Reduction of Heat Load of LCGT Cryostat

T. Tomaru¹, M. Tokunari², K. Kuroda², T. Uchiyama², A. Okutomi², M. Ohashi², H. Kirihara², N. Kimura², Y. Saito¹, N. Sato¹, T. Shintomi¹, T. Suzuki¹, T. Haruyama¹, S. Miyoki², K. Yamamoto² and A. Yamamoto¹

¹High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
²Institute for Cosmic Ray Research (ICRR), University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8585, Japan
³Nihon University, 4-2-1-602 Kudankita, Chiyoda, Tokyo 102-0073, Japan

E-mail: tomaru@post.kek.jp

Abstract. An unexpected large heat load was observed in a cooling test of the cryostat for a prototype cryogenic interferometric gravitational wave detector. By conducting additional studies involving an experiment and a simulation, we found that the large heat load was caused by conduction of thermal radiation in a thermal radiation shield pipe, which was inserted in the beam duct to reduce solid angle from 300 K to 4 K. To achieve the design of LCGT cryogenic system, the heat load had to be reduced below a few percent. By introducing metal baffles in the shield pipe, this requirement was fulfilled.

1. Introduction

A large-scale cryogenic gravitational wave telescope (LCGT) is a next-generation gravitational wave detector proposed in Japan [1]. One of the features of the telescope is that it uses cryogenic mirrors and suspensions to reduce thermal noises. The detailed design of the LCGT has been completed. Figure 1 shows the schematic representation of the design of the LCGT cryostat. Since it is difficult to cool the large interferometer, only parts of the mirror containers are cooled to 4 K. Therefore, the cryostat requires large opening ports for laser beams. To reduce the thermal radiation from the 300 K beam duct into the 4 K cryostat, an aluminum pipe that has a diameter of 0.8 m, length of 20 m and temperature of 100 K is installed as a thermal radiation shield in the beam duct. Figure 2 shows the estimation of the heat load of the LCGT cryostat. A thermal conduction of 820 mW at the main mirror suspensions is considered as the critical limit for cooling [2]. To cool this cryostat, two 4 K vibration-free cryocooler systems [3] with a cooling power of 1.5 W and an 80 K cryocooler system with a cooling power of 50 W are used.

The cryogenic system used in the Cryogenic Laser Interferometer Observatory (CLIO) [4] was similar to that of the LCGT. The CLIO is a prototype cryogenic laser interferometer with 100 m base lines; it was constructed below the ground in the Kamioka mine. In the cooling test of the CLIO cryostat, a large heat load of over 3 W, which is several hundred times larger than the designed value, has been observed. We assume that the large heat load is caused by thermal
radiation through the shield pipe that enabled the cryostat to reach the design temperature when the shield pipe was closed. Here we report the studies of this phenomenon and the reduction method.

2. Conduction Effect of Thermal Radiation

In general, while designing the cryostat, the heat load caused by thermal radiation is estimated using the Stefan-Boltzmann law. This law states that heat is transferred from one surface to another. The CLIO cryostat was also designed by using this law. From another viewpoint of thermal radiation, it consists of infrared lights with a peak wavelength of 20 µm for a 300 K blackbody, and they can be reflected by metal surfaces. Therefore, the large heat load observed in the CLIO cryostat could be caused by the conduction effect of thermal radiation in the aluminum shield pipe.

To investigate this phenomenon, we performed an experiment by using an early prototype of the cryogenic interferometer, called CLIK (See Fig. 3). The cryogenic system of the CLIK is

Figure 1. Schematic representation of the design of the LCGT cryostat.

Figure 2. Estimation of heat load of the LCGT cryostat. SPIM represents the mirror for the suspension point interferometer.
similar to that of the LCGT and the CLIO. We used a calorimetric method to measure the heat load caused by thermal radiation through the shield pipe. Paper was used as a thermal radiation source since it has an emissivity of approximately 0.9. We used a bolometer that consisted of an UB-NiP blackbody coating [5], and it was equipped with a thermometer and calibration heater. From this experiment, we detected a heat load of 390 mW, which was 740 times larger than the value estimated by the Stefan-Boltzmann law.

To analyze this result, we performed a simulation by using a ray-trace model. The heat power $P$ radiated into the cryostat was described by the following equation:

$$P = P_0 \left[ \frac{a^2}{2L^2} + \int_0^L R(N(x)) \frac{a^2}{(x^2 + a^2)^{3/2}} dx \right],$$

where $P_0$ is the heat power radiated at 300 K; $L$, the length of shield pipe; $R$, the IR reflectivity of the pipe; and $a$, the radius of the pipe. $N(x)$ is a function of number of reflections of IR light, which was introduced at a position $x$ from the 300 K side of the pipe. From these calculations and the experimental results, the IR reflectivity of the aluminum shield pipe was estimated as 95.0%.

Moreover, we examined the IR reflectivity of the aluminum shield pipe by using an IR free-electron laser at the IR FEL Research Center, Tokyo University of Science [6]. The result showed that the reflectivity of the pipe at a wavelength of 8.33 μm was approximately 98%. Therefore, both the results were consistent, and we confirmed that the large heat load observed in the CLIO was caused by conduction of thermal radiation in the shield pipe. This result has been reported in reference [7].

3. Reduction Experiment

![Figure 3](image_url)  
**Figure 3.** Experimental setup for the reduction of the conduction effect of thermal radiation in the CLIK. Metal baffles were inserted in the shield pipe to reflect the thermal radiation. In the experiment for verifying conduction effect of the thermal radiation described in section 2, the baffles were not introduced in the same setup.

The conduction effect of thermal radiation in the shield pipe was a critical issue with regard to the design of the LCGT and the CLIO cryogenic systems. In the case of the LCGT, the
Figure 4. Picture of baffles. The aperture size was one third of the pipe diameter. The baffles had thermal contacts made of aluminum foils and springs to provide sufficient cooling.

load due to this effect was 9 W. We assumed that total heat power due to this effect was absorbed in the main mirror and the mirror for the suspension point interferometer (SPIM); this is a reasonable assumption since the mirror materials were not transparent to IR. Based on this assumption, a total heat load of 5.2 W was obtained at the main mirror, including laser absorption and scattering. This value is considerably larger than the heat conduction capacity (820 mW) of the main mirror suspensions. We planned to reduce this effect by introducing metal baffles and experimentally investigated the reduction rate by using the CLIK. Figure 3 shows an experimental setup in the CLIK. With the exception of the baffles, this setup is the same as that used for the experimental verification of the conduction effect of thermal radiation described in section 2. In this reduction experiment, we used two aluminum baffles whose aperture size was the one third of the pipe diameter, which corresponds to the aspect ratio between the mirror diameter and the pipe diameter in the LCGT and the CLIO. Figure 4 shows a picture of the baffles. Thermal contacts made of aluminum foils and springs were placed on the baffles to provide sufficient cooling. They were placed at positions of 3 cm and 120 cm from the 300 K side in the shield pipe. From this experiment, we observed a heat load of 7.9 mW. This means that the reduction rate of 98% was achieved by introducing only two baffles.

When this result was applied to the design of the LCGT, a heat load of 700 mW was estimated at the main mirror. This value is acceptable for the LCGT cryogenics design. Similar baffles have been introduced in the CLIO, and the performance has been found to be satisfactory.

4. Conclusion
We obtained large heat load in the CLIO cryostat, which was several hundred times larger than designed value. We identified that it was caused by the conduction effect of thermal radiation in the pipe. This phenomenon affected the design of the LCGT. We performed an experiment to reduce this effect by introducing metal baffles using the CLIK, and achieved a reduction of 98%. From this result, we obtained a solution to achieve the LCGT cryogenics design.

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