Current status of cryogenic system of KAGRA

KAGRA

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the University of Tokyo

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Contribution

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KAGRA collaboration

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Friedrich-Schiller-Universitaet Jena[K], Jecc Torisha[L], KAGRA collaboration

0. Abstract

Current status

of KAGRA cryogenic system

(1)Cryostat
(2)Cryogenic duct
(3)Cryocooler unit
(4)Cryogenic payload

Contents

1. Introduction

KAGRA :

2nd generation interferometric gravitational wave detector in Japan

Key features of KAGRA project

Silent underground site (Kamioka) : Small seismic motion

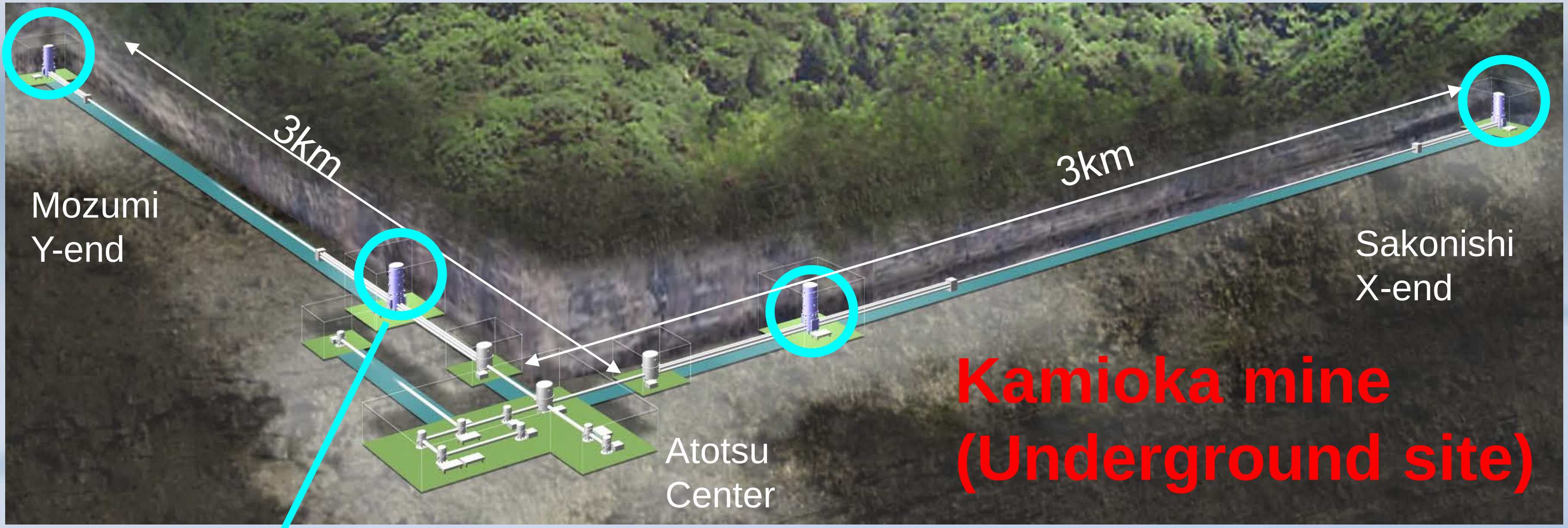
Cryogenic system : Reduction of thermal noise

and so on

1. Introduction

Schematic view of KAGRA interferometer

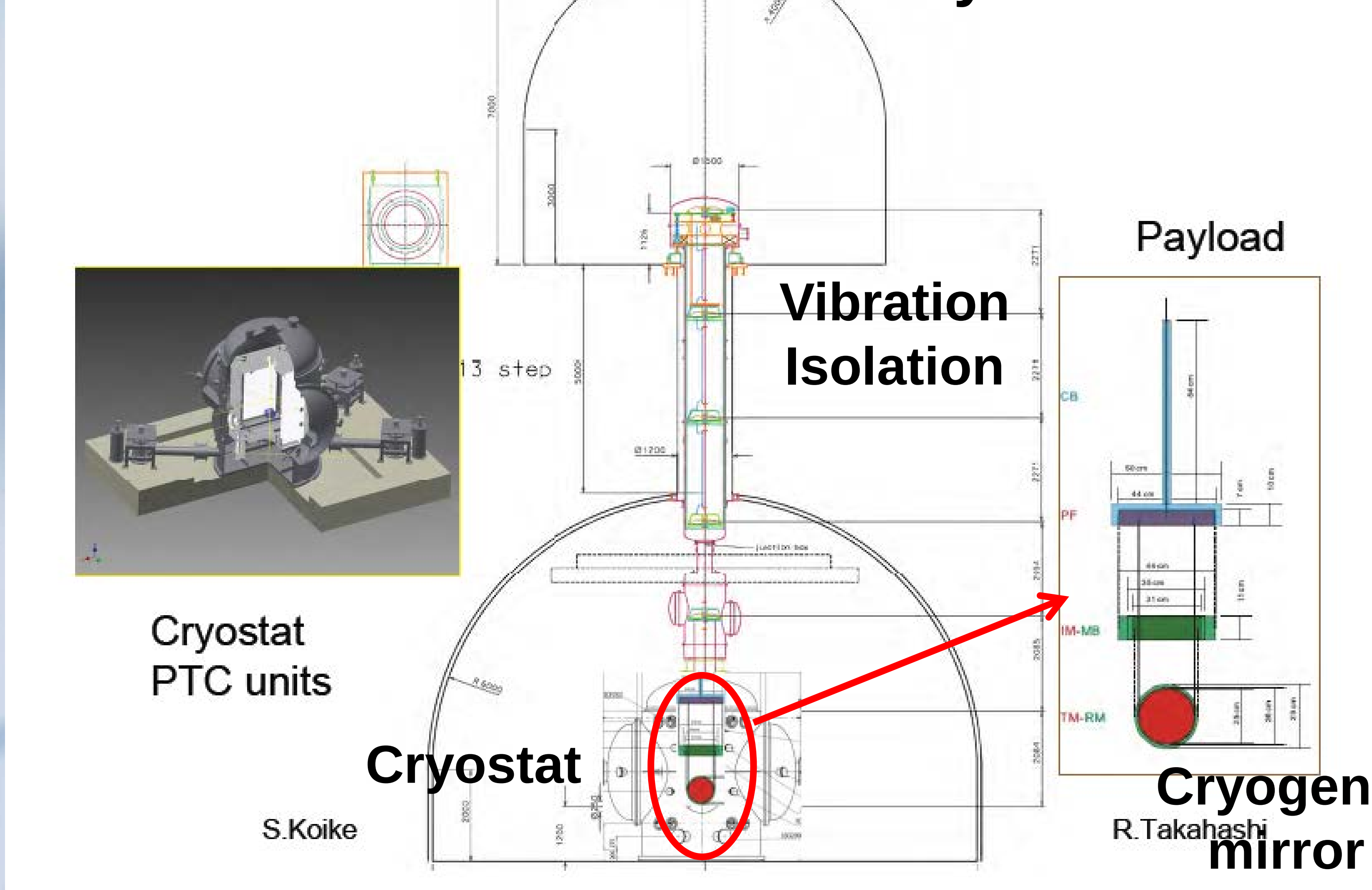
Four mirrors of arm cavity will be cooled.



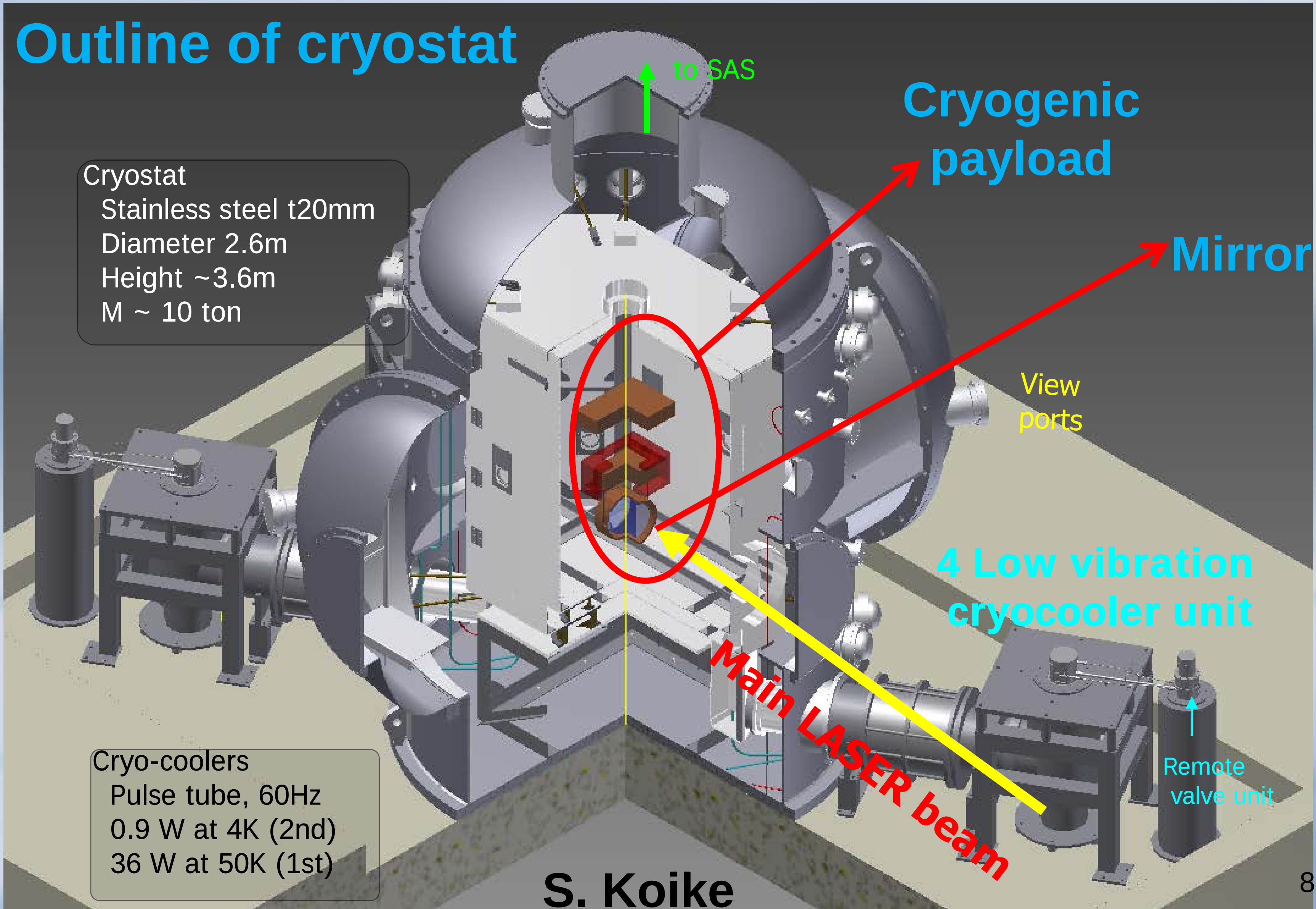
Vibration isolation system, Cryocooler unit, Cryostat, Cryogenic payload

1. Introduction

Outline of vibration isolation and cryostat



1. Introduction



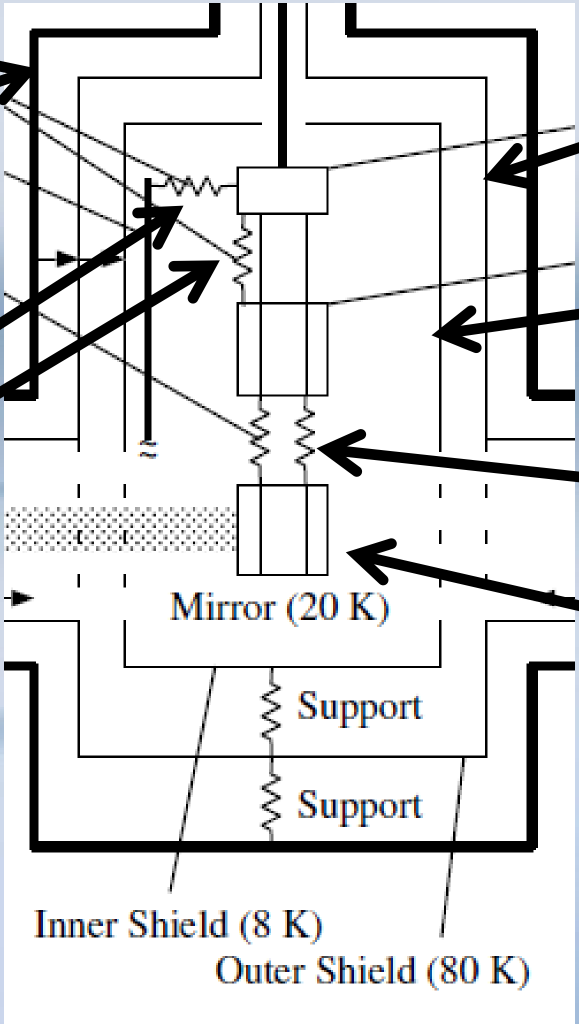
S. Koike

1. Introduction

Outline of cryogenic payload

Vacuum chamber (300K)

Heat links (pure Al)



Outer shield (80K)

Inner shield (8K)

Sapphire fiber

Sapphire mirror (About 20K)

Y. Sakakibara *et al.*, Classical and Quantum Gravity 29 (2012) 205019.

1. Introduction

Cryostat scheme

2 cryocoolers cool radiation shields.
Other 2 cryocoolers cool payload
via separated heat path.

Scattering on mirror : 10 ppm ?
Scatted power is 5 W in radiation shield !

Even if large scattered light attacks shield,
mirror temperature could be low.

2. Cryostat

Progress of assembly of cryostat

Vacuum chamber

at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

Vacuum chamber

at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

Vacuum chamber

2. Cryostat

Progress of assembly of cryostat

Vacuum chamber

at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

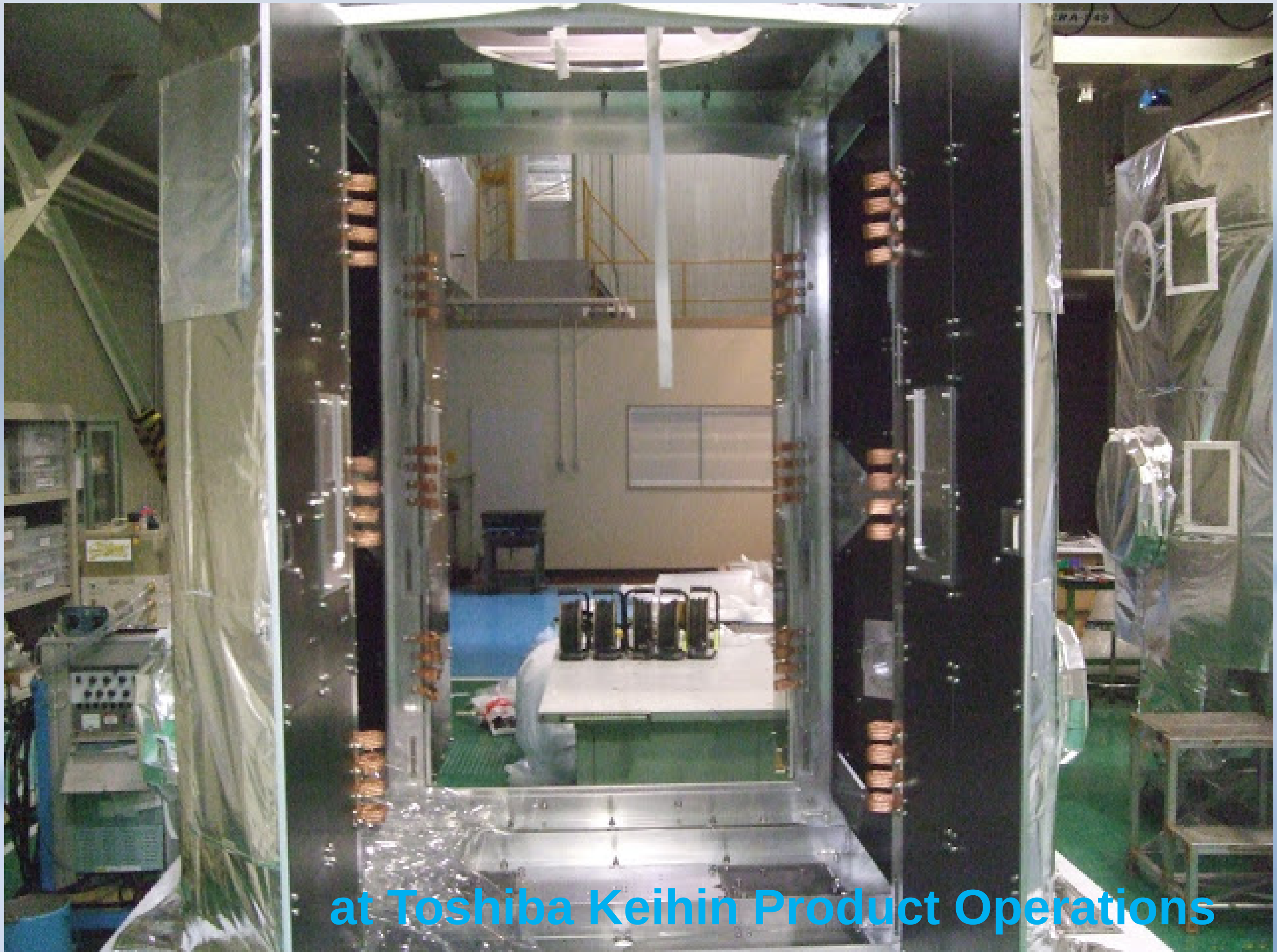
Shield

at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

Shield



at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

Shield in vacuum chamber

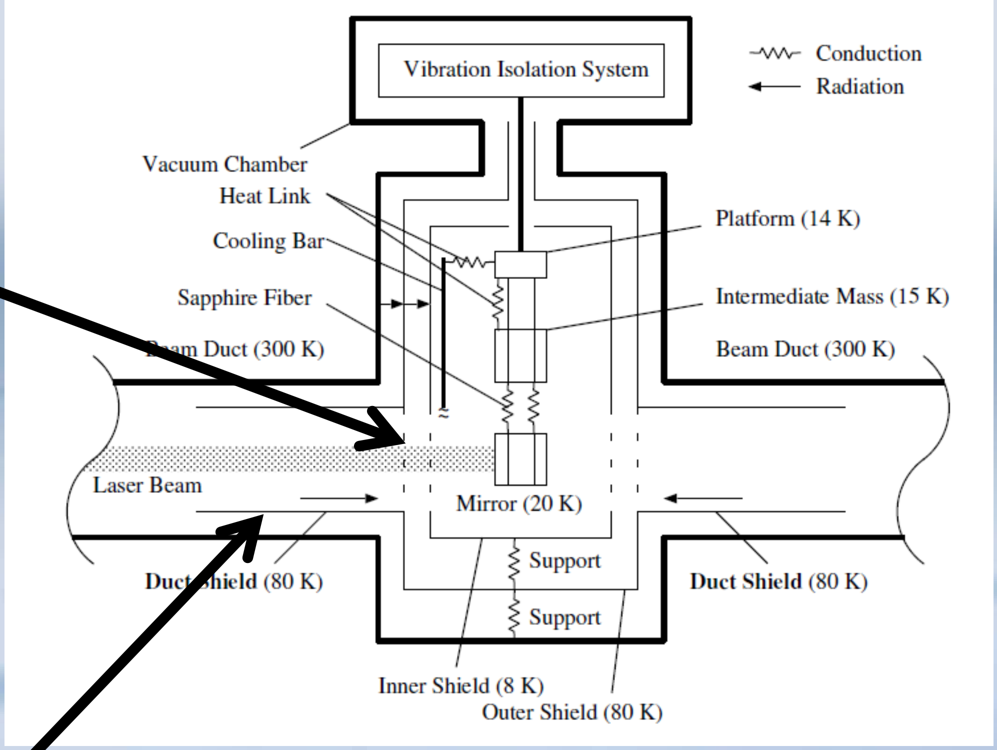
2. Cryostat

Cooling test in Toshiba Keihin Product Operations

December 2012 - March 2013

3. Cryogenic duct

Radiation from hole for laser beam



Large hole (almost same as mirror) for laser beam on radiation shield

Huge 300 K radiation (about 20 W) invades radiation shield.

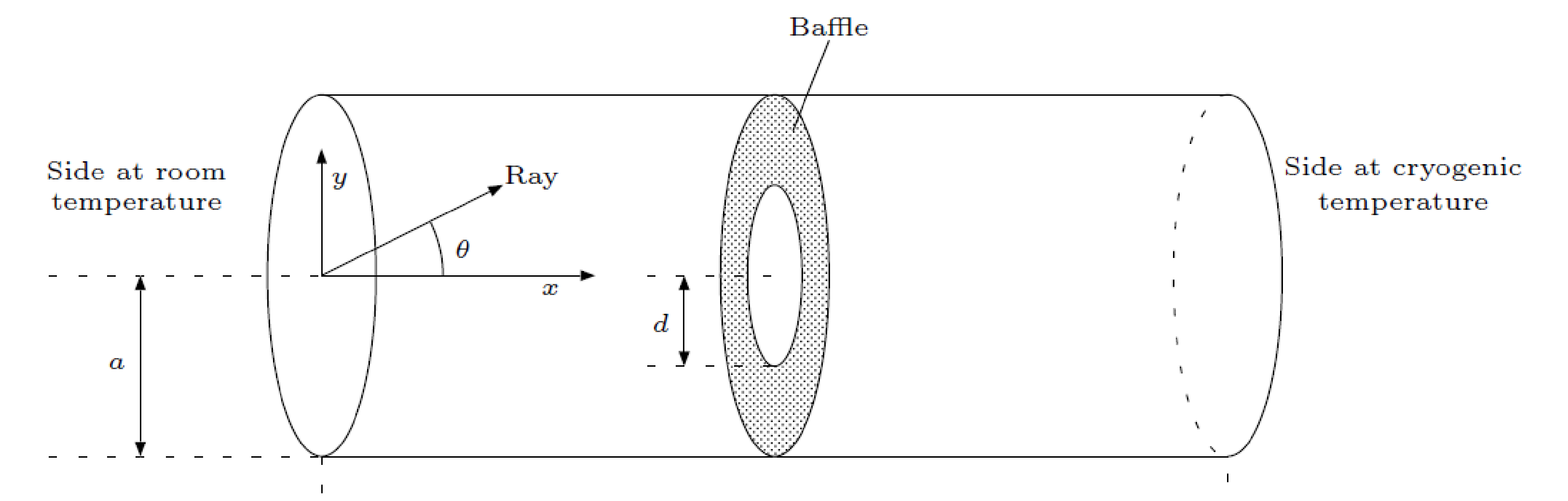
Cryogenic duct (80 K) with baffles are necessary.

T. Tomaru *et al.*, Japanese Journal of Applied Physics 47 (2008) 1771.
T. Tomaru *et al.*, Journal of Physics:Conference Series 122 (2008) 012009.

3. Cryogenic duct

Design of cryogenic duct

Y. Sakakibara developed the code
to evaluate the transmittance of cryogenic duct
and found optimal 5 baffles positions.
Power into shield : 300 mW

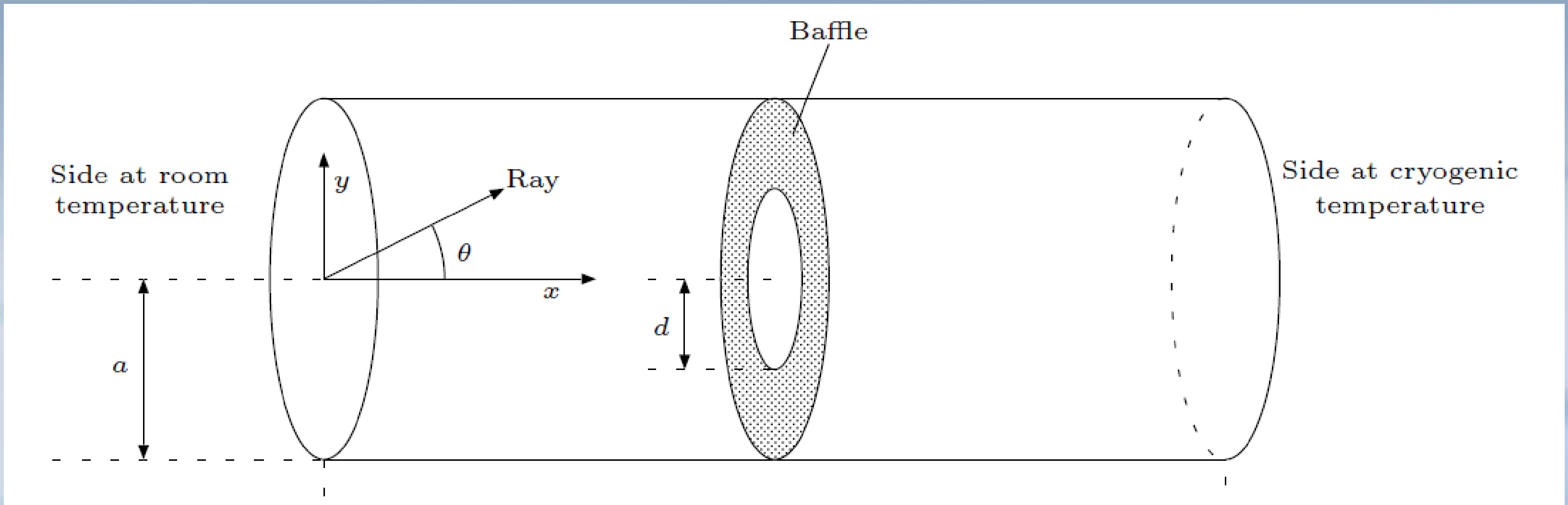


Y. Sakakibara *et al.*,
Classical and Quantum Gravity 29 (2012) 205019.

3. Cryogenic duct

Scattered light noise

T. Akutsu pointed out that the light scattered by the cryogenic duct could be a noise source. The vibration of this duct causes the fluctuation of the phase of light.

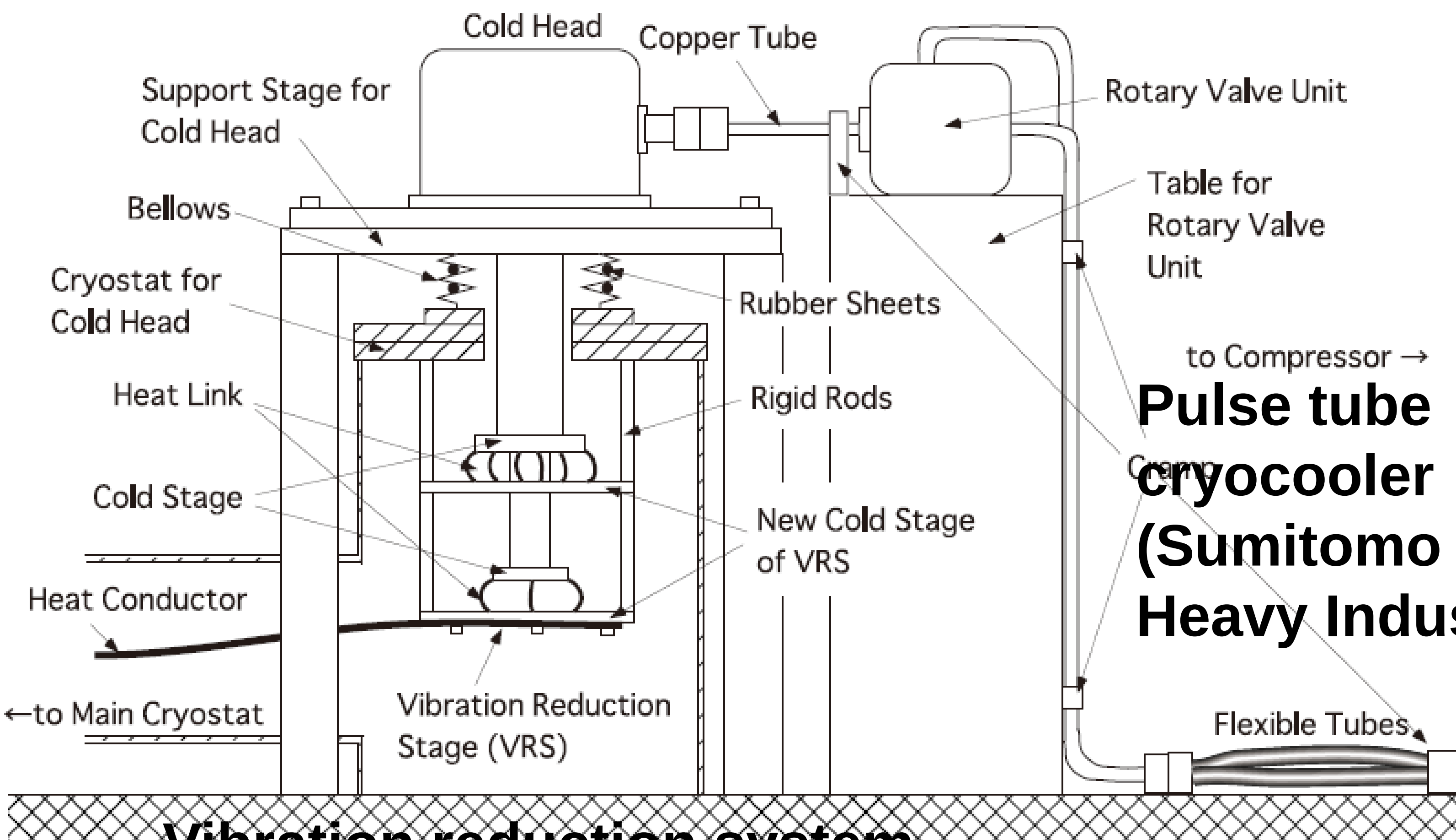


Y. Sakakibara proceeds with the investigation.

4. Cryocooler unit

Outline

Class. Quantum Grav. **21** (2004) S1005–S1008

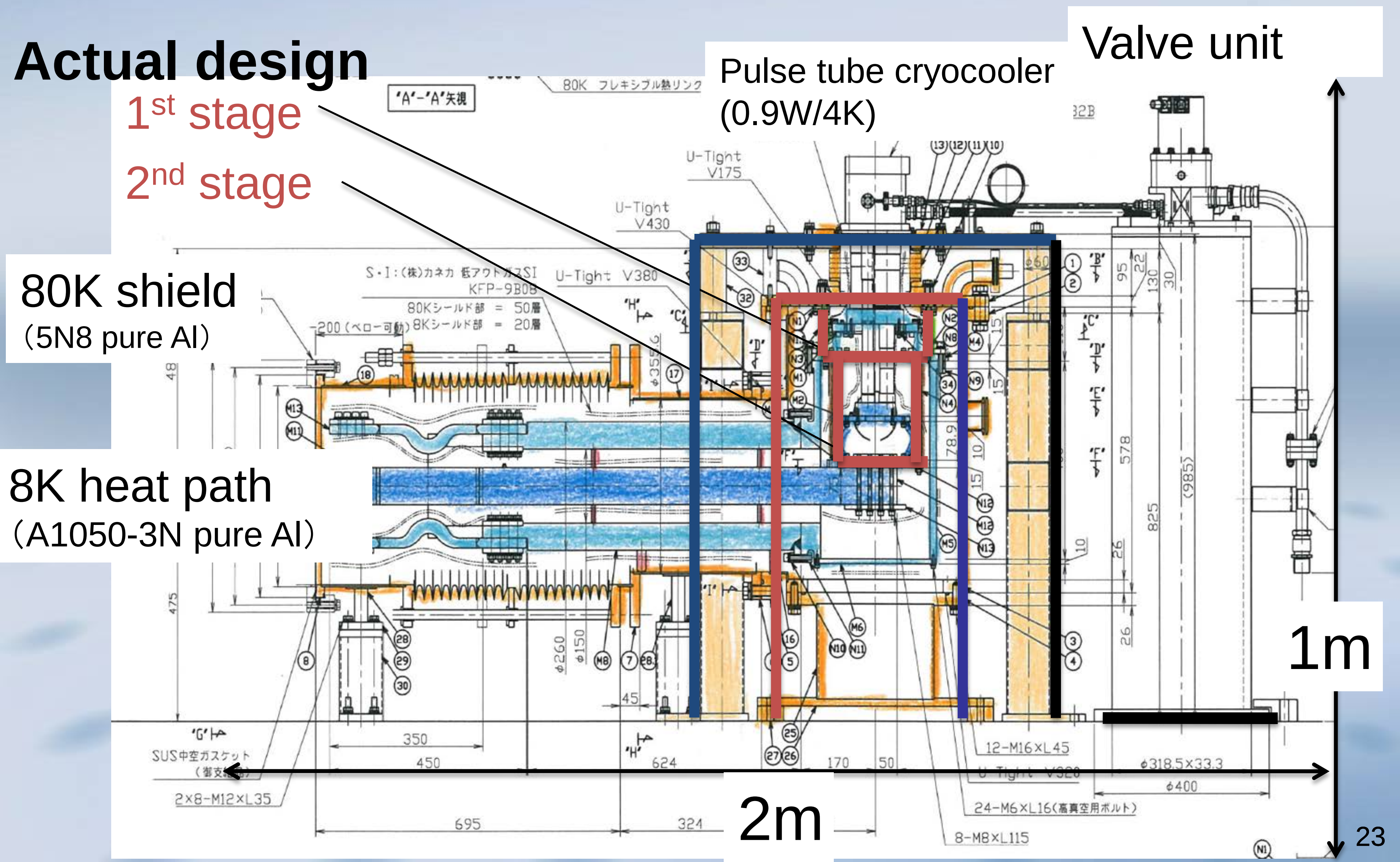


Pulse tube cryocooler (Sumitomo Heavy Industries)

Vibration reduction system

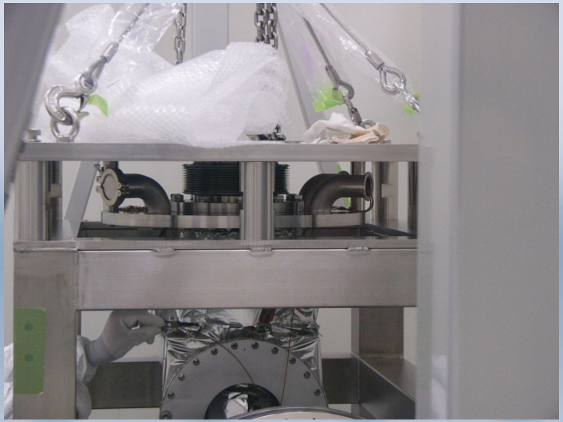
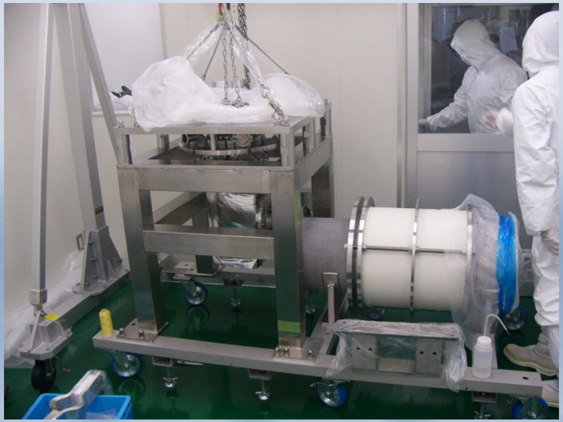
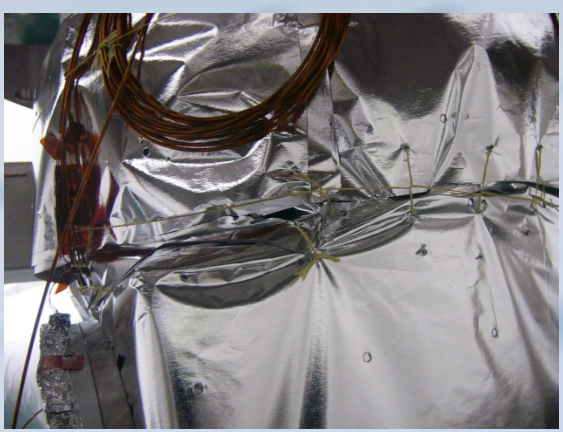
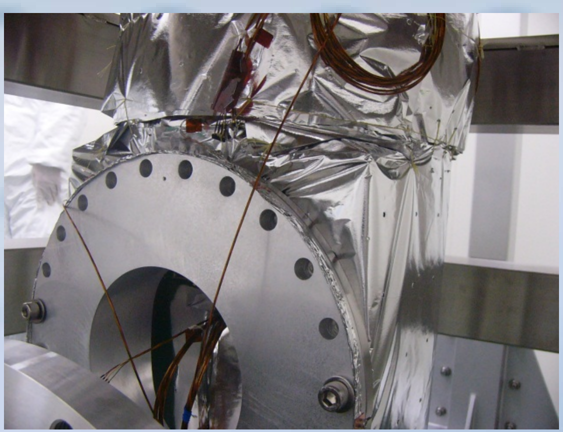
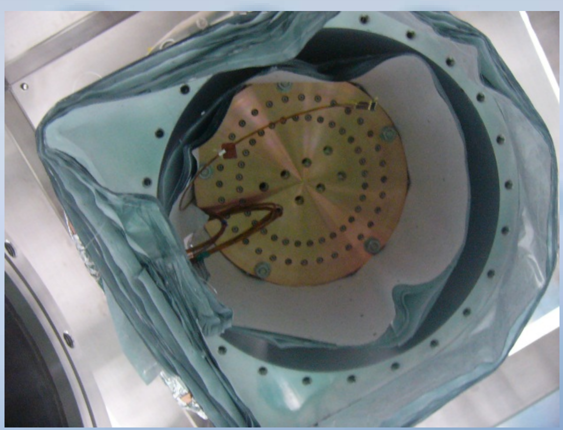
Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

4. Cryocooler unit



4. Cryocooler unit

Assembly **Jecc Torisha Kawagoe Factory**

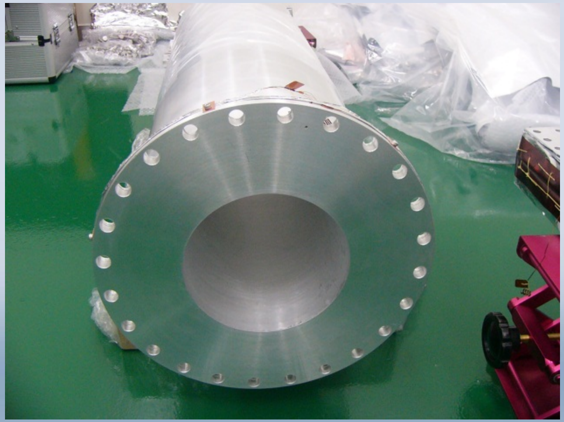







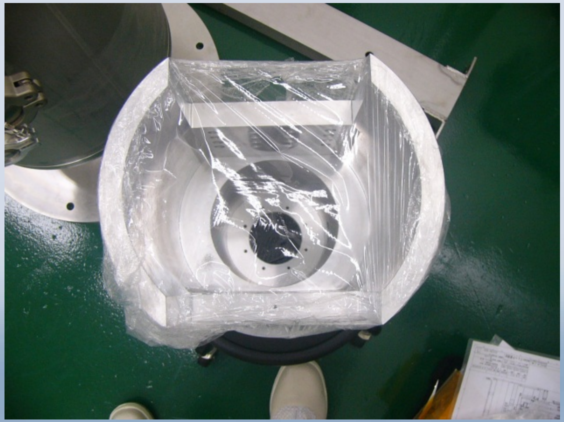
Work progress in clean room with JIS class 7 (US class 10000)

4. Cryocooler unit

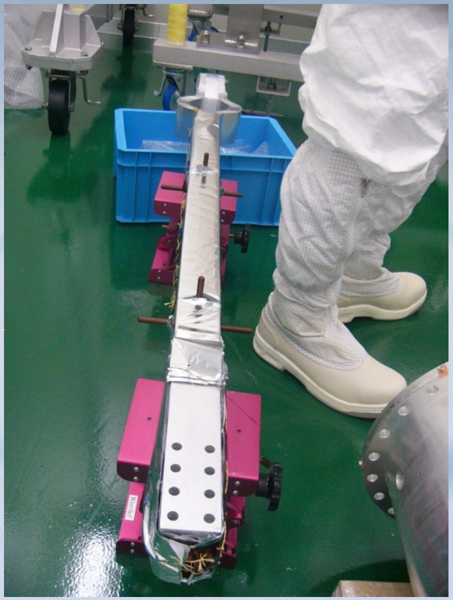
Assembly

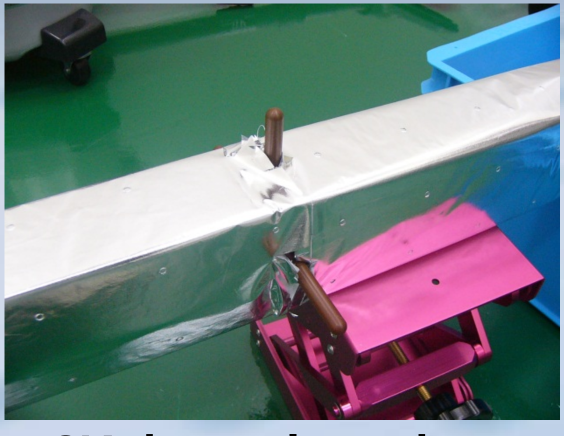
Jecc Torisha
Kawagoe factory



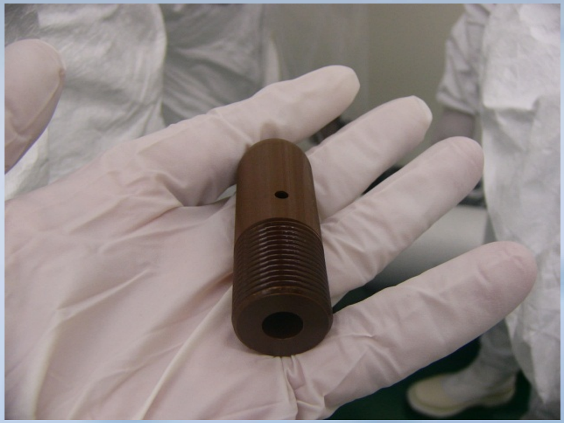


80K thermal conductor





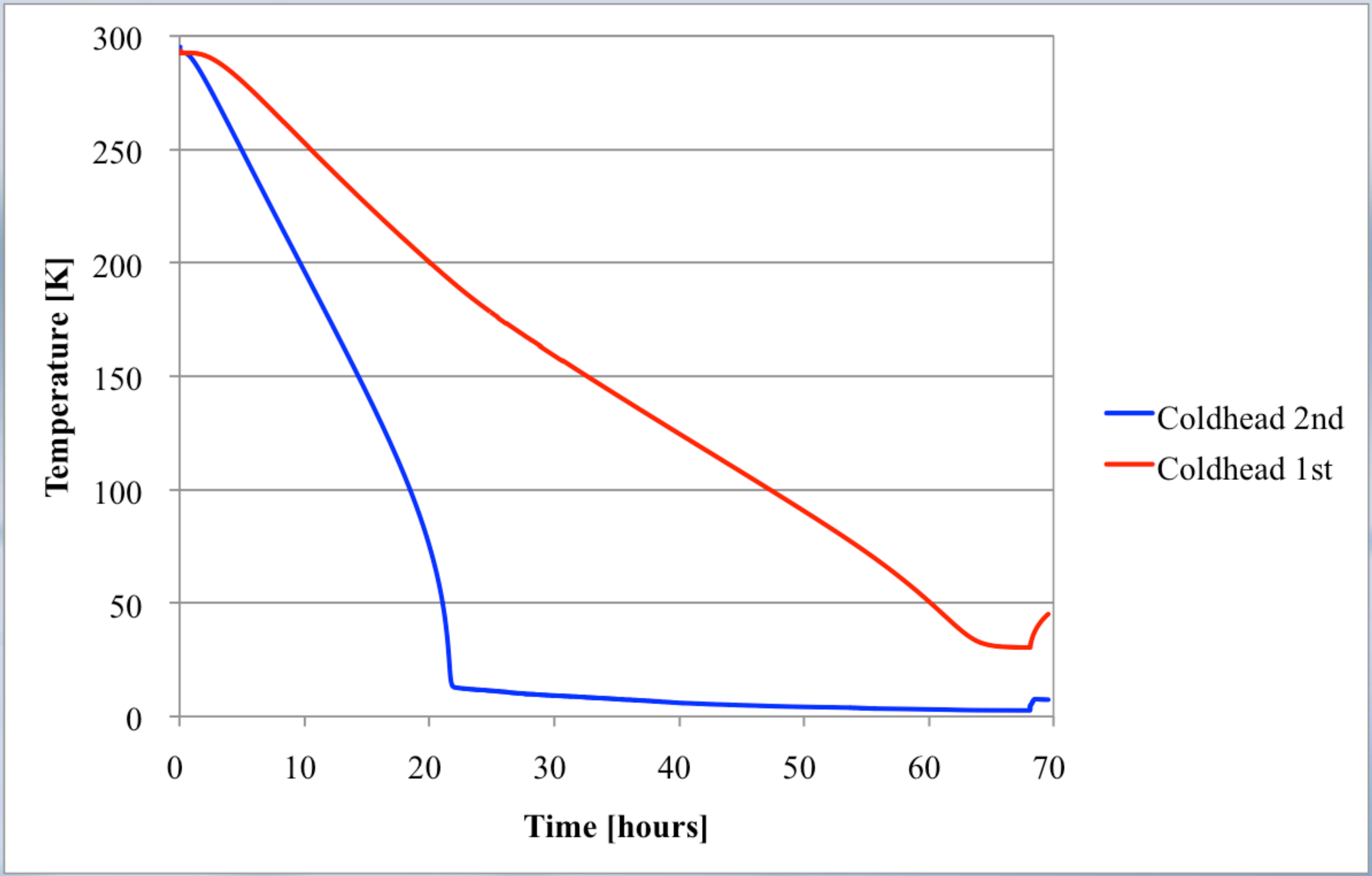
8K thermal conductor



Vespel support rod

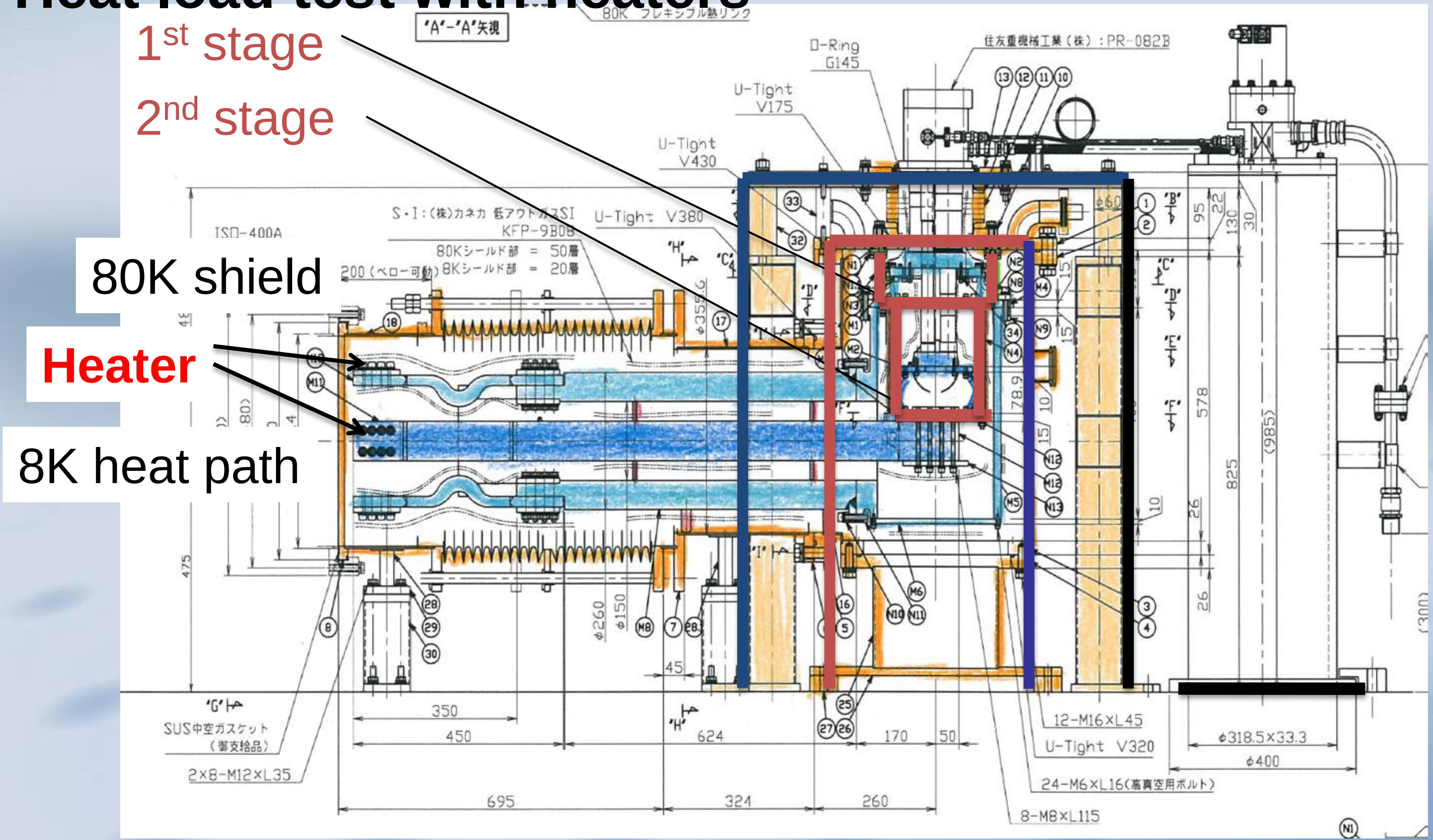
4. Cryocooler unit

Cooling test : Cryocooler works well.



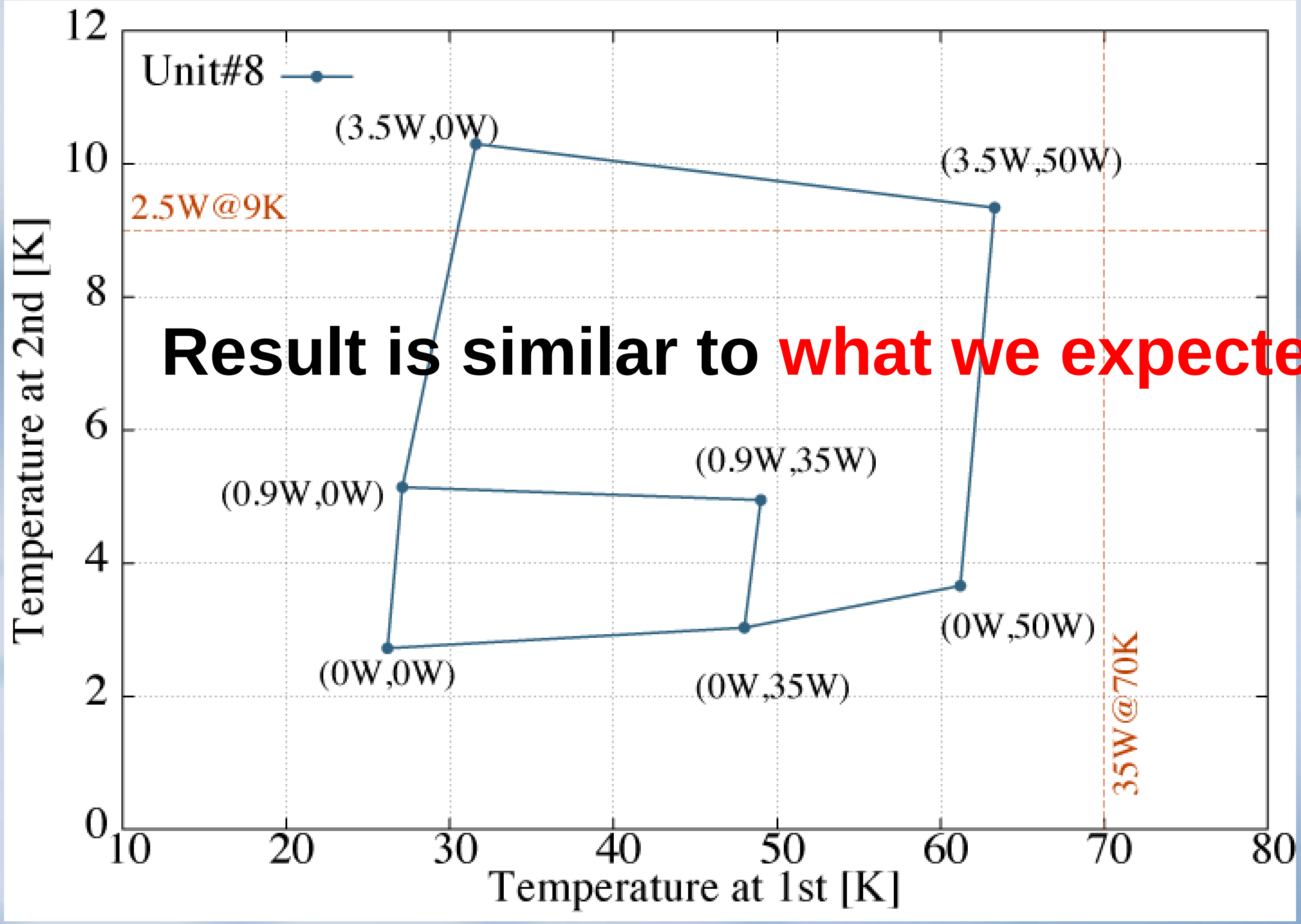
4. Cryocooler unit

Heat load test with heaters



4. Cryocooler unit

Heat load test with heaters



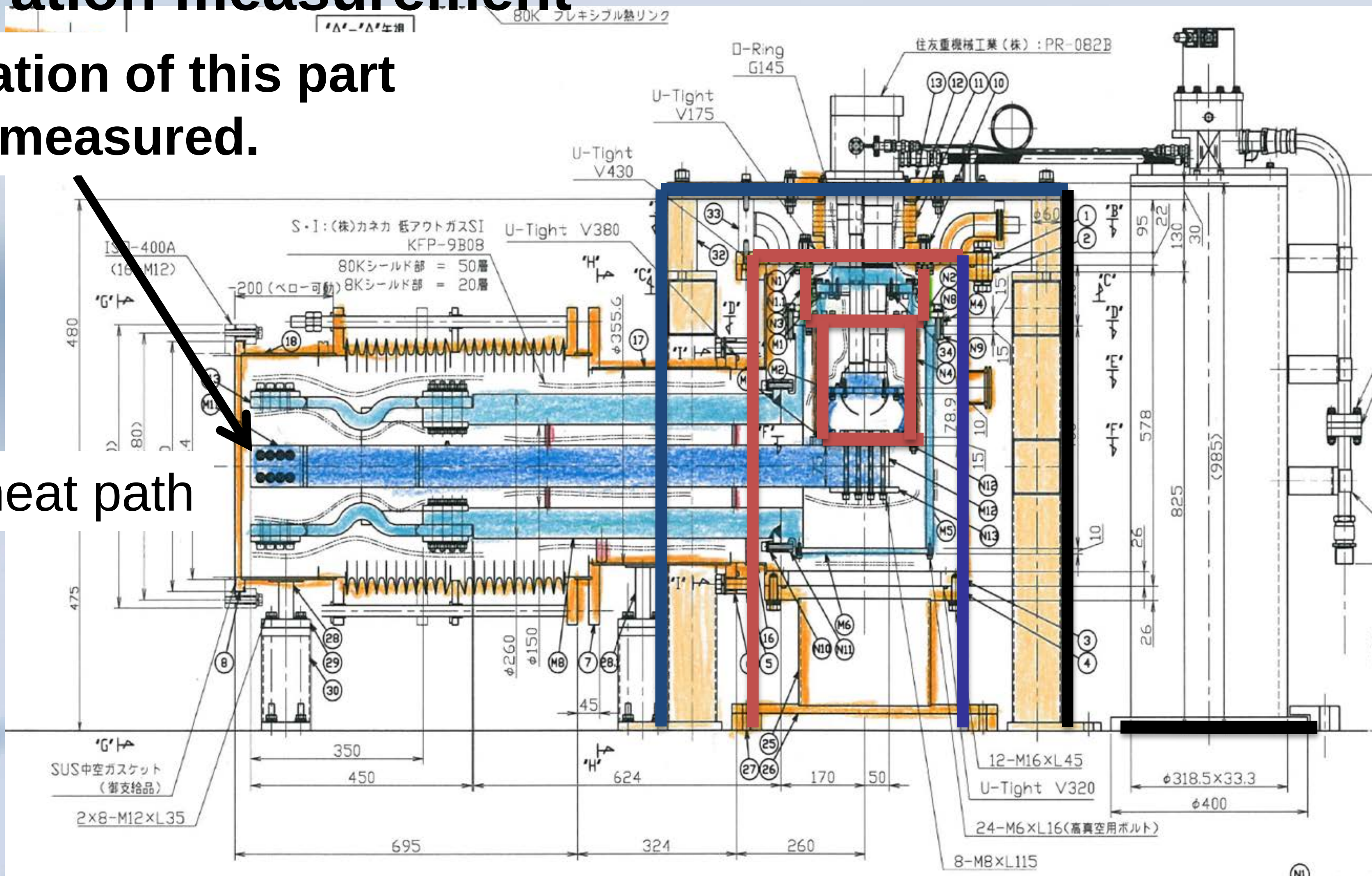
Result is similar to what we expected.

4. Cryocooler unit

Vibration measurement

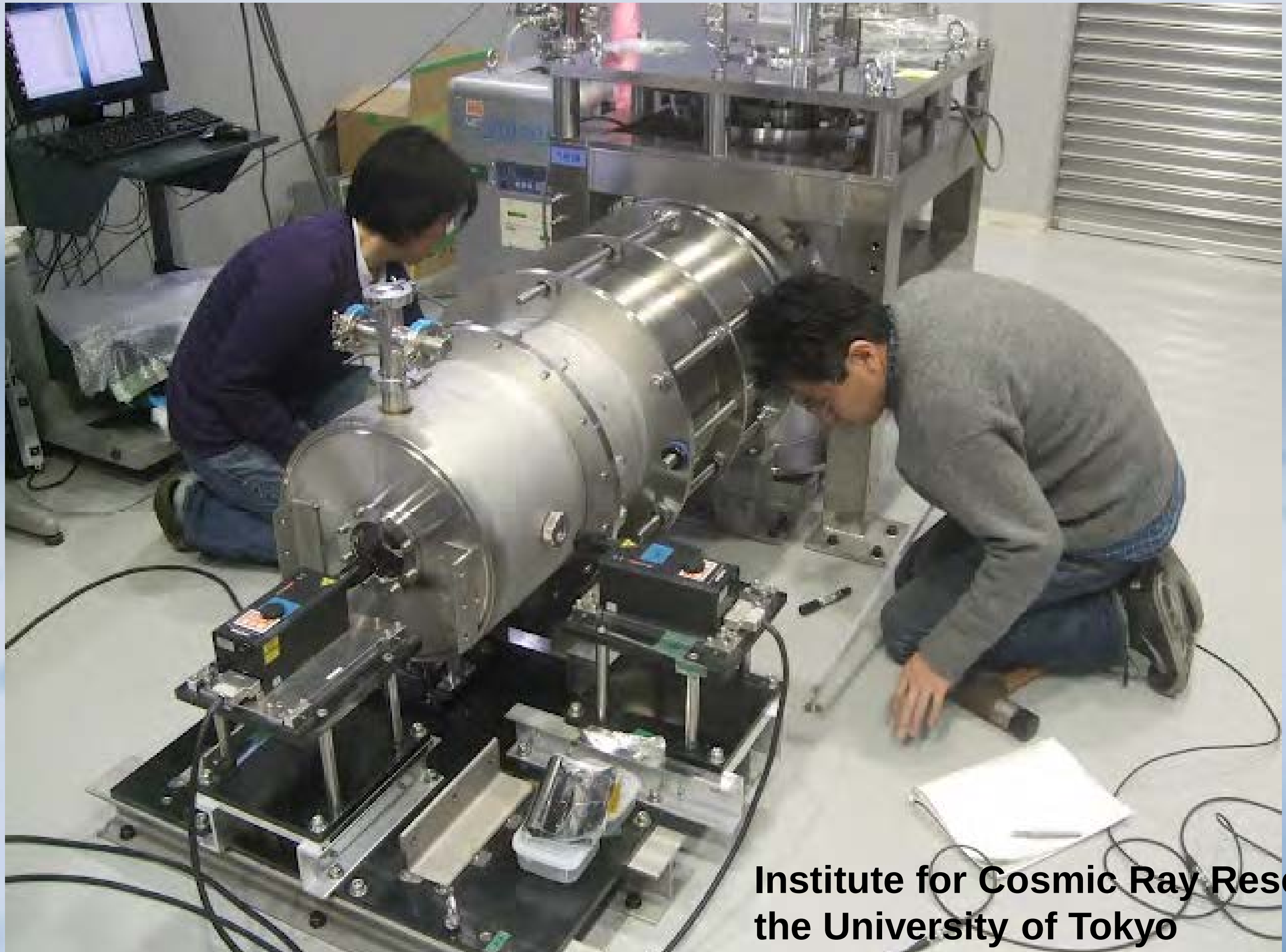
Vibration of this part was measured.

8K heat path



4. Cryocooler unit

Vibration measurement



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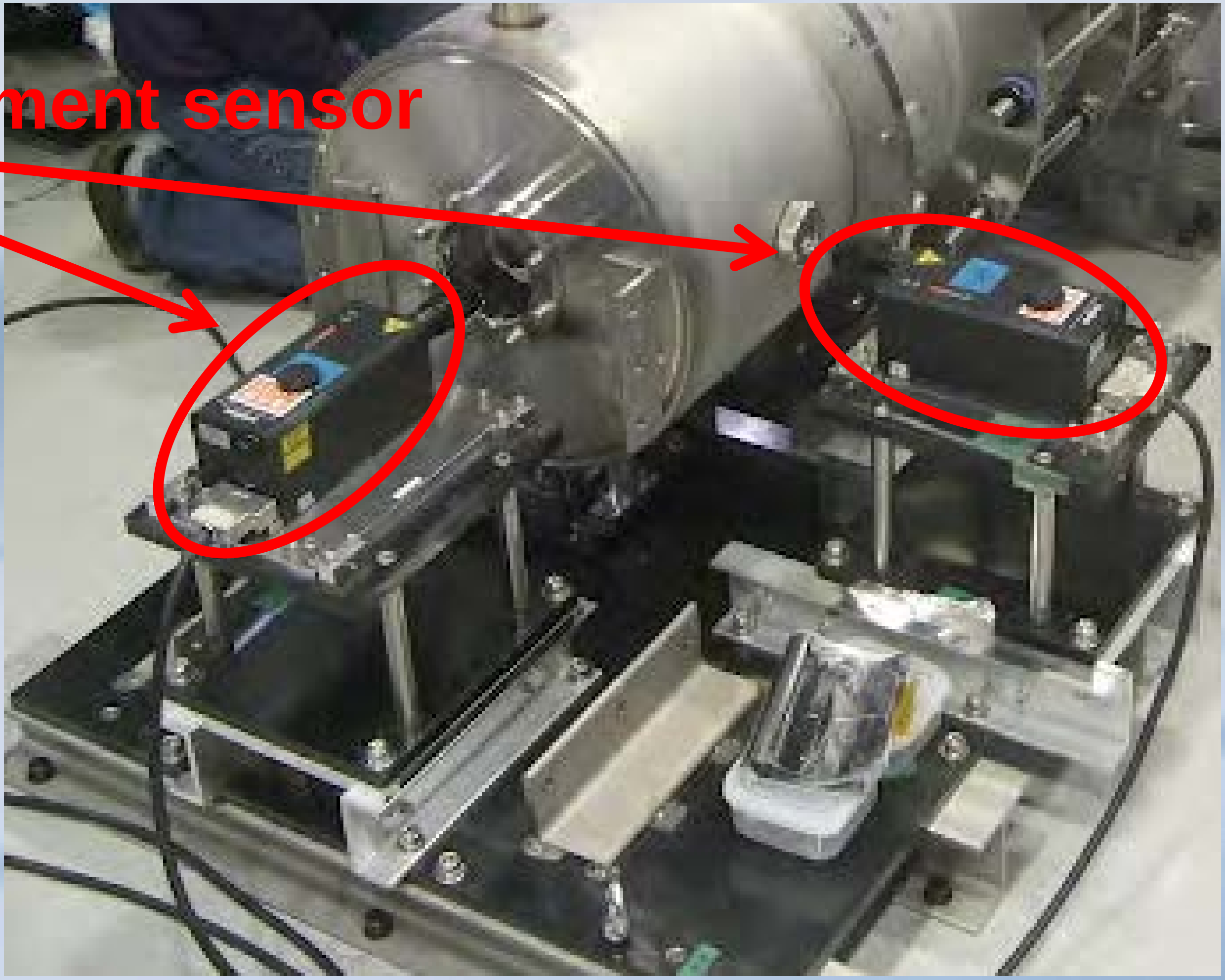
4. Cryocooler unit

Vibration measurement

Displacement sensor

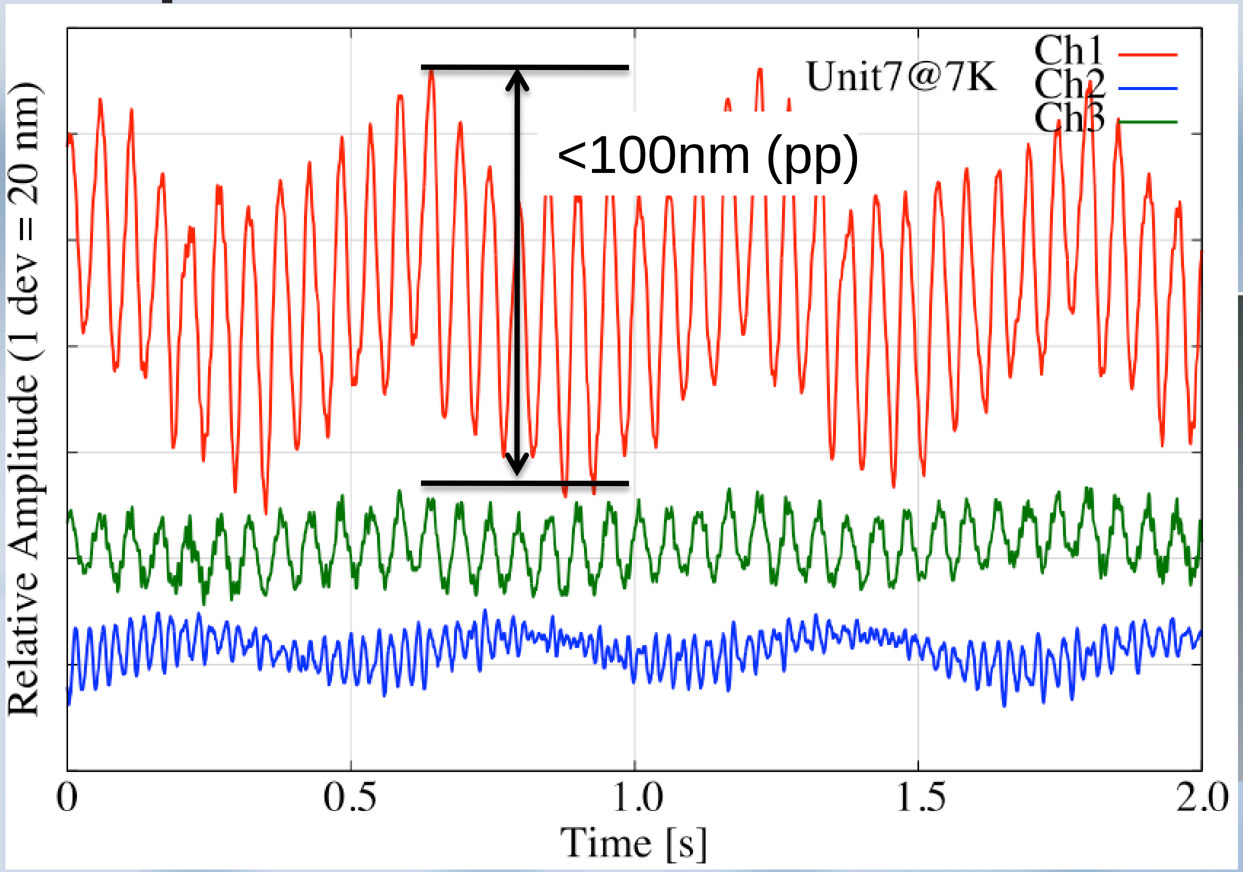


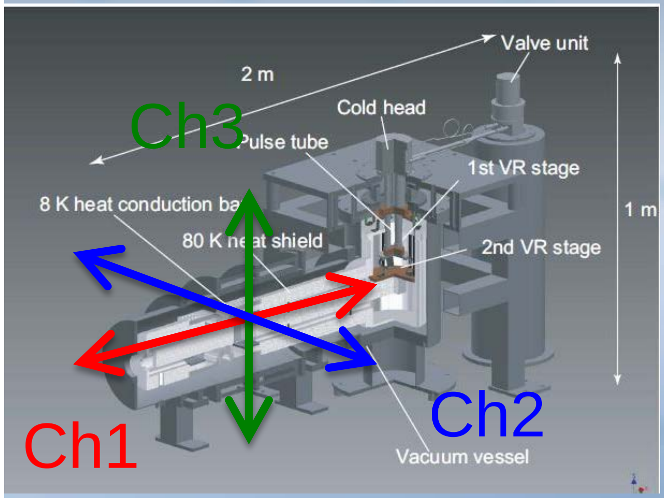
4. Cryocooler unit

Vibration measurement

1.7 Hz vibration by cryocooler head

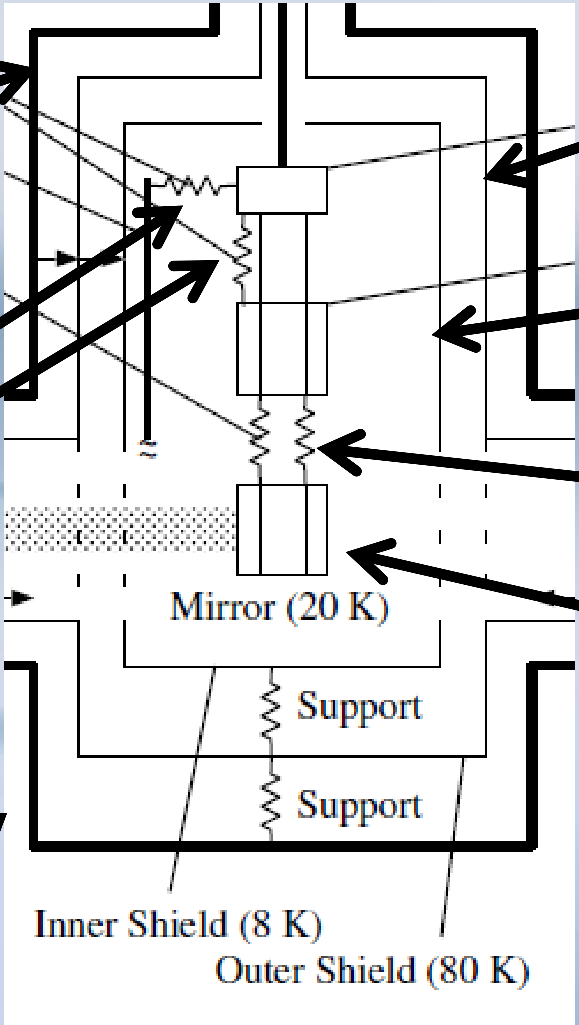
Amplitude is smaller than 100 nm (requirement).





5. Cryogenic payload

Outline of cryogenic payload



Vacuum chamber (300K)

Heat links (pure Al)

Outer shield (80K)

Inner shield (8K)

Sapphire fiber

Sapphire mirror (About 20K)

Y. Sakakibara et al., Classical and Quantum Gravity 29(2012)205019.

5. Cryogenic payload

The development should be in progress for bKAGRA (2016-) in iKAGRA phase.

In iKAGRA phase (before installation in mine)

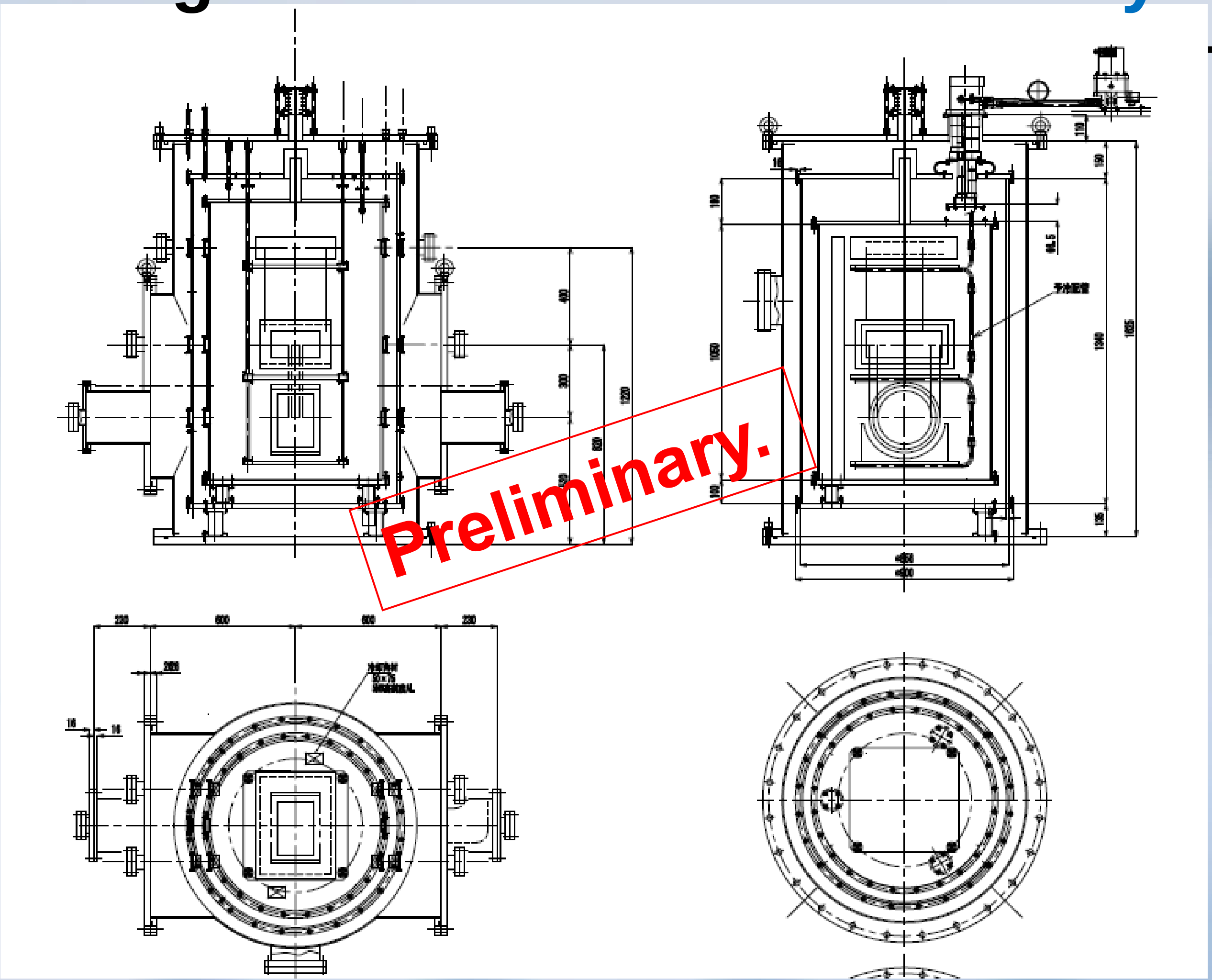
(i) Experiment of 1/4 cryostat in ICRR to check payload performance
1/4 means number of cryocooler, not size.

(ii) Other R&D
- **(b) Initial cooling time**
- **(c) Sapphire fibers with nail heads**
- **(d) Coating mechanical loss**
- **(e) Vibration of shield**

5. Cryogenic payload

(a) Preparation for 1/4 cryostat

Design and discussion for 1/4 cryostat to check payload is in progress.



Bid (for parts) will be opened in this December.

5. Cryogenic payload

(b)Initial cooling time

Initial cooling time of KAGRA cryostat and cryogenic payload is about 2 months (if no tricks).

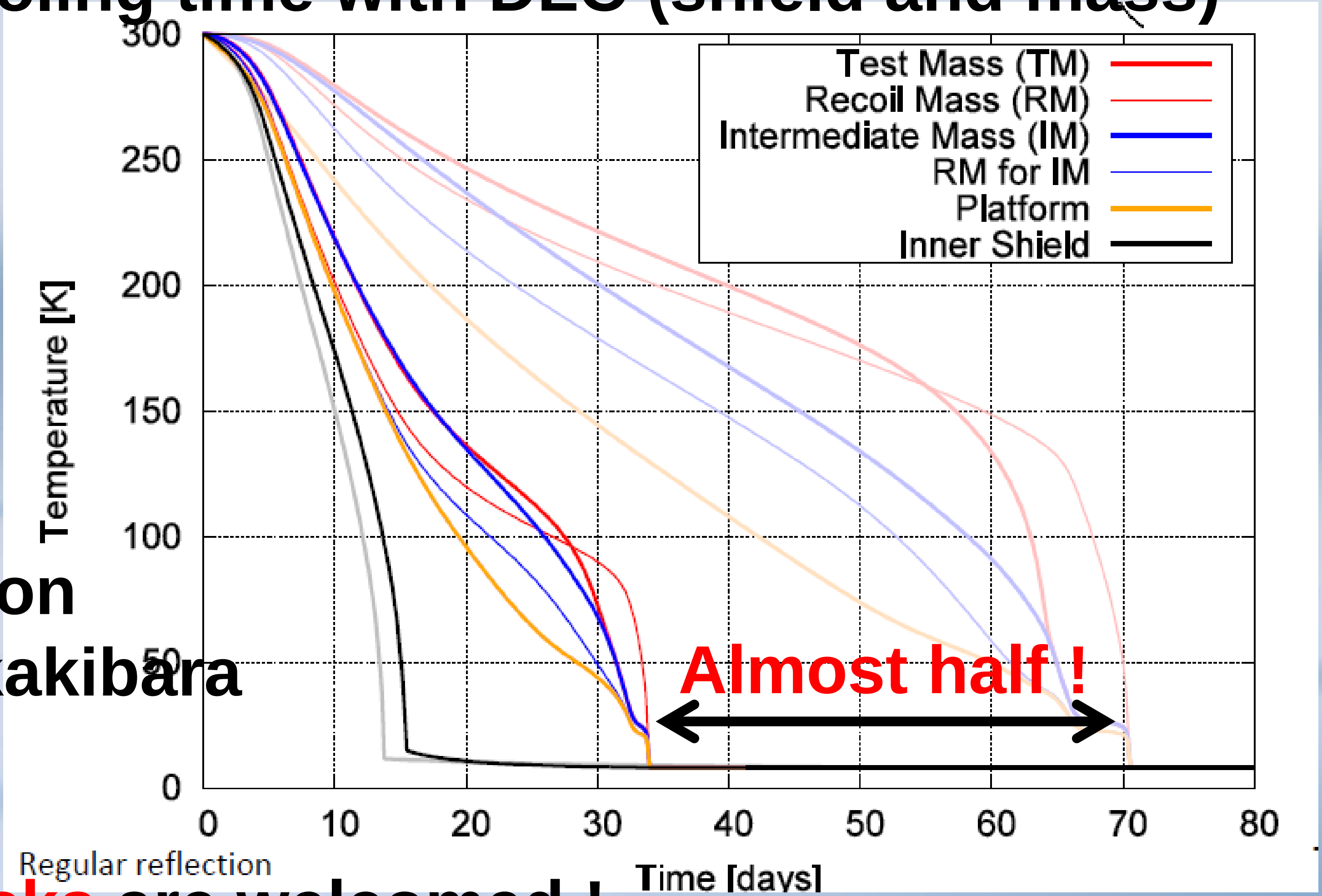
At beginning of initial cooling, heat transfer is dominated by radiation.

Diamond Like Carbon (DLC) coating
(High emissivity, Large radiation)
on shields and payload (except for mirror)

5. Cryogenic payload

(b)Initial cooling time

Initial cooling time with DLC (shield and mass)



Calculation by Y. Sakakibara

Other tricks are welcomed !

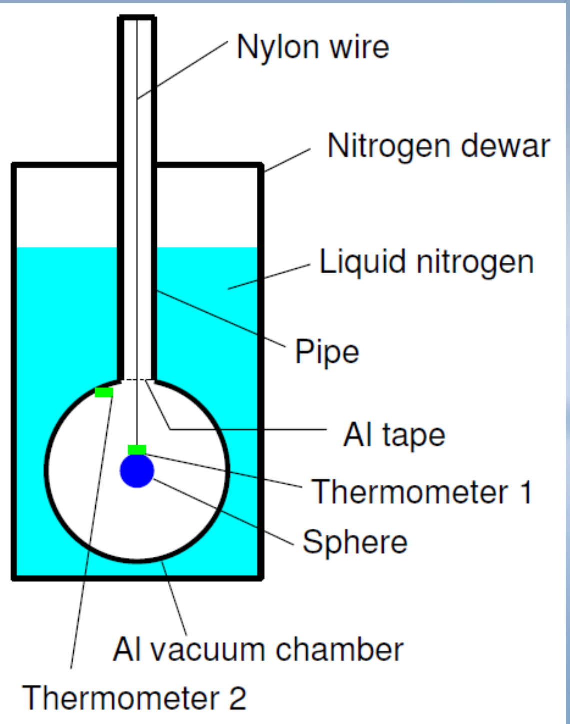
5. Cryogenic payload

(b)Initial cooling time

Experimental test of effect of high emissivity coating (DLC)

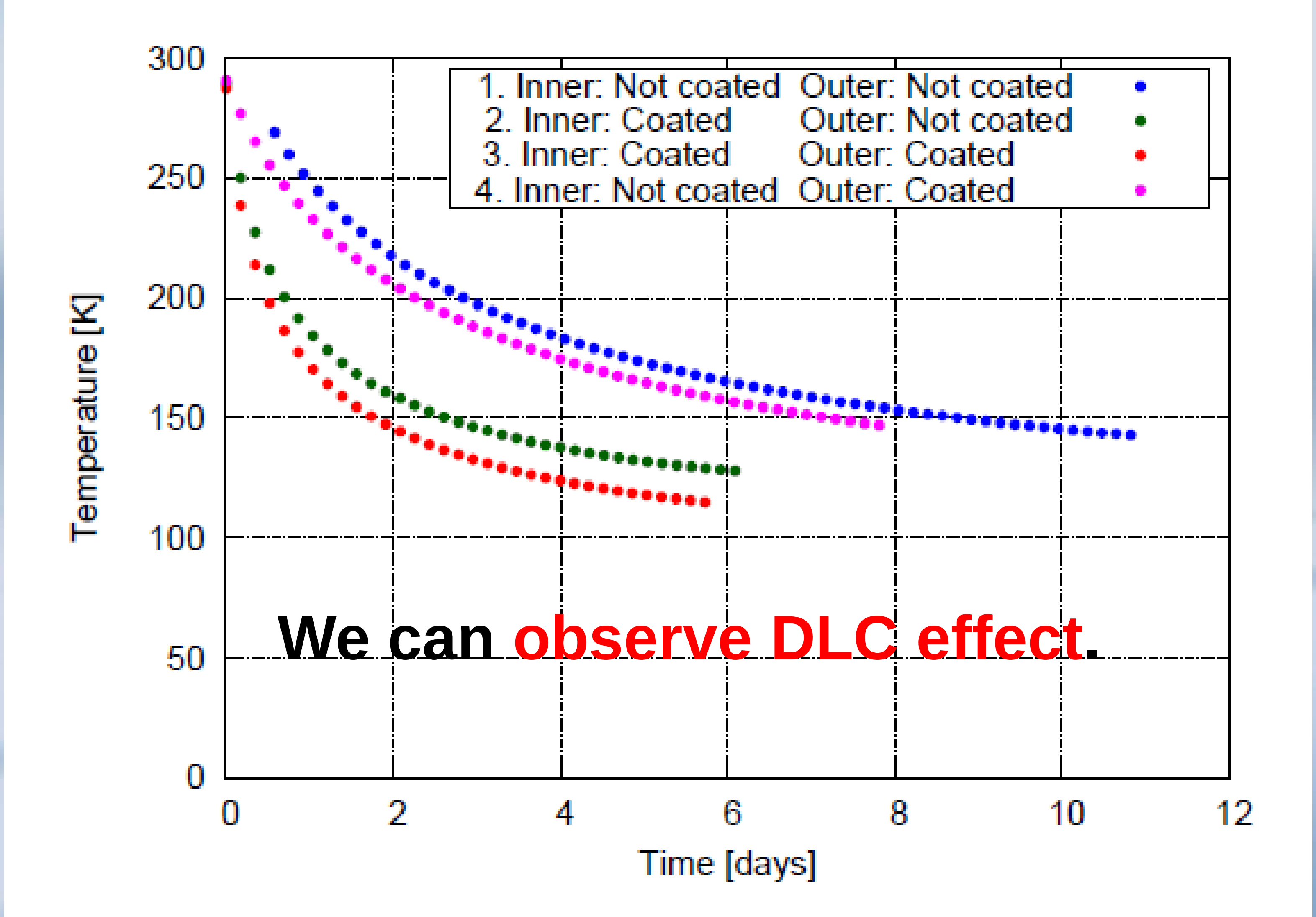
Inner sphere (copper) is suspended
inside outer sphere (aluminum) at 77 K

Cooling time is examined with and without DLC coating



5. Cryogenic payload

(b)Initial cooling time



5. Cryogenic payload

(b)Initial cooling time

We have plans of experiments in Toshiba cooling test of KAGRA cryostat.
We suspend something without heat link inside shield and monitor the temperature of something during cooling test.

What is something ?
Sample 1 : Metal hollow sphere
Sample 2 : Dummy payload (hollow masses)

5. Cryogenic payload

(b)Initial cooling time

Sample 1 : Metal hollow spheres (100 mm in diameter)

Y. Sakakibara's small experiment: 30 mm in diameter

Both spheres have already been prepared.
The sphere without DLC will be suspended in shield the day after tomorrow.

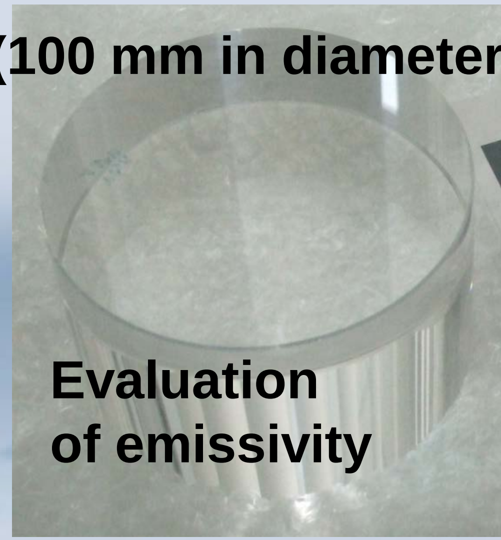
5. Cryogenic payload

(b)Initial cooling time

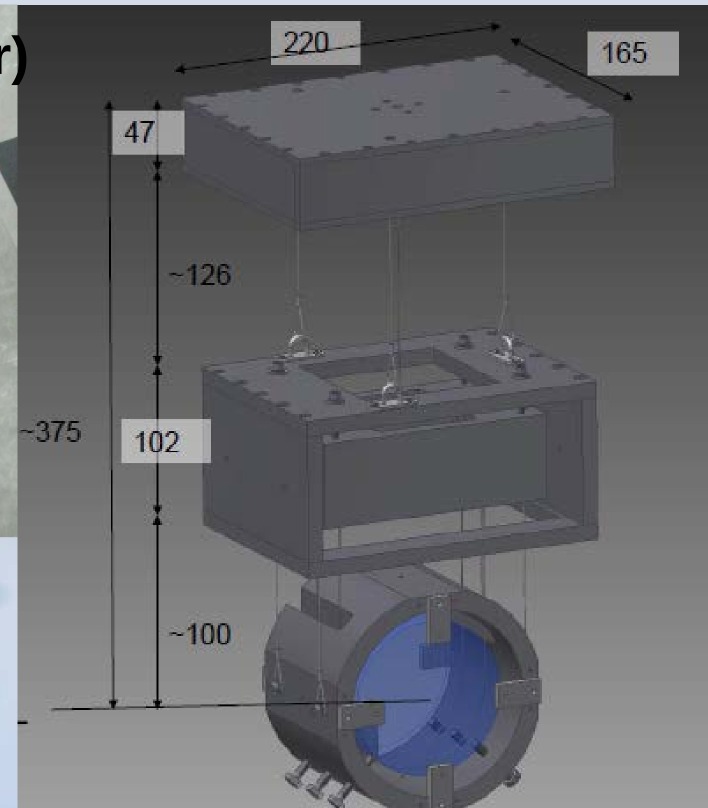
Sample 2 : Dummy payload (hollow masses)

Half size
Hollow masses
(~5 kg)
DLC coating
Sapphire bulk as dummy mirror

(100 mm in diameter)



Evaluation of emissivity



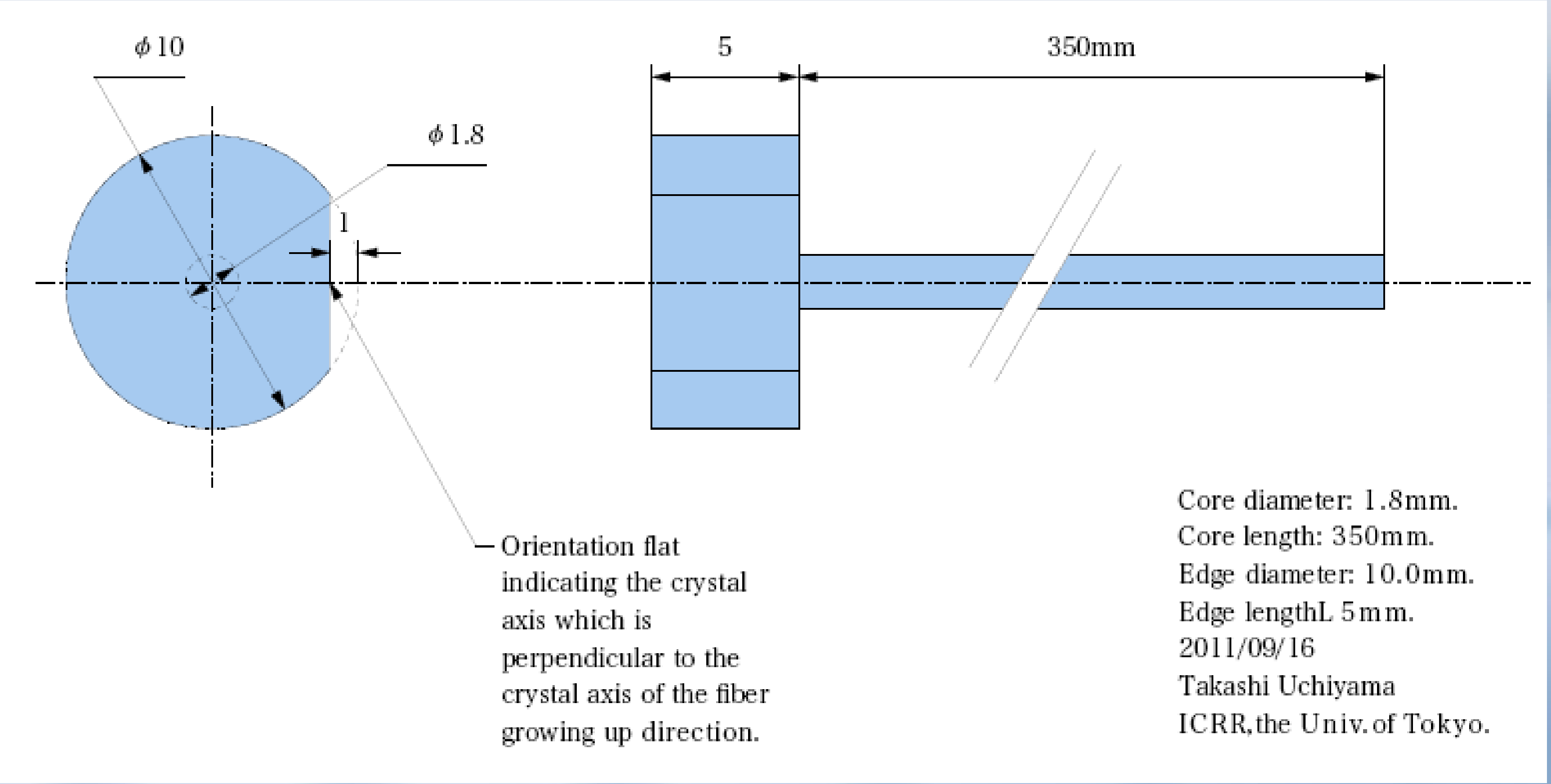
Preparation is in progress.

S. Koike

5. Cryogenic payload

(c) Sapphire fibers with nail heads

Test sample (T. Uchiyama)



5. Cryogenic payload

(c) Sapphire fibers with nail heads

T. Uchiyama asked MolTech GmbH (Germany).
Sapphire fibers have already come !

Length = 350 mm diameter = 1.8 mm
Almost as needed in bKAGRA.
Need to check the quality and improvement .

5. Cryogenic payload

(c) Sapphire fibers with nail heads

Ettore Majorana asked IMPEX HighTech GmbH (German company).

They can make similar fibers (nail heads on the both ends).

Finally ...

5. Cryogenic payload

(c) Sapphire fibers with nail heads

IMPEX fibers arrived !

5. Cryogenic payload

(c) Sapphire fibers with nail heads

Quality check

Q-value and profile of Moltech fibers:
Y. Sakakibara at Glasgow and Jena.

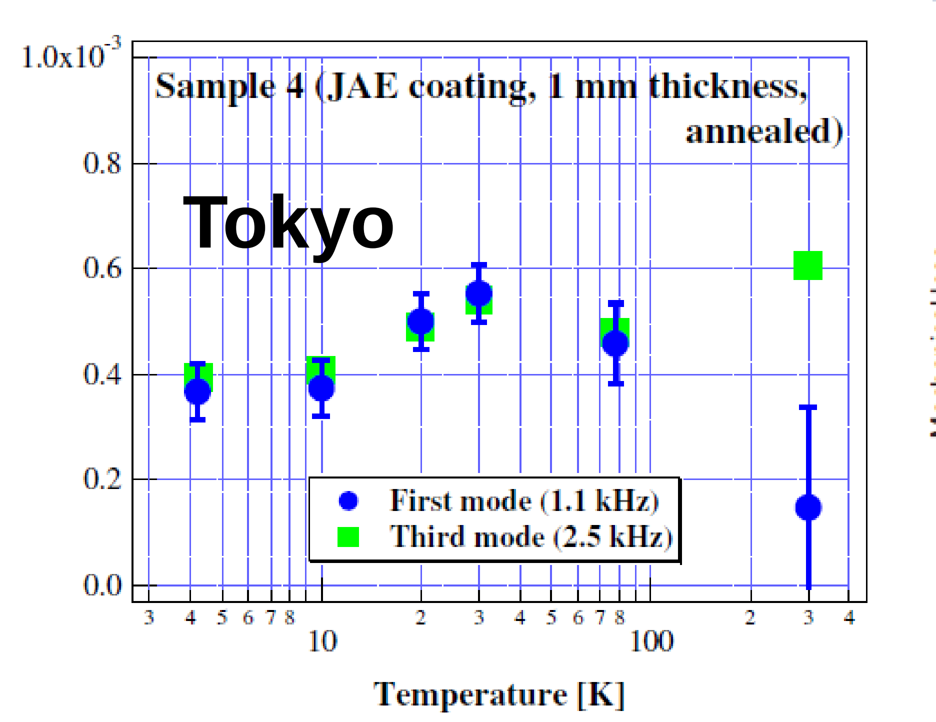
Y. Sakakibara will report his results tomorrow.
Rebecca Douglas presents a poster.

Two IMPEX fibers were sent to Jena.

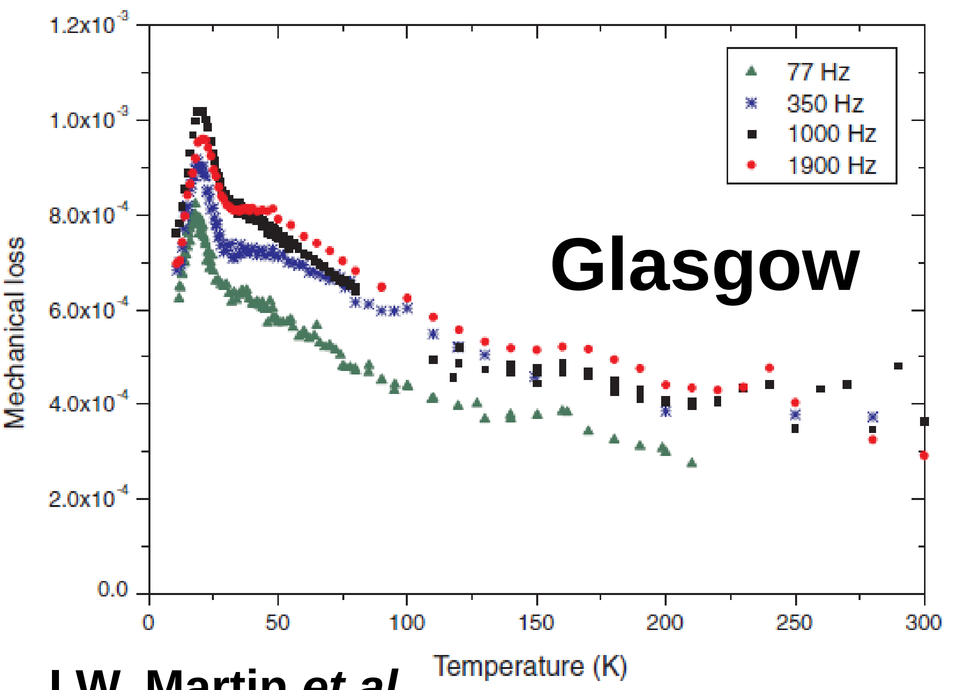
5. Cryogenic payload

(d) Coating mechanical loss

Discrepancy between Tokyo and Glasgow



K. Yamamoto *et al.*,
Physical Review D 74 (2006) 022002.



I.W. Martin *et al.*,
Classical and Quantum Gravity
27 (2010) 225020.

5. Cryogenic payload

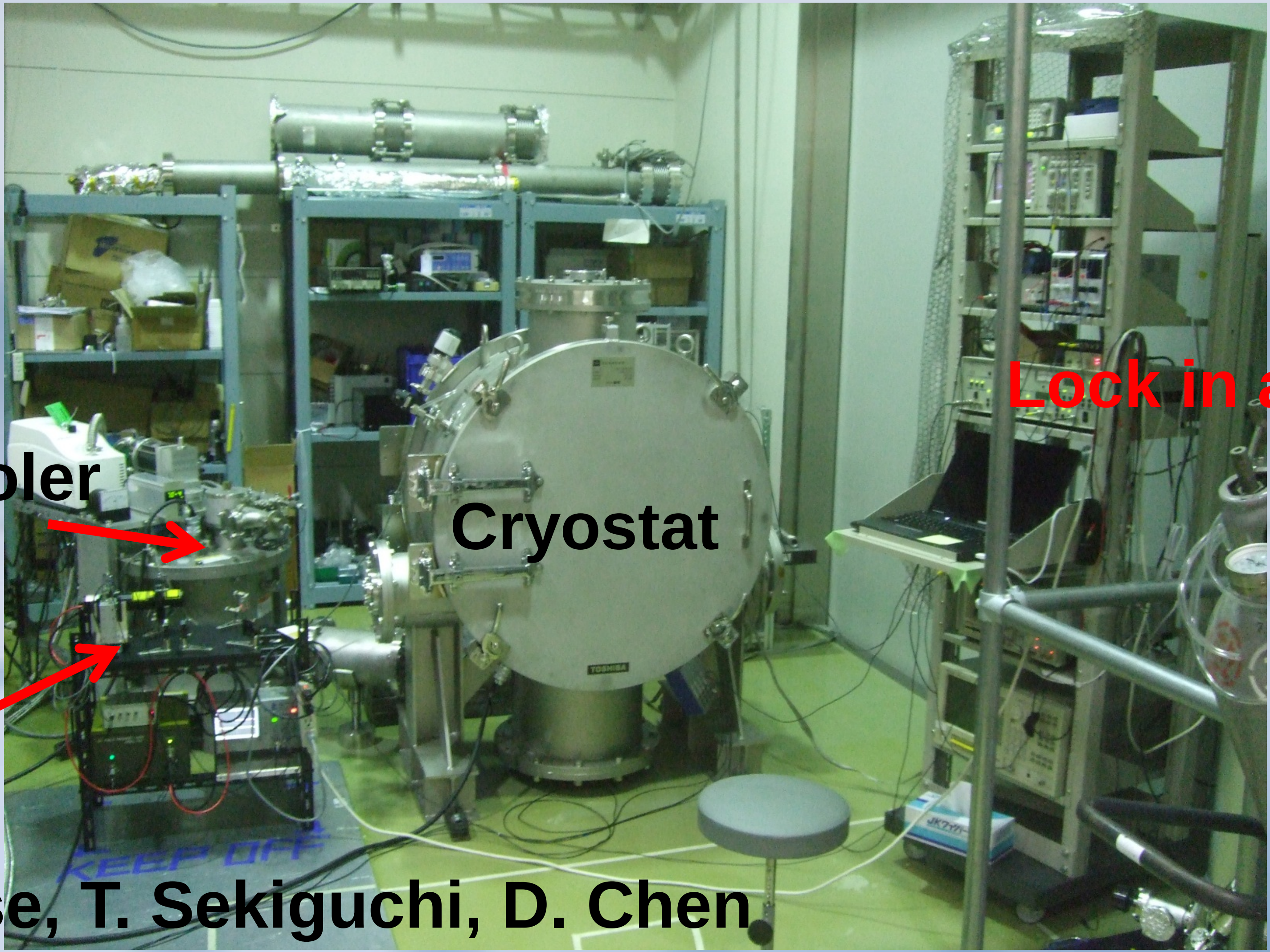
(d) Coating mechanical loss

Some samples of Japanese coating were sent to Glasgow.
Y. Sakakibara measured these samples in Glasgow (room temperature); Detalis are in tomorrow his talk.
Glasgow group continues the mission for the cryogenic temperature.

E. Hirose is measuring mechanical loss of other Japanese samples in ICRR (University of Tokyo).
K. Craig and P. Murray (supported by ELiTES) joined on the October. Measurement is in progress.

5. Cryogenic payload

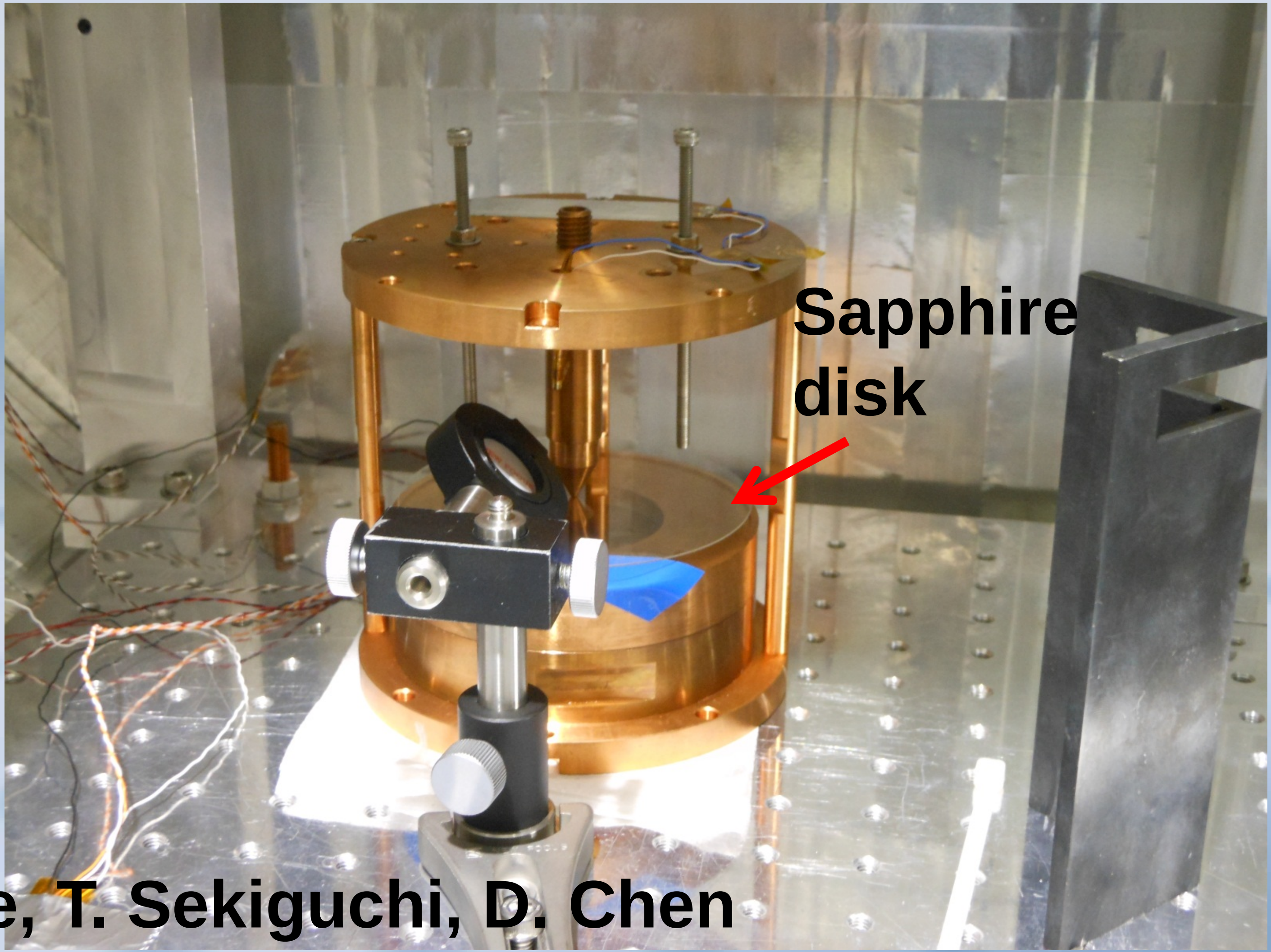
(d) Coating mechanical loss



E. Hirose, T. Sekiguchi, D. Chen

5. Cryogenic payload

(d) Coating mechanical loss



E. Hirose, T. Sekiguchi, D. Chen

5. Cryogenic payload

(e) Vibration of shield

Vibration of shield could be problems.

Vibration via heat links, Scattered light

We must measure the vibration of shield.

This measurement is

at cryogenic temperature and in vacuum.

Luca Naticchioni (supported by ELiTES) and Dan Chen will measure vertical and horizontal vibration of radiation shield of KAGRA in cooling test of Toshiba, respectively.

5. Cryogenic payload

(e) Vibration of shield

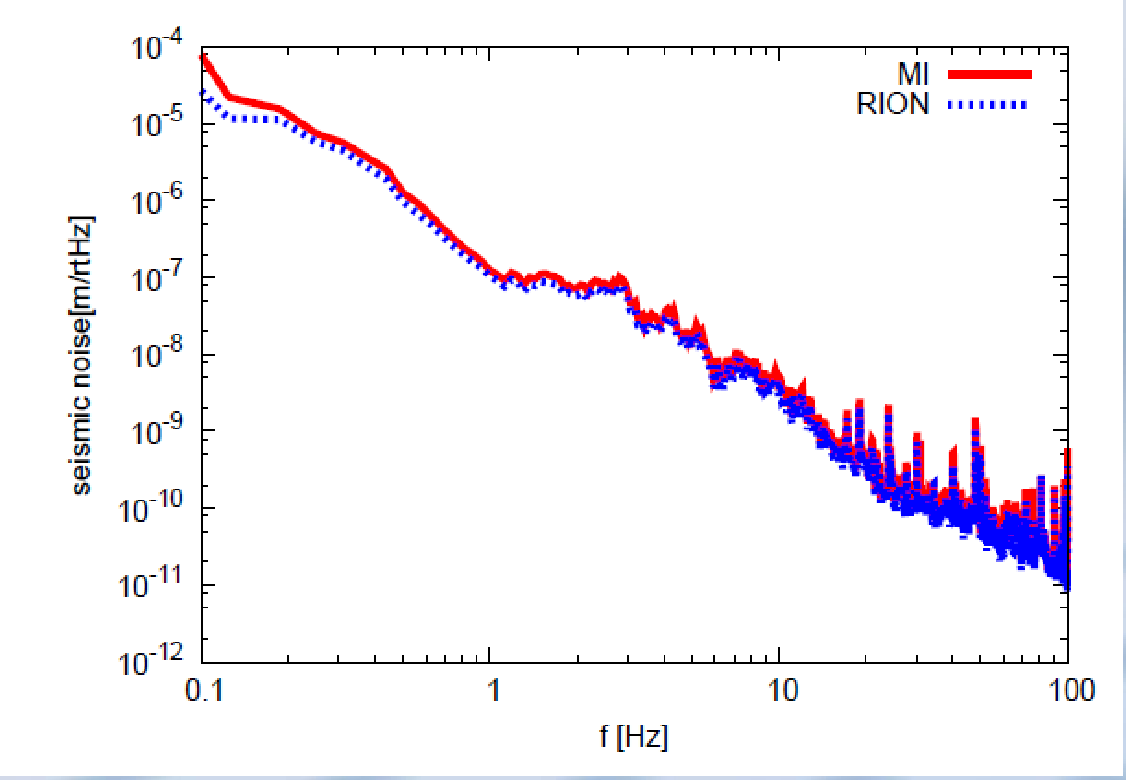
Luca Naticchioni's Accelerometer
F. Ricci's talk

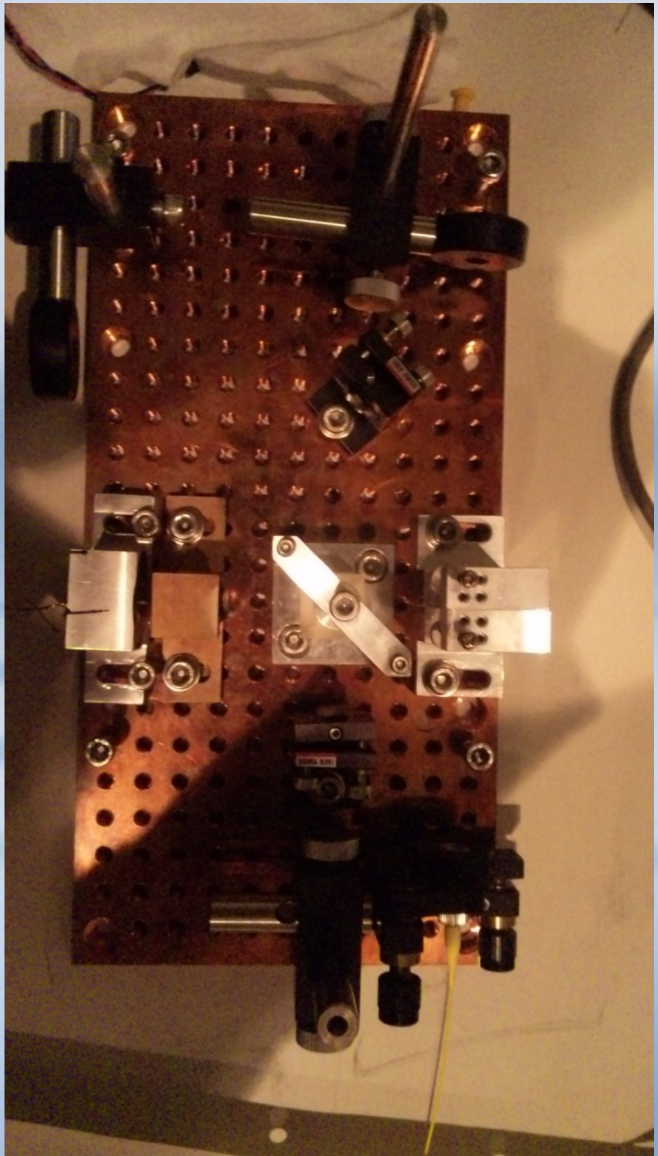
Luca's comment
We are close to the end of the outgassing test of the accelerometer and preliminary results are encouraging.

5. Cryogenic payload

(e) Vibration of shield

Dan Chen's accelerometer





His accelerometer is consistent with commercial one (in air).

5. Cryogenic payload

(e) Vibration of shield

Dan Chen’s accelerometer

He is preparing the cryogenic test before measurement in Toshiba.

6. ELiTES

ELiTES: ET-LCGT interferometric Telescope Exchange of Scientists

Grant for collaboration about cryogenic between KAGRA and ET

European 7th Framework Programme

Marie Curie action (Mar. 2012 - Feb. 2016)

European people can visit Japan for KAGRA.

6. ELiTES

First ELiTES meeting on the 3rd and 4th of Oct.
in Tokyo

6. ELiTES

(1)After this meeting, many European researchers continued their stay in Japan.
Many fruitful discussions and experiments
One example: Coating mechanical loss measurement at cryogenic temperature
(K. Craig and P. Murray)

(2)Measurement of vibration of shield for KAGRA

L. Naticchioni and E. Majorana visited (and will visit) Japan.

6. ELiTES

Although ELiTES supports the fee for European people …

(3) Y. Sakakibara stay in Glasgow and Jena (from October to December) to investigate sapphire fibers and coating mechanical loss.

(4) T. Sekiguchi will stay in NIKHEF from next January to March.

Quite good first step of ELiTES !

7. For future

Some items for future research (not perfect list)

(a)Investigation material properties
(Q, thermal conductivity, strength etc.)
of coating, fiber and so on.
(b)Sapphire bonding, Sapphire fiber clamp
(c)Control and damping scheme
Actuators and sensors at cryogenic temperature
(d) Mechanical and thermal simulation for payload
(e) Vertical spring in cryostat
(f) Reduction of initial cooling time
Thermal resistance of clamp ....
(g) Baffles for scattered light in radiation shield
(h) Assembly procedure

7. For future

If you are interested with KAGRA cryogenic mission, could you work with us ?

(1)Postdoc of Institute for Cosmic Ray Research (ICRR), the University of Tokyo

The application is announced every year.
The deadline of the next application is coming soon (21st of Dec.) !

7. For future

If you are interested with KAGRA cryogenic mission, could you work with us ?

(2)Postdoctoral Fellowships for Foreign Researchers, Japan Society for the Promotion of Science (JSPS)

Standard : 2 years position
Application every half year

Short : 1 year position
Application every two months

7. For future

If you are interested with KAGRA cryogenic mission, could you work with us ?

(2)Postdoctoral Fellowships
for Foreign Researchers,
Japan Society for the Promotion of Science (JSPS)

Full professor or associate professor of our group (T. Kajita, K. Kuroda, S. Kawamura, M. Ohashi, S. Miyoki) shoud be your supervisor.
Please contact them or Kazuhiro Yamamoto.

8. Summary

Cryostat : Assembly is in progress.
Cooling test is coming soon.

Cryogenic duct : Optimum position of 5 buffles
Future work : scattered light

Cryocooler unit :
Cooling test and vibration measurement : OK

Cryogenic payload
Preparation for 1/4 cryostat to check
payload performance is in progress.
Current main R&D topics
Inital cooling time, Sapphire fiber with nail head,
Coating mechanical loss, Vibration of shield

8. Summary

ELiTES has already started and supports the development of KAGRA cryogenic system.

If you want to join our mission, let us know.

Thank you for your attention !

2. Issues

(1)How to assemble
Details of construction, clean room ….

(2)Strength
Tensile strength, development of clamp, sapphire bonding …

(3)Control and damping system to reduce fluctuation and instability
Actuators (what and where), resonant mode (frequency and Q) and so on

2. Issues

(4)Cooling

Temperature of mirror (below 20 K),
initial cooling time,
heat resistance of clamp …

(5)Noise

Thermal noise, vibration via
vibration isolation system and heat links …

2. Cryostat

Design of cryogenic duct

In order to calculate the optimum configuration of the baffles needed to design the duct shield, we studied 560 cases (the number of combinations of 3 taken from 16, ${}_{16}C_3$) of the baffle configuration, where any of the three baffles were placed at $x = 1, 2, 3, \ldots, 16$ m and the other two baffles were fixed at $x = 0$ and 17 m. The result showed that the baffle position of

$$x = 0, 10, 14, 16, 17 \text{ m} \tag{23}$$

afforded the minimum P_i.

The total emitted power can be expressed as

$$P_0 = \epsilon\sigma T^4(\pi a^2) = 29.2 \text{ W}, \tag{24}$$

where $\epsilon = 0.1$ is emissivity of the beam duct (stainless steel, at room temperature). Under these conditions, we have

$$P_i = 0.084^{+0.060}_{-0.031} \text{ W}, \qquad P_r = 8.5^{+1.5}_{-0.9} \text{ W}, \qquad P_a = 21^{-2}_{+1} \text{ W}. \tag{25}$$

The errors given in the superscripts are when $R = 0.96$, and those in the subscript, when $R = 0.92$. The thermal radiation absorbed by the mirror is

$$2\epsilon_{sap} P_i = 0.02 \text{ W}. \tag{26}$$

The emissivity of sapphire, the material the mirror is made of, at 20 K is $\epsilon_{sap} = 0.1$ [18]. The factor 2 in the above equation is due to the fact that two duct shields are installed: one in front and the other behind the mirror. Thus, the value of P_i is one order of magnitude smaller than that of the designed heat (0.9 W) that can be absorbed by the mirror [19]. The thermal radiation through the duct shield can be reduced to the extent that the mirror is sufficiently cooled.

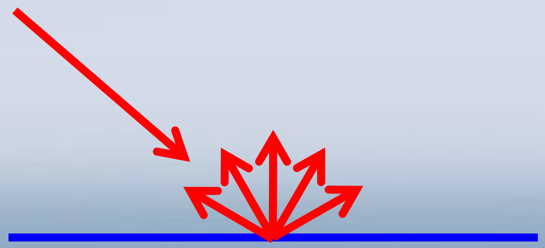
Y. Sakakibara *et al*., Classical and Quantum Gravity 29 (2012) 205019.

Model of heat transfer via radiation

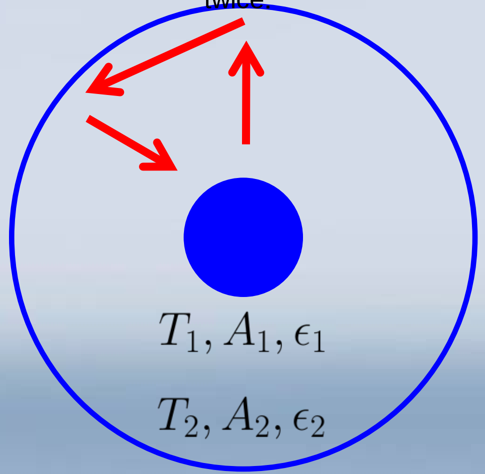
A: surface area
ε: emissivity

Some rays from inner sphere are reflected by outer sphere more than twice.

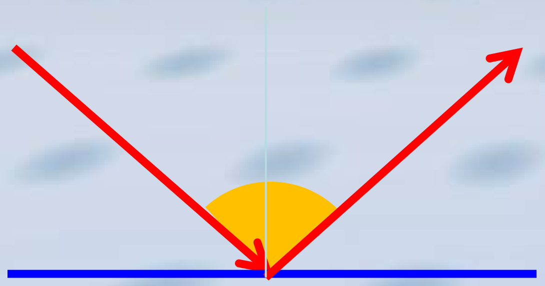
- Gray body model
  - Surface reflects radiation to all angle



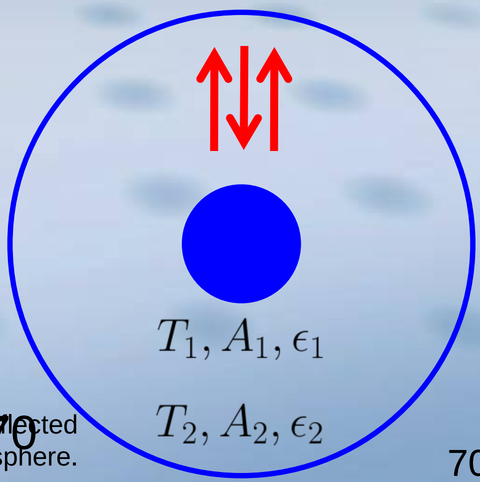
$$Q = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)}$$



- Regular reflection model
  - Surface reflects radiation to the same angle as incident angle



$$Q = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$



All rays from inner sphere are reflected alternatively by outer and inner sphere.

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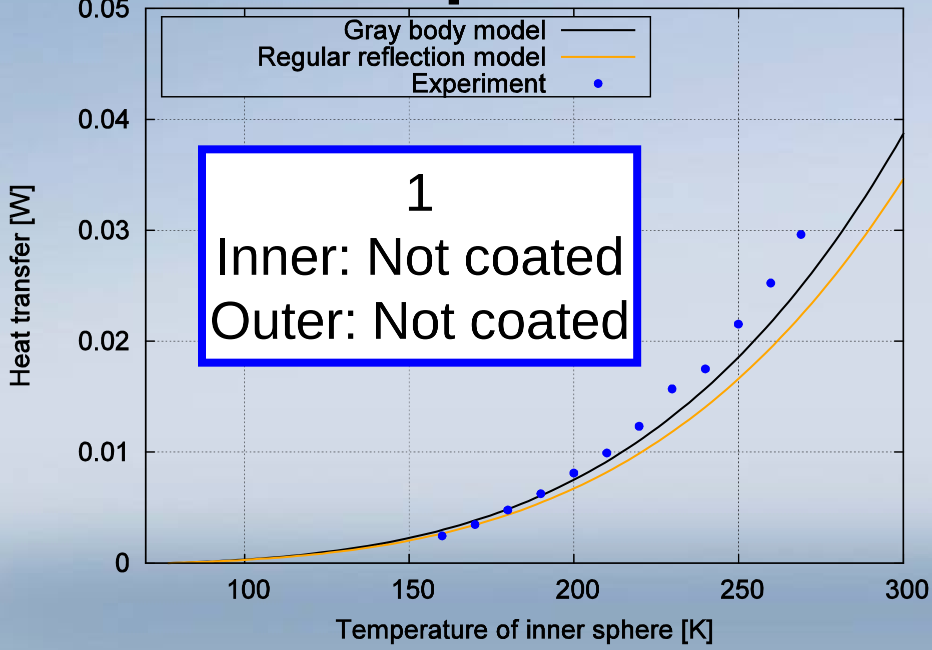
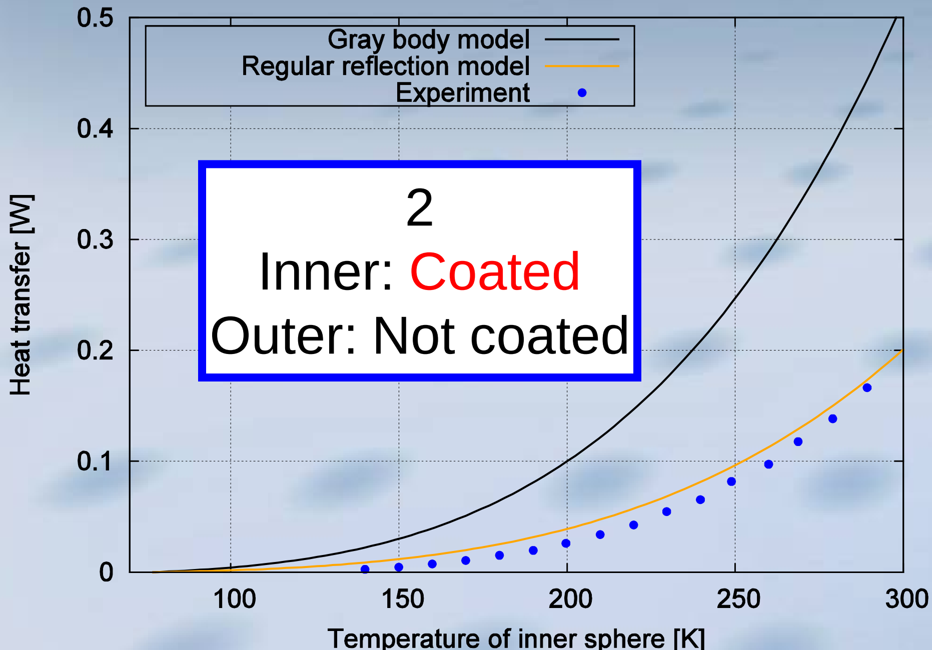
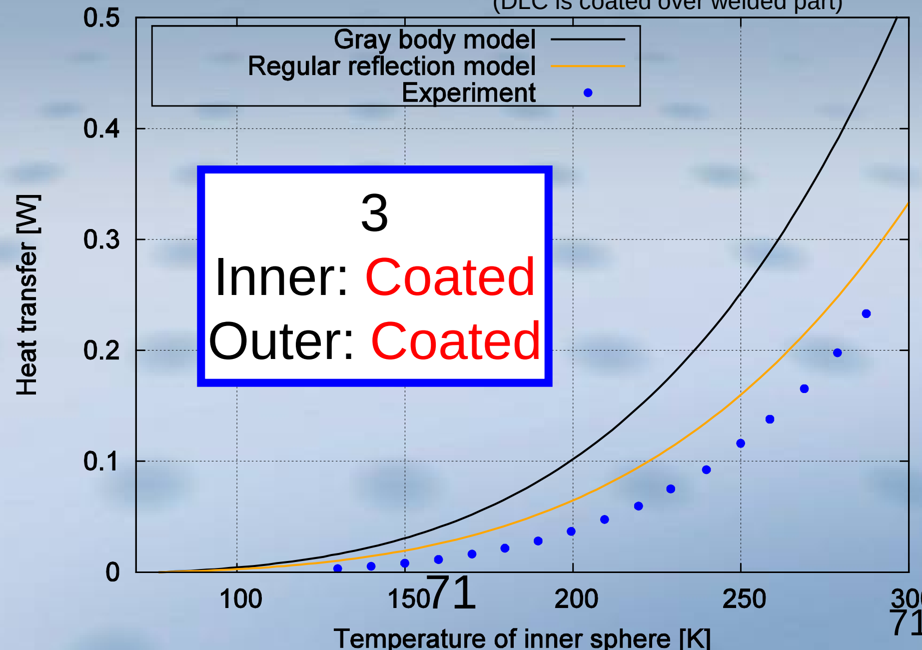
Comparison with two models



- Regular reflection model is better
  - Surface of metal and coating can be regarded as flat planes at wavelength of radiation
- It is necessary to examine reason of discrepancy

Value of emissivity
Copper: 0.03 (measured)
DLC: 0.41 (measured)
Aluminum (CP): 0.06 (measured)
Welded part of aluminum: 0.8(assumption)
Outer sphere without DLC: 0.2
(80 % area: CP, 20 % area: welded part)
Outer sphere with DLC: 0.41
(DLC is coated over welded part)





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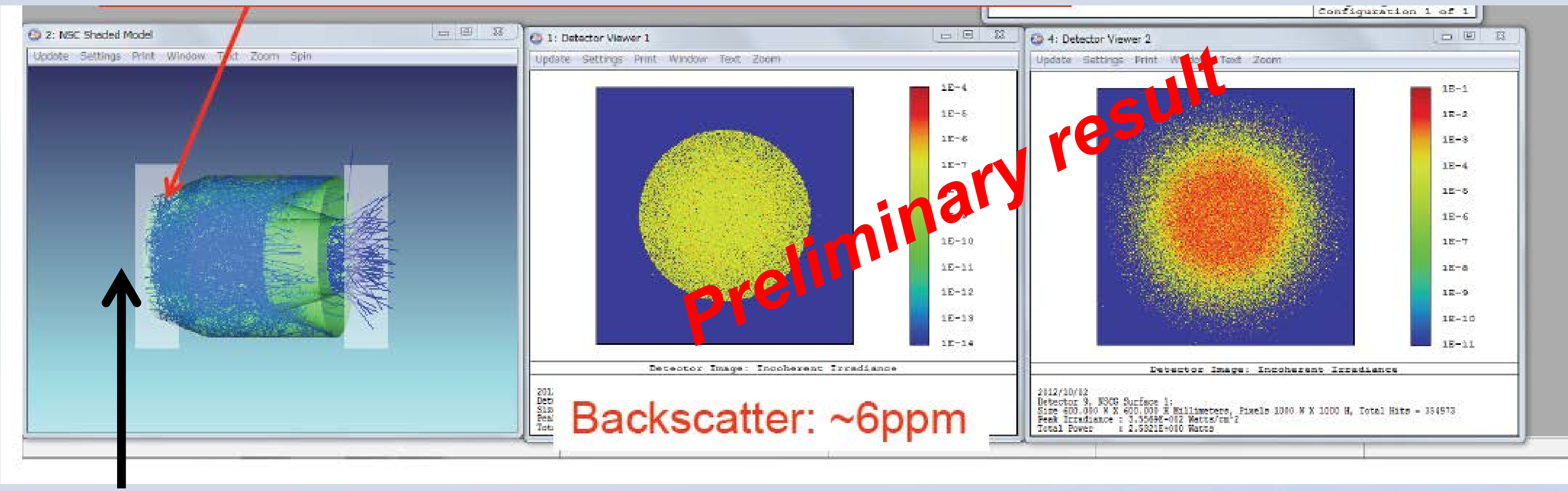
4. Current status

(g) Baffle for large angle scattering in cryostat

Optimal shape : T. Akutsu's talk (yesterday)



Mirror side **Reflection** **Transmission**

With DLC coating

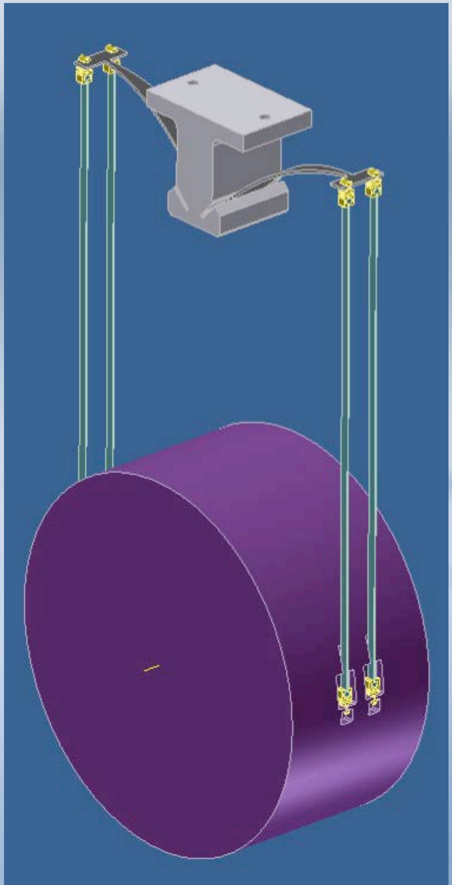
Suspension with heat links (5W!) must be designed !

4. Current status

(h) Other ideas for suspension

Metal wire and sapphire ribbon
W. Johnson : JGW-G1201127, G1201271

Composite mirror suspension
silicon blades, sapphire ribbon, silicon hinge
R. DeSalvo : JGW- G1201101, T1201126



A. Bertolini and A.Conte’s talk in this WP1 session.
ELiTES initiative

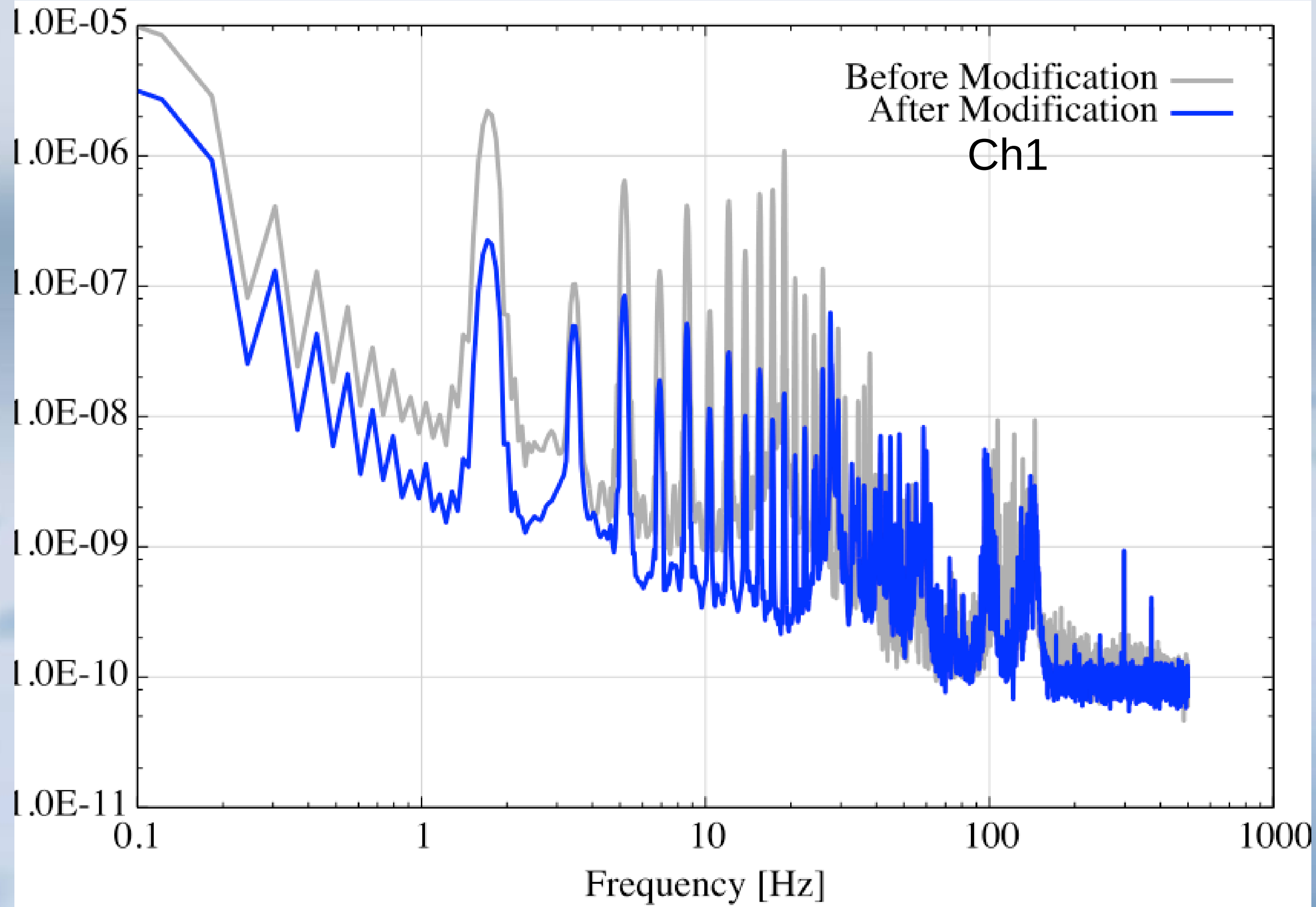
5. KAGRA payload in ELiTES

ELiTES has already started and
supports the development of
KAGRA cryogenic payload.
I expect that these investigations
will also be useful for ET.

4. Cryocooler unit

Vibration measurement

Modification reduces the vibration.



5. KAGRA payload in ELiTES

Some items for future research (not perfect list)

Investigation material properties

(Q, thermal conductivity, strength etc.)

of coating, fiber and so on.

Sapphire bonding, Sapphire fiber clamp

Control and damping scheme

Actuators and sensors at cryogenic temperature

Reduction of initial cooling time

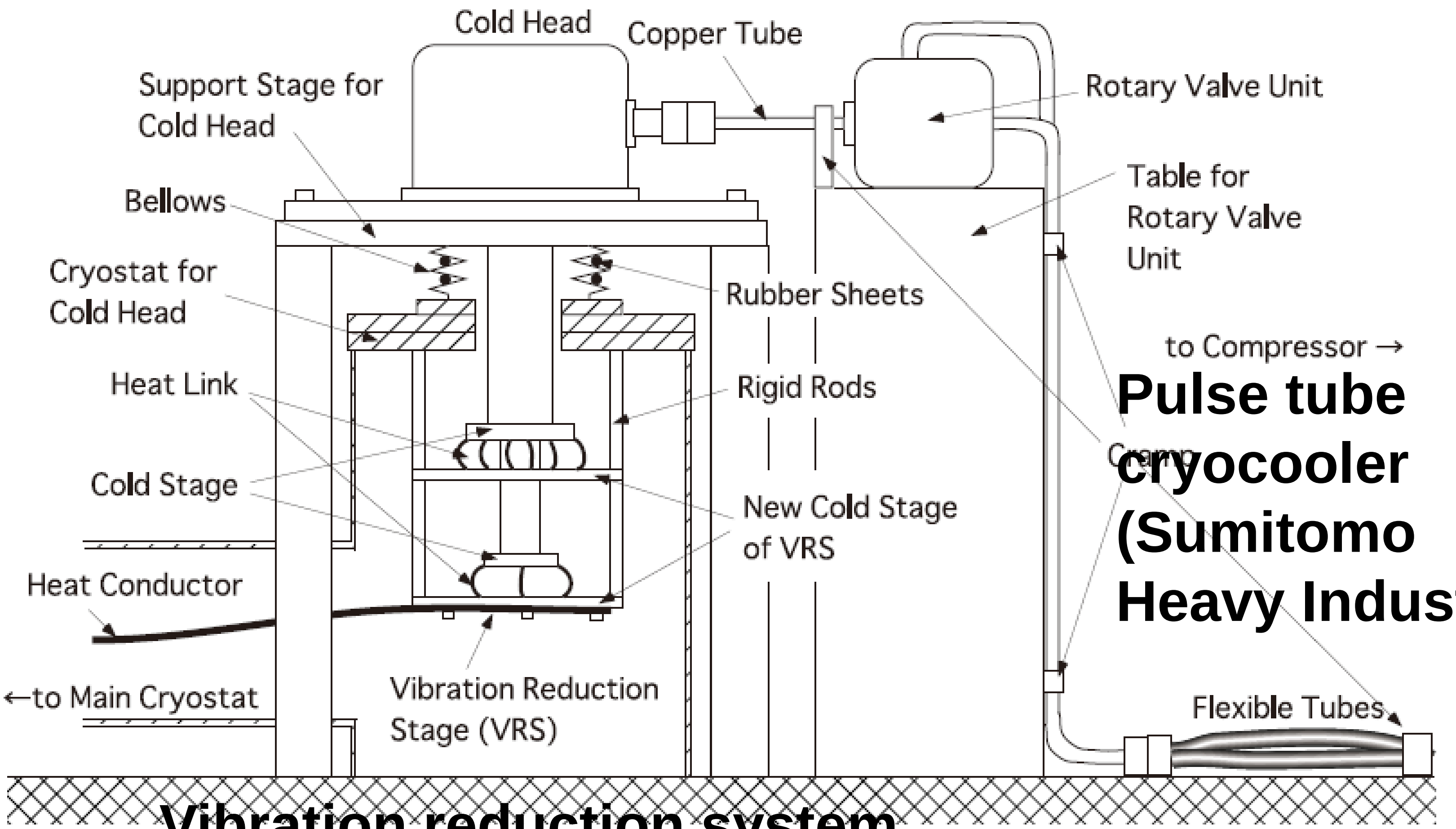
Thermal resistance of clamp .... and so on.

Please give us your opnions and suggestions !

2. Cryocooler unit

1. Outline

Class. Quantum Grav. **21** (2004) S1005–S1008



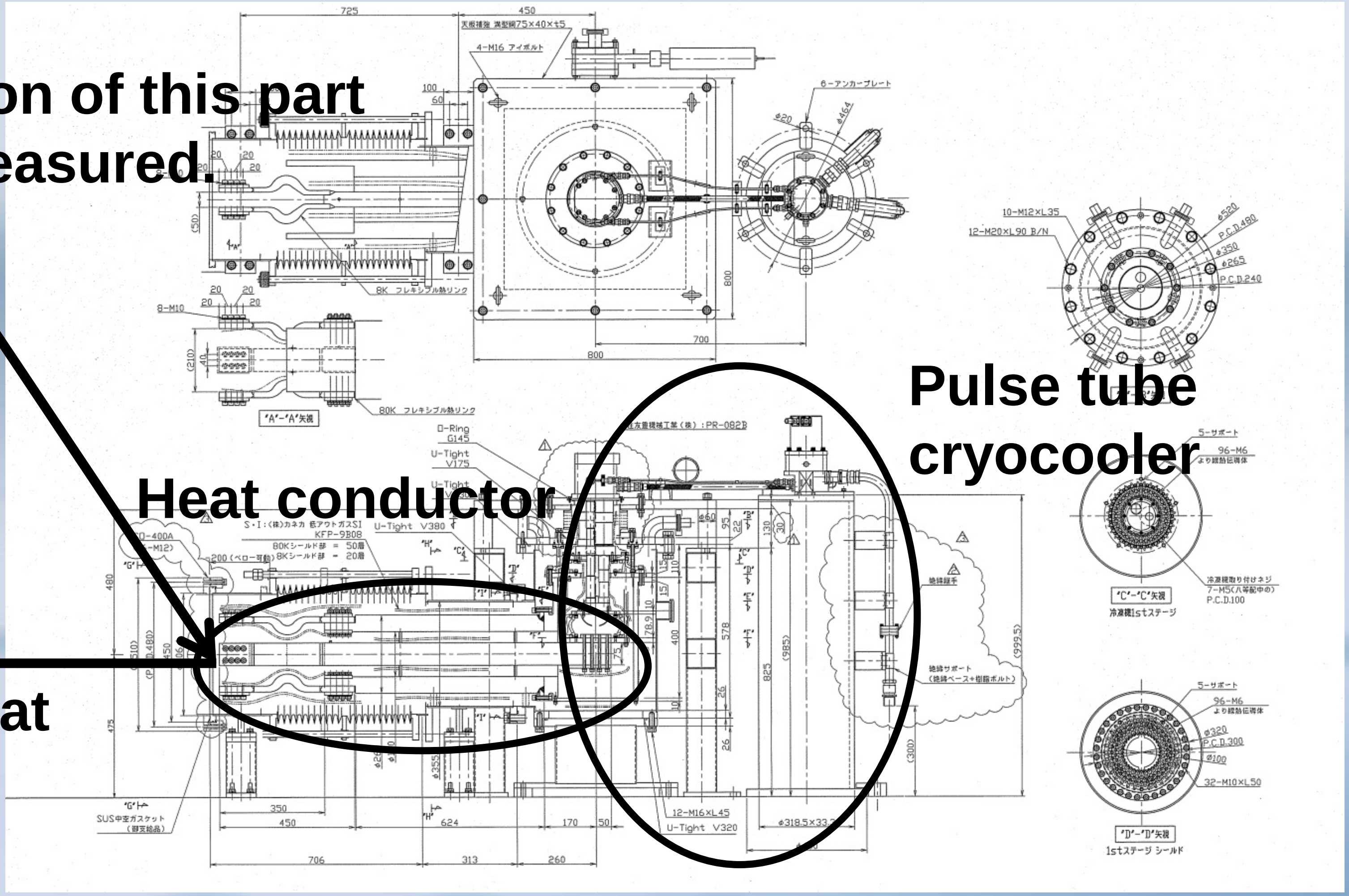
Pulse tube cryocooler (Sumitomo Heavy Industries)

Vibration reduction system

Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

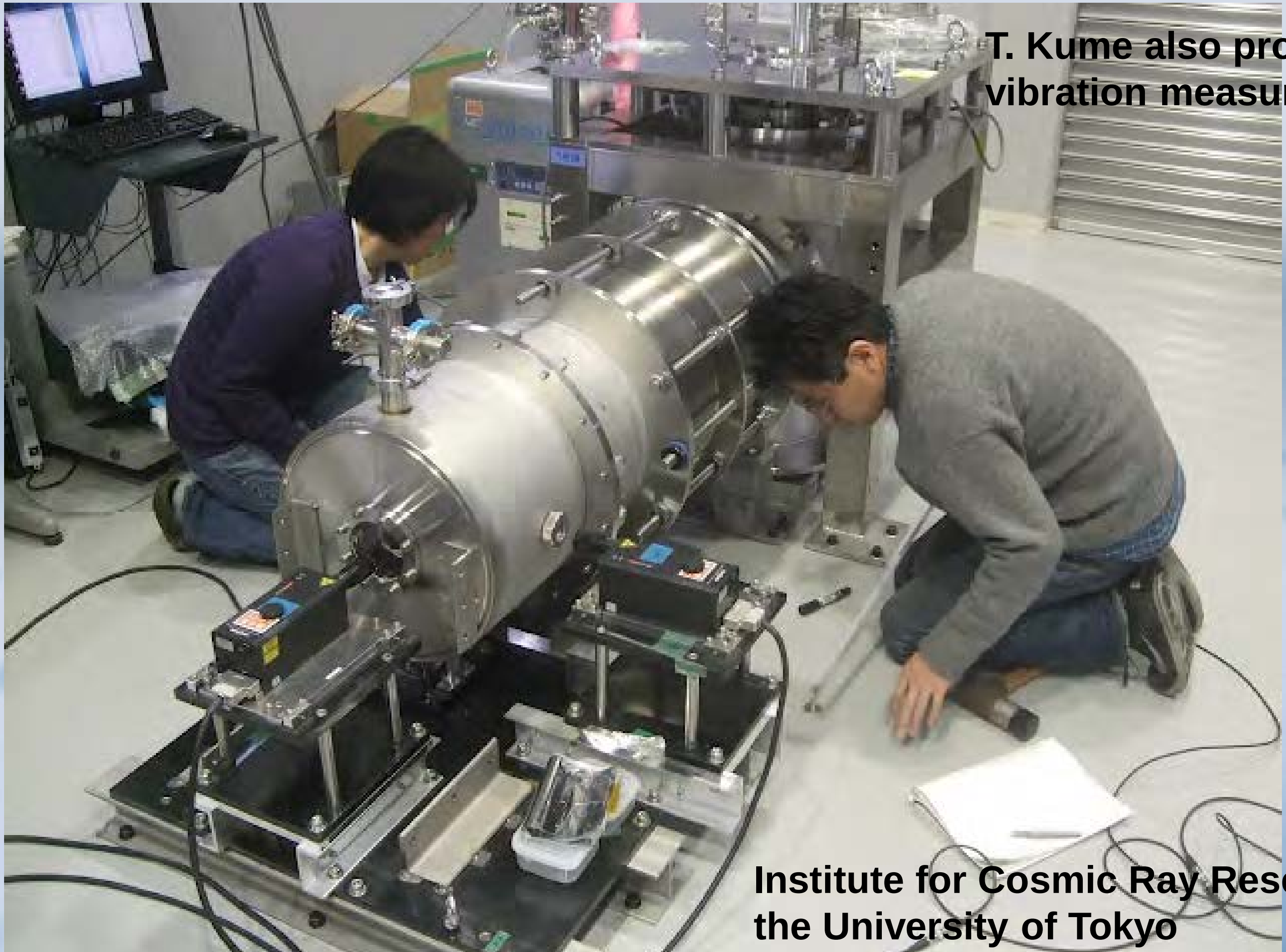
2. Cryocooler unit

4. Vibration measurement



2. Cryocooler unit

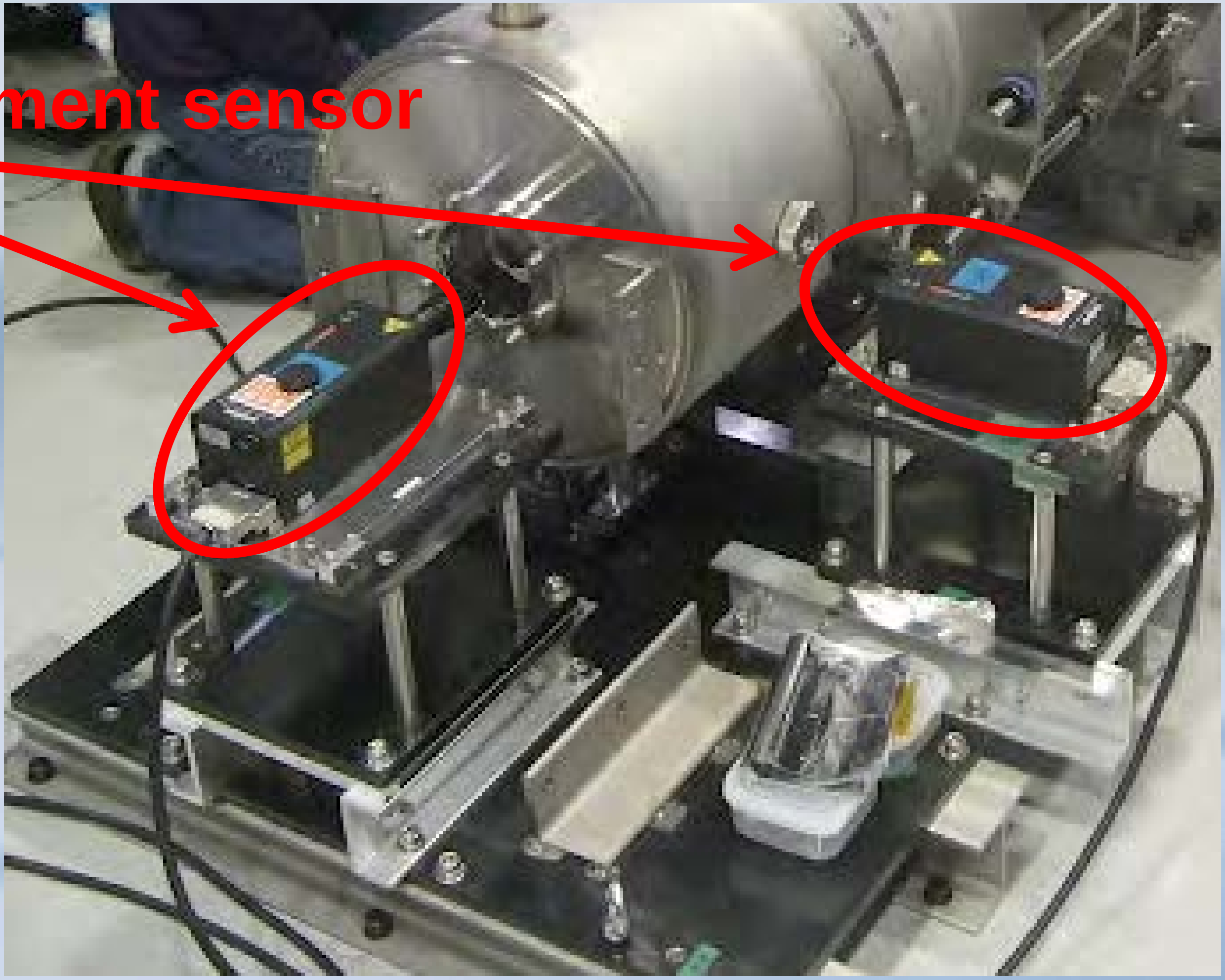
4. Vibration measurement



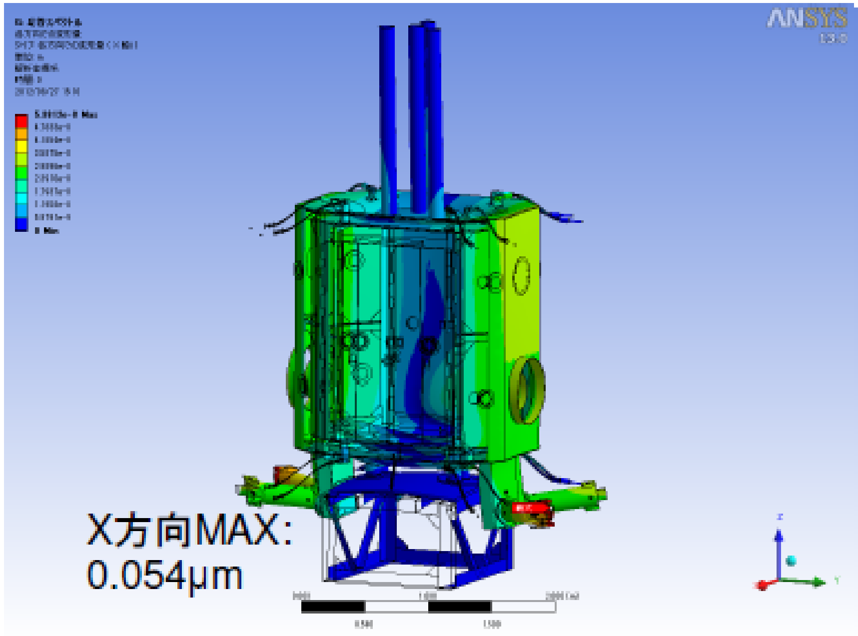
T. Kume also proceeds with vibration measurement.

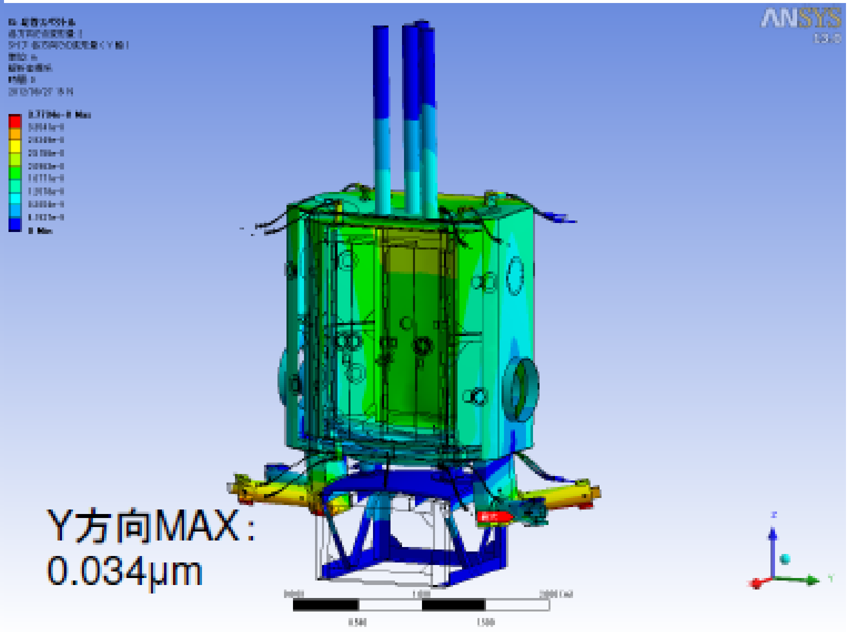
2. Cryocooler unit

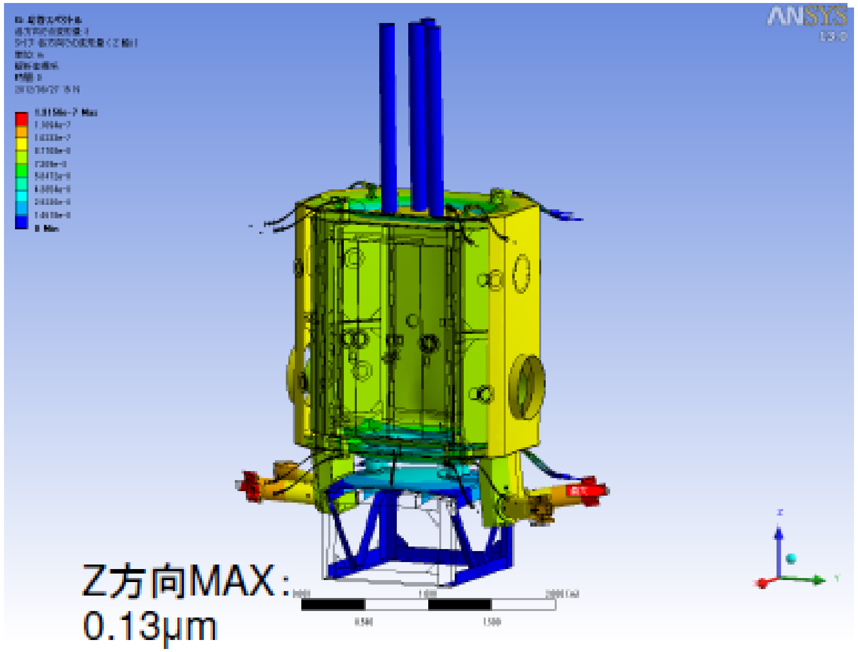
4. Vibration measurement



Displacement sensor



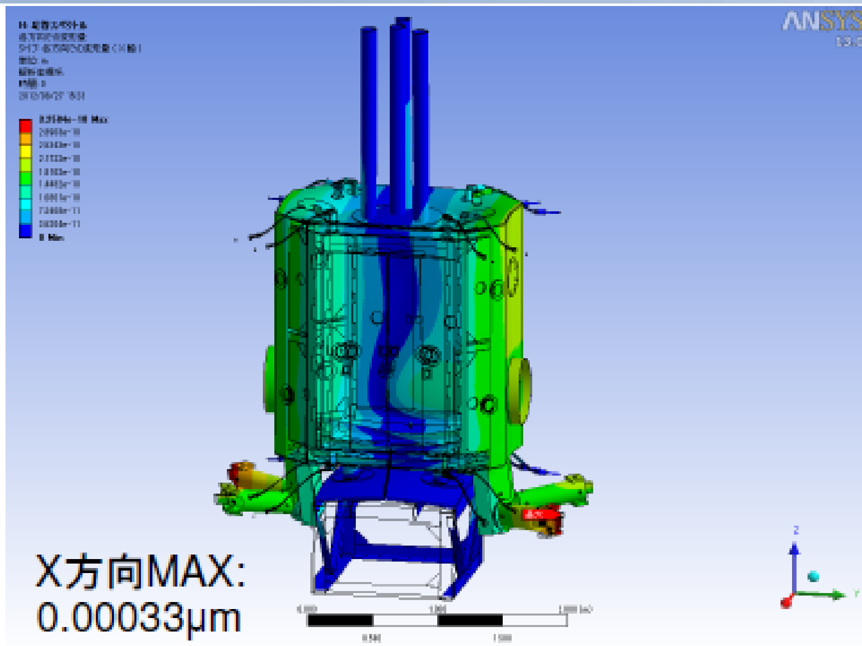


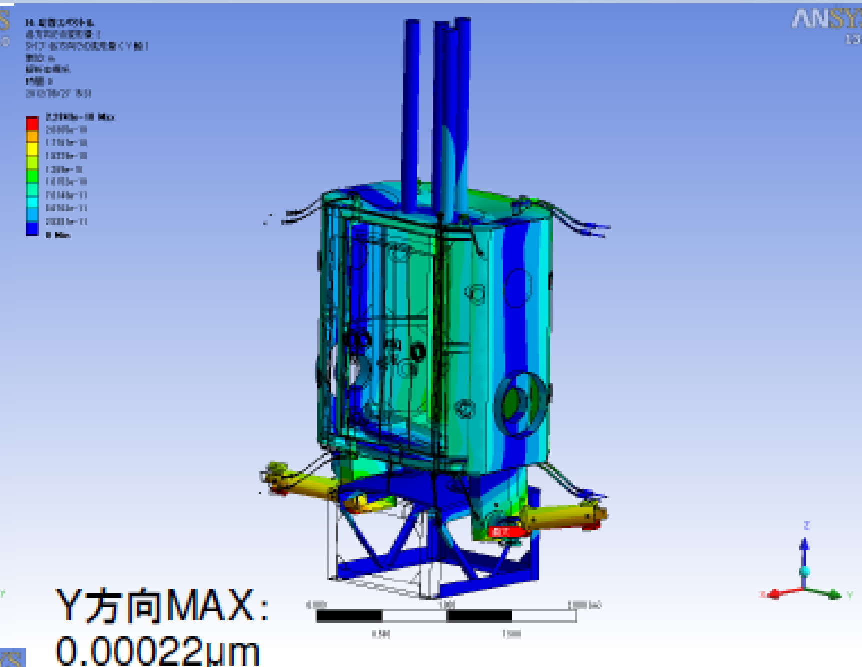


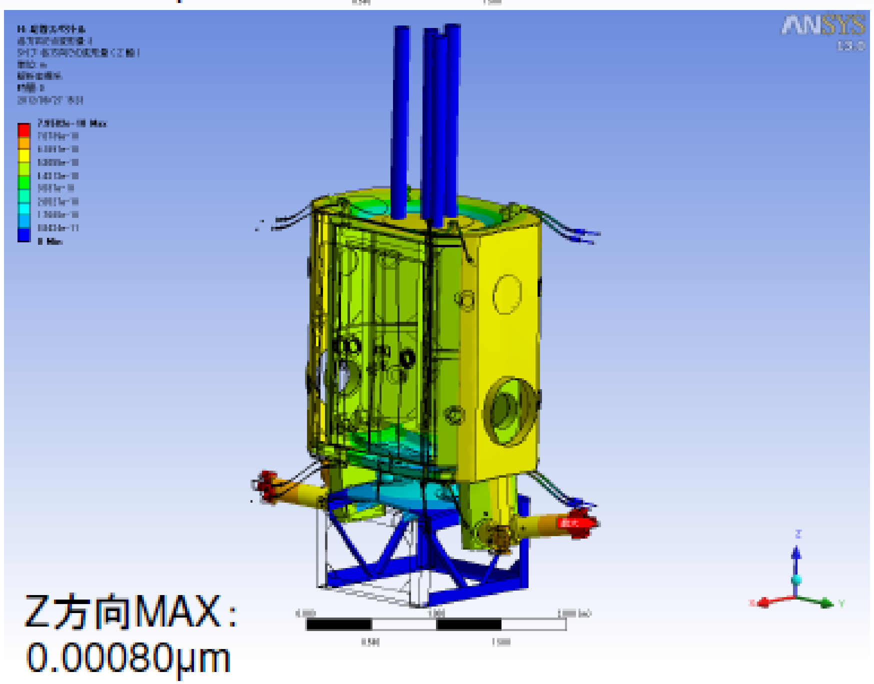
OCLIOの地盤振動の変位スペクトルデータを
8K伝熱バーに入力したときの
応答スペクトル結果
計算方法として自乗和平方根法（SRSS）
を用い減衰率を0.05として
応答の最大値を求めた

X方向MAX:0.054μm←1.5μm
Y方向MAX:0.034μm←0.48μm
Z方向MAX:0.13μm ←0.43μm

2312の場合と比べて変位はX1/30,Y1/15, Z1/3程度
になっている







地震動として入力した場合

○CLIOの地盤振動の変位データを
地震動として固定点に入力
応答スペクトル結果
計算方法として自乗和平方根法（SRSS）
を用い減衰率を0.05として
応答の最大値を求めた

X方向MAX:0.00033μm
Y方向MAX:0.00022μm
Z方向MAX:0.00080μm

S. Koike

Sapphire fibers to suspend sapphire mirrors
Bonding (between sapphire fibers and mirrors)

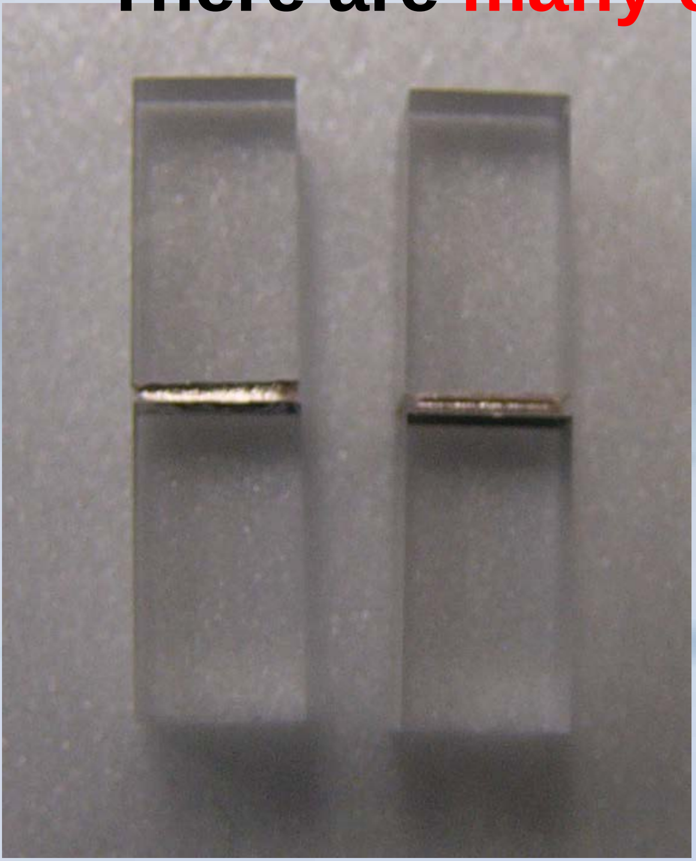
Known methods of bonding

	Precise polish	Interposition material	Temperature treatment	Sapphire-Sapphire	Thermal conductance	Mechanical loss
AFB, Diffusion	Necessary	none	1300~1400 °C	Almost same as bulk ~ 28 MPa	~ 20 W/K	Not yet measured
Direct, SAB1 (~ 2000)	Necessary	None (Ar^+ beam)	300 K	-	-	Not yet measured
Direct, SAB2 (2011)	Necessary	Fe, etc (Ar^+ beam)	300 K	Not yet measured	Not yet measured	Not yet measured
Hyroxy-catalysis, silicate	Necessary	KOH, Na_2SiO_3, H_2O	300 K	~ 7 MPa	~ 7 W/K	Not yet measured
Metalize, soldering	(Not required)	Active metal	< 1000 °C?	Not yet measured	Not yet measured	Not yet measured
Adhesive	Not required	Al_2O_3, $AlPO_4$, H_2O	~ 500 °C	~20 MPa	Not yet measured	Not yet measured

Sapphire fibers to suspend sapphire mirrors

Bonding (between sapphire fibers and mirrors)

There are many candidates.



Thermal conductivity are measuremed by K. Shibata, T. Ushiba, T. Suzuki.

Q-values and strength should be measrued.

Metalize bonding (Kyocera)

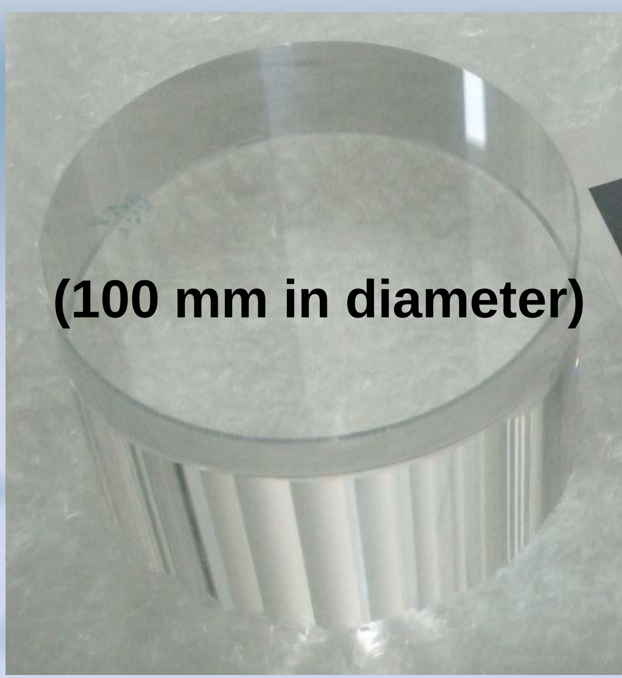
4. Current status

(b)Initial cooling time

Sample 1 for Toshiba experiment:

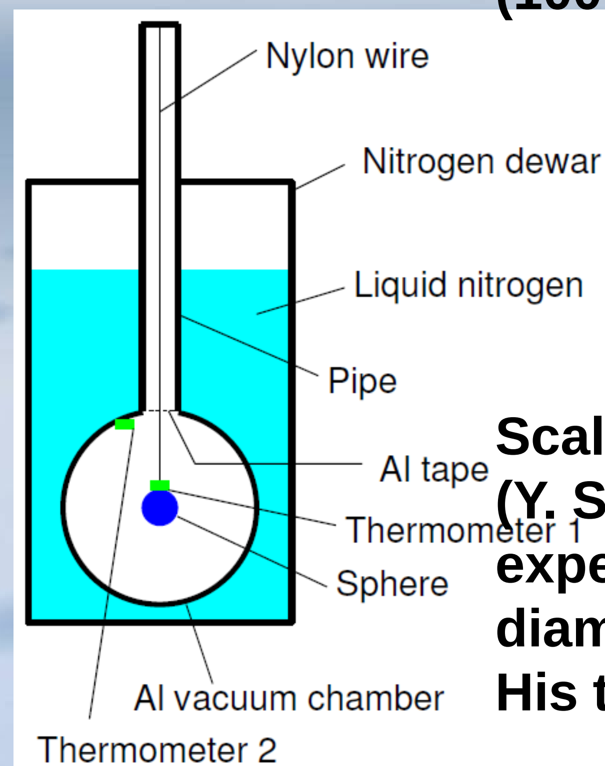
Sapphire and metal hollow sphere

(100 mm in diameter)



(100 mm in diameter)

Evaluation of emissivity



Scaling law
(Y. Sakakibara's small experiment: 30 mm in diameter)
His talk

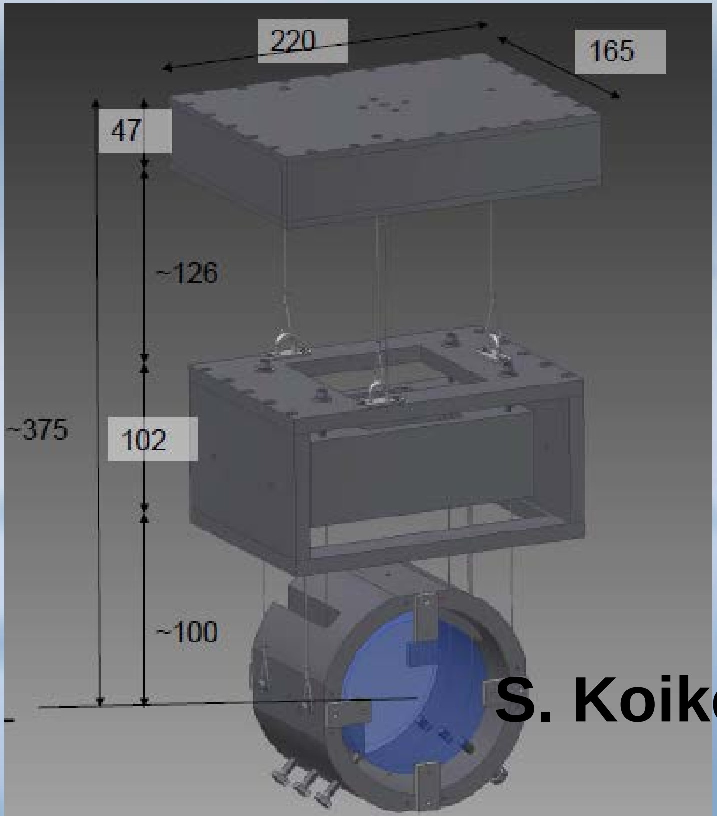
4. Current status

(b)Initial cooling time

Sample 2 for Toshiba experiment :

Dummy payload (hollow masses)

- **Half size**
- **Hollow masses (~5 kg)**
- **DLC coating**
- **Sapphire bulk as dummy mirror**



S. Koike

Preparation is in progress.

3. Cryocooler unit

2. Drawing by Jecc Torisha