Large-scale Cryogenic Gravitational wave Telescope: KAGRA

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Large-scale Cryogenic Gravitational wave Telescope (KAGRA) is a second generation gravitational wave (GW) detector under construction in Japan. KAGRA will have sensitivity of 280 Mpc at the best detector orientation for the GW signal from neutron star binary coalescence, and about 10 events observation is expected every year. This high sensitivity is limited by quantum noises. To realize the quantum noise limited sensitivity, KAGRA uses cryogenic sapphire mirror suspension system and underground site. Cryogenic sapphire mirror and its suspension improves their thermal noises drastically by double effects of low temperature and high mechanical Q of sapphire. This is an original technology and a best feature in KAGRA . It is well known that underground in Kamioka has very small seismic vibration level and has advantage for seismic noise reduction at low frequency range. Seismic vibration of $3 \times 10^{-9}\,\mathrm{m} \cdot \mathrm{Hz}^{-1/2}$ at 1 Hz is confirmed in KAGRA tunnel. Tunnel excavation of KAGRA was completed on Mar. 2014, and installation of major devices such like cryostats and vacuum tubes were done until Mar. 2015. Basic operation test of interferometer and data acquisition are planed in the end of 2015, and its preparation is under progress. This paper reports KAGRA and its status.

1 Introduction

Gravitational wave (GW) is one of the remaining pieces to complete verification of general relativity, and it will be a new tool to explore the universe. Strong evidence for the existence of GW was provided by R. A. Hulse and J. H. Taylor Jr. by long term observation of a binary pulsar system [1]. The BICEP2 experiment, which is a millimeter-wave telescope to search B-mode polarization of cosmic microwave background, claimed the detection of primordial gravitational wave [2], however there are also arguments that the result can be contaminated by foreground radiation [3].

There is a network of large scale ground based laser interferometers around the world for the direct detection of GW signals. The major sources for GW, which can be detected by ground-base laser interferometer, are compact astronomical objects such like black holes and binary neutron stars. These sources can radiate GW at the frequency range between several dozens Hz and kHz. First serious searches of GWs by interferometric detectors like LIGO [4], VIRGO [5], GEO600 [6] and TAMA300 [7], were done in 2000's. Unfortunately, no detection of GWs are reported yet by these first generation GW detectors despite LIGO reached really high sensitivity of $2 \times 10^{-23}\,\mathrm{Hz}^{-1/2}$.

In the year 2010, construction of the second generation of GW detectors began. Advance LIGO (aLIGO) [8] and advanced VIRGO (aVIRGO) [9] are being upgraded from the first gen-

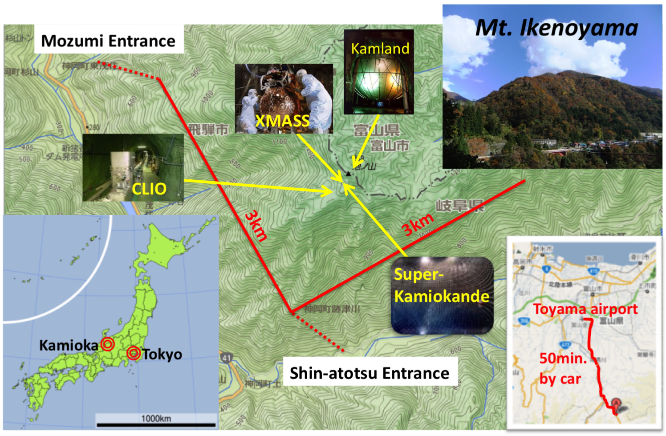

Figure 1 – KAGRA location and layout in Mt. Ikenoyama in Kamioka.

eration LIGO and VIRGO detectors, respectively. GEO-HF [10] is a modified detector from GEO600, which aims to search for high frequency GW signals. Large-scale Cryogenic Gravitational wave Telescope, which is also named as KAGRA, is a new detector under construction in Japan. These detectors will have almost same sensitivity of the order of $10^{-24}\,\mathrm{Hz}^{-1/2}$, and can detect GW signals from neutron-star binary coalescence at $200-300\,\mathrm{Mpc}$ distance. The GW observation network by aLIGO, aVIRGO and KAGRA realizes 100 % sky coverage with half maximum sensitivity and 82 % duty factor. All of these second generation GW detectors will start observation until 2018.

In this paper, KAGRA project and its status are reported.

2 KAGRA project

KAGRA was funded in 2010, and the construction started soon after. Unlike aLIGO or aVIRGO detector, KAGRA is not an upgrade of other Japanese detectors like TAMA300 or CLIO [11]. As an international project, the design and concept of KAGRA is unique as compared to other detectors around the world. The leading institution of KAGRA project is Institute for Cosmic Ray Research (ICRR), University of Tokyo, and co-leading institutions are High Energy Accelerator Research Organization (KEK) and National Astronomical Observatory of Japan (NAOJ). At present, 80 international institutions push forward KAGRA project.

The KAGRA detector is located 200 m underground in Mt. Ikenoyama in Kamioka, Gifu prefecture, japan. The site is about 250 km away from Tokyo and is 50 mins drive from Toyama airport. Figure 1 shows map and layout of KAGRA. The reason for the detector to be located underground in Mt. Ikenoyama is to reduce seismic vibrations. This underground site is an unique feature in KAGRA.

Another unique feature is the use of cryogenic mirror and suspension system to reduce their thermal noises. This technology has been developed in Japan for 20 years, and can be also applied to future third generation GW detectors.

Fundamental design of KAGRA including these special features are described in following subsections.

2.1 Sensitivity and Science

Figure 2 shows design sensitivity of KAGRA. KAGRA will have two operation modes of interferometer; detuned mode (thick black solid-line) and broadband mode (thick black dashed-line). Unless aiming to observe particular GW sources, broadband mode is fine to search GW signals since its observation band is wider than that in detuned mode. Observation band is between several dozens Hz and kHz. The best sensitivity will be $factor \times 10^{-24}\,\mathrm{Hz}^{-1/2}$ at 100 Hz. This

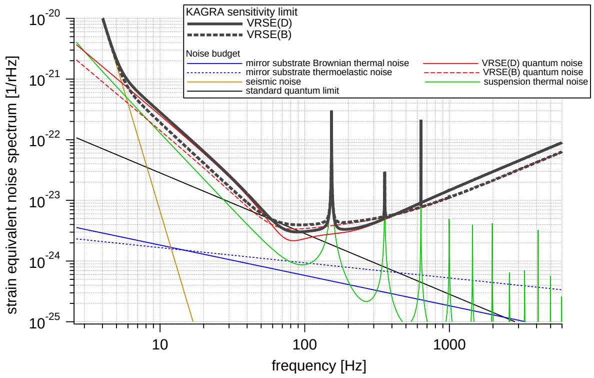

Figure 2 – Design Sensitivities of KAGRA. The thick black solid-line and the thick black dashed-line show the total sensitivities in detuned and broadband mode in interferometer, respectively. Green and blue lines show designed levels of thermal noises, and thin black line shows standard quantum limit.

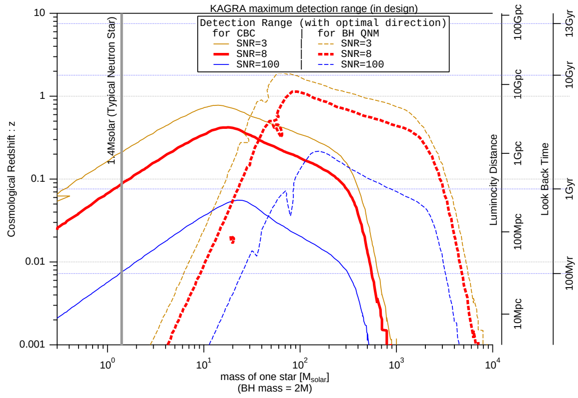

Figure 3 – Detectable range of GW signals from Neutron star binary coalescence (solid lines) and quasi-normal mode of black hole (dashed lines)[13].

sensitivity is limited by quantum noises, that is, radiation pressure noise and photon shot noise. This quantum noise limited condition is realized by suppressing thermal noises of mirror and suspension, which are colored lines in Fig. 2, except for orange line of seismic noise. These noises are well defined in the reference by P. R. Saulson [12]. The suppression of thermal noises are achieved by using semi-monolithic sapphire mirror and suspension cooled to 20 K. Sharp peaks at 130 Hz and at 230 Hz are vertical mode and first violin mode of suspension thermal noise, respectively. These peaks arise from the use of thick sapphire fibers of 1.6 mm in diameter to cool the mirror against heat generation in mirror by laser power absorption. To remove the vertical mode of suspension thermal noise at 130 Hz from the observation band, introduction of vertical springs made of sapphire (14 Hz) in cryogenic payload is planed (see Fig. 6).

KAGRA can detect GW signals from neutron star binary coalescence at 280 Mpc distance in the best detector orientation and from 173 Mpc in whole sky average with signal to noise ratio of 8. Estimated event rate within this distance is about 10 per year. For quasi-normal mode of black hole, generated just after merger of neutron star binary, GW signals from about 1 Gpc are detectable. Figure 3 shows detectable range of GW signals from Neutron star binary coalescence (solid lines) and quasi-normal mode of black hole (dashed lines) [13].

2.2 Interferometer design

Figure 4 shows interferometer design. Dual recycled Fabry-Perot Michelson interferometer with input and output mode cleaners is used. Designed finesse of arm cavity is 1550, and power recycling gain and signal recycling gain are 11 and 15, respectively. One can switch both detuned and broadband mode by changing signal recycling mirror position. In detuned mode, detuning angle of 3.5° is used.

Table 1 lists interferometer and core-optics parameters. Details of the interferometer configuration and parameters are described in references by K. Somiya[14] and Y. Aso[15].

2.3 Underground Site

One of the reason why Mt. Ikenoyama in Kamioka was chosen as KAGRA site is its very small seismic motion. There is also no surface vibration component in KAGRA tunnel since the site is deeper than 200 m from ground surface. Typical seismic vibration level in Mt. Ikenoyama is order of $10^{-9}\,\mathrm{m}\cdot\mathrm{Hz}^{-1/2}$ at 1 Hz, which are one or two orders of magnitude smaller than that at other GW sites. This is the principle advantage of KAGRA site, especially to observe GW signals at dozens Hz range.

Table 1: List of interferometer and core-optics parameters[14,15]. ITM: Input Test Mass, ETM: End Test Mass

Interferometer	
Arm Length	3000 m
Mode cleaner length	26.639 m
Power recycling cavity length	66.591
Signal recycling cavity length	66.591
Michelson asymmetry	3.30 m
Modulation Frequency	$f1$: 16.880962 MHz
	$f2$: 45.015898 MHz
	$f3$: 56.269873 MHz
Arm finesse	1550
Power recycling gain	11
Signal recycling gain	15
Laser wavelength	1064 nm
Laser Power (Input into interferometer)	180 W (80 W)
Laser power input into interferometer	80 W
Storage power in arm cavity	825 W
Mode cleaner finesse	500
Homodyne angle	132°
Detuning angle	3.5°
Test Mass	
Size	D220 mm × L150 mm
Weight	22 kg
Temperature	20 K
Radius of curvature	1900 m
Transmission at 1064 nm	0.004 at ITM, 5 - 10 ppm at ETM
Optical loss at reflective surface	< 45 ppm
Absorption in substrate	20 - 50 ppm
Absorption in coating	0.5 -1.0 ppm
Beam Splitter	
Size	D370 mm × L80 mm
Radius of curvature	Flat
Transmission at 1064 nm	50 %
Optical loss at reflective surface	100 ppm
Power Recycling Mirror	
Size	D370 mm × L80 mm
Radius of curvature	458.1285 m
Transmission at 1064 nm	0.1 %
Optical loss at reflective surface	< 45 ppm
Signal Recycling Mirror	
Radius of curvature	458.1285 m
Transmission at 1064 nm	0.1536 %
Optical loss at reflective surface	< 45 ppm

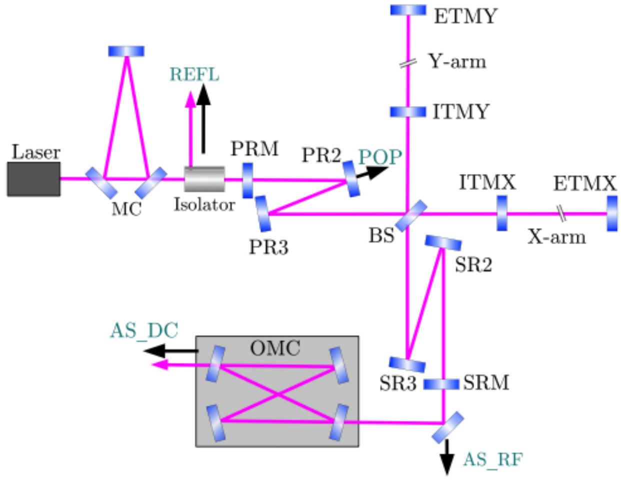

Figure 4 – KAGRA interferometer design. This is dual recycled Fabry-Perot Michelson interferometer configuration with input and output mode cleaners [15].

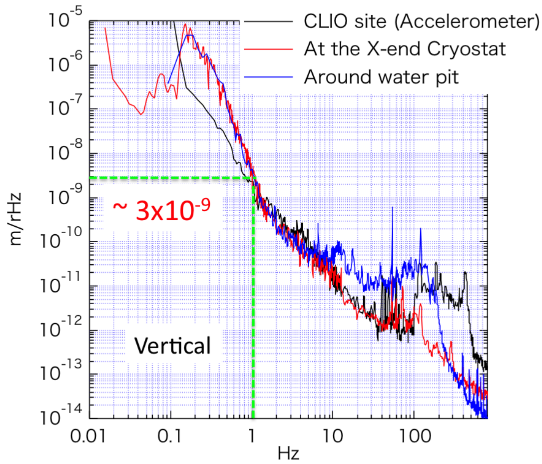

Figure 5 – Measurement result of vertical seismic vibration around main-mirror cryostat in X-end room (red line). Blue line shows vertical seismic vibration level in front of water pit. Both data were measured by a seismometer, Guralp CMG-3T, which has no sensitivity over 200 Hz. Black line shows vertical seismic vibration measured in CLIO site, where is in same Mt. Ikenoyama, by laser accelerometer, which has no sensitivity below 0.1 Hz.

However, one encounters unexpected amount of underground water in KAGRA tunnel. To drain underground water, KAGRA tunnel has 1/300 slant. There is much water flow in side pits in tunnel. This water flow can affect seismic vibration, therefore the seismic vibration in KAGRA tunnel was measured after tunnel excavation.

Figure 5 shows measured result of vertical seismic vibration at the main mirror-cryostat location in the X-end. The seismic vibration level is $3 \times 10^{-9}\,\mathrm{m} \cdot \mathrm{Hz}^{-1/2}$, which is same level as CLIO site, where is in the same Mt. Ikenoyama. Although we observed large excess over 10 Hz range in front of water pit, we found that there is no affect at cryostat location, where is about 10 m distance from the water pit. And we also found existence of large micro-seismic peak at around 0.2 Hz. It is pointed out that the micro-seismic peak in Mt. Ikenoyama had seasonal variation and this can be almost largest value since the measurement was done in January and the Sea of Japan, where is only 30 km from Mt. Ikenoyama, was rough in winter season. So investigation of seismic vibration at the X-end in long term is under progress.

Very stable temperature in underground should be also mentioned. Only 0.1 degree Celsius temperature variation for a week was observed in Kamioka underground. This is a large advantage for stable interferometer operation.

2.4 Cryogenic Mirror and Suspension

Cryogenic sapphire mirror and suspension are one of the most advanced technology in KAGRA. The power of thermal noise is proportional to temperature and inversely proportional to mechanical Q. So cryogenic mirror and suspension is most straightforward method to reduce thermal noises. Moreover, it is well known that mechanical Q of sapphire increases at cryogenic temperature, which values are 1×10^8 for bulk and 1×10^7 for fiber below 20 K [16,17]. However, it is also known that mechanical Q of reflective and anti-reflective coatings are small of $10^3 - 10^4$, and it is large issue to suppress the mirror thermal noise. Fortunately, our cryogenic mirror can overcome this issue by cooling down mirror at 20 K.

A practical issue is how we make real semi-monolithic sapphire suspension system like Fig. 6. Sapphire ears are contacted to the side of sapphire mirror substrate by Hydro-Catalysis Bonding

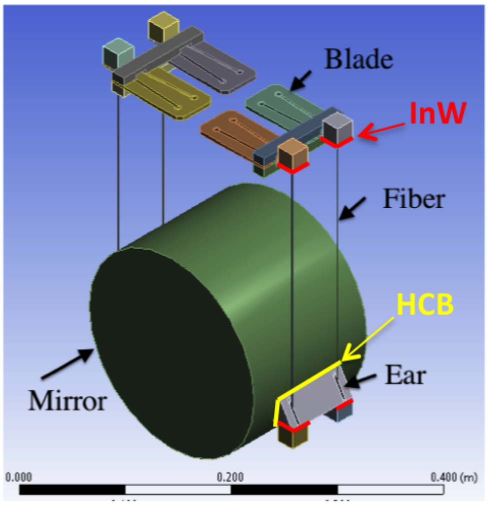

Figure 6 – Sapphire suspension system. HCB: hydro-catalysis bonding. InW: indium welding. HCB is used to contact between two ears and mirror substrate. And InW is used as replaceable contact among blocks at both end of fibers, blades and ears.

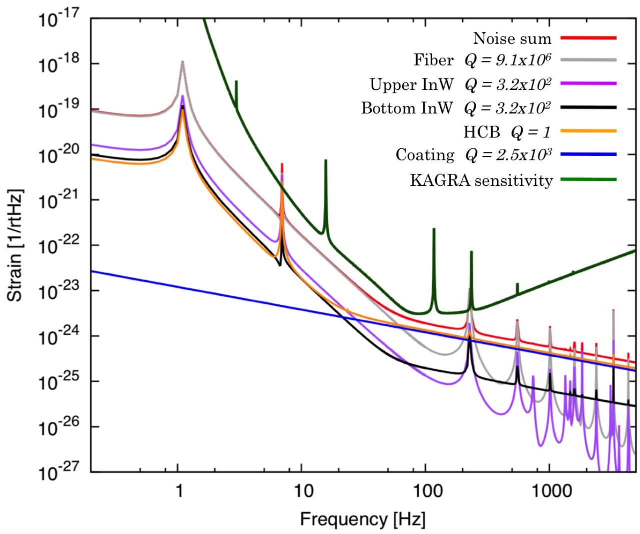

Figure 7 – Estimated thermal noise components with sapphire contacts and coating. Mechanical Q of 1.0 for HCB, 320 for indium welding, 2500 for coating and 9.1×10^6 for fiber are assumed here[20].

(HCB). HCB realizes very thin bonding layer of about 60 nm in spite of large strength, which is sufficient to suspend sapphire mirror of 23 kg. This thin bonding layer gives small contribution to thermal noise even for small mechanical Q, where we assumed Q of 1.0 in a worst case, although Q of 10^4 at cryogenic temperature is reported recently[18]. But fragile sapphire suspension fibers must be replaced easily when they have trouble. In this reason, we developed indium welding (InW) between sapphire blocks at the both ends of fiber and sapphire ears, and between sapphire blocks and sapphire blades[19]. The mechanical Q of the indium welding is 320 at 20 K from our measurement[20,21]. Figure 7 shows estimated thermal noise contributions to KAGRA sensitivity. Even including small mechanical Q of sapphire contacts and coating, estimated thermal noises are lower than KAGRA sensitivity[20].

Figure 8 shows mechanical design of cryogenic payload for sapphire mirror. This cryogenic payload consists of semi-monolithic sapphire suspension, recoil mass, intermediate mass with sapphire vertical blade springs, control stage named Marionette, Marionette recoil mass (not shown) and Geometric Anti-Spring (GAS) filter (not shown). The reason why the Marionette is introduced is to be simple around intermediate mass to keep high Q condition.

The cryogenic payload is suspended by low frequency vibration isolation system (VIS) at room temperature shown in Fig. 9. Steep reduction of seismic noise is achieved by using 14 m long VIS. And this VIS don't need support tower since vertical tunnel is excavated, therefore it is possible to remove structural resonance due to support tower.

An large issue is that heat links for cooling must be connected between cryocoolers and the cryogenic payload. The heat links will be made of the bundle of thin wires of 99.9999 % purity aluminium, which is very soft and very large thermal conductivity material. And ultra-small vibration cryocooler systems developed in CLIO experiment are also used to reduce vibration conduction through heat links[22]. However, we estimate excess of seismic noise at cryogenic payload by vibration conduction through the heat links. Therefore, we plan to introduce an additional vibration attenuator for heat links[20].

Fundamental technologies for cryogenic mirror to reduce thermal noise has been demonstrated in CLIO experiment. It was confirmed that thermal noise of mirror at room temperature around 200 Hz decreased after cooling down to 17 K[11].

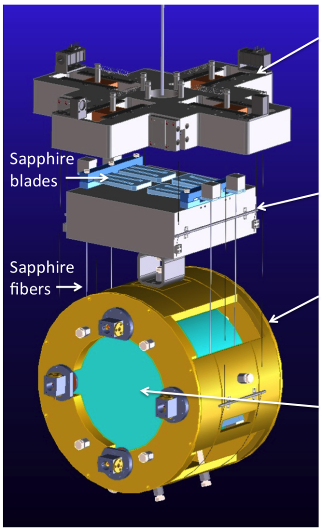

Figure 8 – Mechanical design of cryogenic payload

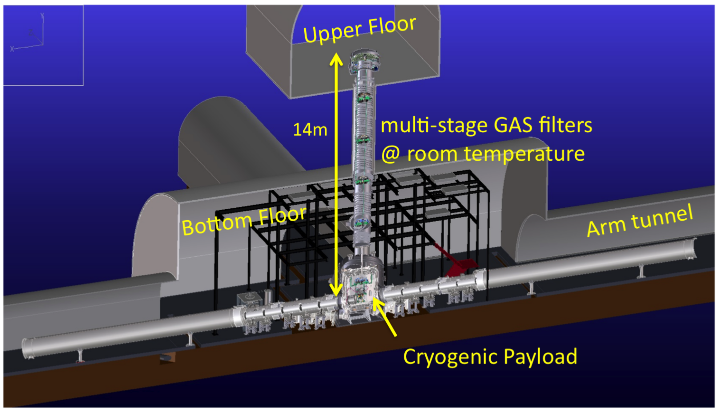

Figure 9 – Vibration isolation system with cryogenic payload.

3 Present Status

KAGRA tunnel excavation was done at March 2014. The total length of the tunnel is about 7 km. The first installed device into the tunnel was a main-mirror cryostat to the Y-end room. The size of the cryostat is about 4.3 m in height and 2.6 m in diameter without flanges. This is comparable size with arm tunnel, and it had to be installed in first. The cryostat was transported along 3 km tunnel by using a special cart. We spent about 12 hours for first cryostat installation. Now all of cryostats have been installed and assembled. After cryostat installation to both end rooms, vacuum tubes of 478 in total were installed into arm tunnels. This work was completed at March 2015.

A big issue is much water leakage in tunnel. Maximum water leakage in tunnel was about 1200 ton/hour in this early spring. Vertical drainage holes are constructed and water leakage issue has gradually improved.

Other devices such as input optics, mode cleaners, clean booths, control electronics and data servers are also being installed rapidly.

4 Conclusion

KAGRA is an unique second generation GW detector with advanced features of cryogenic mirror system and is located underground. The construction of the detector has rapidly progressed and is as per schedule. Early operation test of interferometer with very simple condition at room temperature, named iKAGRA, is planed at the end of 2015. Construction of baseline KAGRA with advanced systems will be done at the end of 2017 and the observation is start thereafter.

Acknowledgments

The KAGRA project is funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan under Leading-edge Research Infrastructure Program, and by the Japan Society for the Promotion of Science (JSPS) under Grant-in Aid for Specially Promoted Research. This work is also supported by JSPS Core-to-Core Program, A. Advanced Research Networks, and by the joint research program of the Institute for Cosmic Ray Research, University of Tokyo. Collaborative support for some fundamental studies in KAGRA are given by European groups on the basis of ELiTES program.

Figure 10 – Installed vacuum tubes in KAGRA tunnel.

Figure 11 – Cryostat for cryogenic payload and cryogenic thermal radiation shield pipe at Y-front room.

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