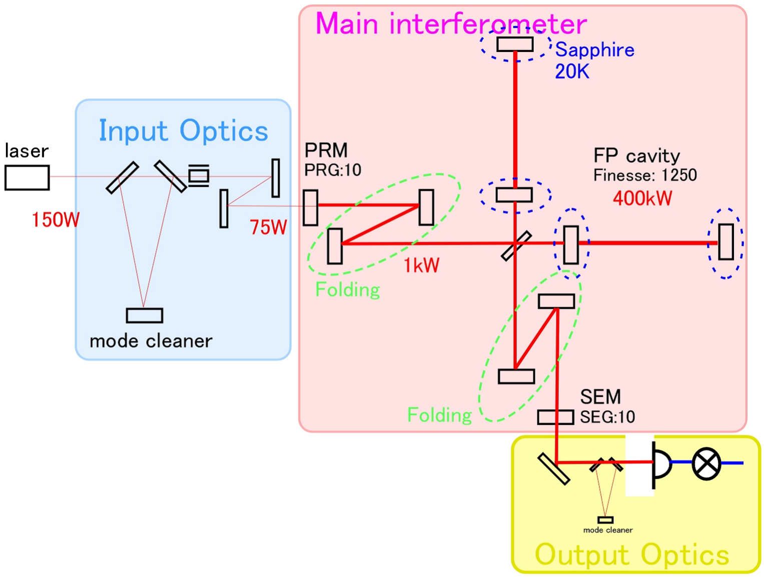

Figure 11: KAGRA Main optical layout

4 KAGRA

Gravitational wave Telescope in Kamioka mine (KAGRA) is the second generation gravitational wave detector. KAGRA use cryogenic technique for sapphire test masses and fibers for thermal noise. It is planed to be cooled down to 20K for sapphire test mass. And it is located in 200 m underground for reduction of seismic motion. Also KAGRA will use the suspension isolation system. This detector arm length is 3 km and it aim for neutron binary star coalescences at 200Mpc away from our galaxy by $S/N = 10$. The design sensitivity is 3×10^{-24} $1/\sqrt{Hz}$ @100Hz. This range is the area of where other ground based detectors have never covered. KAGRA will use Resonant Sideband Extraction (RSE), which also 2nd generation detector advanced LIGO will use. This RSE is expected to enhance the gravitational wave signal. It is designed to optimize the shot noise against the neutron stars coalescence.

Here figure11 is the main KAGRA layout. KAGRA main layout composed 3main parts. Input optics, main interferometer, and output optics.

Input optics Slave laser, power amplifier, double modulations, mode cleaner.

Main interferometer RSE, cryogenic, suspension, SPI,

Output optics Double demodulations, output mode cleaner,

In future plan for upgrading, there are some ideas for reduction of quantum noise using the squeezed light or using composite mirror, for suspension thermal noise using the sapphire ribbon.
In this section, options for upgrading KAGRA are shown and discussed.

LCGT parameters	value
L	3006.69
l	73.2826
ω_0	0.749

Table 4: optical parameters for folding calculation

4.1 Folding

KAGRA has 3km cavities at each arm and use the power recycling mirror for shot noise decreasing. KAGRA has folding power recycling cavity and signal recycling cavity for some reason below. Both lengths of cavities are designed 73.3m.

- Stability of cavity defined by Gouy phase.
  Beam propagates in the space, so it has curved wave front. Gouy phase is the physical quantity that is phase difference between plane wave front and curved. To resolve the degeneracy of the mirrors displacement, folding is one method of the shifting Gouy phase by lengthening the optical length.

- Loop noise
  In addition for loop noise according to LIGO data, Gouy phase shift $\Delta\phi = 20°$ is optimizing. Below this number the sensitivity is degrade by higher mode on resonant. Above this loop noise could increase.

- Separation of cooled input test mass and beam splitter with room temperature To avoid thermal effect on cooling mirrors and to keep cooling efficiency to them.

Without any folding at Power recycling cavity, it's 1.6km from input test mass to keep 20 degree Gouy phase. This value is unrealistic, therefore KAGRA use the folding mirror.

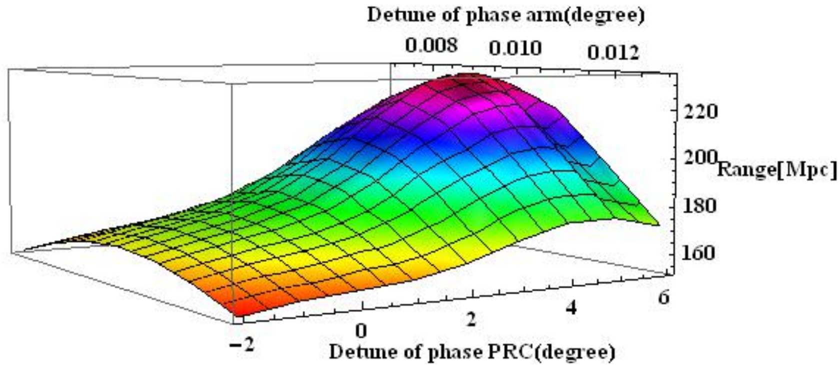

Figure 12: The change of range

4.2 Scope

The KAGRA scope is expected about 270Mpc. However if there were the mirror radius of curvature error, the detector range must be changed. By this simulation, detuning arm length differentially or PRM position, inspiral range could be recovered.

Here is some estimations the number of the curvature error effect by simulator FINESSE.

At the simulation seeing in Figure12, radius of curvature error profiles are North end +2%, north front -2%, east end -2% and east front +2%. And signal extraction mirror has -2% error.

While 1.3 $\sim$ 1.7 times improving of range by detuning the arm length, 1.7 $\sim$ 2.3 times improve by detuning both the arm length and power recycling cavity length. The capability is recovered up to 233Mpc.

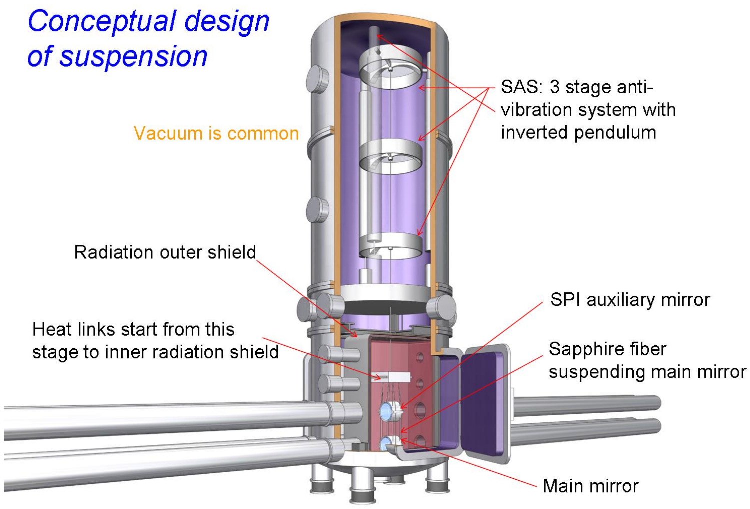

Figure 13: Suspension image

4.3 Suspension fibers for eliminating 100Hz mode

KAGRA applies suspension system for some reasons. [2]

- Seismic isolation
  Above the resonant frequency of suspension, the amplitude could be damped by f^{-2}
- Conveyance of mirror heat
  In KAGRA the test mass ought to be cooled to 20K. Suspension wire works as conveyance of mirror heat.

However applying the suspension fiber causes the annoying modes around 100Hz. which is critical for burst analysis.
The first mode is the vertical mode that is from the vertical coupling depending on the Kamioka mine tilting by 1/300. Other modes are violin mode, that is originated from suspension point vibration. The violin mode frequency is

$$\omega_n \approx n\pi\sqrt{\frac{g}{l}}\sqrt{\frac{M}{m}}.$$

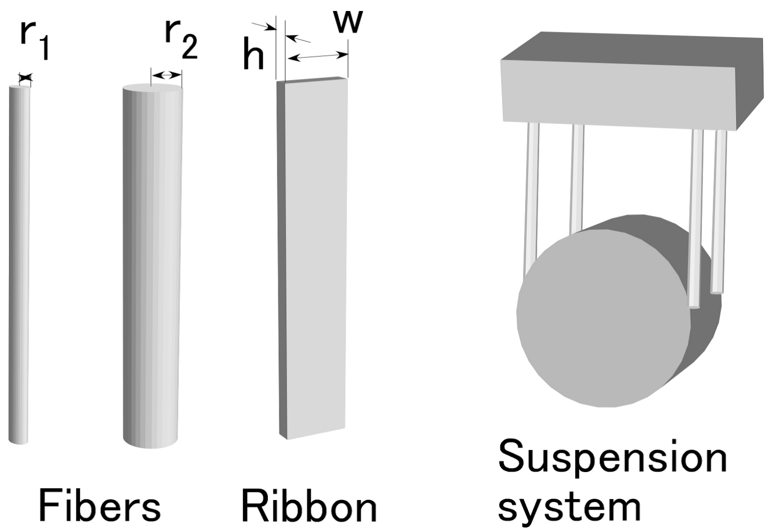

Figure 14: Suspension model for simulation

And the vertical mode frequency is with suspension cross section A

$$\omega_v = \sqrt{\frac{AY/l}{m/4}}.$$

$$\text{peak frequency} \propto \frac{1}{\text{cross section}}$$

$$\text{thermal noise floor} \propto \text{cross section}$$

[3]

These modes could be moved to higher or lower according to the fiber cross section. In addition to this, the mechanical dissipation is reduced by the ribbon that has width and thickness. Large cross section ribbon is realized by wide width and thin thickness, which lead to less mechanical dissipation.

$$\Phi = \frac{1}{2}\sqrt{\frac{YI}{mgL^2}}\phi \tag{41}$$

$$\Phi_{fiber} = \sqrt{\frac{YN_f\pi d^4}{4mgL^2}}\phi_f$$

$$\Phi_{ribbon} = \sqrt{\frac{YN_r wh^3}{12mgL^2}}\phi_r$$

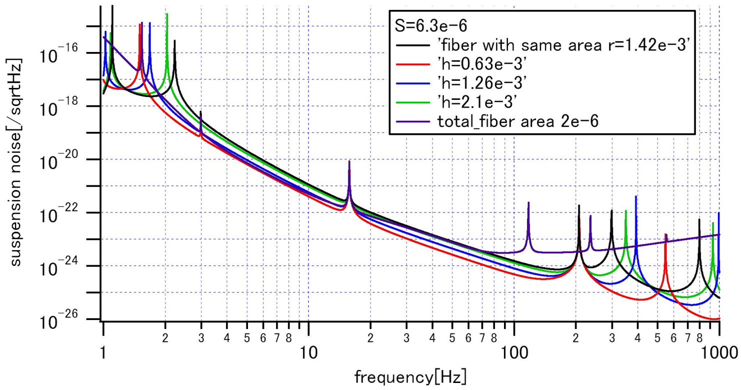

Figure 15:

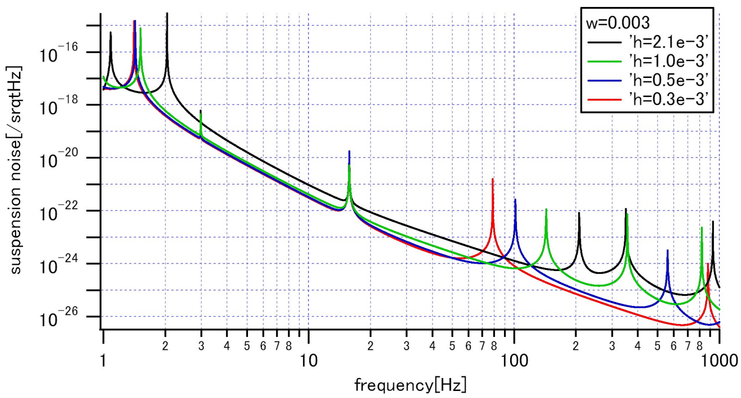

Figure 16:

$$W = \int \frac{A}{l} N \kappa dx \tag{42}$$

On the other hand, cooling effect W is defined by the suspension length l, number of wire N and thermal conductivity κ. In KAGRA, this W is below 1Watt. With this constraint, the modes are calculated (figure16).

The first figure shows that thinner ribbon with same cross section as fibers could move the modes to higher range.

And second figure shows that ribbon whose cross section is smaller could move the modes to lower.

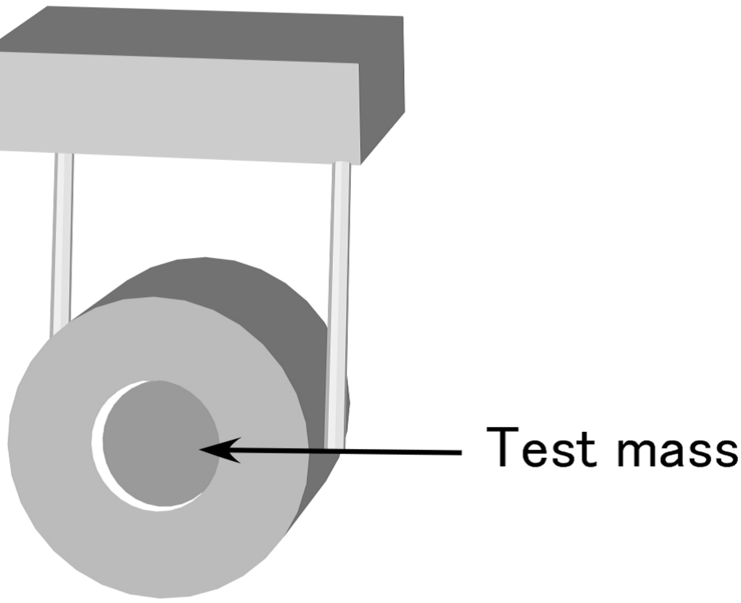

Figure 17: Composite mirror

4.4 Composite mirror for radiation pressure noise

High power laser is recommended for shot noise. However taking account of radiation pressure noise, another solution is needed. The radiation pressure noise S_{rd} is from 40

$$S_{rd} \propto \frac{1}{\text{mass}}$$

For instance, composite mirror shown above. Composite mirror is the mirror with additional weight around it.

Default parameter of test sapphire mass for KAGRA is 30kg weight and 25cm radius. To make this weight 100kg is to attach ring around the sapphire mass which has 70.6cm radius.

However due to process of making crystal, the test mass bulk is restricted.

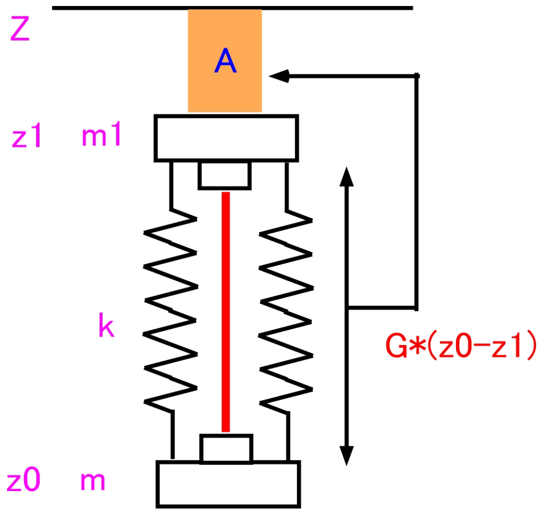

Figure 18: Vertical suspension point interferometer

4.5 Vertical motion isolation

For reduction of violin modes, vertical suspension point interferometer is effective. In this scheme, the equation of motion of mass is follow.

$$m\ddot{z}_0 = -k(z_0 - z_1) - \gamma(\ddot{z}_0 - \ddot{z}_1)$$
$$z_1 = -G(z_1 - z_0) + Z$$

$$\frac{\tilde{z}_0}{\tilde{Z}} = \frac{\frac{\omega_0^2}{1+G} + i\frac{\omega_0}{(1+G)Q}\omega}{\frac{\omega_0^2}{1+G} + i\frac{\omega_0}{(1+G)Q}\omega - \omega^2} \tag{43}$$

$$\omega_0 \equiv \sqrt{\frac{k}{m}}, Q \equiv \frac{m\omega_0}{\gamma} \tag{44}$$

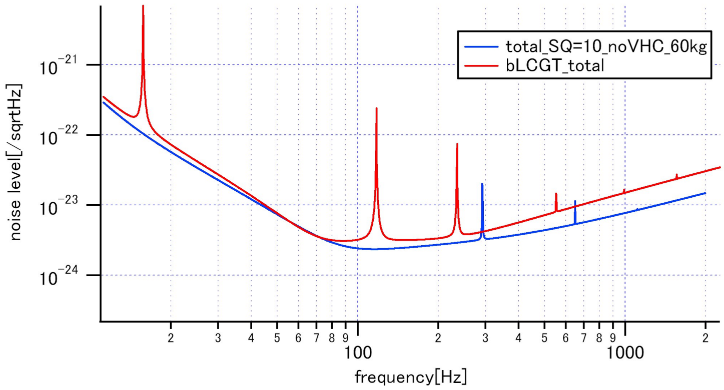

Figure 19: Composite mirror and squeezing effect

4.6 Squeezing for quantum noise

Squeezing is one method of reduction quantum noise. Vacuum field is squeezed by some way, which has the relation between phase and amplitude.

Ponderomotive squeezing Michelson interferometer is one squeezing instrument. Input field from anti-symmetric port is squeezed by end test mass displacement.

Homodyne detection By detuned phase γ, the quantum noise is reduced.

Input squeezing Making input light forward squeezed is more effective for reduction quantum noise.

Filter cavity However this is effective only at particular frequency. Therefore at anti-symmetric port apply the filter cavity to make broad band.

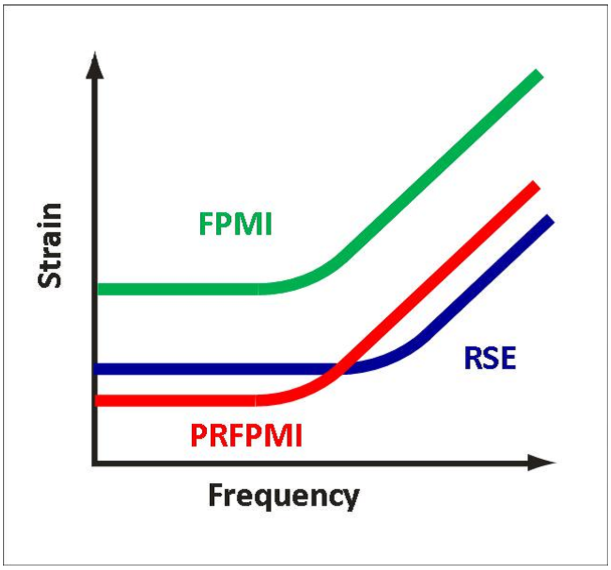

Figure 20: Comparison of shot noise in FPMI, PRFP and RSE

4.7 Resonant sideband Extraction

Resonant Sideband Extraction (RSE) configuration is power recycling Fabry Perot interferometer with signal extraction mirror at anti-symmetric port. In this configuration, it is expected to reduce the quantum noise. [4]

1. Solution for heat problem at the beam splitter
2. High FP cavity finesse
3. Wide signal band width

First item, KAGRA use a high power laser, which means that thermal lens effect could occur or cooling system couldn't work effectively to mirrors. RSE having low power recycling gain and high power finesse cavity, the thermal effect at beam splitter could be eased while the sensitivity kept high.
Shot noise at DC could be improved.
Signal being extracted before cancellation in the IFO, the band width is wider.

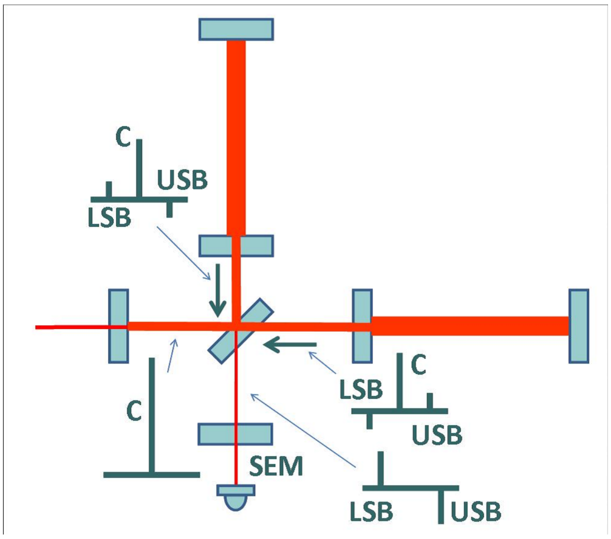

Figure 21: Carrier and sideband condition on RSE

The transfer function H_{RSE} is

$$H_{RSE} = \frac{t_s e^{i\pi/2}}{1 + r_s \left(-r + \frac{t^2 e^{2i\phi}}{1 - r e^{2i\phi}}\right)}. \tag{45}$$

RSE could be the arm cavities finesse high, for instance arm finesse of KAGRA is designed to 1500. If this high finesse cavity used, that would stand for the time in arm being long then the signal of gravitational wave accumulated and cancelled.

Therefore the mirror at antisymmetric port, that is signal recycling mirror (SRM) would be applied. This signal recycling cavity, which is consisted of input test mass and SEM, is on resonance therefore it is possible to make this cavity finesse lower by SEM reflectivity