Ando Lab. 2025 Midterm report meeting

Development Plan of Phase-Ⅲ TOBA

2026/4/27

東京大学理学系研究科物理学専攻
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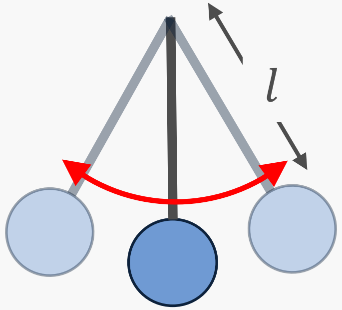
Contents

Contents

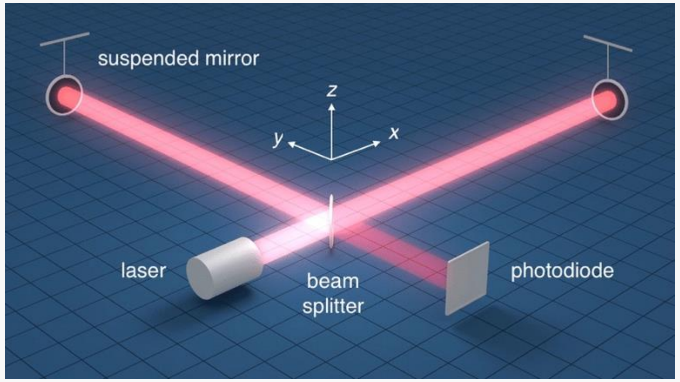
Low frequency GW

Current GW detectors, LIGO, Virgo and KAGRA are Michelson interferometer with suspended mirrors

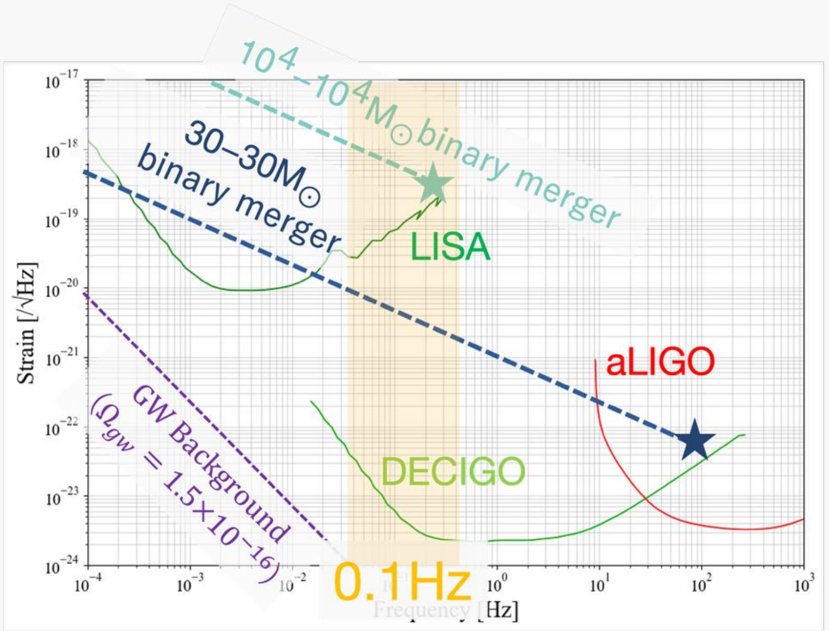
Good sensitivity in 10Hz-1kHz, but not sensitive in lower freq. (below resonant freq. of pendulums)



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$



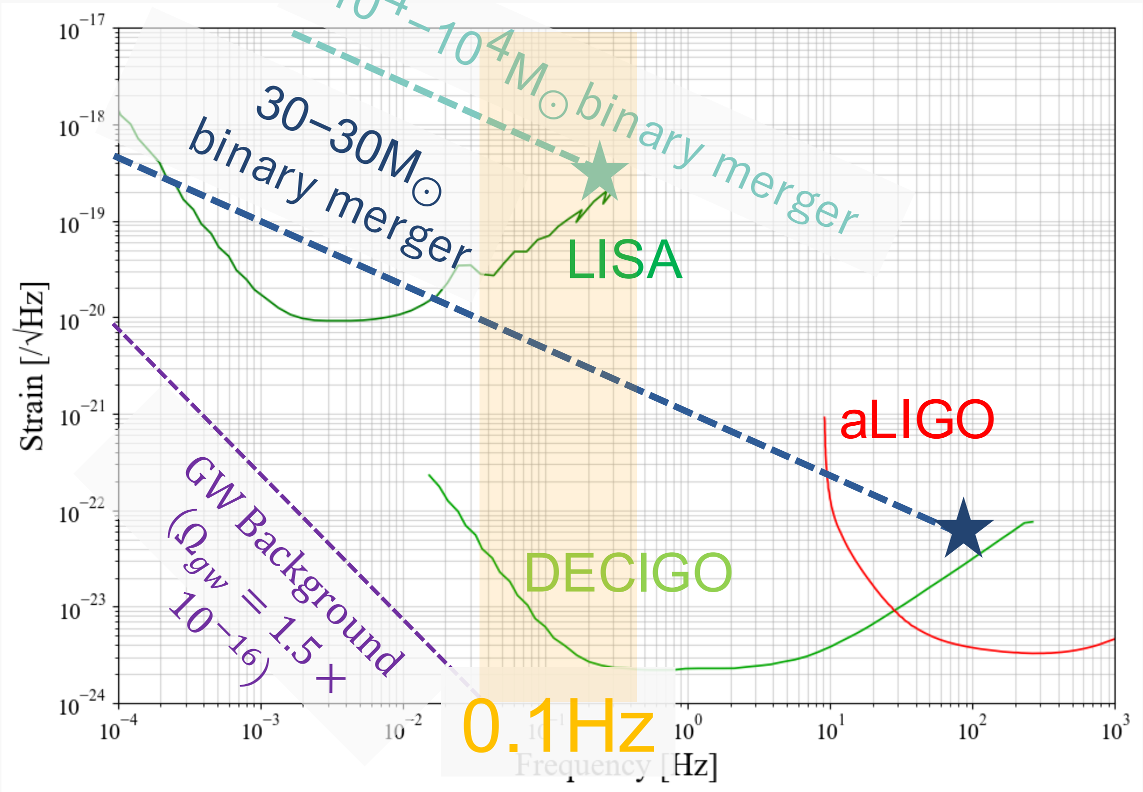
https://www.ligo.caltech.edu.



GW source at 0.1Hz:

- Solar Mass BH binary merger
  → early alert for current detector
- Intermediate Mass BH binary merger
  unveiling the formation process of SMBH
- GW background
  → direct observation of the early universe

Low frequency GW and detectors



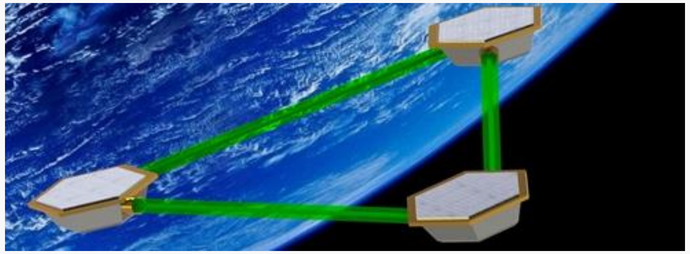
Space born GW detector: escape from seismic noise and make TMs in all freq. range

Space GW detector

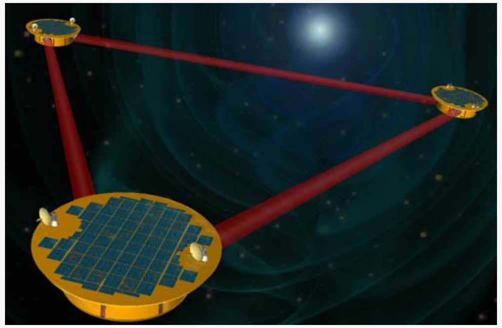
LISA: 10^{-5}-10^{-1} Hz — Scheduled for launch in 2035

DECIGO: 10^{-1}-10 Hz — After 2040

DECIGO



LISA



NASA

High costs and long time…

Low cost and easy maintanance

ground-based detectors are also important

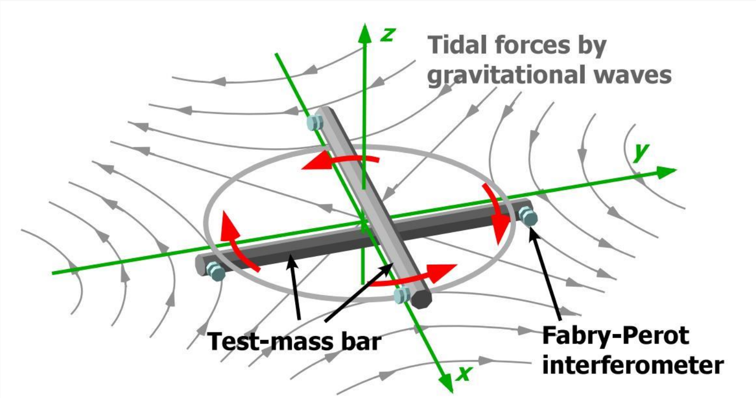
Low freq. Ground-based GW detectors

Resonant freq. of normal pendulum is above 0.1Hz

New vibration isolation method is required

for ground-based detector to 0.1Hz observation

Torsion pendulums

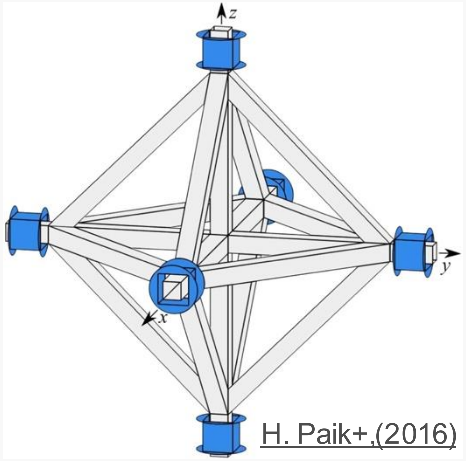


M. Ando+,(2010)

共振周波数の低いねじれ振り子のねじれ回転を計測

- TOBA M. Ando+,(2010)
- TorPeDO S. Chua+,(2023)

Superconducting magnetic levitation

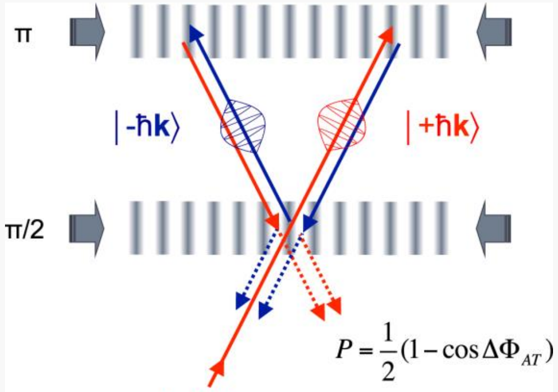


H. Paik+,(2016)

超伝導磁気浮上したマス間の相対運動を計測

- SOGRO H. Paik+,(2016)

Atomic interferometer

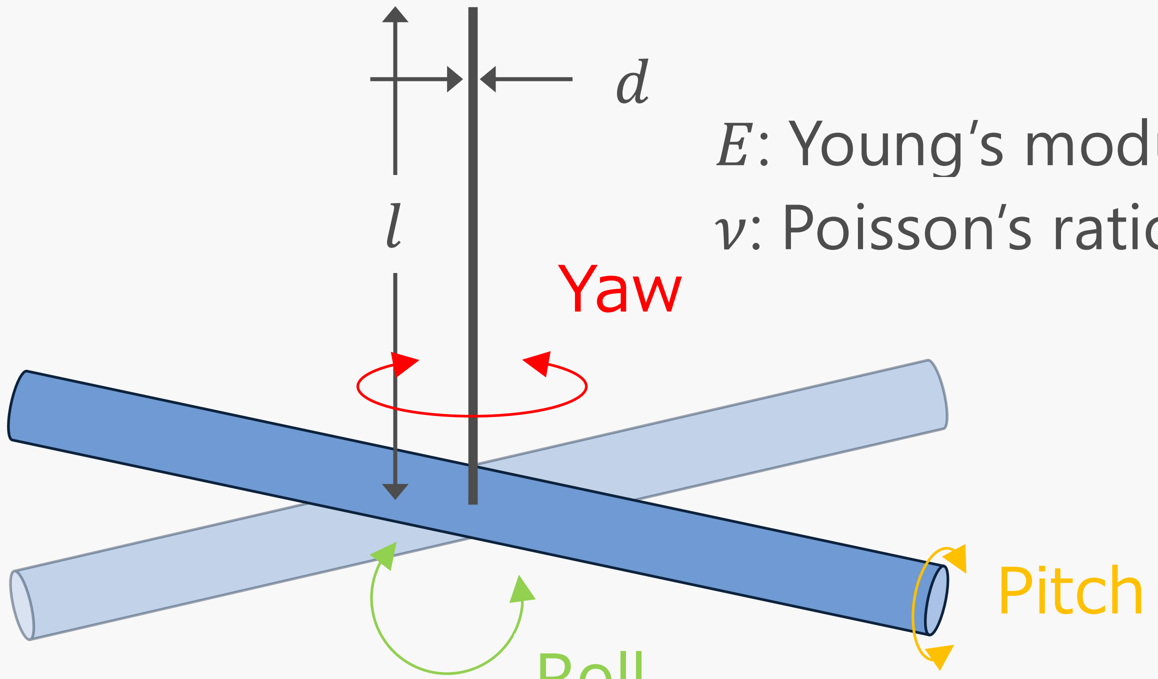


Canuel+,(2018)

自由落下する原子の物質波の干渉を計測

- ZAIGA M. Zhan+,(2020)
- MIGA Canuel+,(2018)

Torsion pendulum



E: Young's modulus
v: Poisson's ratio

I: moment of inertia

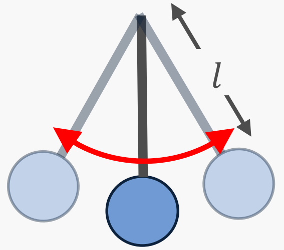
$$f_{\mathrm{Yaw}} = \frac{1}{2\pi}\sqrt{\frac{\pi E d^4}{64 l (1+v) I}}$$

$$f_{\mathrm{Yaw}} = 20\ \mathrm{mHz}$$

when $l = 50\ \mathrm{cm}$, $d = 0.3\ \mathrm{mm}$
$E = 411\ \mathrm{Gpa}$, $v = 0.28$,
$I = 0.016\ \mathrm{kg}\cdot m^2$
(tungsten wire and aluminum TM)

Resonant freq. of torsional mode can be lowered easily!

Normal pendulum



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

$f_0 = 0.7\ \mathrm{Hz}$ when $l = 50\ \mathrm{cm}$
$f_0 = 20\ \mathrm{mHz}$ when $l = 0.6\ \mathrm{km}$

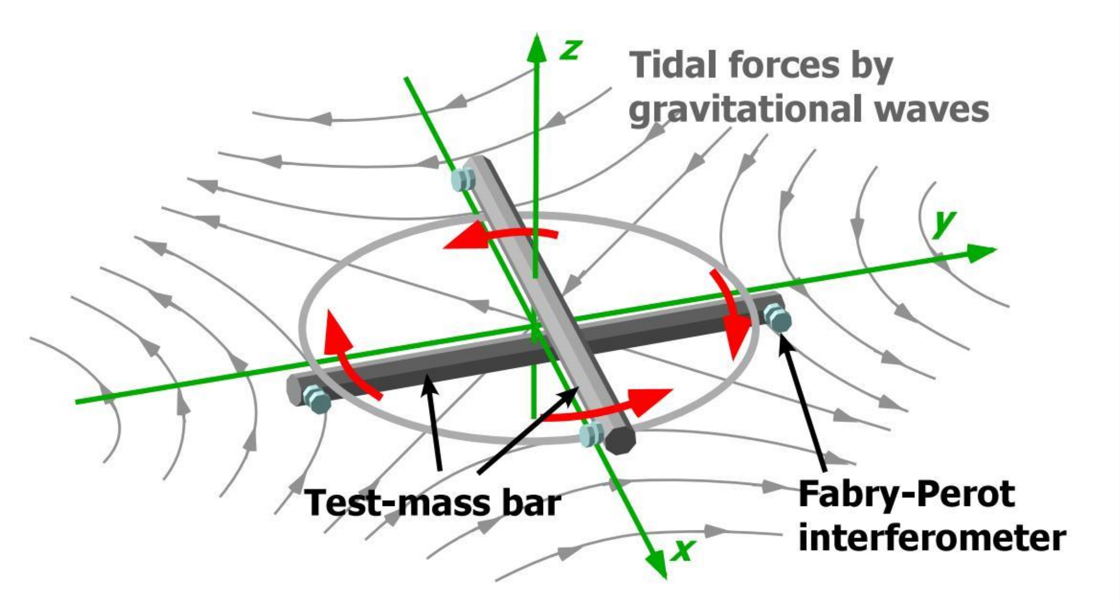
Response of torsion pendulum

Test Masses have to be free masses to detect GW

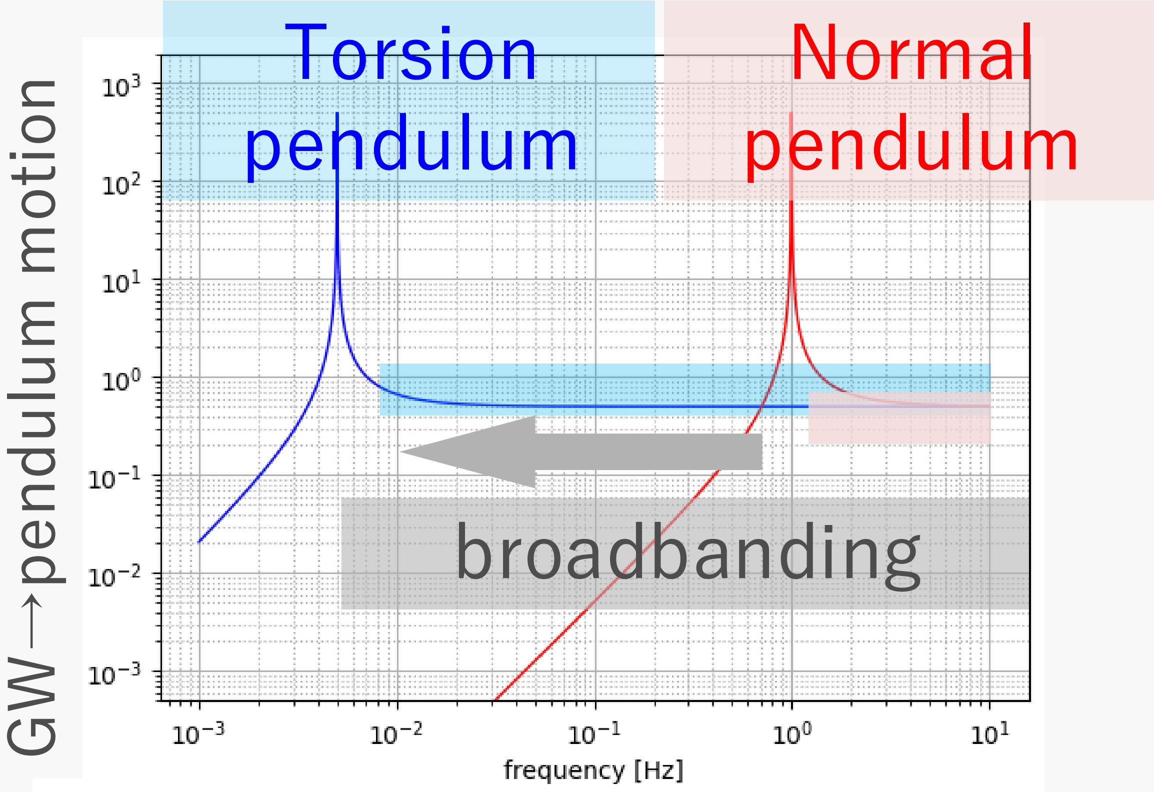
Used normal pendulums, but

broadbanding toward low freq. is limited (resonant freq. $\propto \sqrt{1/l}$)

Resonant freq. of torsion pendulums: ~mHz



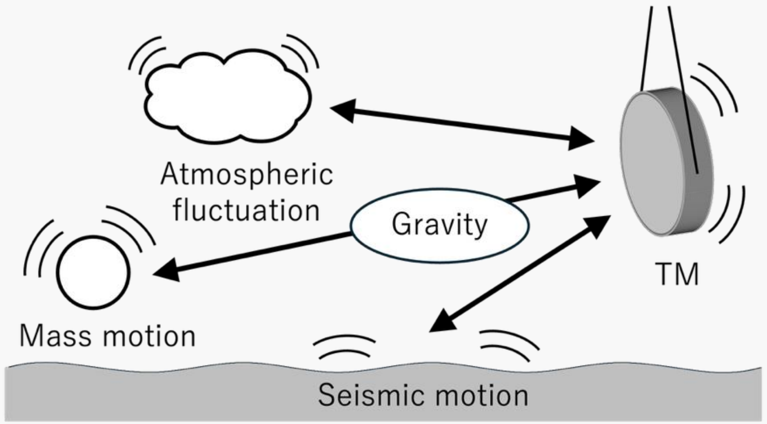
M. Ando+,(2010)



Science by ground-based low freq. GW

Geophysical science

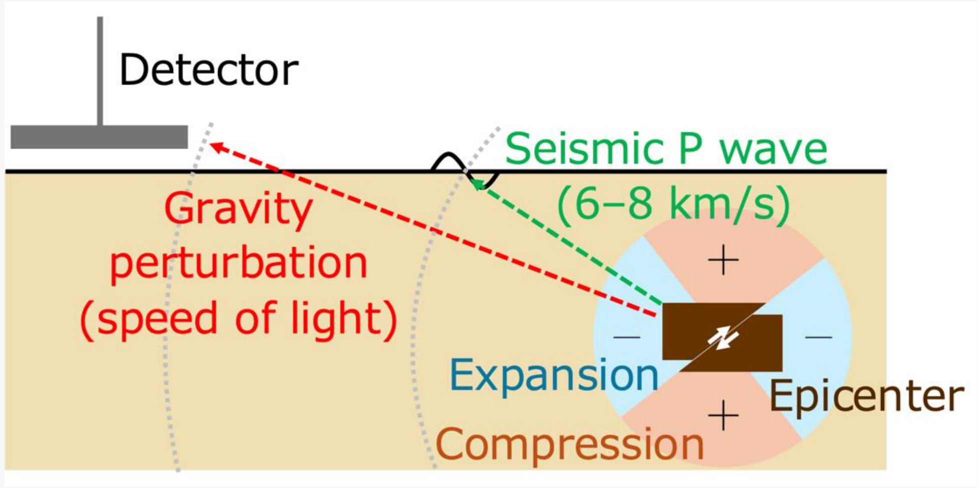
Newtonian noise



- 検出器付近の物体の運動による
  最も原理的な雑音
- 未観測だが、次世代検出器の感度を
  制限すると予想される

contribute
3G detectors

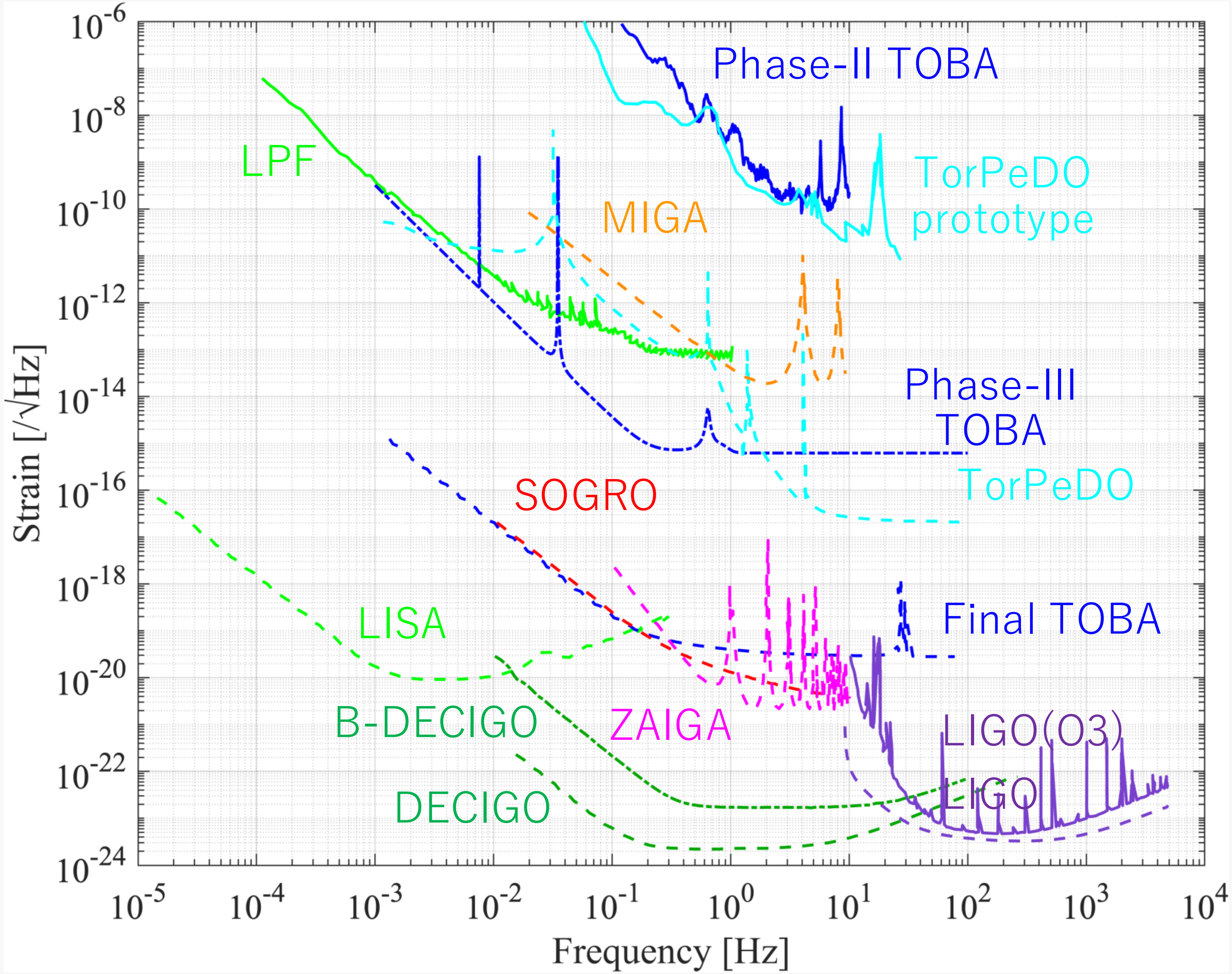
Earthquake alert system



- 地震による重力場変動が光速で伝搬
- 従来より速い地震速報を実現可能

mitigate
disaster damage

Low frequency GW detectors

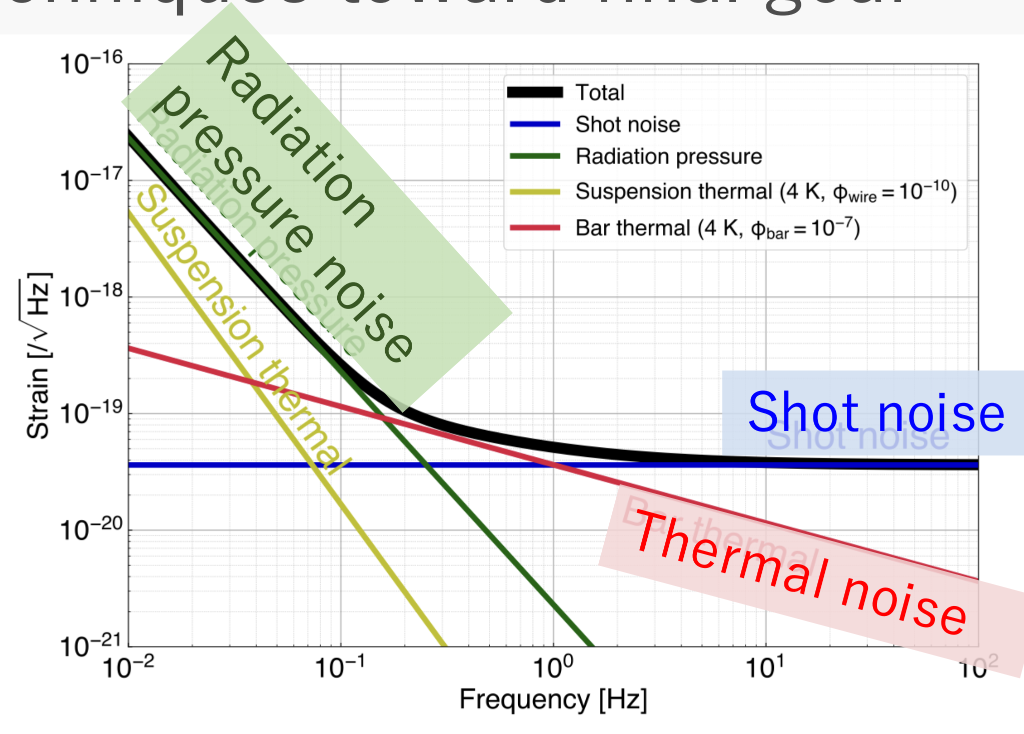


実線: 達成
点線: 提案

10^{-8} /√Hz @0.1Hz
くらいが最高

Gravitational wave detector TOBA

- TOBA; TOrsion Bar Antenna
- Low resonant freq. of torsion pendulum(~mHz) enables low freq. GW observation
- Developing prototype and component techniques toward final goal
- Designed sensitivity is limited by quantum noise and thermal noise



M. Ando+,(2010)

Roadmap of TOBA development

Demonstrate technique and improve sensitivity → Toward GW detection → Future

~2014

Phase I , II

Principle test

demonstration of torsion bar

- 20 cm TMs
- Room temperature
- MI sensor
- Achieved $10^{-8}/\sqrt{\mathrm{Hz}}$
- Set an upper limit on GW background

~Present

Phase III

Development

Cryogenic demonstration, noise reduction

- 30 cm TMs
- cryogenic(4K)
- Fabry-Perot cavity sensor

Target sensitivity: $10^{-15}/\sqrt{\mathrm{Hz}}$ @0.1 Hz

Future

Final

Final goal

upsizing

- 10 m TMs
- cryogenic(4 K)
- FP cavity sensor
- $10^{-19}/\sqrt{\mathrm{Hz}}$

Science of TOBA

Low freq. GW

IMBH binary merger

- ～1 Mpc (Phase-Ⅲ)
- ～10 Gpc (Final)

Unveiling the formation of supermassive BH

GW background

Final

- Ω_{GW}～10^{-7} @0.1 Hz

Direct observation of the early universe

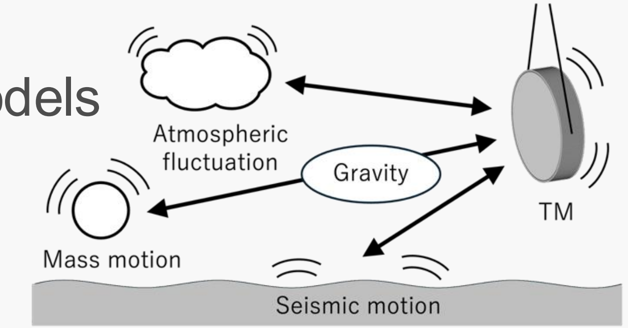
Geophysics

Phase-Ⅲ

Newtonian noise detection

- Expected to limit 3G detector's sensitivity
- not detected yet
- Testing current models

Contribute 3G detector

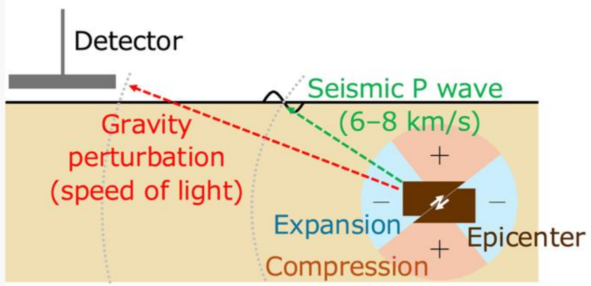


Earthquake alert

Phase-Ⅲ

- Earthquake causes gravity gradient
- GG propagates at the speed of light

Mitigate disaster damage



For Dark Matter search

Differential Torsion Sensor for Dark Matter

- *A new type of differential torsion sensor for vector dark matter detection*

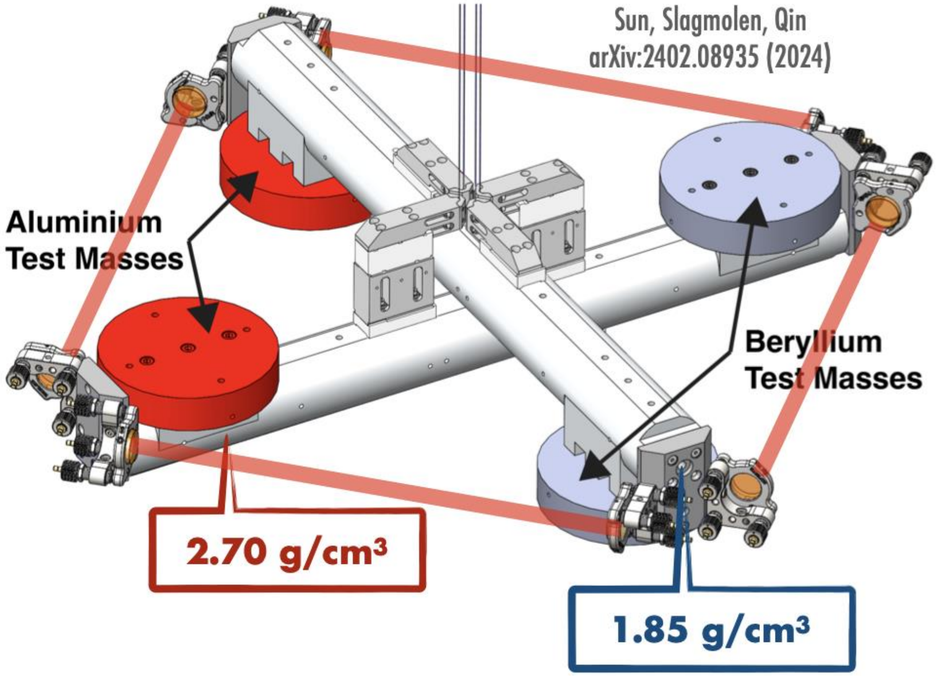
Test mass materials	*Al / Be*
Mass of each test mass	*5 kg*
sensor beam length	*0.6 m*
beam mass (w/ mounting equipment)	*5kg*
Mechanical lever arm	*0.24 m*
Mechanical resonant frequency	*26 mHz*
Suspension wires Q factor	*3000*

➡ *Large common mode rejection*

➡ *Differential angular sensitivity*

➡ *Can achieve enhanced sensitivity without requiring significant upgrades in technology*

[Also see relevant study – Okuma et al., arXiv:2404.00250 (2024)]



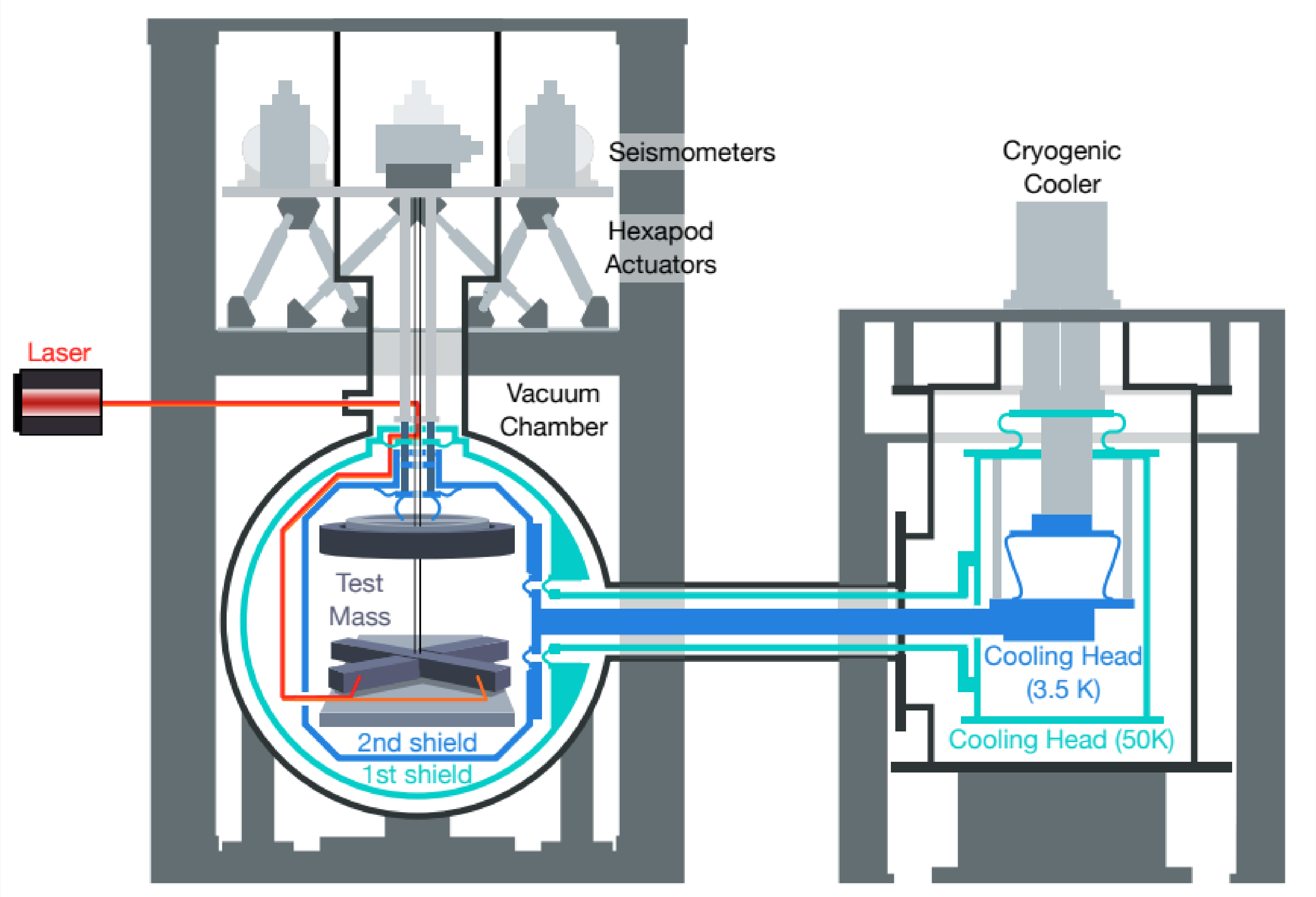
Require same moment of inertia
→ need mechanical engineering to make test masses with the same external dimensions

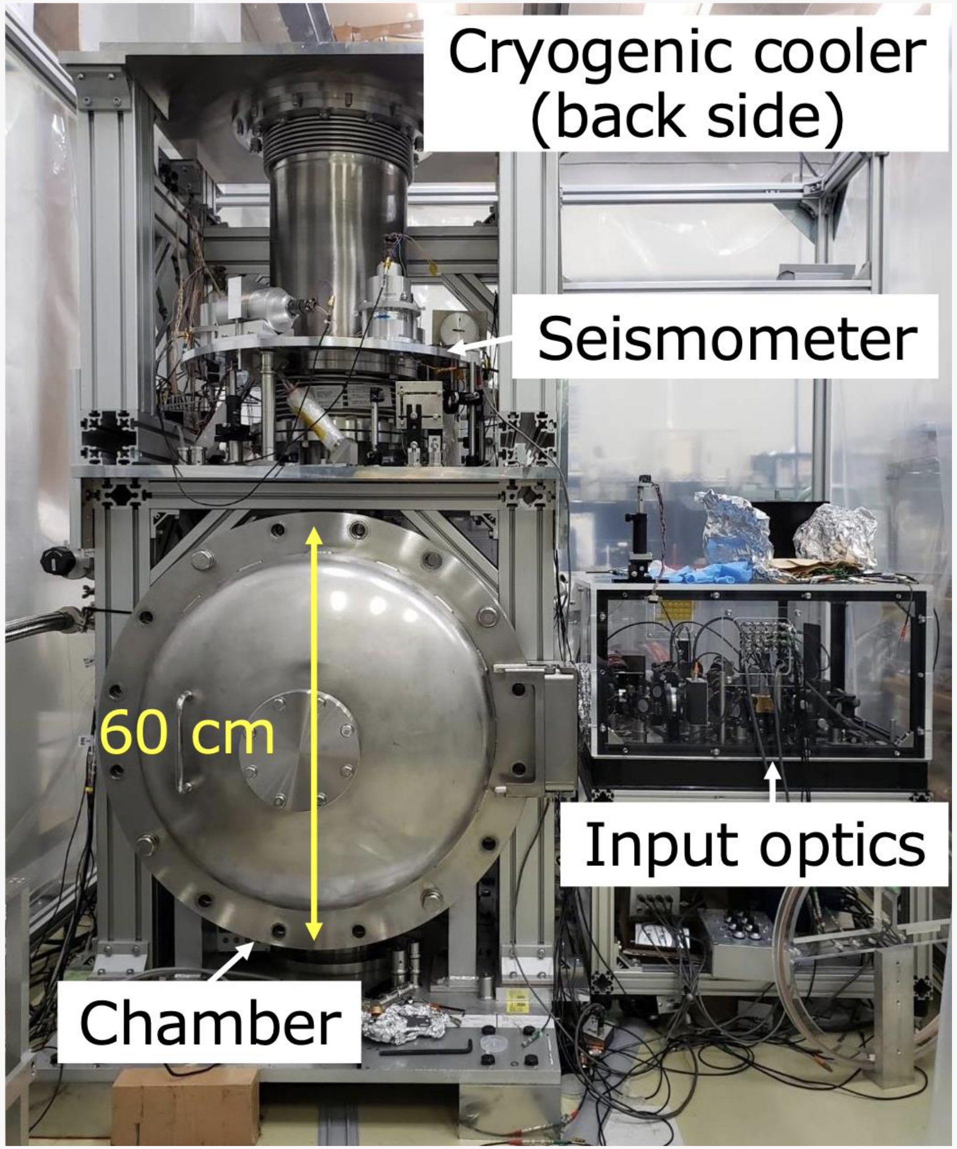
Lily's slide

Contents

Configuration of Phase-Ⅲ TOBA

TOBA consists of VIS, Suspension system, Optical system, Cryocooler





S. Takano+, Galaxies (2024)

Configuration of Phase-Ⅲ TOBA

Vibration isolation system

- Feedback control with seismometer and actuator

Active vibration isolation

Suspension system

- TMs made of silicon
- Suspended by low loss sapphire fiber

TMs respond to GW

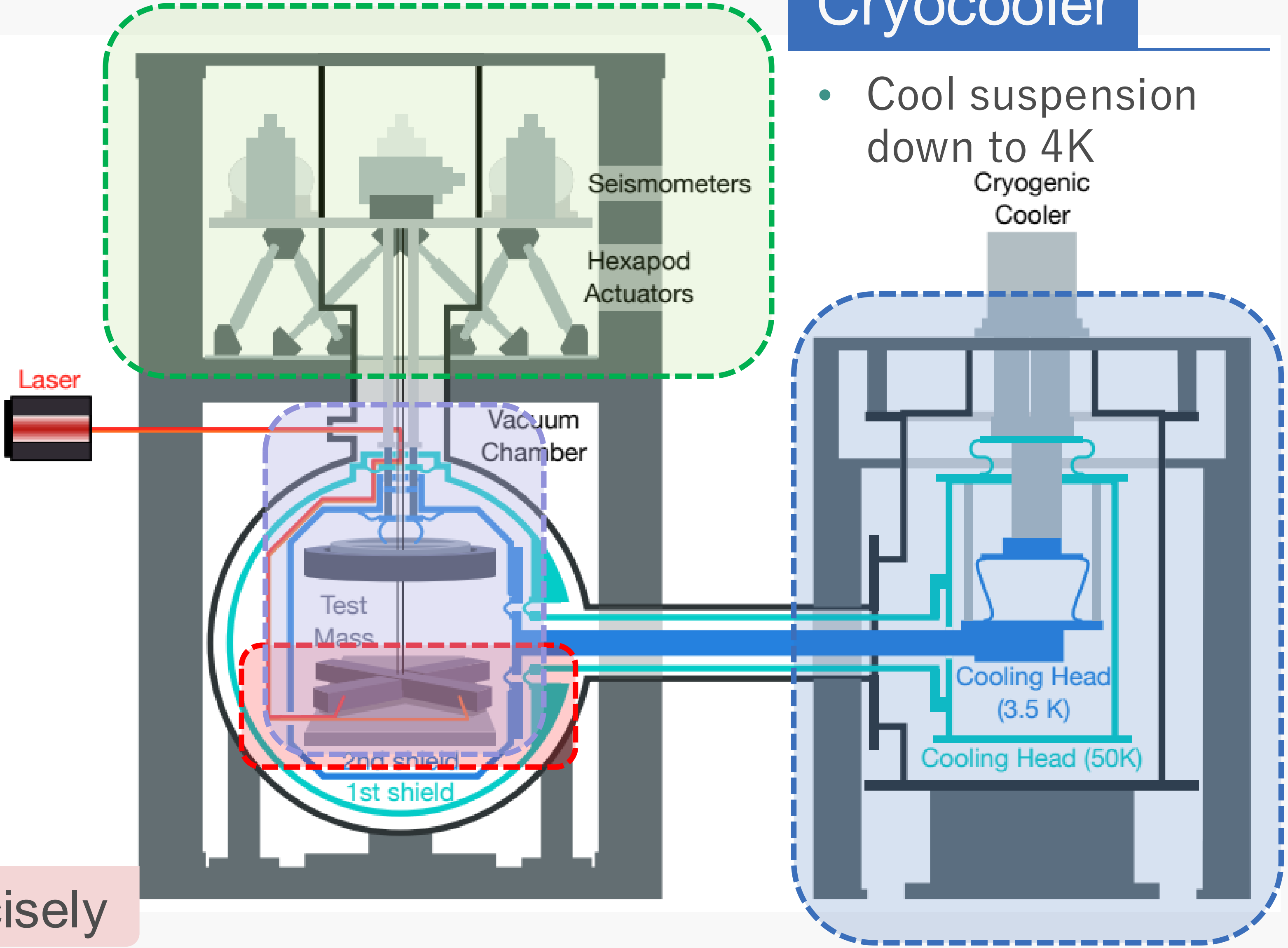
Optical system

- Differential Fabry-Perot cavity

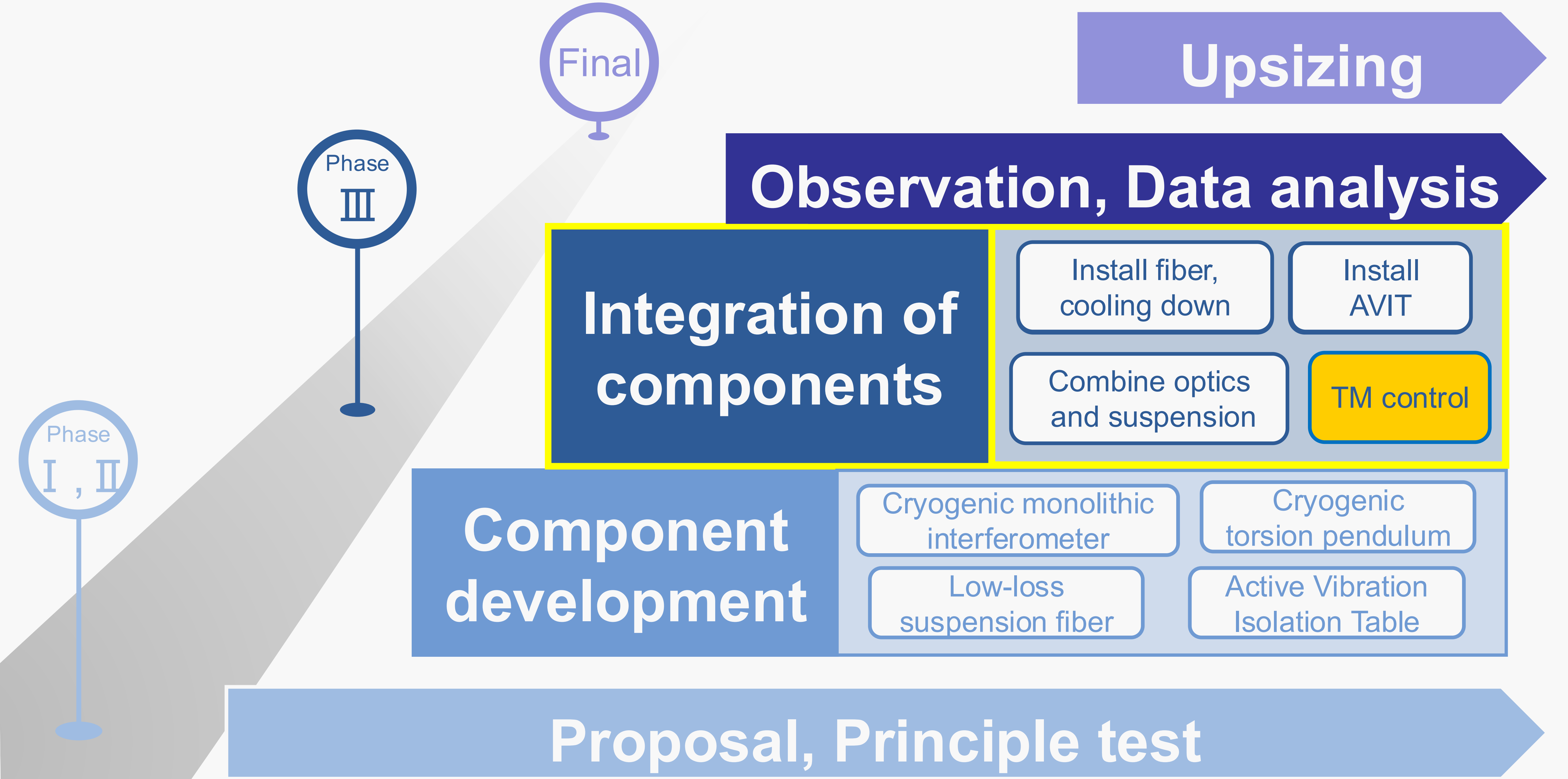
Readout the rotation of TMs precisely

Cryocooler

- Cool suspension down to 4K



Context of my work



Context of this work

Observation, Data analysis

Completion of Phase-Ⅲ TOBA

Integration of components

TM control

My work

TM control and rotation measurement with cavities

install

Combine optics & suspension

Previous research

Y. Oshima, Ph.D Thesis (2024)

Demonstrated suspension but

Cavity lock not yet achieved

Low-loss suspension fiber

Ongoing in another group

Y. Yamaguchi, Master Thesis (2025)

Mitigate thermal noise

AVIT

Future work

Mitigate seismic noise

Context of this work

Observation

Completion of Phase-Ⅲ

Integration of components

- Noise hunting
- Seismic coupling mitigation
- Operation in cryo. Temp.

TM control

TM control and rotation measurement with cavities

install

Combine optics & suspension

Previous research

Y. Oshima, Ph.D Thesis (2024)

Demonstrated suspension

but

Cavity lock not yet achieved

Low-loss suspension fiber

Ongoing in another group

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Mitigate thermal noise

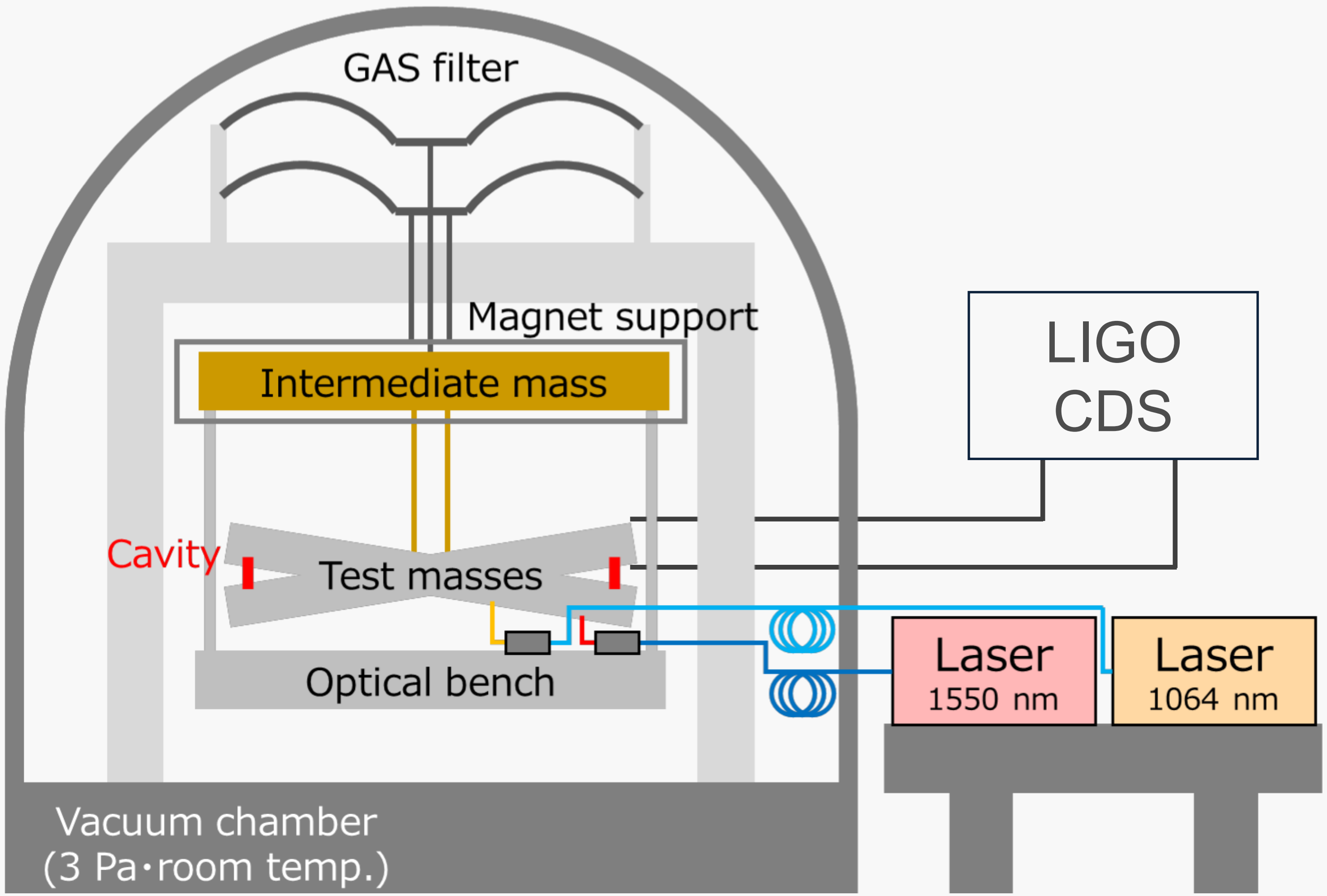
AVIT

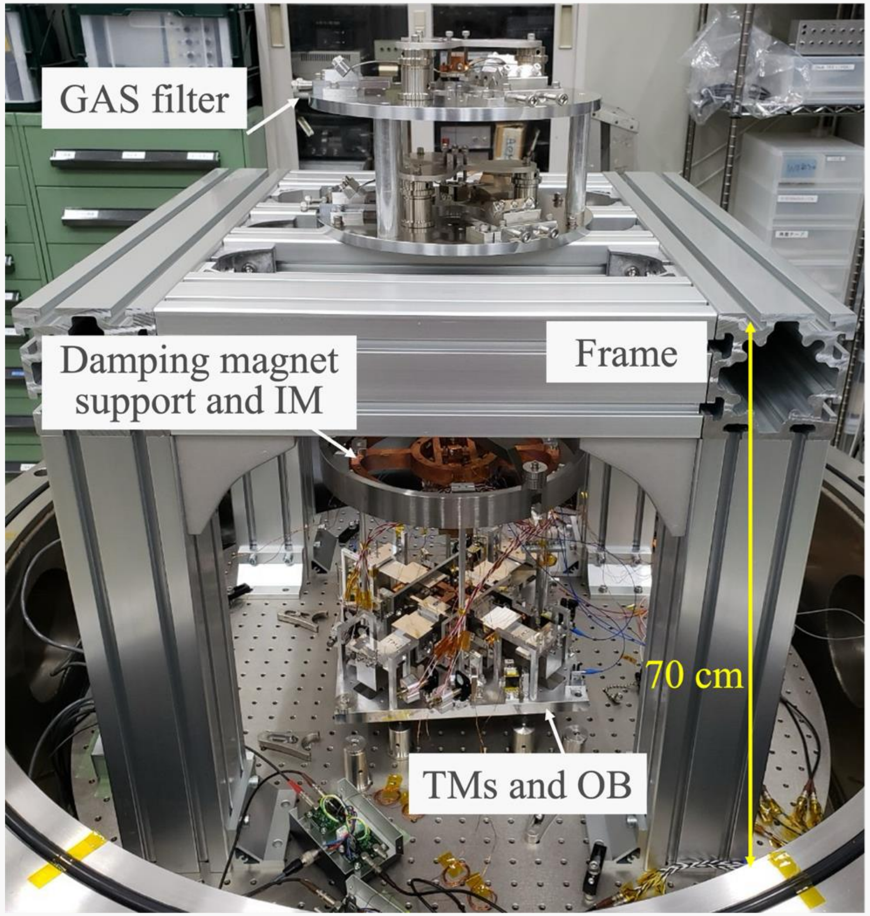
Future work

Mitigate seismic noise

Experimental setup

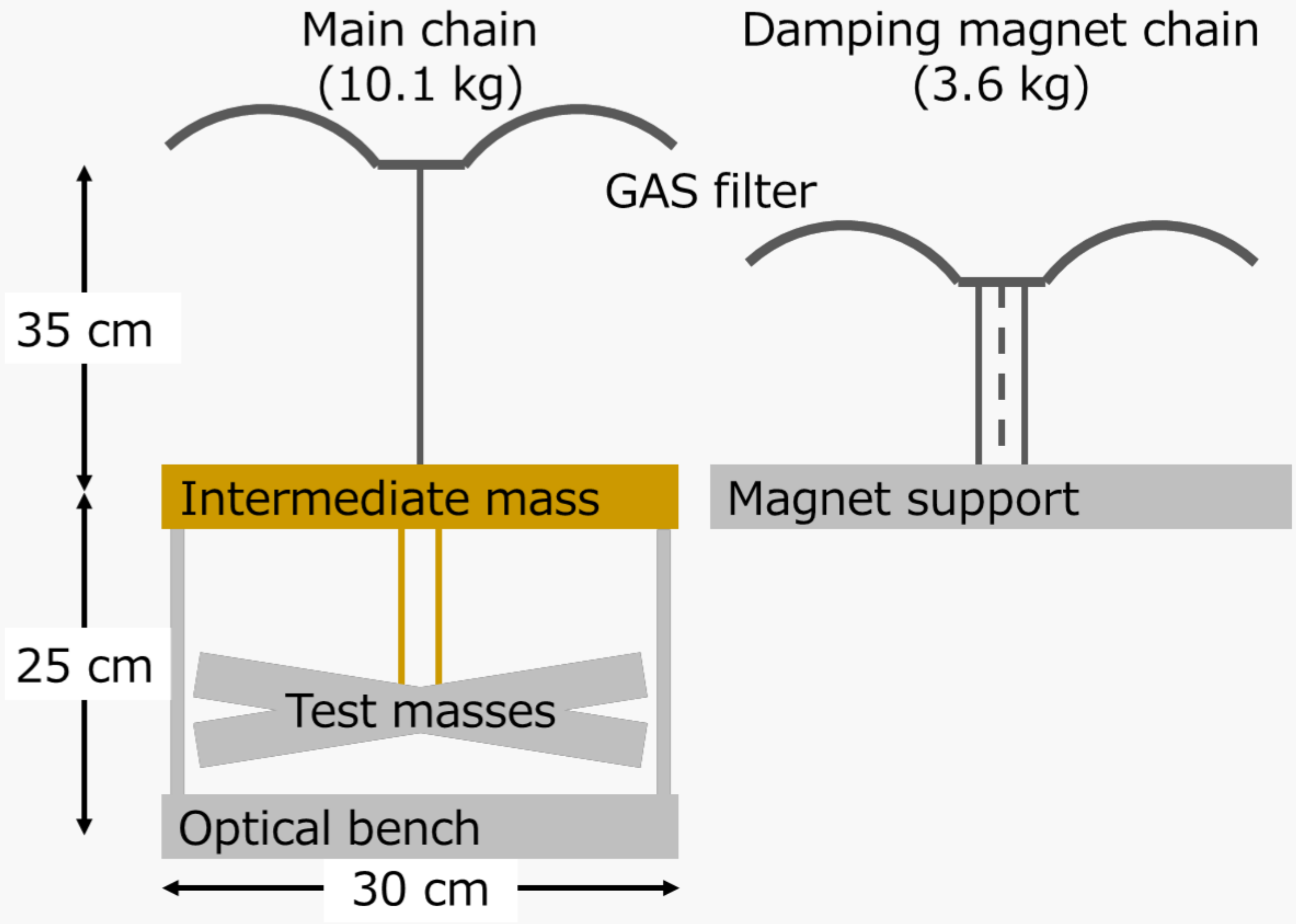
Suspension system is placed in the chamber
Laser beam is introduced to the chamber from the source via fibers

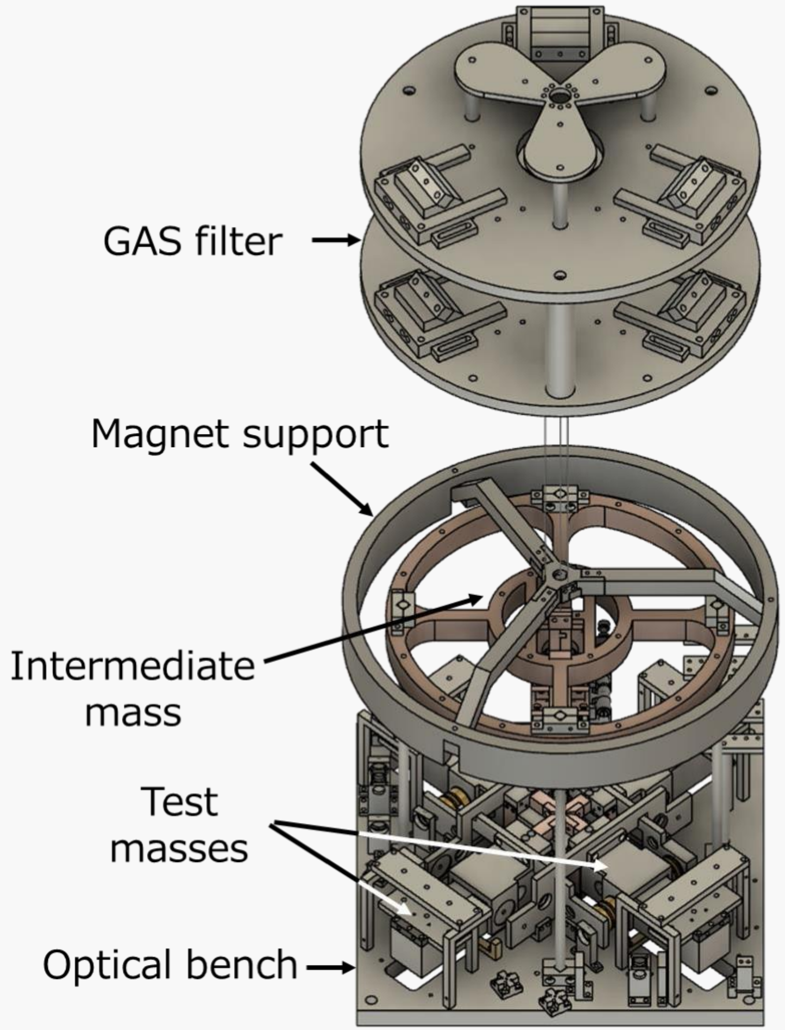




Design of suspension system

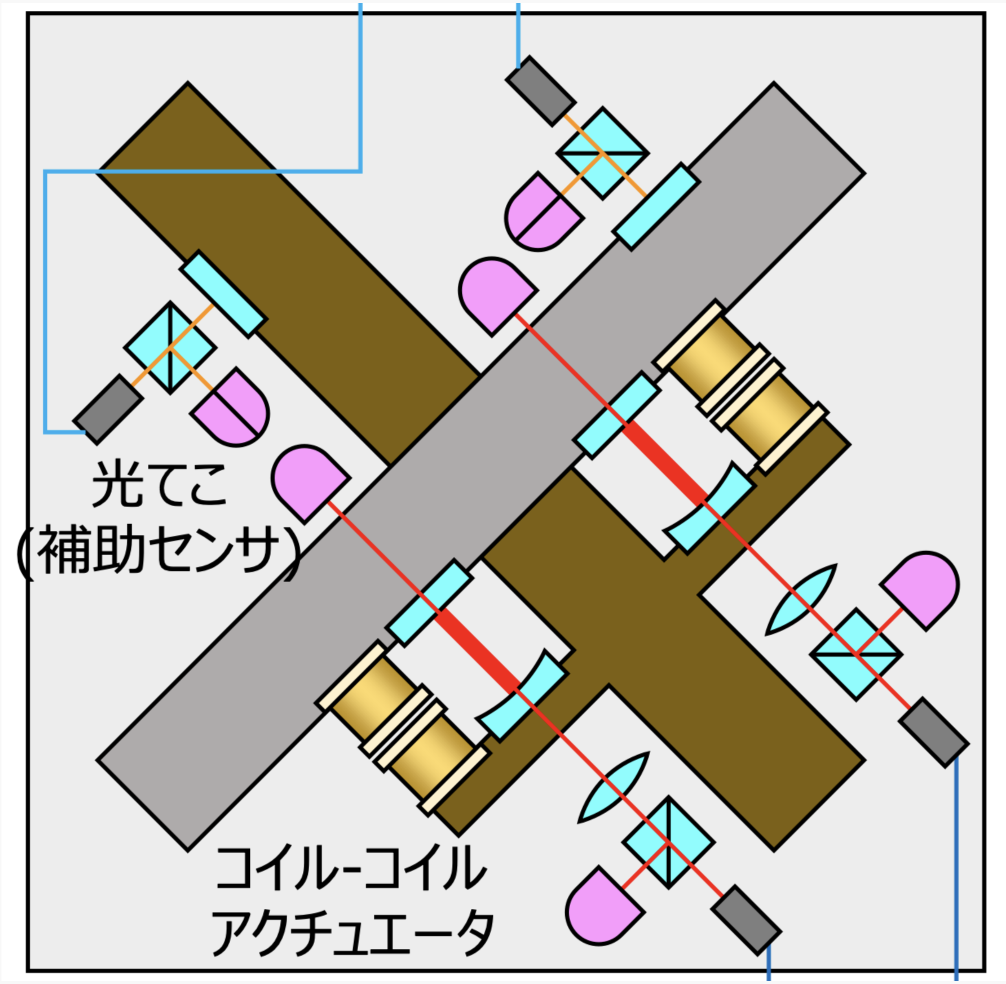
Suspension system consists of two chains





Design of optics

Top view of OB



レーザー 1550 nm
(高さ: 25 mm)

レーザー 1064 nm
(高さ: 35 mm)

Y. Oshima+, JPS(2024)

Differential FP cavities

- 2 FP cavities between TMs to detect differential rotation

Reduce noises from OB vibration

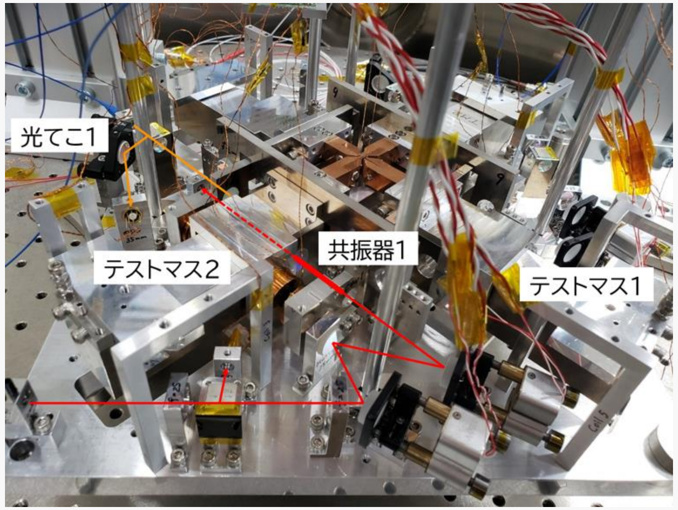
Actuator

- Actuate TMs with coil-coil actuator

Reduce magnetic field noise

OpLev

- Auxiliary sensor

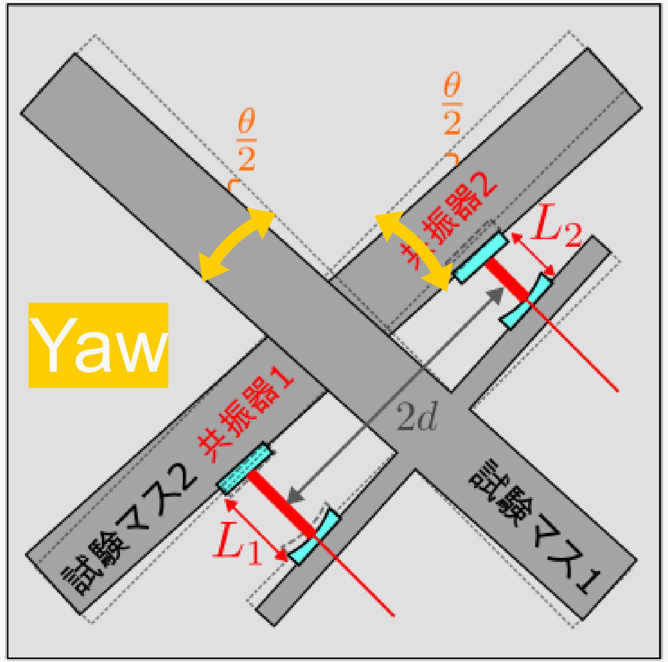


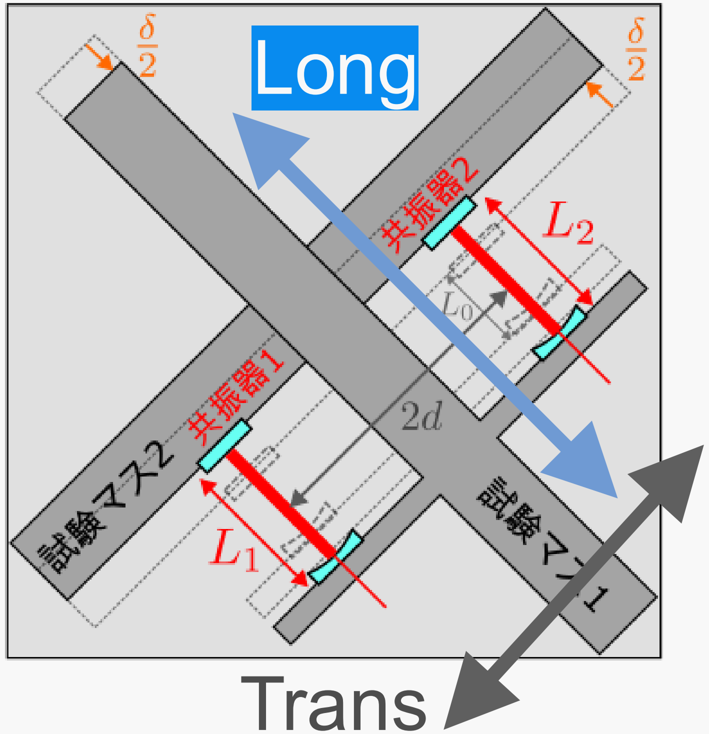
Control TMs' rotational motion with FP cavities

Yaw rotation and **Long movement** changes cavity length

2DoF control is required

Non-obvious method is necessary





Yaw

differential

$$\begin{cases} L_1 = L_0 + d\theta \\ L_2 = L_0 - d\theta \end{cases}$$

Long

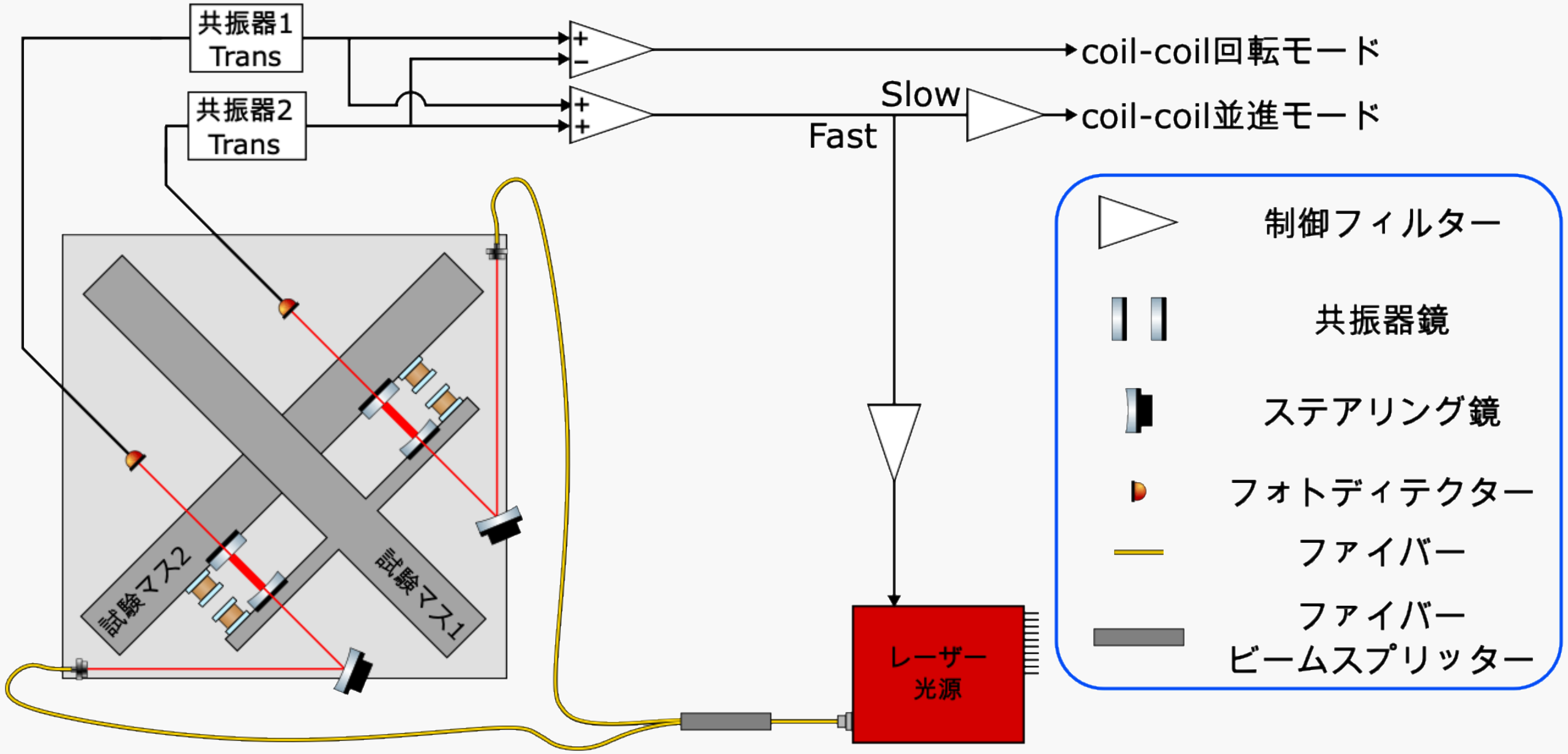
common

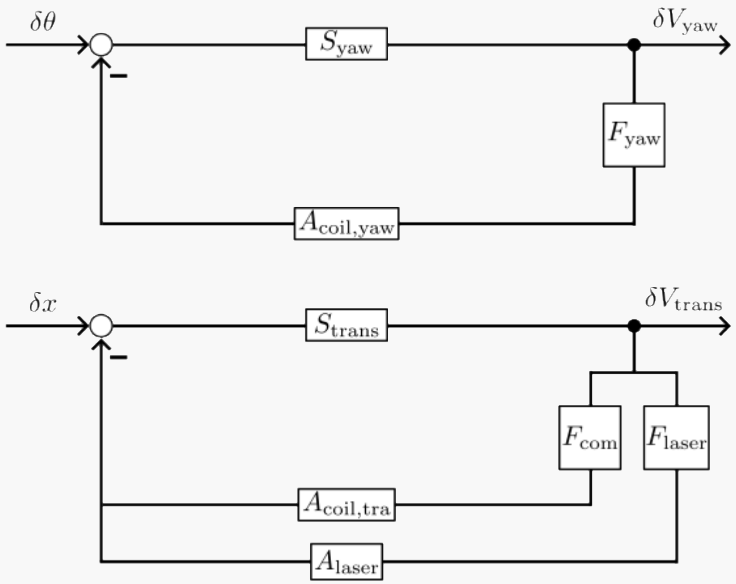
$$L_1 = L_2 = L_0 + \delta$$

Torsion pendulum control with FP cavities

Feed back control for each mode, Yaw and Long

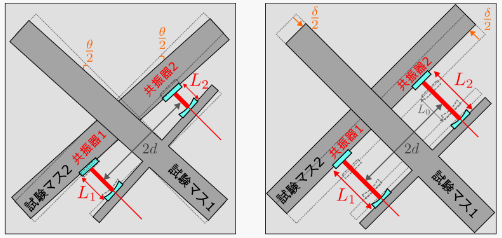
Feed back $\begin{cases} \text{Yaw signal to coil–coil actuator} \\ \text{Long signal to coil–coil and laser frequency actuator} \end{cases}$





Torsion pendulum control with FP cavities

Sensor (Fabry-Perot cavity)



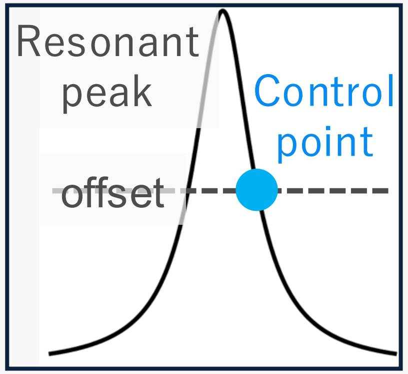
$L_1 = L_0 + d\theta$
$L_2 = L_0 - d\theta$

$L_1 = L_2 = L_0 + \delta$

Yaw error signal from differential signal

Long error signal from common signal

Locking to the cavity transmission slope via DC offset



Offset lock

- Larger control range
- Don't need RF PD

Actuator (coil-coil, laser frequency)

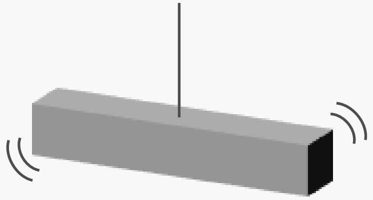
Yaw actuate with differential mode of coil-coil actuator

Long actuate with common mode of coil-coil actuator & frequency actuator

Frequency actuator works symmetrically on both cavities

Lock acquisition

Lock acquisition: the process of acquiring controlled state from un-controlled state



Acquiring controlled state from free-run(un-controlled) state
requires actuator with **high authority & fast response**

In this work…

Requirement

① Bandwidth ~1kHz
② 2DoF lock acquisition

solution

Bandwidth~5kHz

① **laser frequency actuator**

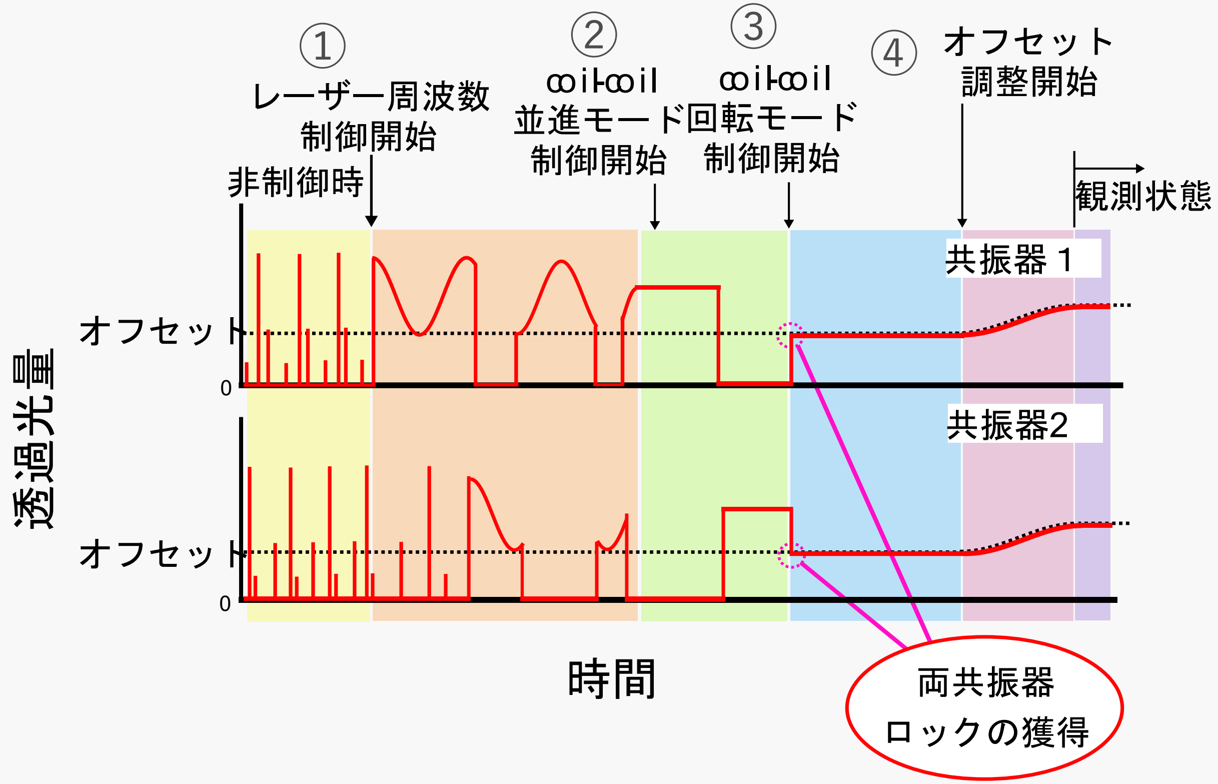
Bandwidth of coil-coil actuator is limited ~50Hz
by CDS delay

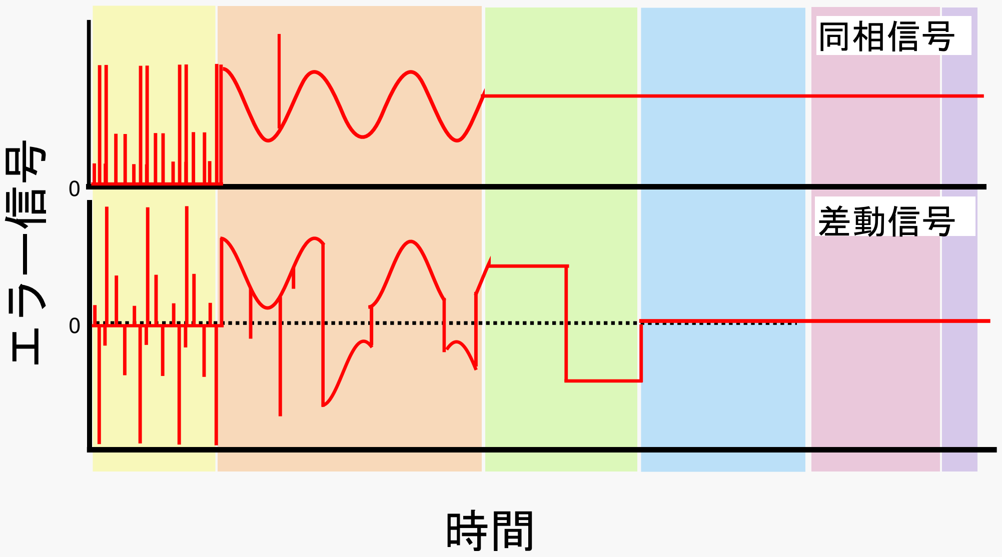
② **Stepwise** lock acquisition(DoF by DoF)

Lock common mode with freq. actuator first.
After that, lock differential mode.

Lock acquisition

Method of lock acquisition

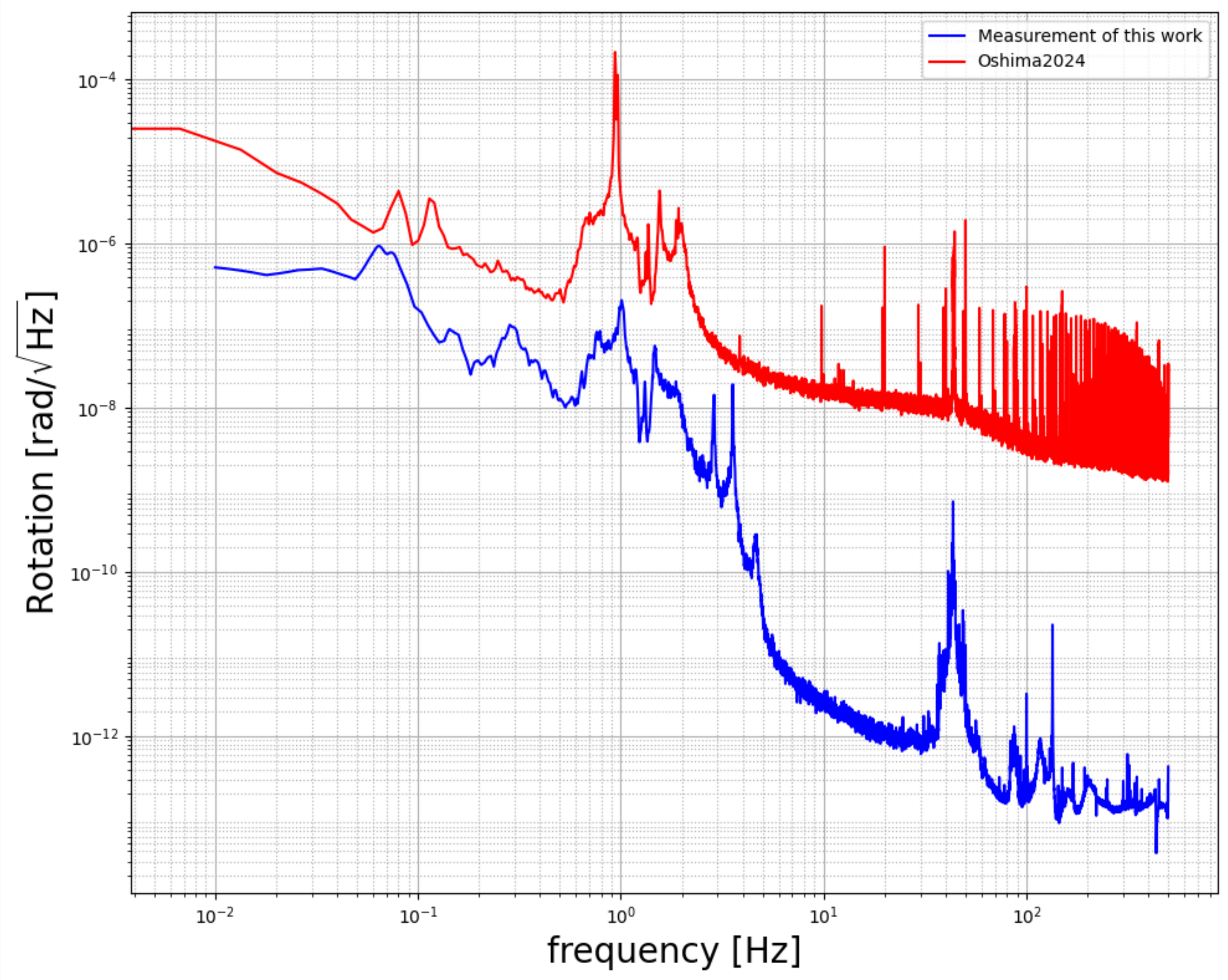




①locking common mode with freq. actuator
②stabilize common mode with coil-coil common mode
③locking differential mode with coil-coil differential mode
④adjusting offset levels

Measurement result

Rotation sensitivity



OpLev in previous research

This work

Y. Oshima, Ph.D Thesis (2024)

Measured TMs' rotation with main sensor; FP cavities

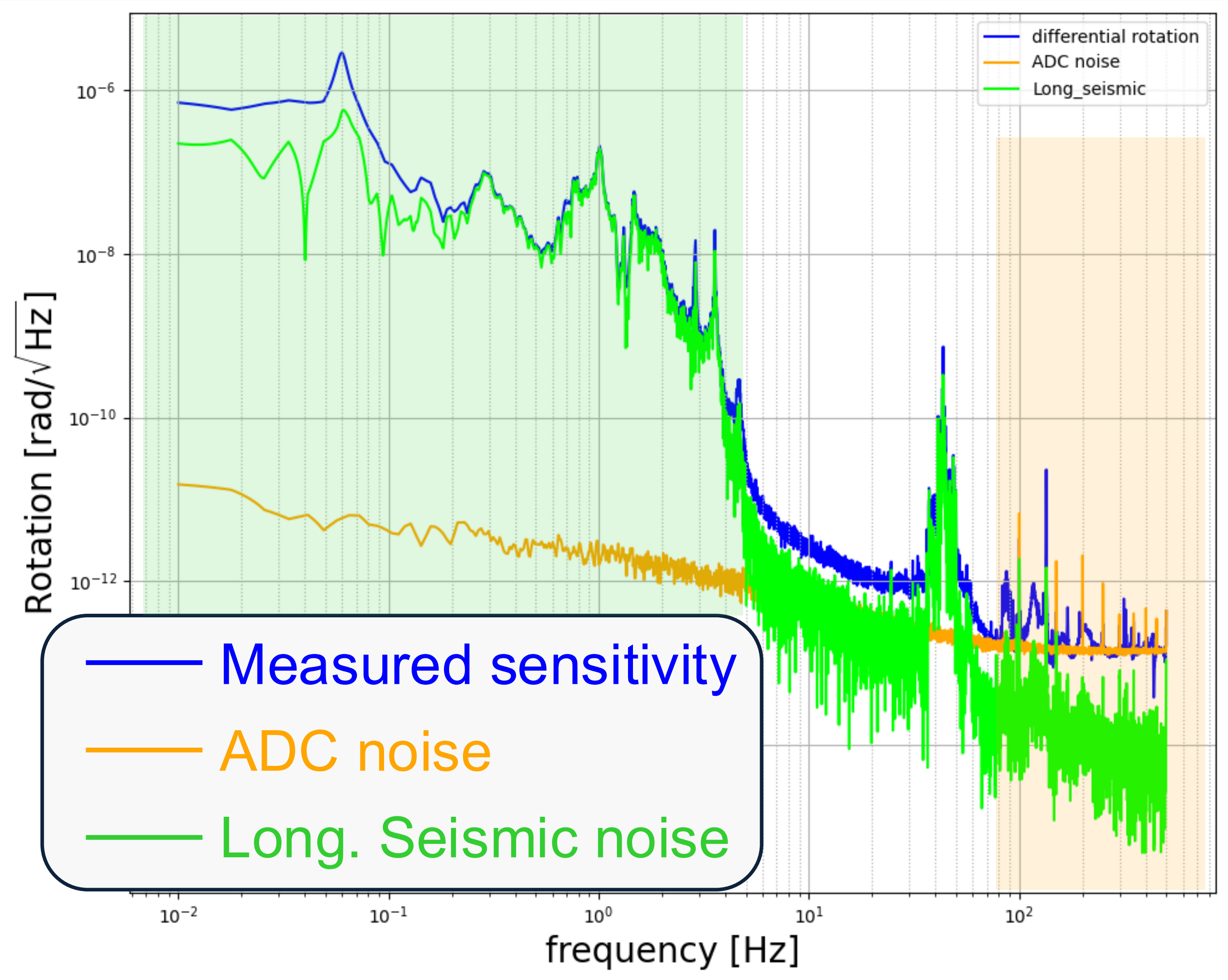
Compared to previous result,
Sensitivity improved
~**2 orders** below 4Hz
~**4 orders** above 4Hz

Mainly due to

- Reduction of sensor noise
- Mitigation of OB vibration noise

Measurement result and noise sources

Rotation sensitivity and Noise budget



0.2-5Hz: seismic noise

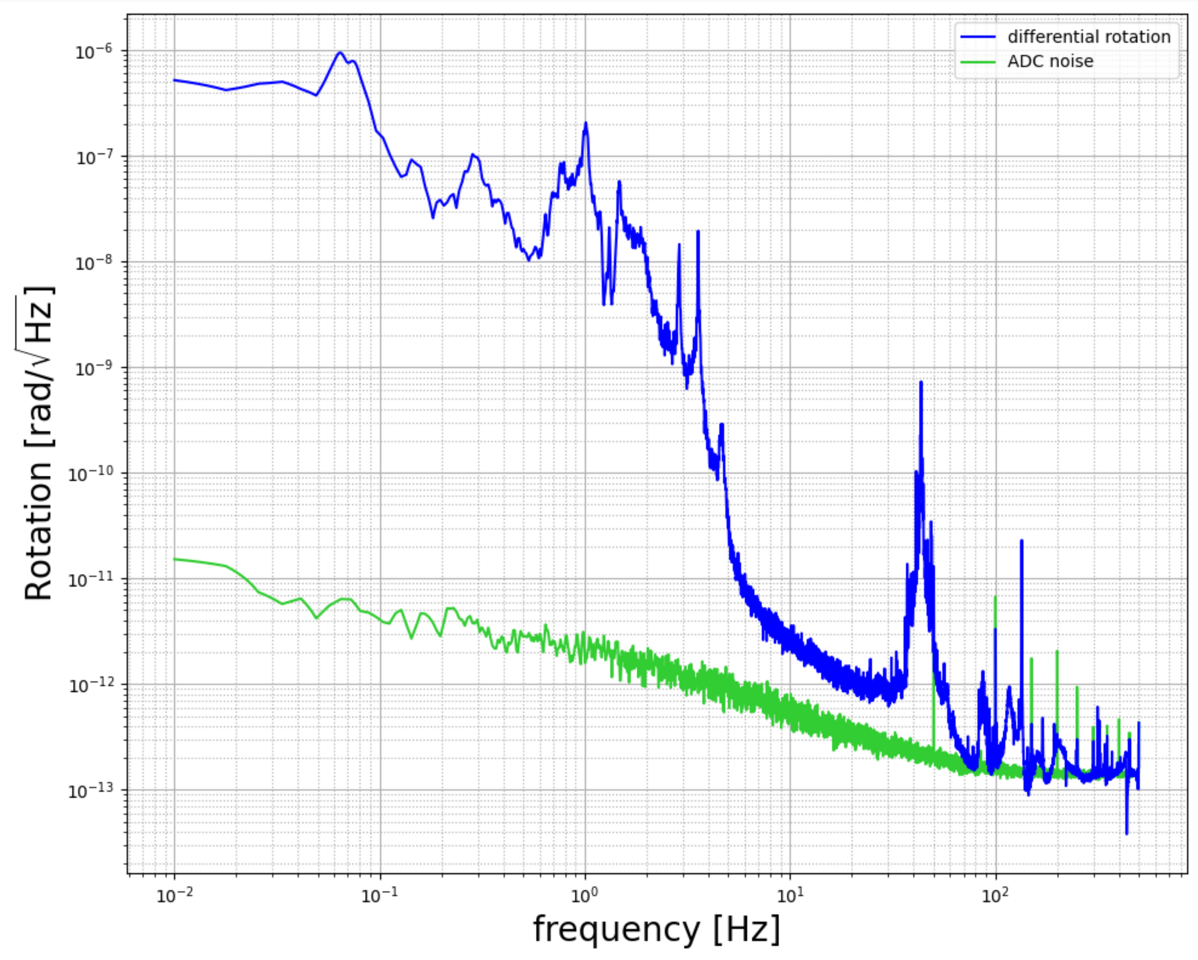
above 60Hz: ADC noise

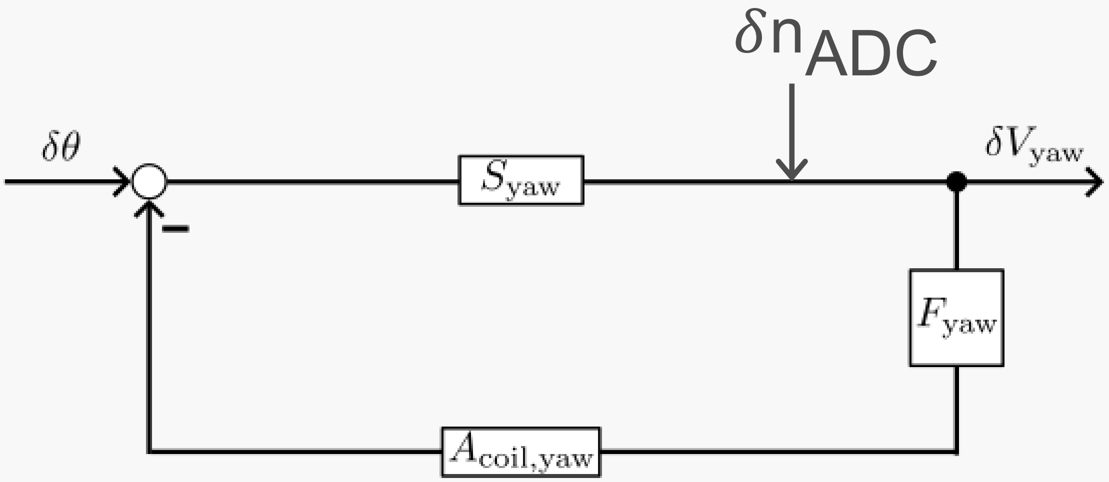
UGF of cavities control is ~20Hz

Discussion of noise source① ADC noise

Digital system noise

Noise floor above 60Hz is limited by ADC noise





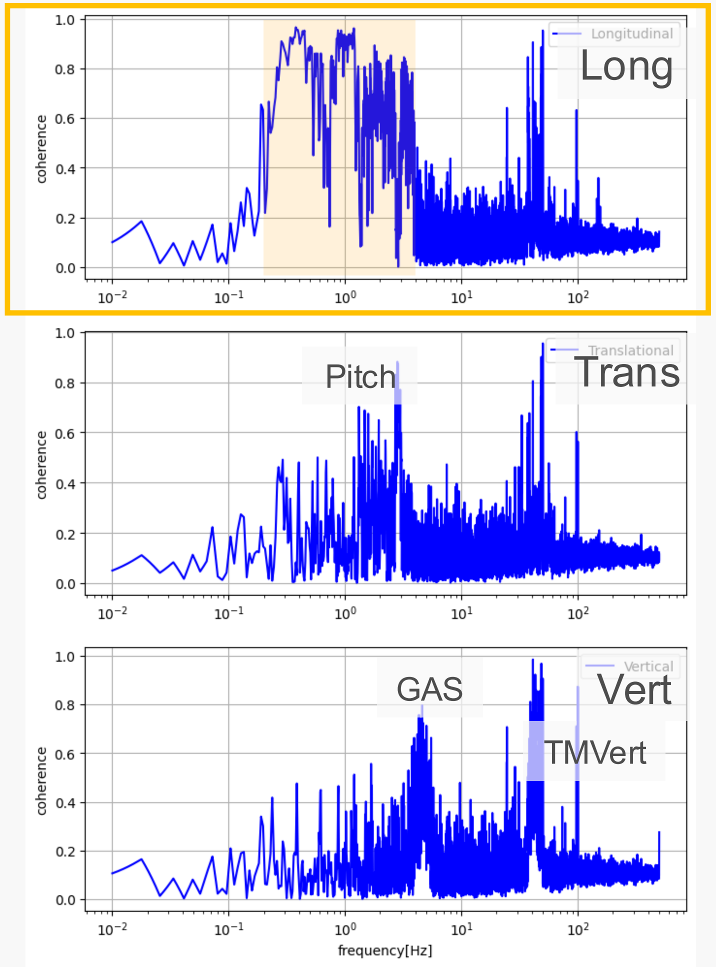
Amplification of the signal before CDS

mitigates ADC noise

Discussion of noise source ② seismic noise

In principle, **Translational seismic motion** is not a noise source,
but it couples to imperfection of system(ex: TM tilt) to be rotational noise

Estimated seismic motion contribution from coherence with seismometer signal

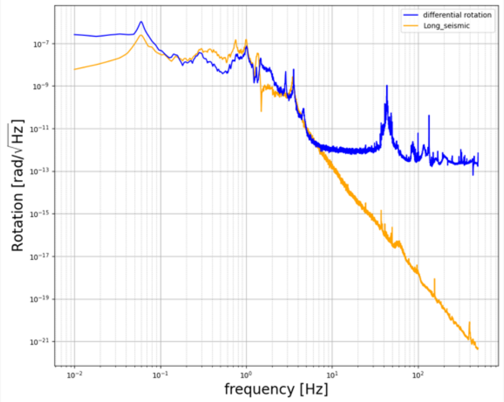


Significant coherence with Long. seismometer

Trans, Vertとも各モードの共振ピークでは
コヒーレンスあり

Long. seismic noise is dominant

Couples to TM1 Pitch tilt,
TM2 Roll tilt



Long地面振動から回転角への伝達関数を測定し、
地面振動雑音のスペクトルを推定した

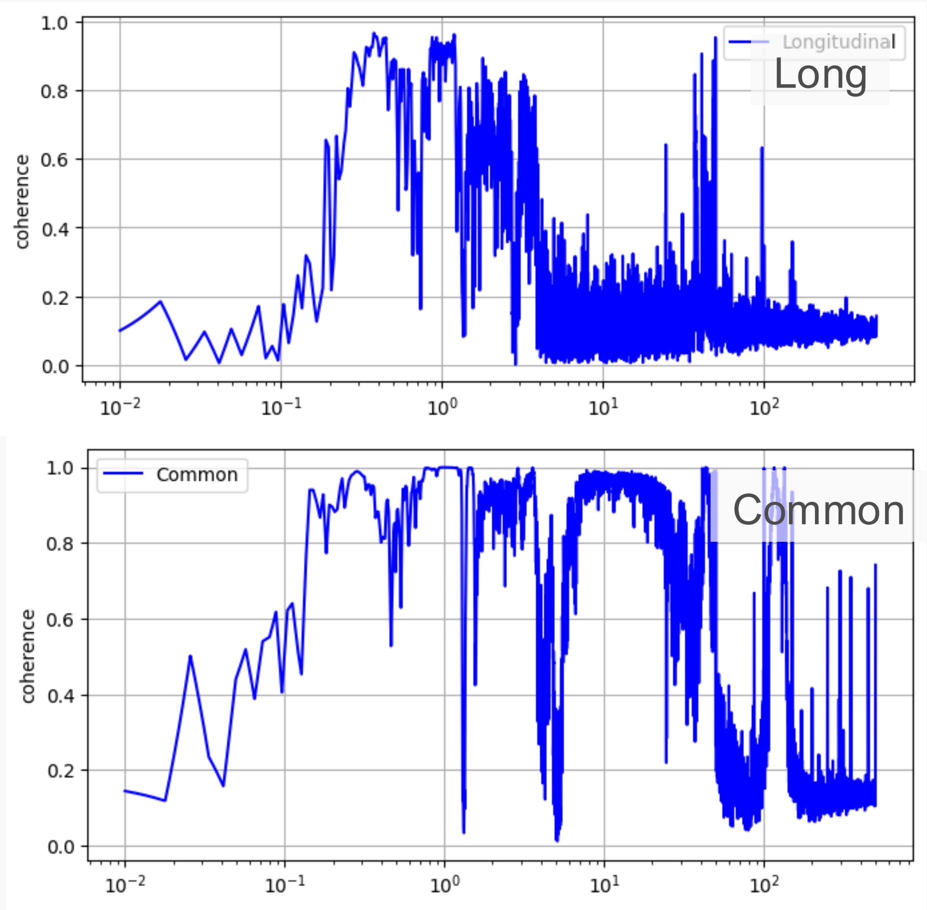
Adjustment of TM DC tilt

mitigates Seismic noise

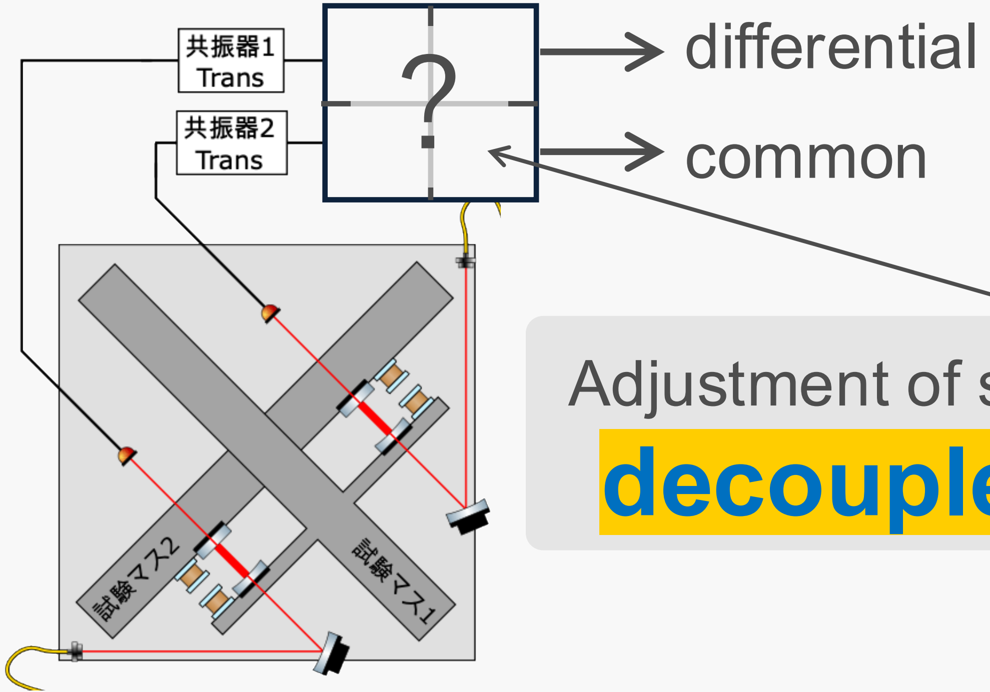
Discussion of noise source ③ signal coupling

If **common/differential decoupling** is insufficient,
longitudinal motion leaks into the rotation signal

As well as coherence with Long., coherence with common signal is also significant



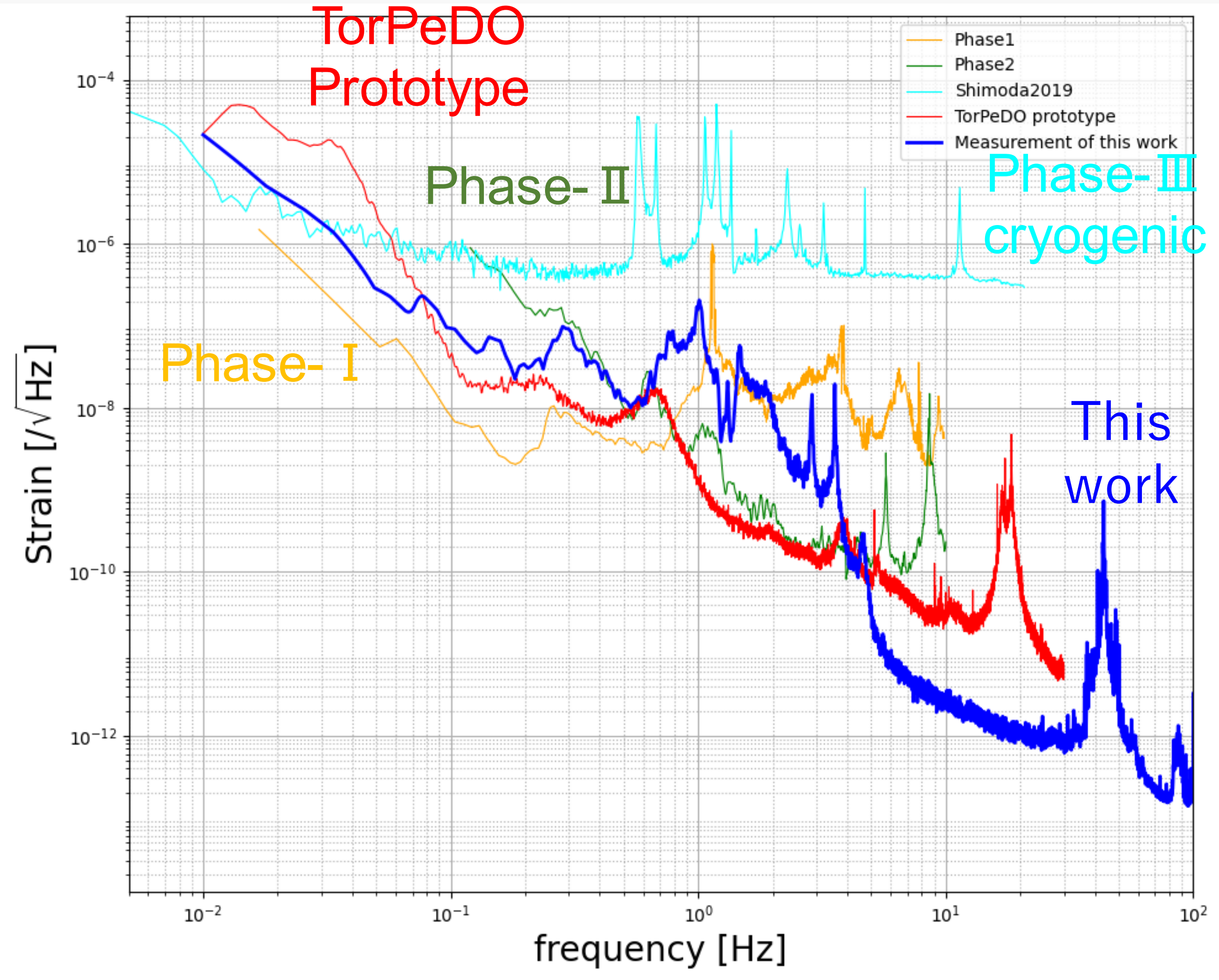
Overestimation of seismic noise



Adjustment of sensor balance
decouples signal

Measurement result

Strain sensitivity



Best sensitivity in Phase- Ⅲ TOBA

Phase- Ⅰ is still best at 0.1Hz

Problem in calibration

Tension in Sensor efficiency of cavity

Measured value
光てこの効率、
coil-coilアクチュエーターの
効率から順に逆算

gap
~3.5

larger smaller

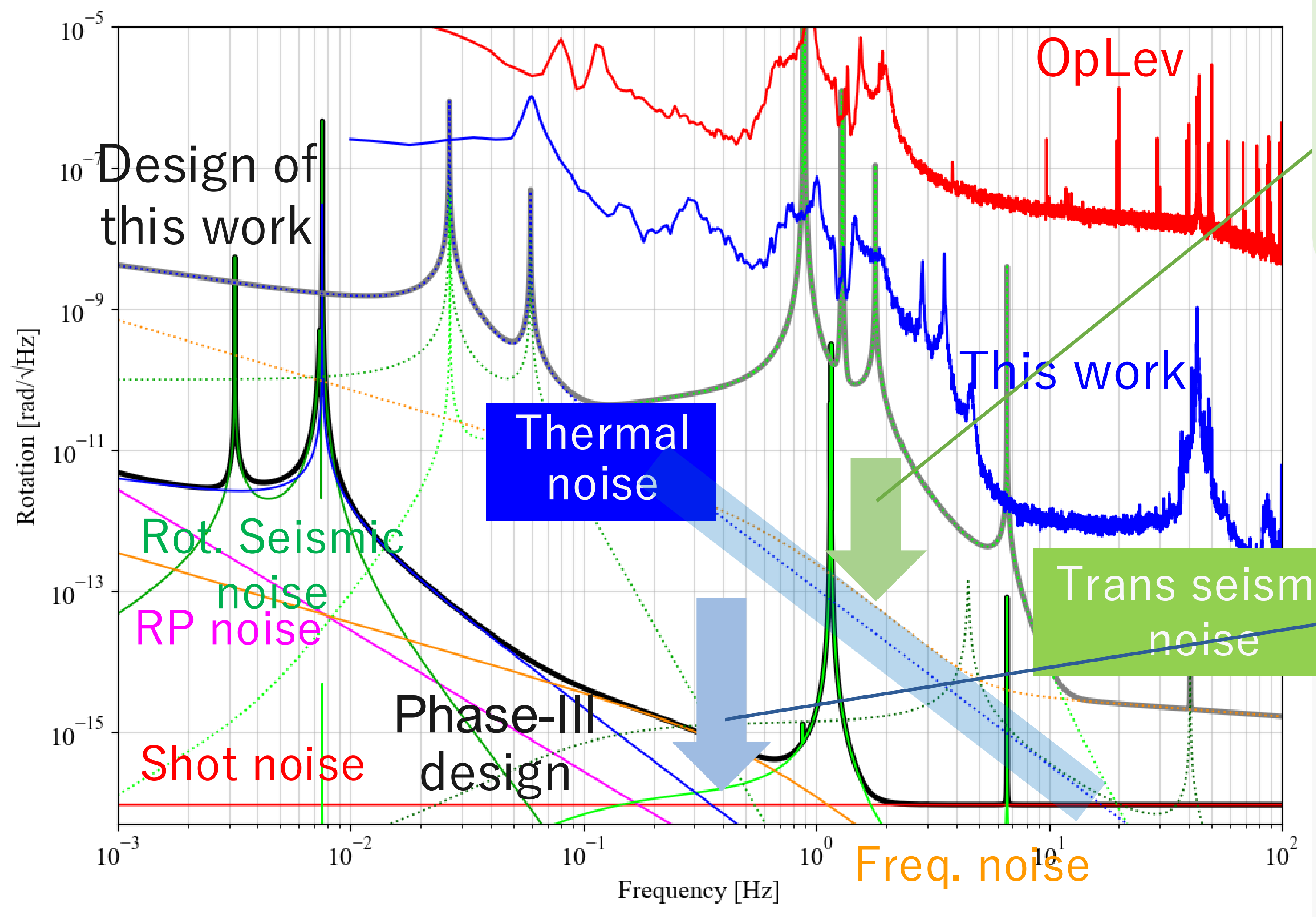
Theoretical value
共振器スキャンのピーク値と
オフセット量から、
制御点での傾きを算出

Generally, measured value can’t be larger than theoretical value
(ミスアラインによるオプティカルゲインの低下から、理論値より低い値となる場合はある)

Due to overestimation of sensor efficiency,
overestimation of sensitivity?

Another calibration method is required

Future prospect



②seismic noise reduction

- TM tilt adjustment

Reach thermal noise level

③thermal noise reduction

- Cooling down

Planned improvement in current setup

- Common / Differential decoupling
  - Injection into frequency actuator(common actuator in principle)
    - Depends on the consistency of two cavities
  - After sensor decoupling, also decouple coil-coil actuator
- Revise calibration method
  - Injection into frequency actuator(Transfer function is known)
  - Not relying on oplev.

Looking back my Master’s work

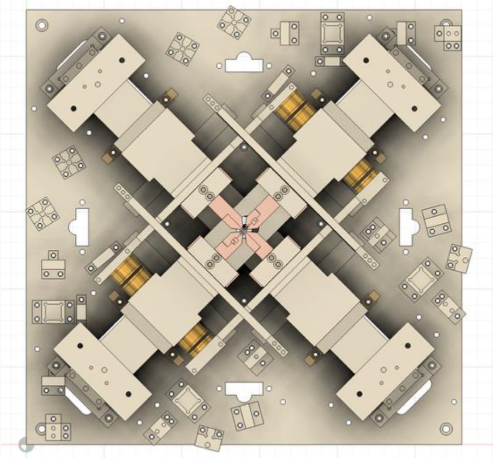
- ミニマムサクセス(キャビティロック)は達成できた
  - 本当は修論でシリコンテストマス導入まで行きたかった
- M1でもう少しTOBAについて勉強しておくべきだった
- 既知の話や細かい部分に時間を割き過ぎてしまった
  - 並進カップリングについては下田さんの修論で確立されていた
  - 実験系の要素が多過ぎて本質を見極めるのが難しかった
  - やはり博士学生(orポスドク)について実験できるのが理想
- 学会や研究会にたくさん行った
  - 行くたびに友達が増えて面白い議論もできた
  - TOBAの宣伝
  - 集中して実験する時間を取るのも大事

Contents

Local sensors

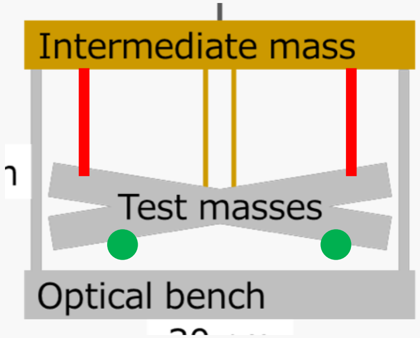
Why local sensors are required?

- Damping for lock acquisition→eddy current damping for TM currently
- Monitor of DC tilt? Maybe not sensitive enough



Severe space constraints

光学ベンチは結構ギチギチ…

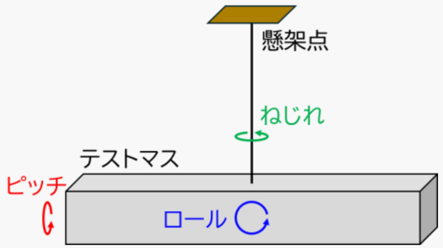


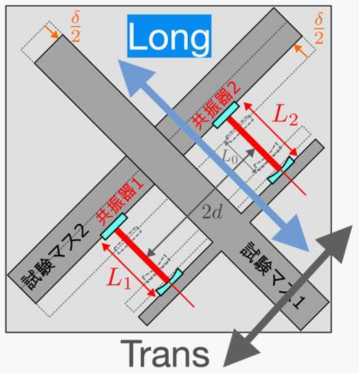
New oplev.

Photo sensor

Desired modes

- Roll(Current oplev.s)
- Pitch(oplev. from IM?)
- Longitudinal/Trans(photo sensor from OB?)
- IM?



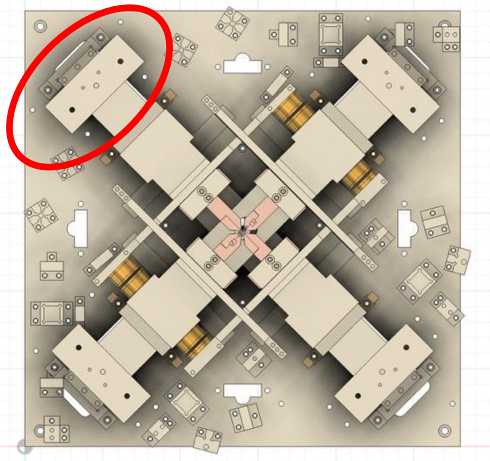


RMS is dominant in Roll & Long. Resonant mode

これらだけでもダンプしたい

Actuators for Roll & Pitch mode

Roll & Pitch actuation for tilt adjustment is required

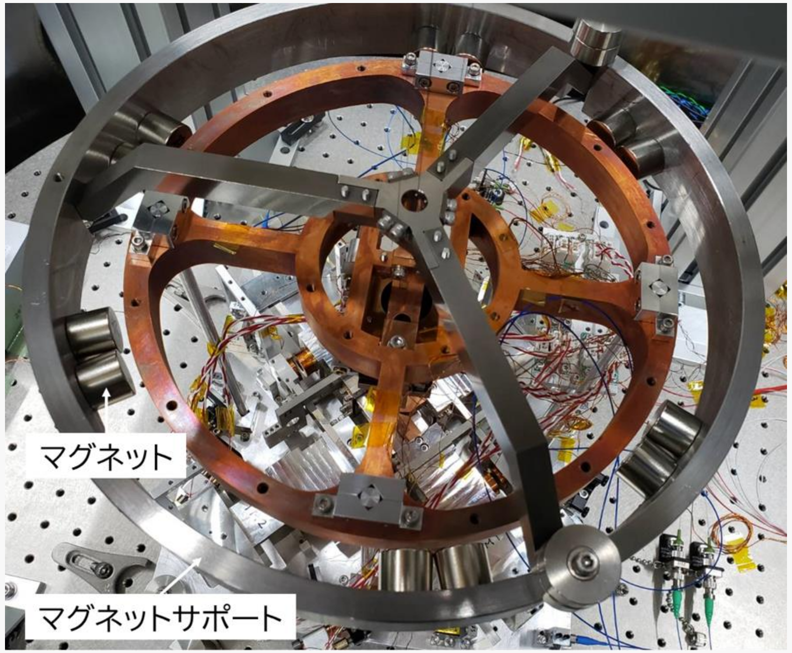


- Slots for Roll & Pitch coil-coil actuators
  - DC actuation from OB
    - Yawの感度を汚さないか？
  - Also useful for damping in lock acquisition

- Piezo driven setscrew
  - Purely adjust center of mass and tilt
  - Cryogenic compatible
  - TMにものはあまり載せたくない

JPE

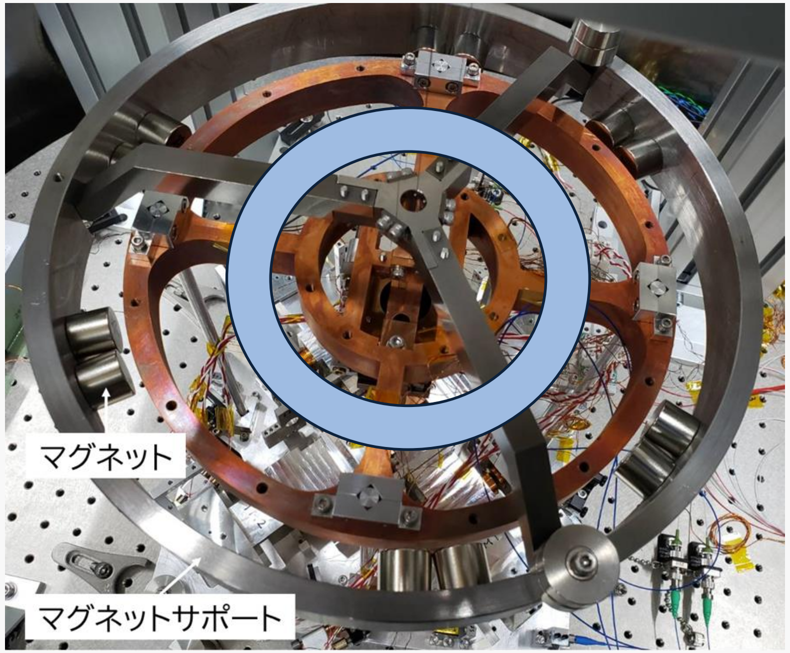
Better damping for Intermediate Mass



Current damping is overdamping for Yaw mode, but trans. Mode should be damped more

Damping from outside of IM tends to be overdamp for Yaw

より内側でTrans. をダンプしたい



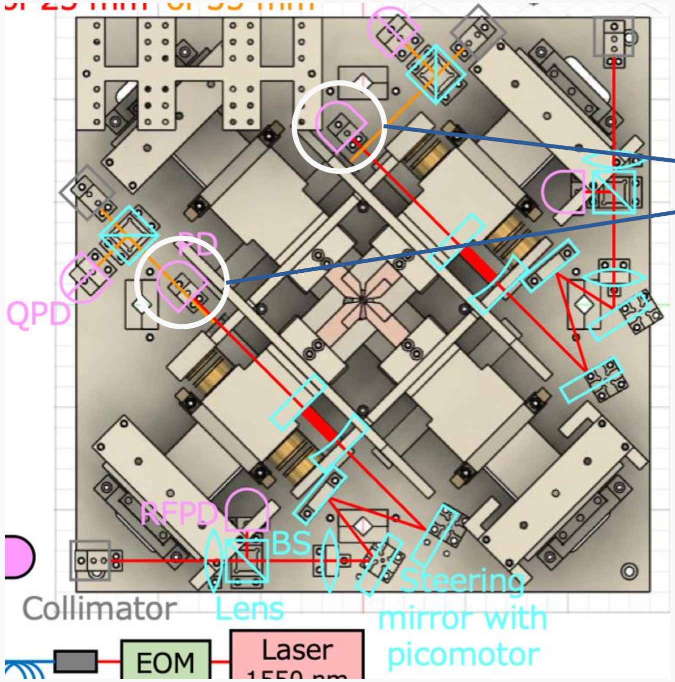
New damping magnets for Trans.

もっと内側の方が良い？

Steering mirrors for trans PDs

そもそも信号読み出しをどうするのか、
反射光でのPDHは低温でのRF読み出しが厳しい

~100kHzの変調で透過光PDH?
一旦は肩ロック継続、いずれにせよ透過光を使う

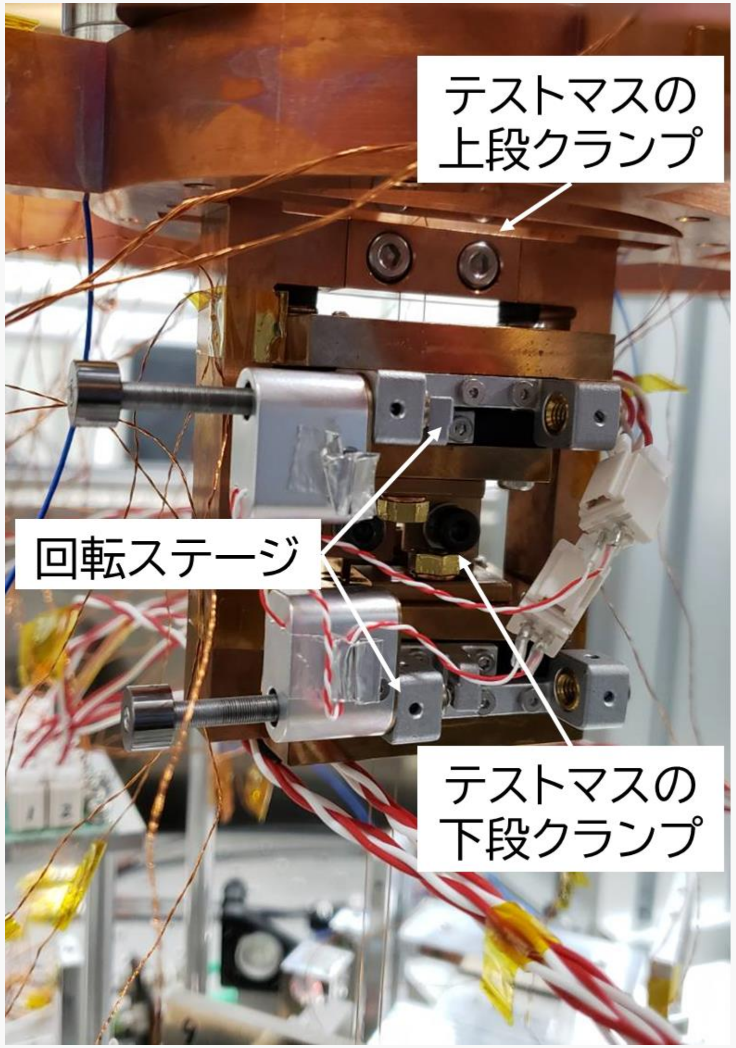


From Oshima-san's slide

PDs for Transmitted light, no steering

どうにかステアリング鏡をねじ込みたい…

360° rotation stage



Range of rotation stage is insufficient to compensate DC drift

360° rotation stage is desirable

228 Motion

Picomotor™駆動回転ステージ

Picomotor™ Rotary Stages

- 0.011°の分解能
- 偏光子や波長板のリモート回転に最適
- 便利な1インチアダプタが付属

Model 8401

分解能が0.011°未満で全体の厚みがたった0.63インチ（16.0 mm）のコンパクトなPicomotor™駆動回転テージは、波長板や偏光子のポジショニングなどのさまざまなアプリケーションに使用できます。各回転ステージには、1インチ（25 mm）径の部品をマウントするためのアダプタが付属しています。モータ駆動ビームステアリングアプリケーションには、モデル9922の45度アダプタをご利用ください。高い精度と再現性が要求されるアプリケーションには、優れた位置フィードバックを提供するエンコーダを内蔵した8410クローズドループPicomotor駆動回転ステージが用意されています。クローズドループバージョンは、マイクロラジアンレベルの精度と連続360度回転をもたらします。

Model 8410

仕様

モデル	8401 (-M)	8410
モータ駆動軸	1	1
角度分解能（°）	<0.011	<0.011
耐荷重（N）	4.4	4.4
最大速度（RPM）	1-2	1-2
マウント方式	8-32ネジ（M4ネジ）	8-32ネジ（M4ネジ）
コネクタタイプ	4ピン	4ピン

推奨モーション コントローラ／ドライバ

モデル	内容
8742	オープンループPicomotor コントローラ／ドライバモジュール、4チャンネル
8743-CL	クローズドループPicomotor コントローラ／ドライバモジュール、2チャンネル

注意：8401（-M）には8742、8410には8743-CLを使用してください。
* P270参照

発注のご案内

モデル	内容
8401(-M)	Picomotor駆動回転ステージ、ステンレススチール製、1 in.、0.5 in.アダプタ付属
8410	クローズドループPicomotor駆動回転ステージ、1 in.径コンポーネント

寸法

Model 8401

Model 8410

Newport

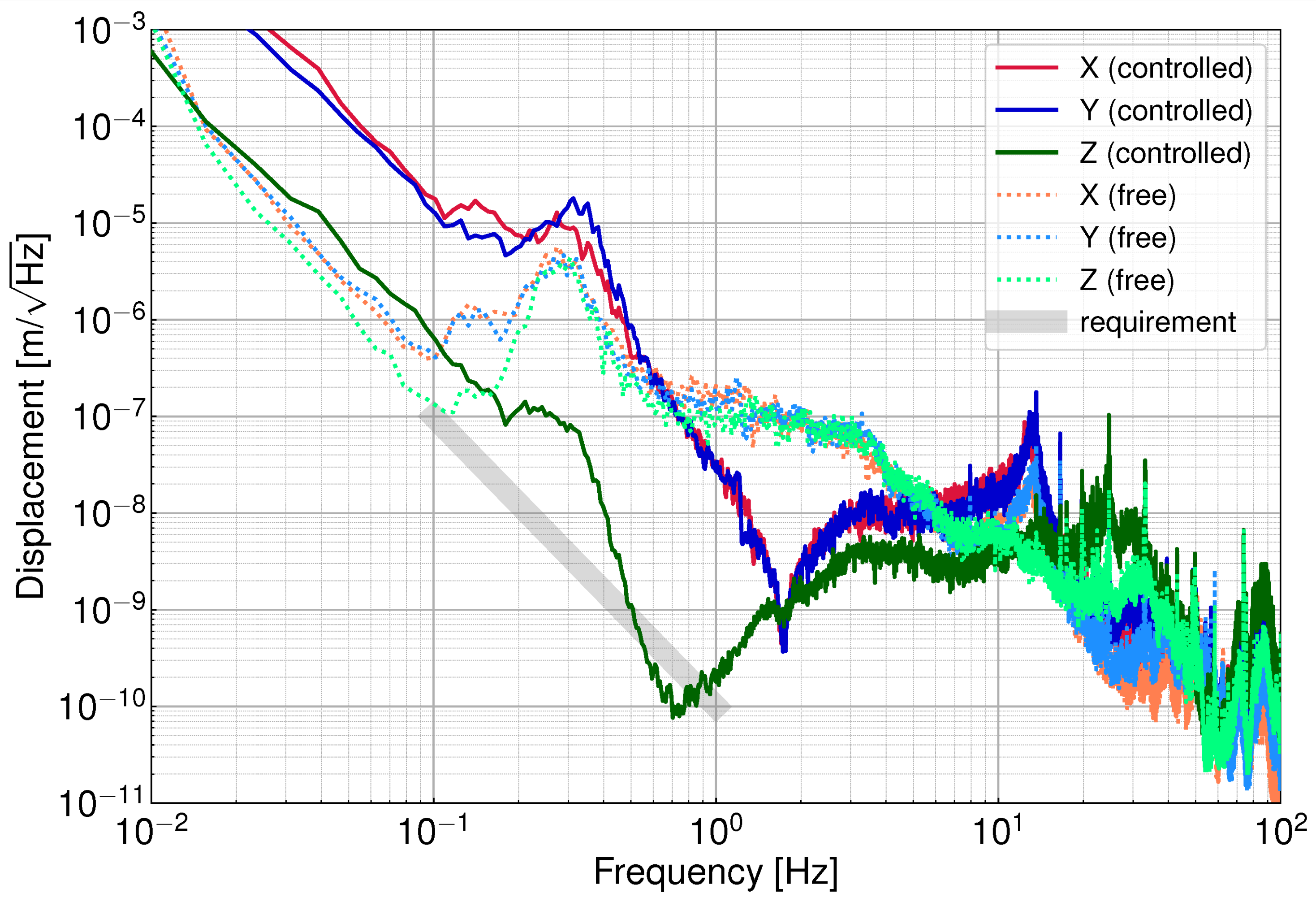
定価は弊社ホームページ(www.newport-japan.jp)にてご確認ください

耐荷重が厳しいかも
将来的には低温対応が必要

Contents

- Introduction of TOBA
- Summary of my master’s work
- Minor update plan for next suspension design
- Toward Phase-Ⅲ, VIS & Cryogenic

AVIT

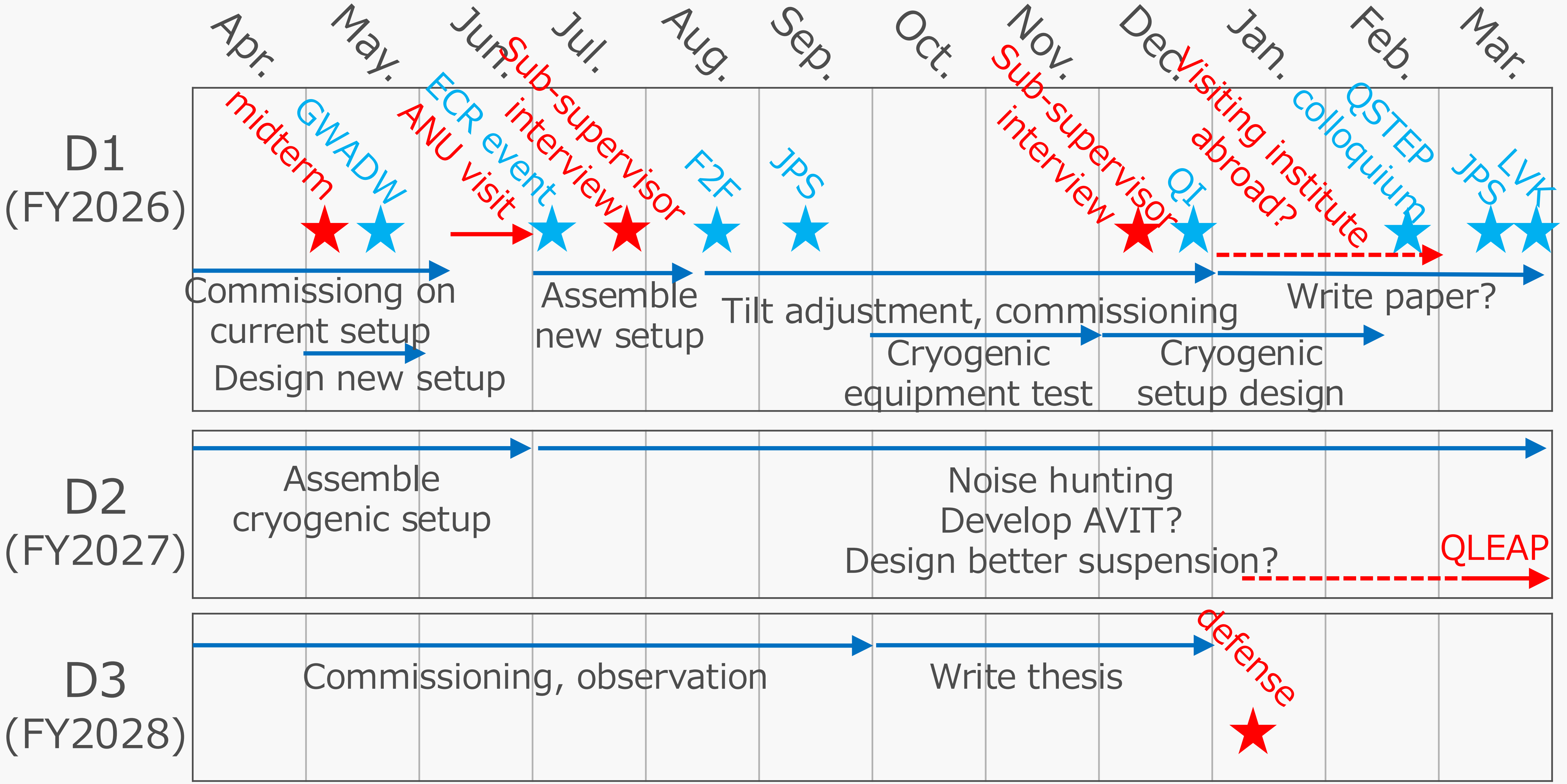


復旧はしておきたい

Cryogenic test

- Steering mirror
- Rotation stage
- PD circuit

Plans toward my master thesis



Summary

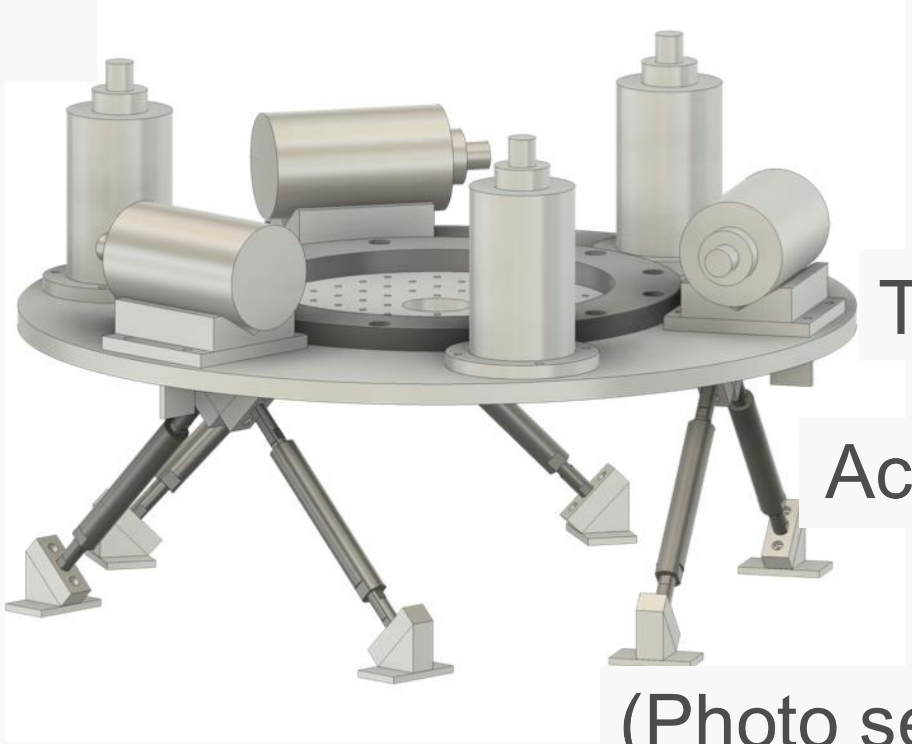
- TOBA is a ground-based GW detector for low frequency using torsion pendulums
- Currently Phase-Ⅲ TOBA is developed in Ando Lab.
- I am mainly developing the suspension and optics
- I managed to lock cavities
- Now I'm trying to reduce seismic noise and thermal noise by tilt adjustment and cooling down

Bonus slides

AVIT; Active Vibration Isolation Table

- Actively isolate vibration on the suspension point(table)
- 3 DoF(x, y, z) control with geophones and piezo actuators

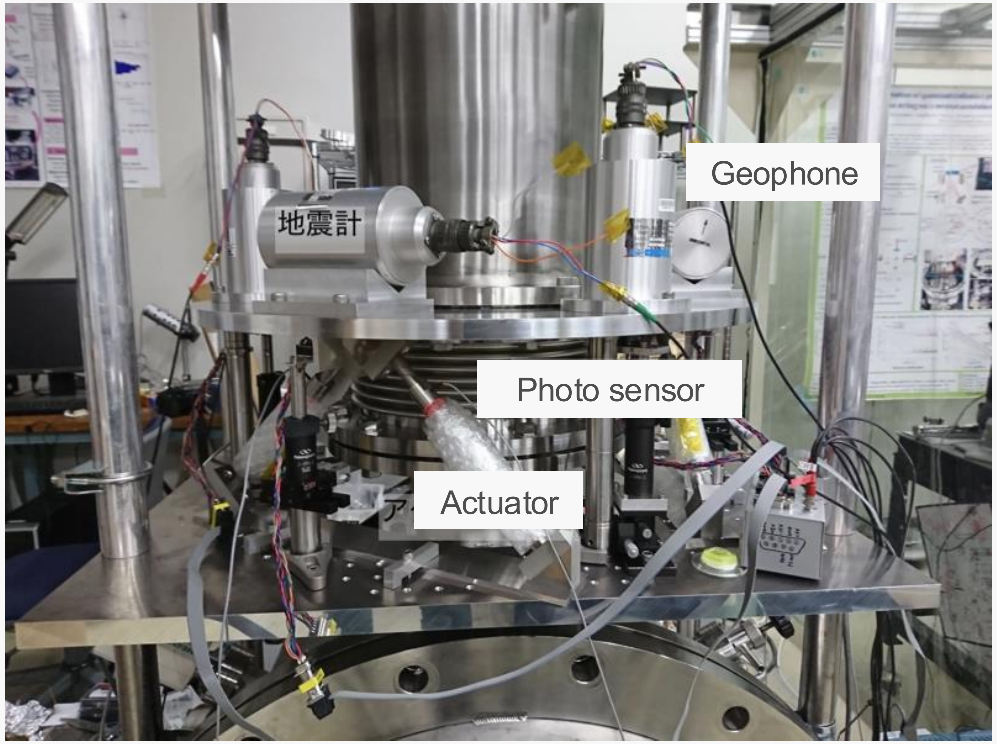
Geophone
×6



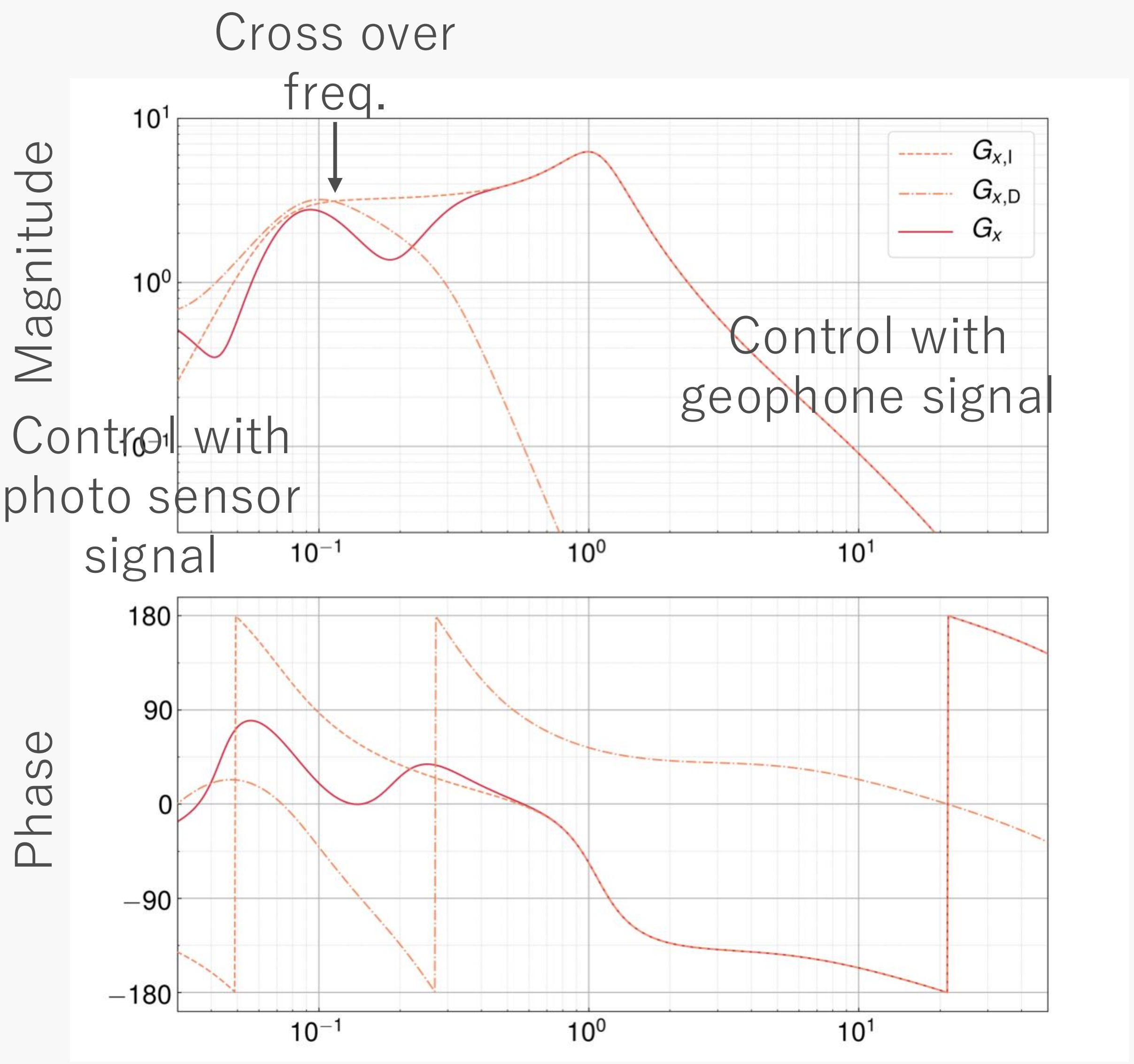
Table

Actuator×6

(Photo sensor×6)



S. Takano(2019)

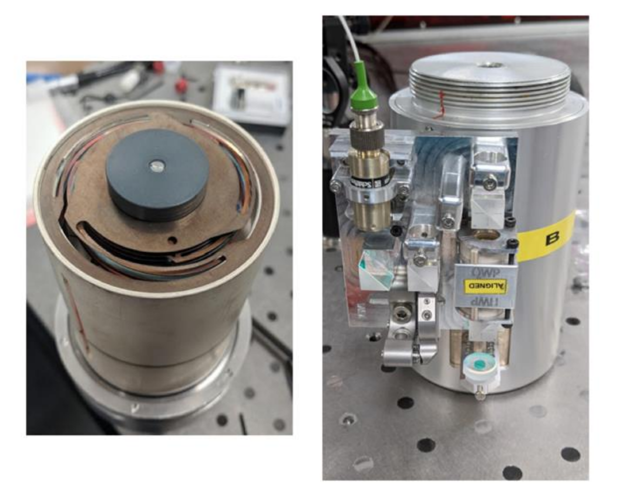


OLTF of x axis control S. Takano(2019)

- Sensor noise of geophone increases in low freq.
  - High pass the signal from geophones
- Blend the signal from photo sensor(as relative sensor) to compensate DC drift
  - Just follow the ground motion in low freq.

- フレームの共振
  - 特注する？

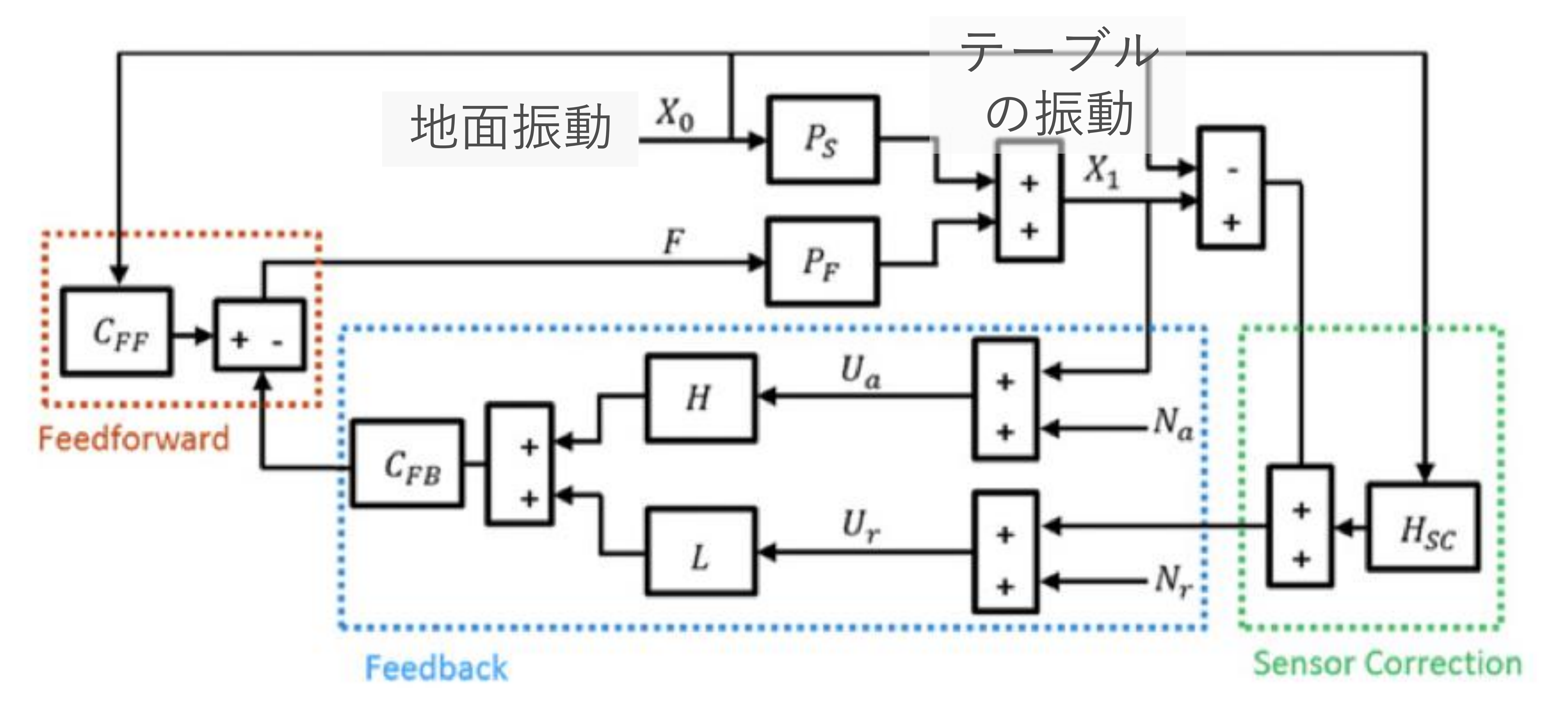
- センサーの感度
  - L-4C自体の感度は十分だが、信号が小さくてアンプの雑音でリミット
  - 高性能なオペアンプが廃盤に？KAGRAでも困っているらしい
  - LIGOではどうしているか調べてみる
  - 干渉計でL-４Cを読み出す？



L-4C with
HOQI readout

CQG. 39 (2022) 075023

- 傾きカップリング
  - 低周波で問題になる
  - 地面振動の傾き成分自体は小さいはず
    →テーブルの歪みが見えている？
  - テーブルを硬くする
    - 荷重との兼ね合い
  - 地面の地震計からフィードフォワードもあり？



CQG. 32 (2015) 185003

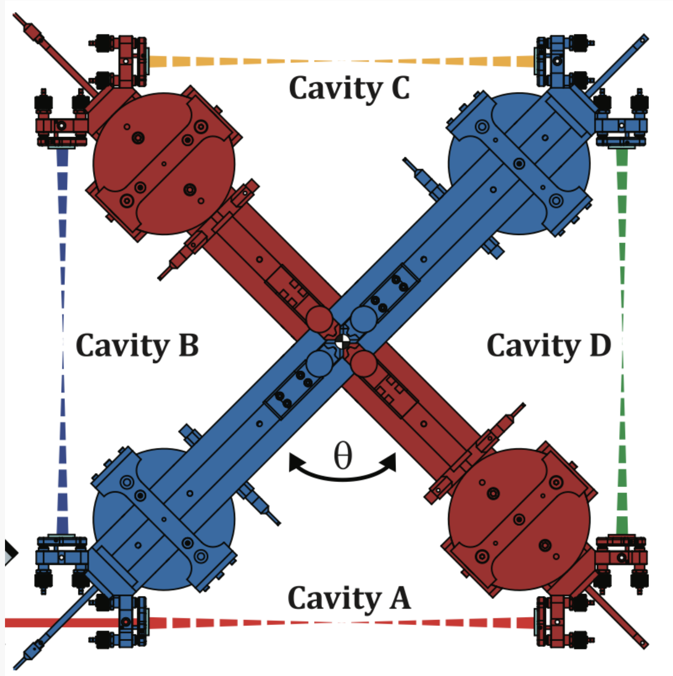
地面の地震計とのコヒーレンスが十分なら、フィードフォワードだけでも良いかも？

フレームの共振もテーブルの歪みも気にしなくて良い

手が回ればやりたいが、人手が欲しい

Random thoughts

- 今の干渉計構成は最適なのか
  - 羽根は仕方ない…?　テストマスが対等でないのも気持ち悪い
  - TorPeDOはcavity4本、レーザー4つでPLL
  - TMのYaw, Trans., Long.相対位置と
    レーザー周波数の4自由度あるので、
    原理的にはレーザー1つで制御できるはず
  - TM表面を鏡として使いたい、
    並進カップリングとの兼ね合い
    - TorPeDOは大きいサスペンションで受動的に防振する思想



- もっと受動的に防振したい
  - Inverted PendulumをAVITの上に入れる？
  - ベローズにスペースはあるはず
  - Ipに関してほとんど何も知らない…
  - TorPeDOのIPを見てきます

LIGO VIS

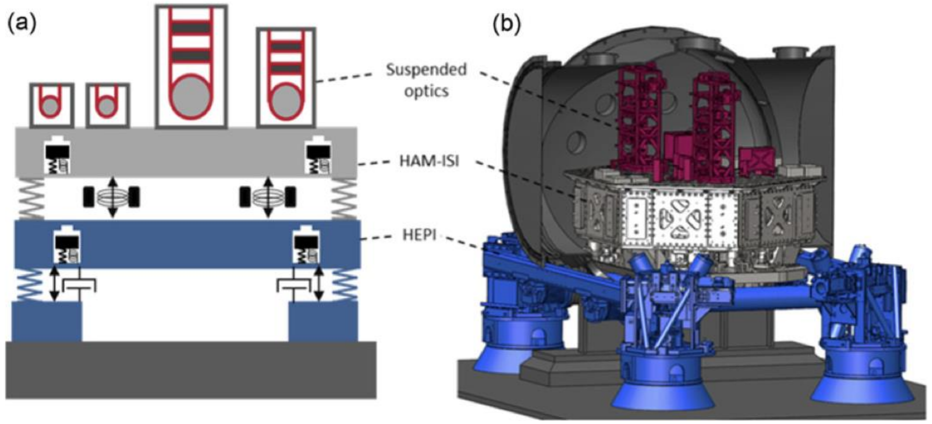
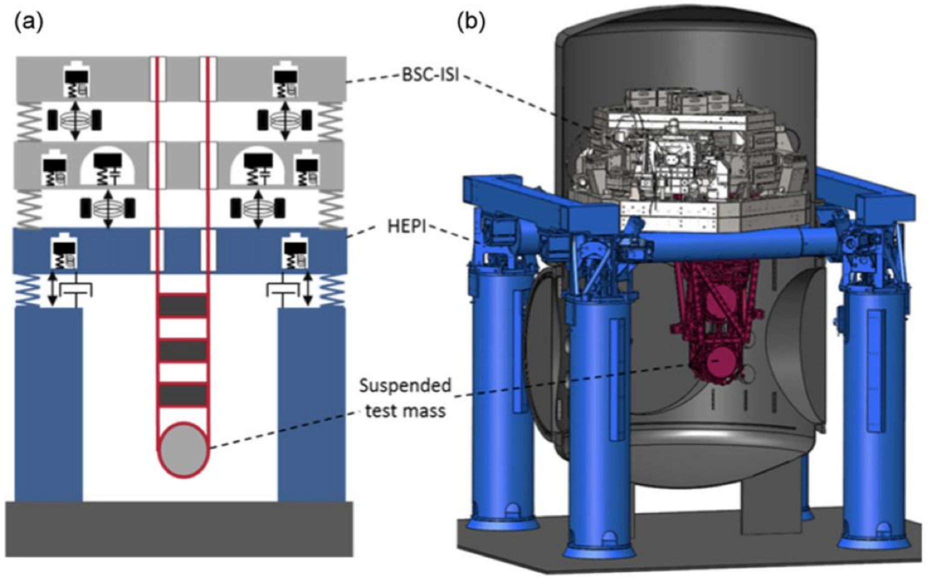
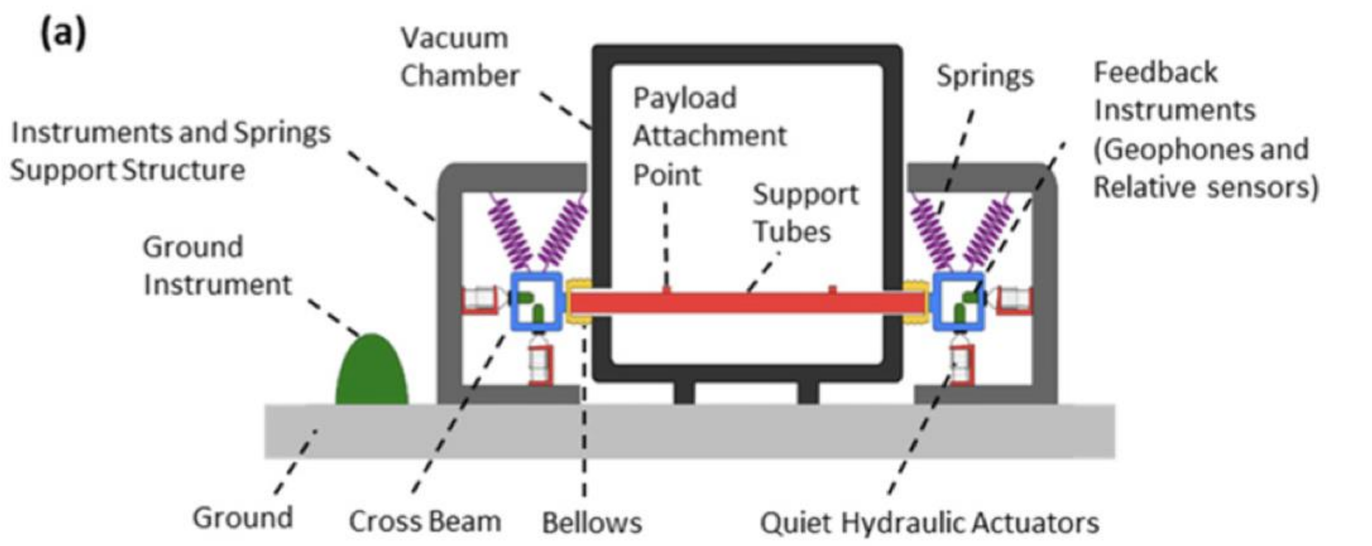
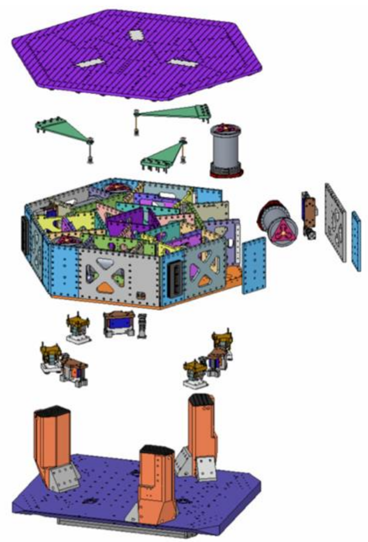
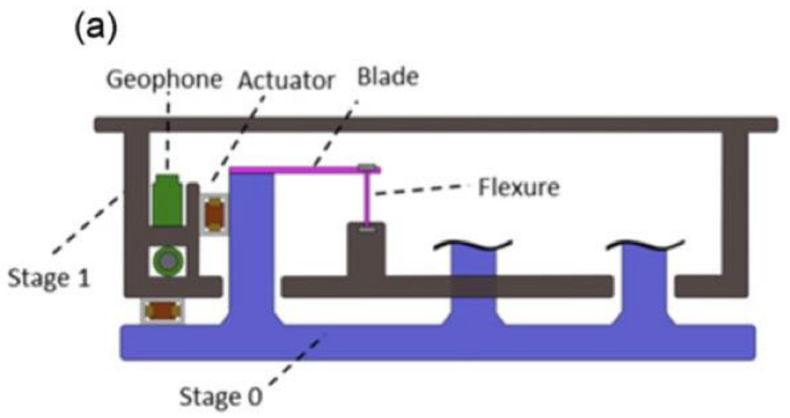


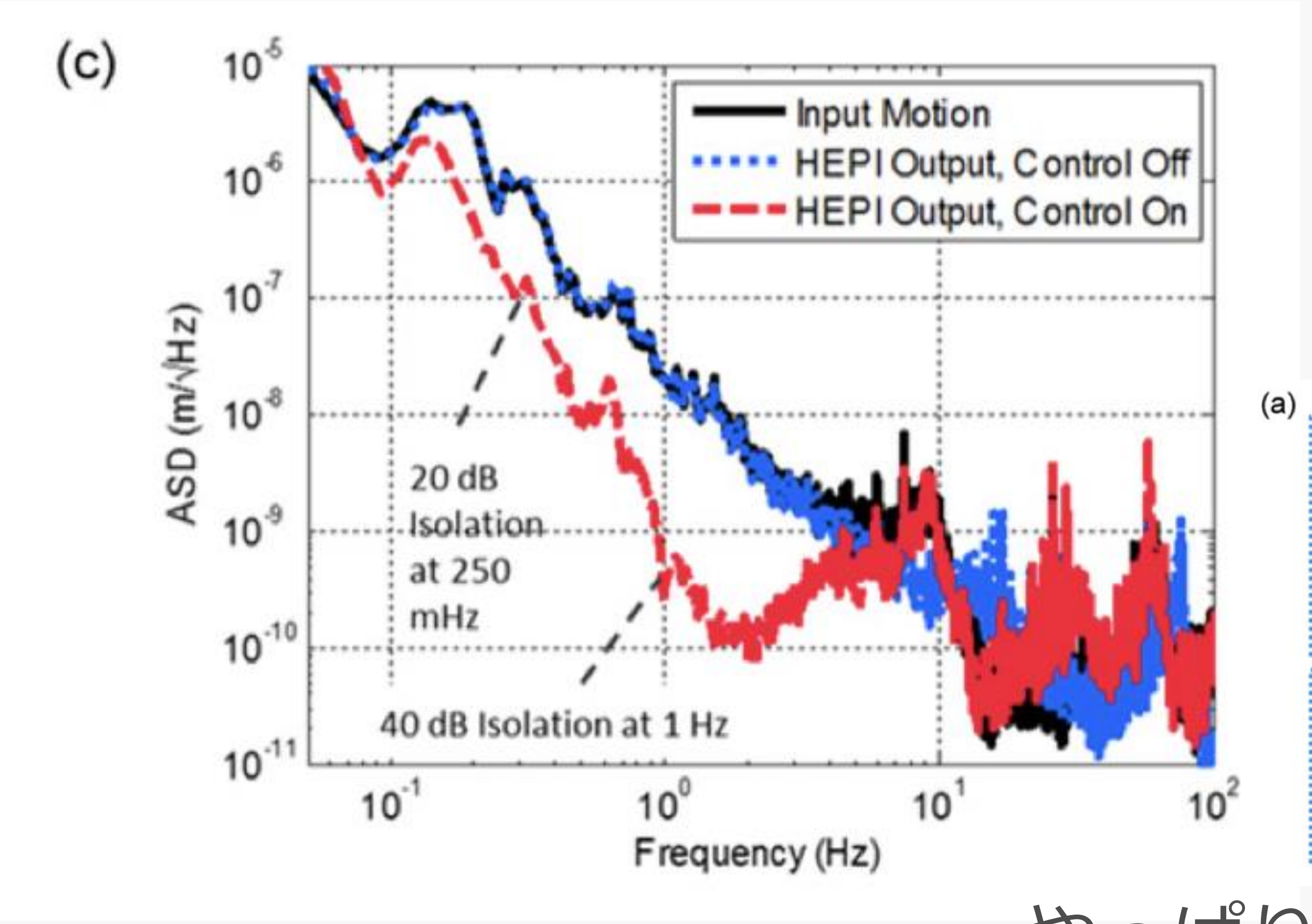
Figure 2. (a) Schematic and (b) CAD model of the isolation systems supporting the auxiliary optics in the HAM chambers.





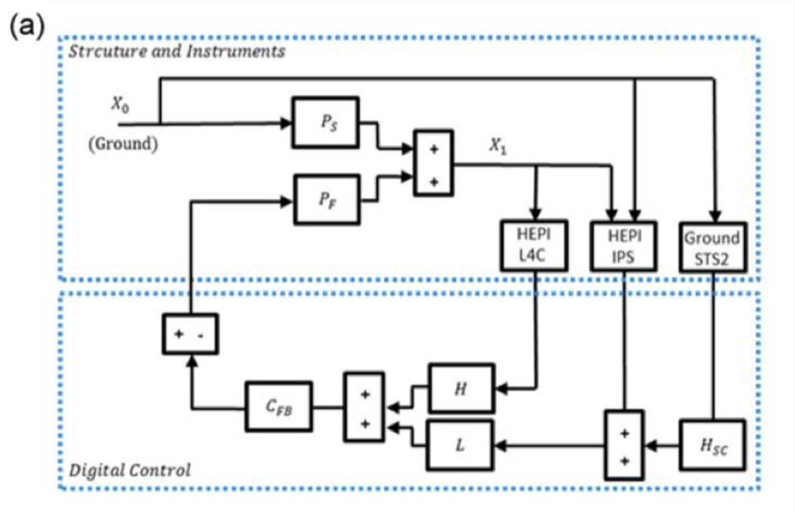






HEPIは完全に能動的な防振装置

AVITでもまずはこれくらいを目指したい



やっぱり地面の地震計でセンサーコレクション

HEPIの防振性能

地震計で6自由度制御しているわけではない

Self Introduction

- **Tatsuya Sugioka/杉岡達哉**
- **Time line**

2002.2 :born in Hyogo

-2020.3 :Rakusei(洛星) high school in Kyoto

-2024.3 :Hokkaido Univ. applied physics

2024.4- :Ando Lab.

- **My Hobby : traveling, watching baseball, stargazing**