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Radiative Cooling of the Thermally Isolated System in KAGRA Gravitational Wave Telescope

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Abstract.

Radiative cooling of the thermally isolated system is investigated in KAGRA gravitational wave telescope. KAGRA is a laser interferometer-based detector and main mirrors constituting optical cavities are cool down to 20 K to reduce noises caused by the thermal fluctuation. The mirror is suspended with the multi-stage pendulum to isolate any vibration. Therefore, this mirror suspension system has few heat links to reduce vibration injection. Thus, this system is mainly cooled down with thermal radiation. In order to understand the process of radiative cooling of the mirror, we analyzed cooling curve based on mass and specific heat. As a result, it was newly found that a cryogenic part called "cryogenic duct-shield" seems to have large contribution in the beginning of the mirror cooling. This finding will help to design new cooling system for the next generation cryogenic gravitational wave detector.

1. Introduction

Large-scale Cryogenic Gravitational wave Telescope KAGRA is a Fabry-Perot Michelson interferometer-based gravitational-wave detector constructed in Japan [1-3]. One of the most advanced features in KAGRA is the cryogenic sapphire mirrors, while other gravitational wave detectors, e.g. LIGO in the USA [4] and Virgo in Italy [5], are using fused silica mirrors at room temperature. One of fundamental noises limiting the sensitivity of interferometer-based detectors is the thermal noise caused by thermal fluctuation of the mirror and its suspension. In KAGRA, to reduce thermal noise, mirrors are cooled down to 20 K; to do so, the mirrors are made of mono-crystal sapphire. The cryogenic mirror is a simple and direct way to reduce thermal noise [6]. However, there are many issues to be considered.

From postulate of general theory of relativity, the cryogenic mirror reflecting a laser beam must be free mass. In KAGRA, moreover, sapphire mirrors are suspended by very tall multi-stage pendulum to isolate seismic vibration effectively. This cryogenic mirror suspension is cooled down with thermal radiation and thermal conduction, and this should not disturb

interferometer operation, i.e. cooling time should be short and vibration via heat links must meet the displacement noise requirement. For the latter, we have overcome this problem by reducing the number of heat links and by installing their vibration isolation system between cryocoolers and the suspension. Considering this situation, it is obvious that radiative cooling has very important contribution to determine total cooling time. Since the cooling time will be observation dead time for KAGRA, the cooling time of the mirror should be reasonably short in order to keep long observation time. Here, it is worth evaluating radiative cooling, which may dominate cooling time.

In this paper, we first briefly explain the cryogenic system of KAGRA. Then, we discuss how radiative cooling works in this system. By focusing on mass and specific heat, we evaluate how much heat can be extracted in time.

2. Cryogenic System in KAGRA

2.1. Cryogenic mirror suspension

A pendulum works as a mechanical filter to attenuate the propagating vibration. The cryogenic mirror is placed at the last stage of the 13.5-m tall 9-stage pendulum to isolate seismic vibration sufficiently, of which only lower 4 stages are cooled down to 20 K. These cryogenic stages consist of, from the top, Platform, Marionette, Intermediate Mass, and Mirror as shown in Figure 1. Two chains with sensors and actuators are suspended from Platform: Mirror chain suspending a mirror and recoil mass chain working as reaction masses. The sensors and actuators are utilized to control the suspension. However, detail of the control system will not be mentioned here because it is outside the scope of this paper [7].

2.2. Cooling system

A cooling system consists of two parts: a cryostat and a cryogenic duct-shield. Since a laser beam is injected into the cryogenic mirror, a cryostat housing the cryogenic mirror is required to open apertures to pass laser beam in front and back side of the mirror. In order to avoid very large thermal radiation at 300 K entering from the apertures, 5-m long cryogenic duct-shields are placed in front and back side of the cryostat.

The cryostat is cooled down with four double-stage 4 K pulse-tube cryocoolers [8]. The cryostat has double radiation shields at different temperatures: outer (~ 86 K) and inner (~ 14 K) radiation shields. While the outer shield is cooled by four of 1st-stages of the 4 K pulse-tube cryocoolers, 2nd-stages of the cryocoolers are used for cooling the inner shield and the suspension system via heat links. The cryogenic duct-shield is cooled down with a single-stage pulse-tube cryocooler and is kept at ~ 120 K in the operation. As a result, this shield reduces thermal radiation at 300 K from about 100 W to 0.1 W per an aperture [9].

Due to the small number of the heat links, suspension cooling is realized by radiative cooling at high temperature and conductive cooling at low temperature. Since most part of cooling will be carried out by thermal radiation, we designed to cool down radiation shields rapidly for enhancing radiative cooling. In order to assist heat exchange, surfaces of the suspension and the inner shield are black-coated with low magnetism SOLBLACK coating [10] and Diamond like carbon coating (DLC), respectively. The lower the temperature of the suspension is, the smaller the contribution of thermal radiation becomes. Instead, thermal conduction will be large at low temperature by using pure metal heat links. In KAGRA, we have newly developed a soft and high thermal conductive heat link with high purity aluminum. The measured maximum thermal conductivity is 18,500 W/m/K at 10 K. Furthermore, we have also installed vibration isolation systems for heat links (HLVIS) to reduce vibration injection through the heat links. Schematic view of the cryogenic system is shown in Figure 1.

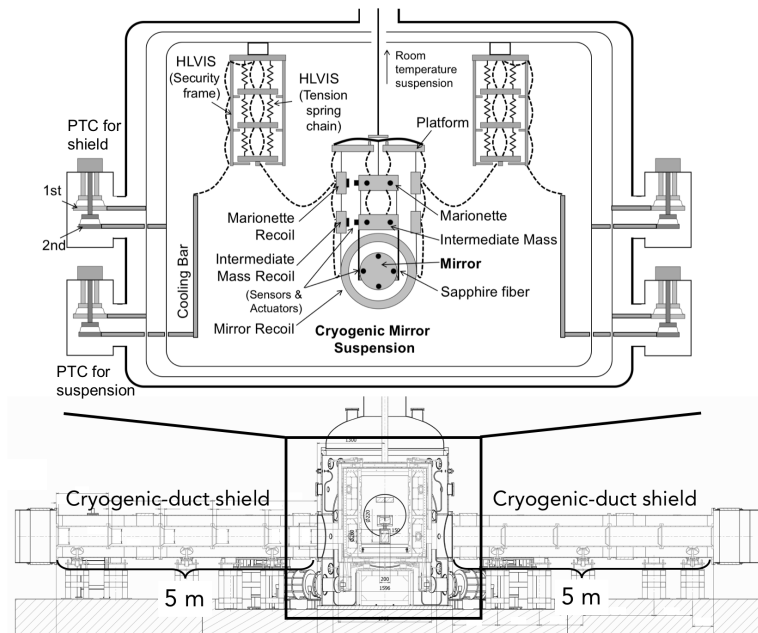


Figure 1. KAGRA cryogenic system. A top figure is a schematic diagram of the cryostat. A 4K pulse-tube cryocooler (PTC) has 2 stages: 1st and 2nd stages. Outer radiation shield, inner radiation shield and cryogenic suspension are cooled down with four 1st stages, two of 2nd stages, and remaining two 2nd stages, respectively. Black dashed line represents heat links. Heat Link Vibration Isolation System (HLVIS) and inner radiation shield are mechanically connected. However, thermally isolated with low thermal conductivity material. Thermal conduction between Mirror and Intermediate Mass is relied on sapphire fibers instead of aluminum heat links. Cryogenic duct-shields are 5-m long each and cooled down with single-stage pulse-tube cryocoolers.

3. Evaluation of radiative cooling of the mirror

Based on practical data, we discuss how radiative cooling works in KAGRA. First, we will show two graphs: temperature curve of nominal cooling and temperature curve when two cryocoolers for suspension were stopped. Comparing above two results, we can know the minimum temperature that can be achieved by only thermal radiative cooling. Then, we will discuss the status of radiative cooling with mass and specific heat.

3.1. Data: Temperature curves

Nominal cooling curve is shown in the left side of Figure 2. The cryogenic duct-shields were started to cool down 1 day before starting cryostat cooling. It took about 27 days to reach minimum temperature namely 23 K at the mirror stage.

Right side of Figure 2 shows temperature behavior when the cryocoolers for the suspension were stopped. In other words, in this term, only thermal radiation was working to maintain suspension cooling. We can see that the warmer the temperature becomes, the smaller the derivative of curves becomes. Therefore, we can consider that thermal equilibrium temperature is around 100 K, and, above this temperature, we can ignore the effect of thermal conduction to discuss suspension cooling.

In the left side of Figure 2, above around 100 K, we can find that the inner shield shows similar temperature behavior with the mirror in contrast to "Cooling Bar" (see Figure 1). It is

inferred that there is large heat exchange with thermal radiation between the inner shield and the suspension.

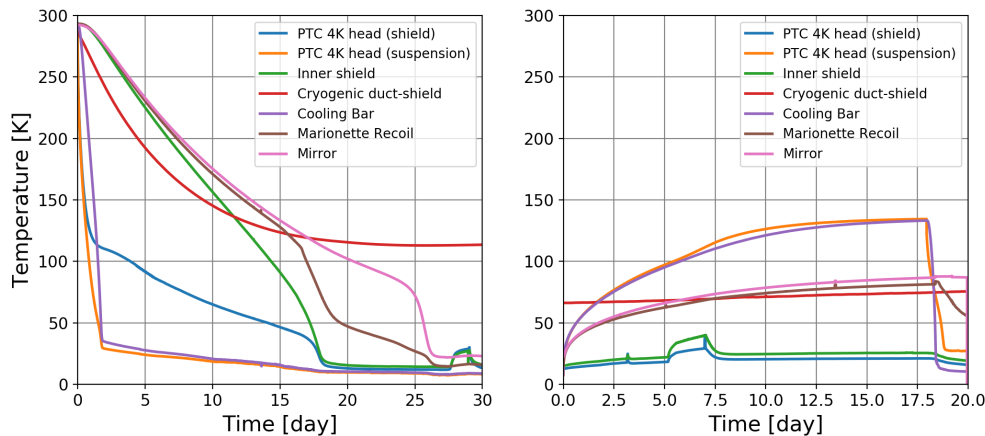


Figure 2. (Left): Nominal cooling curves. It takes 27 days to reach minimum temperature. The temperature increase around 28th day is considered as instability of the cryocoolers for shields. (Right): Warming curves when two cryocoolers for the suspension were stopped. It is also assumed that temperature increase around 6th day is due to instability of the cryocoolers for shields.

3.2. Method

Focusing on mass and specific heat, we can purely study how much heat is extracted from the suspension in time. The advantage of utilizing this method is to avoid to use uncertain parameters like surface area and temperature dependence of emissivity. In addition to this, since the method does not depend on the cooling process, it can be applied both conductive and radiative cooling: radiative cooling in this case.

We define the term "heat extraction per unit time, P [W]" as

$$P = m \int_{T(t_1)}^{T(t_2)} c(T) dT / (t_1 - t_2), \quad (1)$$

where m is mass, c is specific heat, and T is temperature of the mirror. The mirror is made of sapphire and 22-kg weight. The specific heat of sapphire in reference [11] is used for analysis.

3.3. Result and Discussion

Heat extraction from the mirror is calculated as the bottom figure in Figure 3. The latter half can be explained with the fact that both temperatures of the suspension and the inner shield become low. Here, we pay attention to the largest heat extraction occurred in 2.5th day. Since total amount of extracted heat is given by integral of heat capacity, mc , it is worth understanding the cause of the peak. Furthermore, it might help a discussion to reduce cooling time.

In Figure 4, heat extraction is plotted as a function of the mirror temperature. At the peak temperature 275 K, temperature difference between the mirror and the inner shield is not very large. However, cryogenic duct-shields are much colder than the mirror since their cooling speed is faster than the inner shield. Cooled cryogenic duct-shields seem to explain the peak at 275 K although the apertures are just 5% of total surface area of the inner shield. In other words, thermal radiation to duct-shields works at high temperature region and that to inner shield does

at middle temperature region. Further study is needed to investigate the approximate boundary temperature switching above two contributors.

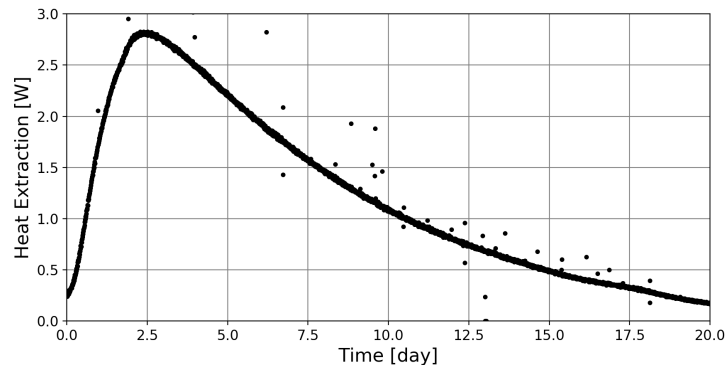


Figure 3. Heat extraction as a function of cooling time. We can see about 3 W of heat is extracted from the mirror at maximum.

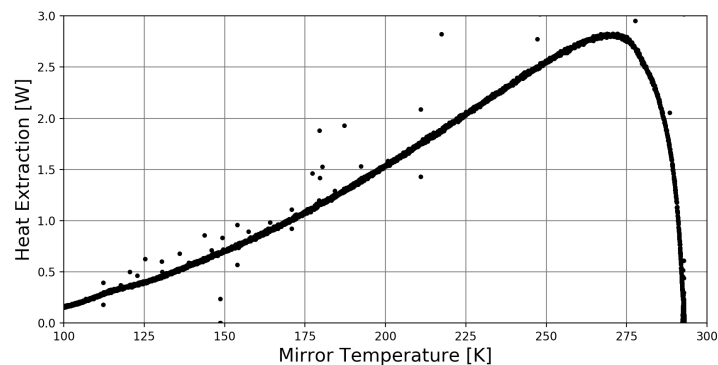


Figure 4. Heat extraction as a function of mirror temperature. The peak is at 275 K.

4. Conclusion

The cryogenic mirror is a unique characteristic of KAGRA, works to reduce thermal noise and will be utilized in future gravitational wave detectors. Whereas, it takes time to cool down the mirror and it will be observation dead time in contrast to room temperature detectors.

In this paper, we introduced a cryogenic system in KAGRA and discussed radiative cooling of the mirror. It was reported that cooling time is currently 27 days and it is mostly dominated by radiative cooling. The cryogenic duct-shields seem to largely contribute to the mirror cooling in the beginning. Detailed investigation will be continued for future improvements.

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