Parameters of cryogenic payload in LCGT

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1 Introduction

2 Outline

The details are also shown in Figs. 1,2. In these figures, no heat links are shown.

- This cryogenic payload is a triple pendulum.
- The mirror is at the bottom.
- The mirror is in a hollow cylinder. This is called recoil mass. The actuators for the mirror are on this recoil mass.
- The mirror and recoil mass are suspended from the intermediate mass.
- The intermediate mass has also its recoil mass.
- The intermediate mass and its recoil mass are suspended from the platform. In this plarform, there is GAS filter. This filter suspends the intermediate mass.
- The platform is suspended from the GAS fileter which is a part of SAS at room temperature.

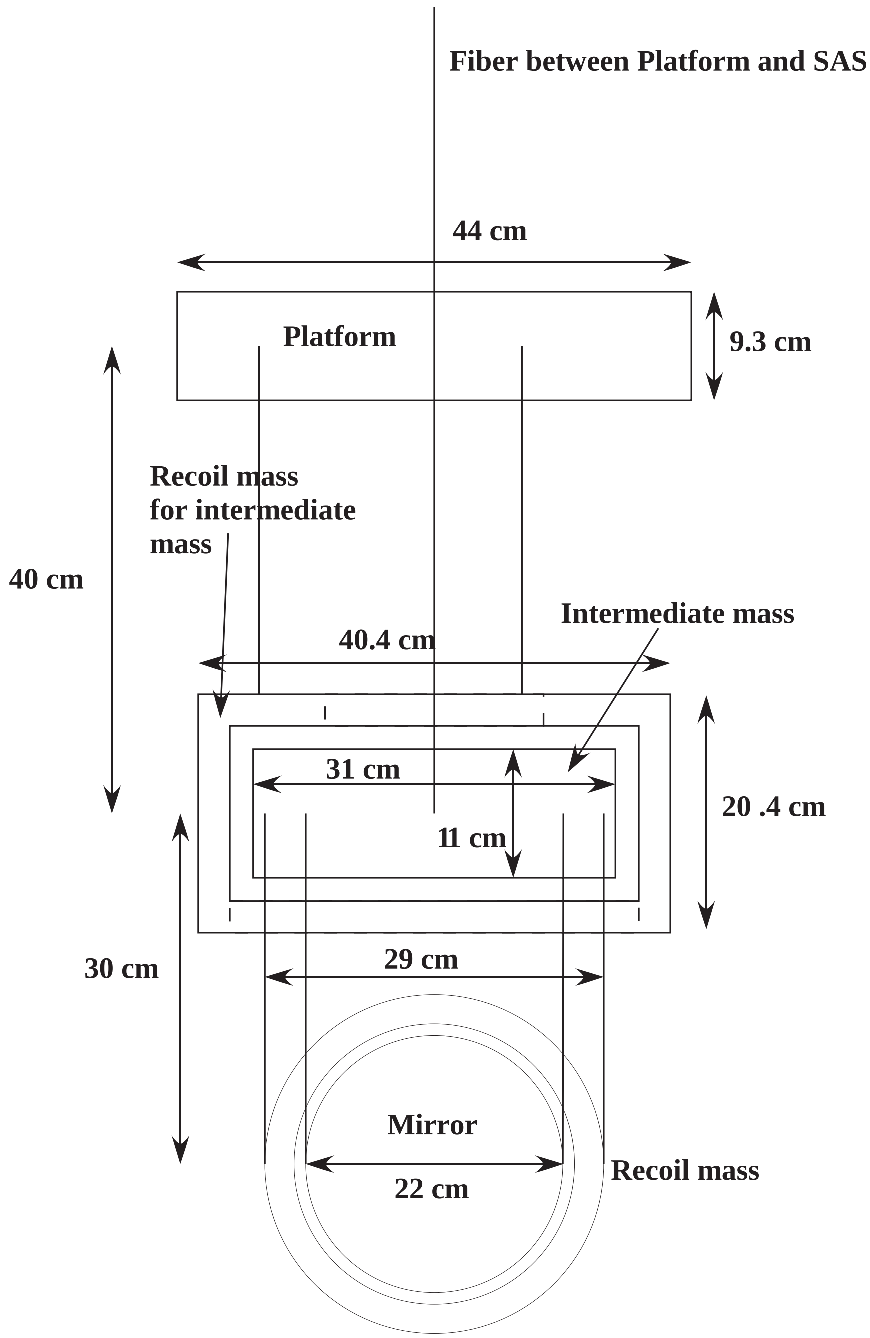

Figure 1: Schematic view of cryogenic payload (from optical axis)

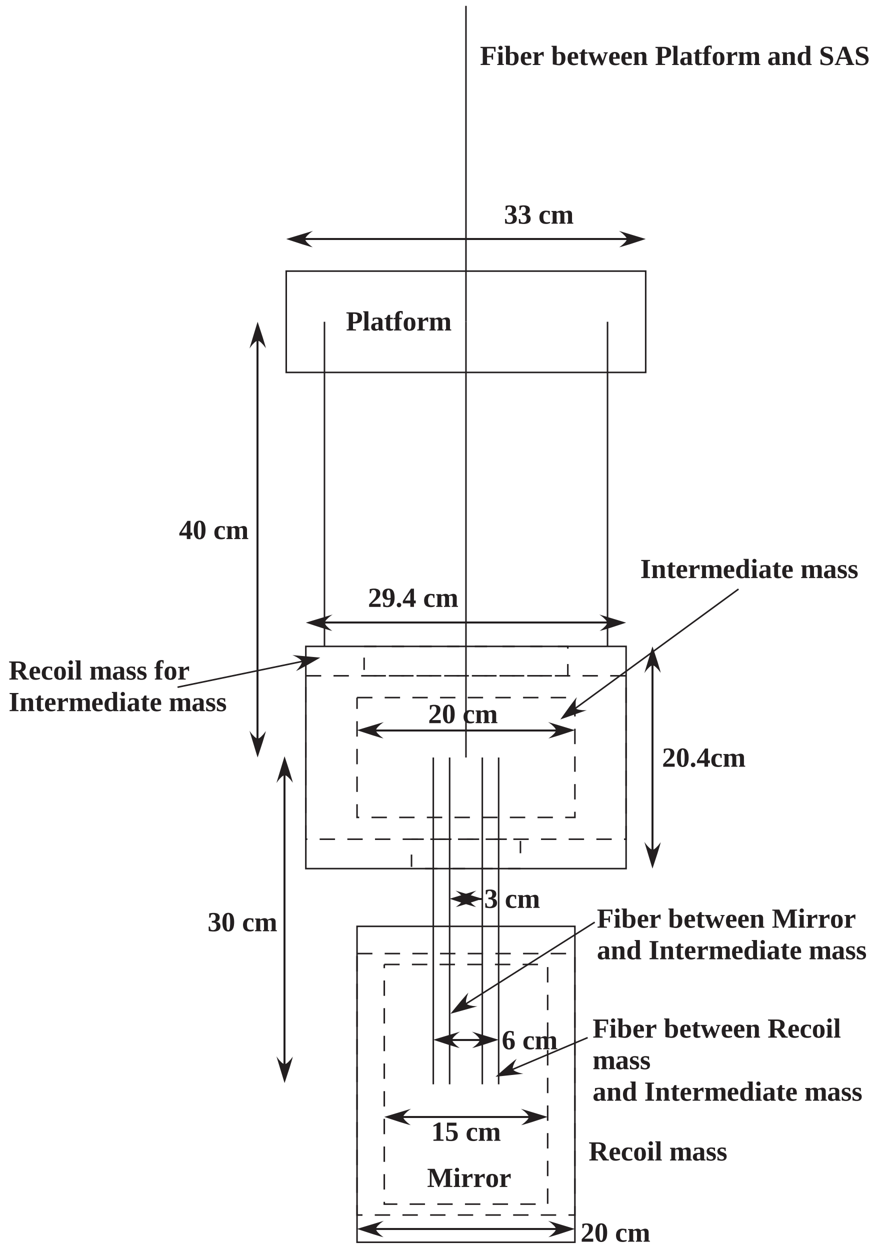

Figure 2: Schematic view of cryogenic payload (from other horizontal axis)

3 Mirror

The mirror is a cylinder[1]. This is suspended by four wires from the intermediate mass.

- Material : Sapphire
  - Density : 4.0×10^3 kg/m^3
  - Young's modulus : 4×10^{11} Pa
  - Poisson ratio : 0.29
- Geometry
  - Diameter : 22 cm
  - Thickness : 15 cm
  - Mass : 22.8 kg
  - Moment of inertia : 0.138 kg m^2 (cylindrical axis), 0.112 kg m^2(the other axis)

You can find data for thermal conductivity and specific heat (sapphire_bulk_con_temp.txt,sapphire_bulk_con.txt, sapphire_sp_temp.txt,sapphire_sp.txt).

3.1 Fiber between Mirror and Intermediate Mass

- Material : Sapphire
  - Density : 4.0×10^3 kg/m^3
  - Young's modulus : 4×10^{11} Pa
  - Poisson ratio : 0.29
- Number : 4
- Cross section : circle
  - Diameter : 1.6 mm
  - Length : 30 cm
- All wires are along the vertical axis.
- Position
  - Distance between the centers of the mirror and the ends of the wires (along the optical axis) : 15 mm

[1] There are flat surfaces on barrel surface for sapphire fiber bonding. If we need 3cm width flat surface, the both side are cut 1 mm.

- Distance between the centers of the mirror and the ends of the wires (along the other horizontal axis) : 110 mm
- Distance between the centers of the mirror and the ends of the wires (along the vertical axis) : 0 mm
- Distance between the centers of the intermediate and the ends of the wires (along the vertical axis) : 0 mm

When we use sapphire fiber, size effect (thermal conductivity depends on the radius of fiber) should be taken into account. The thermal conductivity of fiber (1.6 mm in diameter) is as Fig. 3. Tomaru *et al*[1] investigated fiber (0.16 mm in diameter). Below 35 K, it is supposed that sapphire fiber (1.6 mm diameter) is 10 times larger than Tomaru's result. It is assumed that the thermal conductivity of fiber above 35 K is the same as that of bulk. You can find data (sapphire_fiber_con_temp.txt,sapphire_fiber_con.txt).

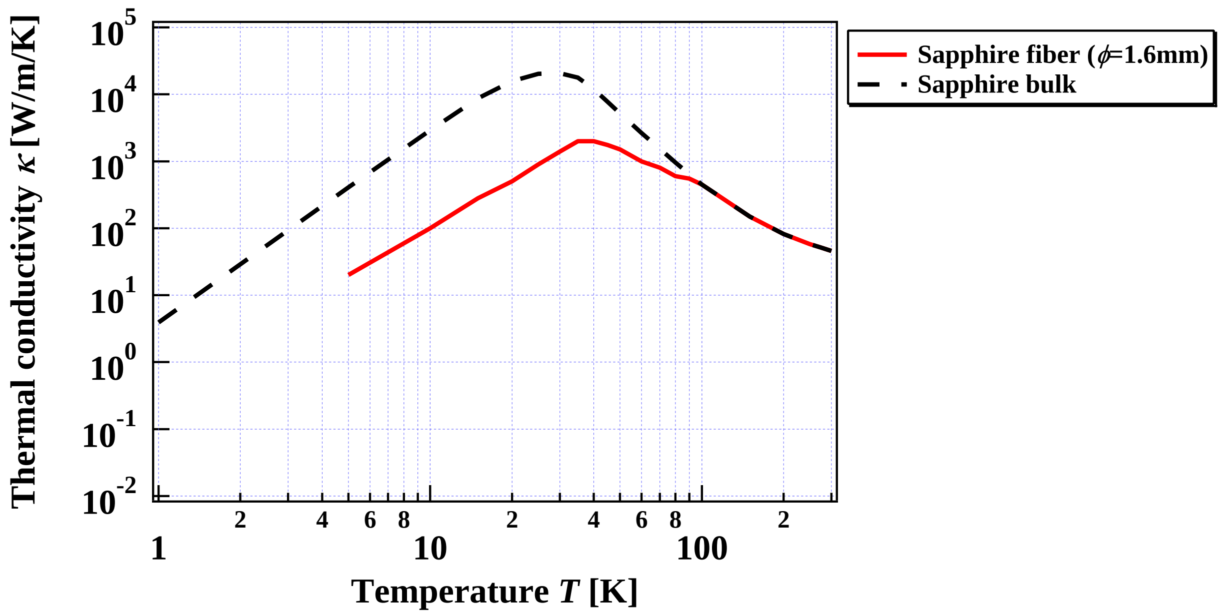

Figure 3: Thermal condcutivity of sapphire

4 Recoil mass

The recoil mass is a hollow cylinder. The mirror is inside the recoil mass. The center of gravity of recoil mass is the same as that of the mirror. There are the actuators for the mirror on the recoil mass. The recoil mass also protects the mirror if the wires for the mirrors are broken. The recoil mass is suspended by four wires from the intermediate mass.

- Material : Copper(RRR=20)
  - Density : 8.93×10^3 kg/m^3
  - Young's modulus : 1.298×10^{11} Pa
  - Poisson ratio : 0.343
- Geometry
  - Outer diameter : 29 cm
  - Inner diameter : 24 cm
  - Thickness : 20 cm
  - Mass : 37.2 kg
  - Moment of inertia : 0.658 kg m^2 (cylindrical axis), 0.453 kg m^2(the other axis)

Thermal conductivity of copper (RRR is 20) is as Fig. 4 [2]. You can find data (Cu_con_temp.txt,Cu_con.txt, Cu_sp_temp.txt, Cu_sp.txt).

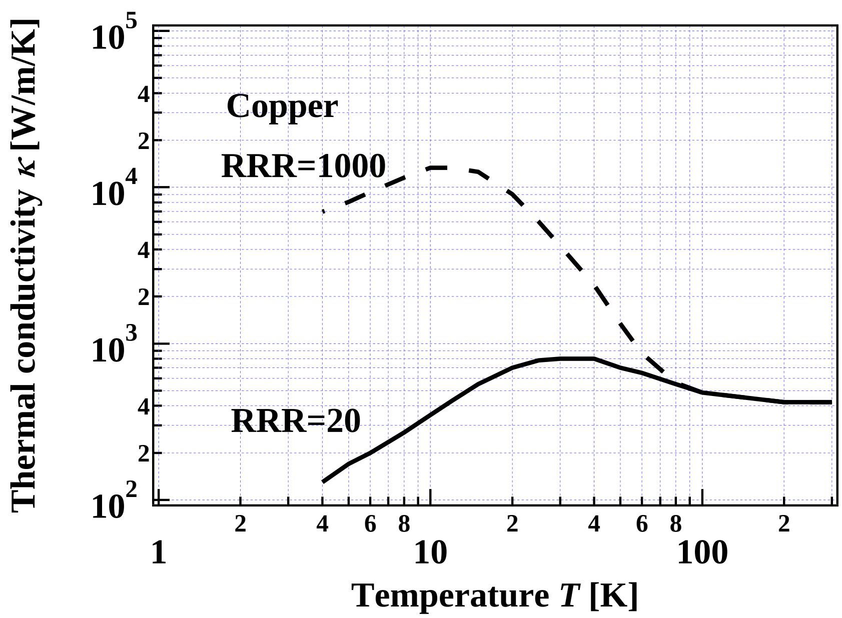

Figure 4: Thermal condcutivity of copper

4.1 Fiber between Recoil mass and Intermediate mass

- Material : Tungsten
  - Density : 19.1×10^3 kg/m^3

  - Young's modulus : 4.0 $\times 10^{11}$ Pa
  - Poisson ratio : ???

- Number : 4
- Cross section : circle
  - Diameter : 0.72 mm
  - Length : 30 cm
- All wires are along the vertical axis.
- Position
  - Distance between the centers of the recoil mass and the ends of the wires (along the optical axis) : 30 mm
  - Distance between the centers of the recoil mass and the ends of the wires (along the othre horizontal axis) : 145 mm
  - Distance between the centers of the recoil mass and the ends of the wires (along the vertical axis) : 0 mm
  - Distance between the centers of the intermediate mass and the ends of the wires (along the vertical axis) : 0 mm

The thermal conductivity should be prepared. But, in thermal analysis, it has no important role.

4.2 Heat links between Recoil mass and Intermediate mass

- Material : Aluminum (RRR=4000)
  - Density : 2.69×10^3 kg/m^3
  - Young's modulus : 7.03×10^{11} Pa
  - Poisson ratio : 0.345
- Number : 4
- : U shape
- Cross section : circle
  - Diameter of heat link : 1.6 mm
  - Diameter of U shape : 30 cm

  - Length of heat link : $\pi/2\times30$ cm $\sim$ 47.1 cm

The size effect is observed if RRR is more than about 10000 [3]. Thus, here, it is not necessary to consider it.

5 Intermediate mass

The intermediate mass is a rectangular parallelepiped. This is suspended by the one wire from the GAS filter in the platform.

- Material : Copper(RRR=20)
  - Density : 8.93×10^3 kg/m^3
  - Young's modulus : 1.298×10^{11} Pa
  - Poisson ratio : 0.343
- Geometry
  - Width : 31 cm
  - Thickness (optical axis): 20 cm
  - Height (vertical axis): 11 cm
  - Mass : 60.9 kg
  - Moment of inertia : 0.549 kg m^2 (cylindrical axis), 0.264 kg m^2(the other horizontal axis), 0.691 kg m^2(the vertical axis)

Thermal expansion, specific heat, thermal conductivity, emissivity are summarzied in section about Recoil mass.

5.1 Fiber between Intermediate mass and Platform

- Material : Maraging steel
  - Density : 8.0×10^3 kg/m^3
  - Young's modulus : 1.95×10^{11} Pa
  - Poisson ratio : 0.3
- Number : 1
- Cross section : circle
  - Diameter : 1.8 mm

- Length : 40 cm

- The wire is along the vertical axis.
- Position
  - Distance between the centers of the intermediate mass and the end of the wire (along the optical axis) : 0 mm
  - Distance between the centers of the intermediate mass and the end of the wire (along the othre horizontal axis) : 0 mm
  - Distance between the centers of the intermediate mass and the end of the wire (along the vertical axis) : 0 mm
  - Distance between the centers of the platform and the end of the wire (along the vertical axis) : 0 mm

The thermal conductivity should be prepared. But, in thermal analysis, it has no important role.

5.2 Heat links between Intermeadite mass and Platform

- Material : Aluminum (RRR=4000)
  - Density : 2.69×10^3 kg/m^3
  - Young's modulus : 7.03×10^{11} Pa
  - Poisson ratio : 0.345
- Number : 5
- : U shape
- Cross section : circle
  - Diameter of heat link : 3 mm
  - Diameter of U shape : 40 cm
  - Length of heat link : $\pi/2\times40$ cm $\sim$ 62.8 cm

Thermal expansion, specific heat, thermal conductivity are summarzied in section about Heat links between Recoil mass and Intermediate mass.

6 Recoil mass for Intermediate mass

The recoil mass for the intermadiate mass is a hollow rectangular parallelepiped. The intermediate mass in inside this recoil mass. There are holes for wires and heat links of the upper and lower sides of this mass. The shape of hole on the upper side is different from the one on the lower side. But, the area of the both holes are the same. Thus, the gravity of the center of this mass is the same as that of the intermediate mass. There are the actuators for the intermediate mass on this recoil mass. This recoil mass also protects the intermediate mass if the wire for the intermediate mass is broken. This recoil mass is suspended by three wires from the platform (not GAS filter in the platform). The details are shown in Fig. 5.

- Material : Copper(RRR=20)
  - Density : 8.93×10^3 kg/m^3
  - Young's modulus : 1.298×10^{11} Pa
  - Poisson ratio : 0.343
- Geometry (the details are in Fig. 5)
  - Outer width : 40.4 cm
  - Inner width : 35 cm
  - Thickness (optical axis): 29.4 cm
  - Outer height (vertical axis): 20.4 cm
  - Inner heignt (vertical axis): 15 cm
  - Mass : 61.7 kg
  - Moment of inertia : 1.78 kg m^2 (cylindrical axis), 0.893 kg m^2(the other horizontal axis), 1.96 kg m^2(the vertical axis)

Thermal expansion, specific heat, thermal conductivity, emissivity are summarzied in section about Recoil mass.

6.1 Fiber between Recoil mass for Intermediate mass and Platform

- Material : Tungsten
  - Density : 19.1×10^3 kg/m^3
  - Young's modulus : 4.0×10^{11} Pa
  - Poisson ratio : ???

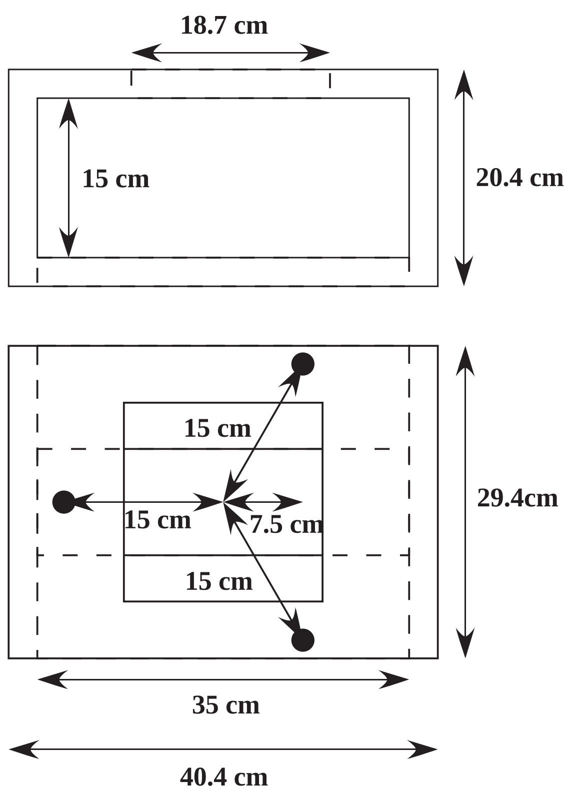

Figure 5: Recoil mass for the intermediate mass. Three black points are the wires from the platfrom. Three wires are at the vertexes of an equilateral triangle. The center of this triangle is the same as that of this recoil mass. The radius of the circumscribed circle of this triangle is 15 cm.

- Number : 3
- Cross section : circle
  - Diameter : 0.6 mm
  - Length : 29.8 cm
- All wires are along the vertical axis.
- Position
  - From top view : Three wires are at the vertexes of an equilateral triangle. The center of this triangle is the same as that of this recoil mass. The radius of the circumscribed circle of this triangle is 15 cm.
  - Distance between the centers of the intermediate mass and the ends of wires (along the vertical axis) : 102 mm (on the top surface)
  - Distance between the centers of the platform and the ends of the wires (along the vertical axis) : 0 mm

The thermal conductivity should be prepared. But, in thermal analysis, it has no important role.

6.2 Heat links between Recoil mass for Intermeadite mass and Platform

- Material : Aluminum (RRR=4000)
  - Density : 2.69×10^3 kg/m^3
  - Young's modulus : 7.03×10^{11} Pa
  - Poisson ratio : 0.345
- Number : 5
- : U shape
- Cross section : circle
  - Diameter of heat link : 3 mm
  - Diameter of U shape : 40 cm
  - Length of heat link : $\pi/2\times40$ cm $\sim$ 62.8 cm

Thermal expansion, specific heat, thermal conductivity are summarzied in section about Heat links between Recoil mass and Intermediate mass.

7 Platform

The platform is a rectangular parallelepiped. This is suspended by the one wire from the lowest GAS filter of SAS at room temperature.

The platform has also a GAS filter. The intermediate mass is suspended from thus GAS filter. The resonant frequency is 250 mHz (The total weight of the intermediate mass, the recoil mass and the mirror is 120 kg). The recoil mass for the intermadiate mass is suspended from the frame, not the GAS filter.

- Material : Copper(RRR=20)
  - Density : 8.93×10^3 kg/m^3
  - Young's modulus : 1.298×10^{11} Pa
  - Poisson ratio : 0.343
- Geometry
  - Width : 44 cm
  - Outer thickness : 33 cm
  - Height : 9.3 cm
  - Mass : 121 kg
  - Moment of inertia : 2.03 kg m^2 (cylindrical axis), 1.18 kg m^2(the other horizontal axis), 3.04 kg m^2(the vertical axis)

Thermal expansion, specific heat, thermal conductivity, emissivity are summarzied in section about Recoil mass.

7.1 Fiber between Platform and SAS

- Material : Bolfur (Unitika)
  - Density : 7.6×10^3 kg/m^3
  - Young's modulus : 1.568×10^{11} Pa
  - Poisson ratio : ???
- Number : 1
- Cross section : circle
  - Diameter[2] : 1.5 mm

[2] Tensile strength is 3.528 Gpa if the diameter is 100 μm.

- Length : 3.1 m

- The wire is along the vertical axis.
- Position
  - Distance between the centers of the platform and the ends of wires (along the optical axis) : 0 mm
  - Distance between the centers of the platform and the ends of wires (along the other horizontal axis) : 0 mm
  - Distance between the centers of the platform and the ends of wires (along the vertical axis) : 0 mm

The thermal conductivity will be measured in KEK. Here, it is assumed that it is the same as that of steinless steel as Fig. 6 [2]. The thermal condcutivity of G10 is 10 times smaller [2]. You can find data (Bolfur_con_temp.txt,Bolfur_con.txt).

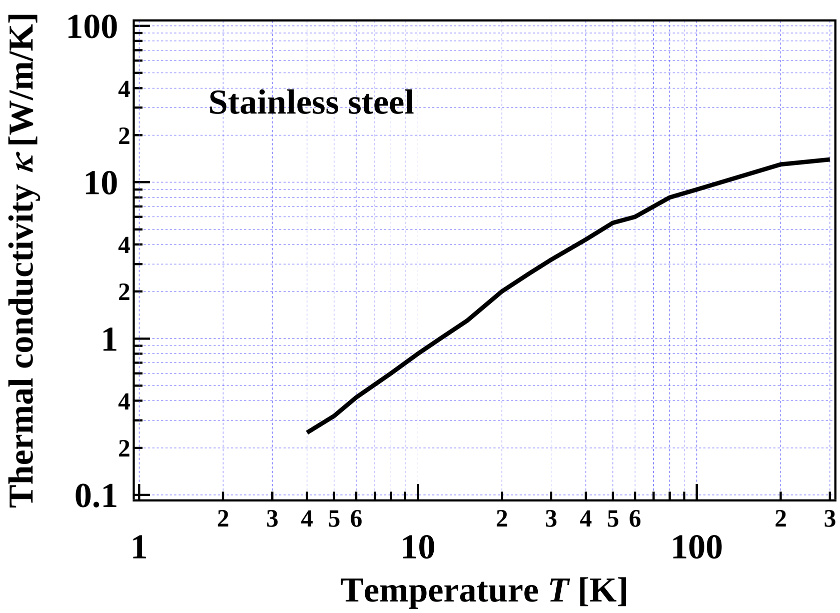

Figure 6: Thermal condcutivity of Bolfur (It is assumed that it is the same as that of steinless steel).

7.2 Heat links between Platform and Inner shield

- Material : Aluminum (RRR=4000)
  - Density : 2.69×10^3 kg/m^3

  - Young's modulus : 7.03×10^{11} Pa
  - Poisson ratio : 0.345

- Number : 7
- : U shape
- Cross section : circle
  - Diameter of heat link : 1 mm
  - Diameter of U shape : 50 cm
  - Length of heat link : $\pi/2\times40$ cm $\sim$ 78.5 cm

Thermal expansion, specific heat, thermal conductivity are summarzied in section about Heat links between Recoil mass and Intermediate mass.

8 Cryocooler power

The power of the 2nd stage of a cryocooler has already been measured [4]. This result is adopted and summarized in Fig. 7. You can find data (cryo_power_temp.txt,cryo_power.txt).

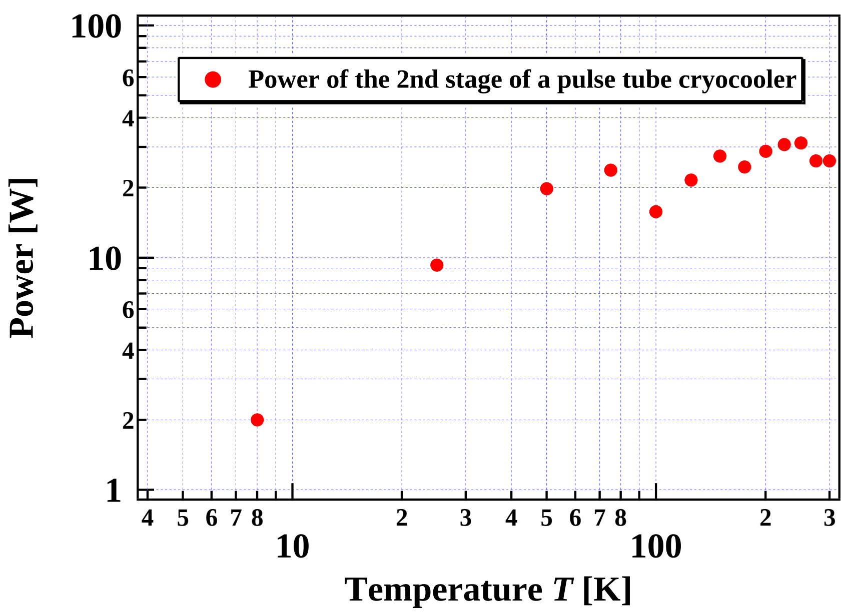

Figure 7: Power of the 2nd stage of a pulse tube cryocooler

9 Radiation

When we consider initial cooling time, radiation can not be neglected. The radiation between mirror (or intermediate mass) and recoil masses should be taken into account. Some kinds of coating make emissivity larger. You can find the emissivity of the sapphire and copper (sapphire_em_temp.txt,sapphire_temp.txt,Cu_em_temp.txt,Cu_temp.txt).

10 Heat load

10.1 Laser light

The absorption of laser light in the mirror is the heat source. The absorption in substrate is written as (in the case of end mirror, it is not necessary to consider it)

$$0.23\ [\mathrm{W}] \left(\frac{P}{75\ [\mathrm{W}]}\right) \left(\frac{G_{\mathrm{PR}}}{10}\right) \left(\frac{a}{20\ \mathrm{ppm/cm}}\right) \left(\frac{t}{15\ \mathrm{cm}}\right), \tag{1}$$

where P, G_{PR}, a and t are the incident power at beam splitter, power recycling gain, absorption per unit length, and thickness of the mirror. The absorption in coating is represented as

$$0.19\ [\mathrm{W}] \left(\frac{P}{75\ [\mathrm{W}]}\right) \left(\frac{G_{\mathrm{PR}}}{10}\right) \left(\frac{\mathcal{F}}{1550}\right) \left(\frac{b}{0.5\ \mathrm{ppm}}\right), \tag{2}$$

where $\mathcal{F}$ and b are finesse of cavity and absorption in coating.

10.2 Heat from duct

According to Sakakibara's calculation [6], the 300 K radiation transmitted by a duct is about 0.1 W. Since buffles on duct work well, almost all of 300 K radiation attack the mirror directly. Thus, in total, 0.2 W radiation arrives at the mirror. Although the emissitivity must be consider, here, it is supposed that the mirror absorps all power of radiation [3].

10.3 Heat from SAS

There are two heat path from SAS, wire and radiation. In both case, heat reaches the platform.

The top end of (Bolfur) wire is at 300 K. If the thermal conductivity of Bolfur is comparable with that of steinless steel, the heat which passes through wire is on the order of 1 mW (you must check it).

[3] In general, emissivity at lower temperature is smaller. The emissitivity of sapphire at 20 K is 0.08[7]. However, as long as I know, the emissivity of coating is unknown.

The power of 300 K radiation is as follows:

$$\sigma_{\mathrm{Stefan-Boltzmann}} A_{\mathrm{platform}} \epsilon_{\mathrm{platform}} \frac{1}{4\pi} \left({T_2}^4 - {T_1}^4\right) \frac{\pi r_{\mathrm{hole}}^2}{d_{\mathrm{hole}}} \tag{3}$$

$$= 85 \text{ [mW]} \left(\frac{A_{\mathrm{platform}}}{0.44 \times 0.33 \text{ [m}^2\text{]}}\right) \left(\frac{\epsilon_{\mathrm{platform}}}{1}\right) \left(\frac{2r_{\mathrm{hole}}}{10 \text{ [cm]}}\right)^2 \left(\frac{0.7 \text{ [m]}}{d_{\mathrm{hole}}}\right) \tag{4}$$

where $\sigma_{\mathrm{Stefan-Boltzmann}}$, A_{platform}, $\epsilon_{\mathrm{platform}}$, $T_2(= 300 \text{ [K]})$, $T_1(= 8 \text{ [K]})$, r_{hole}, d_{hole} are Stefan-Boltzmann constant (5.67×10^{-8} [W/m^2/K^4]), surface area and emissivity of platform, temperature of outside and platform, radius of hole for wire and the distance between platform and hole.

References

[1] T. Tomaru et al., Phys. Lett. A 301 (2002) 215.

[2] Lakeshore, Cryogenic Reference Tables (http://www.lakeshore.com/pdf_files/Appendices/LSTC_appendixI_l.pdf)

[3] K. Kasahara, Master thesis (The university of Tokyo, 2003, in Japanese)

[4] N. Kimura et al.'s measurement.

[5] Y. Sakakibara, 14 June 2011.

[6] Y. Sakakibara, 28 June 2011.

[7] Y. Sakakibara, 8 June 2011.