Status of LCGT

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Abstract

LCGT shall be planned to be the first-generation detector with an advanced technique for employing a cryogenic mirror in order to firstly detect a gravitational wave, and after detection, the detector will serve as an astronomical tool to observe the Universe through gravitational wave radiation. In collaborative observation with the LIGO, GEO and Virgo projects, LCGT desires to contribute to the enterprise of detecting gravitational wave events by earlier funding. This paper summarizes the LCGT project.

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1. Introduction

LCGT was originally planned during the construction of TAMA [1] and at the same time of GEO [2] construction to firstly detect a gravitational wave from the coalescences of a double neutron star (DNS). In order to fulfill this objective by utilizing a similar baseline length (3 km) to that of the initial LIGO [3] and Virgo [4] detectors, LCGT will be equipped with a cryogenic mirror system to reduce thermal noise and be placed underground and using an advanced anti-vibration technique to suppress seismic noise at lower frequencies. Since the desired sensitivity is equivalent to those of advanced designs of the LIGO and Virgo projects, LCGT may be called a second-generation detector. However, except for the adoption of cryogenics, its optical design is conservative, and in future, there is room for sensitivity improvement by optimizing its optical configuration.

Among such projects as LIGO, GEO and Virgo, AIGO is also planned to be built in Western Australia [5]. Since at least three detectors are needed to determine the position of a gravitational wave source, both LCGT and AIGO are strongly expected to be realized in order to enhance the observation efficiency, which is expressed by a statement of the gravitational wave international committee (GWIC) [6]. This paper summarizes the scientific significance and world-wide importance of the LCGT project.

[1] A list of members of the LCGT Collaboration can be found at the end of this issue.

2. Gravitational wave sources and sensitivity

The objective of LCGT is to detect at least one gravitational wave event in one year. The coalescence of DNS is the most important source among others in the sense that its wave form is precisely predicted, and its existence has certainly been confirmed. Nine pairs of DNS are known to exist in our Galaxy and nearby galaxies. The wave form emitted at the time of coalescence should be analytically calculated along with the time evolution until just before the merging moment. Around the moment of its merger, the wave form needs to be numerically solved and its numerical solution is close at hand [7–9]. This signal wave form is used to build a matched filter that increases the signal-to-noise ratio. The coalescence rate is estimated by both the distribution of these DNSs and their lifetime, and for a milky-way equivalent galaxy [10],

$$83.0^{+209.1}_{-66.1}(\text{C.I.}95\%)[\text{events Myr}^{-1}].$$

Since the distribution of galaxies is estimated to be as 0.01 per Mpc^3, LCGT, which has sensitivity to detect a signal up to 250 Mpc[2] at its optimum configuration, is sufficient to detect $\approx$6.4 events in one year. This value is averaged through the whole sky, and also averaged with the directional angles of the orbital axis of the DNS system.

We can detect the coalescence signal of binary neutron stars ($1.4M_\odot + 1.4M_\odot$) up to 165 Mpc by the default design of a broadband-resonant-sideband-extraction (BRSE) scheme and 250 Mpc by a detuned-resonant-sideband-extraction (DRSE) design in the signal-to-noise ratio of ten assuming sources at the optimal direction.

The expected sources of LCGT including the above-mentioned coalescence of DNS are plotted in figure 1 for the BRSE scheme. The quasi-normal mode oscillation of the black hole is observed by its ring down just after the formation of a black hole. If stellar core collapses occur at the Galactic center, they can be well within the scope of the LCGT sensitivity for Dimmelmeier's wave forms (figure 1) [11].

LCGT can detect continuous waves from pulsars by appropriate signal integration, compensating the Doppler effect by the Earth orbital motion around the Sun. Figure 2 estimates such possible candidates for integration times of 2 weeks, 1 year and 10 years, respectively, based on the default BRSE sensitivity.

3. Design of LCGT

The ultimate sensitivity of the planned laser interferometer is determined by seismic noise at low frequencies (10–30 Hz), and by photon shot noise at higher frequencies (more than 300 Hz). The sensitivity of the middle frequencies (30–300 Hz) is limited by the photon recoil force noise. A reduction of thermal noise is attained by cooling both the mirror and the suspension system that suspends the mirror.

The optical configuration is a power-recycled Fabry–Perot–Michelson interferometer with the resonant-sideband-extraction (RSE) scheme (figure 3) [12]. We adopt sapphire for the mirror substrate. Sapphire has a relatively large optical loss inside the substrate. Since high optical power is needed in the cavity, we can increase the cavity finesse by keeping a low power incidence through the input test mass. This results in the optical design of a large finesse of 1550 with a low power recycling gain of 11. Since a high cavity finesse reduces the frequency band width, we apply the RSE scheme in order to resonantly extract the gravitational wave signal, which equivalently expands the frequency bandwidth.

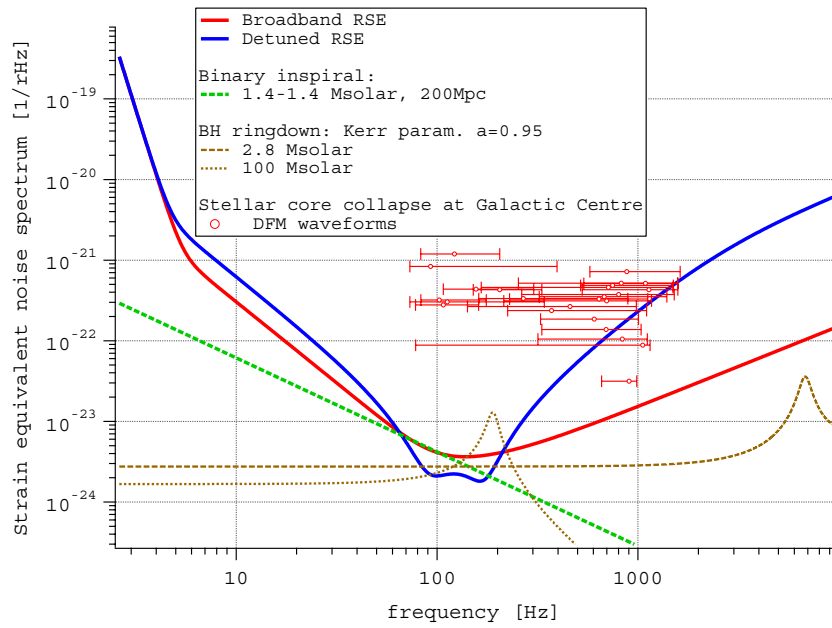[2] So-called horizon distance.

Figure 1. Expected gravitational wave sources of LCGT in the default design. The main source is the coalescence of a binary neutron star.
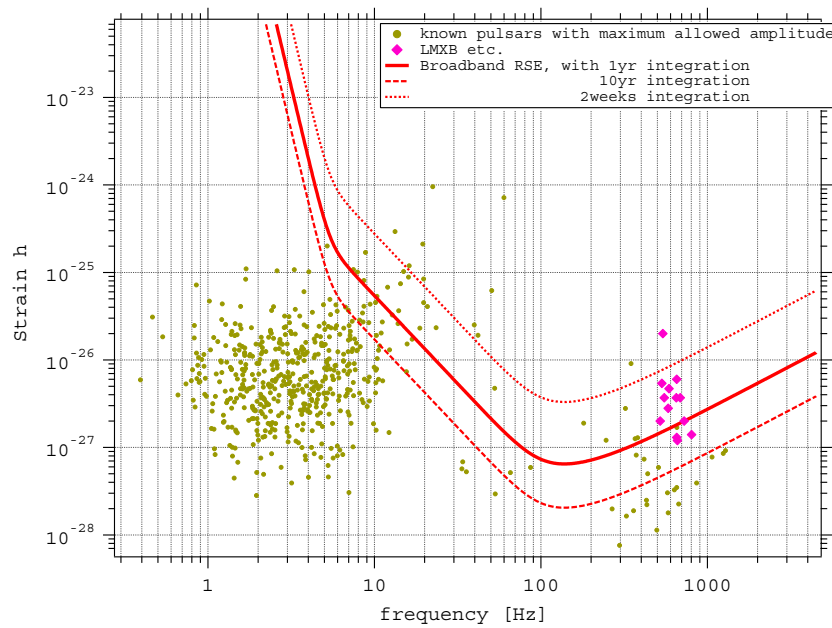

Figure 2. Expected continuous wave sources of a pulsar according to the default design. The circular dots represent the known pulsars with maximum allowed amplitudes, and the diamond symbol represents the possible waves from low mass x-ray binaries.
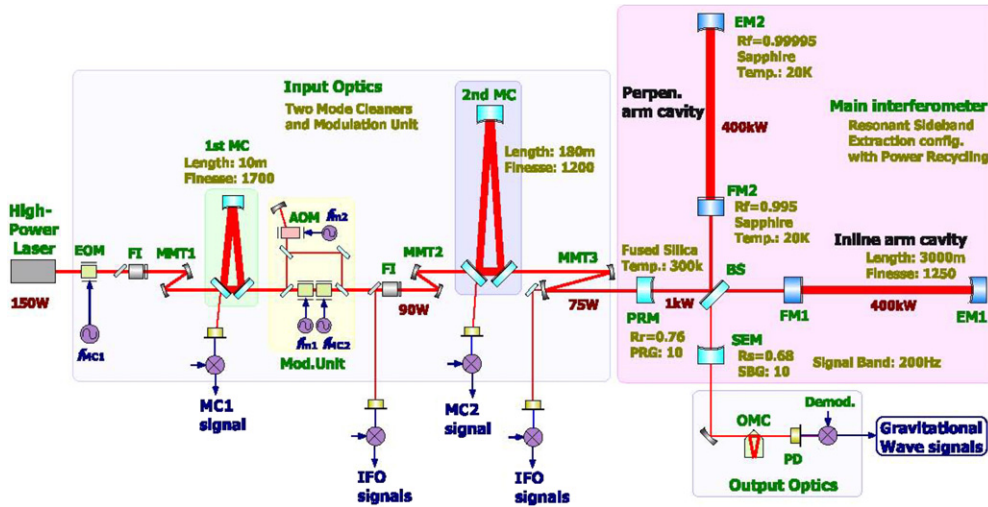
Figure 3. Optical design of LCGT, consisting of a power-recycled Fabry–Perot–Michelson interferometer with a broadband resonant-sideband-extraction scheme, leaving room for further optimization in the future.

3.1. Tunnel construction

The site is located in Gifu prefecture, at an elevation of 400 m in the heart of a high and massive mountain range, approximately 60 km inland from the Sea of Japan. The mountain consists of rocks of amphibolites and gneiss. The mining company (Kamioka Mining Co. Ltd) maintains the infrastructure facility, but mining activity is presently ceased. The cross area of the tunnel is 4.5 m in width times 4 m in height. The arm tunnels of the interferometer are placed well below the slope of the mountain by more than 200 m to maintain an environment of low seismic noise.

3.2. Vacuum system

A vacuum system is placed in the tunnel. The main tube has a 1 m inner diameter and is made of SUS304 (stainless steel). The cryostat housing the main mirror has radiation tubes extending in both directions (roughly 10 m in length), which are installed with infrared optical baffles [13]. We produce 600 tubes of this unit in 12 m length that has a flange on one side and a flange with short bellows on the other side. These tubes are introduced inside the tunnel and connected one by one. Since baking the tube underground is not an easy task, due to limited space and a closed air environment, we apply an electro-chemical buffing (ECB) technique that was applied to the vacuum system of TAMA to eliminate the baking procedure *in situ* [14]. In addition to the ECB technique, each tube product is baked in vacuum prior to transportation to the tunnel in order to assure the gas releasing rate of the tube inside being maintained so as to satisfy the specification.

3.3. Anti-vibration system

The design of the suspension system is at the heart of this cryogenic system, and was published using the figure on the left-hand side of figure 4 [15]. The main mirror is suspended through
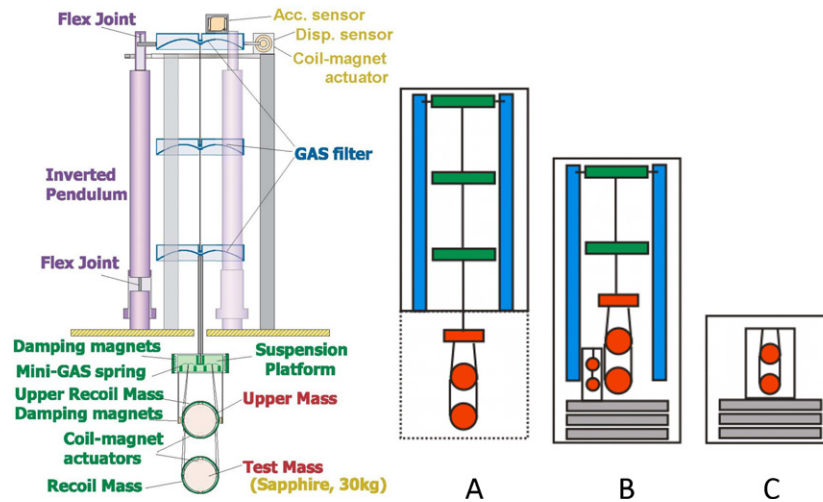
Figure 4. Design of the suspension system is at the heart of this cryogenic system. The main mirror is suspended through an auxiliary mirror of the suspension point interferometer (SPI). The SPI mirror is also suspended by a wire through a radiation shield hole, which is connected to the last stage of the GAS filter system, which is supported by the inverted pendulum system. Three types of anti-vibration systems are used.

an auxiliary mirror of the suspension point interferometer (SPI). The design of heat transfer is crucial when designing the suspension system [16].

We designed three types of anti-vibration systems, as shown in figure 4 as A, B and C. Type A is a SAS (seismic attenuation system), which was originally developed in the Virgo project, and was modified for TAMA under research collaboration with Caltech. The SAS consists of an inverted pendulum and three stages of the GAS (geometric anti-spring) filter. Type A is applied for four main test masses. The mirrors of the beam splitter, power recycling, signal extraction and second mode cleaner are suspended by the type B system, which consists of a SAS of two stages of a GAS filter with an inverted pendulum at room temperature. The most simple system, C, consisting of two stages of suspension on the stack isolation system, is applied to the photo detectors and mirrors of both the first-stage mode cleaner and a matching telescope. The performance of the SAS was tested by the TAMA interferometer. The other anti-vibration systems are conventional, and can be applied to LCGT without any trouble.

4. R&D

The R&D of LCGT consists of independent scientific projects, such as TAMA and CLIO. Apart from these projects, several research items are conducted by individual research groups. A 100 W, single-frequency operation was achieved by an injection-locked Nd:YAG laser [17] and a signal-extraction scheme for RSE was developed [18]. Also an automatic measuring device comprising a high-quality large sapphire piece was developed [19].

4.1. TAMA

TAMA is a 300 m baseline interferometric gravitational wave detector built at the Mitaka campus of the National Astronomical Observatory of Japan (NAOJ); nine observation runs were conducted by 2004. After observation runs, a SAS was installed for four main mirrors to
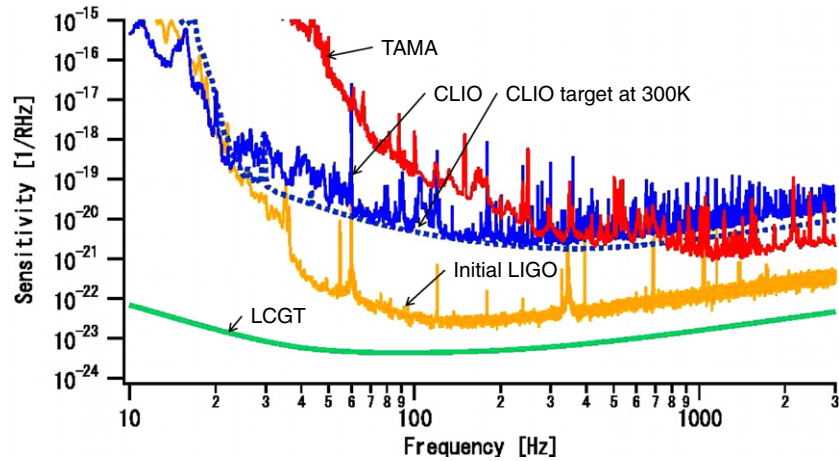
Figure 5. LCGT sensitivity compared with those of CLIO (October 2008, room temperature), CLIO (target, room temperature), TAMA and LIGO (Science run 5). The horizontal axis is frequency (Hz) and the vertical axis represents the sensitivity spectrum for gravitational waves ($\sqrt{\text{Hz}}^{-1}$). Notwithstanding the short baseline length of CLIO, sensitivity comparable to that of LIGO at low frequencies clearly shows the merit of the underground location.

reduce the relatively large seismic noise disturbance [20]. The sensitivity at low frequencies was found to be limited by the so-called up-conversion noise possibly arising from the suspension and actuation system, and could not be further improved without a drastic change in the suspension system by utilizing a more sophisticated actuator.

4.2. CLIO

After conducting several basic experiments on the cryogenic mirror system [21], we constructed a 100 m baseline length cryogenic interferometer (CLIO) placed underground at Kamioka. The objective of this project is to practically present the feasibility of the cryogenic mirror system for LCGT [22]. The cryogenic mirror system possibly reduces the thermal noise of the mirror and suspension system for frequencies of 30–300 Hz, with the reduction in the temperature. This is correct only if the mechanical loss of the system does not decrease with temperature reduction. That is, the power spectrum of the thermal noise is proportional to T/Q, where T is the temperature and Q^{-1} represents the mechanical loss of the system. Since the mechanical loss of fused silica at low temperatures increases, silica material cannot be used in the cryogenic mirror system. In place of silica, we adopt sapphire material for the mirror substrate and fibers that suspend the mirror. Since we cannot obtain a low-optical-loss sapphire substrate, we keep a low power recycling gain under the condition of a relatively high finesse of the arm cavity. Although the thermal noise of the mirror coating is non-negligible for a room-temperature interferometer, it has no harmful effect on the cryogenic one [23]. Thermally noise-limited sensitivity at room temperature was achieved [24], and cryogenic sensitivity is being pursued by adding minor technical changes.

4.3. Sensitivity improvement

Figure 5 compares the sensitivity curve of LCGT with those of TAMA, CLIO, and LIGO (initial LIGO). The sensitivity of LCGT at low frequencies is attained by the SAS with the
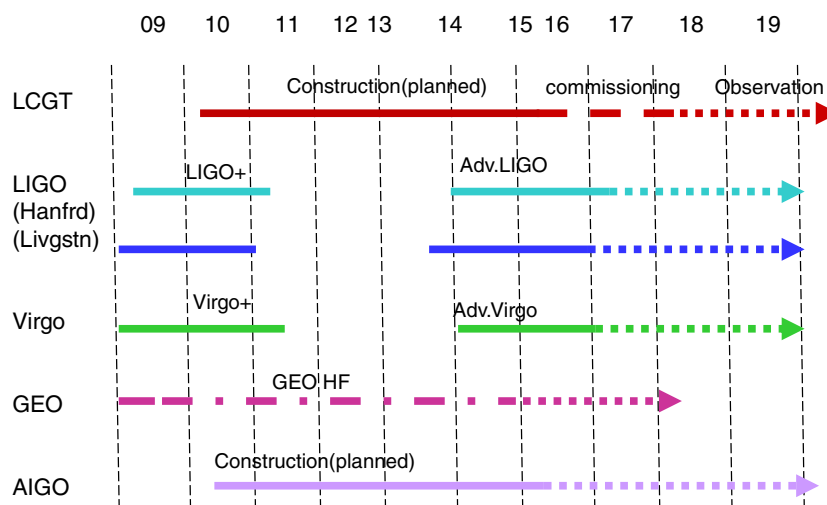
Figure 6. Budget request starting with construction in April 2010 submitted to the Ministry of Education, Sports, Culture, Science and Technology. We aim to finish construction in 5 years and begin observation after 2 years of commissioning.

underground installation, and that at higher frequencies is attained by a higher laser power. The mid-frequency region is improved by using a cryogenic mirror and suspension system. The improvement of two orders of magnitude at low frequencies, is adventurous, but not impossible.

5. Schedule, manpower organization, project support and international collaboration

The schedule planed for LCGT is illustrated along with that for other projects in figure 6, which shows that LCGT is to be constructed in 5 years, and will start observations after 2 years of commissioning. We submitted a budget request to the University of Tokyo for starting construction in 2010, and it was passed to the Ministry of Education, Sports, Culture, Science and Technology (MEXT) in June 2009[3].

LCGT collaboration consists of 80 domestic researchers belonging to 21 universities or research institutes and 32 overseas members belonging to 18 organizations. The total members were 112 researchers in the summer of 2009. The task of the domestic collaboration member was roughly determined, and that of overseas members will be discussed after knowing the results of submitting our request from the government to the diet, which usually happens in December. GWIC, under PaNAGIC (one of subcommittees of IUPAP), made a statement supporting earlier funding of LCGT in 2008. In 2009, the combined subcommittee (IAU, Astronomy & Astrophysics) of the Science Council of Japan made a resolution to endorse LCGT.

In order to determine the source position by a single detector, we need to collaborate with other observatories that are placed relative to each other far away on a global scale with similar sensitivity. With the advanced LIGO and possible advanced Virgo, LCGT may contribute to

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[3] However, this request was not passed to the Ministry of Finance, which does not mean the denial of the project. We only lost the chance of funding for FY 2010.

achieving an extremely high observation duty cycle for whole-sky coverage [25]. Also, if we can add AIGO to this network, the efficiency of observations could expand more.

6. Conclusion

Interferometer techniques (power recycling, Fabry–Perot–Michelson interferometer, and control system) were acquired by the TAMA project; also, the feasibility of the cryogenic mirror is under an evaluation process by CLIO. If LCGT is funded soon, we should be able to reliably detect a GW for the first time, or at least an early time in collaboration with other world-wide observatories, such as Adv. LIGO, Adv. Virgo, GEO HF and AIGO. We are now at the corner where long time-consuming R&D should produce a successful outcome of detecting gravitational waves.

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