Mirror coating losses and their thermal noise effects at low temperature

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0. Abstract

(i) Our research proved that there are large differences

between the real thermal noise

of the mirror with inhomogeneous loss

and the estimation of traditional method.

Especially, mechanical loss of reflective coating is problem.

(ii) We measured the mechanical loss of coating at low temperature

and derived the thermal noise of cryogenic detector.

Contents

1. Introduction

○ Thermal noise of mirror

⟶ fundamental noise of GW detectors

⟶ It is important to estimate thermal noise.

○ Modal expansion

⟶ traditional method to estimate thermal noise

(thermal noise of system)

= Σ (thermal noise of each resonant mode)

However ...

some theoretical researches suggest

that modal expansion is invalid

when the loss is distributed inhomogeneously.

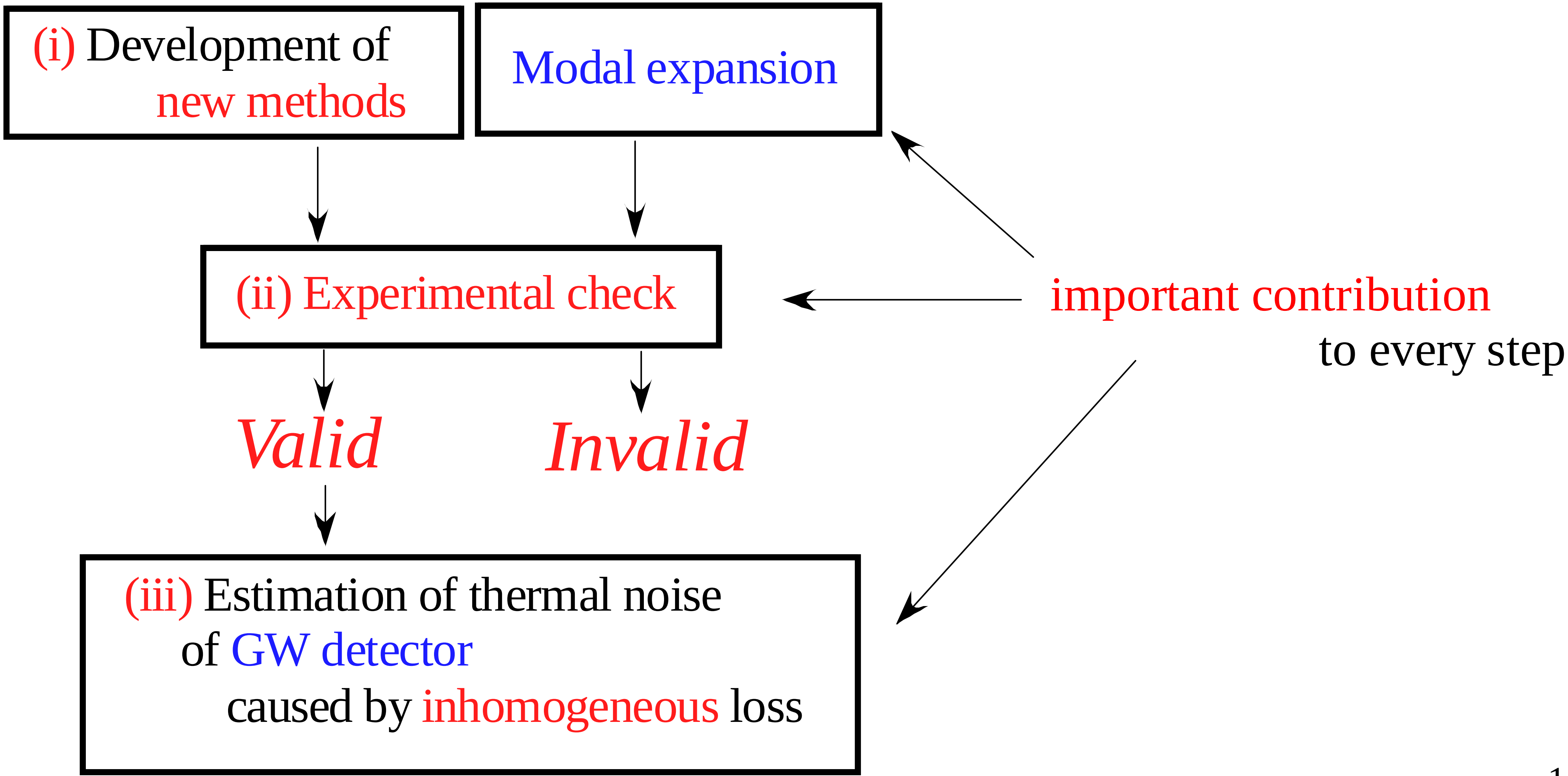
This problem has not been researched fully.

→ We tried this problem.

○Summary of our results

(My Ph.D. thesis, http://t-munu.phys.s.u-tokyo.ac.jp/theses/yamamoto_d.pdf)

Almost all the problems were solved by our research !



(i) Development of new estimation methods

Advanced modal expansion

Other groups developed other new methods.

(ii) Experimental check

Our results proved that

(1) modal expansion breaks down.

(2) new estimation methods are valid.

This is the first experimental check.

leaf spring : Phys.Lett.A 280 (2001) 289
oscillator like a mirror : Class. Quantum Grav. 19 (2002) 1689

(iii) Estimation of thermal noise of GW detector using new method

(1) Our calculation [Phys.Lett.A 305 (2002) 18] shows that there are large differences between the real thermal noise of the mirror with inhomogeneous loss and the estimation of traditional method.

Our research proved that

(i) loss near beam spot (coating) : serious problem

(ii) loss far from beam spot (glued magnets) : not serious problem

Main topic of this talk

is thermal noise caused by mechanical loss of coating.

(i) calculation of thermal noise of mirror with coating

(ii) experimental check of estimation method

(iii) measurement of mechanical loss of coating loss at low temperature

2.Calculation of thermal noise of mirror with coating

[Phys.Lett.A 305 (2002) 18]

2-1. Outline of calculation

(i) Thermal noise of mirror with inhomogeneous loss
is calculated using new method
with which our experiments agree.

(ii) Thermal noise of mirror is also calculated using modal expansion
which is traditional but invalid.

(iii) The differences are derived.

(iv) Evaluated values are compared with goal sensitivity.

2-2. Estimation method

(i) New method

Levin's approach [Phys.Rev.D 57(1998)659]

(i) pressure applied on the mirror

↓ Solving equation of motion directly

(ii) dissipated power in the mirror

↓ Fluctuation-dissipation theorem

(iii) thermal noise

Our calculation [Phys.Lett.A 305 (2002) 18]

Method of calculation of dissipated power : Finite element method (ANSYS)

numerical calculation finite mirror

Other groups (cross check)

Y. Levin [Phys.Rev.D 57 (1998) 659] : not strict discussion

G.M Harry et al., [Class. Quantum Grav. 19 (2002) 897]

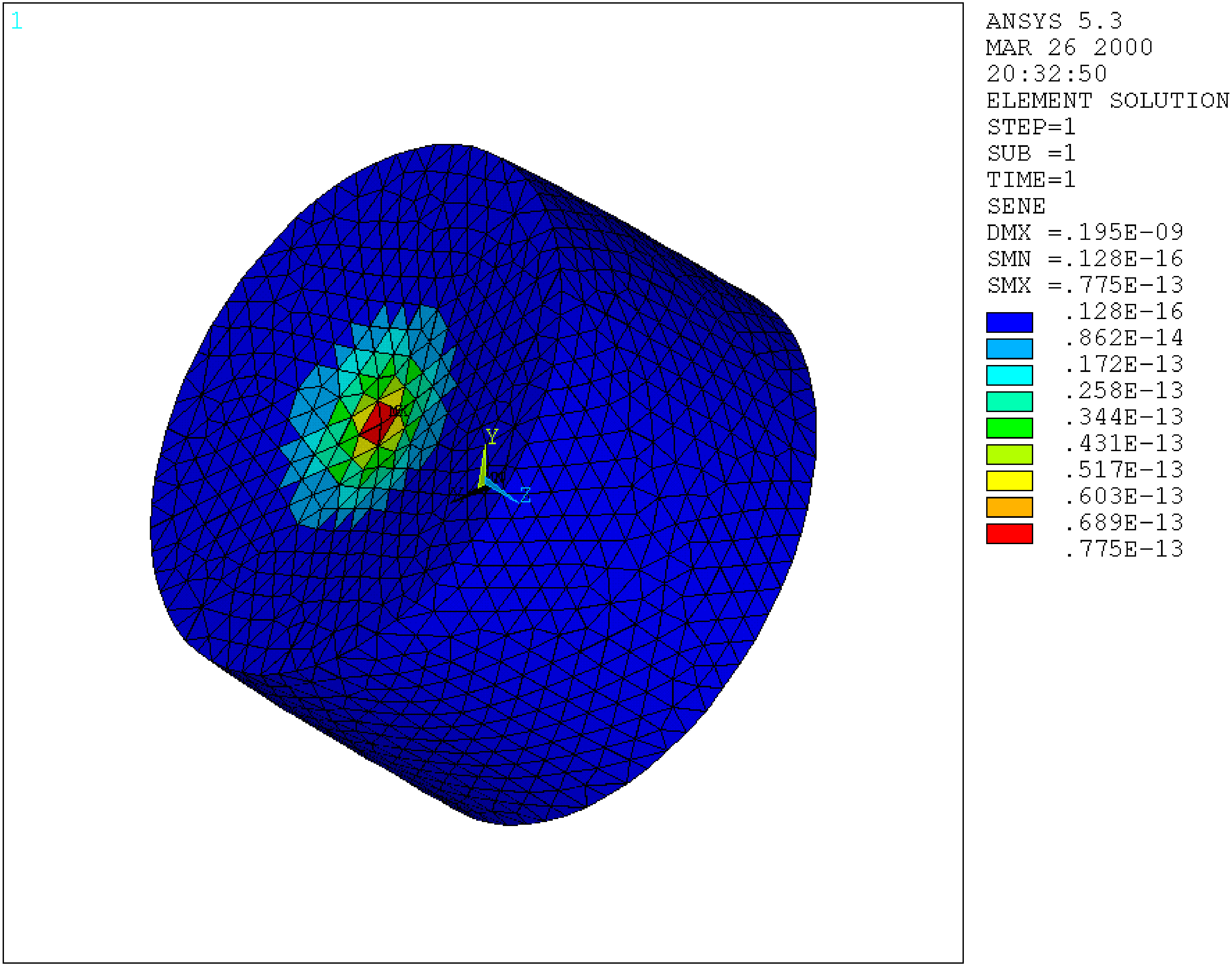
analytical calculation half-infinite mirror

N. Nakagawa et al., [Phys. Rev. D 65 (2002) 102001]

not dissipated power, but Green function

analytical calculation half-infinite mirror

Harry's result agrees with Nakagawa's.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MAR 26 2000
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SUB =1
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SENE
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SMN =.128E-16
SMX =.775E-13
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.172E-13
.258E-13
.344E-13
.431E-13
.517E-13
.603E-13
.689E-13
.775E-13
Y
Z

(ii) Traditional method

Modal expansion

$$G = \Sigma \frac{4k_BT}{m_i\omega_i^2Q_i}\frac{1}{\omega}$$

m_i : effective mass

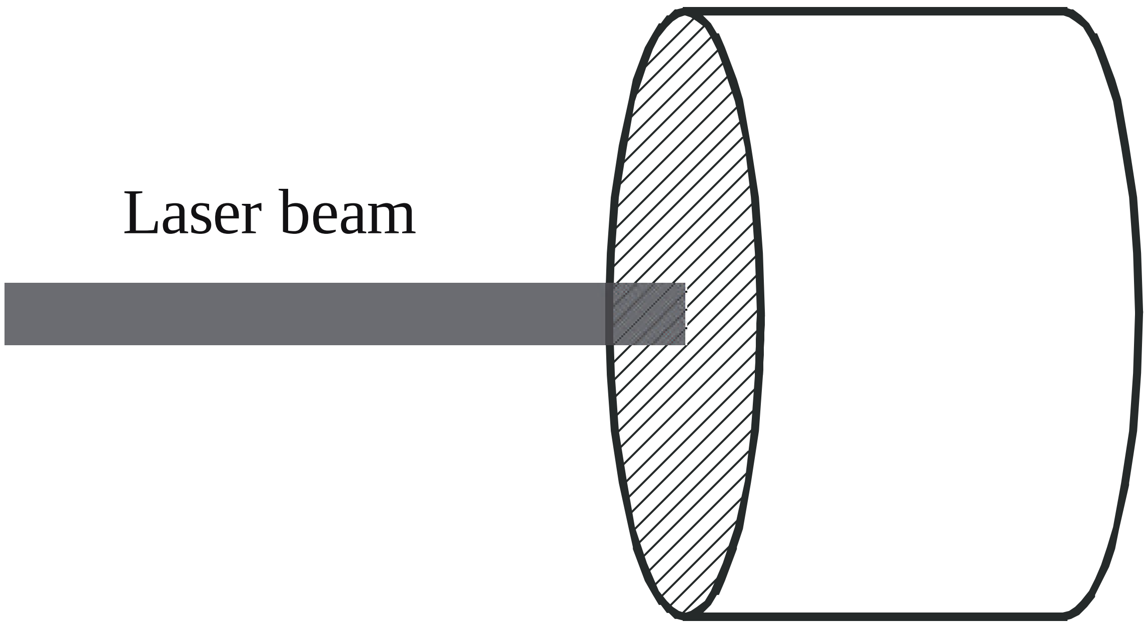
ω_i : resonant angular frequency

→ Hutchinson's method
(semi-analytical simulation of resonance)

Q_i : Q-value

→ Hutchinson's method + loss distribution

2-3. Loss distribution

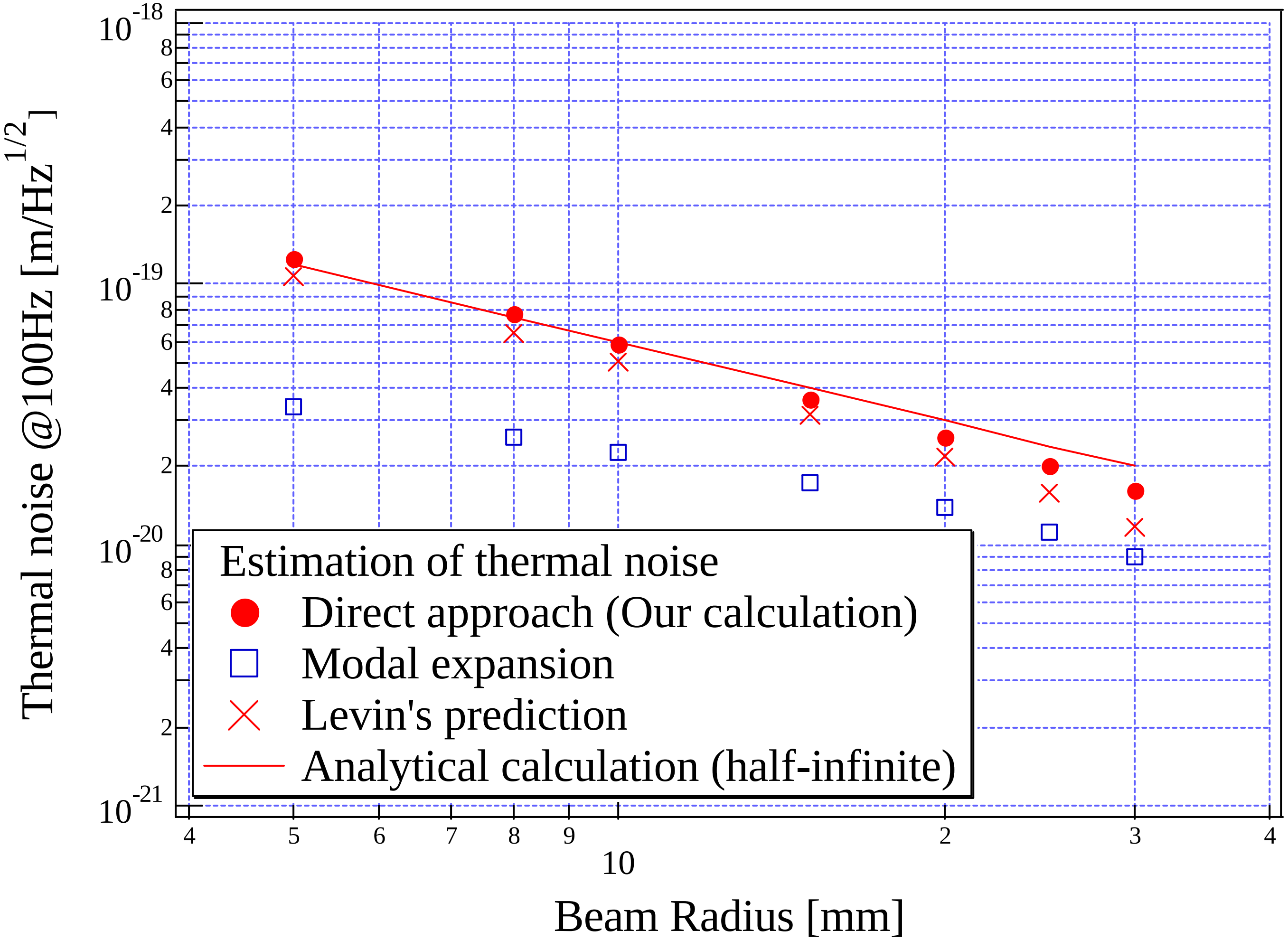


- loss layer :

  Thickness : 5μm, $\phi=4*10^{-4}$ (our measured value)

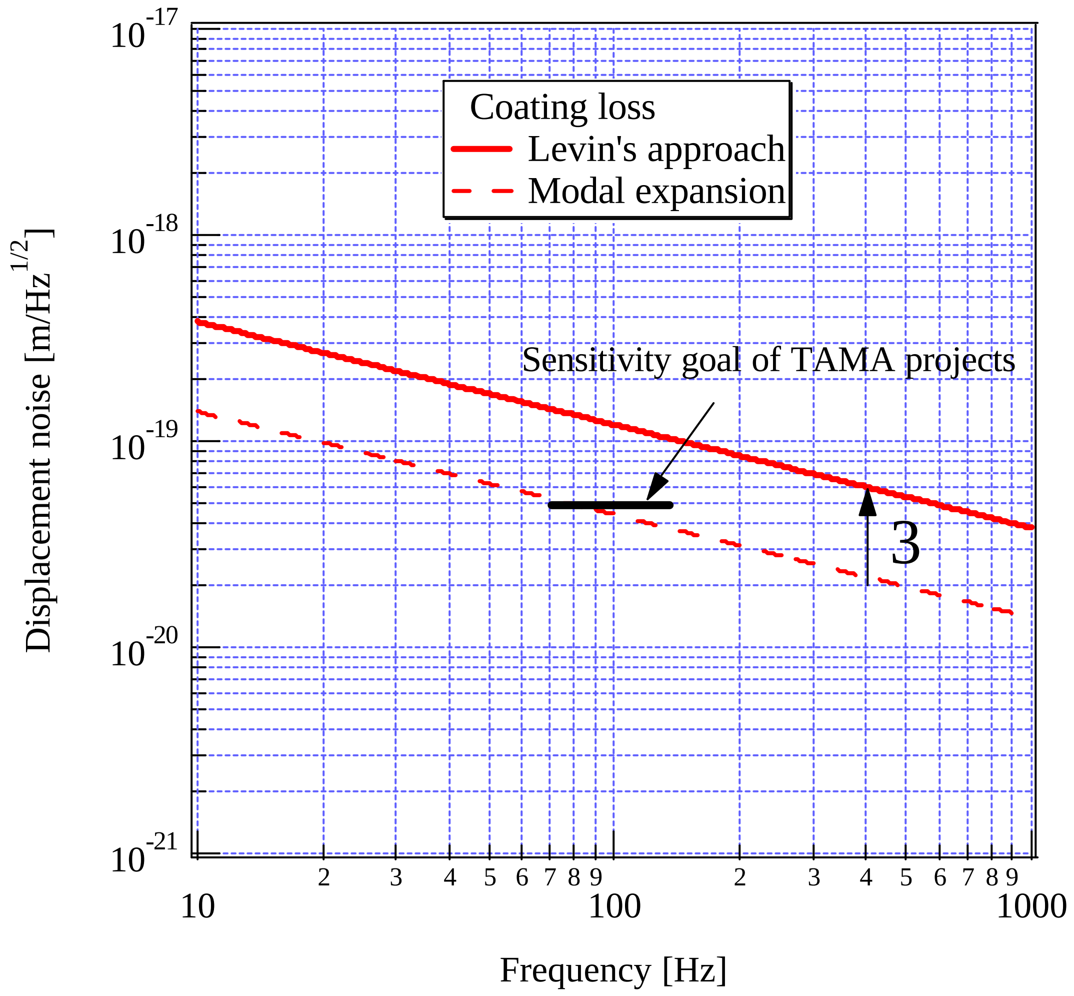
- no other loss
- structural damping
- beam radius dependence

2-4. Result (i) beam radius dependence



(ii)Thermal noise in interferomter

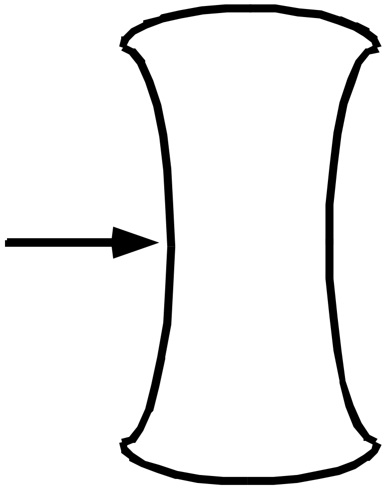
TAMA



Serious problem !

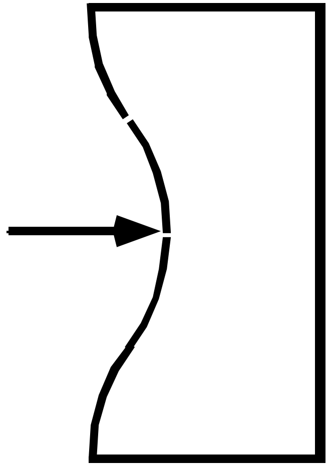
2-5. Discussion : reason of difference

(i) At resonant frequency



energy : homogeneous

(ii) In observation band
(<< resonant frequency)



energy : inhomogeneous

coating : large energy

2-6. Summary of estimation

(i) There are large differences

between the real thermal noise and modal expansion.

(ii) Modal expansion : Coating loss is not serious problem.

→ But, this is serious.

3. Experimental check of calculation method

3-1.Outline [Class. Quantum Grav. 19 (2002) 1689]

Experimental check of modal expansion and new methods

→ Measurement of the thermal noise of the mirror with inhomogeneous loss

Direct measurement of thermal noise of real mirror: difficult

(i) Mechanical model of mirror : drum

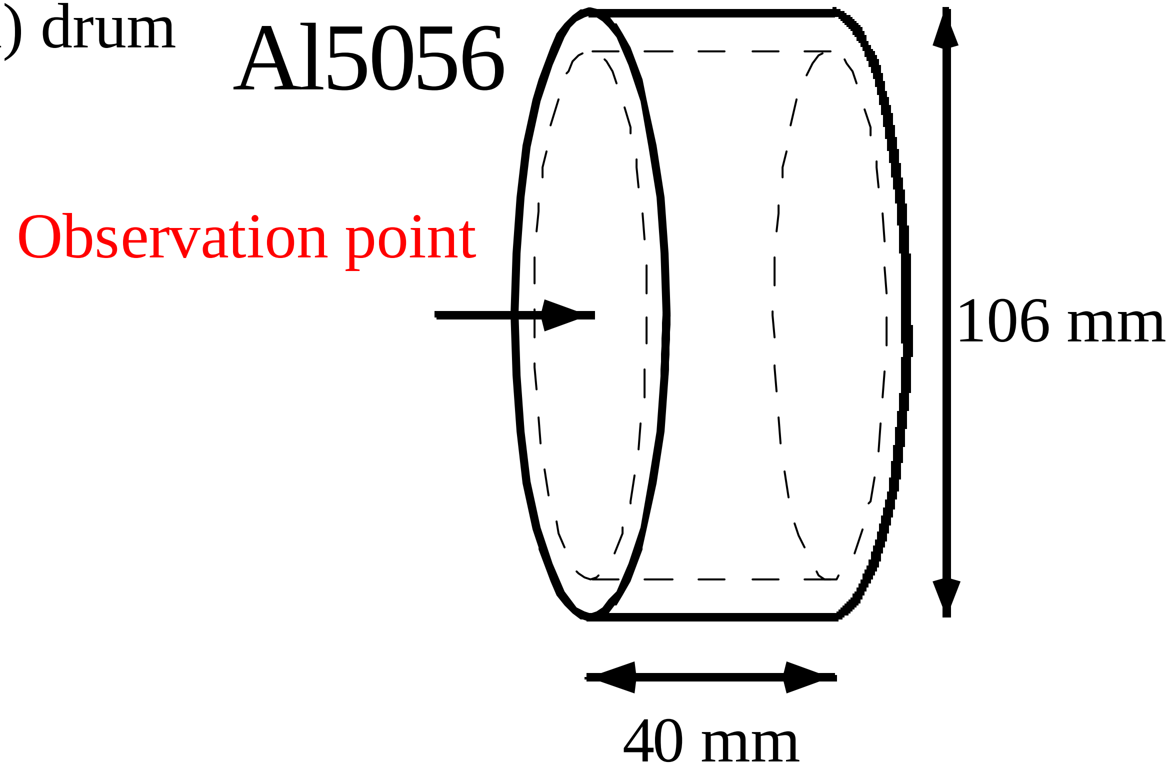
(ii) Measurement of mechanical response

→ Fluctuation-dissipation theorem

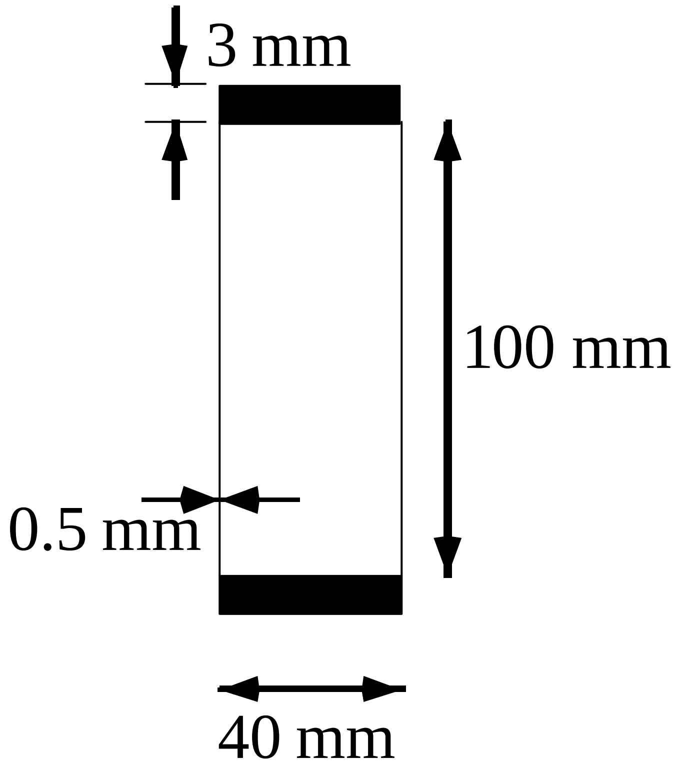
first experimental check using oscillator like mirrors

3-2.Experiment

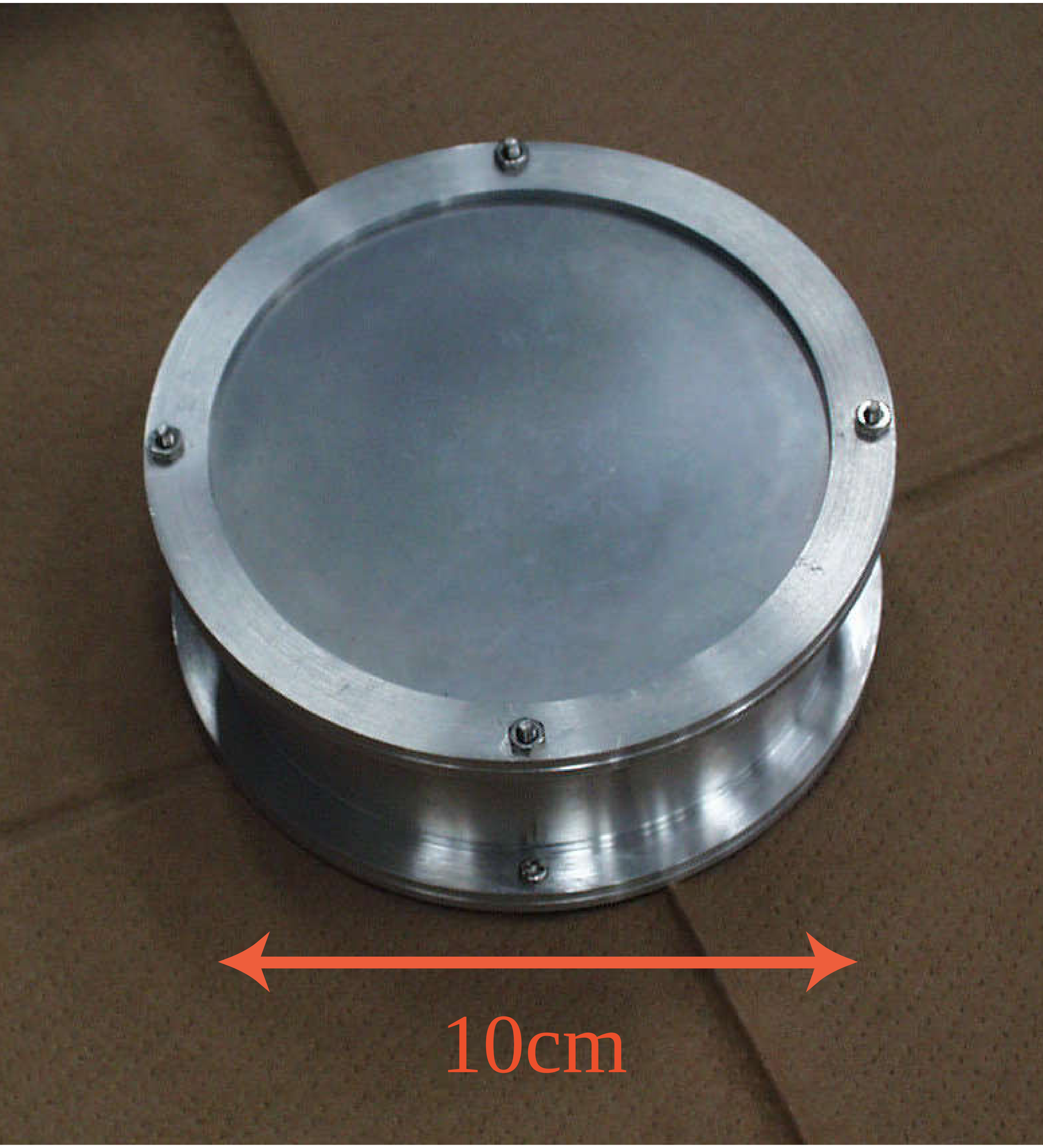
(i) drum



(ii) Cross section



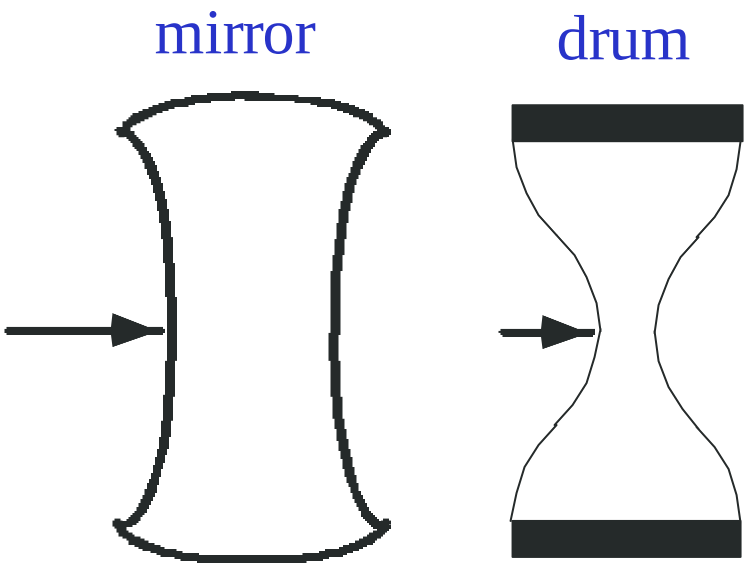
Observation band : lower than resonant frequencies



Drum (front view)

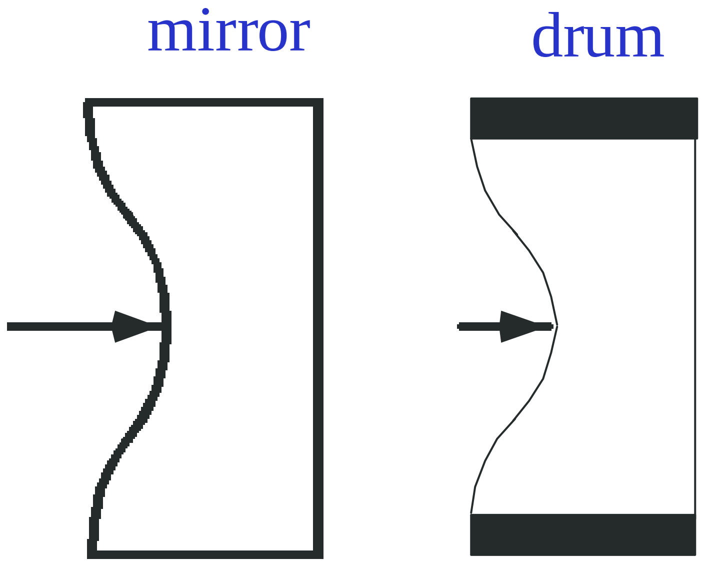
comparison between mirror and drum

(1) At resonant frequencies



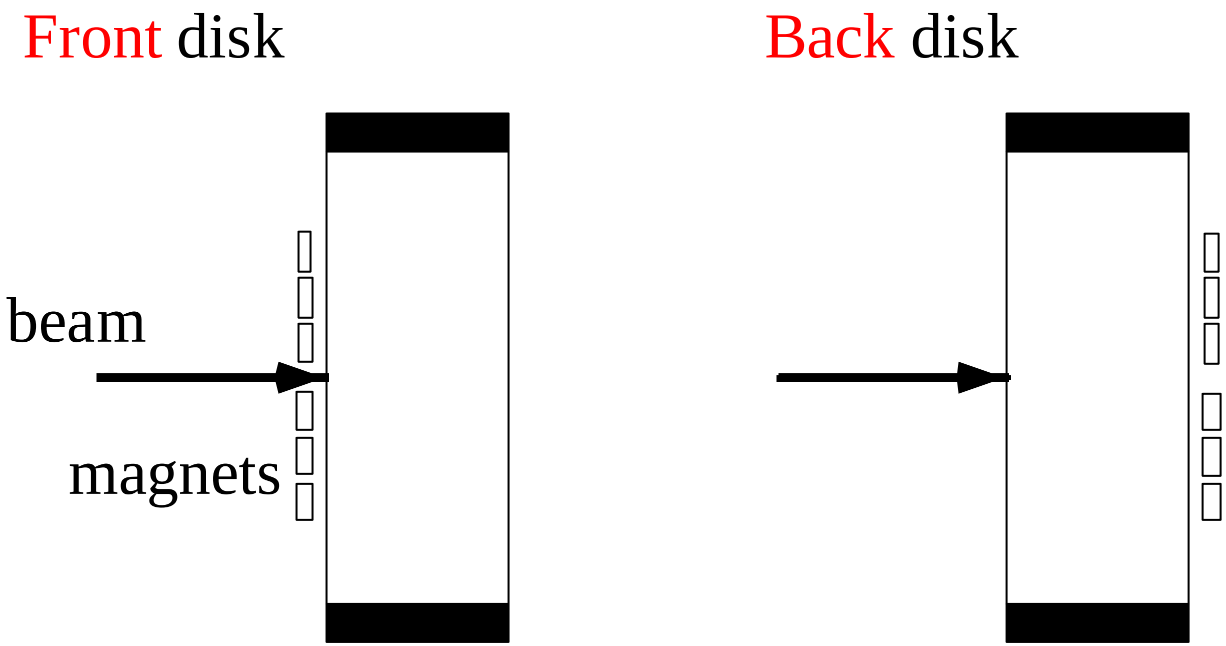
Both sides vibrate.

(2) In observation band
(<<resonant frequencies)

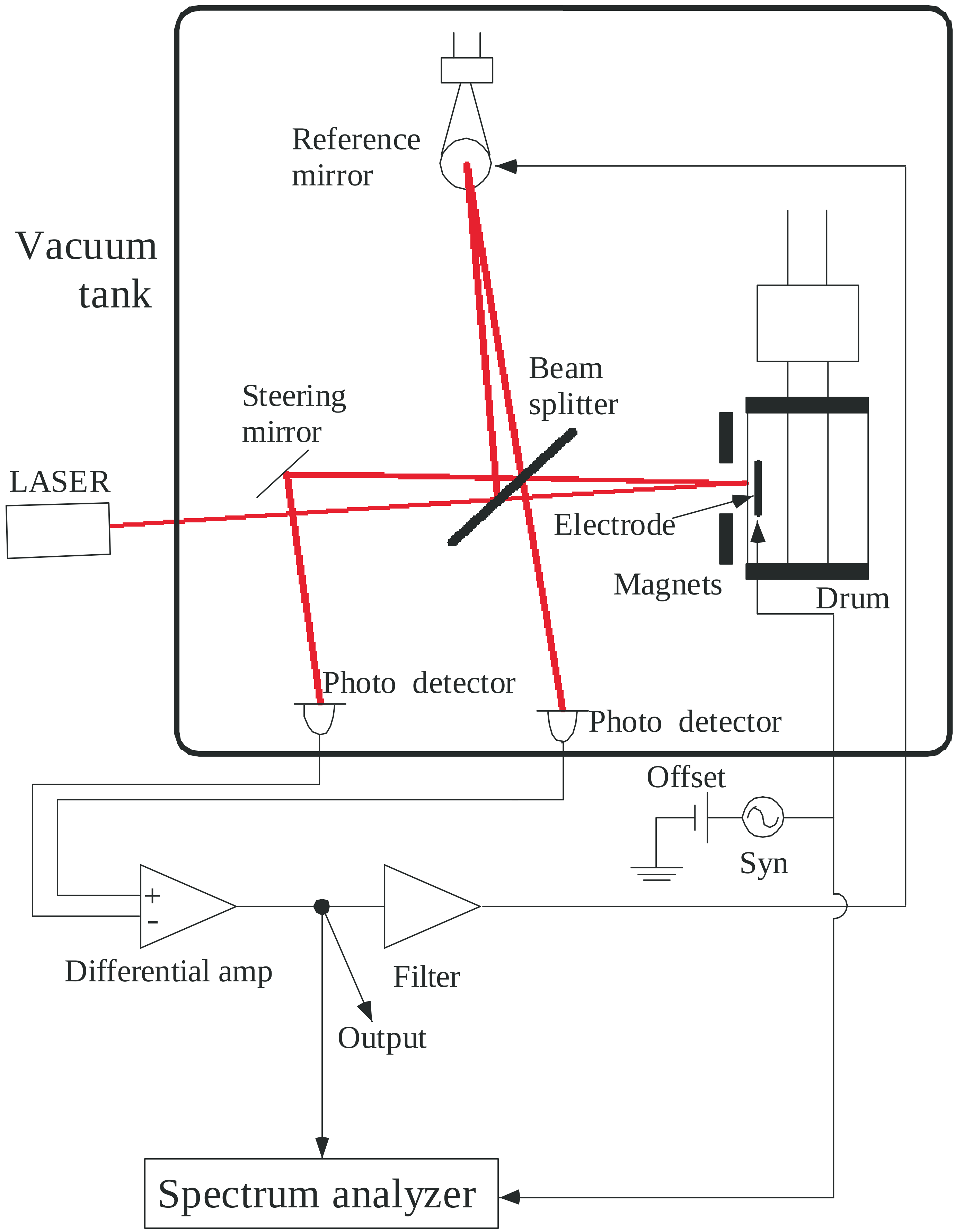


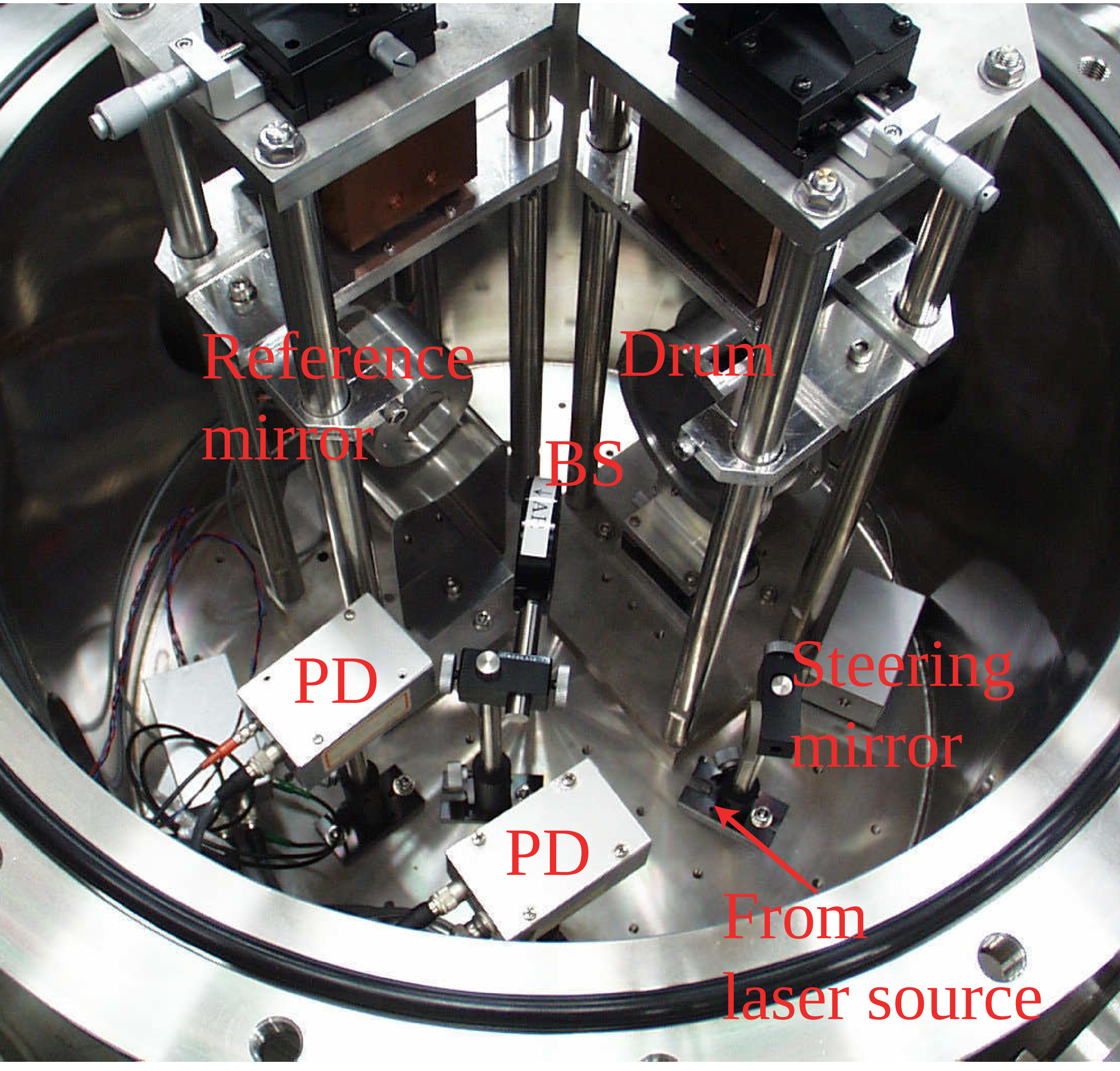
Only one side vibrates.

loss distribution



Experimental apparatus



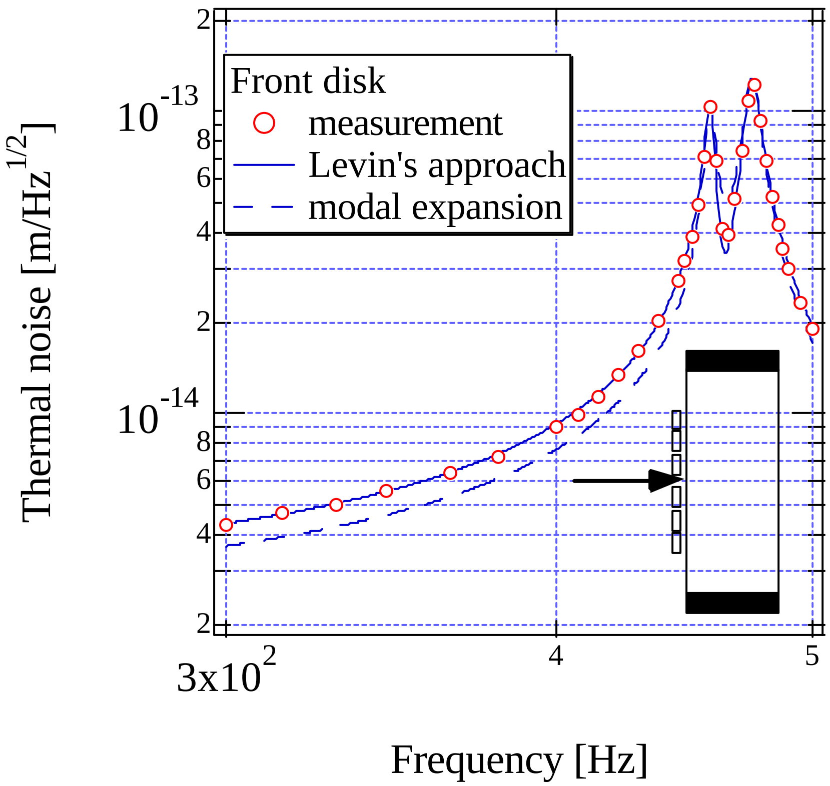


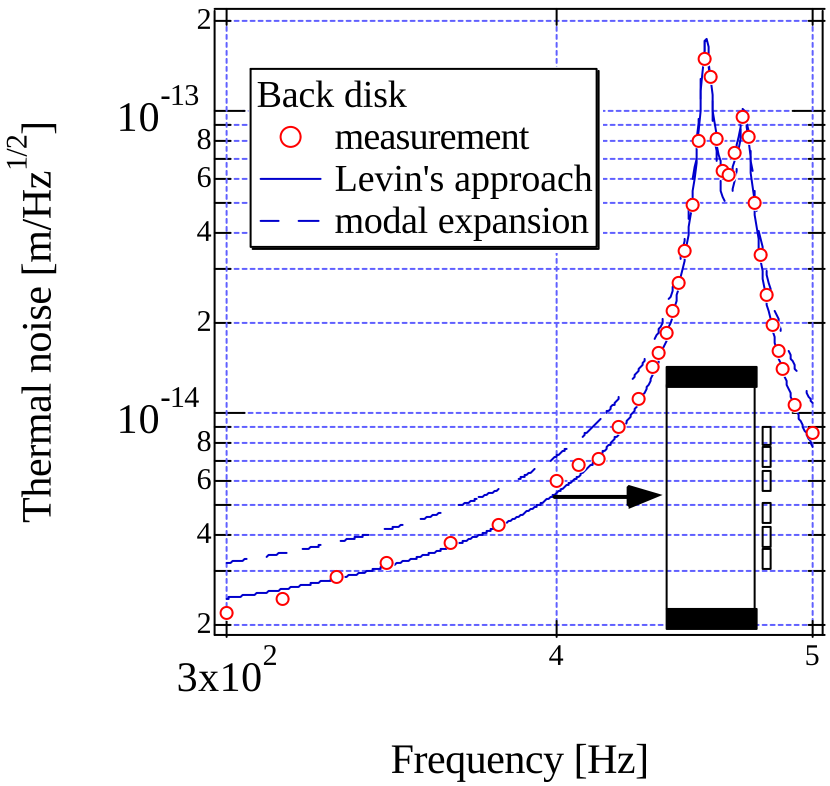
Interferometer
in vacuum tank

3-3. Results

direct approach : valid

modal expansion : ***invalid***





3-4. Summary of drum experiment

(i) Experimental results

new methods : valid

modal expansion : invalid

(ii) First experimental check using the oscillator like a mirror

4. Measurement of mechanical loss of coating at low temperature

4-1. Introduction

Our calculation and experiment proved that coating loss is a serious problem.

Some groups measured
the mechanical loss of coating at room temperature.

D.R.M. Crooks et al., Class. Quantum Grav. 19(2002)883.
G.M. Harry et al., Class. Quantum Grav. 19(2002)897.

Low temperature ?

(i) LCGT : future Japanese project to construct

the cryogenic interferometric gravitational wave detector (20K)

→ measurement of the loss of the coating at low temperature

4-2. Outline of experiment

(i) Sapphire disk with and without coating

(ii) Measurement of decay time of resonant motion
at low temperature → Q-values

(iii) Estimation of coating loss from the measured Q-values

Advantage of this experiment

(i) Thin disk : large effect of coating loss

(ii) Resonant frequencies (>1000Hz)
are near the observation band (about 100Hz).

(i) Sapphire disk and coating

Sapphire disk : f 100 mm   t 0.5 mm and t 1 mm

commercial polish (both sides)

Shinkosya (Japanese company)

Coating : IBS @ National Astronomical Observatory of Japan

(K.Waseda)

and Japan Aviation Electronics Industry, Ltd.

(TAMA mirror coating by JAE.)

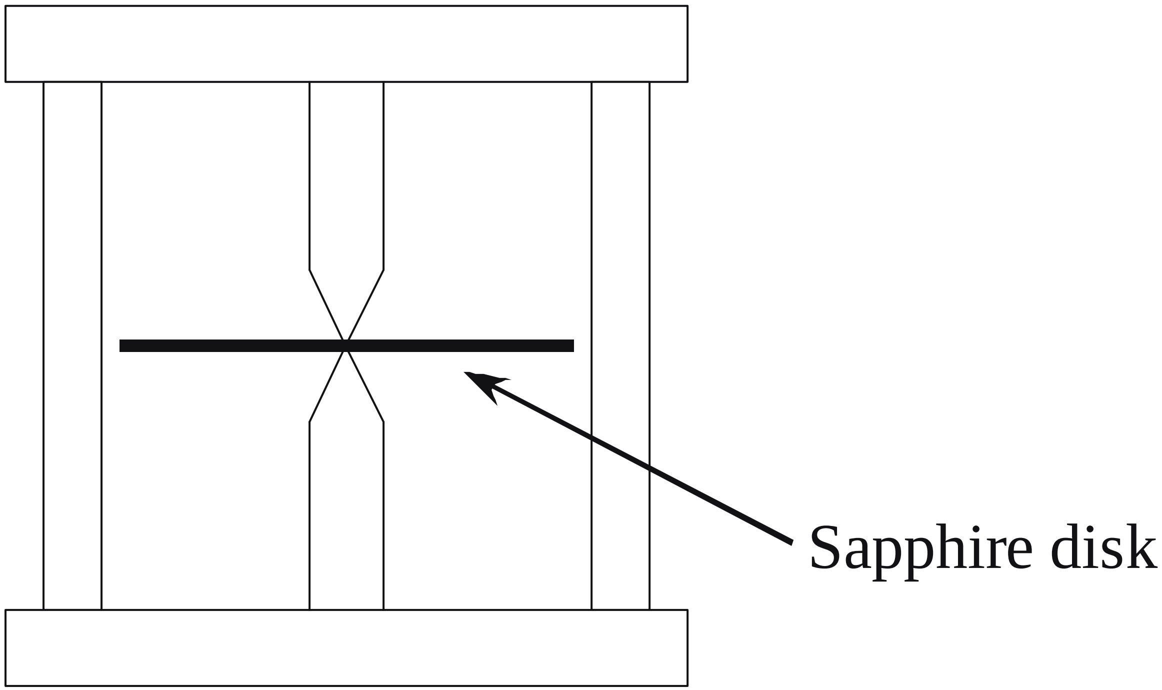
Ta_2O_5/SiO_2 (31 layers) : typical material

Reflectivity is the same

as that of typical end mirror (>99.99%).

(ii) Support system

Nodal support system (K.Numata et al., Phys.Lett.A 276(2000)37.)

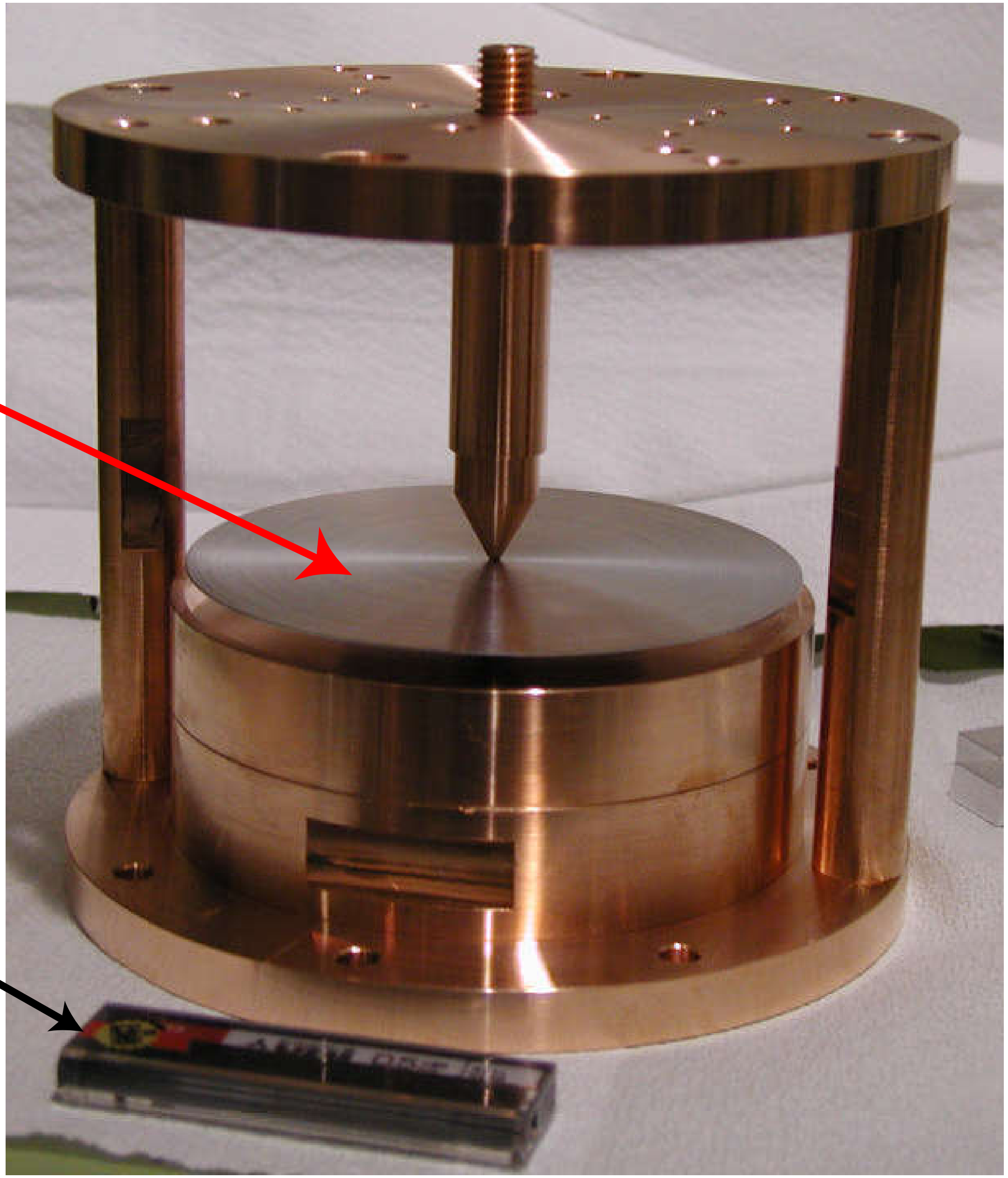


Our system : Copper (for cooling)

Nodal support system

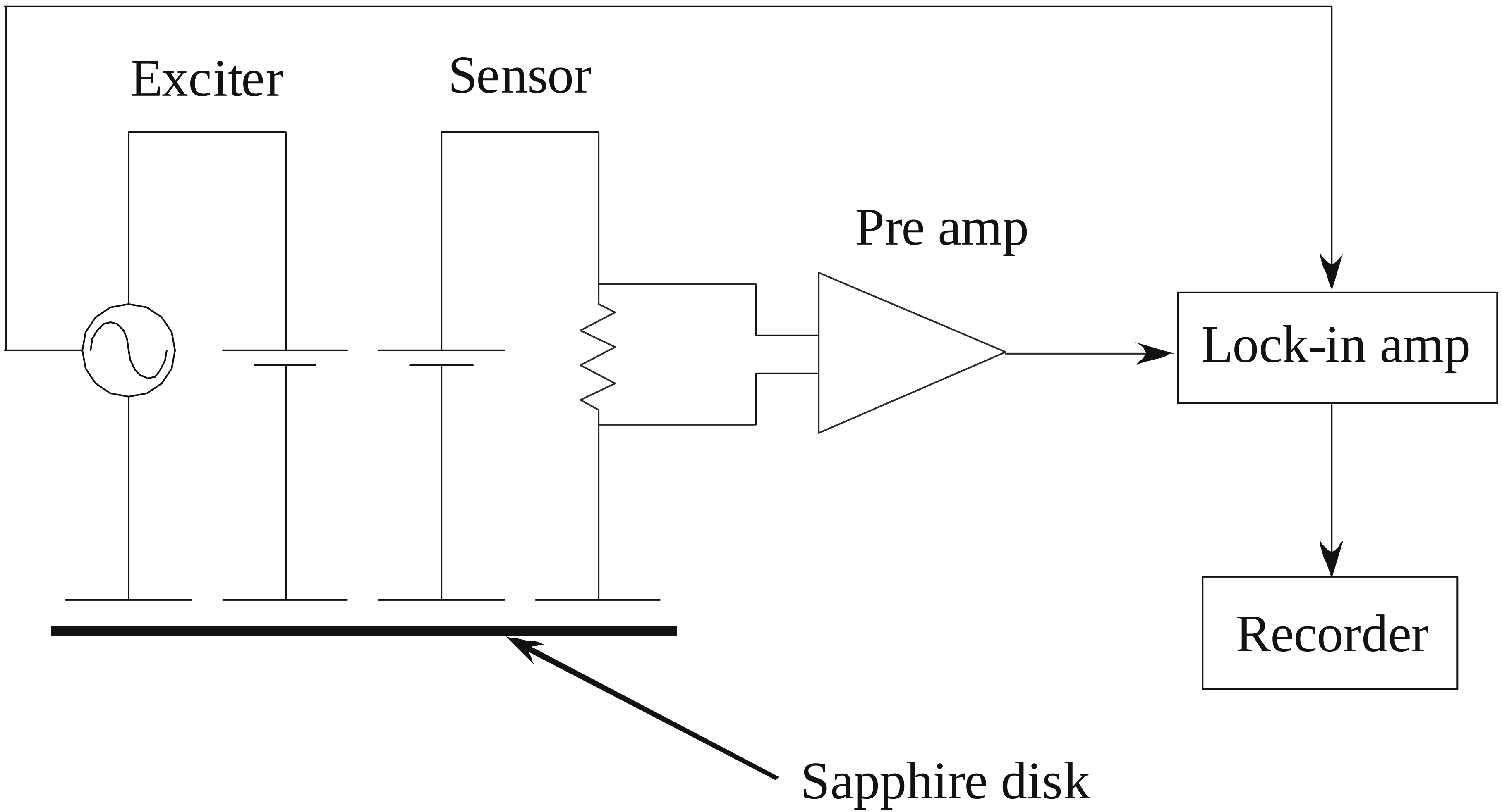
Disk

Case of lead of automatic pencil

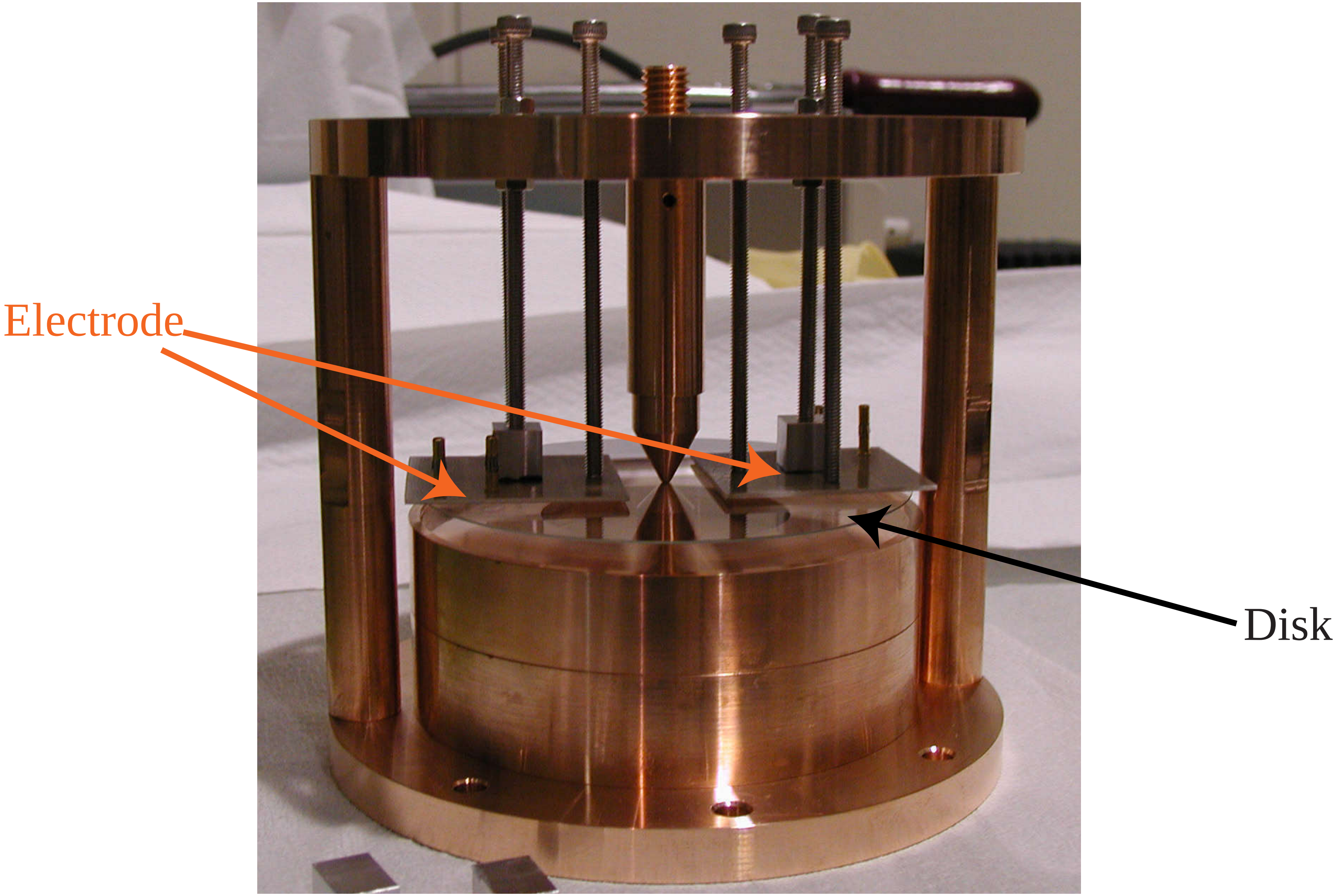


(iii) Exciter and sensor

electrostatic actuator and electrostatic transducer



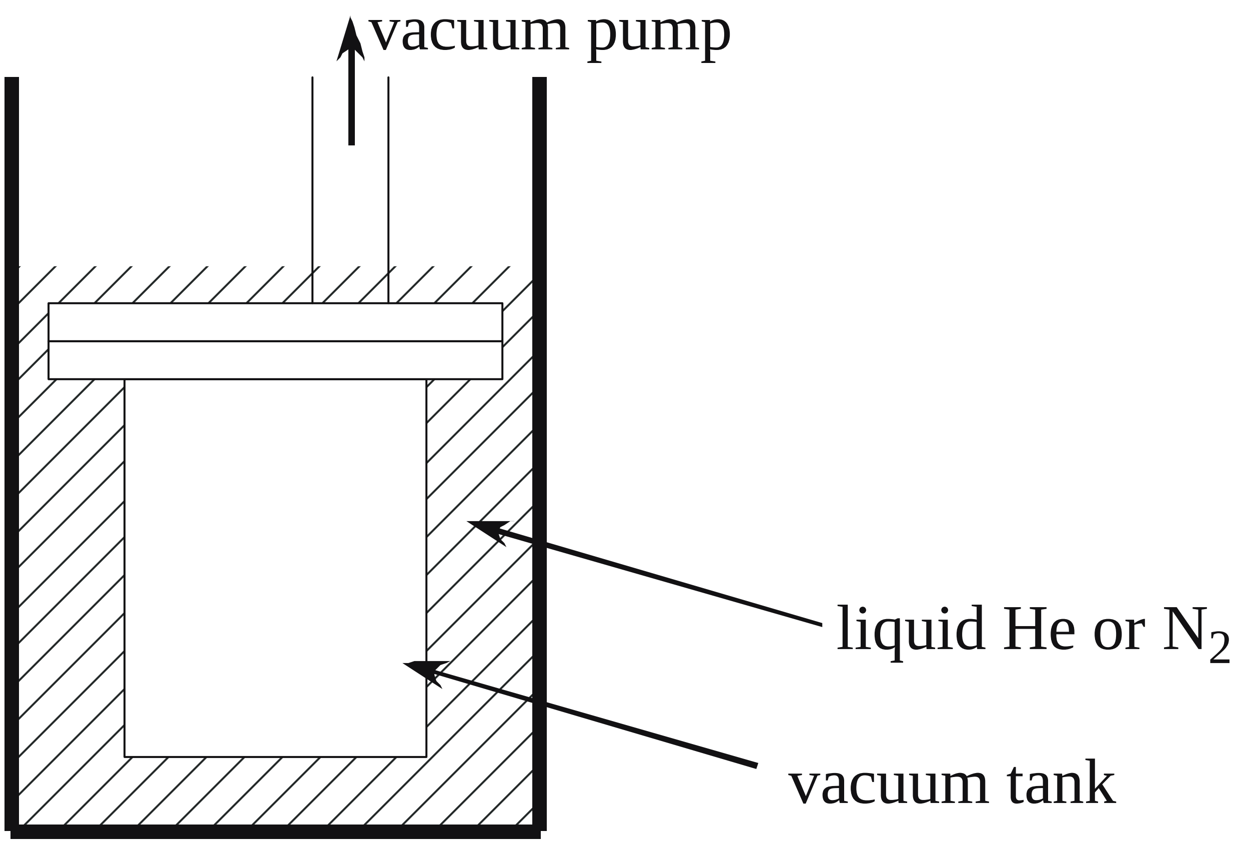
Exciter and sensor



(iv) Cooling

Vacuum tank in liquid He or N_2

at KEK(High Energy Accelerator Research Organization)



4-3.Result

(i) Samples

measured sapphire disks

NAO coating : t 0.5, 1 mm disk , without annealing

JAE coating : t 1 mm disk , with and without annealing

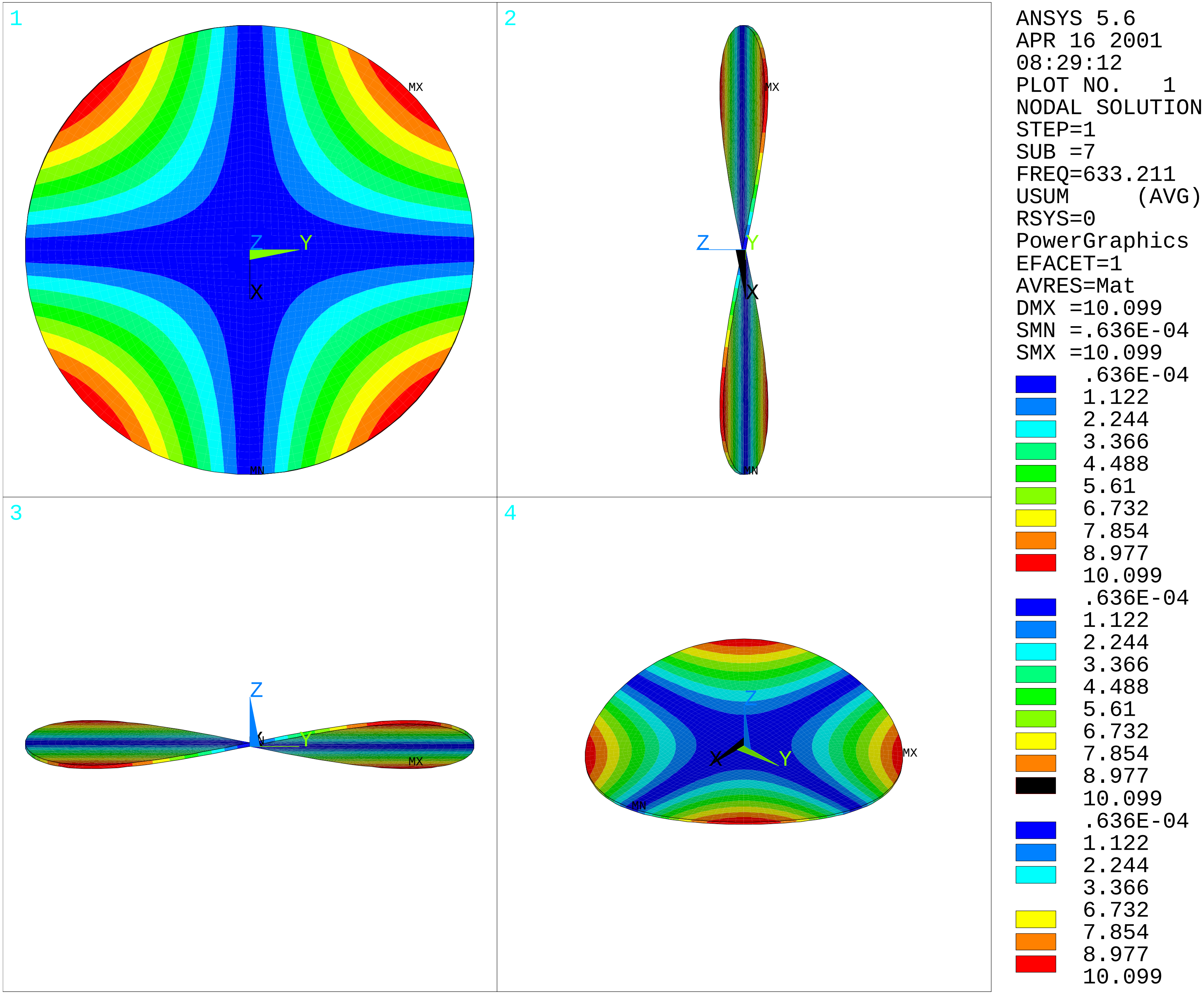
no coating : t 0.5, 1 mm disk

measured modes : first and third mode

	first mode	third mode
t 0.5 mm	520 Hz	1200 Hz
t 1 mm	1100Hz	2500 Hz

K. Numata measured Q-values of fused silica disk at room temperature.

(NAO coating)



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3
4
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MN
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RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
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SMN =.636E-04
SMX =10.099
.636E-04
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2.244
3.366
4.488
5.61
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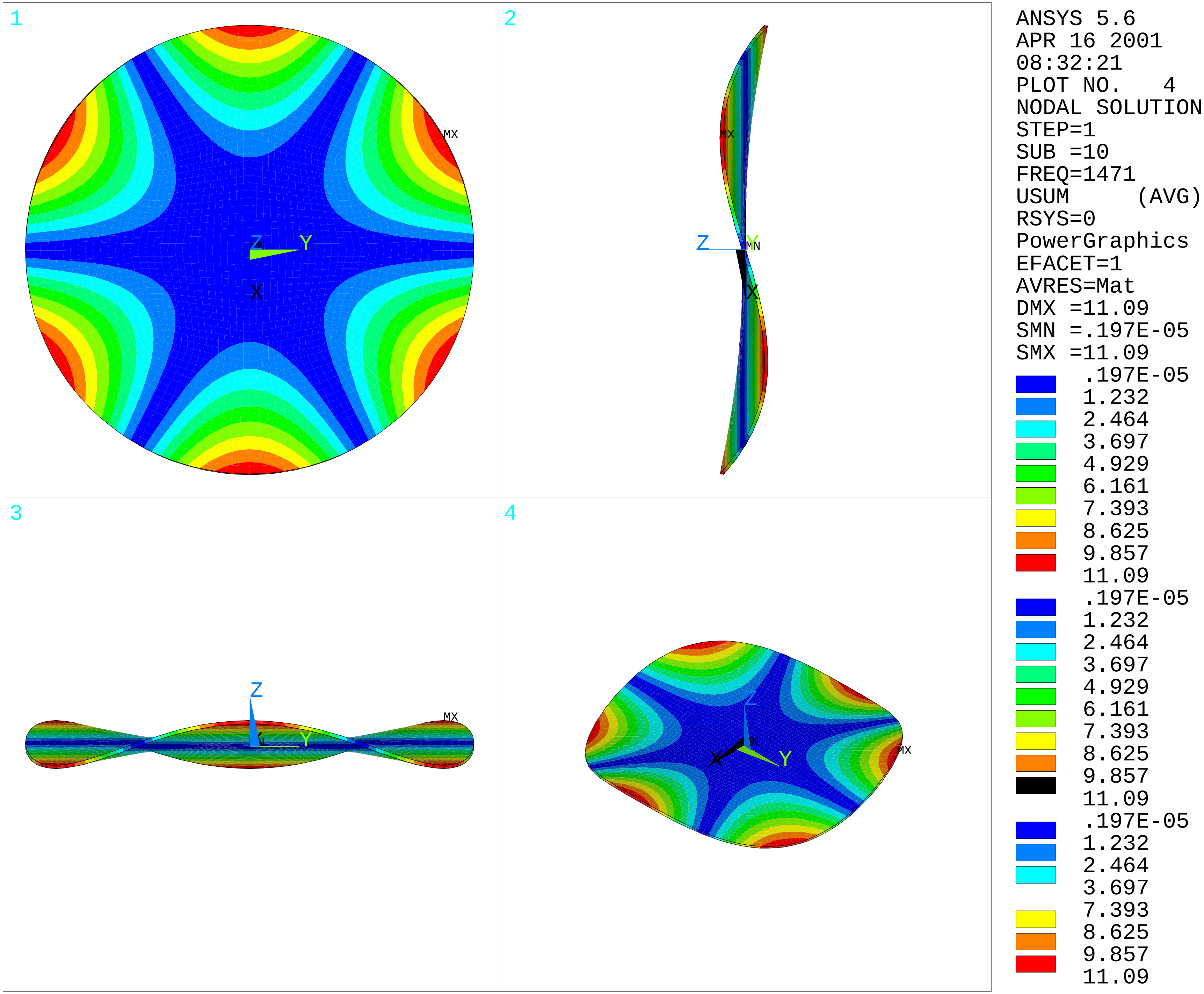
7.854
8.977
10.099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SMX =11.09
.197E-05
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7.393
8.625
9.857
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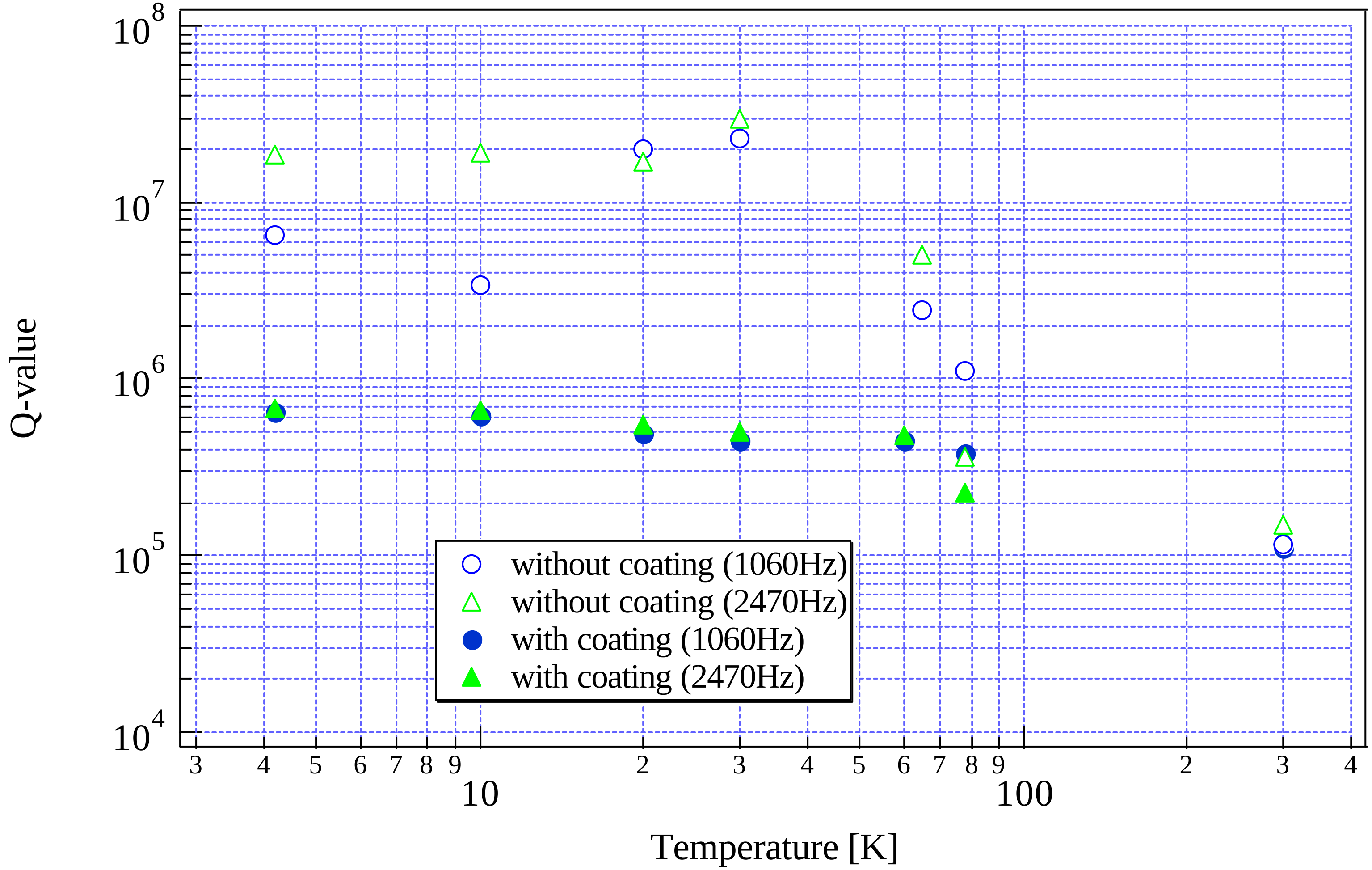
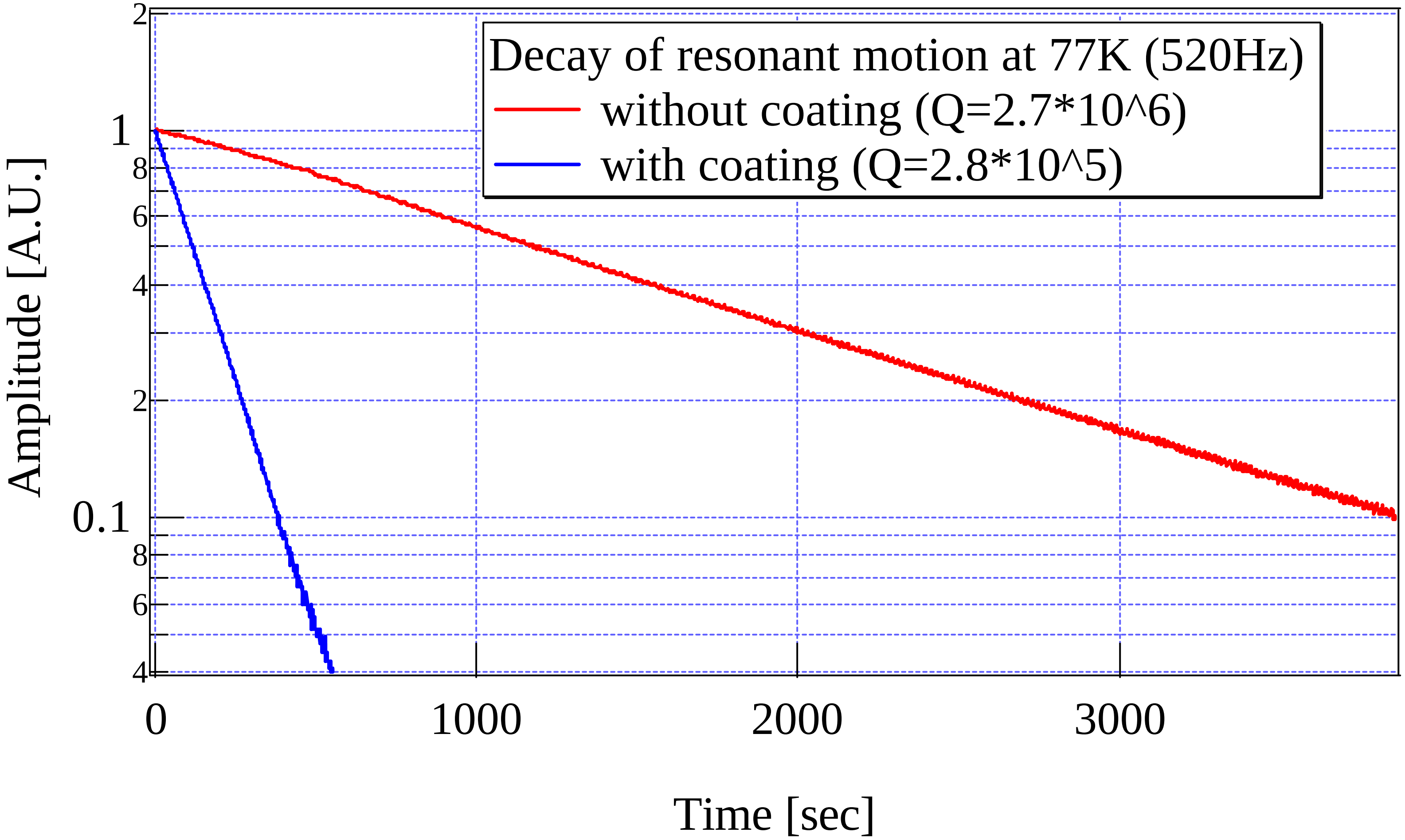
3.697
4.929
6.161
7.393
8.625
9.857
11.09
.197E-05
1.232
2.464
3.697
7.393
8.625
9.857
11.09

(ii) Measured Q-values

JAE coating on t 1mm disk with annealing

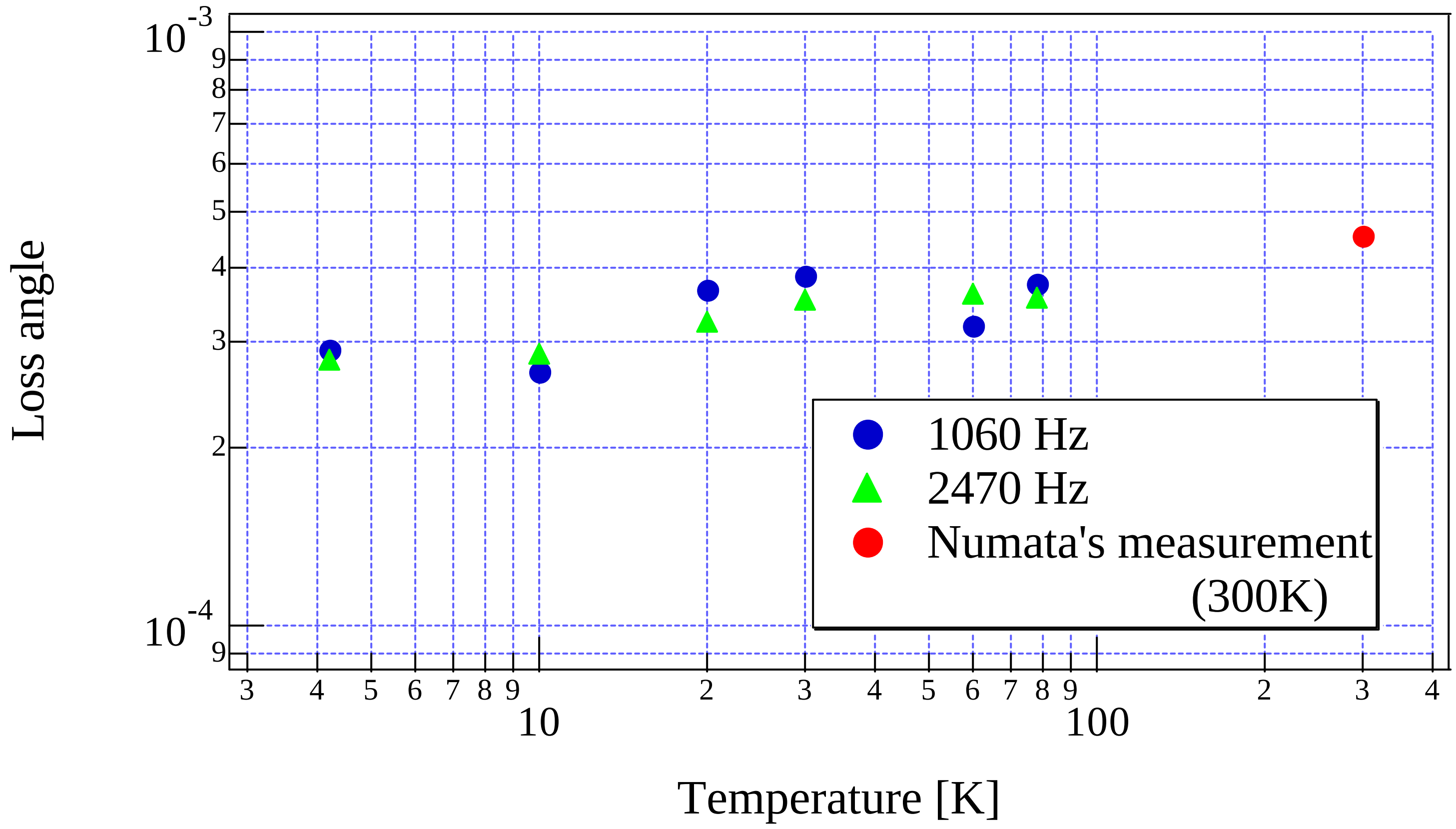


Decay of resonant motion

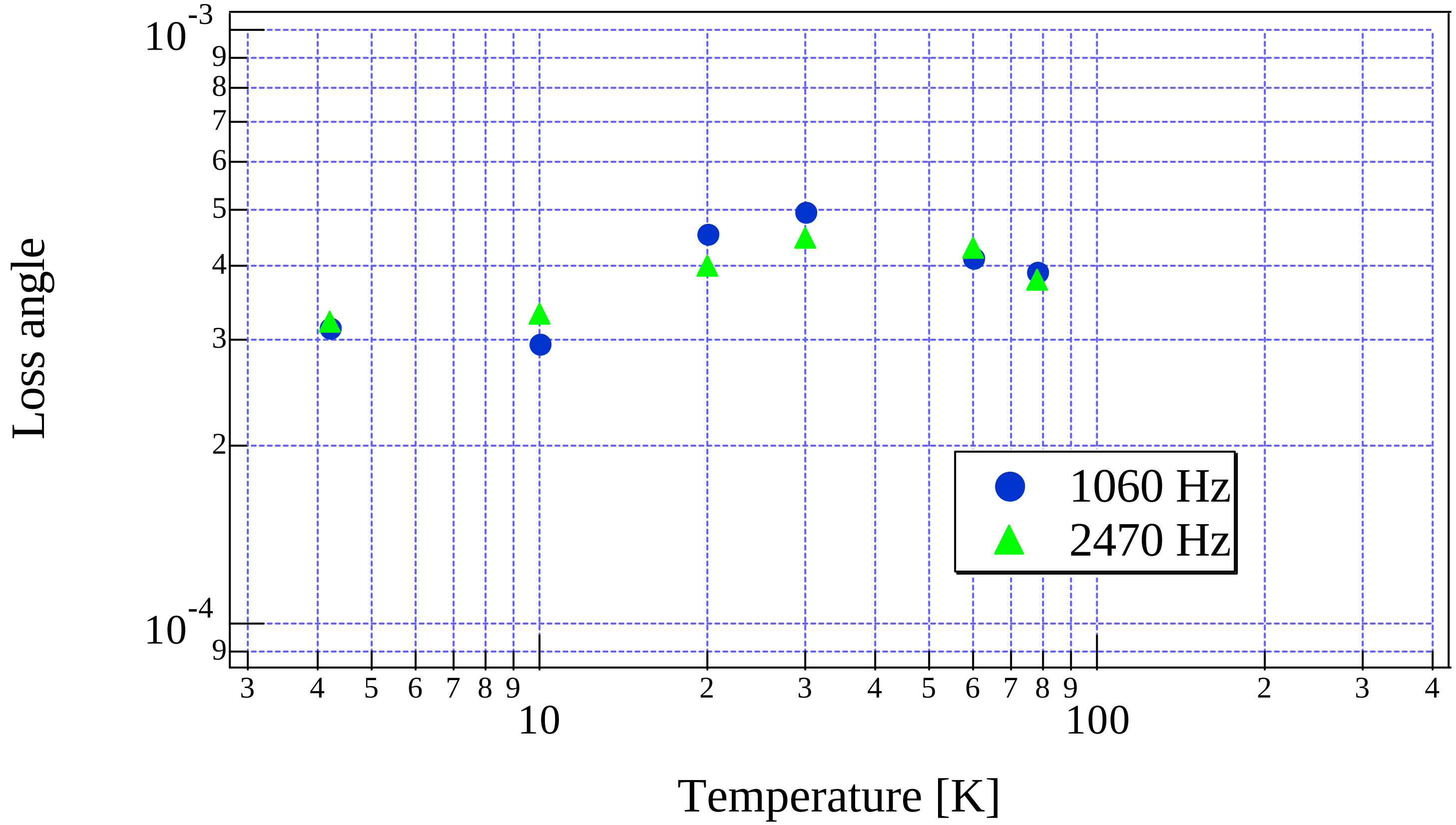


(iii) Loss angle of coating

NAO coating on t 1mm disk without annealing



JAE coating on t 1mm disk
with annealing



(iv) Summary of results

- Loss angle of coating is about $4*10^{-4}$.

  This value is not so good.

  Measurement of other groups at 300K : $6*10^{-5}$ - $4*10^{-4}$

- Loss angle of all samples in all cases are the same.

  Loss of JAE coating is as large as that of NAO coating.

  Loss angle of coating does not depend on temperature, resonant frequency, thickness of sapphire disk.

  Annealing does not affect loss of coating.

4. Discussion

(i) Property of coating loss

- Loss angle is independent of temperature (4.2K-300K).

  Thermal noise of coating loss is proportional to $T^{1/2}$.

  ex.) (thermal noise at 20 K) = (thermal noise at 300 K) /4

  → advantage of cryogenic interferometer

- Loss angle is independent of temperature (4.2K-300K).

  Expectation : Coating loss becomes larger at low temperature

  because loss of cool SiO_2 is large.

  ↓

  Coating loss is not dominated by intrinsic loss of SiO_2.

- Loss angle is independent of resonant frequency and mode.

  → Structure damping model is valid.

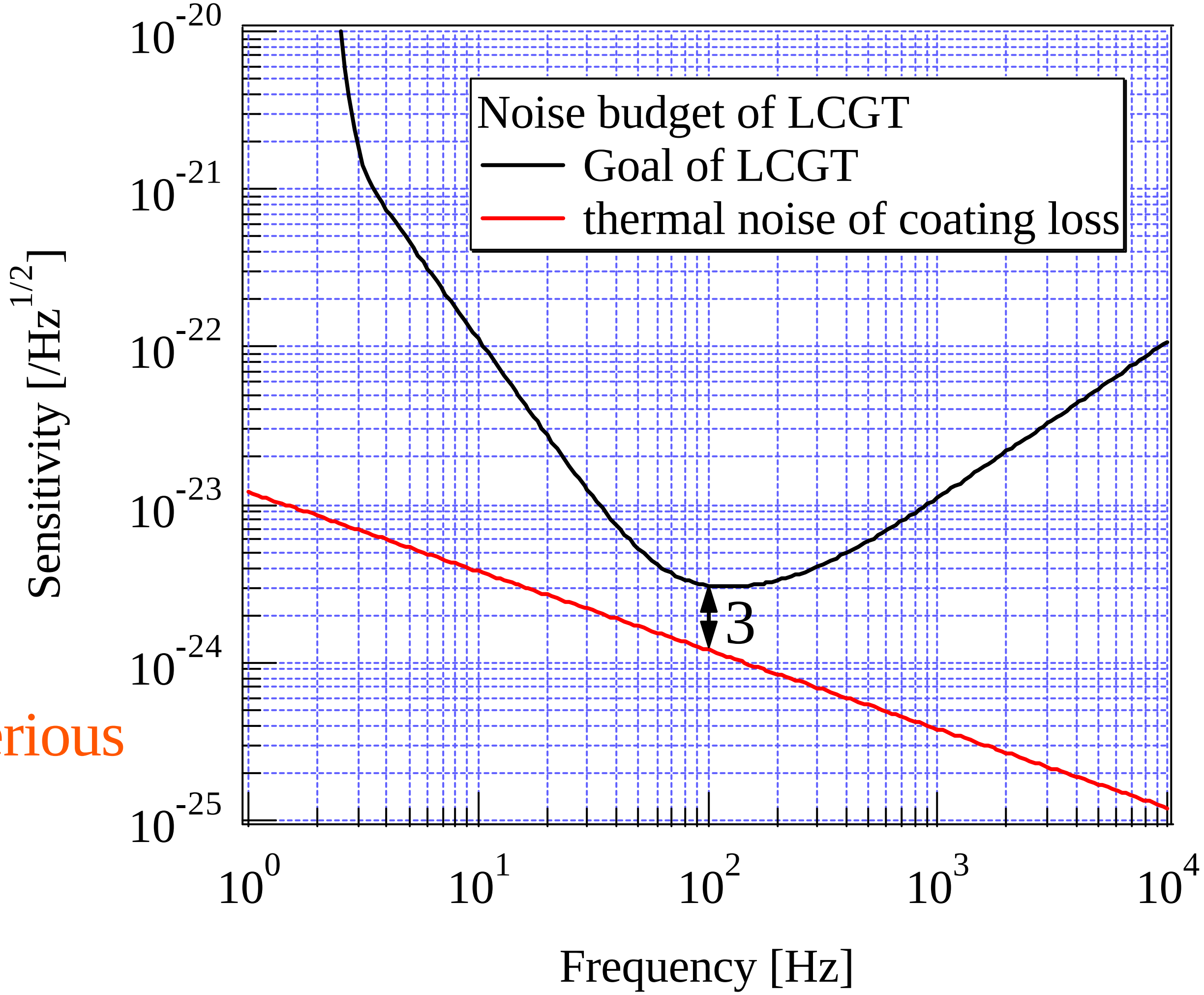
- Loss angle is independent of thickness of disk.

  → Strain does not increase loss.

- Annealing does not change the loss angle.

  → Strain does not increase loss.

(ii) Thermal noise in LCGT



coating loss : not serious

4-6.Summary of measurement of coating loss

(i) Measurement of mechanical loss of reflective coating at low temperature.

(ii) Coating loss is independent of temperature (4.2K-300K).

→ advantage of cryogenic interferometer

(iii) Coating loss is not a serious problem in LCGT.

5. Summary

(i) Our calculation proved that thermal noise caused by mechanical loss of reflective coating is larger than the estimation of modal expansion, traditional method.

(ii) Our experimental check using the oscillator like a mirror supports our calculation.

(iii) We measured mechanical loss of reflective coating at low temperature.

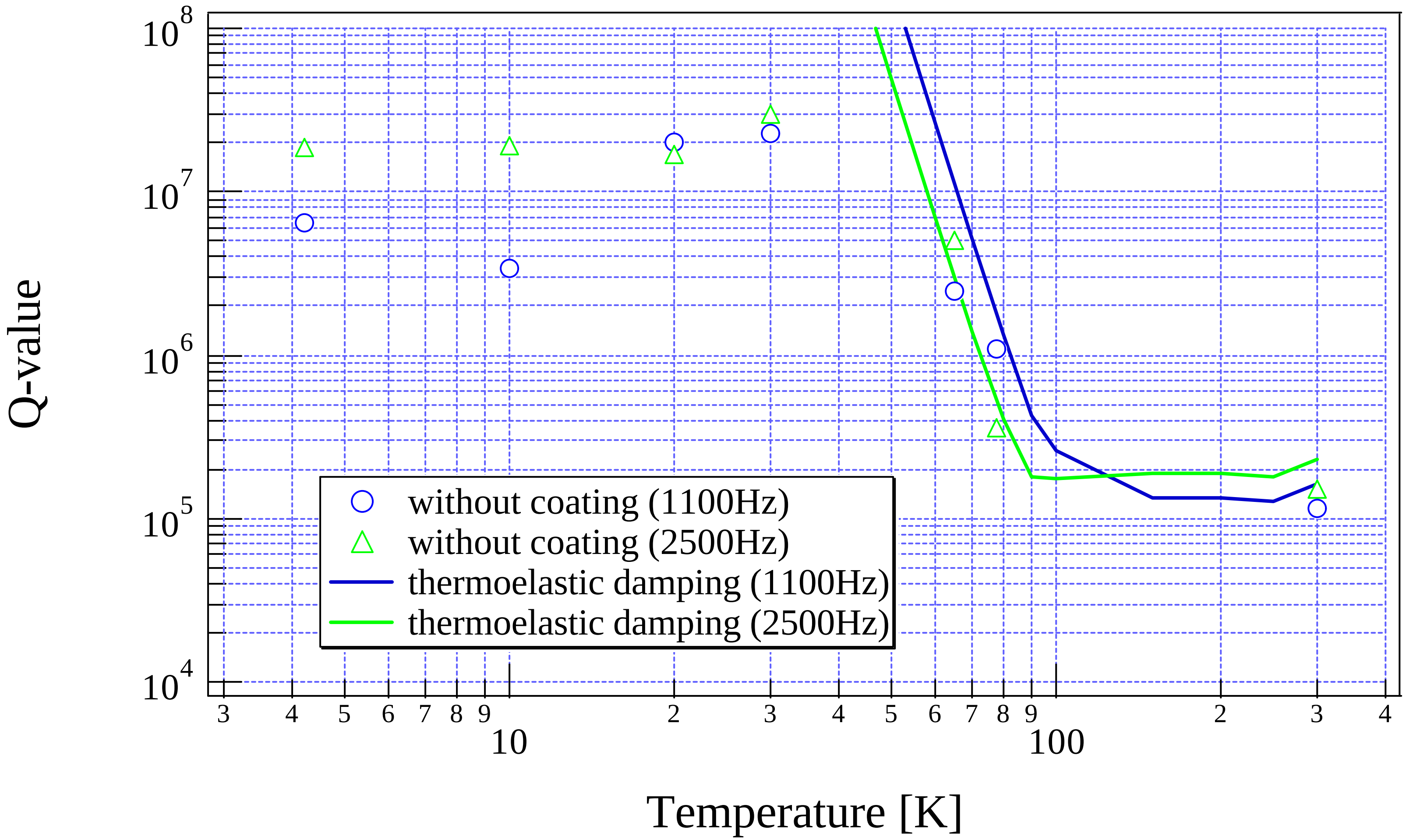
Coating loss is independent of temperature.

→ advantage of cryogenic interferometer

In LCGT, coating loss is not a serious problem because of cooling.

Thermoelastic damping

t 1 mm



Measurement of other group