Status of Cryogenics for Large Cryogenic Gravity Telescope, KAGRA

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[E] Institute for Cosmic Ray Research/University of Tokyo/ICRR

abstract

- KAGRA is a name of project for Large Cryogenic Gravity Telescope, LCGT, having 3 km base line length in Japan,

  and was accepted by MEXT[1] on FY2010.

- The notable characteristic features of KAGARA are a power-recycled Fabry-Perot-Michelson interferometer using mirrors cooled down to 20 K, and placed underground at Kamioka mine. The characteristic design policy of KAGRA is to reduce thermal noise by cryogenic mirror, and escape from thermal lens effect that may reduce the optical power in Fabry-Perot cavities.

- The fundamental technique of cryogenic mirror was developed by a research with Cryogenics Science Center of KEK.

- A group in Cryogenics Science Center of KEK grapples with KAGRA cryogenic design, and start production of cryostats with very low vibration cryocooler units under MOU exchanged among KEK, ICRR[2] and NAOJ[3].

- [1]) Ministry of Education, Culture, Sport, Science and Technology in Japan
- [2]) Institute for Cosmic Ray Research (ICRR) of the University of Tokyo
- [3]) National Astronomical Observatory of Japan

KAGRA

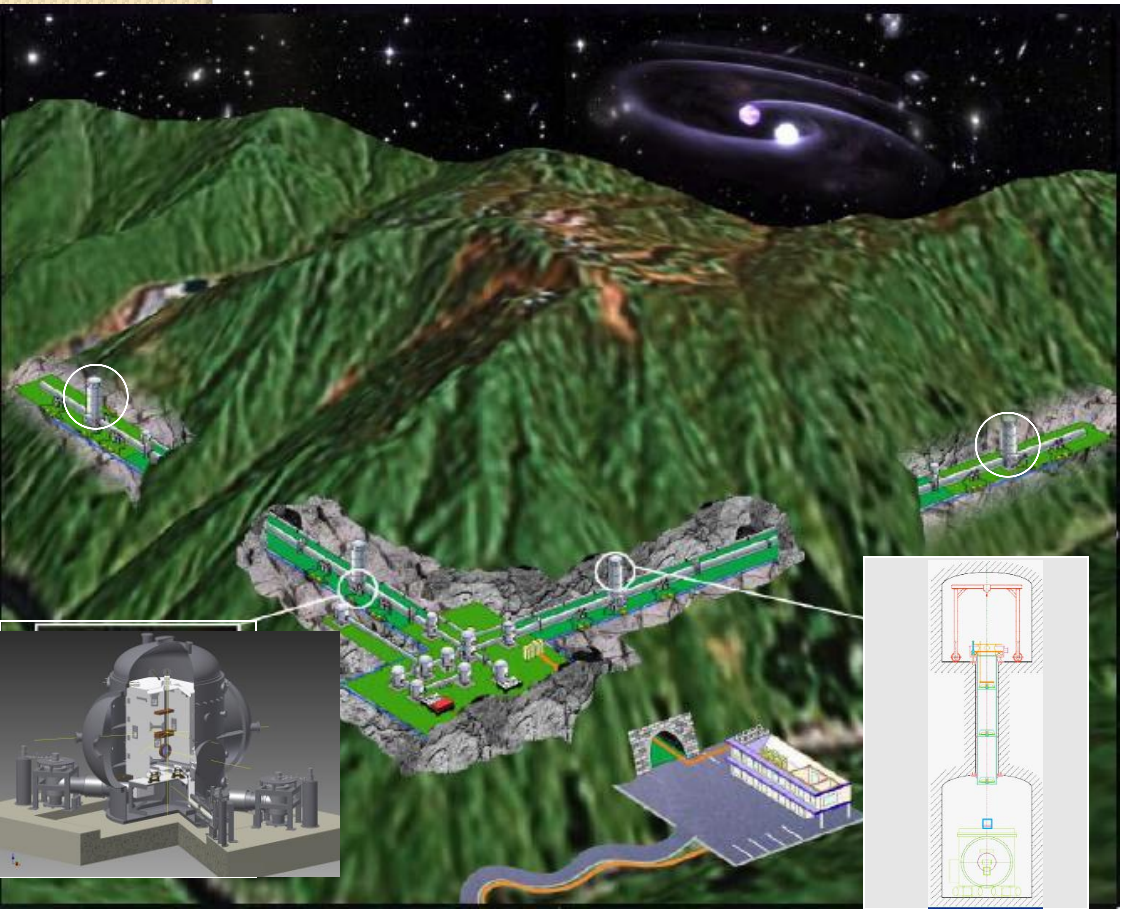
Outline

- ✓ Overview of KAGRA
- ✓ Required specifications for the KAGRA Cryogenics
- ✓ Cryogenic design
  - Components
  - Mechanical Analysis
  - Thermal Analysis
  - Performance of the proto-type cryo-cooler unit
- ✓ Schedule
- ✓ Summary

Over View of KAGRA
Large-scale Cryogenic Gravitational wave Telescope (abbreviation of the project name)

Objectives

1. Detect gravitational wave for the first time.
2. Begin gravitational wave astronomy.



Peculiarities:

(1) Underground tunnel

Ikenoyama, Kamioka, Gifu

From the surface

Vertical > ~200m

Horizontal > ~400m

(2) Arm length 3km

(3) Cryogenic Mirrors

T=20 K, Sapphire Mass=30 kg

Target: In-spiral of Neutron Star binary.

Summary of detector parameters

Laser
- Nd:YAG laser (1064nm)
- Master Laser + Power Amplifier
  - Power : 180 W

Main Interferometer
- Broad band RSE configuration
  - Baseline length : 3km
  - Beam Radius : 3-5cm
  - Arm cavity Finesse : 1550
  - Power Recycling Gain : 11
  - Signal Band Gain : 15
  - Stored Power : 771kW
  - Signal band : 230Hz

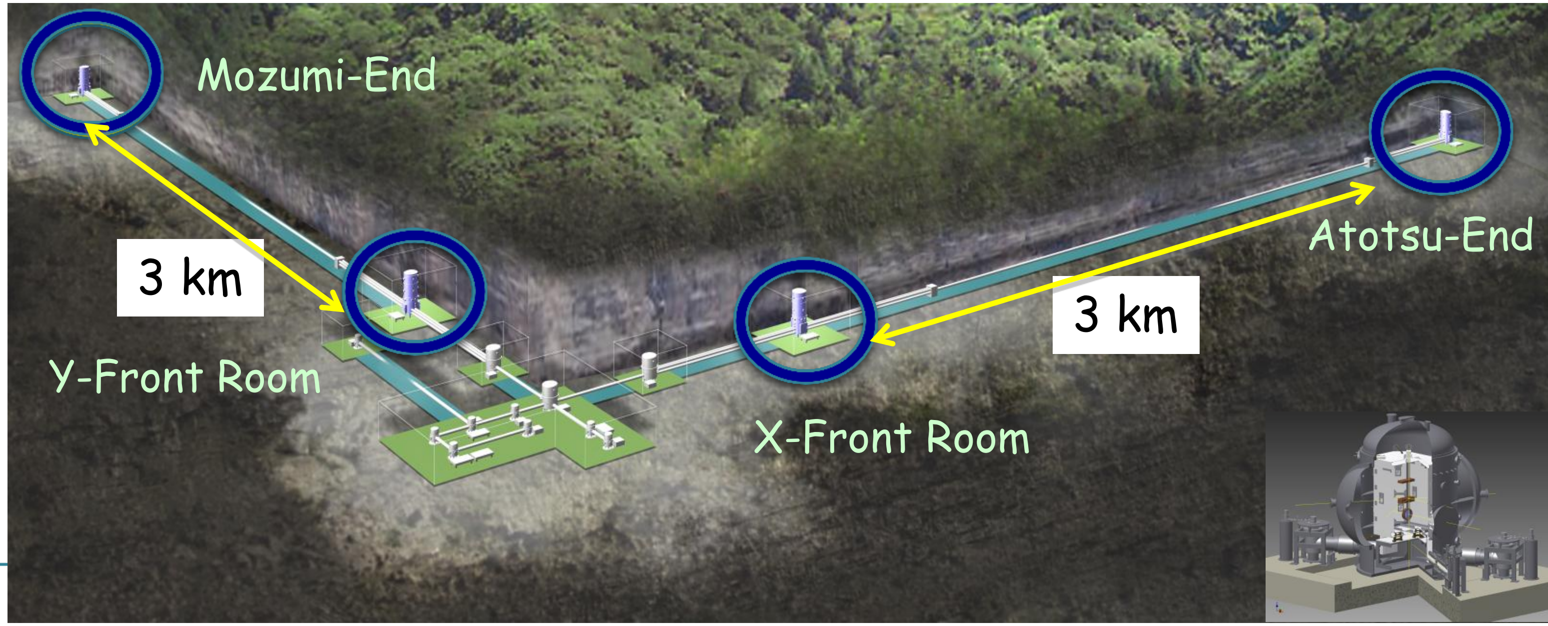
Vacuum system
- Beam duct diameter : 80cm
- Pressure : 10^{-7} Pa

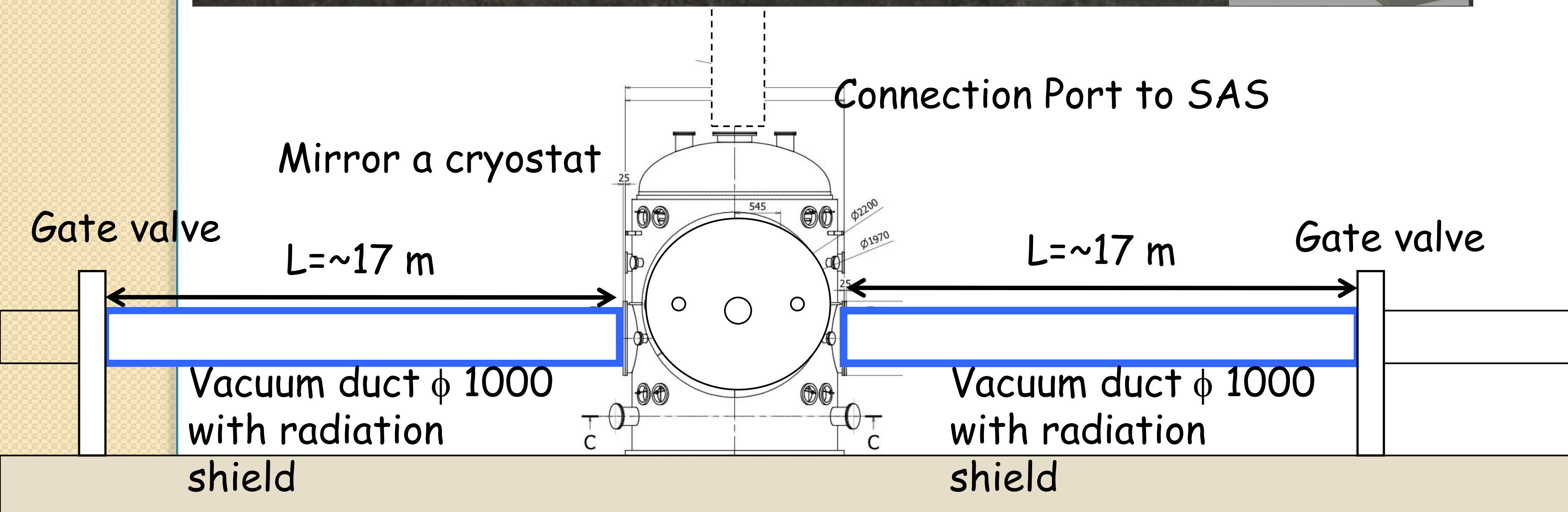
Mirror
- Sapphire substrate + mirror coating
  - Diameter : 25cm
  - Thickness : 15cm
  - Mass : 30 kg
  - Absorption Loss : 20ppm/cm
  - Temperature : 20 K
  - $Q = 10^8$
  - Loss of coating : 10^{-4}

Final Suspension
- Suspension + heat link with 4 Sapphire fibers
  - Suspension length : 30cm
  - Fiber diameter : 1.6mm
  - Temperature : 16K
  - Q of final suspension : 10^8

by Dr. M. Ando (NAOJ)

Location of Four Mirror Cryostats with the Cryo-coolers for the KAGRA

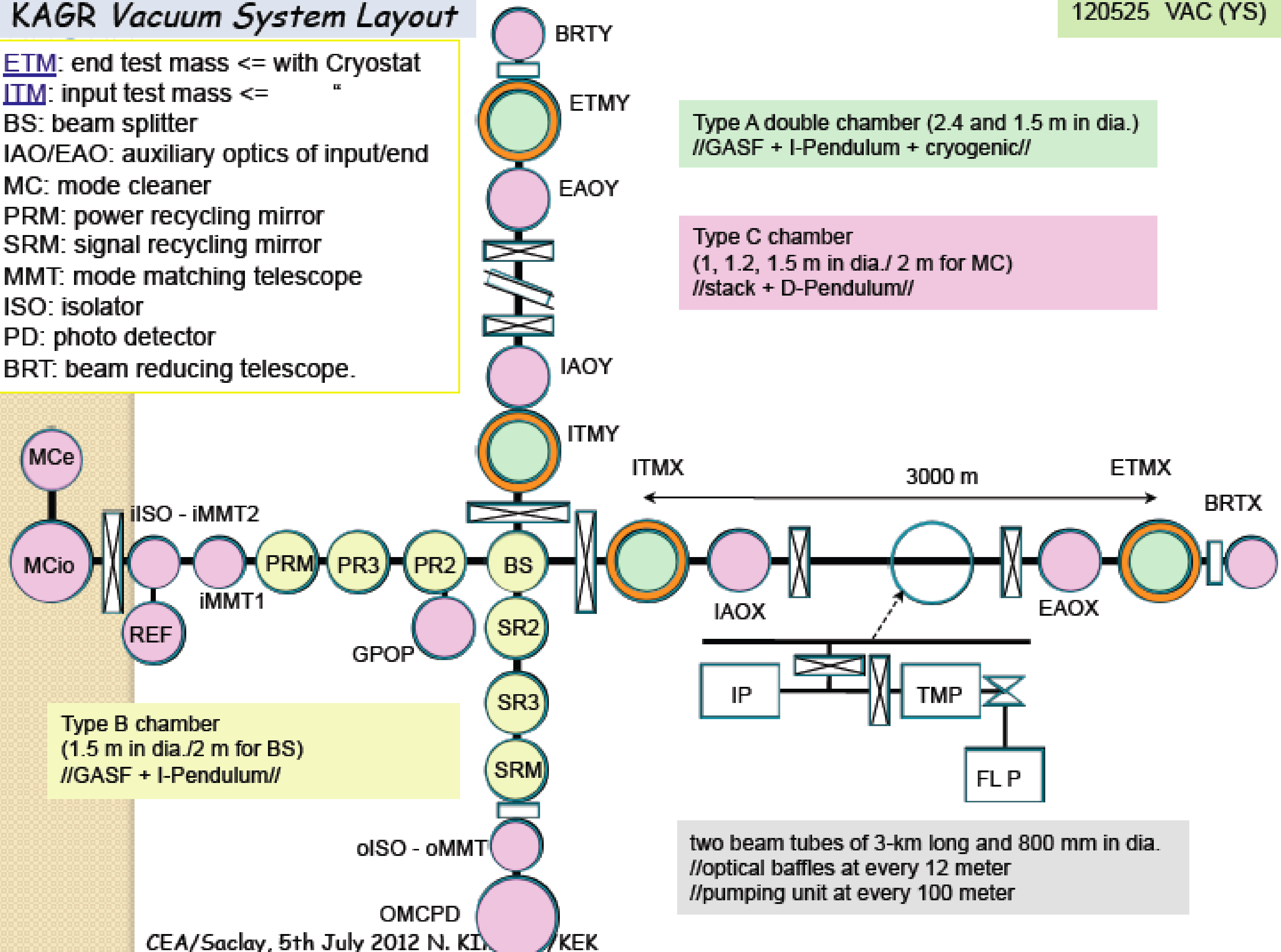


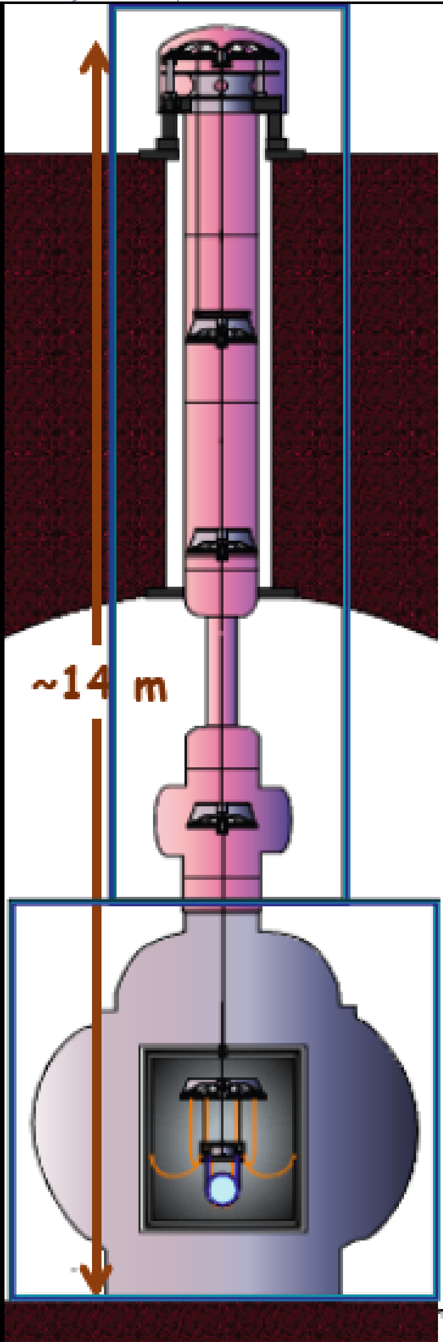


KAGR Vacuum System Layout

120525 VAC (YS)

ETM: end test mass <= with Cryostat
ITM: input test mass <= "
BS: beam splitter
IAO/EAO: auxiliary optics of input/end
MC: mode cleaner
PRM: power recycling mirror
SRM: signal recycling mirror
MMT: mode matching telescope
ISO: isolator
PD: photo detector
BRT: beam reducing telescope.





Structure of the vacuum tank for KAGRA Test Mass

- The vacuum tank for KAGRA Test Mass has two layer structure having ~14 m height.
- Two layers are connected with each other vacuum pressure level less than ~10^{-7} Pa.
- Upper layer of the tank is installed three Seismic Attenuation Systems for KAGRA Test Mass.
- Lower layer of the tank is installed mono crystal sapphire mirror with a cryogenic suspension cooled down to less than 20 K.

Required specification for the KAGRA Cryogenics

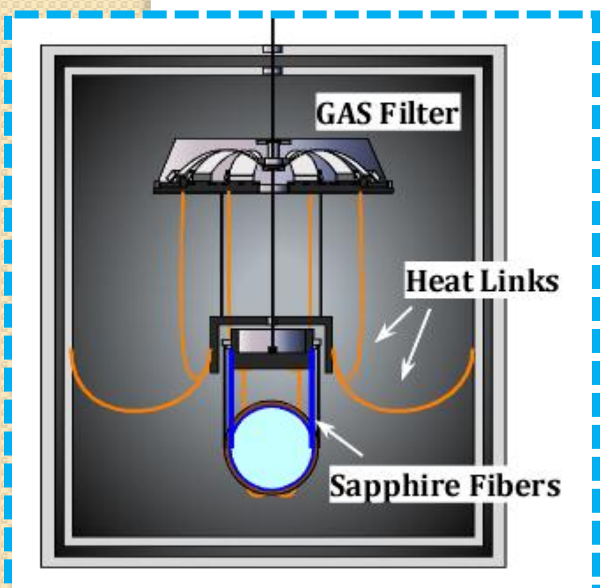
- Temperature of the mirror (mono crystal sapphire, mass=30 kg) < 20 K.
- Inner radiation shield have to be cooled < 8 K.
- The mirror have to be cooled without introducing excess noise, especially vibration from the cryo-coolers.
- Accessibility and enough space for the installation work around the mirror in the cryostat.
- Satisfy ultra high vacuum specification $< 10^{-7}$ Pa.

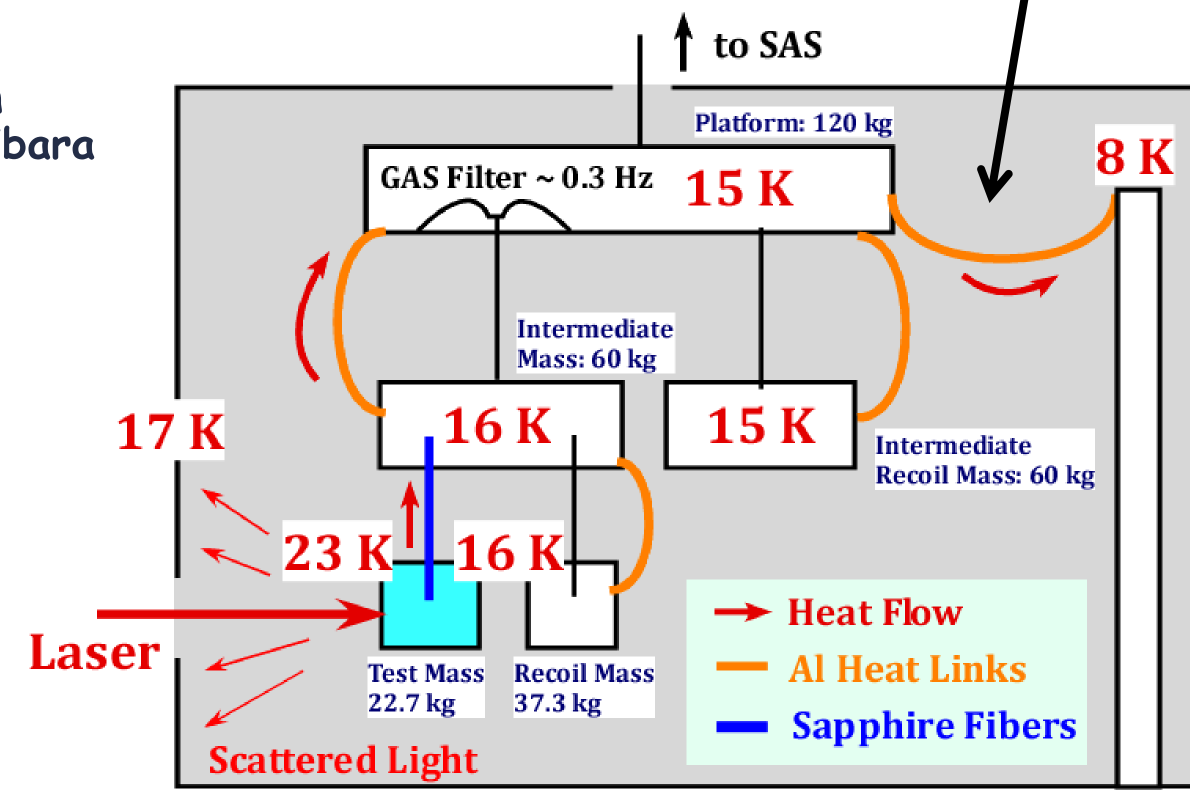
Cooling Scheme of the mirror

- Heat transferred via **pure aluminum heat links.**

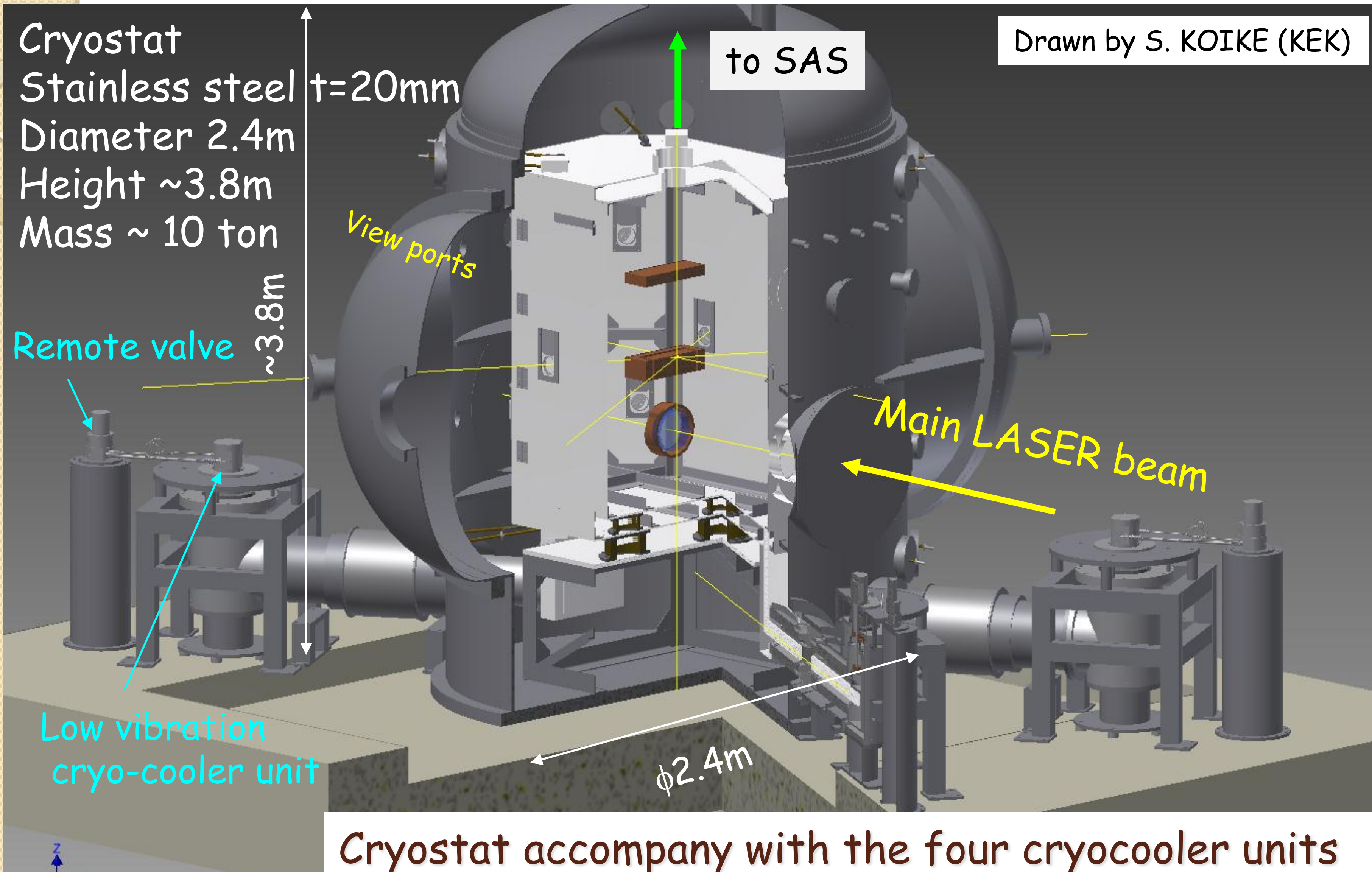
We need Φ1 mm, L=1 m heat links x 7~8

Thermal simulation
Done by Y. Sakakibara



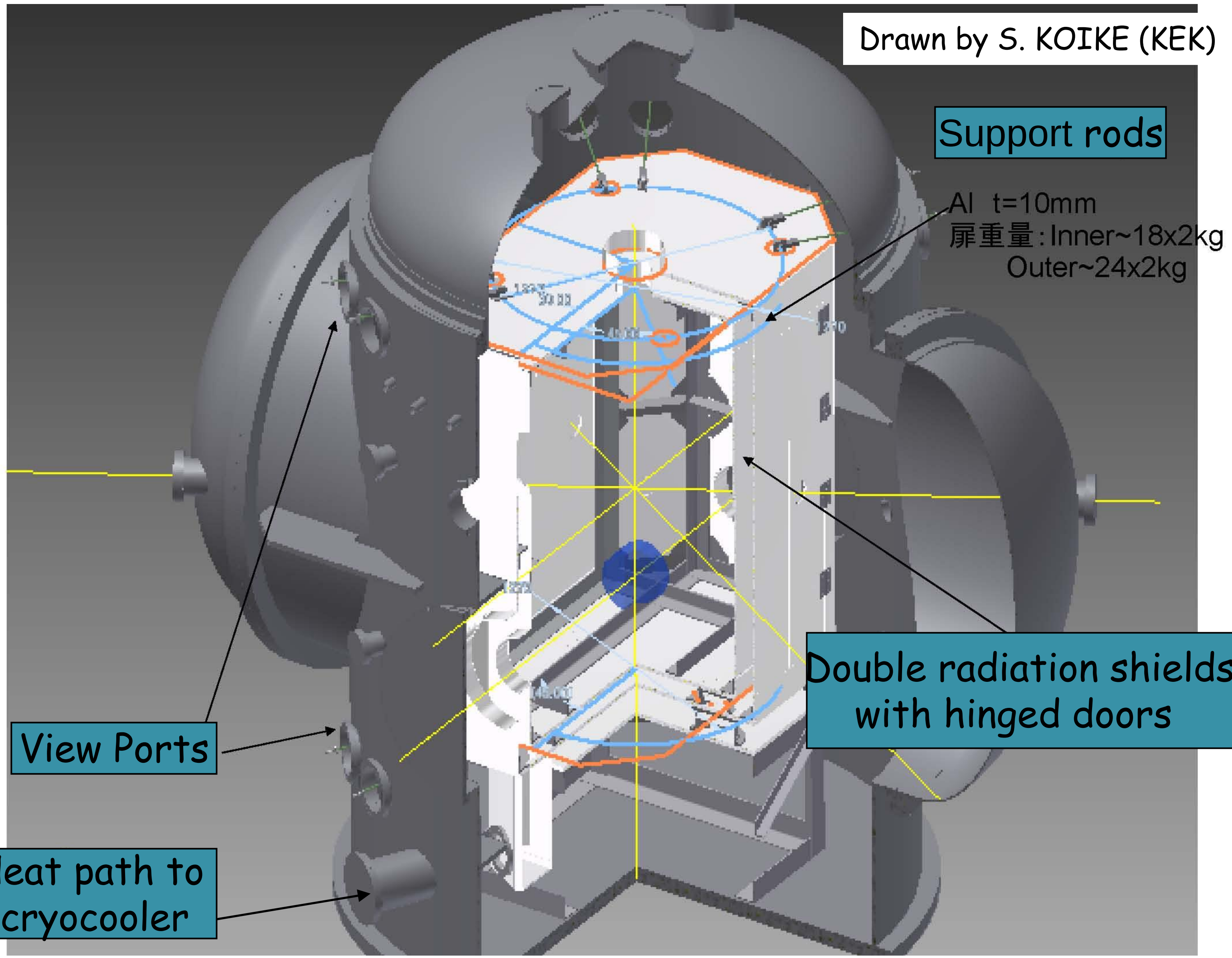


Components of Mirror Cryostat



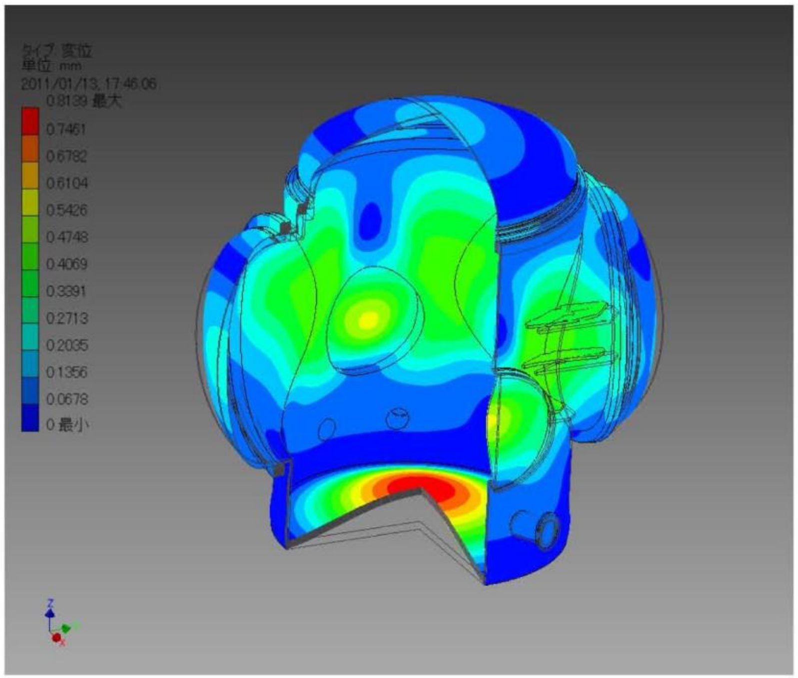
Cryostat accompany with the four cryocooler units

The interior of the cryostat

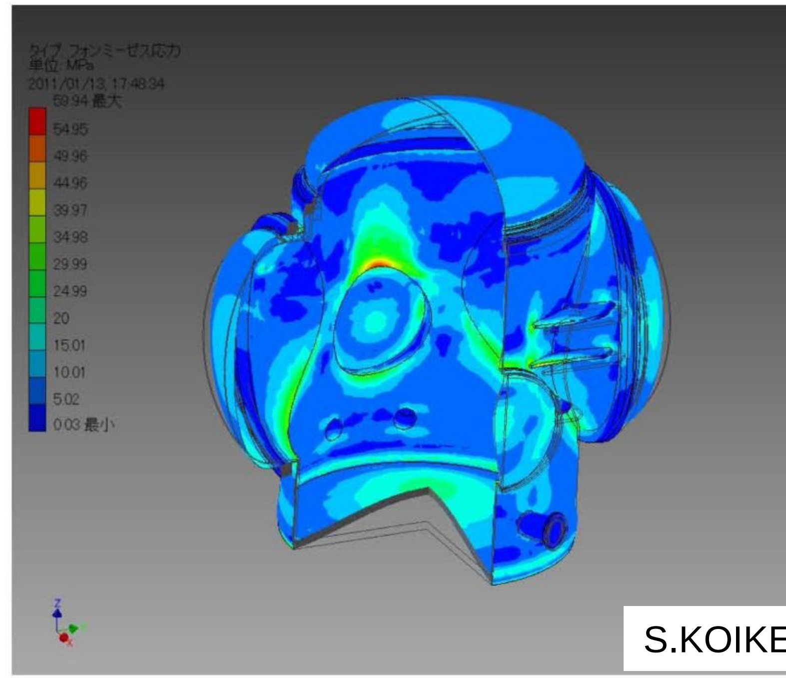


Mechanical Analysis
Example of static deformation analysis

Deformation under the atmospheric pressure and the gravity



Maximum deformation : 0.8 [mm]



Maximum stress : 59 [Mpa]

- Main vacuum duct and the duct to SAS are not connected.
- periphery of the bottom are fixed on the floor

Modal analysis

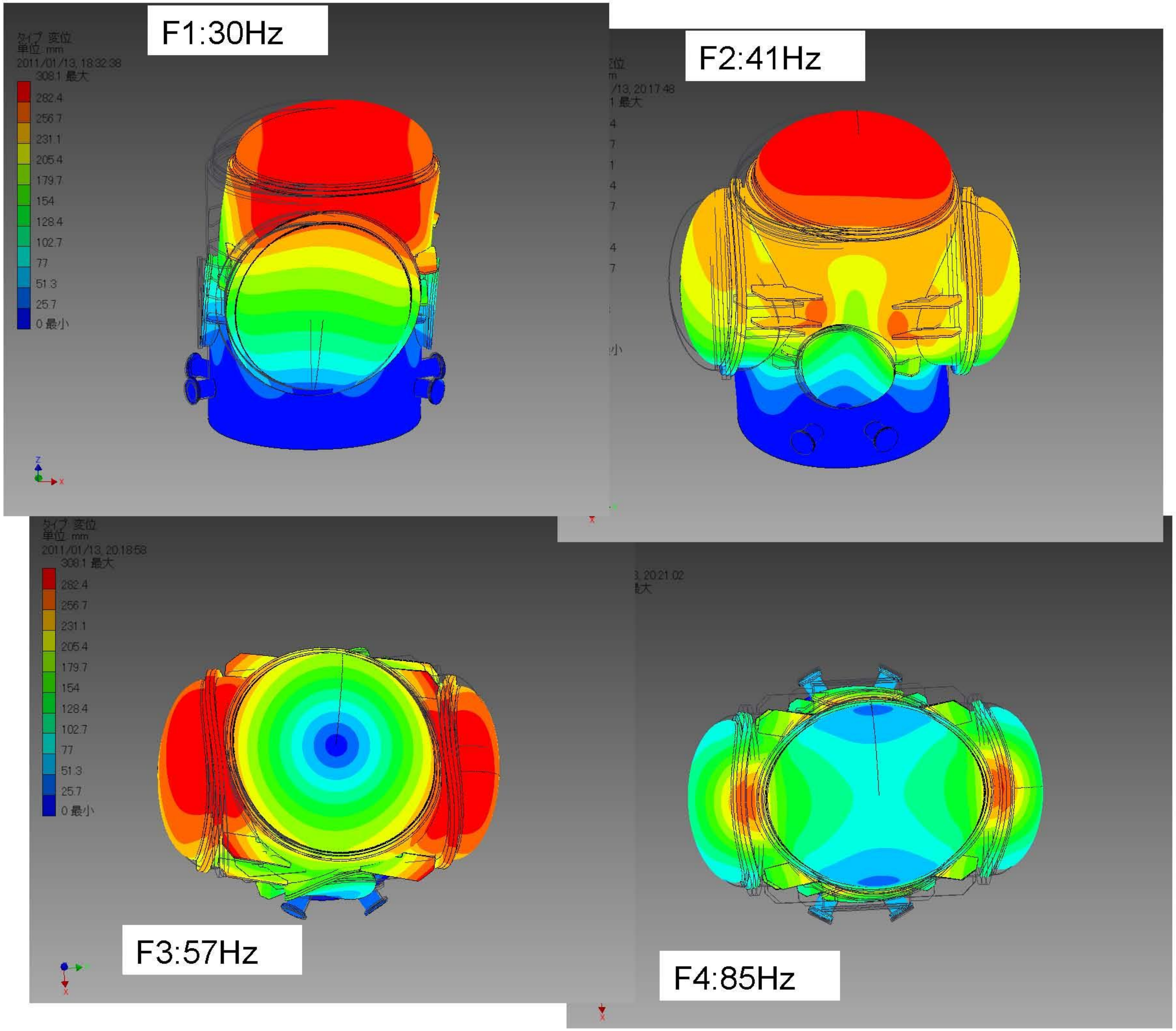
Boundary condition: fix the perimeter of the bottom

* Interface to SAS is not fixed at the moment.

S. Koike

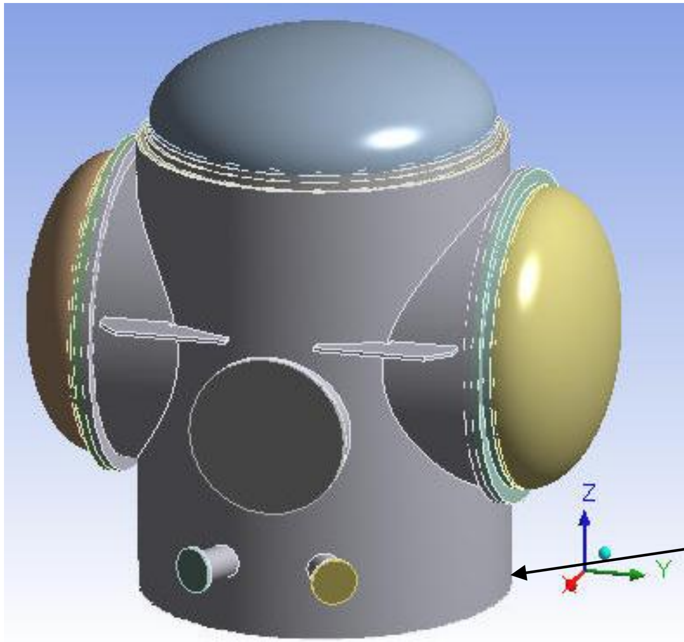
Resonance Frequency

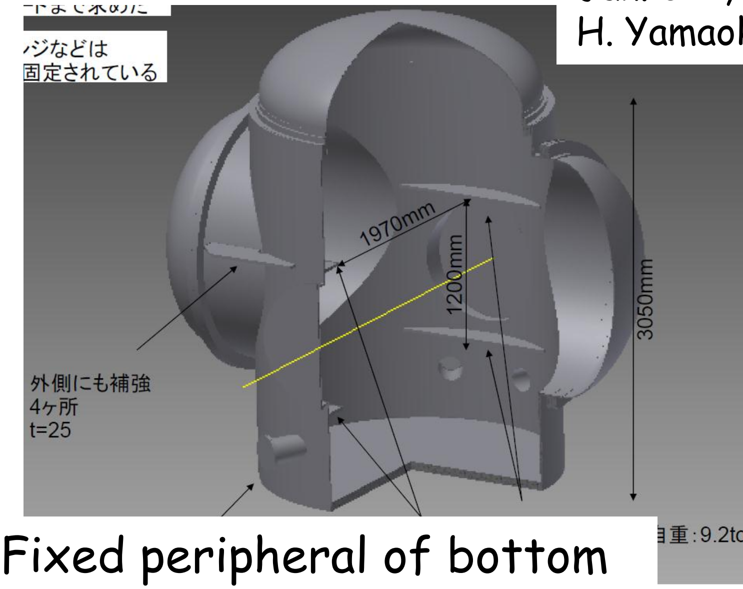
F1 29.86 Hz
F2 41.27 Hz
F3 57.22 Hz
F4 85.01 Hz
F5 89.68 Hz
F6 93.33 Hz
F7 111.81 Hz
F8 120.70 Hz



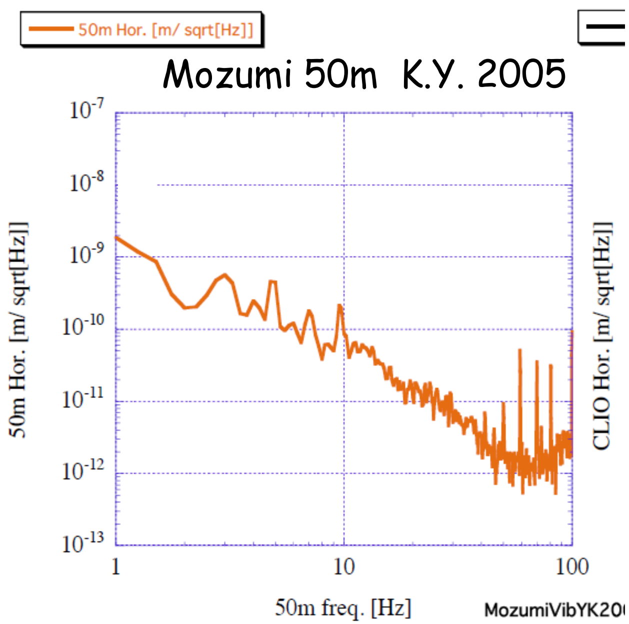
Response to ground motion

Jan. 31st,2011
H. Yamaoka

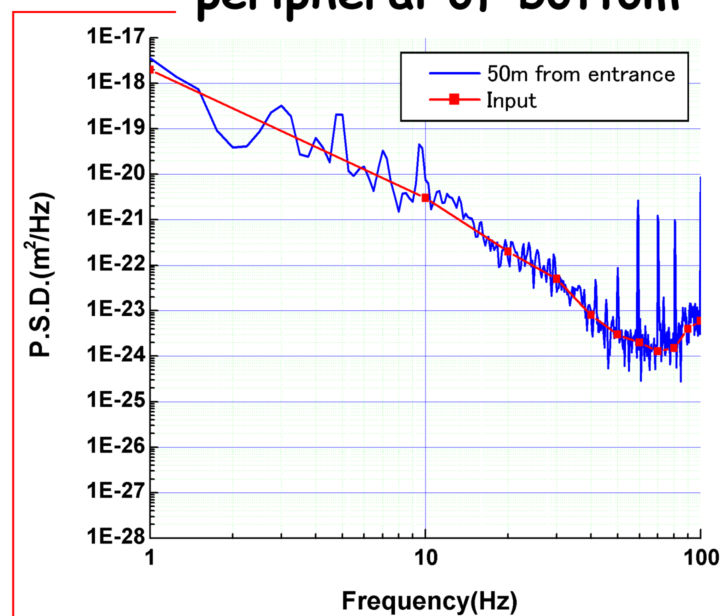




Fixed peripheral of bottom on the ground

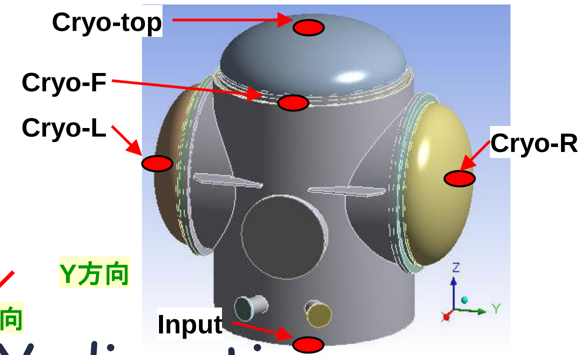


Input ground motion to peripheral of bottom



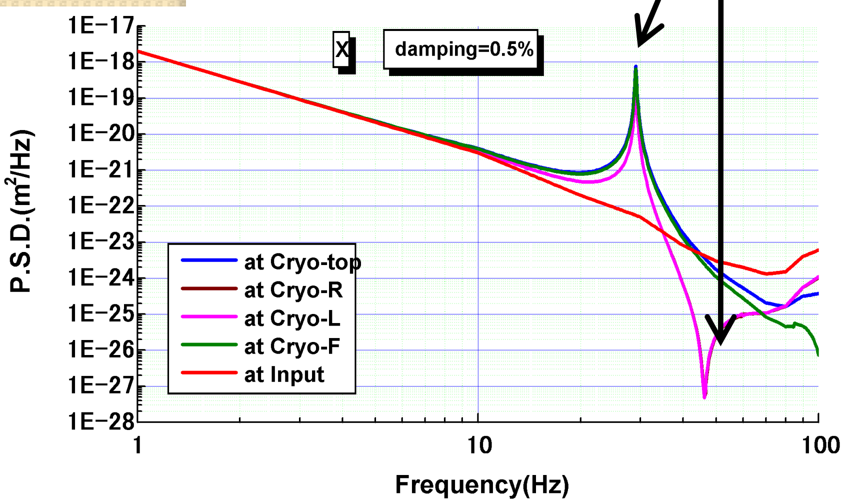
CEA/Saclay, 5th July 2012 N. KIMURA/KEK

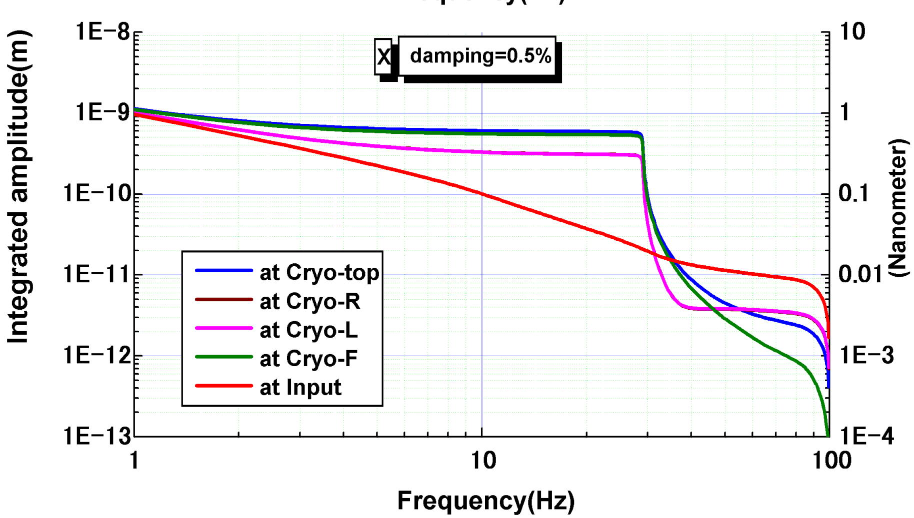
Analyzing of Response to ground motion



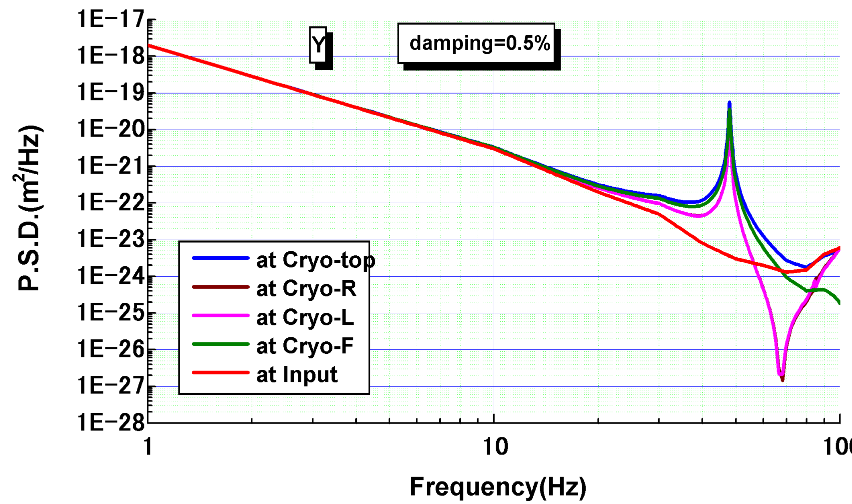
resonant frequency

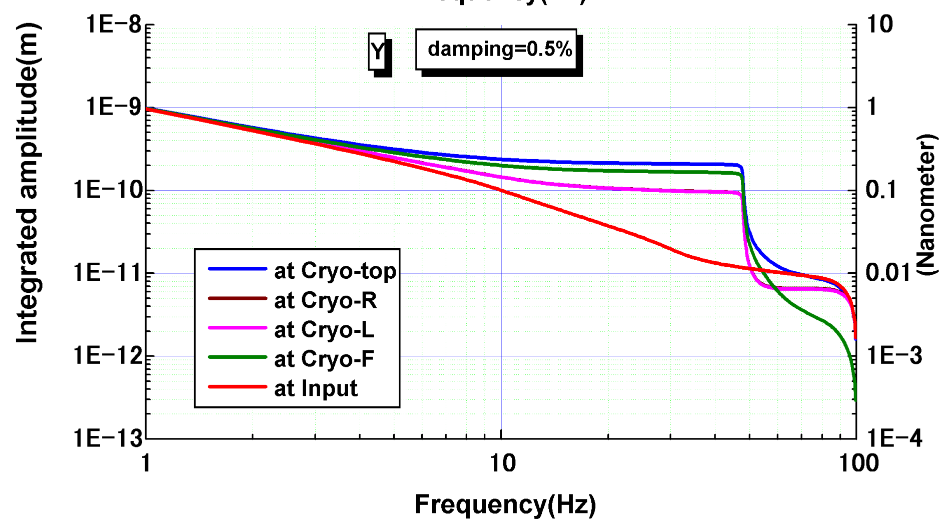
X-direction





Y-direction





Modal analysis of outer shield

S.KOIKE

Mode frequency

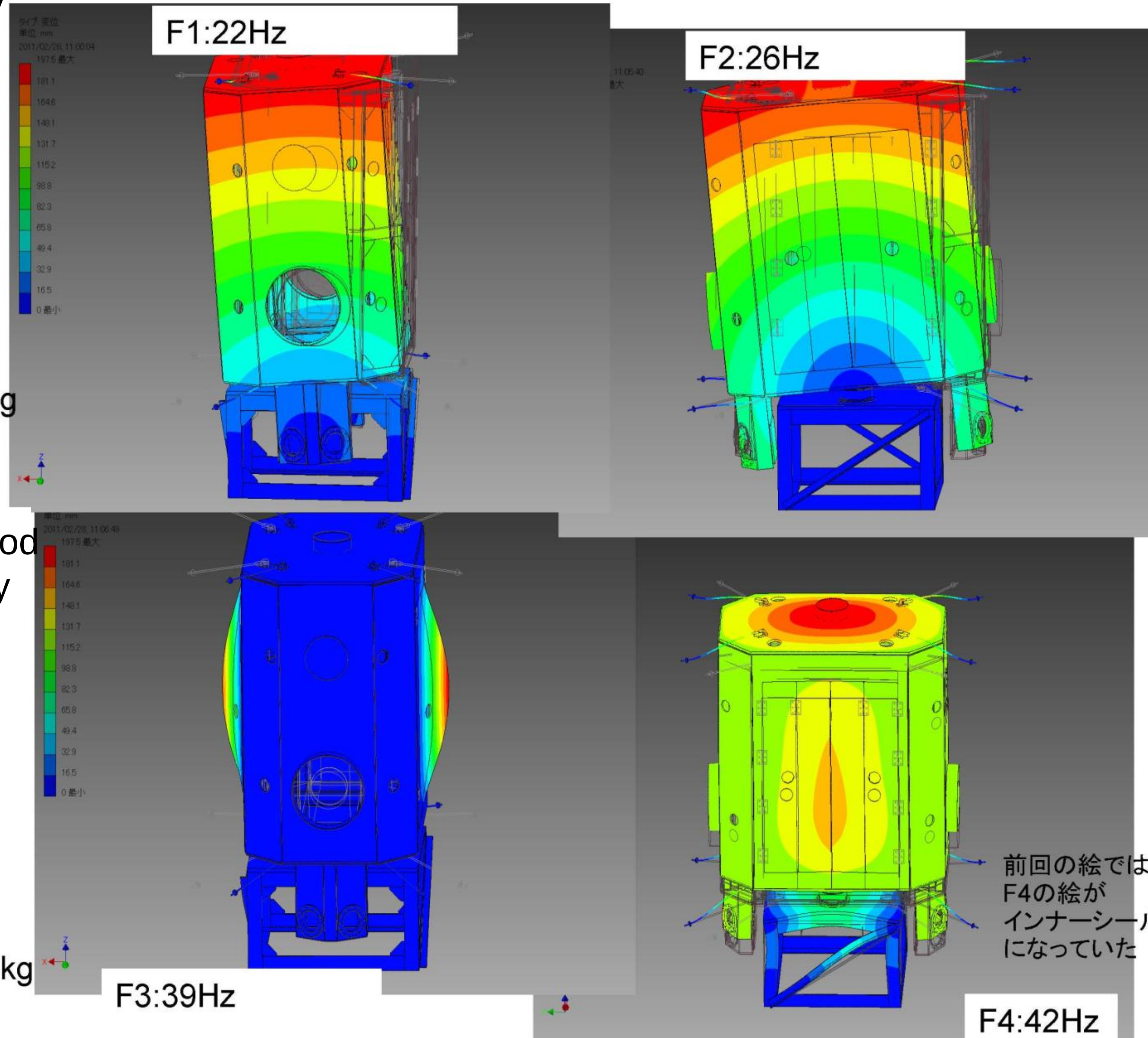
F1 22.31 Hz
F2 25.98 Hz
F3 39.47 Hz
F4 41.79 Hz
F5 46.22 Hz
F6 57.38 Hz
F7 59.04 Hz
F8 76.29 Hz

Mass=893.429 kg

Remove support rod
Mode Frequency

F1 7.86 Hz
F2 16.80 Hz
F3 39.18 Hz
F4 41.78 Hz
F5 43.01 Hz
F6 44.96 Hz
F7 57.11 Hz
F8 58.41 Hz

Mass=889.352 kg



The Newest Estimated Heat load of the cryostat

1st Cold stage

- Outer Shield (W)
  - Duct Shields 8.2
  - Eleven View Ports 7.8
  - Radiation From 300 K 40.7
  - Support post and Rods 4.8
  - Electrical wires 3×10^{-4}
  - Cryo-cooler units 15 x 4

Total 61.5 (W)

/unit 30.3 (W)

2^{nd} stages of two cryo-cooler units will be connected with the inner shield.
Left 2^{nd} stages of two cryo-cooler units will be connected with the mirror via cryogenic suspensions.

2nd Cold stage

- Inner Shield (W)
  - Radiation From 80 K 1.3
  - Support post and Rods 0.8
  - Electrical wires 3×10^{-4}
  - Scattering Light 8
    (400kW x 20 ppm)
  - Cryo-cooler units 0.5 x 2

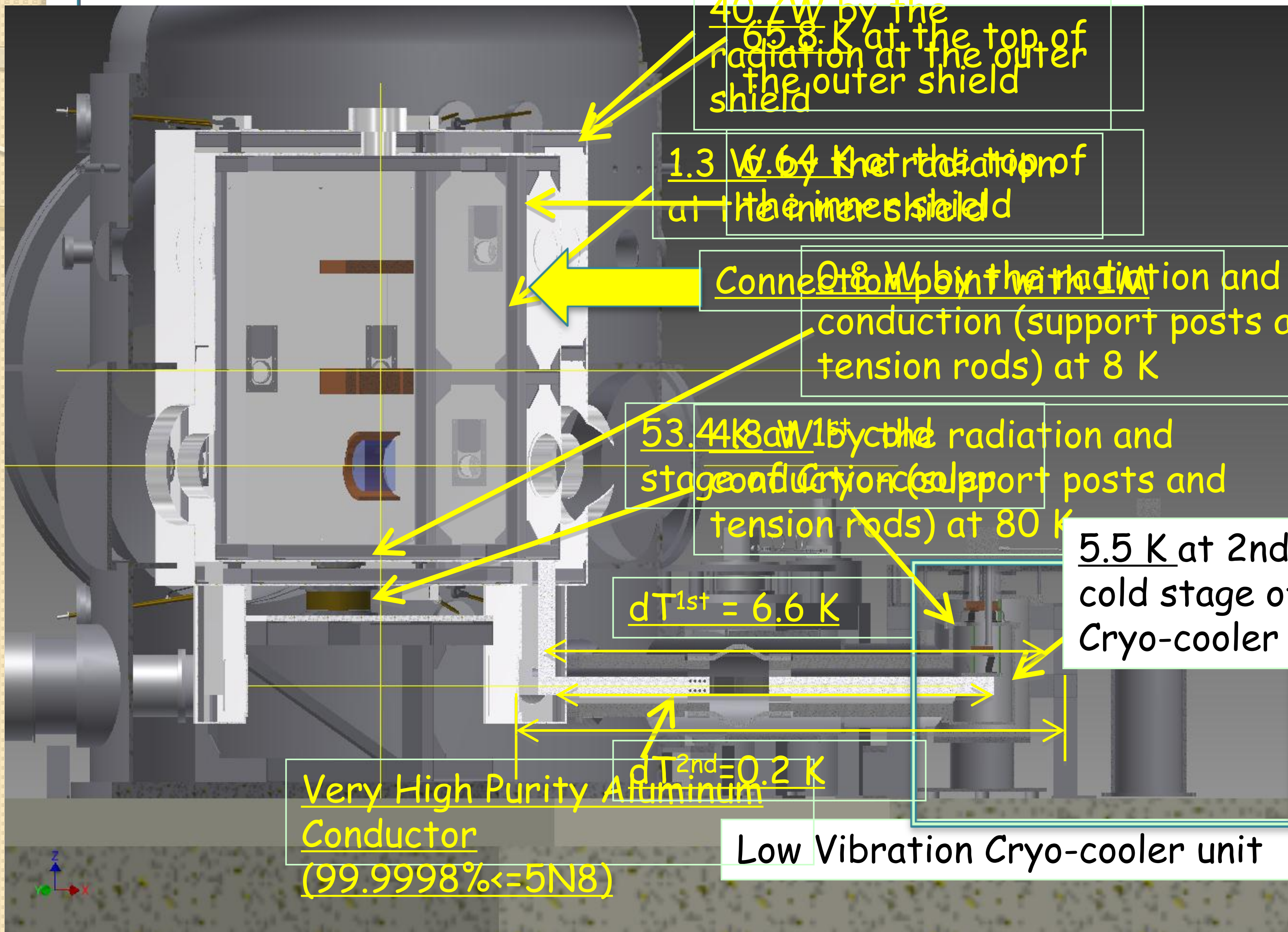
  Total at Inner Shield 11.1

  W/unit 5.6
- Mirror (W)
  - Duct Shields ~ 0.02
    (Beam and SAS)
  - Eleven View Ports 0.8
  - Mirror Deposition? 0.9
  - Cryo-cooler units 0.5 x 2

  Total at the mirror 2.7

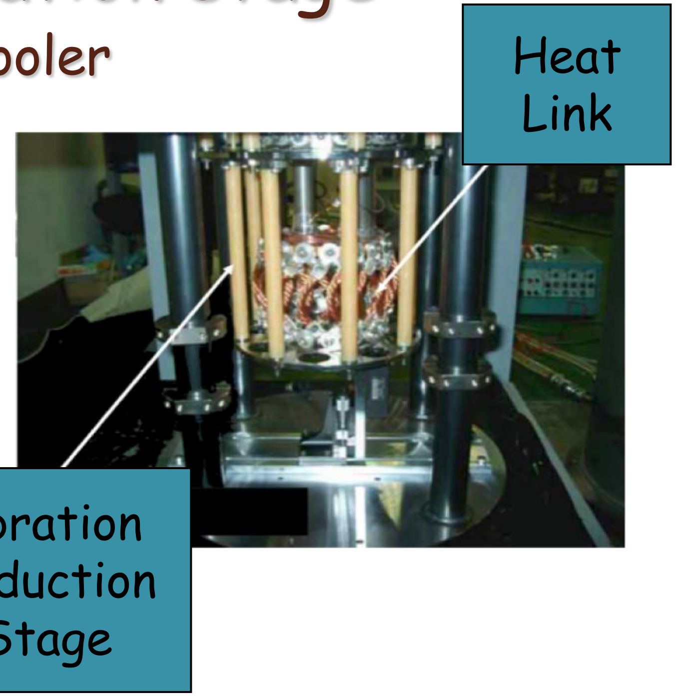
  W/unit 1.3

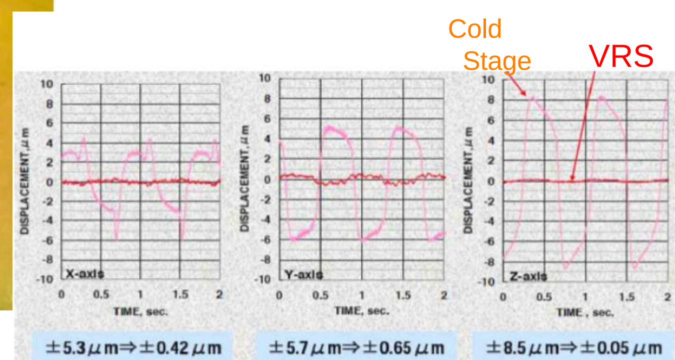
Estimated Thermal Budget

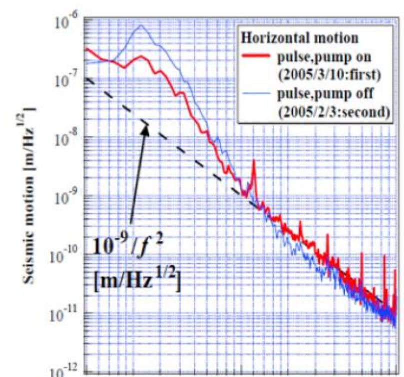


Cooling Option: Conductive cooling by cryo-coolers with low vibration stage

Our decision: Use CLIO type Cryo-cooler with low vibration mount for KAGRA







CLIO is prototype for KAGRA constructed at Kamioka mine.

Achieved very vibration level < few nm!

Advantage and Disadvantage of CLIO type cryocooler unit

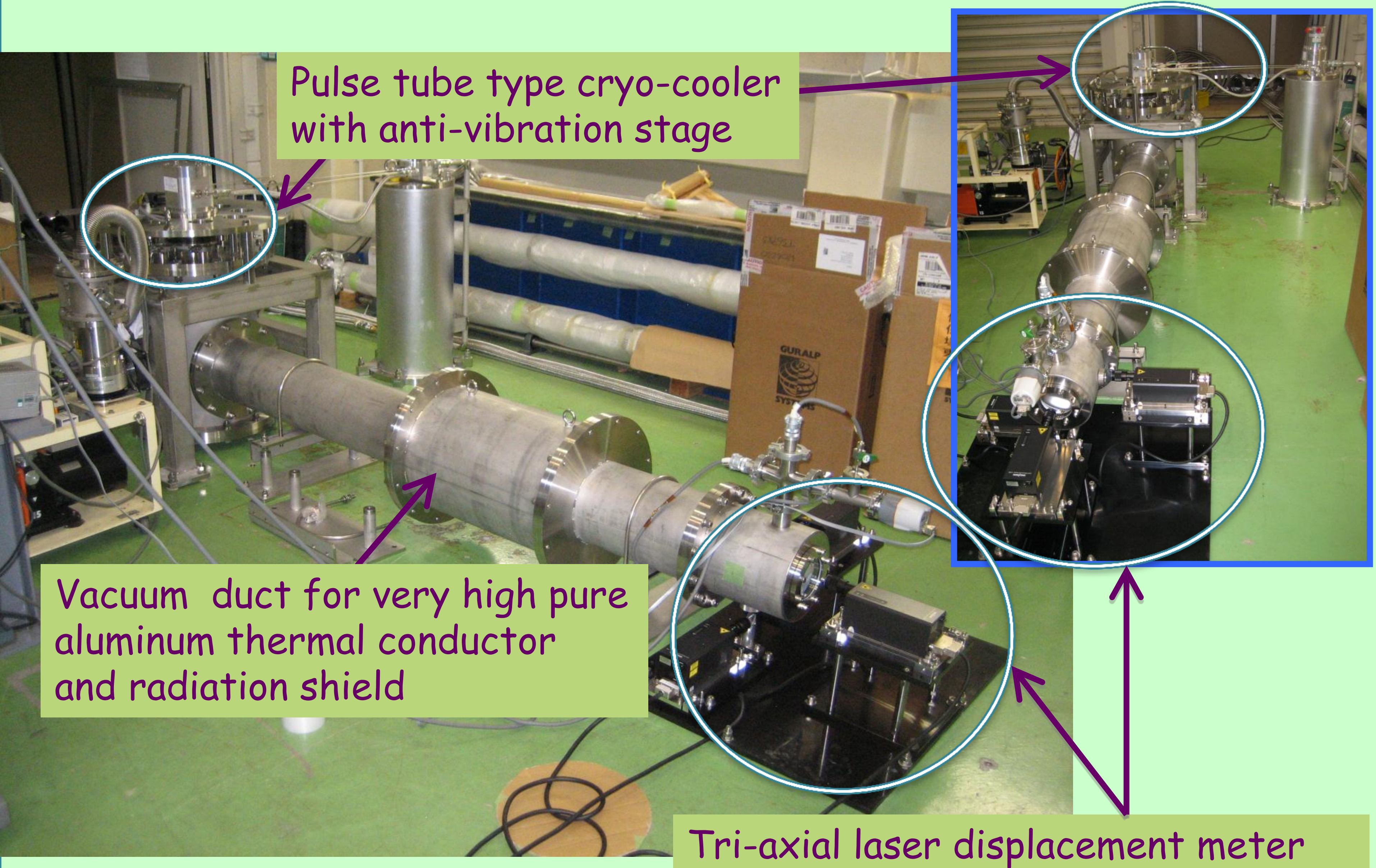
<u>Discontinued Items</u>

- Ready to use Cryo-Cooler equipped special cold stage, such as CLIO type
- Aluminum FRP tube as anti-vibration support rods
- High pure aluminum thin wire less than ϕ0.12 mm for heat link.

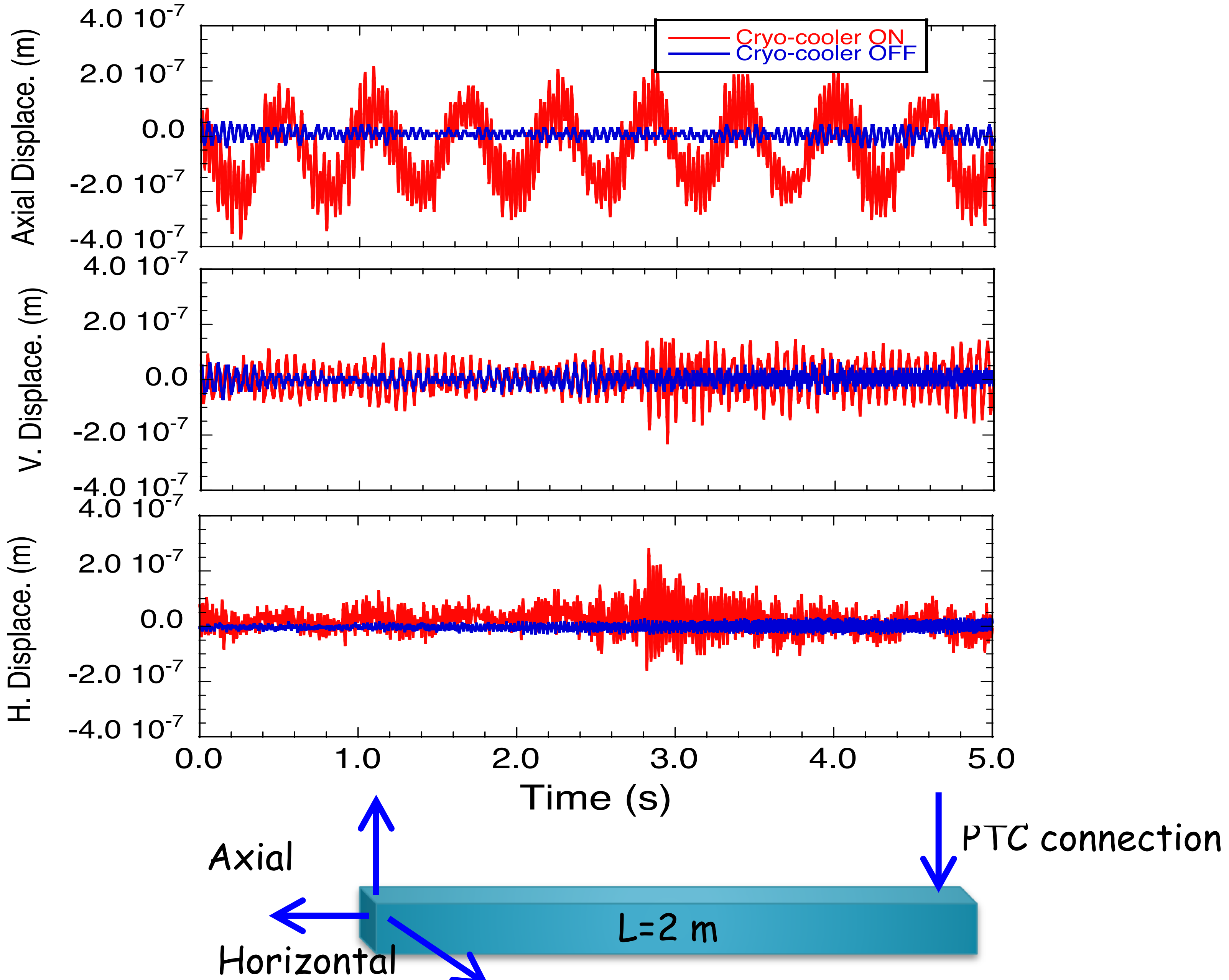
<u>Substitutes for the Items</u>

- Attach new design of cold stage flanges to mass-produced 1W/4K PTC
- Replace to Carbon FRP tube as anti-vibration support rods (stiffness AFRP > CFRP > GFRP)
- Start R&D work with new company for development of high pure aluminum thin wire less than ϕ0.12 mm.

Proto-type cryocooler unit under the performance test



Vibration Level at edge of AL thermal conductor



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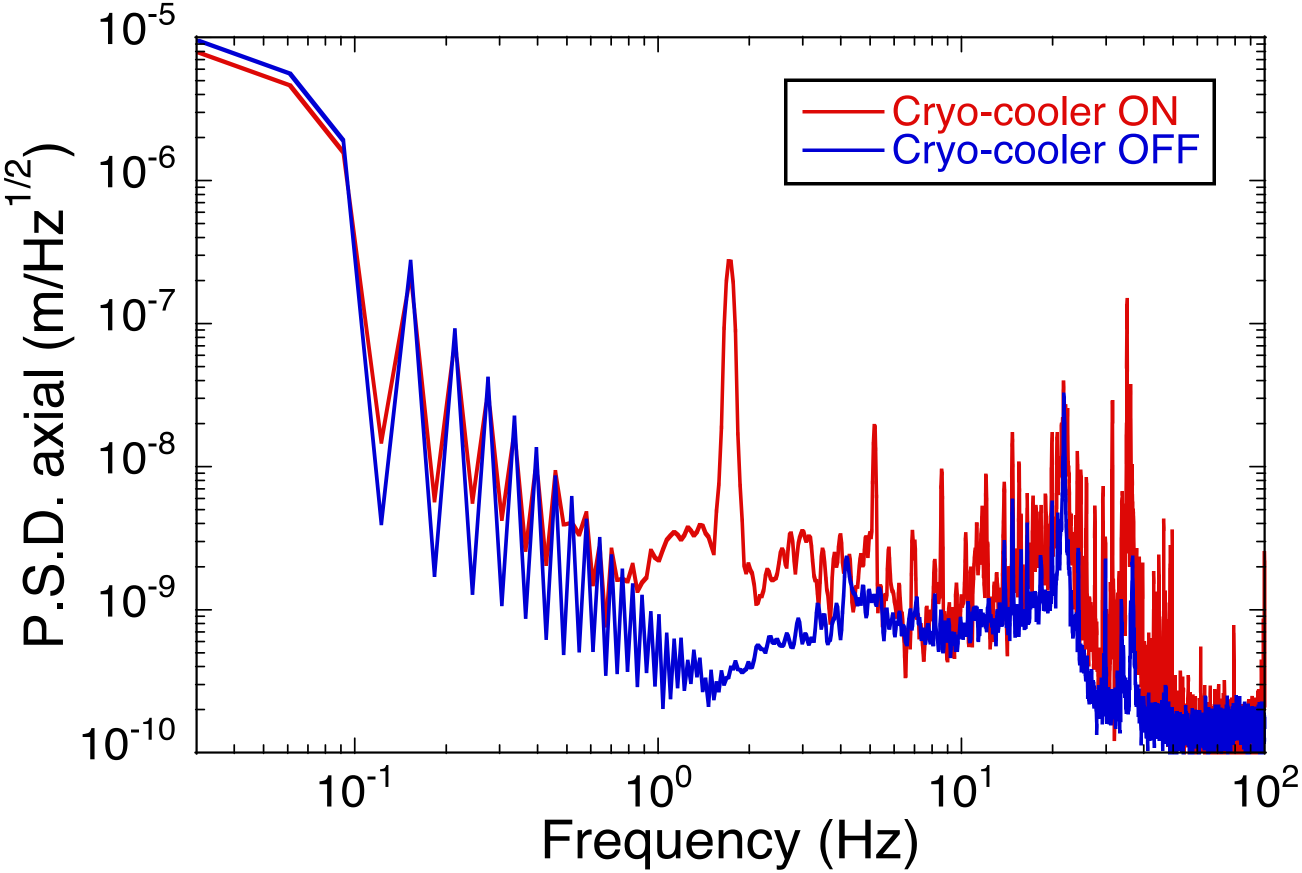
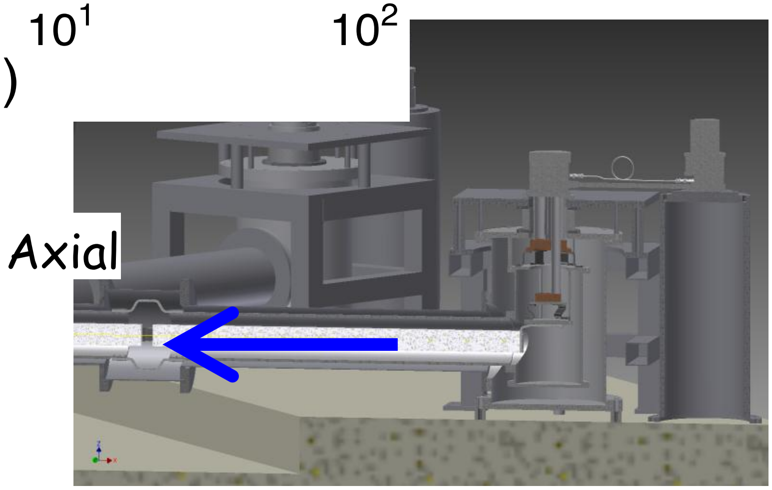
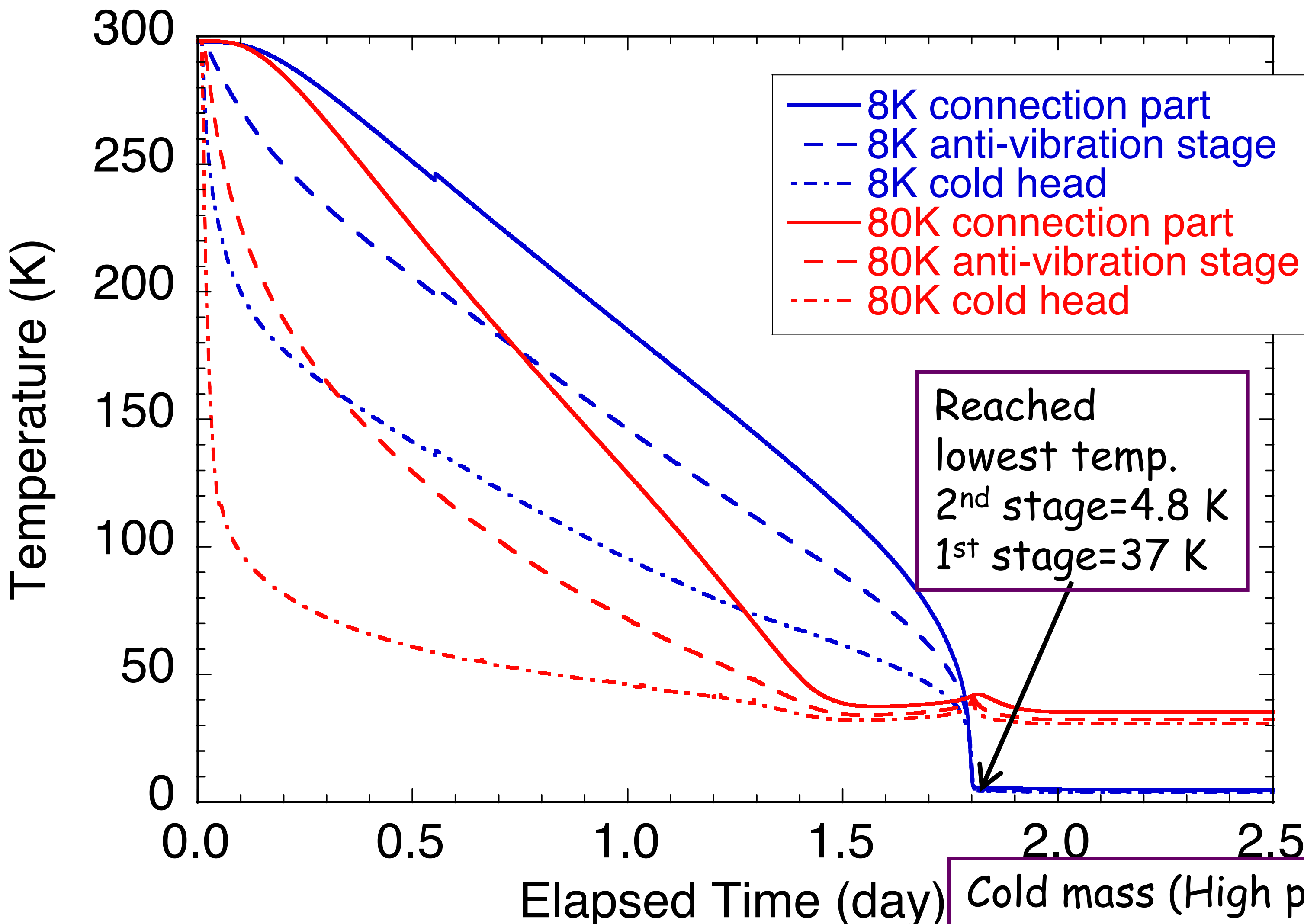
F.F.T. analysis (Ex. Axial direction)



Results of displacement at connection point
Axial < 200 nm
Vertical < 50 nm
Horizontal < 10 nm

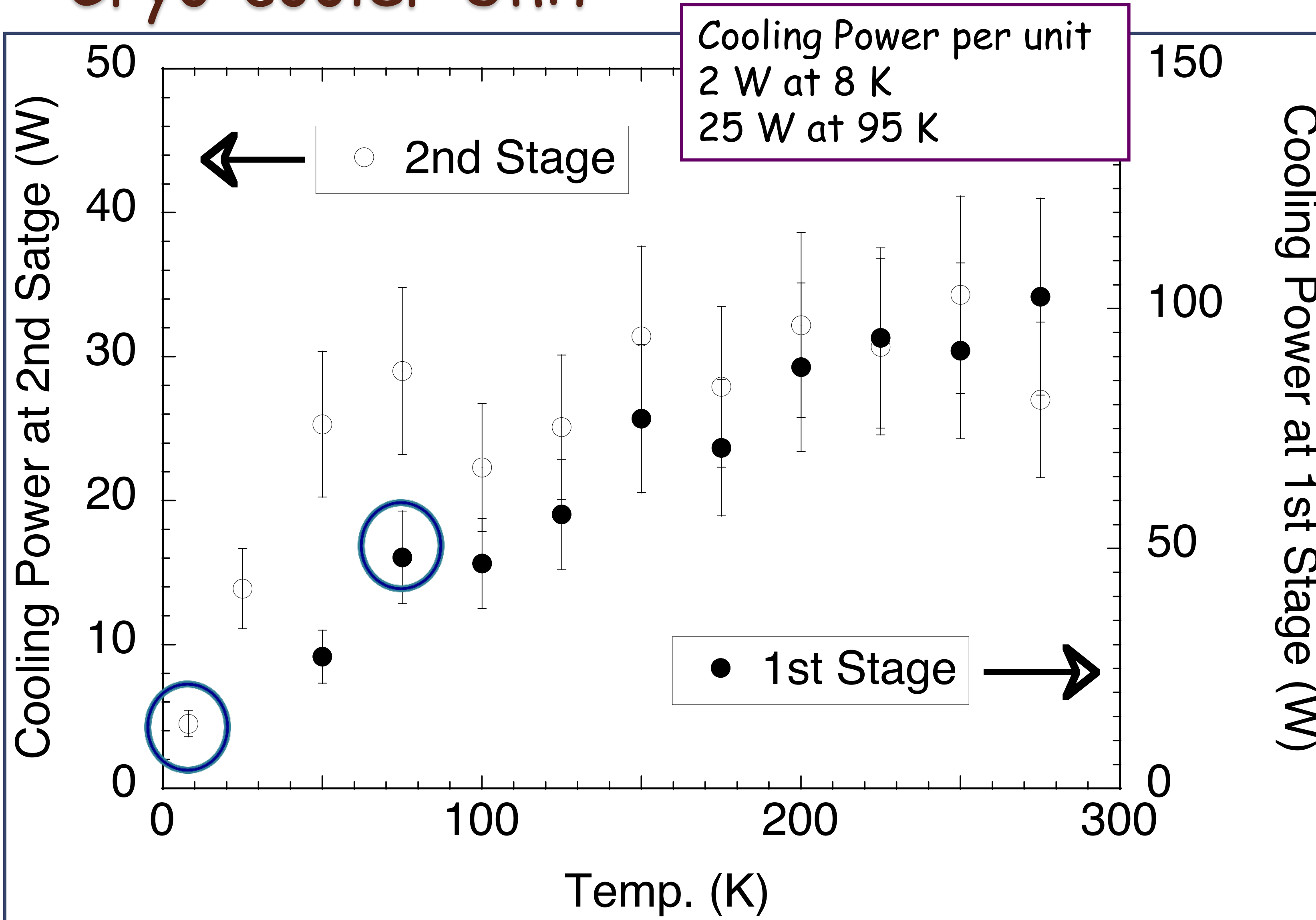


Cooling curve of proto-type cryo-cooler unit



Cold mass (High pure AL)
2nd stage= 25 kg

Cooling Performance of Proto-type Cryo-cooler Unit



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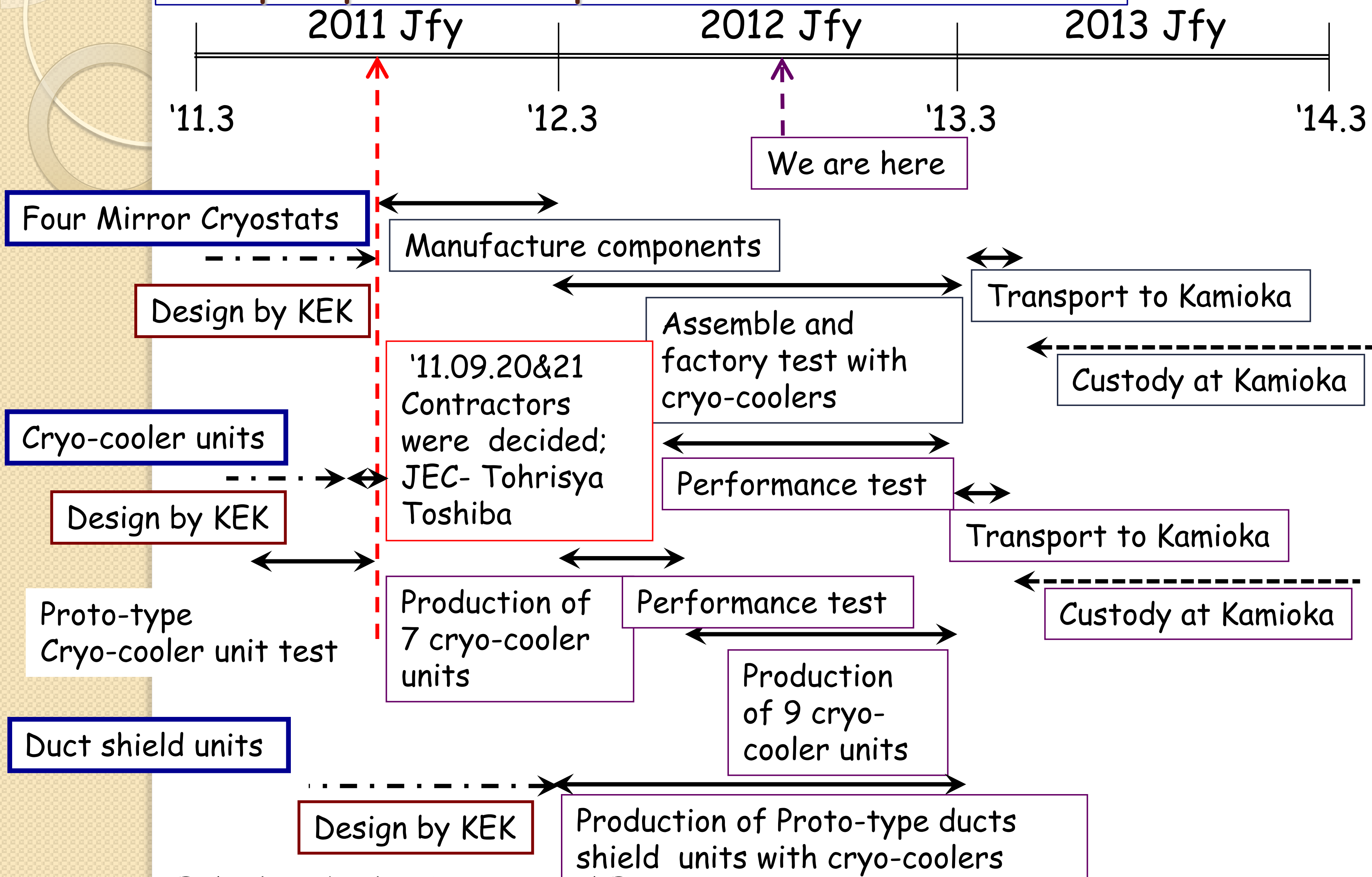
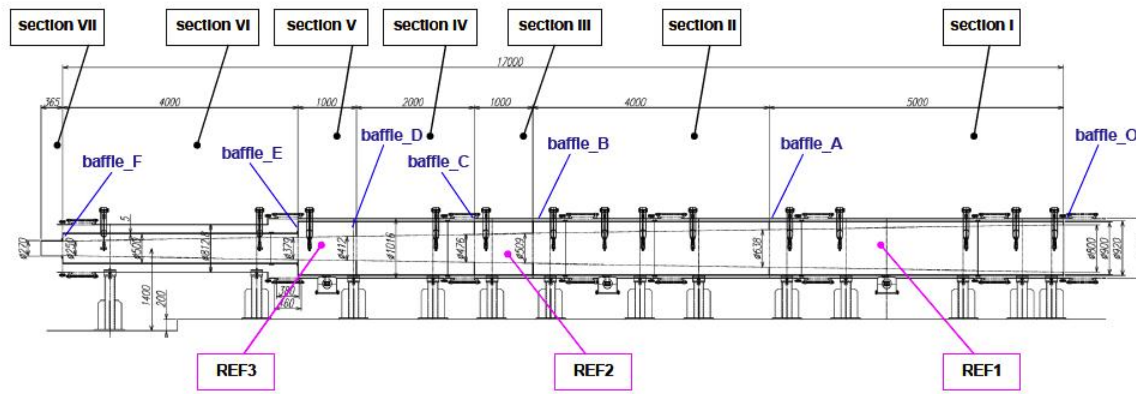
Production plan of KAGRA mirror cryostats and peripheral components

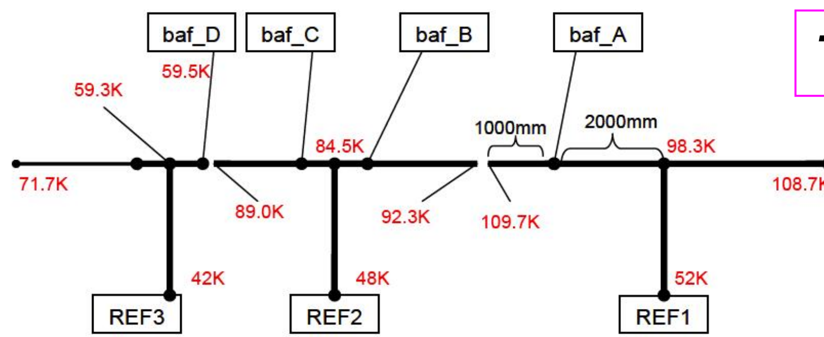


Status of KAGRA cryogenics

2012.05.29 Tue.
Collaboration Meeting
T. Suzuki

- Cryostat
  - Welding and machining finished for components.
  - Components are waiting for the next process.
  - Vacuum chambers (4). Top caps (4). Side service ports (4).
  - Radiation shields (2x4)
- Shield duct
  - Design is in progress
  - A cost reduction is under consideration





Tentative

Summary

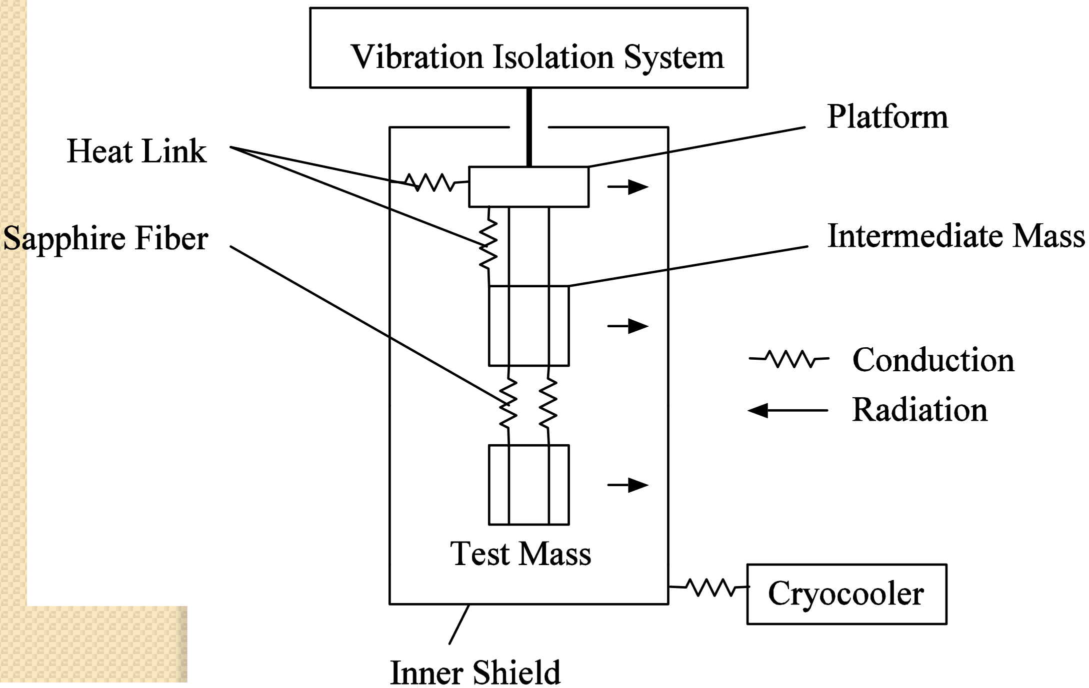
- The design of the cryostat and cryo-cooler for KAGRA were finished.
- The production of the components for the cryostat have started in this September 2011.
- The performance of the cryo-cooler unit with anti-vibration stage have almost confirmed, but need some modification to clear the specification.
- Performance of the first cryostat will be demonstrated on the mid of 2012 Jfy.
- Total performance of the first cryo-cooler will be confirmed on the mid of this August.

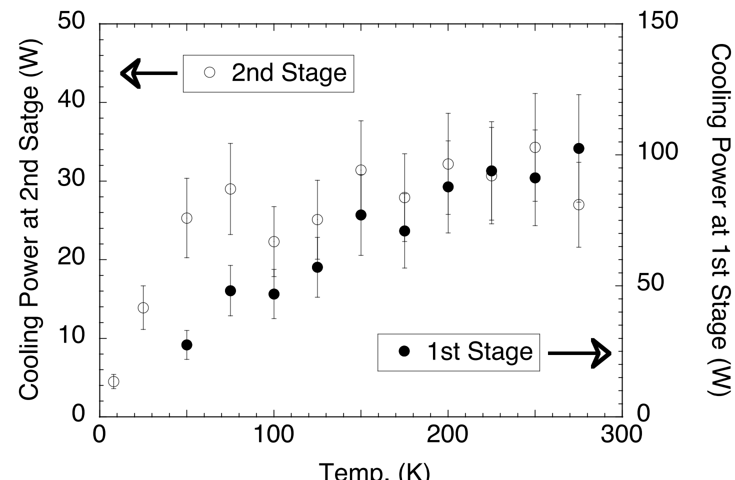
Back UP

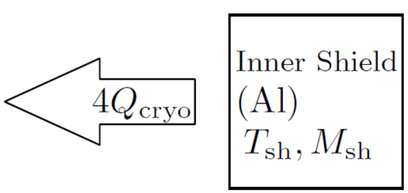
Estimation cooling characteristics

Y.SAKAKIBARA

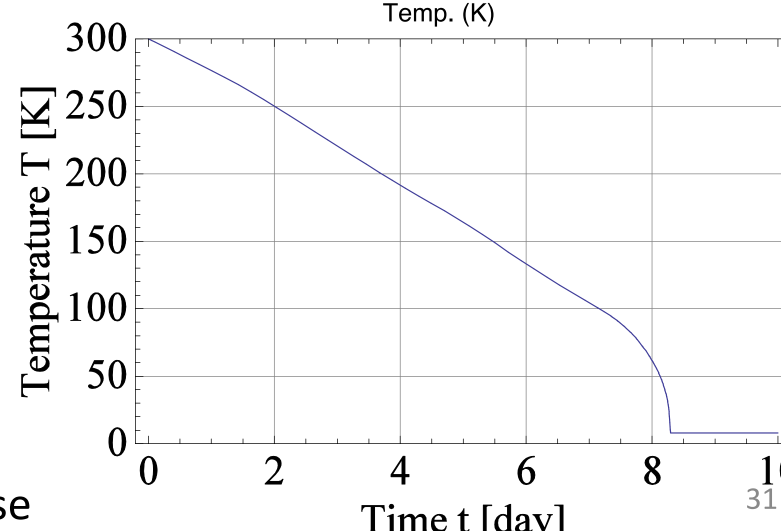
- Model is constructed to estimate initial cooling time
- Heat is transferred by conduction in sapphire fibers and heat links and radiation
- Inner shield of 410 kg is connected to the 2nd stages of 4 cryocoolers
  - Cooling power is derived from test result of proto-type cryo-cooler







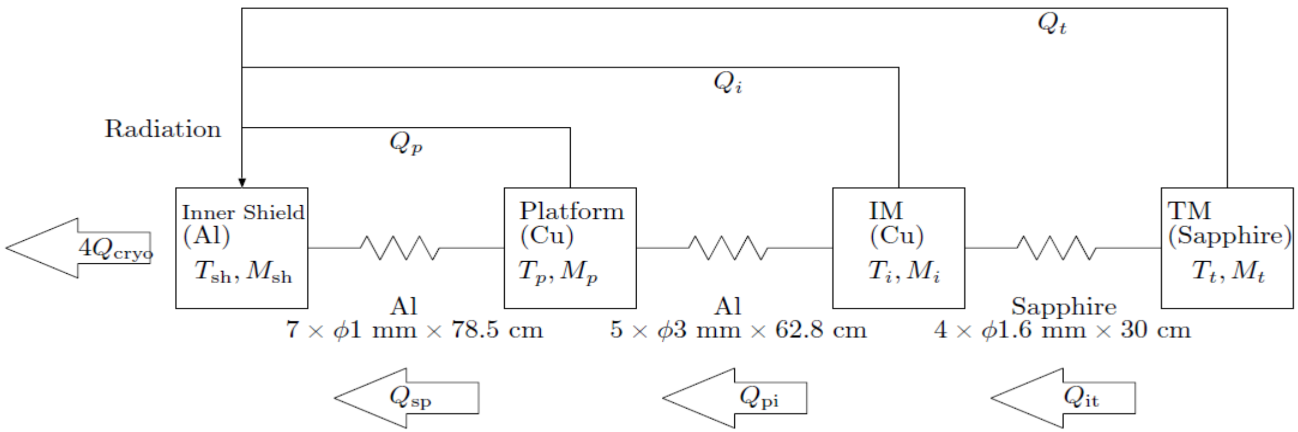
$$\frac{dT_{sh}}{dt} = -\frac{4Q_{cryo}(T_{sh})}{M_{sh}C_{Al}(T_{sh})}$$

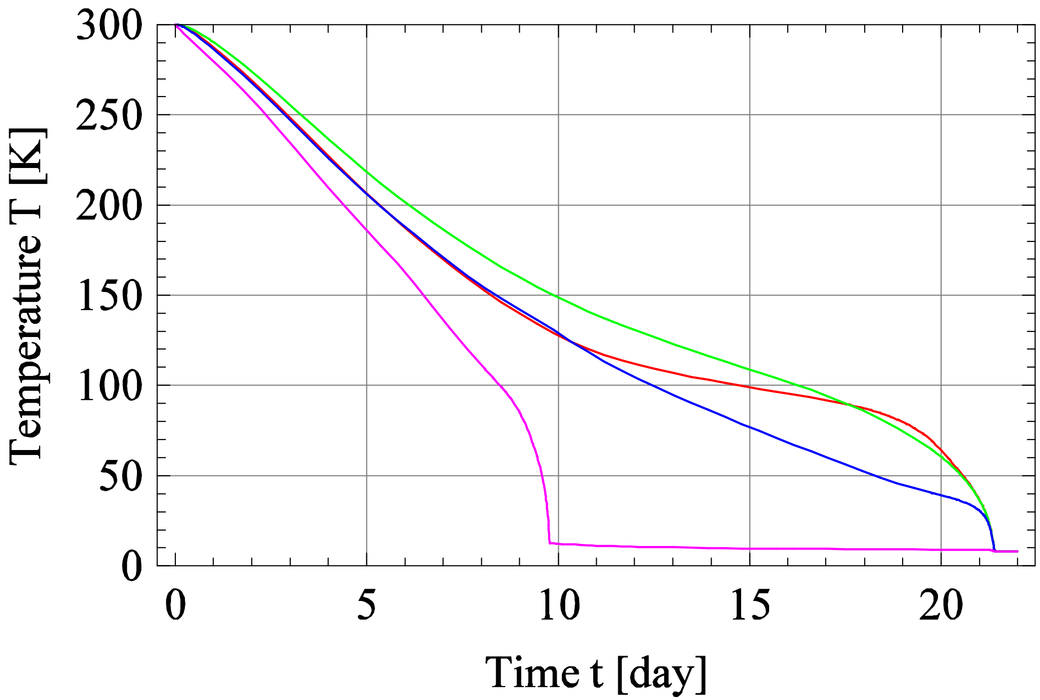


Suspension from isolation system is excluded in this case

Effect on Diamond Like Carbon coating

Y.SAKAKIBARA

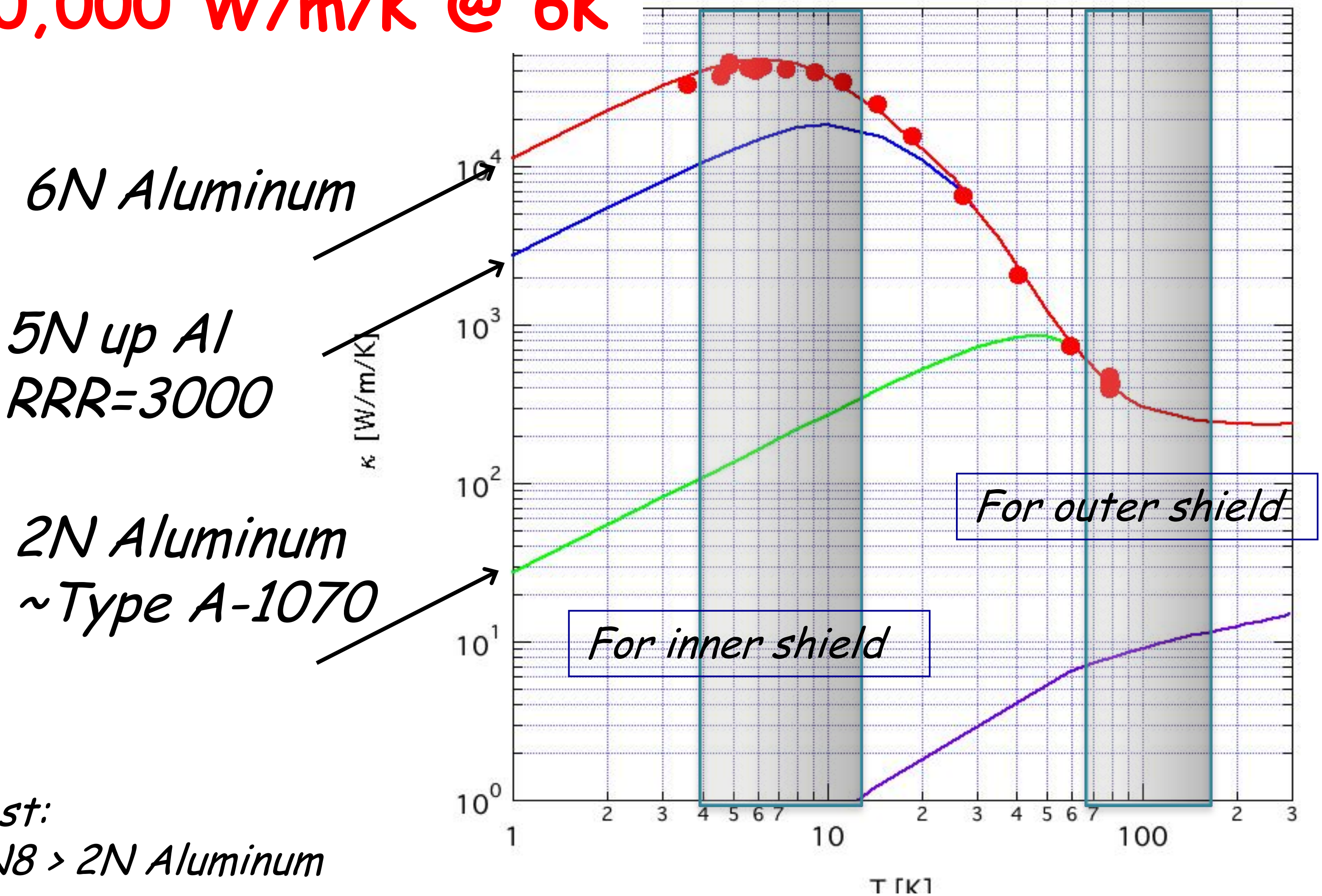




- Increased radiation by platform, intermediate mass, and inside of inner shield coated with DLC (Diamond Like Carbon)
- Absorptivity of DLC at 10 um is 0.41
  (cf. emissivity of Cu and Al is 0.03)
  - We assume that it equals emissivity

Example of Thermal Conductivity of 6N-class Very High Pure Aluminum*

40,000 W/m/K @ 6K



Cost:
5N8 > 2N Aluminum

We must put the right material in the right position.