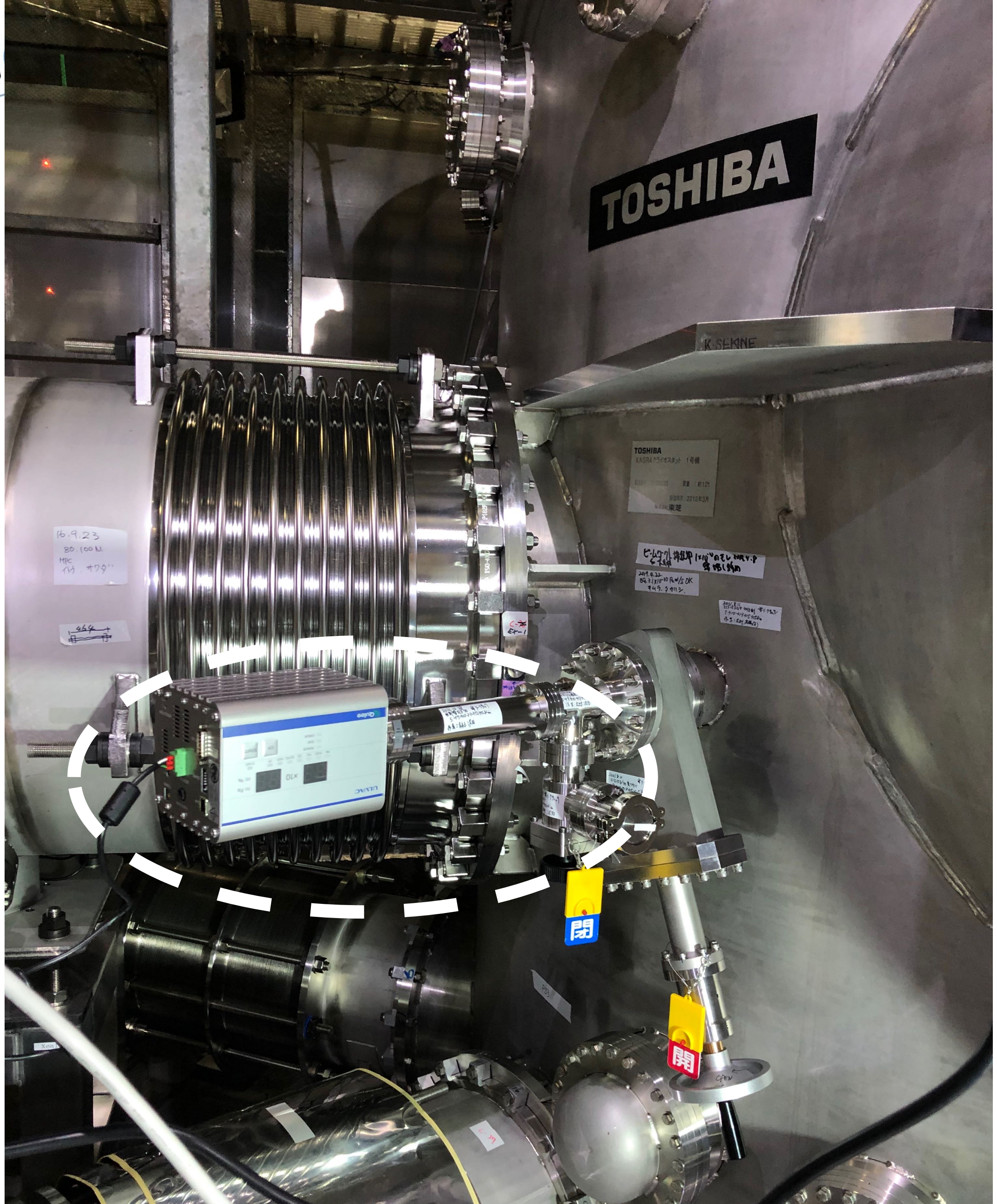
Cooling characteristics of the duct shield for EXC

Pressure distribution in the vacuum vessel comprising the EXC



Duct shields reached in operational temperature, pressure in the EXC was reached ~10^-6 Pa .

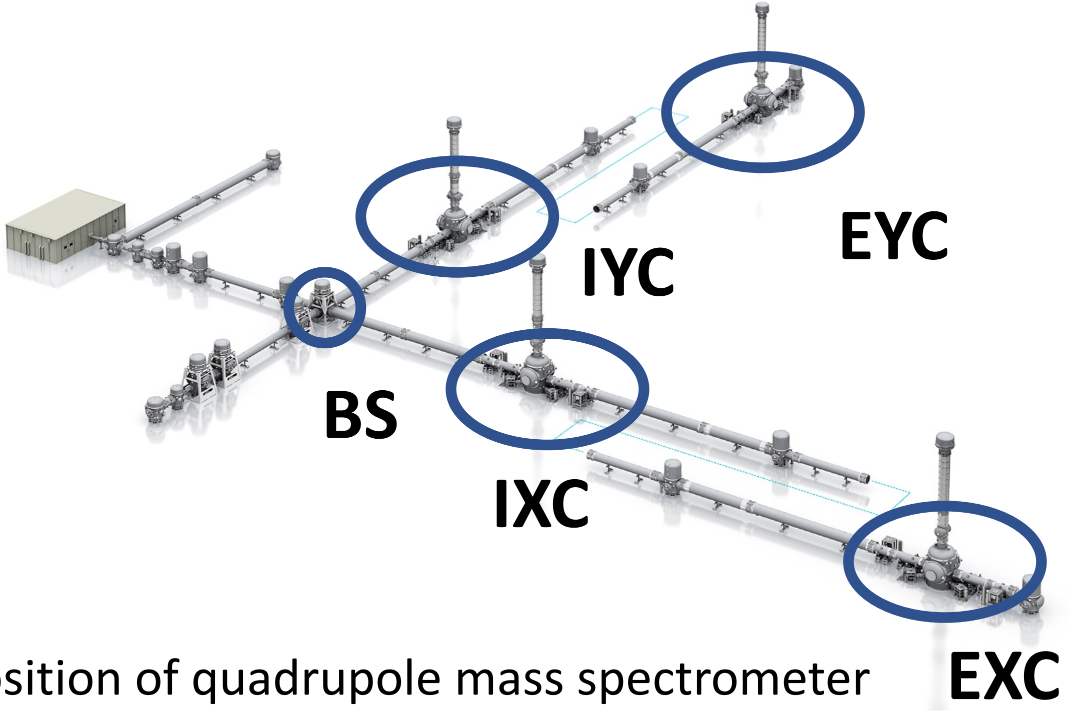




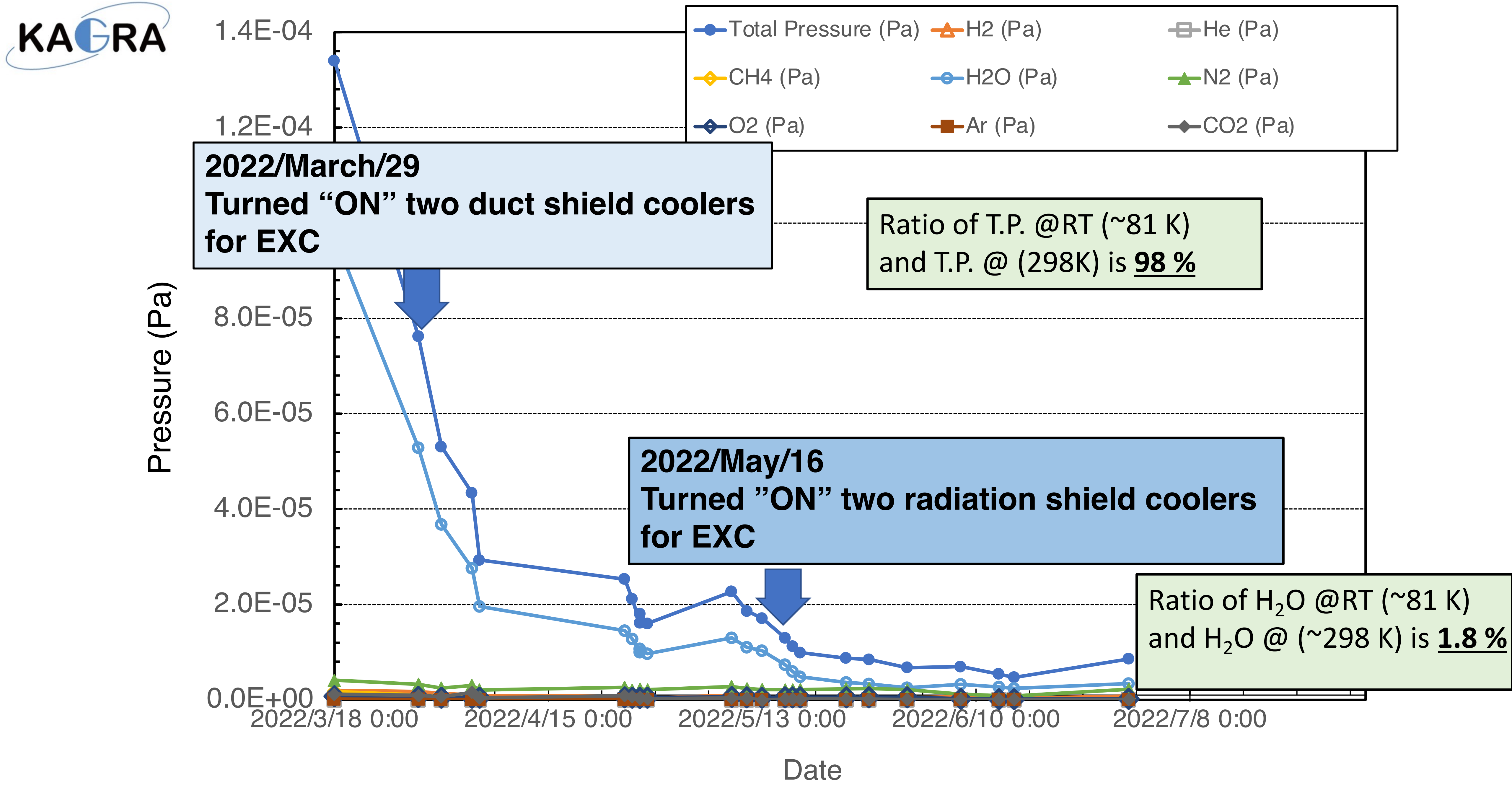
Residual gases measurement

Residual gases in the vacuum were measured with quadrupole mass spectrometers.

Photo shows the quadrupole mass spectrometer which connected EXC vacuum vessel.



Position of quadrupole mass spectrometer



Tendency of decreasing residual gas components by the cooling of radiation shield in EXC

Summaries

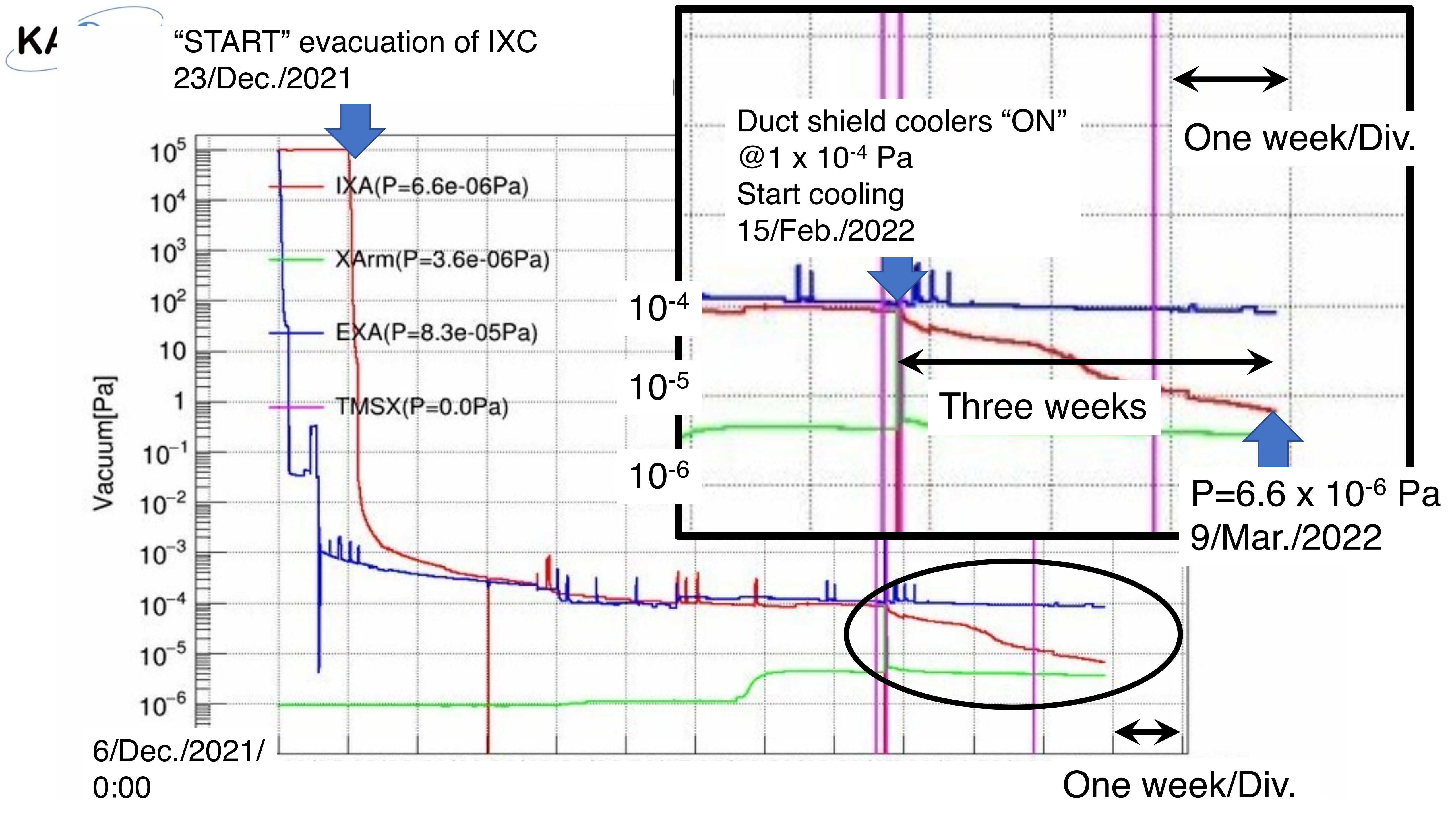
- Based on our cooling strategy confirmed by IYC experiment, we stated pumping down and cooling of IXC & EXC.
- When the duct shields in IXC, EXC & IYC reached in operational temperature, pressure in the cryostats were reached **~10^-6 Pa**.
- During the cooling of IXC, EXC & IYC, we have conducted residual gas components.

  It was confirmed main component of residual gas in the cryostat was **H2O.**

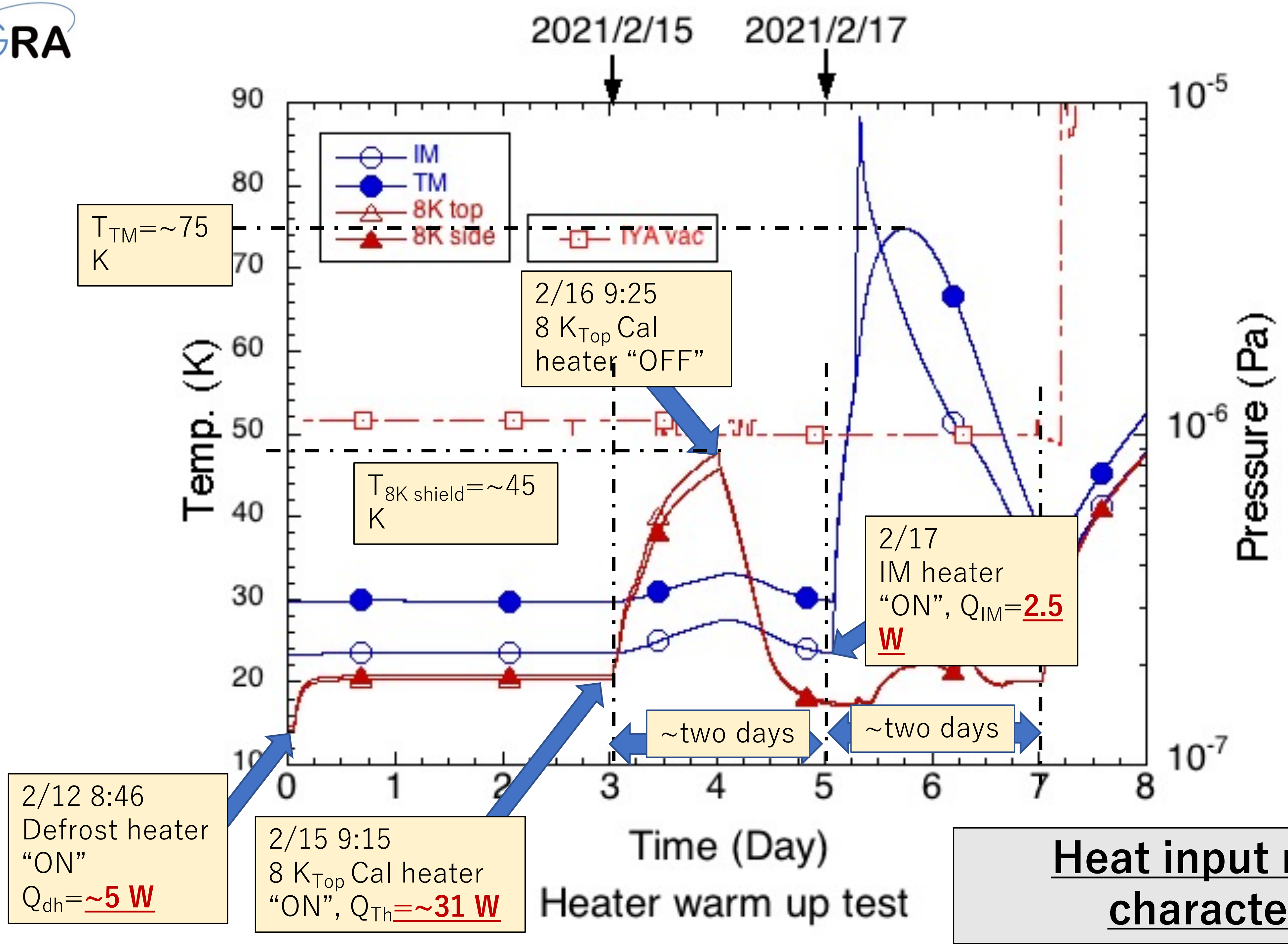
  Moisture adsorption rate by duct shield was **~98 % of moisture** at room temp.
- There are no frost on the test masses when radiation shields in EXC and IYC ducts shields are in operations.
- We can successfully keep ~1450 of finesse at X-arm, and keeping it.
- We are now preparing cooling down of EYC based on our confirmed the cooling strategy.
- We need a discussion to determine the cooling temperature of the mirror before O4a.
    - At present
        - IX: Cryo-duct shields are cooled by refrigerators. ITMX temp became 250K.
        - EY: Cryo-duct shields and 2-layers radiation shields are cooled. ETMX temp: 82K !! by only "radiation cooling".
            - For over one month, ~1450 finesse was kept in X-arm FP.
        - EY: at room temperature.

Thank you for your attention !

Backup



KA
"START" evacuation of IXC
23/Dec./2021
IXA(P=6.6e-06Pa)
XArm(P=3.6e-06Pa)
EXA(P=8.3e-05Pa)
TMSX(P=0.0Pa)
Vacuum[Pa]
6/Dec./2021/
0:00
One week/Div.
Duct shield coolers "ON"
@1 x 10-4 Pa
Start cooling
15/Feb./2022
One week/Div.
Three weeks
P=6.6 x 10-6 Pa
9/Mar./2022

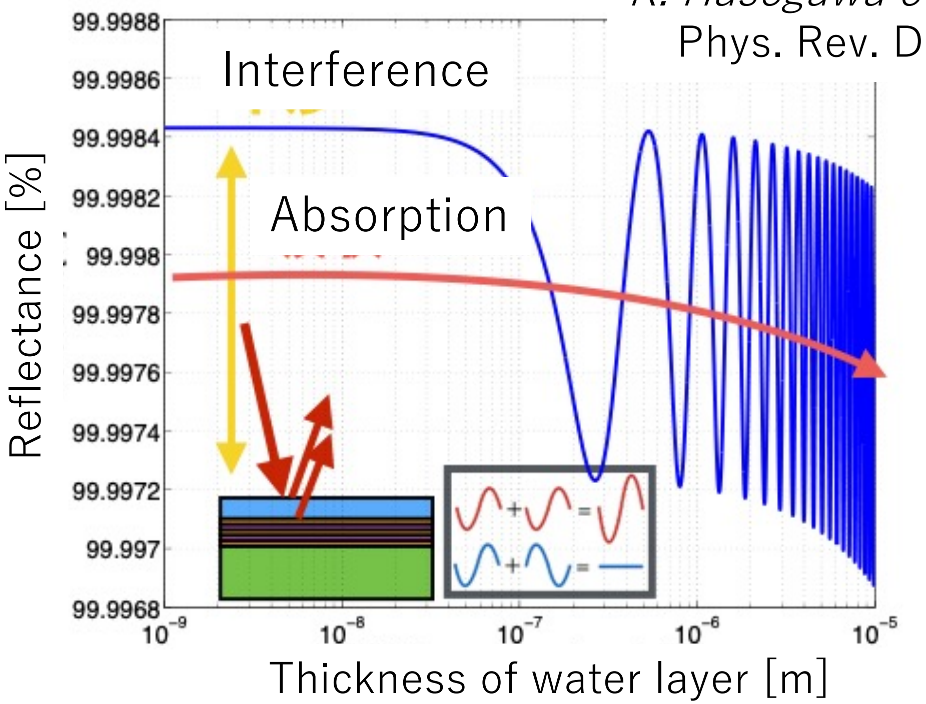


Heat input response characteristics

Experimental Test in KAGRA Cryostat

Analytical Model

K. Hasegawa, Ph. D thesis, Univ. Tokyo (2020)
K. Hasegawa et al, Phys. Rev. D 99, 022003 (2019)

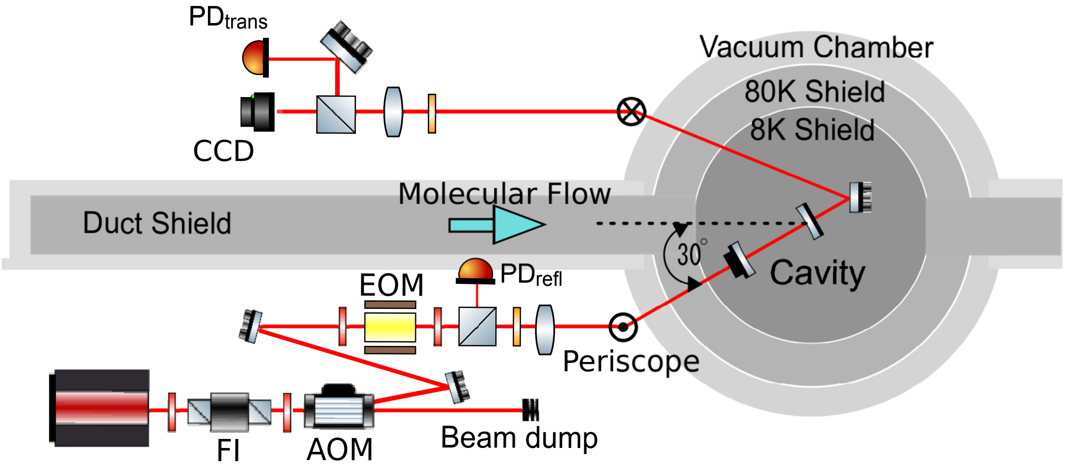


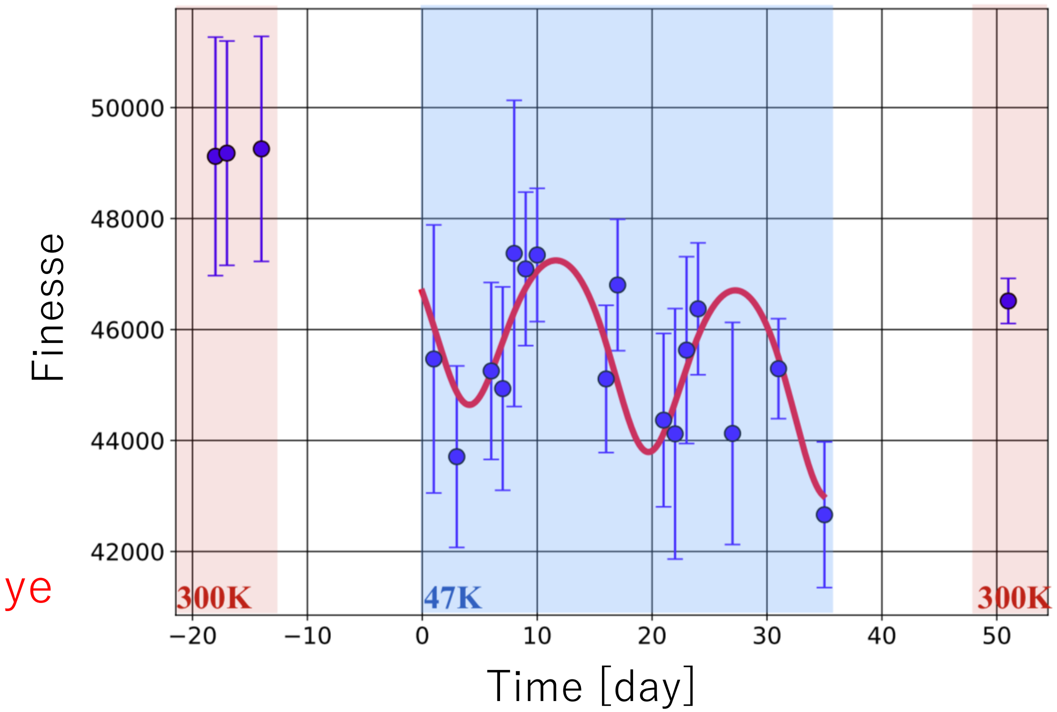
$$\mathcal{F} = \frac{\pi\sqrt{(\rho_{\mathrm{vm}} + \rho' e^{-2i\delta_{\mathrm{mol}}})(1+\rho_{\mathrm{vm}}\rho' e^{-2i\delta_{\mathrm{mol}}}) r_2 r_{\mathrm{loss}}}}{\rho_{\mathrm{vm}} + \rho' e^{-2i\delta_{\mathrm{mol}}} - (1+\rho_{\mathrm{vm}}\rho' e^{-2i\delta_{\mathrm{mol}}}) r_2 r_{\mathrm{loss}}}$$

Reflectivity change of Mirror by molecular laye

Reflectivity of molecular surface

Experimental Setup





Estimated Speed of Molecular Layer Formation on a Cryogenic Mirror

at Design Pressure （1×10^{-7} Pa）

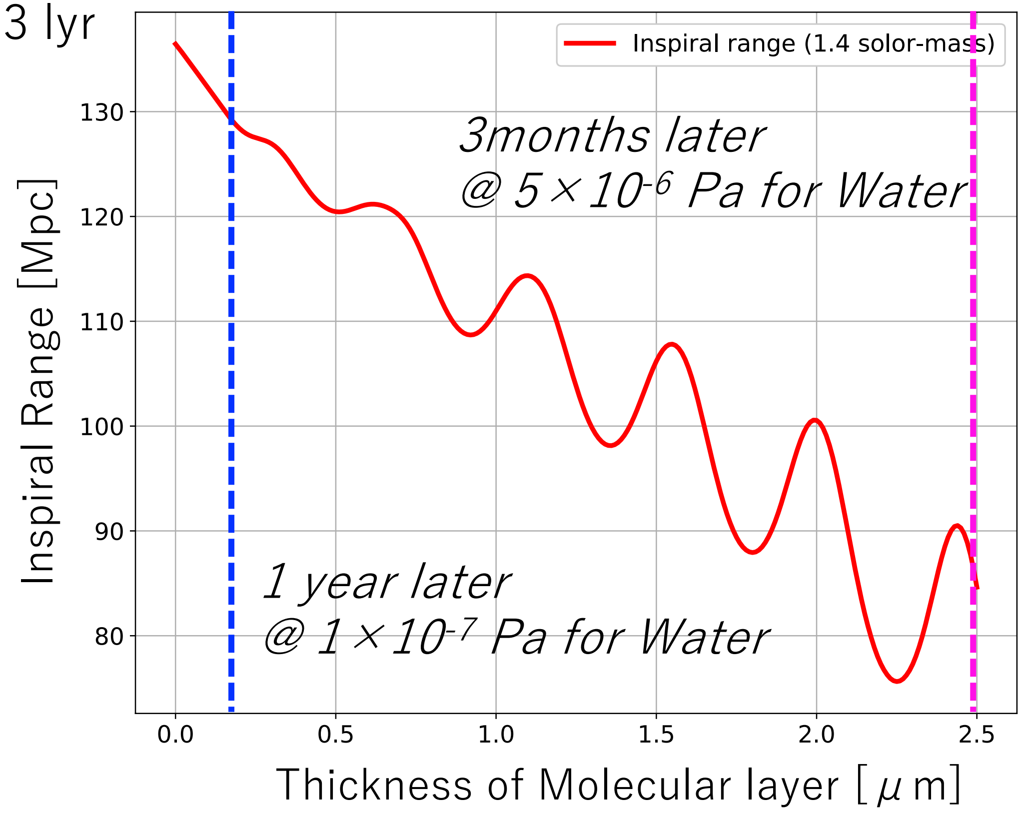
	Speed	1 month	1 year
H2O	0.56 nm/day	16.8nm	204nm
N2	0.3 nm/day	9nm	110nm
O2	0.23 nm/day	6.9nm	84nm

at Present Pressure （5×10^{-6} Pa）

	Speed	1 month	1 year
H2O	28nm/day	750nm	10um
N2	15nm/day	450nm	5.5um
O2	11.5nm/day	345nm	4.2um

Estimated Detection Range of GWs
from Binary Neutron Star Coalescence

1pc = 3.3 lyr



Defrosting heaters are installed on cryogenic mirror suspension in this stage.

In 5×10^{-6} Pa, the detection range of BNS will reduce from ~130Mpc to ~75Mpc