

Current status of cryogenic system of KAGRA



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the University of Tokyo**

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Albert Einstein Institut Hannover, Hannover, Germany
4th December 2012**

Contribution

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KAGRA collaboration**

**ICRR.UT, NAOJ^A, KEK^B, Phys.S.UT^C, Astro.S.UT^D, E.UT^E, S.TIT^F,
Sannio Univ.^G, INFN^H, Louisiana State Univ.^I, University of Glasgow^J,
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***
- 2. Cryostat***
- 3. Cryogenic duct***
- 4. Cryocooler unit***
- 5. Cryogenic payload***
- 6. ELiTES***
- 7. For future***
- 8. Summary***

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

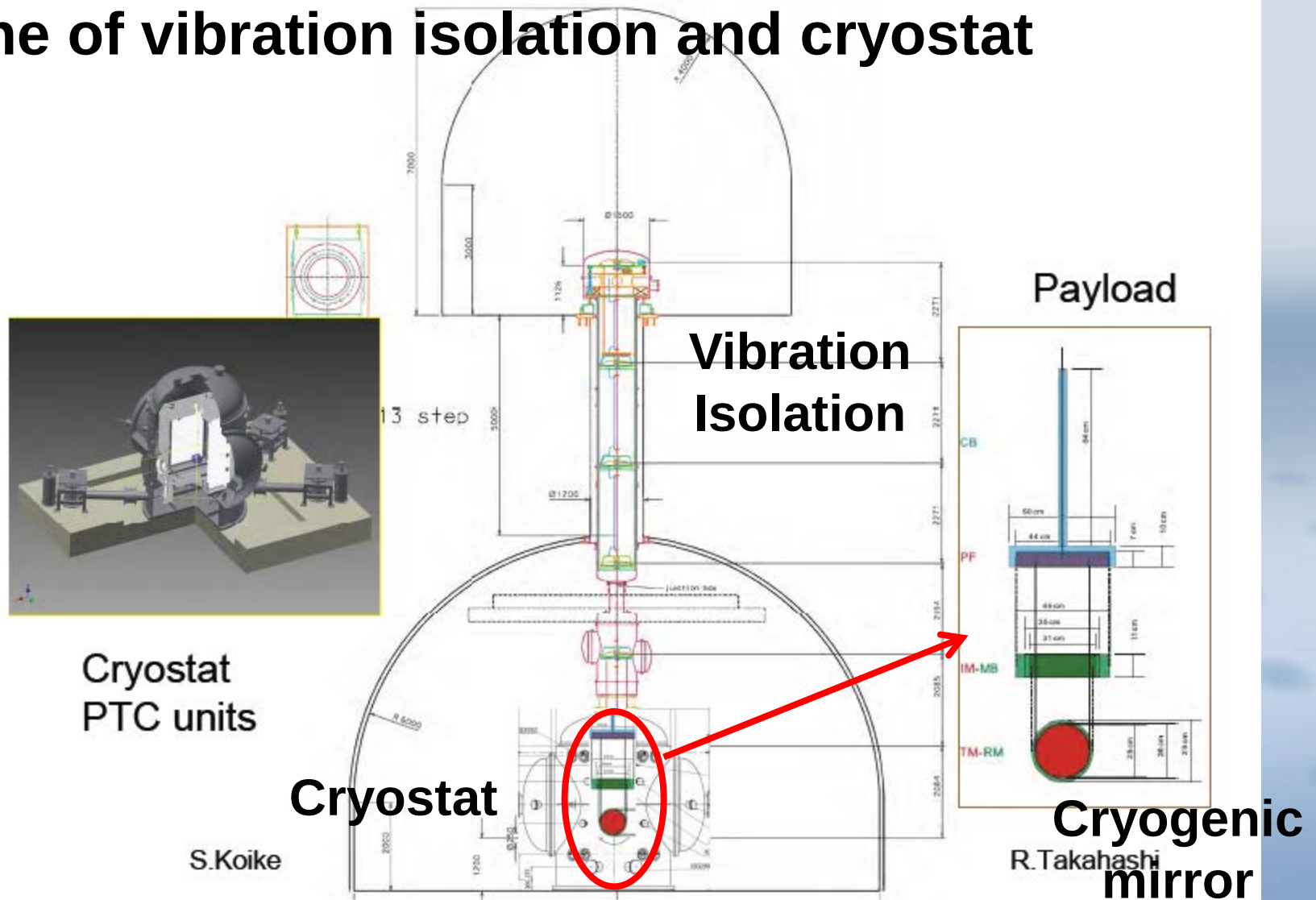
Schematic view of KAGRA interferometer
Four mirrors of **arm cavity** will be **cooled**.



Vibration isolation system, Cryocooler unit, Cryostat, Cryogenic payload

1. Introduction

Outline of vibration isolation and cryostat

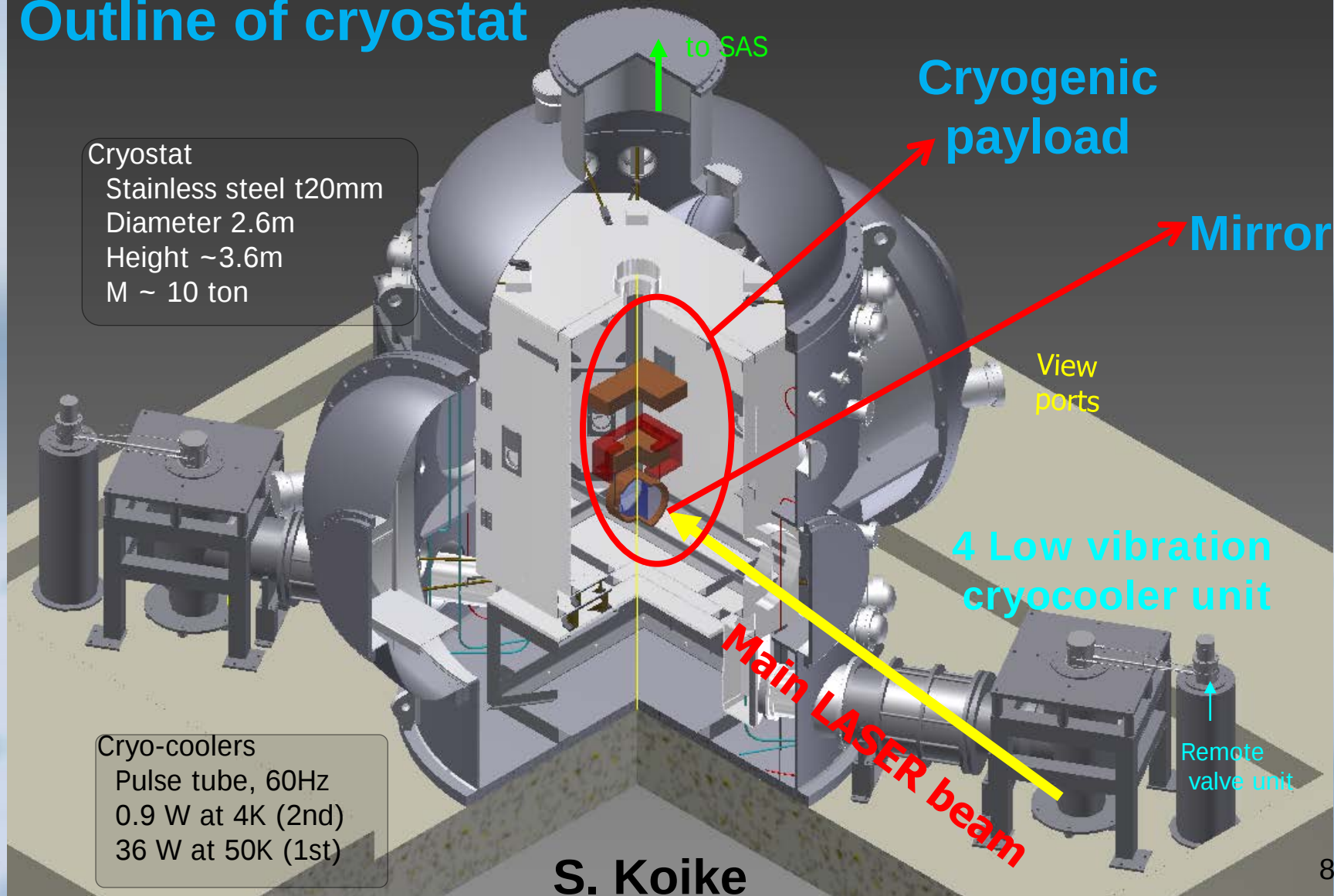


1. Introduction

Outline of cryostat

Cryostat
Stainless steel t20mm
Diameter 2.6m
Height ~3.6m
M ~ 10 ton

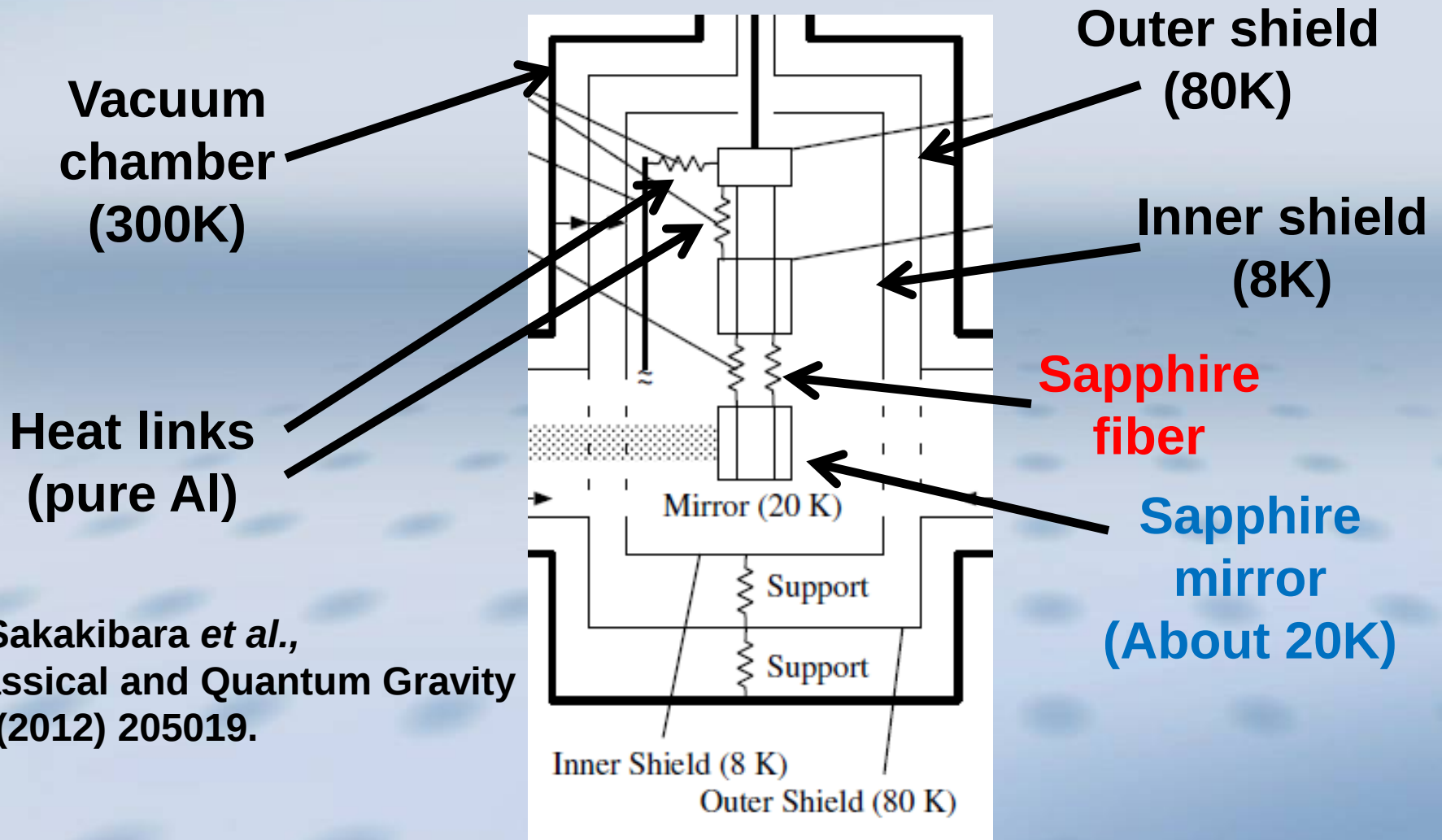
Cryo-coolers
Pulse tube, 60Hz
0.9 W at 4K (2nd)
36 W at 50K (1st)



S. Koike

1. Introduction

Outline of cryogenic payload



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 ?

Scattered 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**



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

Shield

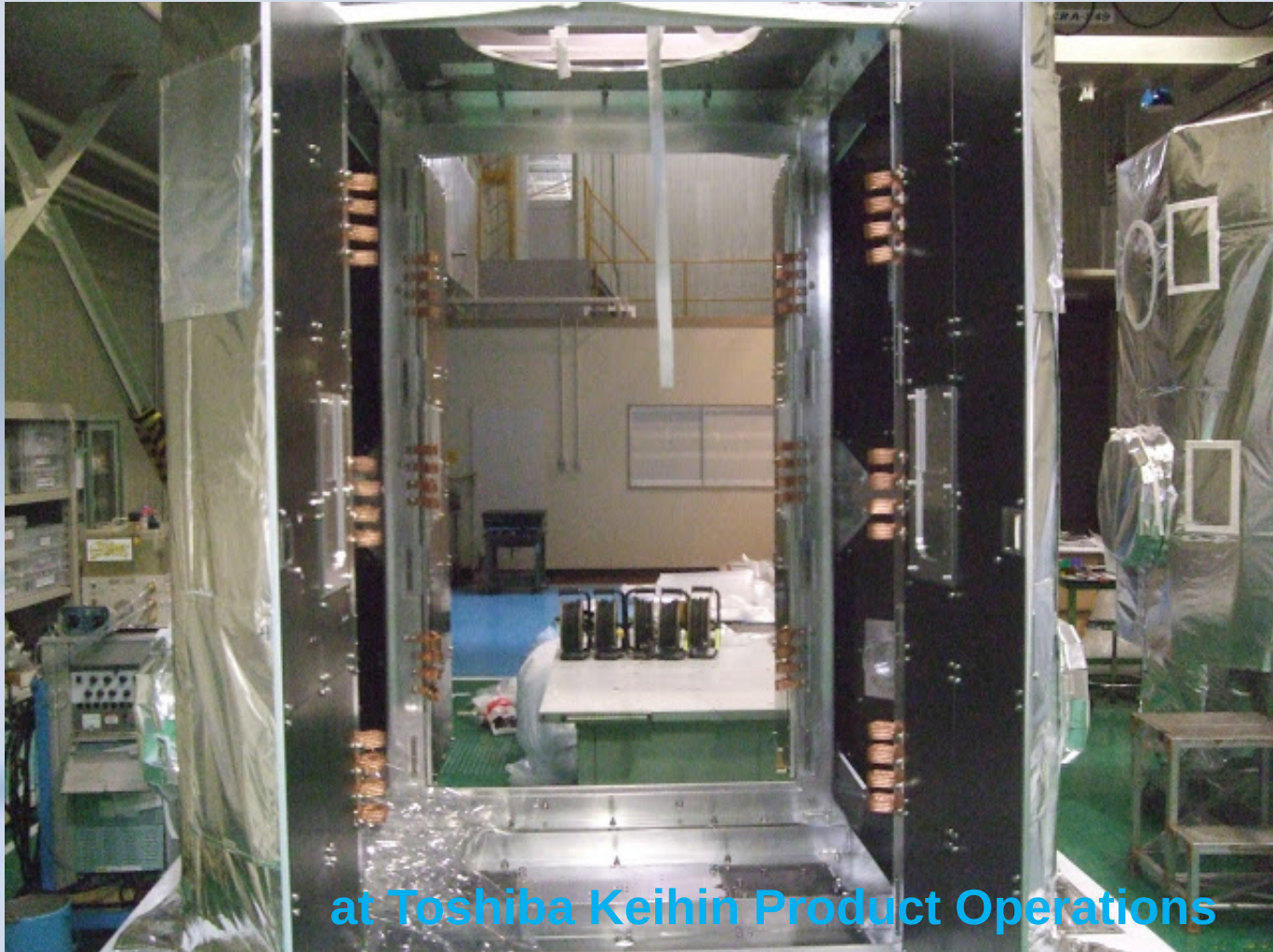


at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

Shield



at Toshiba Keihin Product Operations

2. Cryostat

Progress of assembly of cryostat

**Shield in
vacuum
chamber**



at Toshiba Keihin Product Operations

2. Cryostat

Cooling test in Toshiba Keihin Product Operations

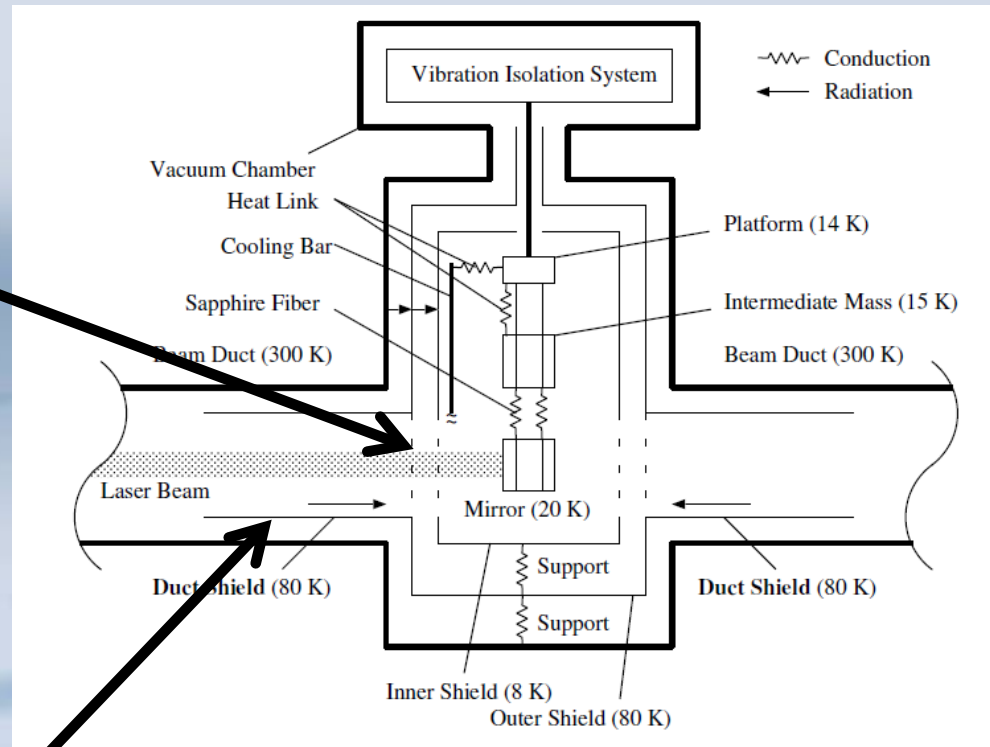
December 2012 - March 2013

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.

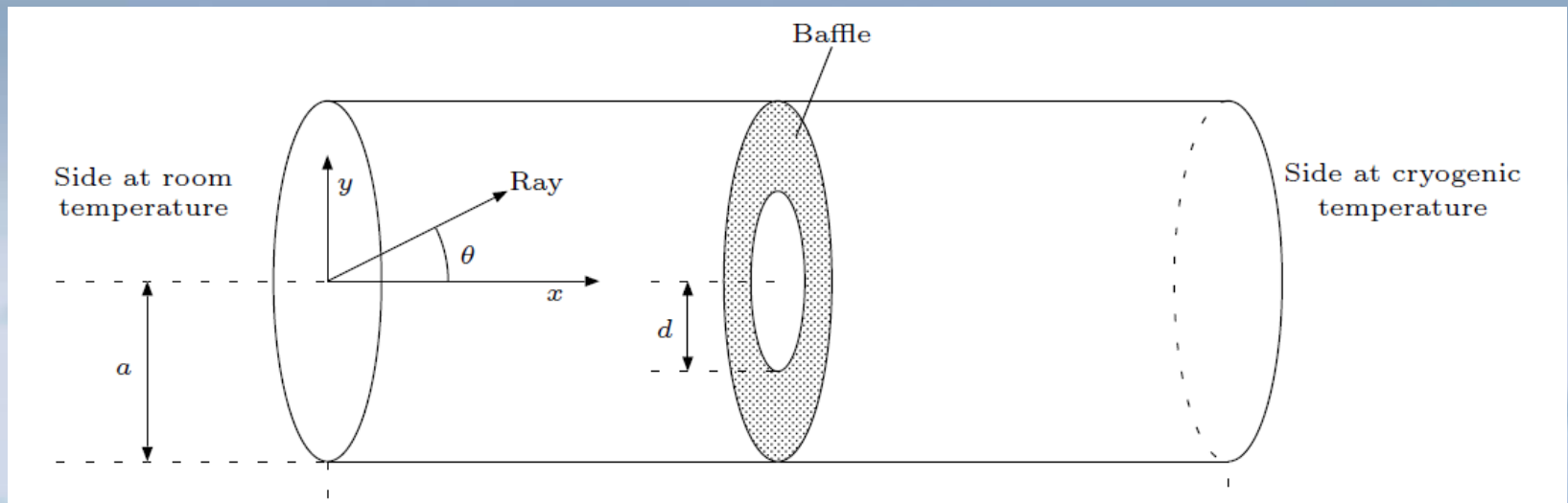
T. Tomaru *et al.*, Japanese Journal of Applied Physics 47 (2008) 1771.

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**

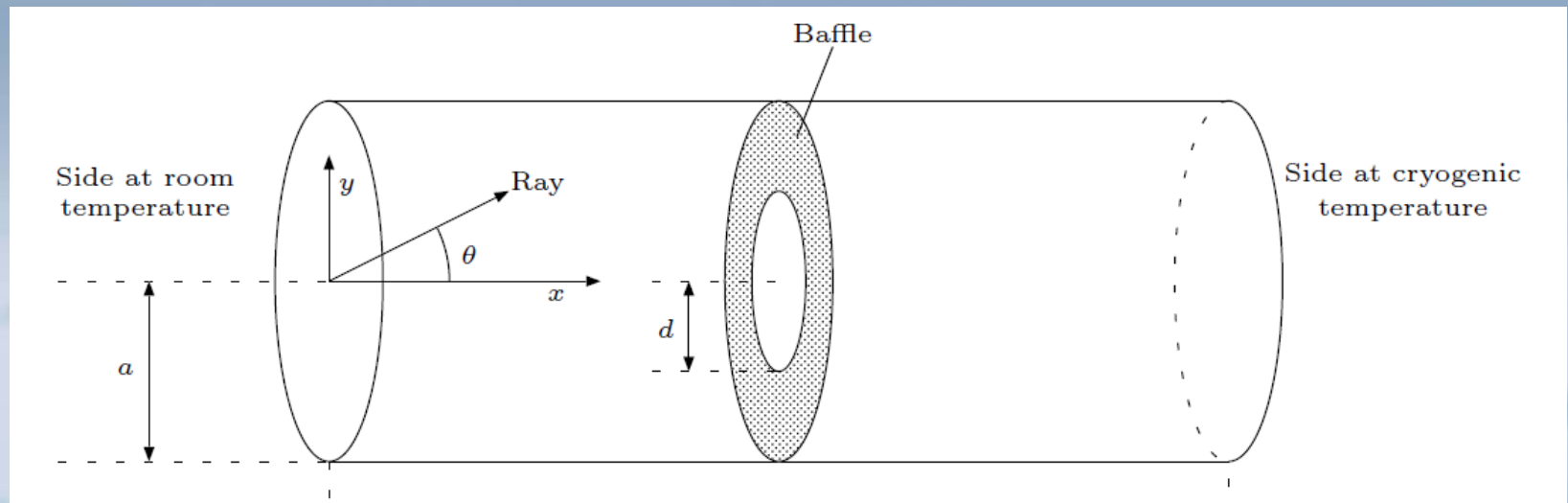


Y. Sakakibara *et al.*,
Classical and Quantum Gravity 29 (2012) 205019.

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

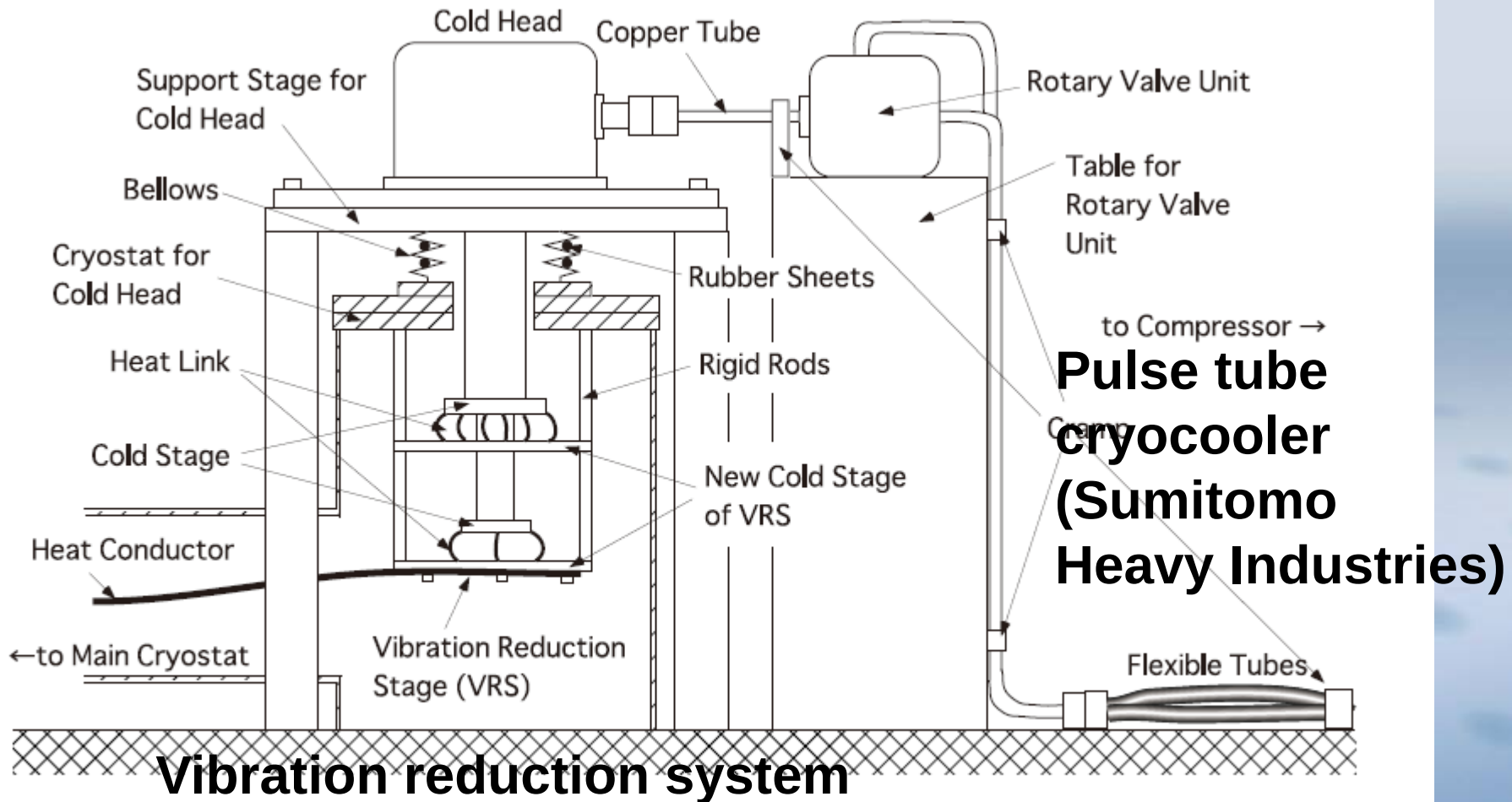


Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

4. Cryocooler unit

Actual design

1st stage

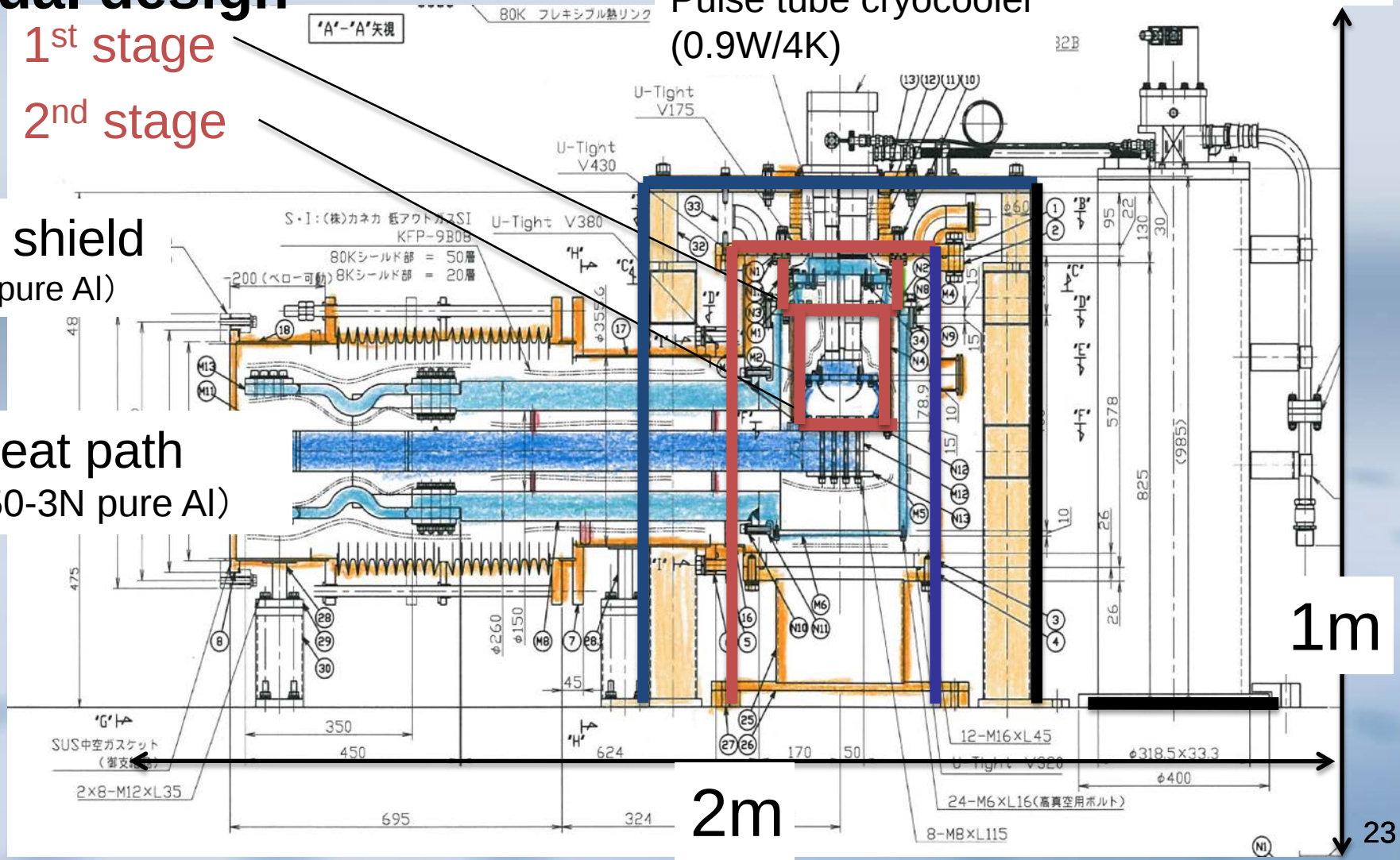
2nd stage

Valve unit

Pulse tube cryocooler (0.9W/4K)

80K shield
(5N8 pure Al)

8K heat path (A1050-3N pure Al)



1m

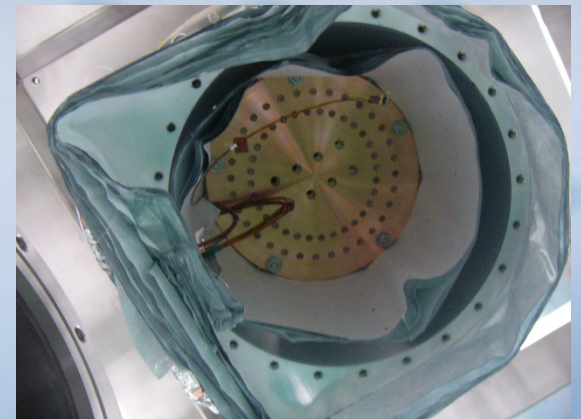
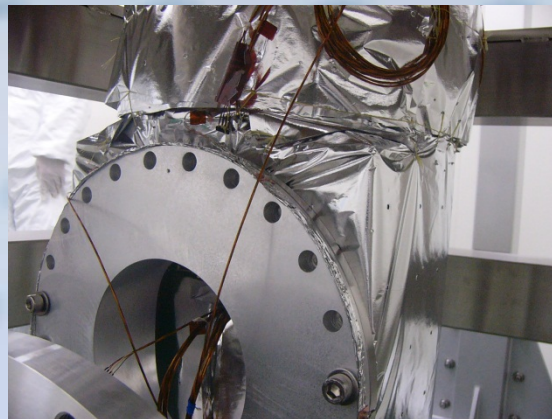
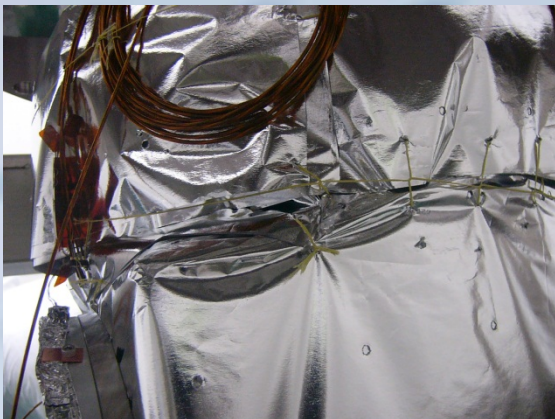
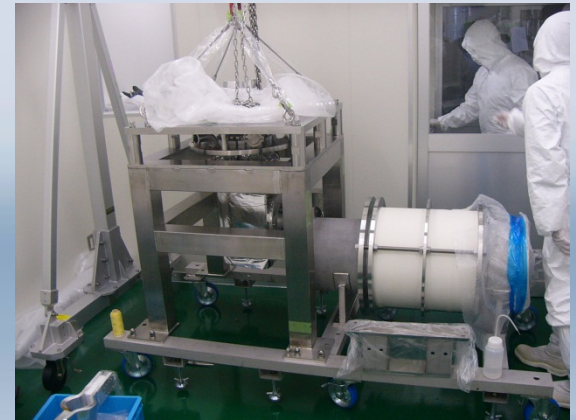
 $2m$

23

4. Cryocooler unit

Assembly

Jecc Torisha Kawagoe Factory

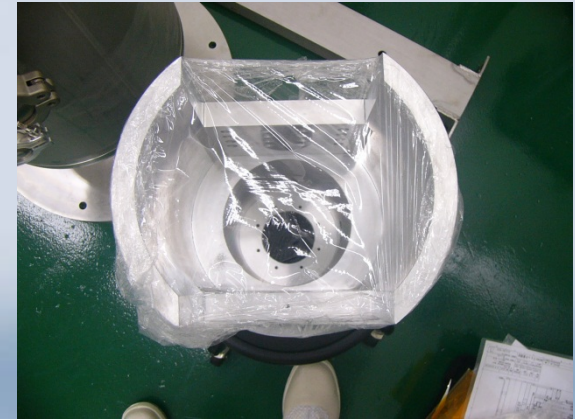
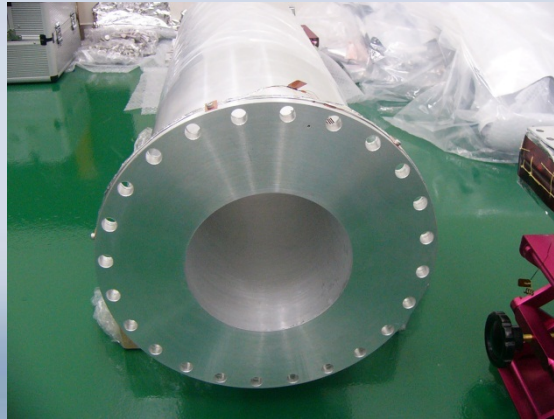


Work progress in clean room with JIS class 7 (US class 10000)

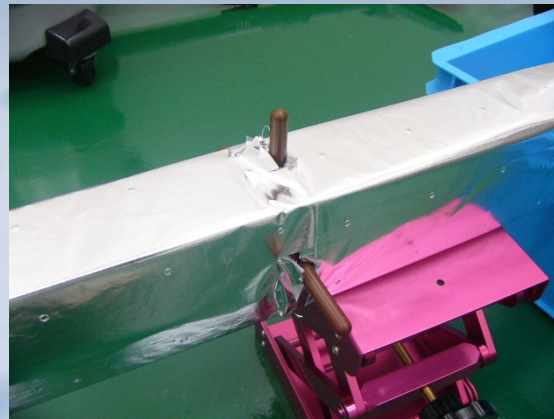
4. *Cryocooler unit*

Assembly

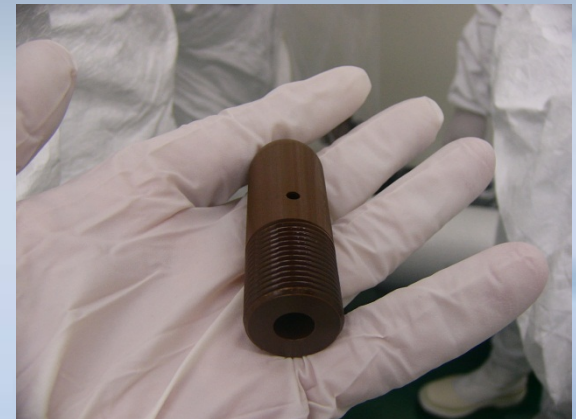
Jecc Torisha
Kawagoe factory



80K thermal conductor



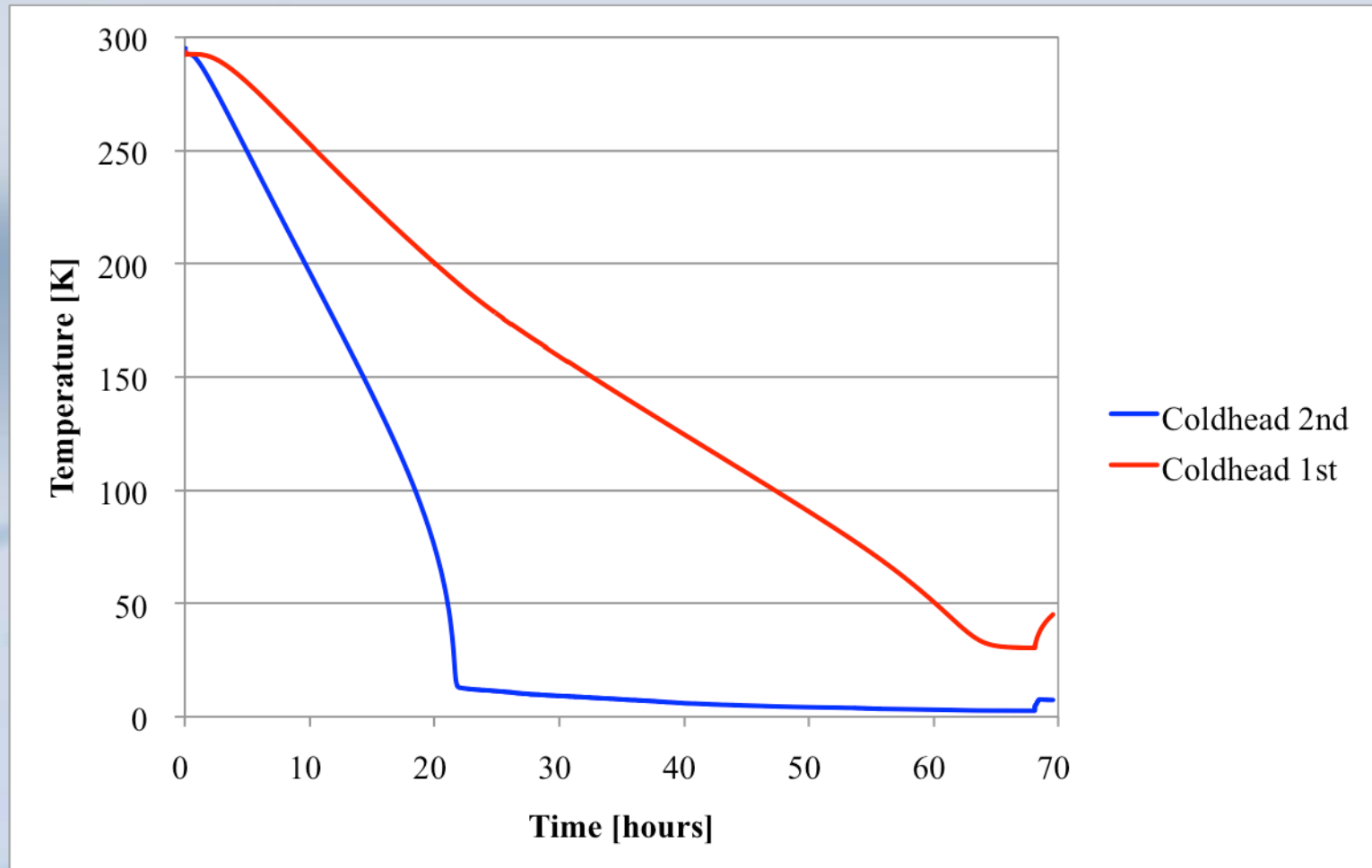
8K thermal conductor



Vespel support rod

4. Cryocooler unit

Cooling test : Cryocooler **works well**.



4. Cryocooler unit

Heat load test with heaters

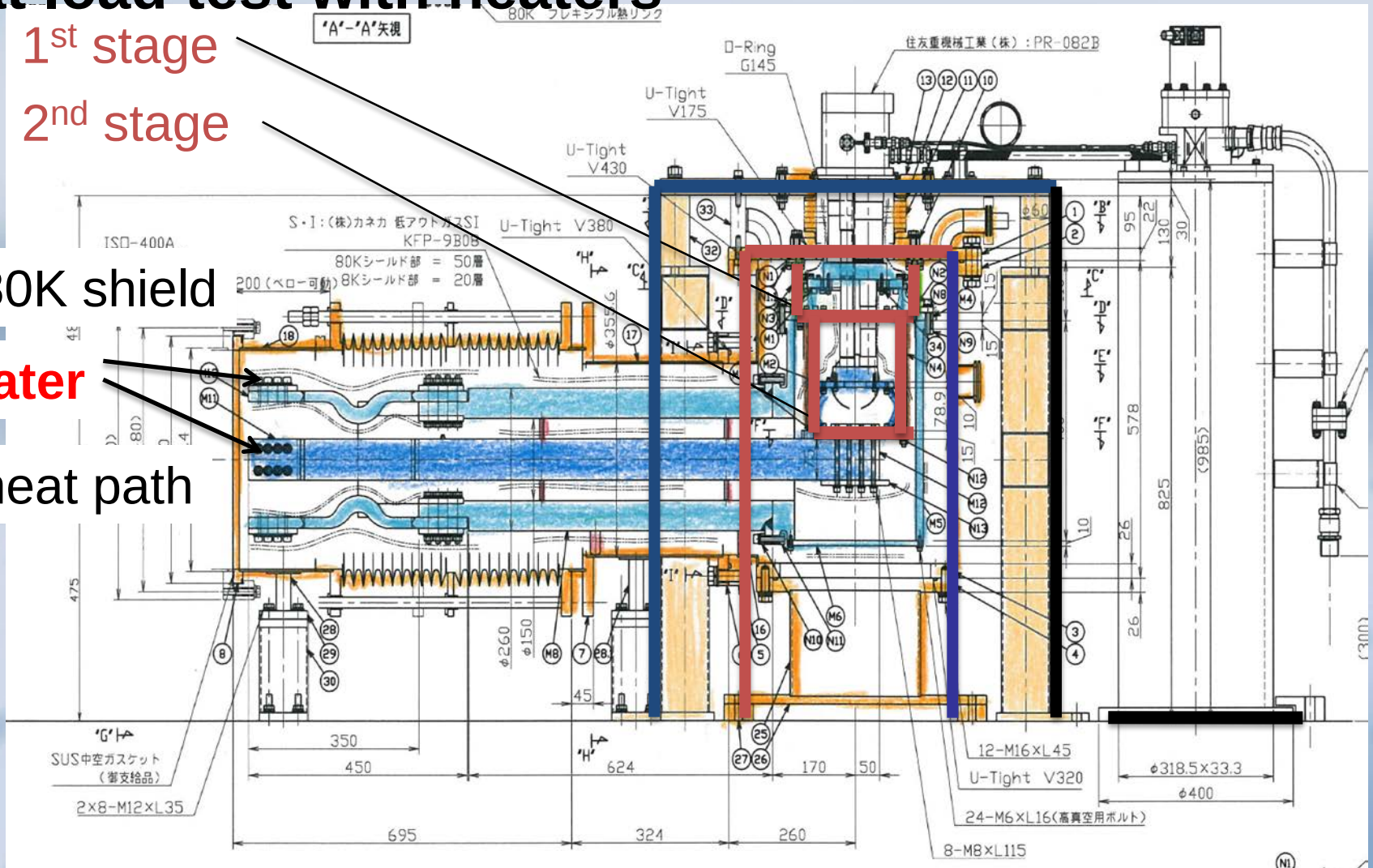
1st stage

2nd stage

80K shield

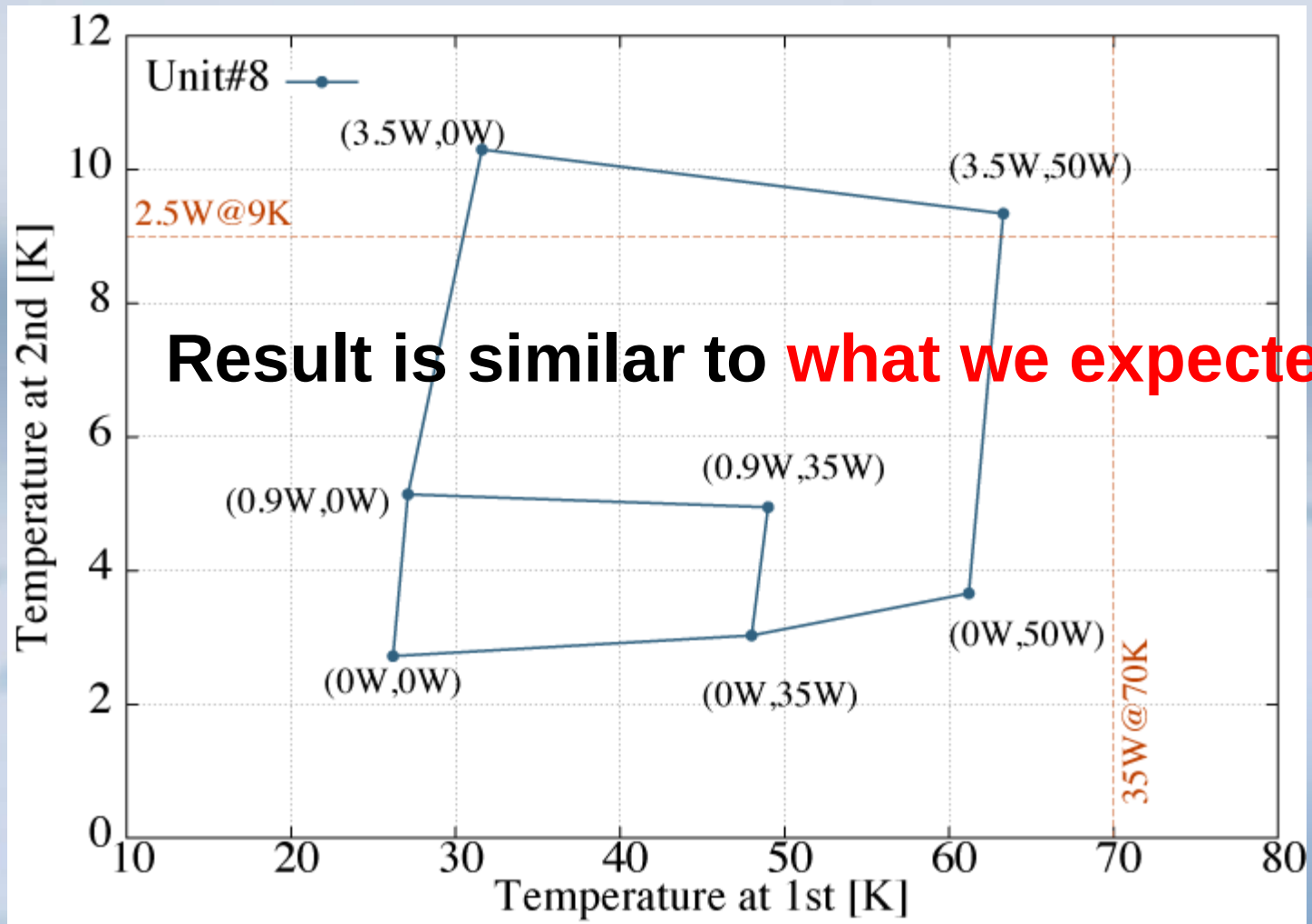
Heater

8K heat path



4. Cryocooler unit

Heat load test with heaters



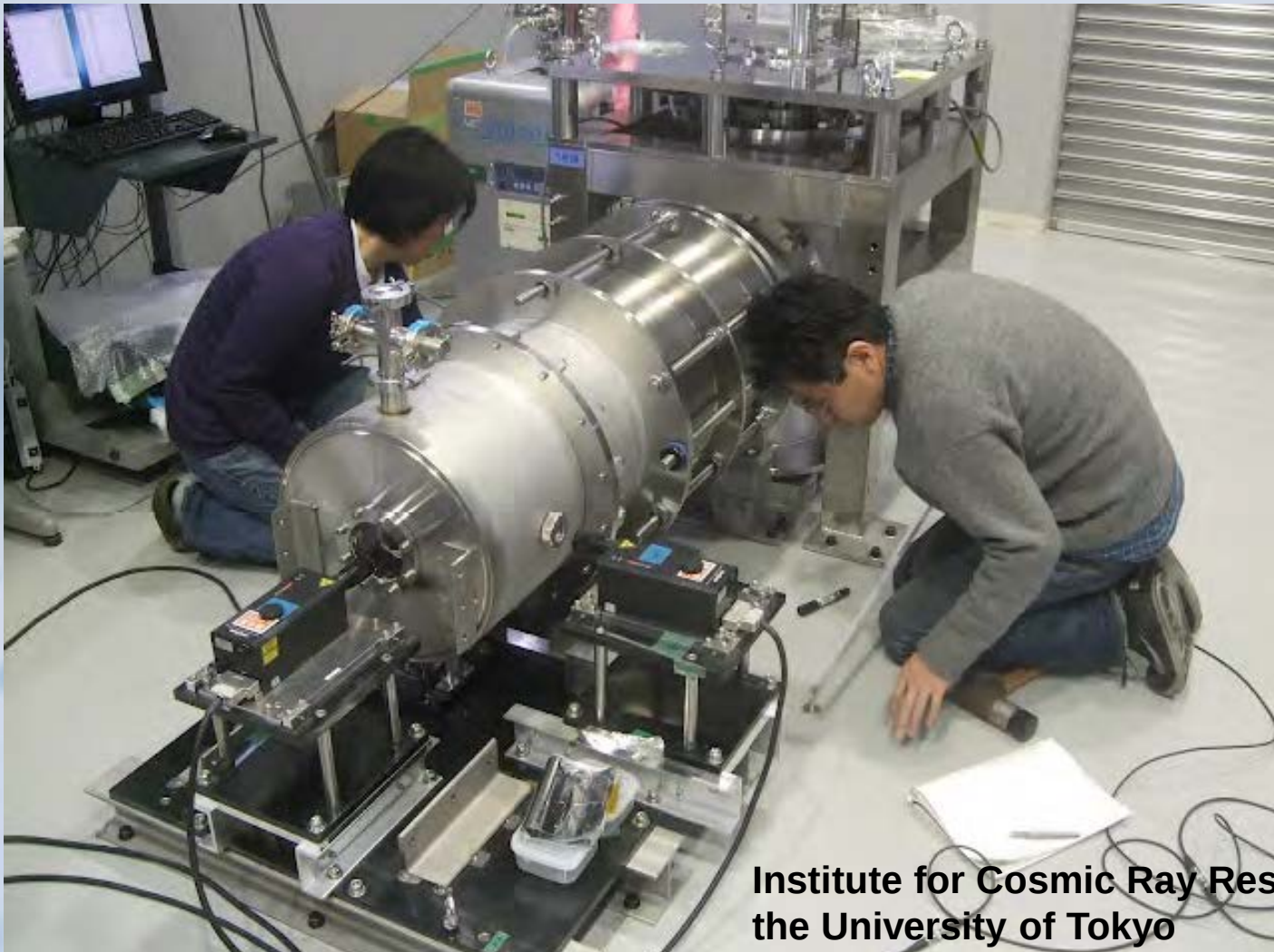
Vibration measurement

8K heat path



4. *Cryocooler unit*

Vibration measurement

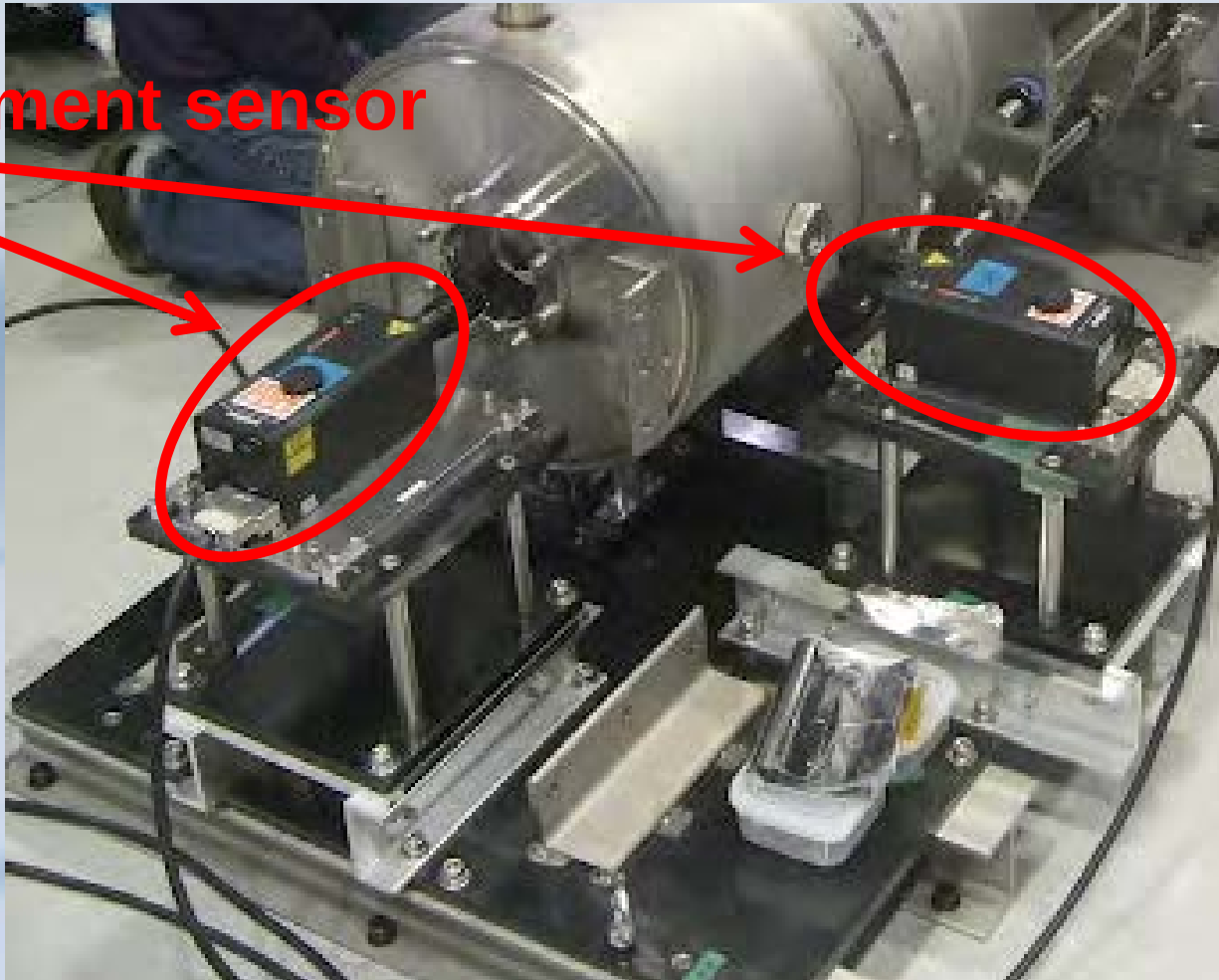


Institute for Cosmic Ray Research,
the University of Tokyo

4. Cryocooler unit

Vibration measurement

Displacement sensor

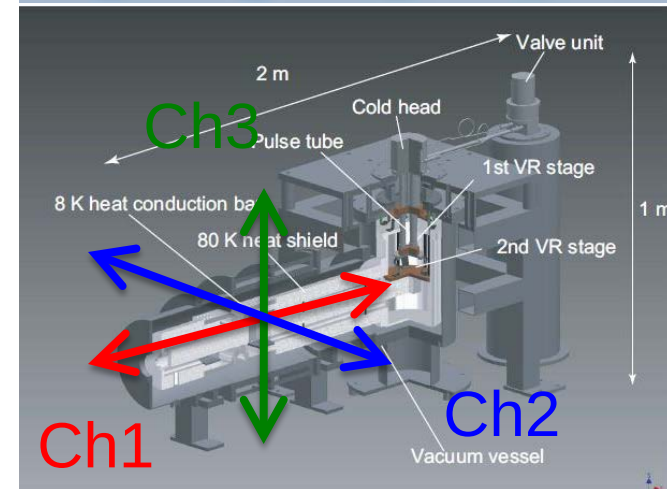
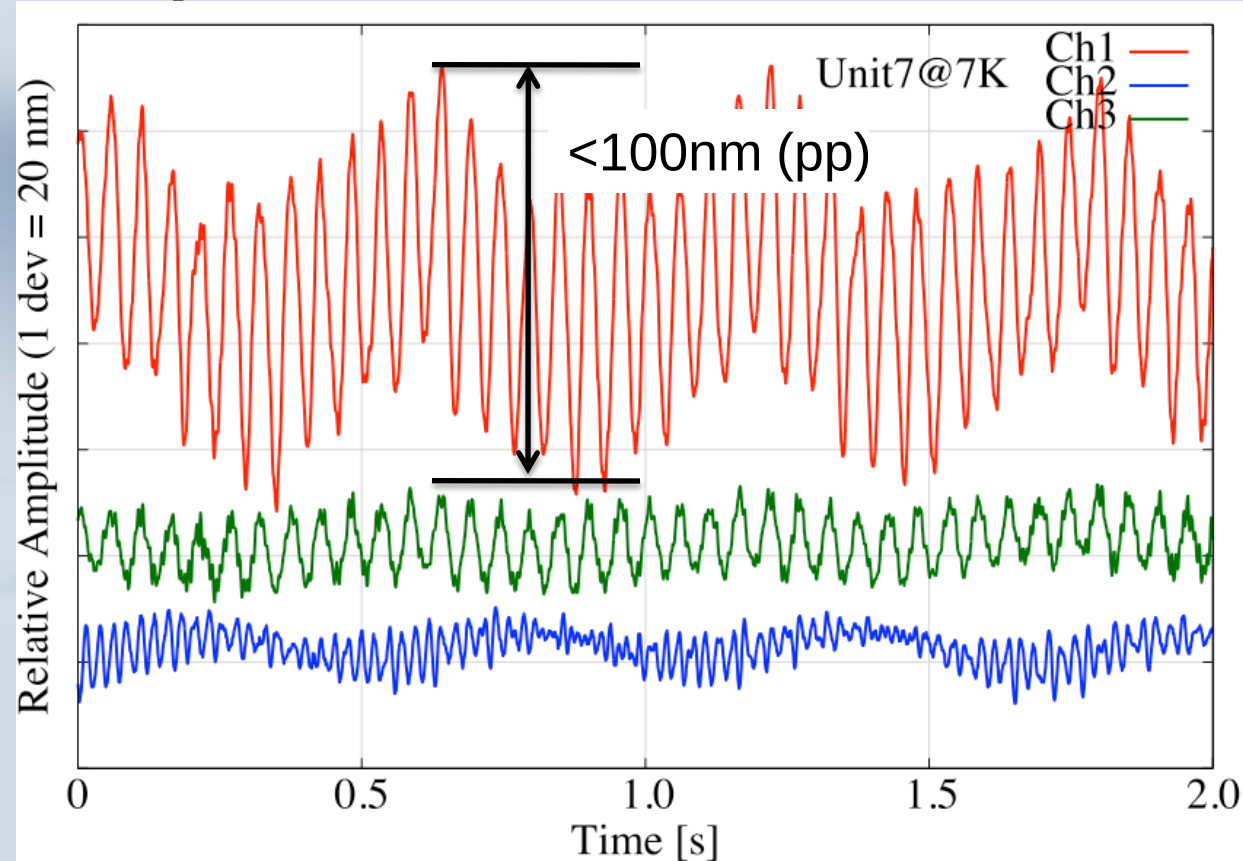


4. Cryocooler unit

Vibration measurement

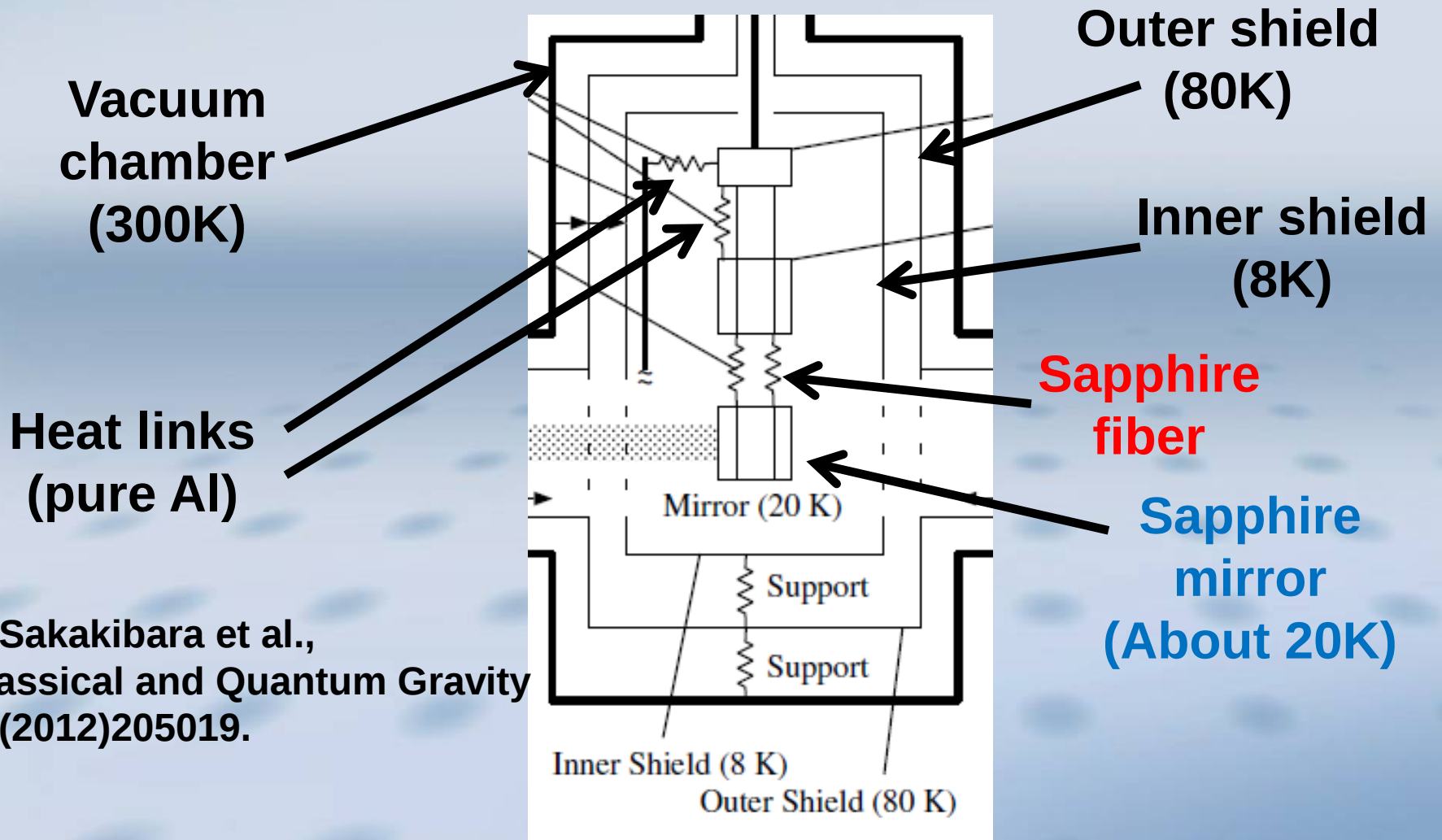
1.7 Hz vibration by cryocooler head

Amplitude is **smaller** than 100 nm (**requirement**).



5. Cryogenic payload

Outline of cryogenic payload



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

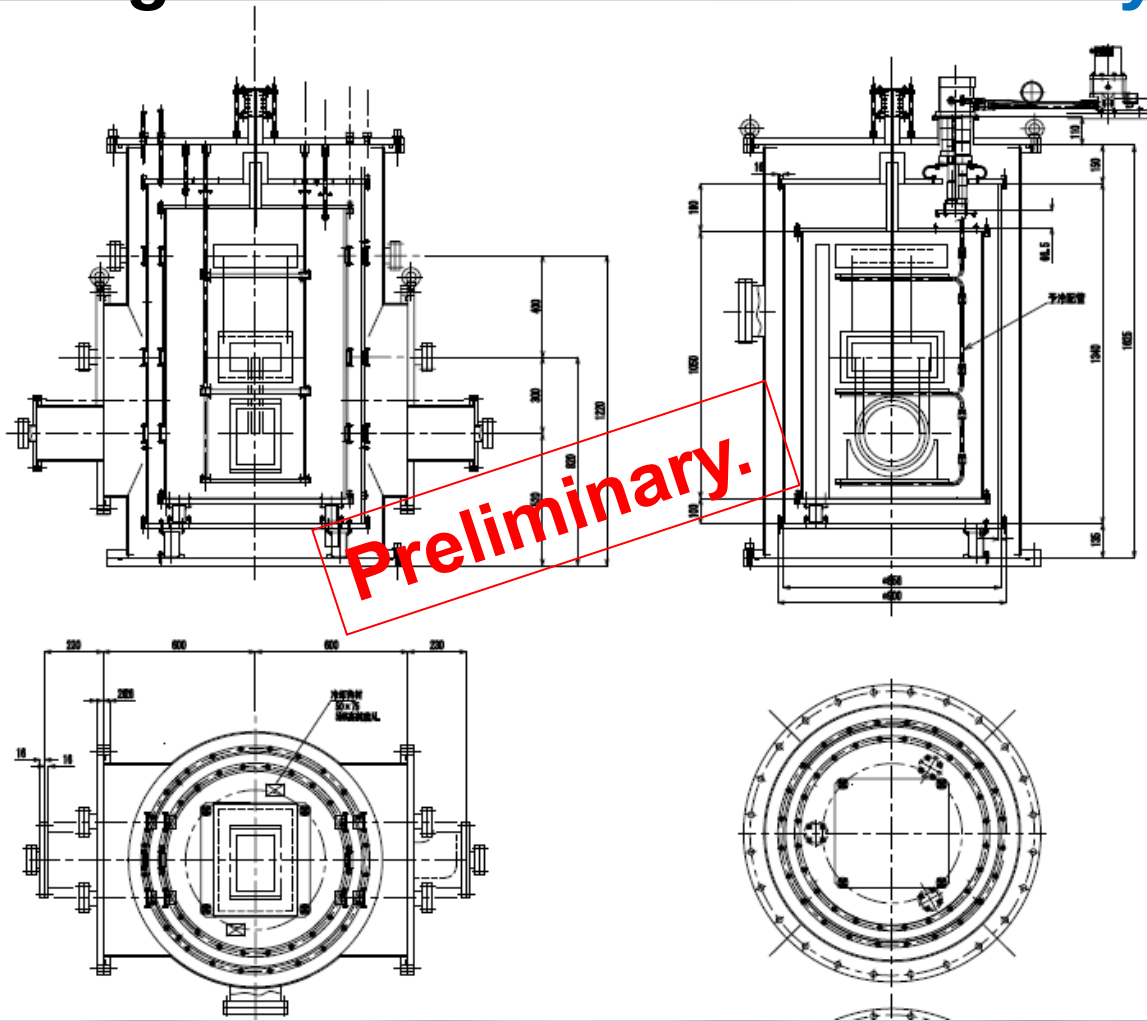
5. Cryogenic payload

(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).**

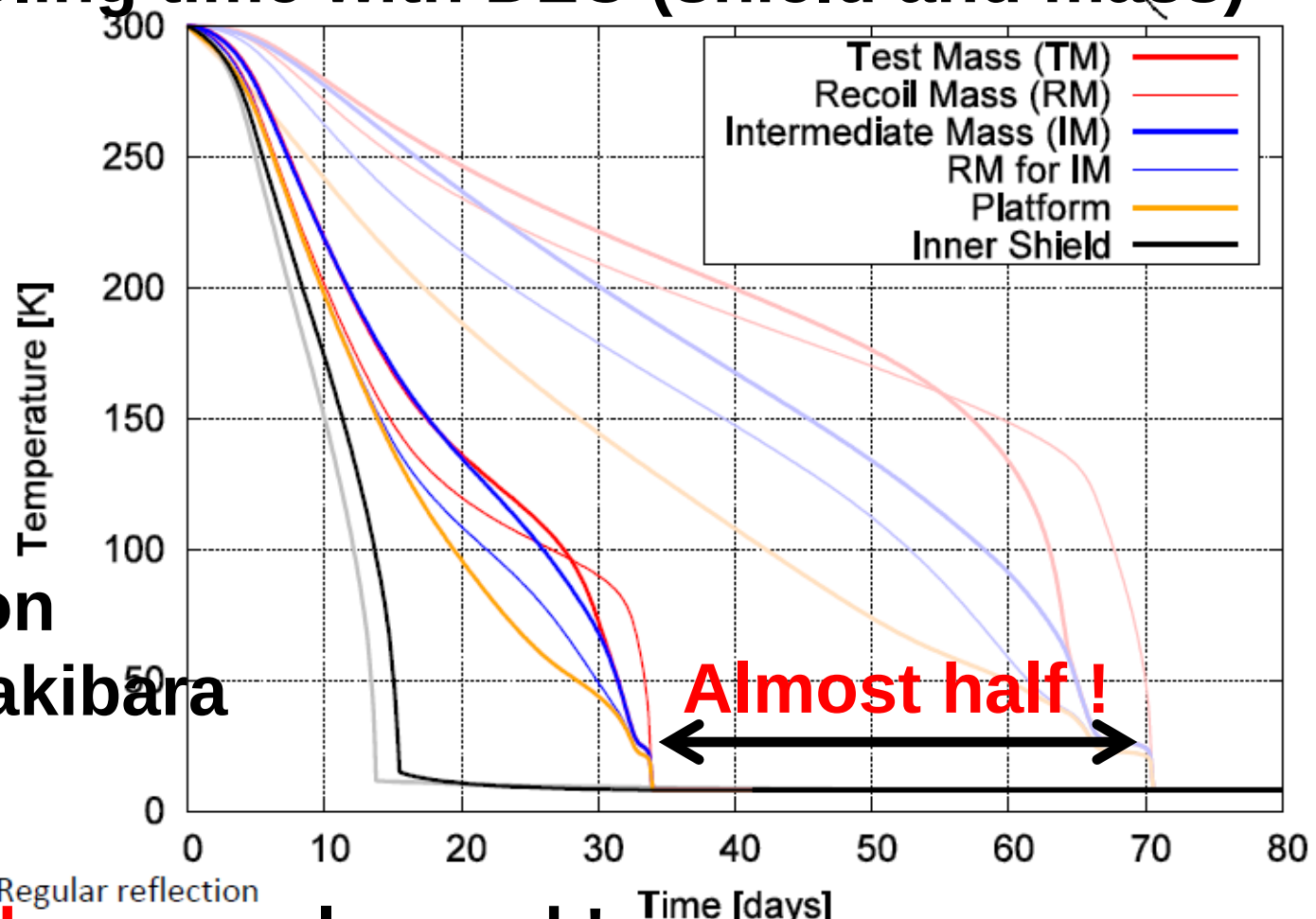
**At beginning of initial cooling,
heat transfer is **dominated** by **radiation**.**

**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

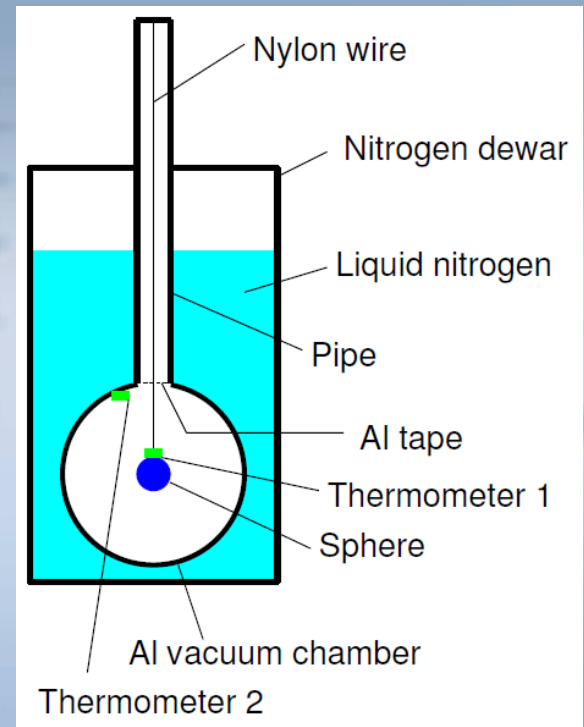
(b) Initial cooling time

Experimental test of effect of high emissivity coating (DLC)

Inner sphere (copper) is suspended

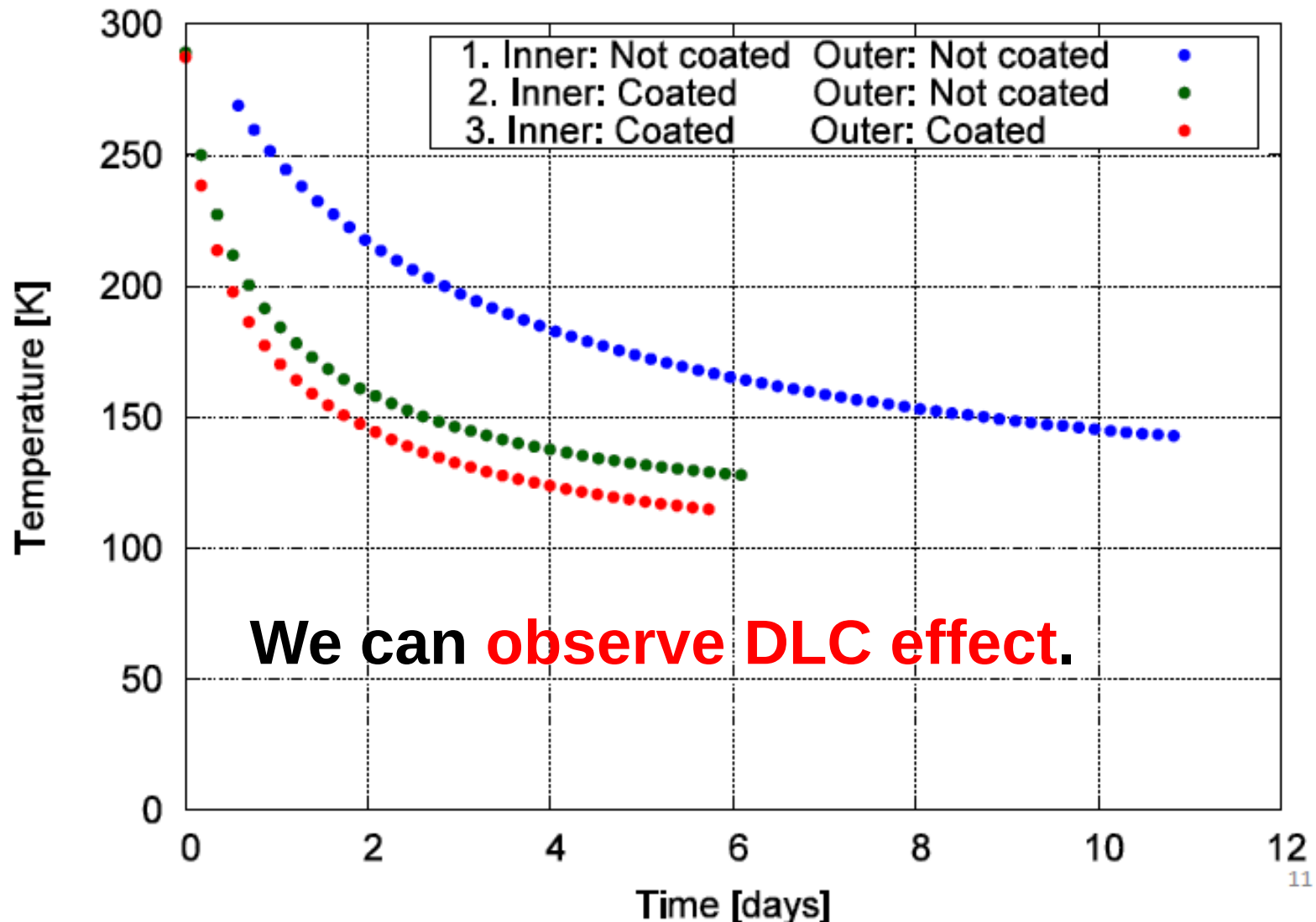
inside outer sphere (aluminum) at 77 K

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

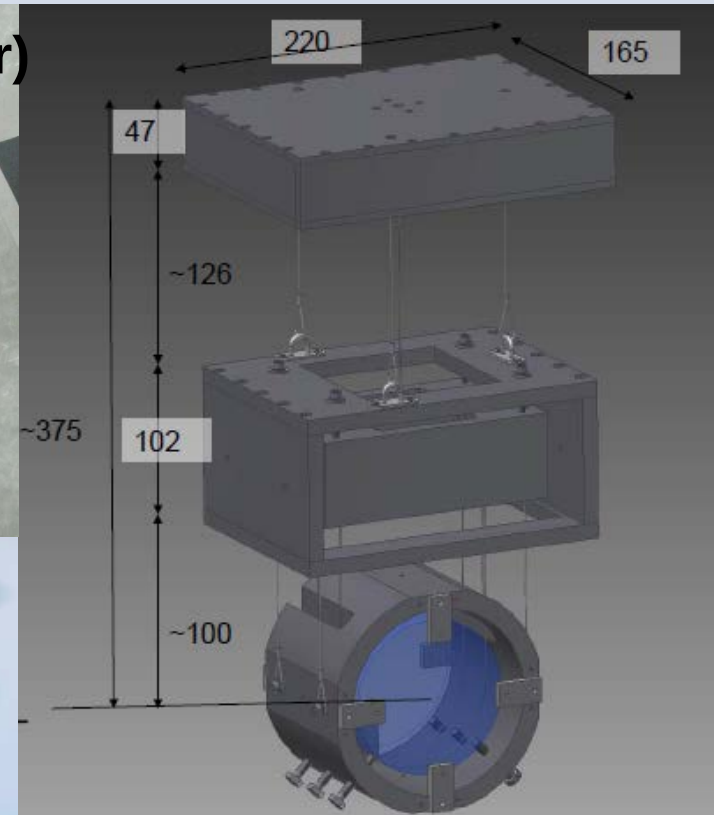
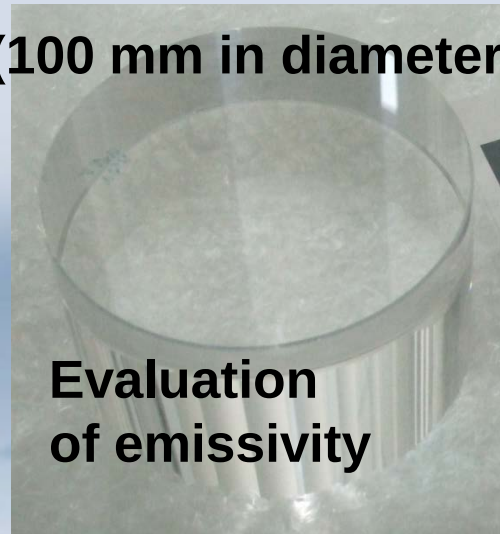
(~**5 kg**)

DLC coating

Sapphire bulk as
dummy mirror

Preparation is in progress.

(100 mm in diameter)

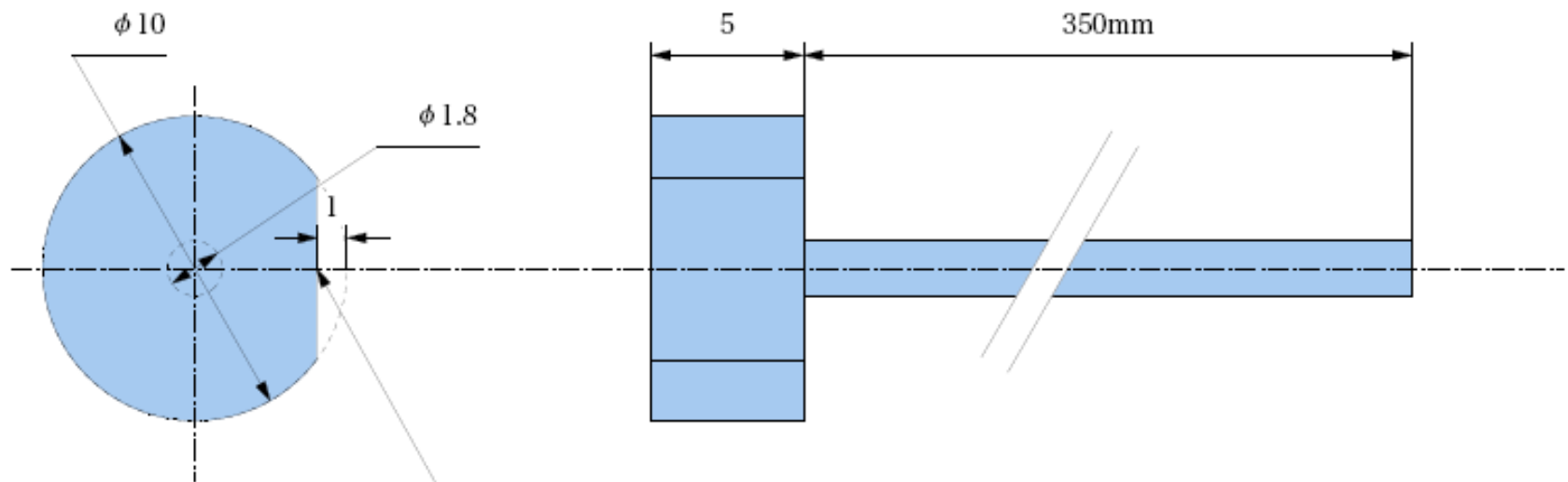


S. Koike

5. Cryogenic payload

(c) Sapphire fibers with nail heads

Test sample (T. Uchiyama)



— Orientation flat
indicating the crystal
axis which is
perpendicular to the
crystal axis of the fiber
growing up direction.

Core diameter: 1.8mm.
Core length: 350mm.
Edge diameter: 10.0mm.
Edge length: 5mm.
2011/09/16
Takashi Uchiyama
ICRR, the Univ. of Tokyo.

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.

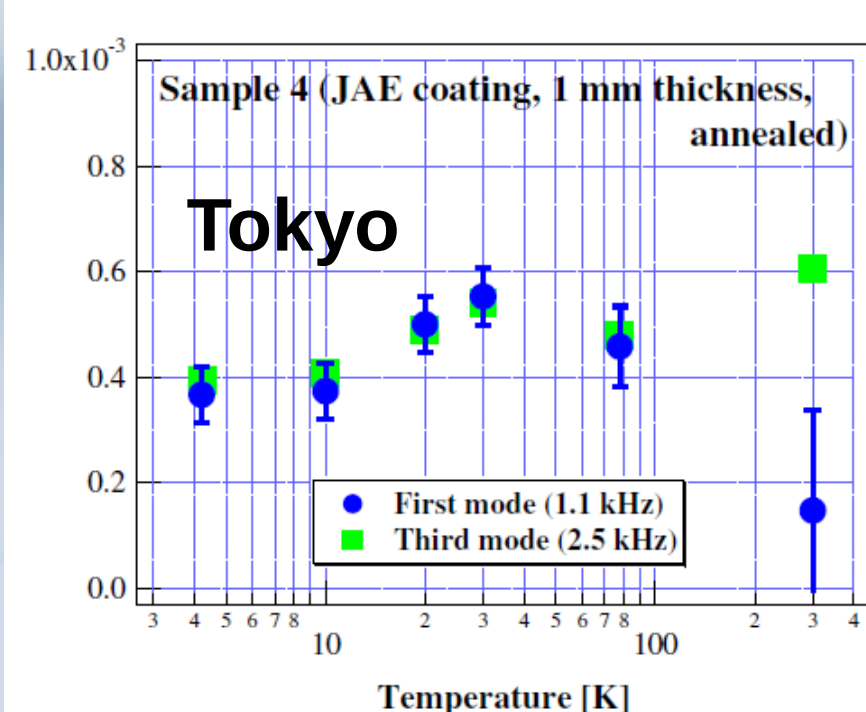
Rebecca Douglas presents a poster.

Two IMPEX fibers were sent to Jena.

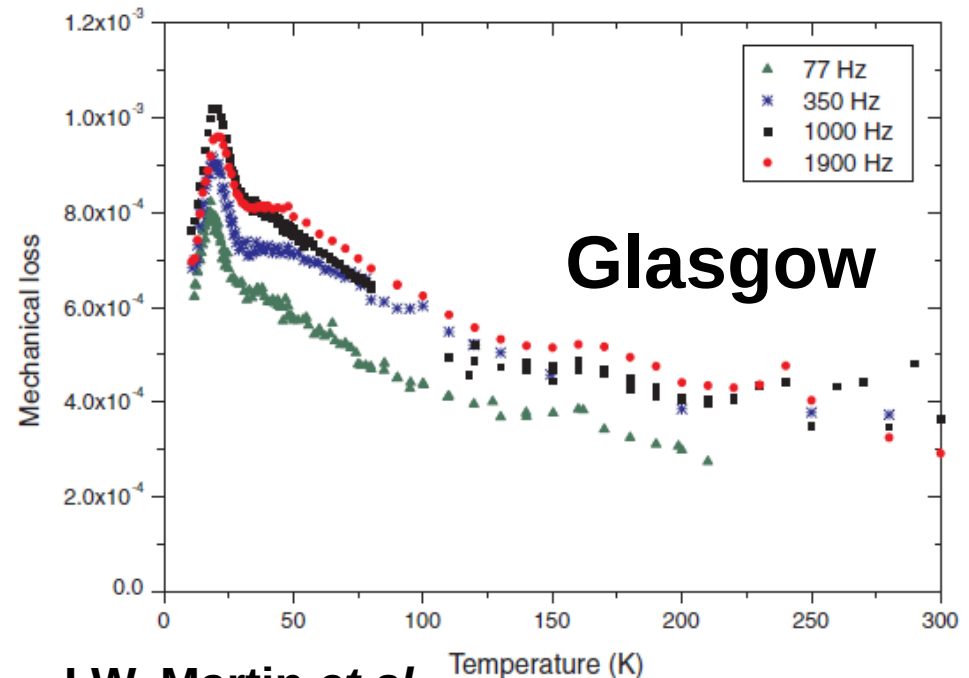
5. Cryogenic payload

(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**.

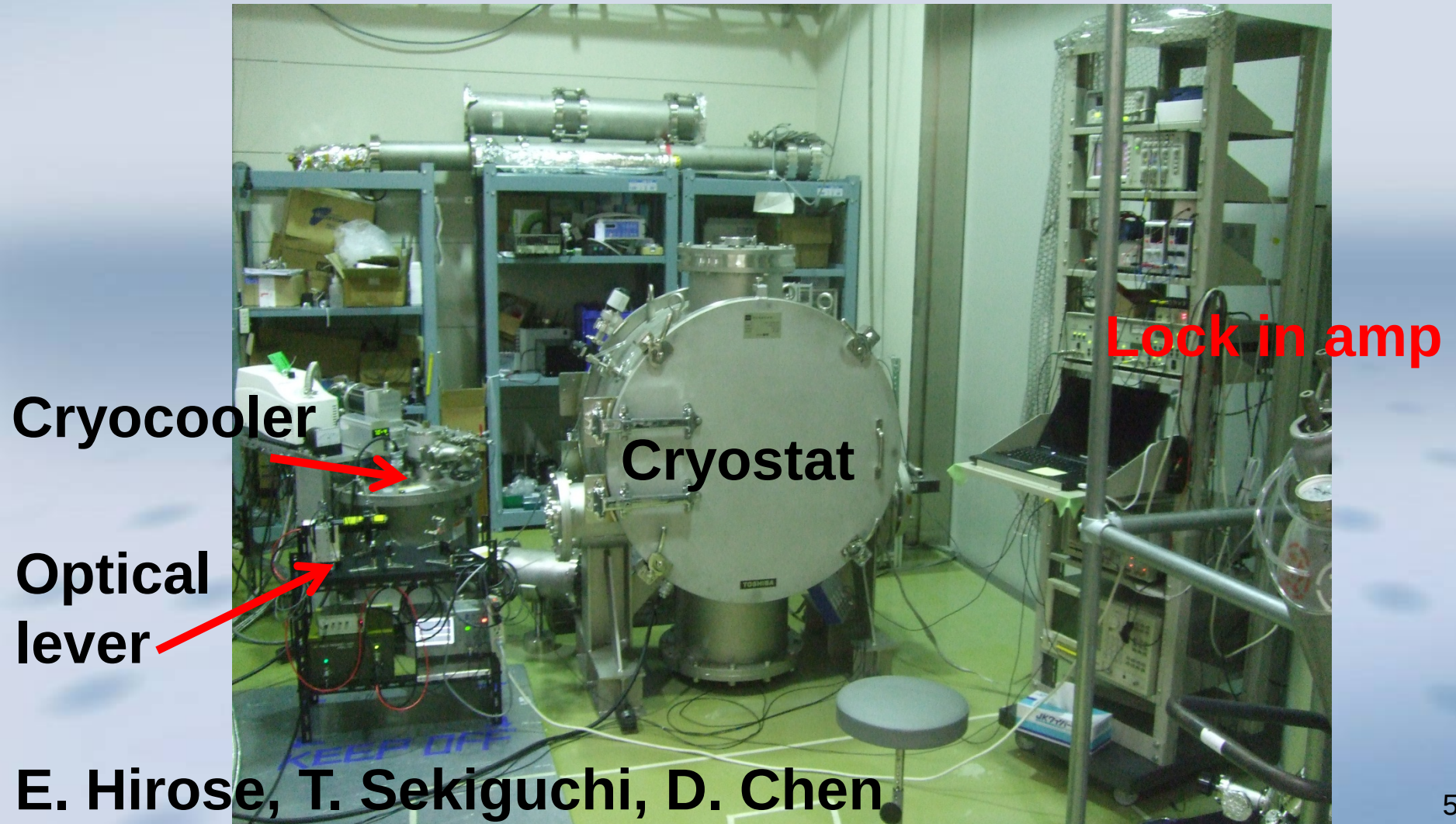
Y. Sakakibara measured these samples in Glasgow (**room temperature**); Details are in tomorrow his talk. Glasgow group **continues** the mission for the **cryogenic temperature**.

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.

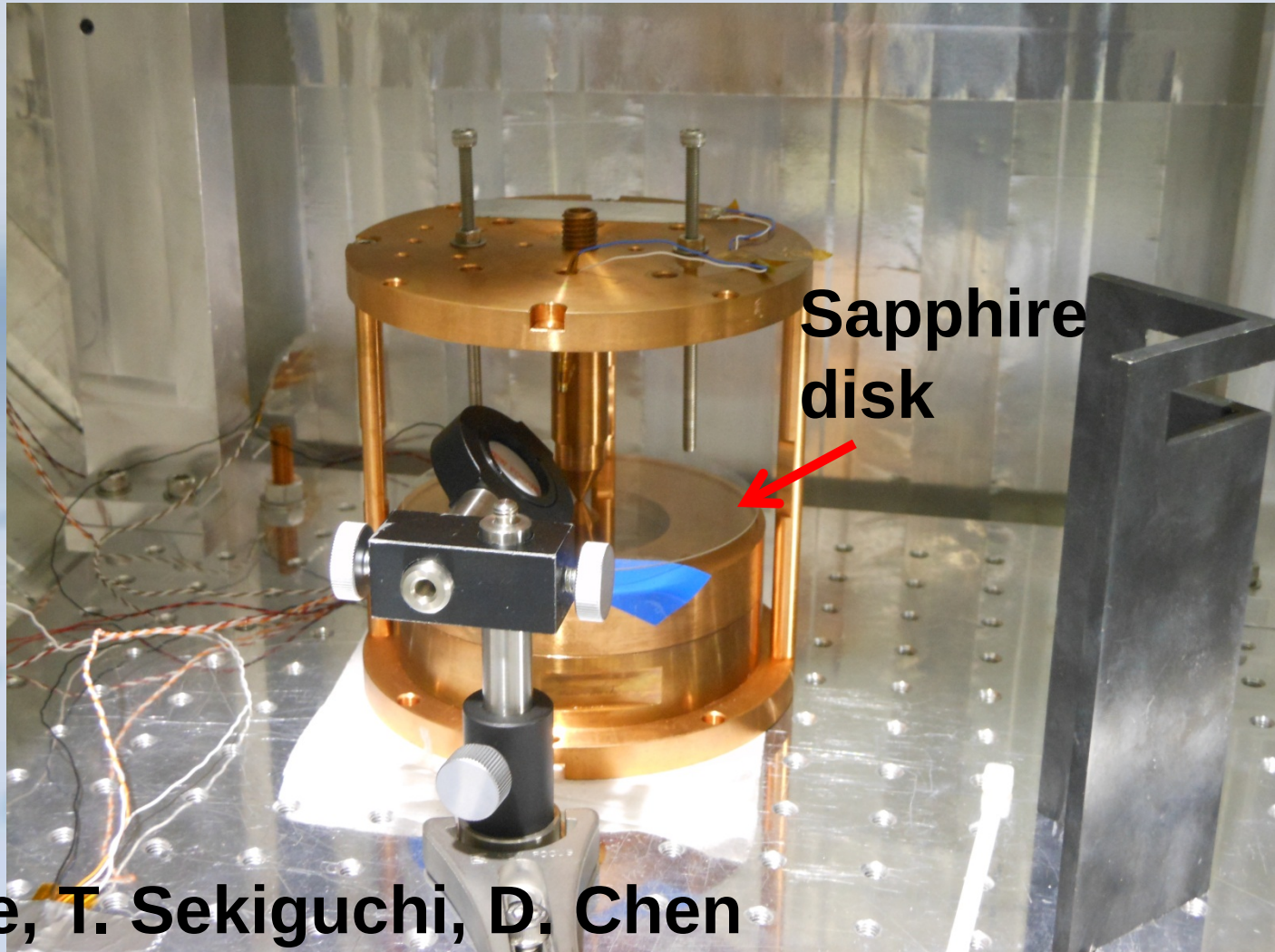
5. Cryogenic payload

(d) Coating mechanical loss



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

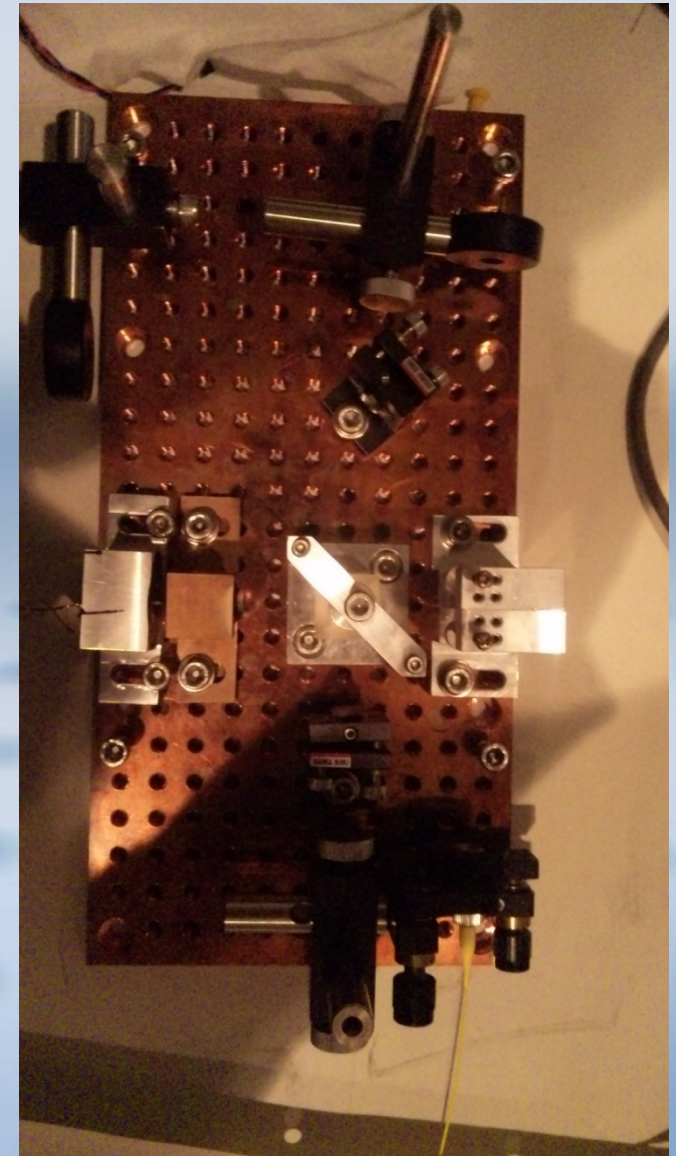
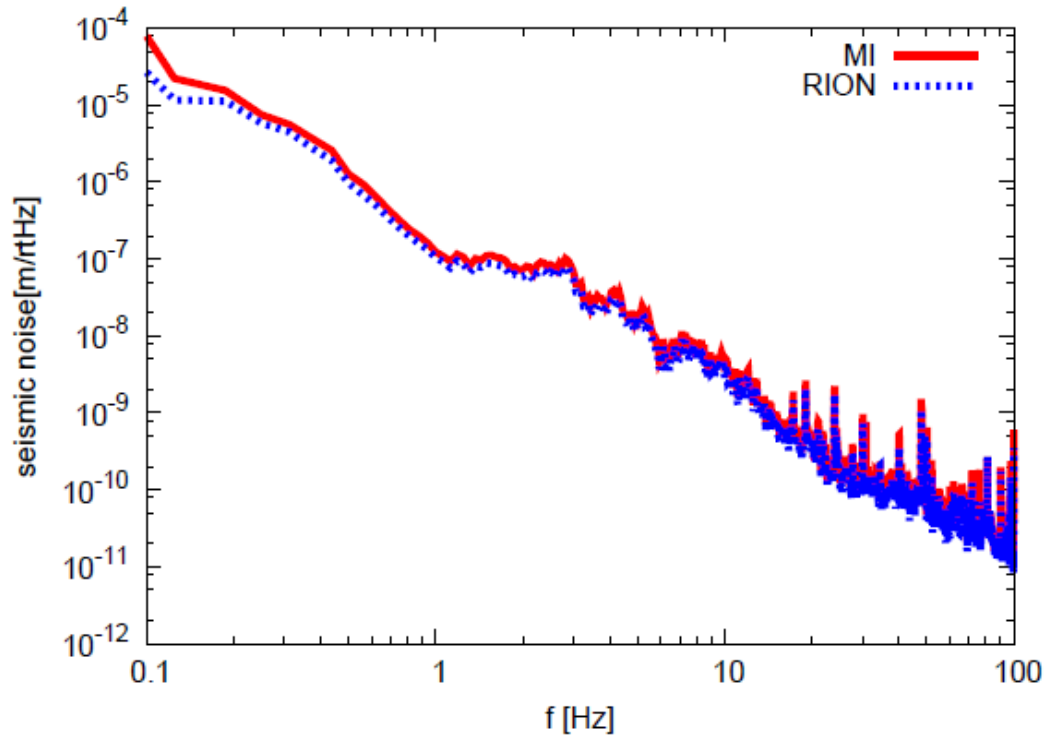
**Luca Naticchioni's
accelerometer**



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) should 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 baffles

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

**Initial 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 $x = 1, 2, 3, \dots, 16$ m and the other two baffles were fixed at $x = 0$ and 17 m. The result showed that the baffle position of

$$x = 0, 10, 14, 16, 17 \text{ m} \quad (23)$$

afforded the minimum P_i .

The total emitted power can be expressed as

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

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

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

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

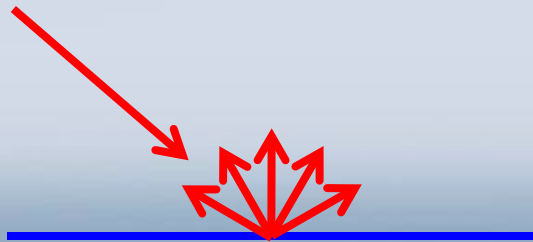
$$2\epsilon_{\text{sap}} P_i = 0.02 \text{ W}. \quad (26)$$

The emissivity of sapphire, the material the mirror is made of, at 20 K is $\epsilon_{\text{sap}} = 0.1$ [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.

Model of heat transfer via radiation

- Gray body model

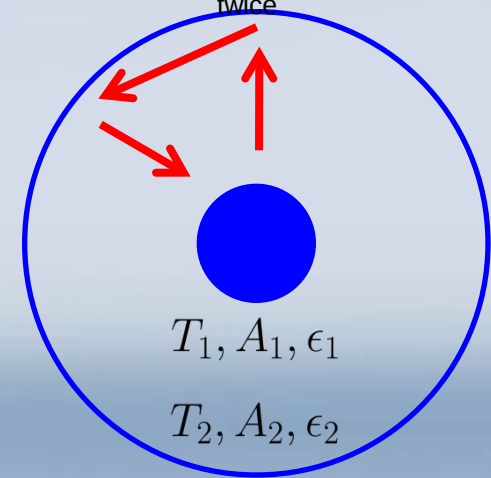
- Surface reflects radiation to all angle



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

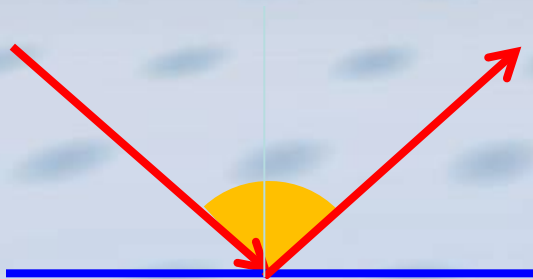
A: surface area
 ϵ : emissivity

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

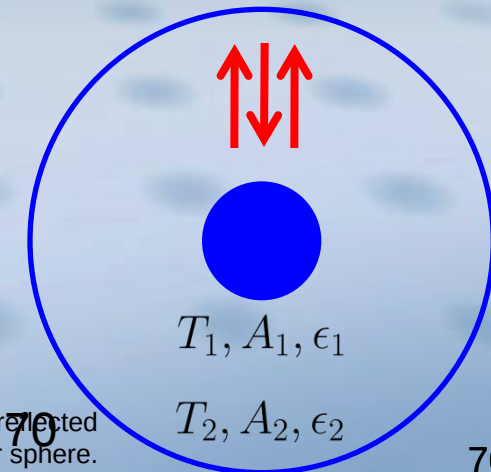


- Regular reflection model

- Surface reflects radiation to the same angle as incident angle

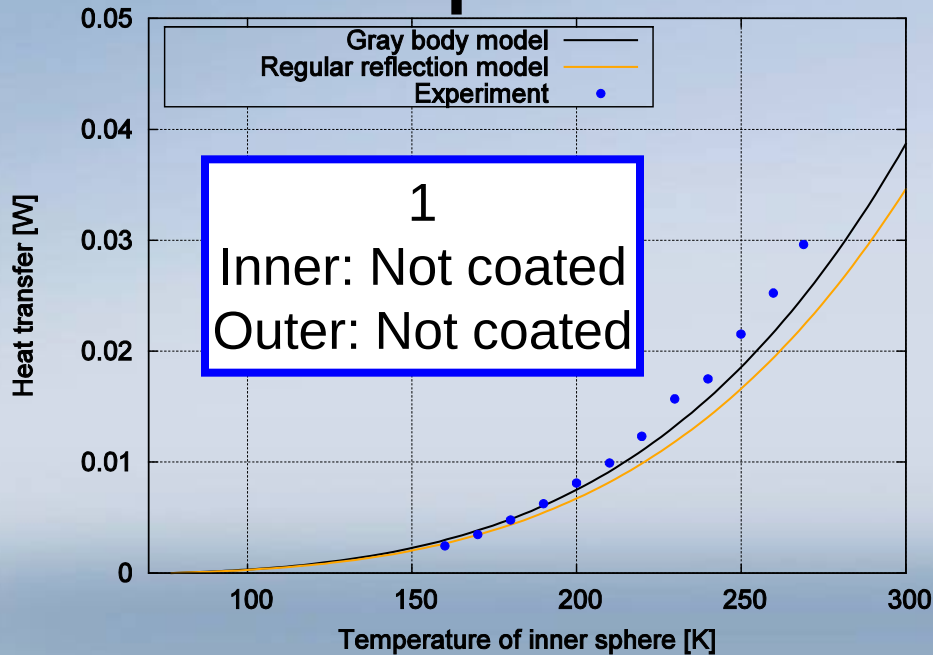


$$Q = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$



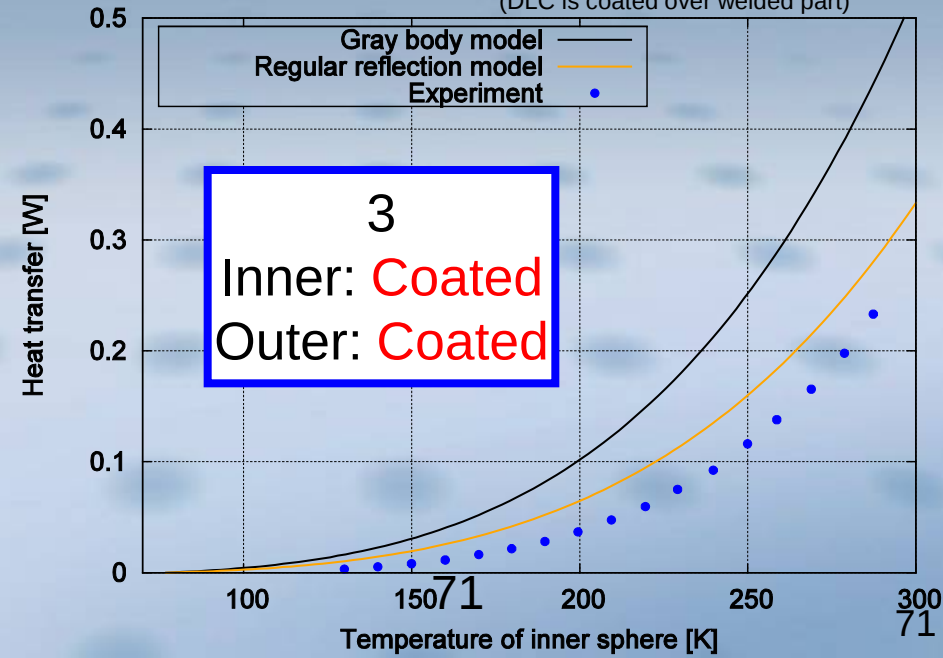
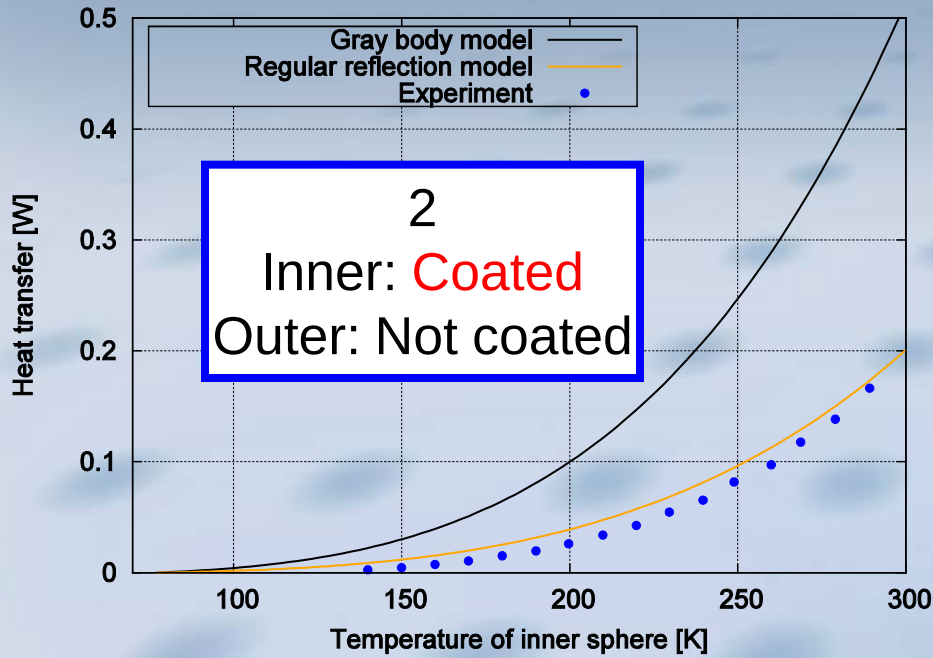
All rays from inner sphere are reflected alternatively by outer and inner sphere.

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

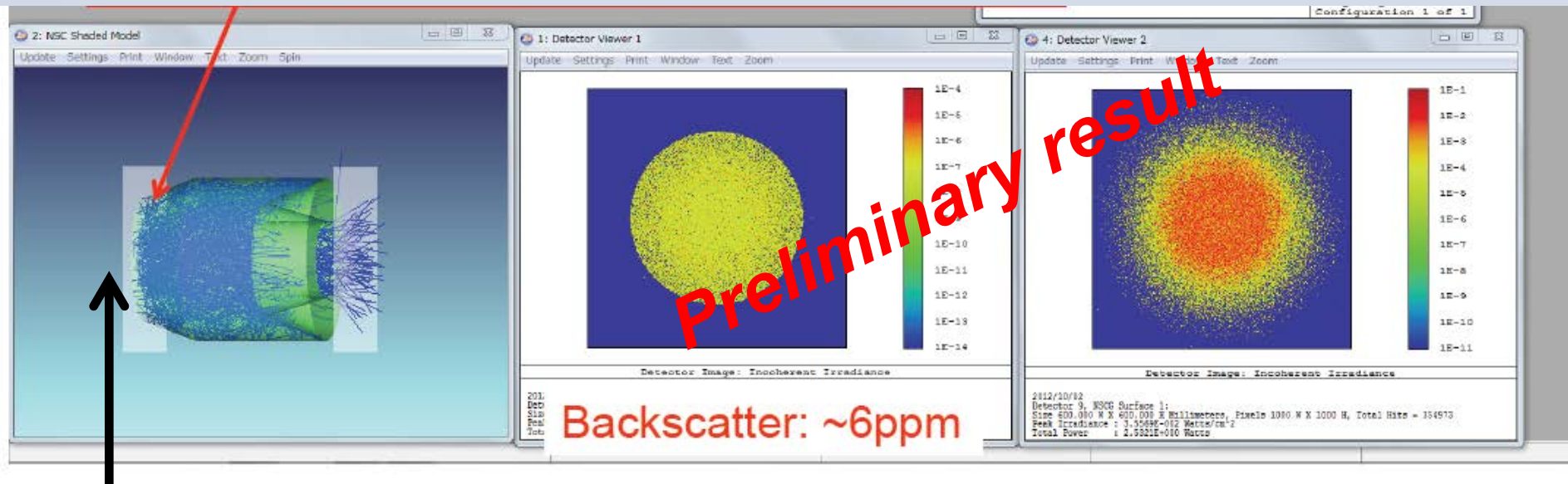
Value of emissivity
 Copper: 0.03 (measured)
 DLC: 0.41 (measured)
 Aluminum (CP): 0.06 (measured)
 Welded part of aluminum:
 0.8 (assumption)
 Outer sphere without DLC: 0.2
 (80 % area: CP, 20 % area: welded part)
 Outer sphere with DLC: 0.41
 (DLC is coated over welded part)



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

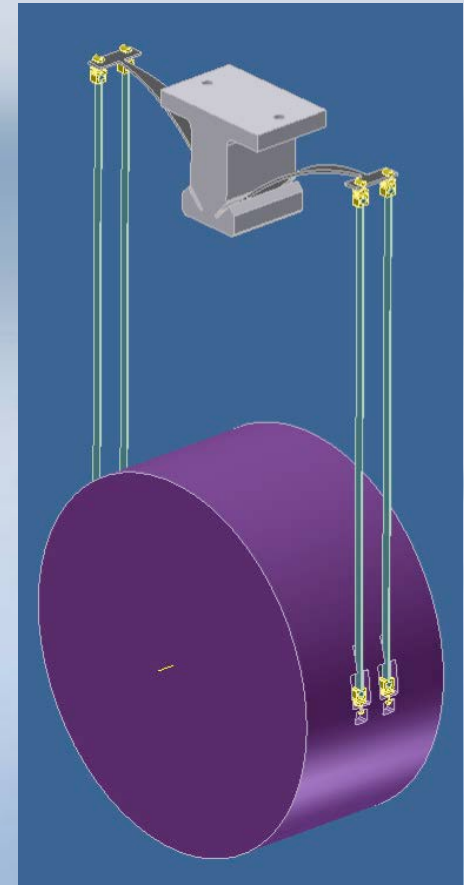
W. Johnson : JGW-G1201127, G1201271

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**



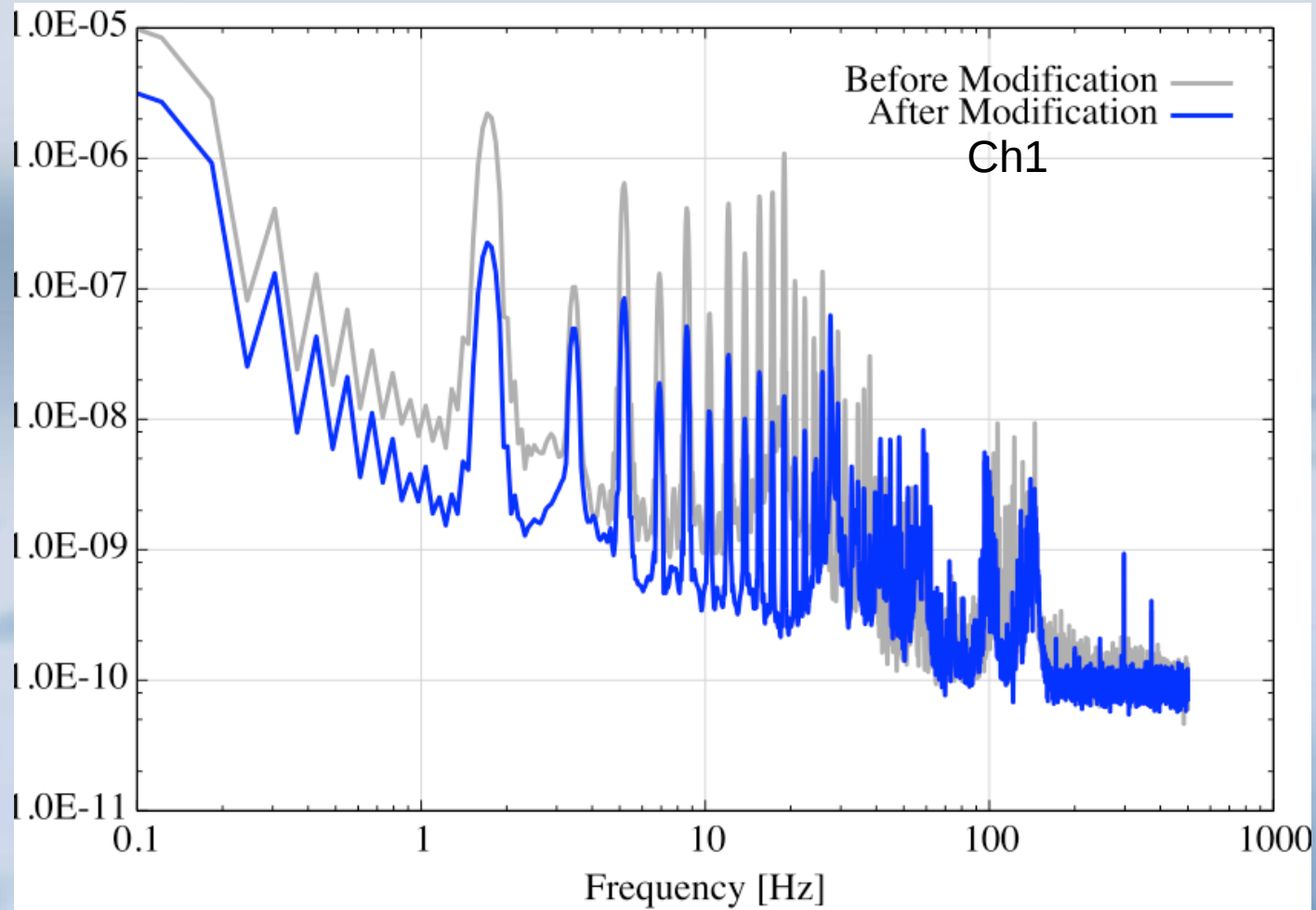
5. KAGRA payload in ELiTES

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 opinions and suggestions** !

2. Cryocooler unit

1. Outline

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

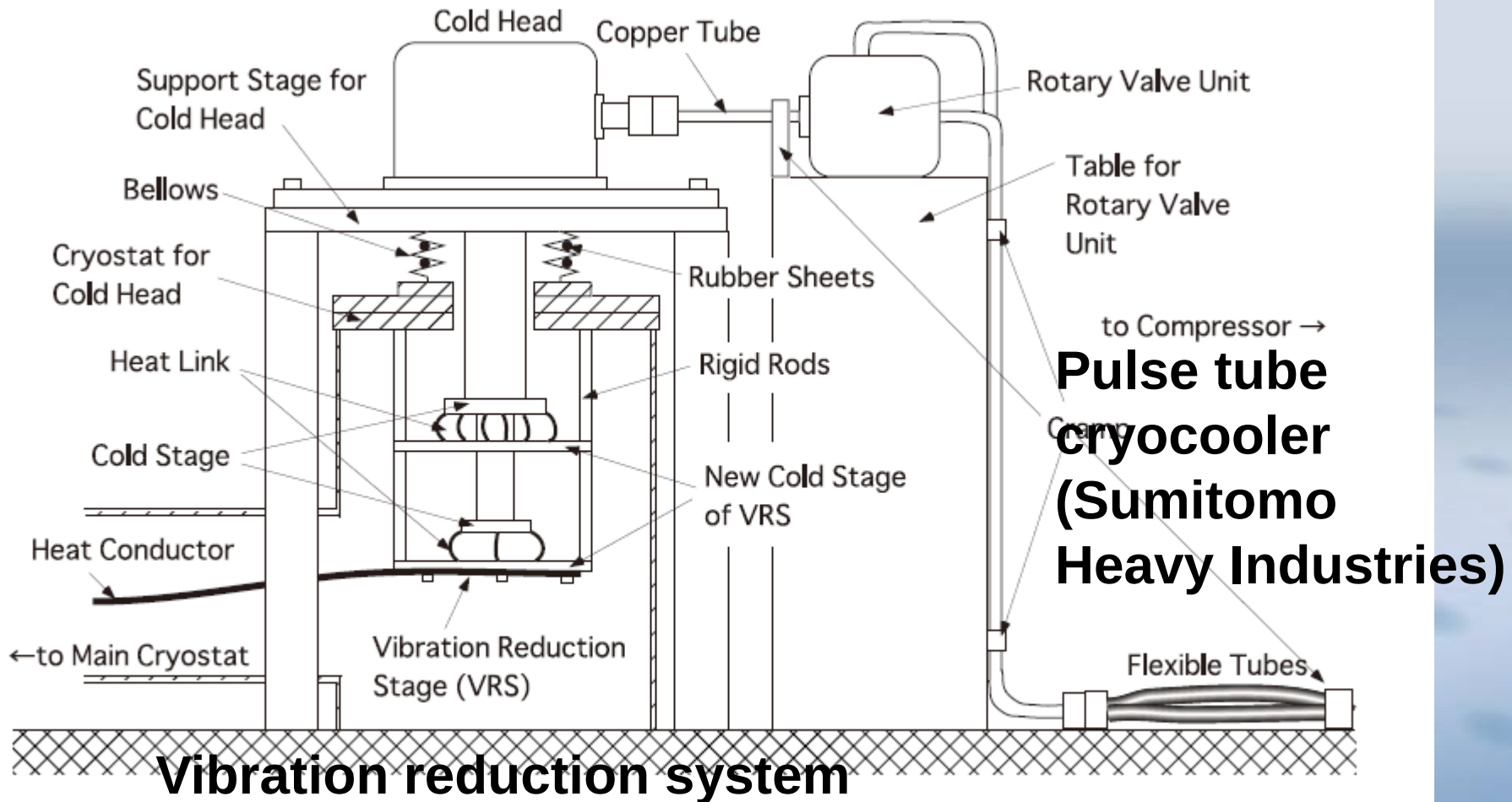


Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

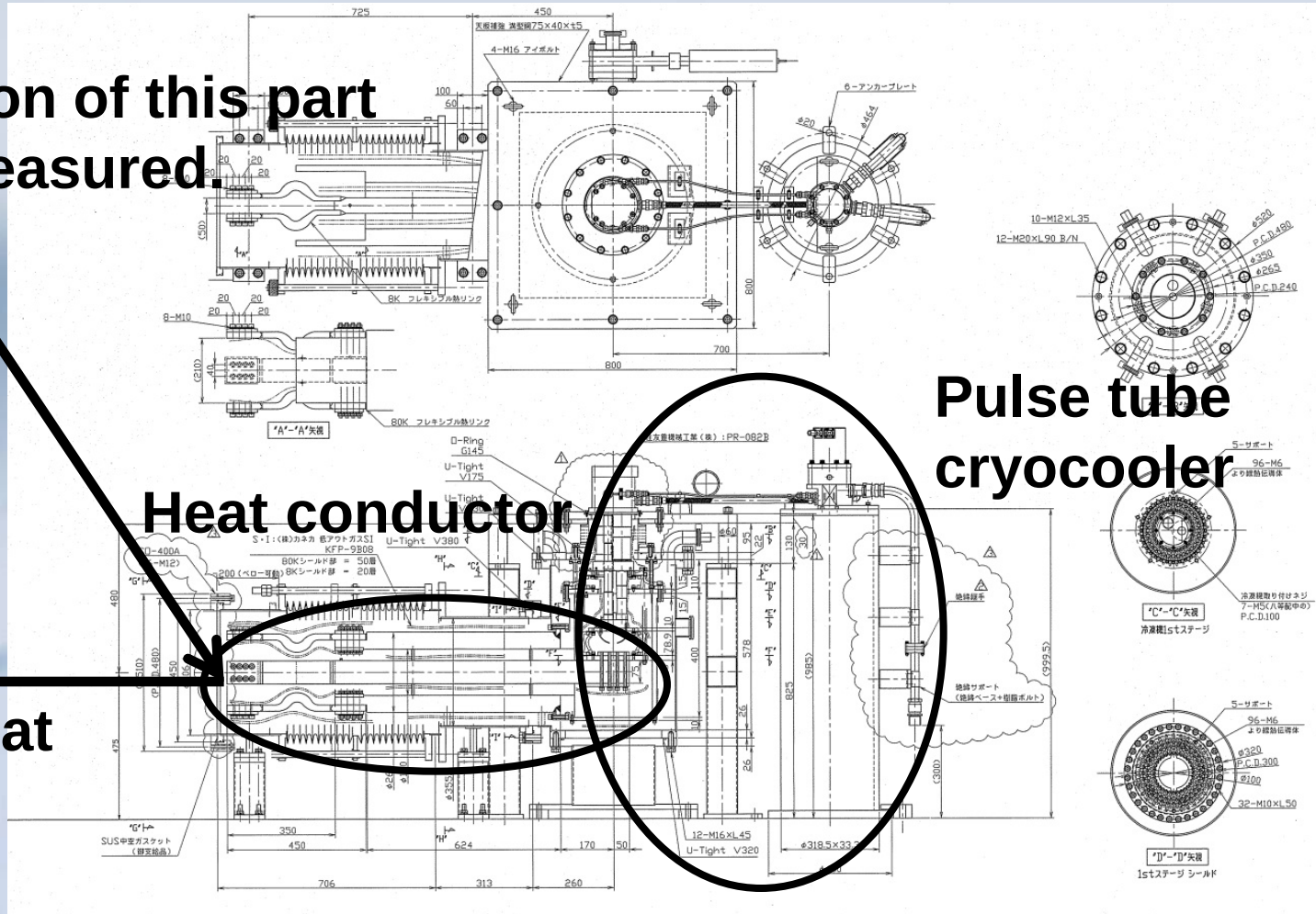
2. Cryocooler unit

4. Vibration measurement

Vibration of this part was measured.

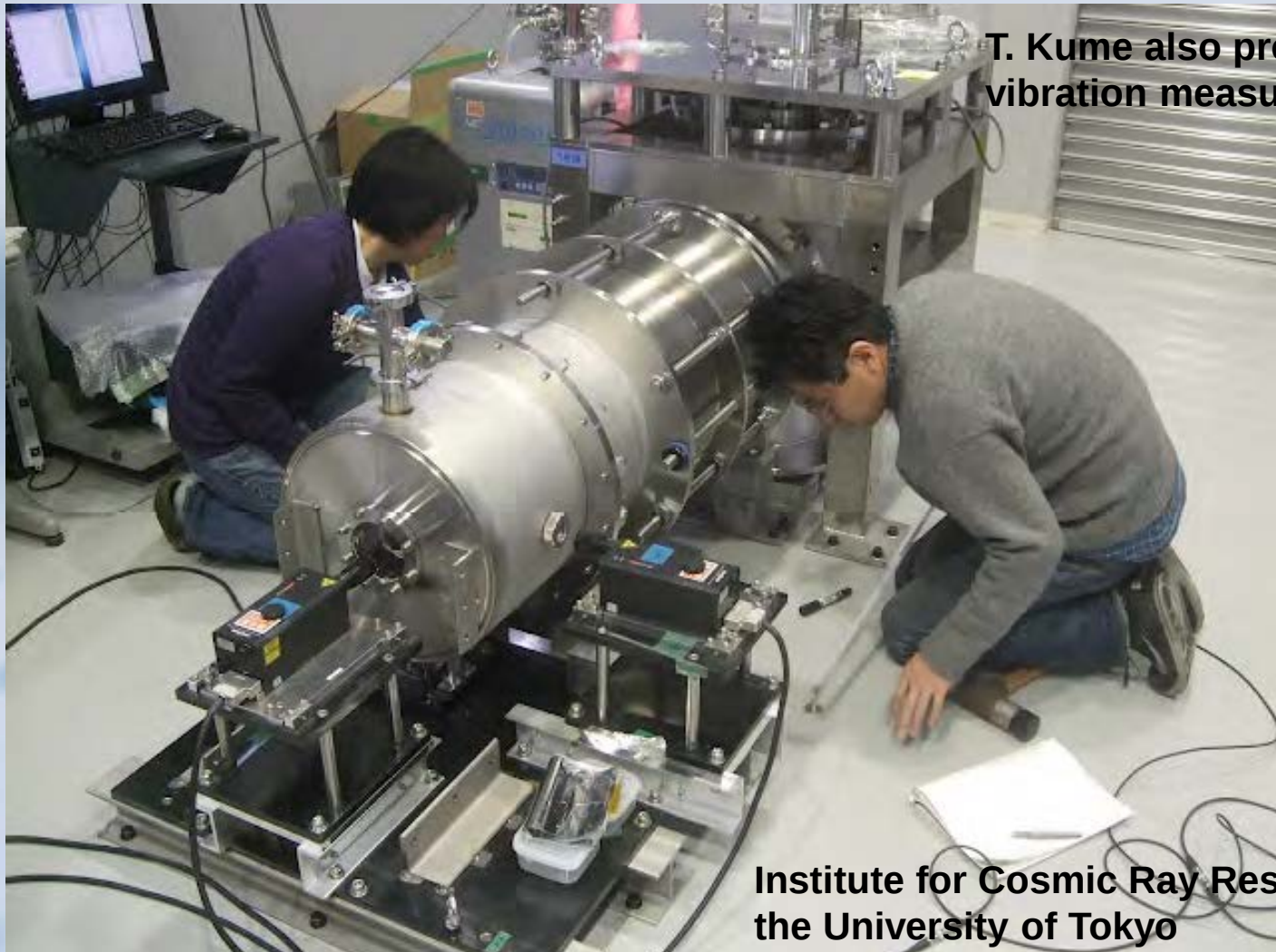
Heat conductor

Cryostat



2. Cryocooler unit

4. Vibration measurement



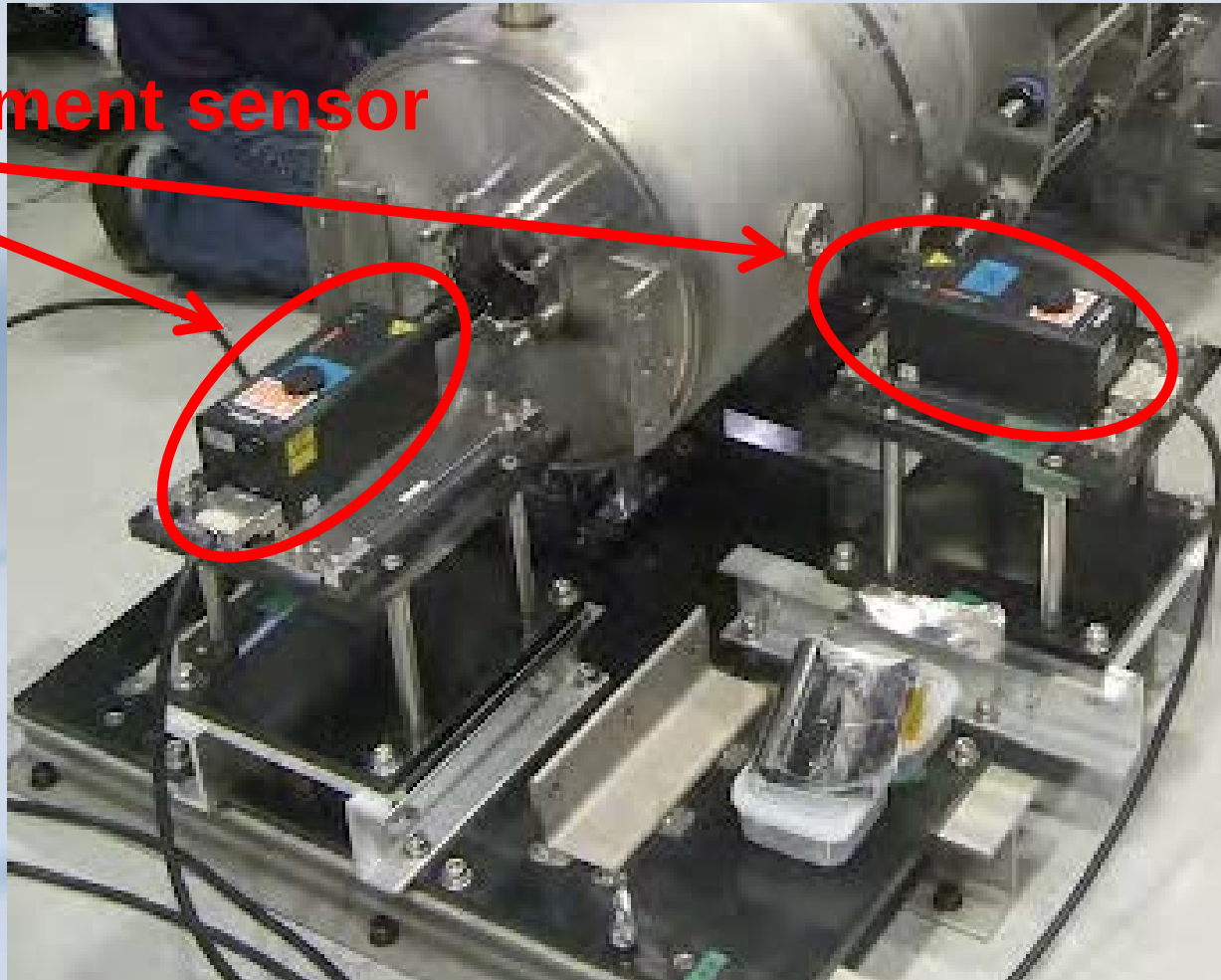
T. Kume also proceeds with vibration measurement.

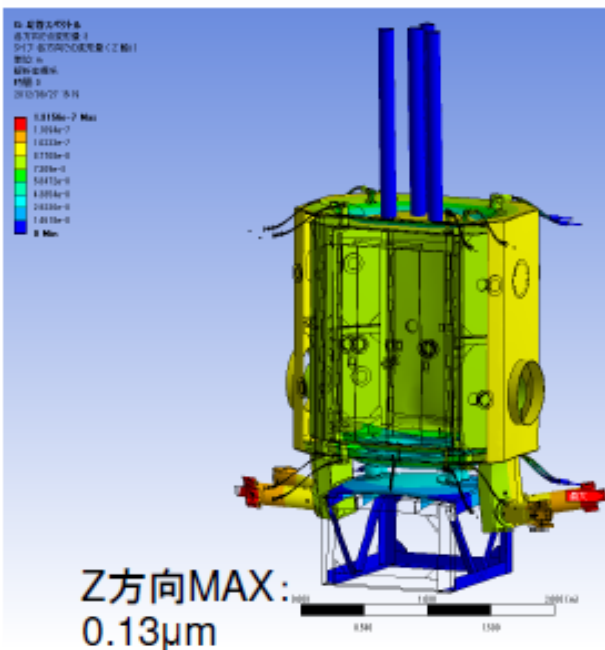
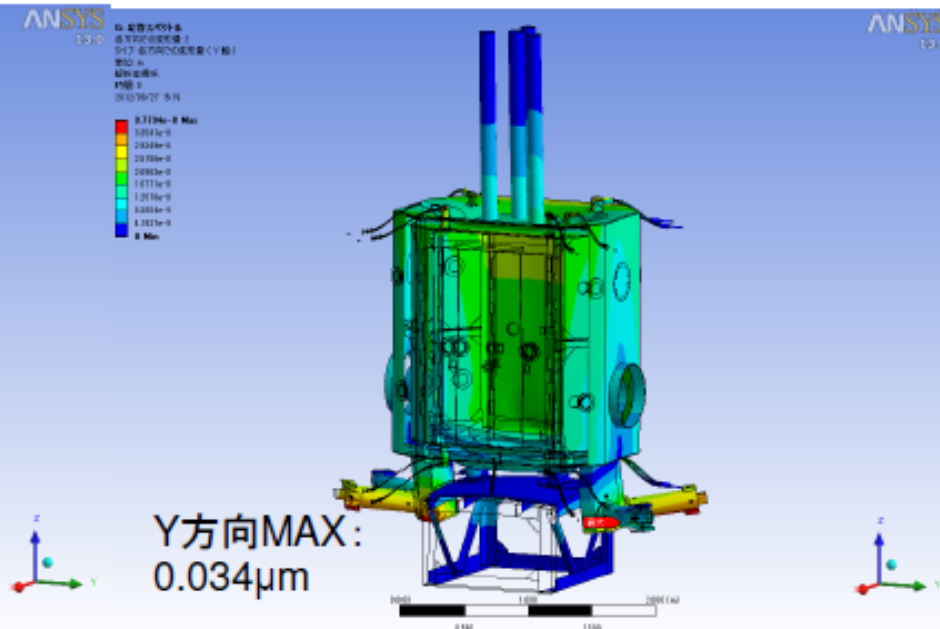
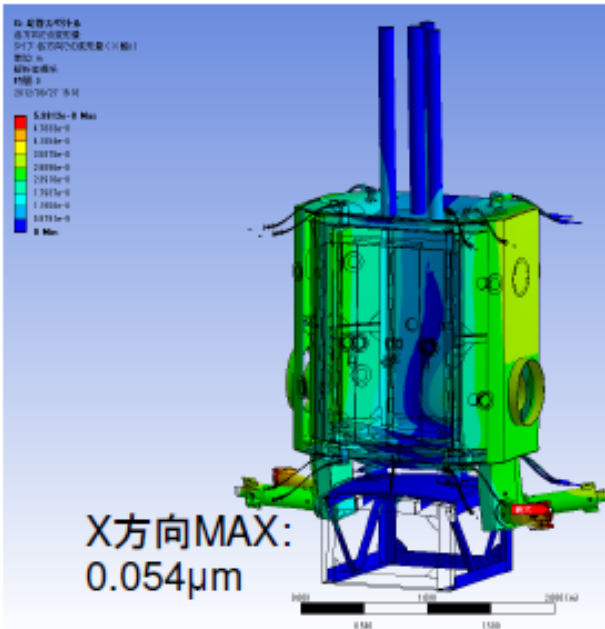
**Institute for Cosmic Ray Research,
the University of Tokyo**

2. *Cryocooler unit*

4. Vibration measurement

Displacement sensor





OCILIO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

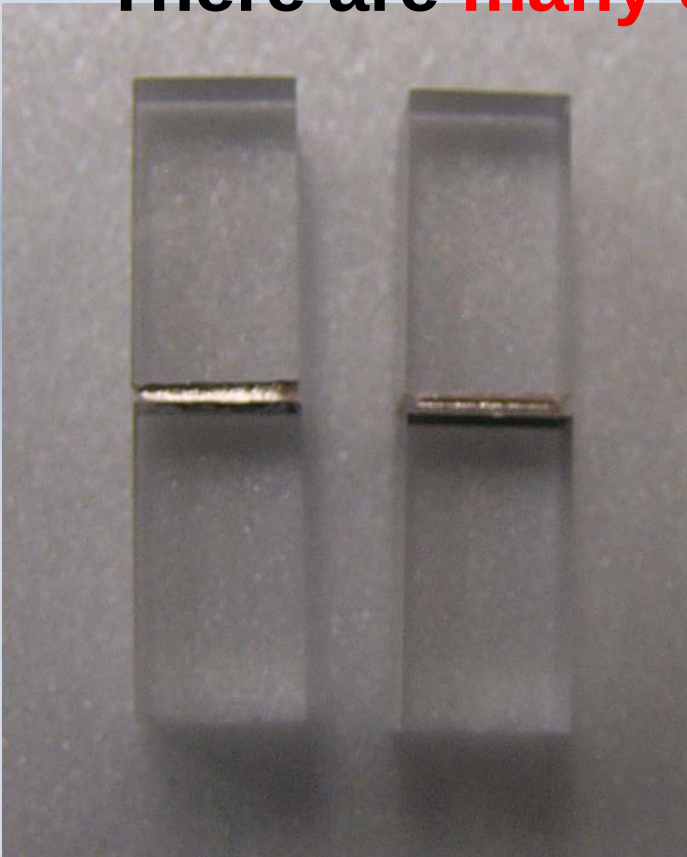
Sapphire fibers to suspend sapphire mirrors

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
Hydroxy-catalysis, silicate	Necessary	KOH, Na ₂ SiO ₃ , H ₂ O	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 ₂ O ₃ , AlPO ₄ , H ₂ O	~ 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
measured by K. Shibata,
T. Ushiba, T. Suzuki.

Q-values and strength should
be measured.

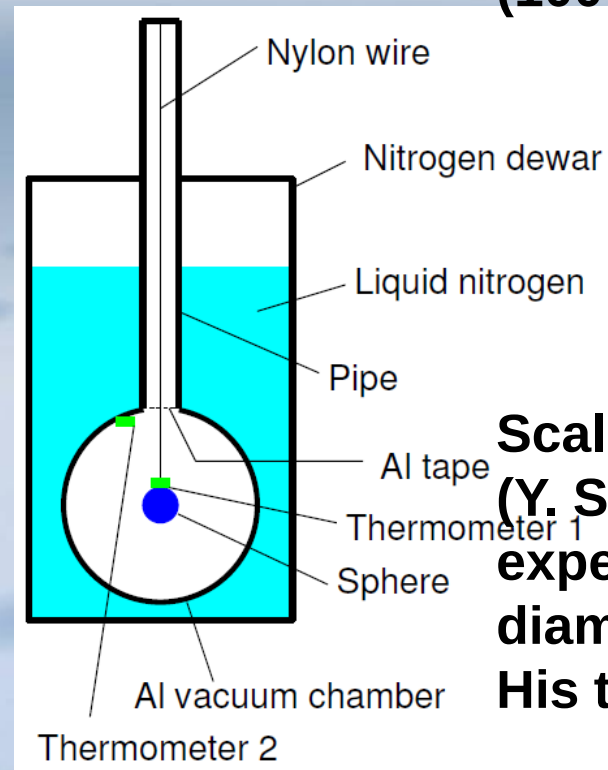
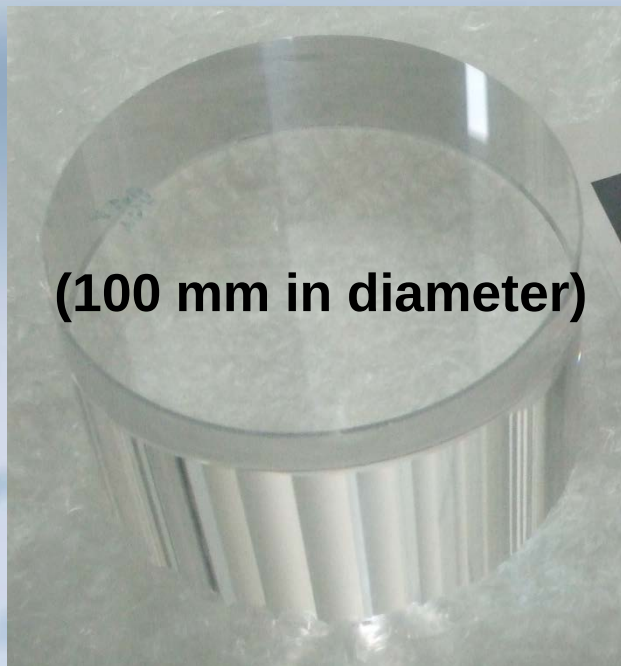
Metalize bonding (Kyocera)

4. Current status

(b) Initial cooling time

Sample 1 for Toshiba experiment:

Sapphire and metal hollow sphere
(100 mm in diameter)



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

Evaluation of emissivity

4. Current status

(b) Initial cooling time

Sample 2 for Toshiba experiment :

Dummy payload (hollow masses)

Half size

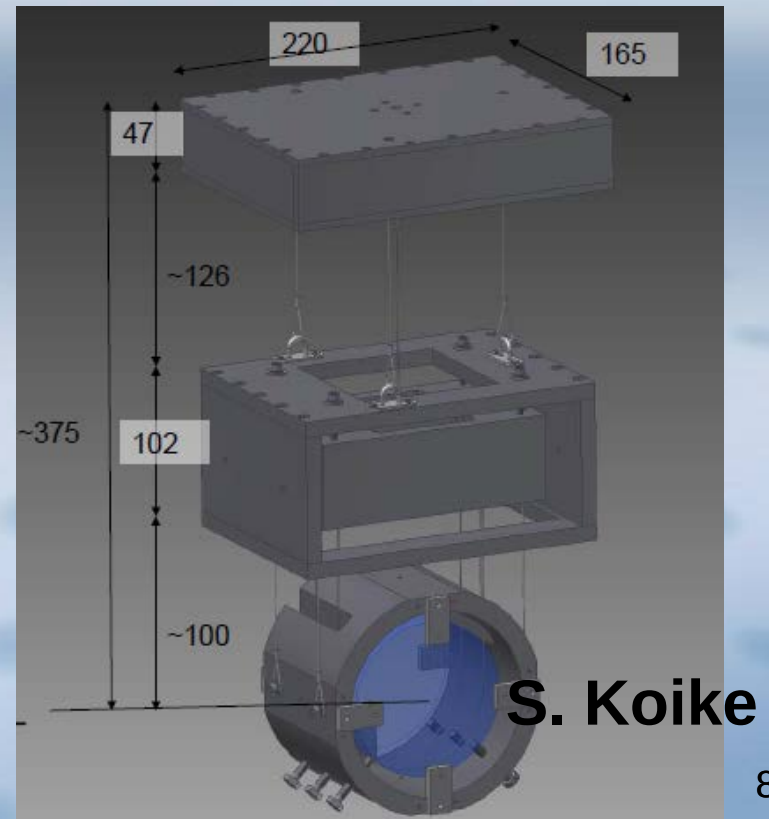
Hollow masses

(~**5 kg**)

DLC coating

Sapphire bulk as
dummy mirror

Preparation is in progress.



2. Drawing by Jecc Torisha

