Study report on the new LCGT setup with 22cm mirrors

LCGT Special Working Group

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1 Overview and Summary

We decided to purchase all the Sapphire mirrors for bLCGT within the first 3 years. Accordingly the detector design should be refined with the new speculation of the mirror that is currently available.

The goal of LCGT is the regular observation of gravitational waves. The most promising wave source is a neutron-star binary inspiral, for which the event rate and the waveform can be well estimated with our knowledge. Let us assume a 90 % duty cycle, signal-to-noise ratio of 8, a 10 % safety factor, and the normal incidence of the waves, then the inspiral range (IR) of 240 Mpc is required to detect more than 2 events per year with a 90 % probability [1].

This 240 Mpc represents the target sensitivity of LCGT. At the same time, as is discussed in Ref. [1], the broad bandwidth of the detector is important to observe gravitational waves from other sources and to estimate parameters of the source with high precision. The inspiral range of LCGT before this report has been 273 Mpc, which satisfies the LCGT requirement [2].

The original and the new setup parameters are as follows (here $\mathcal{F}$ is finesse, ϕ is detune phase, ζ is DC readout phase, $T_{\rm IM}$ is intermediate mass temperature, and T is the test mass temperature):

[original] IR=273 Mpc
$P_{\rm prc}$ =825 W, m =40 kg, T =20 K, $\mathcal{F}$ =1550, R_s =85 %, ϕ =3.5 deg, ζ =135 deg,
$T_{\rm IM}$ =15 K, $\ell_{\rm sus}$ =30 cm, d_w =1.6 mm,
substrate absorption=20 ppm/cm, coating absorption=0.5 ppm

[recommend] IR=238 Mpc
$P_{\rm prc}$ =516 W, m =22.8 kg, T =20 K, $\mathcal{F}$ =1550, R_s =85 %, ϕ =3.5 deg, ζ =132 deg,
$T_{\rm IM}$ =13.2 K, $\ell_{\rm sus}$ =30 cm, d_w =1.6 mm,
substrate absorption=50 ppm/cm, coating absorption=1.0 ppm

[alternative] IR=245 Mpc
$P_{\rm prc}$ =825 W, m =22.8 kg, T =20 K, $\mathcal{F}$ =1240, R_s =85 %, ϕ =5.6 deg, ζ =133 deg,
$T_{\rm IM}$ =16.1 K, $\ell_{\rm sus}$ =30 cm, d_w =2.0 mm,
substrate absorption=50 ppm/cm, coating absorption=1.0 ppm

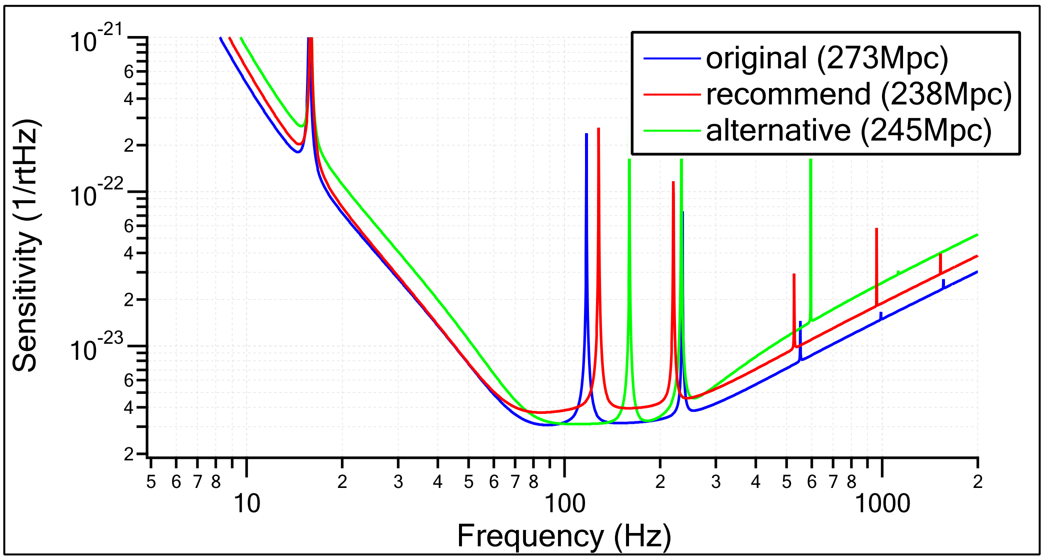

Figure 1: Sensitivity curves.

Besides the recommended setup, the alternative setup is selected as a backup plan with a higher sensitivity, though it cannot be the baseline design until more investigation for the thick fiber suspension and the high detune phase is done.

Figure 1 shows the sensitivity spectra with the three setups. More detailed discussions are to be made in the following sections.

2 Background

We decided to purchase all the Sapphire mirrors for bLCGT within the first 3 years on the budget of the *Leading-edge Research Infrastructure Program*. There are mainly two reasons for the decision:

- We can expect a mirror company to make better Sapphire mirrors only after we order the actual mirrors.
- It is too risky to expect additional money to buy Sapphire mirrors in the future.

It takes more than 2 years for the company to make a Sapphire mirror. Waiting for the possible extra money, we would take a risk of not having a good Sapphire mirror when it is necessary.

Since we do not have as much time as expected to develop the Sapphire mirror (namely to measure the quality of a sample mirror and feed the information back to the mirror company), the mirror speculation shall be given from the one that is currently available. The mirror size will be smaller (ϕ25 cm $\rightarrow$ ϕ22 cm) and the substrate absorption will be higher (20 ppm/cm $\rightarrow$

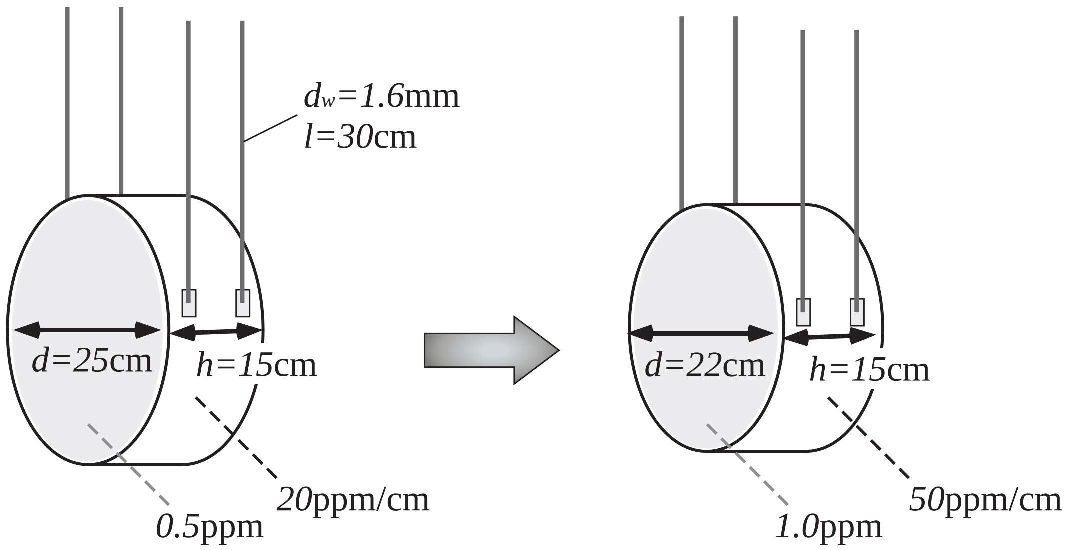

Figure 2: Mirror.

50 ppm/cm), as is shown in Fig. 2. The absorption could be better but this is the reasonable number from the actual measurement where the absorption ranged 32 $\sim$ 67 ppm/cm [3].

With the new mirror speculation, radiation pressure noise and suspension thermal noise increase for using a lighter mirror, and suspension thermal noise and mirror thermal noise increase for the higher temperature according to the more heat absorption.

The mirror size reduction could be circumvented by taking one of the following ways:

- To use the small C-axis ITM and a large A-axis ETM
- To use a Kamaboko mirror [4]

but neither of them was taken. As for the A-axis ETM, the radiation-pressure noise level could be the same as the original if the ETM can be as heavy as 44 kg, but suspension thermal noise of the ITM remains, and also the violin mode frequencies are different between the ITM and the ETM unless a thinner fiber is used for ETM. As for the Kamaboko mirror, it is pointed out that the polishing of the Kamaboko might be not as easy as that of the cylinder [5].

In this report, we consider the new optimal setup under the new condition. Besides the new mirror speculation, we shall include two more missing factors. One is that the coating absorption may be not as low as 0.5 ppm. The other is that the scattering light on the mirror surface will hit and heat up the inner radiation shield and the temperature of the shield may increase if the total heat exceeds the limit of the cryo-cooler capacity [6]. See Sec. 4 for more detailed explanations of the heat-flow model.

3 Possible answers

Full power, high temperature With the same finesse, full incident power, and the same suspensions, the temperature of the mirror increases and so do mirror and suspension thermal noise levels.

Reduced power, 20 K The incident power is reduced so that the mirror temperature can be 20 K even with the high absorptions.

Reduced power, 20 K, lower finesse It is known that the inspiral range for the neutron-star binaries can be higher with a lower finesse when the incident power is reduced. The optimal detune phase is higher and the bandwidth becomes a bit narrower.

Full power, 20 K, thicker suspensions Increasing d_w even more, the heat extraction via fiber increases and the mirror temperature can be 20 K even with the full incident power, though suspension thermal noise increases.

Other choices Alternative choices would include *extreme RSE*, *half cool operation*, etc.

4 Heat-flow model

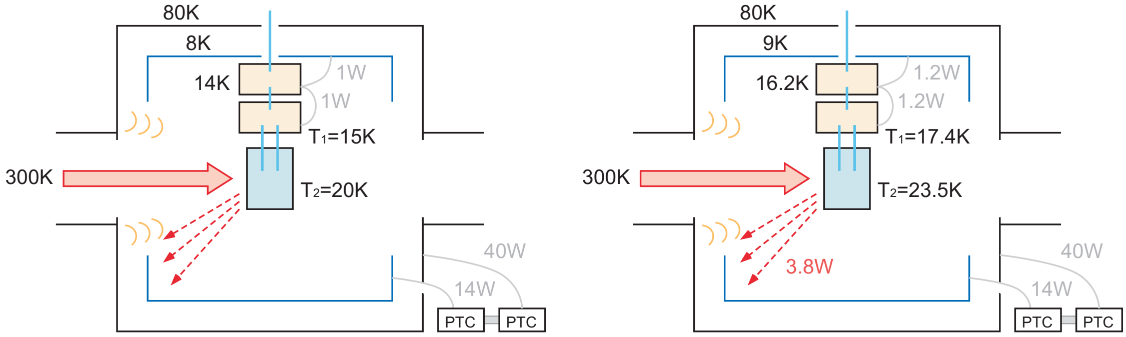

Figure 3: Heat flow (left: old, right: new).

The heat flow from the mirror that absorbs the heat from the laser beam to the pulse-tube cooler (PTC) is roughly modeled as follows (see Fig. 3).

- PTC cools the inner shield down to 8 K with 14 W total heat to be absorbed. We estimate that the shield temperature $T_{\rm is}$ increase by $T_{\rm is} = 8 + (P_{\rm sc} - 2)/2$ [K] where $P_{\rm sc}$ is the power from the scattering light that is absorbed at the inner shield.
- Most of the large-angle scattering light caused by point-like defects on the mirror surface is absorbed by the inner shield that is coated by diamond-like carbon (see Ref. [7] for more discussions); $P_{\rm sc} = P_{\rm arm} \times 10$ ppm where $P_{\rm arm}$ is the power in each arm cavity.

- Thermal conductivity of a pure Aluminum peaks at around $10 \sim 20$ K so that we can roughly say that it does not depend on the temperature in this region. We estimate that the extractable heat between the inner shield and the platform or that between the platform and the intermediate mass be simply proportional to the temperature difference.

- ITM absorbs the heat of $P_{\rm arm} \times 1$ ppm $+ P_{\rm prc}/2 \times 1500$ ppm and ETM absorbs the heat of $P_{\rm arm} \times 1$ ppm, where $P_{\rm prc}$ is the light power in the power-recycling cavity ($P_{\rm arm} = P_{\rm prc} \times \mathcal{F}/\pi$; $\mathcal{F}$ is the finesse of the arm cavity).

- Heat will be also introduced from the 300 K radiation and so on [8]. The total of those miscellaneous heats is estimated to be 200 mW.

The original requirement for the absorption rate was 0.5 ppm for the coatings and 20 ppm/cm for the mirror substrate, but it has turned out to be hard to realize. The new, realistic estimate is 1.0 ppm for the coatings and 50 ppm/cm for the mirror substrate.

With the full power ($P_{\rm prc} = 825$ W), the mirror temperature will be 23 K instead of 20 K. Decreasing the incident power, the temperature decreases and reaches 20 K when $P_{\rm prc} \to$ 516 W. These underlined numbers depend on the finesse of the arm cavity as is shown in Fig. 4.

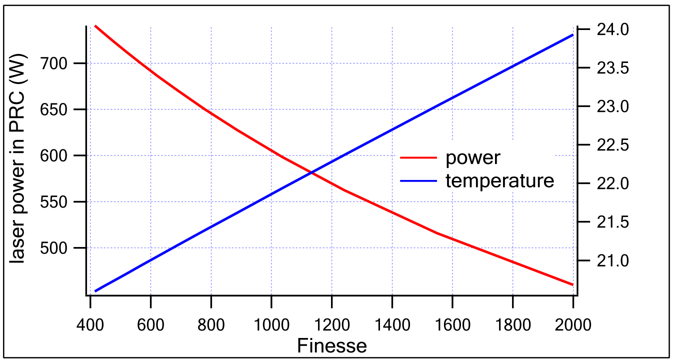

Figure 4: Power and temperature as functions of arm-cavity finesse.

5 Sensitivity curves

Sensitivity spectra are calculated according to the heat-flow model. Thermal parameters of Sapphire substrate depend on the temperature and also thermal conductivity of the Sapphire fiber depends on its thickness [9]. These facts are taken into account in the calculation.

Figure 5 shows contour plots of the inspiral range (IR) as a function of ITM transmittance ($\simeq 2\pi/\mathcal{F}$) and the SRM transmittance. Here the IR is calculated with the assumption that the gravitational waves come from the top of the sky. Detune phase and DC-readout phase are chosen at each point to maximize the IR. The bandwidth is not shown but it tends to be

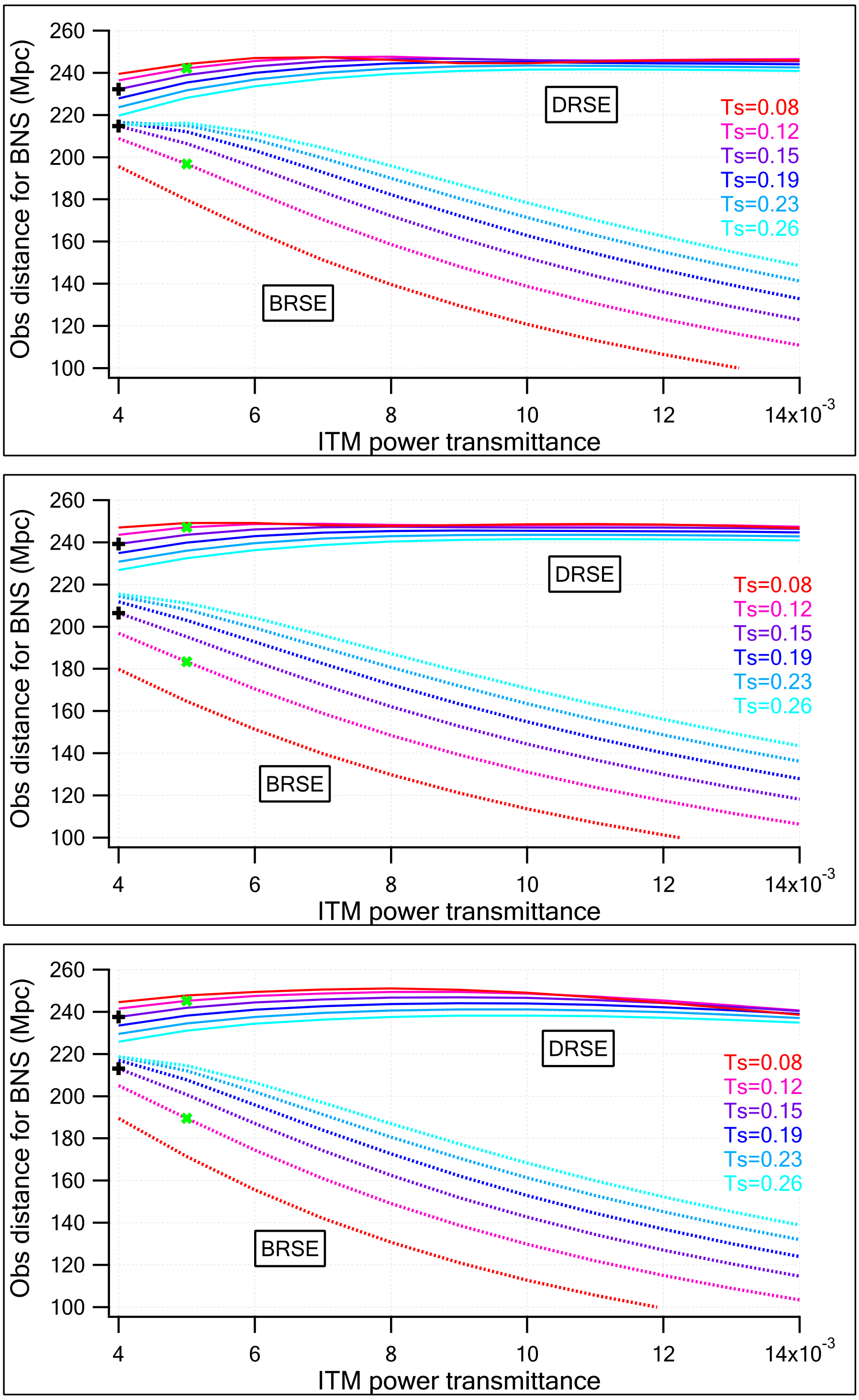

Figure 5: Contour plots of IR. *Top*: Full power, $T_{\rm m} = 23$ K, 1.6 mm fiber, *Middle*: low power, $T_{\rm m} = 20$ K, 1.6 mm fiber, *Bottom*: Full power, $T_{\rm m} = 20$ K, 2.0 mm fiber.

narrow when the IR for detuned RSE (DRSE) is much higher than that for the broadband RSE (BRSE) with the same optical parameters.

We have chosen a pair of parameter sets in each plot. One is for the high IR with DRSE and the broad range with BRSE (green $\times$). The other is for the decent IR and quite broad range with DRSE (black +). We can change from DRSE to BRSE when we change the target from the NS binaries to other sources, which is especially important in the former case. It can be done without changing the mirrors, namely just by changing the control offset on the signal-recycling mirror. Let us see the sensitivity spectra to downselect the candidates.

Figure 6 shows the sensitivity spectra. The [red, gray] pair on the top (bottom) panel corresponds to the black + (green $\times$) pair in the top panel of Fig. 5. The [blue, light blue] pair on the top (bottom) panel corresponds to the black + (green $\times$) pair in the middle panel of Fig. 5. The black dotted curve on the top (bottom) panel corresponds to the black + (green $\times$) on the DRSE curve in the bottom panel of Fig. 5. Sensitivity curves of different colors in each panel are compatible, that is, they can be realized by changing the detune phase and the incident power, except for the black dotted curve that is realized by changing the suspension fiber. The finesse and the SRM reflectivity are different between the two panels.

Table 1 shows the summary of the setup parameters with the inspiral range and the sensitivity at 1 kHz ($1/\sqrt{\mathrm{Hz}}$). For the candidate A, the mirror temperature is calculated with the heat-flow model (Sec. 4). For the candidate B, the fiber thickness is changed to 2.0 mm so that the mirror temperature can be 20 K according to the heat-flow model. For the candidate C and D, the fiber thickness is 1.6 mm, and the incident power is changed to 516 W and 562 W, respectively, so that the mirror temperature can be 20 K. One issue of realizing C or D is that the detune phase is higher than that for the original setup ($\phi = 3.5$ deg). In the case that the detune phase is limited to 3.5 deg, the candidate C and D will change to C' and D', respectively. The candidate E is similar to the candidate B but with a lower finesse. Actually the mirror temperature of E is slightly lower than B; 20.3 K for B and 19.7 K for E.

	description	T_{m}	P_{prc}	ϕ	IR	h(1kHz)
A	full power	23 K	825 W	2.9 deg	232 Mpc	1.3e-23
B	full power, 2.0mm fiber	20 K	825 W	3.4 deg	238 Mpc	1.5e-23
C	low power, high finesse	20 K	516 W	6.1 deg	239 Mpc	2.1e-23
C'	C with decent detune	20 K	516 W	3.5 deg	238 Mpc	1.9e-23
D	low power, low finesse	20 K	562 W	6.3 deg	247 Mpc	3.6e-23
D'	D with decent detune	20 K	562 W	3.5 deg	226 Mpc	2.1e-23
E	B with low finesse	20 K	825 W	5.6 deg	245 Mpc	2.6e-23

Table 1: Setup parameters of the candidates.

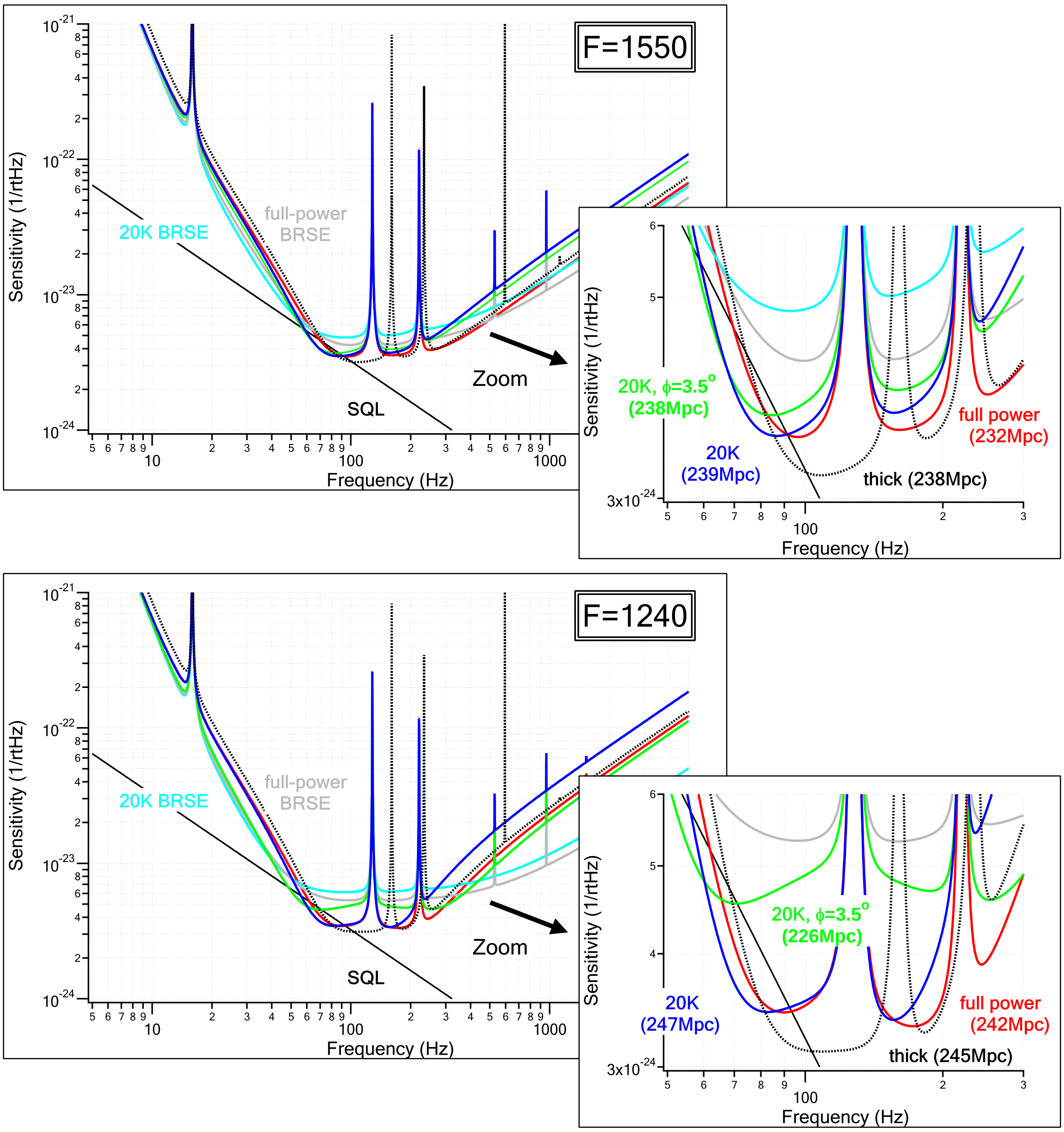

Figure 6: *Top*: $\mathcal{F} = 1550$, $R_s = 85$ %, *Bottom*: $\mathcal{F} = 1240$, $R_s = 88$ %. The spectra in a same graph are compatible by altering the incident power or by changing the detuning, except that the suspension fiber has to be changed to realize the dotted-curve spectrum.

6 Data-analysis point of view

6.1 Estimation of the source parameters for NS binaries

Measurement of the source characteristics is an important task in the data analysis. Especially, the arrival time accuracy will become important in the determination of the source direction. Table 2 shows the estimation error of chirp mass[1]($M_{\rm c}$), the ratio of effective mass and total mass (η), and arrival time ($t_{\rm arr}$) that are obtained from a NS-NS binary inspiral. The broader the bandwidth, the less the estimation error. While the IRs of D and E are higher than other candidates, the estimation error levels are also high for the two candidates.

	NS-NS	BH-BH	$\Delta M_{\rm c}$	$\Delta\eta$	$\Delta t_{\rm arr}$
A	494 Mpc*	1155 Mpc*	7.0e-5*	7.5e-3*	0.29*
B	498 Mpc	1174 Mpc	8.2e-5	8.3e-3	0.32
C	504 Mpc	1199 Mpc	7.2e-5	8.4e-3	0.39
C'	500 Mpc	1186 Mpc	6.8e-5	7.9e-3	0.36
D	522 Mpc	1253 Mpc	7.7e-5	9.6e-3	0.54
D'	476 Mpc	1122 Mpc	6.5e-5	7.9e-3	0.37
E	517 Mpc	1233 Mpc	8.8e-5	9.5e-3	0.44
aLIGO	655 Mpc	1546 Mpc	2.0e-5	3.2e-3	0.14
AdV	508 Mpc	1166 Mpc	7.2e-5	7.6e-3	0.30

Table 2: Parameter estimates.

6.2 Gravitational waves from supernovae

We have compared a highly narrowband DRSE configuration with low thermal noise (T=20 K, low power) and a decent narrowband DRSE configuration with low shot noise (T=23 K, full power) in terms of the detection of gravitational wave bursts from supernovae, using the waveforms in 6 catalogs collected in Ref. [10]. The number of waveforms including both the Newton model and the relativistic model is 356. Expected signal-to-noise ratios for supernovae located at 10 kpc from the earth are calculated using characteristic strain h_c and frequency f_c defined in Ref. [11]. Note that we use $P_{\rm prc} = 275$ W instead of 516 W in this argument. With the low-power configuration, 112 waveforms are detected, and with the full-power configuration, 75 waveforms are detected with SN$\geq$5. According to our simulation, the low-power configuration is preferable for supernovae. One may think that the broad bandwidth be preferable, but the best sensitivity in the spectrum matters more indeed.

7 Discussions and conclusion

A (23 K, 825 W) The inspiral range of the detector with this setup is 232 Mpc, which is lower than the others. In addition, this setup owns a risk that some uncertain thermal parameters such as heat absorption of the mirror and thermal conductivity of fibers may be

[1]total mass $\equiv M_t = m_1 + m_2$, $\eta = m_1 m_2 / M_t^2$, chirp mass $\equiv M_{\rm c} = M_t \times \eta^{3/5}$

worse than expected and decrease the sensitivity. The inspiral range will decrease to 225 Mpc if the temperature increases to 25 K, for example. Note that the risk is lower in the other setups since mirror thermal noise, especially substrate thermoelastic noise, does not limit the sensitivity much at 20 K.

B (20 K, 825 W, thick fiber) Both mirror thermal noise and shot noise are low but suspension thermal noise increases in this setup. There is a risk in this setup that the sensitivity could not be recovered much even if the thermal parameters be better than expected. In addition, some more investigation would be necessary for pitch/yaw modes.

C/C' (20 K, 516 W) Mirror thermal noise is low but shot noise is high in this setup. The inspiral range is not so different between C and C' while the detune phase of C' is lower, for which control noise would be lower, thus there would be no point of choosing C over C'. The inspiral range is not higher but as high as the LCGT target (240 Mpc).

D/D' (20 K, 562 W, low finesse) In the case of the low-power operation, the inspiral range can be recovered by decreasing the finesse and increasing the detune phase. The inspiral range with the setup D is higher than the LCGT target. On the other hand, the parameter estimation accuracy is lower than the others. Another issue is the high detune phase. With $\phi = 3.5$ deg, the setup D', the inspiral range decreases remarkably.

E (20 K, 825 W, thick fiber, low finesse) In this setup, the inspiral range can be recovered by decreasing the finesse and increasing the detune phase as well as the setup D, since suspension thermal noise is high and radiation pressure noise does not limit the sensitivity. The inspiral range of this setup is higher than the LCGT target.

Conclusion The setup C' seems to be the safest of all the candidates above. The only issue is the inspiral range slightly lower than the LCGT target (and also the range of AdVirgo). The setup E can be the backup plan. After more investigation of the heat absorption of the mirror and the pitch/yaw mode thermal noise of the thick suspension fiber, we may change the baseline design from C' to E.

A Opinions of the working group members

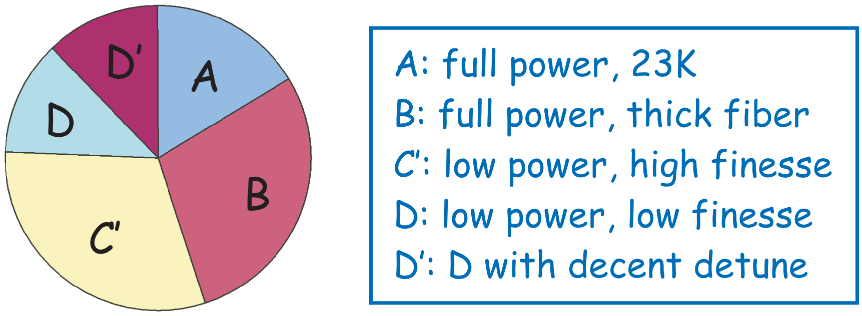

Figure 7: Popularity chirt.

Opinions of the working group members that were corrected after the meeting on 2011.9.22 are as follows. We compared the candidates A∼D' and took a vote. The candidate E shown in Table 1 was not included in the discussion.

- More investigation is necessary before we could decide to use thicker fibers. (Aso)
- The large peak at 110Hz should be removed somehow. (Kanda)
- C seems better than D as the IR drops quite badly in D when the detune phase cannot be so high. (Akutsu)
- It does not sound right to set the low-power operation the default design. (Miyakawa)
- Thicker fibers can be troublesome. (Uchiyama)
- C' would be the most robust one, which shall be the base design. After more investigation on the cryo-suspension and mirror absorption, we can change to B. (Ando)
- A is risky as some thermal parameters are unknown. With B, we will have no choice to recover the high IR even if some parameters be better than expected. Only D has the IR higher than AdV. (Somiya)

Figure 7 shows the popularity of the candidates at a vote in the working group.

B Consideration of the extreme RSE

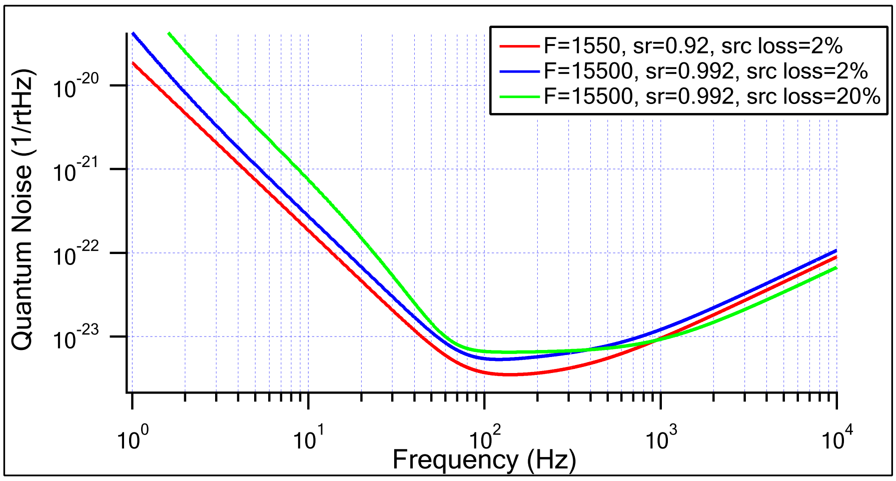

Figure 8: Extreme RSE.

Increasing the finesse and decreasing the power transmitting through the ITM substrate could be one way to solve the heat problem. It would be challenging to control high finesse arm cavities together with two recycling cavities. It would be thus rather a reasonable choice to further increase the finesse and remove the power-recycling cavity (extreme RSE). The total heat would be less than a half of the dual-recycled RSE.

However, it turns out that quantum noise of the extreme RSE cannot be as good as the dual-recycled RSE for the signal reduction due to optical losses. Figure 8 shows quantum noise curves of dual-recycled RSE and extreme RSE. Let us first compare the green curve and the red curve. The extreme RSE in green is worse at low frequencies and slightly better at high frequencies, but this is because the optical loss of the signal-recycling cavity increases the bandwidth of the interferometer. If the optical loss of the signal-recycling cavity were equal to that of the dual-recycled RSE, the bandwidth would be the same but the sensitivity would be worse at all the frequencies (blue curve).

C List of other parameters

parameter	value
beam radius on ITM	3.5 cm
beam radius on ETM	4.0 cm
optical loss of the test mass	45 ppm
transmittance of ETM	10 ppm
loss at photo-detection	10 %
density of Sapphire	4000 kg/m^3
Young's modulus of Sapphire	400 GPa
Poisson ratio of Sapphire	0.29
Substrate Q	10^8
thermal conductivity of Sapphire (20 K)	15700 (W/m/K)
thermal conductivity of Sapphire (23 K)	19600 (W/m/K)
heat capacity of Sapphire (20 K)	2760 ($J/m^3/K$)
heat capacity of Sapphire (23 K)	4280 ($J/m^3/K$)
expansion rate of Sapphire (20 K)	5.6e-9 (1/K)
expansion rate of Sapphire (23 K)	8.5e-9 (1/K)
number of coating doublets on ITM	9
number of coating doublets on ETM	18
mechanical loss of Silica coating	3.0e-4
mechanical loss of Tantala coating	5.0e-4
mechanical loss of Sapphire fiber	2e-7
mechanical loss of Tungsten fiber	1e-4
mechanical loss of BeCu fiber	5e-6
mechanical loss of clump	1e-3
vertical-horizontal coupling	1/200

References

[1] LCGT Special Working Group, "Study report on LCGT interferometer observation band," JGW-T0900056-v1 (2009)

[2] The inspiral range of aLIGO and AdVirgo are 309 Mpc and 243 Mpc, respectively.

[3] E.Hirose, K.Watanabe, and N.Mio, "Sapphire for the LCGT project," JGW-G1100626-v1 (2011)

[4] K.Somiya, "Optical Configuration Review," JGW-G1000267-v1 (2010)

[5] private communication with Prof. Ohashi.

[6] N.Kimura *et al.*, "Refrigerator and Cryostat Design for LCGT," talk at GWADW, Elba, JGW-G1100442-v1 (2011)

[7] K.Somiya, H.Yamamoto, Y.Sakakibara, and N.Kimura, "Point-like defect and the heat flow" JGW-G1100580-v1 (2011)

[8] Y.Sakakibara, "Incident Thermal Radiation through Duct Shield and Cooling Time of Mirror," talk at LCGT f2f meeting, Kashiwa, JGW-G1100540-v1 (2011)

[9] $\kappa_{\rm sus} = 5270 \times d_w \times T_{\rm sus}^{2.34}$ [W/m/K] ,
$\kappa_{\rm mir} = (0.272 \times T_{\rm m}^{-2.2} + 6.22 \times 10^{-9} \times T_{\rm m}^{3.04})^{-1.25}$ [W/m/K] ,
$C_{\rm s} = 0.227 \times T_{\rm m}^{3.14}$ [J/m^3/K] ,
$\alpha = 7.21 \times 10^{-13} \times T_{\rm m}^{2.99}$ [1/K] .

[10] http://www.stellarcollapse.org/gwcatalog

[11] K.S.Thorne, "Gravitational Radiation", a chapter in *"Three Hundred Years of Gravitation"*, edited by S.W.Hawking and W.Israel, p.330-458, Cambridge University Press, 1987