

# KAGRA Cryogenic Suspension Control toward the Observation Run 3

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## Abstract.

We have newly developed a vibration isolation system to reduce vibration via heat links, which would be one of the obstacles in the control of KAGRA gravitational wave detector. KAGRA adopts cryogenic mirrors for main optics to reduce thermal noise, which is a fundamental noise source in ground-based gravitational wave detectors in 100 Hz region, and achieves the best sensitivity in this frequency region in the world. The cryogenic mirror needs to be cooled down rapidly not to waste observation time and quietly not to disturb the mirror suspension system. For the former, radiative cooling works effectively with black coatings in high temperature region. Conductive cooling will strongly work with heat links in low temperature. However, according to our calculation, it was revealed that vibration via heat links impairs the detector sensitivity in several dozen Hz. The cryogenic suspension with heat links needs to be properly controlled up to almost same frequency region, thus, we have focused on reducing transmitting vibration with Heat Link Vibration Isolation System. In this paper, we will introduce the cryogenic suspension system, cooling system and Heat Link Vibration Isolation System in KAGRA.

## 1. Introduction

KAGRA is an interferometer based gravitational wave detector constructed in the underground tunnel in Mt. Ikenoyama, which is the same mountain where Super Kamiokande is located [1,2]. Coming gravitational wave distorts spacetime, therefore, distance between two objects is changed although it is very small. In order to detect this tiny change with laser interferometer, KAGRA has two advanced features: underground site and cryogenic mirrors. Underground site is suitable place to construct gravitational wave detector since seismic vibration affects stability of the interferometer operation. Seismic vibration level of KAGRA site is smaller than that of urban area by two order of magnitude at the observation band. Cryogenic mirror is one solution to reduce thermal noise, which is fundamental noise limiting sensitivities of ground based gravitational wave detectors in 100 Hz region [3]. Cryogenic mirror is a simple and direct way to reduce thermal noise, however, there are many issues to be considered.

In this paper, we focus on vibration via heat links and present their impact to the sensitivity. We start describing the cryogenic suspension system and the cooling system in KAGRA. We then show calculation results of effects of heat links. Finally, we explain that new system, Heat Link Vibration Isolation System, attenuates vibration via heat links to meet the displacement noise requirement.



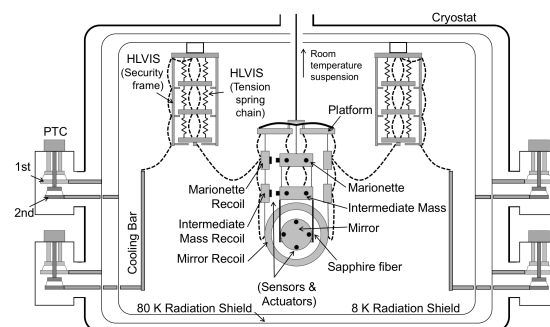
## 2. Overview of KAGRA cryogenic system

### 2.1. Cryogenic suspension

The pendulum works as a mechanical filter to attenuate the propagating vibration. The cryogenic mirror is placed on the last stage of 13.5 m tall 9-stage pendulum to be strictly isolated from seismic vibration and only lower 4 stages are cooled down to 20 K. 4 stages consist of, from the top, Platform, Marionette, Intermediate Mass, and Mirror as shown in Figure 1. This cryogenic suspension needs to be actively controlled to maintain the position, damp resonant modes of the suspension and lock the interferometer. It has 2 chains with sensors and actuators; Mirror chain suspending a mirror and recoil mass chain working as reaction masses.

### 2.2. Cooling system

Cooling time is one of restrictions to start observation, thus, it must be rapid. Concerning vibration through heat links, their number should be small, so the cryogenic suspension is closed to thermally isolated system. In this situation, radiative cooling must work effectively, therefore, we put effort into the cooling of radiation shield surrounding cryogenic suspension, and increase emissivities of surfaces of the shield and suspension with DLC [4] and SOLBLACK [5], respectively. Radiative cooling is powerful when temperature of the suspension is high, typically above 100 K, however, at low temperature, conductive cooling gets dominating suspension cooling. Cooling of the radiation shield and suspension is performed by 4 pulse-tube cryocoolers with ultra-low vibration [6]. Schematic view of the cryogenic system is shown in Figure 1.



**Figure 1.** KAGRA cryogenic system is shown. A pulse-tube cryocooler (PTC) has 2 stages: 1st and 2nd stages. 80 K radiation shield, 8 K radiation shield and cryogenic suspension are cooled down with 4 of 1st stages, 2 of 2nd stages, and remaining two 2nd stages, respectively. Black dashed line represents heat links. HLVIS and 8 K radiation shield are connected, however, thermally isolated. Thermal conduction between Mirror and Intermediate Mass is relied on sapphire fibers instead of heat links.

## 3. Heat Link Vibration Isolation System

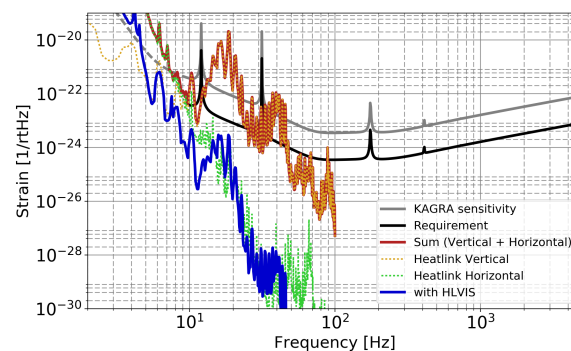
### 3.1. Issue of heat link vibration

Heat links need be connected to the suspension for thermal conduction, however, they may introduce additional vibration to the vibration-isolated stage from many sources: radiation shield, cryostat, cryocoolers, ground and so on. According to our calculation, direct connection of heat links impairs the detector sensitivity and there are some crests at around 20 Hz and 40 Hz, which correspond to resonances of radiation shield, as shown in Figure 2. We can find that transmitted vertical vibration dominates the sum above 10 Hz. This is due to 2 reasons: the suspension and KAGRA tunnel issues. First, cryogenic suspension is designed to be worked at cryogenic temperature, so we've avoided the complex structure not to be largely influenced

by thermal contraction and changes of material properties. Due to this relatively simple design, vertical vibration isolation ratio is not so high. Second, KAGRA tunnel has 0.3% slope to drain spring water, so laser axis is not horizontal. Thus, transmitted vertical vibration couples to the longitudinal degree of freedom of the interferometer.

### 3.2. Design and expected performance

One solution to tackle this issue is to install the vibration isolation system for heat links between the cooling bar and suspension, this is called as Heat Link Vibration Isolation System (HLVIS, Figure 1). In order to obtain low spring constant in vertical direction at cryogenic temperature, we adopted tension springs made by Stainless Steel 316. To prevent rotation of HLVIS, each stage is suspended by 2 right- and 2 left-handed springs which are placed diagonally. HLVIS consists of 3 stages and each resonant frequency is designed to be approximately at 3 Hz. Therefore, the transfer function of this suspension system has a slope of  $f^{-6}$ , where  $f$  is frequency, above 10 Hz. In Figure 2, we can clearly see that HLVIS can strongly attenuate transmitted vibration via heat links to be less than requirement.



**Figure 2.** Comparison with noise requirement and vibration via heat links are shown. The requirement, which is 1/10 of the sensitivity (grey line), is shown with black line. Calculated vertical vibration, horizontal vibration and sum of them are plotted with yellow, green and red, respectively. In design performance, HLVIS attenuates vibration as shown with blue line.

## 4. Summary and future prospects

We have given an overview of the cryogenic suspension, cooling system and HLVIS in KAGRA. HLVIS was designed to attenuate vibration via heat links, which perhaps impairs the detector sensitivity, to the negligible level. Practical vibration attenuation ratio measurement is in progress. By installing HLVIS and cooling mirrors, we aim to increase the inspiral detection range and detect gravitational waves with high signal-to-noise ratio in O3 and afterwards. Cryogenic mirrors are considered for next generation detectors: Einstein Telescope and LIGO Voyager, therefore, HLVIS should also play an important role in future detectors.

## References

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