Cooling time reduction

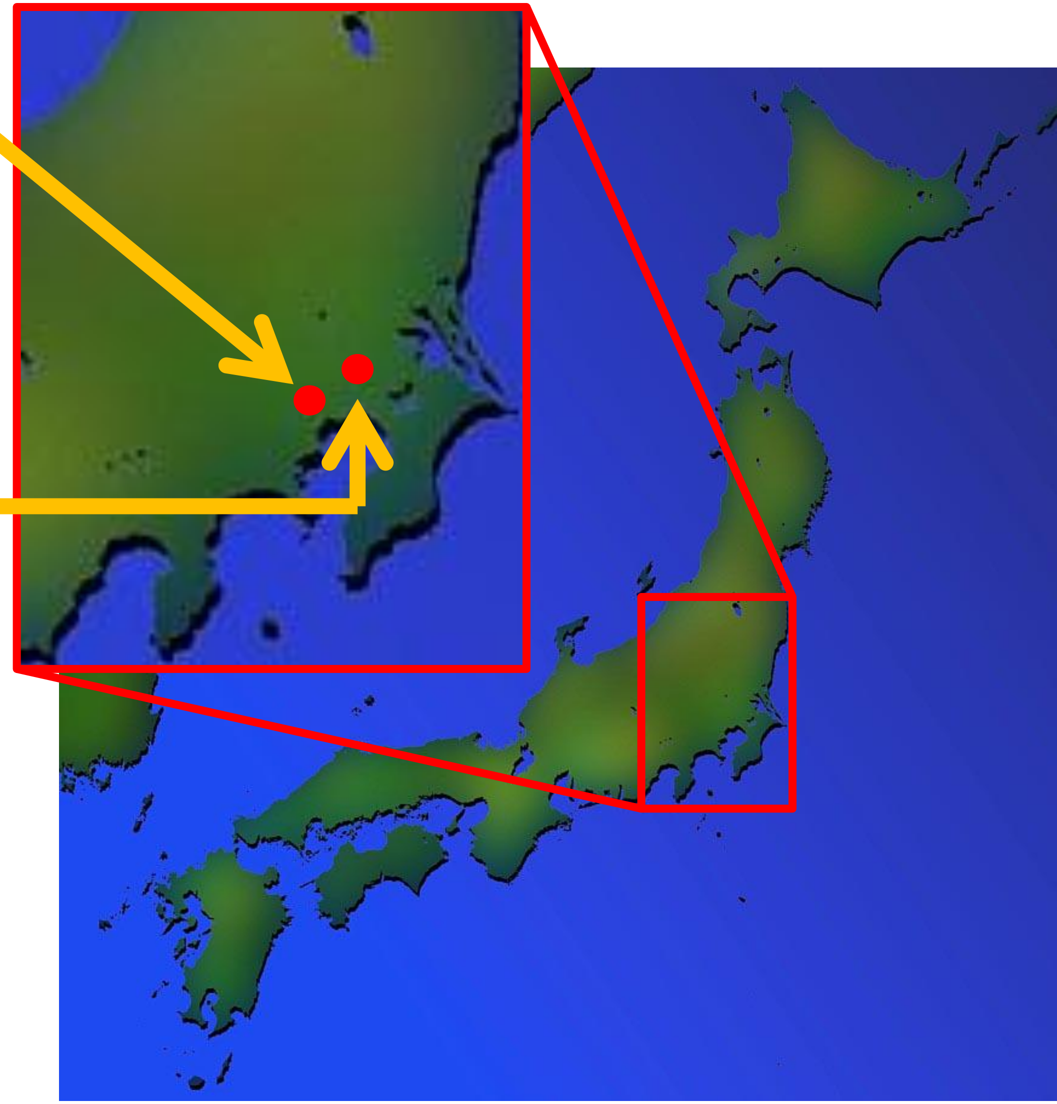
ICRR, Univ. of Tokyo

Yusuke SAKAKIBARA

2012.8.17 Workshop in German

Introduction

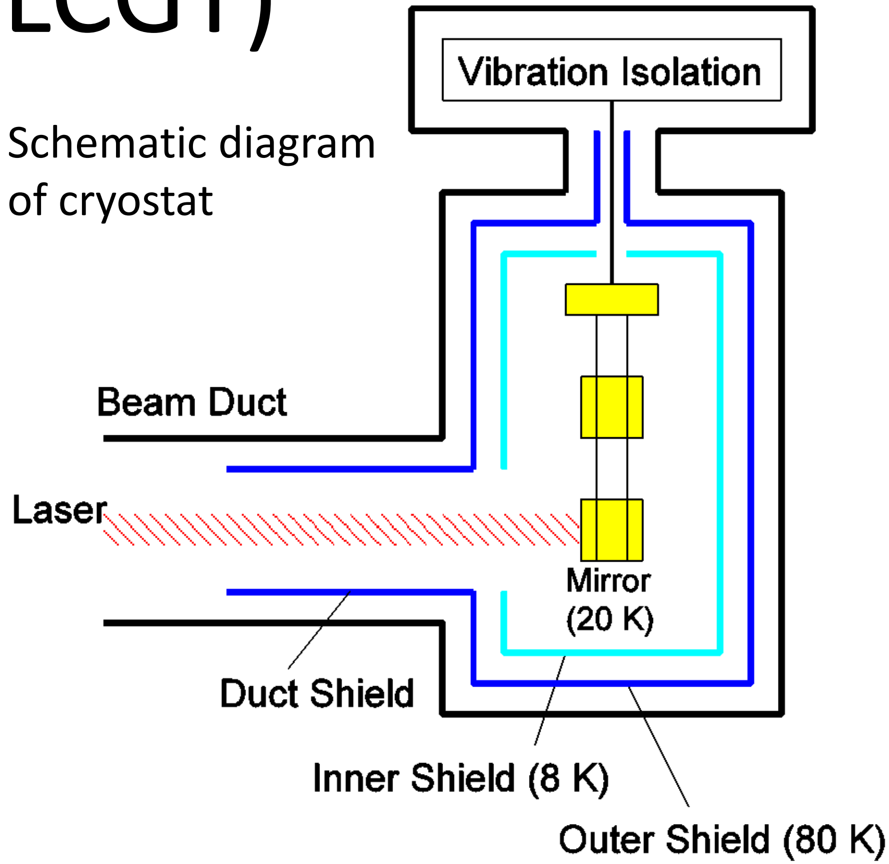
- University of Tokyo
  - Main campus is in Hongo (Tokyo)
  - Another campus is in Kashiwa (Chiba)
    - ICRR (Institute for Cosmic Ray Research)



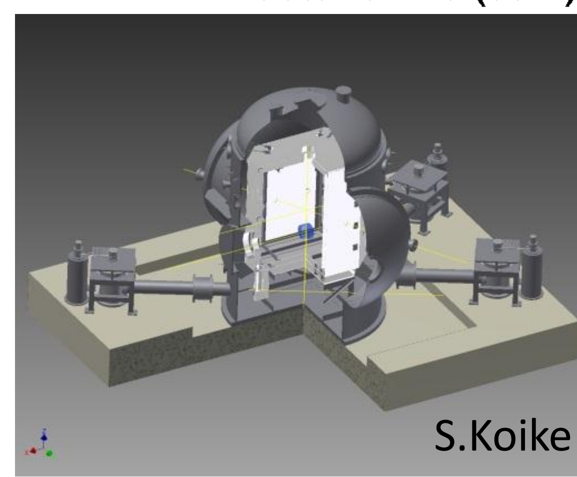
KAGRA (LCGT)

http://www.gw.hep.osaka-cu.ac.jp/openworks/whatisgw.html

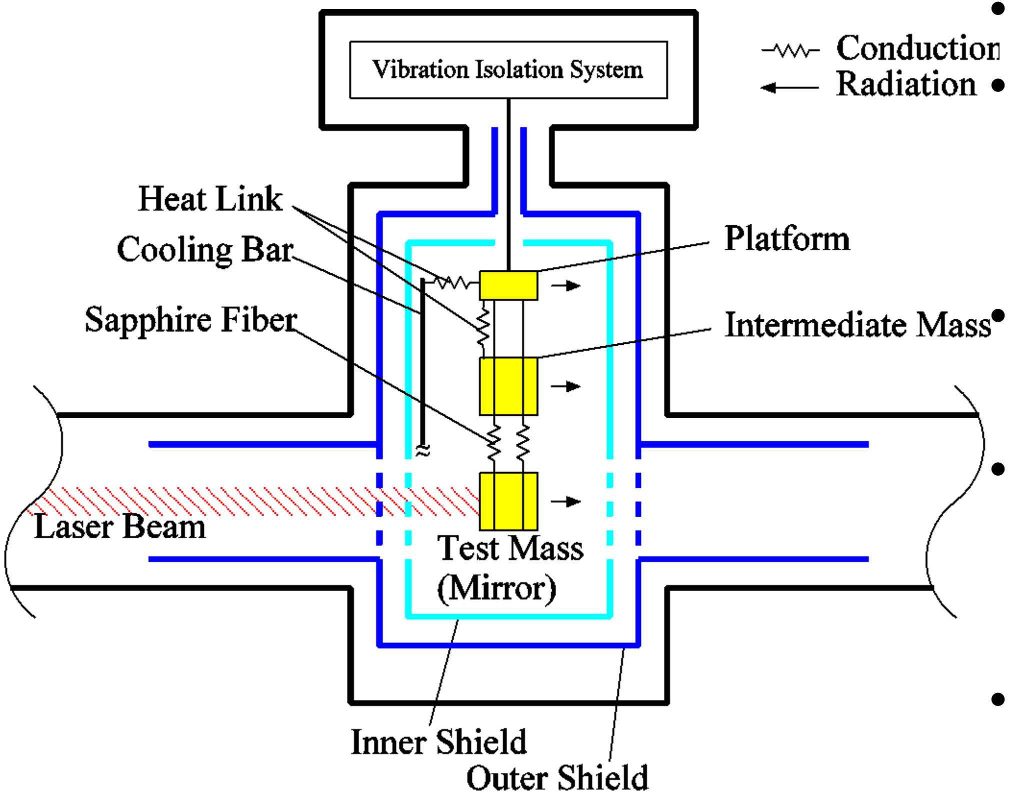
Schematic diagram of cryostat

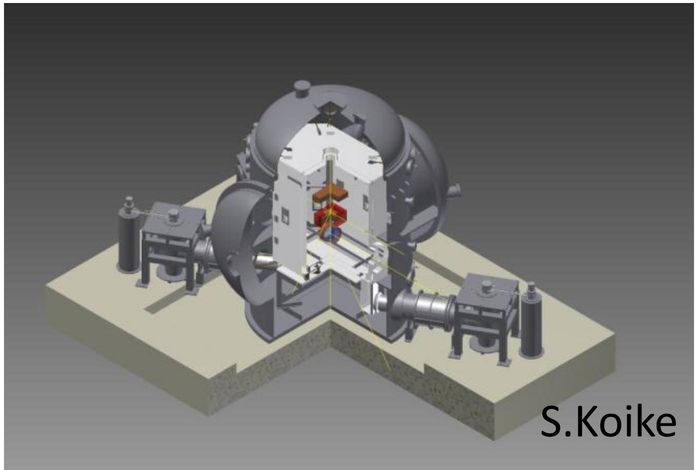


- Interferometer with 3 km arms
- Features
  - Kamioka underground with small seismic motion
  - Sapphire mirrors are cooled down to 20 K
    - Reduce thermal noise



Contents

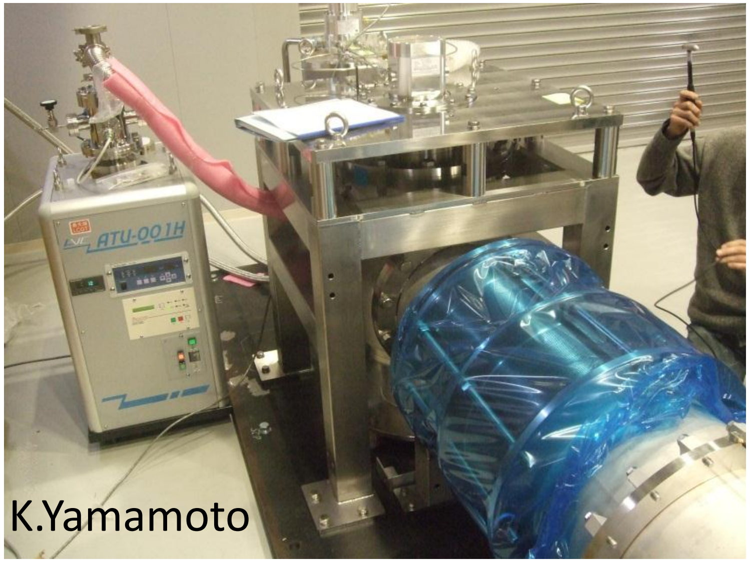




- In vacuum
- Thin wires for vibration isolation
  - Sapphire fibers
  - Aluminum heat links
- Cryogen is difficult to use underground
  - Cryocoolers will be used
- How to cool
  - Thermal conduction
  - Thermal radiation
- Initial cooling time may be long and decrease efficiency of observation
- It is necessary to reduce cooling time
- Calculation of cooling time
  - Reduction by high emissivity coating
    - Calculation
    - Experiment

KAGRA cryocooler

- To estimate cooling time of KAGRA, cooling power was measured.



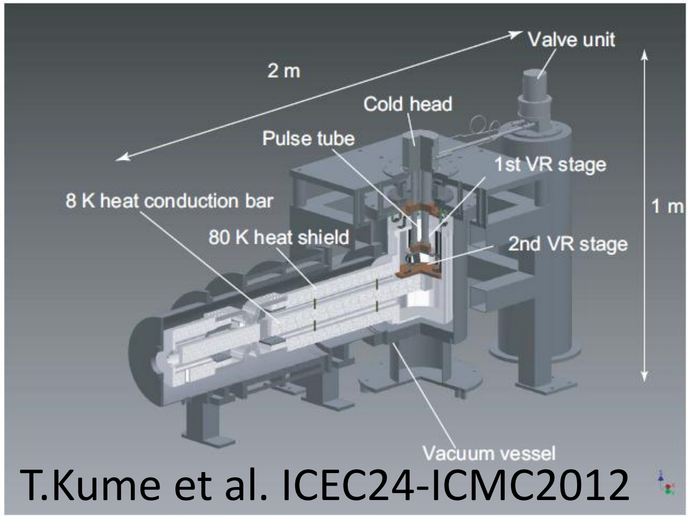
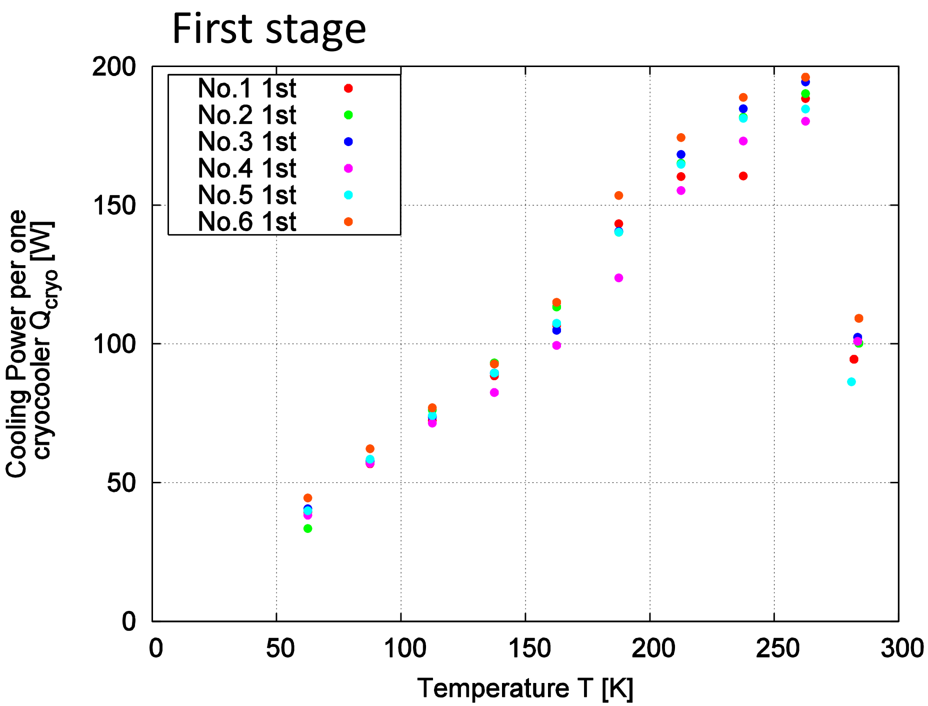
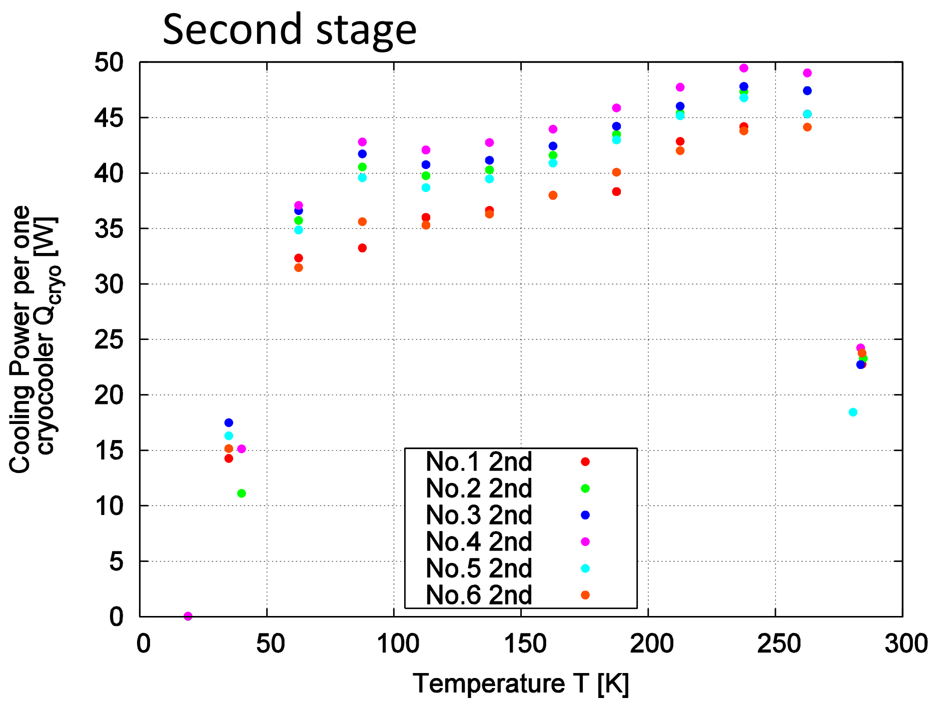


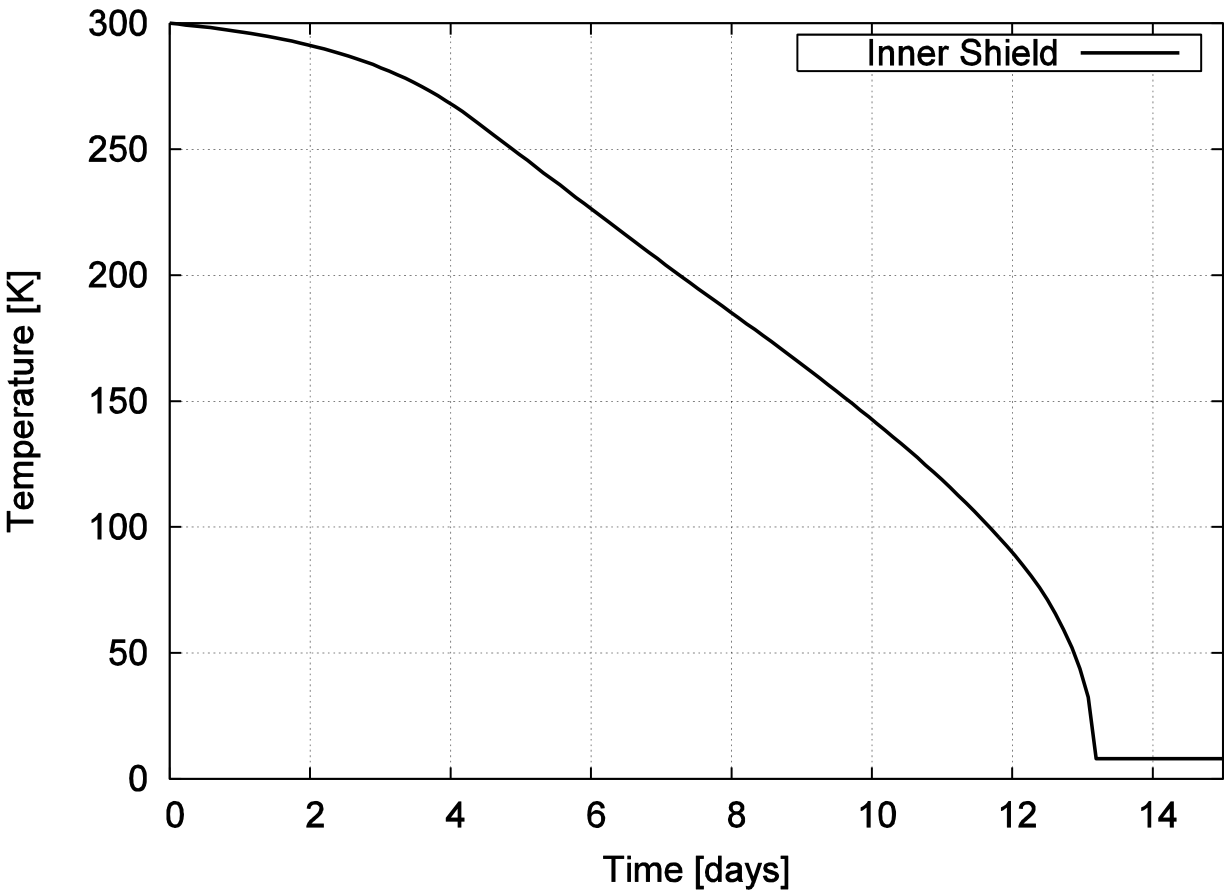
Figure 4: 3D drawing of the developing cryocooler unit

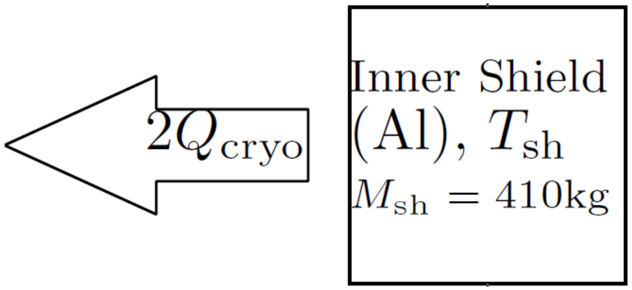




Cooling of inner shield

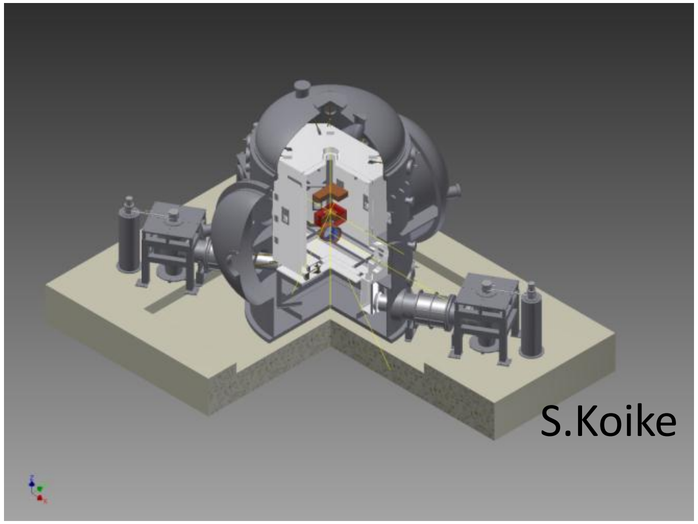
- Model is constructed to estimate initial cooling time
- Inner shield of ~400 kg is connected to the 2nd stages of 2 cryocoolers
  - The other 2 cryocoolers are connected to suspension system via cooling bar
- Suspension system is excluded first.

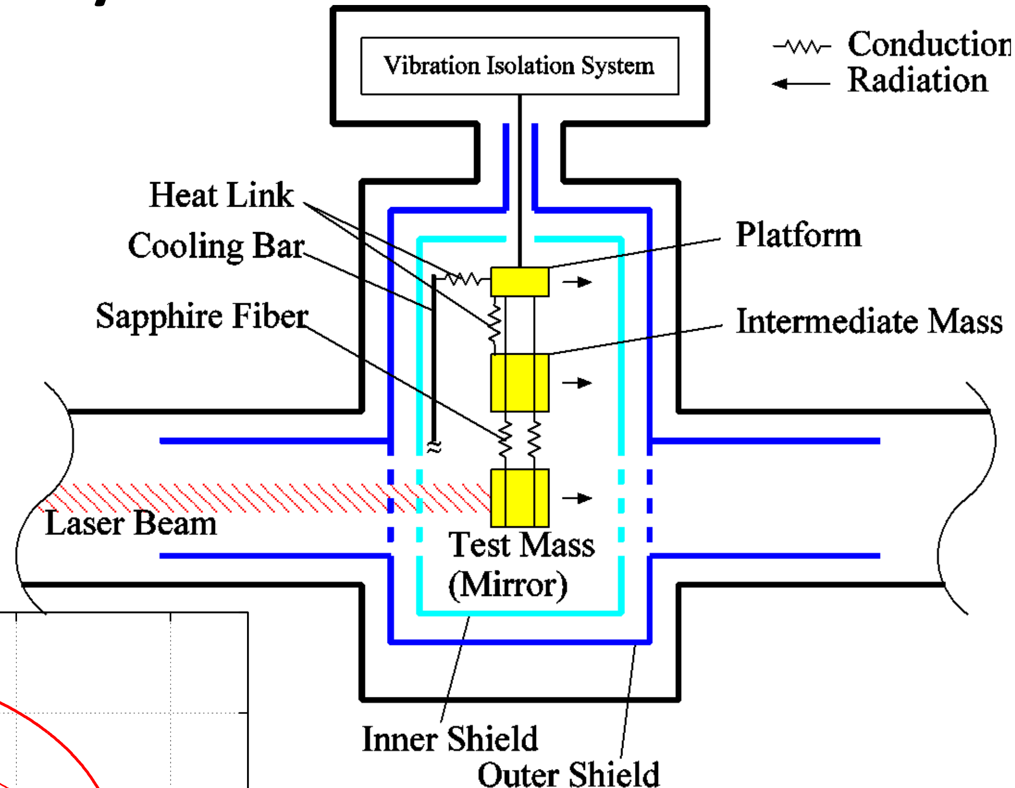


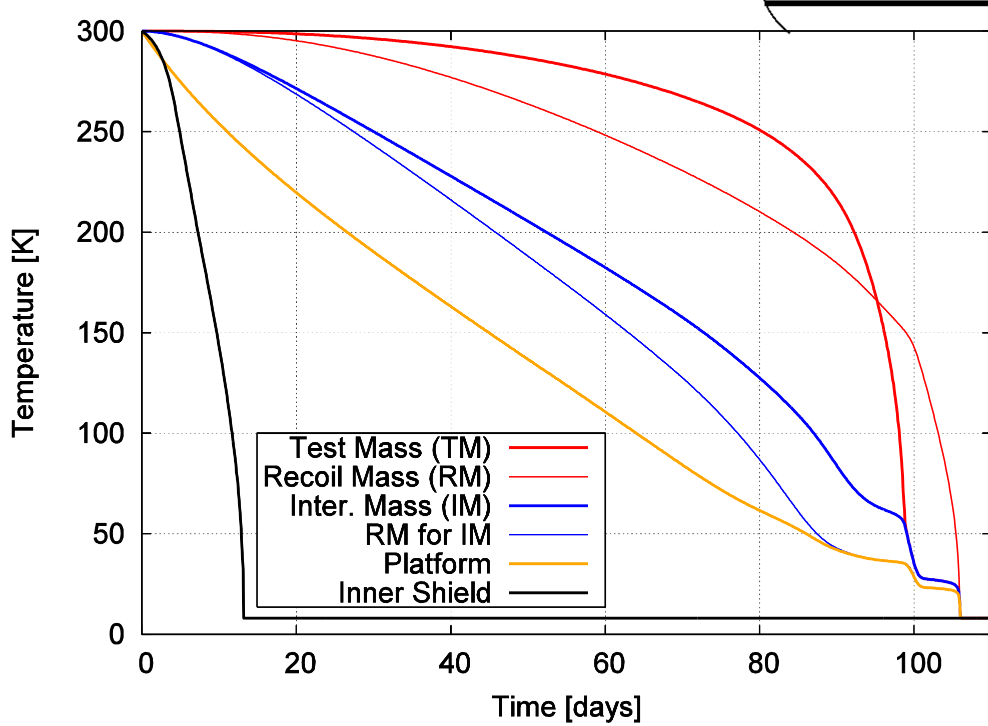


$$\frac{dT_{\mathrm{sh}}}{dt} = -\frac{2Q_{\mathrm{cryo}}(T_{\mathrm{sh}})}{M_{\mathrm{sh}} C_{\mathrm{Al}}(T_{\mathrm{sh}})}$$

Cooling suspension by thermal conduction

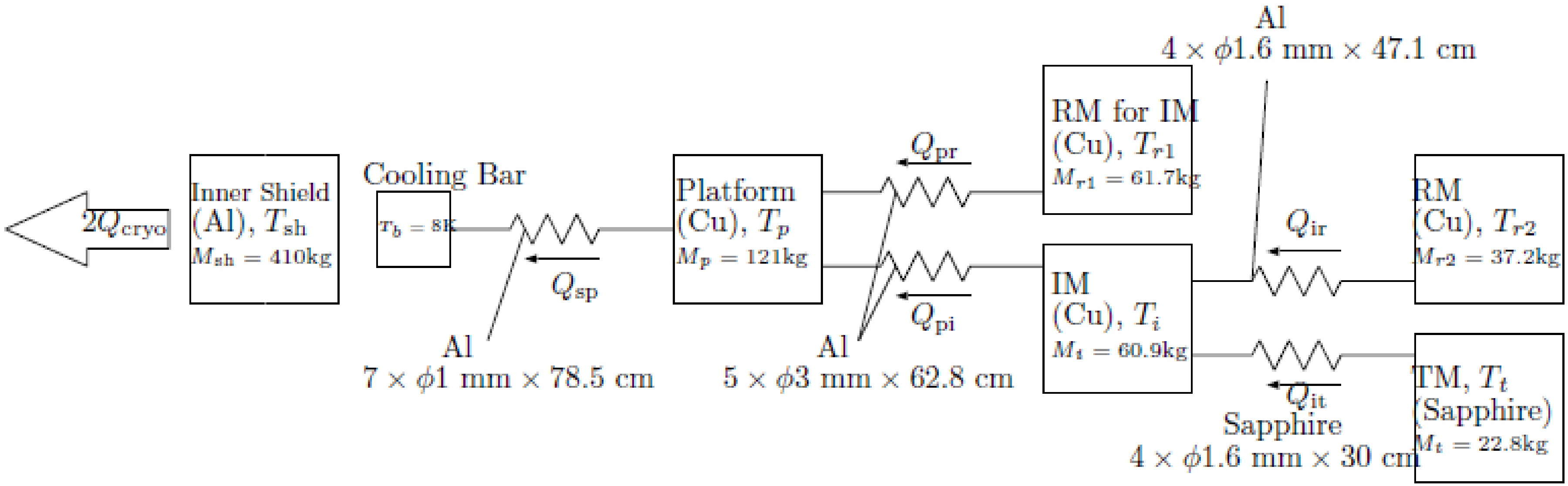


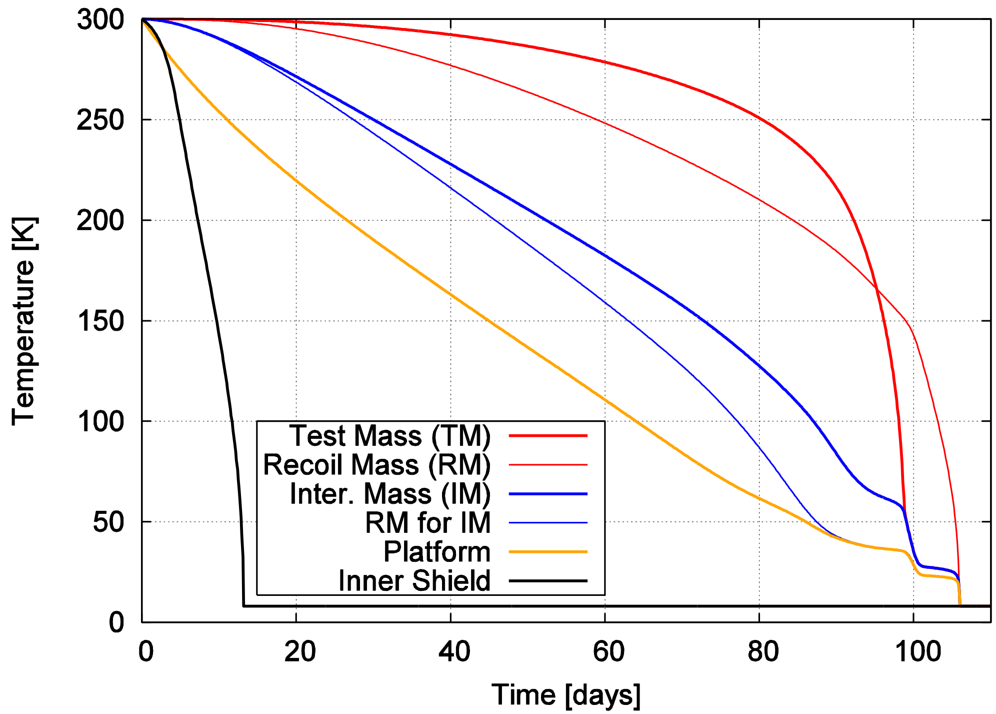




Thin fibers limit thermal conduction.
Cooling takes long time.

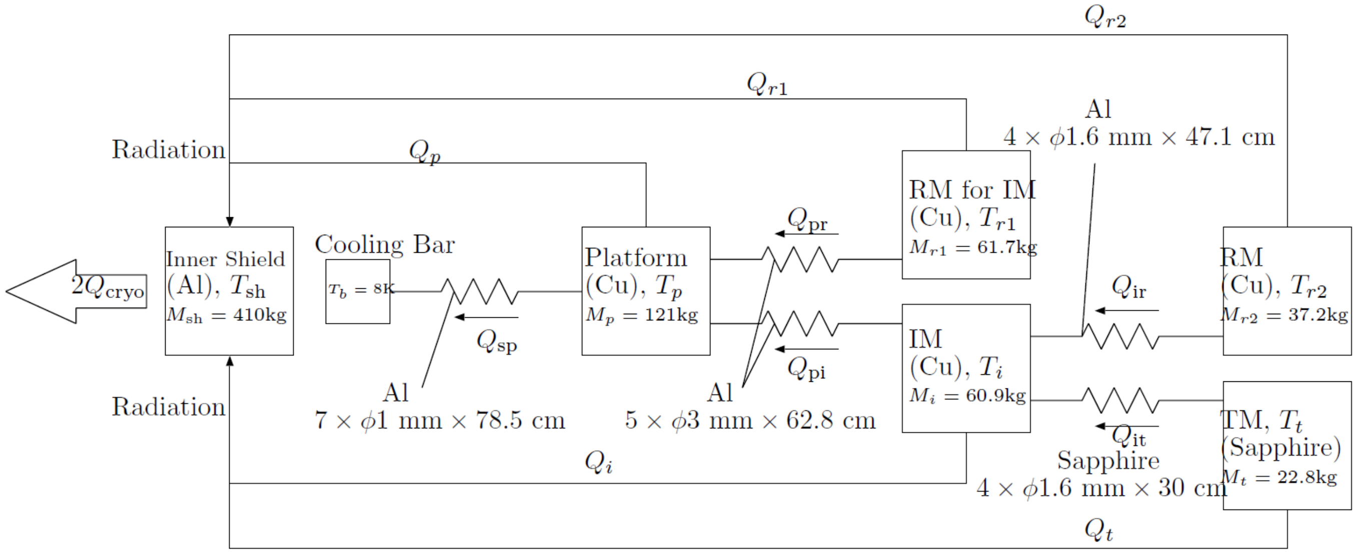
Cooling suspension by thermal conduction

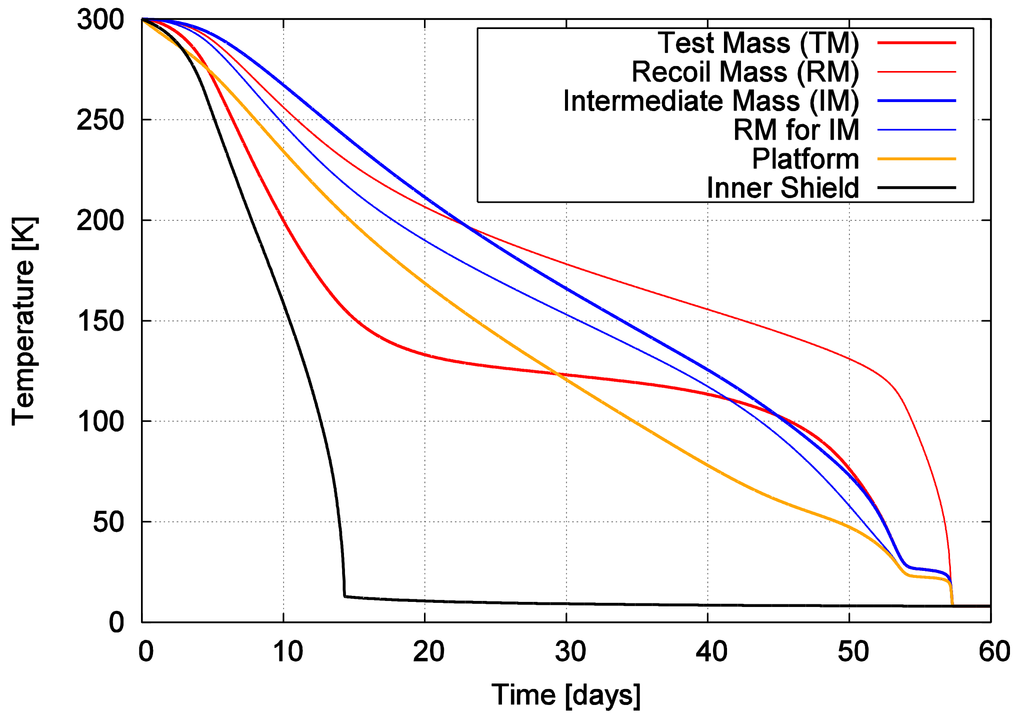




Thin fibers limit thermal conduction.
Cooling takes long time.

Thermal conduction and radiation



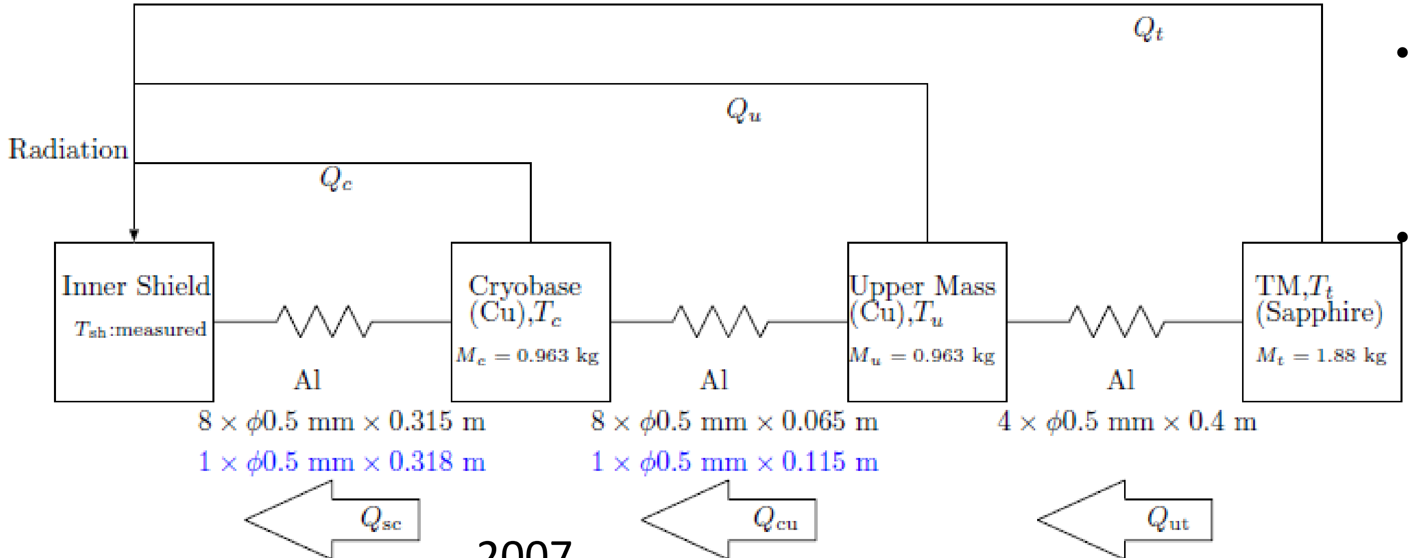


Radiation dominates above 150 K

Conduction dominates below 150 K

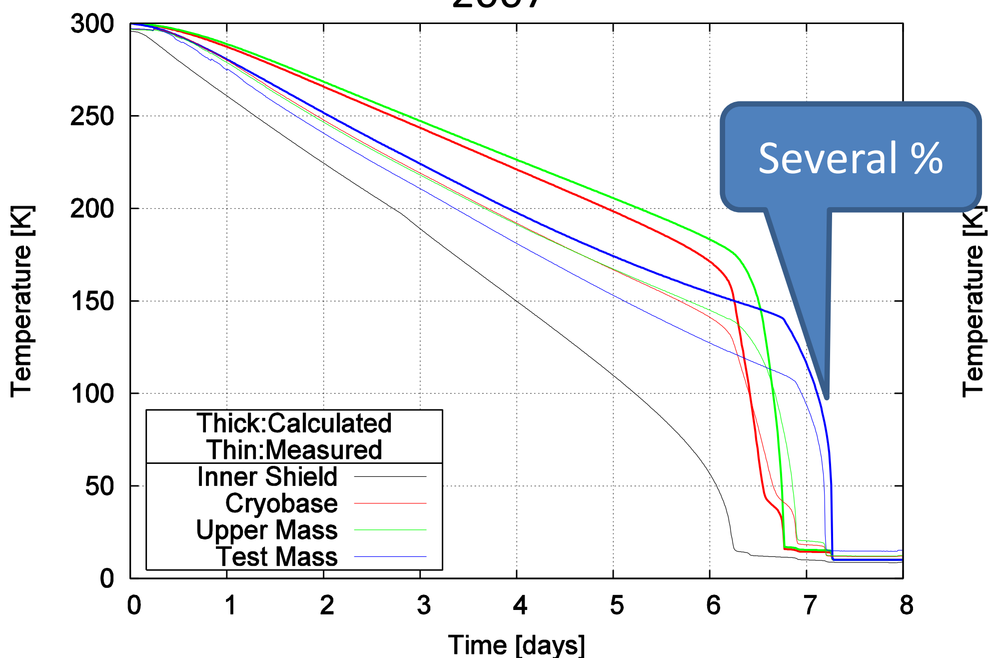
Radiation is important.

Verification of calculation model （comparison with KAGRA prototype, CLIO）

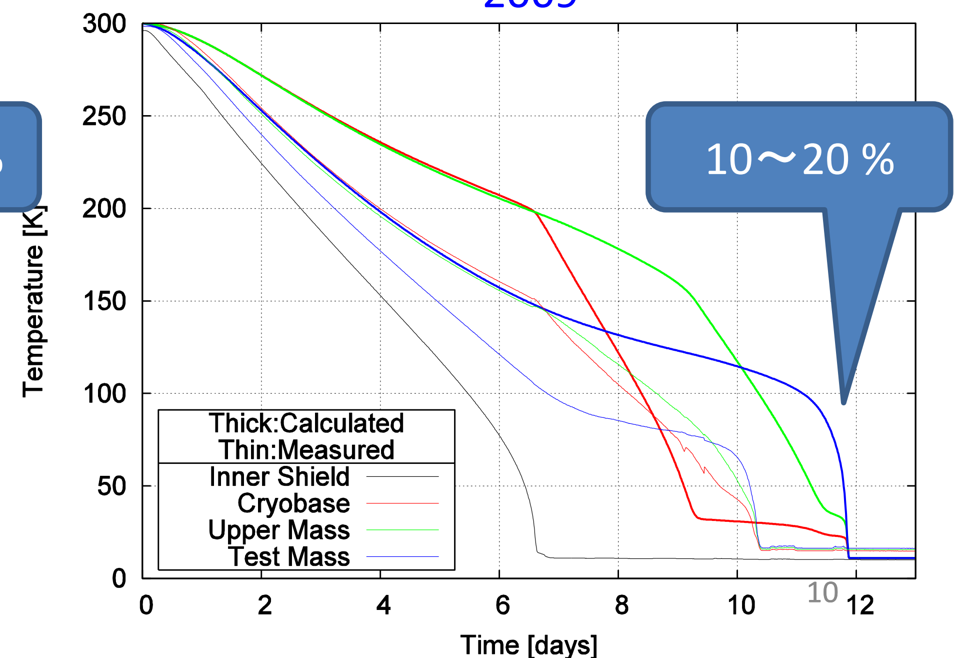


- Radiation
  - Measured is faster
  - Higher emissivity
- Conduction
  - Calculation is faster
  - Thermal resistance of contact can be estimated

2007



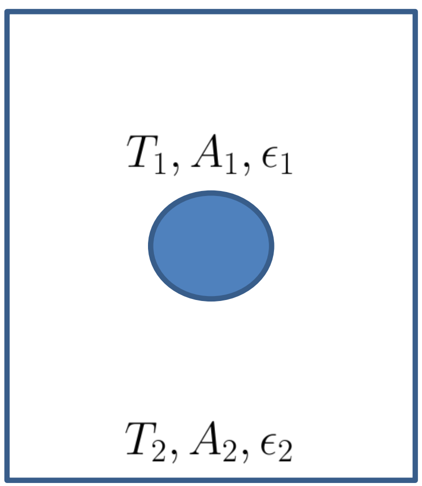
2009

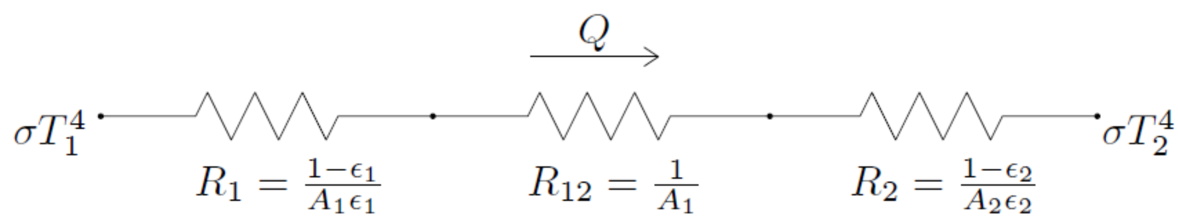


High emissivity material increases radiation

- Material with high emissivity (ε)
  - Radiation is increased → cooling becomes faster

A: surface area

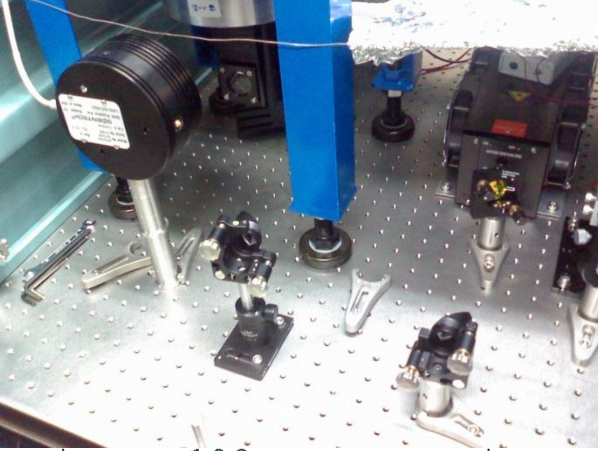




$$Q = \frac{\sigma(T_1^4 - T_2^4)}{R_1 + R_{12} + R_2} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)}$$

- It is necessary to measure emissivity
- Reflectivity is measured at 10 µm, where 300 K black body radiation has largest intensity

Reflectivity measurement (wavelength 10.6 μm)



1. Measurement at room temperature

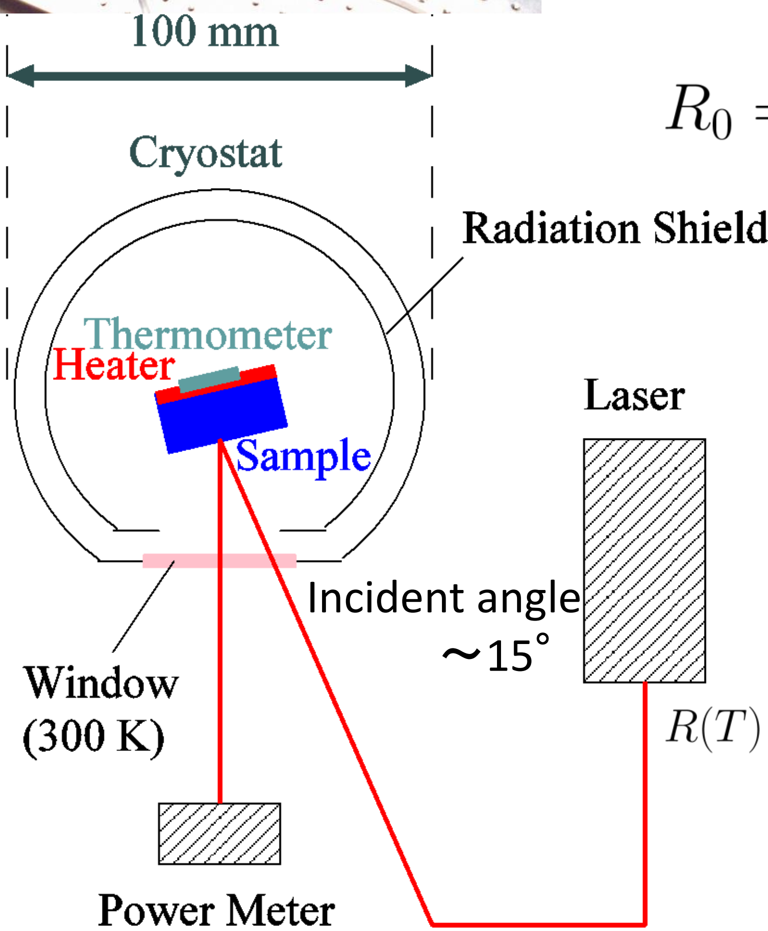
$$R_0 = \left(\frac{\mathcal{P}}{\mathcal{P}_0}\right)^{1/\mathcal{N}}$$

- $\mathcal{P}$ Power after reflection
- $\mathcal{P}_0$ Power before reflection: several W
- $\mathcal{N}$ Number of reflection

2. Measurement at 50 K-300 K
   - Relative values were measured
   - Conditions except temperature of sample were unchanged

$$R(T) = R_0 \frac{\mathcal{P}(T)}{\mathcal{P}(T = 300\ \mathrm{K})}$$

- $R(T)$ Reflectivity at temperature T
- R_0 Reflectivity at 300 K
- $\mathcal{P}(T)$ Power at temperature T

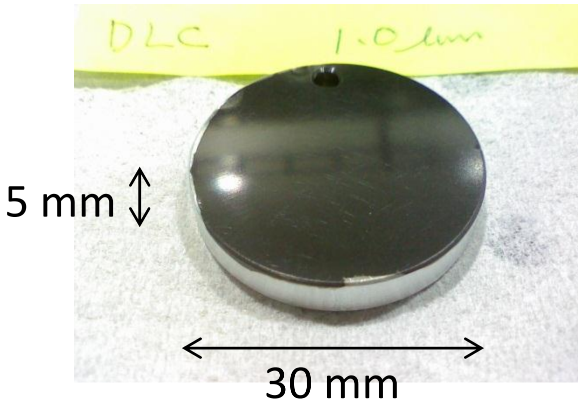


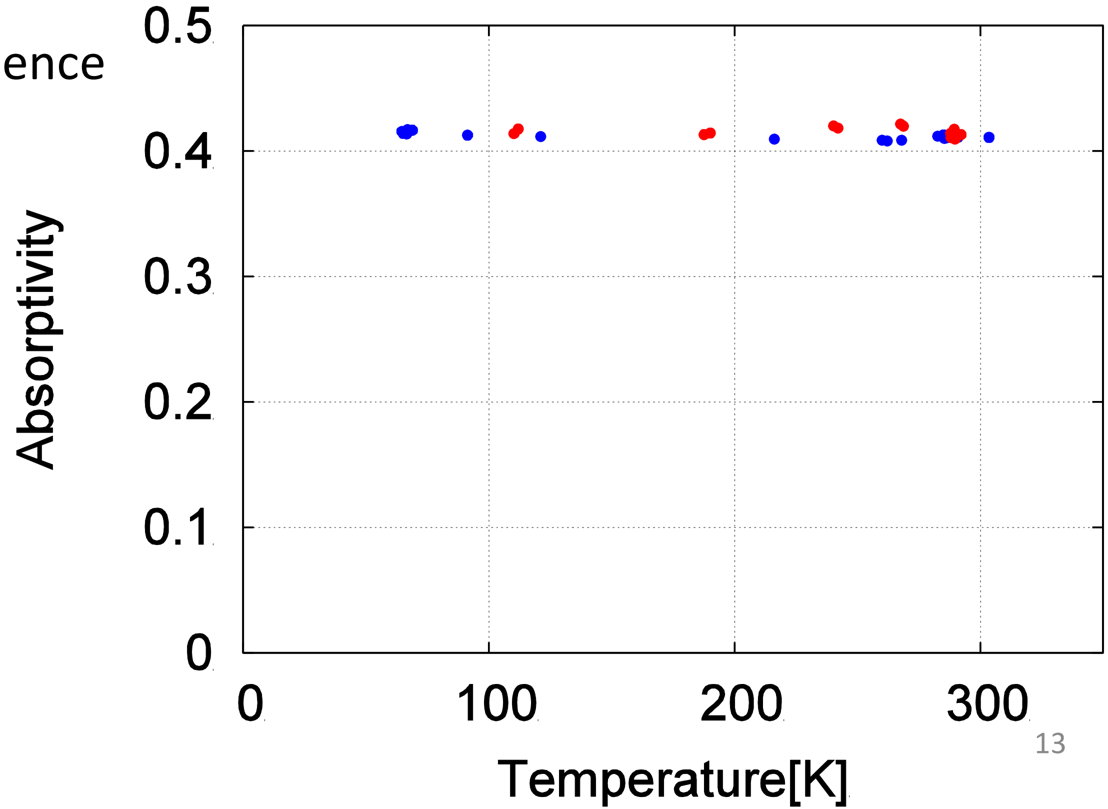
Set up for measurement in cryogenic temperature

High emissivity material

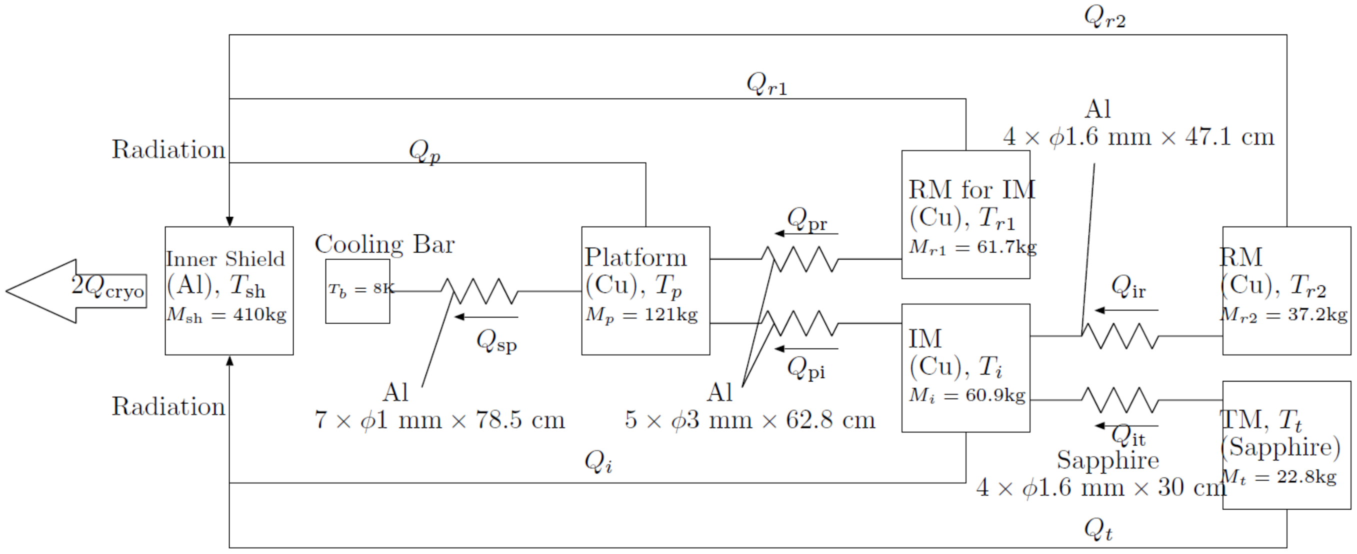
- Sample
  - A1070+CP+DLC(Diamond Like Carbon, 1.0 μm in thickness)

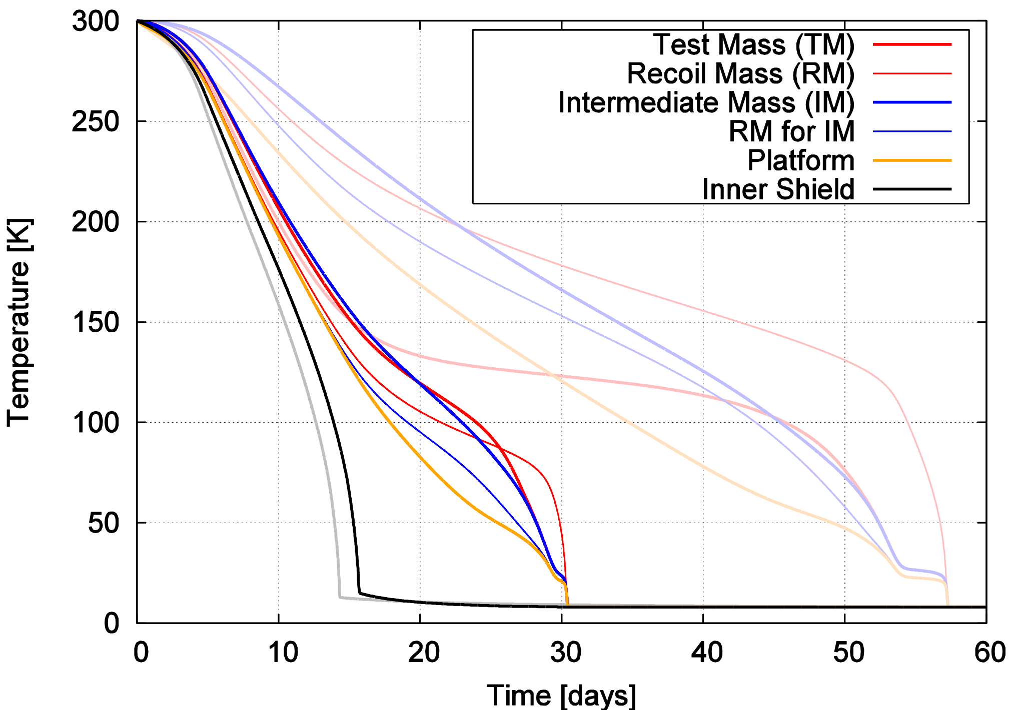
- Result
  - Absorptivity 0.41±0.02
  - No temperature dependence





Increased radiation



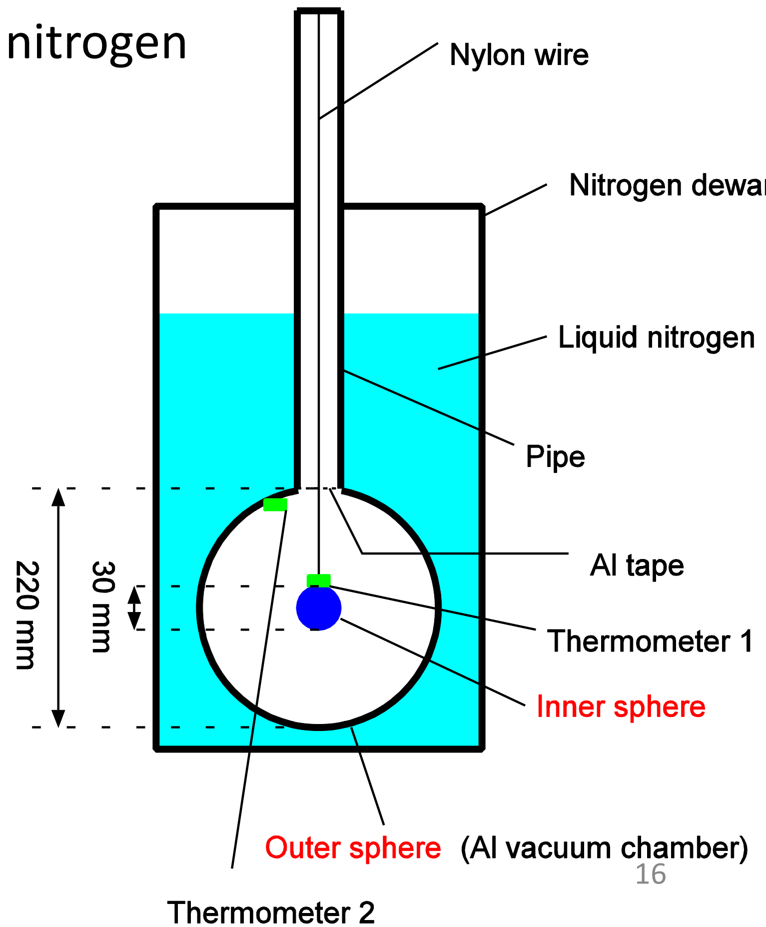


- Increased radiation by platform, IM, IRM, and inside of inner shield coated with DLC (Diamond Like Carbon)
- Emissivity of DLC is assumed 0.41
  (cf. emissivity of Cu and Al is 0.03)

Experiment

Experiment with small apparatus

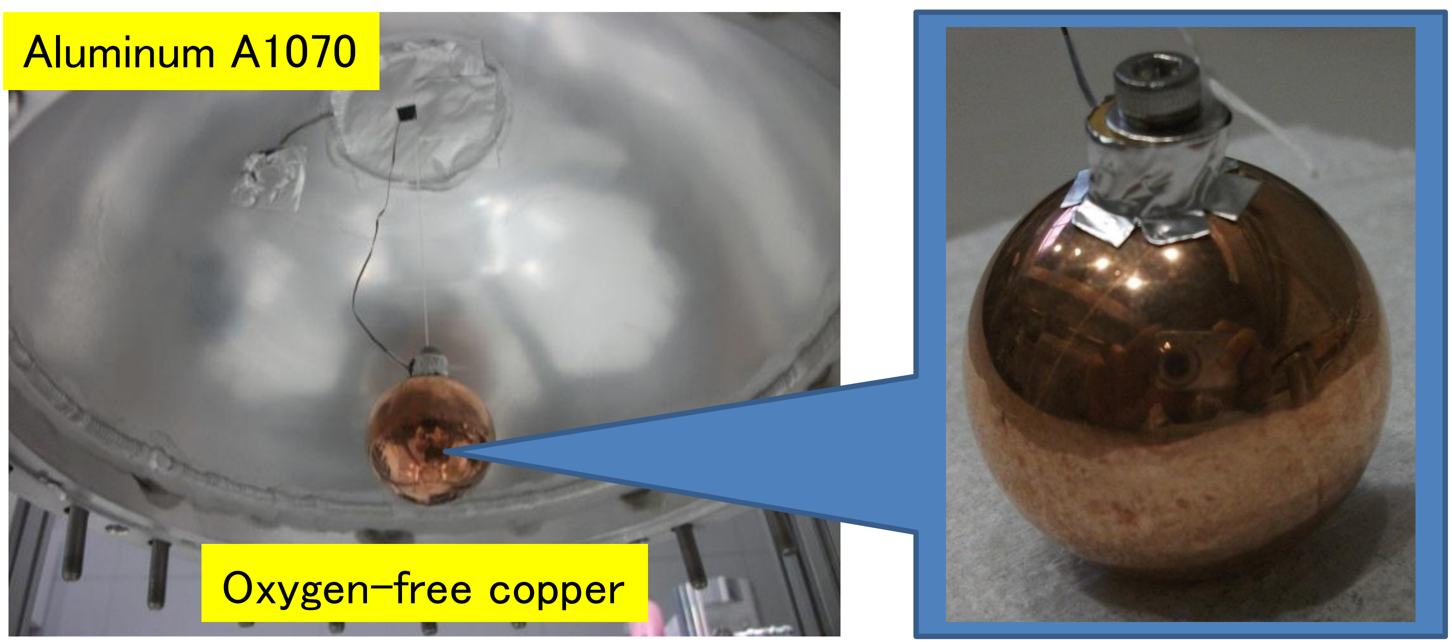
- Experimental verification is necessary
  - Test mass (inner sphere) is suspended inside outer sphere
  - Vacuum less than 10^{-3} Pa
  - Outer sphere is kept at 77 K using liquid nitrogen



Experiment with small apparatus

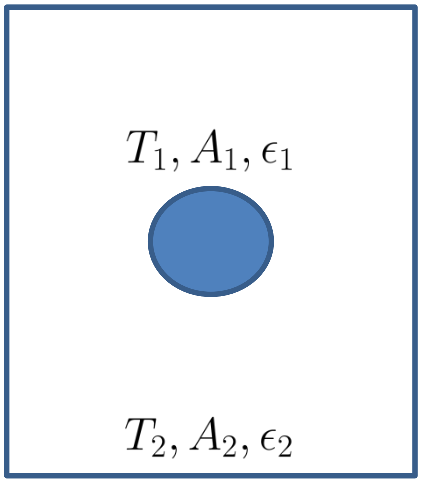
- Material and surface treatments to be measured

	Inner sphere		Outer sphere	
	Material	Surface	Material	Surface
1	Oxygen–free copper	Buffing #400	Aluminum A1070	Buffing #400+CP
2	Oxygen–free copper	DLC coating	Aluminum A1070	Buffing #400+CP
3	Oxygen–free copper	DLC coating	Aluminum A1070	DLC coating

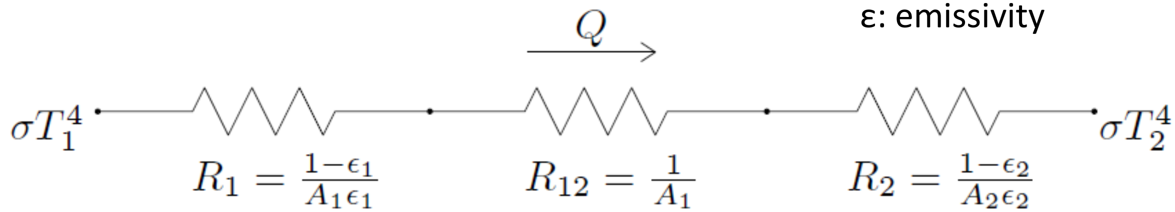


Equation of radiation

- Outer sphere is much larger than inner sphere
  - $A_1/A_2=0.019$



A: surface area
ε: emissivity



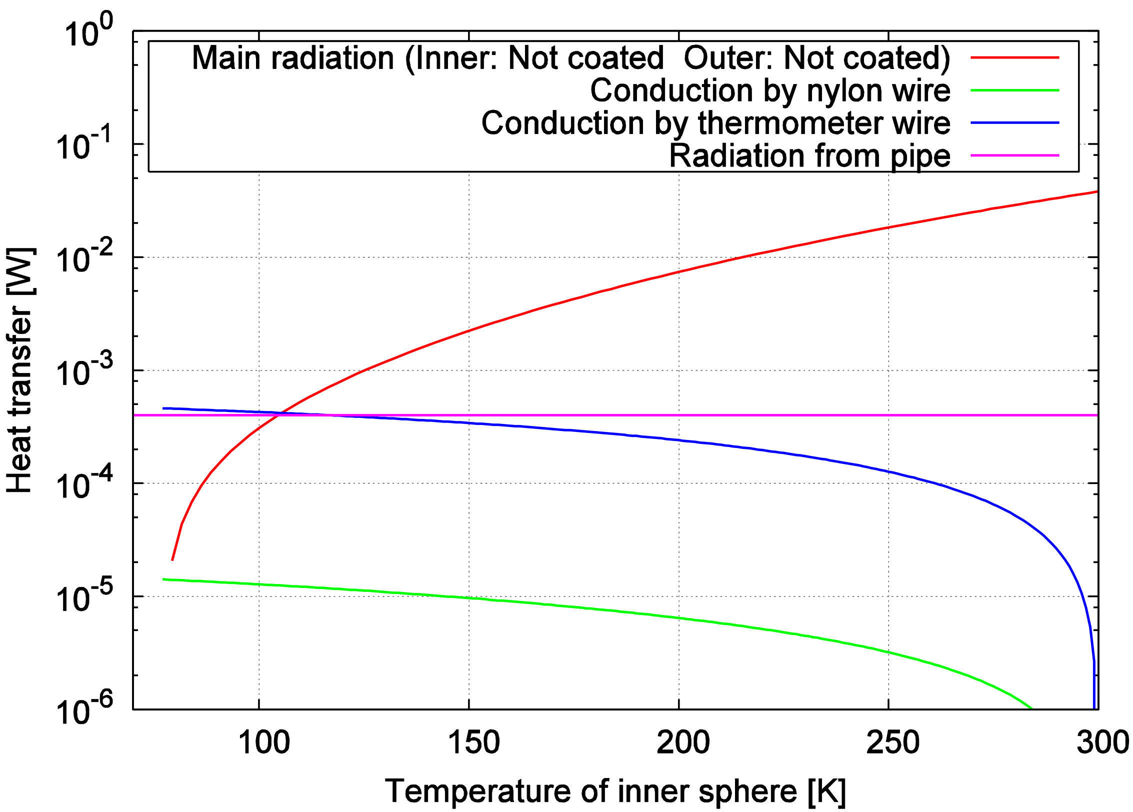
$$Q = \frac{\sigma(T_1^4 - T_2^4)}{R_1 + R_{12} + R_2} = \frac{A_1\sigma(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)} \sim \epsilon_1 A_1 \sigma (T_1^4 - T_2^4)$$

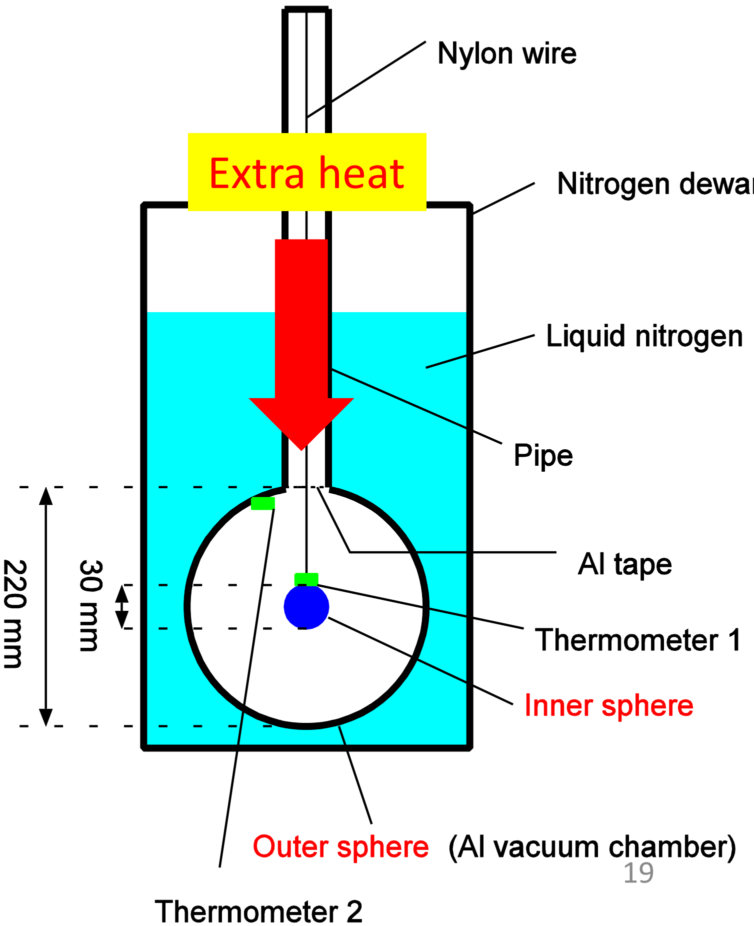
- Main error
  - Emissivity ε_1
    - 0.03±0.01 -> error of 30 %
  - Surface area of inner sphere A_1
    - Thermometer occupies several % of total surface area -> error of several %

Estimation of extra heat transfer

- Extra heat transfer compared to main radiation
  - Thermal conduction by nylon wire and thermometer wire
  - Radiation from the pipe
- Negligible above 150 K

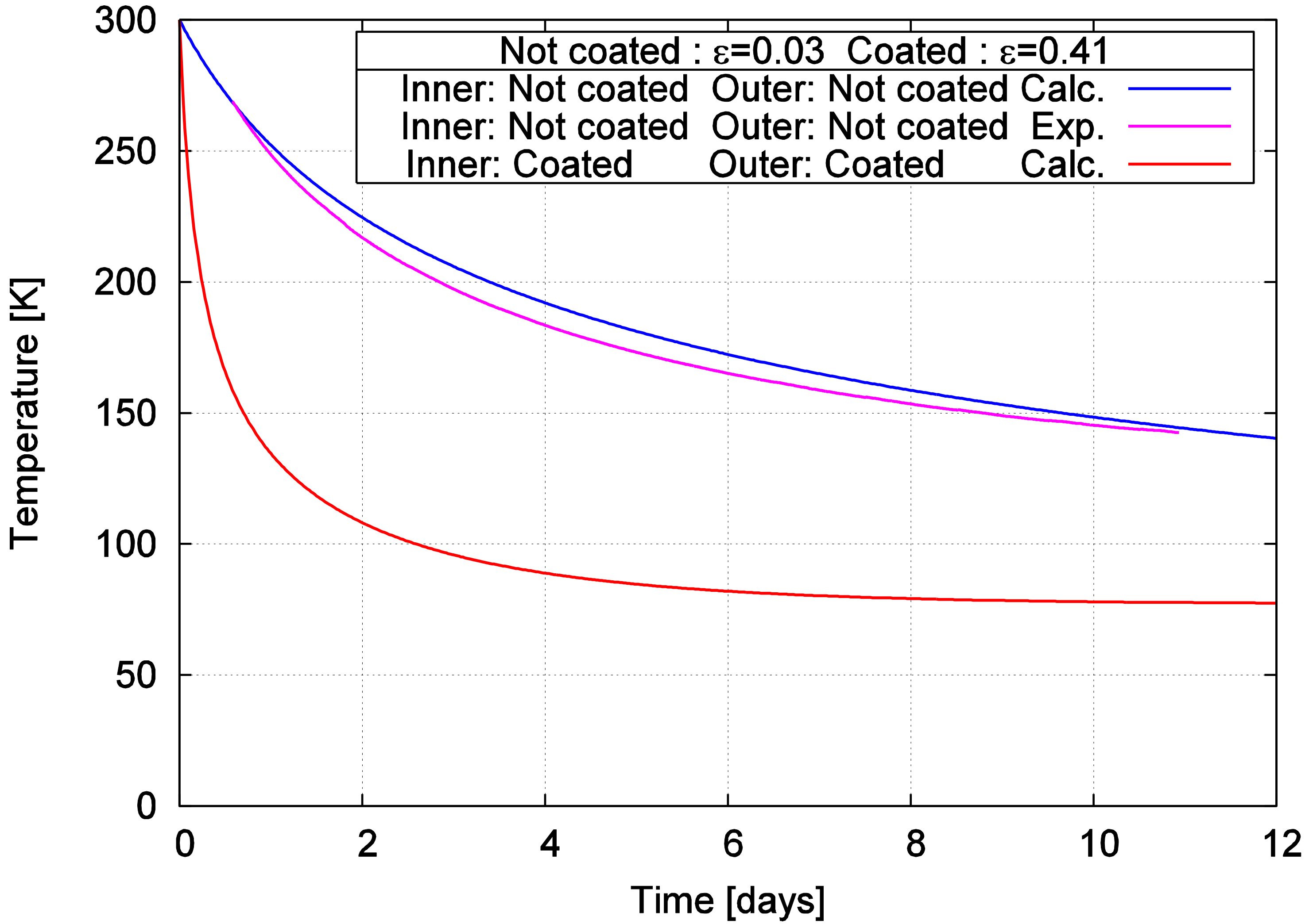
$$Q_{\text{main}}(T_1, T_2) = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)}$$





Result so far

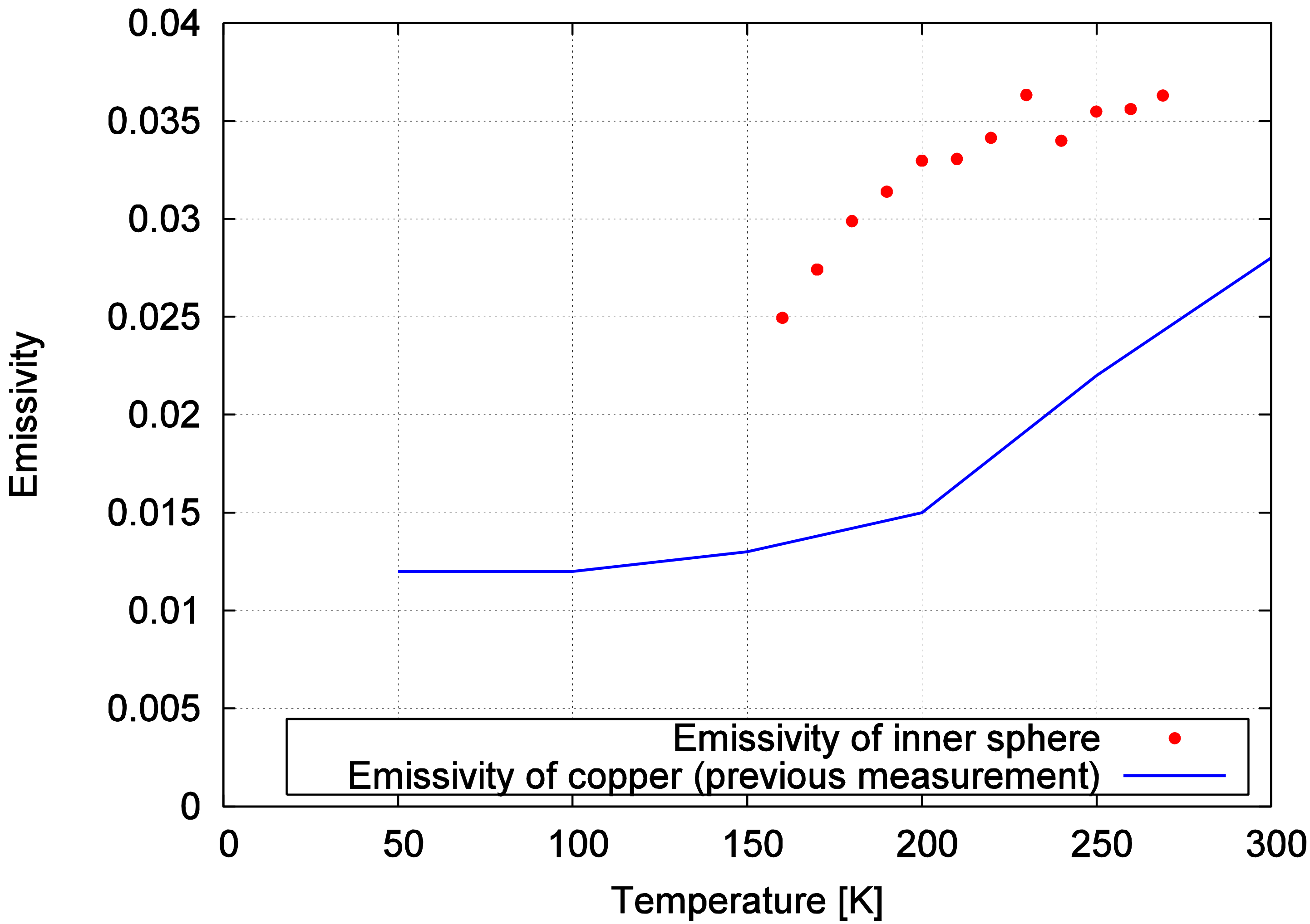
- Consistent with calculation
  - Cooling is at maximum 20 % faster than calculation
  - Within uncertainty of emissivity 30 %



Result so far

In English
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=862

- From experimental data, emissivity of inner sphere is calculated
  - Emissivity decreases as temperature decreases
  - Larger than previous measurement (Y. Sakakibara master thesis 2012)
    - Emissivity depends largely on subtle surface condition



- Summary
  - Initial cooling time of KAGRA is calculated
    - High emissivity coating can reduce cooling time to 1 month
  - Experiment with small apparatus to verify the effect of high emissivity coating is in progress

- Future work
  - Large-scale experiment using KAGRA cryostat in Toshiba or 1/4 cryostat in ICRR
  - R&D of another method to reduce initial cooling time

Appendix

プロトタイプ試験（イタリア）

- 冷却に時間がかかる
  - Basti F et al. Astrophys **35** (2011)

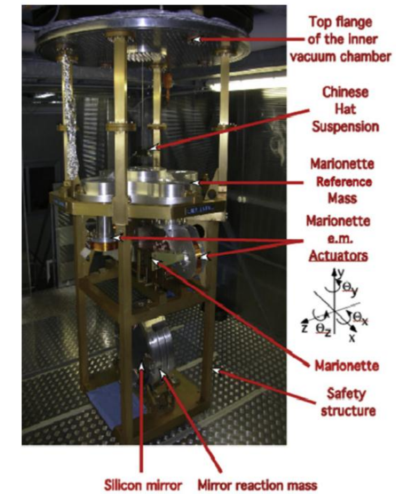


Fig. 9. The cryogenic payload surrounded by its assembling frame (the golden structure in the photo).

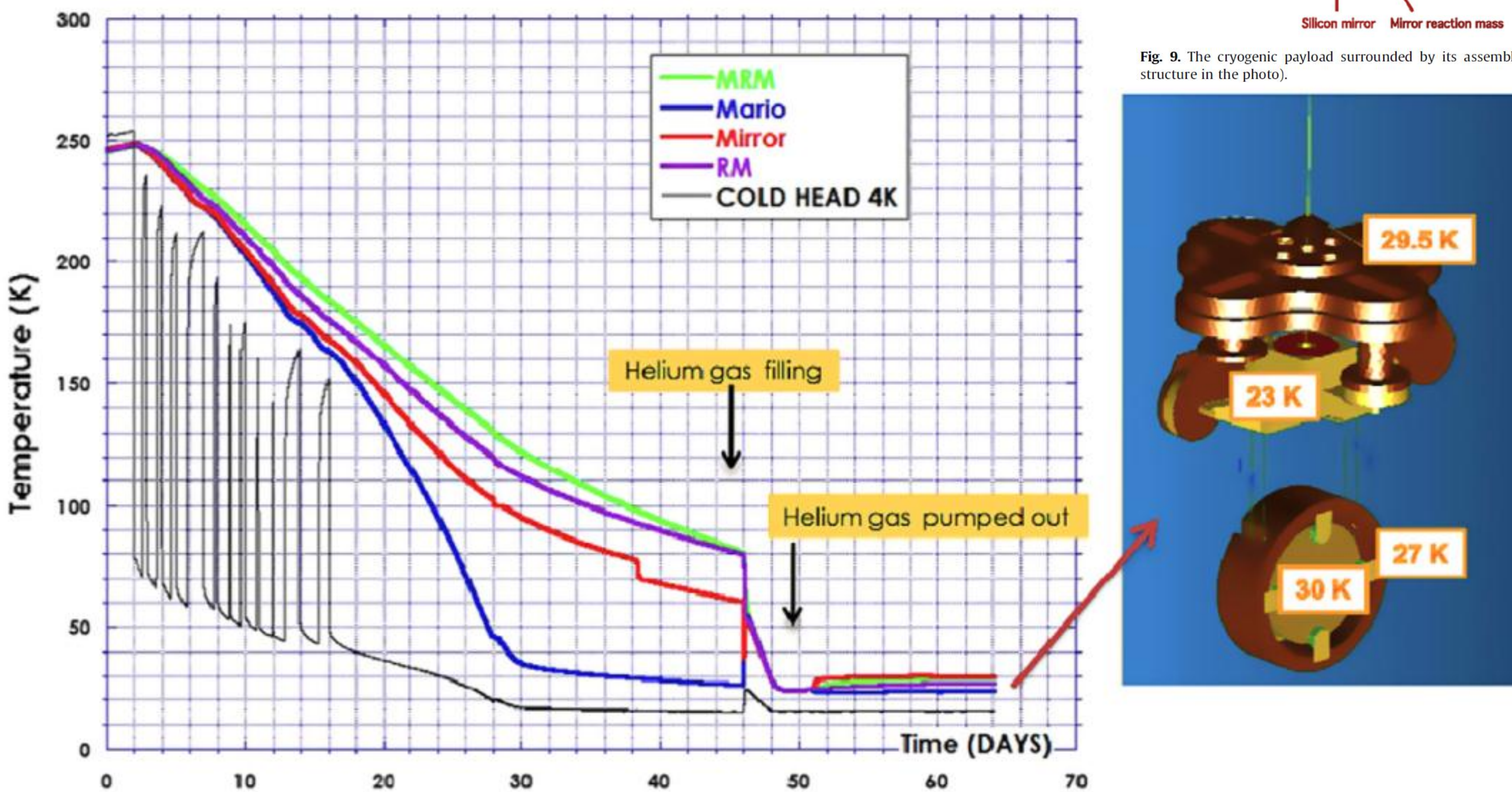
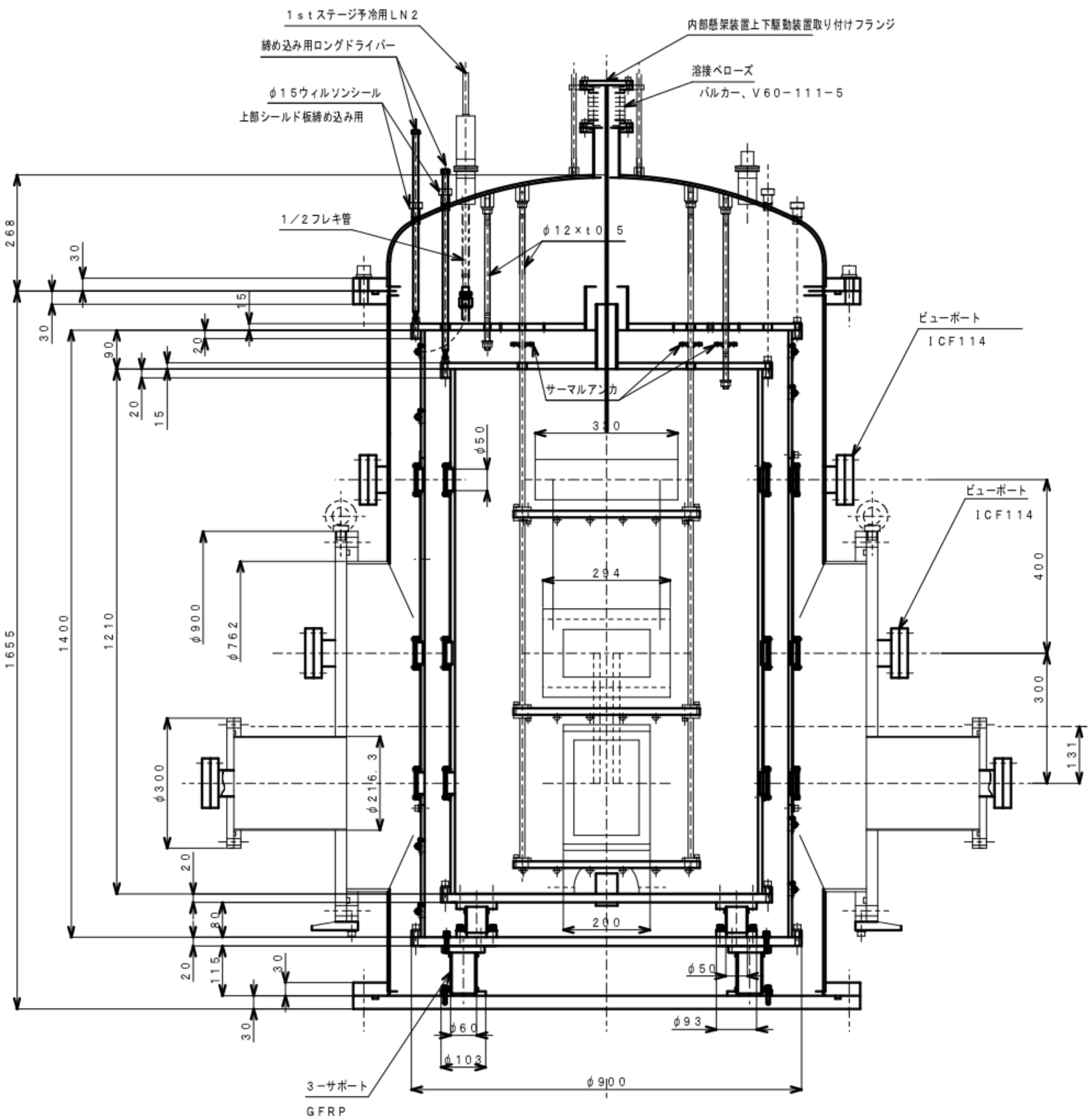


Fig. 12. On the left the temperatures of different mechanical elements of the payload as a function of cooling down process time. At the beginning of the run the pulse tube cryo-coolers were stopped many times, because of failure in the water refrigeration system of their compressors. On the right side it is put in evidence the steady state temperatures of the mechanical elements during the TF measurements.

Future work : 1/4 cryostat in ICRR



- It will be verified that high emissivity coating can reduce initial cooling time.