Mechanical Loss in Coatings at Cryogenic Temperatures

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LIGO-G080327-00-R

0. Abstract

Review of coating mechanical loss at cryogenic temperatures

(i) Studies in past

Measurement

Application (Parametric instability suppression)

(ii) Current and Future work

Loss reduction

Thermoelastic damping

Contents

1. Introduction

Thermal noise of coating mechanical loss

Fundamental limit of precision optical measurements

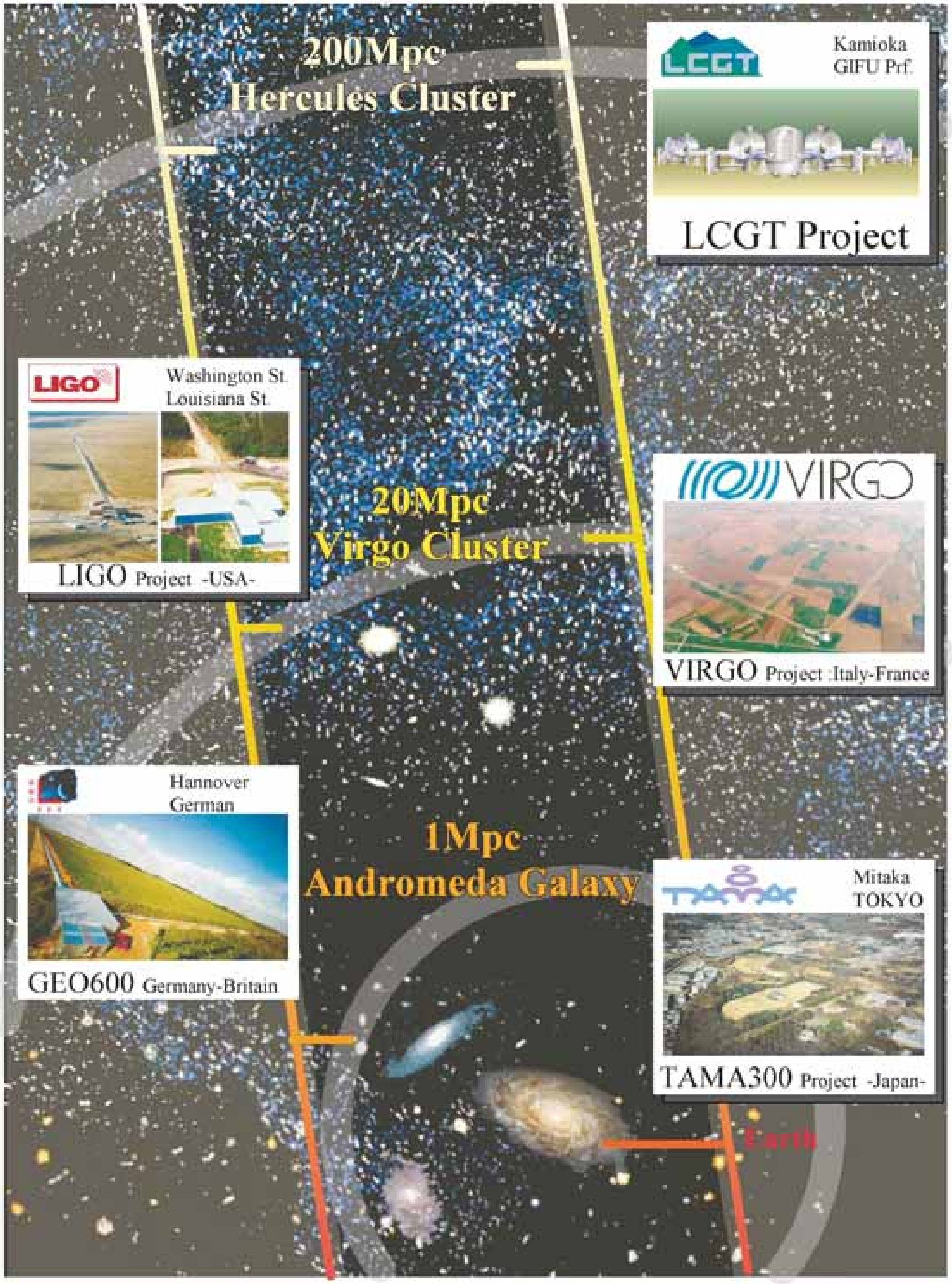
Gravitational wave detection,
Laser Frequency stabilization,
Quantum Optics, etc.

An idea to decrease coating thermal noise : cooling mirror

For example,

LCGT (Large-scale Cryogenic Gravitational wave Telescope:
Japanese future interferometric
gravitational wave detector project)

Kuroda talk (previous LSC meeting)



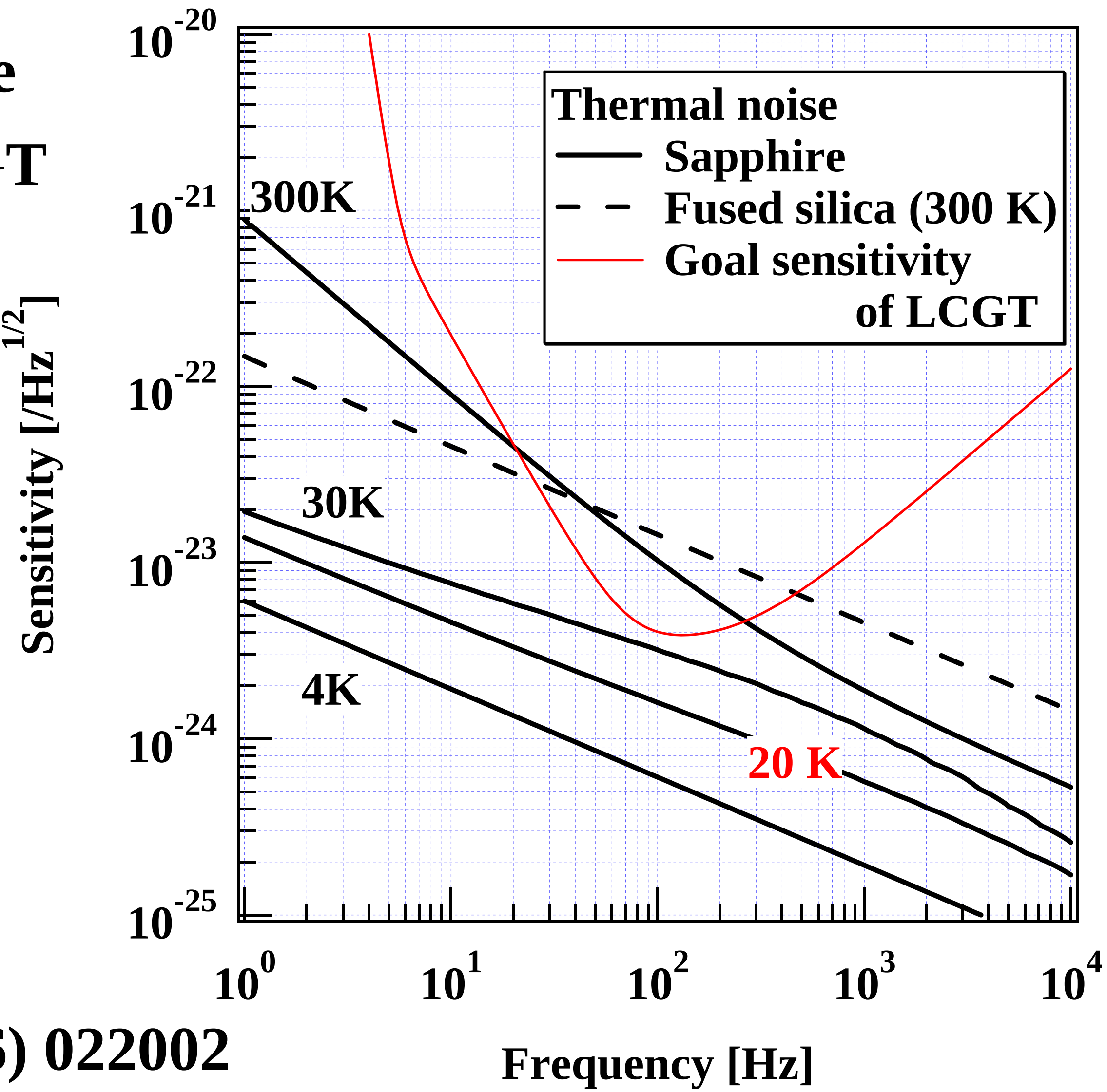
Interferometer project

Future project
(second generation)
LCGT, Adv LIGO
Chirp range : 200 Mpc
A few chirp events/year

Current project
(first generation)
LIGO, VIRGO
Chirp range : 20 Mpc

(third generation)
ET
(Einstein Telescope: Europe)
Cryogenic

Mirror thermal noise in LCGT



K. Yamamoto et al.,

Phys. Rev. D 74 (2006) 022002

How much must mirror temperature be ?

Temperature dependence of thermal noise

↓

Temperature dependence of coating mechanical loss

Review of researches about coating mechanical loss at cryogenic temperature

A few researches in past

Current and future work

2. Studies in Past

2-1. Measurement of coating mechanical loss

3 experiments (in refereed journal)

(1) University of Tokyo
K. Yamamoto et al., Physical Review D 74 (2006) 022002
First measurement

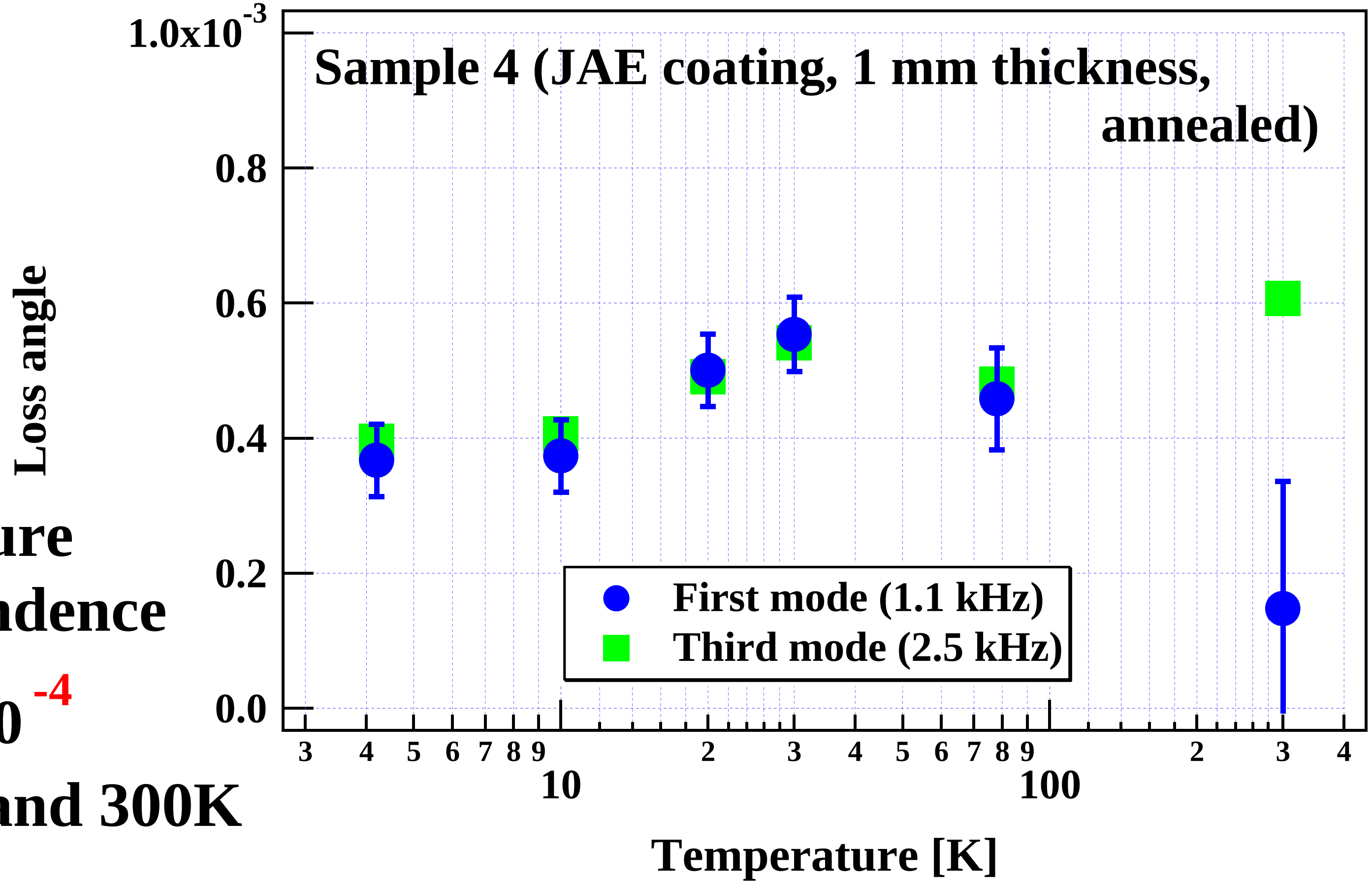
(2) Friedrich-Schiller-University Jena
R. Nawrodt et al., New Journal of Physics 9 (2007) 225
Coating on grating

(3) University of Glasgow
I. Martin et al., Classical and Quantum Gravity 25 (2008) 055005
TiO_2 doping

(1)University of Tokyo

K. Yamamoto et al., Physical Review D 74 (2006) 022002

First measurement SiO_2/Ta_2O_5 **coating**



Weak temperature dependence

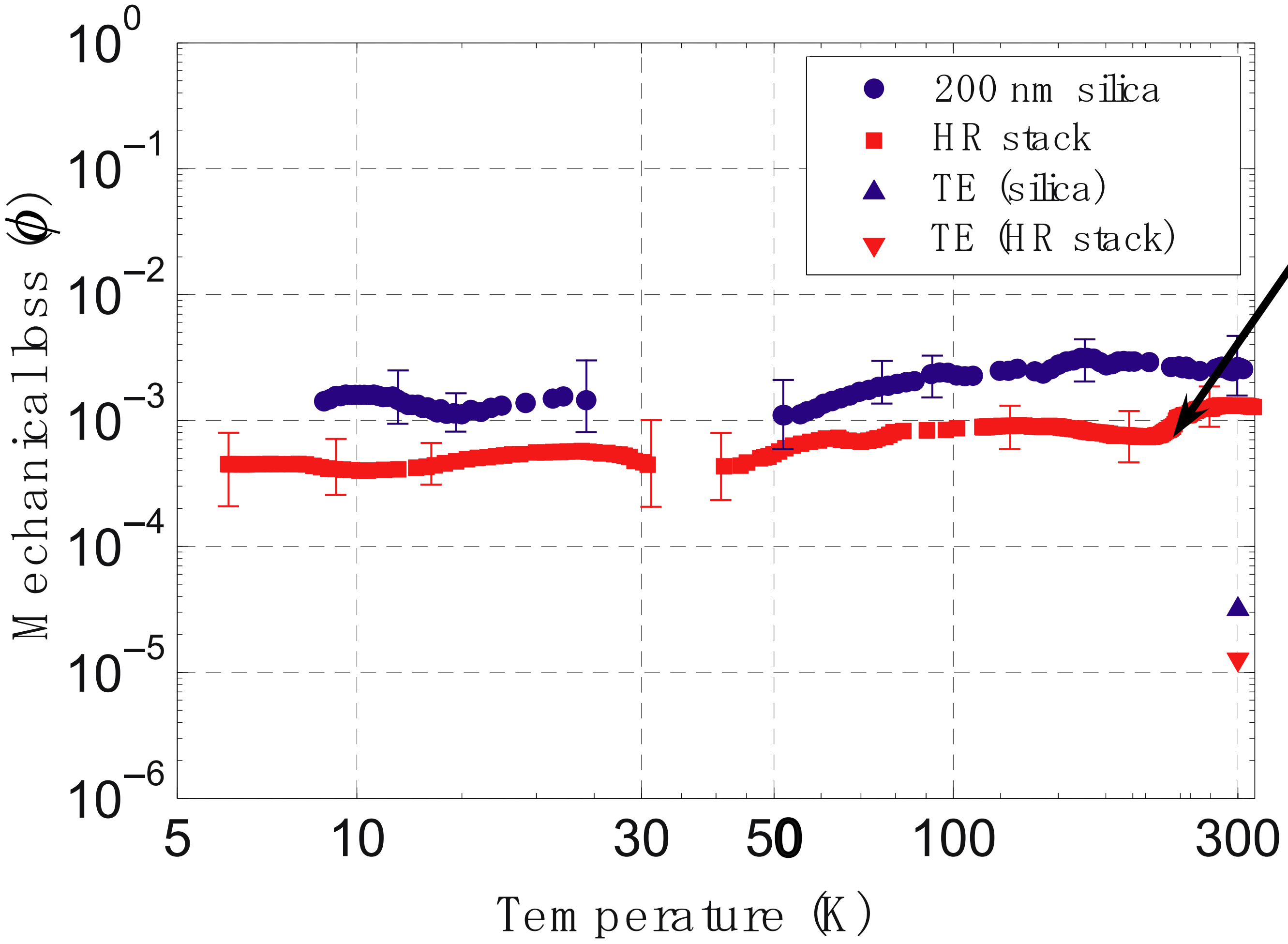
$\phi = (4 - 6) * 10^{-4}$

between 4K and 300K

(2) Friedrich-Schiller-University Jena

R. Nawrodt et al., New Journal of Physics 9 (2007) 225

SiO_2/Ta_2O_5 coating on grating



Red squares
SiO_2/Ta_2O_5 coating loss

Weak temperature dependence

ϕ = 4*10^{-4} at 10K

They said that this is comparable to the values reported by (1) University of Tokyo.

(3) University of Glasgow

I. Martin et al., Classical and Quantum Gravity 25 (2008) 055005

Ta_2O_5 doped with TiO_2 **(and his talk)**

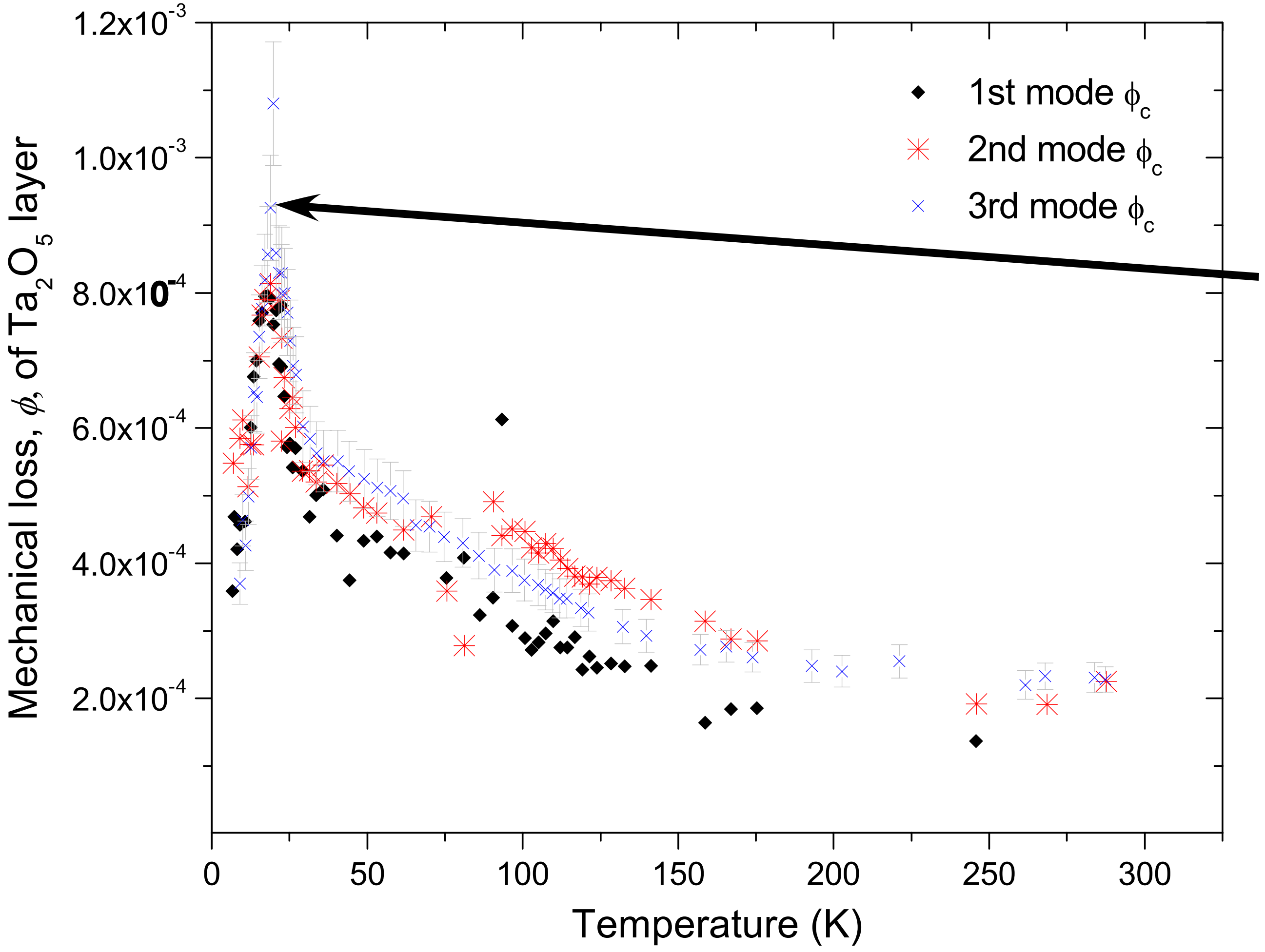


Figure 4. Temperature dependence of the loss of the doped Ta_2O_5 coating.

Peak at 20 K

This peak is comparable to the values reported by (1) University of Tokyo and (2) Friedrich-Schiller-University Jena.

smaller loss than that without doping except for 20K

Summary of measurement of coating mechanical loss

(I) SiO_2/Ta_2O_5 (Tokyo and Jena)

ϕ = several times 10^{-4}

Weak temperature dependence between 4 K and 300K

Loss angle is constant ⟶ thermal noise : $T^{-1/2}$

20K : 4 times smaller (Gravitational wave detection)
4K : 10 times smaller (Frequency stabilization and quantum optics)

(II) Ta_2O_5 doped with TiO_2 (Glasgow)

Peak at 20K

This peak is comparable to the values without doping.

smaller thermal noise than that of coating without doping
(2 times at most)

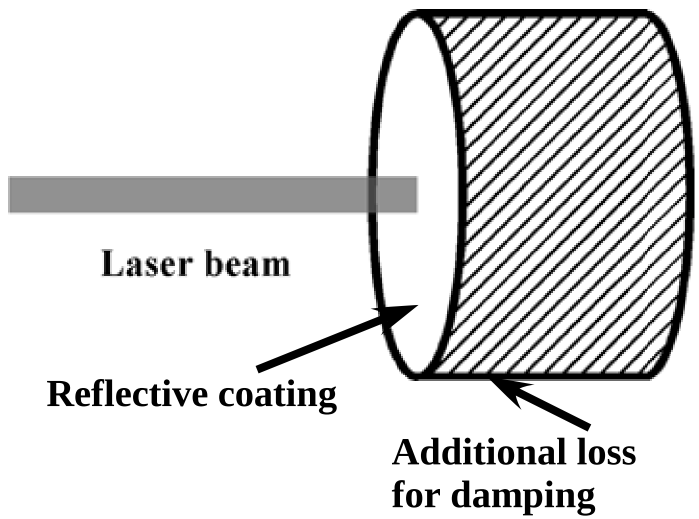
2-2. Application (for parametric instability suppression)

Parametric instability : excitation of optical and elastic mode

V.B. Braginsky et al., Physics Letters A 287 (2001) 331.

An instability suppression method : elastic Q reduction

S. Gras et al., Journal of Physics: Conference Series 32 (2006) 251.



0.2 mm thickness Ta_2O_5 (without doping) coating on barrel surface for LCGT

Effective at low temperature (Weak temperature dependence)

K. Yamamoto et al., Journal of Physics: Conference Series (accepted, proceedings of Amaldi7)

3. Current and future work

2 topics

(A) Mechanical loss reduction
(B) Thermoelastic damping at low temperature

3-1. Mechanical loss reduction

Annealing (coating doped with TiO_2)

Suggestion in
I. Martin et al., Classical and Quantum Gravity 25 (2008) 055005

Doping (except for TiO_2)

Other material Hafnia (E. Chalkley talk)

Investigation about loss mechanism

Optical properties check

3-2. Thermoelastic damping at low temperature

Thermoelastic damping : relaxation of thermal gradient by inhomogenous strain or media

lower limit of mechanical loss

2 problems (similar problems about thermorefractive noise: Andri Gretarsson talk)

(1) Formula of thermal noise

(2) Material properties of coating

(1) Formula of thermal noise

V.B. Braginsky et al., Physics Letters A 312 (2003) 244

M.M. Fejer et al., Physical Review D 70 (2004) 082003

Their formulae are not valid at low temperature.

Because laxation time of thermal gradient with beam size is smaller than period of gravitational wave at low temperature.

(2) Material properties of coating

thermal expansion, thermal conductivity, specific heat, Young modulus, Poisson ratio, density

Measurement is necessary.

Clue ?

Loss in SiO_2/Ta_2O_5(without doping)

: weak temperature and frequency dependence

Thermoelastic damping : strong temperature and frequency dependence in general

Some constrains on material properties ?

4. Summary

Review of researches about coating mechanical loss at cryogenic temperature

(A) Studies in past

(1) SiO_2/Ta_2O_5 ϕ = **several times 10^{-4}**

Weak temperature dependence → **thermal noise : $T^{1/2}$**

(2) Ta_2O_5 doped with TiO_2

Peak at 20K → **smaller mechanical loss except for 20K**

(3) Parametric instability suppression: Ta_2O_5 coating

(B) Current and future work

(1) Mechanical loss reduction

Annealing (coating doped with TiO_2), doping (except for TiO_2), other material...

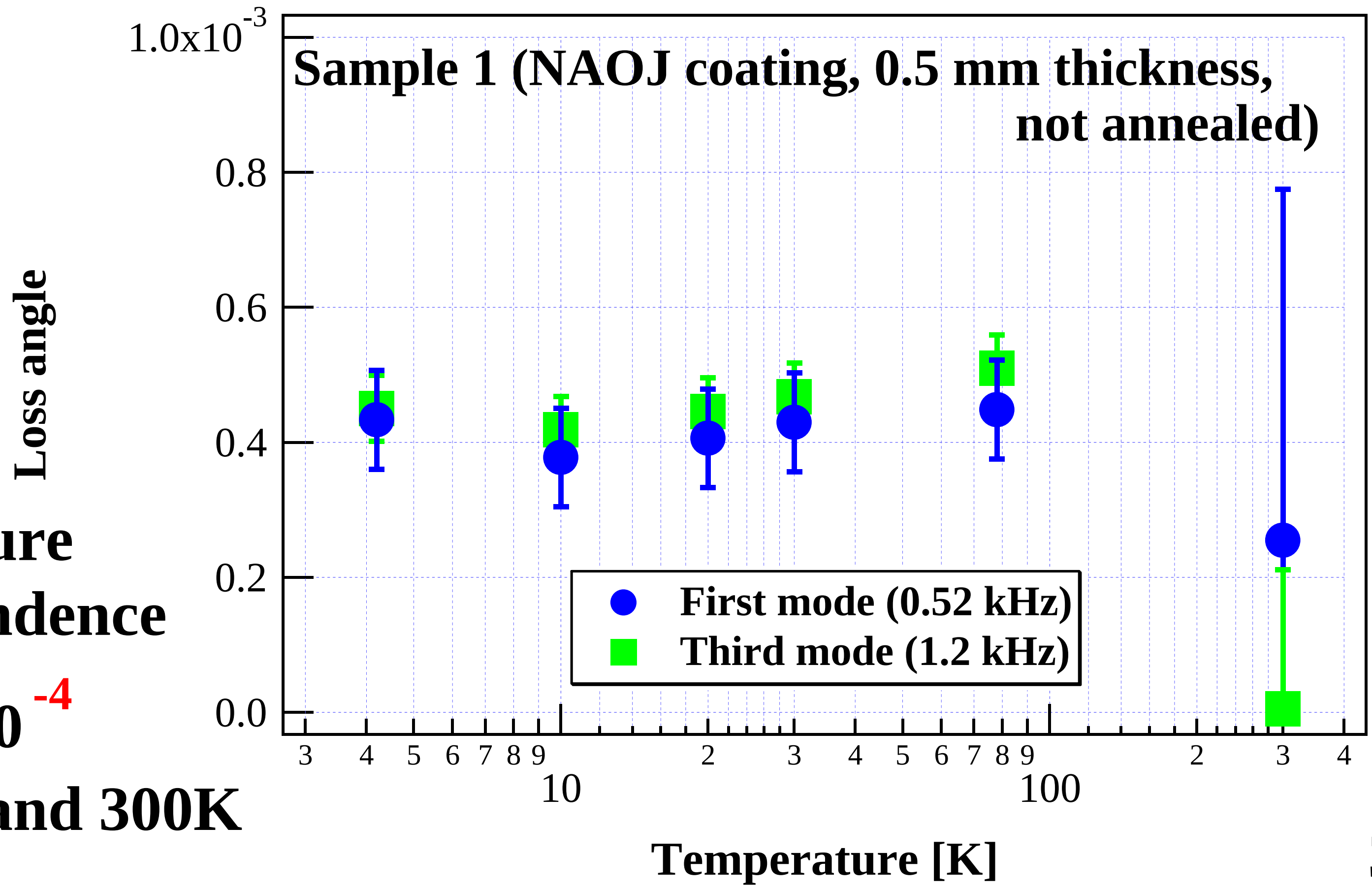
(2) Thermoelastic damping

Formula of thermal noise, material properties of coating

(1)University of Tokyo

K. Yamamoto et al., Physical Review D 74 (2006) 022002

First measurement SiO_2/Ta_2O_5 **coating**



Weak temperature dependence

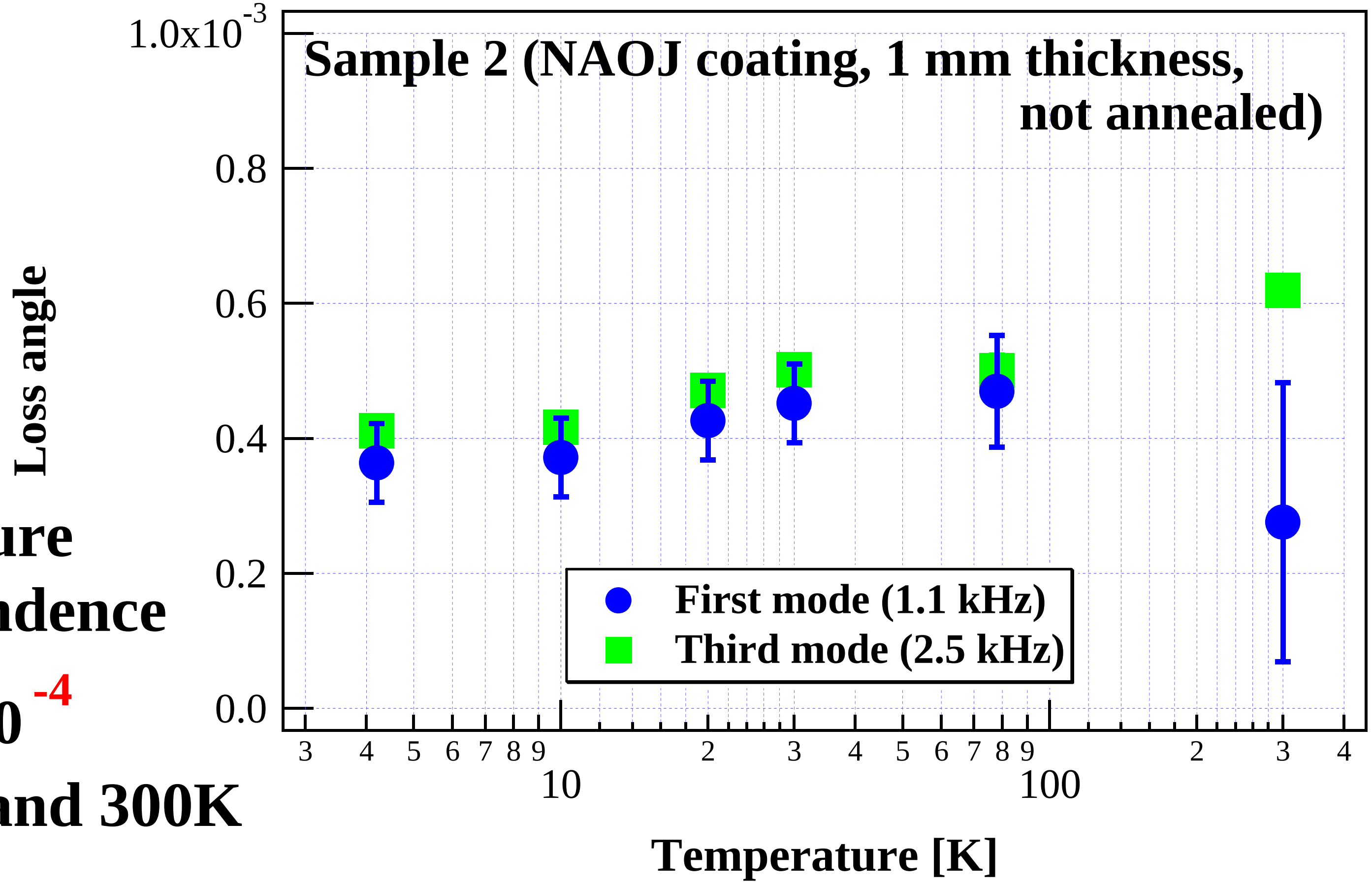
ϕ = (4 - 6) $*10^{-4}$

between 4K and 300K

(1)University of Tokyo

K. Yamamoto et al., Physical Review D 74 (2006) 022002

First measurement **SiO_2/Ta_2O_5 coating**



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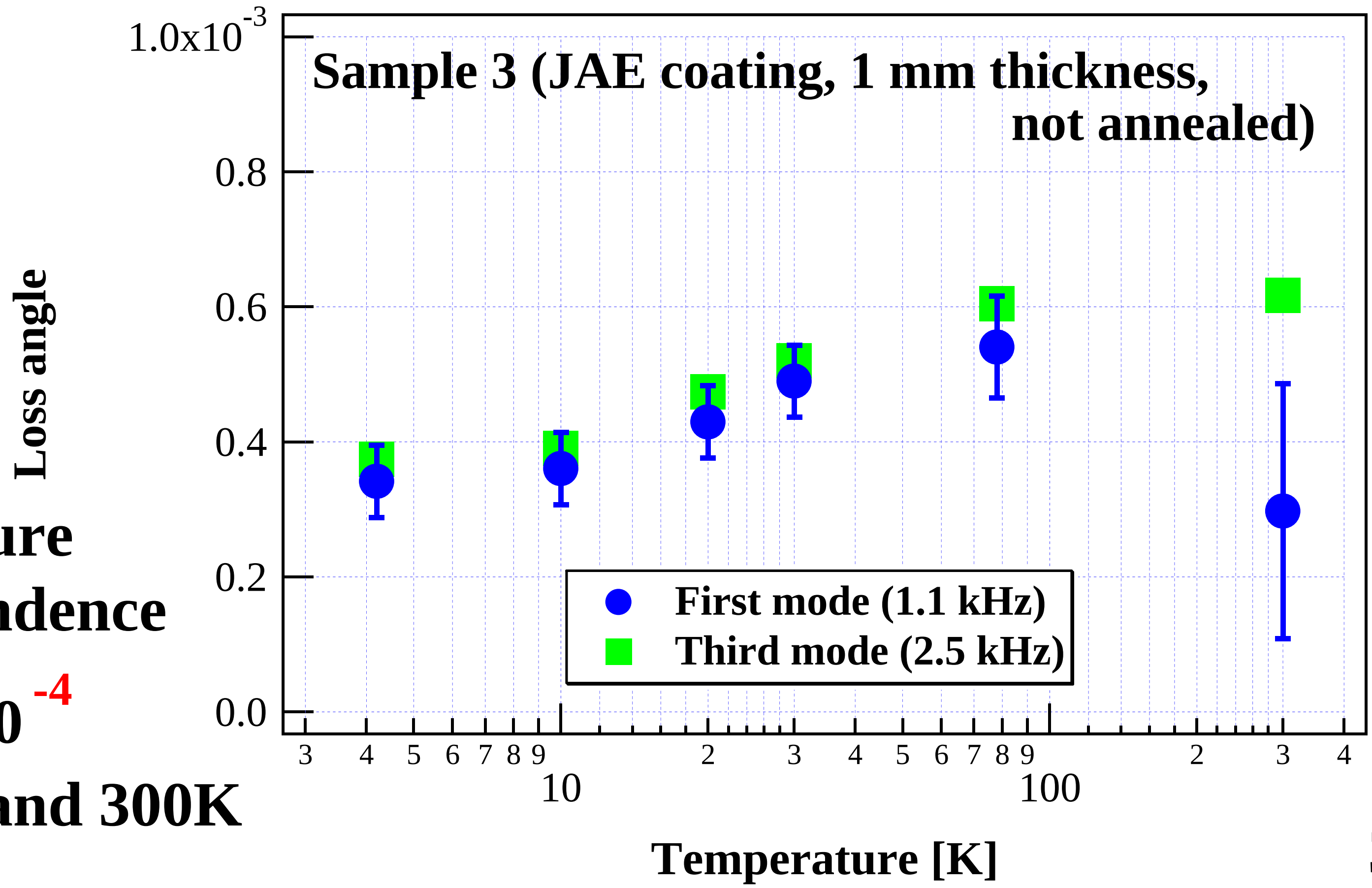

Weak temperature dependence

ϕ = **(4 - 6)** *10^{-4}

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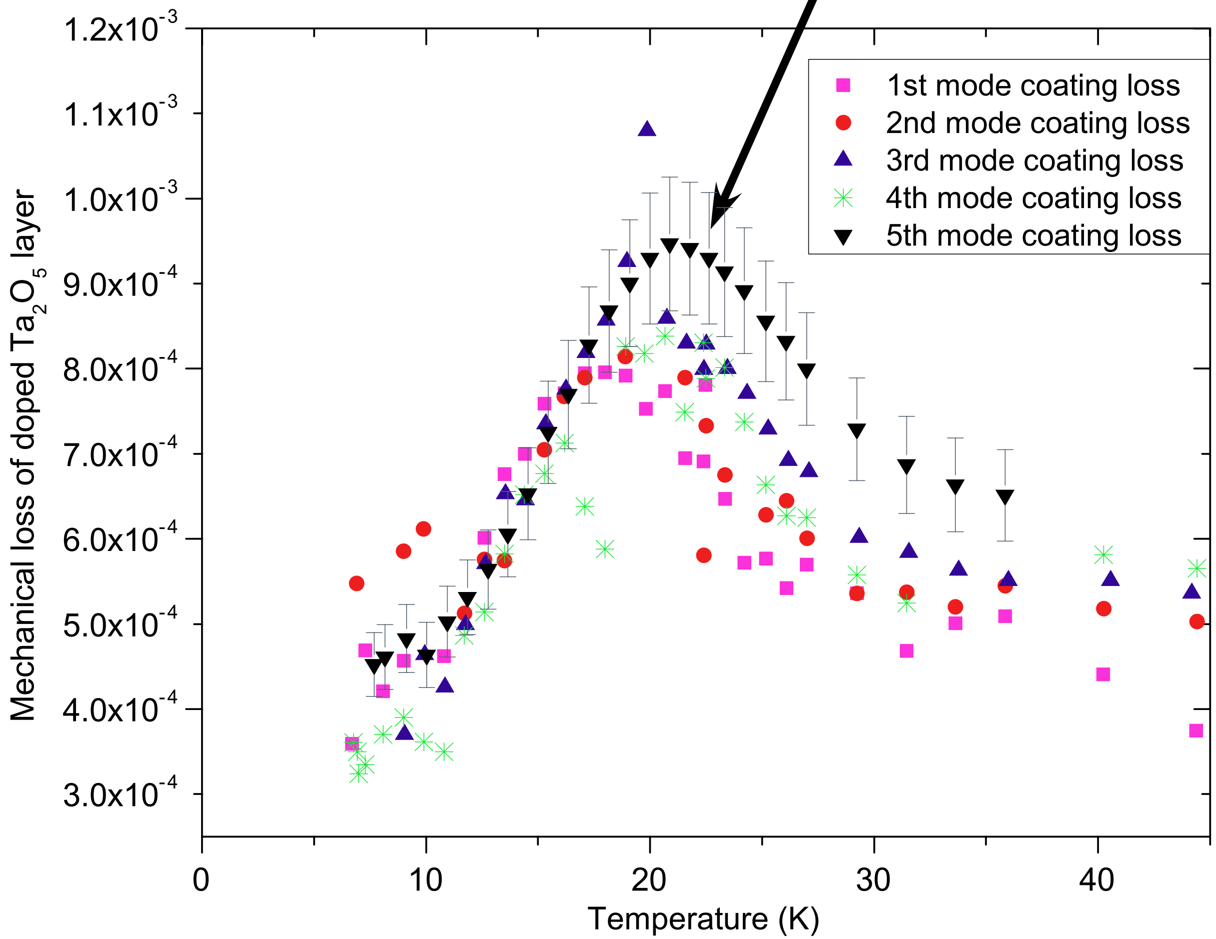
(3) University of Glasgow

I. Martin et al., Classical and Quantum Gravity 25 (2008) 055005

Ta_2O_5 doped with TiO_2 **(and his talk)**

Peak at 20 K



This peak is comparable to the values reported by (1) University of Tokyo and (2) Friedrich-Schiller-University Jena.

smaller loss than that without doping except for 20K

Massachusetts Institute of Technology
M.R. Abernathy et al., Physics Letters A 372 (2008) 87
Heating (300 K-330 K)

SiO_2/Ta_2O_5

$\phi = (4 - 6)*10^{-4}$

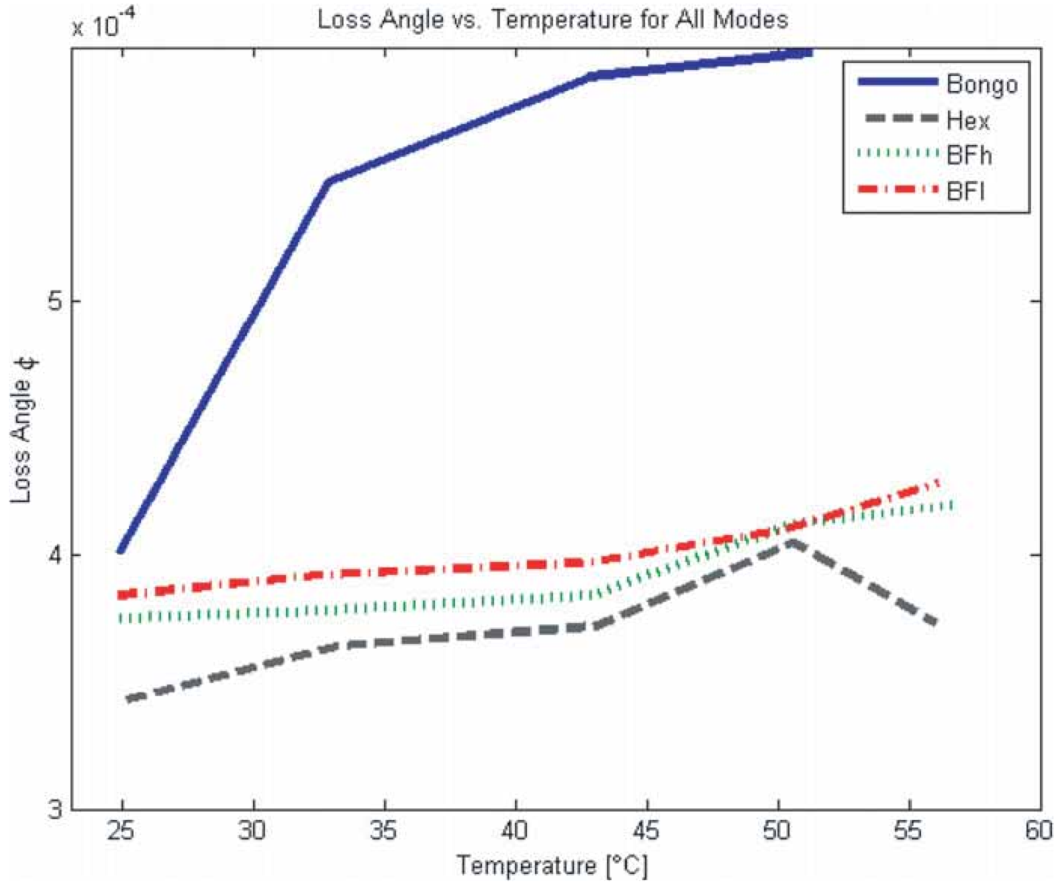
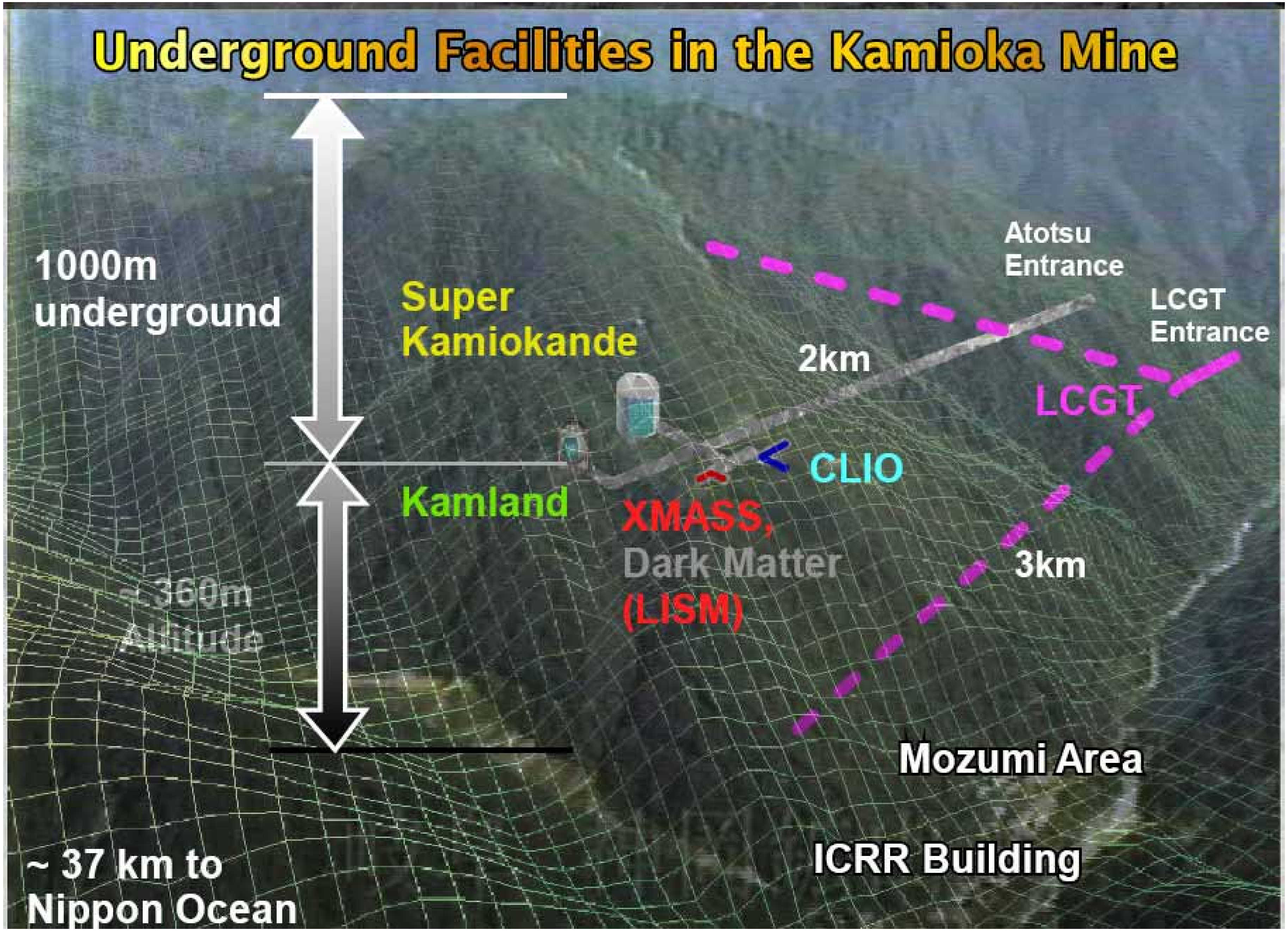
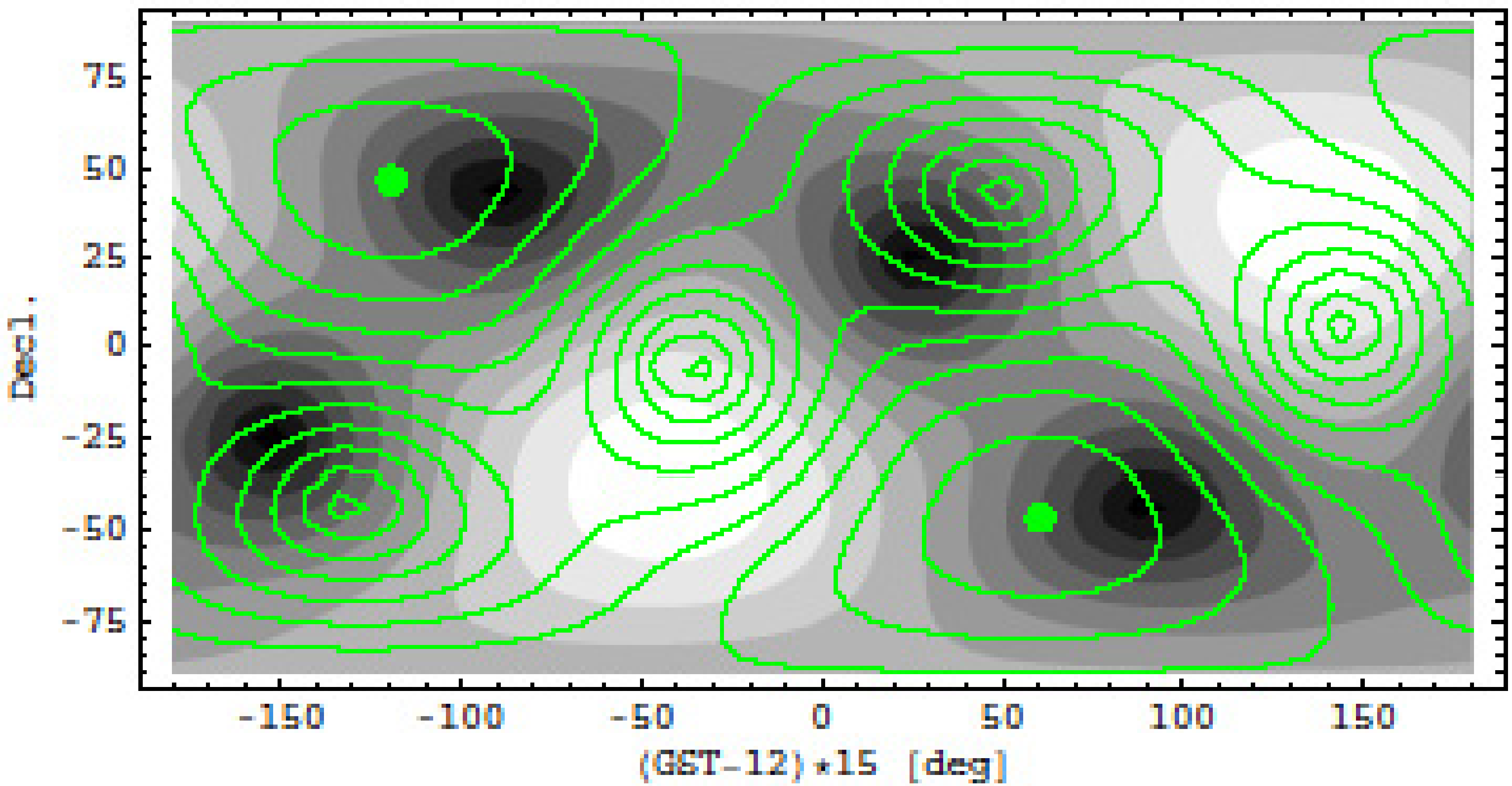


Fig. 1. Loss angle vs. temperature for each of the measured normal modes: Bongo 9400 Hz, Hex 6100 Hz, Bf-high (BFh) and Bf-low (BFl) 2700 Hz. The effect of temperature is more pronounced at higher frequencies.

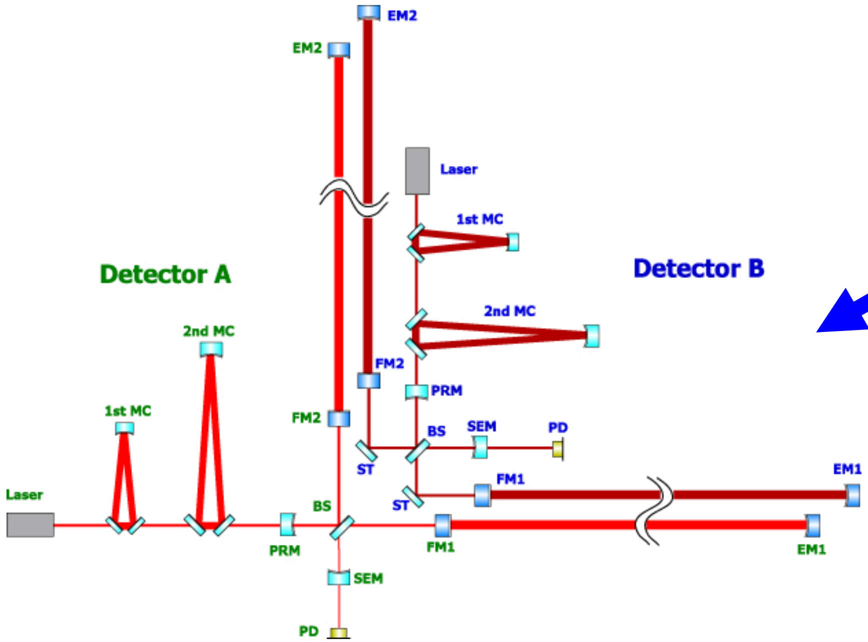


Underground Facilities in the Kamioka Mine
1000m
underground
Super
Kamiokande
Kamland
~360m
Altitude
XMASS,
Dark Matter
(LISM)
CLIO
2km
Atotsu
Entrance
LCGT
Entrance
LCGT
3km
Mozumi Area
ICRR Building
~ 37 km to
Nippon Ocean

LCGT contributes the international observation by the coverage of a complimentary sky to other detectors:
LCGT, grey scale, LIGO (Hanford), green contour curves.

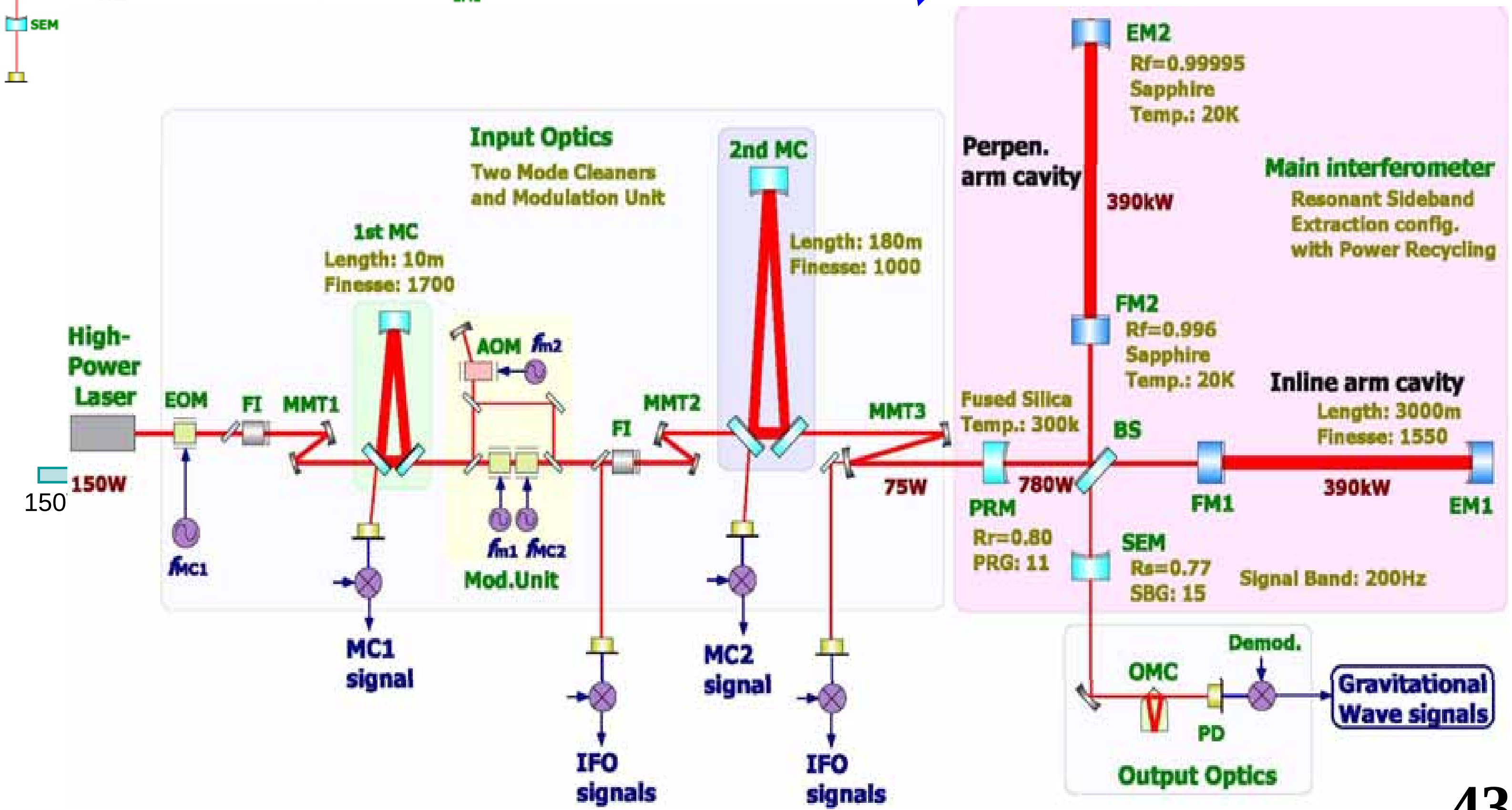


Optical design of LCGT

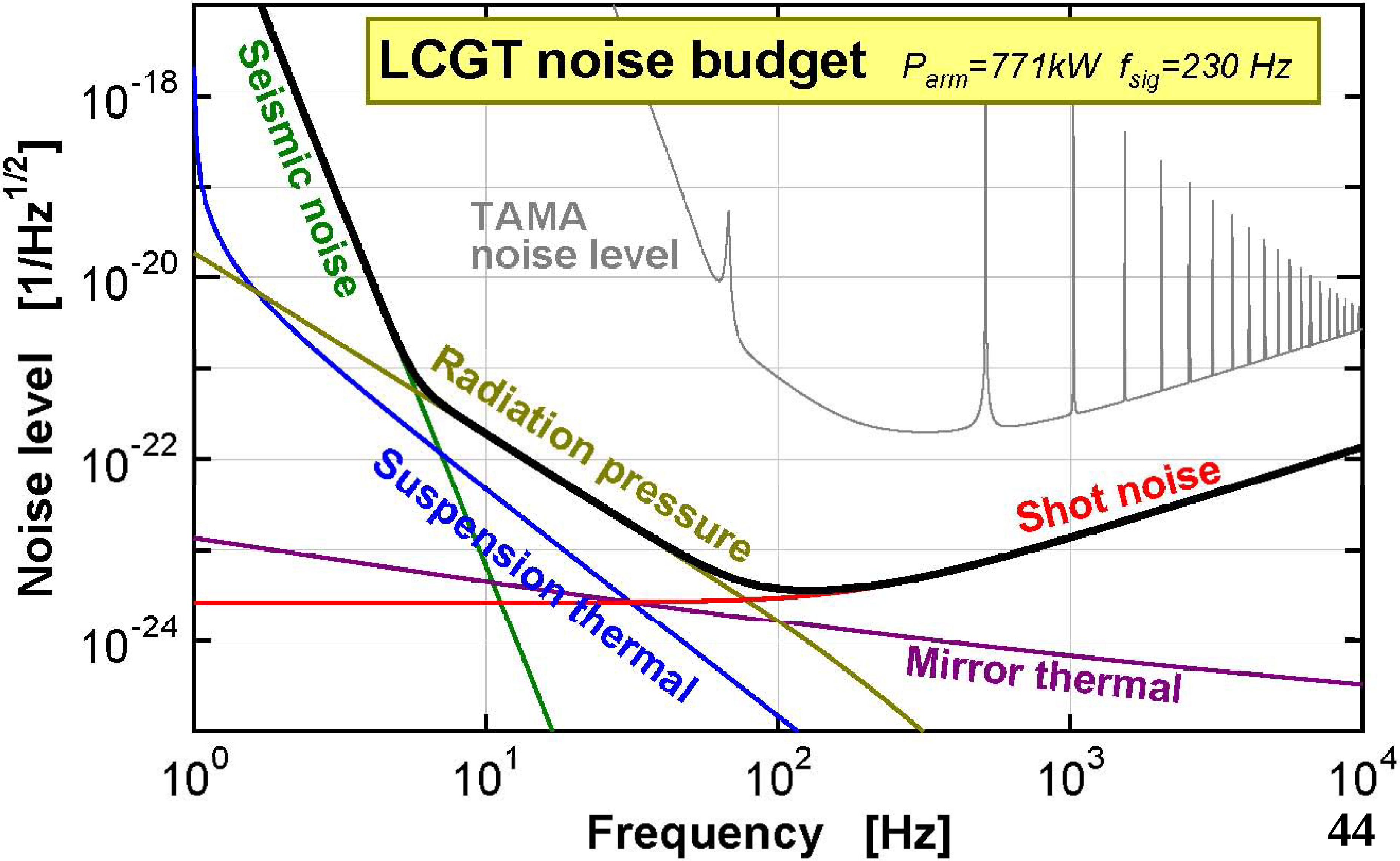


Two interferometers are arranged not to interfere in the same vacuum system.

Optical design of the basic interferometer



Sensitivity is limited only by quantum noises around at observational frequency band.



Optical Design Parameters

- Main Interferometer
  - Resonant Sideband Extraction
    with power recycling, broad band configuration
  - Arm cavity length 3000 m
  - Power in arm cavities 780 kW
  - Signal bandwidth 230 Hz
  - Arm cavity finesse 1550
  - Power recycling gain 11
  - Signal band gain 15

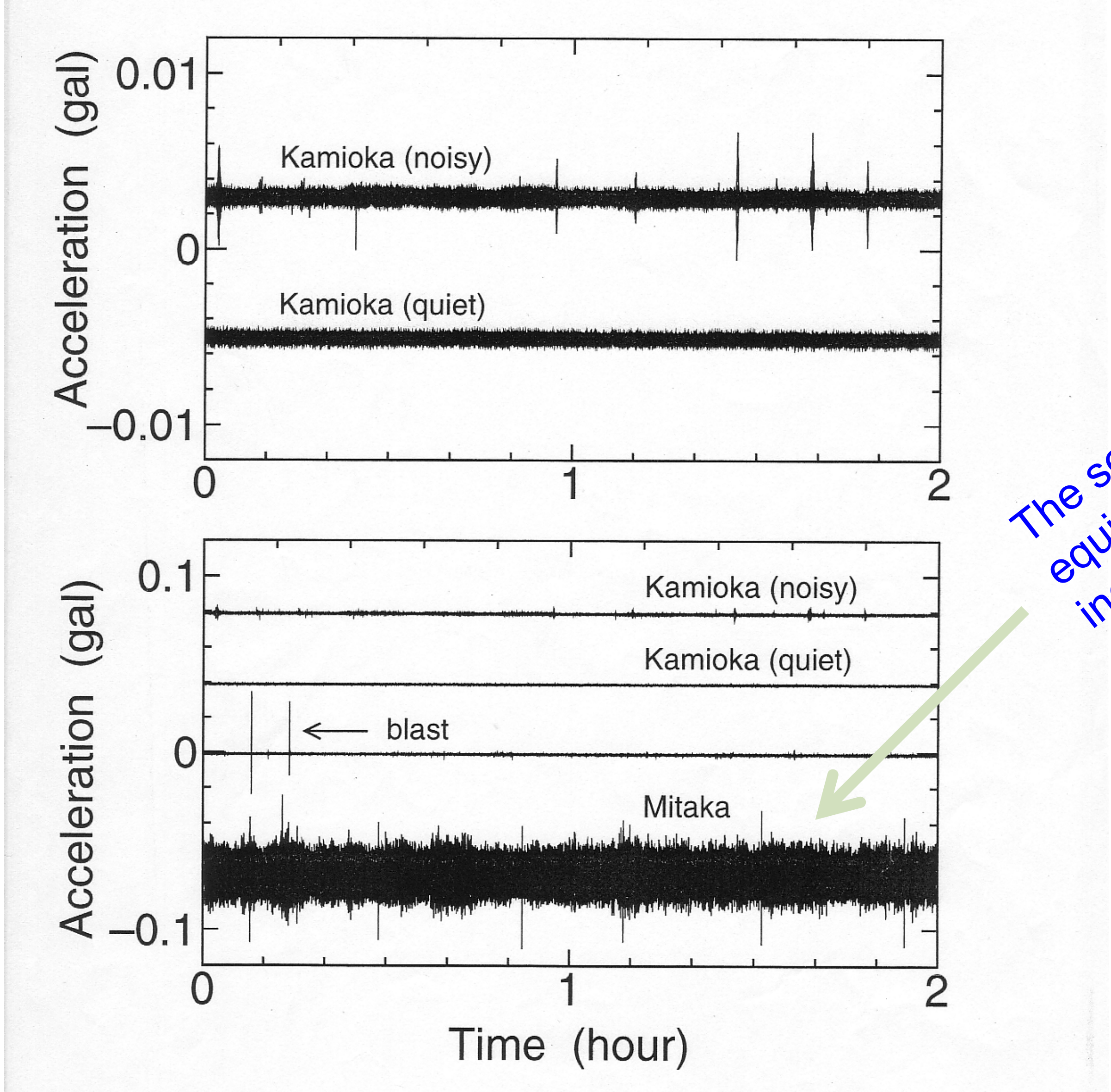
- Laser source
  - Output power 150W
  - Wavelength 1064nm

- Input optics
  - Power transmittance 33.3%
  - Modulation sidebands 15 MHz, 50 MHz
    - 1st Mode cleaner 10m Triangle ring cavity, 4.5kHz, FSR 15 MHz
    - 2nd Mode cleaner 180m Triangle ring cavity, 350Hz, FSR833kHz
- Core optics
  - Main Mirror: sapphire, 20K, 25cm, 15cm, 30kg, curvature 7km
  - Substrate optical loss 500ppm/15cm; heat absorption 20ppm/cm

- PRM, SEM, BS, MC mirrors: Fused silica

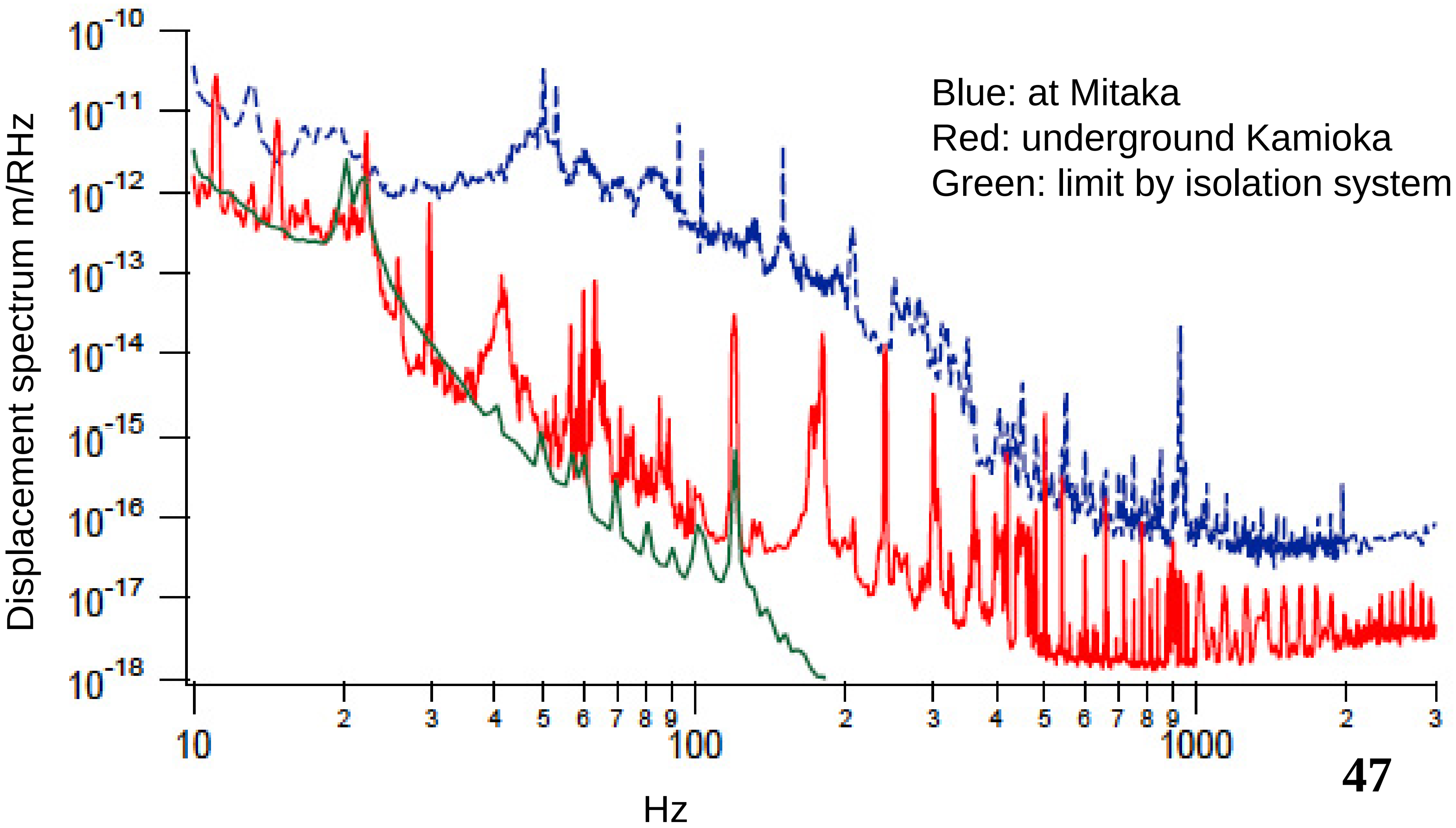
Why do we go underground?

In Kamioka low frequency noise is less than Mitaka by 30 times.



The seismic noise of Mitaka is equivalent to continuous blasting in Kamioka underground.

When the **20m** interferometer was moved from Mitaka to Kamioka mine, the noise at 100Hz was decreased by **4** orders and the spectrum limit by the anti-vibration system was achieved at frequencies less than 100Hz.

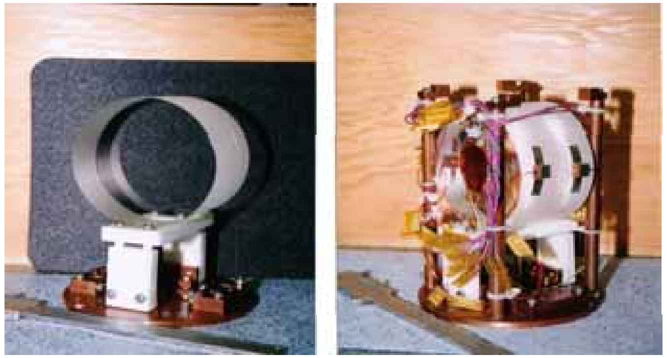


Why do we apply cryogenic?

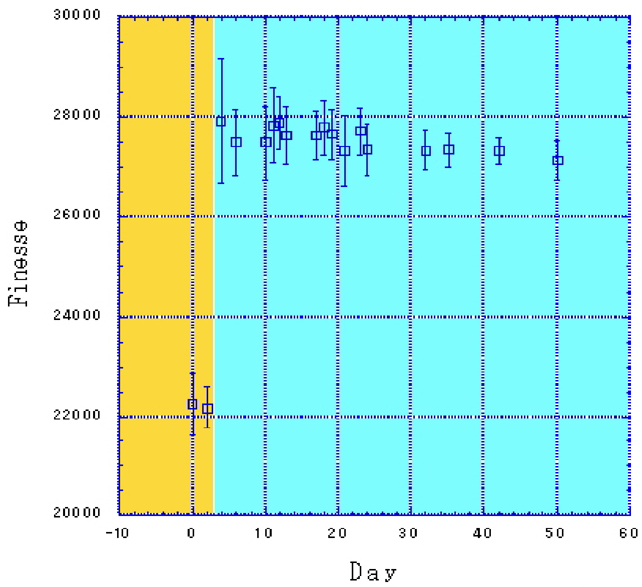
- Direct way to reduce thermal vibration noise
- Optical coating loss of mirrors vanishes
- No thermal lens effect
- Good refrigerators have been developed
- A challenging technique

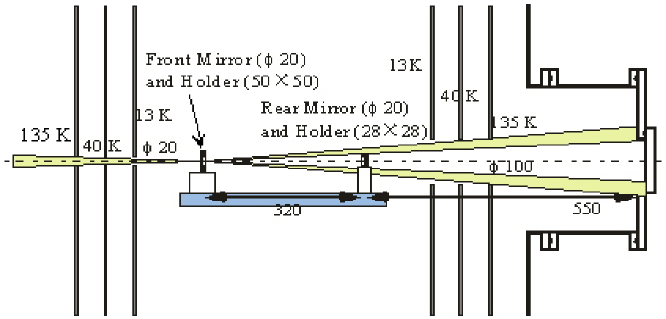
Cryogenic mirror was established by several basic experiments.

Cooling test

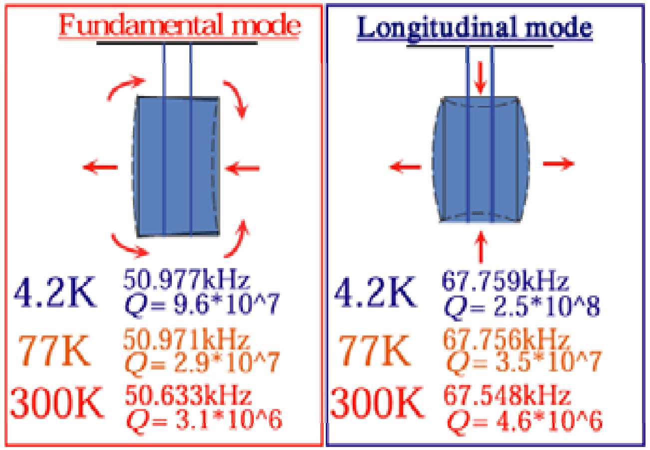


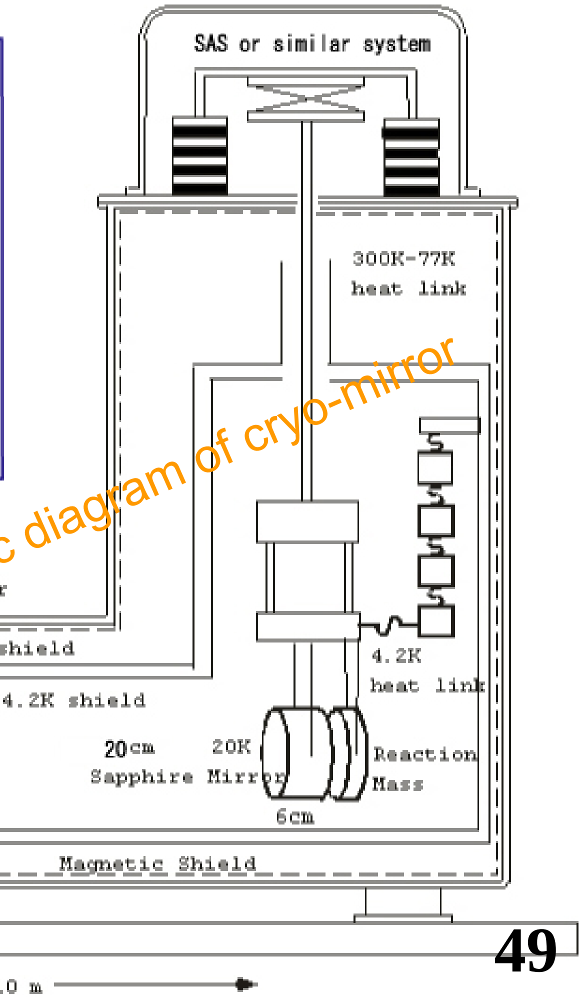
Contamination test



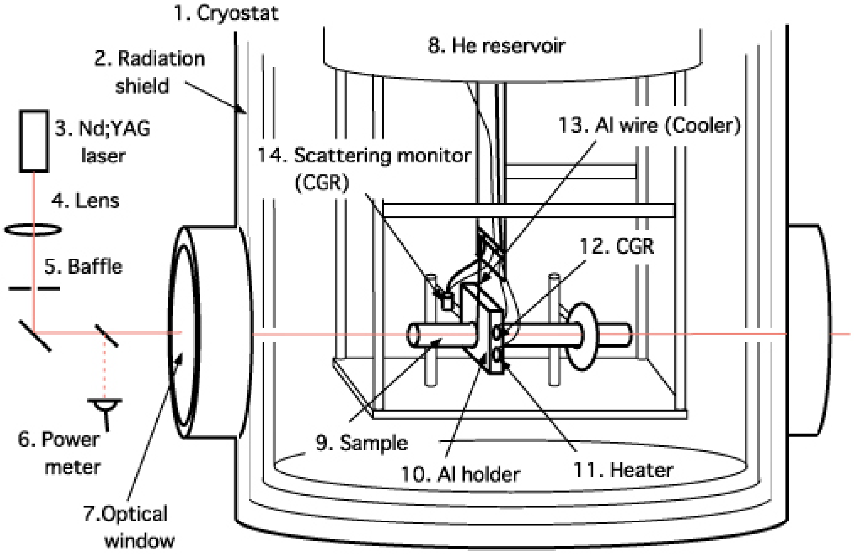


Mechanical Q test





Newly purchased sapphire has optically lower absorption.



by T. Tomaru

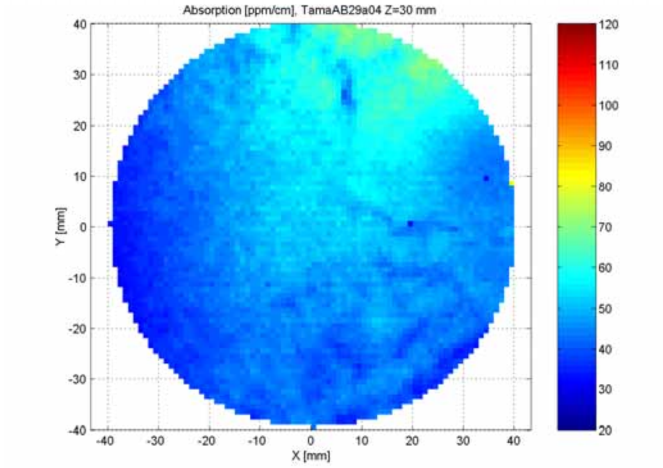
purchased in 1997

Sample	LCGT (5K)	Stanford	UWA
Hemex	-	-	24
Hemlite	90 - 99	-	-
CSI White	88 - 93	-	-
CSI White	-	-	3.4
CSI White	-	-	40
CSI White	-	47	-
CSI White	-	25	-

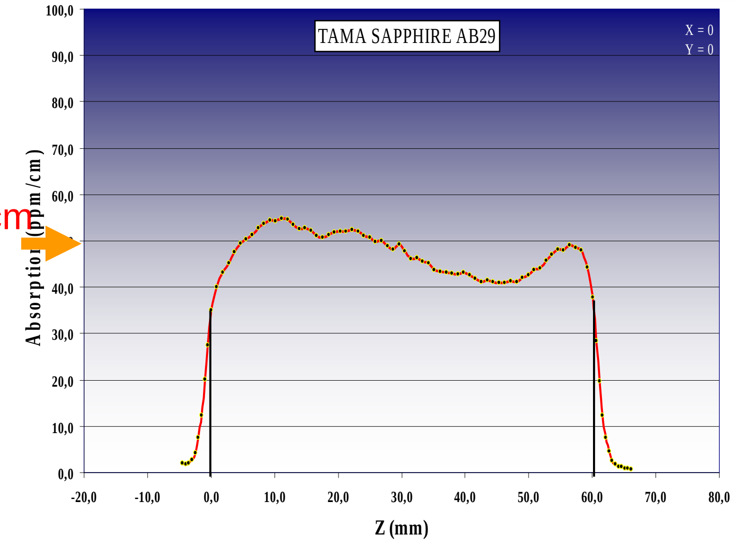
ppm/cm

The optical absorption may be controllable.
33ppm/cm is the object value.

Hemlite sample
purchased in 2003



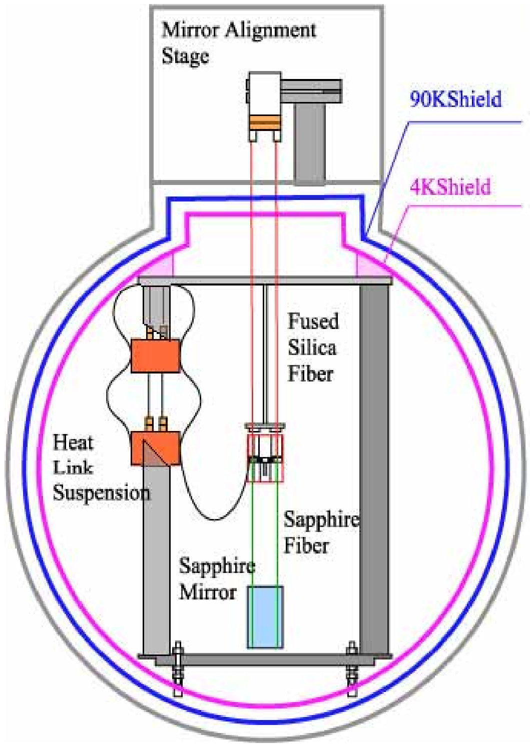
50ppm/cm

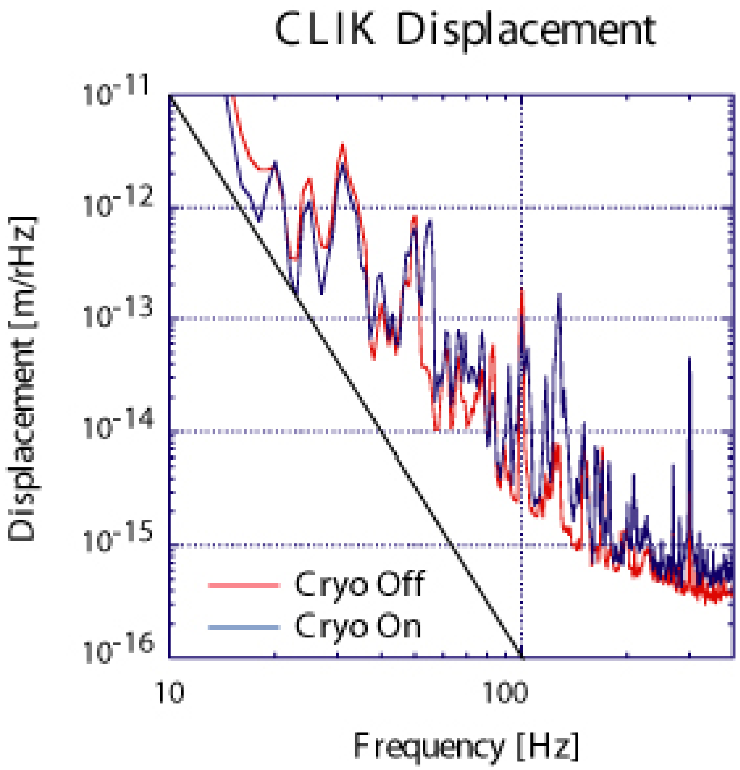


measured by

Suspension prototype was tested in Kashiwa campus in ICRR, in 2001.

Fabry-Perot cavity was locked at cryogenic temperature and requirements on refrigerator were studied.

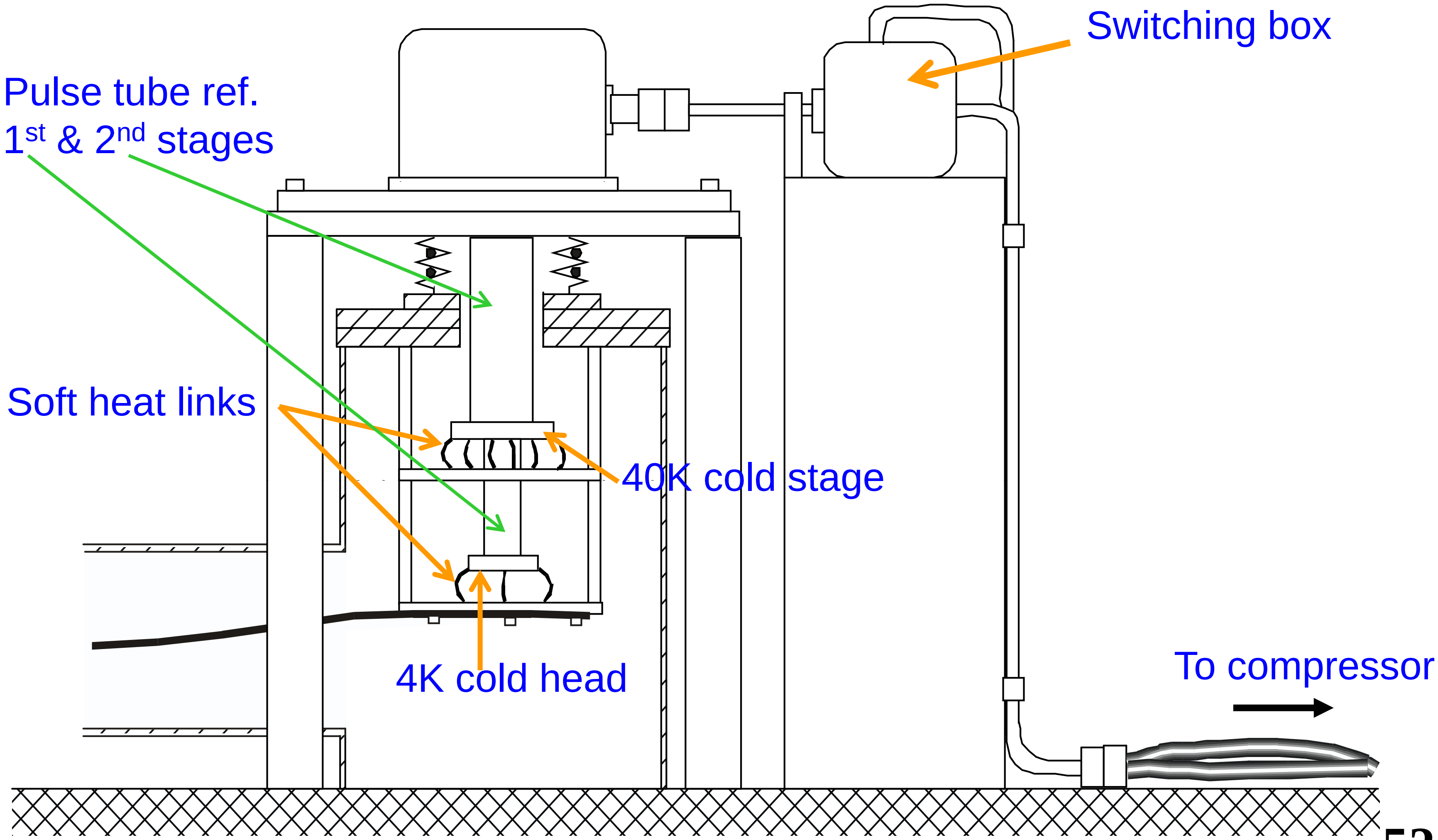




This result makes us to develop quieter refrigerator and softer heat link design.

Quiet refrigerator was developed (design in 2003)

F-6: Class. Quantum Grav. (Accepted), Pr-1: Proc. 28th ICRC (2003),
patent: Pa-3 Tomaru et al., 2003; Suzuki et al., 2003.

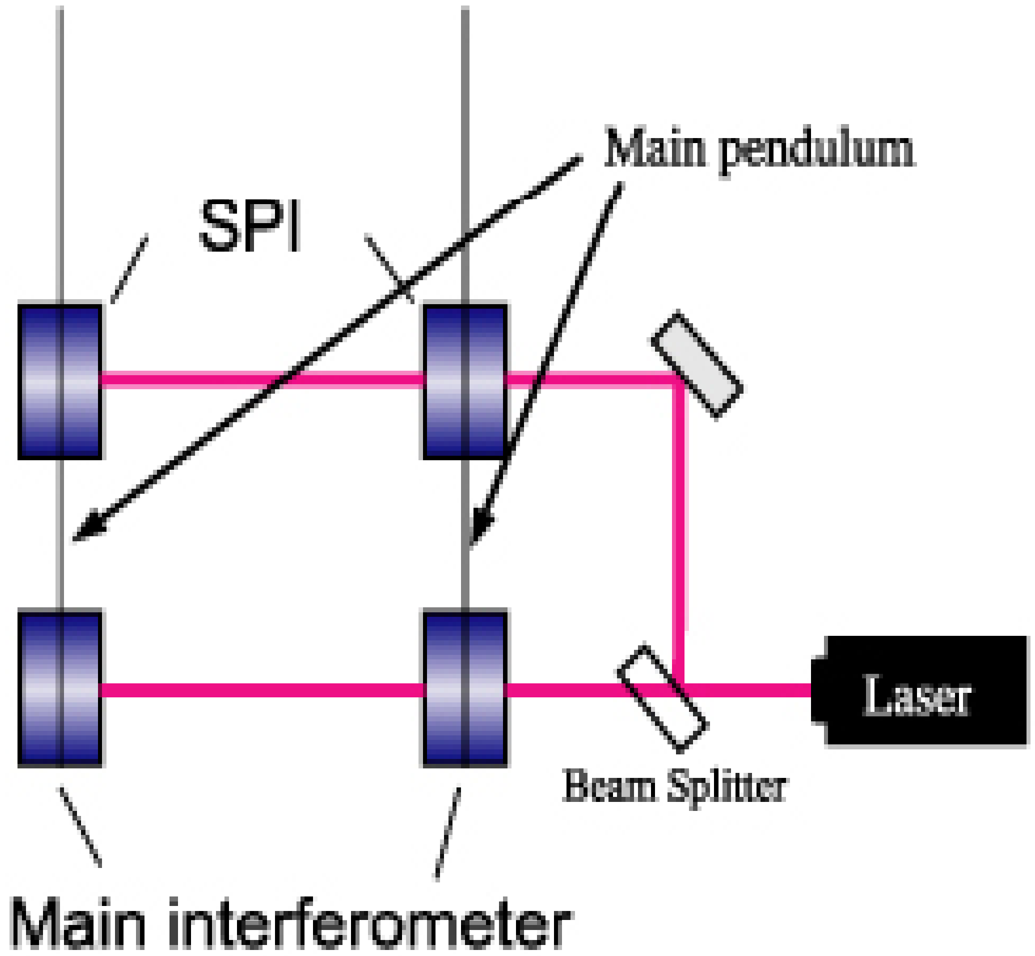


Large heat production is avoided by RSE

- Broad band RSE is applied.
- Power recycling gain is set 11.
- Finesse of the cavity is 1550, which means that observational band becomes to be lower than required.
- RSE keeps the frequency band unchanged.

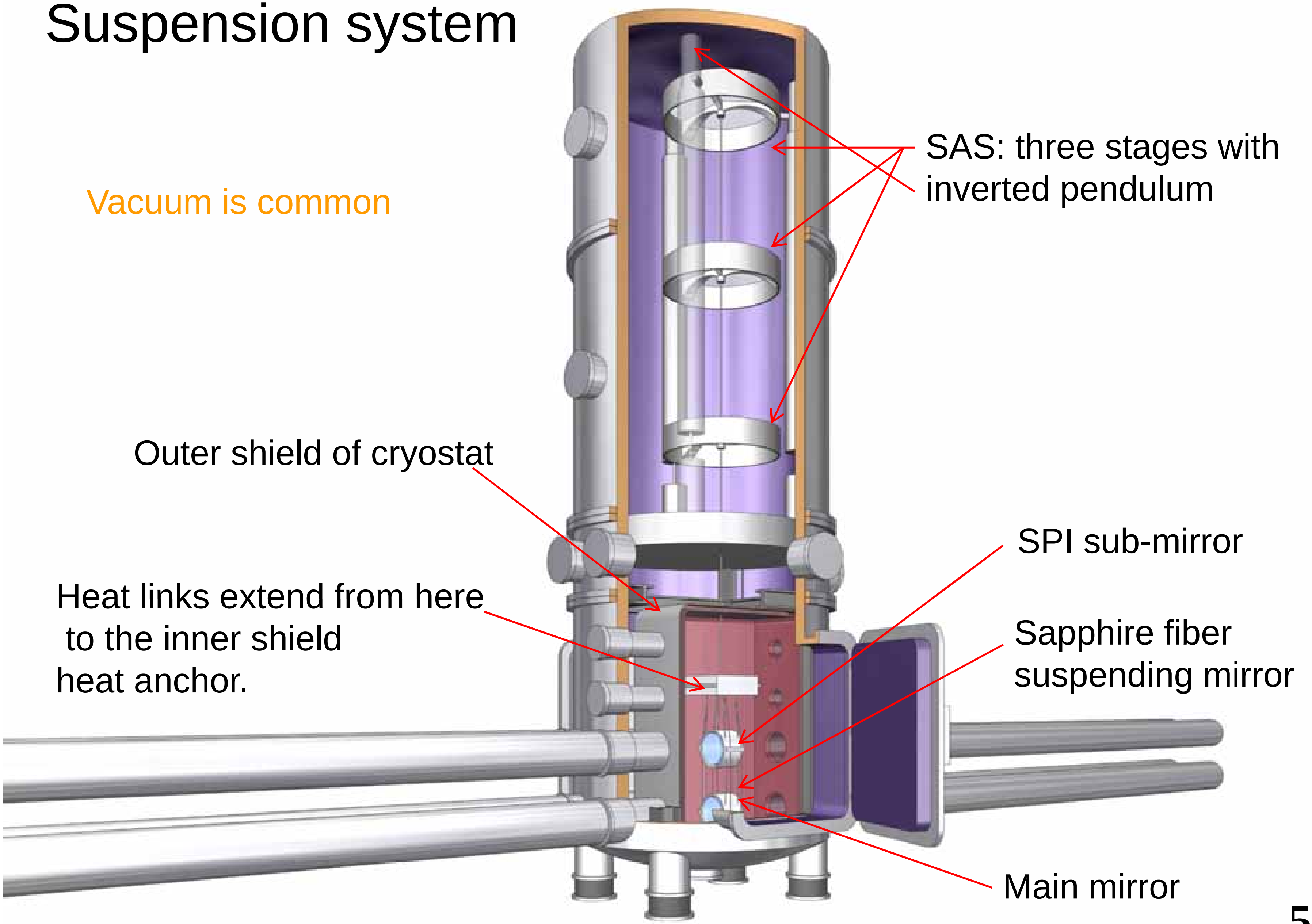
Refrigerator noise is avoided by SPI

Test mass of LCGT is connected to a cooling system by a heat link that introduces mechanical noise. A suspension point interferometer (SPI) is introduced to maintain high attenuation of seismic and mechanical noise without degrading high heat conductivity.



Suspension system

Vacuum is common



Summary of LCGT

- It is a 3km Fabry-Perot MI with a power recycling scheme and equipped with a broadband RSE. The laser power is 150W.
- Main mirrors made of sapphire are cooled at 20K. A SPI impedes the refrigerator- vibration.
- It is built underground in Kamioka.
- Two independent interferometers are installed in a vacuum system.
- The main target is the coalescence of BNS, which can be detected 1.3-33.3 events per year at confidence level of 95% for mass 1.4Msun and S/N=10.

1. Introduction

LCGT : future Japanese project

to construct the interferometric gravitational wave detector

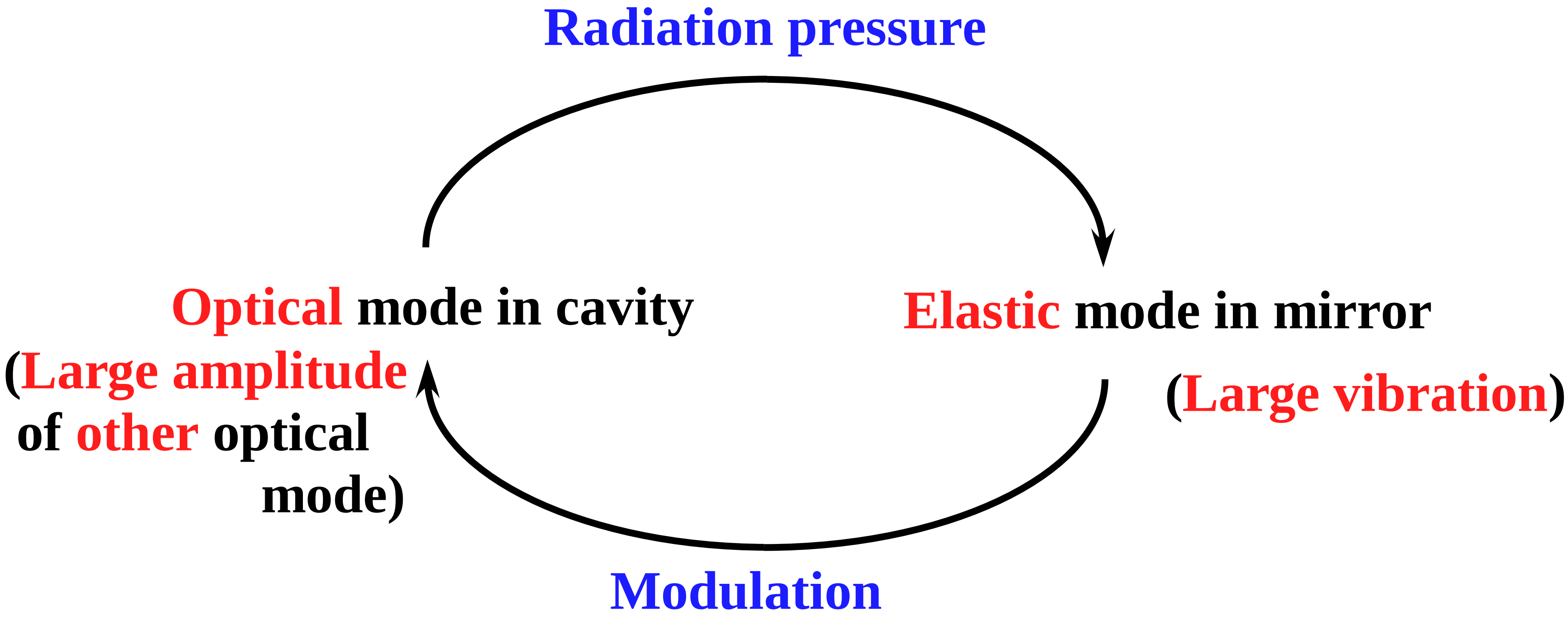
Long Fabry-Perot cavity : ~ 3 km

⟶ Interval of optical mode in cavity : ~ 10 kHz

Interval of elastic mode in mirror : ~ 10 kHz

Parametric instability

Phys. Lett. A 287 (2001) 331.



Formula of parametric instability   Phys. Lett. A 287 (2001) 331.

$R > 1$: **instable elastic mode**

Spatial overlap between optical and elastic modes

Power

Q of mirror

$$R \sim \sum \frac{2PQ_mQ_o}{McL\omega_m^2}\frac{\Lambda_o}{1+\Delta\omega^2/\delta_o^2} < 4000$$

Frequency of elastic mode

Frequency difference between optical and elastic modes

Width of optical mode

$$\delta_o^2 = \omega_o/2Q_o$$

Serious problem in Advanced LIGO (U.S.A.)

??? in LCGT

ω_m, Λ_o : Finite element method (ANSYS)

4. Discussion

4-1. Number of unstable modes

Advanced LIGO : 20 ~ 60

LCGT : 2 ~ 4

(i) Elastic mode density : ~ (Sound velocity)$^{-3}$

Advanced LIGO (Fused silica) : 6 km/s

LCGT (Sapphire) : 10 km/s

5 times smaller

(ii) Optical mode density

Advanced LIGO : 7 modes / FSR

LCGT : 3 modes / FSR

2 times smaller

Larger beam radius for thermal noise reduction
(Advanced LIGO)

(iii) Summary

Product of elastic and optical mode densities : 10 times smaller

Number of unstable mode
Advanced LIGO : 20 ~ 60
LCGT : 2 ~ 4

4-2. Mirror curvature

Advanced LIGO : *R* strongly depends on mirror curvature.

LCGT : *R* weakly depends on mirror curvature.

***R* is function of optical mode frequency.**

Interval of transverse optical mode

Advanced LIGO : 15 Hz/m

LCGT : 0.58 Hz/m

30 times smaller

Larger beam radius for thermal noise reduction

(Advanced LIGO)

6. Summary

(i) Estimation of parametric instability in LCGT interferometer

(ii) Less serious problem (than that of Advanced LIGO)

Number of unstable modes

Advanced LIGO : 20 ~ 60 LCGT : 2 ~ 4

Mirror curvature

Advanced LIGO : *R* strongly depends on mirror curvature.
LCGT : *R* weakly depends on mirror curvature.

Larger beam and mirror material (fused silica) makes problems.
(Advanced LIGO)

← Thermal noise reduction

(iii) 1.03 times smaller mirror has no unstable modes.

Error of elastic mode frequency ?

Higher modes ?

(iv) Future work

Higher modes
Other methods for instability suppression

Other methods for instability suppression

Investigation in LIGO (UWA)

Phys. Lett. A 355 (2006) 419.

(1) Thermal tuning

(2) Q reduction

(3) Feedback control

Thermal tuning

Heating a part of mirror for curvature control

Not useful method in LCGT

(i) Small thermal expansion and high thermal conductivity in cold sapphire mirror

(ii) R weakly depends on mirror curvature.

Problems in Advanced LIGO

(i) Slow thermal response due to low thermal conductivity of fused silica

(ii) It is impossible to suppress instabilities of all modes.

Feedback control

(i) Tranquilizer cavity (short external cavity)

Phys. Lett. A 293 (2002) 228.

(ii) Feedback to mirror

(iii) Feedback to light

Number of instable modes must be small.