Update on the cryogenic suspension - KAGRA sapphire suspension - - Vibration from the cooling system -

Presenter: Dan Chen (ICRR)

ELiTES meeting on 9th/10th Feb. 2015

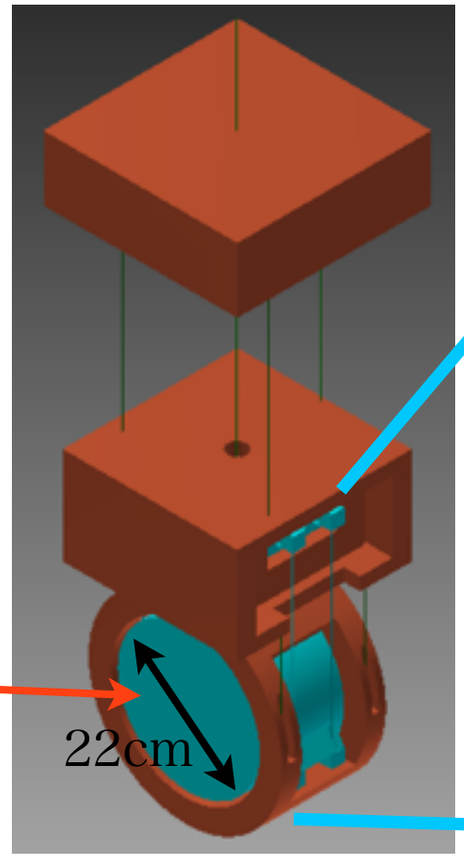
Abstract

We performed several experiments for the cryogenic sapphire suspension system.
We estimated the influence from the radiation shield vibration.

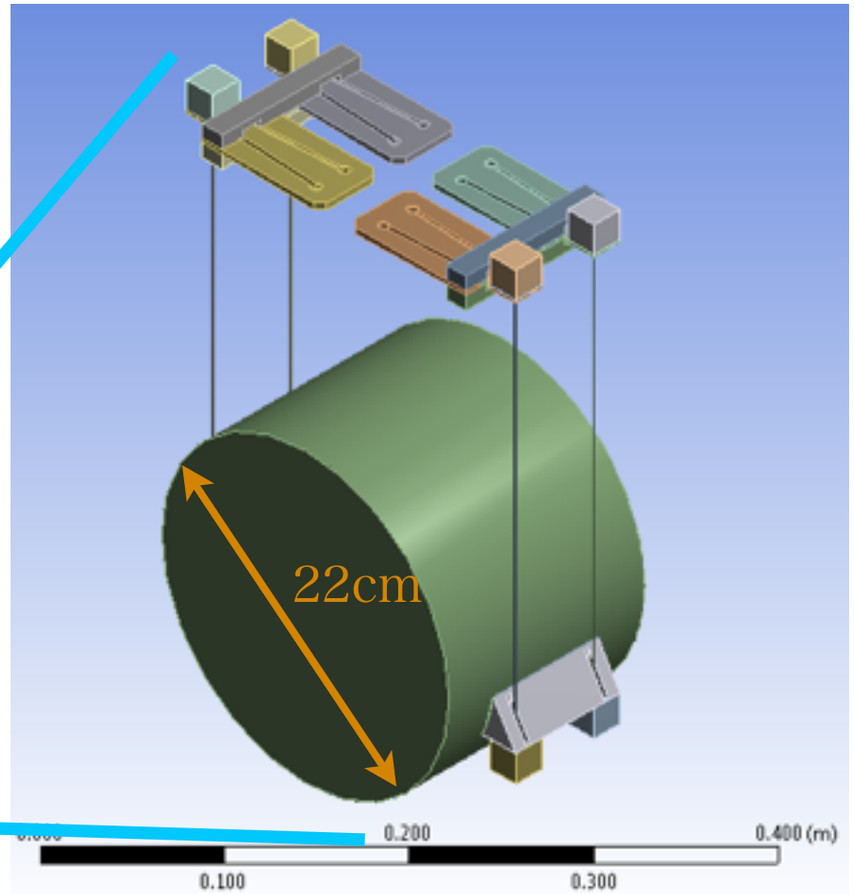
○ main mirror

Collaboration with INFN,
Jena, Glasgow, KEK...

Cryogenic suspension



Cryogenic sapphire suspension



1.We designed a sapphire suspension system. Thermal noise, mirror temperature and strength are acceptable.

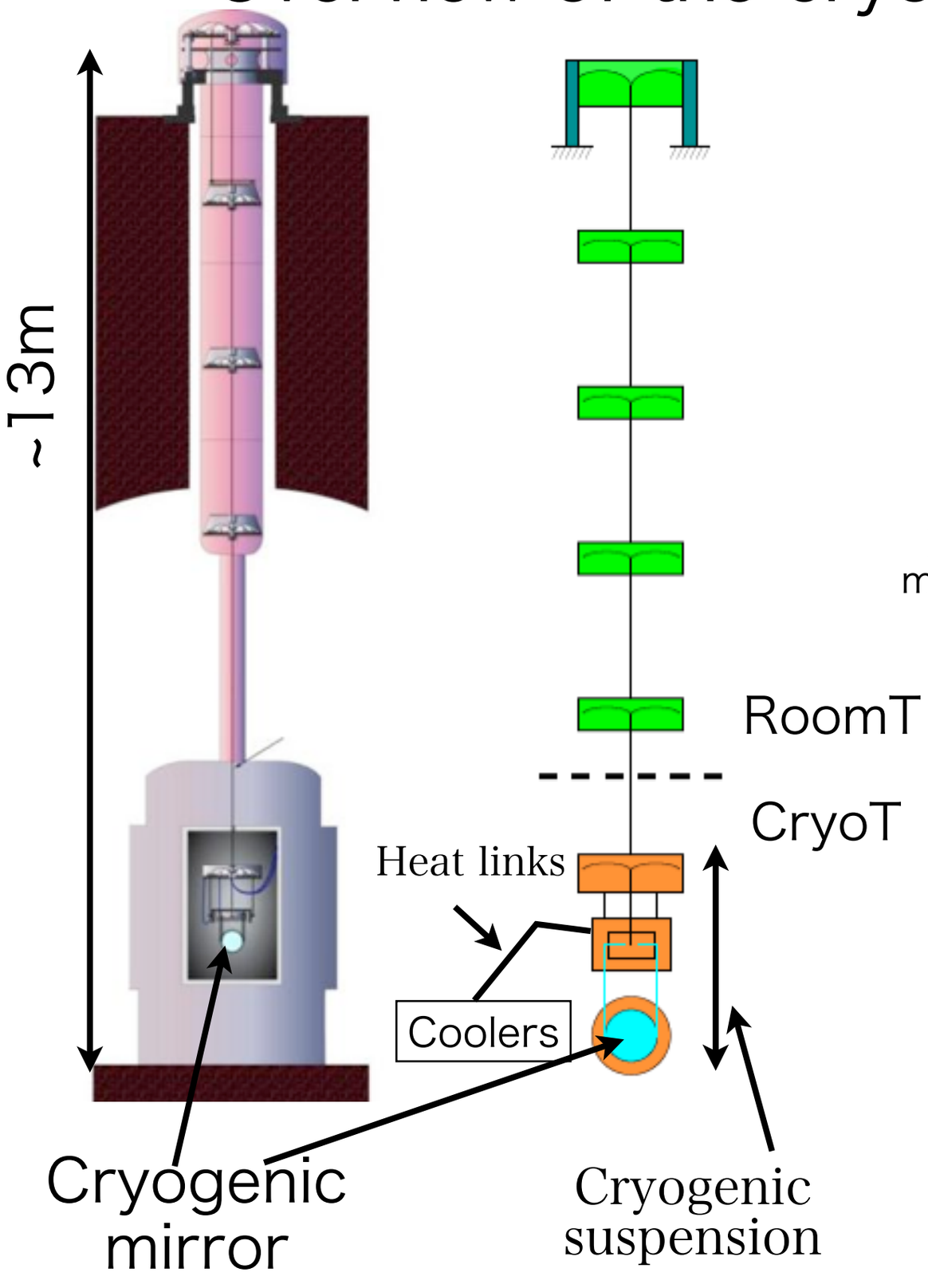
2.The vibration noise from the cooling system can be suppressed under the KAGRA design sensitivity.

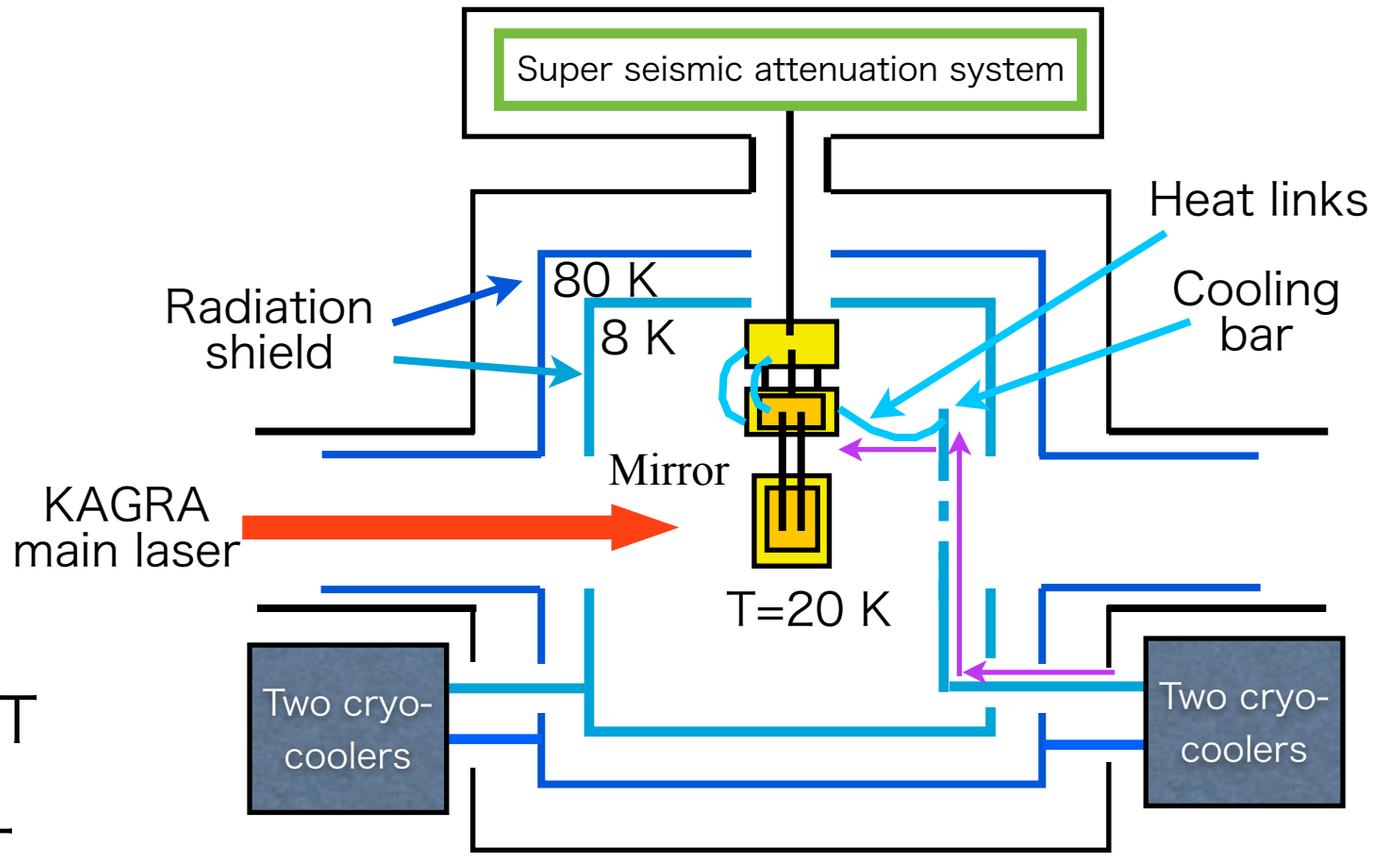
Contents

Contents

KAGRA cryogenic suspension

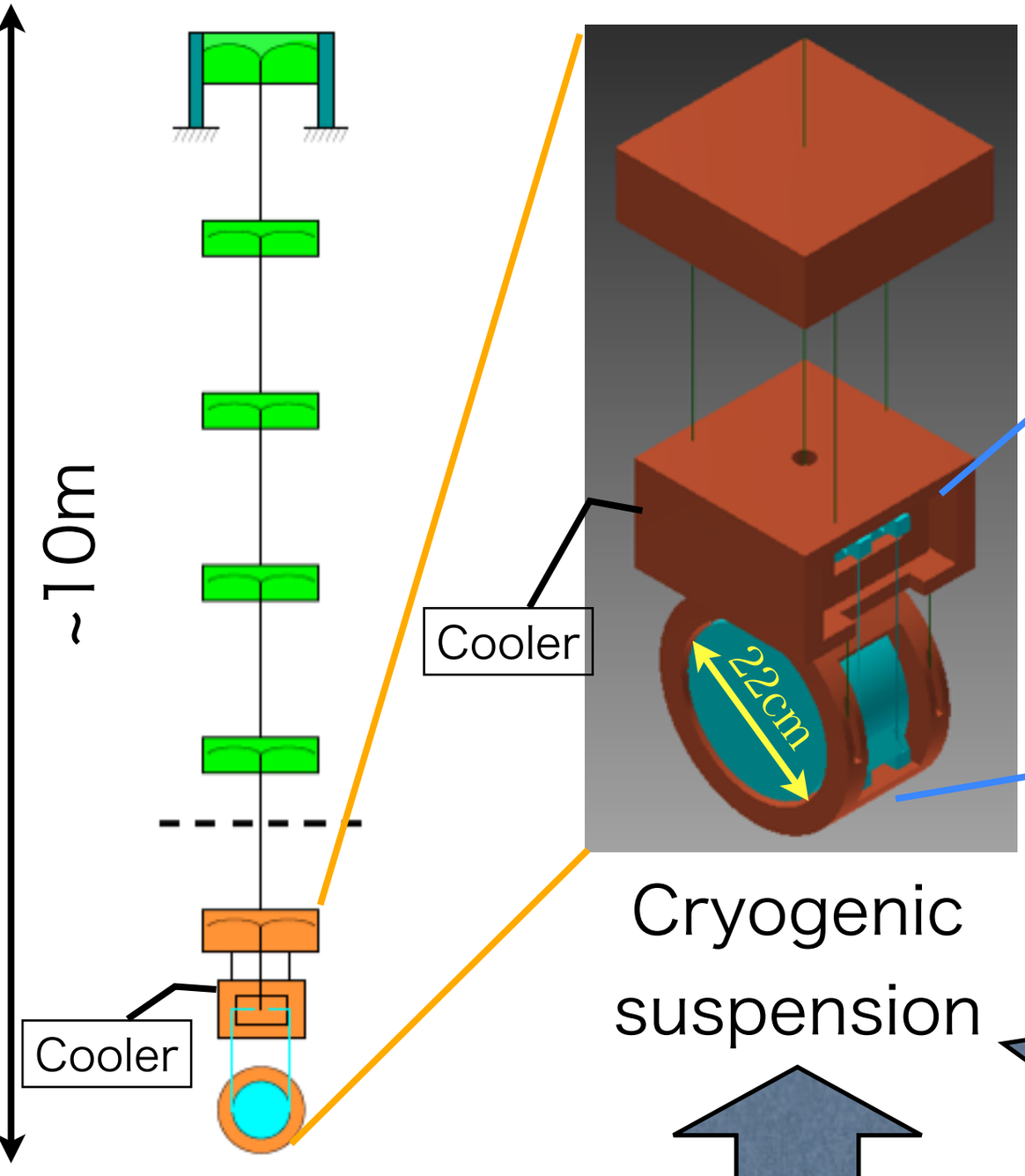
- Overview of the cryogenic suspension system -





The cryogenic suspension and the radiation shield is connected by the heat links.

KAGRA cryogenic suspension

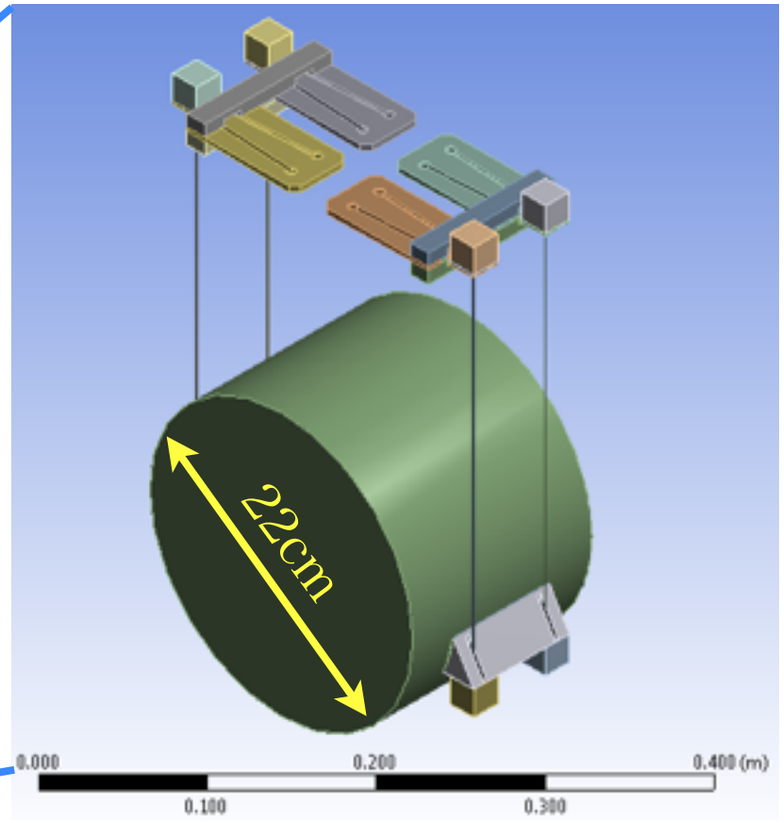


Cryogenic suspension

Estimation of the influence from cooling.

Sapphire at lowT:
Low loss
High conductivity

Mirror control
Vibration isolation



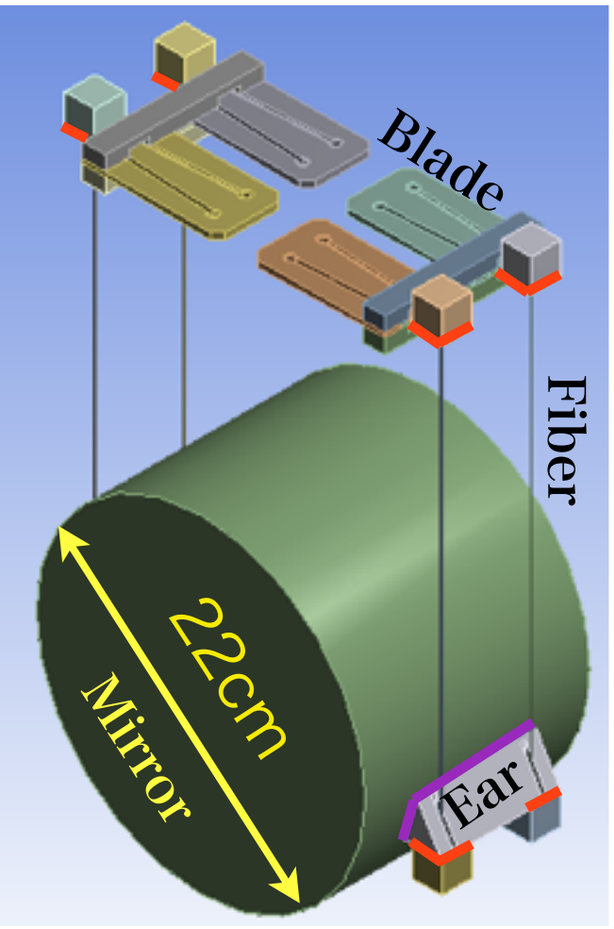
Cryogenic sapphire suspension

Design and component tests

We need to suppress the thermal noise.

Overview of the cryogenic suspension

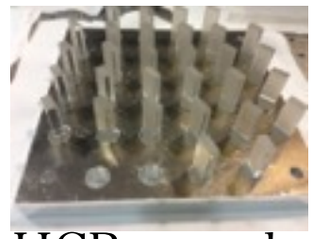
Suspend the mirror under low temperature and low thermal noise



Indium bonding
Hydroxide catalysis bonding

★**Hydroxide Catalysis Bonding (HCB) 60nm**

- ✦Strong chemical bonding (Na_2SiO_3)
- ✦Technique used also in satellites (e.g. Gravity Probe B)
- ✦High pressure and temperature are not necessary

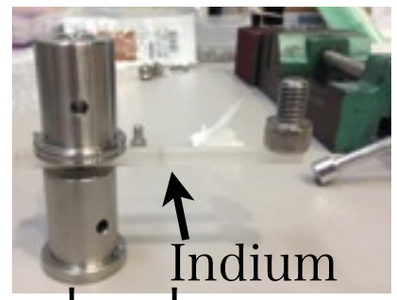


HCB sample

★**Ear**

★**Indium Bonding (InB) 1um**

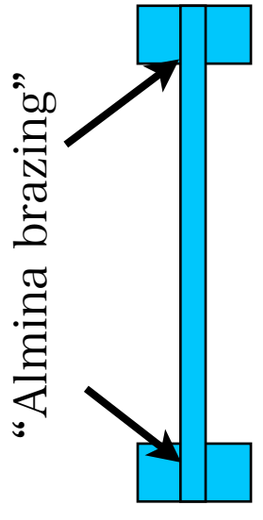
- ✦We can detach this when the fiber or blade are broken



★**Fiber ϕ1.6mm, L300mm**

- ✦Two heads are connected using alumina brazing
- ✦Suspend the mirror
- ✦Keep the mirror temperature

Test fiber
(Made by Impex)



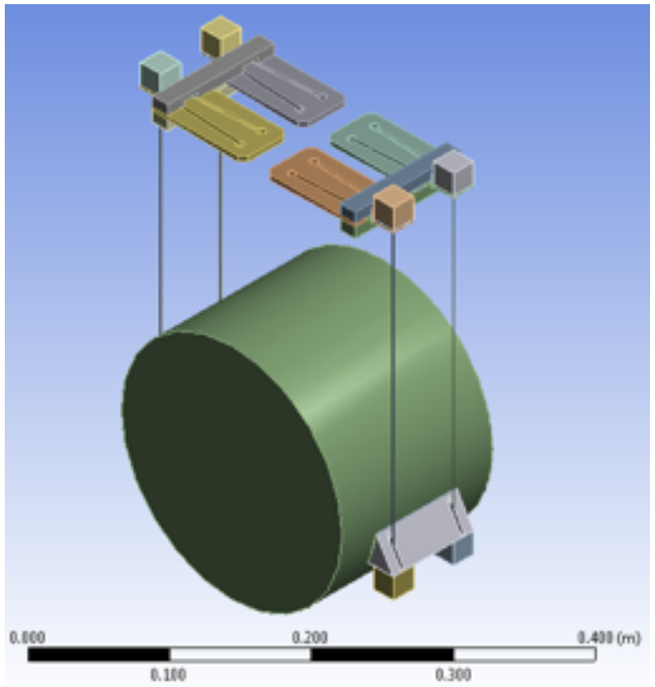
★**Blade**

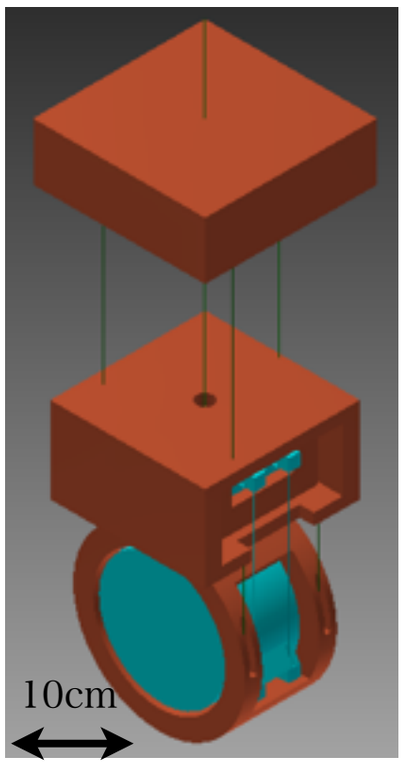
- ✦Cancel the length difference of the fibers

Blade(made by Shinkoshya)

参照: http://www.gravity.ircs.titech.ac.jp/GWADW2014/slide/Rahul_Kumar.pdf

Overview of the cryogenic suspension





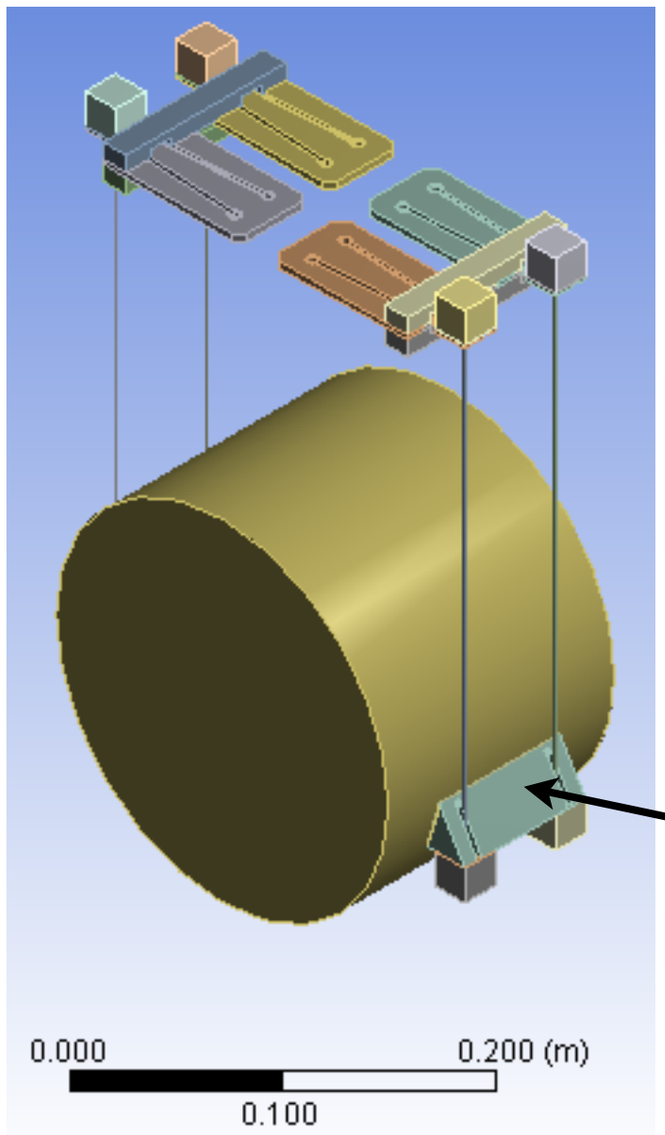
What we want to report

- ★Cryogenic sapphire suspension
  - ✦Design
  - ✦Strength test
    - (Fiber←performed by Glasgow and Roma team)
    - HCB
  - ✦Mechanical loss measurement
    - Fiber
    - Indium bonding
  - ✦Thermal conductivity measurement
    - Fiber
    - Indium bonding
    - HCB
- ★Vibration from the cooling system

All of the parts should satisfy all of the requirements.
Otherwise the design should be adjusted.

Contents

Sapphire suspension
- Design -



Cryogenic sapphire suspension

Design of the cryogenic sapphire suspension:

- For low thermal noise, energy density of each points should be small.
- Bending length: coupling of the tilt and longitudinal movement.
- Keep the violin mode away from the source frequency.
- Keep the temperature of the mirror during operation.

etc

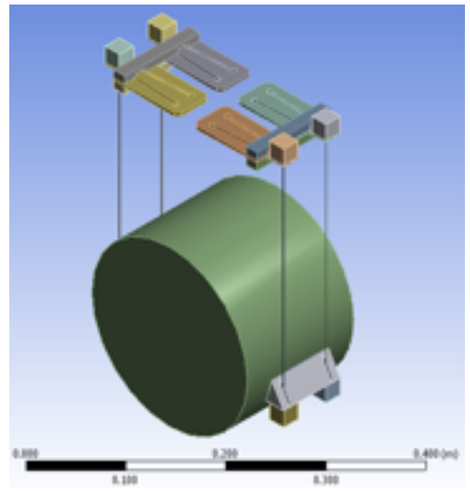
Example:

In order to reduce the thermal noise from HCB, the mass of the ears is reduced as possible.
The ears are attached on the low sides.

Contents

Sapphire suspension requirement

- Strength -



Fiber:

Weight suspended by a fiber:

5.7kg

Strength test
(Glasgow and Rome group)

Samples were 10cm fibers.

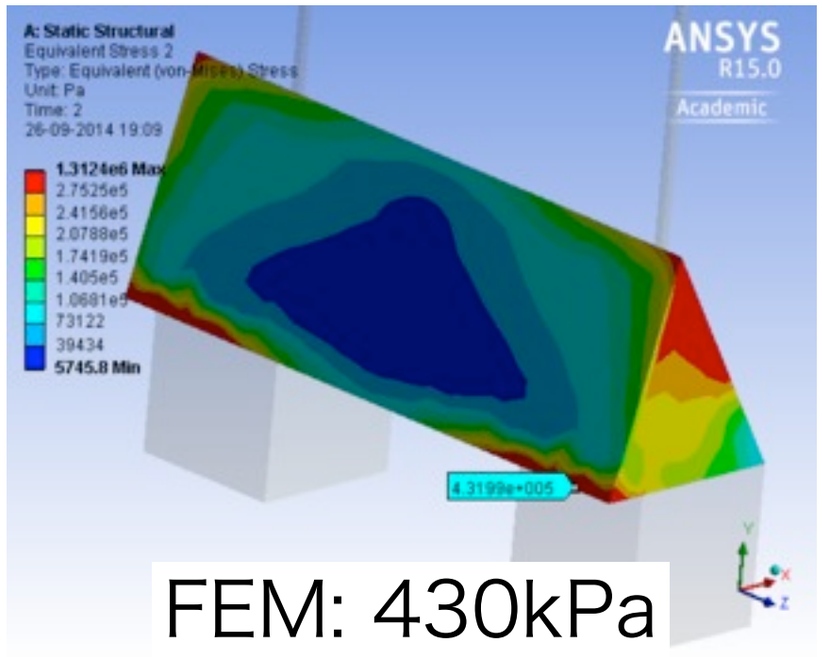
Weight:15kg

Amp:5-7mm

Fibers
survived

HCB:

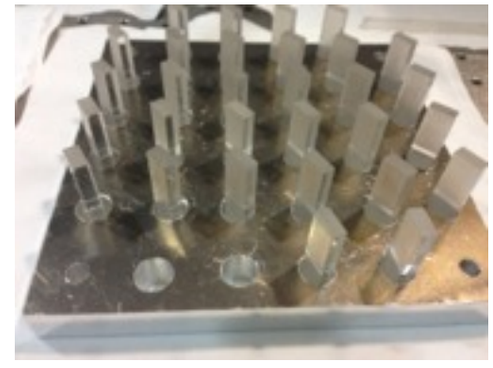
Stress on the bond surface

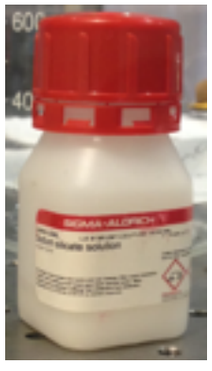


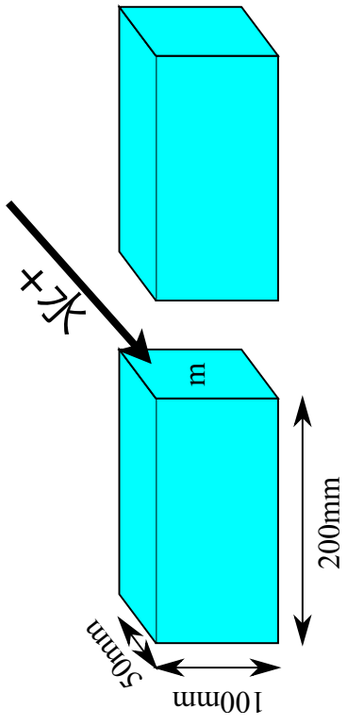
FEM: 430kPa

Requirement for HCB: 1MPa

Strength test
- HCB sample -







Strength tests were performed after thermal cycles.

After cleaning of the surfaces, the solution ($Na_2O(SiO_2)_x \cdot xH_2O$) was put between the sapphires.

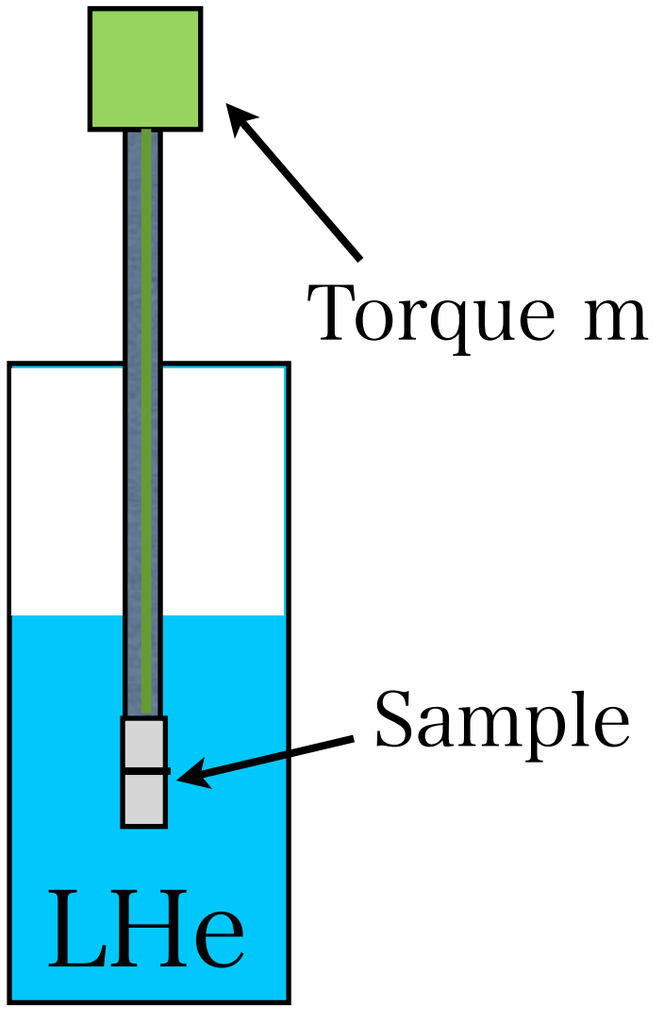
Curing time is 4 weeks at least.

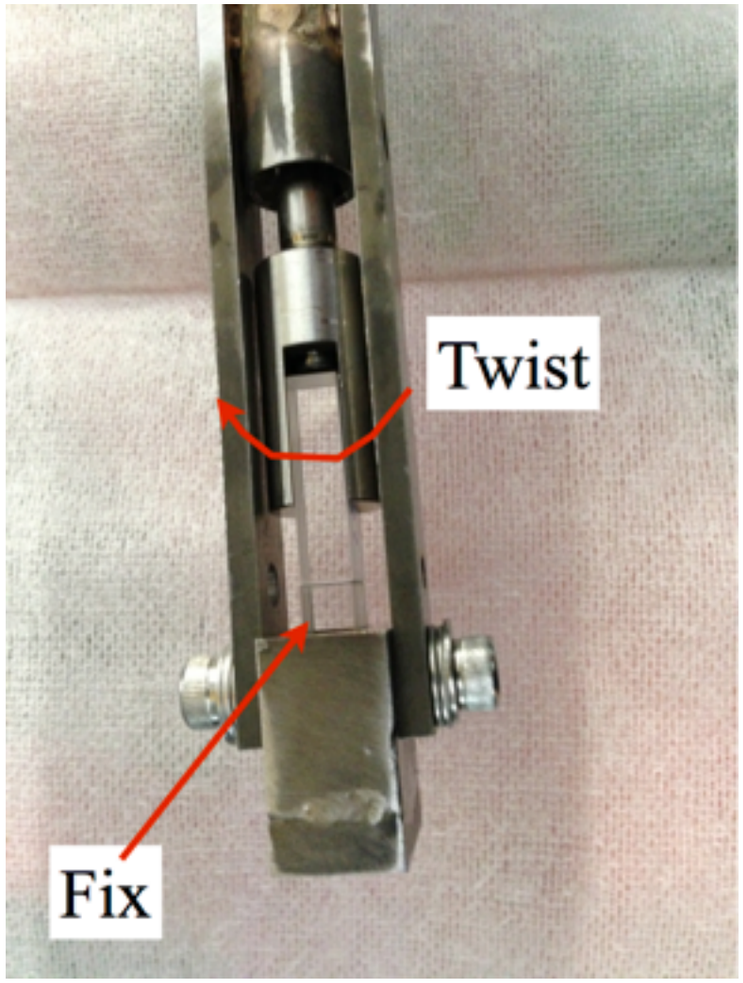
Thermal cycle (Room T ⇄ 20K)	200°C experience (30min) after cycles	No 200°C experience
0	3 sets	7 sets
10	2 sets	8 sets
20	2 sets	8 sets

200℃ is the temperature which doesn't affect the coating.

Strength test
- HCB experiment setup -

@KEK

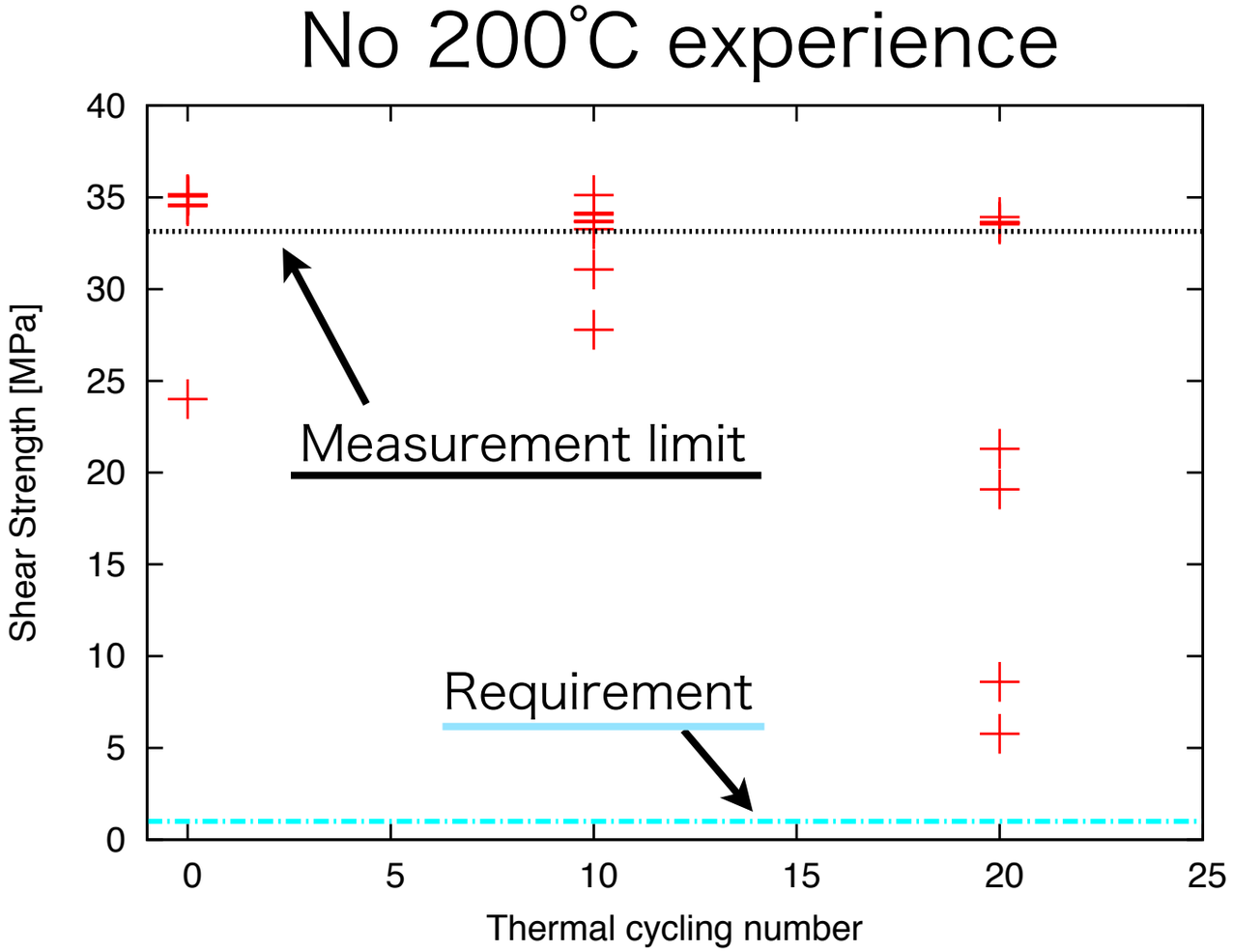


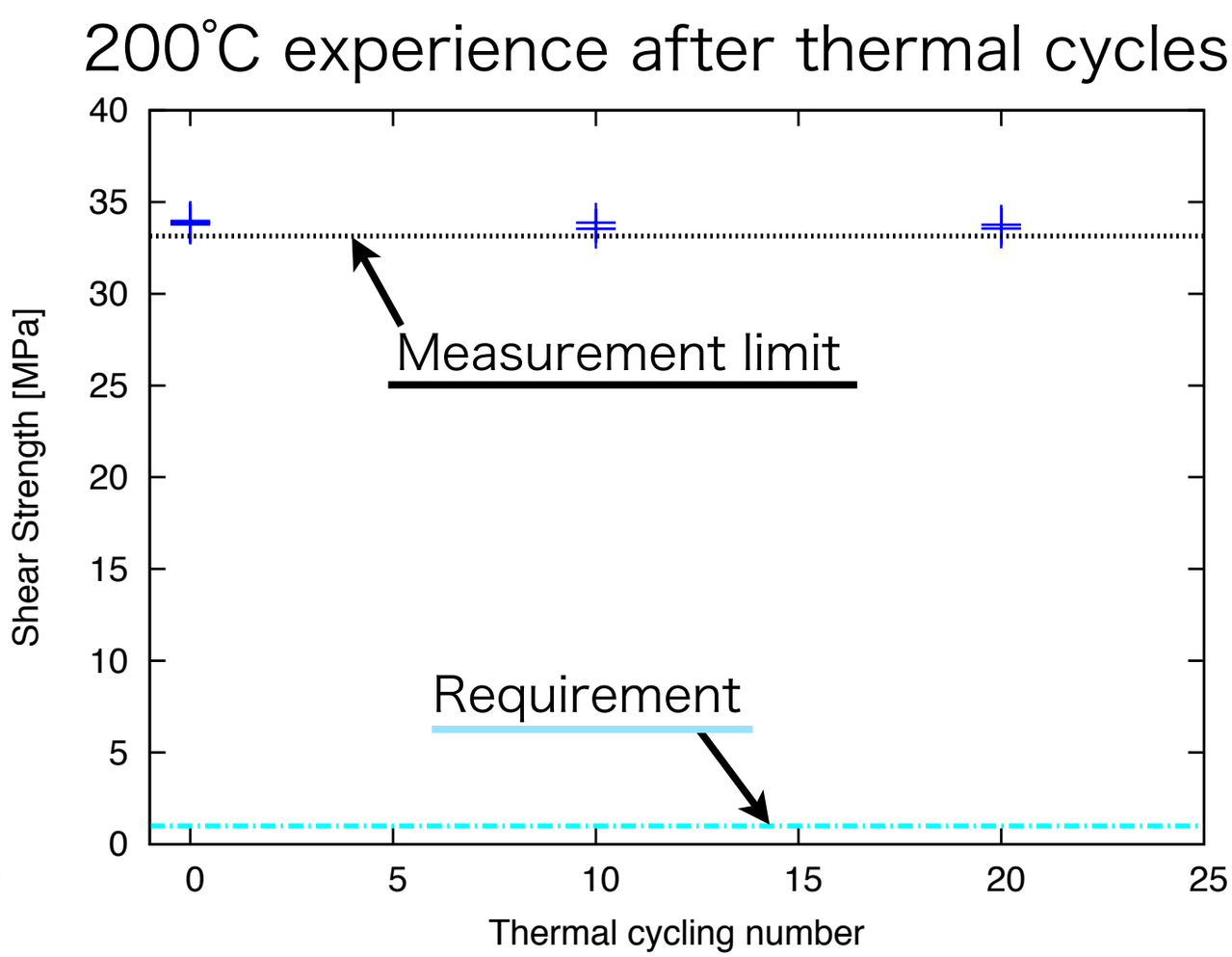


The tests were performed in liquid helium.

One sapphire was fixed, the other sapphire was twisted by know torque.
Experiment limit: 33MPa

Strength test
- HCB result -





All of the 200°C experience samples were over the measurement limit

⇒ Heating can enhanced the strength

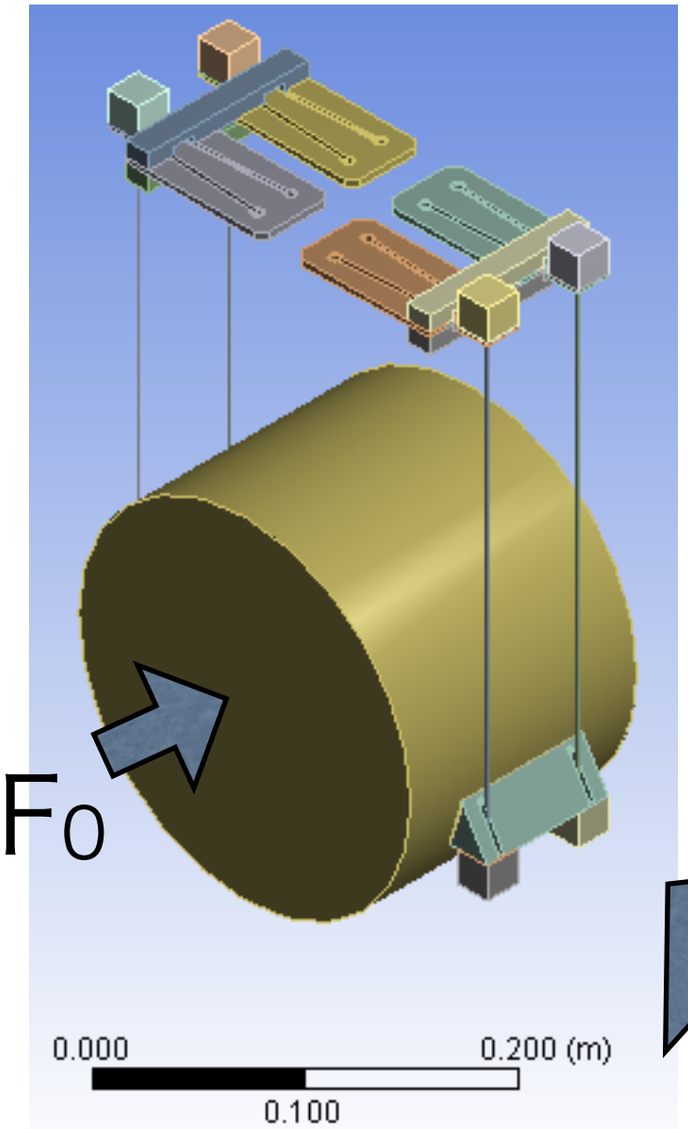
Even the strength changed by the thermal cycles, all of the samples had enough strength

Contents

Sapphire suspension requirement
- Thermal noise -

Calculation by the Levin's method.

Yu. Levin PRD (1998) **57** 659



Thermal noise:

$$x^2(f) = \frac{2k_B T}{\pi^2 f^2} \frac{W_{\mathrm{diss}}}{F_0^2}$$

$$W_{diss} = 2\pi f \int u(\vec{r})\phi(\vec{r})\mathrm{d}V$$

Mechanical loss:

We need measure.

Elastic energy density at each points ← FEM

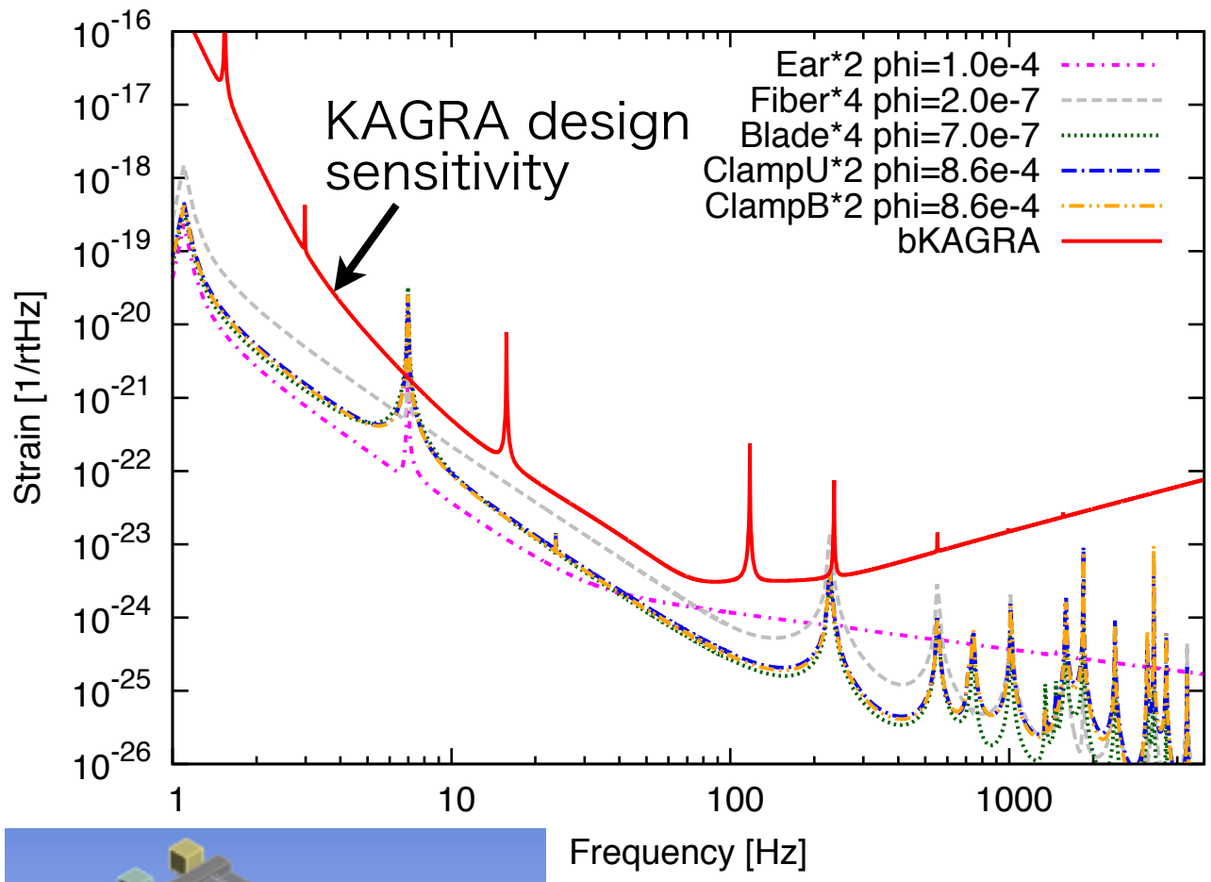
Design it as low energy density as possible.

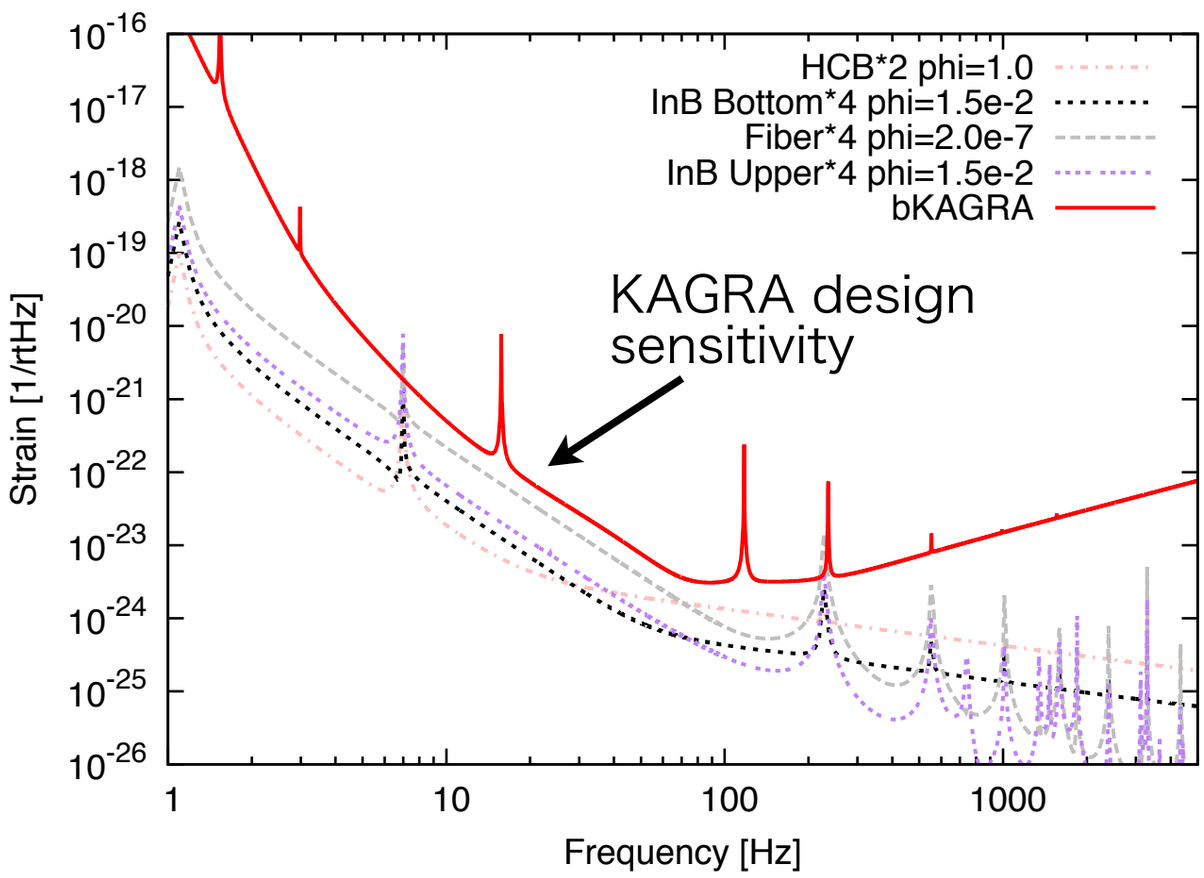
We can calculate the influence on the thermal noise from each parts.
The requirement of mechanical loss can be calculated.

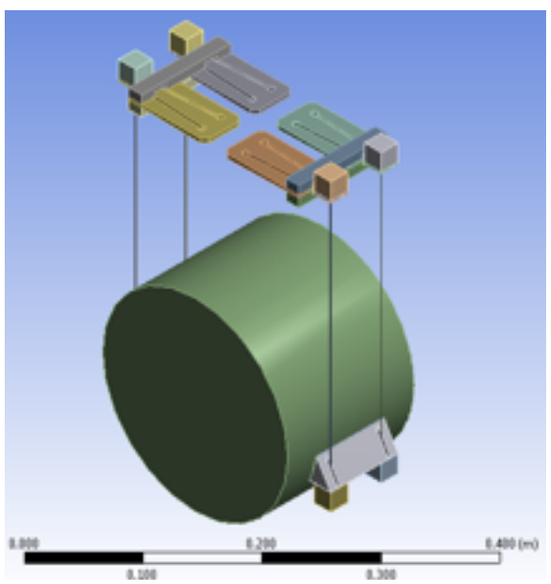
Sapphire suspension requirement

- Thermal noise -

Basically, the requirements of the thermal noise from each parts are set to be half as low as the KAGRA design sensitivity. At the low frequency region, because the thermal noises from the fibers are expected as high as the requirement, the thermal noises from other parts are set to be one-third as low as the fiber requirement.







Component	Req of loss
Fiber	2.0×10^{-7}
Indium bonding (1 μm)	1.5×10^{-2}
HCB (60nm)	1.0

Other sapphire parts should be satisfiable.
(The loss of sapphire bulk is 4×10^{-9} at low T.)

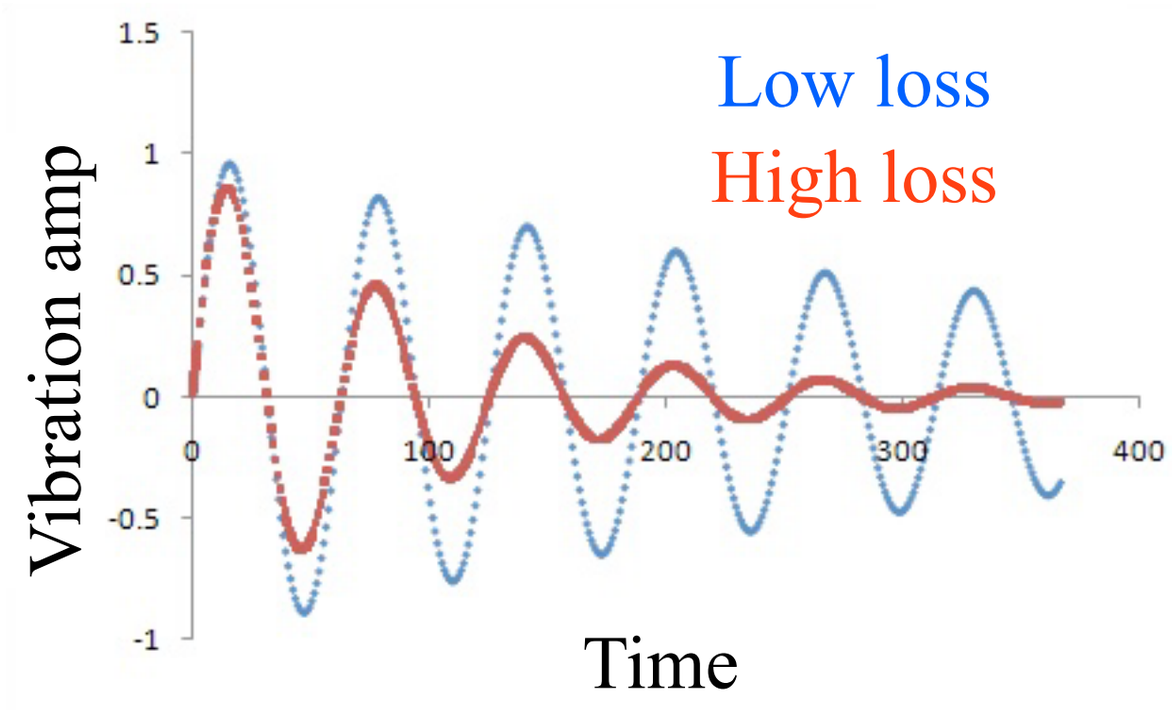
Mechanical loss measurement

- Measurement principle -

Decay line measurement

Mechanical loss

$$f(t) = A\sin(2\pi f_0 t)e^{-\pi f_0 \phi t}$$

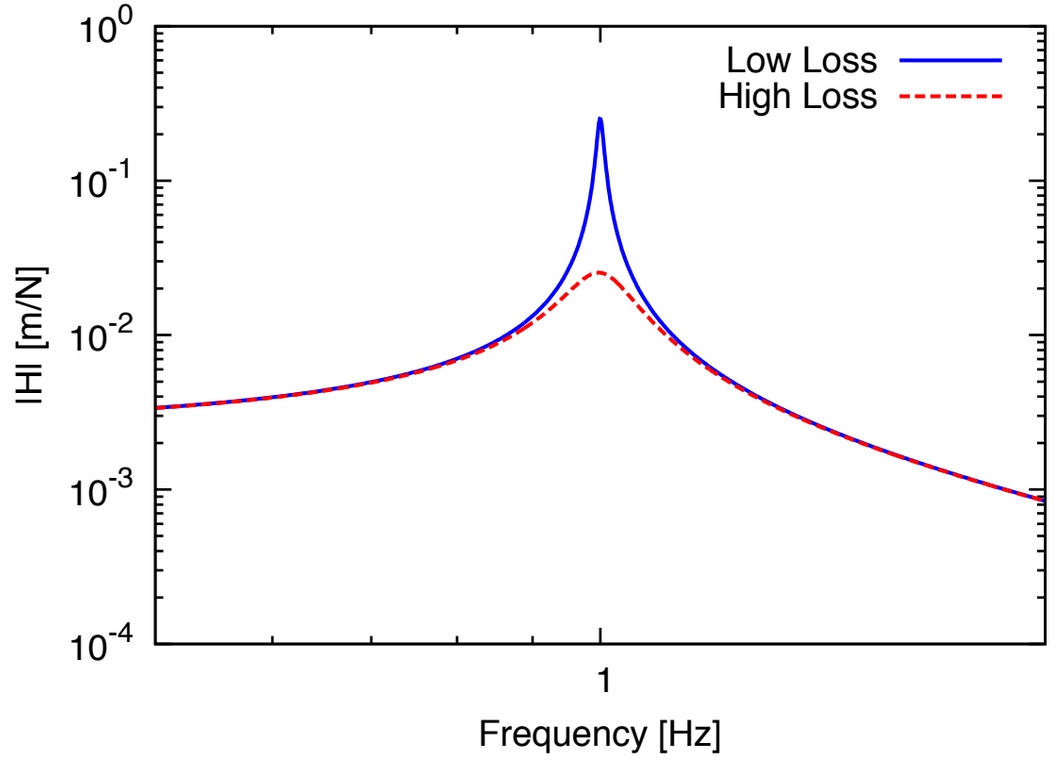


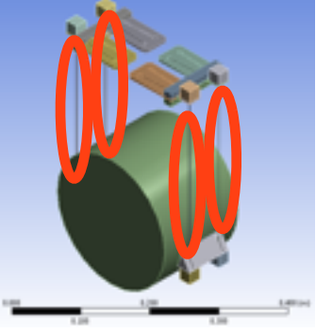
Spectrum measurement

Mechanical loss

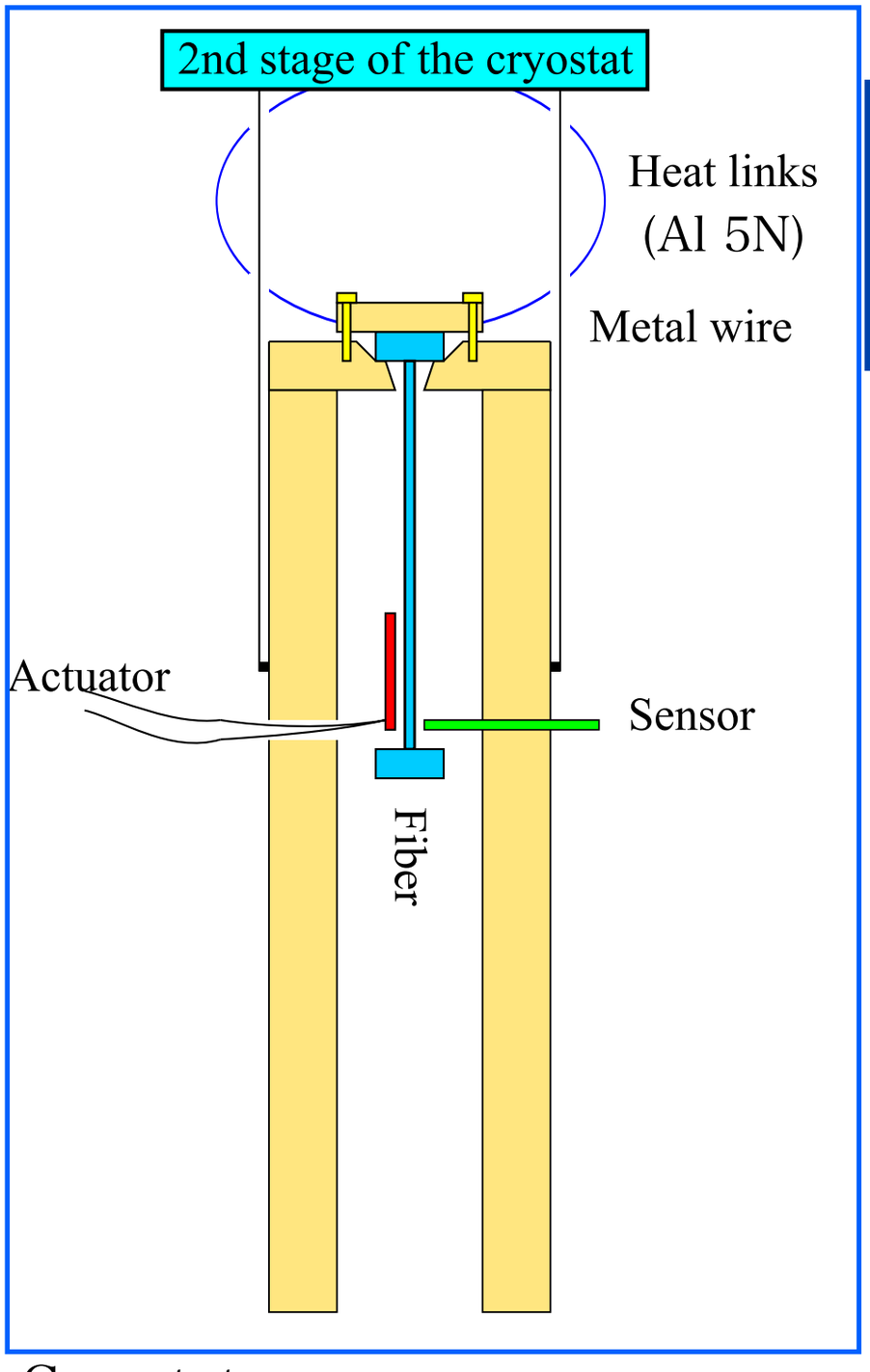
$$\Delta\omega_0 = \omega_0\phi$$

$$\left|H\left(\omega_0 \pm \frac{\Delta\omega_0}{2}\right)\right|^2 = \frac{|H(\omega_0)|^2}{2}$$

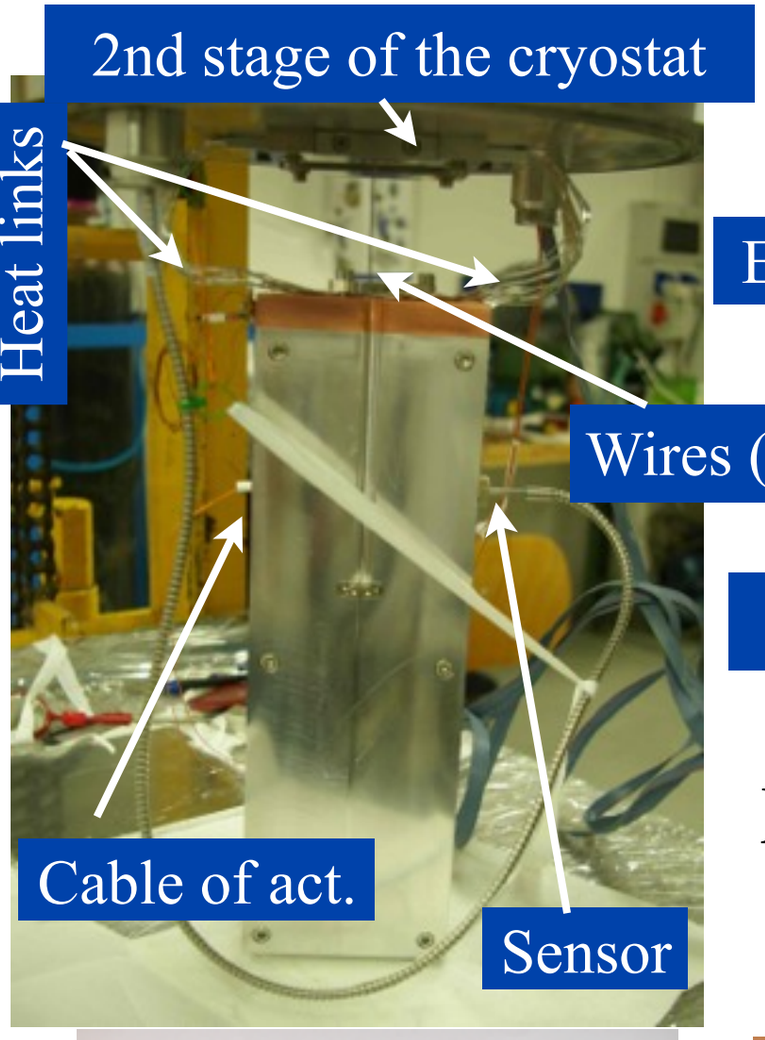


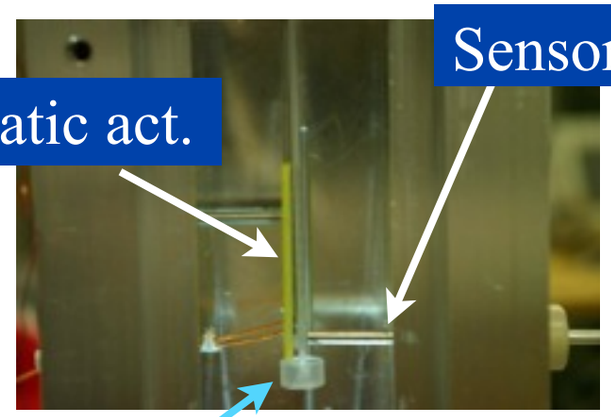


Mechanical loss measurement @Rome
- Measurement system of a fiber -

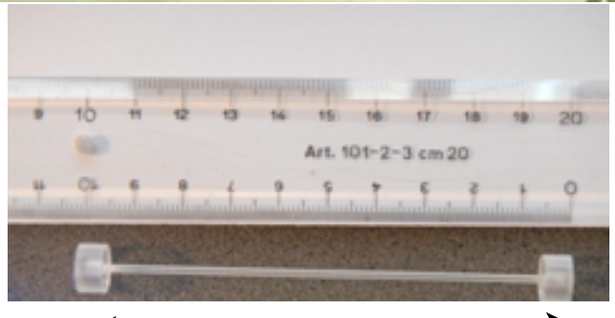


Cryostat
(Lowest T: ~15K)

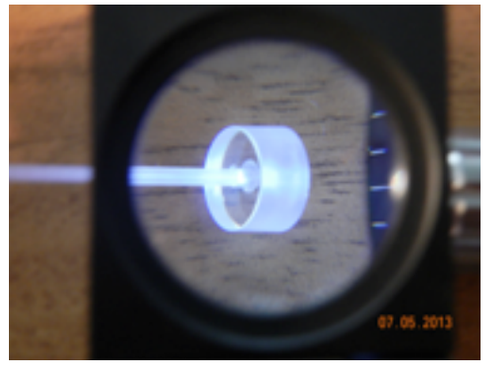




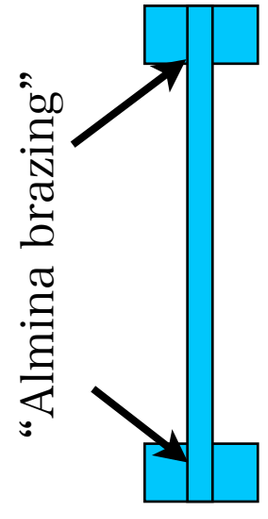
Actuation by a ES act.
Monitor the decay line
by a optical sensor.



~10cm
Fiber samples



Non-monolithic
Thermo-polish
HEM quality



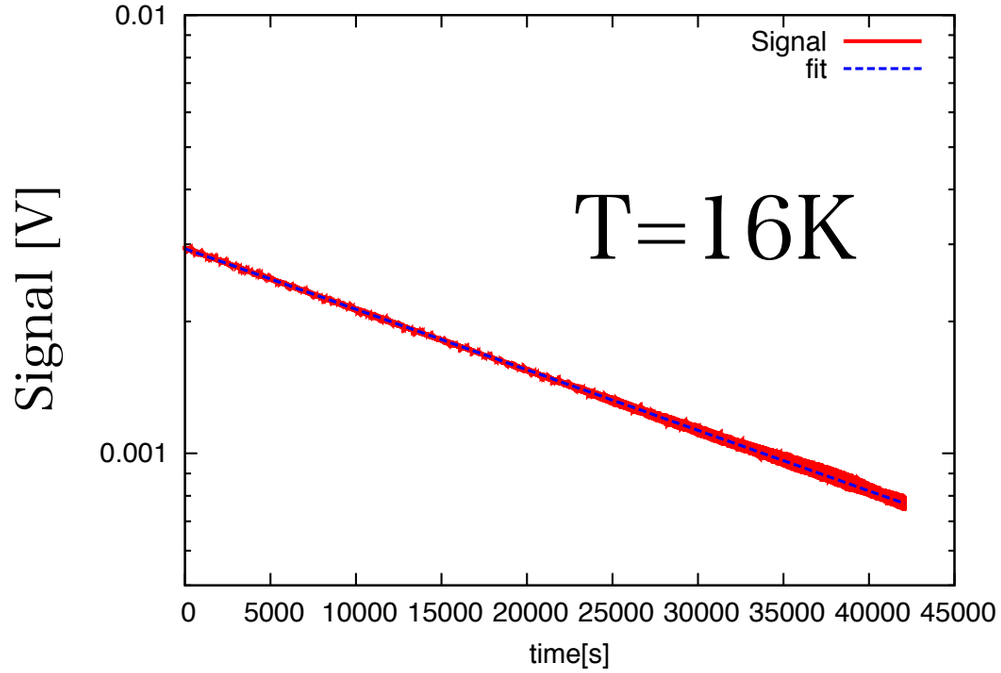
Mechanical loss measurement

- Result of fiber measurement -

Measured main mode

~90Hz

An example of decay line



Fitting result

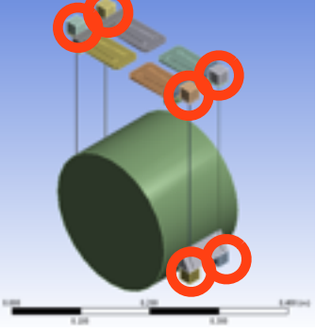
$$f(t) = \alpha e^{-\pi f_0 \phi t}$$

$\phi_{req} = 2.0 \times 10^{-7}$

Lower than the requirement

$$\phi = 1.1 \times 10^{-7} \quad (\mathrm{T=16K})$$

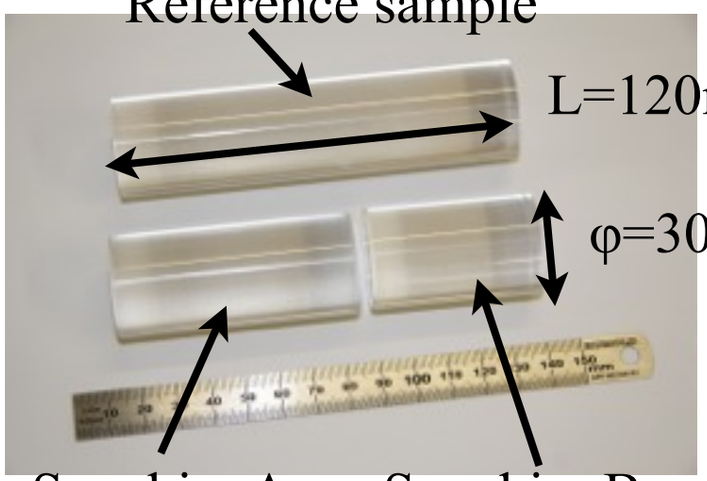
This fiber is suitable.

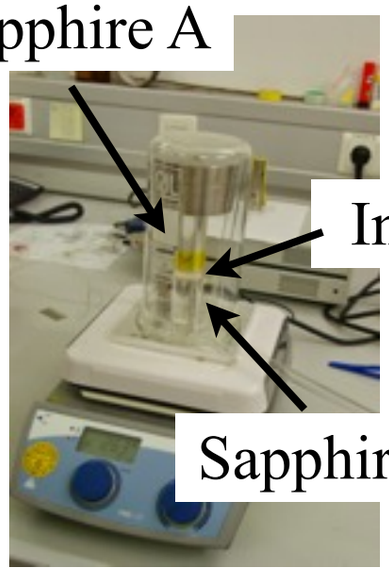


Mechanical loss measurement @Jena

- Indium bonding measurement setup -

Samples



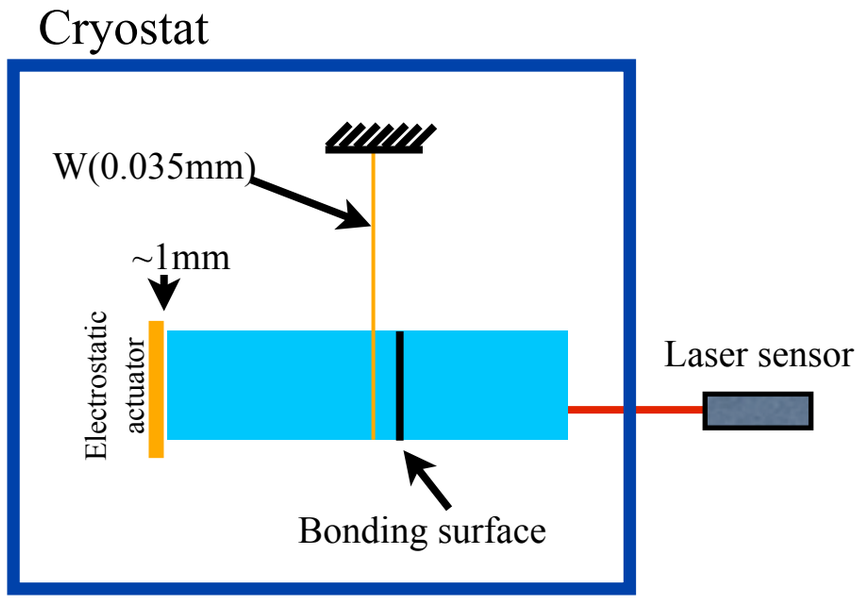


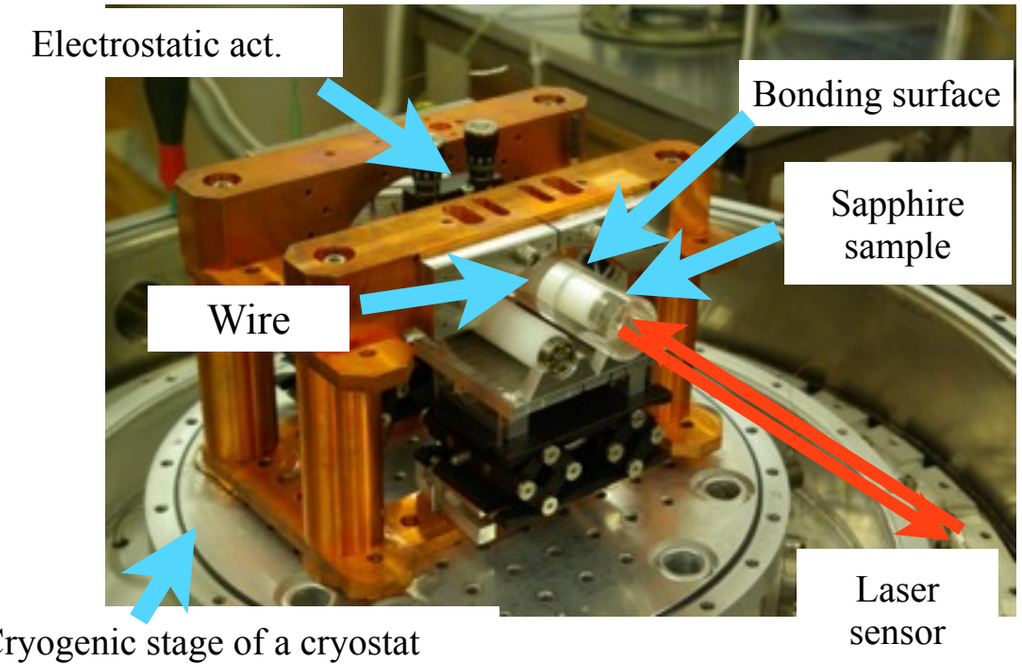
1.Clean the surfaces (H2SO4, HCl)
2.Evaporate indium on the surfaces(~300nm)
3.Insert an In foil between sapphires
4.Keep 200℃ for 3h

Measured thickness was ~10um

Thicker bonding is easier to be measured.

Measurement setup

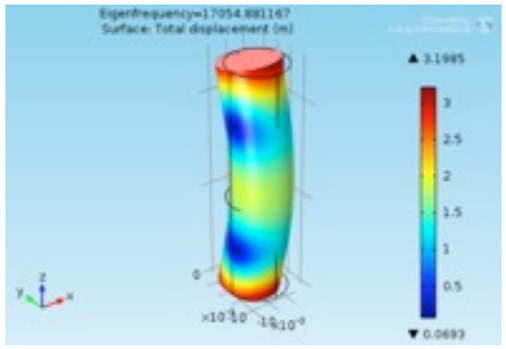




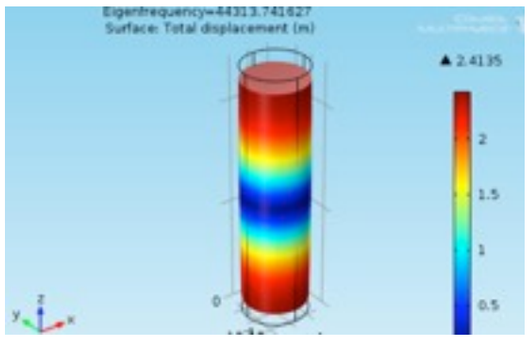
In order to calculate the loss of bond, we compared the reference sample and the bonded sample.

Mechanical loss measurement
- Measurement result of the indium bonding -

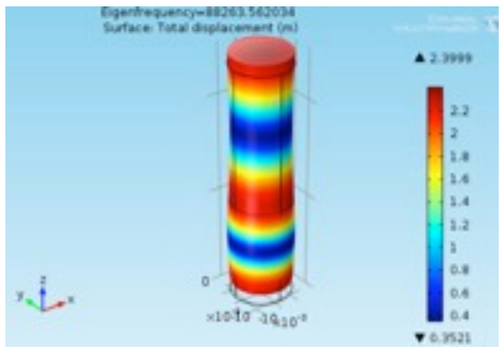
Measured mode



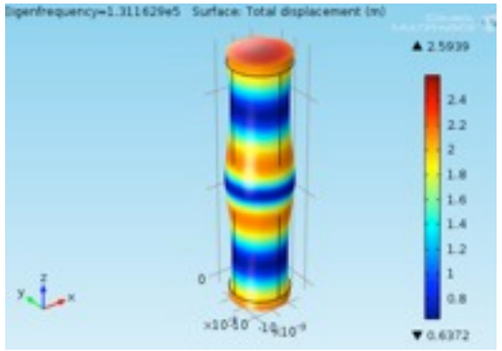
Mode1=17kHz



Mode2=44kHz

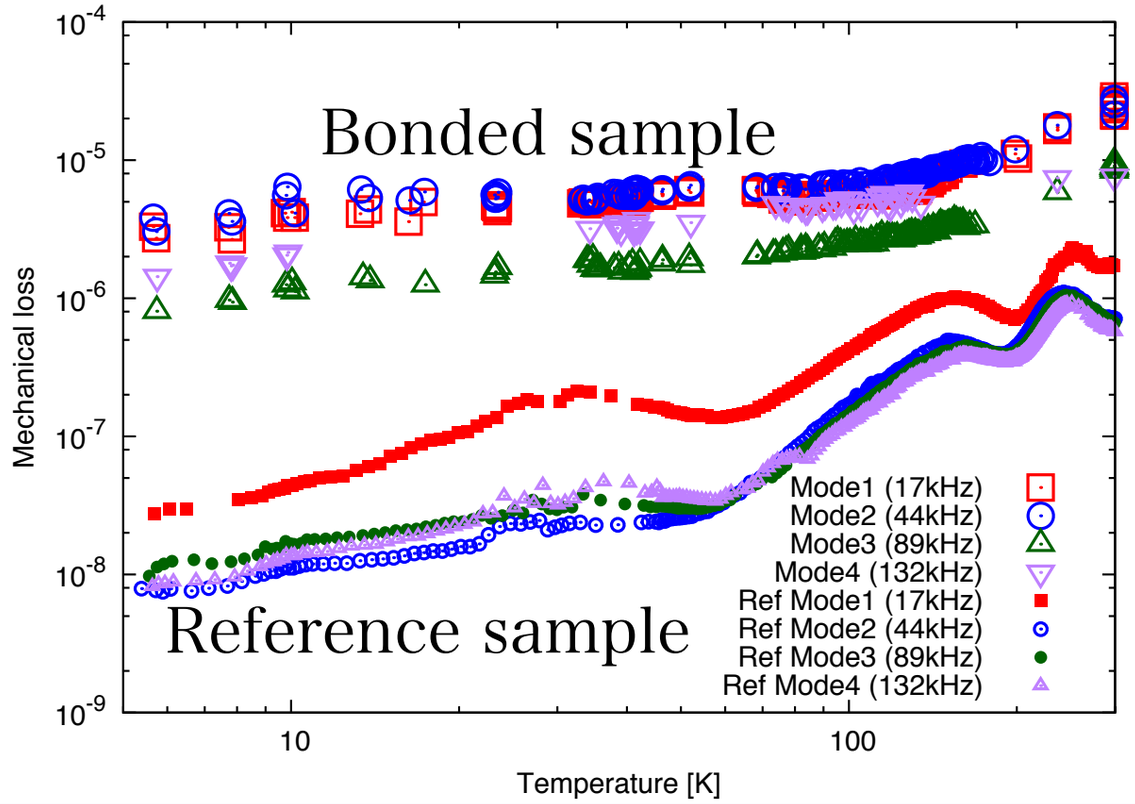


Mode3=89kHz

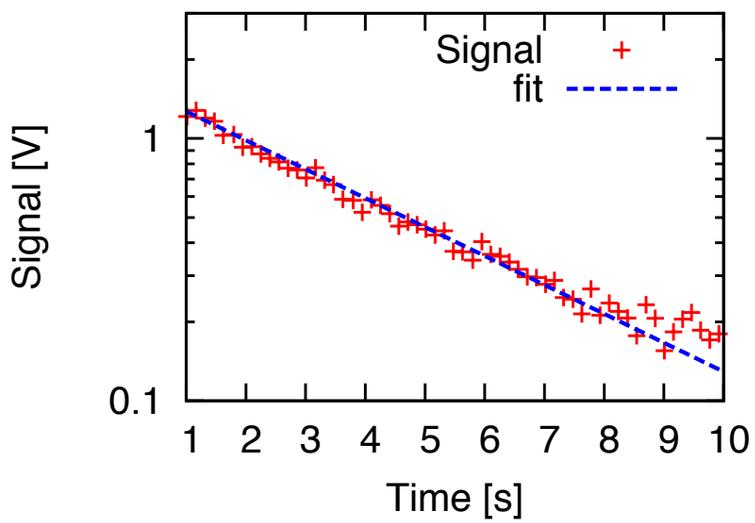


Mode4=132kHz

Measurement result



An example of a decay line



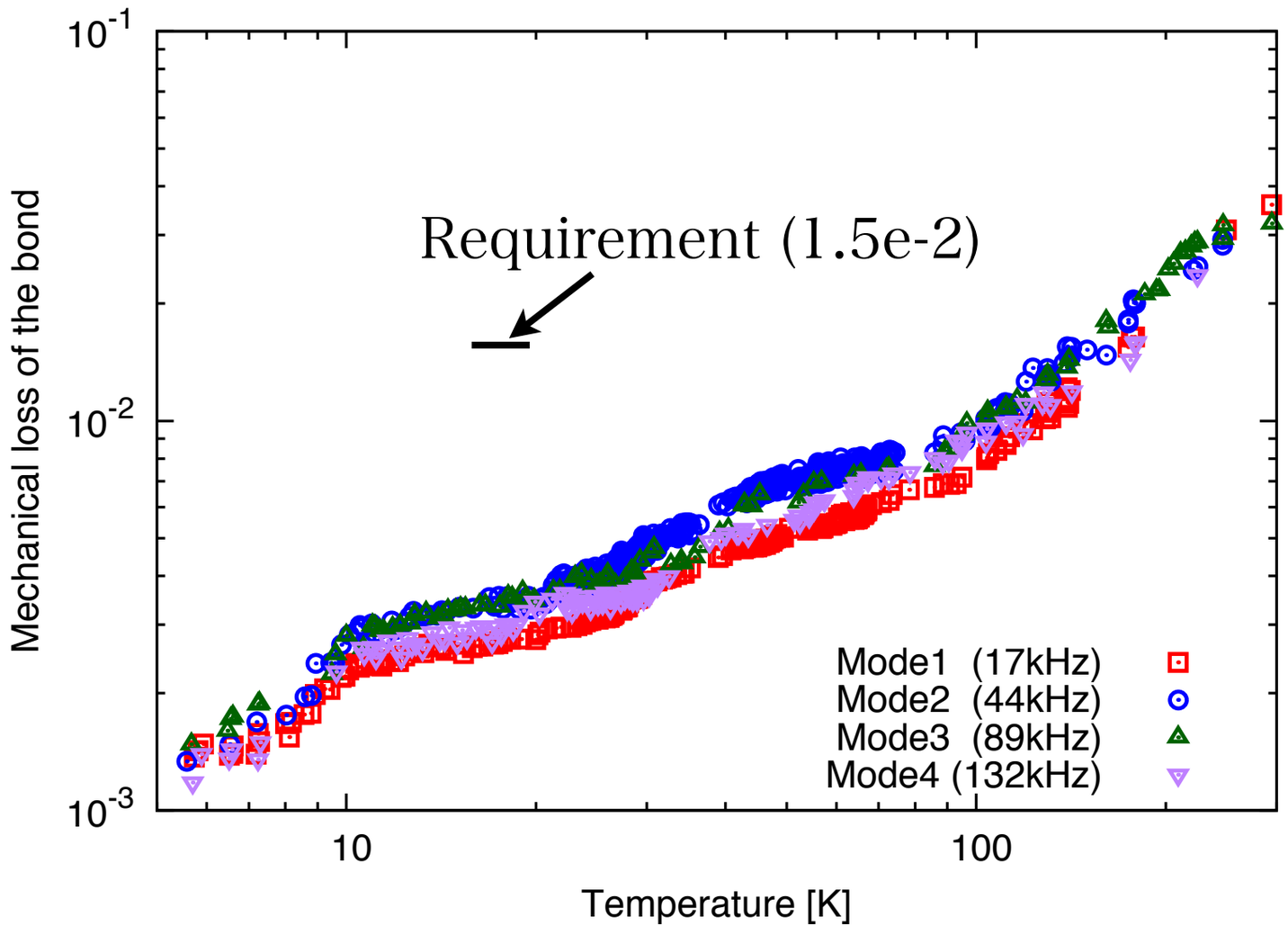
Calculation of the loss of bond

$$\phi_B \simeq \frac{E_{tot}}{E_B}\phi_{meas} \qquad \frac{E_B}{E_{tot}} << 1 \qquad \frac{\phi_{sub}}{\phi_{meas}} << 1$$

Measurement

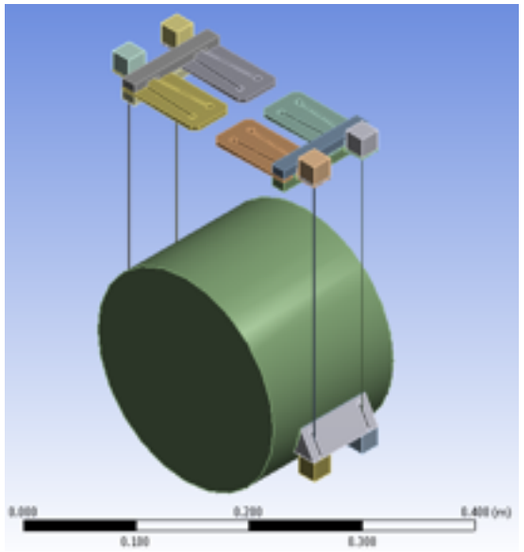
Calc by a FEM

Mechanical loss measurement
- Measurement result of the indium bonding -



Mechanical loss of the indium bonding was smaller than the requirement.

Contents

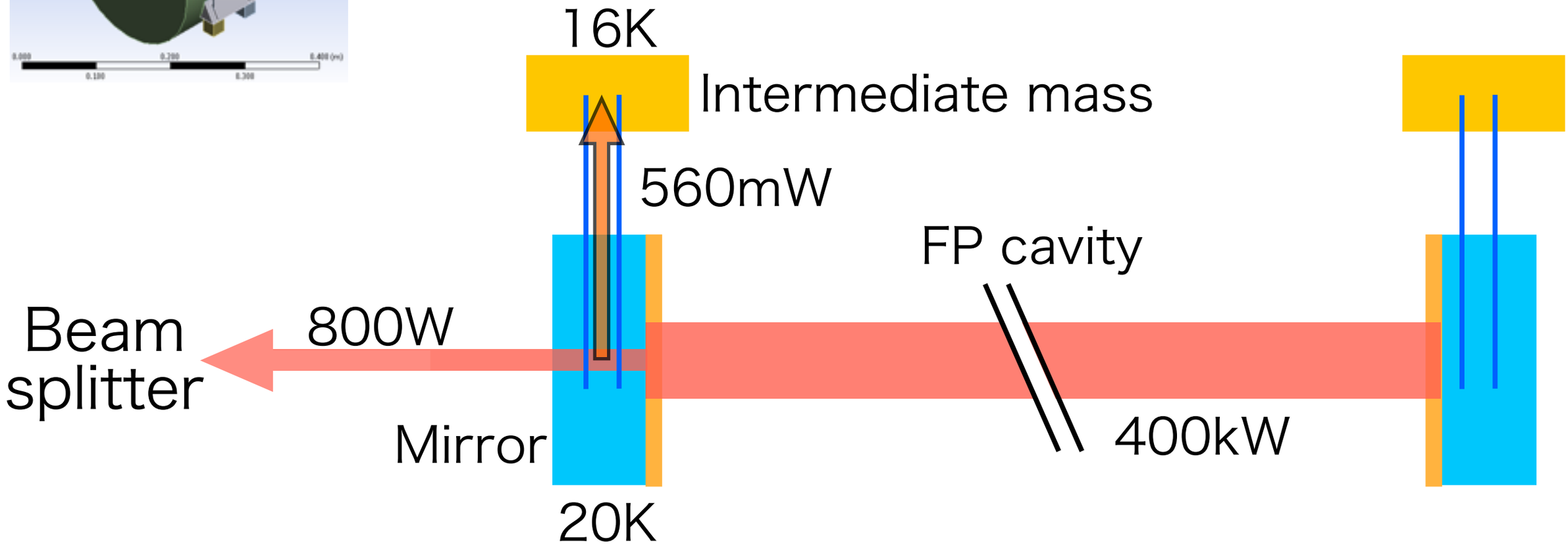


Sapphire suspension requirement

- Thermal conductivity -

The mirror will absorb 560mW during the interferometer operation.

This heat should be let loose into the IM otherwise T of the mirror would goes up.



Req of a fiber:

Keep the mirror at 20K.

Test for a fiber with almina brazing heads.

Req for the bonds:

Temperature gradient is lesser than 0.1K.

$$HCB : \alpha > 1000 W/m^2/K \quad (A = 48 cm^2)$$

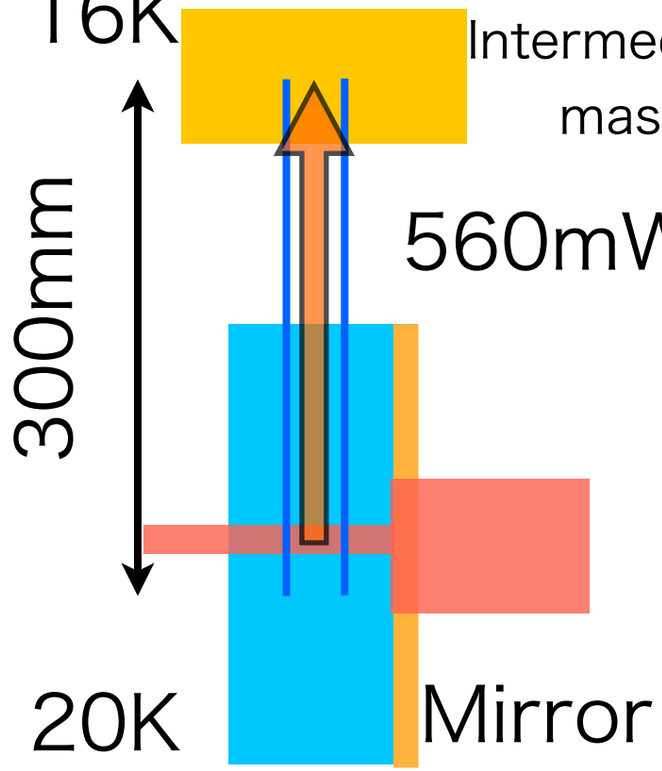
$$InB : \alpha > 3000 W/m^2/K \quad (A = 16 cm^2)$$

Heat-tranfer coefficient

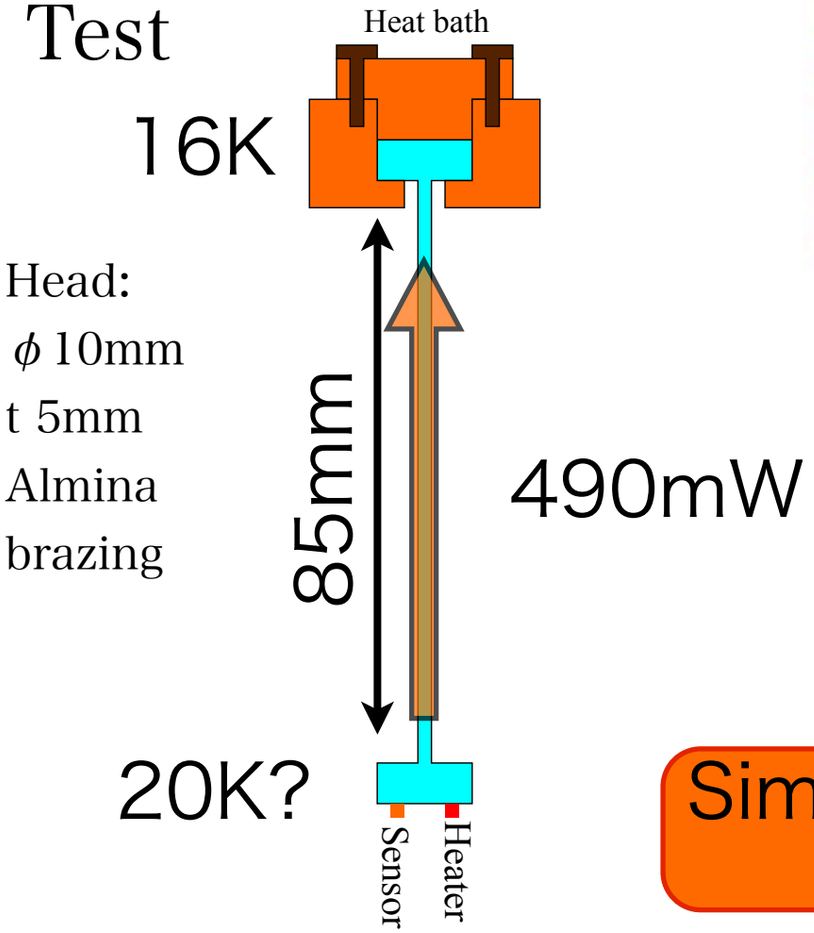
Heat extraction measurement

- Fiber -

KAGRA



Test

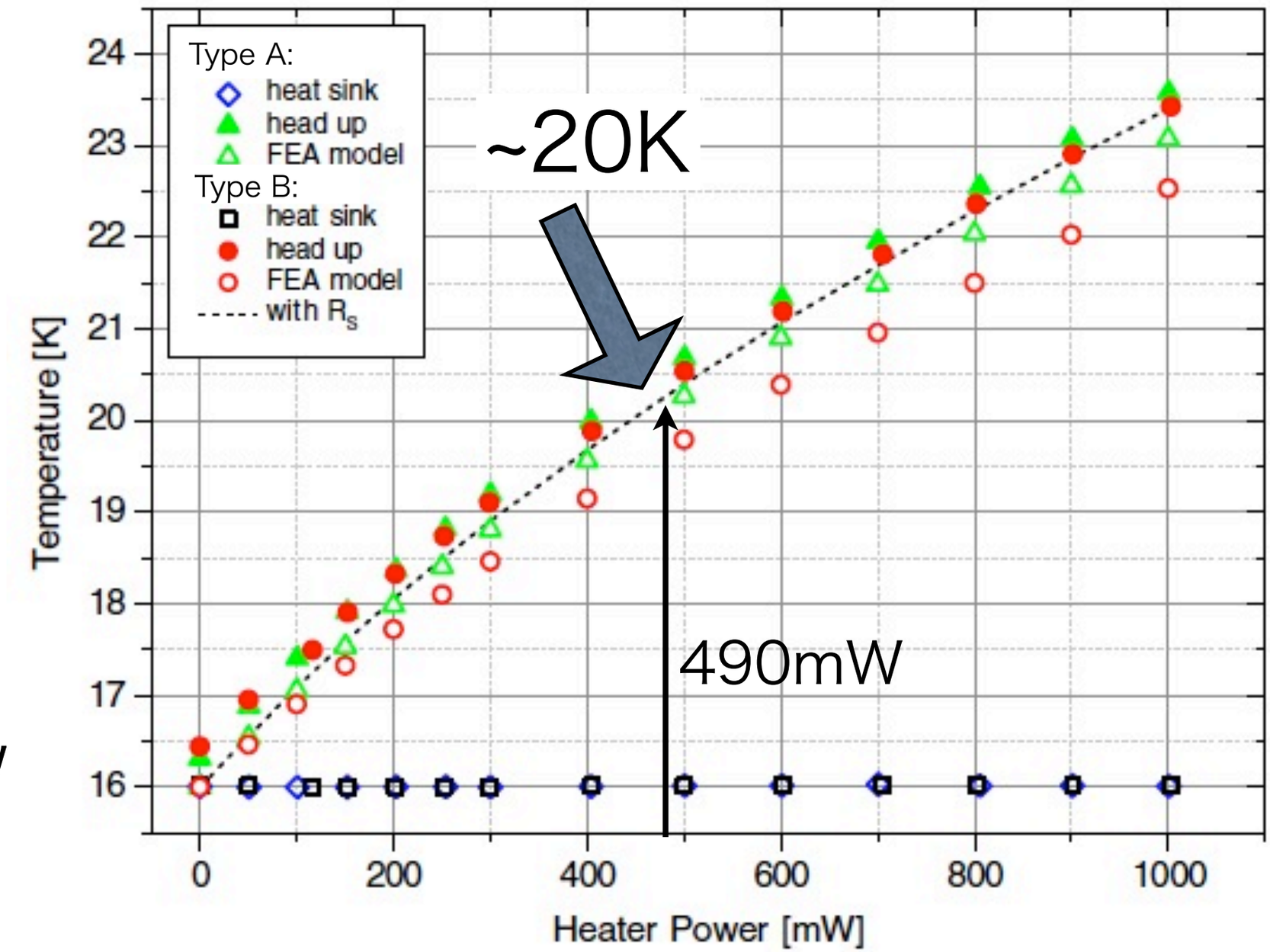


Evaluation of heat extraction through sapphire fibers for the GW observatory KAGRA

Class. Quantum Grav. **31** (2014) 105004 (11pp)

A Khalaidovski[1], G Hofmann[2], D Chen[1], J Komma[2], C Schwarz[2], C Tokoku[1], N Kimura[3], T Suzuki[3], A O Scheie[4], E Majorana[5], R Nawrodt[2] and K Yamamoto[1]

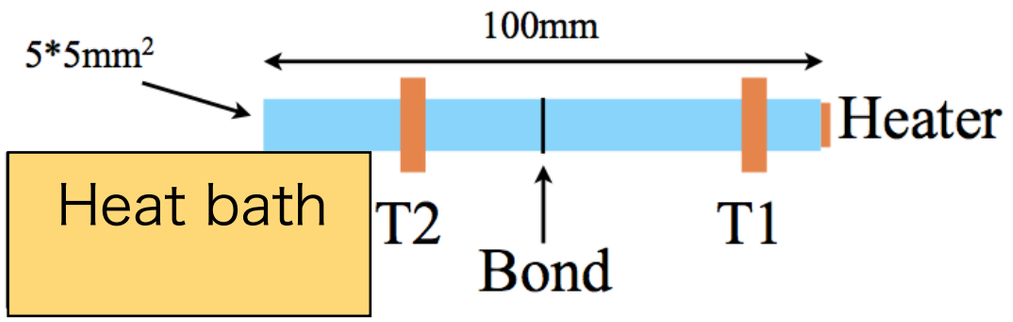
The same sample as the loss measurement



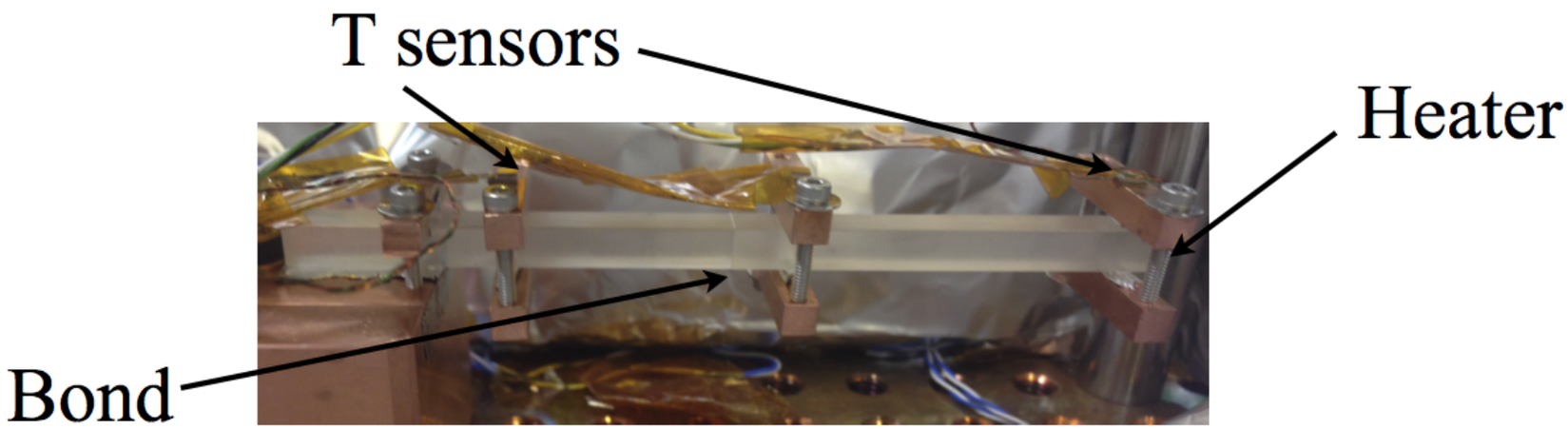
Simulate the same as KAGRA. In the result the fiber head was ~20K.

Heat transfer measurement

- Bonding sample -



Measure the heat transfer



$$\Delta P = A\alpha\Delta T$$

Applied heat

Temperature difference

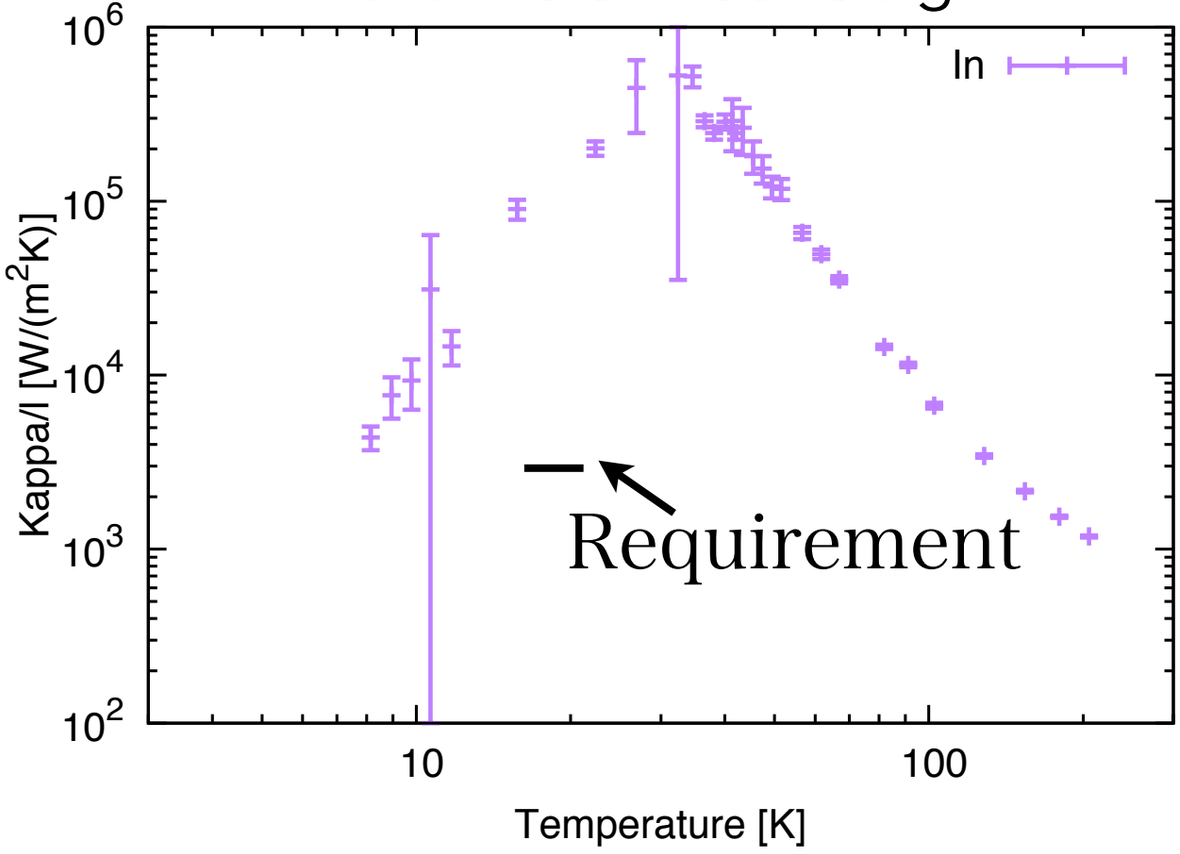
Heat transfer coefficient

Cross section area

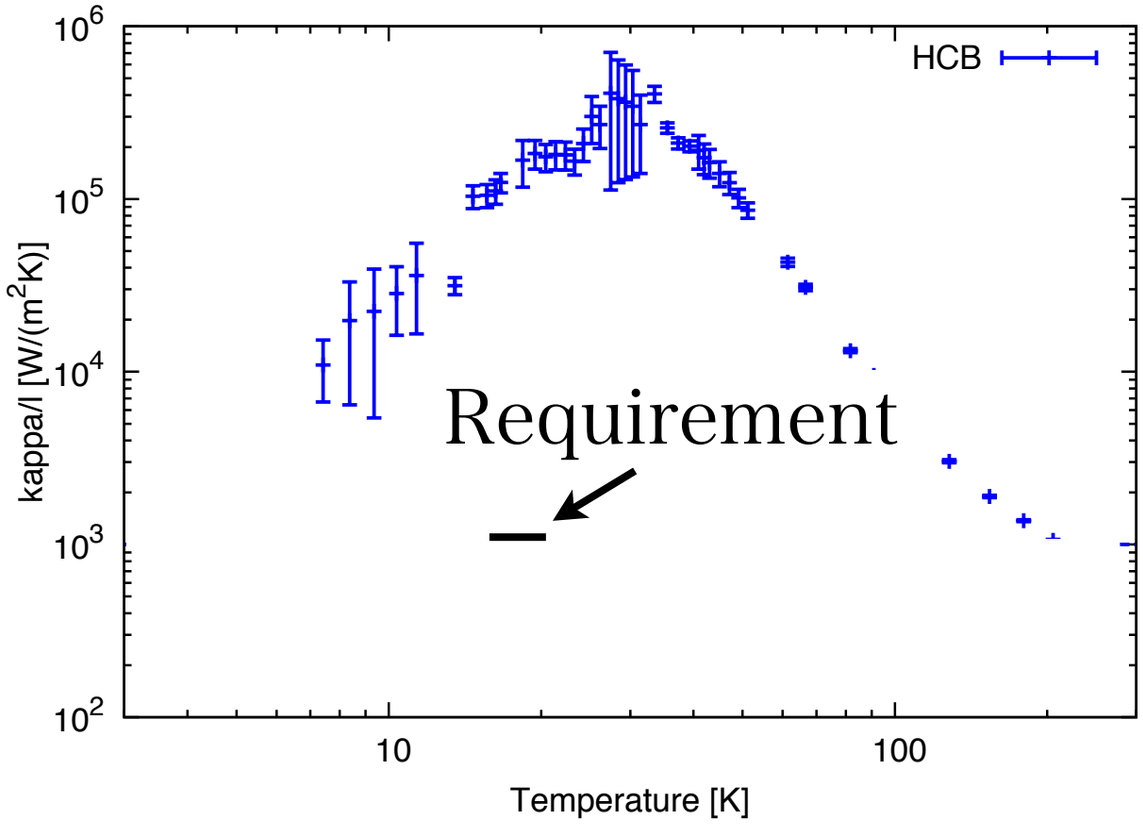
Heat transfer measurement

- Bonding sample -

Heat transfer coefficient of the indium bonding



Heat transfer coefficient of the HCB

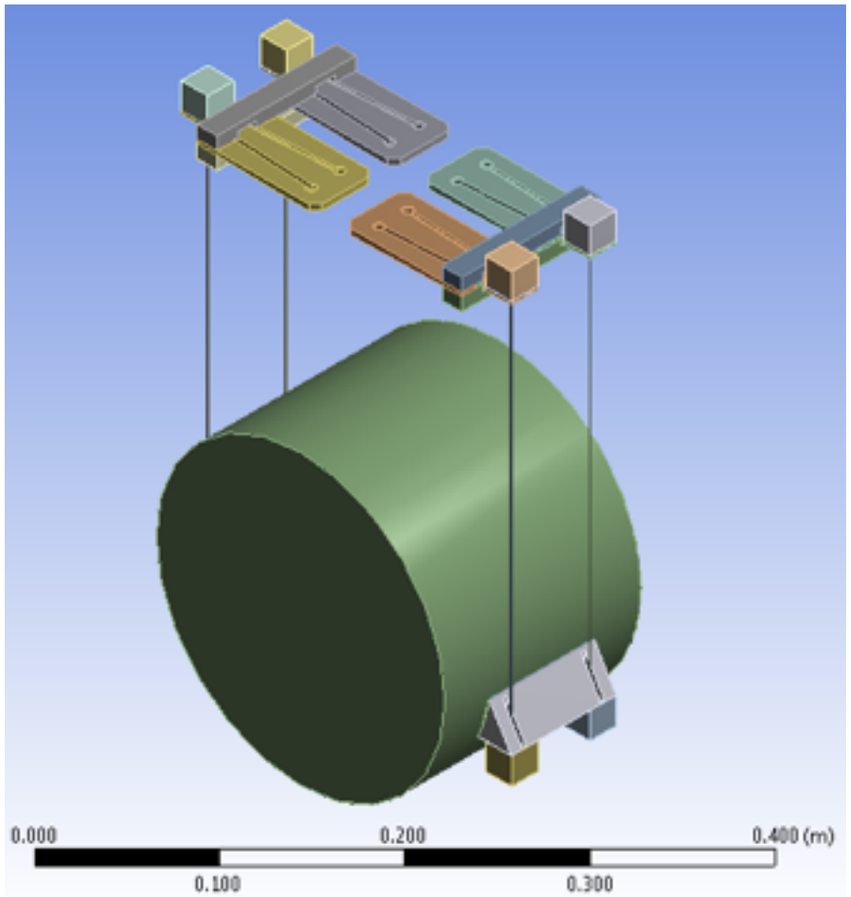


Measured value were enough higher than the requirement

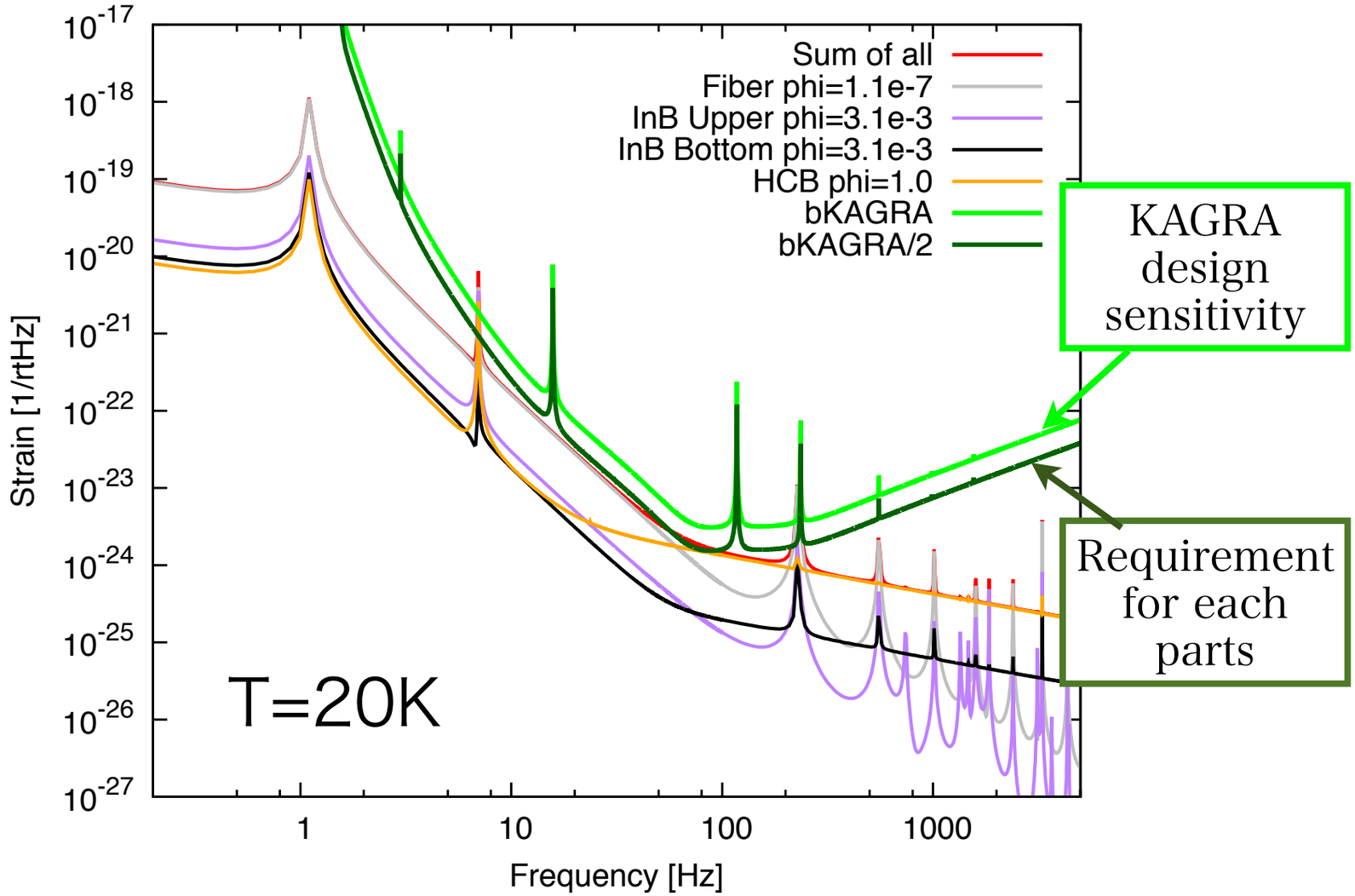
Thermal resistance of the indium bonding and HCB can not be problems

Summary of the sapphire suspension

All of the parts satisfied the reuirements of loss, thermal conductivity and strength.



Suspension TN calc with measured losses



Thermal noise is lower than the KAGRA design sensitivity

Contents

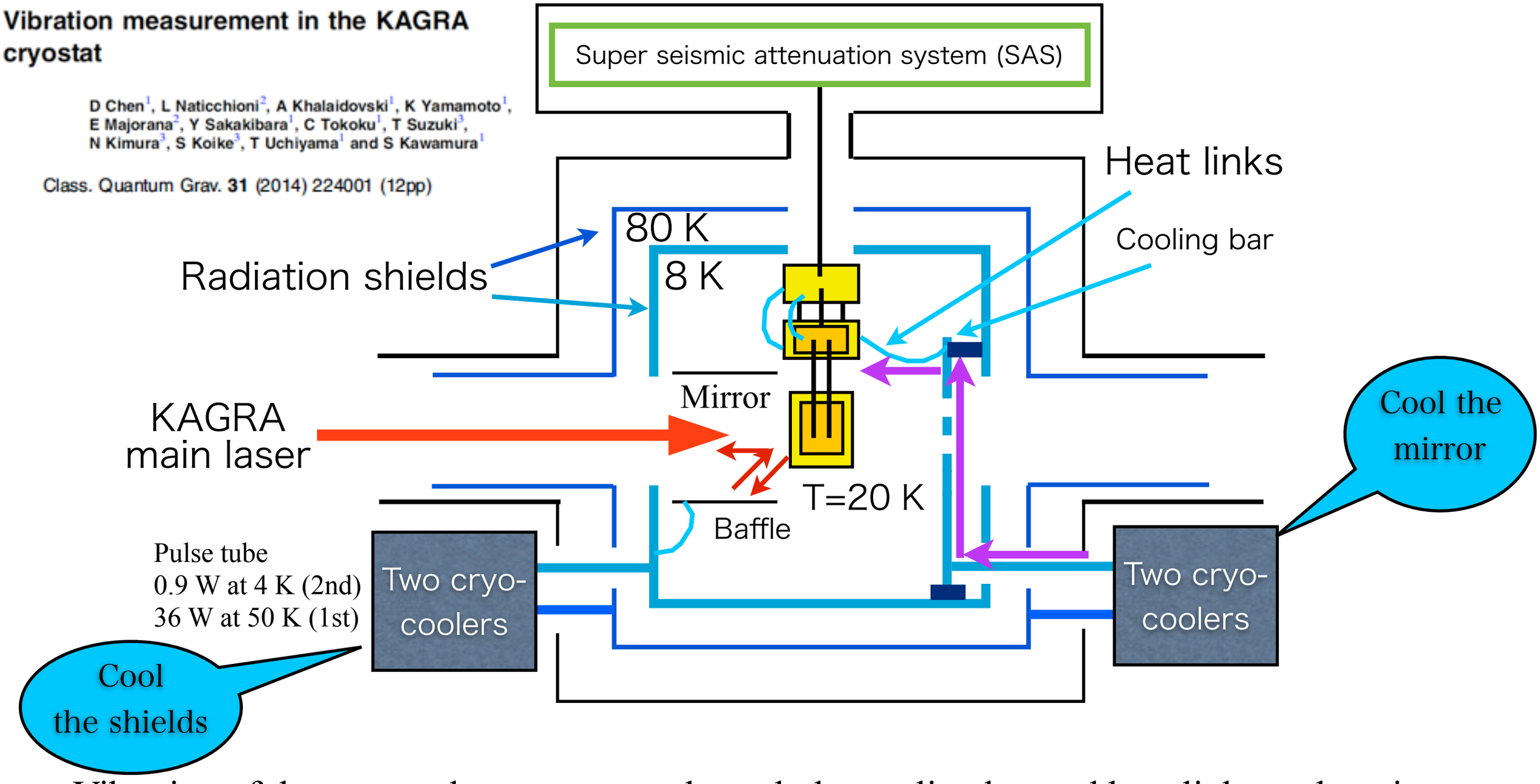
Vibration measurement

- KAGRA cooling system -

Vibration measurement in the KAGRA cryostat

D Chen[1], L Naticchioni[2], A Khalaidovski[1], K Yamamoto[1], E Majorana[2], Y Sakakibara[1], C Tokoku[1], T Suzuki[3], N Kimura[3], S Koike[3], T Uchiyama[1] and S Kawamura[1]

Class. Quantum Grav. **31** (2014) 224001 (12pp)

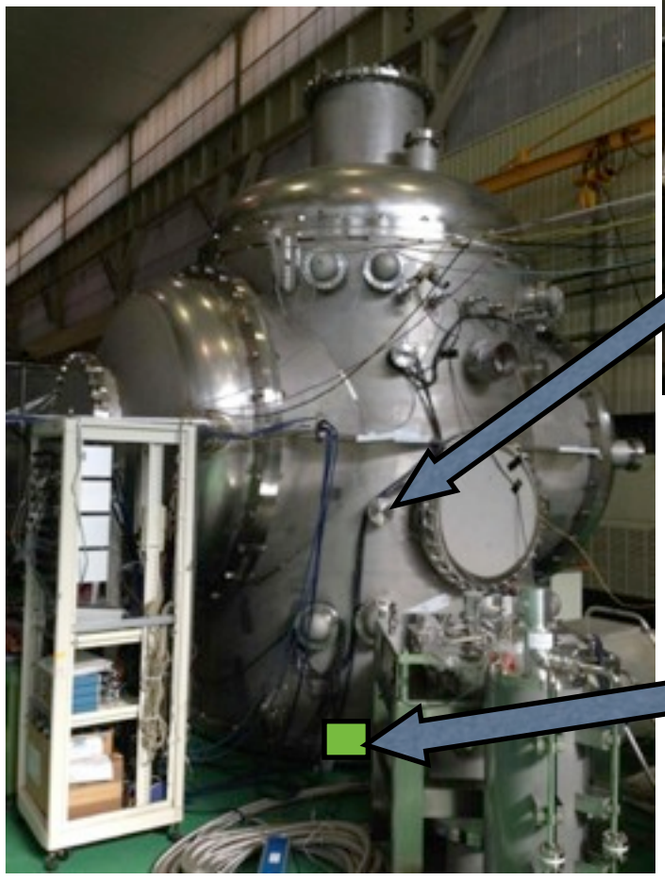


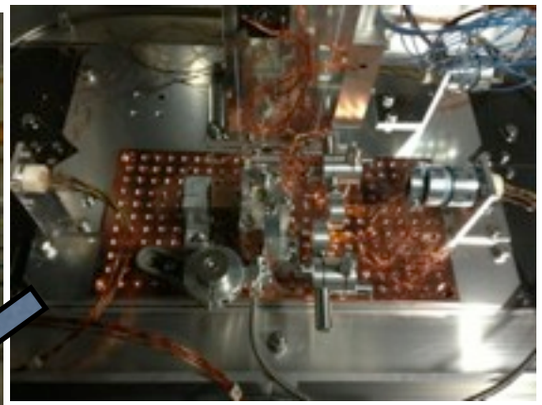
Vibration of the cryocoolers propagate through the cooling bar and heat links to the mirror.
The cooling bar is assumed to be fixed at the shield in order to suppress the vibraiton.
We measured the vibration of the shield during cooling test at the Toshiba factory in order to estimate the influence before the install in the tunnel.

Vibration measurement

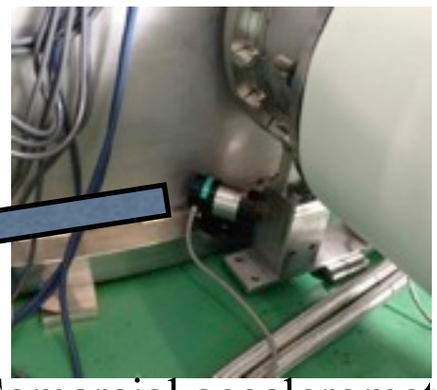
- Measurement condition -

KAGRA cryostat



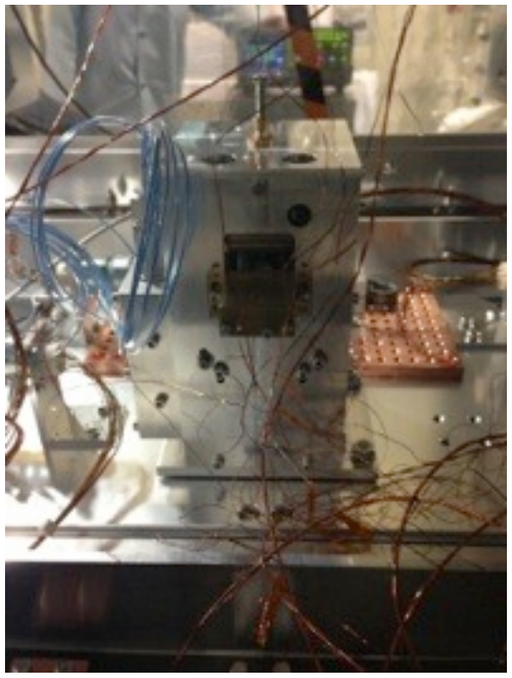


Two cryo accelerometers

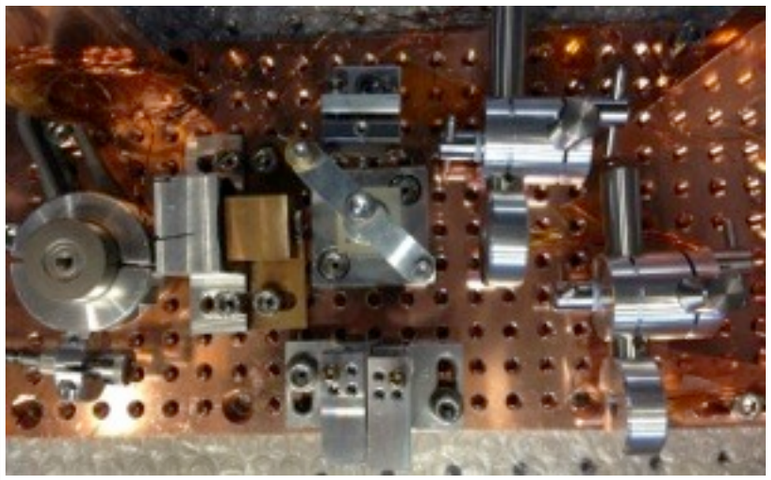


Comercial accelerometer (RION)

Cryogenic accelerometers on the radiation shield.



Roma Univ. developed.
Vertical measurement



ICRR developed.
Horizontal measurement

Measurement 1

Compare the vib. of outside and inside the cryostat.

Measurement 2

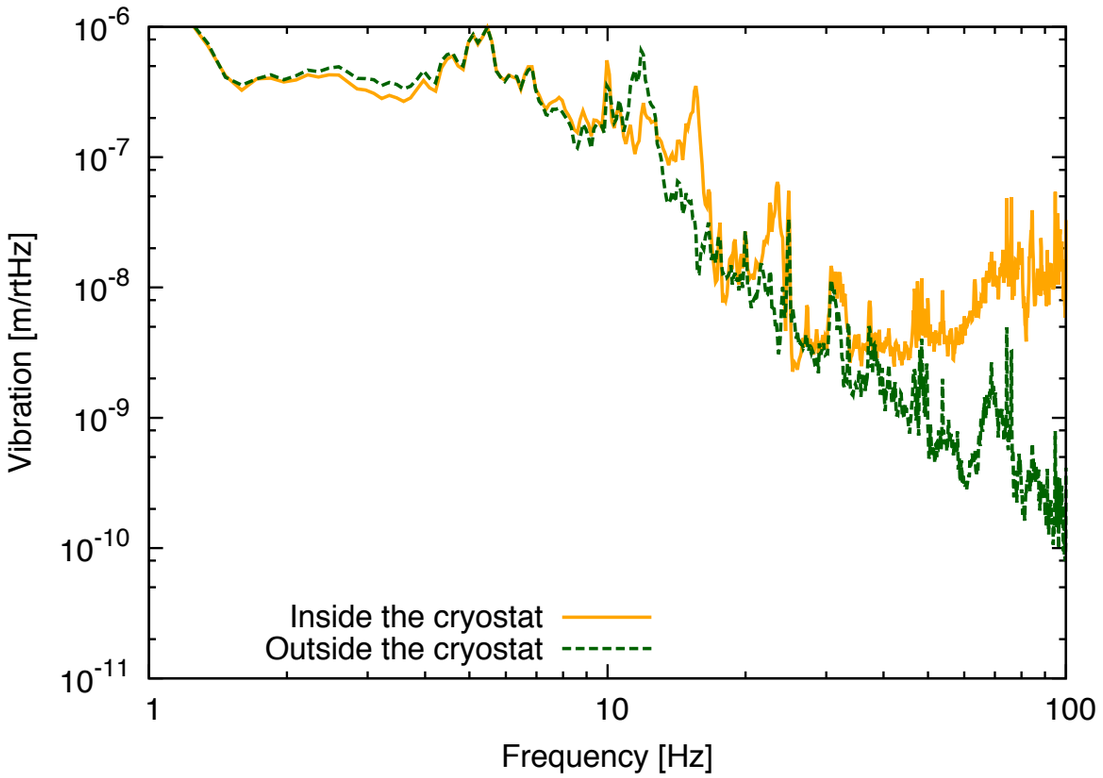
Compare the vib. with cryocooler ON/ OFF.

Meas. \

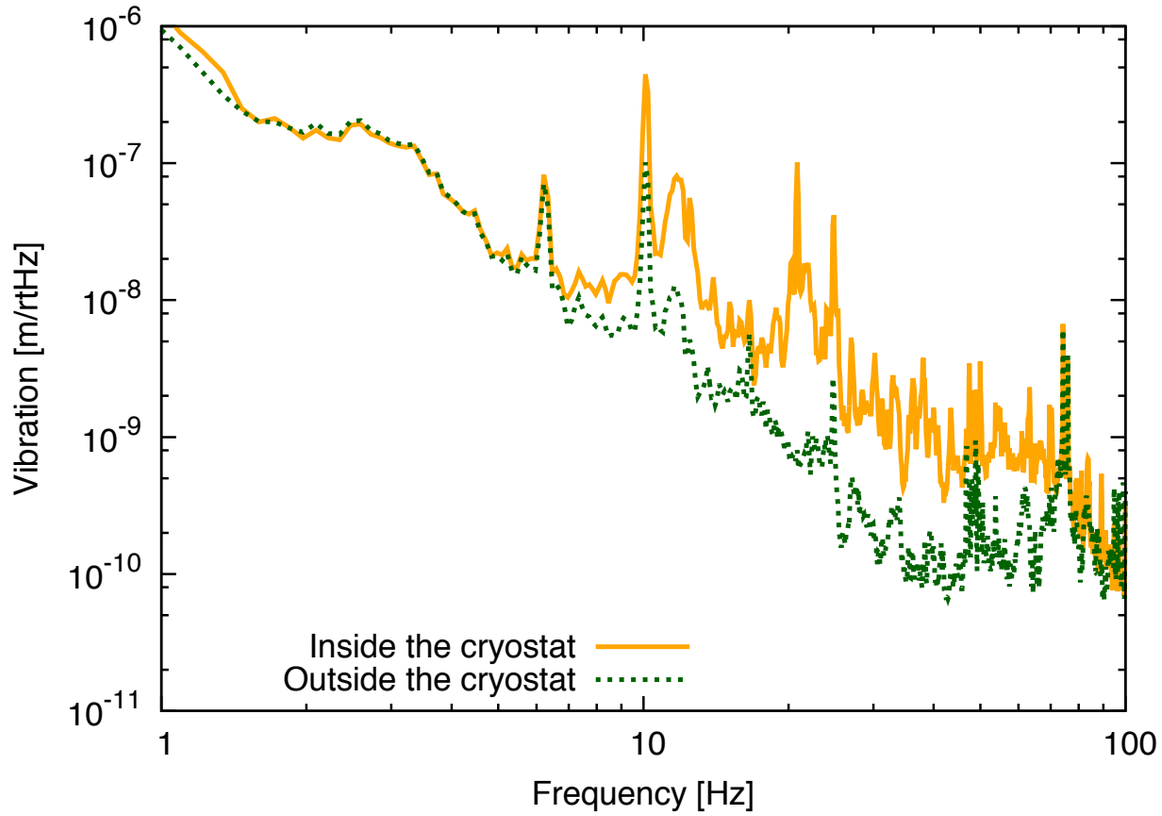
Vibration measurement

- Difference between outside and inside the cryostat (10K) - Coolers were OFF.

Vertical vib.



Horizontal vib.



Vib. in the cryostat is higher than the outside at high frequency.

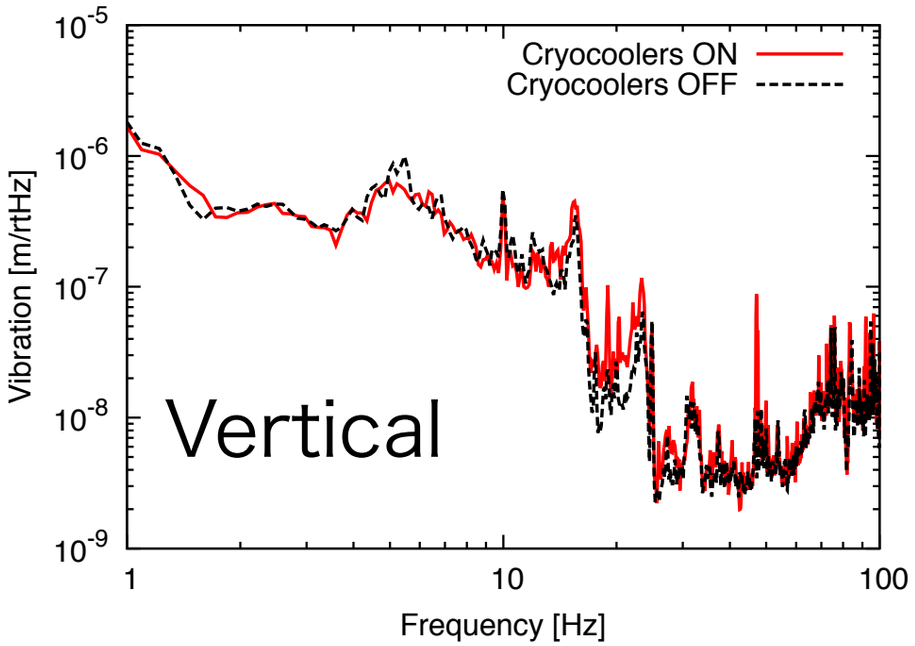
Resonant freqnencies of the cryostat appear from 10Hz.

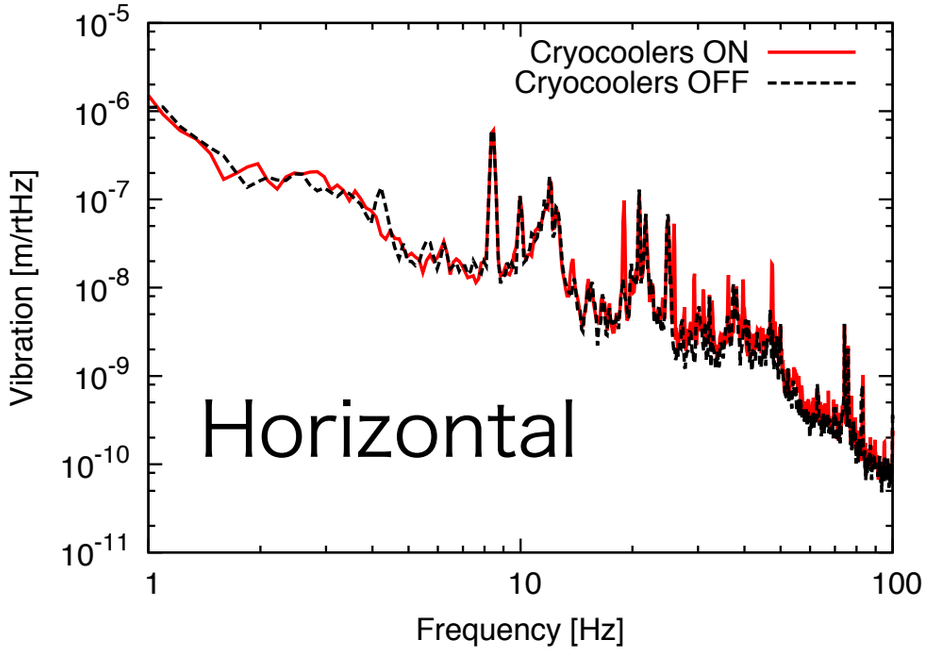
The ratio of the vibraiton inside/outside is the same as in Kamioka.

Meas.2

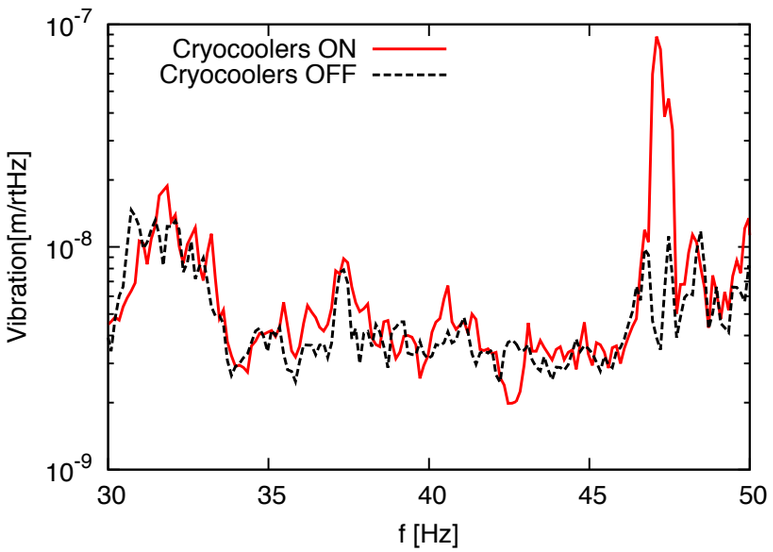
Vibration measurement

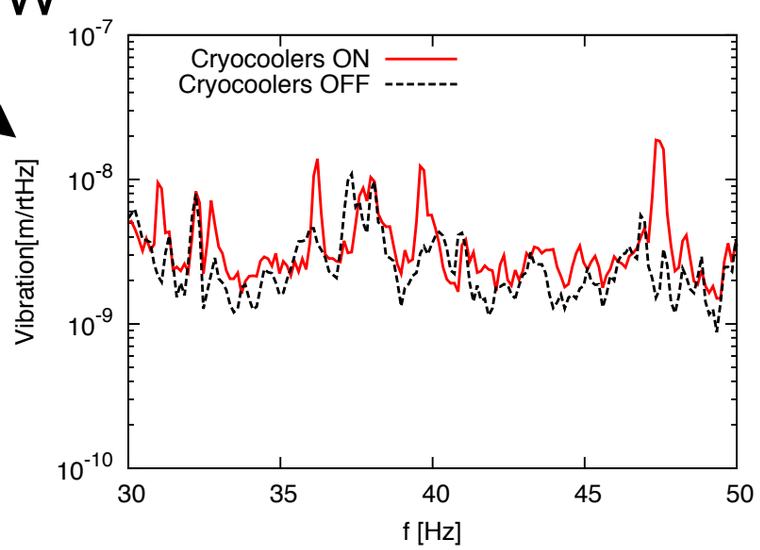
- Different between coolers ON and OFF (10K) -





Enlarged view





Peaks by the coolers appear.

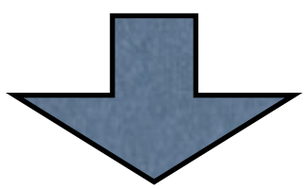
These peaks will also appear in Kamioka at the same frequency and the same level.

Vibration measurement

- Estimated vibration in the Kamioka mine -

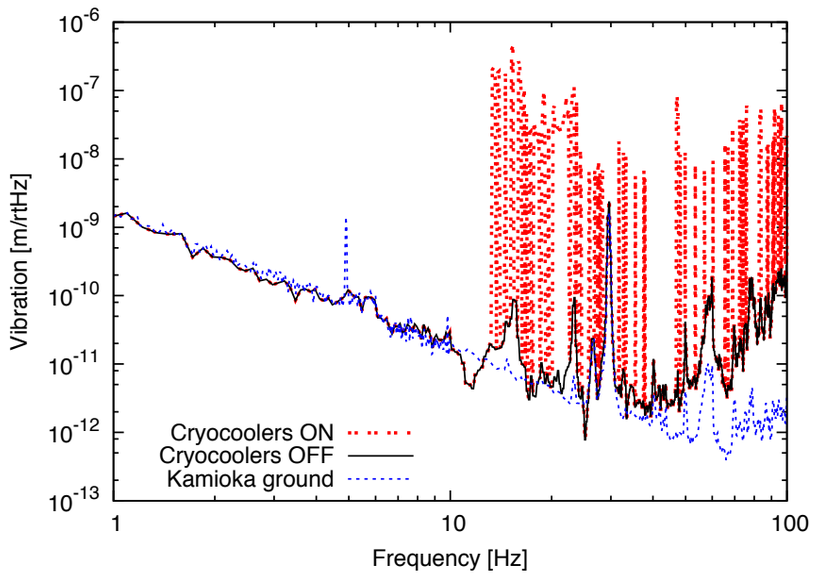
Calculate the ratio to estimate the floor level at Kamioka.

Assume the same peak level at Kamioka as the factory

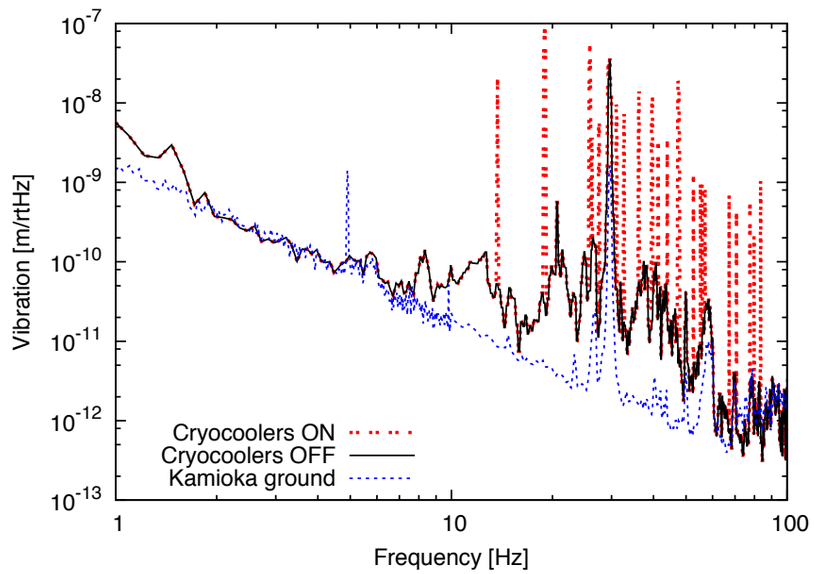


Vibration of the radiation shield at Kamioka

Vertical vib.



Horizontal vib.

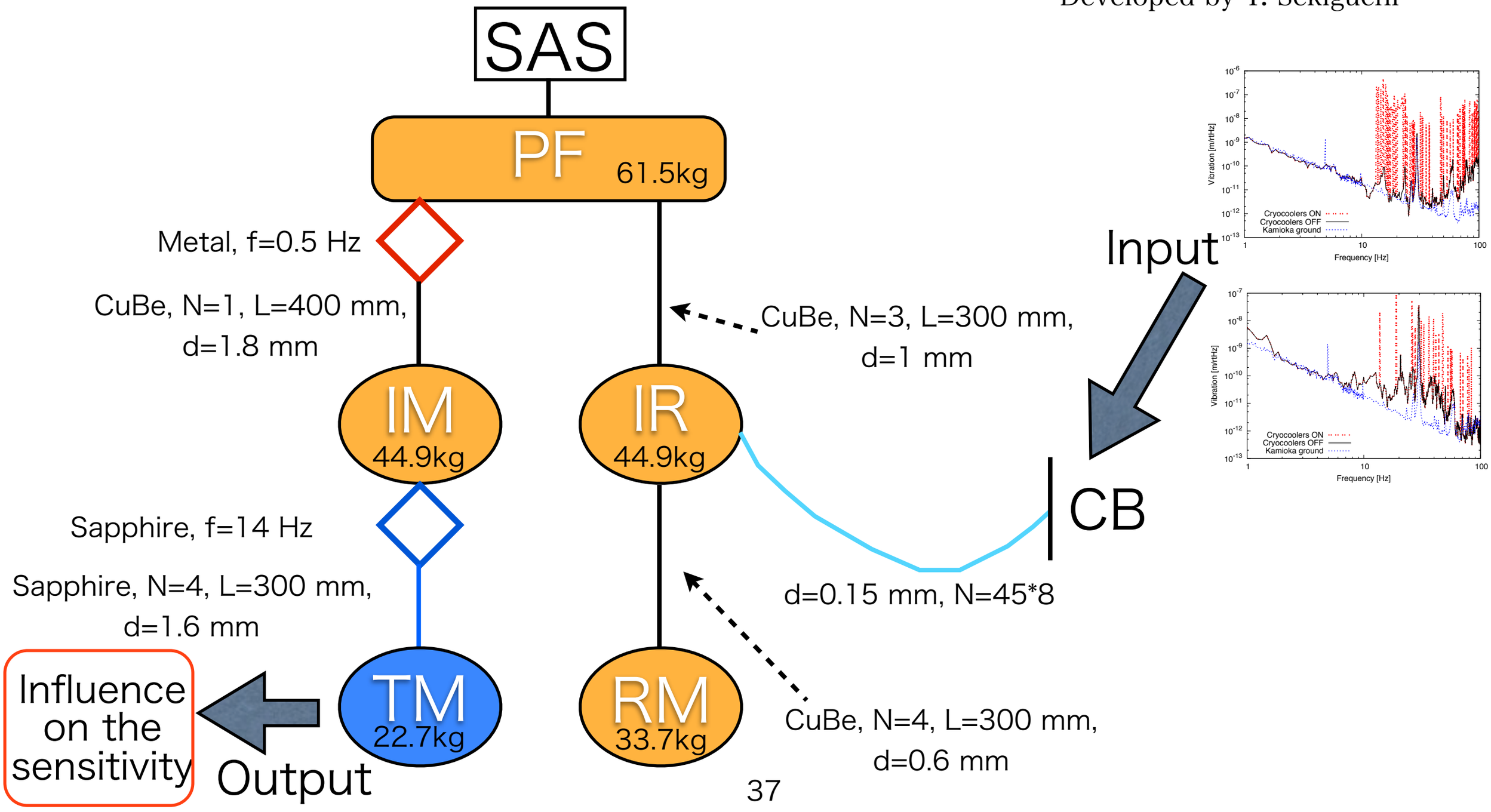


Vibration measurement

- Influence on the vibration noise of the mirror -

We calculaed the influence on the mirror from the radiation shiled vibration using a Mathematica code “SUMCOM”

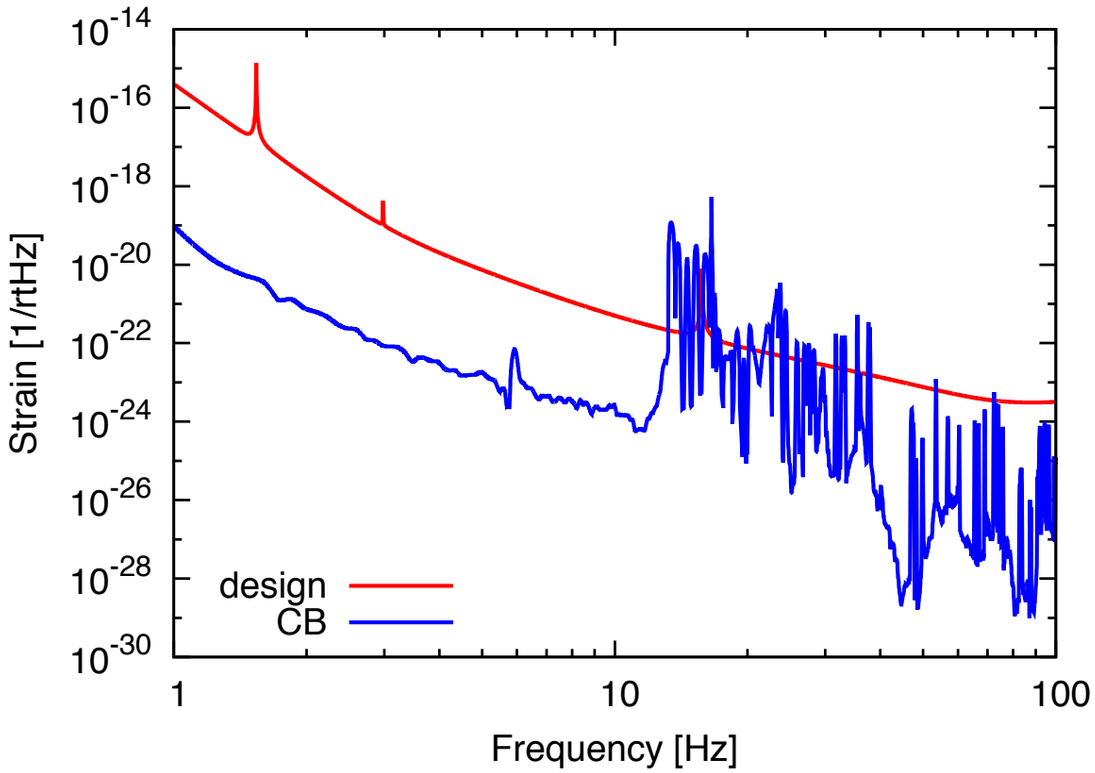
Developed by T. Sekiguchi



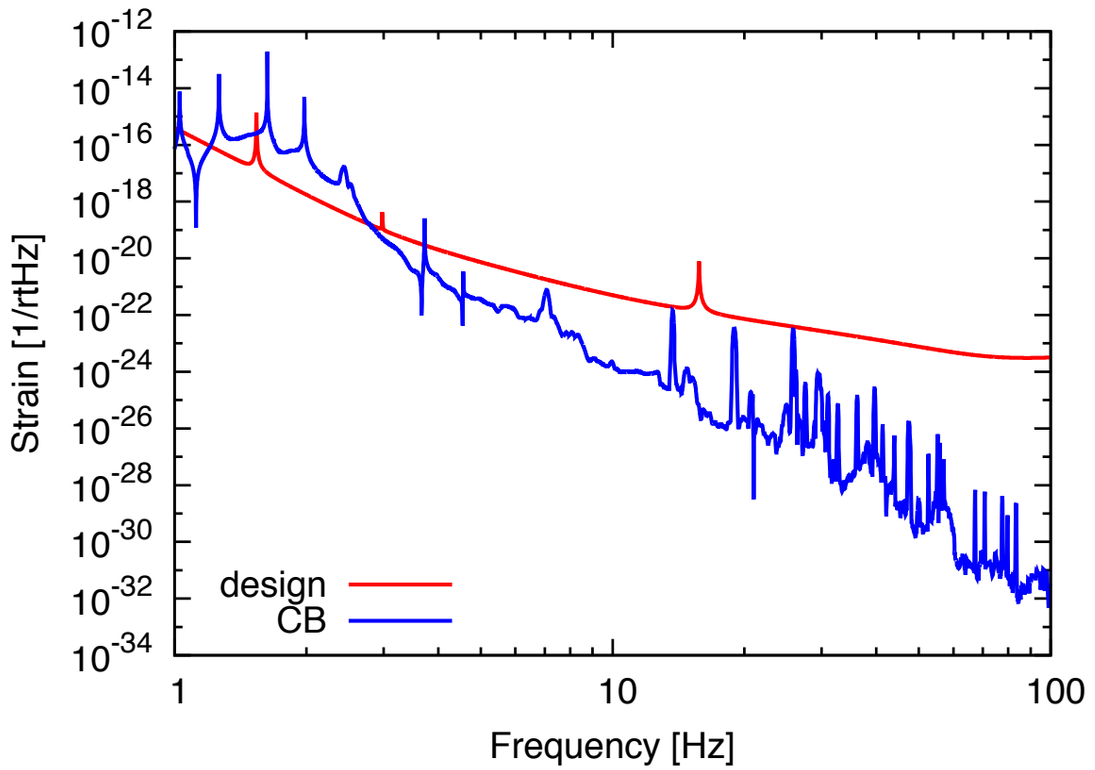
Vibration measurement

- Compare to the KAGRA design sensitivity -

Vertical vib.



Horizontal vib.



The vertical noise is over the design sensitivity between 10 and 40Hz.

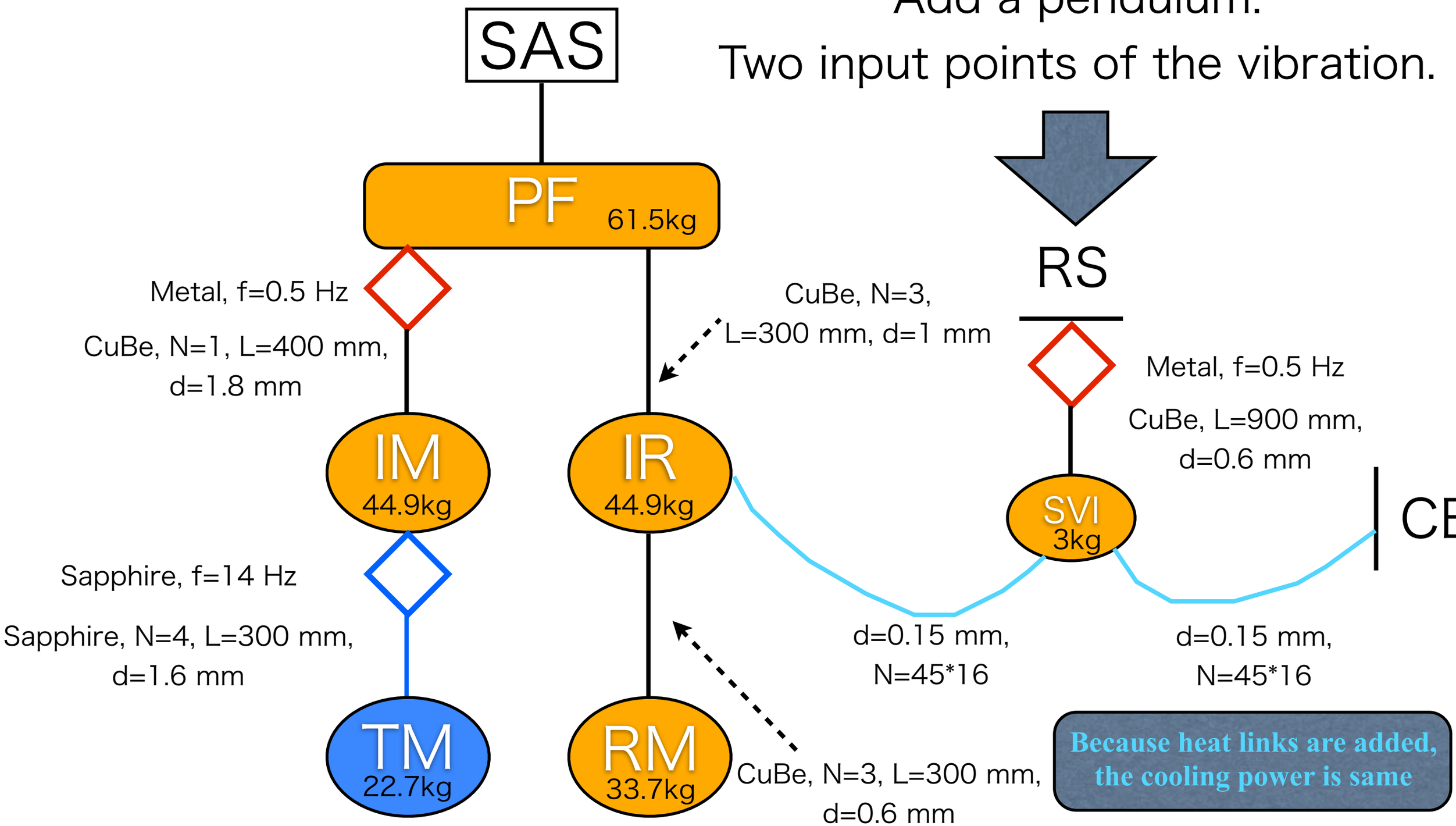
We need improvement.

Vibration measurement

- Suppression of the radiation shield vibration -

Add a pendulum.

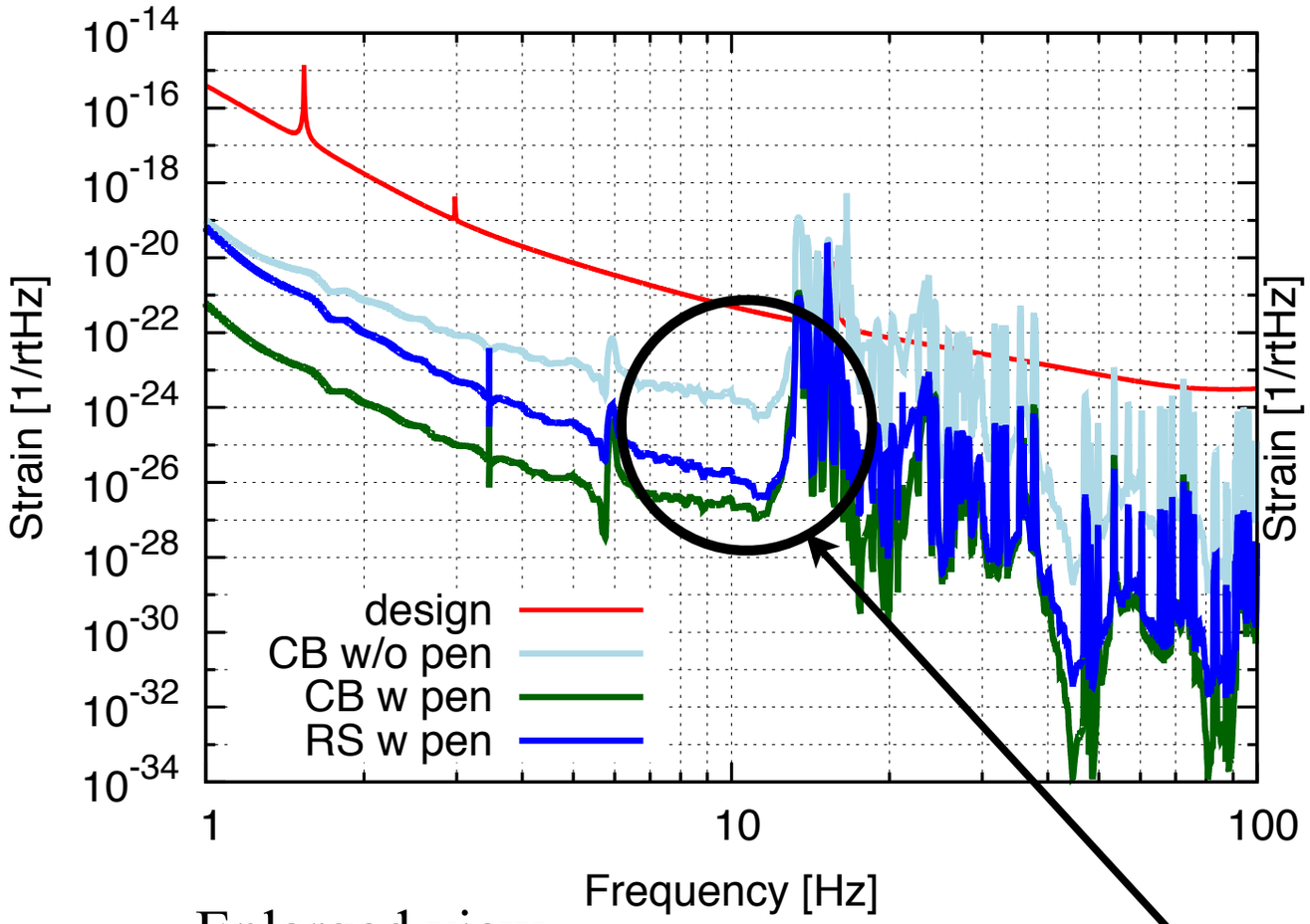
Two input points of the vibration.



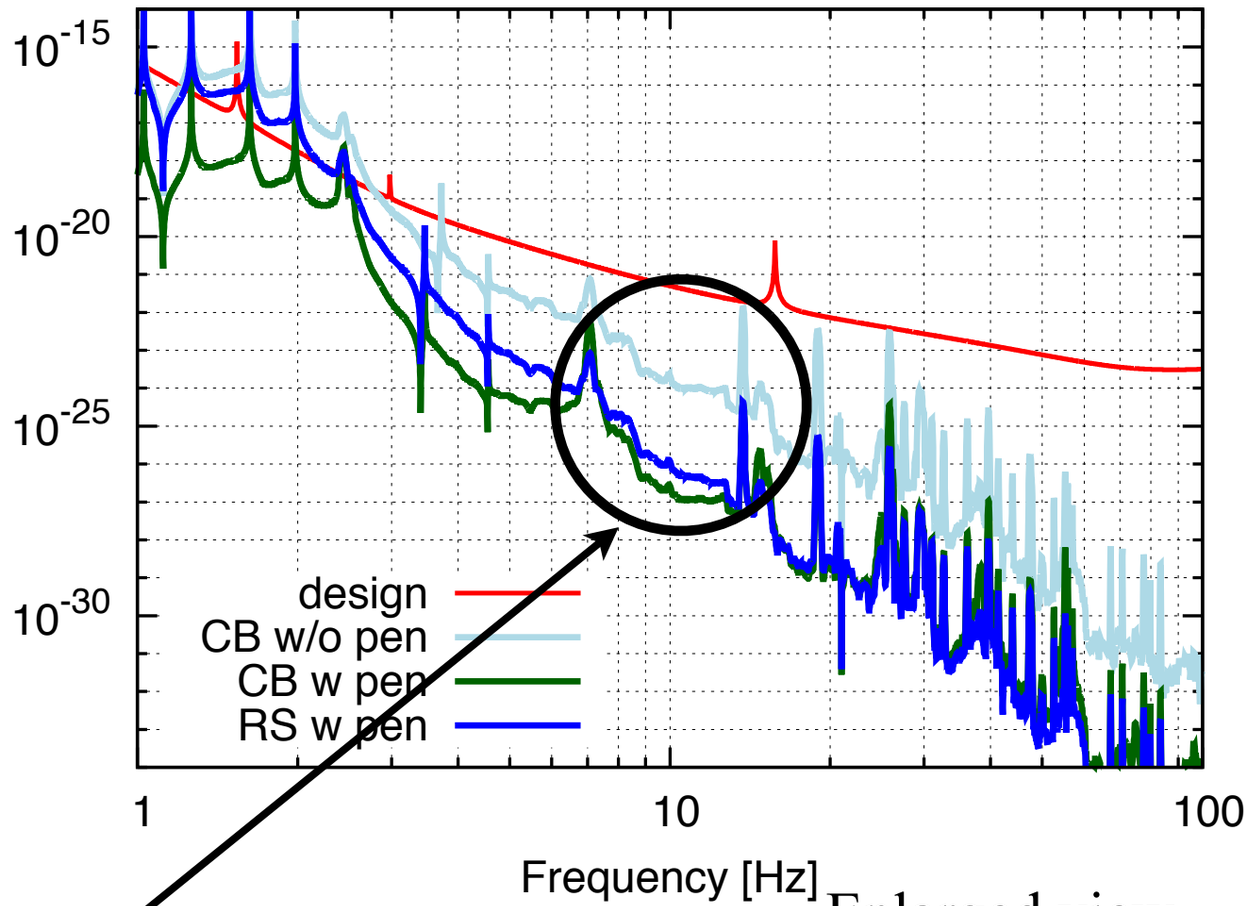
Vibration measurement

- Impact of the additional pendulum -

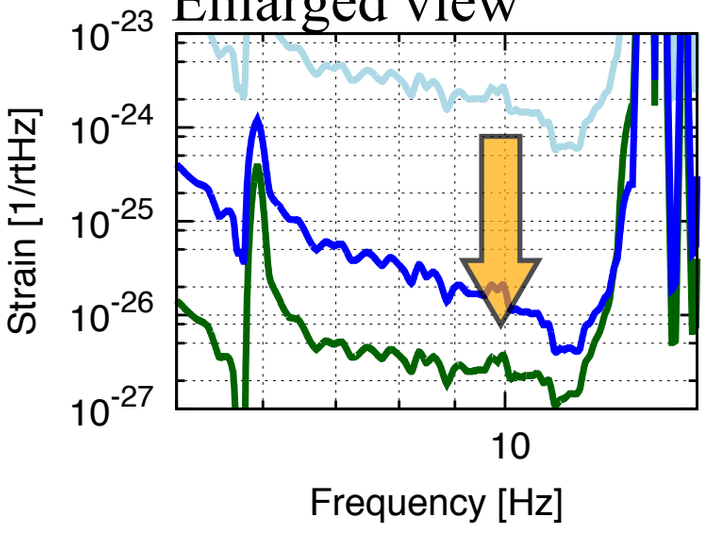
Vertical vib.



Horizontal vib.

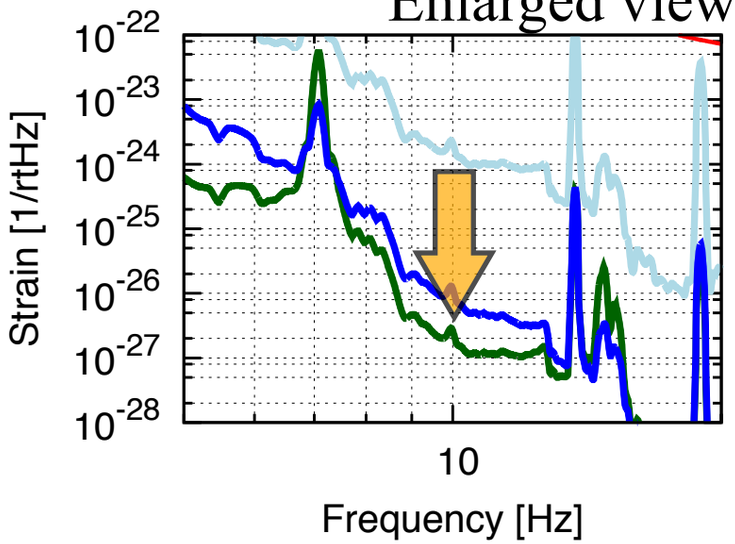


Enlarged view



The vibration is suppresed by two orders at 10Hz.
Compare to the KAGRA design sensitivity...

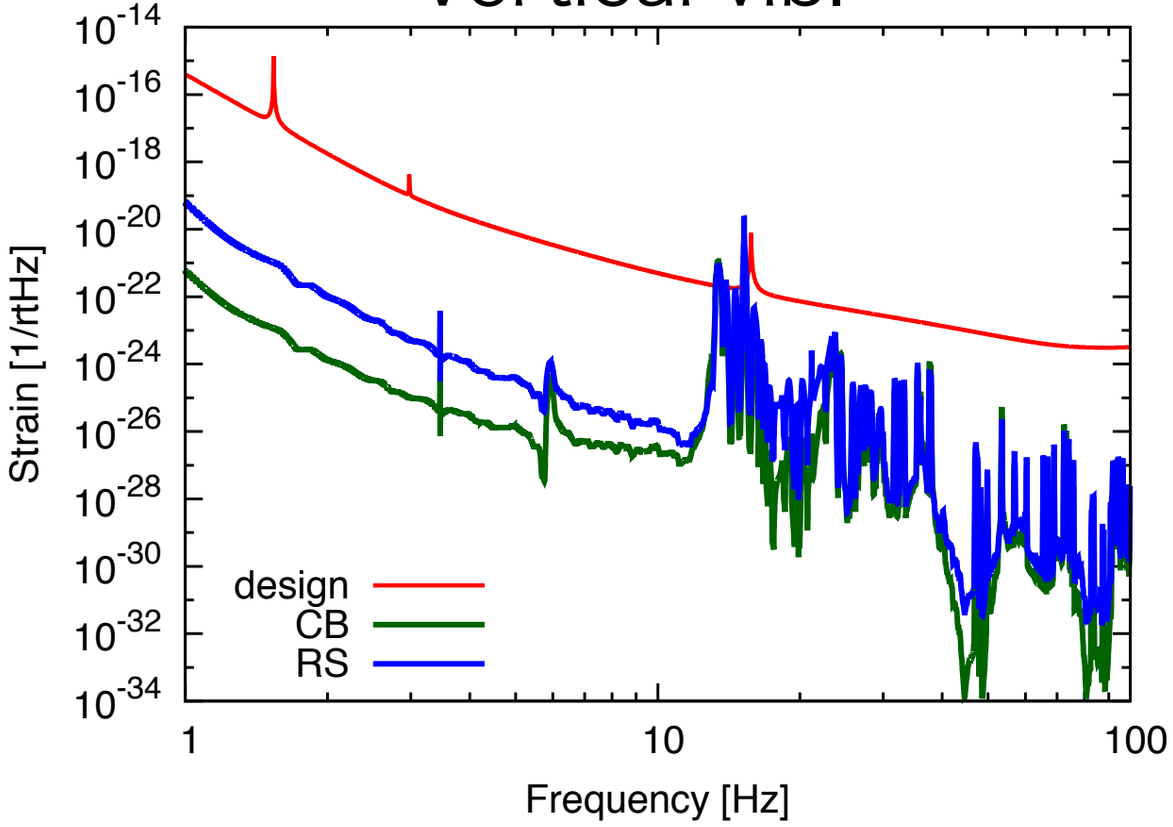
Enlarged view



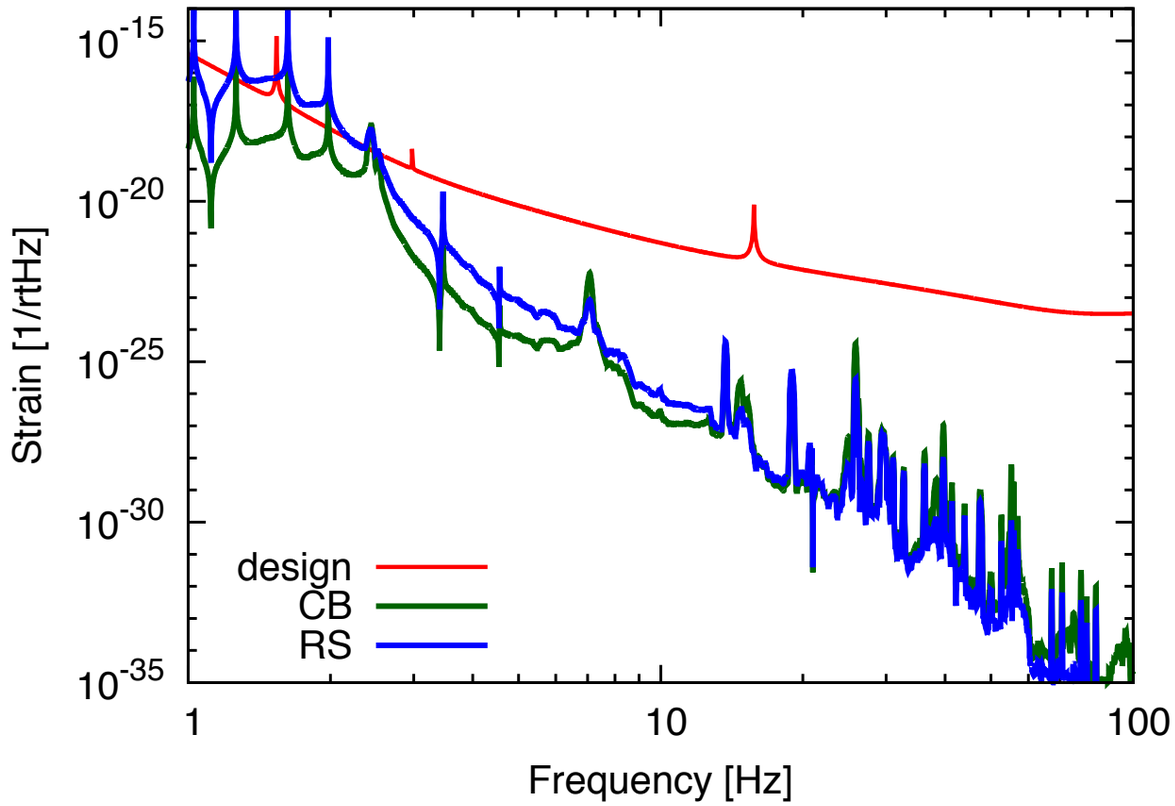
Vibration measurement

- Impact of the additional pendulum -

Vertical vib.



Horizontal vib.



Both of them are lower than the design sensitivity

The influence of the cooling system vibration is suppresed below the KAGRA design sensitivity by the additional pendulum

Summary

★KAGRA will be the first km-scale cryogenic gravitational wave detector

✦Based on the quiet under ground in the Kamioka mine.

✦**In order to suppress the thermal noise, cryogenic mirrors will be used.**

★We reported one of the key points: cryogenic suspension system

✦**Design** of the sapphire suspension and **the component experiments**

- Mechanical loss measurement

➡Fiber and indium bonding **satisfied the requirements**.

- Thermal resistance measurement

➡Fiber, indium bonding and HCB, **satisfied the requirements**.

- Strength test

➡Fibers had enough strength.

➡Strength of HCB after thermal cycles was **enough strong**.

✦Estimation of the vibration noise from the cooling system.

➡The cooling vibration **can be suppressed below the design sensitivity**.

These studies are important not only for KAGRA but also for ET!

End