KAGRA
-Large-scale Cryogenic Gravitational wave Telescope-

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KAGRA is a second generation gravitational wave (GW) telescope under constructing in Japan. Features in KAGRA are underground site and cryogenic mirror systems. It is well studied that underground site of Mt. Ikenoyama in Kamioka has over two orders of magnitude smaller seismic vibration than that of typical urban area, and it is very effective to reduce seismic noise. The cryogenic mirror system is an unique technology developed in Japan to reduce mirror and suspension thermal noises in GW interferometer. These two unique features allow KAGRA to aim to detect GWs from neutron-star binary coalescence from 280 Mpc away in best direction. The details of these features and their status, including the status of the constructions site of KAGRA are reported in this paper.

Keywords: gravitational wave, KAGRA, cryogenic, seismic noise, thermal noise

1. Introduction

It is expected that new avenues in the field of GW astronomy will be opened by second generation interferometric gravitational wave (GW) telescopes. In the case of ground base interferometric GW telescopes, main observation band is around between several dozens Hz and several kHz. The GW sources with such high frequencies are limited. Compact and heavy astronomical objects such as binary neutron-star coalescence, black-hole binary coalescence, supernova, pulsar are promising targets of observation. Especially, it is expected that the GWs radiated from black-hole just after merger of binary neutron-stars has peculiar waveform and one can investigate strong gravity field. However, such astronomical events occur in very rare rate, and sensitivity to be able to search 200 - 300 Mpc range is required to detect several GW events every year. Now five second generation GW telescopes in the world are under constructing to realize the sensitivity. Advanced LIGO (aLIGO, two telescopes)[1] in USA and advanced VIRGO (aVIRGO)[2] in Italy are 3 - 4 km scale large interferometers upgraded from 1st generation detectors. GEO-HF[3] in Germany is also upgraded interferometer with 600 m length, but it chose different strategy from others; high frequency GW search. KAGRA is a new GW telescope with 3 km arm length under constructing in Japan. KAGRA has two unique features; underground site and cryogenic mirror system.

2. KAGRA project

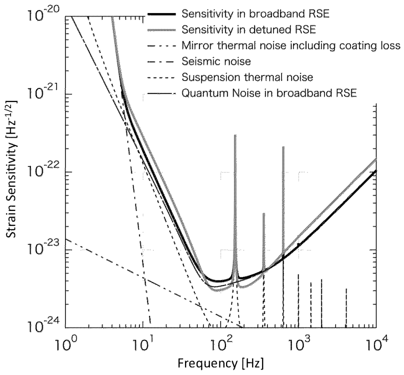

Fig. 1. Design sensitivity of KAGRA with major noises.

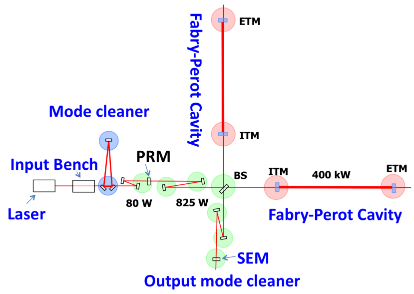

Fig. 2. Layout of KAGRA. This configuration is called as Dual Recycled Fabry-Perot Michelson Interferometer.

KAGRA can detect GW signals from neutron-star binary coalescence and the range of the detector is 280 Mpc in best direction and is 173 Mpc in whole sky average. Figure 1 shows design sensitivity of KAGRA. The best sensitivity is orders of $10^{-24}/\sqrt{\mathrm{Hz}}$ at 100 Hz. KAGRA has two operation modes; broadband resonant sideband extraction (RSE) and detuned RSE[5]. A RSE mirror exists at the dark port in interferometer shown in Fig. 2 and acts as GW signal amplifier. By tuning the position of RSE mirror, two modes are switched. In both the modes, quantum noise limited sensitivity, which consists of photon shot noise and radiation pressure noise[4], are realized. The Fabry-Perot cavities in arms and the power recycling mirror (PRM) helps in increasing the laser power inside the arm cavities, and they also help in reducing photon shot noise. The arm cavities store 400 kW of laser power.

The sensitivity of the KAGRA detector will be limited by quantum noise, however, there are important noise sources such as seismic noise and thermal noise from the mirrors and suspensions, which must be reduced. In KAGRA, these two noise sources are reduced by, (a) having an underground site and (b) employing cryogenic mirror suspension system.

3. Underground Site

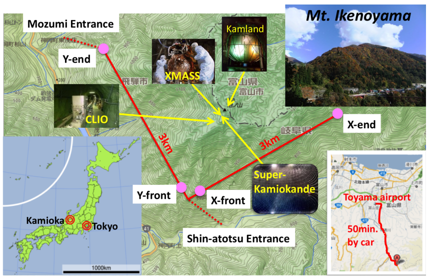

Fig. 3. Underground site of KAGRA.

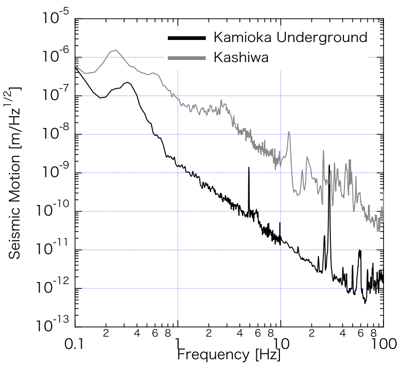

Fig. 4. Spectrum of seismic vibration at University of Tokyo in Kashiwa and Kamioka underground. Data for Kamioka was measured at about 1000 m underground of Mt. Ikenoyama from ground surface.

The seismic noise is a noise induced by mirror vibration due to steady ground motion. A lot of seismic vibration attenuators for mirror are developed, however, still the seismic noise dominated the sensitivity below several dozens Hz. We decided to construct KAGRA in an underground site with very small seismic motion. Figure 3 shows underground site of KAGRA in Kamioka in Japan. Figure 4 is a comparison of seismic vibration in Mt. Ikenoyama in Kamioka with typical urban area in Kashiwa. Apparently, seismic motion in Kamioka underground is two or three orders of magnitude smaller than that in Kashiwa, and is also about one order of magnitude smaller than that in aLIGO site. Hence the underground site at Kamioka is ideal for the construction of a GW interferometer

Figure 5 shows vibration attenuation strategy for main mirror in the KAGRA tunnel. A 14 m tall pendulum is installed to have low frequency seismic attenuation. Usually, this is not easy since one also needs tall tower to suspend tall pendulum and structural resonance of the tower contami-

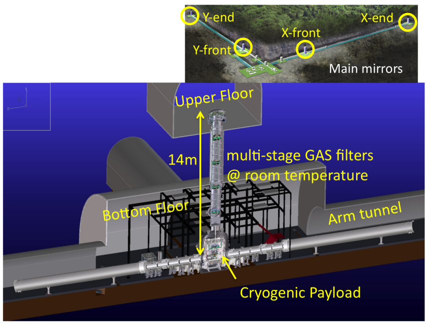

Fig. 5. Vibration Attenuation for main mirror in the KAGRA tunnel.

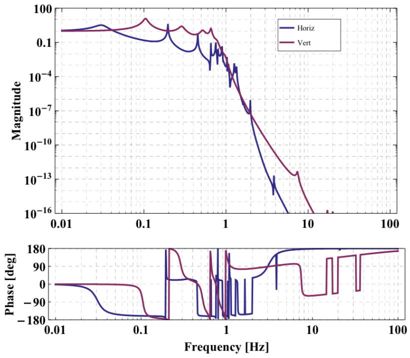

Fig. 6. Estimated transfer function of vibration attenuator system for a main mirror.

nates seismic attenuator performance. But it is possible to excavate vertical tunnel in the KAGRA site, so a tower-free tall vibration attenuator is realized. This tall pendulum has a structure of five stage pendulum at room temperature and cryogenic mirror suspension. Each stage of room temperature pendulum has Geometric Ati-Spring (GAS) filter[6] to attenuate vertical seismic motion. Figure 6 is an estimated transfer function of this vibration attenuator system[7]. And cryogenic mirror suspension is another feature in KAGRA, which is described in next section.

4. Cryogenic Mirror System

The best sensitivity range of around 100 Hz in an interferometer can be limited by mirror and suspension thermal noises. Thermal noise is a kind of Brownian motion of mirror and suspension wires, and they cause mirror vibration. To realize quantum noise limited sensitivity, it is important to suppress the thermal noises. The thermal noise amplitude is proportional to the square of the temperature and mechanical loss. Where mechanical loss means acoustic dissipation in material. So low temperature and use of materials with small mechanical loss are critical to reduce thermal noises. The aLIGO and the aVIRGO focused to use mirror and suspension materials with very small mechanical loss; fused silica at room temperature. On the other hand, the KAGRA chose another story, development of cryogenic sapphire mirror and suspension. Cryogenic sapphire realizes not only low temperature but also very small mechanical loss. It is well studied that mechanical loss of sapphire at cryogenic temperature decreases about one or two orders of magnitude from that at room temperature[8,9]. So by the effect of both low temperature and small mechanical loss, we can expect about one order of magnitude smaller amplitude of thermal noise than that at room temperature.

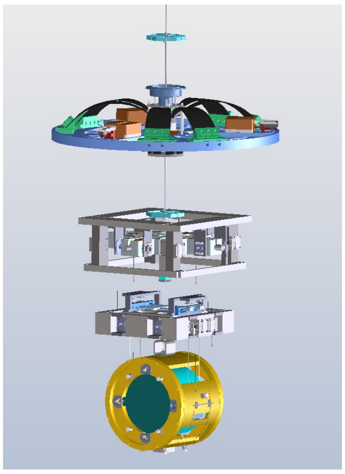

Fig. 7. A drawing of cryogenic sapphire mirror system with cryogenic suspension.

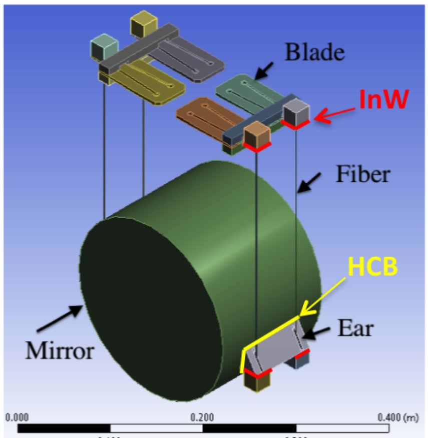

Fig. 8. Semi-monolithic sapphire suspension.

Figure 7 shows a drawing of cryogenic mirror and suspension system. This is a four-stage pendulum. The top part is a GAS filter. The GAS filter attenuates vibration through heat links to cool the cryogenic pendulum. The second part from the top is a tilting control stage named Marionette. The third is a intermediate mass and the last part is a mirror and its recoil mass. Figure 8 shows CAD model of mirror and suspensions made of sapphire to obtain ultra low mechanical loss. The suspensions system consists of sapphire mirror, sapphire ears to be hanged by sapphire fibers with sapphire blocks and sapphire blade as vertical spring. These parts have to be assembled with keeping small mechanical loss condition. Two type of contact technologies, Indium Welding[10] and Hydro-Catalysis Bonding[11], are developed. Studies have shown that using very thin layer of bonds is essential to obtain low mechanical loss in the suspensions, and these two contacts satisfies the requirement[10].

And extremely quiet cooling technologies have also been developed[12]. A small vibration pulse-tube cryocooler unit was developed and it has been observed that this system has same vibration level with Kamioka seismic motion. Soft heat links with large thermal conductivity were also developed. We plan to use 6N pure aluminium stranded cable and it is effective to reduce vibration conduction through cooling path.

The fundamental technologies of cryogenic mirror has been demonstrated in CLIO experiment, which is a prototype cryogenic interferometer in Kamioka[13].

5. Construction Status of KAGRA

Fig. 9. Assembled cryostat at X-front location.

Fig. 10. Vacuum tubes in an arm tunnel.

Excavation of KAGRA tunnel was done at March 2014. Soon after, installations of major devises were started. The first installed device inside tunnel was the cryostat for cryogenic mirror at Y-end location. The size of cryostat is 4.3 m in height and 2.6 m in diameter, and this is comparable size with the KAGRA tunnel. After installing two cryostats to both ends, vacuum tubes were installed into arm tunnels. A single vacuum tube size is 800 mm in diameter and 12 m in length, and 482 tubes and 16 tanks are installed in total. About 90 % vacuum vessels were connected in this stage, and no vacuum leakage over 10^{-10} Pa m^3/s were found. Figure 9 and 10 show pictures of installed cryostat and vacuum tubes.

We plan to have brief test of KAGRA by using simple Michelson interferometer at the end of 2015. At between 2016 and 2017, high performance vibration attenuators, cryogenic mirror systems and a high power laser are installed, and a science run will be done by the end of 2017.

6. Conclusion

KAGRA is an unique 2nd generation GW telescope, which will employ advanced features like underground site and cryogenic mirror systems. KAGR will detect GW signals from 280 Mpc in the best detector orientation. Installation of vacuum vessels have been almost completed and optical components and vibration attenuators are being installed rapidly. The construction of the KAGRA detector is expected to be completed by the end of 2017, following which the science runs will begin.

Acknowledgments

This project was supported by MEXT, JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, MEXT Grant-in-Aid for Scientific Research on Innovative Areas 24103005, JSPS Core-to-Core Program, A. Advanced Research Networks, and the joint research program of the Institute for Cosmic Ray Research, University of Tokyo."

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