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Present status of large-scale cryogenic gravitational wave telescope

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Abstract

The large-scale cryogenic gravitational wave telescope (LCGT) is the future project of the Japanese gravitational wave group. Two sets of 3 km arm length laser interferometric gravitational wave detectors will be built in a tunnel of Kamioka mine in Japan. LCGT will detect chirp waves from binary neutron star coalescence at 240 Mpc away with a S/N of 10. The expected number of detectable events in a year is two or three. To achieve the required sensitivity, several advanced techniques will be employed such as a low-frequency vibration-isolation system, a suspension point interferometer, cryogenic mirrors, a resonant side band extraction method, a high-power laser system and so on. We hope that the beginning of the project will be in 2005 and the observations will start in 2009.

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1. Introduction

The direct detection of gravitational waves (GWs) will provide not only experimental evidence of Einstein's theory of general relativity, but also the start of gravitational wave astronomy. Experimentalists have innovated and evolved GW detectors since Weber's experiment [1]. Recently, five interferometric GW detectors of more than 300 m arm length have been developed in the world, such as TAMA [2], GEO600 [3], LIGO [4] and VIRGO [5]. Several detectors among them have already implemented observation runs[17], and at least our galaxy is in our sight. The sensitivity is, however, not sufficient to detect a few GW events in one year. Thus, detectors that have much higher sensitivity than the current ones are desired. LIGO II [6] in USA, EGO [7] in Europe and the large-scale cryogenic GW telescope (LCGT) [8] in Japan are advanced detector projects aiming at the detection of GWs. We expect that LCGT has a potential to detect GWs for the first time in the world and will play an important role as a corner of a network of GW detectors around the world. LCGT is a five-year project from 2005, and in 2009 observations will start.

LCGT consists of two sets of underground-based laser interferometric GW detectors with a 3 km arm length. Two detectors will be built in the same tunnel of Kamioka mine in Japan. The main reason for two sets of the same detector built side by side is to reject false events. The side-by-side arrangement causes a slight difference in GWs arrival time at each detector, which will contribute to decreasing the possibility of mixing signals with false events.

We expect that LCGT will detect GWs from chirp waves from neutron-star binary coalescence, burst waves from supernovae, GWs at the ring down phase after the coalescence of a black-hole binary and continuous waves from pulsars. Neutron-star binary coalescence is the most important target, because its wave form is well known and a matched-filter analysis can be applied.

Figure 1 shows the present design sensitivity of LCGT. The sensitivity is limited by the quantum noise, which is the summation of the shot noise and radiation-pressure noise at frequencies higher than 3 Hz, and reaches $3 \times 10^{-24}\ \mathrm{Hz}^{-1/2}$ at 100 Hz. The detector can see a chirp wave from neutron-star binary coalescence within 240 Mpc with a S/N of 10. The number of coalescence events within 240 Mpc is expected to be 0.6–430/yr [9] or 2–17/yr (CL 68%) [10].

In order to achieve the design sensitivity, we must reduce the detector noise. To decrease seismic noise, a vibration-isolation system, a suspension point interferometer (SPI) [11] and the quietness of the site in the Kamioka mine are key features. To overcome thermal noise, cryogenic techniques are adopted. To minimize the shot noise, a high-power laser system [12] and a broad-band resonant side-band extraction (RSE) method [13] are important. All these items characterize the LCGT design. In this paper, we introduce the present design and status of LCGT.

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[17] There are many articles corresponding to recent results of observations and data analysis in this journal.

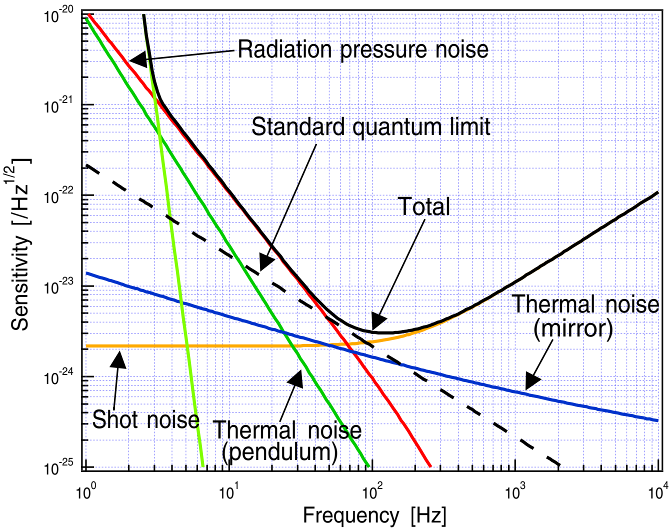

Figure 1. Design strain sensitivity and noise budgets of LCGT. Seismic noise limits the sensitivity at frequencies less than 3 Hz. Radiation-pressure noise and shot noise limit the sensitivity in other frequency regions. The seismic noise and thermal noise must be reduced to less than the quantum noises in this frequency region. The best sensitivity is 3×10^{-24} Hz$^{-1/2}$ at 100 Hz.

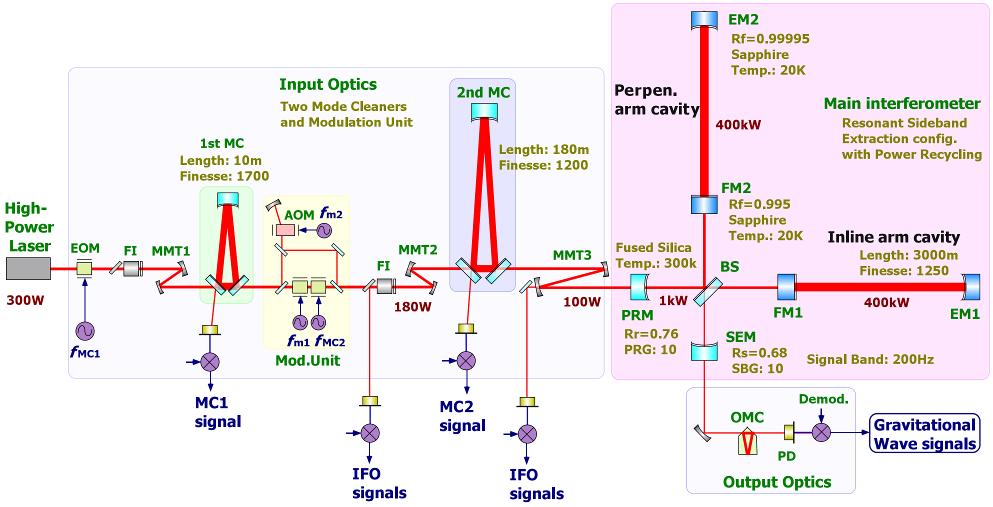

Figure 2. Optical configuration of LCGT. The interferometer consists of four parts: a high-power laser, input optics, a main interferometer and output optics.

2. Optical configuration

Figure 2 shows a schematic view of the optical configuration of LCGT. The detectors consist of four parts: a laser system, input optics, a main interferometer and output optics. All optics from the input optics to the output optics are installed in the same vacuum system at a typical vacuum pressure of 2×10^{-7} Pa.

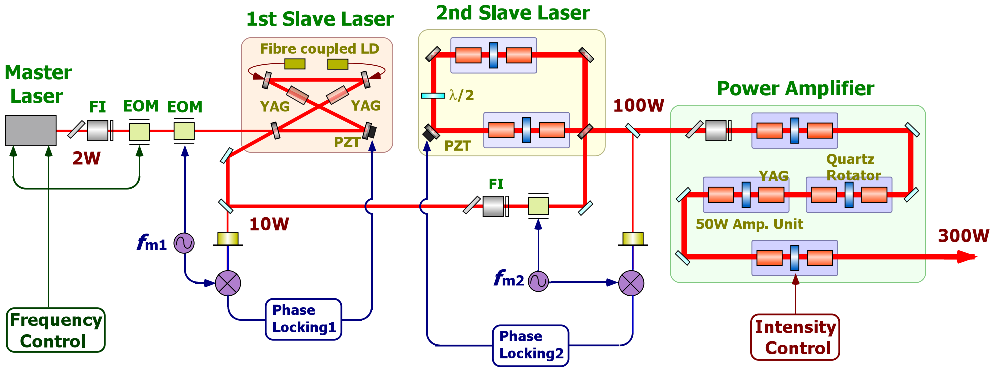

Figure 3. Block diagram of the LCGT laser system. Wavelength of the laser beam is 1064 nm.

The laser system for LCGT is required to have an output power of 300 W at 1064 nm and high stability. The conceptual design of the laser system is a combination of the injection-locking technique and laser-power amplification, as shown in figure 3 [12]. The master laser is a LD-pumped monolithic Nd:YAG laser with an output power of 2 W. The master laser beam is amplified by injection locking of the 10 W and 100 W slave lasers. The laser beam is further amplified to 300 W by a four-stage power amplifier. This design would provide high power and a stabilized laser source.

The input optics has two ring-shaped mode cleaners, a modulator unit and three mode-matching telescopes. The arm lengths of the first and the second mode cleaner are 10 m and 180 m, respectively. The first mode cleaner eliminates higher modes in the laser output beam and reduces the laser intensity noise around the radio frequency. It also serves as a frequency reference of the laser frequency stabilization. After the first mode cleaner a modulation is applied by the modulator unit and led into the second mode cleaner. The second mode cleaner reduces the wave-front distortion caused by the transmission of the modulator unit. The beam transmitted through the second mode cleaner is introduced to the main interferometer using a mode-matching telescope. The beam power is maintained at 100 W at the input of the interferometer.

The main interferometer is a power-recycled Fabry–Perot Michelson interferometer with a broad-band RSE method [13]. Both the power recycling and the RSE are required to reduce the shot noise that limits the sensitivity at frequencies higher than 100 Hz. Another important reason for using the RSE is the reduction of heat production by optical absorption in the cooled sapphire mirror. The RSE makes it possible to achieve the same shot-noise level with less laser power in the mirror substrate. The 3 km arm length Fabry–Perot cavities have a finesse of 1250. The stored laser power is 400 kW. Both the signal and power recycling gains are 10. The band width of the cavity is 200 Hz.

The four main mirrors making up two 3 km length Fabry–Perot cavities are made of monolithic sapphire with a reflective coating on one side. The sapphire cylinder has a diameter of 300 mm and a thickness of 180 mm and its weight is 50 kg. All other mirrors and optics are made of fused silica.

The output optics consists of photodiodes for high-power detection and a small-ring mode cleaner (OMC). GW signal sidebands are transmitted through the mode cleaner and detected by the photodiodes, although the unwanted higher modes caused by the thermal lens effect are effectively rejected by the mode cleaner.

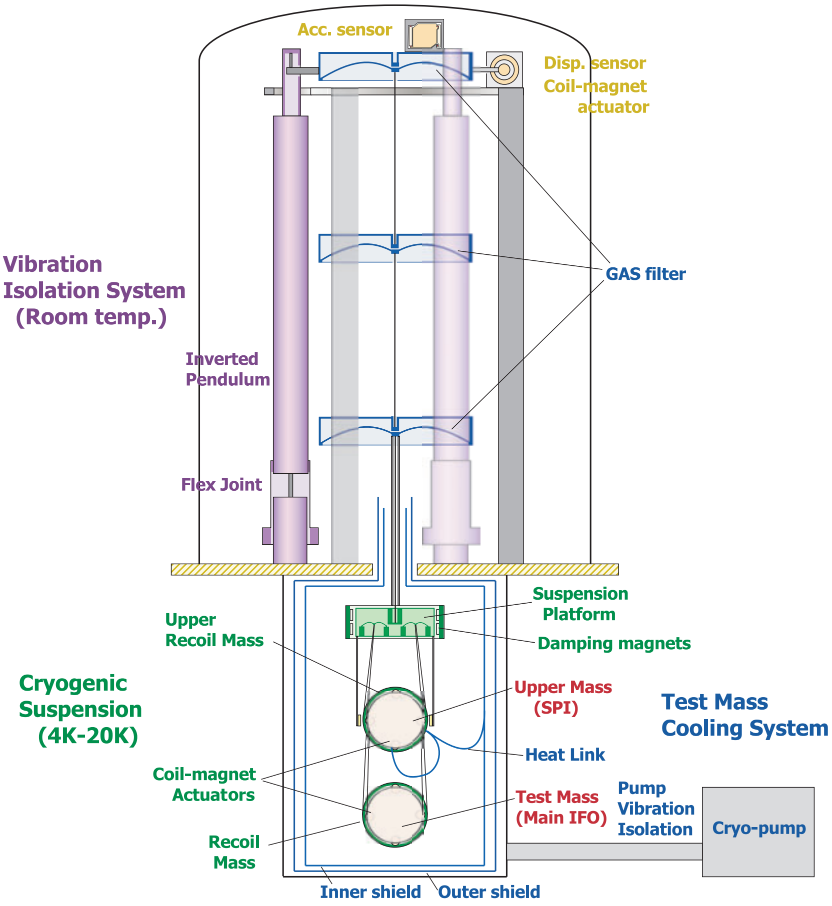

Figure 4. Schematic view of the mirror suspension and vibration-isolation system of LCGT. The suspension system has two temperature regions. The lower region is the cryogenic part, where the temperature is under 20 K, and the upper region for the vibration-isolation system, which is kept at room temperature. Both regions are in the same vacuum system.

3. Mirror suspension system

Figure 4 shows a schematic view of the mirror suspension of LCGT. The suspension system has two temperature regions. The lower region is a cryogenic part where the temperature is under 20 K and the upper region is kept at room temperature. Both regions are in the same vacuum system.

In the cryogenic region there are two mirrors: a lower main mirror and an upper mirror. The upper mirror is a part of a SPI [11] for vibration isolation. A suspension platform connects these cooled mirrors and the vibration-isolation system at room temperature. All items are installed in a cryostat that has two radiation shields. The temperatures of the inner and outer shields are about 8 K and 100 K, respectively. The main mirror is cooled to 20 K to reduce the thermal noise and is suspended from the upper mirror (14 K) by sapphire fibres. Heat caused by optical absorption in the main mirror is transferred to the upper mirror by the sapphire fibres, and then transferred to the inner shield by a heat link that is a thermal conductor made of high-purity aluminium wires. From the main mirror to the inner shield, heat of 1 W is transferred and finally absorbed by a refrigerator. The main mirror and the upper mirror are controlled by actuators with permanent magnets and coils, where the coils are attached to the recoil masses.

A low-frequency vibration-isolation system is installed in the room-temperature region. It has an inverted pendulum for horizontal vibration isolation and three stages of geometrical anti spring (GAS) for vertical vibration isolation. Typical resonant frequencies of the inverted pendulum and the GAS are 10 mHz and 200 mHz, respectively. The vibration-isolation system has a local control system. The suspension platform in the cryostat is suspended by low thermal-conductivity wires from the final stage of the GAS.

4. Reduction of seismic noise

The key features to reduce the seismic noise are the quietness of the Kamioka mine, the vibration-isolation system and SPI, as mentioned in the introduction. The target displacement by the seismic noise of each mirror is 1.5×10^{-18} m Hz$^{-1/2}$ at 3 Hz.

Kamioka mine is in Gifu prefecture and about 250 km north-west from Tokyo. The mine is 1 km underground from the top of a mountain. Seismic motion in the mine is 10^{-10} m Hz$^{-1/2}$ at 3 Hz. This is less by two orders than that at the TAMA site, which is in the campus of National Astronomical Observatory (NAO), west of Tokyo. This is the primary reason for choosing Kamioka mine.

LISM (laser interferometer small observatory in Kamioka Mine) [14] is the first underground-based interferometric GW detector with 20 m arm length. The LISM detector was first placed at the NAO campus in 1991, and then moved to the mine in 1999. Observations started in 2000, and the project was completed early in 2003. Many achievements have been realized, such as an enhancement of the sensitivity, especially in the low-frequency region, long-term stable operation, coincidental observations with TAMA [15].

Not only small seismic motion, but also stableness of the temperature and humidity are the merits of conducting experiments in the mine. In the case of LISM, the temperature and humidity in the experiment room were kept within 0.1 °C and 1%, respectively. These stabilities contributed to stable operation of the detector.

Even though the seismic motion in the mine is small, vibration isolation is necessary to satisfy the target sensitivity. The vibration-isolation ratio taken by the low-frequency vibration-isolation system is more than −160 dB at 3 Hz. The vibration-isolation system is an application of the seismic attenuation system (SAS) [16]. The SAS has been prepared for installation at TAMA.

SPI [11] is equipped for vibration isolation of the upper mirror. The main purpose of SPI is to reduce the vibration due to the heat link. The upper mirrors make a Fabry–Perot cavity of 3 km length. The cavity acts as a position sensor for position control of the upper mirror. SPI is effective from low frequency and the expected vibration-isolation ratio is −40 dB at 3 Hz. Study of SPI is being carried out at the University of Tokyo.

5. Thermal noise

The prime reason for using cryogenic mirrors is to reduce the thermal noise of the suspension and the mirror [17]. The amplitudes of the thermal noise depend on the dissipation and temperature of the suspension and the mirror. The suspension thermal noise is the pendulum motion excited by a fluctuation force due to the dissipation of the structure damping in the

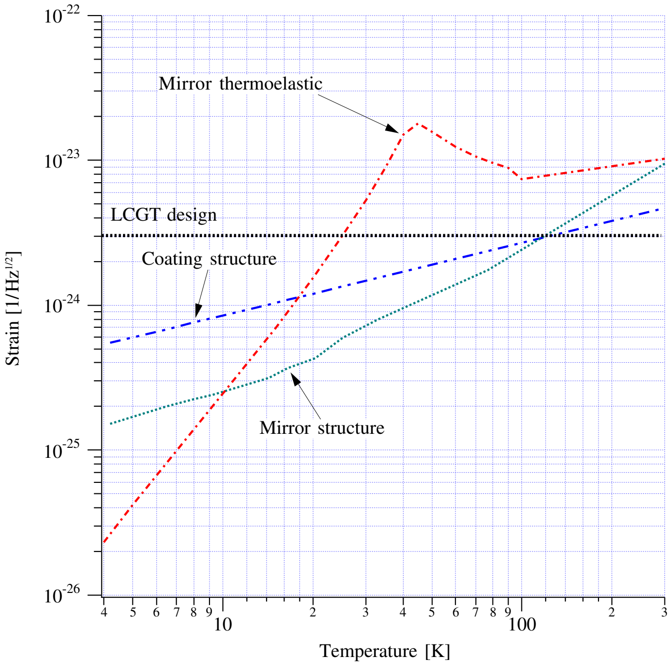

Figure 5. Temperature dependence of the mirror thermal noise at 100 Hz. Thermal noise caused by dissipations due to the structure damping and the thermoelastic damping in the substrate and the structure damping in the coating are shown. Under 20 K all contributions of the mirror thermal noise are lower than the design sensitivity of LCGT, 3×10^{-24} Hz$^{-1/2}$. From this figure, the target temperature of the mirror is decided to be 20 K.

sapphire fibres. According to our measurement [18], the expected dissipation of the pendulum motion is 10^{-8} at 14 K, which is the temperature at the clamping points of the fibre. In the mirror, there are three kinds of dissipation mechanisms: structure damping and thermoelastic damping in the substrate and structure damping in the coating. Our measurement showed that the dissipation of the structure damping of the substrate and the coating at 20 K is 10^{-8} [19] and 4×10^{-4} [20], respectively. The dissipation due to thermoelastic damping is estimated from the material properties [21]. Figure 5 shows the temperature dependence of the mirror thermal noise at 100 Hz, derived from our dissipation measurement and the theoretical formulae for the thermal noise. From figure 5, the target temperature of the mirror is 20 K.

6. Cryogenic

The mirror is always heated by optical absorption. In the case of LCGT, the heat in the front mirror is 400 mW. The optical absorption ratios of 360 ppm (20 ppm cm^{-1}) in the substrate and 0.1 ppm in the coating are assumed for an estimation. The mirror must be kept under 20 K in this condition. Figure 6 shows a schematic view of the cryogenic system for the end mirror of the main cavity. Figure 7 shows the heat-transfer path from the mirror to the refrigerator.

The cryogenic system consists of three parts: a cryostat, a 20 m cryogenic vacuum pipe and refrigerator units. The cryogenic laser interferometer in Kashiwa (CLIK) [14] is a prototype

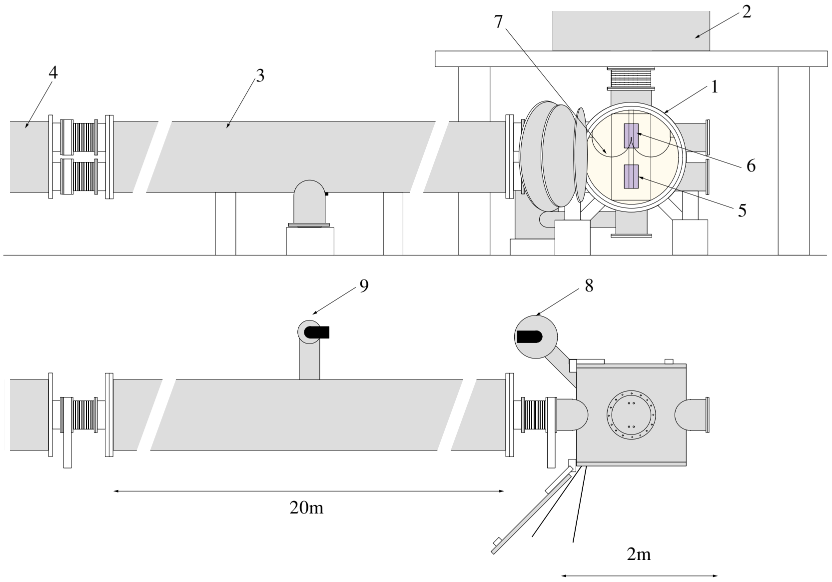

Figure 6. Schematic view of the cryogenic system for the end mirror of the main cavity. Top: a side view and bottom: a top view. (1) Cryostat (the inner shield is 8 K and the outer shield is 100 K). (2) Vacuum chamber (room temperature). (3) Cryogenic vacuum pipe (100 K). (4) Vacuum pipe (room temperature). (5) Sapphire mirror (20 K). (6) Upper mirror (mirror for the suspension point interferometer, 14 K). (7) Heat link. (8) Refrigerator unit for the cryostat (4 K, two-stage pulse-tube refrigerator). (9) Refrigerator unit for the cryogenic vacuum pipe (80 K, one-stage pulse-tube refrigerator).

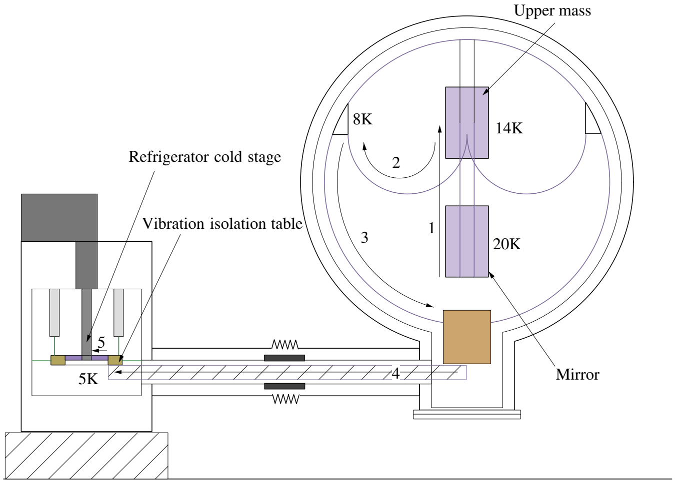

Figure 7. Schematic view of the heat flow from the cryogenic main mirror to the refrigerator. (1) Sapphire fibre suspension. Four sapphire fibres of 50 cm length and 1.8 mm diameter. (2) Heat link made of 30 high purity aluminium wires (made by Hitachi Cable, Ltd). The diameter of aluminium wire is 0.5 mm and the radius of the U-shape is 20 cm [29]. (3) The inner shield. (4) Thermal conductor between the inner shield and the refrigerator unit. (5) The refrigerator cold stage and a vibration-isolation table. The table is fixed to the shield in the refrigerator unit by G10 rods which have a very low thermal conductivity.

cryogenic system. It has two cryostats and a 7 m cryogenic vacuum pipe. These items are cooled by two refrigerators attached to each cryostat. We made a 7 m Fabry–Perot cavity with cooled sapphire mirror in this cryogenic system. The finesse of the cavity was 3000 at 20 K and the displacement noise was 4×10^{-16} m $\mathrm{Hz}^{-1/2}$ at around 100 Hz.

Vibration noise caused by the refrigerator was the most serious problem in this system. The refrigerator had two kinds of vibration noise [22]. One was the vibration of a cold stage of the refrigerator. It is a series of spike noises whose peaks were at the operation frequency of around 1 Hz and its harmonics. The other was acoustic noise, which had a broad-band shape around 100 Hz. To overcome these vibrations, we developed a vibration-isolation scheme for damping the spikes and a quiet refrigerator for the small acoustic noise. The target amplitude of the vibration in the cryostat is the seismic motion in the mine.

In order to avoid the vibration of a refrigerator cold stage, as shown in figure 7, there is a vibration-isolation table in the refrigerator unit. The table is fixed rigidly to the shield with low thermal conductivity. Bundles of high-purity aluminium wires connect between the table and a cold stage of the refrigerator with high thermal conductivity. Because the mechanical stiffness of the bundle is weak, the vibration noise of the cold stage is damped. Another thermal conductor connects the table and the inner shields in the cryostat or the cryogenic vacuum pipe.

A candidate for the quiet refrigerator is a pulse-tube refrigerator. Because the pulse-tube refrigerator does not have any mechanical piston in it, the vibration noise is expected to be much lower than other kinds of refrigerators. Actually, the pulse-tube refrigerator is much quieter around 100 Hz by two orders of amplitude than a Gifford–Macmahon refrigerator, which is used in the CLIK [22]. The pulse-tube refrigerator will be used for the cryogenic system of the CLIO (cryogenic laser interferometer observatory) project [23]. A 500 mW, 4 K, two-stage pulse-tube refrigerator for the cryostat and a 100 W, 80 K, one-stage pulse-tube refrigerator for the cryogenic vacuum pipe are planned to be used in CLIO.

There are two purposes of the cryogenic vacuum pipe. One is to reduce the radiation heat from the room-temperature wall into the mirror. The other is to avoid contamination of the mirror by molecules from the room-temperature vacuum duct [24, 25]. In the case of LCGT, the length of the cryogenic vacuum pipe is 20 m. Two pipes are connected to the cryostat for the front mirror, and one pipe is connected to the cryostat for the end mirror. Thus, six cryogenic pipes are equipped in a detector.

The mirror suspension is installed in the cryostat. The cryostat is a vacuum chamber with two layered radiation shields. The temperatures of the inner and the outer shield are 8 K and 100 K, respectively. These radiation shields are cooled by the refrigerator. The purposes of the shields are also to reduce the radiation heat from the outside and to prevent the mirror from contamination. Because the cooled shields act as panels of the cryo-pump, the vacuum pressure in the cryostat during cooling operation will satisfy the LCGT requirement of 2×10^{-7} Pa.

In order to maintain the mirror at 20 K, a thermal conductor is necessary to transfer the heat in the mirror to the inner shield. Not only thermal conduction, but also vibration noise must be taken into account for designing the thermal conductor. The thermal conductor is divided into two parts. One is from the mirror to the upper mirror, the final stage of the suspension. The other, the heat link, is from the upper mirror to the inner shield. Since heat of 400 mW in the mirror is estimated, we designed a thermal conductor that can transfer twice that much heat, almost 1 W, from the 20 K mirror to the 8 K inner shield.

The thermal noise of the final stage of the suspension is an important issue. Since both high thermal conductivity and low dissipation are necessary for the suspension wires for the cryogenic interferometric GW detector, a sapphire fibre was chosen for it [18, 26, 27]. Four

Table 1. Schedule of CLIO and LCGT.

	2004	2005	2006	2007	2008	2009
CLIO						
Vacuum	Install					
Optics		Install				
Observation		Start				
LCGT						
Tunnel			Construct			
Vacuum		Design	Construct		Install	
Optics			Design		Make	Install
Electric					Make	Install
Observation						Start

sapphire fibres, 1.8 mm diameter and 50 cm length, are adopted. The sapphire fibre is attached to the mirror by a bonding technique, which provides small thermal contact resistance [28]. In the case of LCGT, the temperature of the upper mirror is estimated to be 14 K. The dissipation of the pendulum is 10^{-8}.

Even though SPI is equipped, transferring the vibration of the inner shield to the upper mirror through the heat link is a problem, because the shield vibrates at the same amplitude as the seismic noise. Addressing the problem, the conductor must be mechanically weak for vibration isolation of the upper mirror. The present design of the heat link is high-purity aluminium wires curved like a ‘U’ shape. The mechanical stiffness of the U-shape wire is proportional to the quadrature of its diameter. On the other hand, the thermal conductivity is proportional to the square of the diameter of the wire. This means that a larger number of thinner wires are better for our requirement. In the current design, the heat link is 30 U-shape aluminium wires 0.5 mm in diameter; The radius of the U-shape is 20 cm. The thermal conductivity of the aluminium wire (made by Hitachi Cable Ltd) for the heat link is more than 2×10^4 W^{-1} m^{-1} K^{-1} at 10 K [29].

7. Current status

LCGT consists of many projects presently on-going. TAMA is the most active project in Japan, and has many important roles to play; for example, to study interferometer operation, a data supplier to study data analysis and to study the advanced vibration-isolation system, SAS. CLIO is also an interferometric detector project that has another important role. This role is to prove the feasibility of a cryogenic interferometric GW detector in Kamioka mine. The cryogenic and underground aspects are the most important features of LCGT. CLIO is a 100 m arm length locked Fabry–Perot interferometer. The CLIO project is already going, since 2002, and details of its present condition are given in some references [14, 24]. This is a four-year project, and thus will continue until the end of 2005. Studies of other important items such as a high-power laser system [12], the broad-band RSE method [13], SPI [11] and so on are also on-going.

8. Schedule, cost and manpower

We hope that the LCGT project will start its construction from 2005 and observations from 2009. Table 1 gives the schedules of CLIO and LCGT. Table 2 lists the estimated budget. We are now asking the Japanese government for construction money for LCGT according to

Table 2. Estimated budget list of LCGT (unbudgeted).

Item	Billion Japanese Yen	Million US $
Tunnel	3.4	28
Vacuum	12.1	100
Cryogenics	0.4	3.3
Optics	0.8	6.7
Suspension system	0.26	2.2
Laser source	0.4	3.3
Control system	0.1	0.8
Date acquisition	0.2	1.7
etc	0.34	2.8
Total	18	150

table 2. About 50 scientists and students have joined the LCGT project from 15 universities and institutes in Japan.

9. Summary

The LCGT project is aiming at the first direct detection of GWs for experimental evidence of general relativity and opening a new window for GW astronomy. Feasibility studies for techniques to realize LCGT are steadily progressing at TAMA, the forthcoming CLIO and many other projects. We have asked the Japanese government for construction money for LCGT to be started in 2005. We hope that observations will start from 2009.

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