PROCEEDINGS OF SCIENCE

Status of KAGRA

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The gravitational wave detectors LIGO and Virgo have so far detected gravitational wave signals from 90 compact binary coalescences including two from neutron star binary mergers. Those detections are revolutionizing our understanding of the universe. This ongoing revolution will be accelerated by more accurate localizations of the gravitational wave sources and by longer coincident observation by multi-detectors, which will be made possible using as many detectors as possible. KAGRA is a gravitational wave detector built at Kamioka in Gifu prefecture, Japan, well away from the LIGO and Virgo detectors, with unique features of having cryogenic mirrors and being built underground. KAGRA can be a prototype for next-generation gravitational wave detectors and our experiences benefit those detectors that would have those features to achieve further sensitivity to gravitational waves. In this presentation, the status of KAGRA is given.

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1. Introduction

The Laser Interferometer Gravitational-wave Observatory (LIGO) [1] which comprises two detectors at Hanford and Livingston in the US detected gravitational waves (GWs) from a black hole binary merger in 2015, and this epoch-making detection has opened up a new field in astronomy by means of gravitational wave observation. In August 2017, the Virgo gravitational wave detector [2] joined the second observing run conducted by LIGO and three detectors soon detected GWs from a black hole binary on August 14. It was just three days later that the two LIGO detectors and Virgo detected GWs from a binary neutron star (BNS) merger named GW170817, where associated gamma-ray emission was observed 1.7 seconds later from GWs. The worldwide follow-up campaign was conducted with electromagnetic telescopes for years, giving us a clue into the long-standing mystery of the origins of gamma-ray bursts. This event then was one of the beginnings of multi-messenger astronomy.

It is noteworthy that the signal-to-noise ratio for GW170817 of Virgo was just 2, yet that smallness allowed for better localization of the GW source than that could be achieved by two LIGO detectors. In fact, observing GW signals with multi-detectors is essential to localize GW sources, thereby making multi-messenger astronomy possible [3]. Also interesting to note is that finding the number of the polarization states of GWs, as a test of general relativity, is possible with multi-detector observation [4]. As such, the fourth GW detector KAGRA [5, 6] is long-awaited in the GW and multi-messenger astronomy communities.

KAGRA has two key features as a GW detector to mitigate two of the most troublesome obstacles against GW detections: it has cryogenic mirrors and is built underground. LIGO, Virgo, and KAGRA are all laser interferometers. As typical GW amplitudes are extremely small, efforts to detect GWs have mostly been those to mitigate noise from various origins. Those include the seismic motion of the ground, thermal fluctuations of the mirrors and their suspensions in the interferometer, radiation pressure and shot noise of the laser, interference by scattering and stray light, frequency and intensity fluctuation of the laser, acoustic vibration, and so on. In fact, even LIGO took 13 years for its first detection since its first observing run in 2002 with its BNS range of ~ 200 kpc, which tells how far on average over the sky the detector can see if a source is BNS and is a figure of merit of the detector sensitivity. Being built underground, we see the reduction of the noise due to the seismic motion in the KAGRA data, while we mitigate thermal noise by using cryogenic mirrors. A lower seismic noise level is also important for stable operation. These two features would be adopted to some extent in designs of next-generation GW detectors like Einstein Telescope [7]. KAGRA provides valuable information on the pros and cons of those features as a prototype for those next-generation detector plans [8].

The KAGRA project was approved in 2010. The tunnel excavation started in 2012 and finished in 2014. In 2019, KAGRA finished all installations with the designed configuration, which we call the baseline-design KAGRA. We conducted the test operation using room temperature mirrors in 2016 (the iKAGRA operation) and with the cryogenic mirrors in 2018 (the bKAGRA phase-I operation), and finally conducted the joint observing run with the GEO600 GW detector in Germany [9] in 2020 April, called O3GK [10]. At that time the BNS range was approximately 500 kpc on average. Since then, we have been working on improving both sensitivity and stability of the detector [11]. While Virgo was still under commissioning, the two LIGO detectors and KAGRA started the fourth observation run called O4 on May 24, 2023. The BNS ranges are ~ 150 Mpc for the LIGO detectors and was ~ 1.3 Mpc for KAGRA. The observing run will last 20 calendar months but KAGRA stopped the observation as previously planned, and we work for further improvements in sensitivity as well as stability and plan to rejoin the run in 2024 spring. This contribution reviews our efforts before O4 and the recent detector status.

2. KAGRA and its O4a run

The O4 run is split into at least two segments, O4a and O4b. We realized a power-recycled Fabry-Pérot Michelson interferometer (PRFPMI) with a DC-readout configuration in O4a. We dedicated a week to calibration and detector characterization work from May 17 to 24. The calibration and detector characterization in KAGRA are described in [12, 13]. Our observation started on May 24 and ended on June 21, while LIGO continues its observation. The duty factor (the ratio of the time the detector is capable of taking observing data to the total calendar days) was 80% while it was 53% in O3GK. It was found that earthquakes were the main cause of making the interferometer out of operation. With the BNS range of 1.3 Mpc on average, no GW candidate has so far been detected by KAGRA. The sensitivity curve during the O3GK run and various noise contributions are shown in Fig. 1.

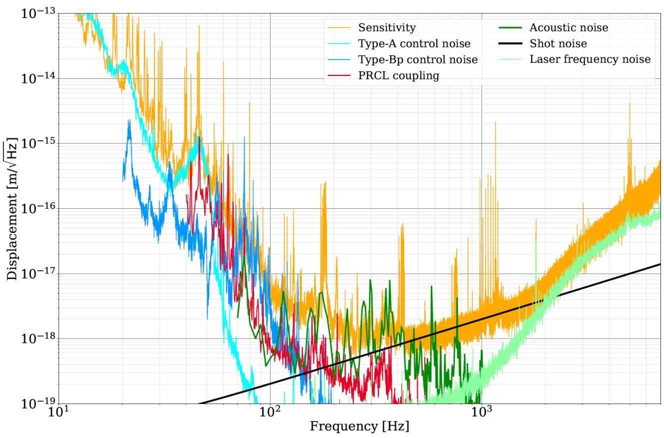

Figure 1: The KAGRA sensitivity curve during O3GK and various noise sources. The O4a sensitivity curve shall be presented in our forthcoming paper. The Type-A control noise had a large impact at lower frequencies and thereby the BNS range. In the KAGRA O4a run, we succeeded in reducing the Type-A control noise in lower frequencies and laser noises in higher frequencies.

We plan to adopt the resonant-sideband-extraction (RSE) technique to achieve the design sensitivity. Figure 2 shows the optical configuration of the interferometer. We plan to cool the four sapphire mirrors at ETMX(Y) and ITMX(Y) to cryogenic temperature in future observation runs but at this moment only ETMX has been cooled down to around 87 K while ITMX, ETMY, and ITMY are at 250 K by radiation cooling. In fact, we have succeeded in a continuous cryogenic operation of over a year at the cryogenic x-arm end test mass chamber. The finesse values are ~ 1420 and ~ 1350 for the X-arm and Y-arm Fabry-Pérot cavities, respectively.

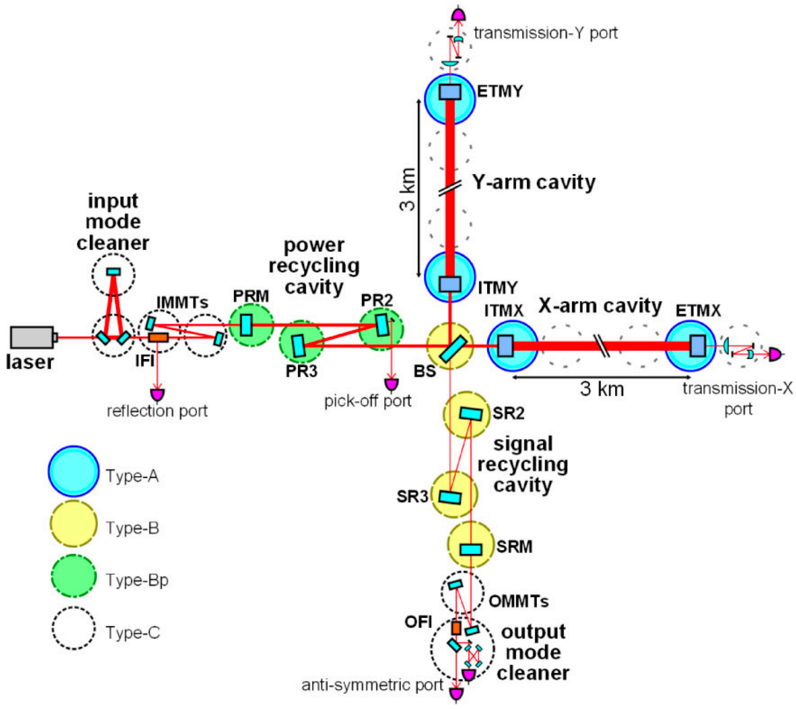

Figure 2: KAGRA schematic optical layout. KAGRA is a resonant sideband extraction (RSE) detector with the Fabry-Pérot, power-recycling, and signal-recycling cavities. All mirrors with labels are suspended inside the vacuum tanks with four types of vibration isolation systems, e.g., test masses (TMs) by the Type-A suspension system. ITMX (Y): input test mass X(Y), ETMX (Y): end test mass X (Y), BS: beam splitter, PRM: power recycling mirror, SRM: signal recycling mirror, IMMT (OMMT): input (output) mode-matching telescope, IFI (OFI): input (output) Faraday isolator

3. Recent efforts and achievements for sensitivity improvements and better stability

We worked on various things and achieved improved performance of the detector toward our participation in the O4a run. Here we briefly explain some of the major improvements and achievements. Parts of the efforts and achievements for the O4 run shall be presented in more detail by other contributions at this conference.

3.1 Cryogenic system

We had seen frosting on sapphire mirrors when those were cooled down, resulting in unacceptably low finesse. For a resolution, we have taken the following measures. We set a new regulation on acceptable vacuum leak level from 10^{-9} Pa m^3/sec to 10^{-10} Pa m^3/sec. Mass spectrometers were introduced in each cryostat for monitoring N_2, O_2, and H_2O molecules. We have established a sophisticated multi-step cooling procedure to reduce the amount of frost. We also installed heaters at the intermediate mass to enhance the speed of the heating, preparing for emergencies where we may have to heat the mirrors to room temperature quickly. As a result of all the measures above, we see no serious reduction in finesse until now.

Frosting on the windows of the cryo-chambers where the optical lever lights pass through was also a problem, giving us unreliable information on the mirror alignments. This in turn resulted in unreliable pitch and yaw damping control for the mirrors. We thus installed heaters at the inner and outer radiation shields, seeing no serious frosting now, although we need to watch the shields carefully when those will be cooled down at and below 40 K.

When the cryo-payload was cooled down, the physical stiffness of the suspensions was enhanced and the suspended mirrors were lifted up, troubling the interferometer alignment control. We implemented a new system to measure the heights of the mirrors using already installed cameras called TCam.

The birefringence of the sapphire mirrors is one of the biggest and long-standing problems in KAGRA. We developed an optical simulator for the interferometer that enables us to study the effects of the sapphire birefringence. See also [14, 15] for the sapphire mirrors and [16, 17] for vibrations of the cooling system.

3.2 High-power laser

We installed a new high-power laser (HPL) in the pre-stabilized laser (PSL) room with the maximum power being 60 W (40 W at the time of O3GK). Locks of the input mode cleaner (IMC) with this HPL were realized. The laser intensity stabilization system was improved and we achieved relative intensity noise (RIN) of 10^{-8}, which meets the requirement for the O4b run. Indeed, this is 1-1.5 orders of magnitude better RIN compared with the system during the O3GK run. Adjustment of this HPL at the KAGRA site is ongoing.

3.3 Alignment sensing and control

We successfully implemented the alignment sensing and control (ASC) system including the waveform sensing (WFS) and the beam position control (BPC), except for the power-recycling mirror 3 (PR3) chamber and input test masses (ITMs). Drastic enhancement of the intra-cavity power and its stability have been observed. The resulting smaller contrast fluctuation at the anti-symmetric port will allow for injecting more laser power into the interferometer. We expect a noticeable reduction of shot noise in the O4b run.

3.4 Vibration isolation system, baffles, and vacuum

We found some faults in all the type-A suspensions almost 2 years ago after the O3GK run. The repair work and health checks on the type-A suspensions were completed before pumping the vacuum tanks. The checks were on sensor spectra, transfer functions, actuator performance and balance, low actuator coupling, securing proper positions of the instruments and sensors, and resonance damping systems among others. We verified that there were no unintentional contacts among the instruments and no disorders inside the suspensions, except for one geometric-anti-spring (GAS) filter. In addition, we installed ribbon heaters and introduced a temperature control system to stabilize the GAS filters in the suspensions. For VIS control, low-noise linear variable differential transformers (LVDT) were installed for IX, EX, IY, and EY. The control scheme will be refined with these new LVDTs. With all the efforts above, we have successfully reduced the control noise to a quite low level in the type-A/B/Bp suspensions except for the type-A suspension for the ETMX. See [18–21] about details of our pre-O4a work on VIS.

Mid-size baffles were installed in the center area and optical dumps were installed in the tanks housing the input Faraday isolator (IFI), input mode matching telescope (IMMT), output mode cleaner (OMC), output mode matching telescope (OMMT) to mitigate scattered or stray light. In fact, stray light causes non-stationary noise, and mitigation of it is the key to achieving better sensitivity and quality of the data from the current KAGRA detector. We will make a quantitative study on the effects of these baffles on sensitivity and data quality. As for OMC, repair work was completed and lower loss was realized.

We installed gate-valves to separate the central area from the housings for the signal recycling mirrors and the power recycling mirrors. These additional gate-valves saved time for the repair work for the IFI and OMC vacuum tanks. We have realized the leak level of 10^{-10} Pa m^3/sec, although serious leaks at the hermetic pins at the beam splitter and around the Y-end are found.

4. Outlook

Approved two decades later than the LIGO and Virgo projects, the KAGRA project has been showing remarkably rapid progress. Being built underground and the use of cryogenic mirrors are the two key features that would be adopted in next-generation GW detector plans. After the successful participation in the early O4a run, KAGRA is now in commissioning. We plan to join the O4b run in spring 2024 with improved sensitivity of the BNS range of 3~10 Mpc hopefully. In the meantime, investigation of the effects of the environmental disturbances on the detector performance and post-data-taking noise reduction techniques have been studied [22–25].

After the O4 run, the international GW detector network would conduct O5 run [26].[1] Toward future runs, we are working on possibilities of introducing a frequency-dependent squeezing technique to tackle the standard quantum limit [27, 28], obtaining larger sapphire mirrors, a higher power laser, and so on. KAGRA will contribute to the international GW detector network in the near future. KAGRA is expected to provide invaluable information about underground cryogenic interferometer construction and operation for future GW detector plans such as the Einstein Telescope.

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[1] See https://observing.docs.ligo.org/plan/ for the latest information.

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