Detector configuration of KAGRA—the Japanese cryogenic gravitational-wave detector

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Abstract

The construction of the Japanese second-generation gravitational-wave detector KAGRA (previously called LCGT) has been started. In the next 6–7 years, we will be able to observe the spacetime ripple from faraway galaxies. KAGRA is equipped with the latest advanced technologies. The entire 3 km long detector is located in the underground to be isolated from the seismic motion, the core optics are cooled down to 20 K to reduce thermal fluctuations and quantum non-demolition techniques are used to decrease quantum noise. In this paper, we introduce the detector configuration of KAGRA, its design, strategy and downselection of parameters.

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1. Introduction

KAGRA (previously called LCGT for Large-scale Cryogenic Gravitational-wave Telescope) is a Japanese 3 km optical interferometer currently under construction in the Kamioka mine. The aim of this detector is the frequent observation of gravitational waves from faraway galaxies and to obtain unique information on the universe. The observation will be performed with other detectors in the US (advanced LIGO [1]) and Europe (advanced Virgo [2] and GEO-HF [3]), which are now being upgraded after several years of observations in the initial configurations. KAGRA and the other three detectors are called second-generation gravitational-wave detectors.

There are two unique features in the detector configuration of KAGRA. One is that the entire detector is constructed in the underground. Both seismic noise and gravity gradient noise (GGN) are low in the underground. In addition, the low rms motion relaxes the requirement on the interferometer control and reduces electro-magnetic noise. The other special feature is the cryogenic operation of the interferometer. The sapphire test masses are cooled down to 20 K and mirror thermal noise is lower than that of room-temperature detectors. Another benefit of the cryogenic operation is that the mirror causes almost no thermal lensing effect,
Figure 1. Schematic view of KAGRA. The test masses are installed in the cryostats and are isolated from room-temperature optics by more than 20 m. The mirrors for iKAGRA will be installed in vacuum chambers next to the cryostats for the smooth transition to bKAGRA. Here MC/OMC stand for mode-cleaner/output mode-cleaner.

which is one of the biggest issues for the room-temperature detectors, for the high thermal conductivity of sapphire at 20 K.

The unique features of KAGRA come along with unique issues. The baseline length is limited by the size of a mountain. The floor is tilted for the water drainage system. The mirror is made up of sapphire instead of classic fused silica. The laser power is limited by the amount of the absorbed heat that can be extracted through the suspension fibers. The detector configuration of KAGRA is designed with these issues fully considered. Some of our knowledge of the underground cryogenic interferometer will be useful for a third-generation gravitational-wave detector, Einstein Telescope [4] for example, which is planned to be built underground and operated in a cryogenic temperature.

Figure 1 shows the schematic view of the KAGRA detector. The optical configuration is a Michelson interferometer with high-finesse arm cavities and folded recycling cavities. The signal-recycling cavity reduces the storage time of the signal fields resonating in the arm cavities in order to retain a broad bandwidth; this system is called resonant-sideband extraction (RSE) [5]. The four test-mass mirrors in the arm cavities are cooled down to 20 K to reduce thermal fluctuations. These mirrors are made up of sapphire and suspended by sapphire fibers. The mass of the sapphire mirrors ranges between 23 and 30 kg, depending on the availability. The laser power after the mode-cleaner ranges between 50 and 80 W, depending on the absorption of the sapphire mirror; the lesser the absorption, the more power we can inject. The power recycling gain is about 10 and the finesse of the arm cavity is 1550. The power reflectivity of the signal-recycling mirror is 85% and the resonant condition of the signal-recycling cavity is detuned by $\sim 3.5^\circ$ to increase the detector sensitivity to the gravitational waves from the neutron–star binaries (the major parameters are listed in
the appendix). Our primary target source is the neutron–star binaries since the event rate can be well estimated and the waveform during the inspiral is predictable. In the end, the observable distance of the neutron–star binary inspirals with KAGRA ranges between 240 and 280 Mpc, with which we will be able to detect 6–10 neutron–star binary signals per year [6–8]. Here, the normal incidence of the wave is assumed in the calculation of inspiral range.

The KAGRA project was approved by the Japanese government in 2010. The initial phase will be the room-temperature operation without the recycling cavities. This is called initial KAGRA or iKAGRA. A short-term observation of iKAGRA is planned for 2015. The test masses of iKAGRA are 10 kg silica mirrors provided by courtesy of LIGO. In the second phase, the test masses will be replaced by the 23 kg (or 30 kg) sapphire mirrors to be cooled down. The suspension system is being upgraded and the recycling mirrors are being introduced. This is the baseline-design KAGRA or bKAGRA. Observations with bKAGRA will start in 2017–2018.

2. Estimated noise budget

Figure 2 shows the estimated noise budget of KAGRA². Hereafter, we assume the safest parameter set, namely the 23 kg mass and the 50 W laser. The sensitivity is limited by quantum noise at most frequencies, and also suspension thermal noise is close to limit the sensitivity at low frequencies (20–100 Hz). This reflects quite well the characteristic of the detector. While mirror thermal noise is low for the cryogenic operation, shot noise is higher than other advanced detectors due to the low laser power for the cryogenic operation. The lighter mass increases quantum radiation pressure noise and suspension thermal noise. The fiber thickness is not determined by its strength but by the amount of the heat transferred from the test mass to the upper stages that are connected to the cryo-cooler. The thick fiber increases suspension thermal noise. The peak of suspension thermal noise at 130 Hz is the vertical-mode resonance and the peaks starting at 230 Hz are the violin modes. The peak at 16 Hz is the vertical resonance of the wire suspending the recoil mass.

² This estimated noise spectrum is slightly different from the official sensitivity curve of KAGRA provided in the web page (http://gwcenter.icrr.u-tokyo.ac.jp/en/researcher/parameter), which is calculated with the most optimistic parameter set.
We discuss more in detail about each noise curve in the following sections. Seismic noise and GGN are discussed in section 3, thermal noise is discussed in section 4 and quantum noise is discussed in section 5.

3. Underground observatory

On the left side of figure 3 are shown the schematic views of type-A and type-B suspensions. The type A is a 2-story suspension with short- and steady-inverted pendula on the top floor, four geometric anti-spring (GAS) filters in the middle and the triple pendulum at the bottom for the cryogenic test masses. The type B is for the beamsplitter and the recycling mirrors. While the type-A suspension system has more GAS filters and the isolation ratio is better than type B at low frequencies, vibrations of the cryo-cooler transferred through the heat link limit the noise performance above a few Hz. In the end, the noise levels of type A and type B are nearly equal in the observation band.

The seismic motion of the KAGRA site in the Kamioka mine is $\sim 100$ times lower than that of the TAMA site at 1–100 Hz [9]. The temperature and the humidity fluctuations measured in the mine are 0.01 $^\circ$C per day and 0.08% per day, respectively [9].

On the right side of figure 3 are shown the seismic noise spectra with the type-A and type-B suspensions together with the GGN spectra, which were simulated by courtesy of Jan Harms at Caltech using seismic data of the Kamioka region provided by a research group in NIKHEF [10]. The test masses are located at least 200 m away from the surface of the mountain. It is an advantage of the underground observatory that GGN from the surface of the mountain is suppressed.

4. Cryogenic operation

4.1. Heat transfer

Figure 4 shows the schematic view of the cryogenic system that contains a sapphire test mass suspended by sapphire fibers in the cryostat vacuum chamber. The outer/inner radiation
Figure 4. Schematic view of the cryostat. The heat absorbed from the laser light is transferred from the test mass to the upper stages and then extracted to the PTC. The radiation shield is extended along the vacuum duct over 20 m in order to reduce the heat from the 300 K radiation.

The last three stages of the suspension system are inside the radiation shields. The platform is connected to the inner shield through the seven pure aluminum heat links of 1 mm diameter, and the intermediate mass suspended under the platform is connected to the platform through the five heat links of 3 mm diameter. The heat absorbed in the test mass is transferred to the intermediate mass through the suspension fiber and then transferred to the upper stages through the heat links.

The transferable heat from an object at temperature $T_2$ to an object at temperature $T_1$ is given by the following equation:

$$K = \int_{T_2}^{T_1} \frac{\pi d_w^2}{4 \ell_{\text{sus}}} N_w \kappa (d_w, T) dT,$$

where $d_w$, $\ell_{\text{sus}}$, $N_w$, and $\kappa$ are diameter, length, number, and thermal conductivity of the fiber or the heat link, respectively. The thermal conductivity depends on the fiber diameter due to the surface scattering and also depends highly on the temperature. While the thermal conductivity can be calculated using the Debye model [12], we use the following simple equation that is derived from measurement results and is good below $\sim 40$ K: $\kappa \simeq 5270 \times d_w (T/1 \text{ K})^{2.24} \text{ (W}^{-1} \text{ m}^{-1} \text{ K}^{-1})$.

With the full laser power injected, about 800 W light transmits through the input test mass (ITM) and 400 kW light is stored in the cavity. The absorption of the sapphire substrate ranges between 32 and 67 ppm cm$^{-1}$ in a recent measurement [13]. The absorption of the silica/tantala doublet coatings measured at 20 K is 0.4–0.5 ppm [14]. To be on a safer side, we assume 50 ppm cm$^{-1}$ for the substrate and 1.0 ppm for the coatings. There is additional 200 mW heat introduced through the radiation from the apertures and the view ports. In total, about 1.2 W heat is absorbed by the test mass with the full power. There are point-like defects on the mirror surface and about 10 ppm of the light in the cavity is scattered around to
contribute to increase the temperature of the inner radiation shield. The inner shield is coated with the diamond-like carbon (DLC) to reduce time to cool down the test masses before the operation. The absorptivity of the 1.0 μm DLC coating on the CP aluminum at 10 μm is as high as 0.41, so that the mirror can be cooled faster with the radiation from the mirror to the inner shield [15]. On the other hand, the scattered light is also absorbed by the inner shield more effectively. Most of the scattered light, about 3–4 W, is absorbed and the heat can increase the temperature of the inner shield to ~9 K. All of these facts taken into account, the test-mass temperature would become 23 K with the full laser power.

As is shown in the left panel of figure 5, mirror thermal noise, especially substrate thermoelastic noise, increases with the mirror temperature. The inspiral range of the neutron–star binary with the full-power operation decreases from 250 to 230 Mpc when the mirror temperature increases from 20 to 23 K. It is then rather better to decrease the laser power. The mirror temperature can be 20 K with about 60% of the laser power. Shot noise increases and thermal noise decreases. The inspiral range is then 240 Mpc.

An alternative solution for the increasing heat absorption would be to use thicker fibers. Replacing the 1.6 mm fiber by a 2.0 mm fiber, we could retain the mirror temperature of 20 K with the full laser power injected in return to an increase of suspension thermal noise. The inspiral range would be then slightly higher, but this strategy takes away the possibility of the sensitivity improvement in the case the absorption be lower than the estimate.

4.2. Mirror thermal noise

The mirror thermal noise curve in figure 2 is the sum of substrate Brownian noise, coating Brownian noise and substrate thermoelastic noise. Coating thermo-optic noise is supposedly low at 20 K and is ignored here.

The substrate Brownian noise and coating Brownian noise levels for each mirror are given by [16, 17]

\[ S_{\text{sub}}(\Omega) = \frac{4k_B T}{\Omega} \frac{\phi_s}{\sqrt{\pi w_0}} \times \frac{1 - \nu_s^2}{Y_s^2} \],

\[ S_{\text{coa}}(\Omega) = \frac{4k_B T}{\Omega} \frac{d_s \phi_c}{\pi w_0^2} \times \frac{Y_c^2(1 + \nu_c)^2(1 - 2\nu_c)^2 + Y_s^2(1 + \nu_s)^2(1 - 2\nu_s)}{Y_c^2 Y_s(1 - \nu_c^2)} \].

Figure 5. Left: temperature dependence of mirror thermal noise. Right: dissipation and temperature profiles of a suspension fiber.
respectively. Here \( k_B \), \( T \), \( \Omega/2\pi \), \( d_c \), \( w_0 \), \( \nu_j \) and \( \phi_j \) are the Boltzmann constant, mirror temperature, frequency, coating thickness, beam radius, Poisson ratio, Young’s modulus and mechanical loss angle, respectively, with the subscript \( j \) indicating substrate for \( s \) and coatings for \( c \). As for the coatings, the total thermal noise level is a sum of the noise level for silica layers and the noise level for tantala layers.

KAGRA has two strong points and one weak point on the Brownian noise levels. One strong point is certainly the low temperature. The Brownian noise level is proportional to \( T \).

The other strong point is the high Young’s modulus of sapphire. Table 1 shows the comparison of the last fractions in equations (2) and (3) for different substrate materials. The weak point is the mechanical loss of the coating materials at 20 K. Table 2 shows the mechanical losses of the coating layers measured in the University of Tokyo and the University of Glasgow. It is reported in Glasgow that the mechanical loss can be decreased by doping titanium or by choosing a proper annealing temperature. It has not yet been reported if both effects can be accumulated. The experiment in Tokyo does not see any effect of changing the annealing temperature, but the mechanical loss is lower than what is measured in Glasgow. The experiment in Tokyo is planned to be restarted and more investigations will be done to achieve the goal.

Substrate thermoelastic noise at an arbitrary temperature is derived by Cerdenio and the low-temperature approximation is introduced by Yamamoto [22, 23]:

\[
S_{\text{TE}}(\Omega) = \frac{4k_B T^2(1 + \nu_j)^2 \alpha_j^2}{\sqrt{\pi \kappa_j C_j \Omega}} \quad \text{(low temperature; } \Omega \ll 2\kappa_j / C_j w_0^2) \tag{4}
\]

where \( \alpha_j \), \( \kappa_j \) and \( C_j \) are thermal expansion rate, thermal conductivity and specific heat per volume, respectively. Note that the thermoelastic noise level at low temperature does not depend on the beam radius. The thermal parameters \( \alpha_j \), \( \kappa_j \) and \( C_j \) depend highly on the mirror temperature\(^3\), for which thermoelastic noise increases remarkably with the mirror temperature as is shown in the left panel of figure 5.

Table 1. The last fractions in equations (2) and (3) that consist of Young’s modulus and Poisson ratio (in the unit of 1 Pa\(^{-1}\)). The sapphire substrate has an advantage that these coefficients are low.

| Material    | Young’s modulus (GPa) | Substrate | Silica layer | Tantala layer |
|-------------|------------------------|-----------|--------------|---------------|
| Sapphire    | 400                    | 2.3e\(^{-12}\) | 1.3e\(^{-11}\) | 6.4e\(^{-12}\) |
| Silica      | 72                     | 1.3e\(^{-11}\) | 2.1e\(^{-11}\) | 2.3e\(^{-11}\) |
| Silicon     | 188                    | 5.0e\(^{-12}\) | 1.4e\(^{-11}\) | 8.0e\(^{-12}\) |

Table 2. Measured mechanical losses of the coating layers. The average loss is calculated by \((\sum \Phi_j d_c \phi_j)/(\sum \Phi_j d_c)\) with the Poisson ratios ignored [21].

|            | Tantala | Silica | Average |
|------------|---------|--------|---------|
| 290 K [18] | 2.0e\(^{-4}\) | 5.0e\(^{-5}\) | 1.3e\(^{-4}\) |
| 20 K, measured in Tokyo [14] | –       | –       | 5.0e\(^{-4}\) |
| 20 K, 600 °C anneal [19]    | 1.0e\(^{-3}\) | 5.0e\(^{-4}\) | 7.8e\(^{-4}\) |
| 20 K, 600 °C anneal, Ti-doped [19]| 8.0e\(^{-4}\) | 5.0e\(^{-4}\) | 6.7e\(^{-4}\) |
| 20 K, 300 °C anneal [20]    | 6.0e\(^{-4}\) | –       | –       |
| 20 K, 300 °C anneal, Ti-doped| –       | –       | –       |
| Goal for KAGRA               | 5.0e\(^{-4}\) | 3.0e\(^{-4}\) | 4.1e\(^{-4}\) |

\(^3\) Temperature dependence of each thermal parameter is given as follows, fitted to measurement results: \( \kappa_j = (0.272 \times T_m^{-2.2} + 6.22 \times 10^{-9} \times T_m^{1.04})^{-1.25} \) (W m\(^{-1}\) K\(^{-1}\)), \( C_j = 0.227 \times T_m^{1.14} \) (J m\(^{-3}\) K\(^{-1}\)), \( \alpha = 7.21 \times 10^{-13} \times T_m^{2.09} \) (1 K\(^{-1}\)), where \( T_m \) is in Kelvin.
Reduction of mirror thermal noise by decreasing the temperature is observed at CLIO, a 100 m prototype interferometer for KAGRA. The sapphire ITMs in the arm cavities are cooled down to $\sim 20$ K and the sensitivity is improved at around 100–200 Hz [24].

### 4.3. Suspension thermal noise

Heat absorbed in the test mass is transferred to the intermediate mass through the sapphire suspension fibers. In order to extract a sufficient amount of heat, the fibers have to be as thick as 1.6 mm in diameter. The suspension thermal noise level at low frequencies is roughly given by the following equation [25]:

$$S_{\text{sus}}(\Omega) \approx \frac{4k_B T}{m \Omega^2} \sqrt{\frac{4\pi Y_w g}{m} \left( \frac{d_w}{L_{\text{sus}}} \right)^2 \phi_w},$$

with $g$, $Y_w$, and $\phi_w$ being gravity acceleration, Young’s modulus of fiber and mechanical loss of fiber, respectively, and one can see that the effect of low $T$ is compensated by large $d_w$.

For the actual noise calculation, we use the model developed for Virgo [26]. The model treats the 3-mass system and the dissipations of the intermediate mass and the recoil mass are included. In KAGRA, the intermediate mass is planned to be suspended by tungsten fibers and the recoil mass is planned to be suspended by BeCu fibers. Though the temperature of these masses is lower than that of the test mass, the mechanical losses of the tungsten and BeCu fibers are higher than the loss of sapphire, so that the dissipations of these fibers dominate suspension thermal noise at frequencies below 30 Hz.

The dissipation of the pendulum is mainly at the top and bottom ends of the fiber (see the right panel of figure 5). The effective temperature to calculate suspension thermal noise in the horizontal mode is then the average of the test-mass temperature and the intermediate-mass temperature. Besides, contribution of thermal noise in the vertical mode is non-trivial and the effective temperature for this mode is the average over the fiber according to the temperature profile.

The peak of suspension thermal noise at 130 Hz is the vertical-mode resonance and the peak at 230 Hz is the first violin mode. These peaks standing in the middle of the observation band can be troublesome as the peaks can be broadened by couplings to other noise sources such as seismic noise or laser intensity noise. However, the vertical resonance is inversely proportional and the first violin-mode frequency is proportional to a square root of the fiber cross section, and vice versa to the fiber length, so that there is no solution to remove both peaks from the observation band by changing the fiber dimensions. A study to use a non-uniform fiber is under way.

### 5. Quantum non-demolition techniques

Beating the standard quantum limit (SQL) in KAGRA is important for two reasons. One is that the laser power is lower than other advanced detectors. Absence of the thermal lensing problem will let us increase the laser power more smoothly, but we will have to stop increasing the power at a certain point when thermal noise starts limiting the sensitivity. With the limited power, a quantum non-demolition (QND) technique is a way to further improve the sensitivity. The other reason is that the expected gain of the QND technique is high with the low thermal noise level. The control scheme may become slightly complicated to implement QND techniques, but it is worth putting in some extra efforts.

We use two QND techniques. The first one is back-action evasion (BAE). Let us assume that we operate the interferometer with zero detuning. With the conventional readout in
Quantum noise in strain (1/qrtHz)

Figure 6. Left: schematic view of the BAE readout. The output of the interferometer contains reference light, signal and quantum fluctuation fields. Adjusting the offset to choose a proper readout quadrature, one can compensate radiation pressure noise (rp noise) with shot noise in the amplitude quadrature. Right: quantum noise spectra of the variable RSE system in different operations.

the phase quadrature, shot noise that decreases with the laser power and quantum radiation pressure noise that increases with it are not correlated so that the sensitivity does not exceed a limit by simply changing the power:

\[
S_{sh} = \left( \frac{1}{4F} \right)^2 \frac{\hbar \lambda \pi c}{I_{RSE}} \frac{\gamma^2 + \Omega^2}{\gamma^2}, \quad S_{rp} = \left( \frac{4F}{m\Omega^2} \right)^2 \frac{\hbar I_{RSE}}{\lambda \pi c} \frac{\gamma^2}{\gamma^2 + \Omega^2},
\]

\[
S_{\text{conv total}} = S_{sh} + S_{rp} \geq S_{\text{sql}} = \frac{2\hbar}{m\Omega^2}.
\]

Here \( F, \hbar, \lambda, c \) and \( \gamma/(2\pi) \) are the finesse of the arm cavity, reduced Planck constant, wavelength, speed of light and cavity pole of the arm cavity, respectively, and \( I_{RSE} \) is the frequency-dependent effective laser power of the RSE system given by [28]

\[
I_{RSE} = I_{BS} \left( 1 - r_s^2 \right) \frac{1 + r_s^2 + 2r_s \cos \left( 2 \arctan \left( \frac{\Omega_1}{\gamma} \right) \right)}{2 \arctan \left( \frac{\Omega_1}{\gamma} \right)},
\]

with \( I_{BS} \) and \( r_s \) being the laser power at the beamsplitter and amplitude reflectivity of the signal-recycling mirror, respectively. Note that radiation pressure noise in equation (6) is for a single mirror, so the mass \( m \) should be replaced by the reduced mass \( m/4 \) for the four-mirror system. The BAE introduces a correlation between shot noise and radiation pressure noise, which is realized by changing the readout quadrature. Since the source of radiation pressure noise is quantum fluctuations in the amplitude quadrature, one can measure it together with the source of shot noise in the phase quadrature and compensate radiation pressure noise. The total quantum noise spectrum reads

\[
S_{\text{BAE total}} = S_{sh} + (\sqrt{S_{rp}} + \sqrt{S_{sh} \cot \gamma})^2,
\]

which can be lower than \( S_{\text{sql}} \) at around a certain frequency depending on the readout quadrature \( \gamma \).

The left panel of figure 6 explains how one can change the readout quadrature. The reference field that couples to gravitational-wave signals for the conventional measurement in the phase quadrature is the carrier light leaking from the arm cavity due to the intentional offset on the mirror position. This scheme is called the DC-readout scheme. There is also carrier light in the amplitude quadrature, which leaks through due to the reflectivity imbalance
of the two arm cavities. Applying sufficient amount of the offset, one can measure the signal almost in the phase quadrature, but tuning the amount of the offset, one can choose the readout quadrature [27]. Since the reference light has to be weaker than that for the phase quadrature measurement, junk light must be well suppressed to realize the BAE readout.

The second QND technique is to use an optical spring, which can be realized by detuning the signal-recycling cavity [28]. With the detuning, the gravitational-wave signal in the phase quadrature reflects back to the interferometer in an intermediate quadrature. The amplitude quadrature component couples with the laser light to produce radiation pressure on the test masses. The motion caused by the radiation pressure generates a signal in the phase quadrature. In the end there is a loop of the signal, which makes the optical spring, enhancing the susceptibility of the interferometer to the external force at a certain frequency depending on the laser power, mass and the detune phase $\phi$. The equation to calculate the quantum noise level of the detuned interferometer is shown in [28]; we shall omit to write it down here.

KAGRA will employ a so-called variable RSE system. The tuned and the detuned configurations can be switched simply by changing the offset in the control loop of the signal-recycling cavity. The BAE readout is applied with the tuned configuration and the optimal $\zeta$ to maximize the inspiral range for the neutron–star binaries is chosen. In the case of the detuned configuration, the optimal $\zeta$ and $\phi$ are chosen to maximize the inspiral range with the optical spring. In fact, a highly detuned configuration can increase control noise [29]. In the baseline design, the detune phase $\phi$ is set to 3.5° while the optimal one is 4.2°. The inspiral ranges of the various setups are shown in table 3. With the variable RSE system, we will start the operation in the detuned configuration to detect gravitational waves from neutron–star binaries, the primary target source, and then we can choose to extend the observation bandwidth with the tuned configuration.

The finesse of the arm cavities and the reflectivity of the signal-recycling mirror are carefully chosen in terms of the bandwidth and the inspiral range. Figure 7 shows the inspiral

**Figure 7.** Inspiral range with different finesse and signal-recycling mirror reflectivity.

| $\phi$ (°) | $\zeta$ (°) | Range (Mpc) |
|-----------|-----------|-------------|
| Tuned RSE (conventional) | – | 90 | 196 |
| Tuned RSE (BAE) | – | 116 | 206 |
| Detuned RSE | 3.5 | 132 | 238 |
| Detuned RSE | 4.2 | 137 | 239 |
range with different finesse and different reflectivity of the signal-recycling mirror. The laser power is determined with a condition that the mirror temperature is 20 K. At each point, the readout quadrature and the detune phase (for the detuned configurations) are chosen to maximize the inspiral range. A tuned RSE and a detuned RSE with the same finesse and the same reflectivity are compatible. With the finesse being decreased, the range of detuned RSE increases up to a certain level that is determined by the mirror thermal noise level, but the range of tuned RSE decreases much faster so that we do not see much benefit in this direction. Besides, the optimal detune phase with the low finesse configuration is quite high and the bandwidth of the interferometer is narrow. This leads to degraded estimate accuracy of the arrival time of gravitational waves. On the other hand, with the finesse and the signal-recycling mirror reflectivity increased too much, the optical loss in the signal-recycling cavity degrades the sensitivity even though one can keep the mirror temperature to 20 K with more power in the arm cavities. In the end, we choose the parameter set indicated by the pair of + marks: finesse of 1550 and signal-recycling mirror reflectivity of 85%.

6. Summary

We introduced in this paper the configuration of the Japanese second-generation gravitational-wave detector KAGRA (previously called LCGT). With the underground site, the cryogenic operation and the quantum non-demolition techniques, the KAGRA will realize its extremely high sensitivity and observe gravitational waves in the next 6–7 years. Together with other advanced detectors in the world, we will open the window toward gravitational-wave astronomy.

Appendix. List of parameters

| Parameter list of the bKAGRA. |
|-------------------------------|
| Finesse | 1550 |
| Test-mass diameter | 22–25 cm |
| Test-mass thickness | 15 cm |
| Mass | 22.8–30 kg |
| Laser power at the beamsplitter | 515–825 W |
| Mirror temperature | 20 K |
| Absorption in ITM substrate | 20–50 ppm cm$^{-1}$ |
| Absorption in coatings | 0.5–1.0 ppm |
| Optical loss of a test mass | 45 ppm |
| Transmittance of ETM | 10 ppm |
| ITM/ETM radii of curvature | 1680/1870 m |
| Beam radii on ITM/ETM | 3.5/4.0 cm |
| Power/signal-recycling mirror reflectivity | 90/85% |
| Sapphire fiber length | 30 cm |
| Sapphire fiber diameter | 1.6 mm |
| Tunnel tilt | 1/300 |
| Vertical–horizontal coupling | 1/200 |
| Mechanical loss of substrate | 1e-8 |
| Mechanical loss of silica/tantala coatings | 3e-4/5e-4 |
| Mechanical loss of fiber | 2e-7 |
| Vacuum level | 2e-7 Pa |
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