KEKセミナー　　2004.5.7
「高エネルギー物理学と宇宙像」

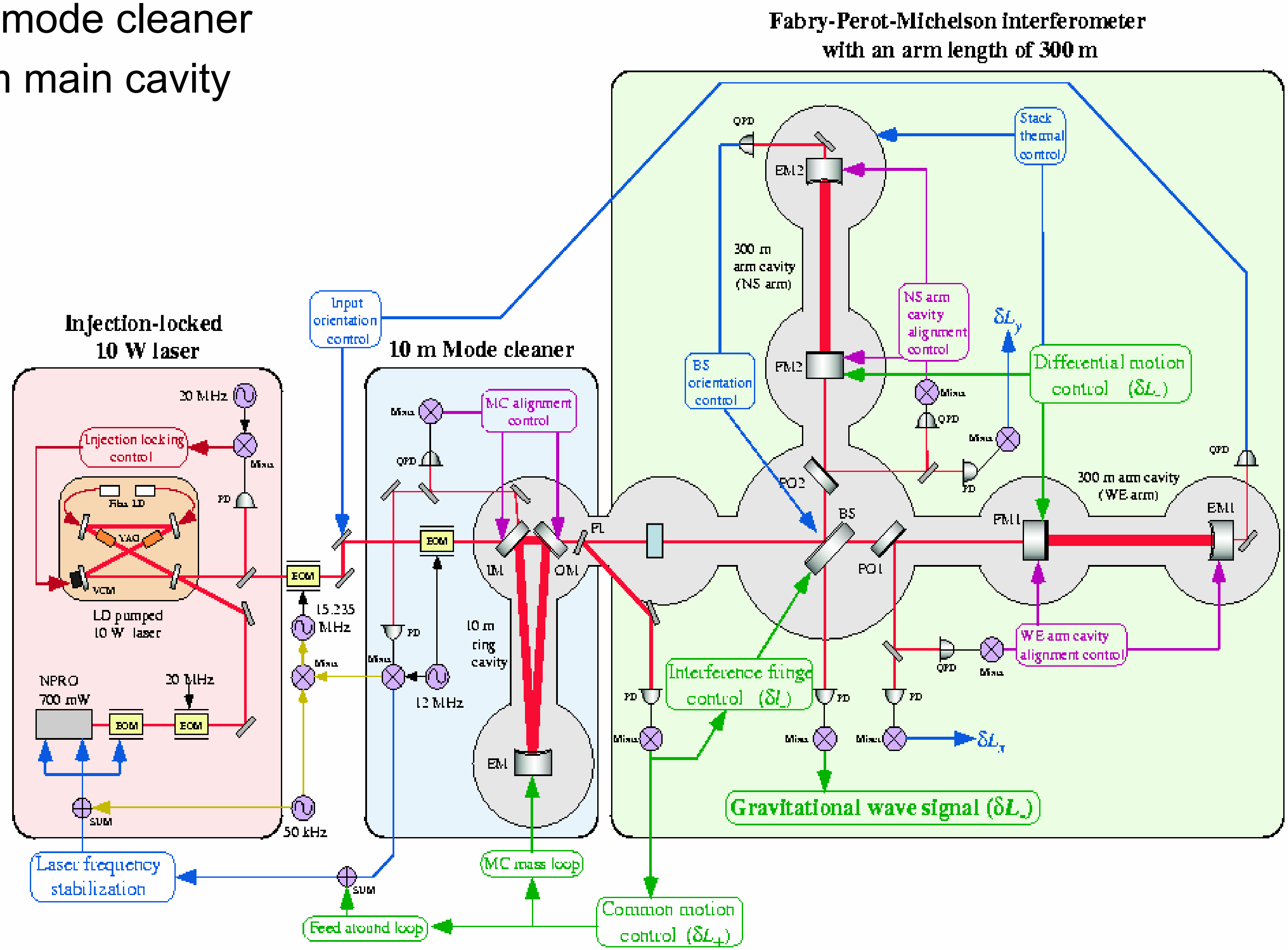
重力波実験と精密重力実験 その二

東京大学宇宙線研究所
黒田和明

TAMAから CLIO / LCGTへ

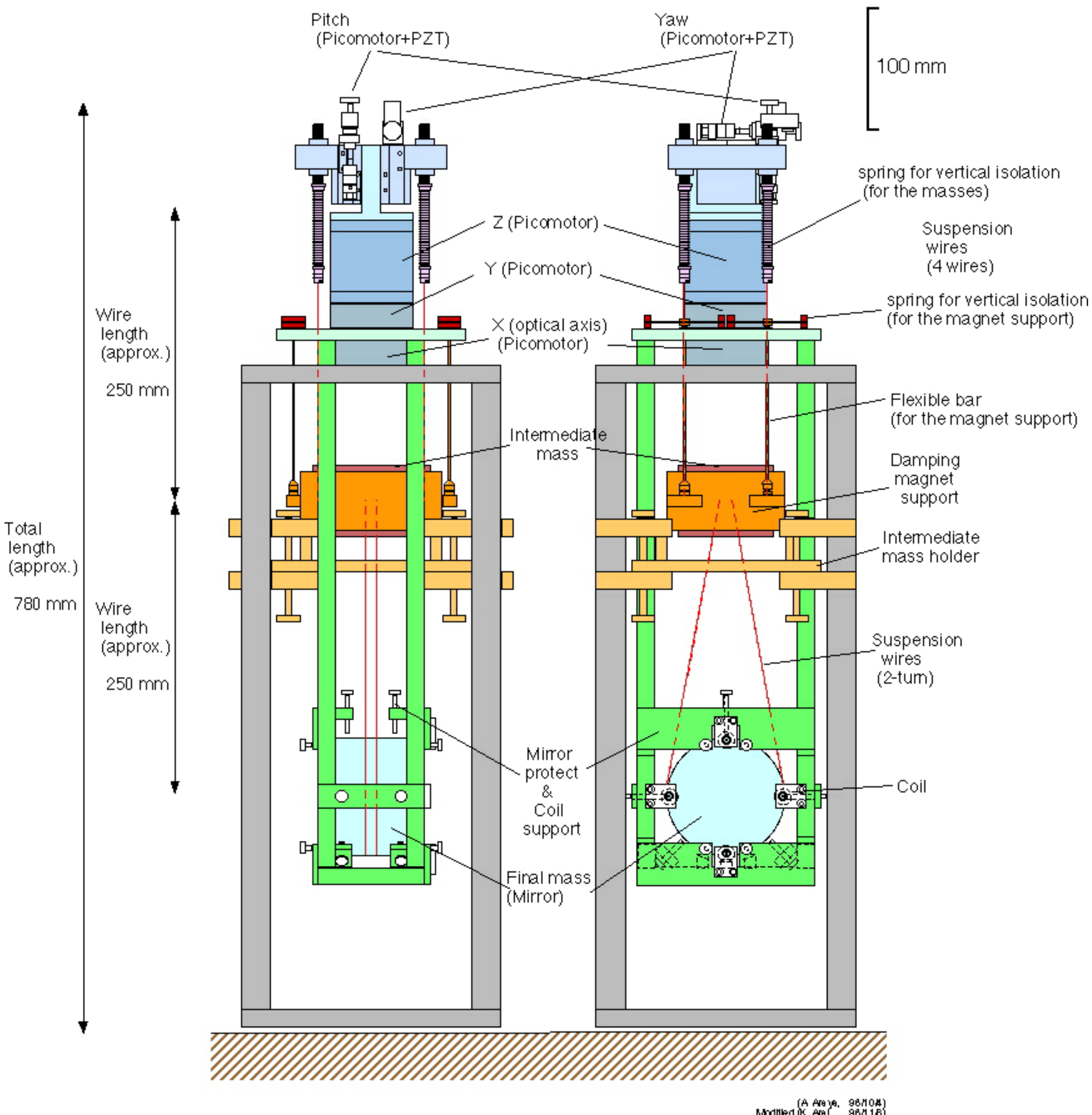
Optical layout of TAMA300

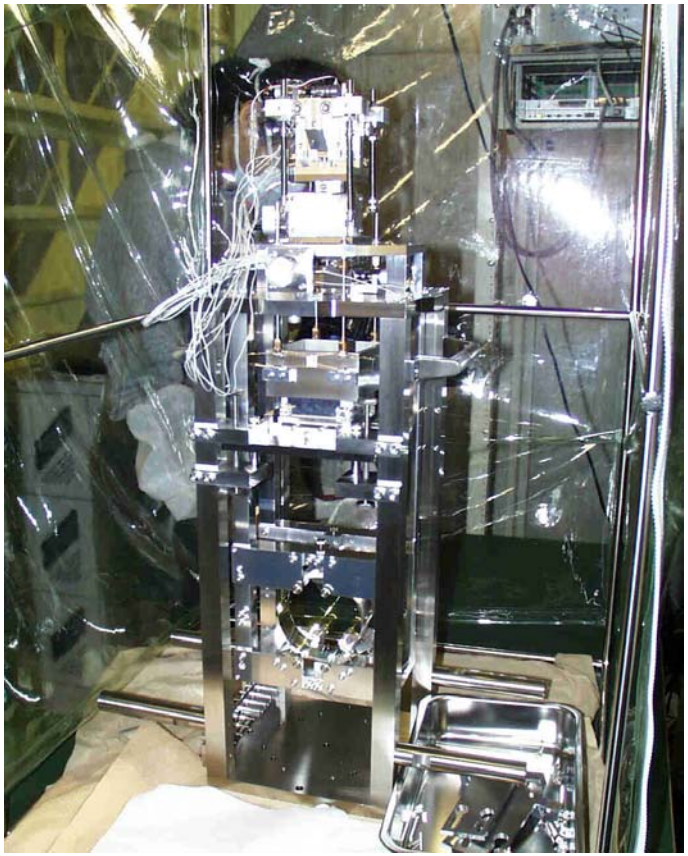
- 10W LD pumped Nd:YAG laser
- 10m mode cleaner
- 300m main cavity



The most uncompleted item of TAMA

Prototype of TAMA300 suspension



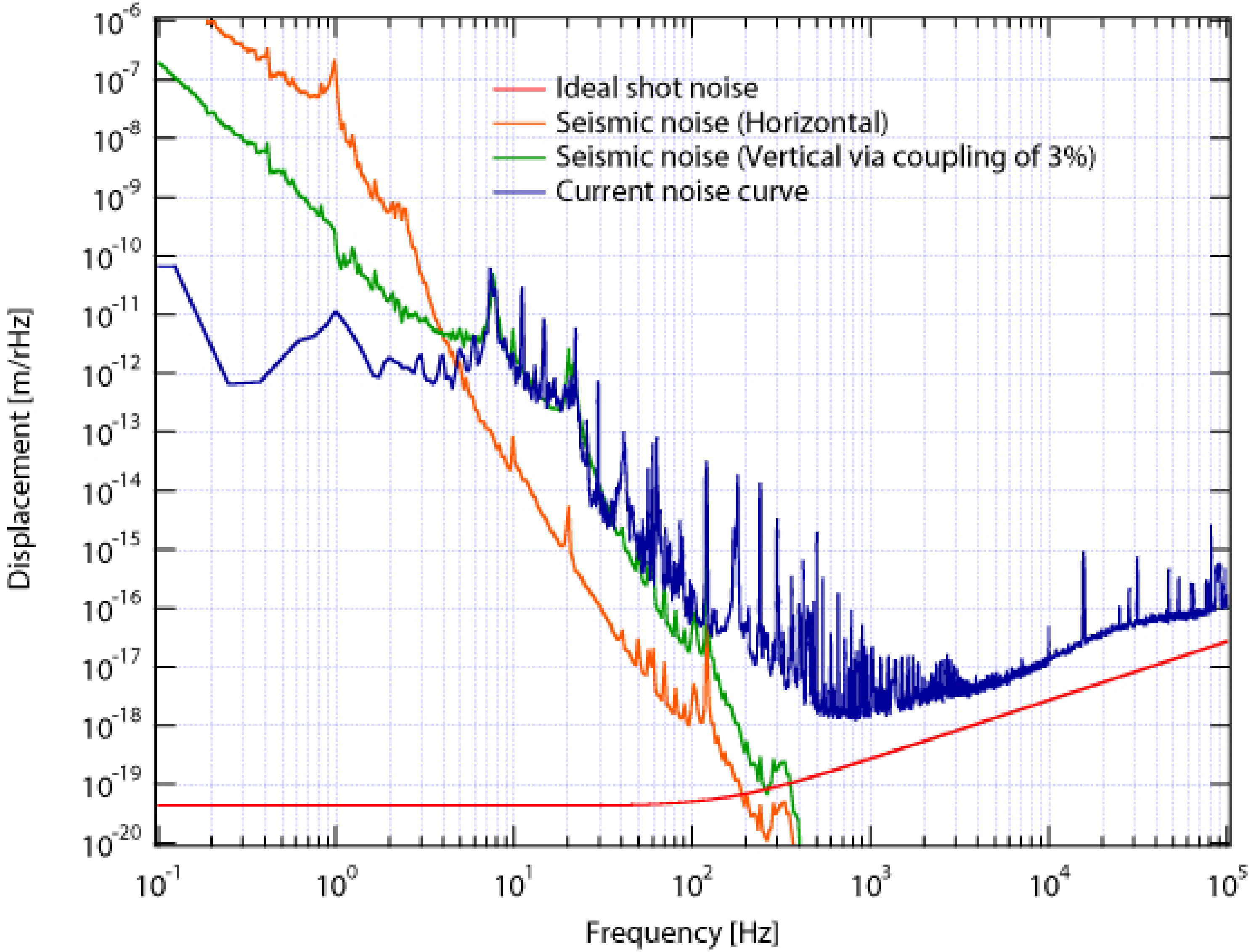


Evaluation of TAMA Components

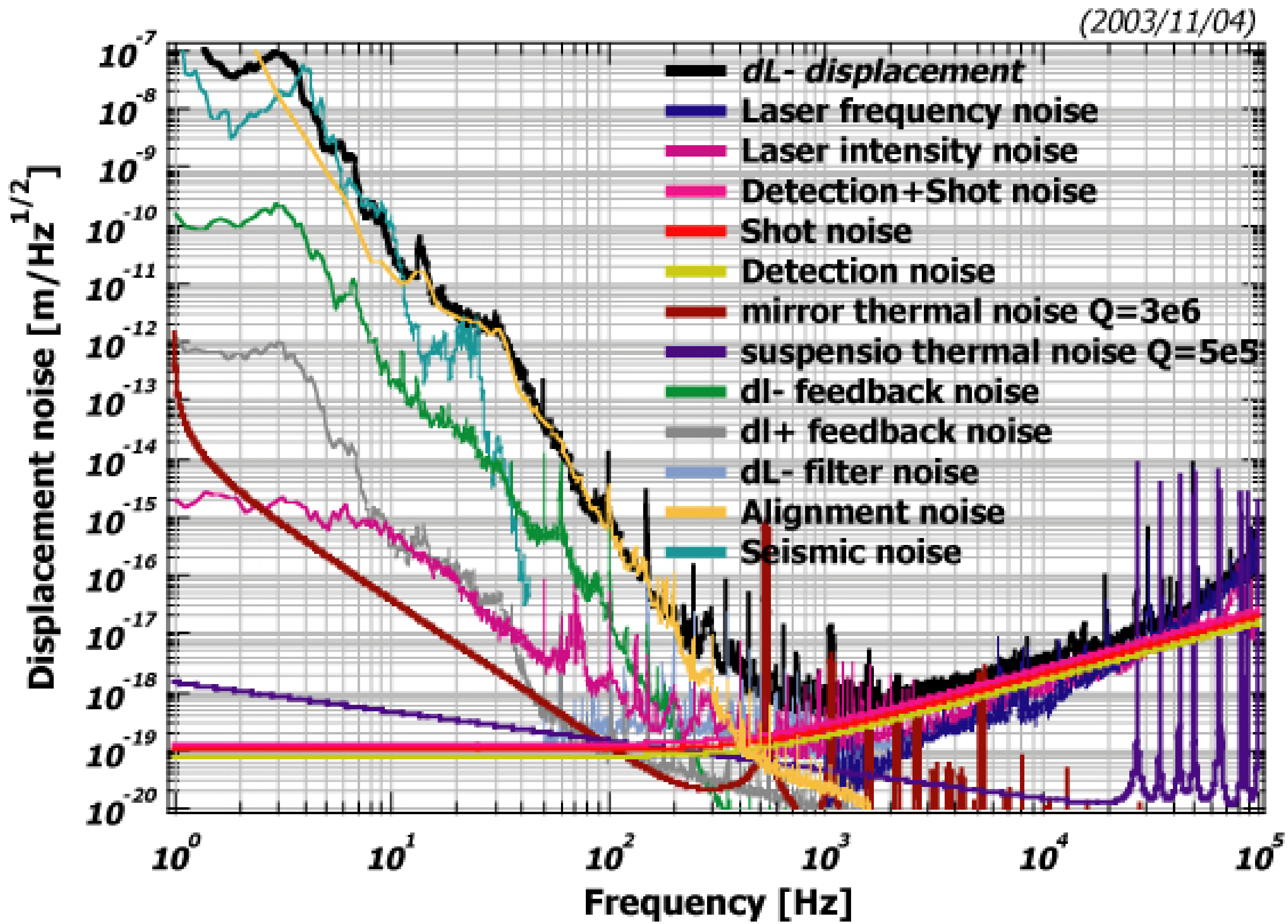
• Laser	3
• Mirror, Optical pieces	5
• Anti-vibration system, suspension system	1
• Vacuum	4
• Control system	4
• Data collecting system	5
• Others	5

From LISM noise spectrum – prototype of TAMA suspension

Cross coupling determined the sensitivity in loq frequencies



Noise source of TAMA（with p. recycling）



TAMA research plan in future

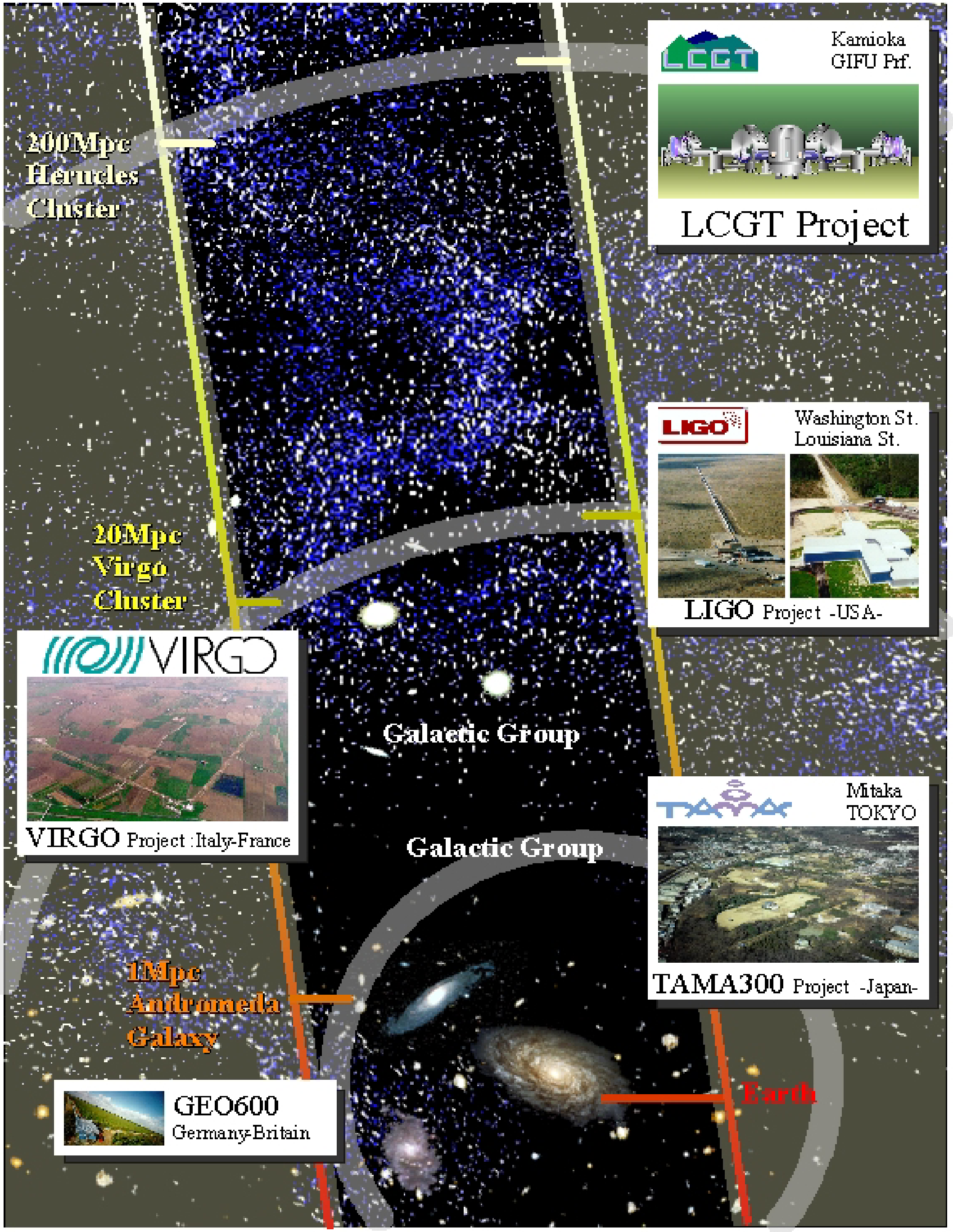
- Noise hunting
  - In Recycled Michelson
  - Back scattering light noise
  - Modulation induced noise
- Seismic Attenuation System
  - Caltech-Pisa Univ.-Tsubono group
  - 2005
- Power recycling gain →10

Since BNS exist and the signal of the coalescence is precisely predicted, the event is the most important target of the ground based interferometric detectors.

However, since the event rate is 10^{-5}～10^{-6} per year per matured galaxy as ours, we have to wait many years on average by the sensitivity to observe the VIRGO cluster（20Mpc). Because there is less than one galaxy per cubic Mpc.

Therefore, it is clear to everyone to develop more sensitive detector to see more remote galaxies. LCGT can see the event of nominal coalescence of BNS at 244Mpc (s/N=10, optimal direction & polarization, single detector).

View Ranges of Gravitational Wave Detectors



Observed neutron star binaries

- PSR B1534+12 (0.5kpc) 10^{-6} in Galaxy
- PSR B1913+16 (7.3kpc) 10^{-7} in Galaxy
- PSR B2127+11C (10.6kpc) in M15
- PSR J0737+3039 (0.5-0.6kpc) $\sim 10^{-5}$ in Galaxy

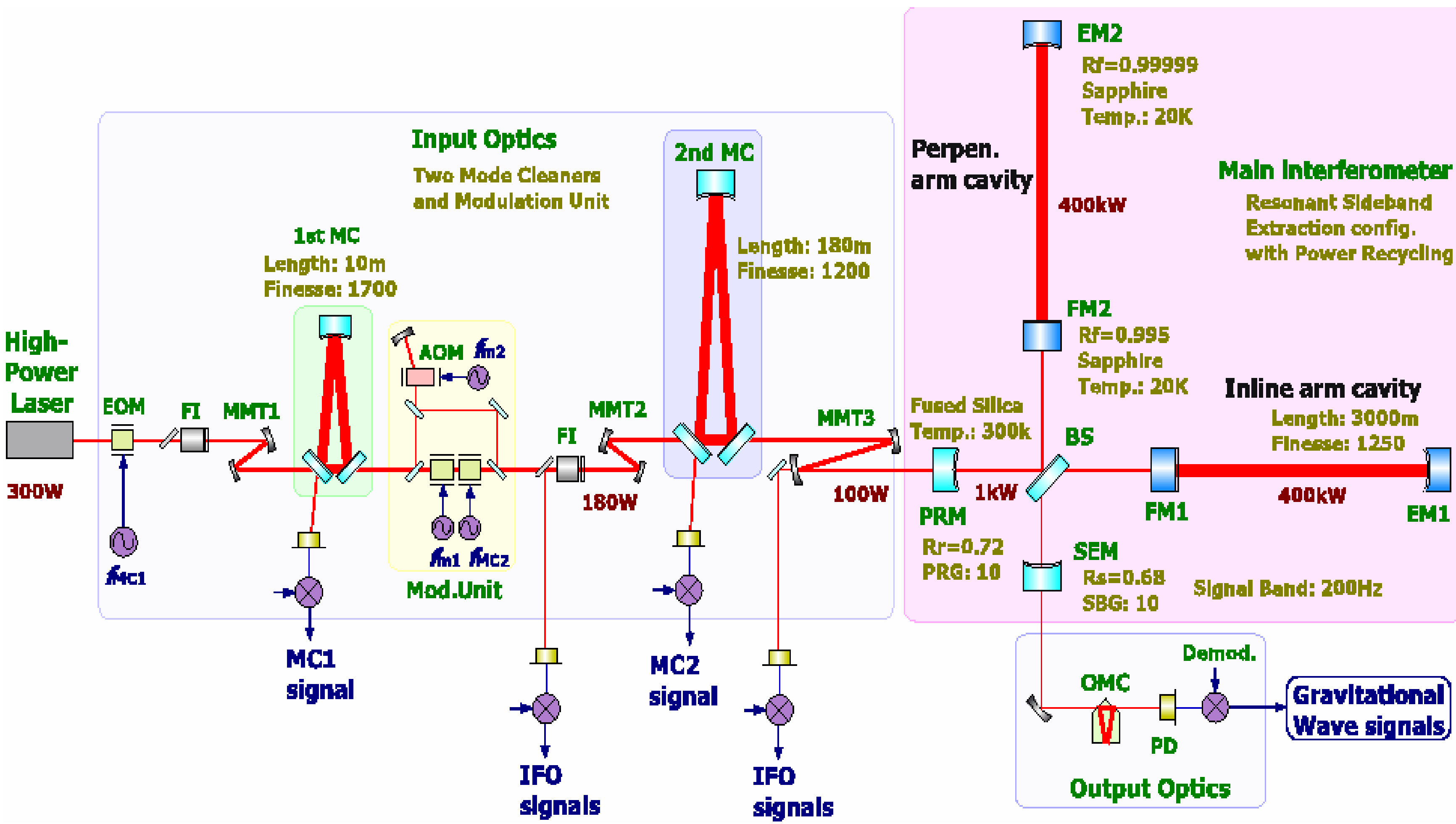
Characteristic of LCGT

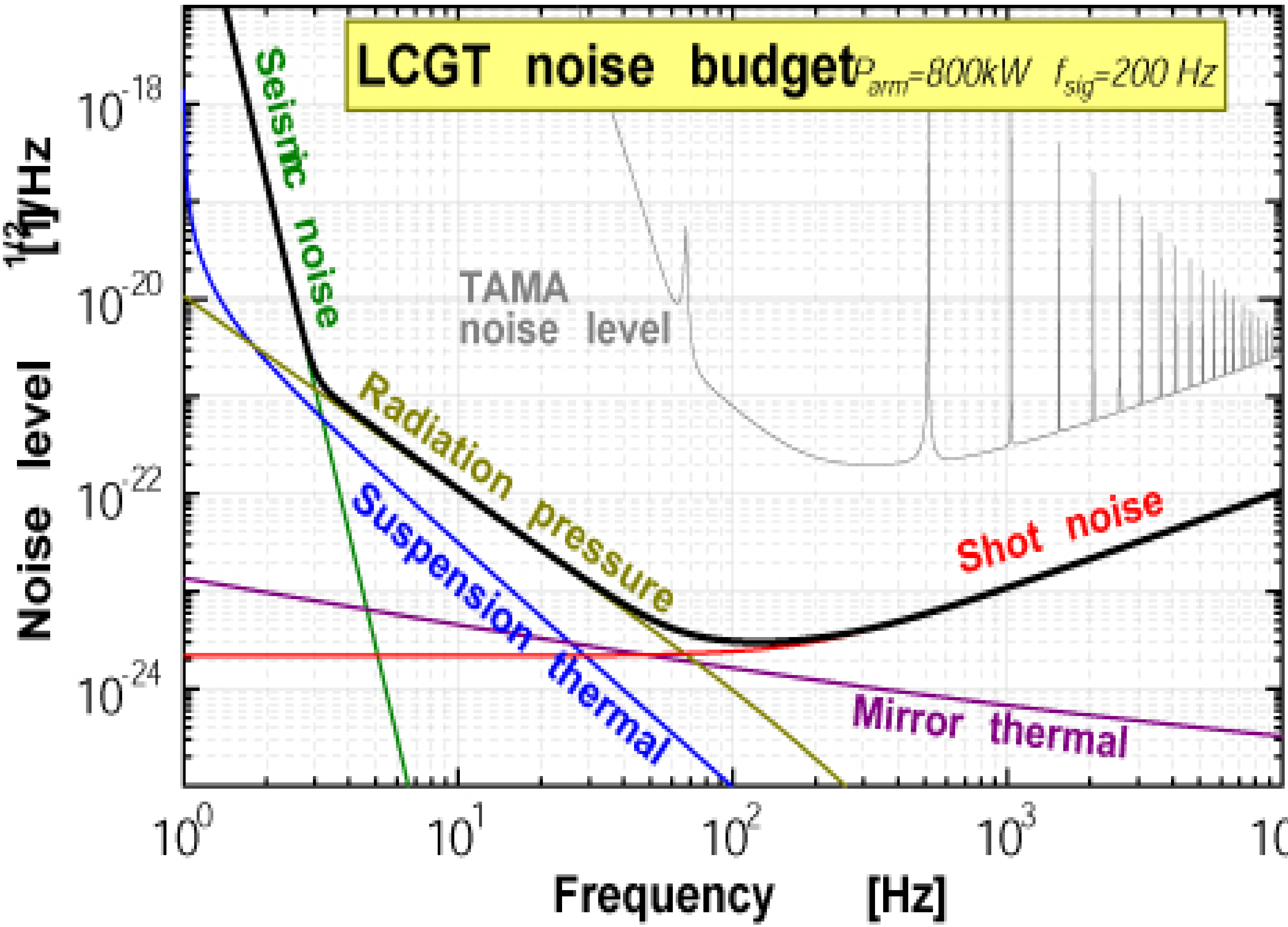
- Cryogenics
  - 20K sapphire mirror
- Underground
  - Stable & hard rock
- Two Parallel Interferometers
  - Coincidence Observation

Fake elimination using parallel Interferometers

- Assumption of the TAMA fake event << 1 / 1hour
- Coincidence analysis of two identical interferometer placed side by side
- Probability detecting noise in Δt is $p^2 \Delta t$
- $\Delta t \sim 0.5ms \times 3$
- Expected rate of the signal event is assumed as 1 event/year -> 3×10^{-8} /s
- $p^2 \Delta t < 0.27\% \times \{3 \times 10^{-8}\} = 8 \times 10^{-11}$ / s $= 2.7 \times 10^{-3}$ / year
- $p < 2.3 \times 10^{-4} = 1 / (1.2$ hour$)$

An Optical Design of LCGT interferometer





LCGT noise budget P_{arm}=800kW f_{sig}=200 Hz
Seismic noise
TAMA noise level
Radiation pressure
Suspension thermal
Shot noise
Mirror thermal
Noise level [1/√Hz]
Frequency [Hz]
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

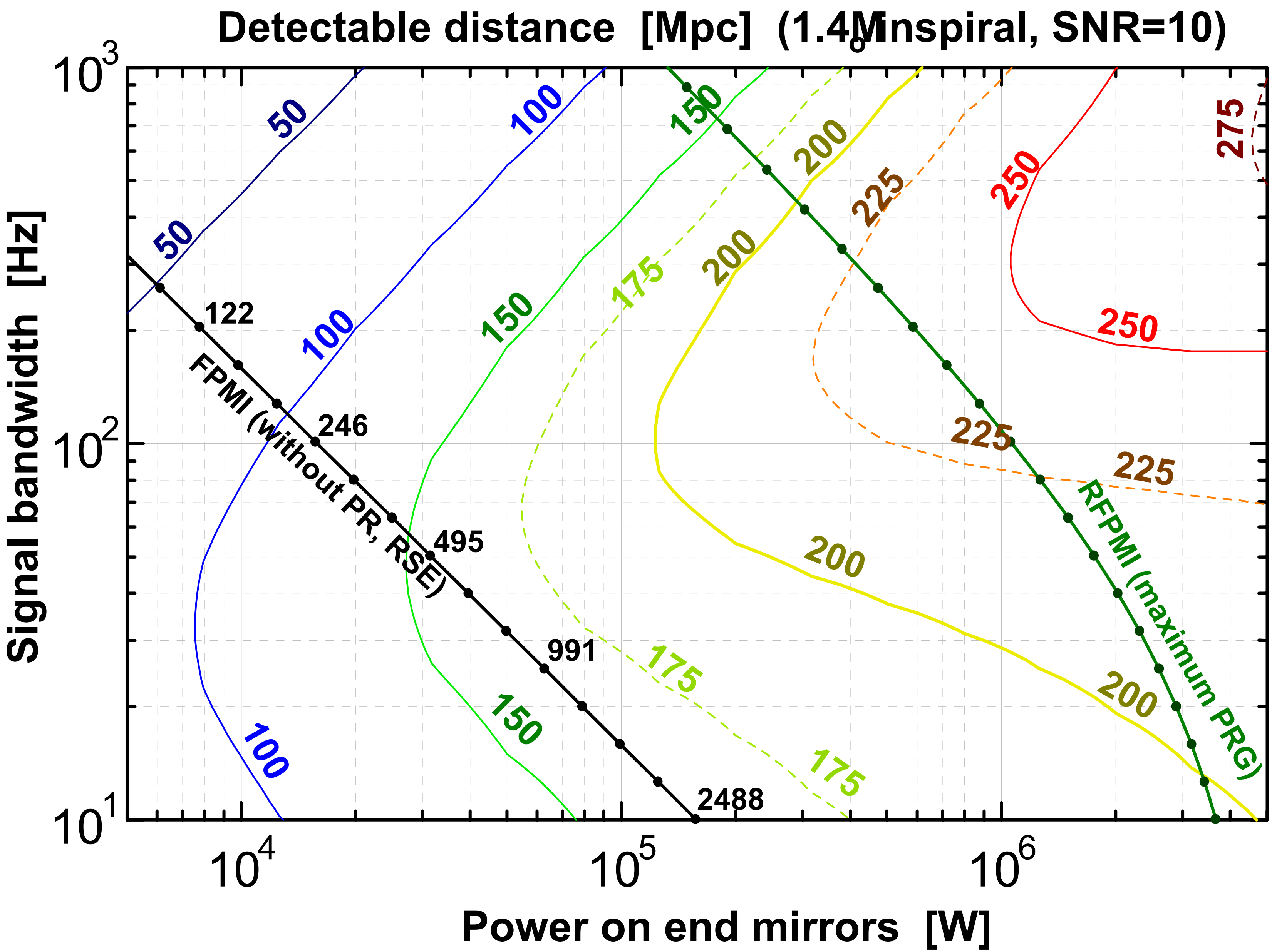
Optical Design Parameters

- Main Interferometer
  - Resonant Sideband Extraction
    with power recycling, broad band configuration
  - Arm cavity length 3000 m
  - Power in arm cavities 800 kW
  - Signal bandwidth 200 Hz
  - Arm cavity finesse 1250
  - Power recycling gain 10
  - Signal band gain 10

- Laser source
  - Output power 300W
  - Wavelength 1064nm

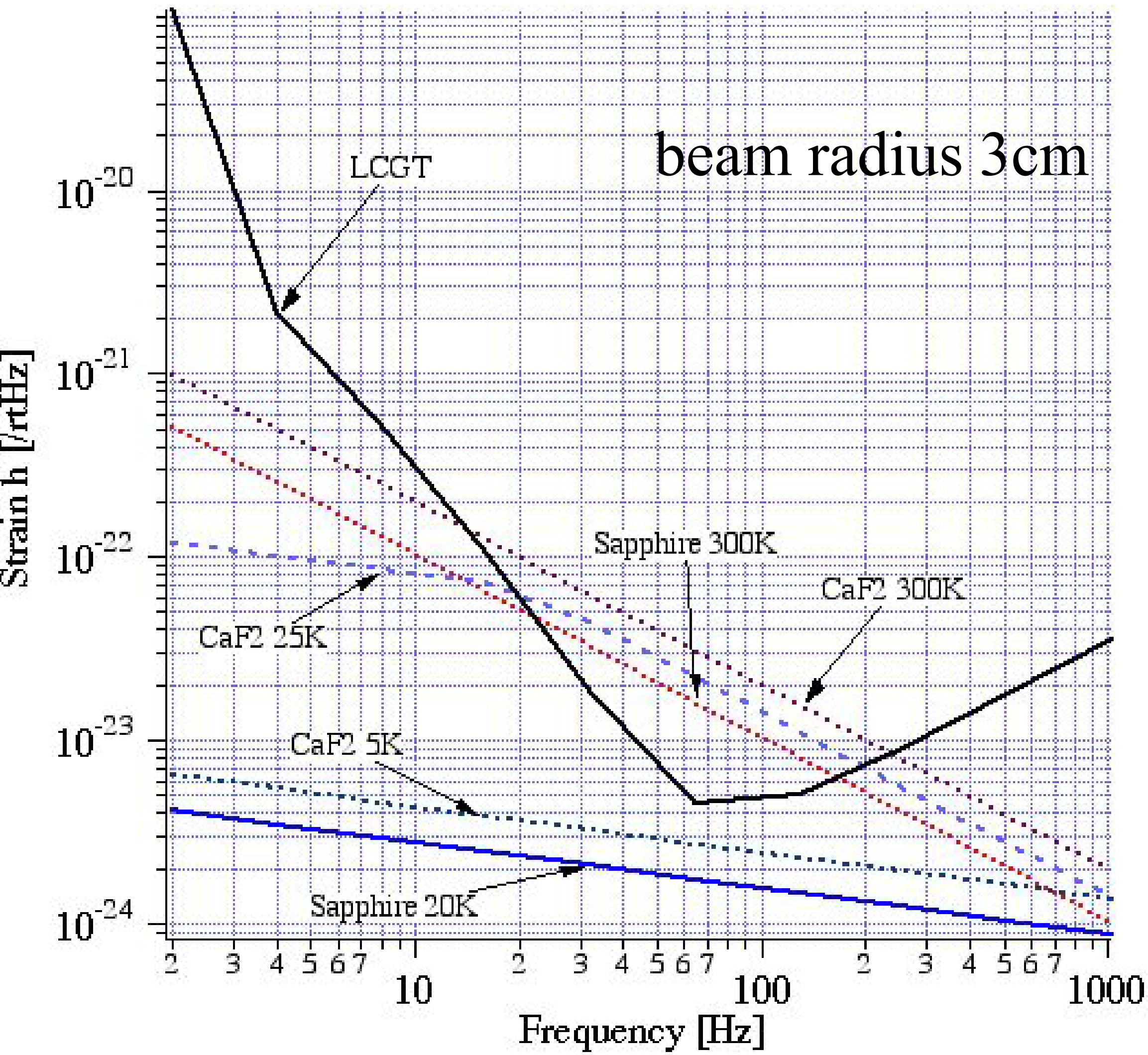
- Input optics
  - Power transmittance 33.3%
  - Modulation sidebands 15 MHz, 50 MHz
    - 1st Mode cleaner 10m Triangle ring cavity, 4.5kHz, FSR 15 MHz
    - 2nd Mode cleaner 180m Triangle ring cavity, 350Hz, FSR833kHz
- Core optics
  - Main Mirror: sapphire, 20K, 30cm, 18cm, 50kg
  - Substrate optical loss 500ppm/18cm; heat absorption 20ppm/cm

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



Detectable distance [Mpc] (1.4M☉ inspiral, SNR=10)
Signal bandwidth [Hz]
Power on end mirrors [W]
FPMI (without PR, RSE)
RFPMI (maximum PRG)
122
246
495
991
2488
50
100
150
175
200
225
250
275

Why did we choose sapphire?

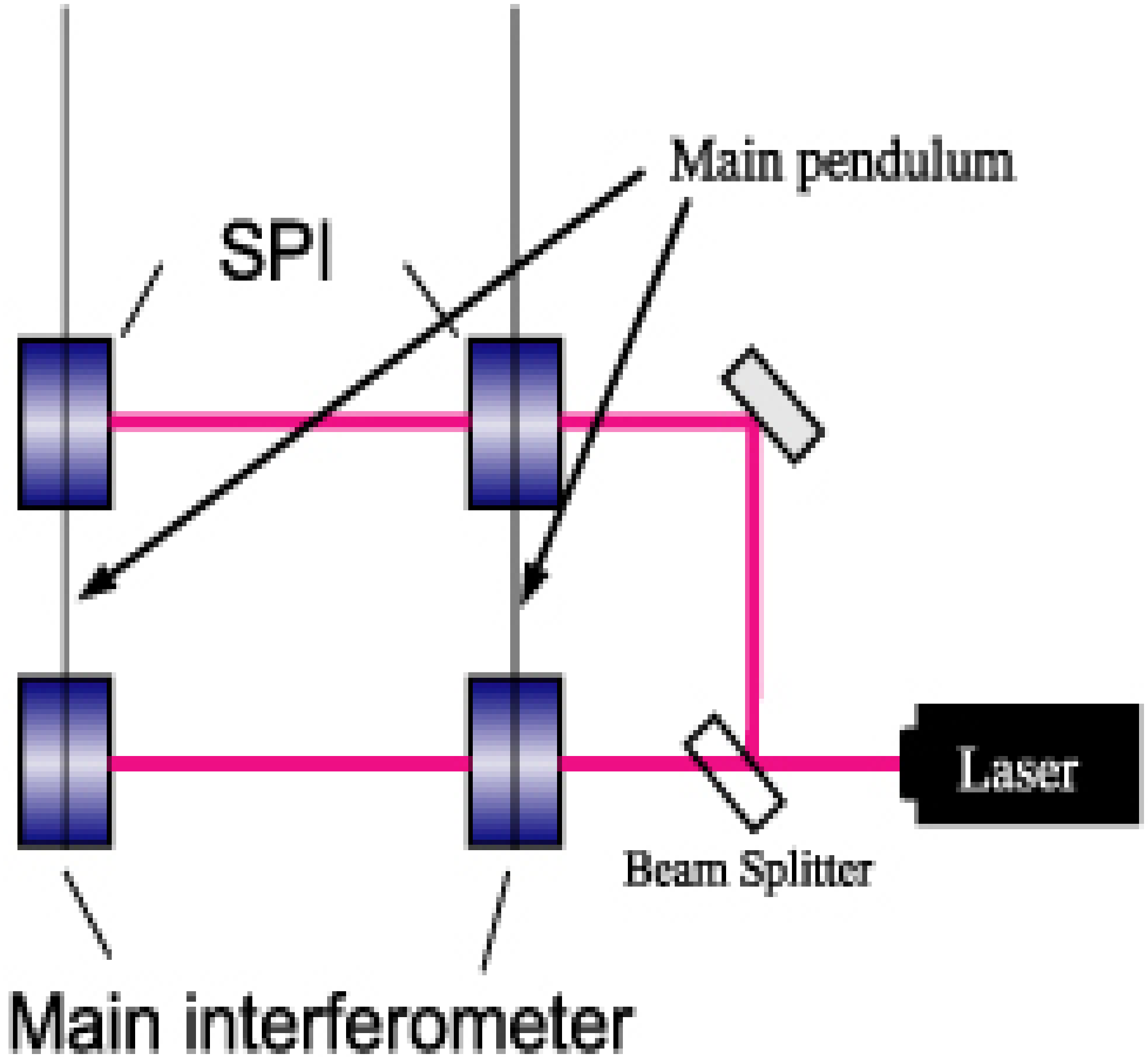


To improve by one order in room temperature.

Radius -> 4.6times ($10^{2/3}$) -> 14cm

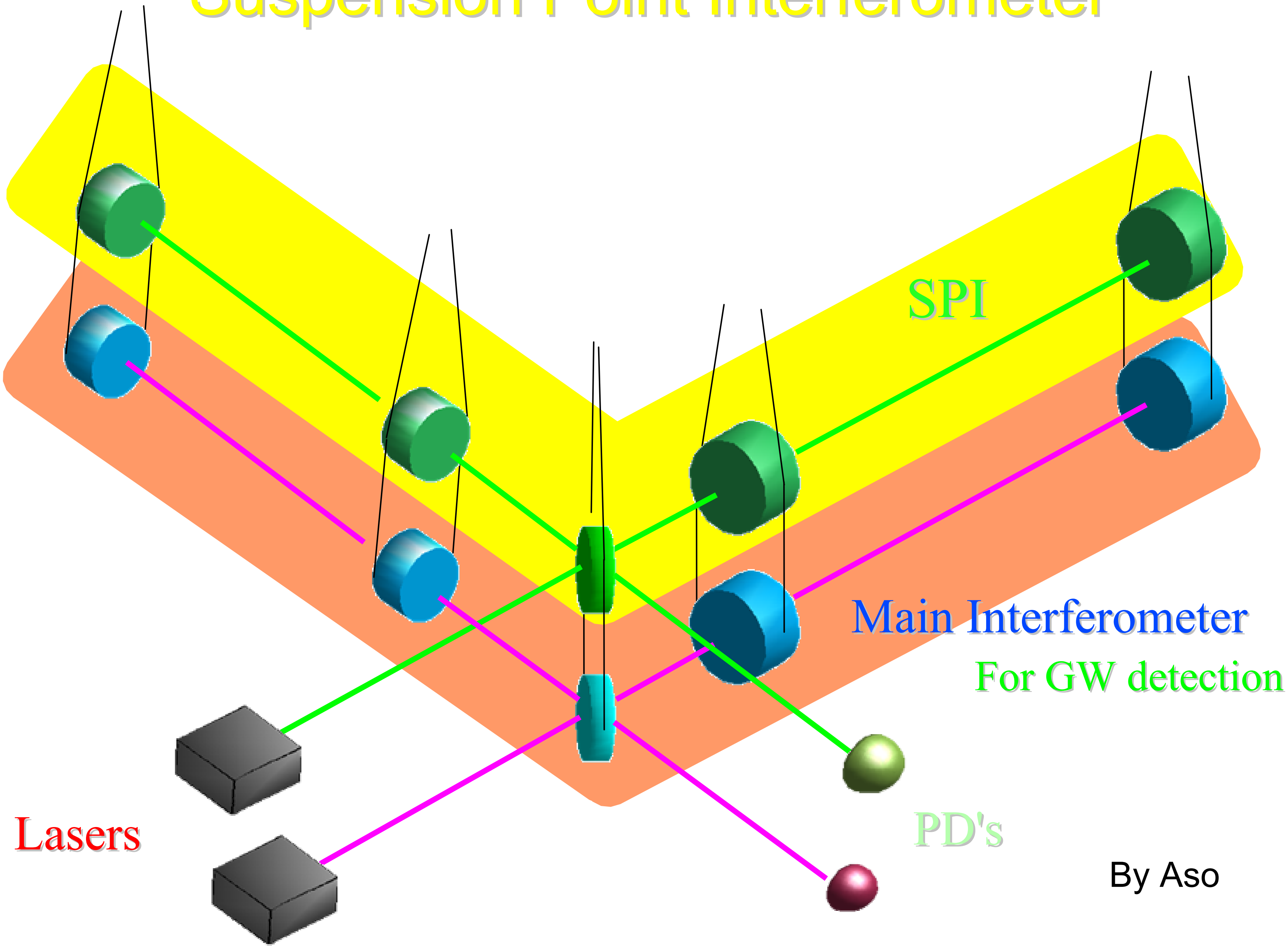
By Uchiyama

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

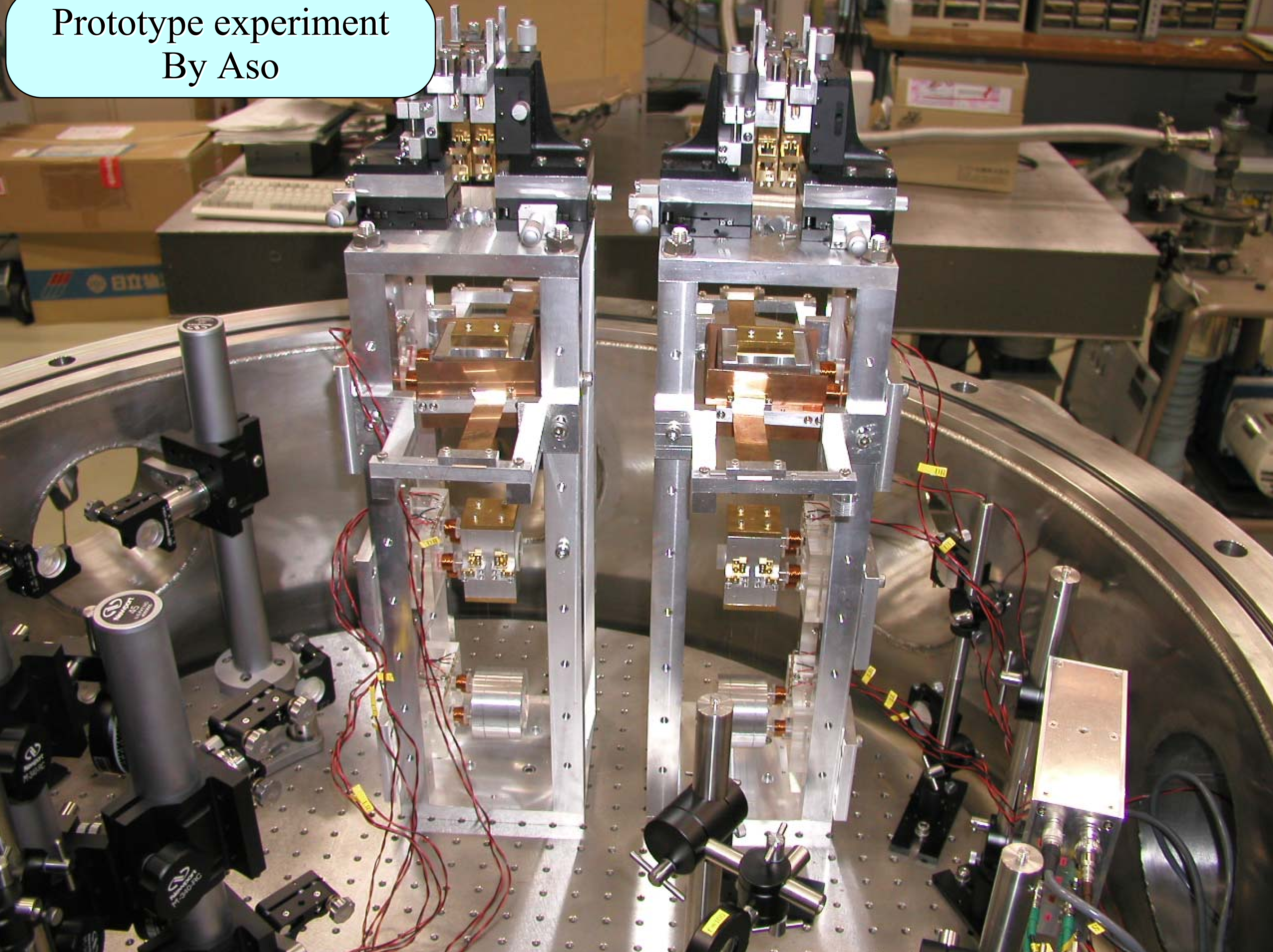


By Aso

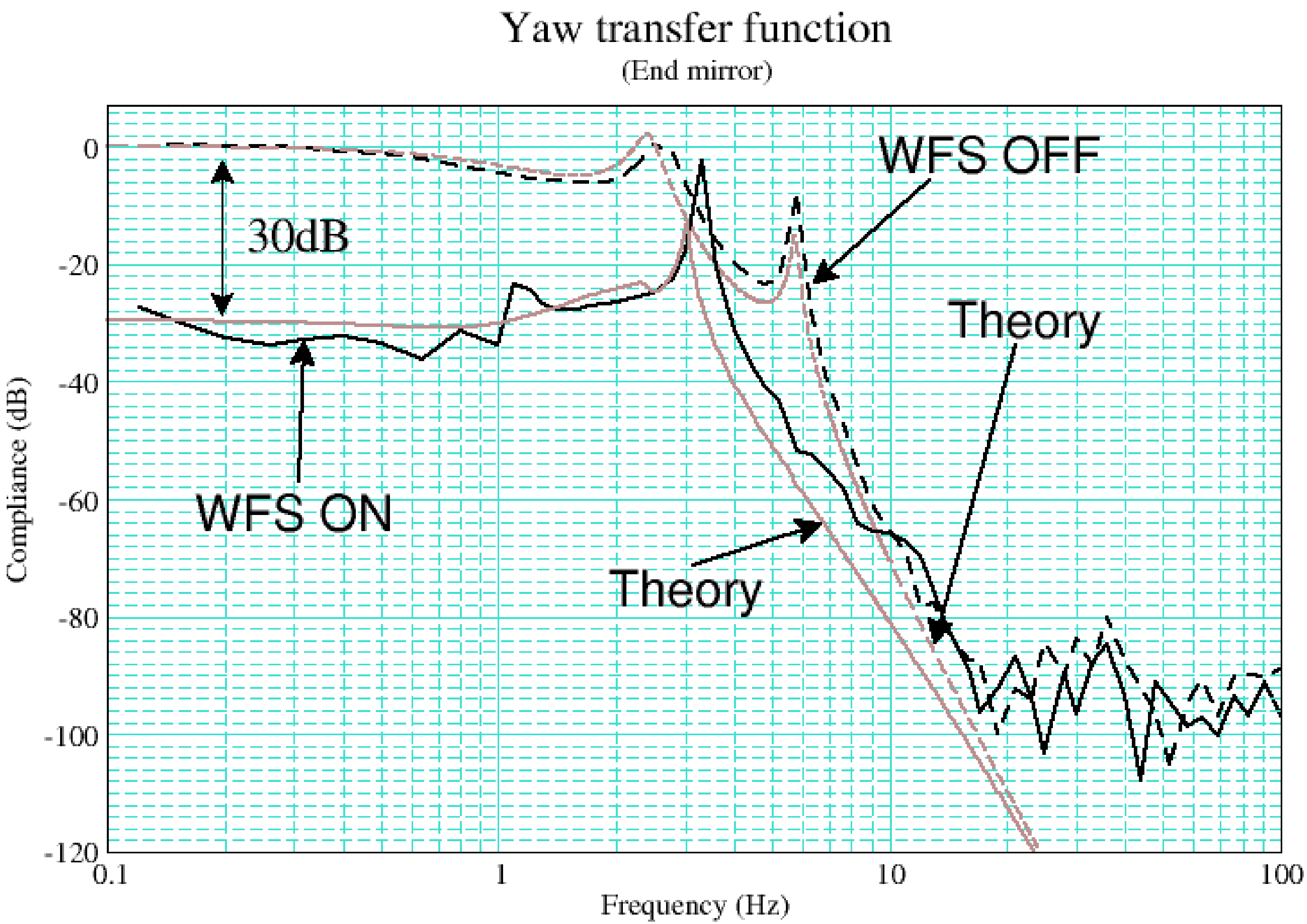
Suspension Point Interferometer



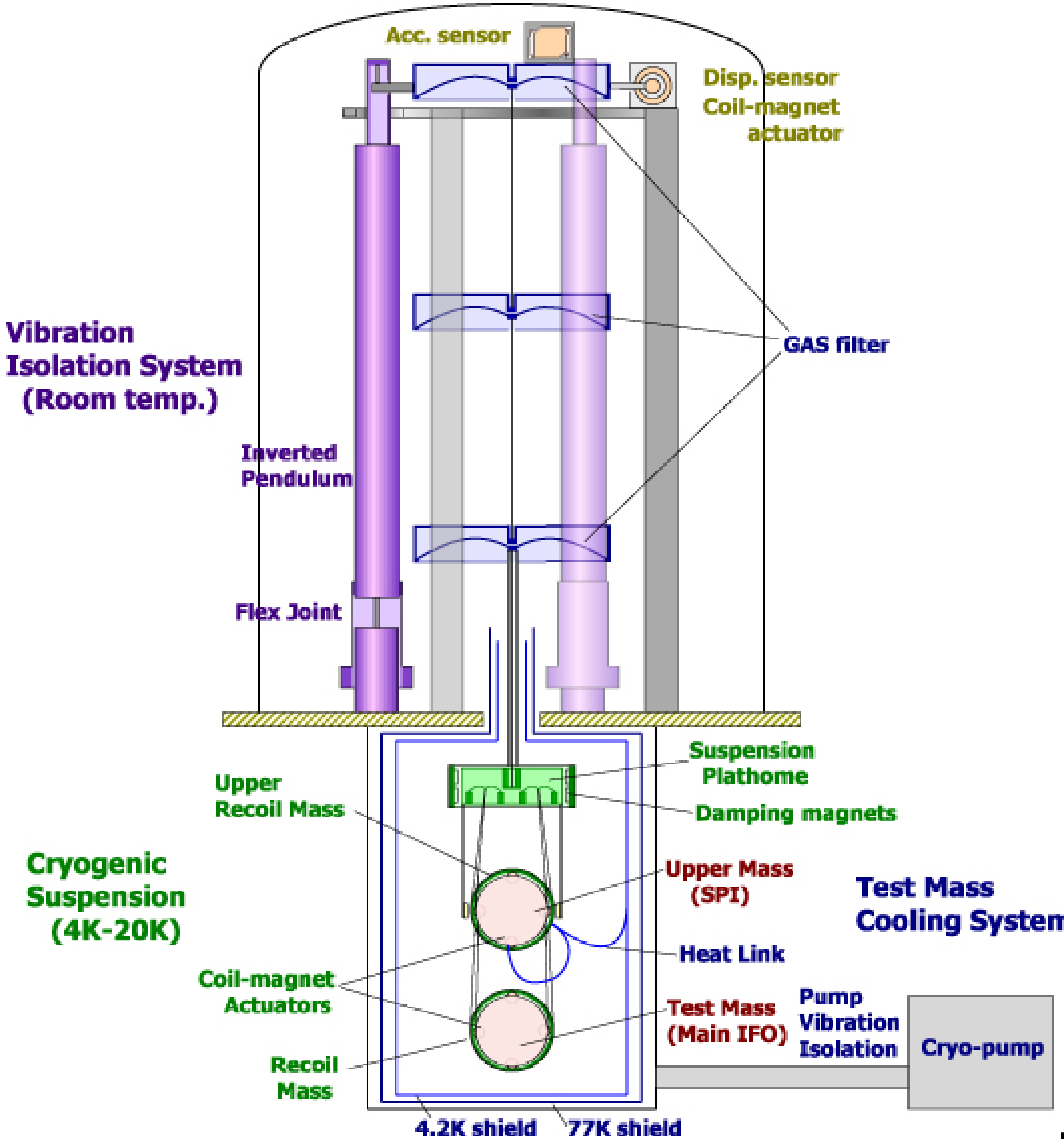
Prototype experiment
By Aso



WFS test

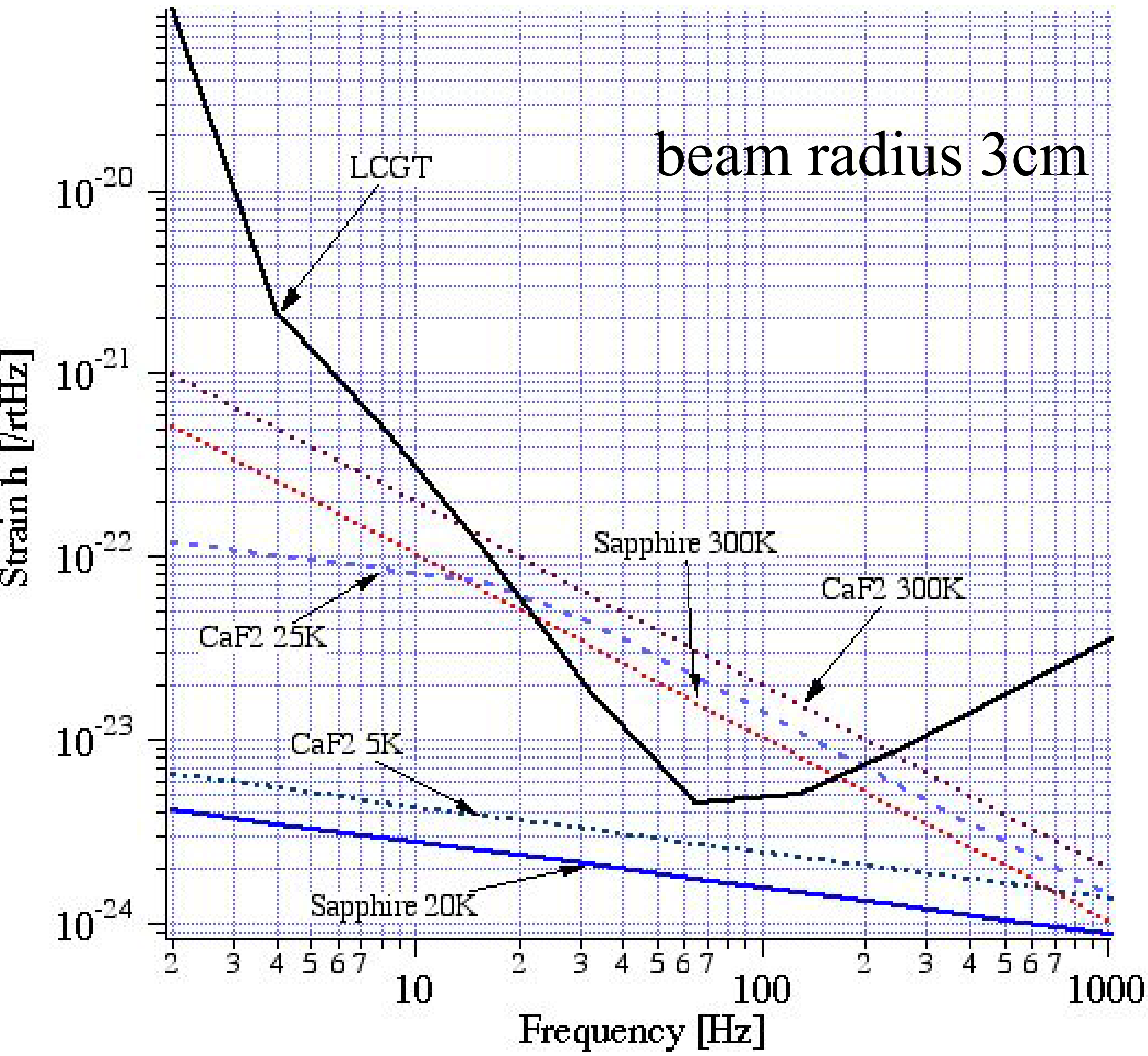


By Aso


Acc. sensor
Disp. sensor
Coil-magnet
actuator
Vibration
Isolation System
(Room temp.)
GAS filter
Inverted
Pendulum
Flex Joint
Suspension
Plathome
Damping magnets
Upper
Recoil Mass
Cryogenic
Suspension
(4K-20K)
Upper Mass
(SPI)
Test Mass
Cooling System
Heat Link
Coil-magnet
Actuators
Test Mass
(Main IFO)
Pump
Vibration
Isolation
Cryo-pump
Recoil
Mass
4.2K shield
77K shield

By Ando

Why did we choose sapphire?



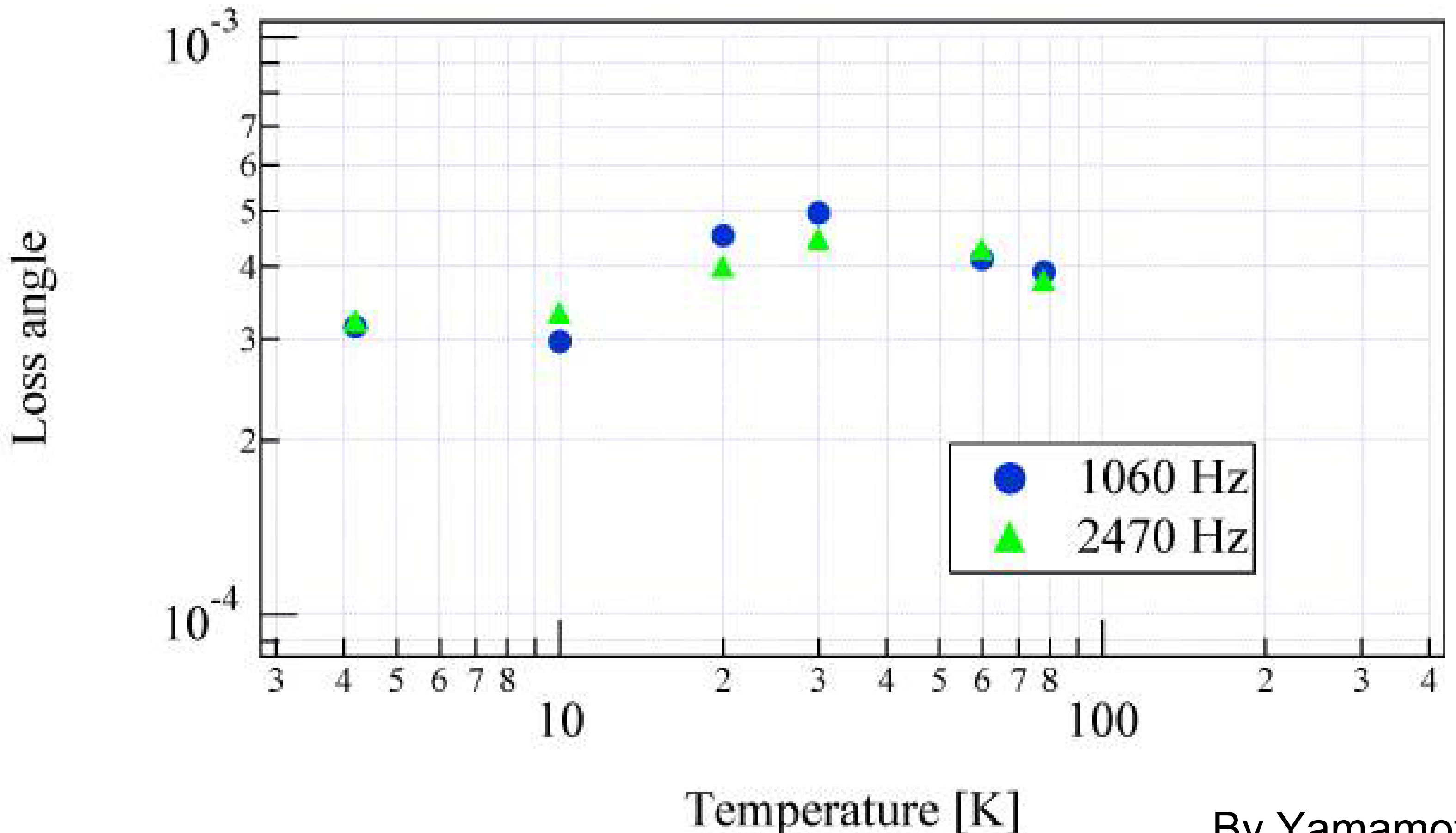
To improve by one order in room temperature.

Radius -> 4.6times ($10^{2/3}$) -> 14cm

By Uchiyama

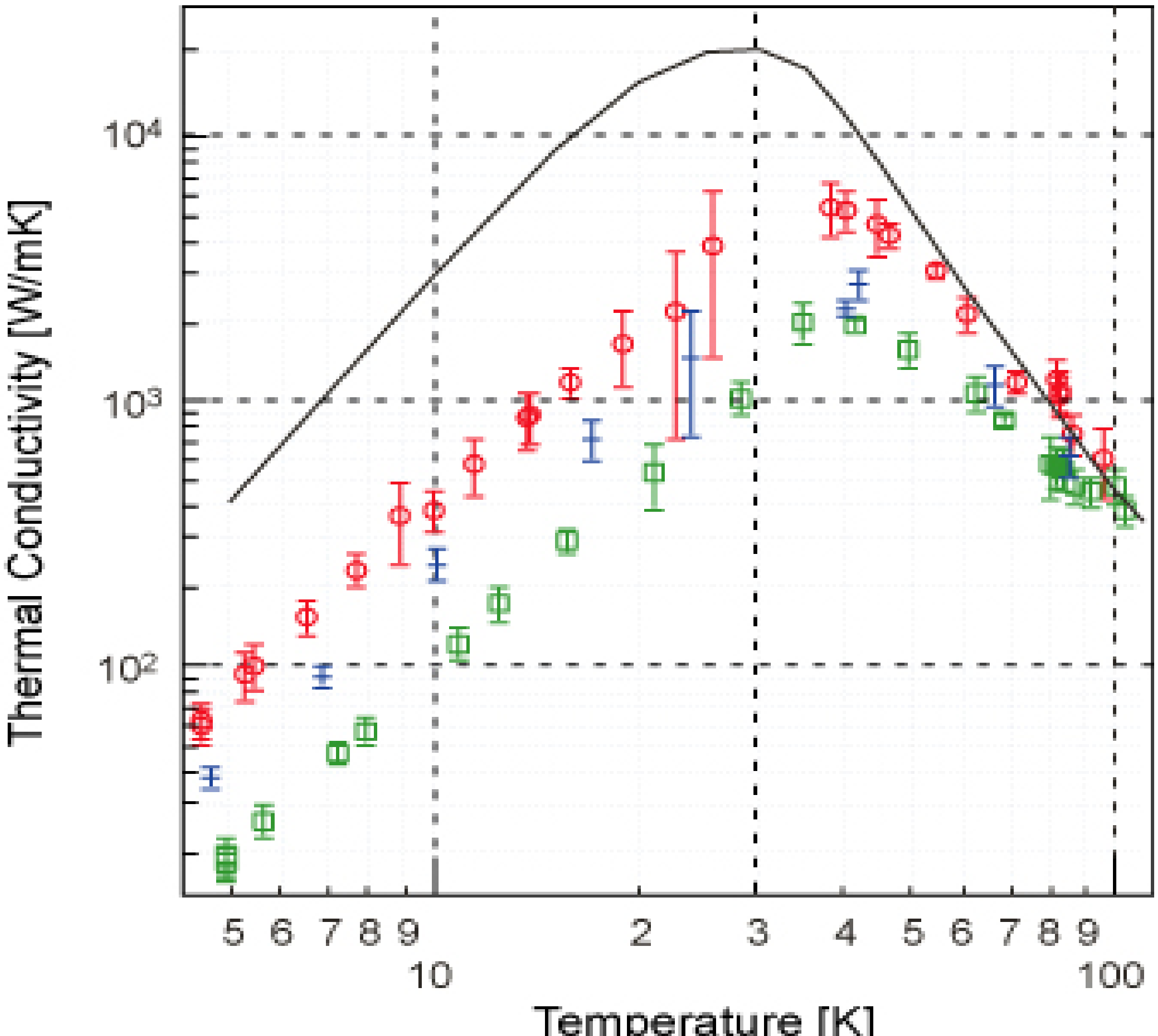
Optical coating on sapphire substrate was measured and its mechanical loss was evaluated.

JAE coating on t 1mm disk

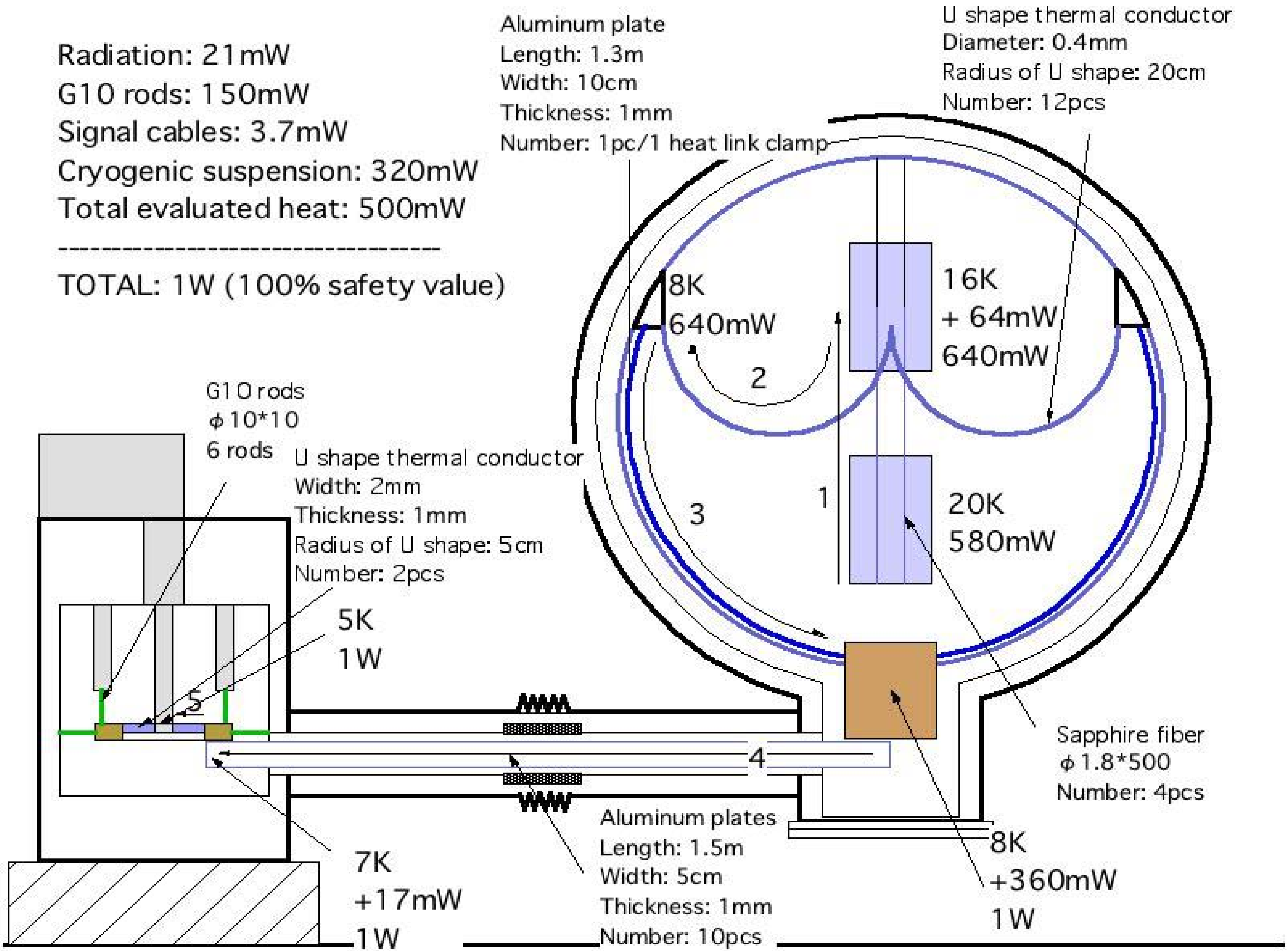


By Yamamoto

Another example of the measured heat conductivity of sapphire fibers.
The sharp peak is believed to be a manifestation of goodness of the crystal.
This measurement proved the dependence of the fiber heat conductivity
On its diameter. Capacity varies with the third power of its diameter.

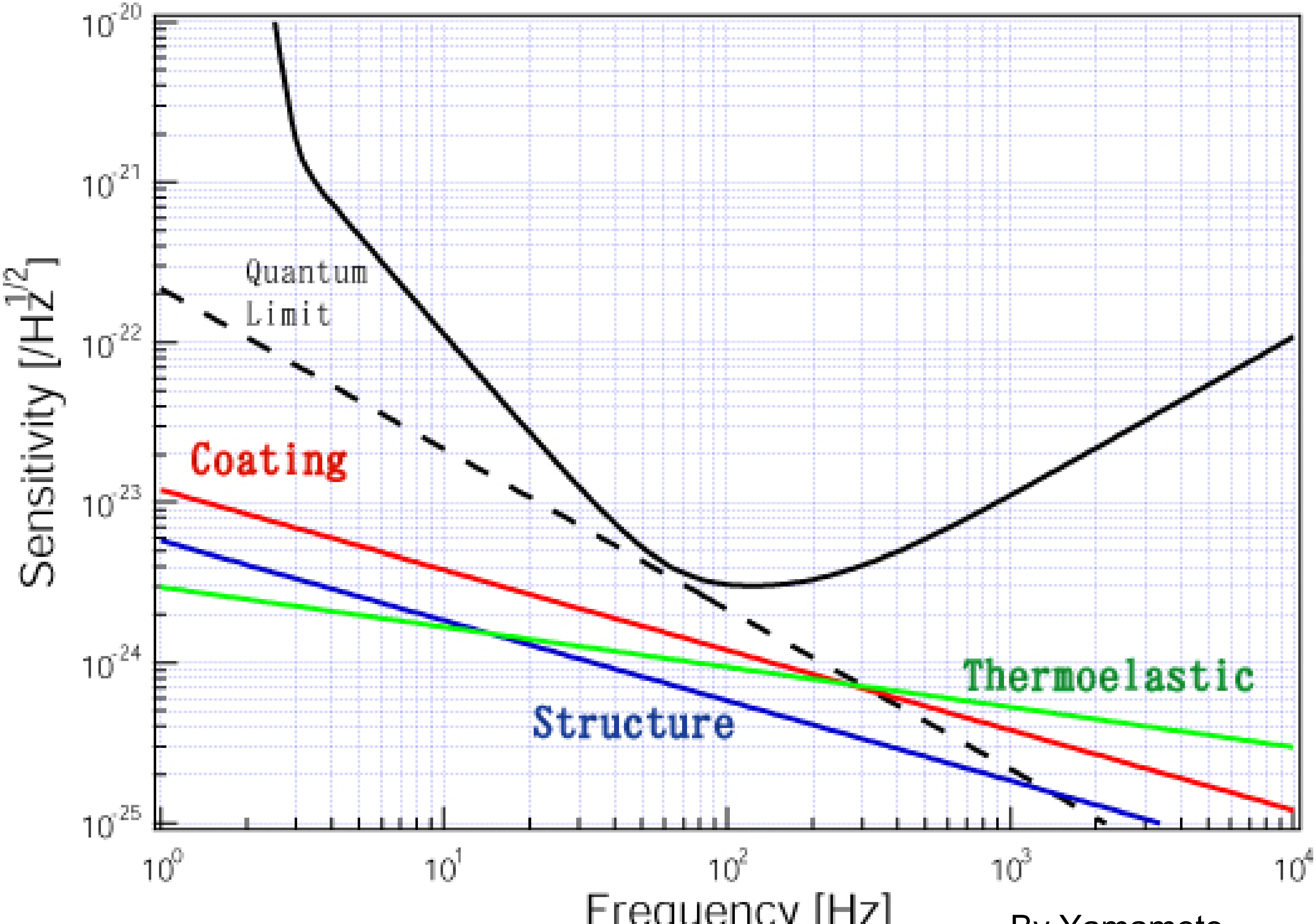


By Tomaru


Radiation: 21mW
G10 rods: 150mW
Signal cables: 3.7mW
Cryogenic suspension: 320mW
Total evaluated heat: 500mW
TOTAL: 1W (100% safety value)
Aluminum plate
Length: 1.3m
Width: 10cm
Thickness: 1mm
Number: 1pc/1 heat link clamp
U shape thermal conductor
Diameter: 0.4mm
Radius of U shape: 20cm
Number: 12pcs
8K
640mW
16K
+ 64mW
640mW
2
G10 rods
φ10*10
6 rods
U shape thermal conductor
Width: 2mm
Thickness: 1mm
Radius of U shape: 5cm
Number: 2pcs
1
3
20K
580mW
5K
1W
5
4
Sapphire fiber
φ1.8*500
Number: 4pcs
Aluminum plates
Length: 1.5m
Width: 5cm
Thickness: 1mm
Number: 10pcs
7K
+17mW
1W
8K
+360mW
1W

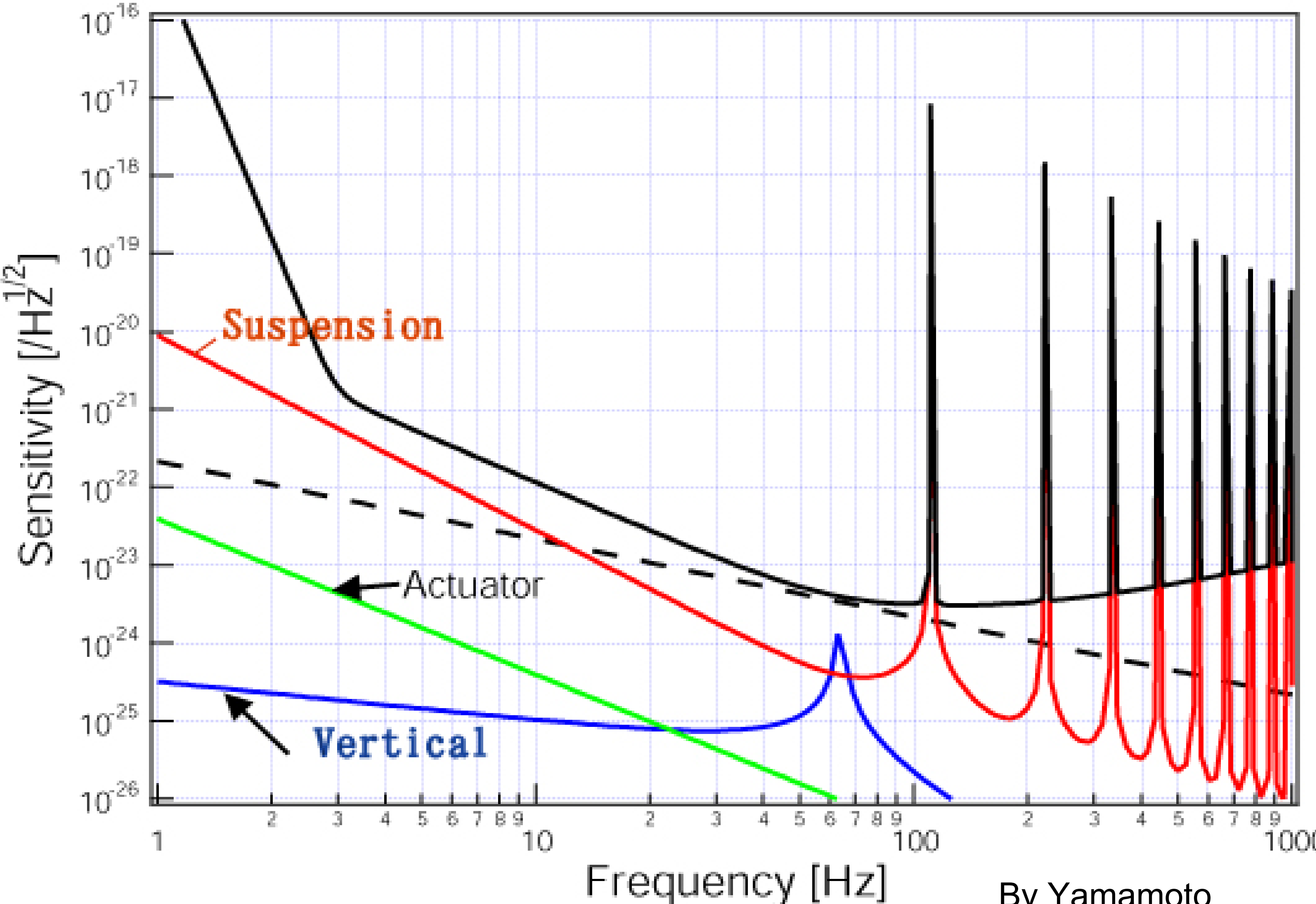
By Uchiyama

Thermal noise of mirror (LCGT)



By Yamamoto

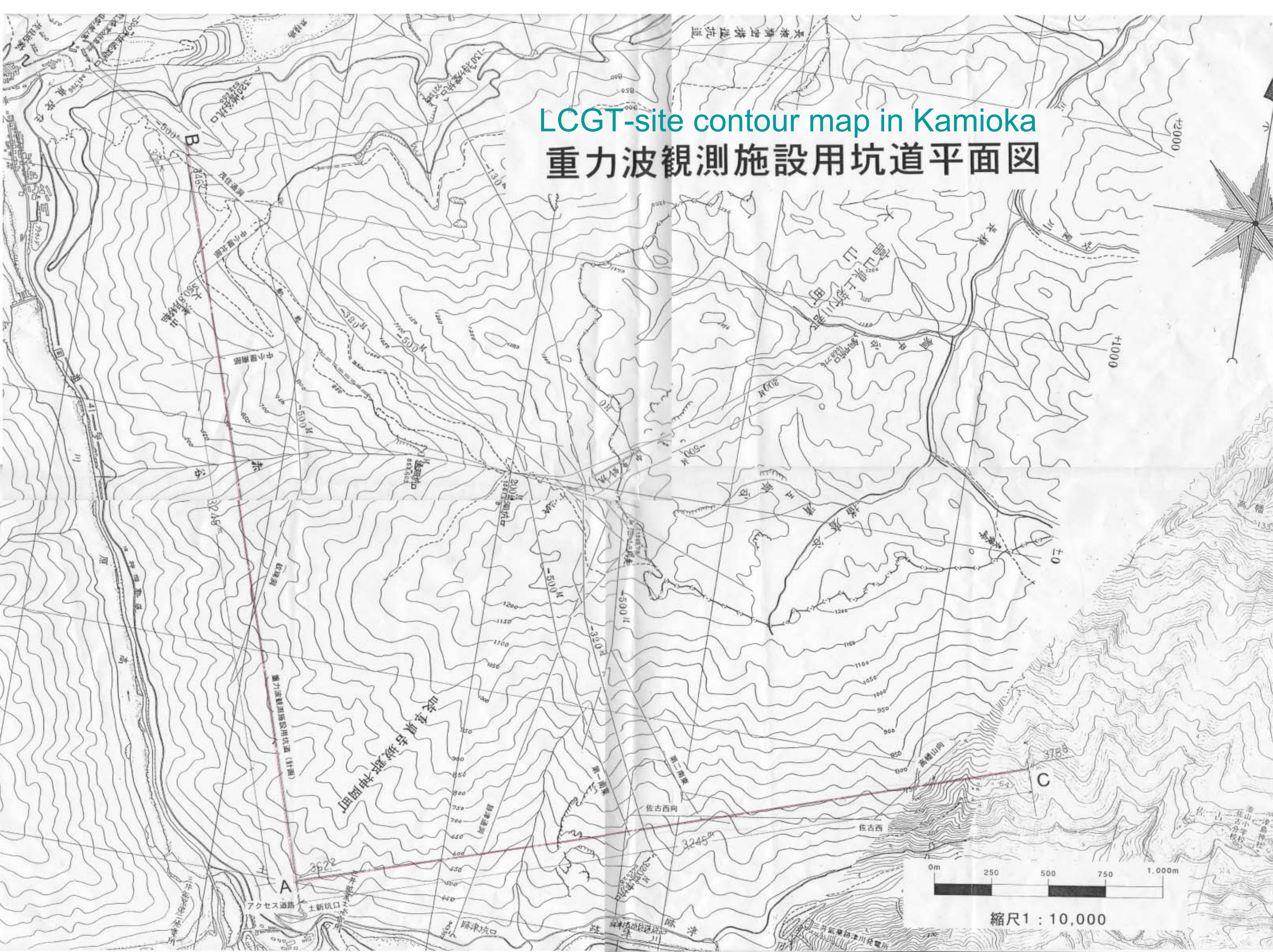
Thermal Noise of Suspension (LCGT)



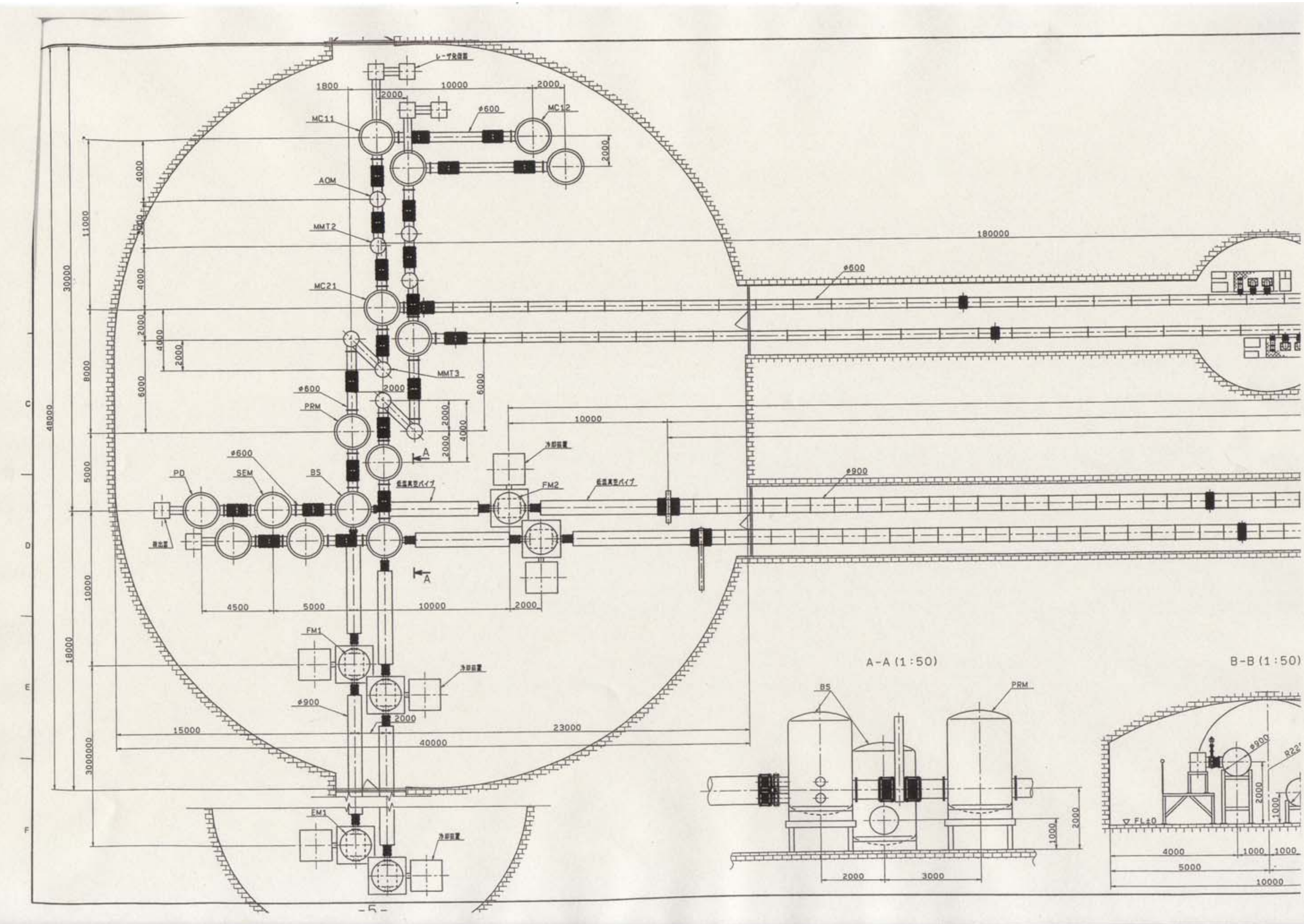
By Yamamoto

LCGT-site contour map in Kamioka

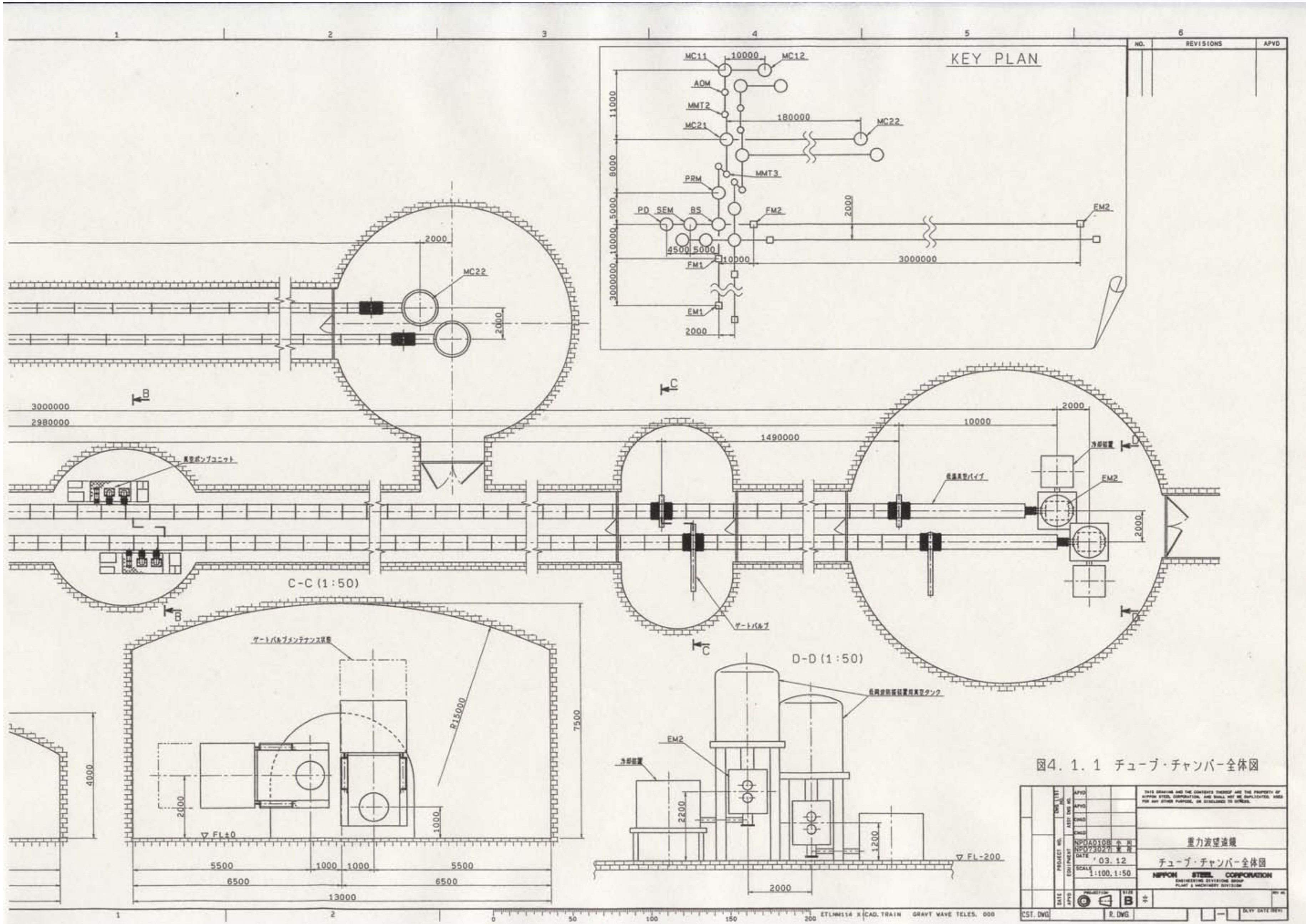
重力波観測施設用坑道平面図



LCGT Vacuum design for cost-estimation (1)



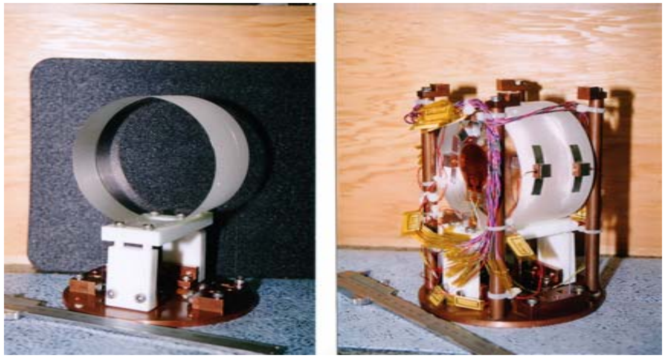
LCGT Vacuum design for cost-estimation (2)



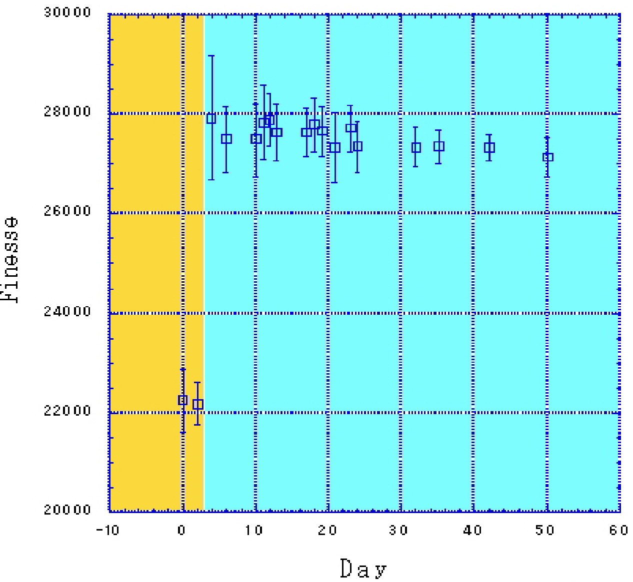
Efforts to establish cryogenic mirror

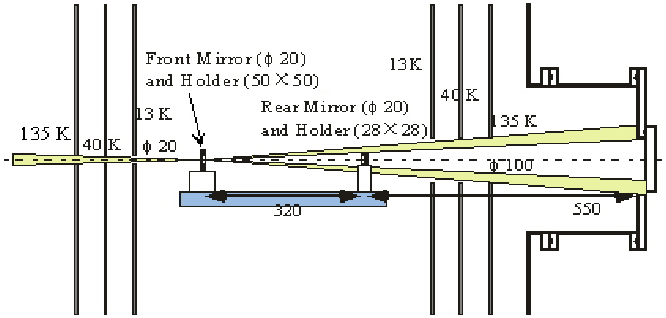
R&Ds for Cryogenic mirror

Cooling test

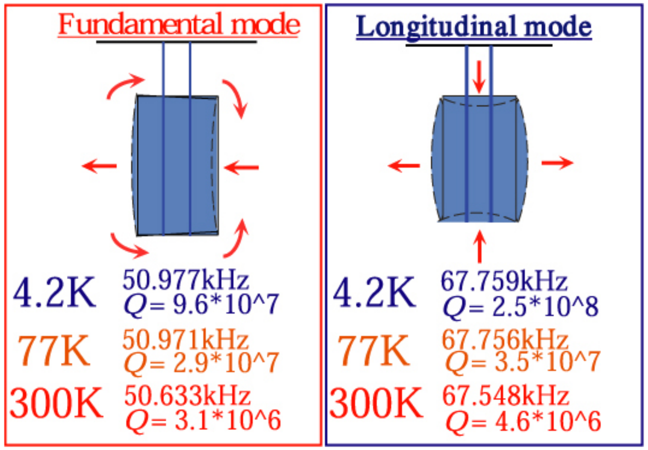


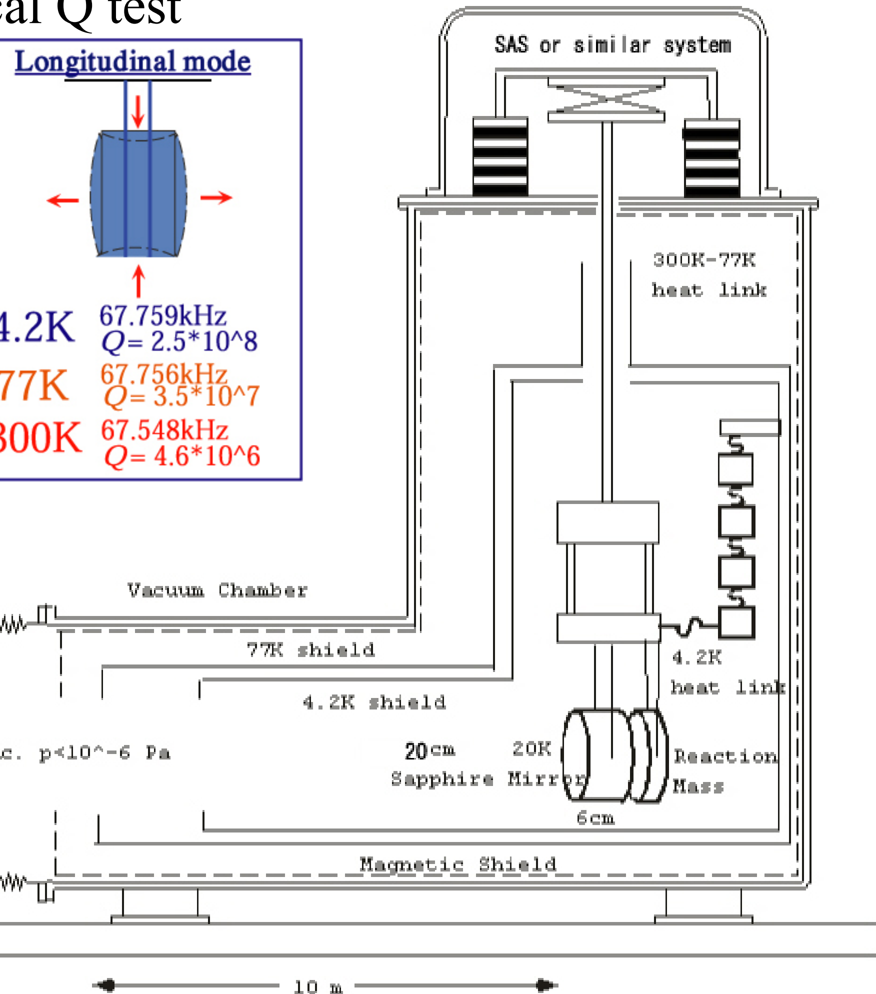
Contamination test



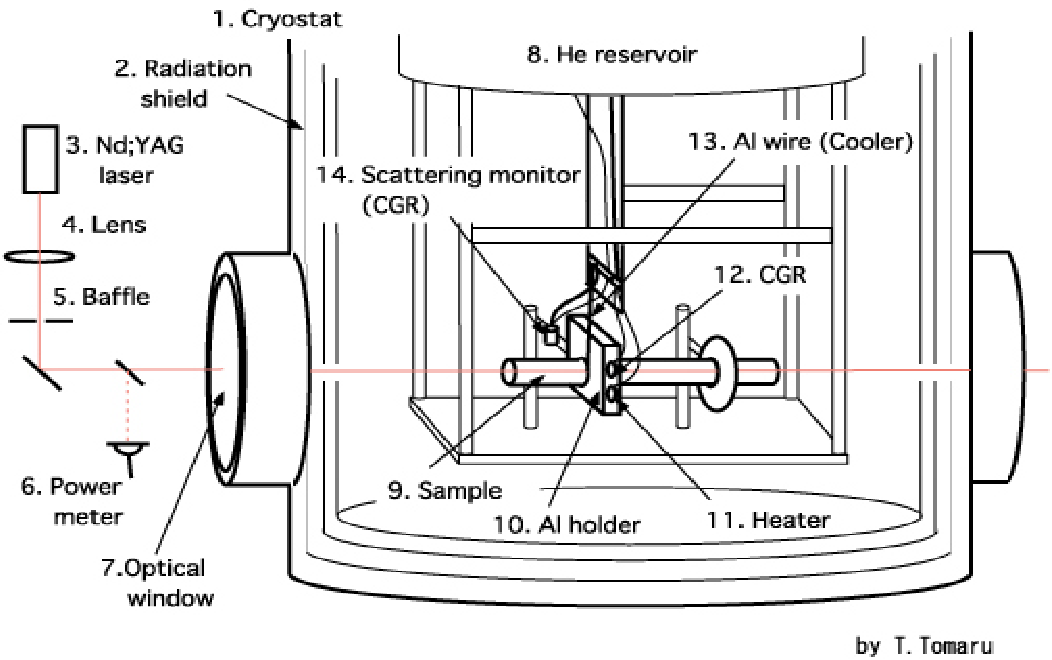


Mechanical Q test





Optical absorption measurement in Sapphire

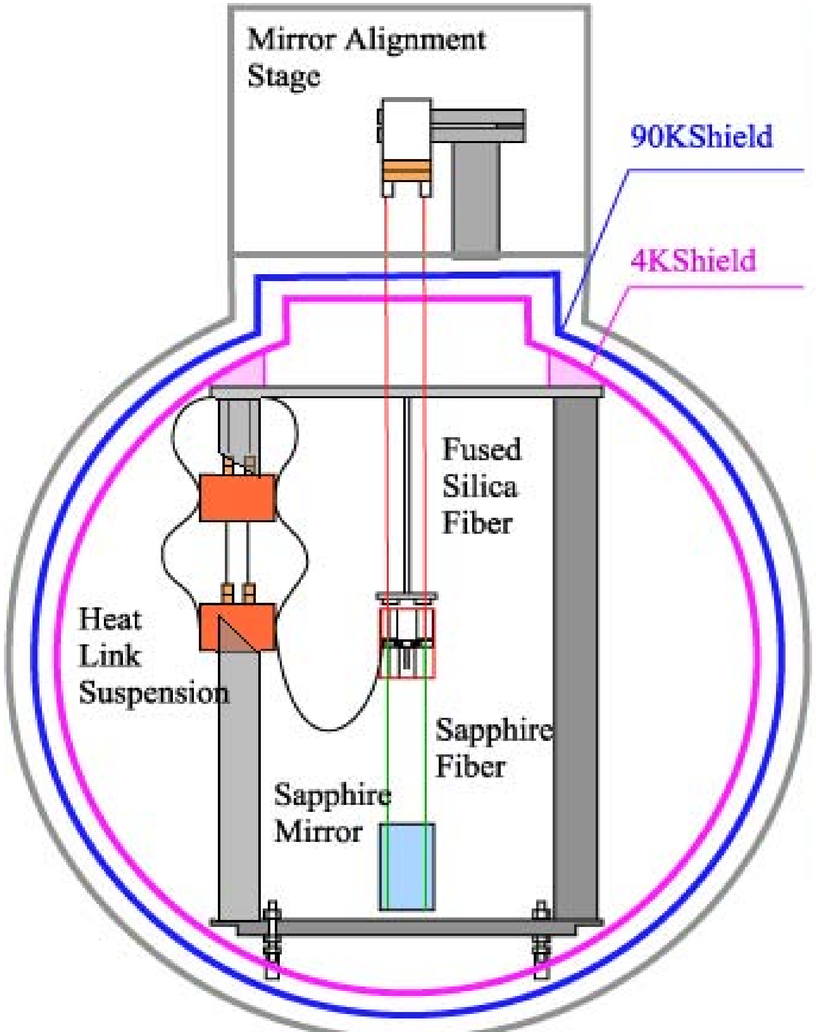


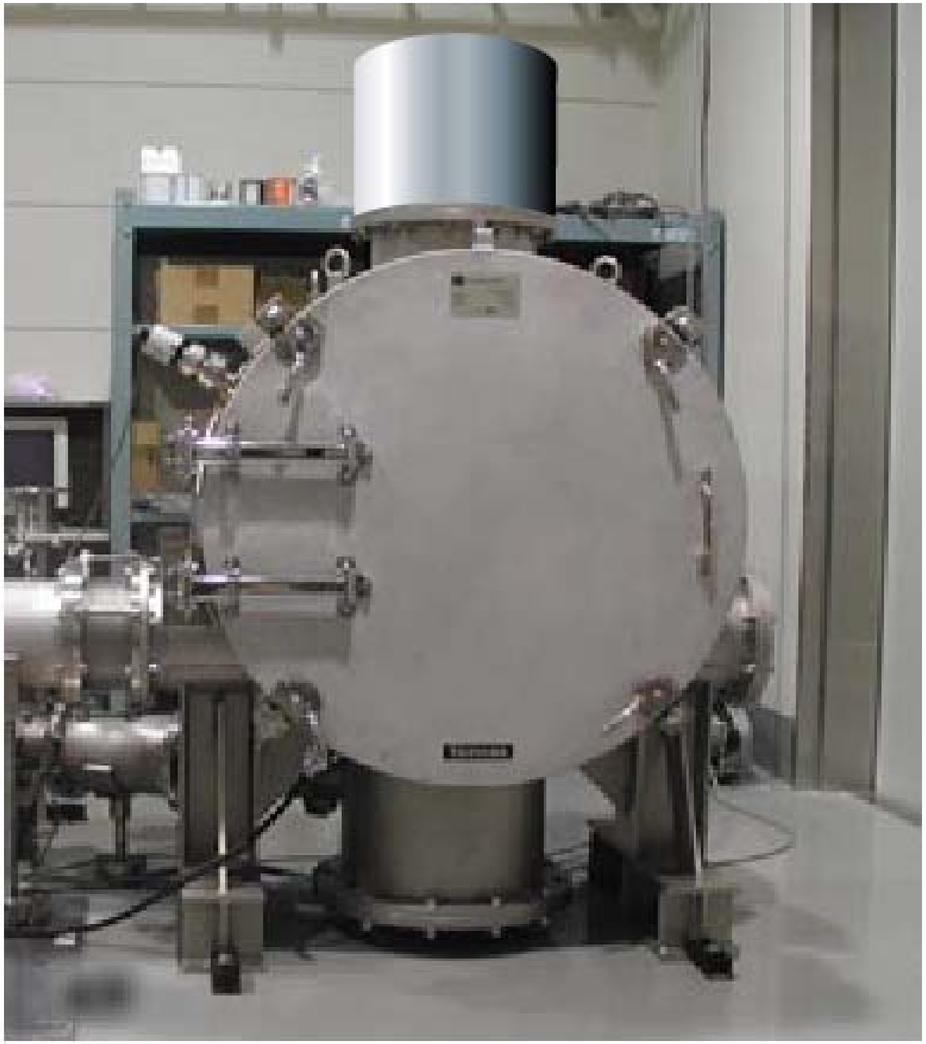
Sample	LCGT (5K)	Stanford	UWA
Hemex	-	-	24
Hemlite	90 - 99	-	-
CSI White	88 - 93	-	-
CSI White	-	-	3.4
CSI White	-	-	40
CSI White	-	47	-
CSI White	-	25	-

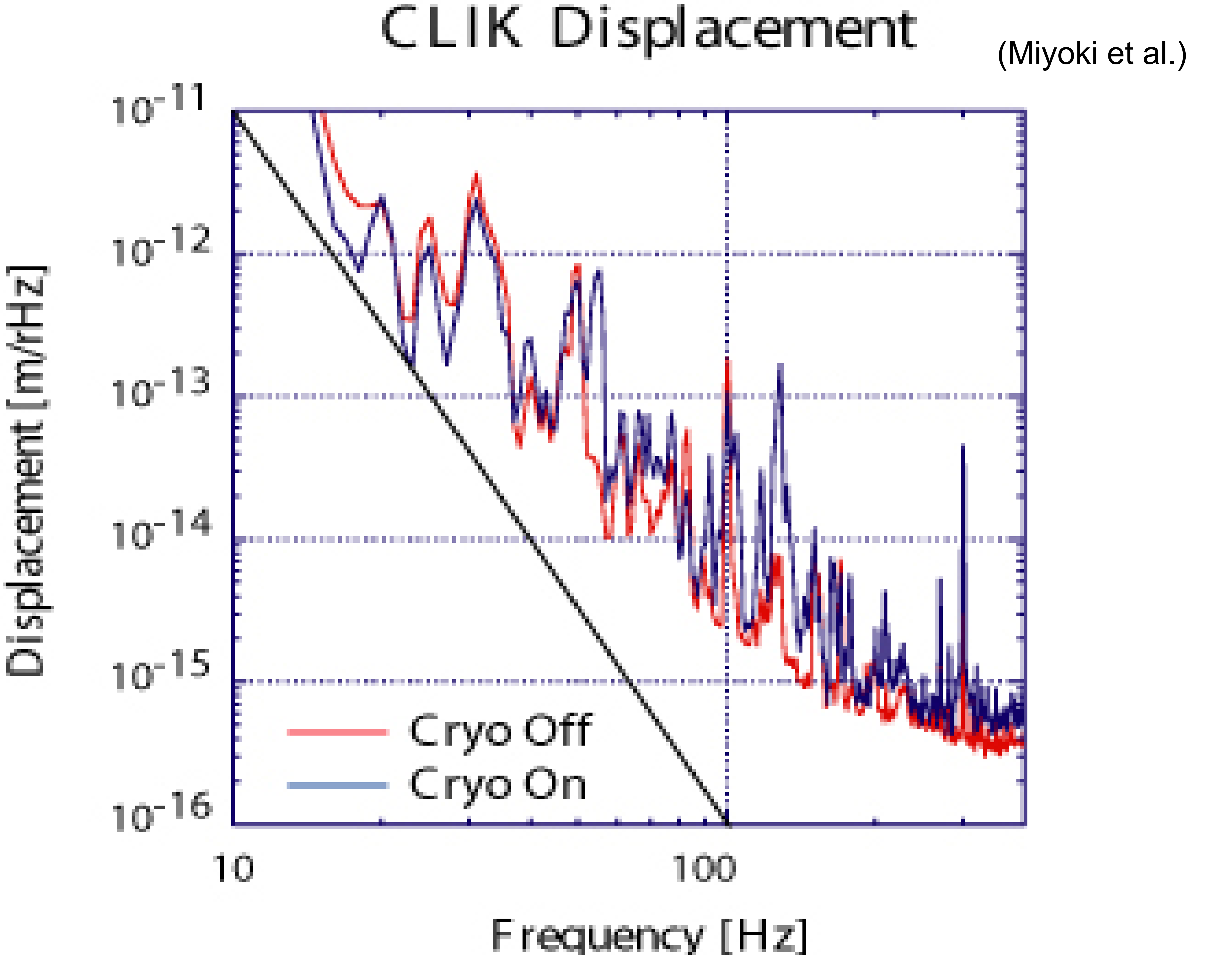
ppm/cm

- Sapphire is the best candidate of mirror of LCGT
- Calorimetric measurement of optical loss
- Suppress the loss by annealing
- Calorimetric measurement can be applied to the loss less than 0.1 ppm

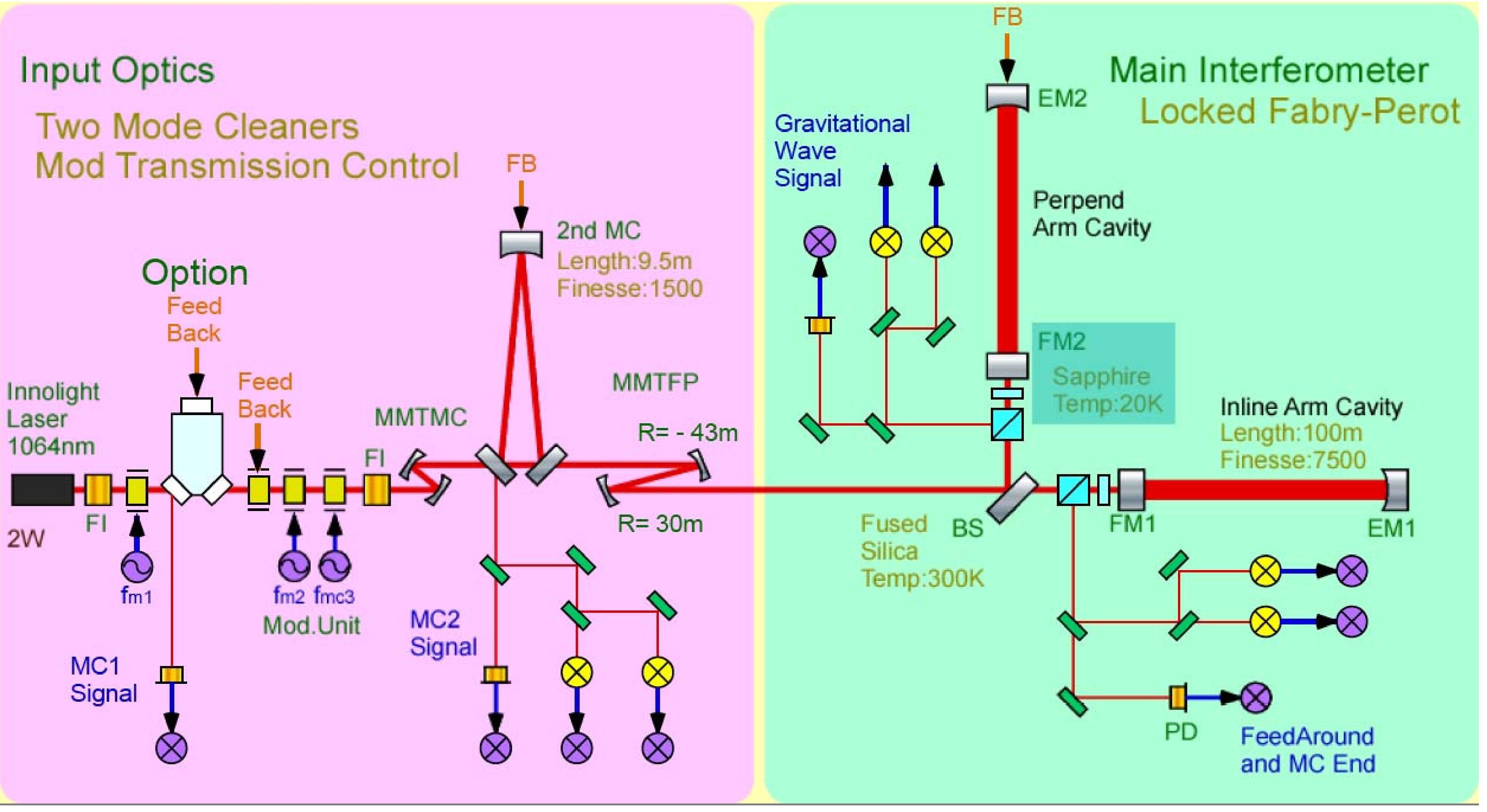
Suspension prototype was tested in Kashiwa campus in ICRR, in 2001.






CLIK Displacement
(Miyoki et al.)
Displacement [m/rHz]
Frequency [Hz]
Cryo Off
Cryo On
10
100

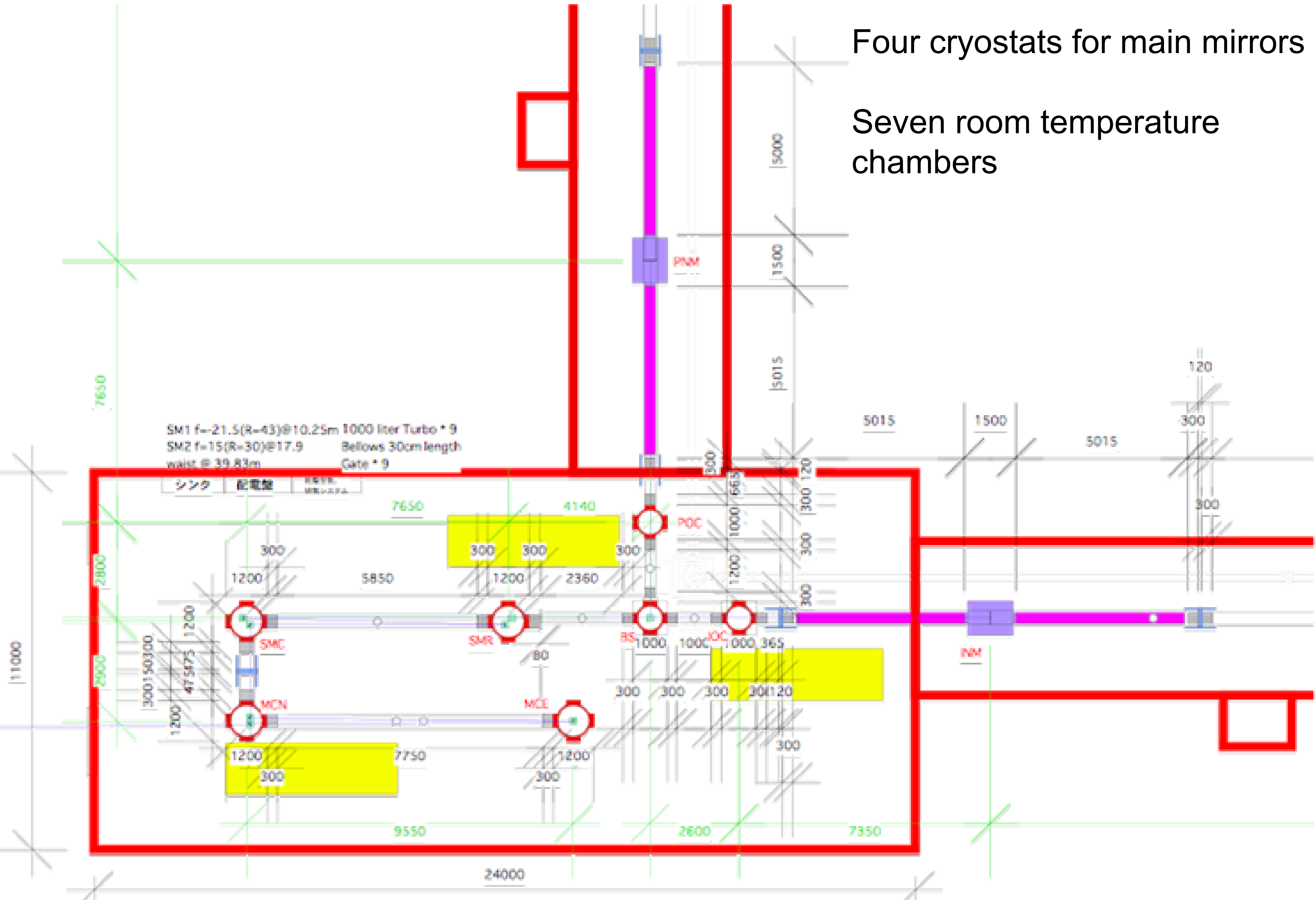
CLIO is a locked Fabry-Perot Interferometer



CLIO vacuum configuration

Four cryostats for main mirrors

Seven room temperature chambers



CLIO site in Kamioka mine in 2003

Geophysical strain meter is installed before CLIO construction (under)

Entrance (upper)

CLIO construction

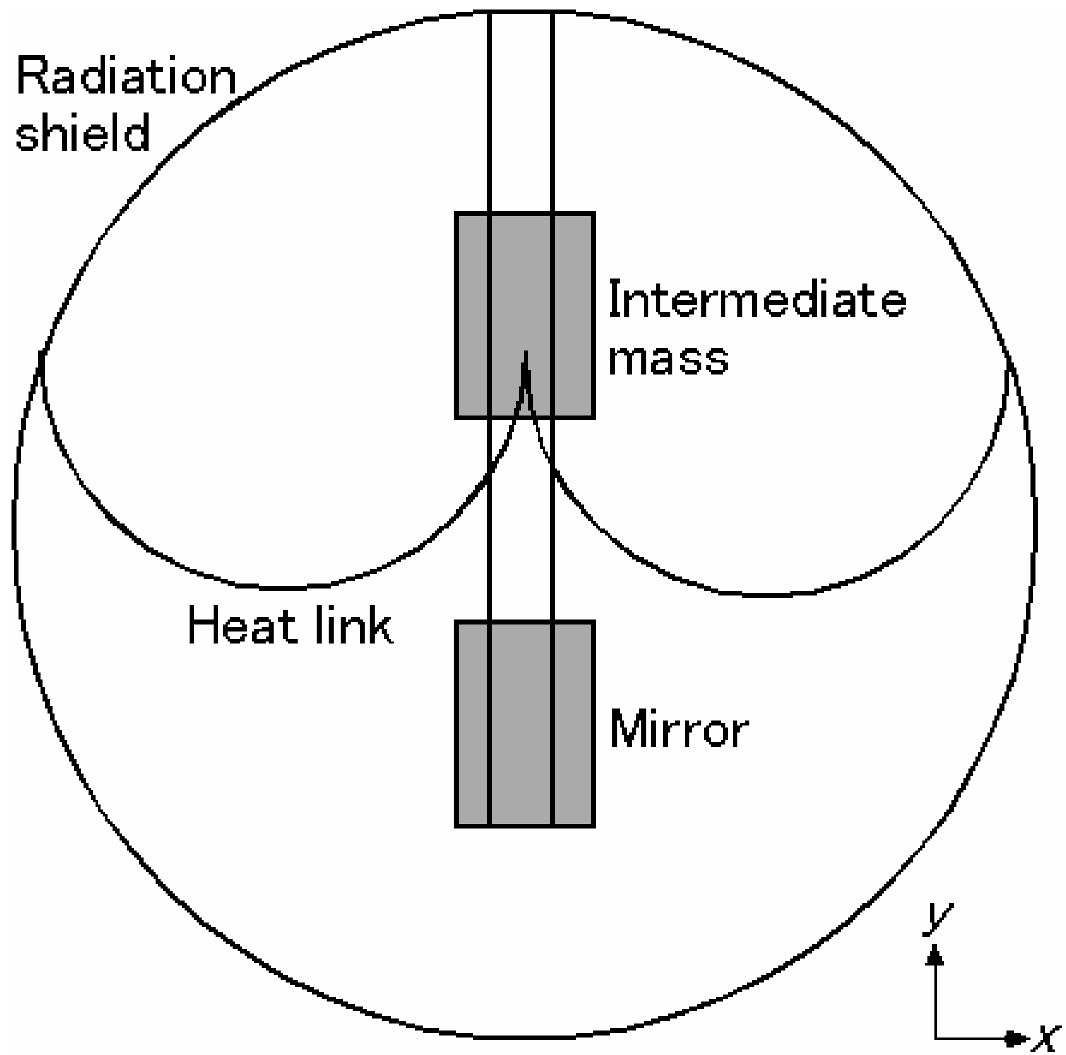
Mode cleaner vacuum chambers are installed with a connecting vacuum duct (left) in December, 2003.

Vacuum test has been finished (right)

金属細線の熱伝導率の実測　　　by Kasahara

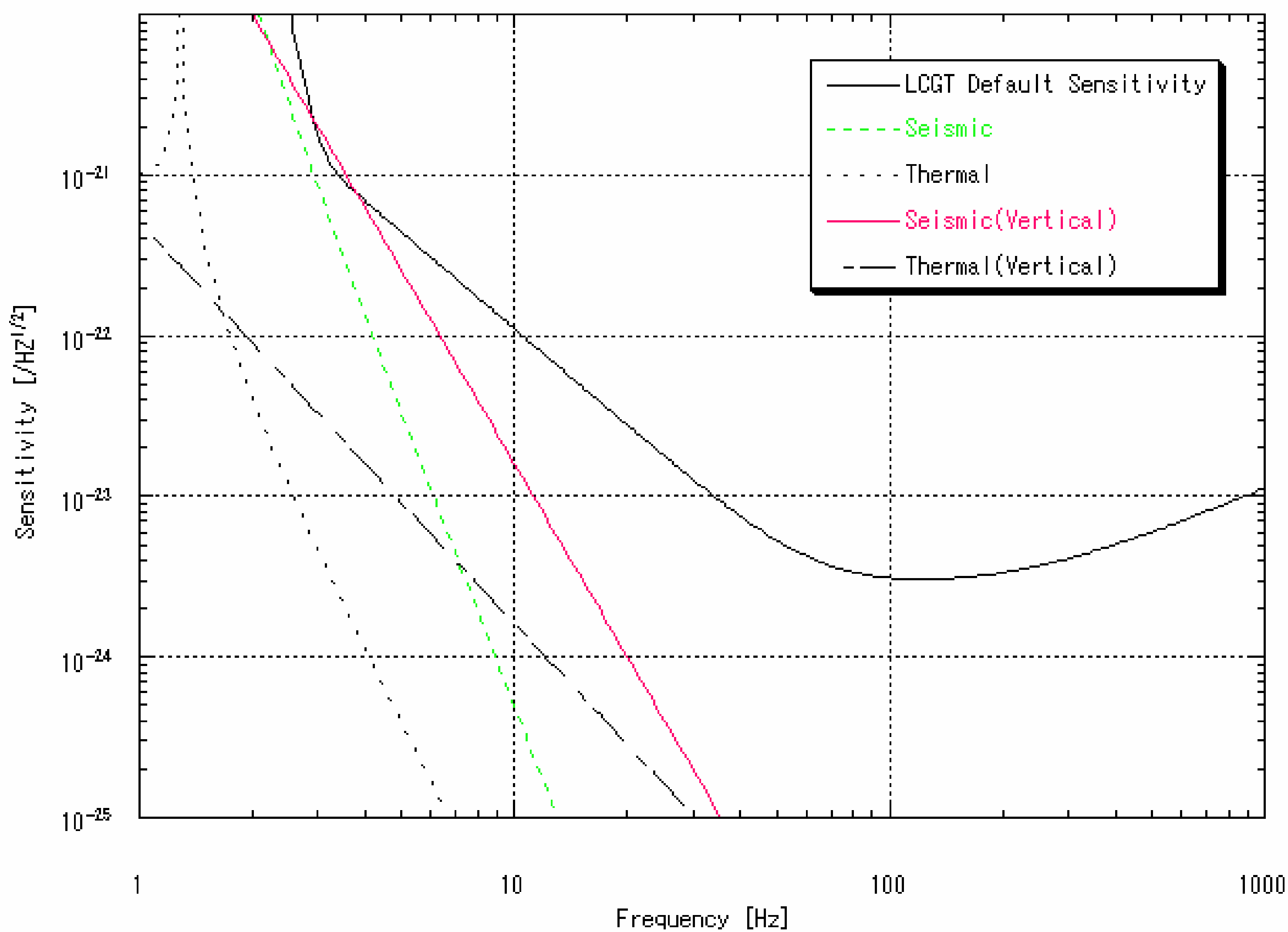
	Diameter [mm]	0.20	0.50	1.00	1.99
Al	RRR	2900	4800	5500	6200
	Ratio of RRR	0.53	0.87	1.0	1.1
	Mean free path of electrons [mm]	0.029	0.048	0.056	0.063
Cu	RRR	960		4100	
	Ratio of RRR	0.23		1.0	
	Mean free path of electrons [mm]	0.027		0.12	

Model of the heat link



By Kasahara

Noises introduced from the heat link



By Kasahara

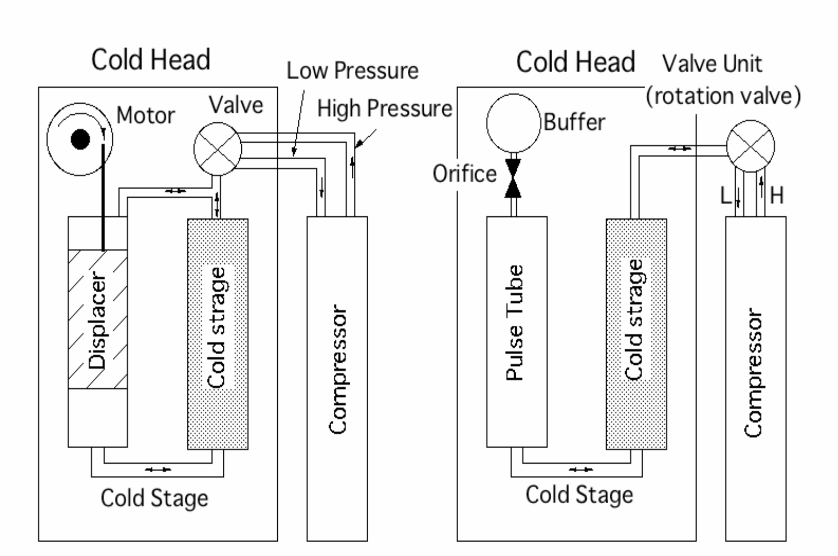
Quiet refrigerator development

(b) 小型冷凍機の振動測定(2002年)　　測定法

N-1: 低温工学 Vol. 38 No. 12,
F-7 Meas. Sci. Tech.,Cryogenics

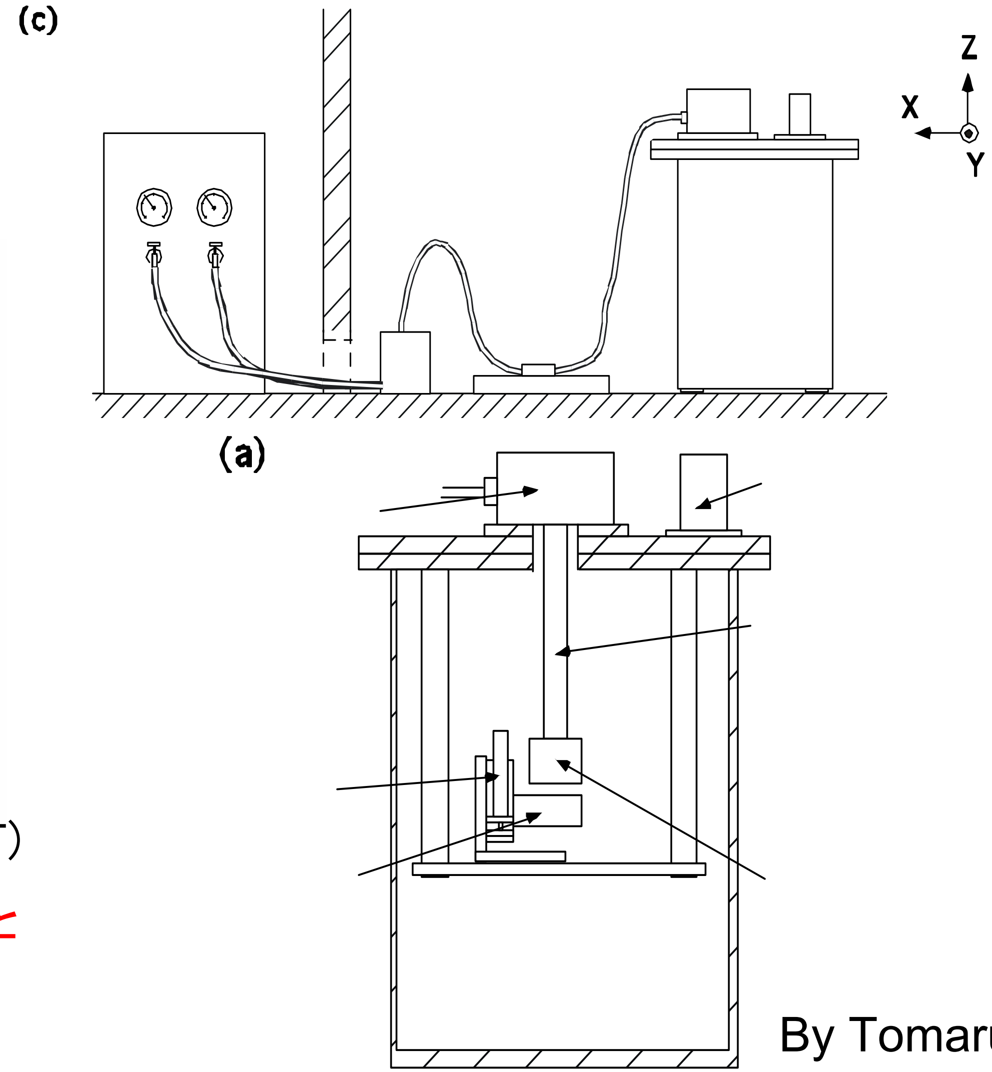
・Cold StageとCold Headの振動を分離計測
・熱平衡状態で計測

代表的な小型冷凍機の概念図

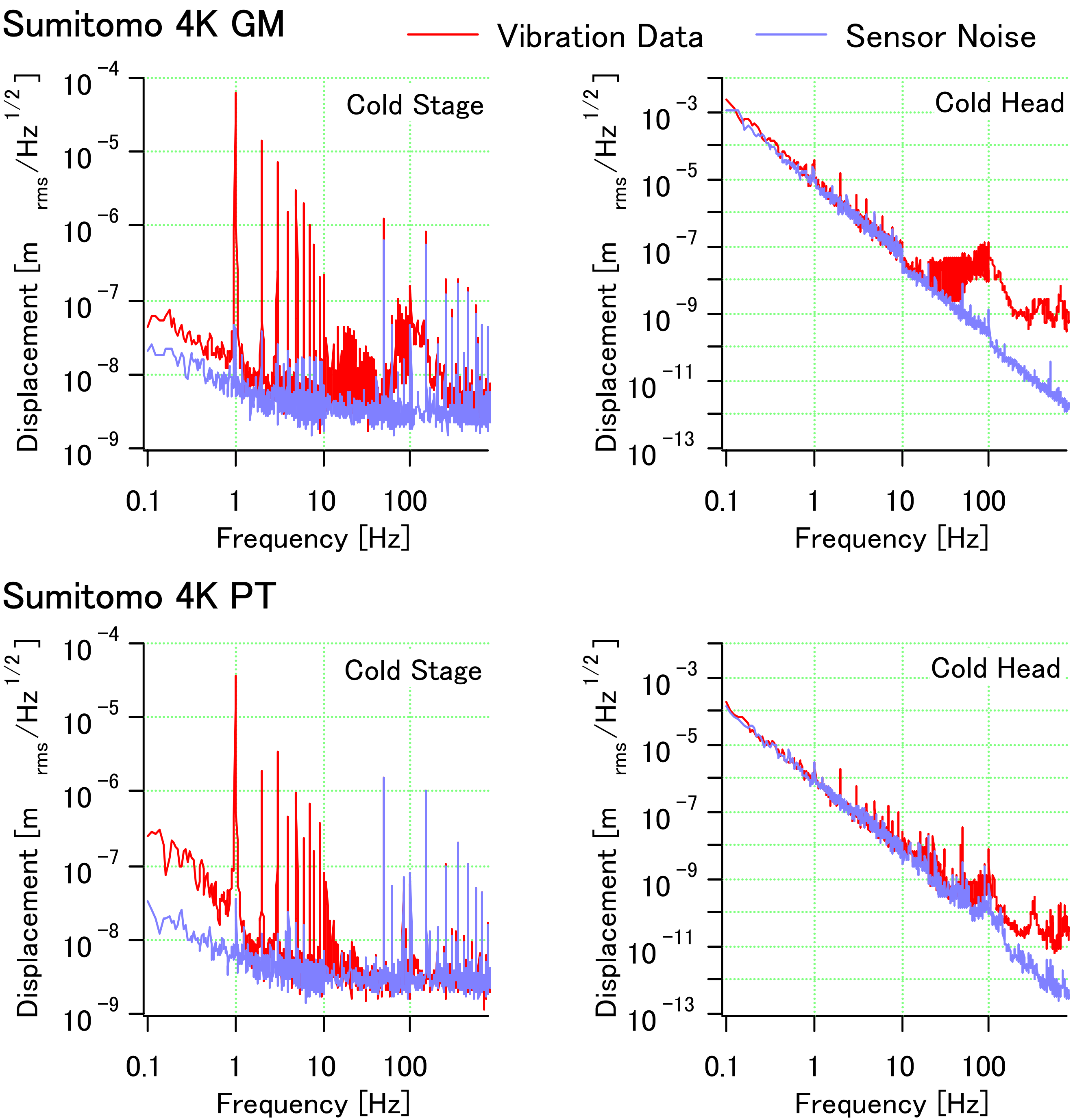


Gifford-McMahon (GM)　Pulse-Tube (PT)

しかし、これらの冷凍機の振動をきちんと評価した例は少なかった。



By Tomaru



Cold Headの振動は
PT型がGM型より
2桁低振動。

Cold Stageの振動は
PT型もGM型も同
程度。

このような振動の
相違が初めて明らか
となった。

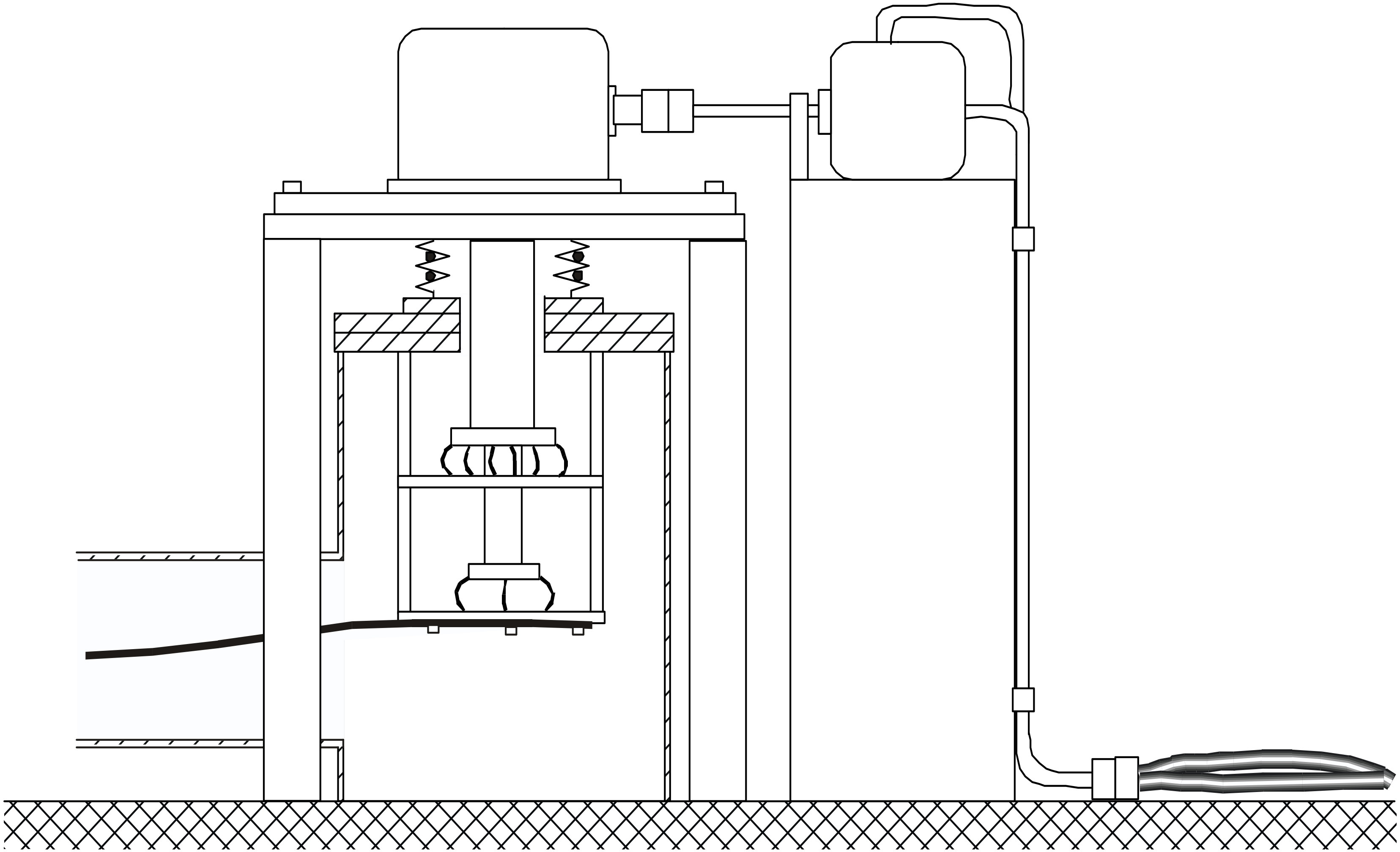
・シミュ
レーション
・スペクトル
解析

Cold Stageの振動は、
振動ガス圧による
シリンダーの弾性変形
に起因する

By Tomaru

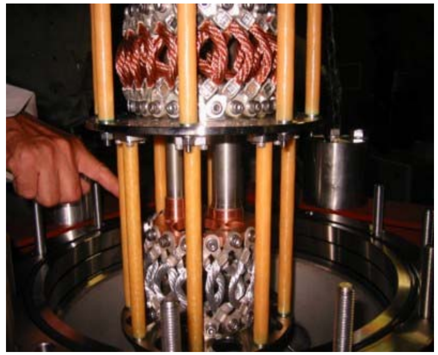
(c) 重力波検出器用低振動冷凍機の開発（2003年）

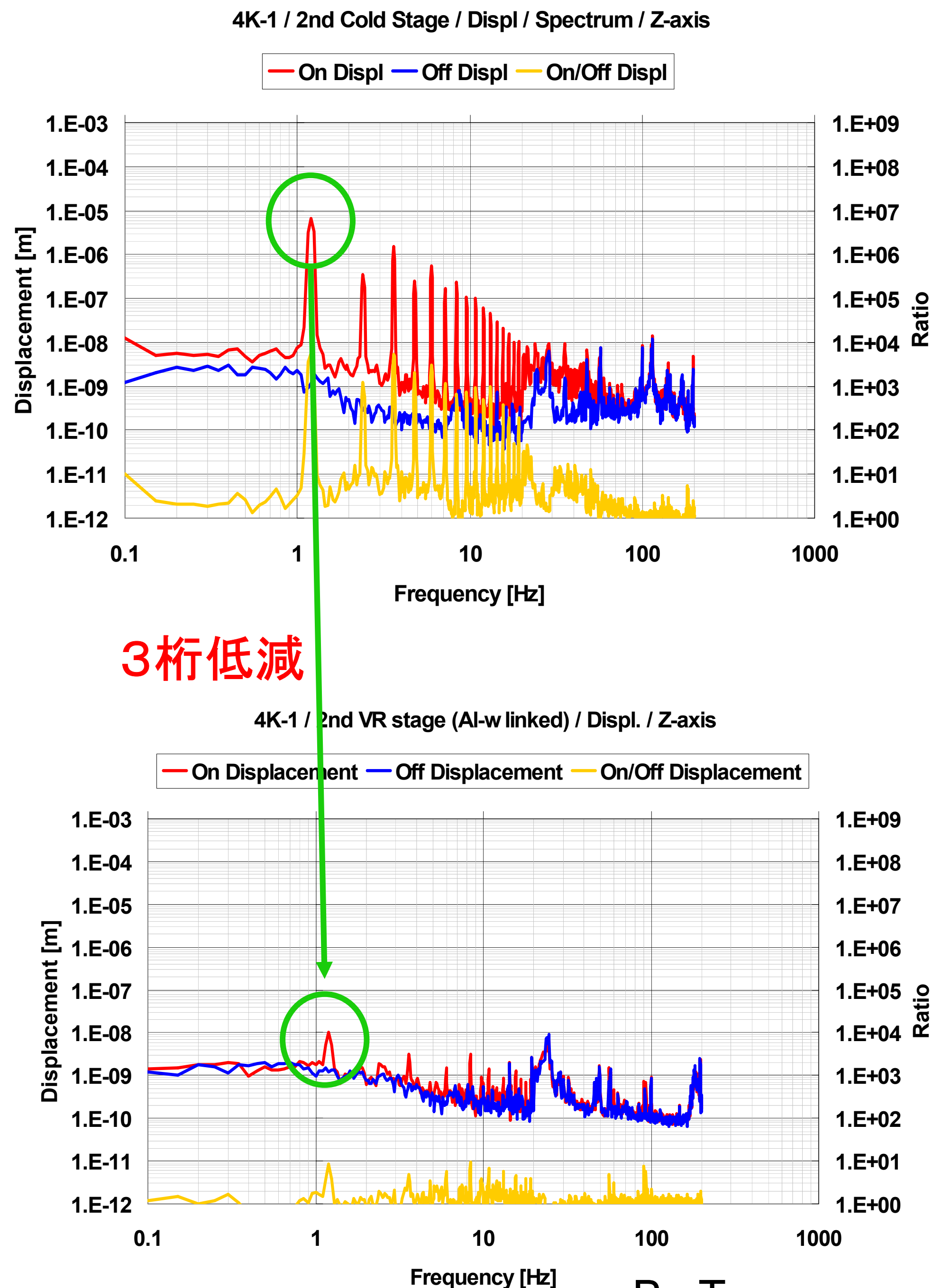
F-6: Class. Quantum Grav. (Accepted), Pr-1: Proc. 28th ICRC (2003), 特許: Pa-3
ICC13で正式公表予定



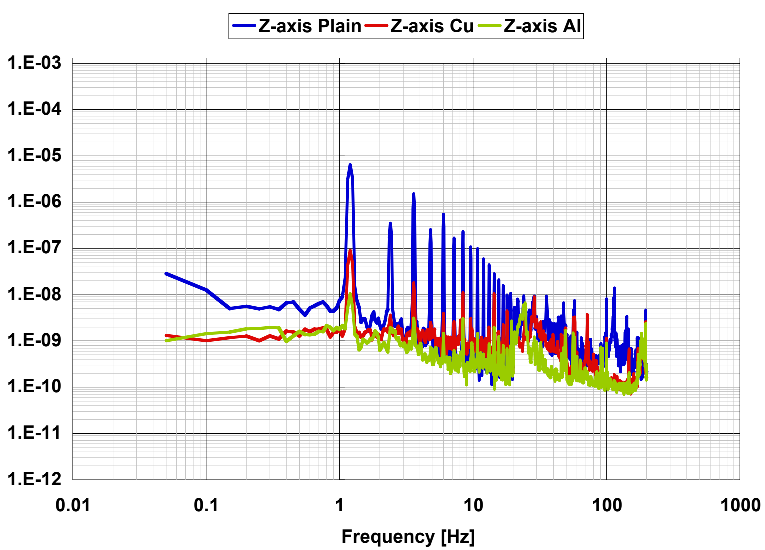
By Tomaru

Cold Stage振動



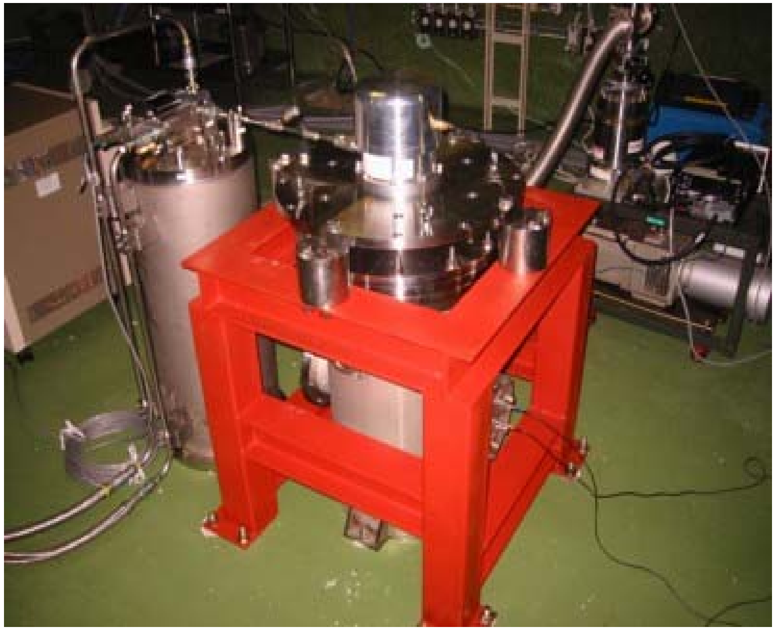


ヒートリンクを銅撚線から純アルミ撚線
に変更することで、さらに1桁振動低減



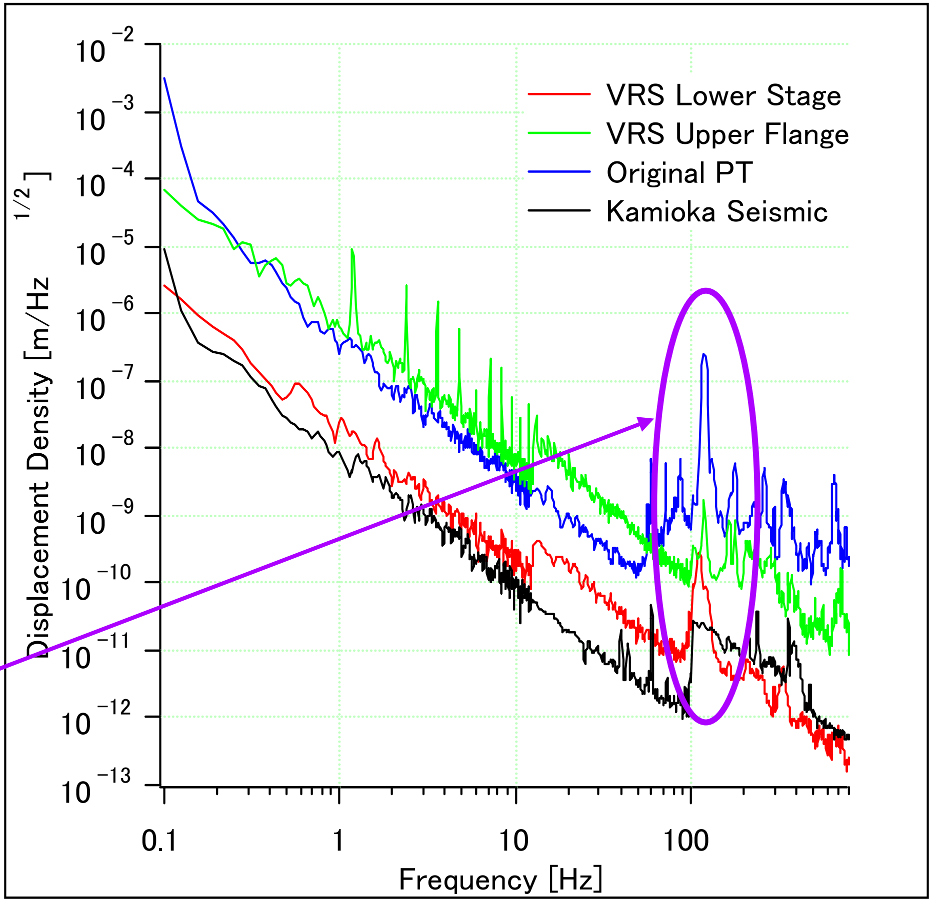
By Tomaru

Cold Head振動



加速度計用のジグの共振で、
冷凍機の振動ではないことを
確認

神岡鉱山内での振動測定結果



神岡鉱山内の地面振動レベルを達成できていると言って良い

冷凍性能をほとんど落とさず、**Cold Stage、Cold Head共に2〜3桁の低振動化に成功**

By Tomaru

LCGT Man Power

ICRR	6 +3	
NAO	8 +1	
KEK	5 +0	
Physics Dept, UT	2 +3	
Material science Dept, UT	2 +2	
ILS, UEC	2 +0	
ERI	2	
Kyoto University	2	data
Osaka University	1	data
Osaka City University	1 + α	data
Niigata University	1+1	data
	32 +10 + α	

LCGT Schedule

	1st year	2nd year	3rd year	4th year	5th year
Tunnel	*******	*******	*****fin		
Vaccum		*******	*******	install	
Optics	**	**	**	*******	install
Electric				*******	***
Data					***

Estimated budget (to be revised)

• Tunnel Construction	3400	M JpnYen
• Vacuum system	12100	
• Cryogenics	400	
• Optics	800	
• Suspension system	260	
• Laser system	400	
• Control system	100	
• Computer	200	
• Others	340	
Total	18000	

第二幕のまとめ

- TAMAの経験を生かしてkmスケールの計画を策定した
- 低温技術を導入するためのＲ＆Ｄを行ってきた
- LCGT実現に必要な技術はすべて手がけた
- 実現していない未確認技術（レーザー等）予算次第で解決できる
- 予算化のための努力を継続中