大型重力波望遠鏡 KAGRA における防振装置のための制御系の開発(II)

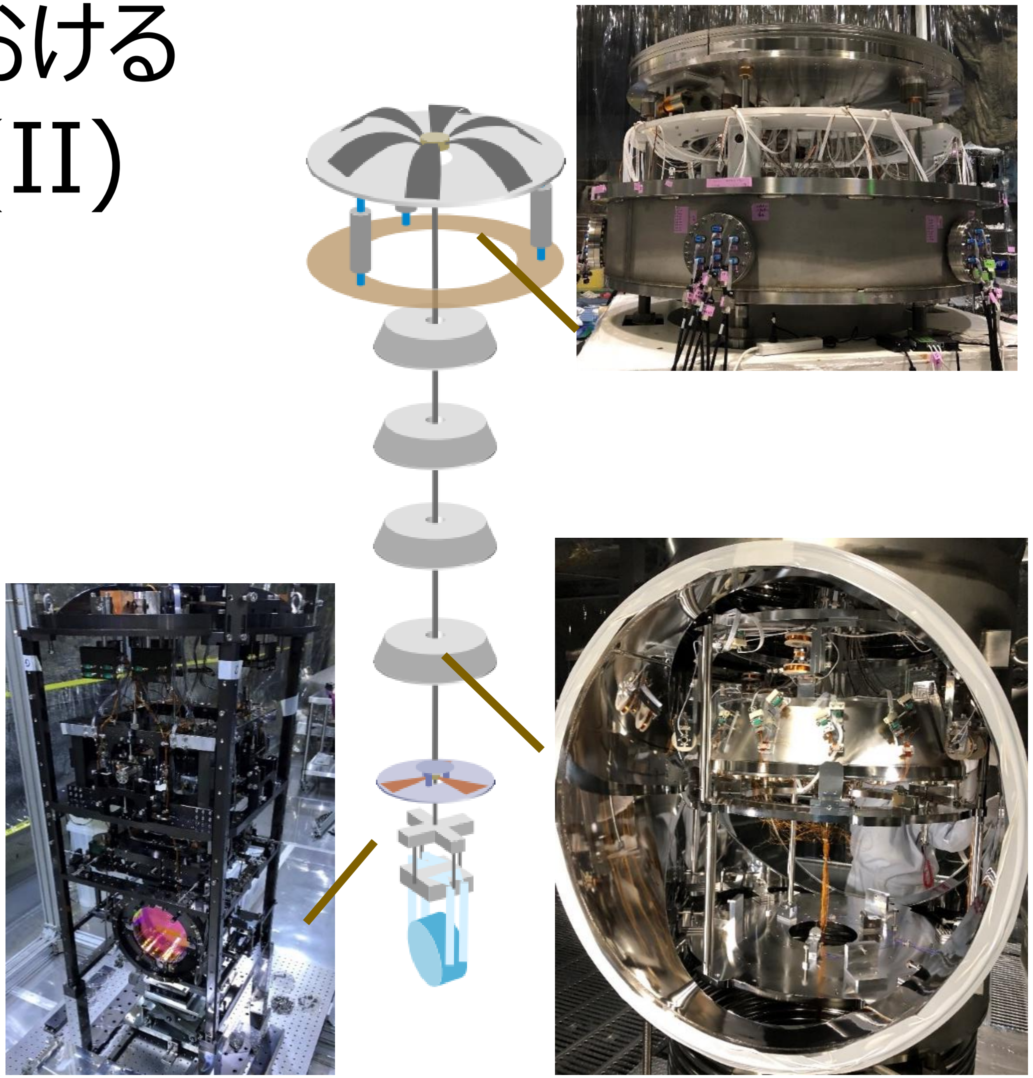
藤井善範

東京大学 理学系研究科 天文学専攻 博士課程3年
国立天文台 重力波プロジェクト推進室

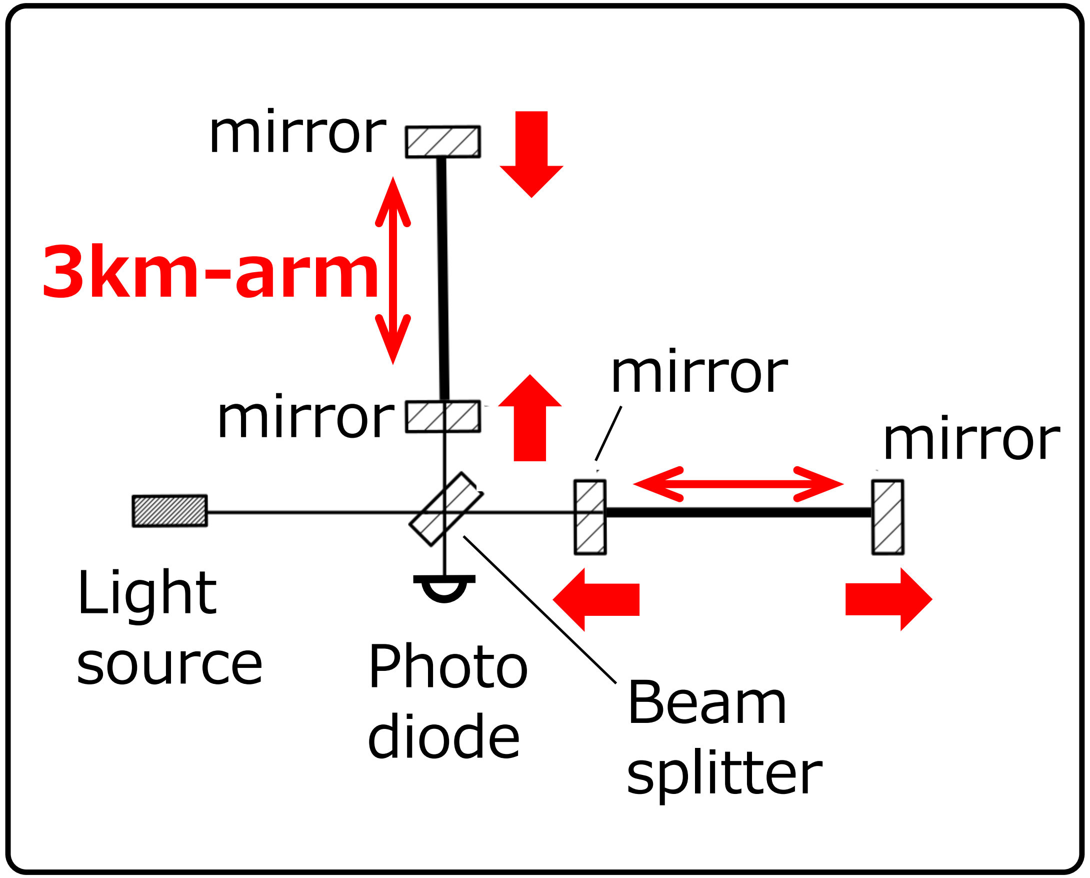
高橋竜太郎, L. Trozzo, 正田亜八香, 阿久津智忠, 佐藤直久, 石崎秀晴, E. N. T. SanMartin,
M. Barton, 平田直篤, 麻生洋一,都丸隆行, R. Flaminio(国立天文台), 奥富弘基,
F. P. E. Arellano, 宮本昂拓, 牛場崇文, 三代浩世希, 山本尚弘, 宮川治,
上泉眞裕, (東大宇宙線研), 和泉究(宇宙研),
on behalf of the KAGRA collaboration

大型重力波望遠鏡 KAGRA における防振装置のための制御系の開発(II)

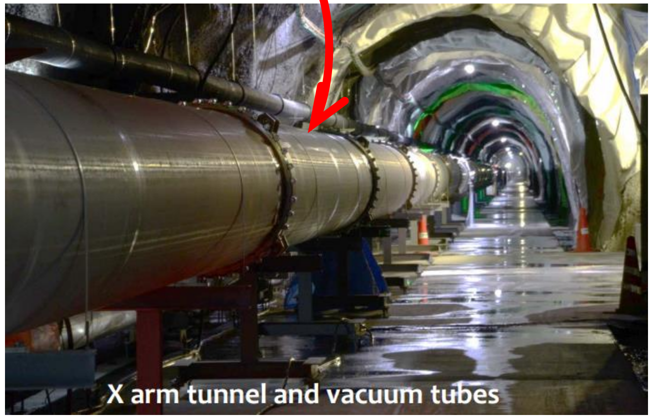
内容： ロック引き込み/観測中のメイン鏡用の防振装置の制御系の開発状況



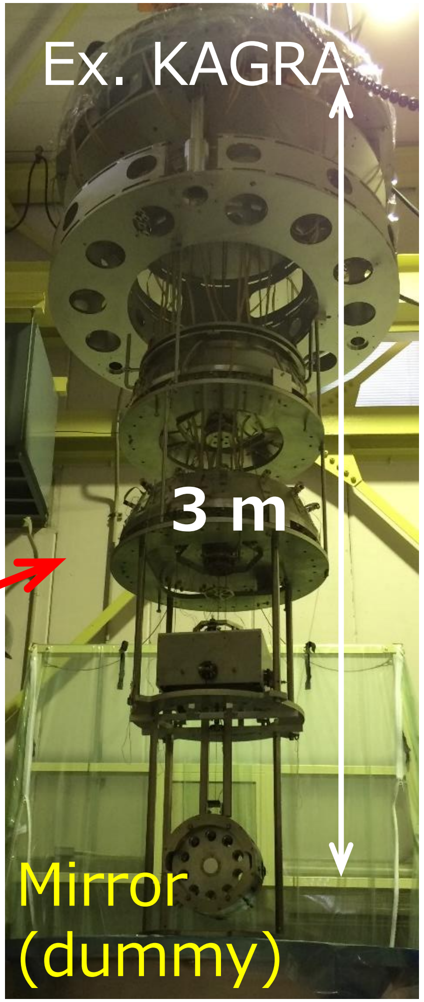
重力波検出器と、サスペンション



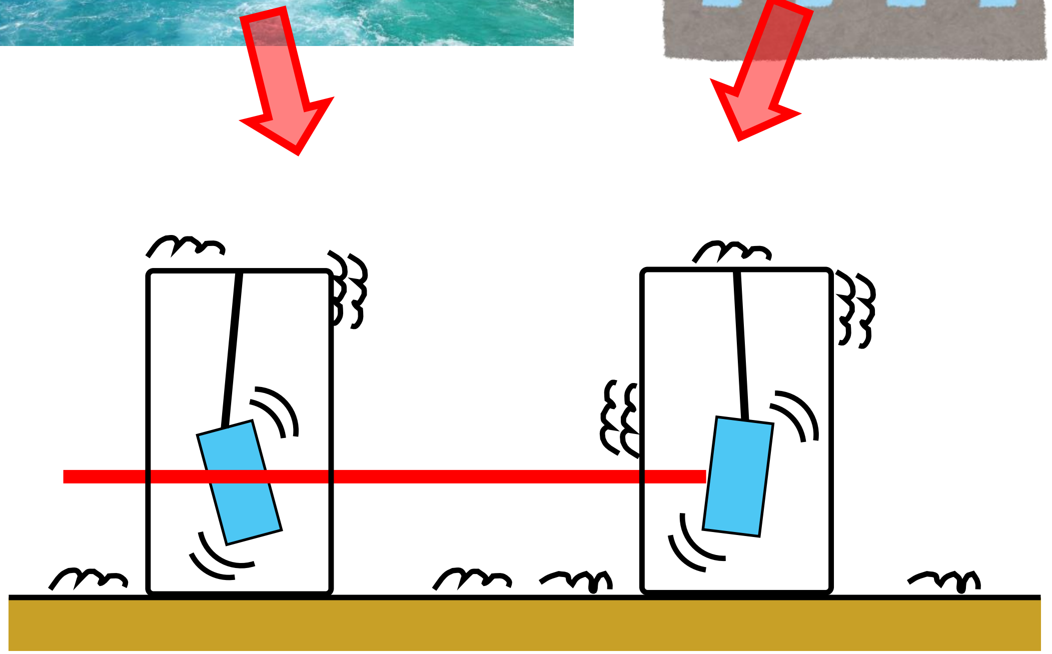
1) Michelson-based interferometer
2) Fabry-Perot cavities
3) 3km-arm

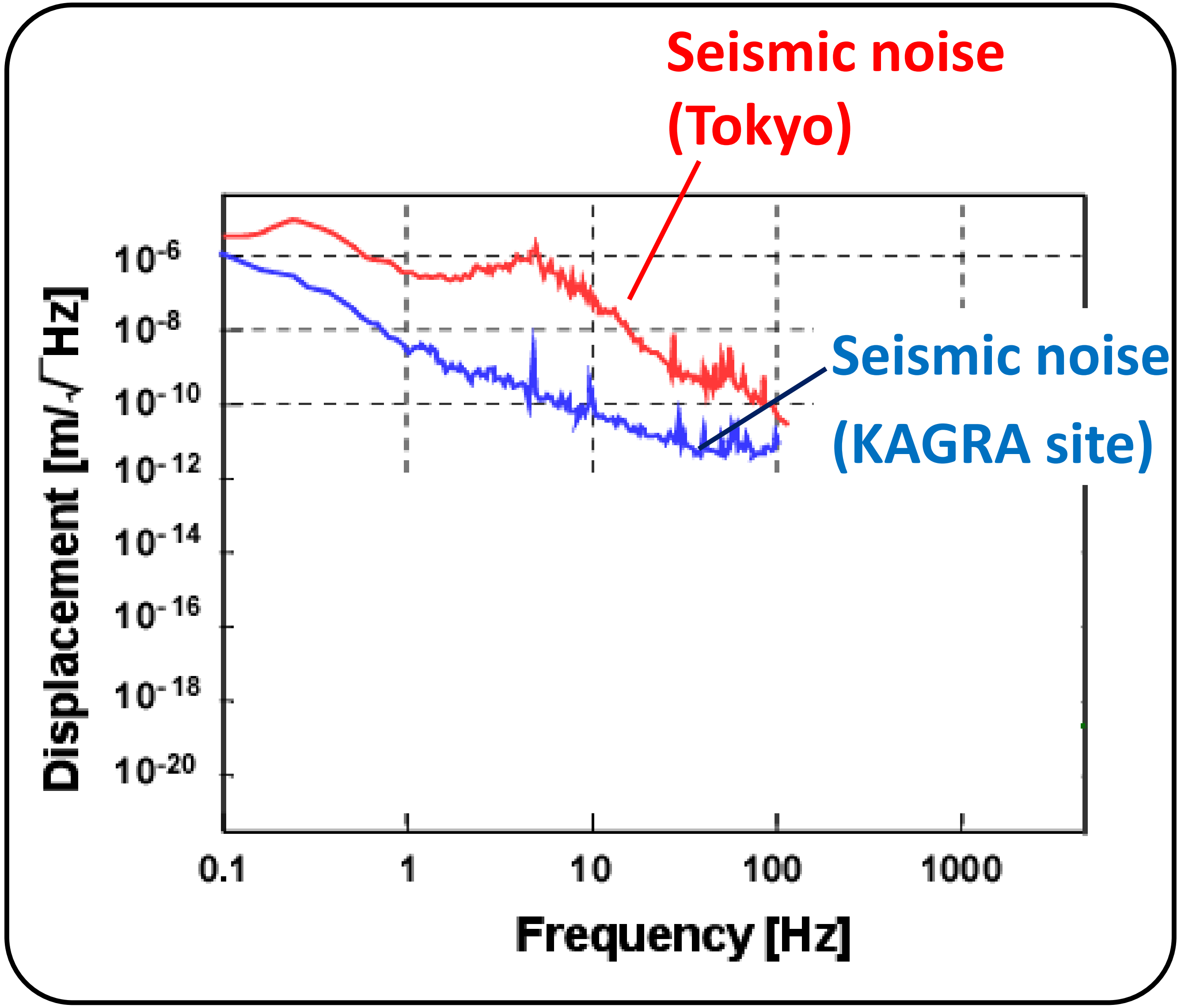


4) Suspended core optics

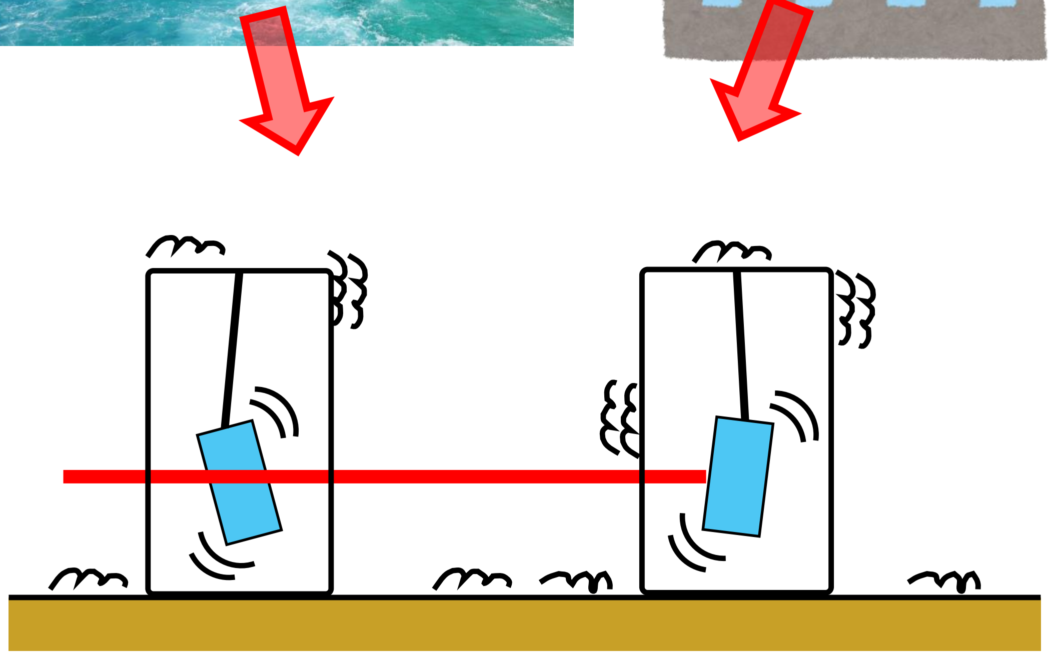


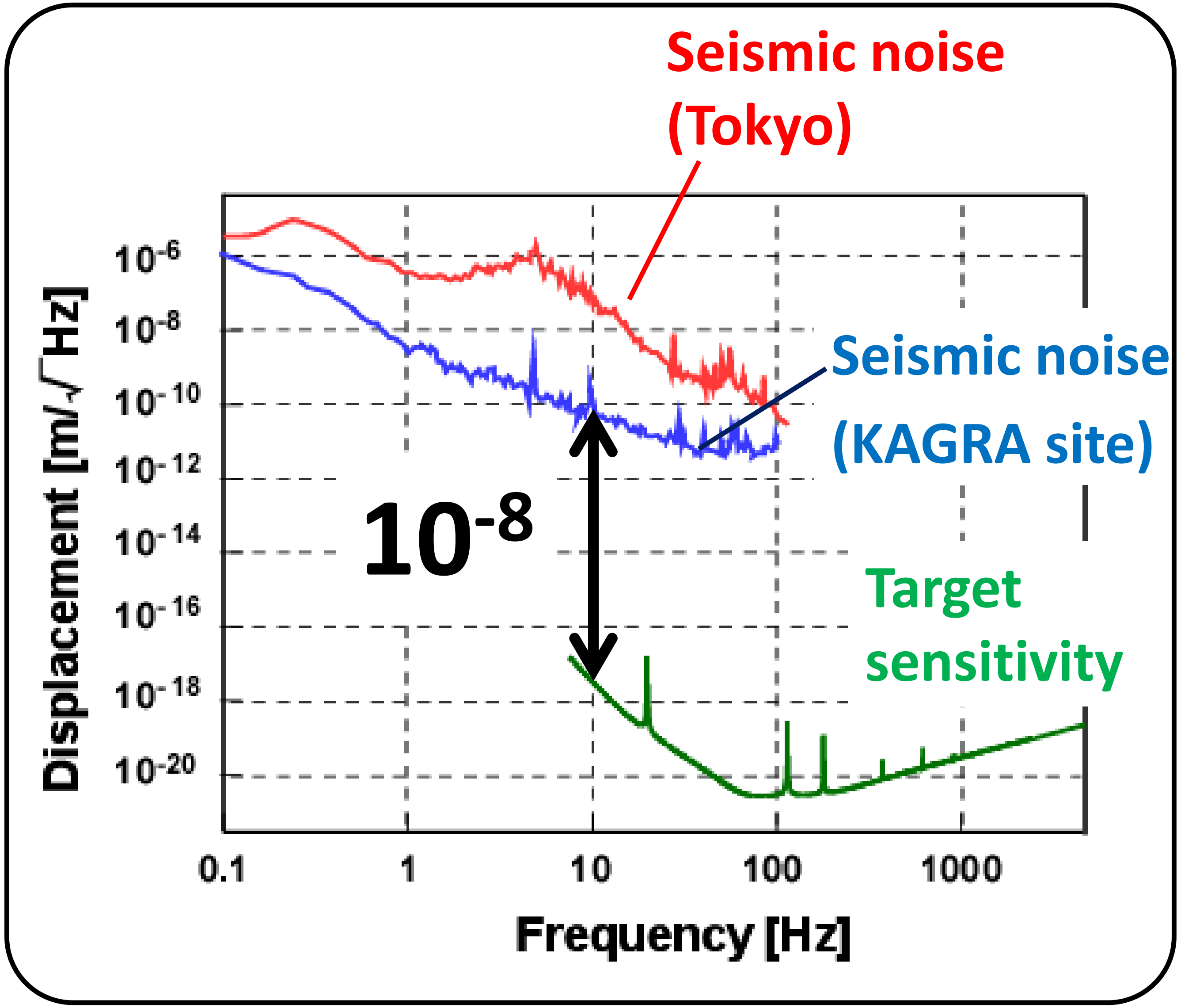
地面振動雑音




Seismic noise
(Tokyo)
Seismic noise
(KAGRA site)
Displacement [m/√Hz]
10-6
10-8
10-10
10-12
10-14
10-16
10-18
10-20
0.1
1
10
100
1000
Frequency [Hz]

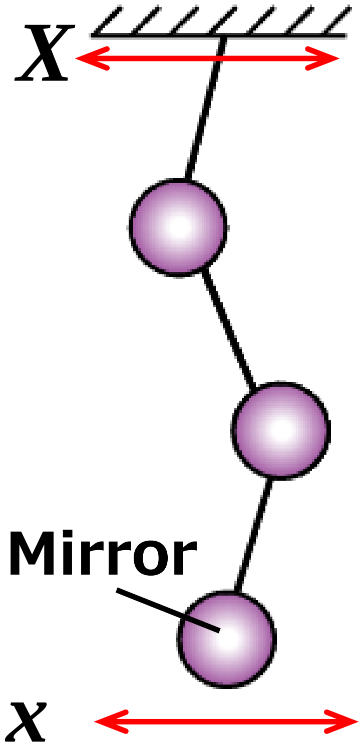
地面振動雑音

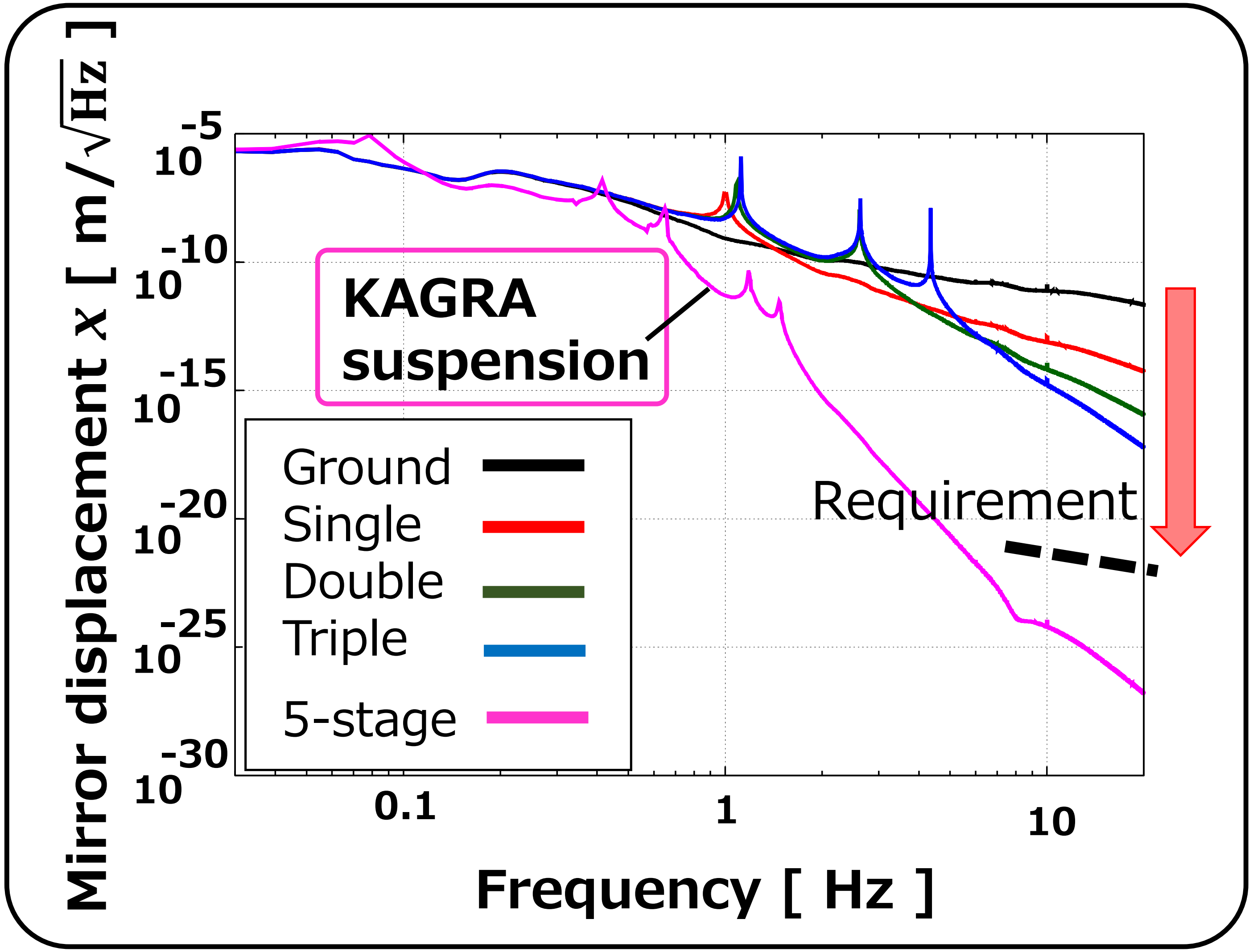




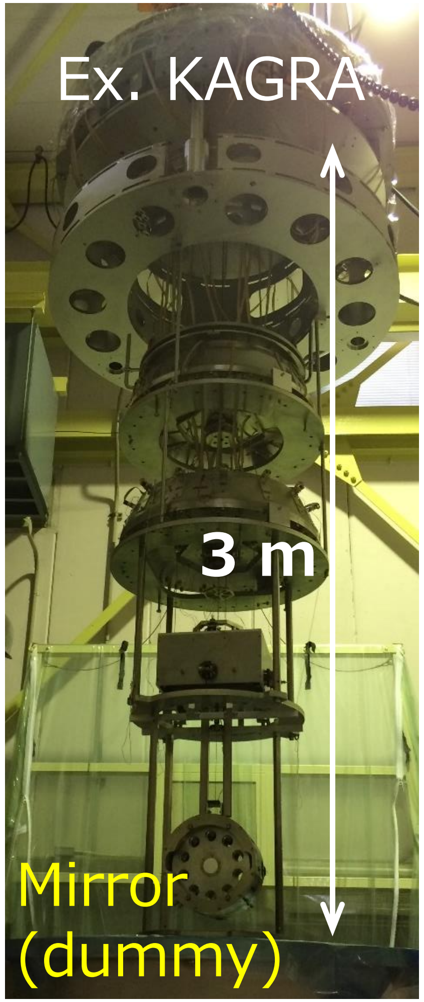
Seismic noise
(Tokyo)
Seismic noise
(KAGRA site)
Target
sensitivity
10^{-8}
Displacement [m/√Hz]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
0.1
1
10
100
1000
Frequency [Hz]

地面振動雑音の低減　→ 振り子



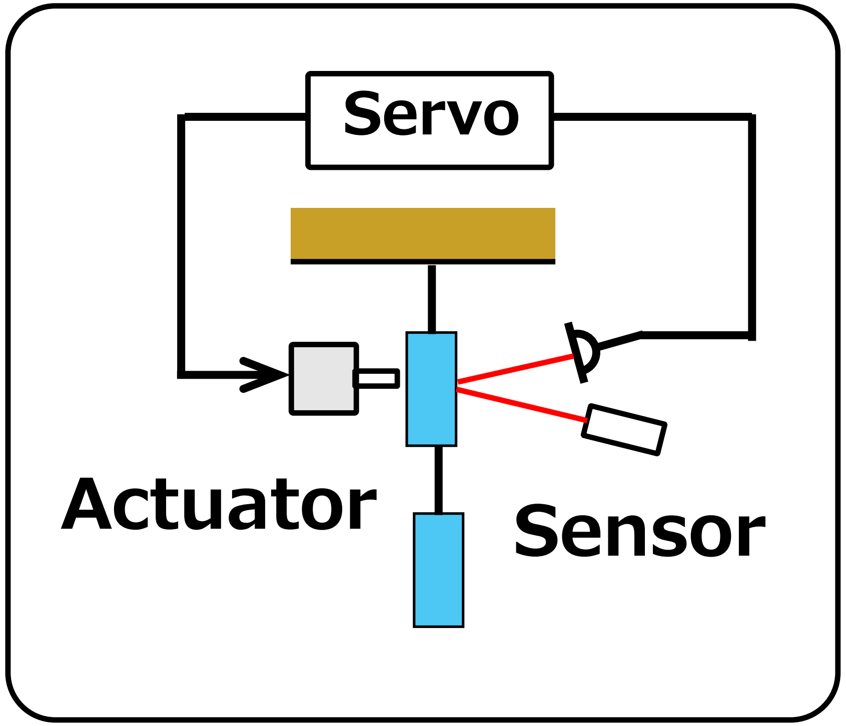


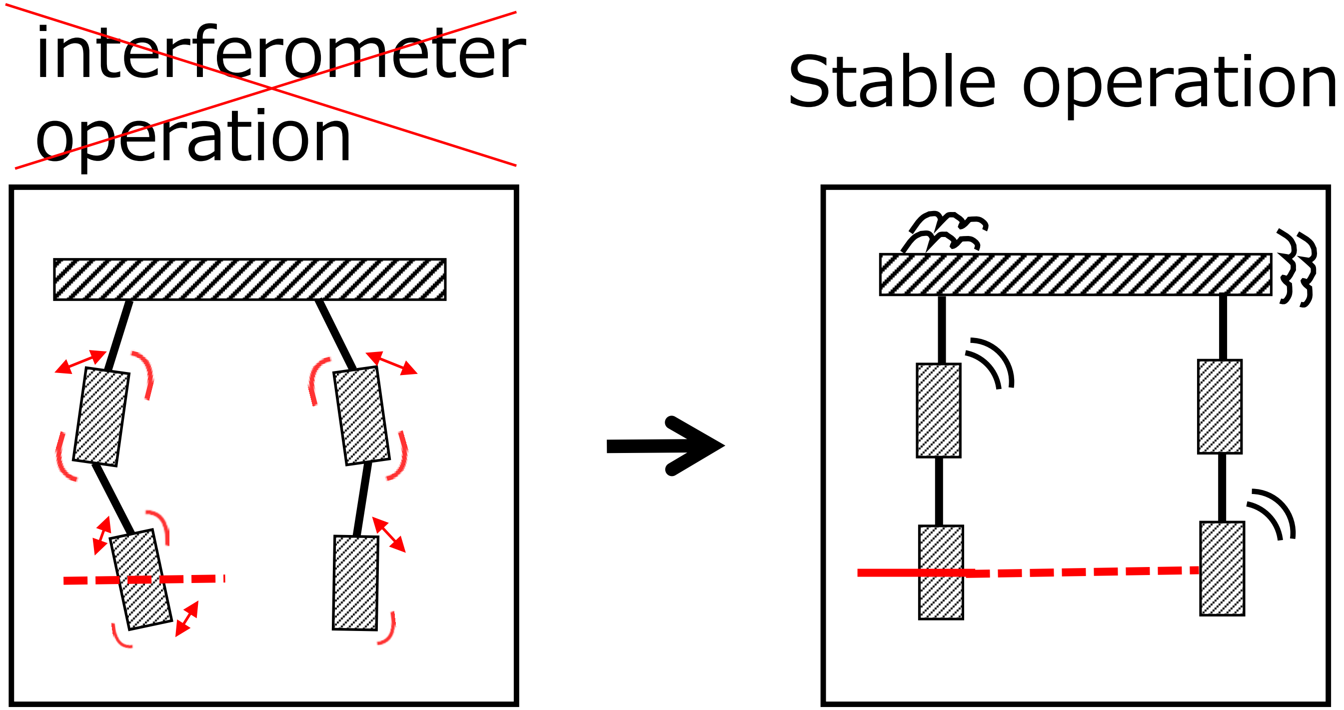
(BS/SRs-suspension case)



共振のダンピング / 鏡のアラインメント

→ アクティブに防振

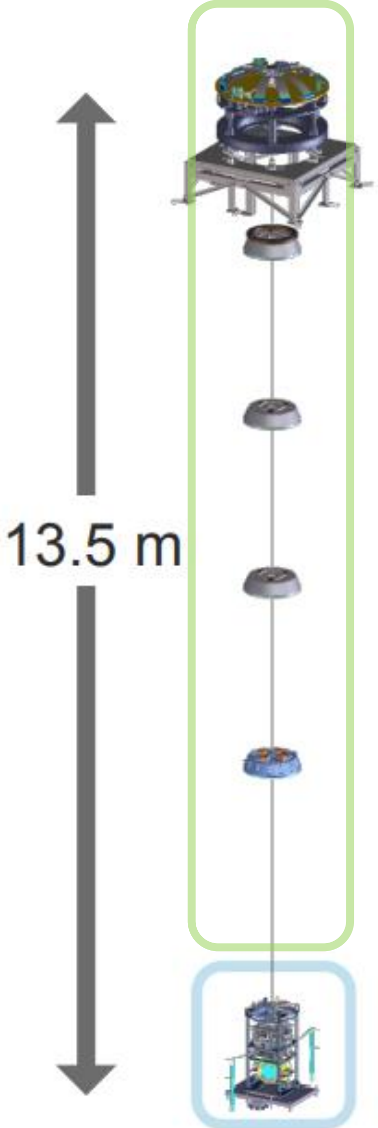


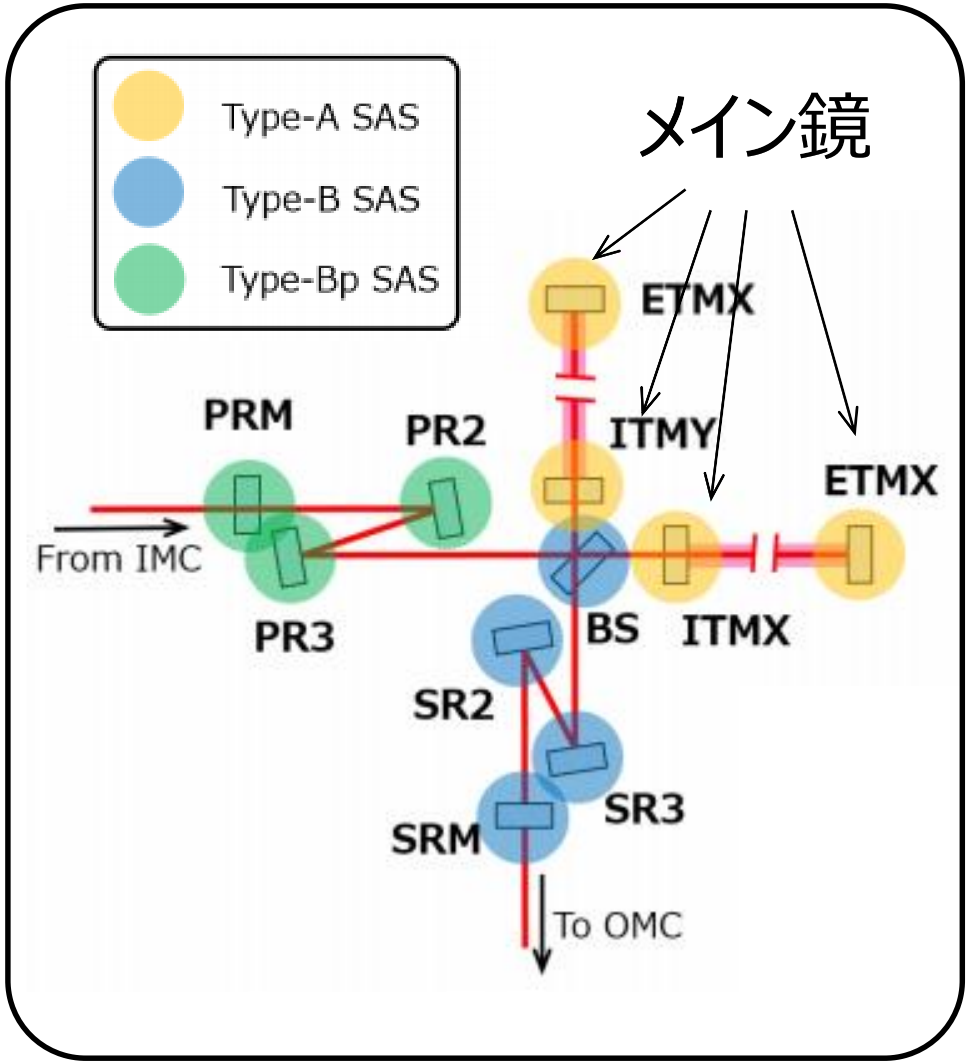


共振 → とにかく抑える
制御雑音 → 気にしない

揺れ(RMS)→ 抑える
制御雑音 → 抑える

本題: メイン鏡用の防振装置

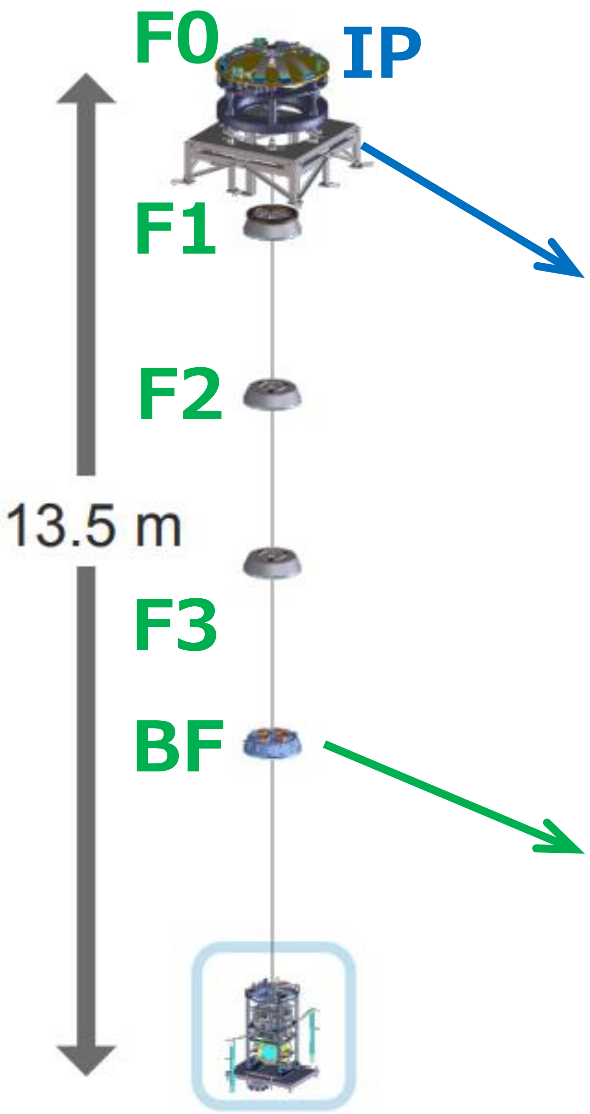


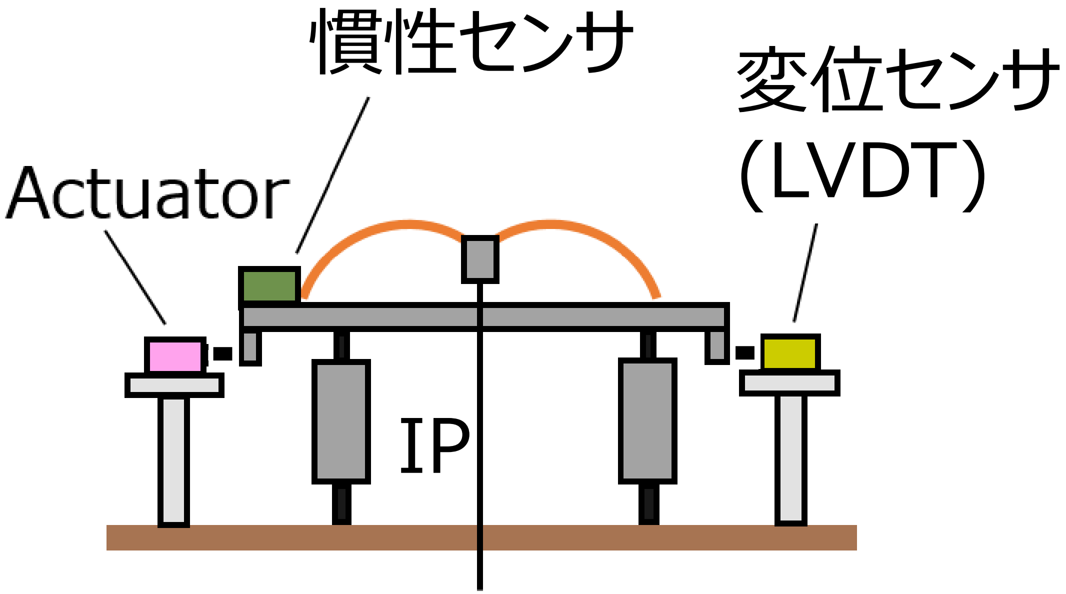


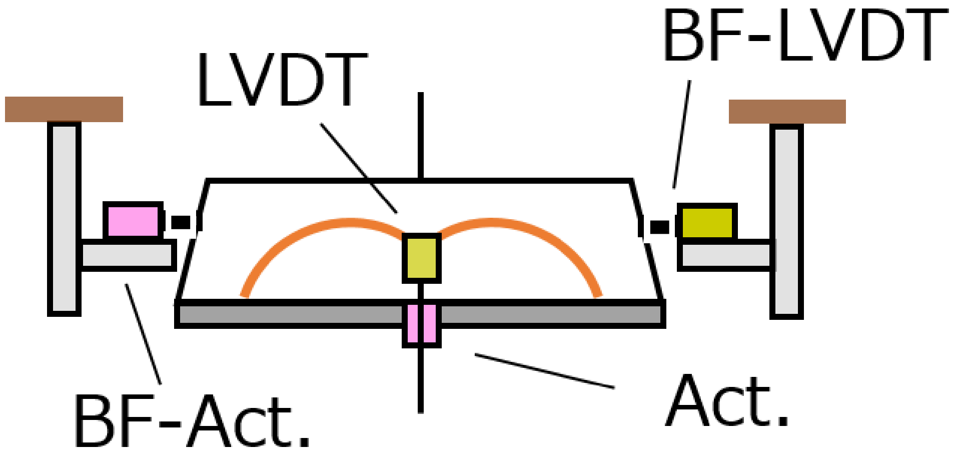
- Upper 5 stages:
  room-temperature

- Lower 4 stages:
  cryogenic-temperature

本題: メイン鏡用の防振装置





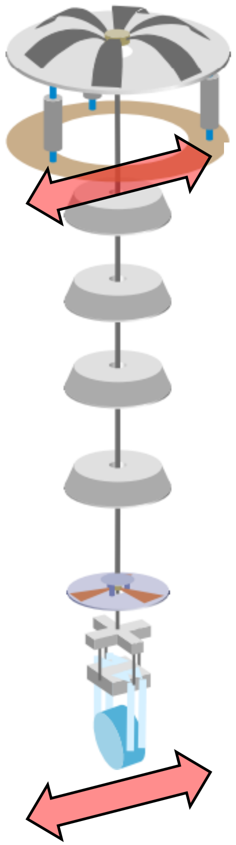


倒立振り子
IP: ~70 mHz

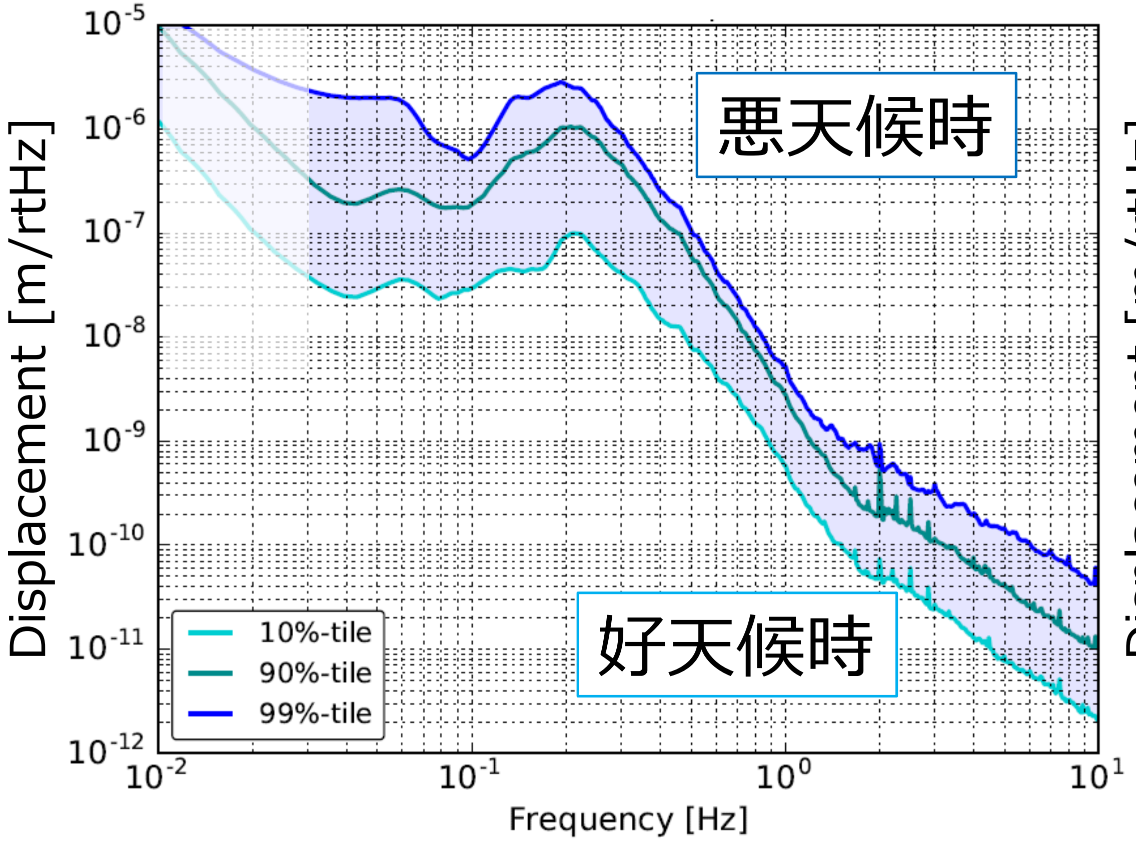
幾何反バネ
(GAS) フィルタ
F0 – BF: ~0.4Hz

→ メカものは全て インストール済み

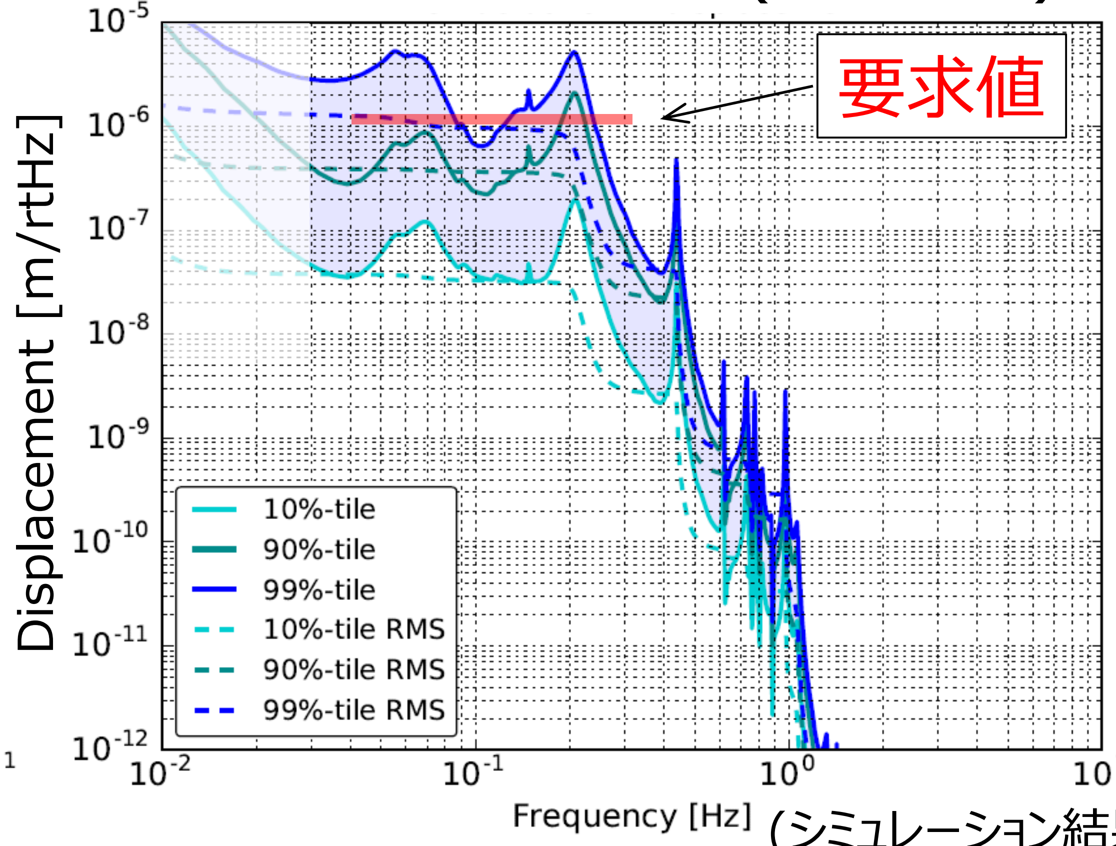
KAGRAサイトでの地面振動レベルと、サスペンションの応答



KAGRAサイトの地面振動



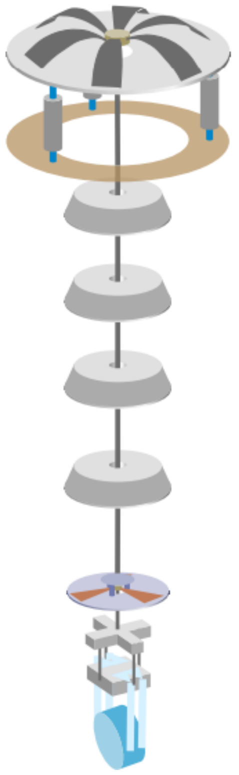
そのときの鏡の振動 (制御無し)



(シミュレーション結果)

Ref: https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=10436

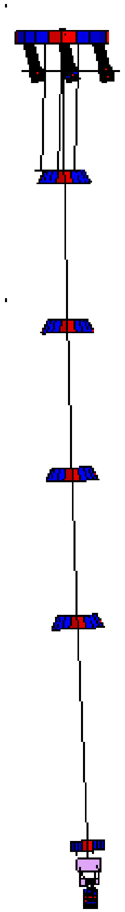
神岡での地面振動レベルと、サスペンションの応答

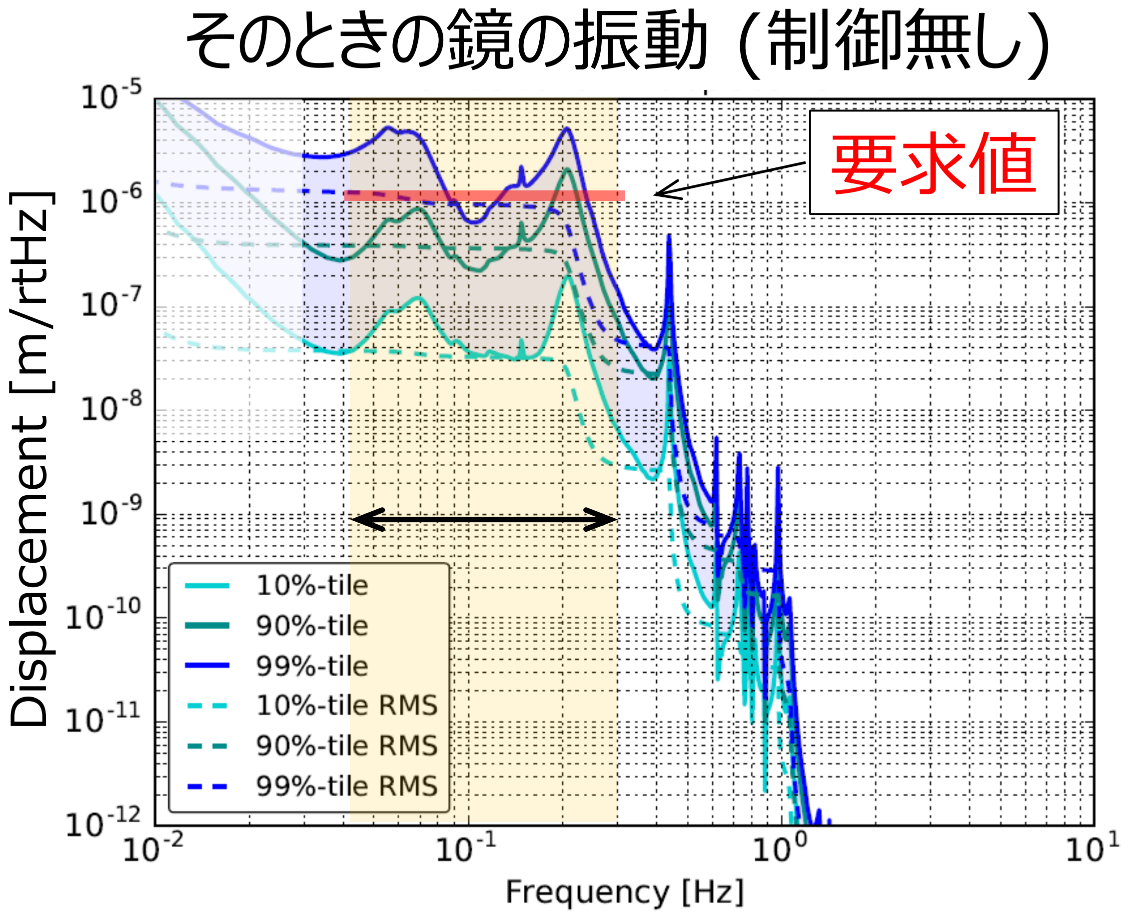


-- 好天候時
→ 要求値を満たせる

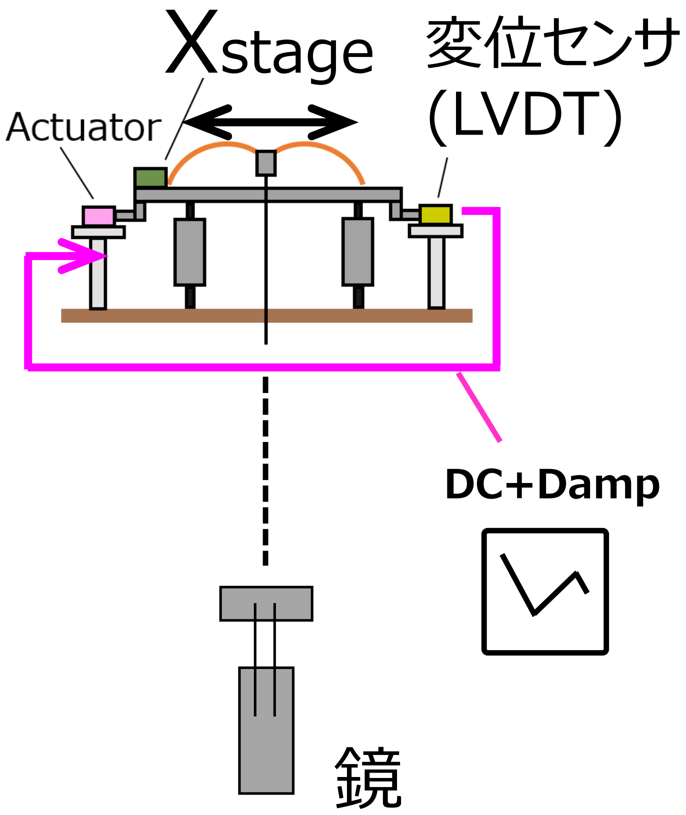
-- 悪天候時(特に冬場)
→ 要対処 at 上段

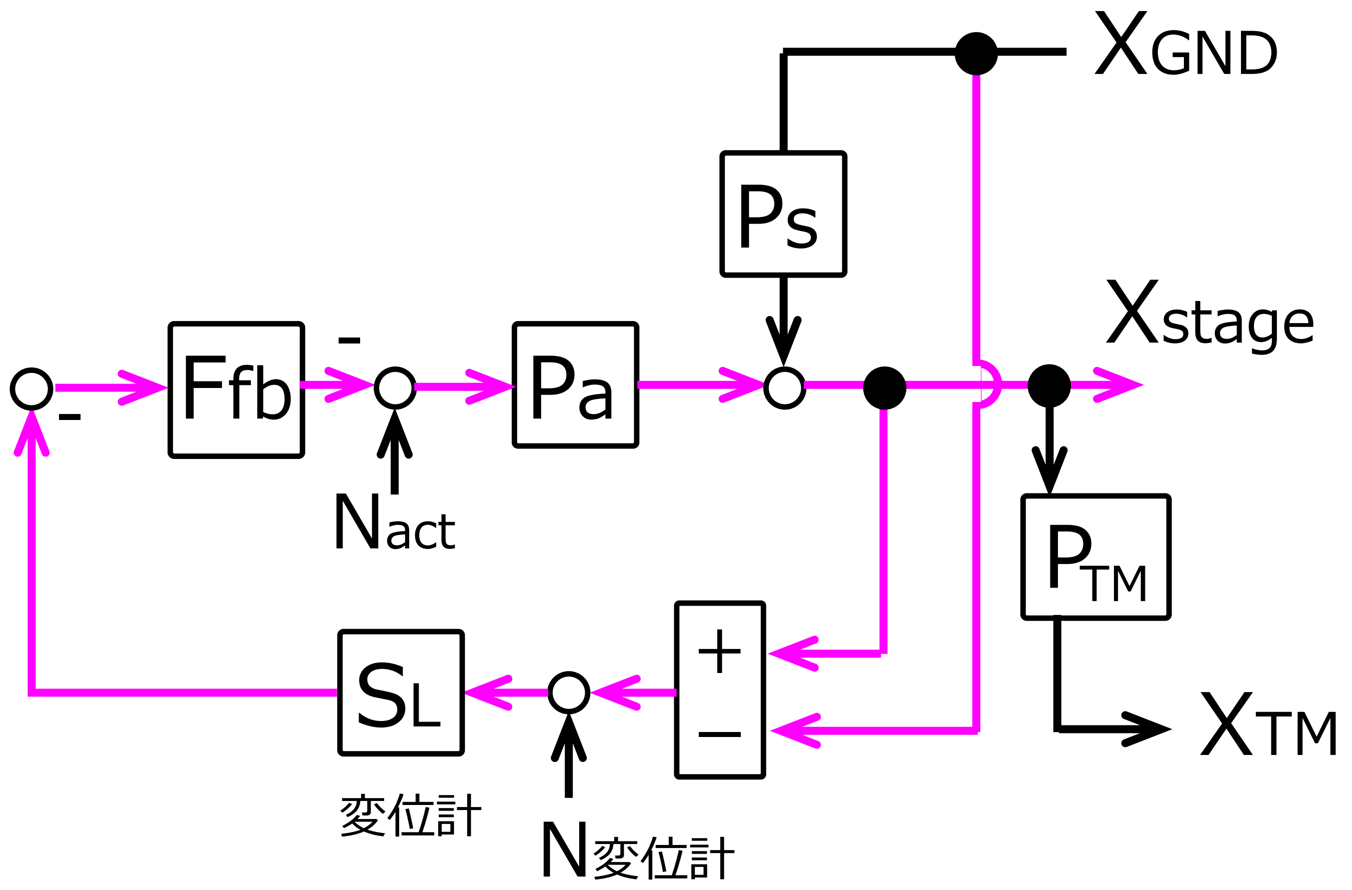
- RMSの寄与が大
→ 抑制が必要
→ at 上段





今回考える制御系 (Lのみ):



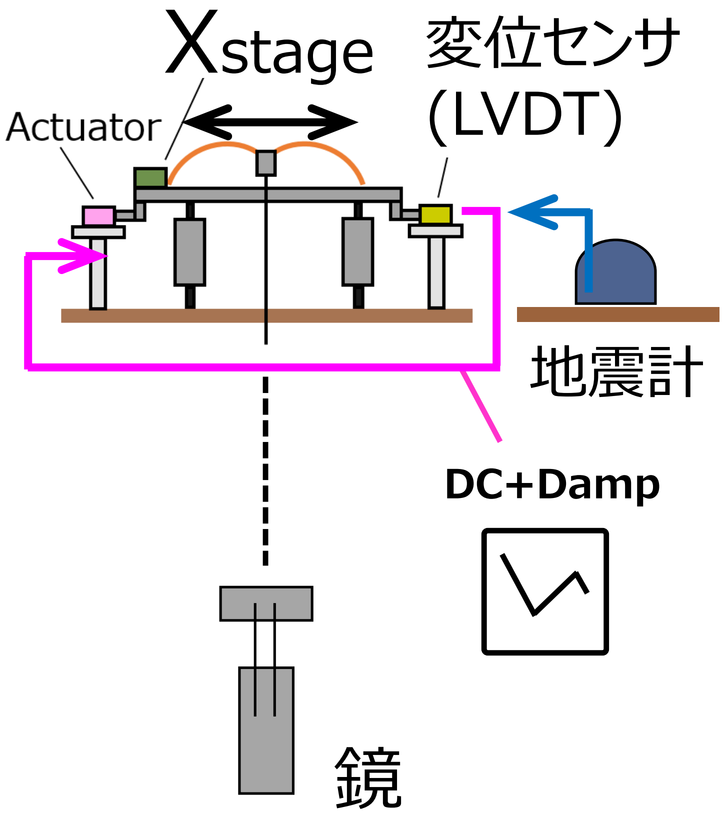


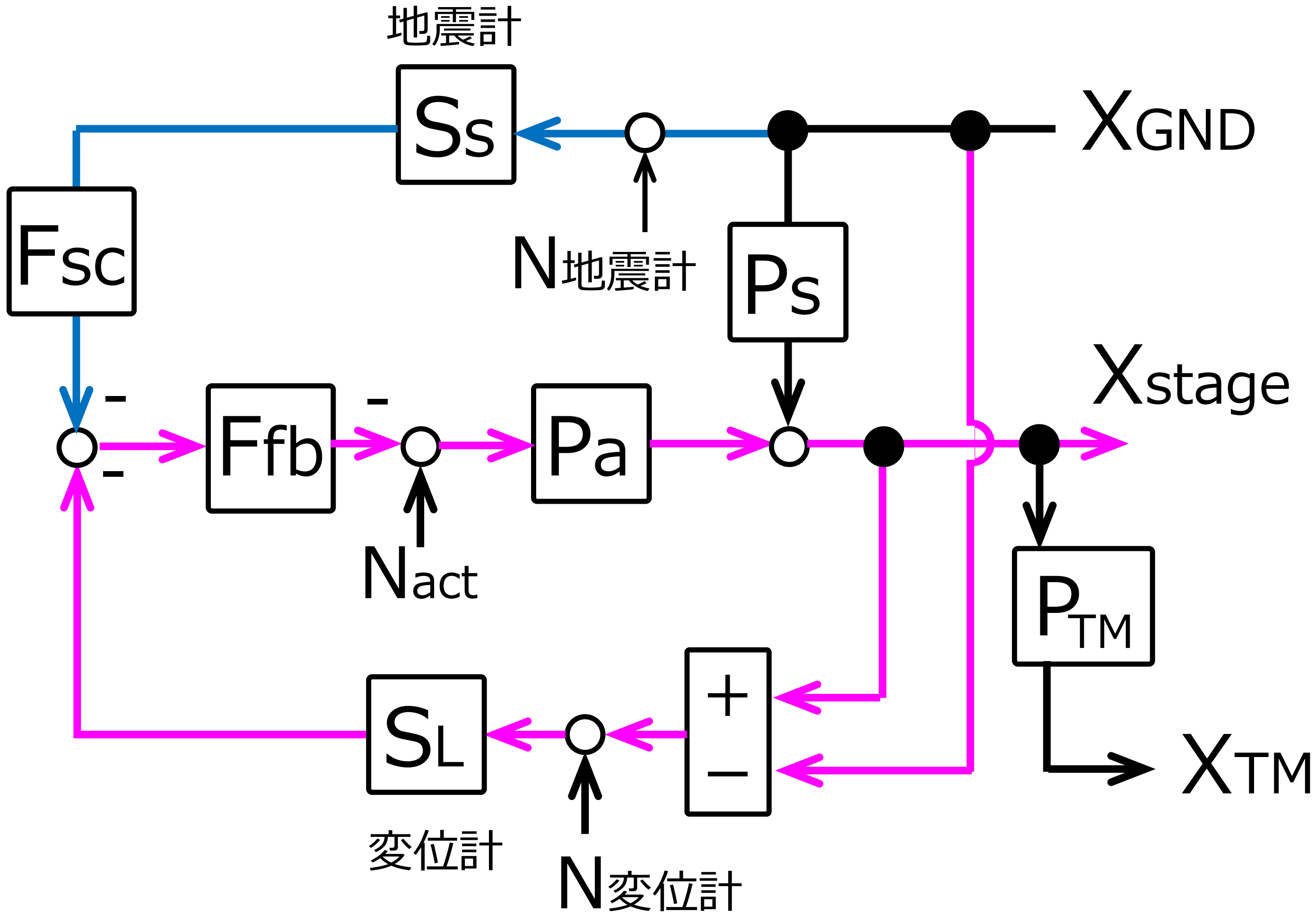
変位計:
(Xstage − XGND)
で制御

→

Xstage ~ XGND
地面程度は揺れる

今回考える制御系 (Lのみ):

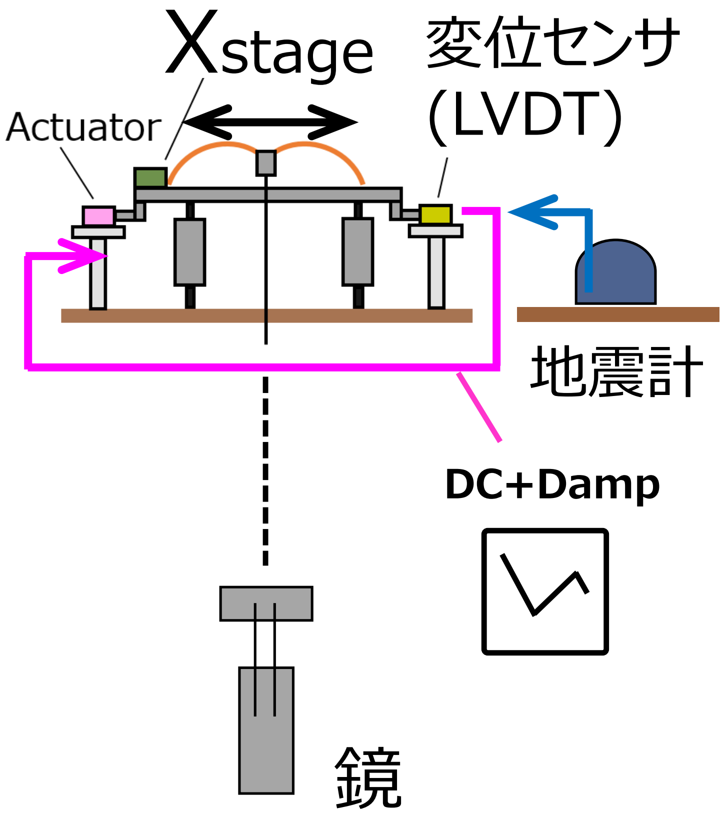


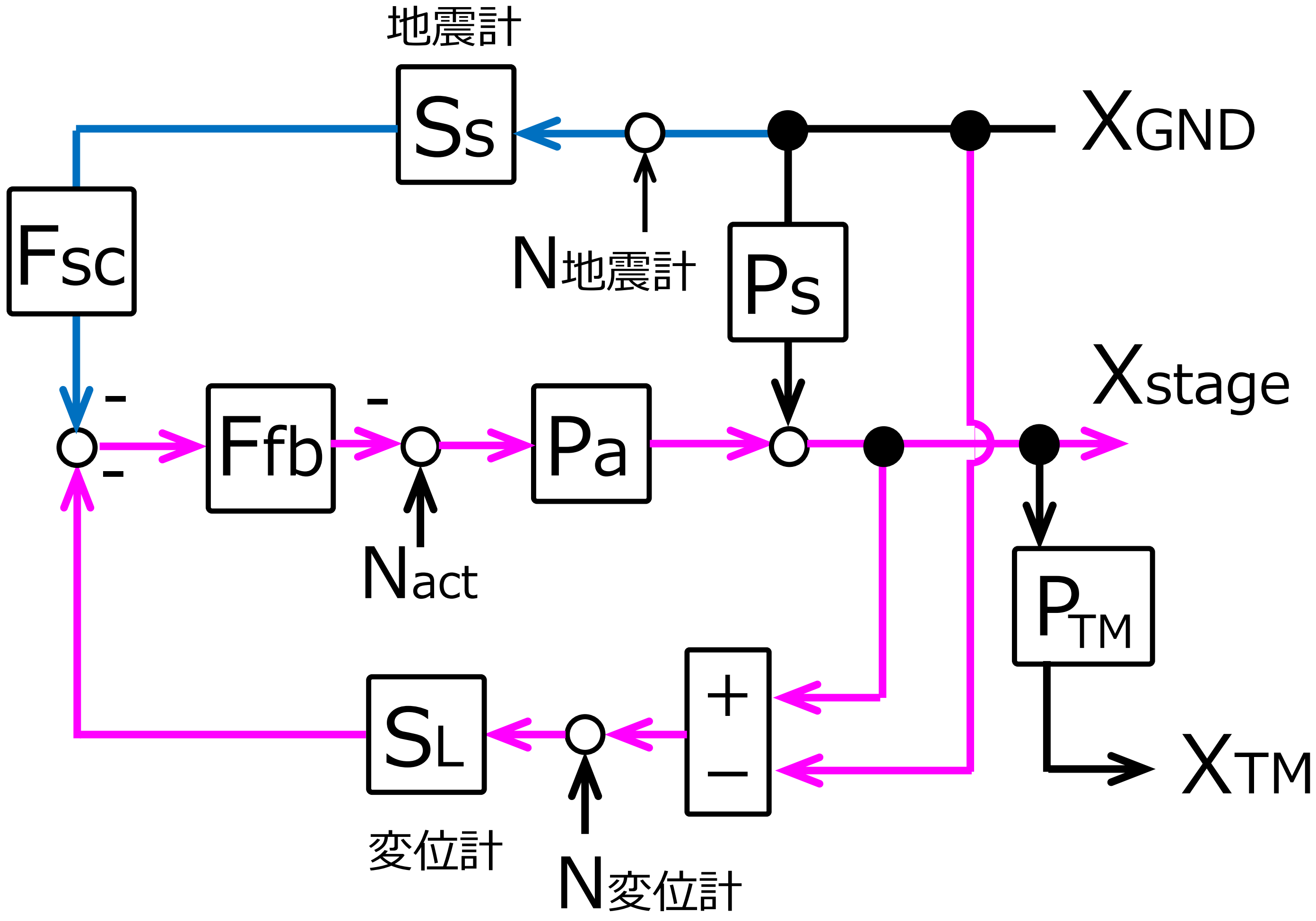


$$X_{stage} = \frac{1}{1+G}\left[G\left(1 - F_{sc}\frac{S_S}{S_L}\right) + P_s\right] X_{GND}$$

$$(\ G = P_a\, F_{fb}\, S_L\ )$$

今回考える制御系 (Lのみ):



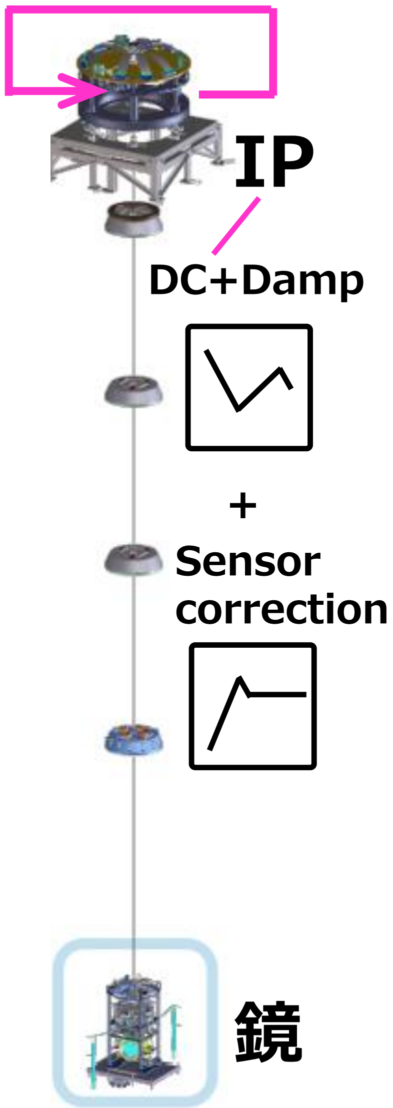


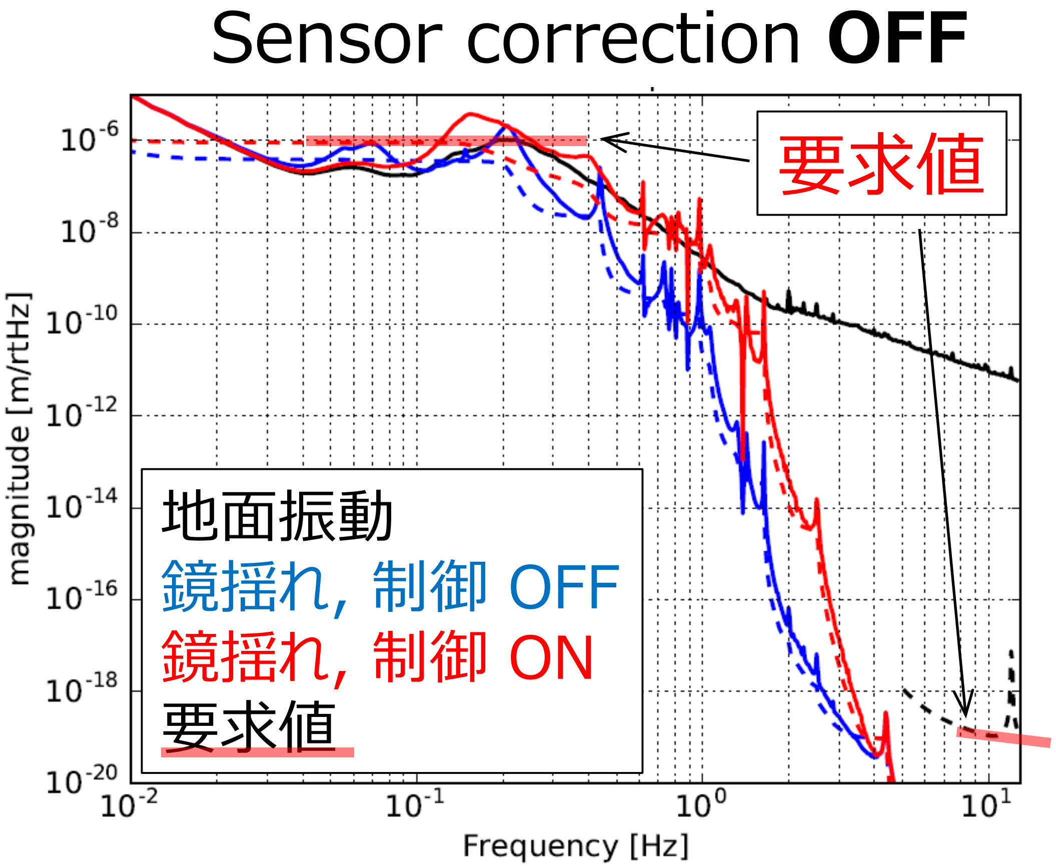
$F_{sc} = S_L/S_S$ にて :

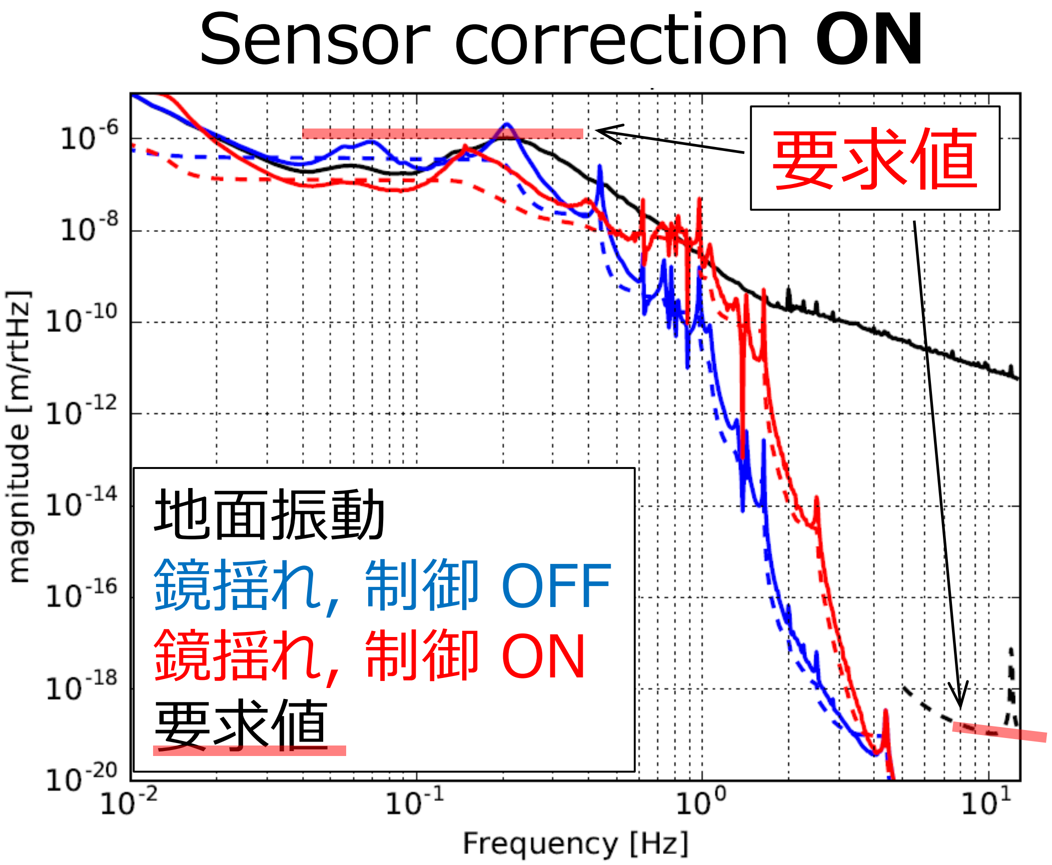
$$X_{stage} = \frac{1}{1+G}\left[G\left(1 - F_{sc}\frac{S_S}{S_L}\right) + P_S\right] X_{GND}$$

変位計経由の地面振動流入 カット → Sensor correction

シミュレーション: 90%tile 地面振動を仮定のときの、鏡揺れ

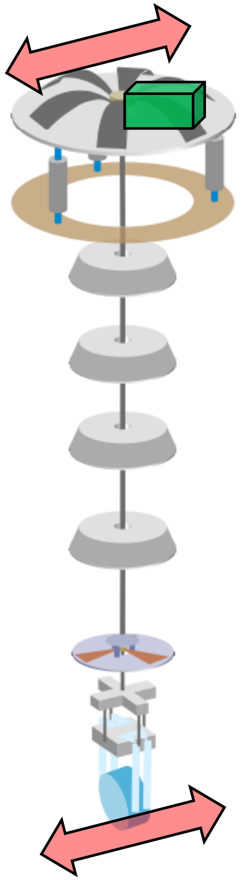


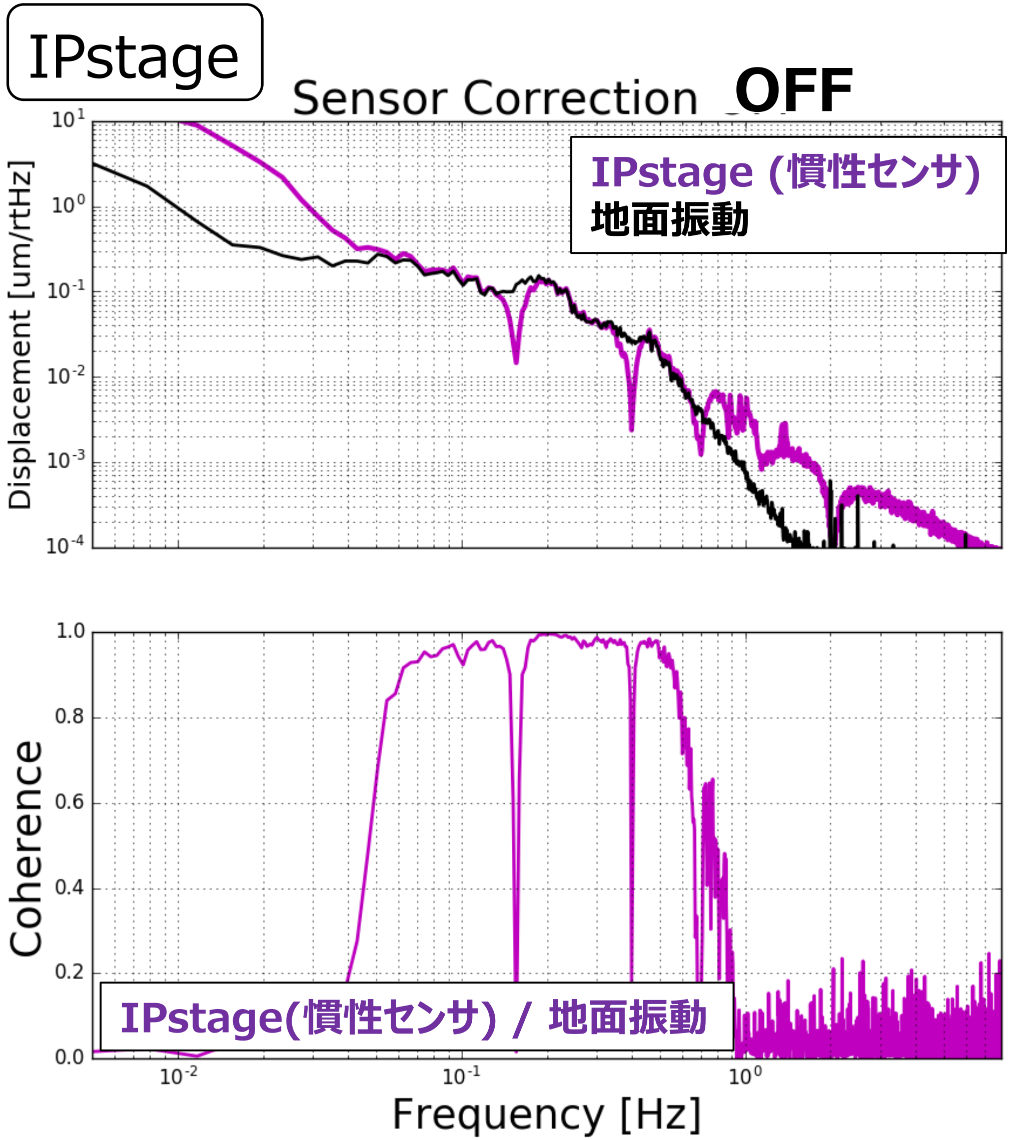


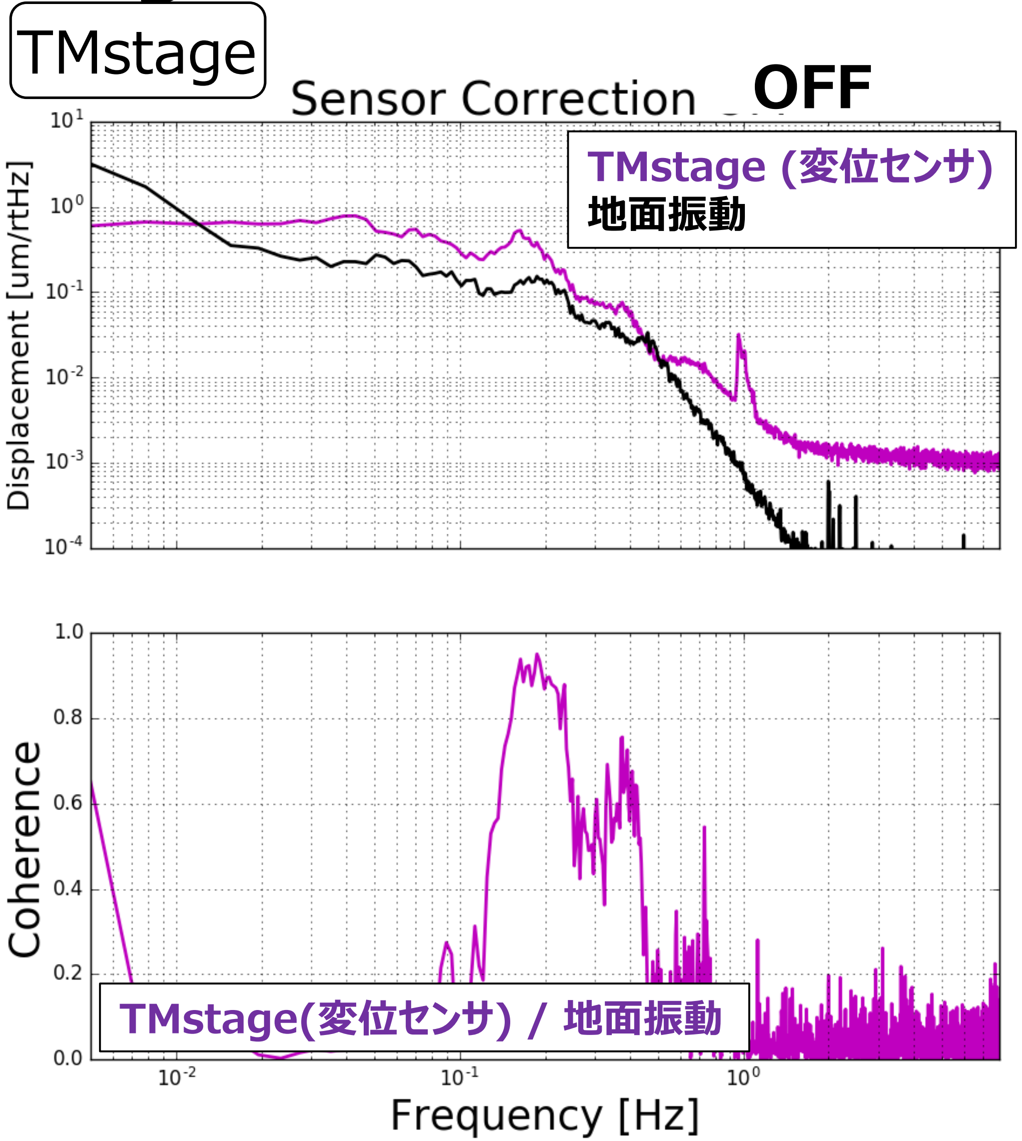


→ Sensor correction を用いて、要求値を満たせる。

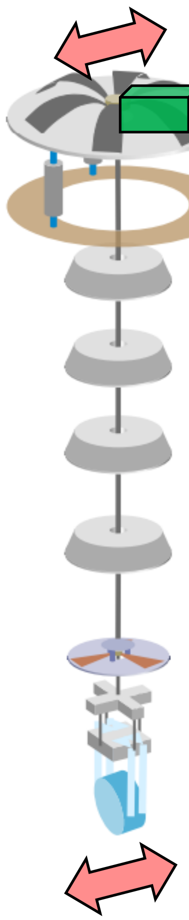
テスト実装: 1つのサスペンションのIP-stageに実装

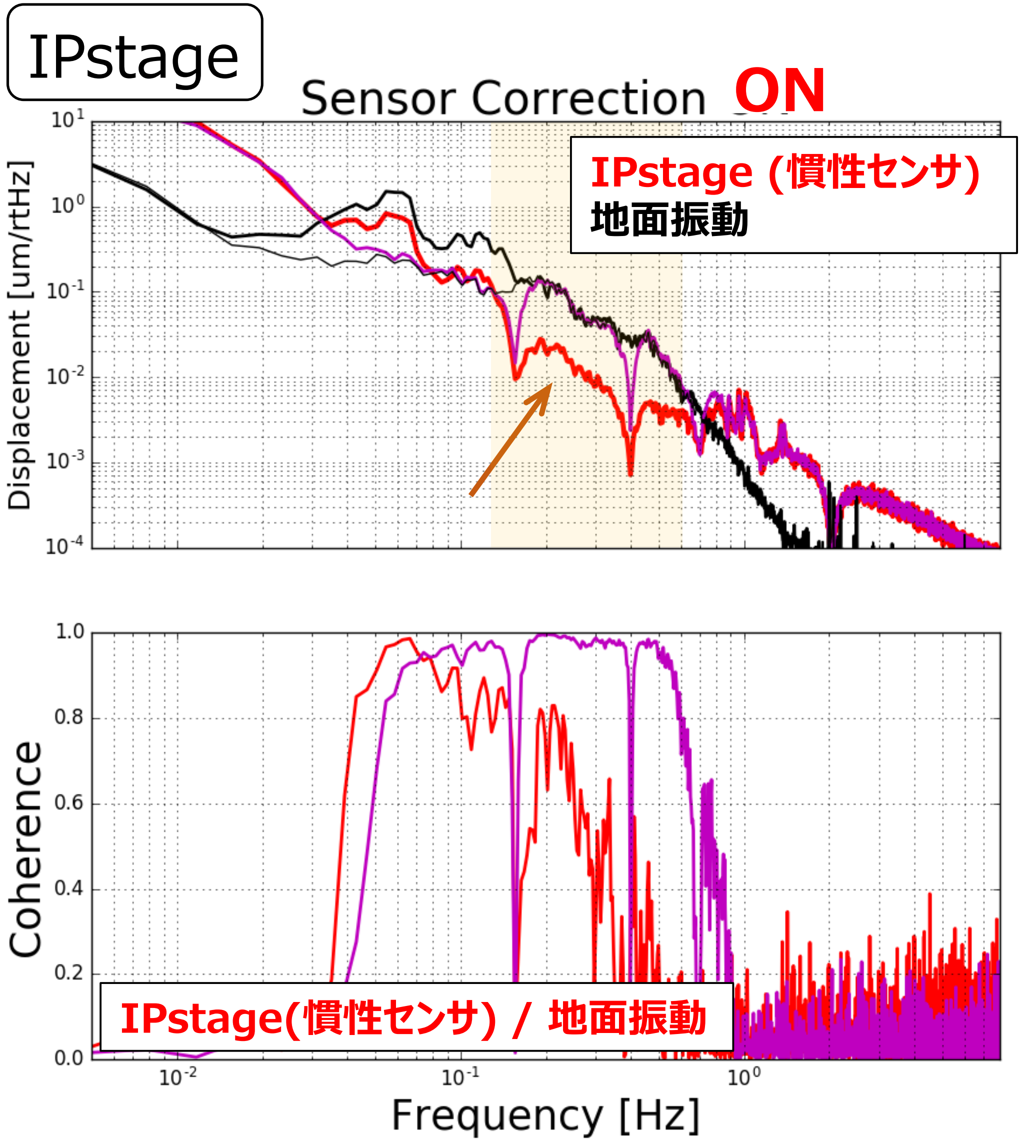


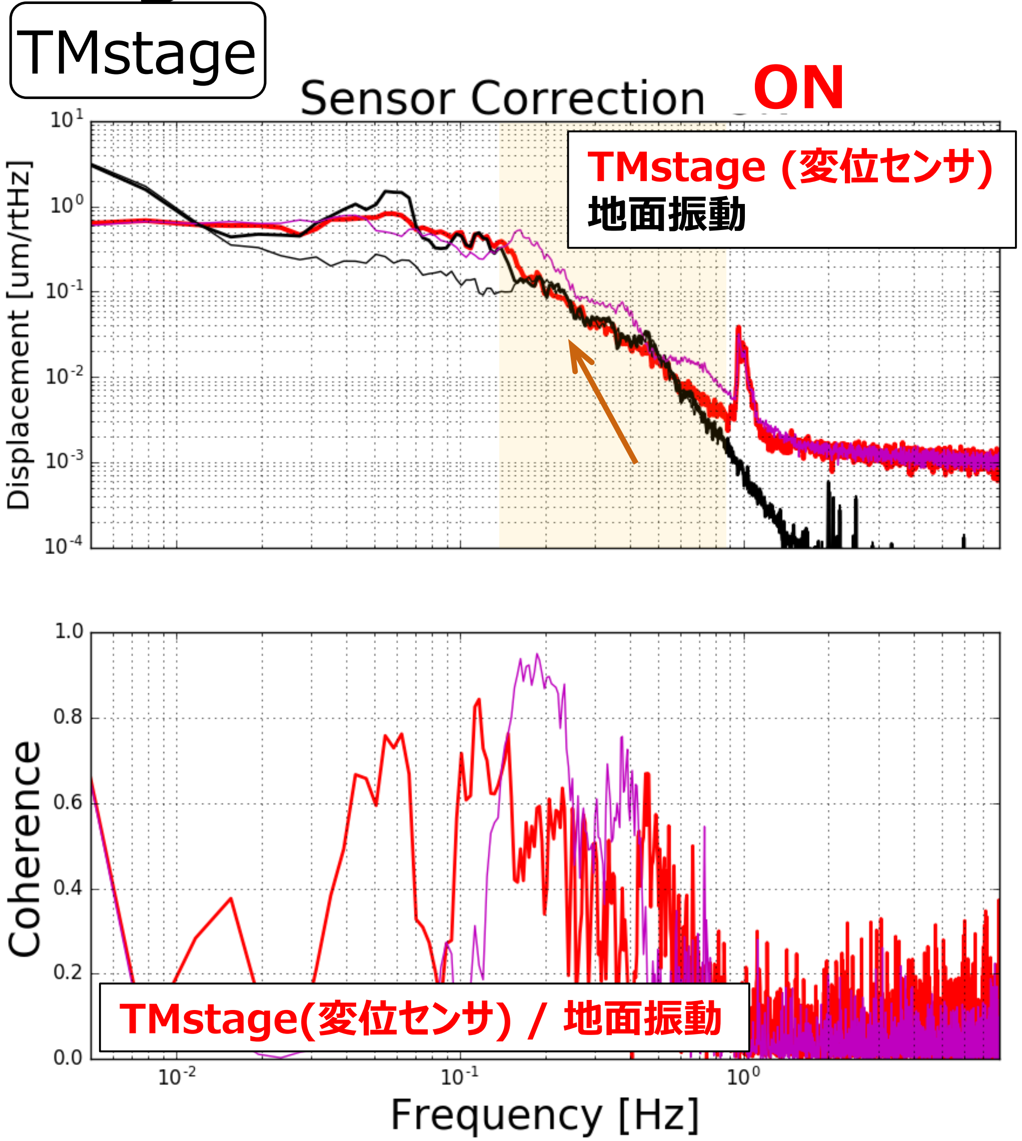




テスト実装: 1つのサスペンションのIP-stageに実装







→ SC worked at 0.15 ~ 0.7Hz.

まとめ:

-- 変位センサと、地面に置いた地震計とを用いて、
鏡のRMS揺れを抑える制御系を作成し、
-- simulation上にて、要求値を満たすことを確認した。
-- 試験的に実装し、以下を確認した:

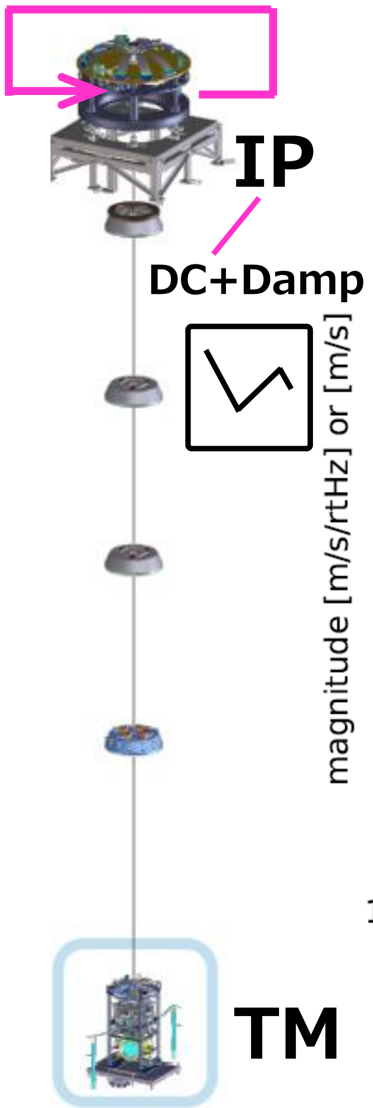
-- local / global ともに 0.15 ~ 0.6 Hzでは、振動は低減されが、
< 0.15 Hz では悪化(の様子)
とくにRMS の改善なし
→ (今回の試験の)低周波帯での性能: 要 調査

今後:

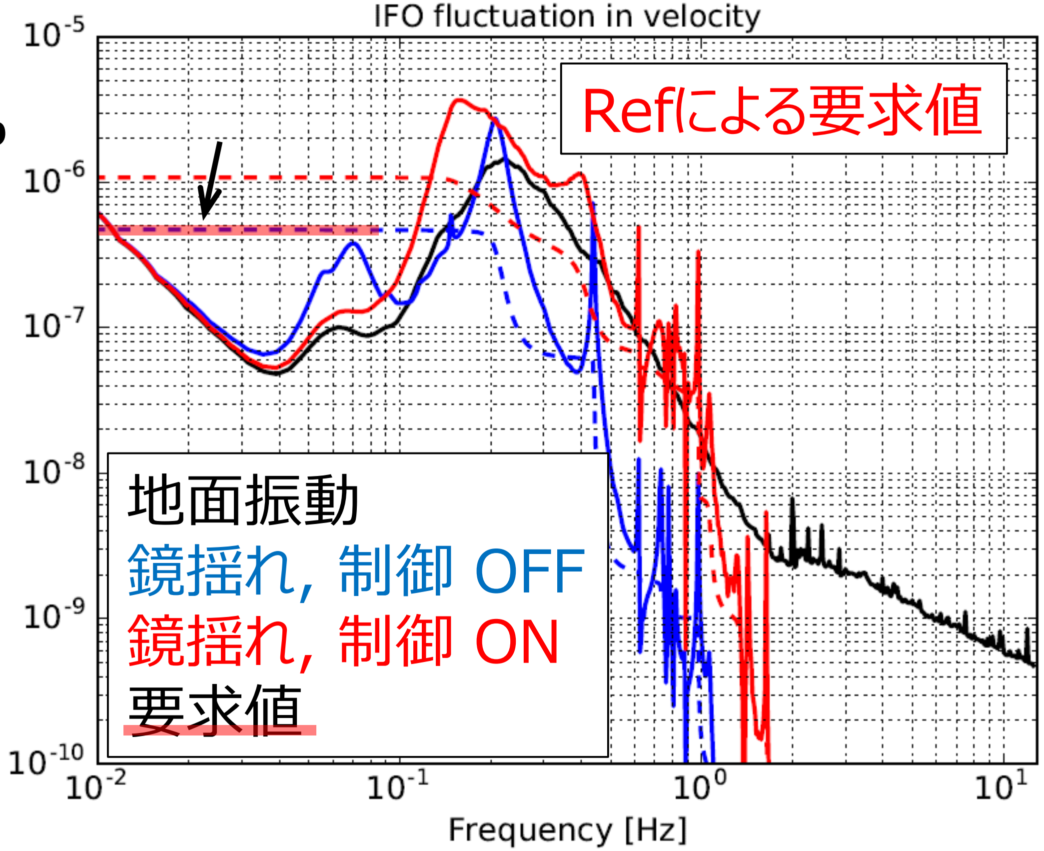
- ☐ SCフィルタの改良
- ☐ 99%-tileの地面振動 を想定した制御系の作成
- ☐ 0.15 Hz のピーク (両サスペンションのresidual) の低減

Backup

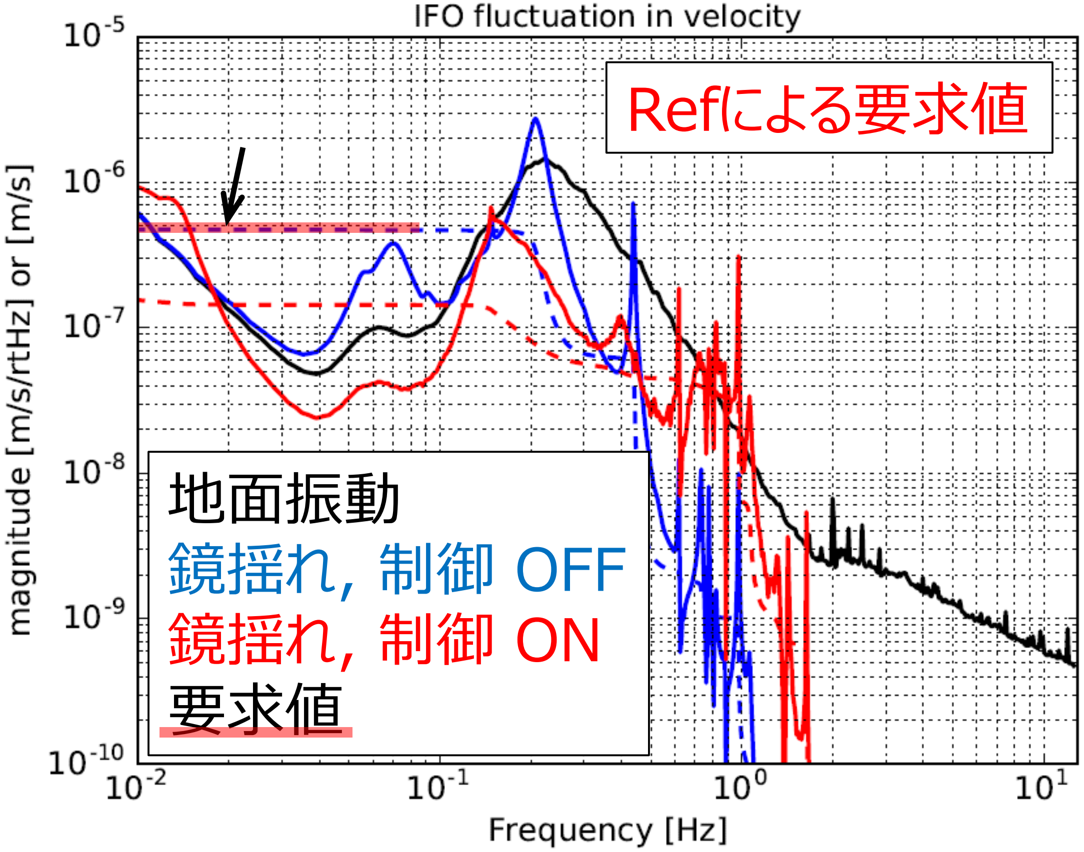
シミュレーション: 90%tile 地面振動を仮定のときの、鏡揺れ(速度)



Sensor correction **OFF**



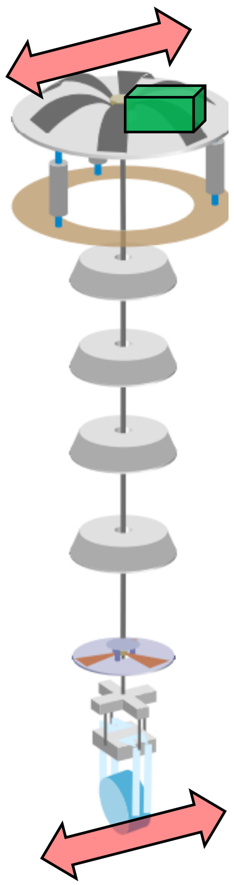
Sensor correction **ON**



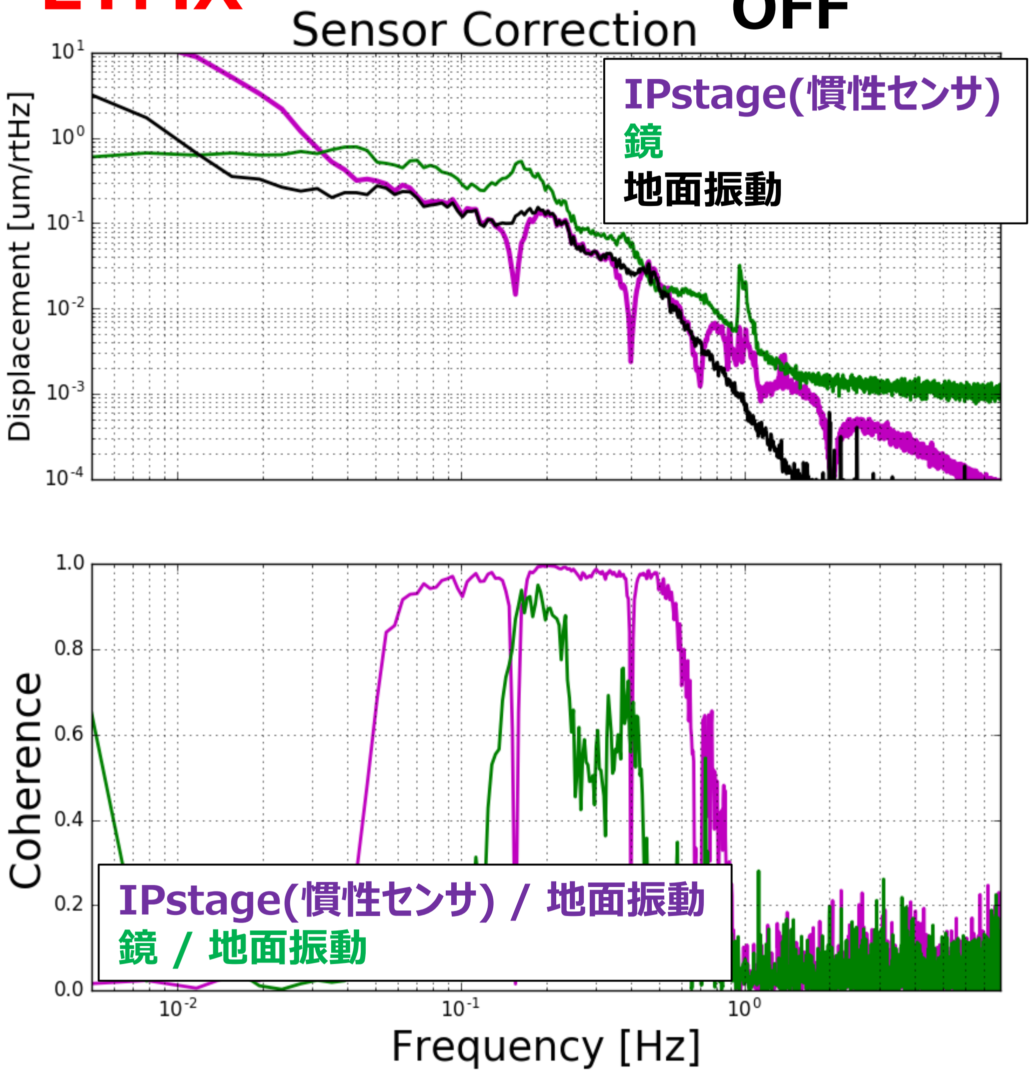
→ Sensor correction を用いて、要求値を満たせる。

Ref: p.55 in https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=6060, or p.90 in https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=4155

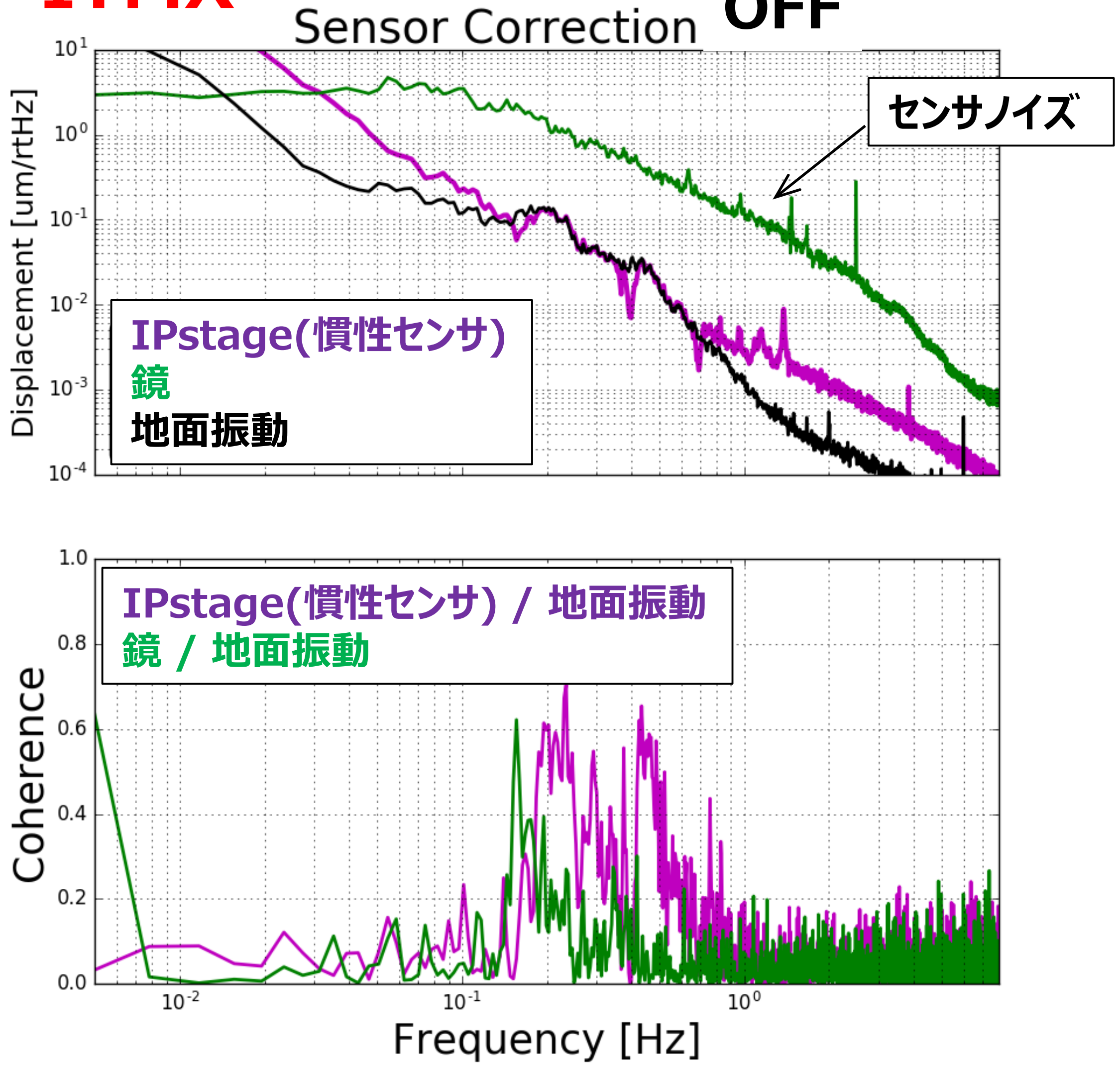
テスト実装: 2つのサスペンションのIP-stageに実装、local で見ると



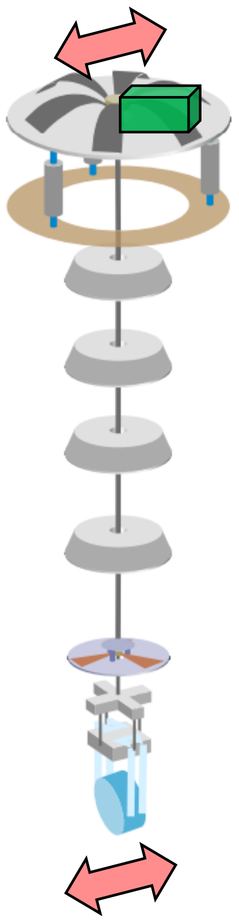
ETMX

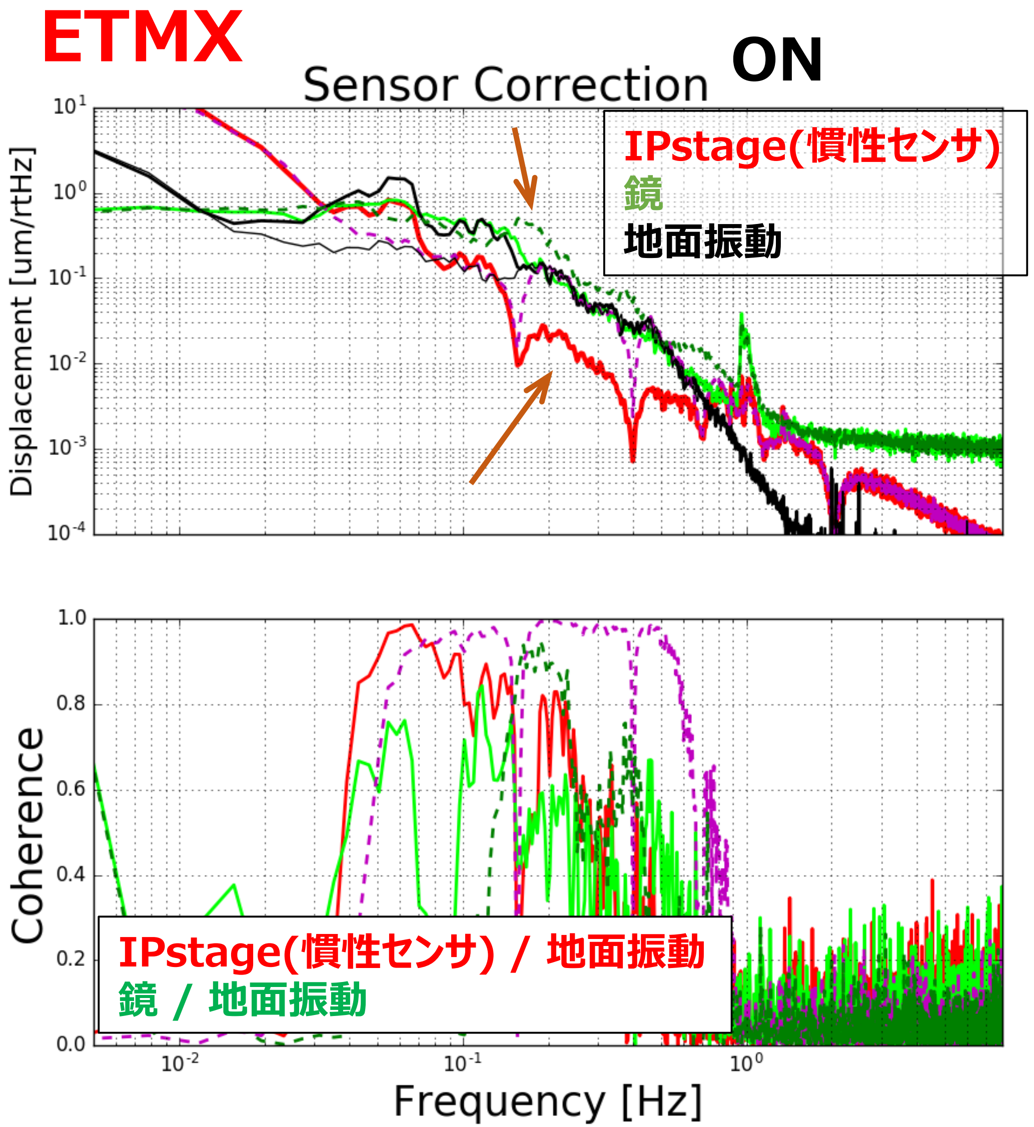


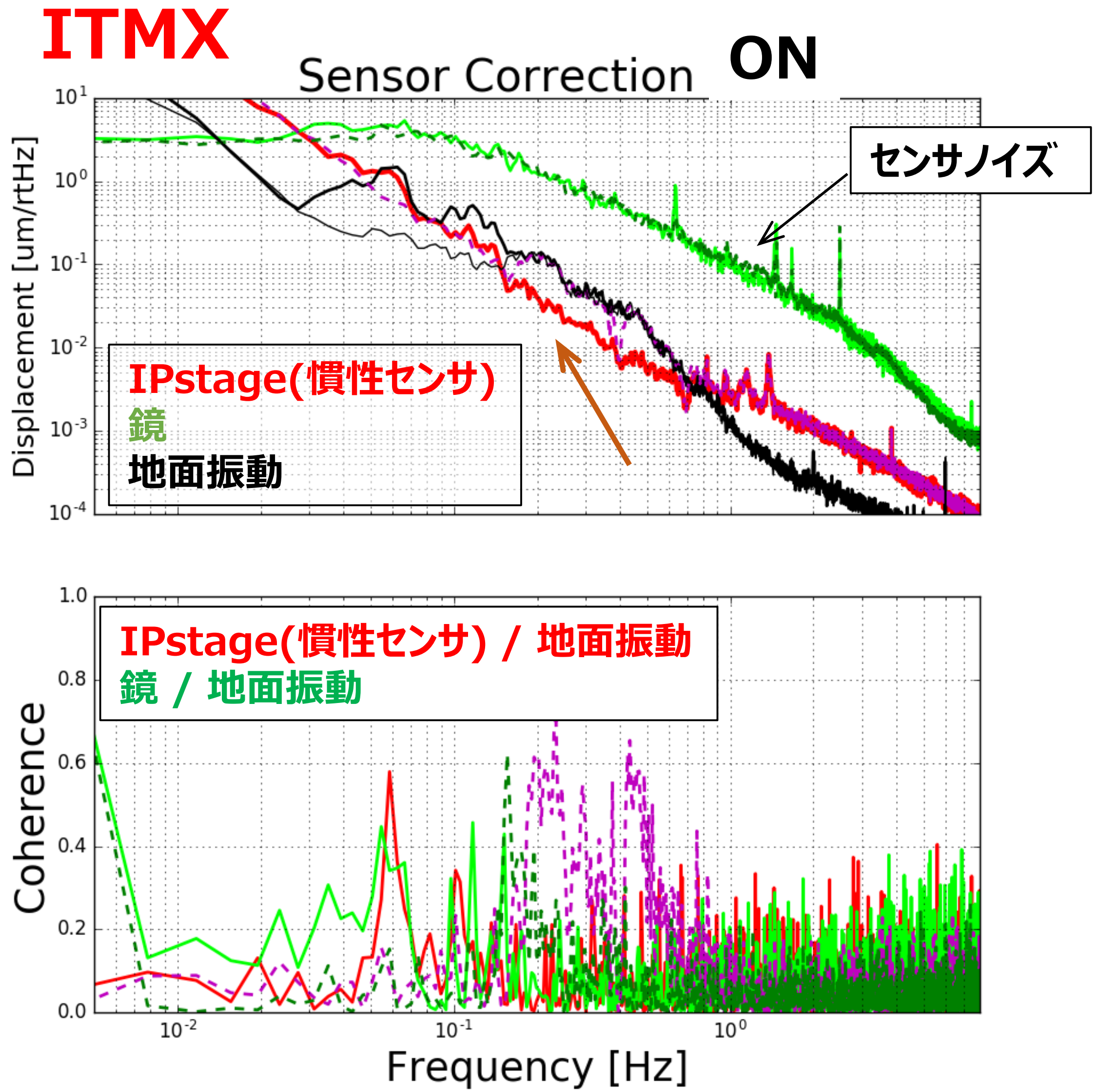
ITMX



テスト実装: 2つのサスペンションのIP-stageに実装、local で見ると



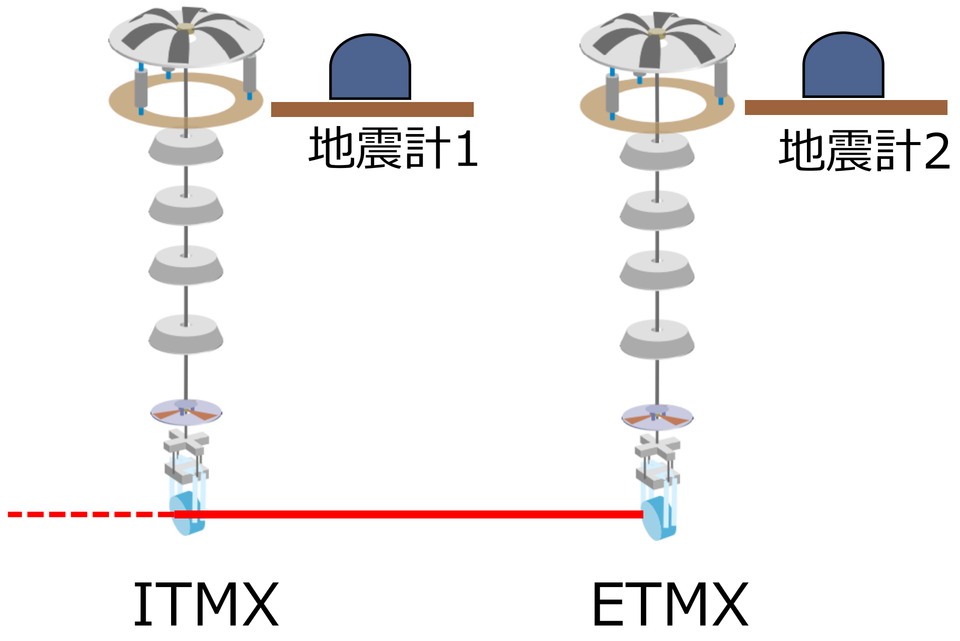


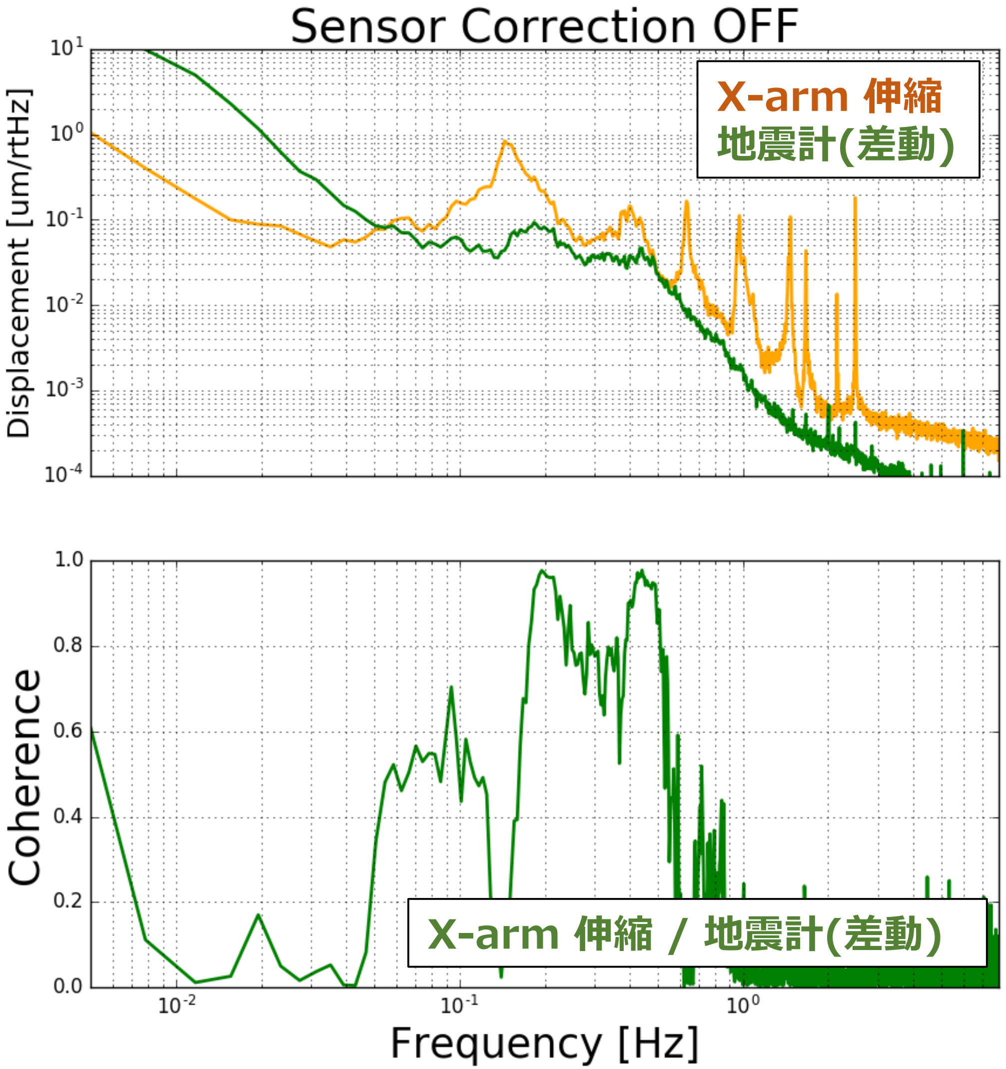


→ 0.12 – 0.7Hz で揺れが低減された様子。詳細はセンサノイズ/地面振動に隠れた.

テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

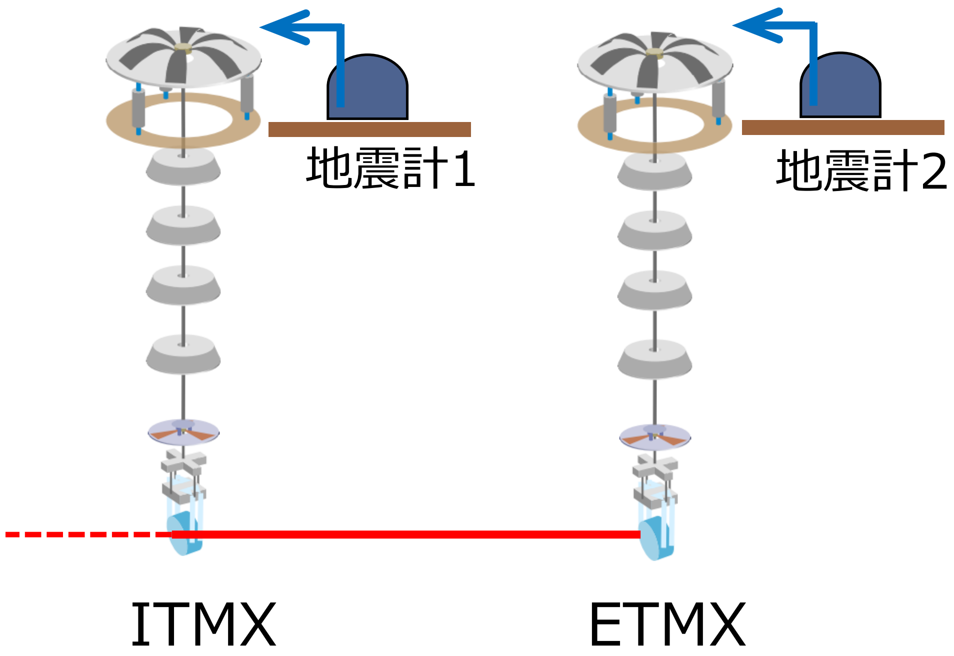
→ ETMX と ITMX に実装
  → 0.15 ~ 0.7 Hzにて同様な改善あり
→ X-arm (FP cavity) の共振器長の確認

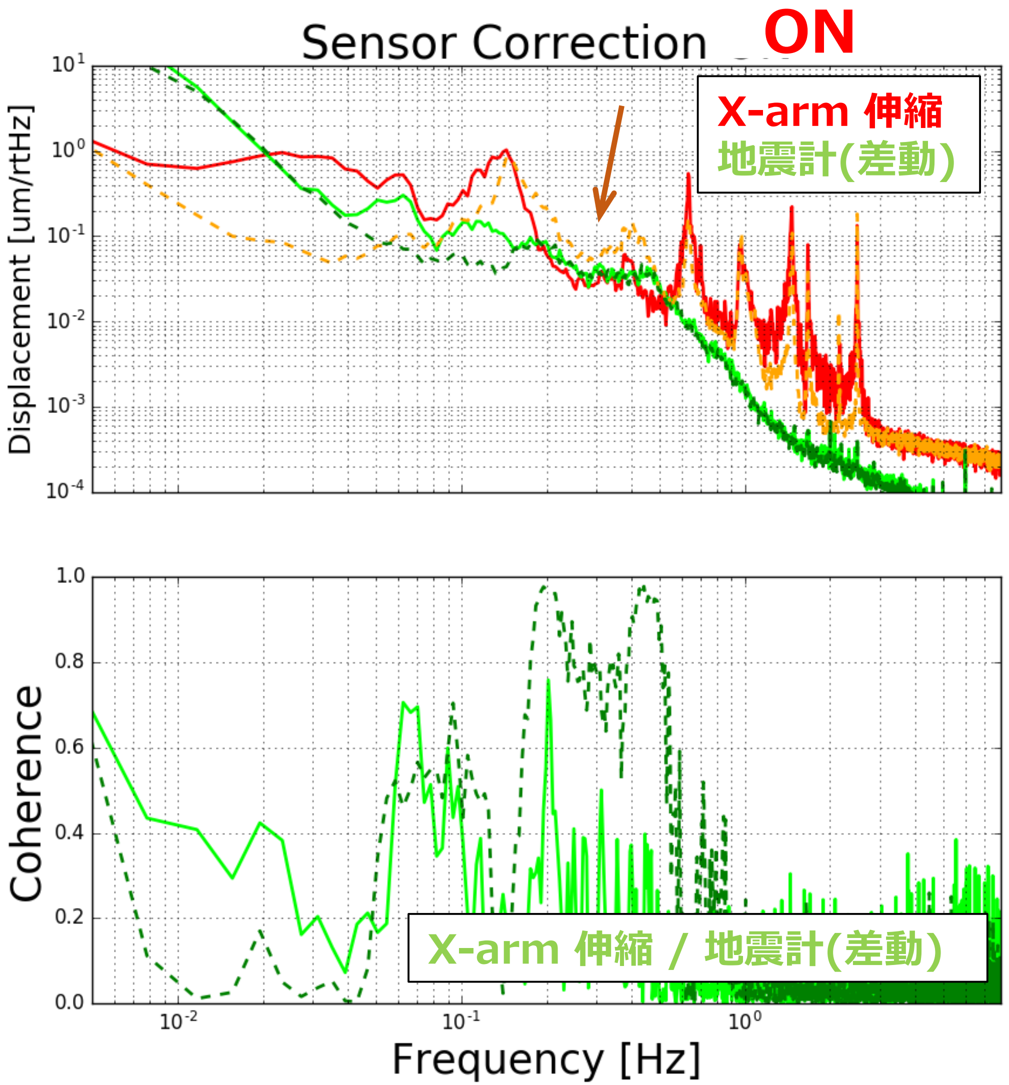




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

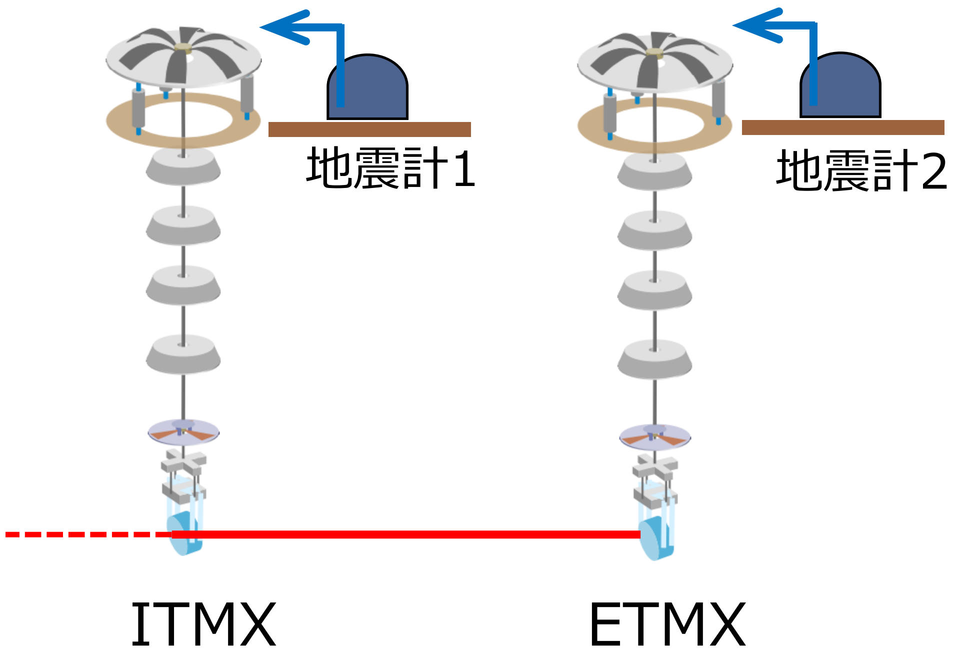
→ X-arm (FP cavity) の共振器長では

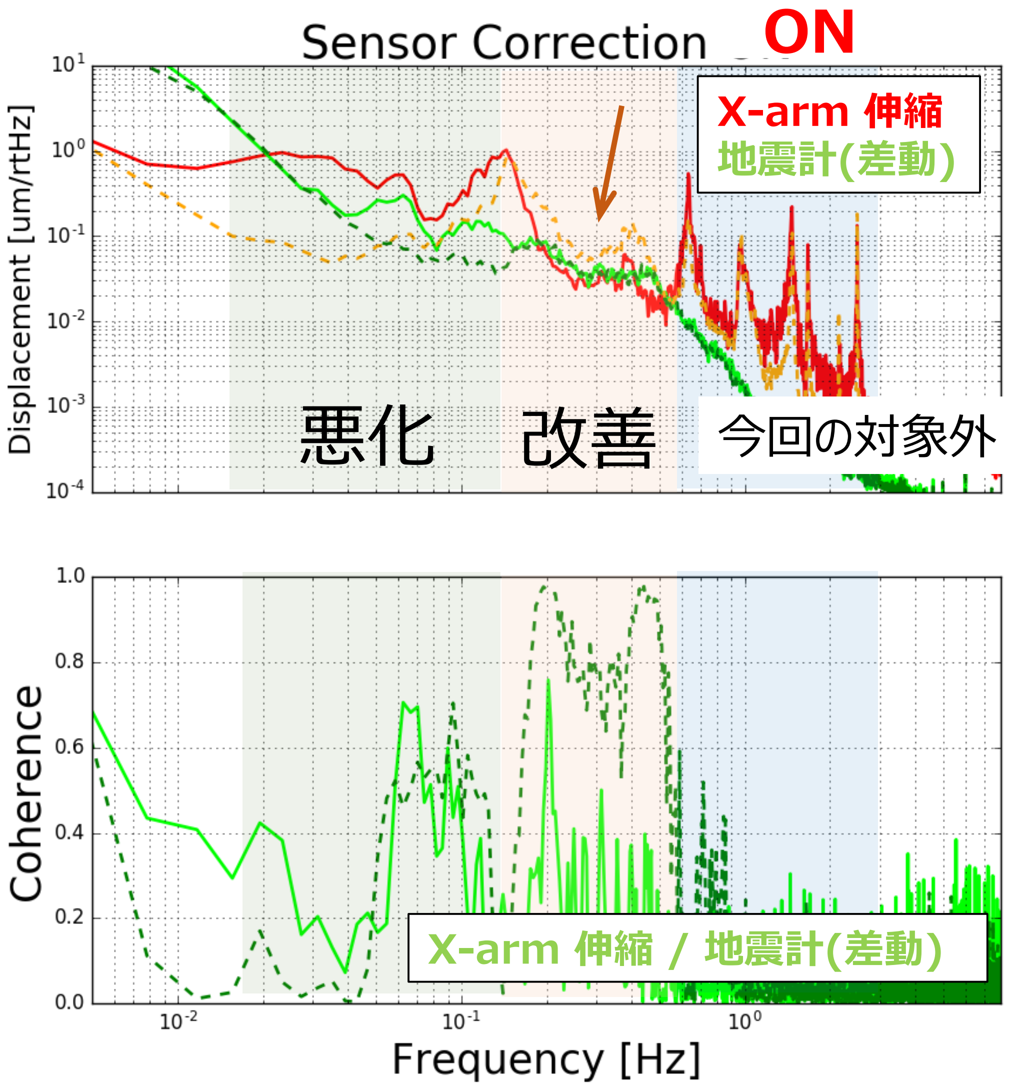




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

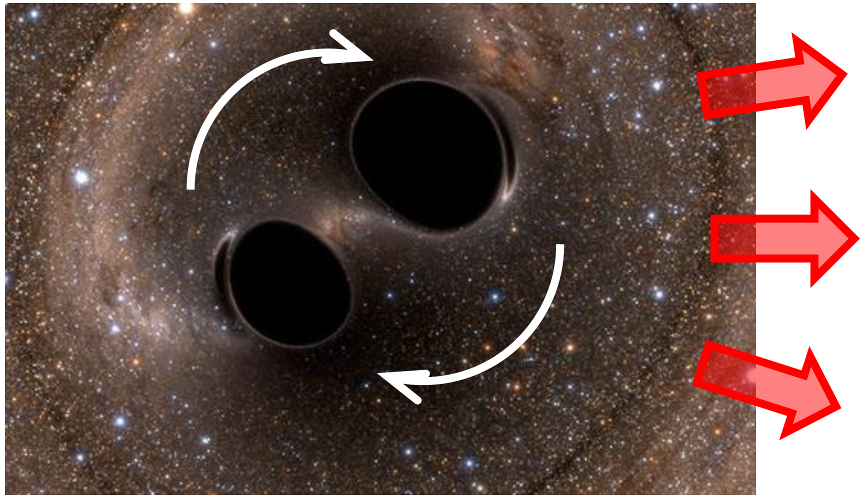
→ X-arm (FP cavity) の共振器長では

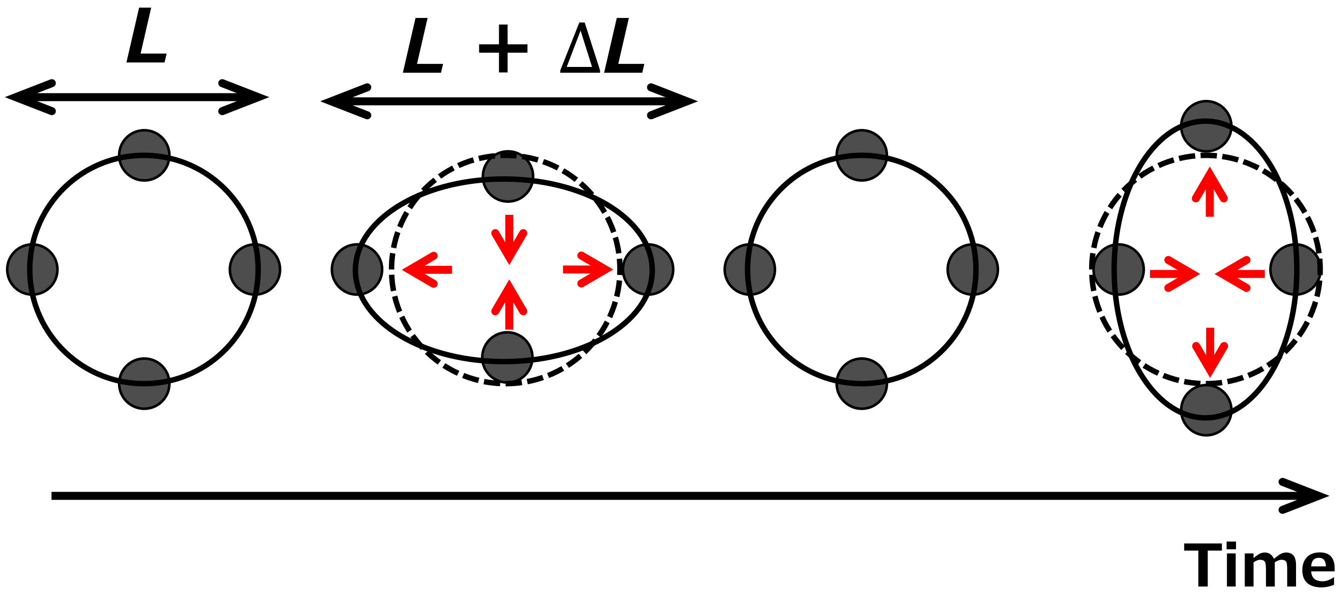


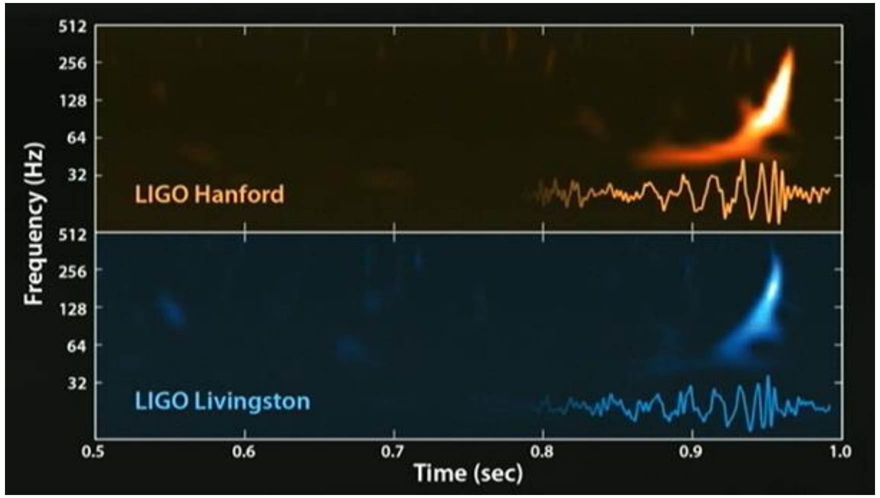


-- SC worked at 0.15 ~ 0.6Hz.
-- 低周波: 悪化
→ SC filterからの地震計の雑音の流入ほか
→ To be investigated.

重力波?



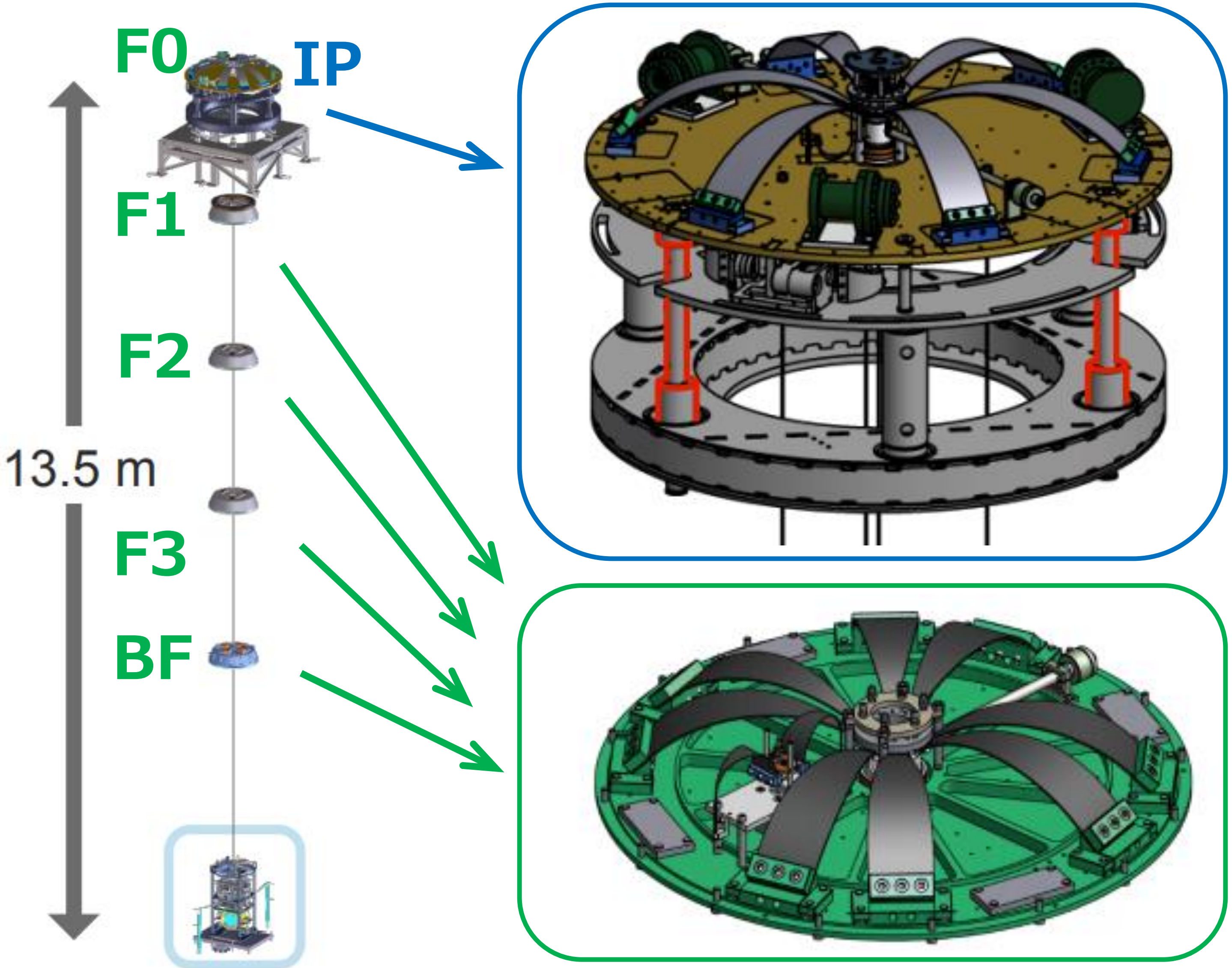




- 2015.9.14 初検出!
- BBH, BNS 検出!

→ **新しい天文学!**

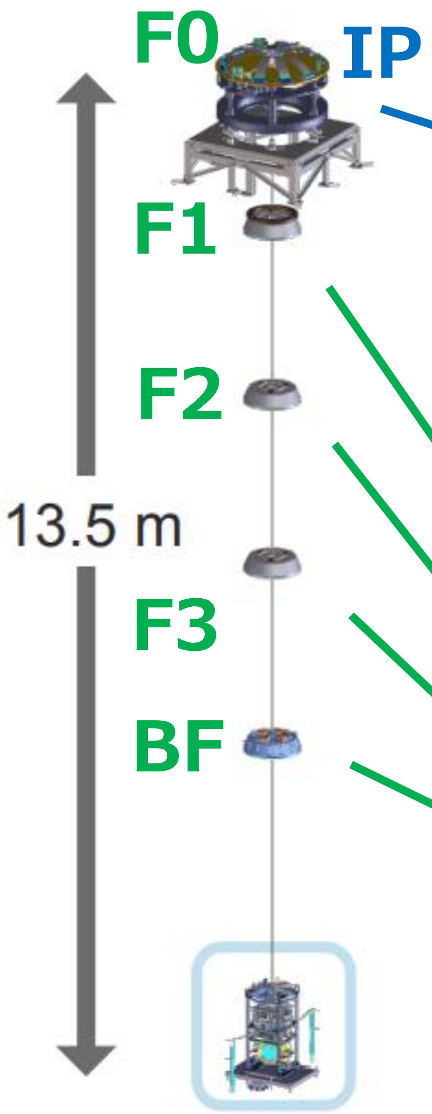
メイン鏡用の防振装置

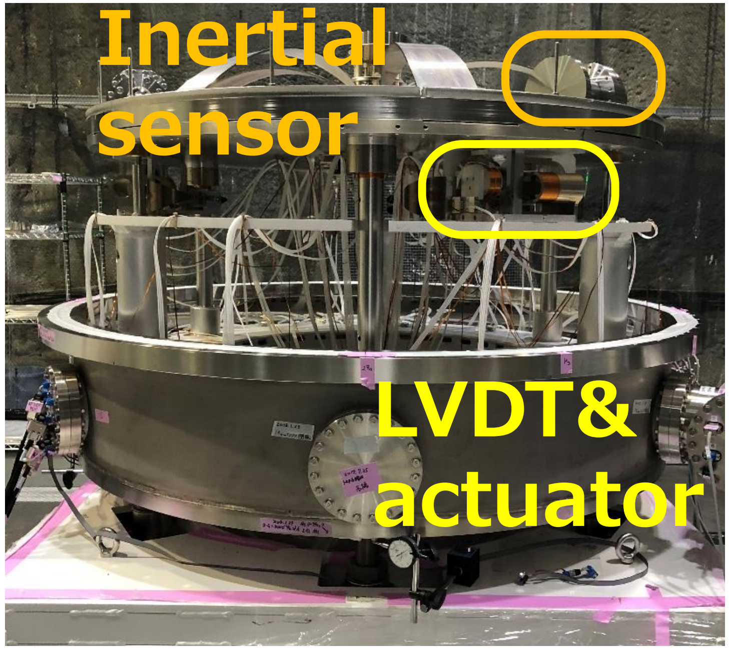


INVERTED PENDULUM
(~ 70 mHz)

GEOMETRIC-ANTI SPRING
(~ 0.4 Hz)

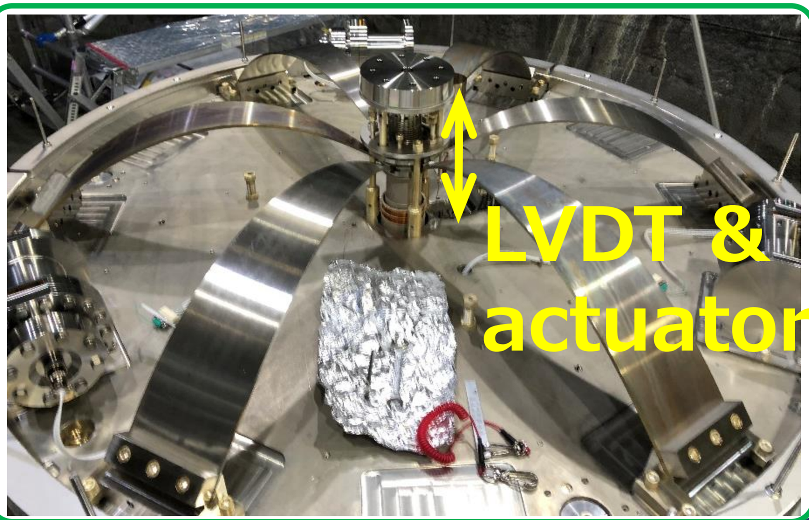
メイン鏡用の防振装置





Inverted Pendulum

with 3 horizontal
-- LVDT & actuator units
-- inertial sensors

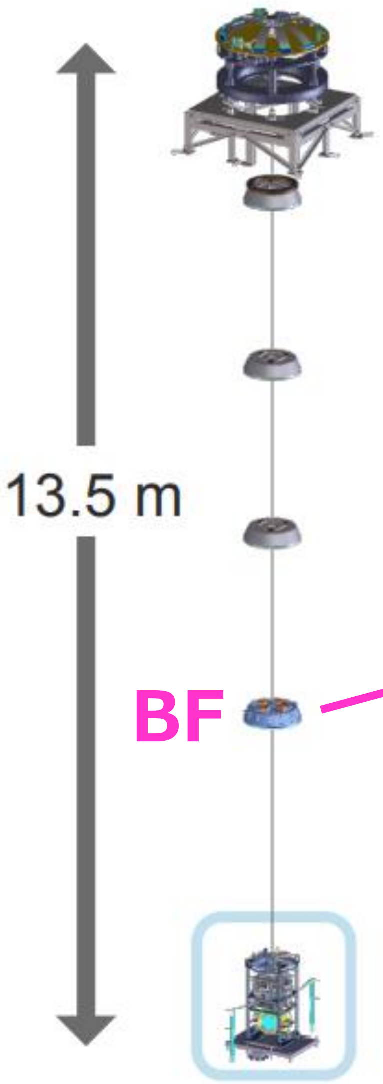


Geometric-Anti Spring

with 1 vertical
LVDT & actuator unit

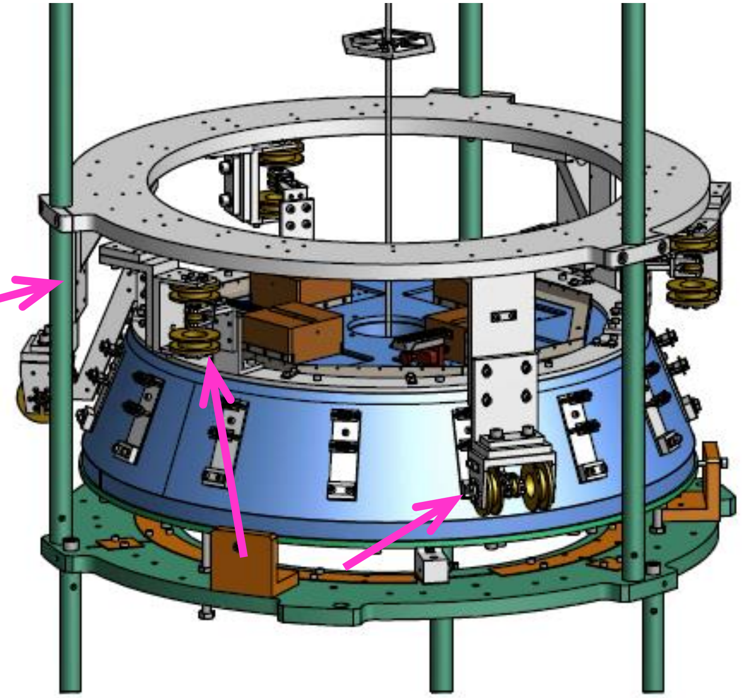
メイン鏡用の防振装置

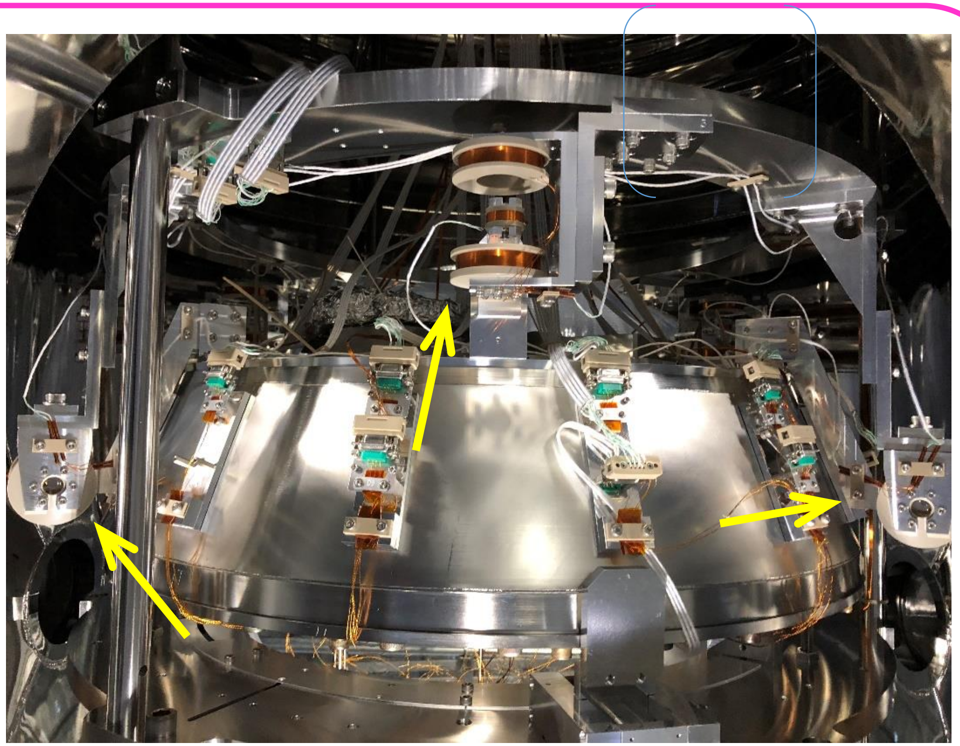
(イタリアのグループの協力のもと開発)



Bottom-Filter DAMPER

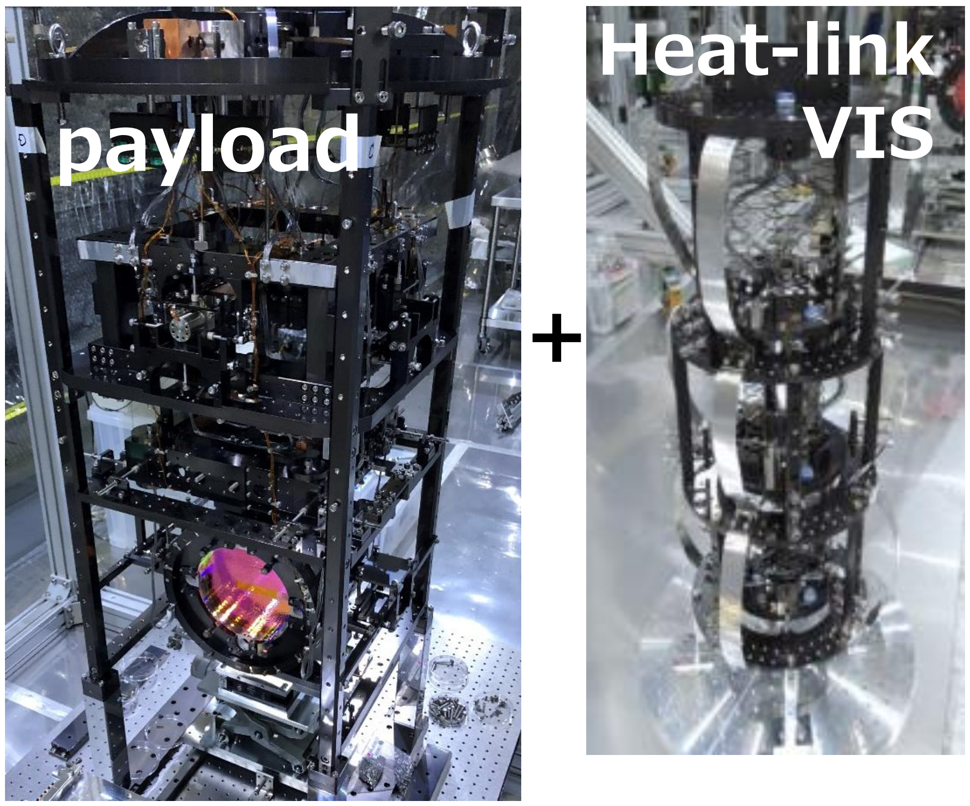
with 3 horizontal & 3 vertical LVDT & actuator units





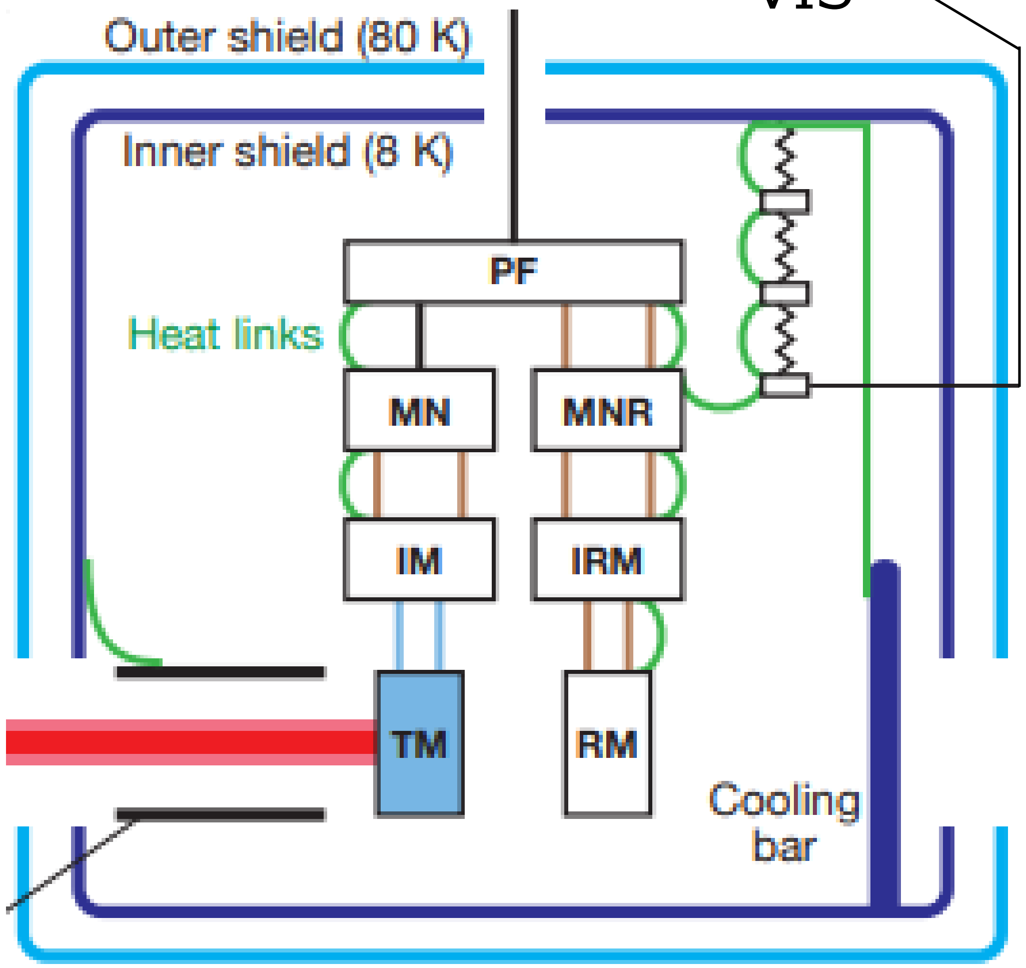
メイン鏡用の防振装置

クライオスタットの中



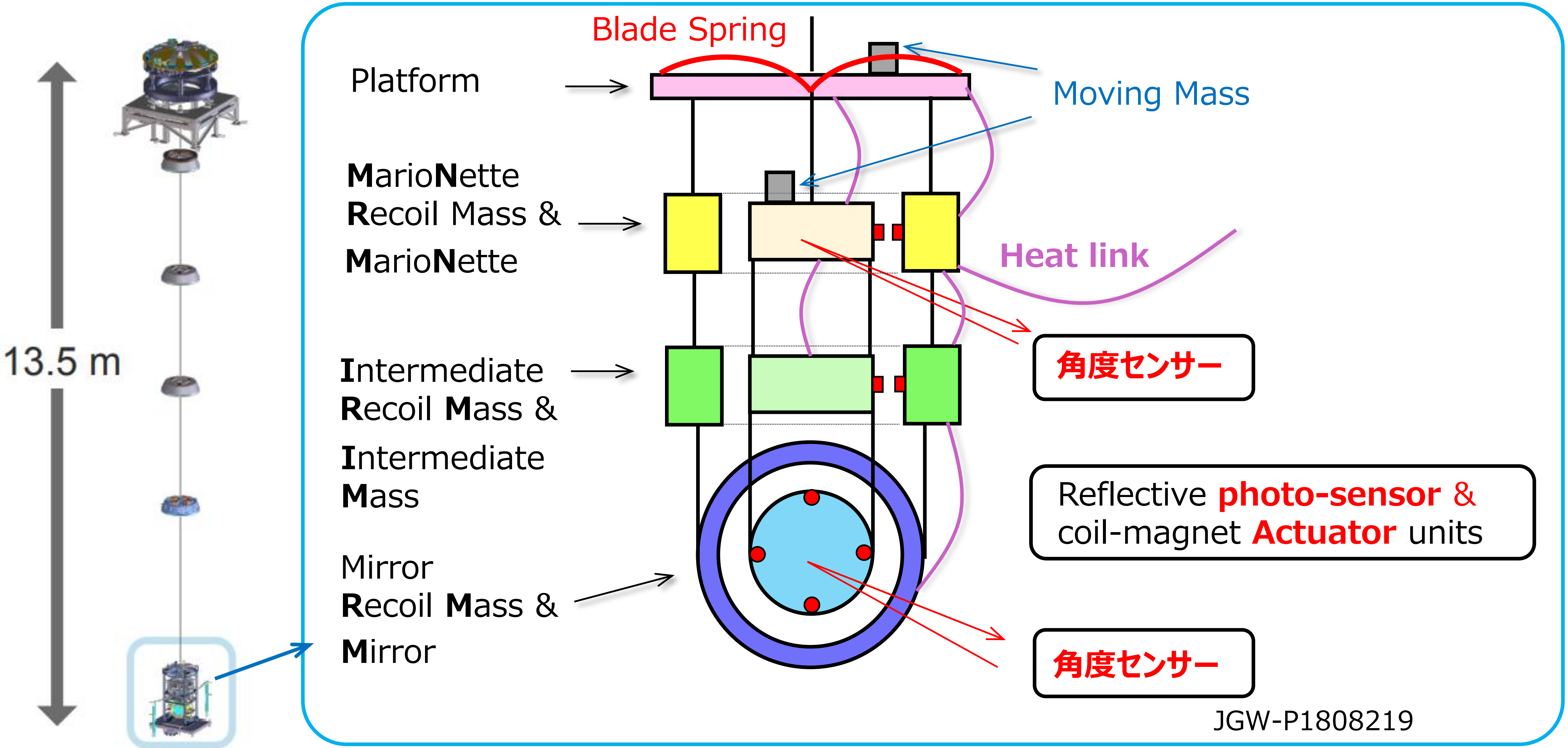
(+ Wide-angle baffle)

Heat-link VIS



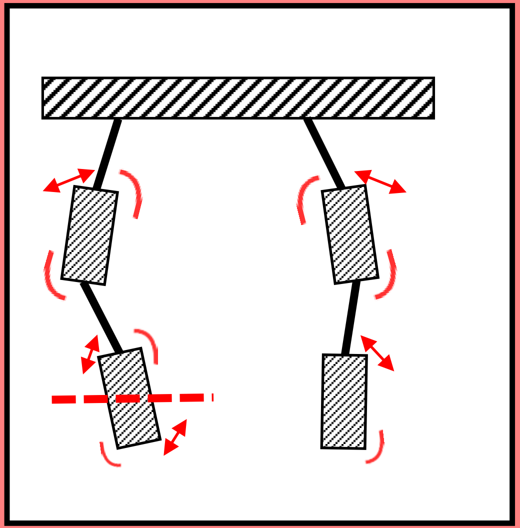
JGW-P1809347

メイン鏡用の防振装置


13.5 m
Blade Spring
Platform
Moving Mass
MarioNette
Recoil Mass &
MarioNette
Heat link
Intermediate
Recoil Mass &
Intermediate
Mass
角度センサー
Reflective photo-sensor &
coil-magnet Actuator units
Mirror
Recoil Mass &
Mirror
角度センサー
JGW-P1808219

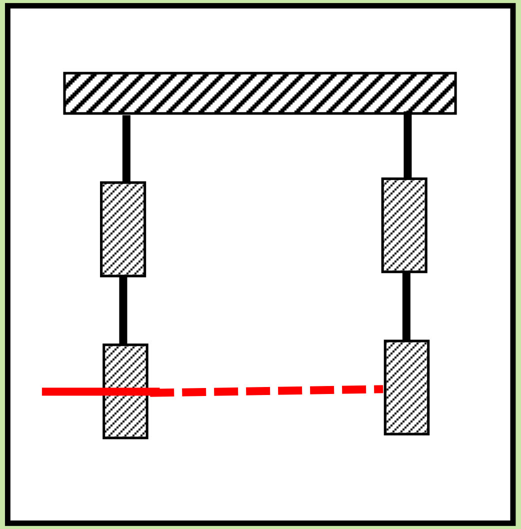
Designing active control system / Control phase

1. Calm-down phase



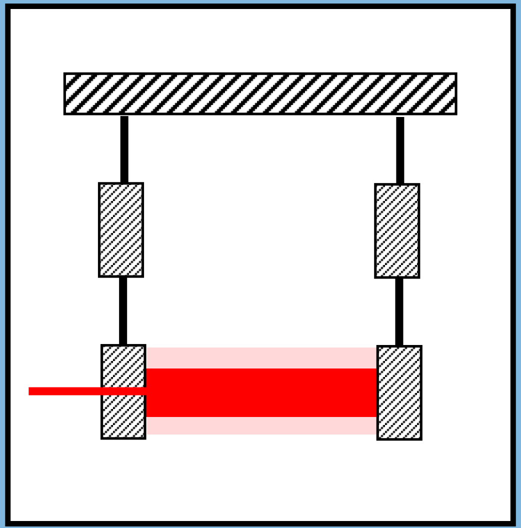
Suppress
large disturbance

2. Lock-acquisition phase



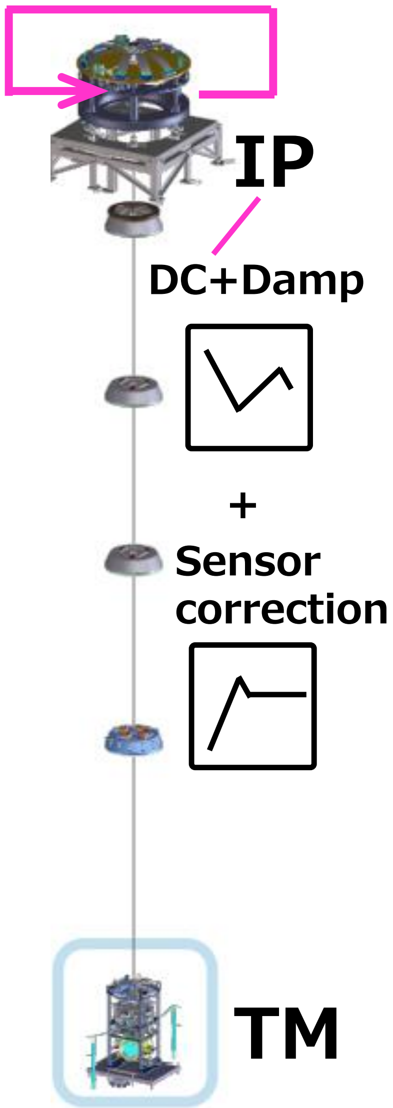
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

3. Observation phase

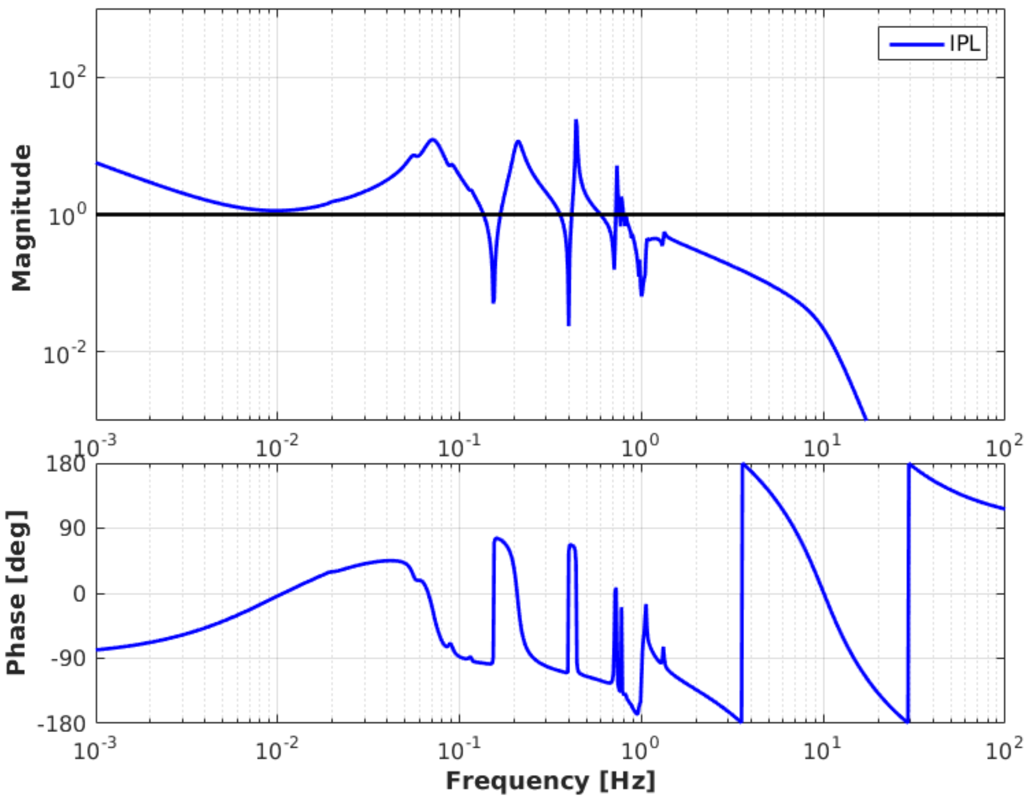


Keep position
with low noise
control

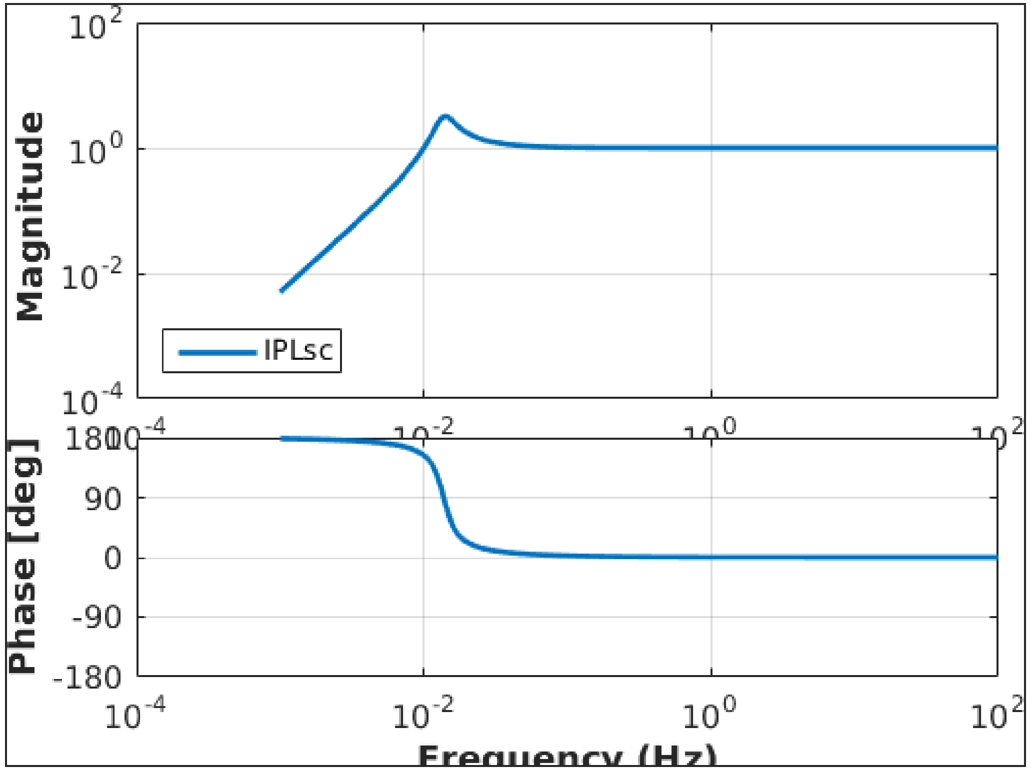
制御ループ at IP-stage:



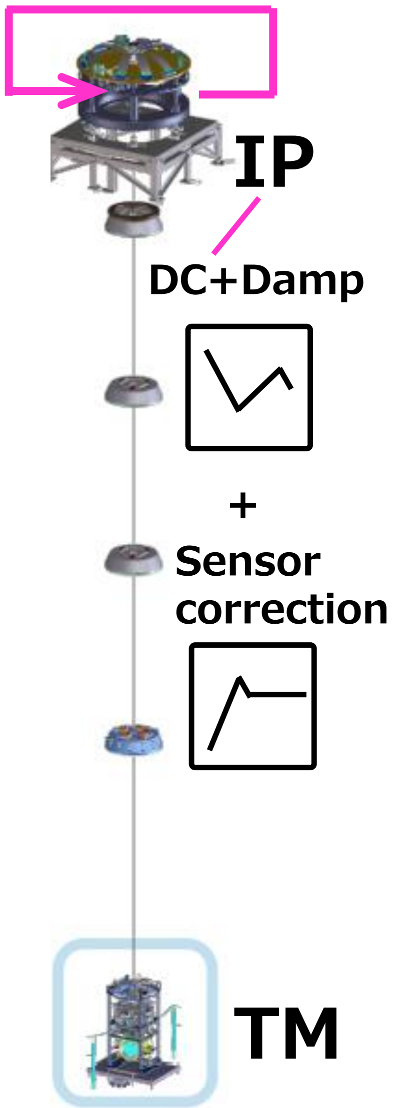
1. OLTF for IP-LVDT

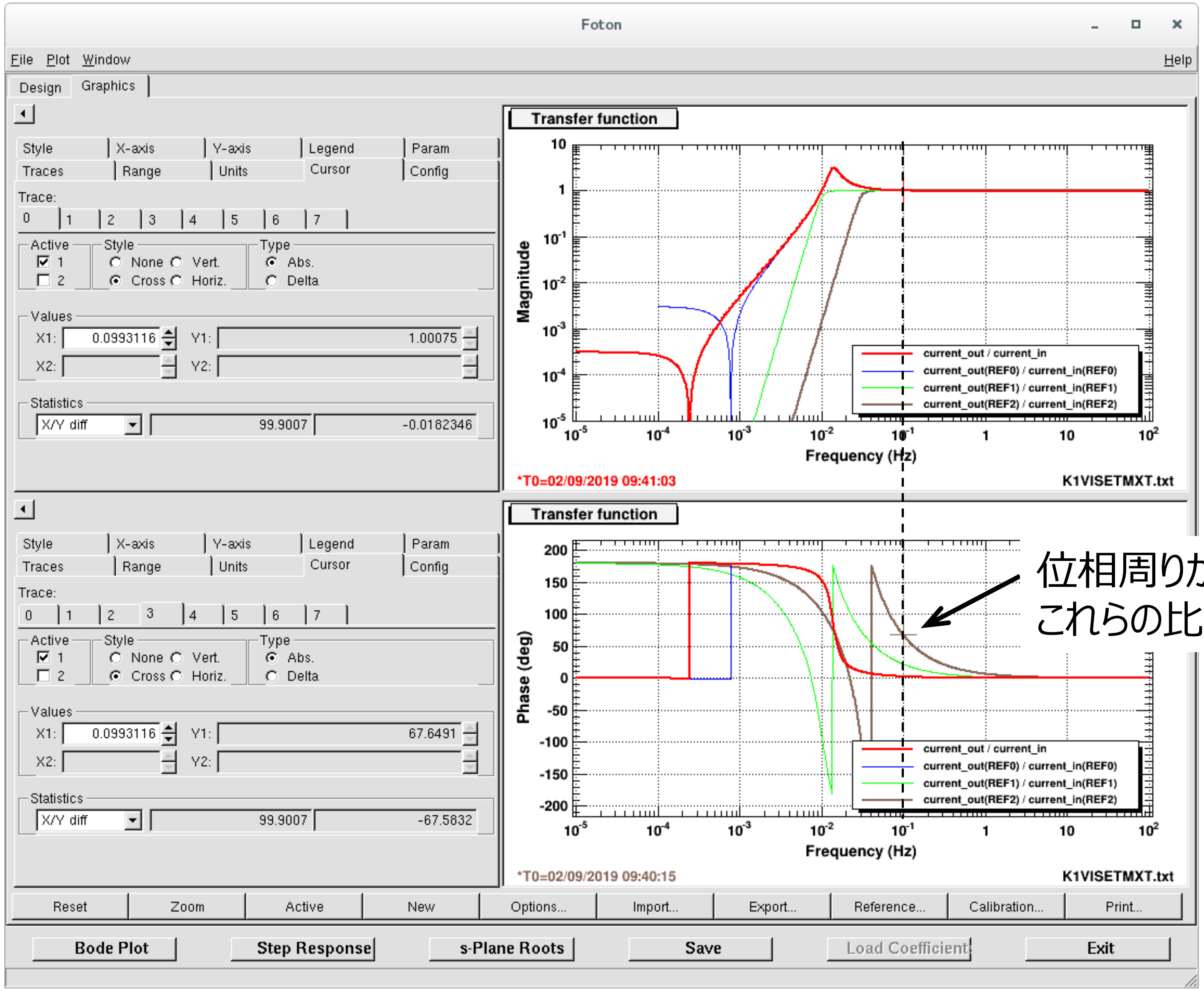


2. Sensor correction filter



Sensor correction filter の検討

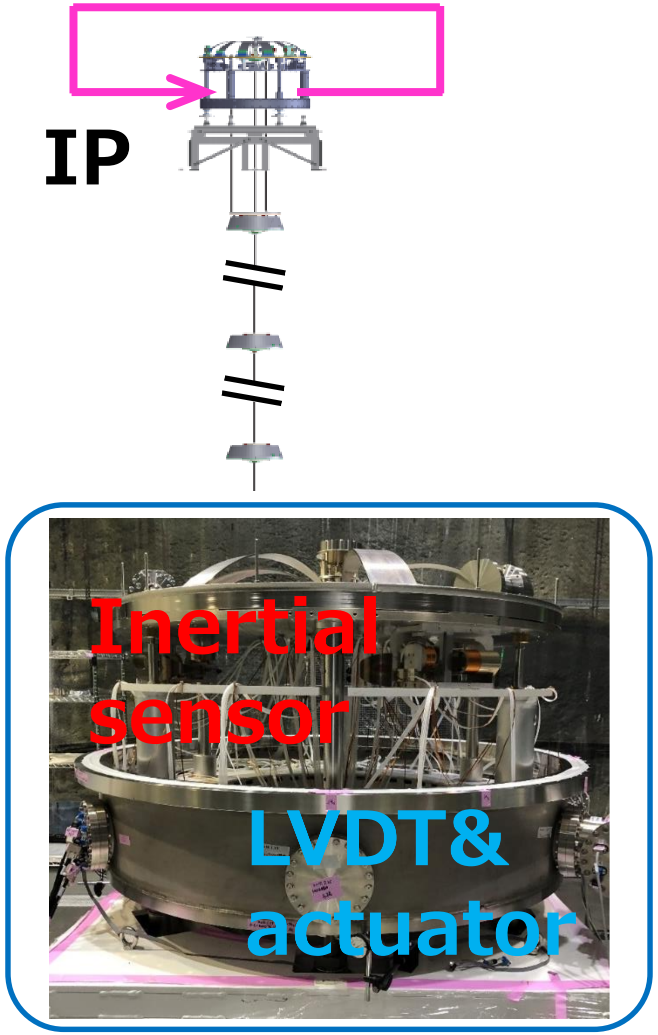


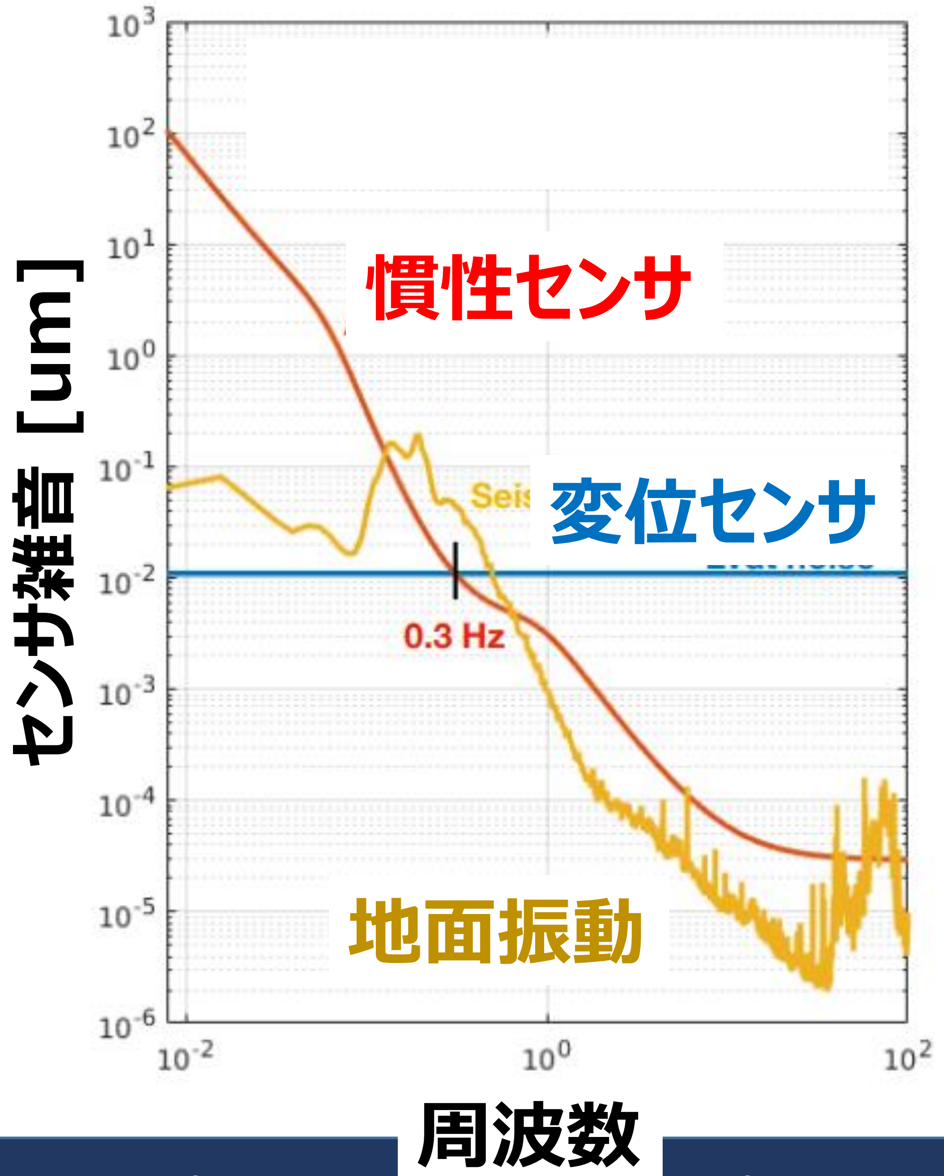


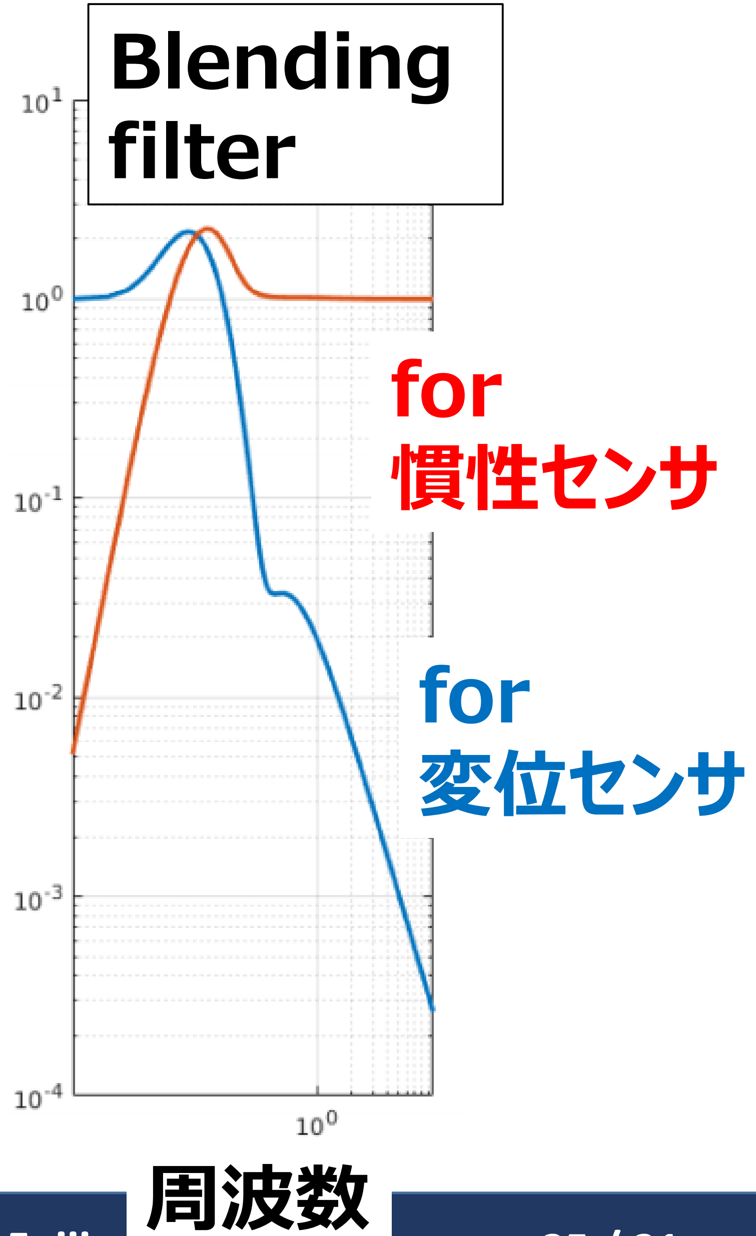
位相周りがなるべく少ないものを採用した。
これらの比較plotを作成しておく。

Sensor blending & inertial damping

(From JGW-G1909932)

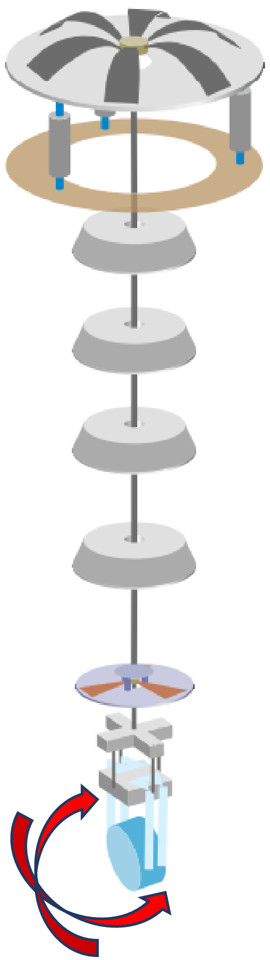


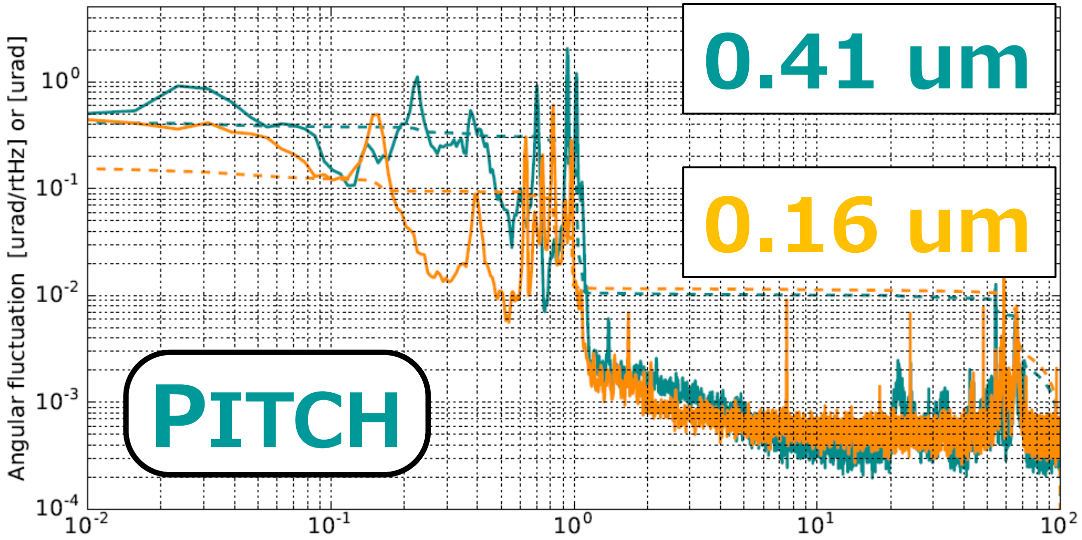




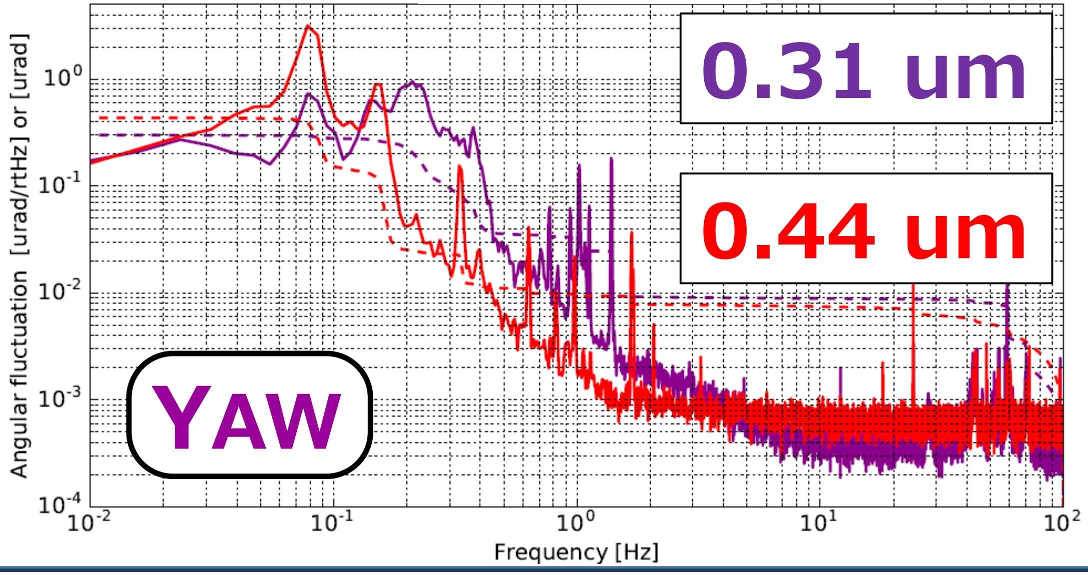
Sensor blending & inertial damping

ITMX

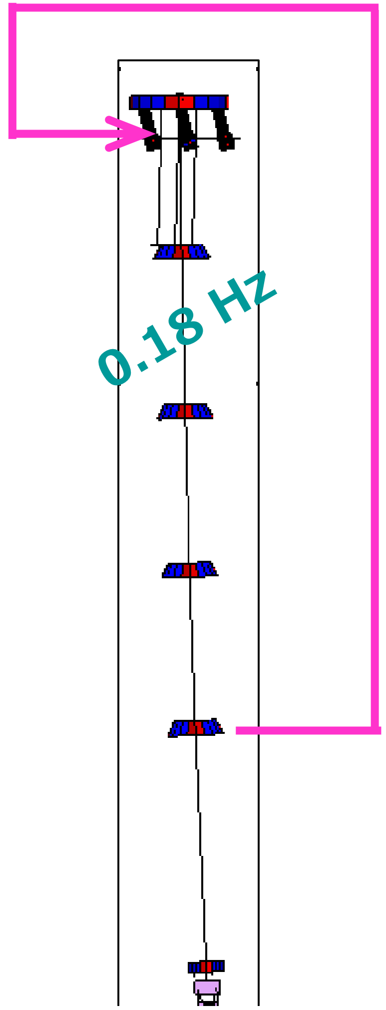




w/ inertial damping



w/ inertial damping



(*)異なる日の測定。ただし地面振動レベルは同程度。

より高周波側(~0.6Hzとか?)でのBlendingは、試してもよいかも?

大型重力波望遠鏡 KAGRA

(From JGW-G1909822)

直近の目標:
LIGO/Virgo - O3への参加

主な進捗:
- サファイアミラーの完成
- 防振システムの組立て完了
- 3km共振器の制御
など他

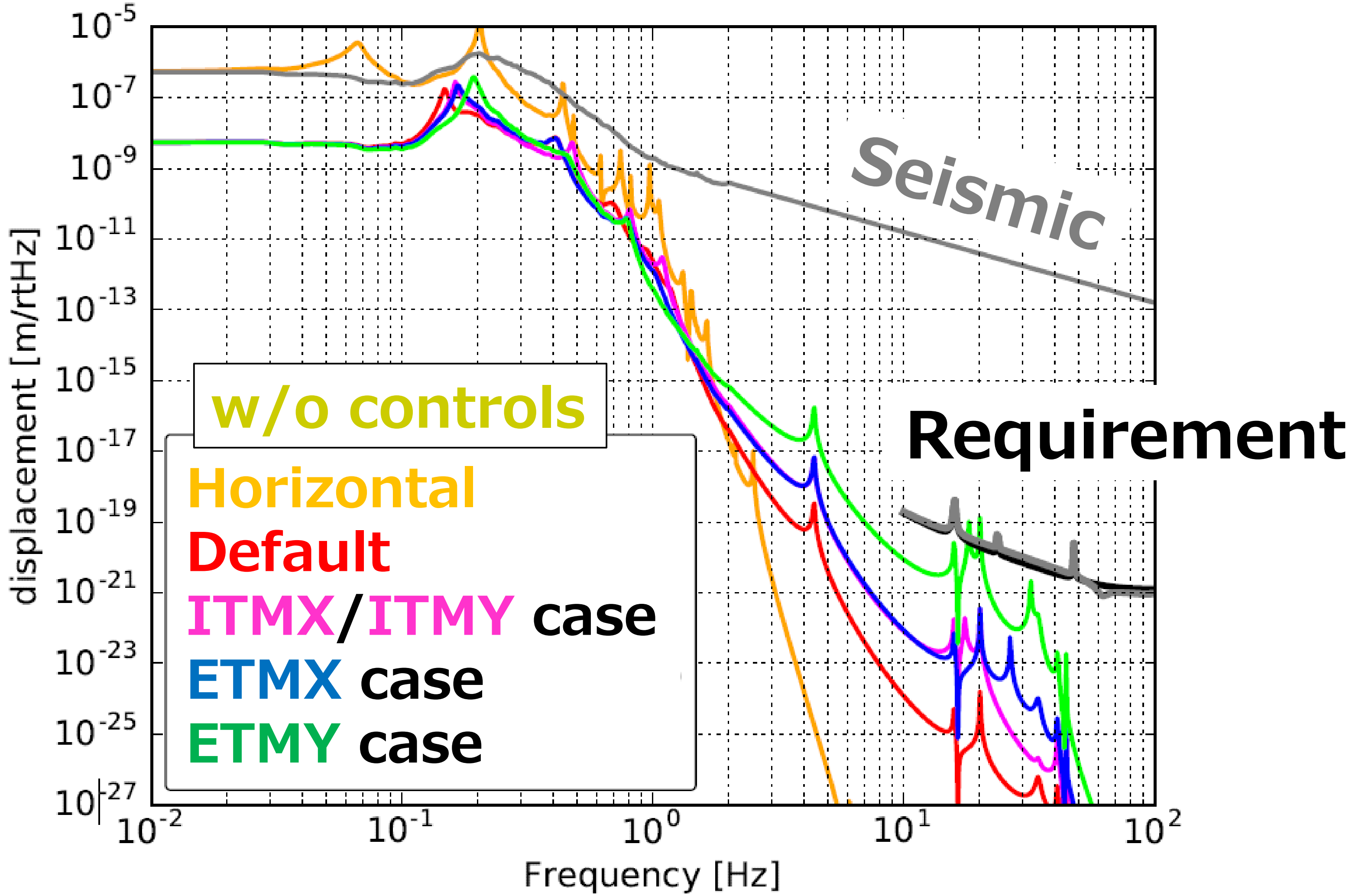
Requirements, Type-A suspensions

Calm-down phase		
Item	Requirement	For/Determined by
$1/e$ modal decay time	< 1 min	Quick recovery
RMS displacement (L)	$< 50\ \mu$m	Smooth transition to next phase
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	$< 50\ \mu$m	Smooth transition to next phase
Lock acquisition phase		
Item	Requirement	For/Determined by
RMS velocity (L)	$< 240\ \mu$m/s	Auxiliary laser locking
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 880 nrad	Optical gain degradation $< 5\%$
Observation phase		
Item	Requirement	For/Determined by
Displacement noise (L) @ 10 Hz	$< 8 \times 10^{-20}$ m/Hz$^{1/2}$	Sensitivity
Displacement noise (V) @ 10 Hz	$< 8 \times 10^{-18}$ m/Hz$^{1/2}$	Sensitivity (1% coupling to L)
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 200 nrad	Beam spot fluctuation < 1 mm
DC drift (P, Y)	< 400 nrad/h	Sustainable lock for 1 day left

(P, Y) are set as $50\,\mu$m and $50\,\mu$rad, respectively [28]. The RMS displacement for the other translational DoFs (T, V) are required for another reason which is mentioned shortly later.

Mechanical installation has done! HOWEVER ..

According to a simulation, assuming 1% coupling,



"acceptable
for the O3-run"

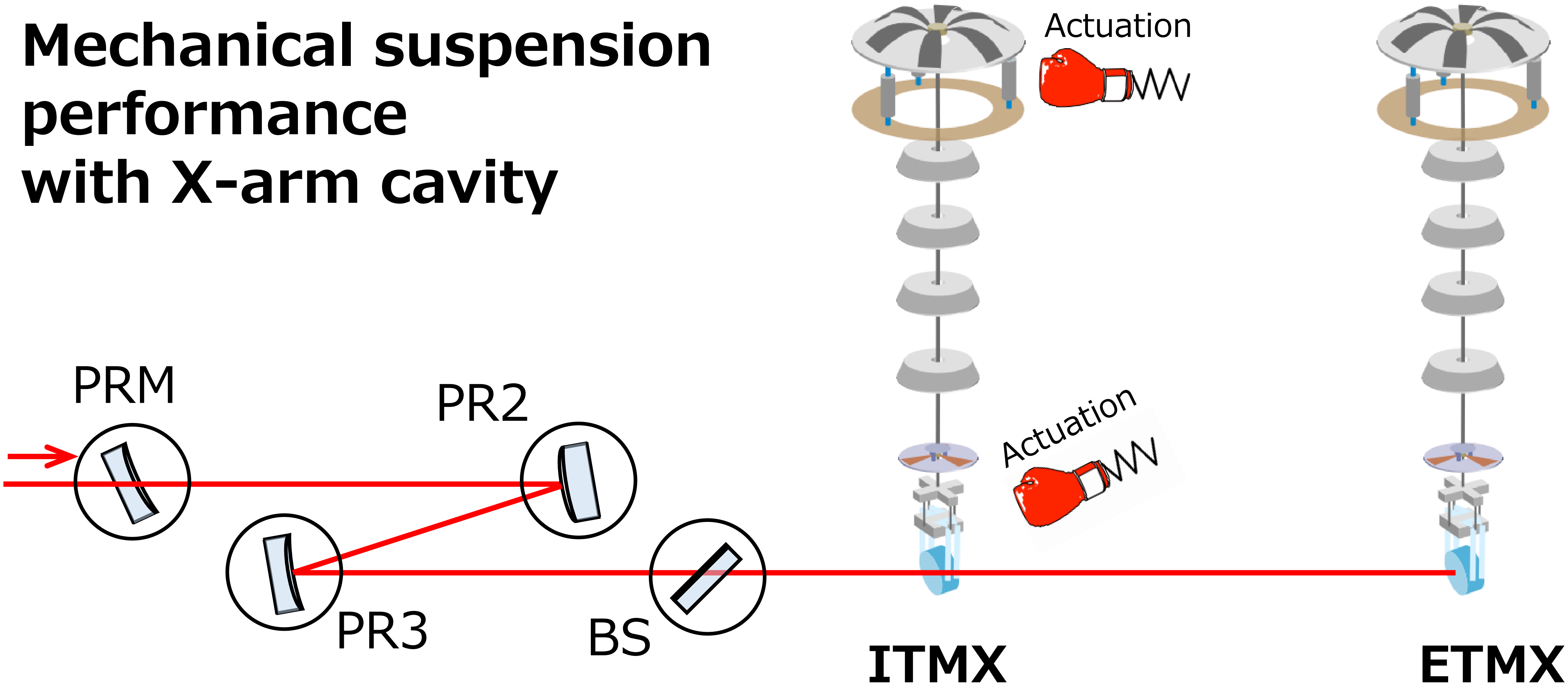
(should be)

Note:
-- Modeled w/o Heat-links
-- params are not tuned.

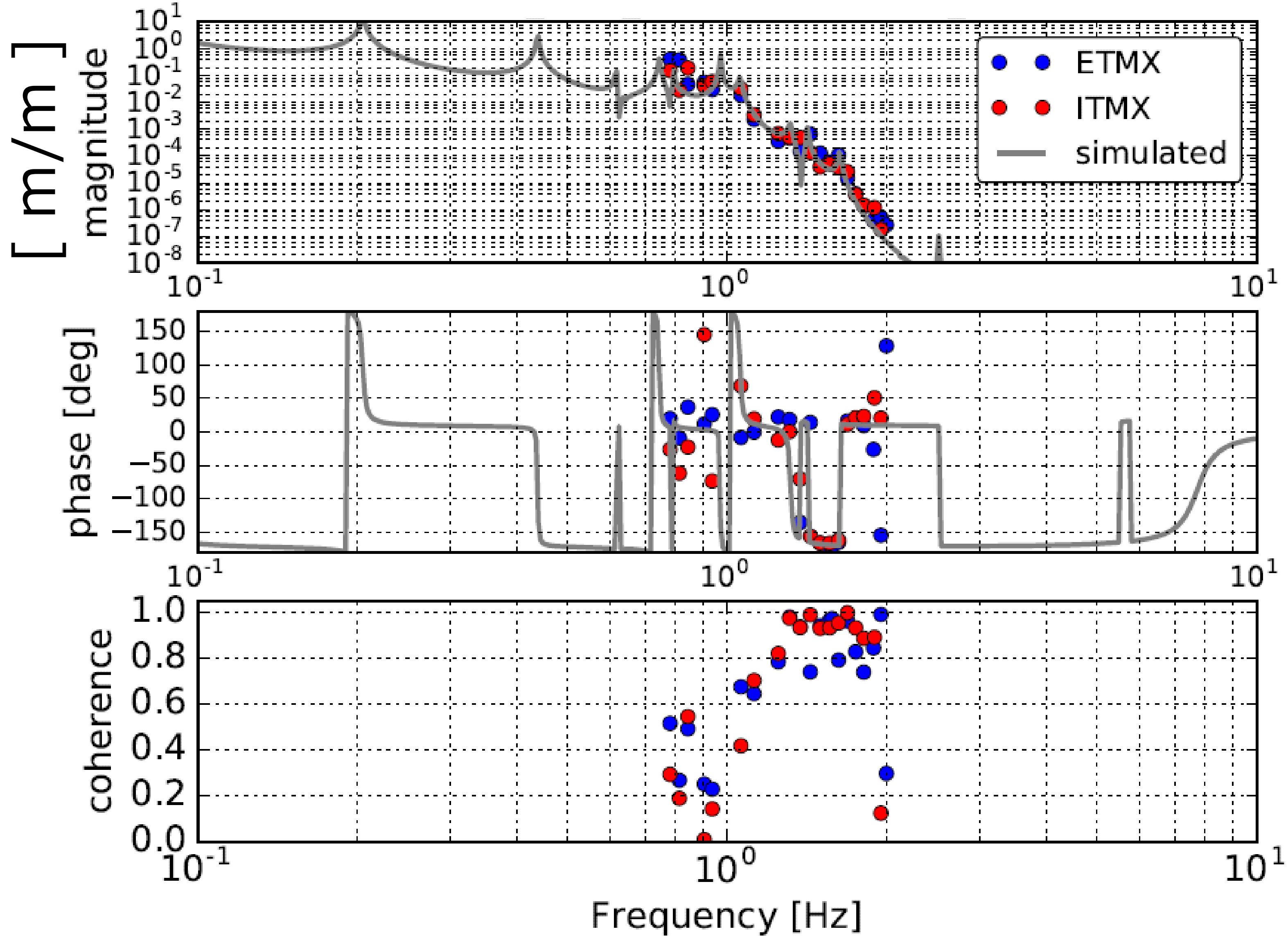
Verification of suspension performance

Measurement:

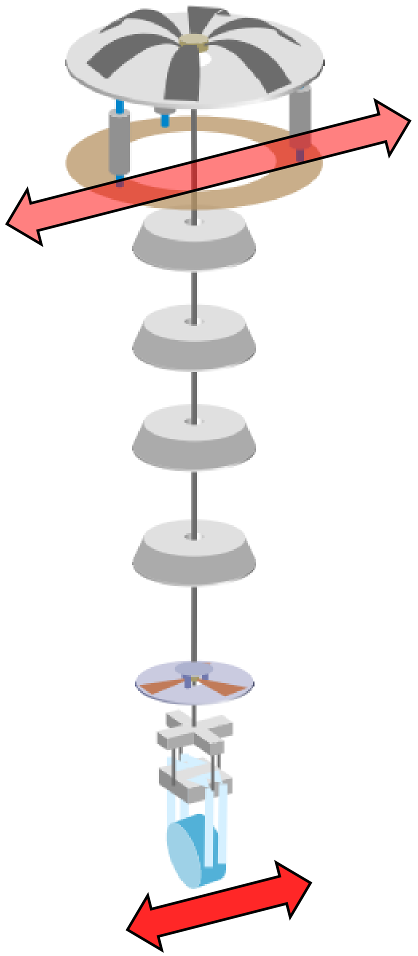
Mechanical suspension performance with X-arm cavity



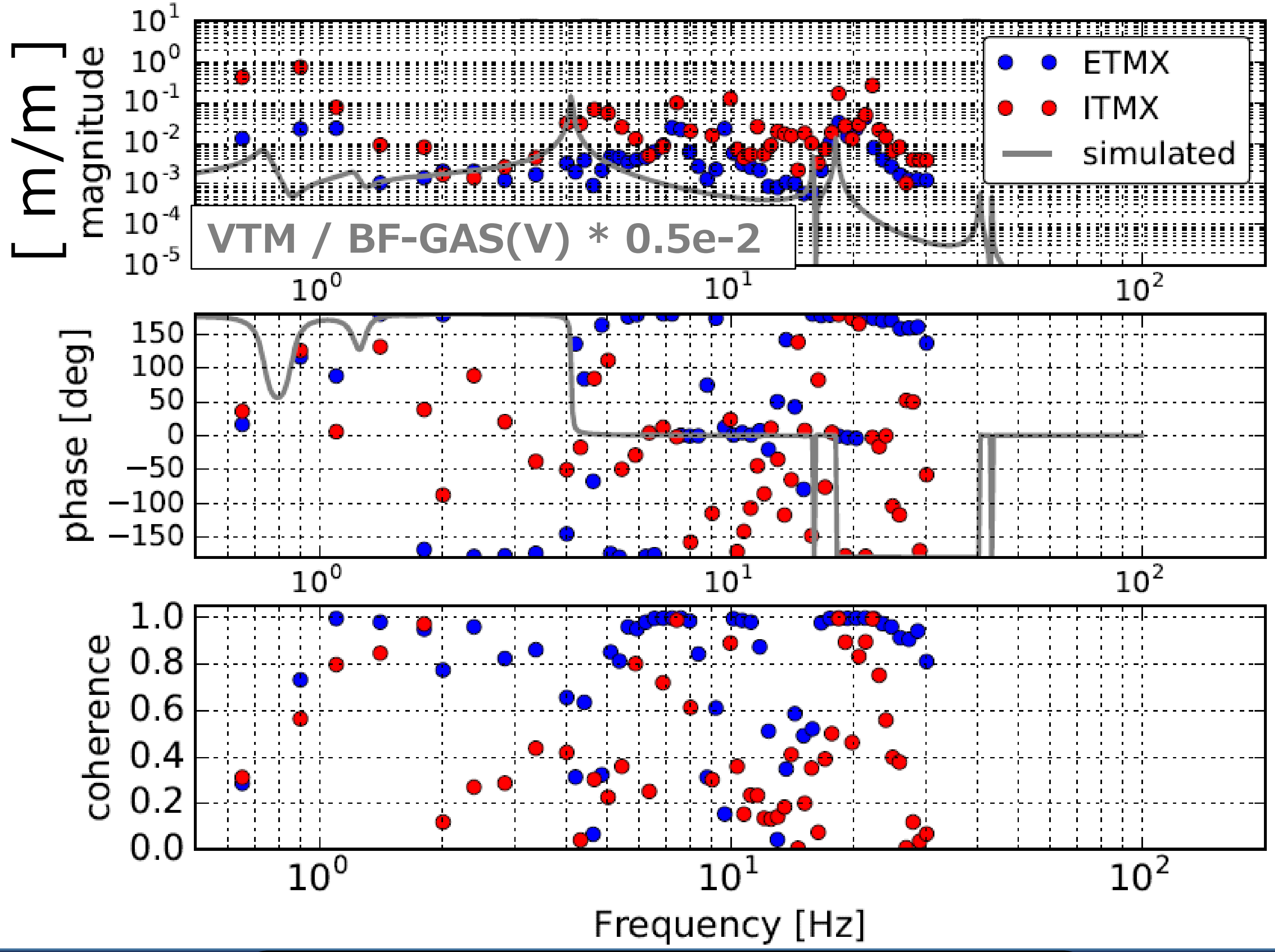
Vibration isolation ratio, [Good news!]



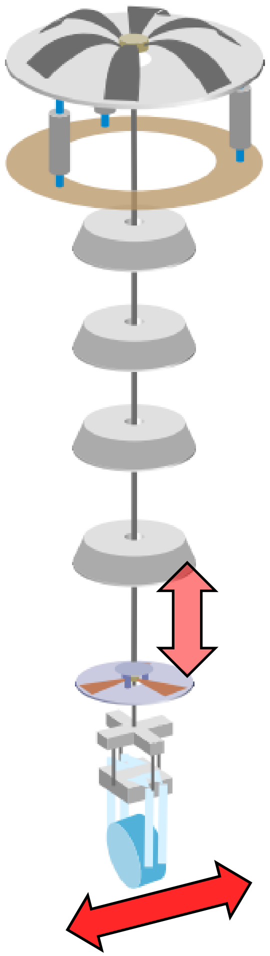
From ground to TM



V to L coupling, [System is not yet identified..]

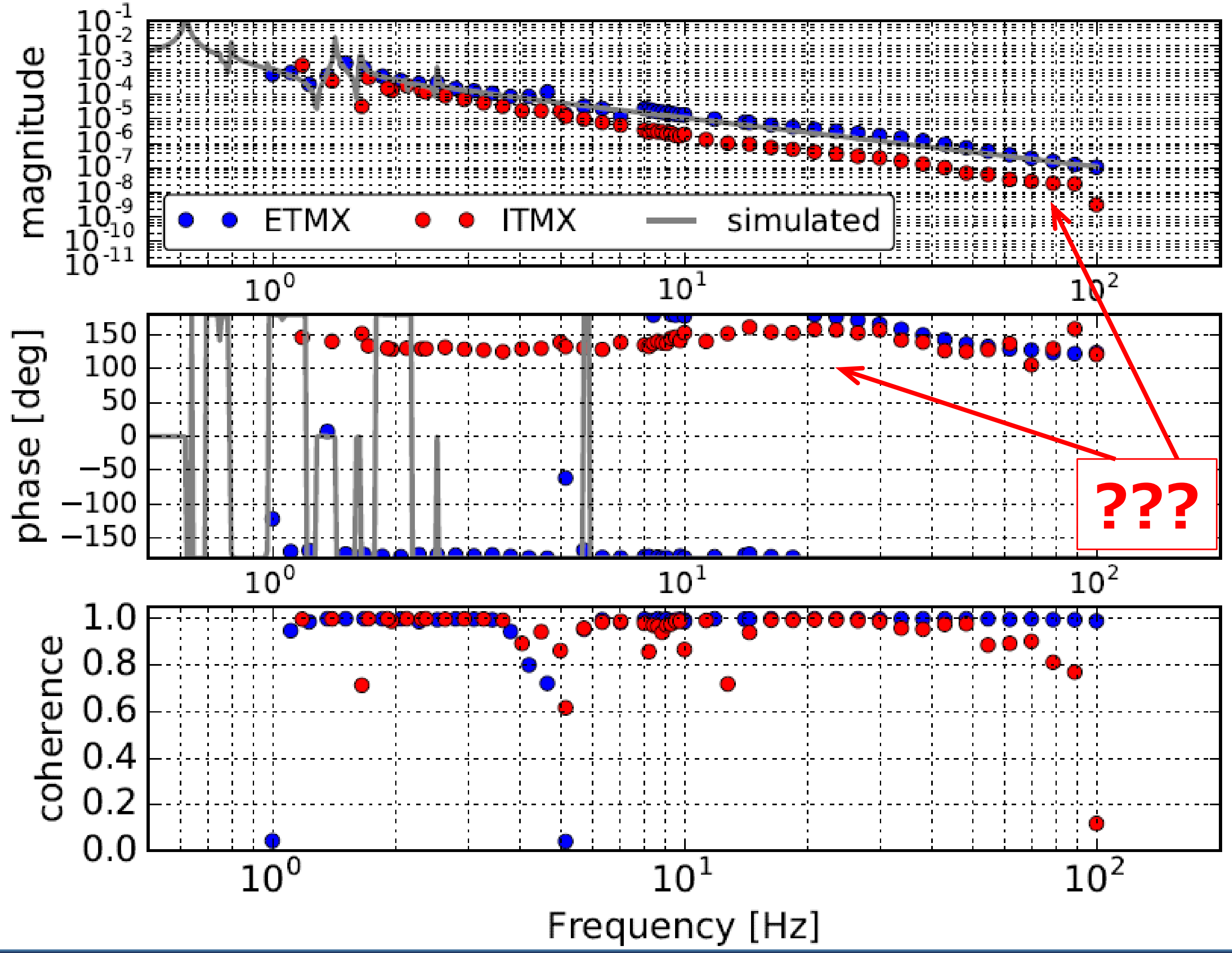


From BF-GAS to TM

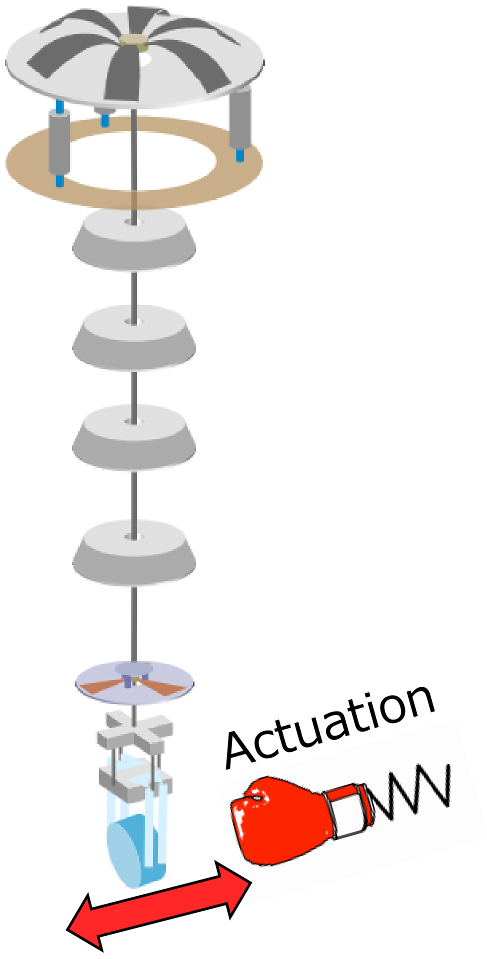


Real was not so simple..

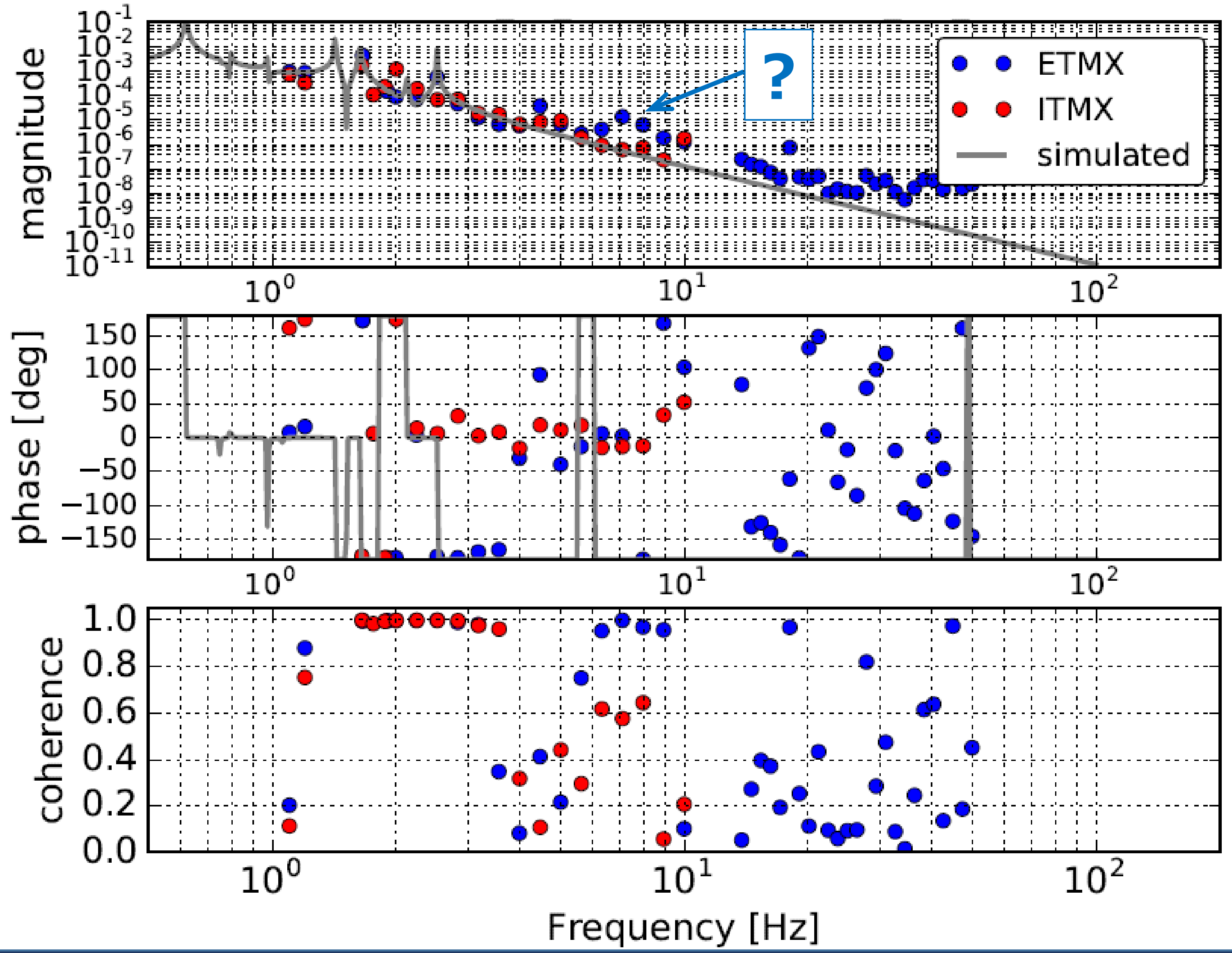
Force transfer functions



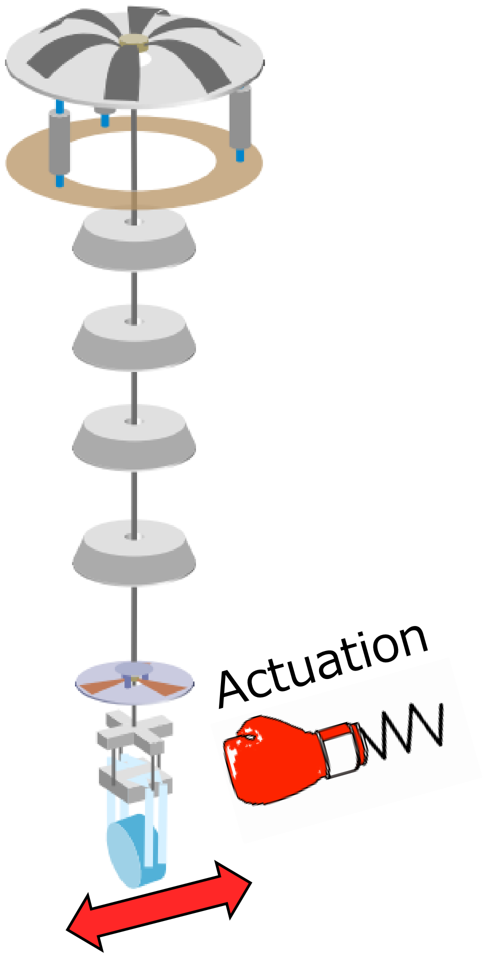
From (TM-RM)-act to TM



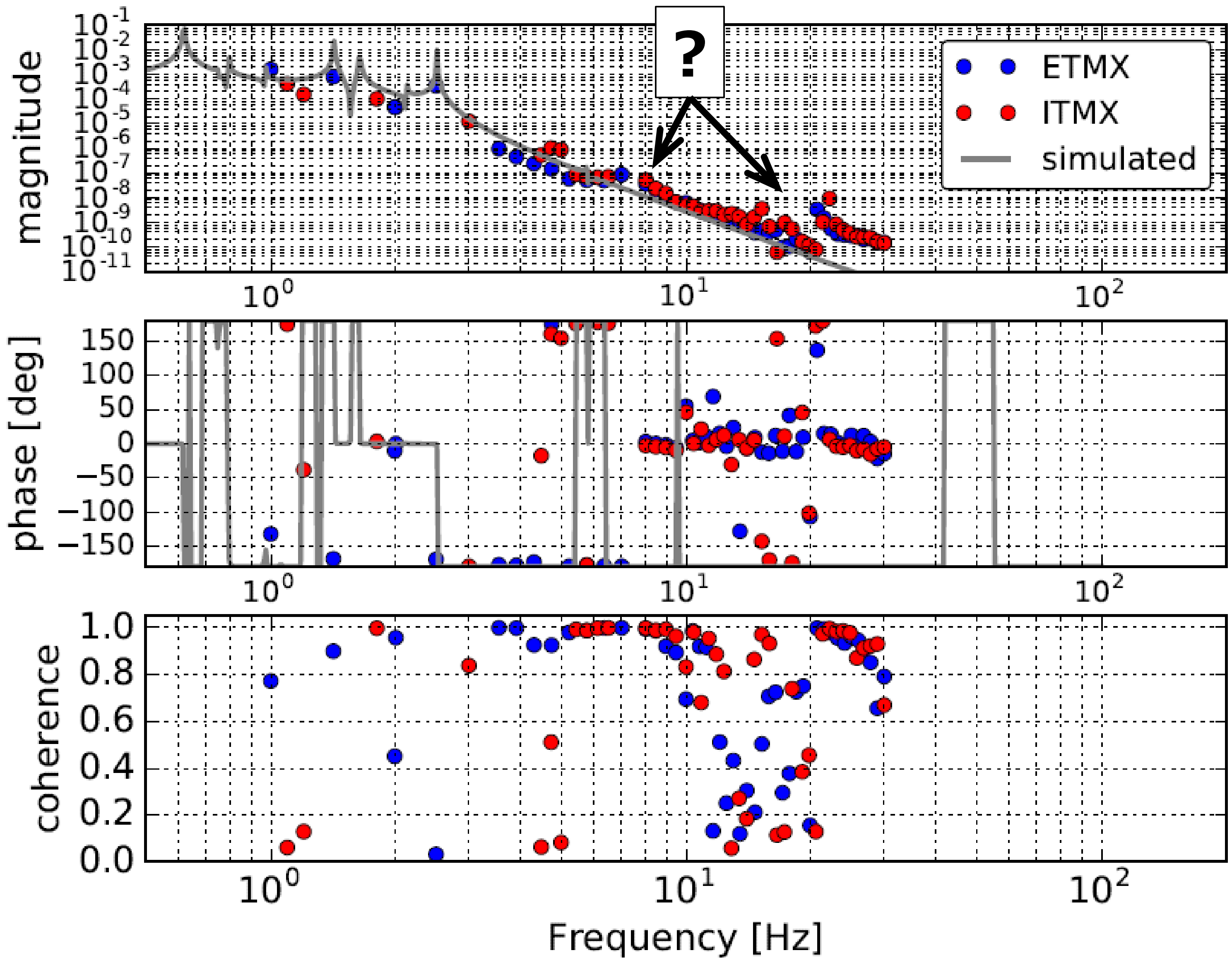
Force transfer functions



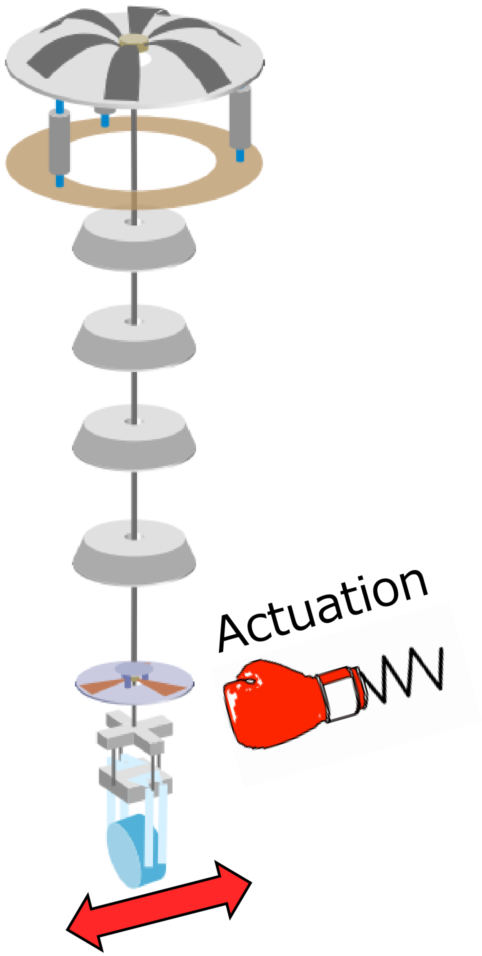
From (IM-IMR)-act to TM

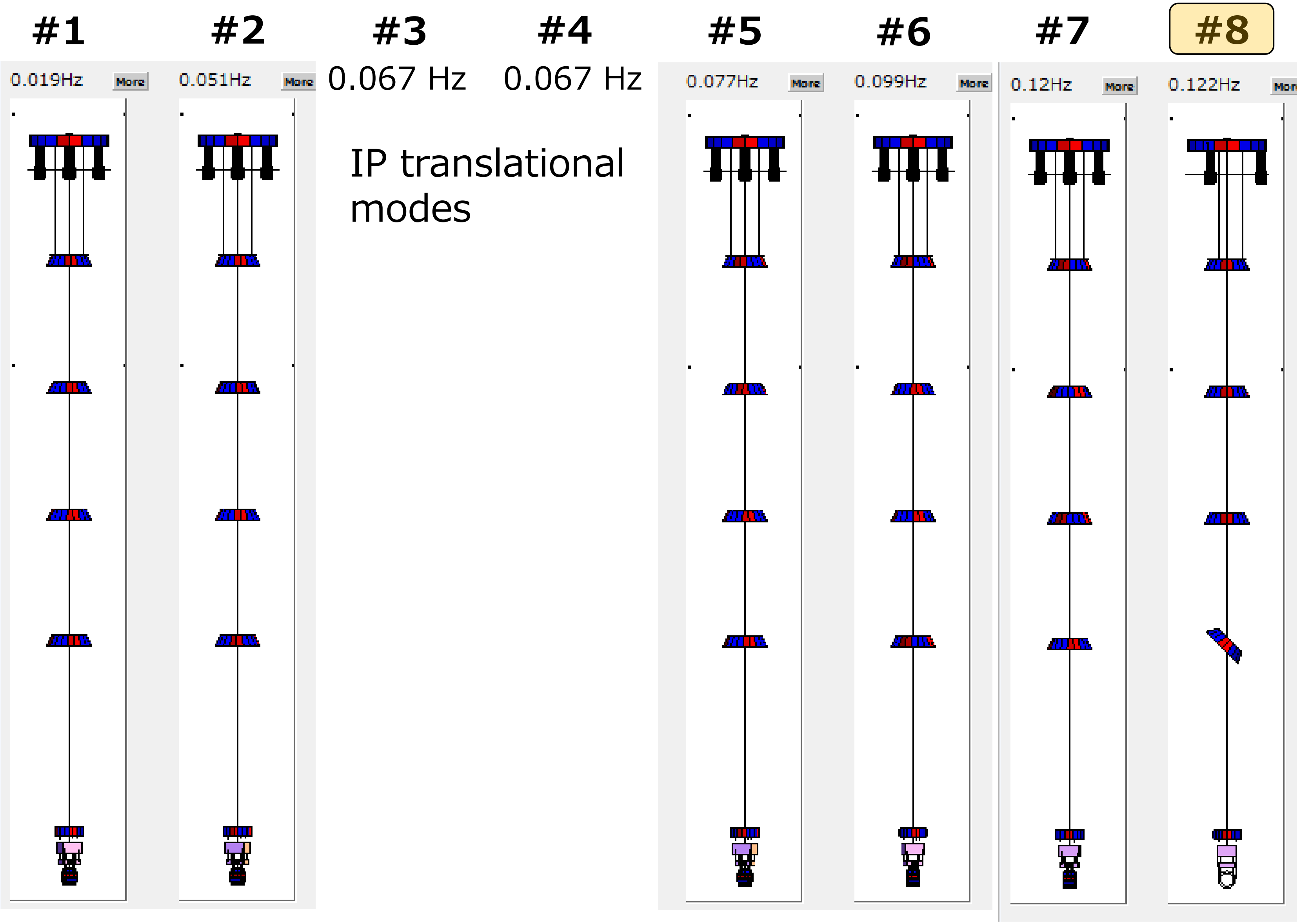


Force transfer functions



From (MN-MNR)-act to TM



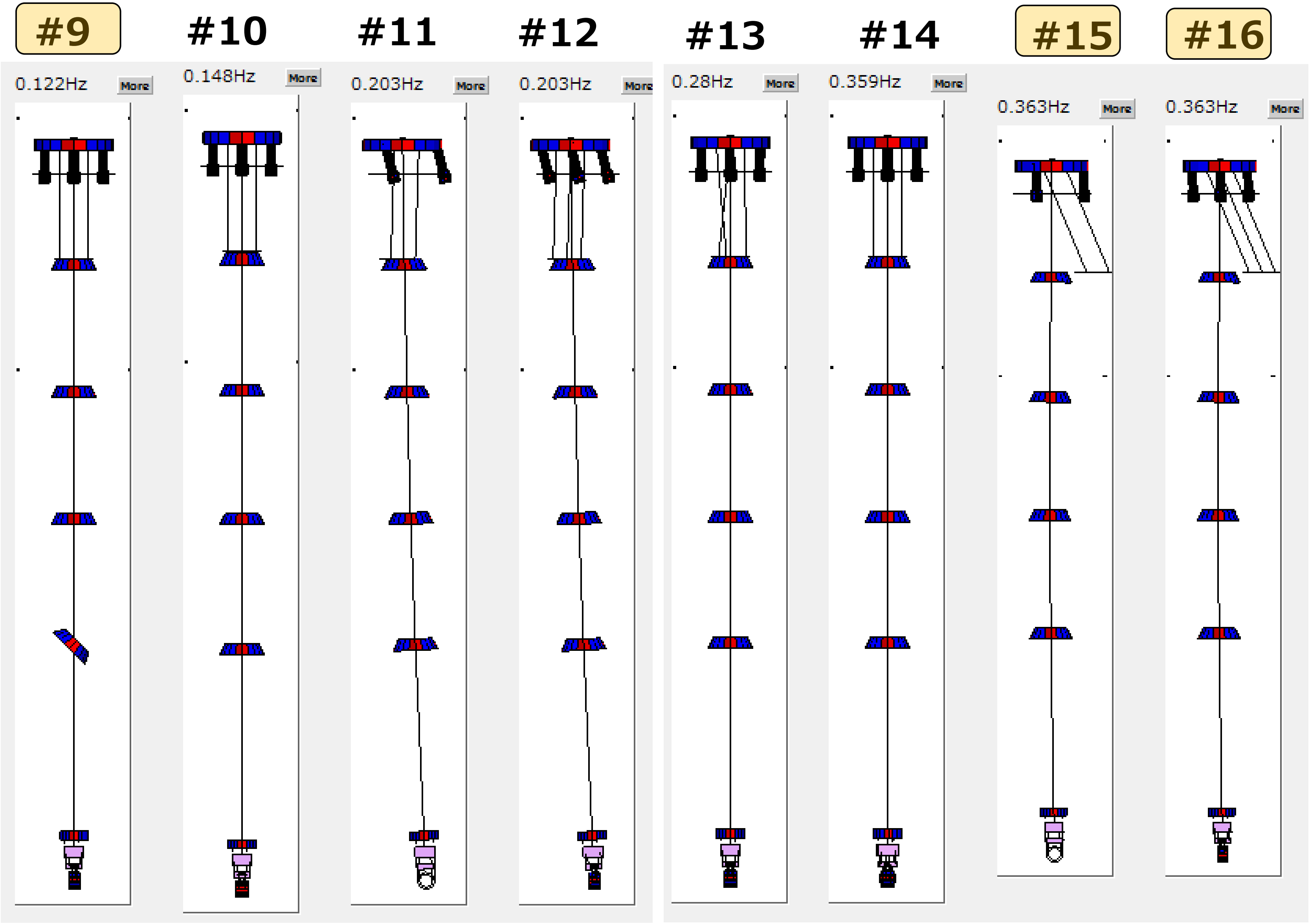


Type-A SAS,

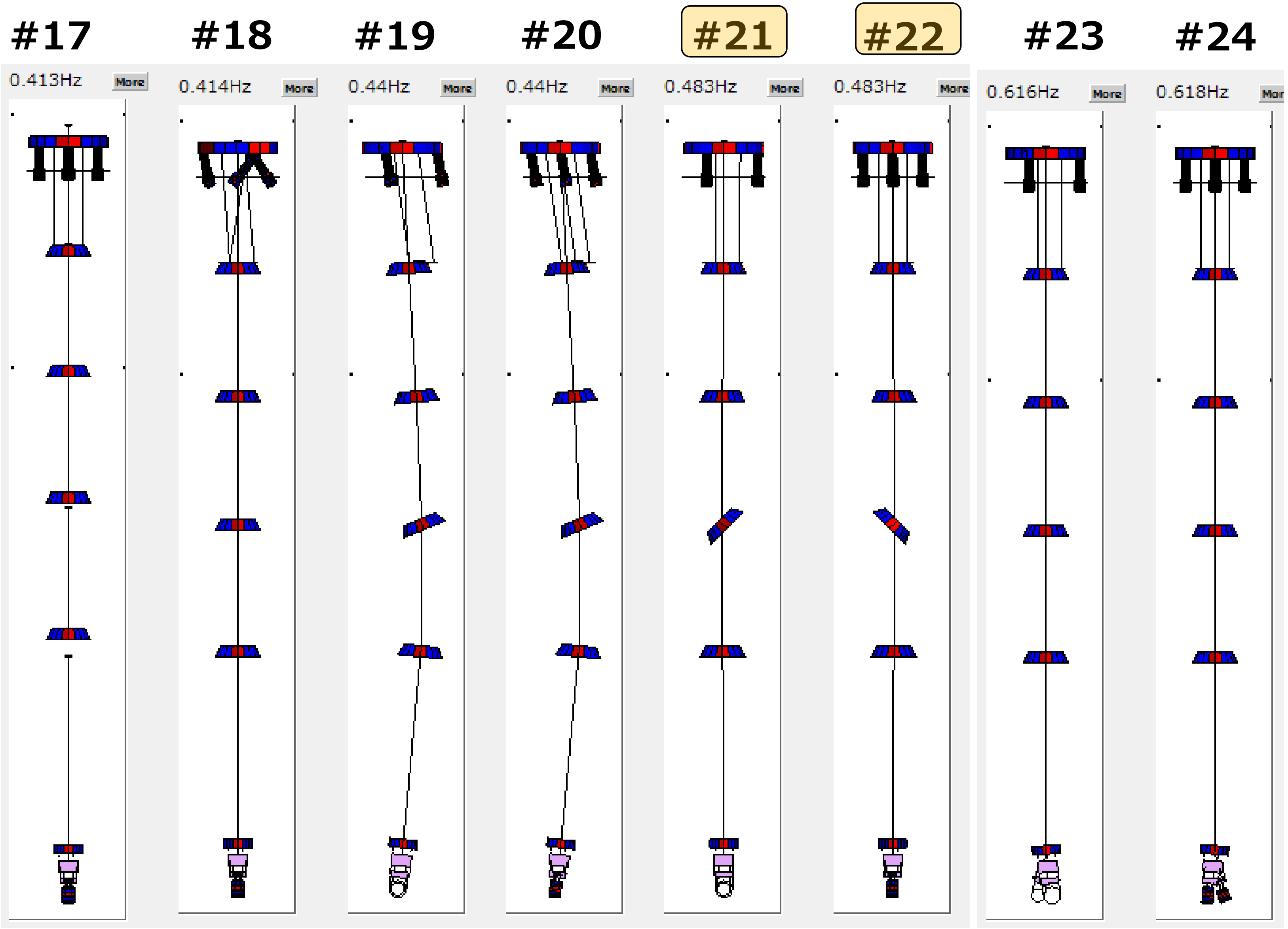
'TyrpeA180429_20K'

Eigen mode: 75 modes

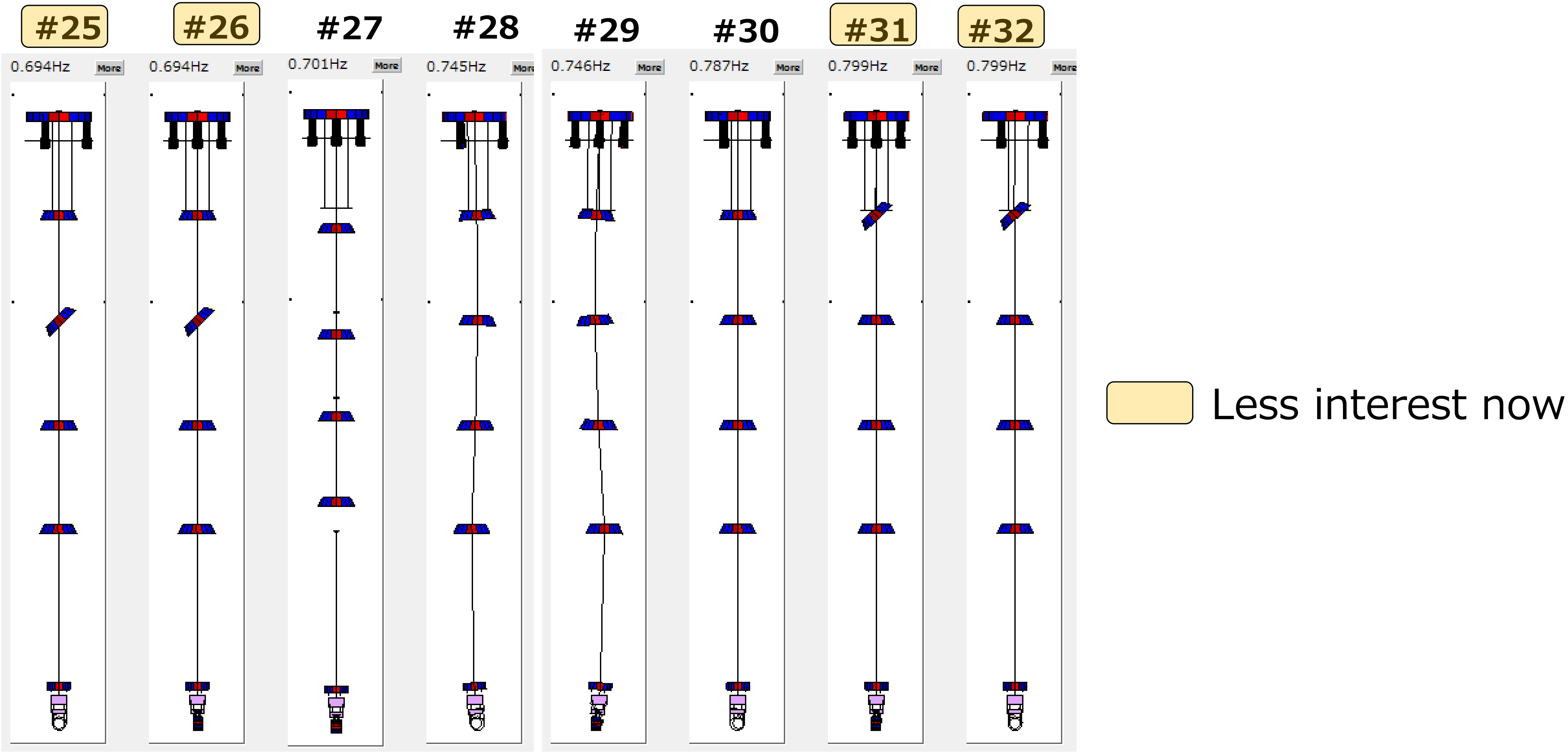
Less interest now

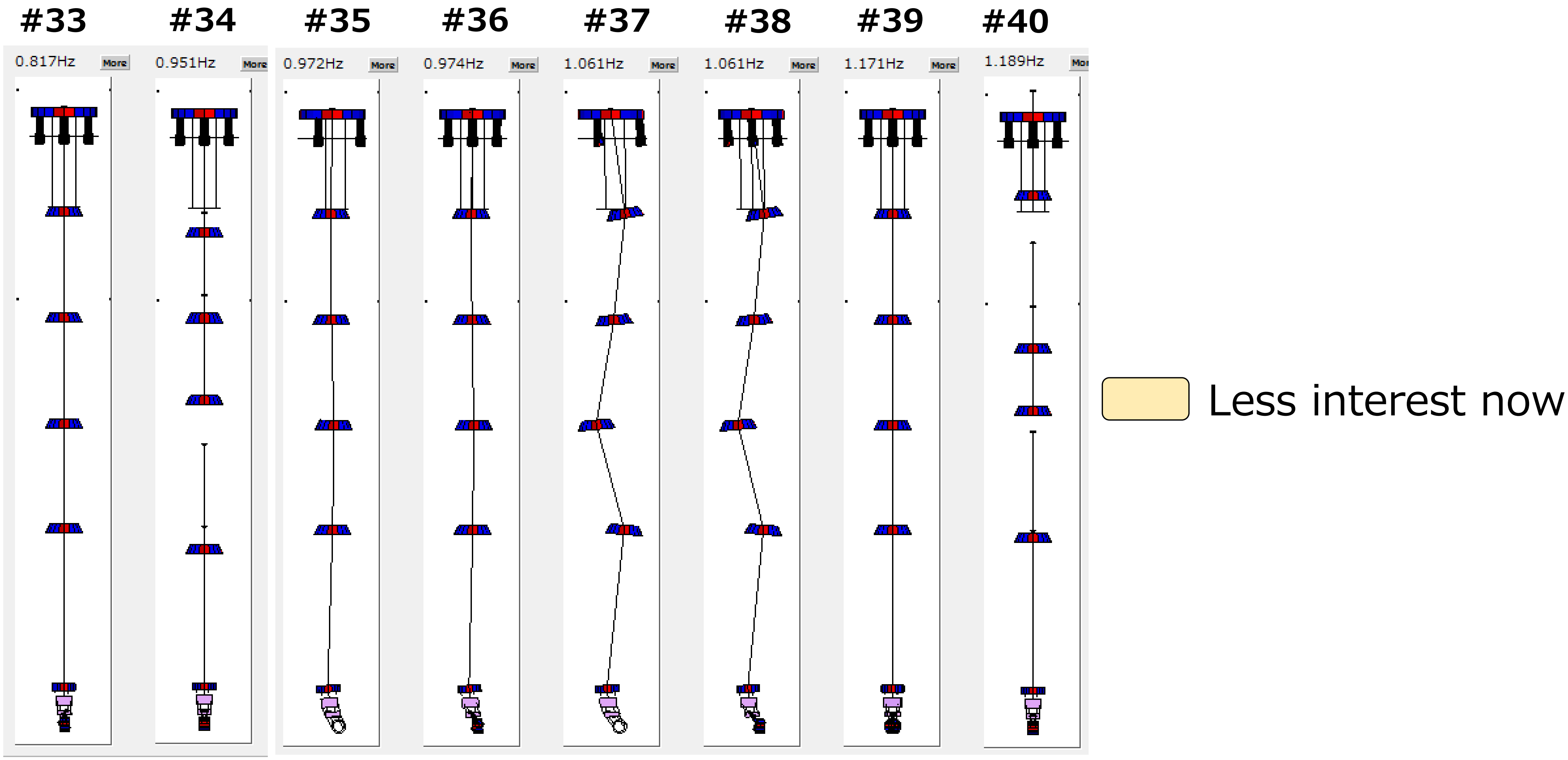


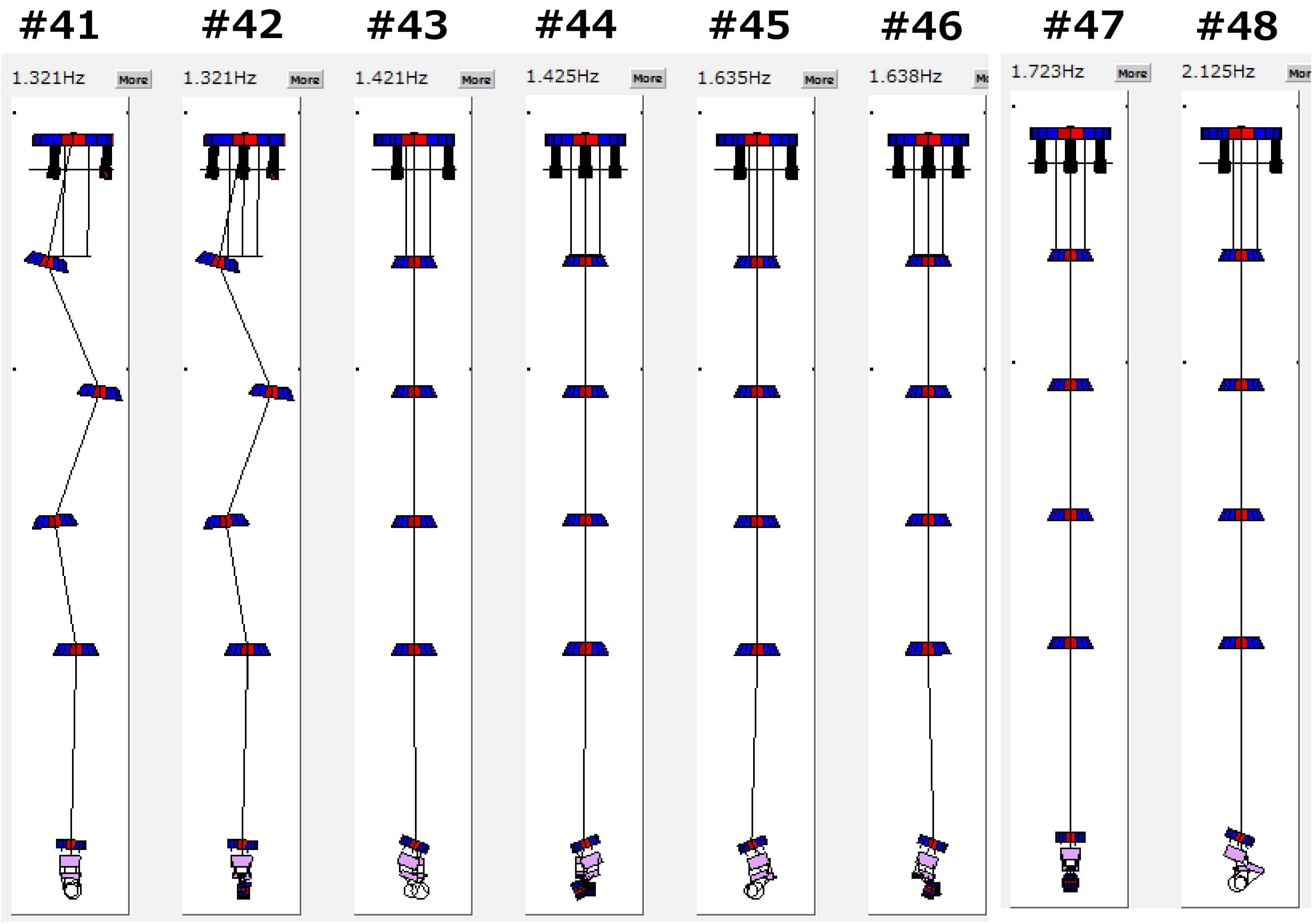
Less interest now



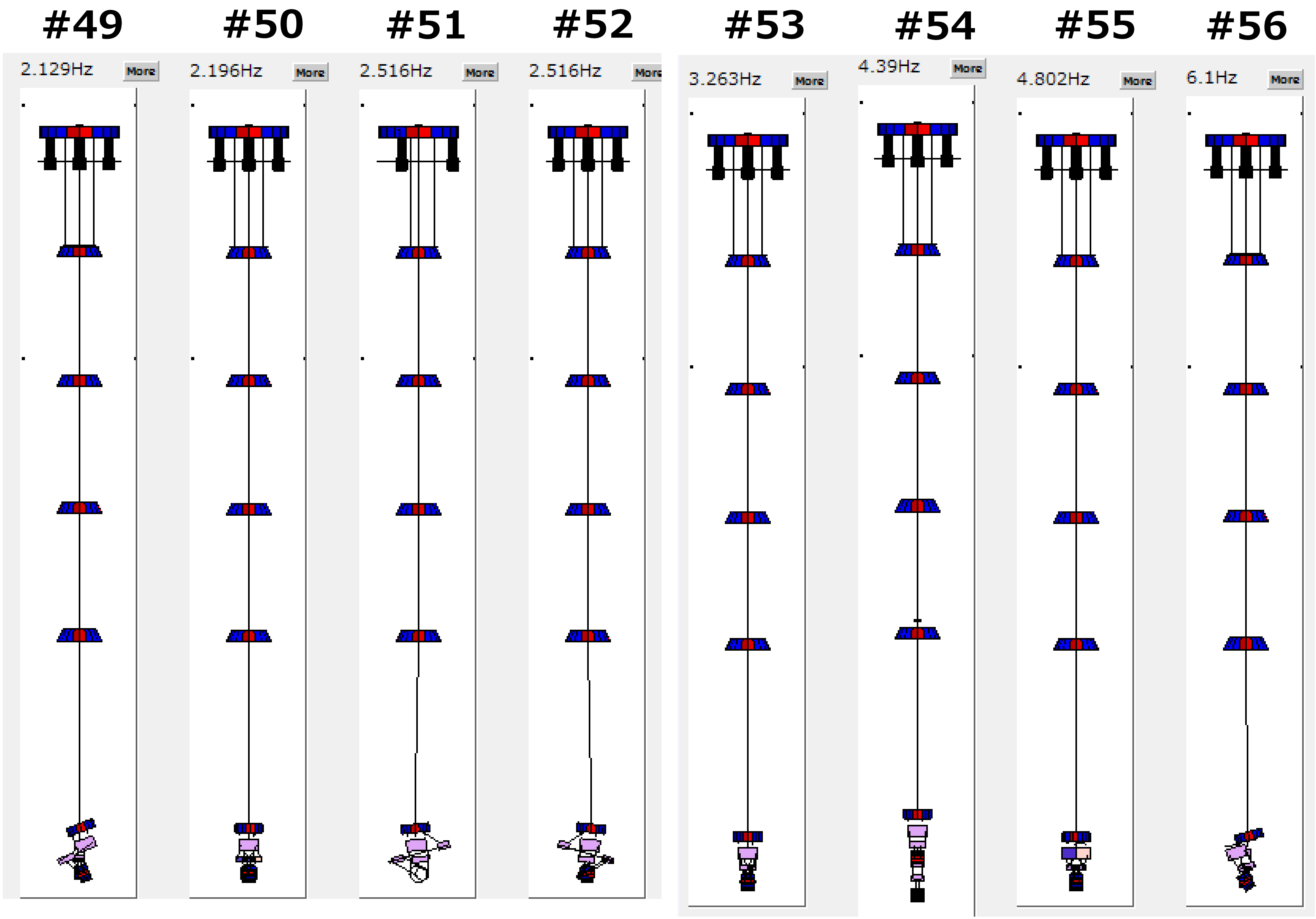
Less interest now


#25
#26
#27
#28
#29
#30
#31
#32
0.694Hz
More
0.694Hz
More
0.701Hz
More
0.745Hz
More
0.746Hz
More
0.787Hz
More
0.799Hz
More
0.799Hz
More
Less interest now

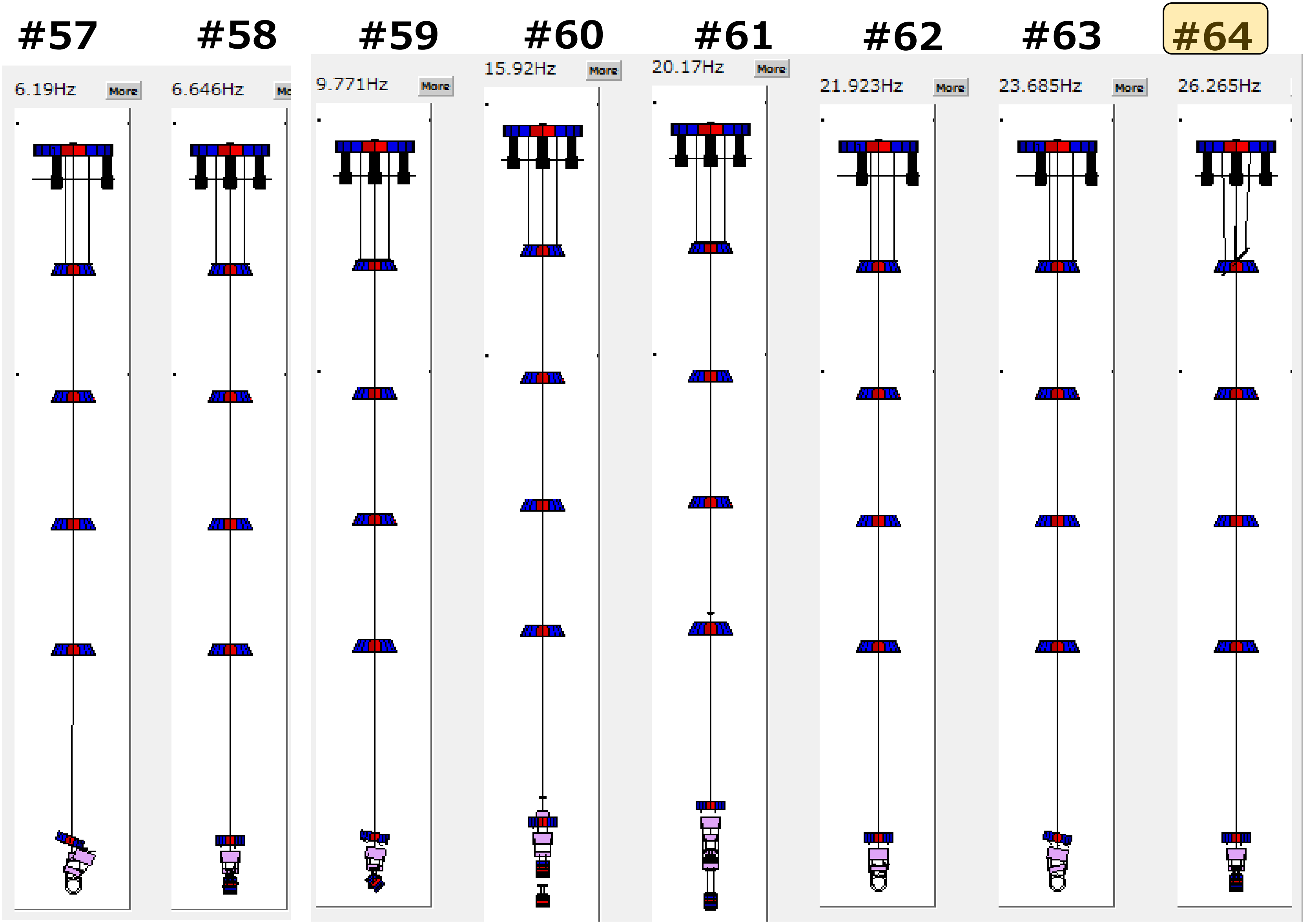

#33
#34
#35
#36
#37
#38
#39
#40
0.817Hz
More
0.951Hz
More
0.972Hz
More
0.974Hz
More
1.061Hz
More
1.061Hz
More
1.171Hz
More
1.189Hz
Less interest now



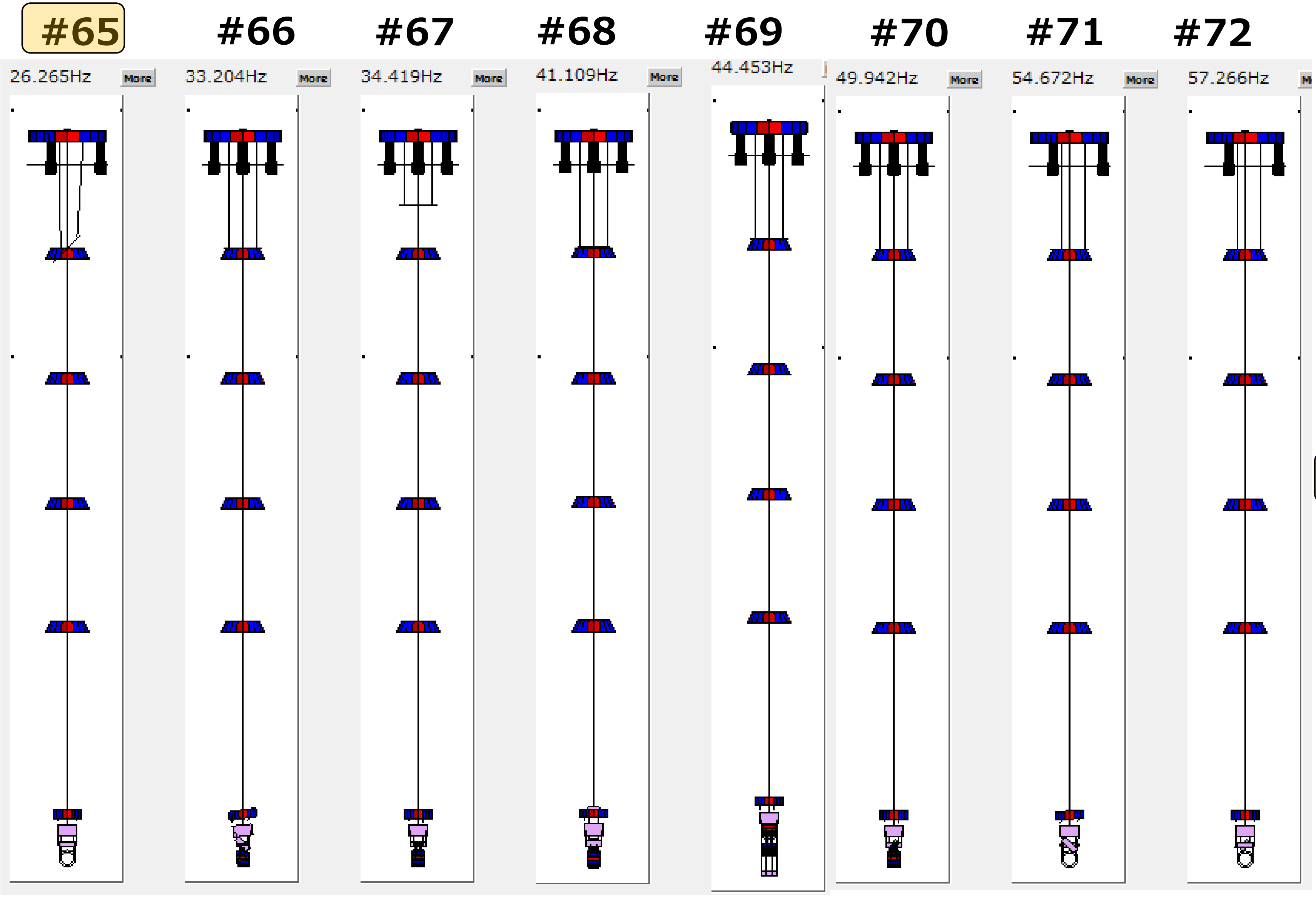
Less interest now



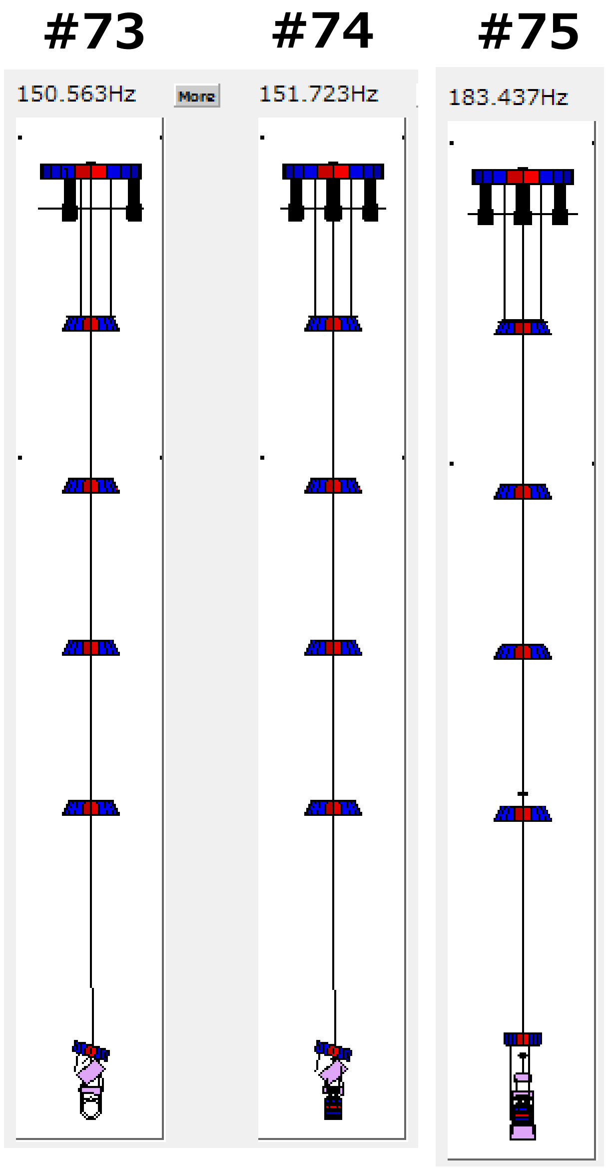
Less interest now



Less interest now



Less interest now



Less interest now

Detector noise

- Quantum noise
- Thermal noise

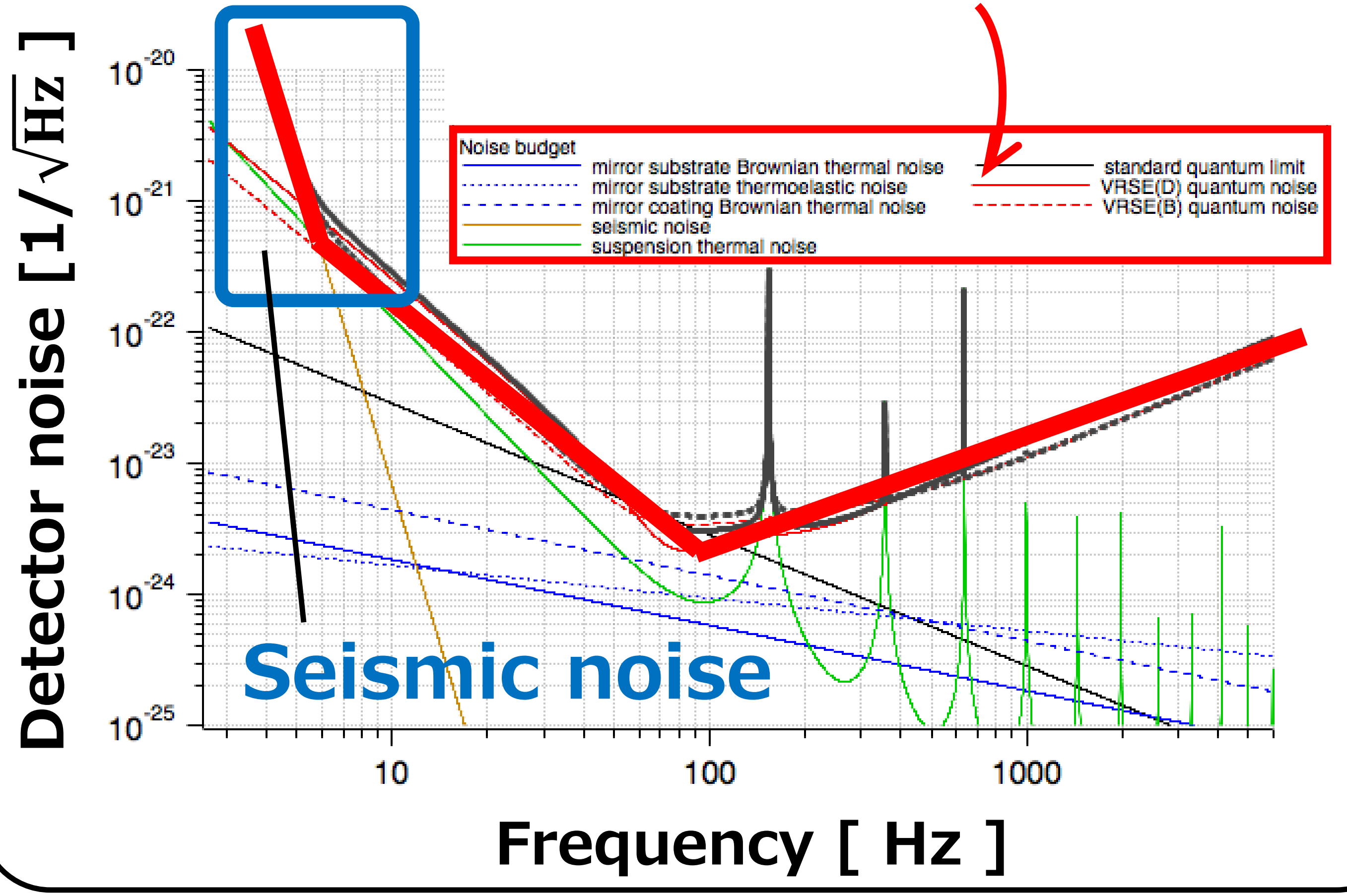
…

- **Seismic noise**

mirror oscillation

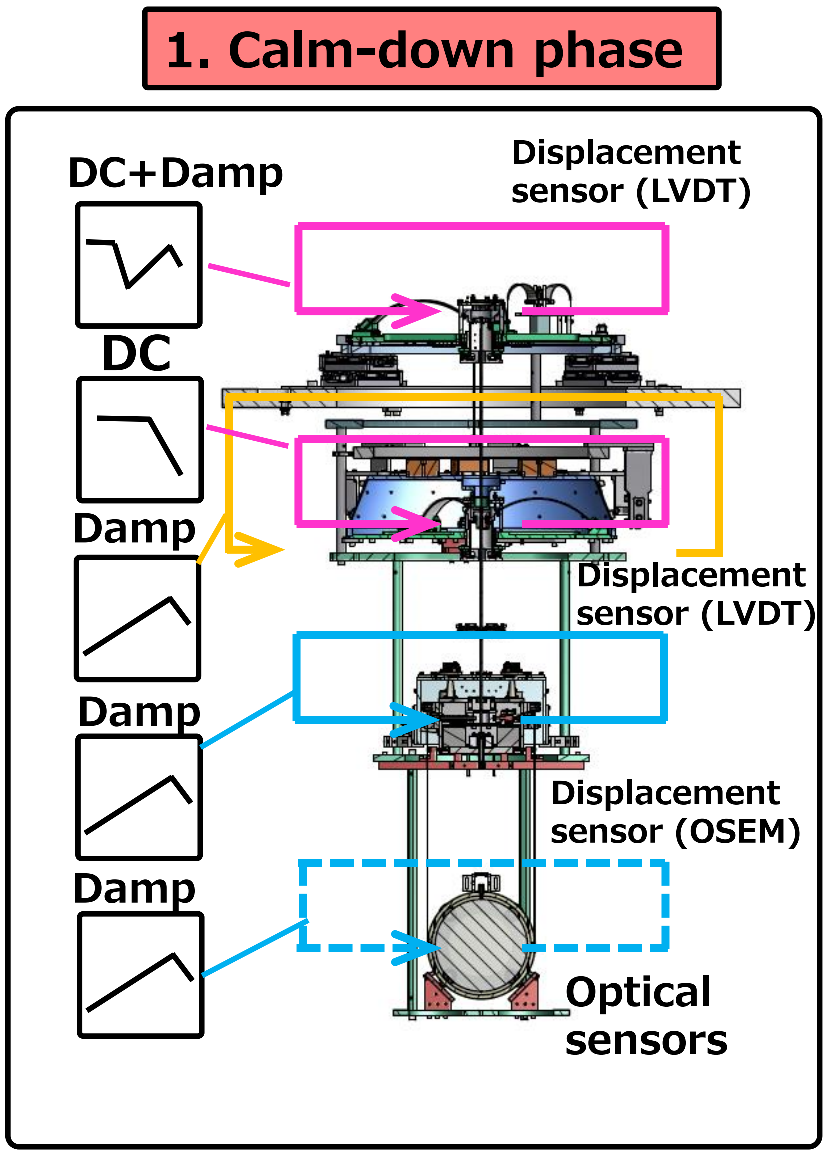
→ Necessary to suppress

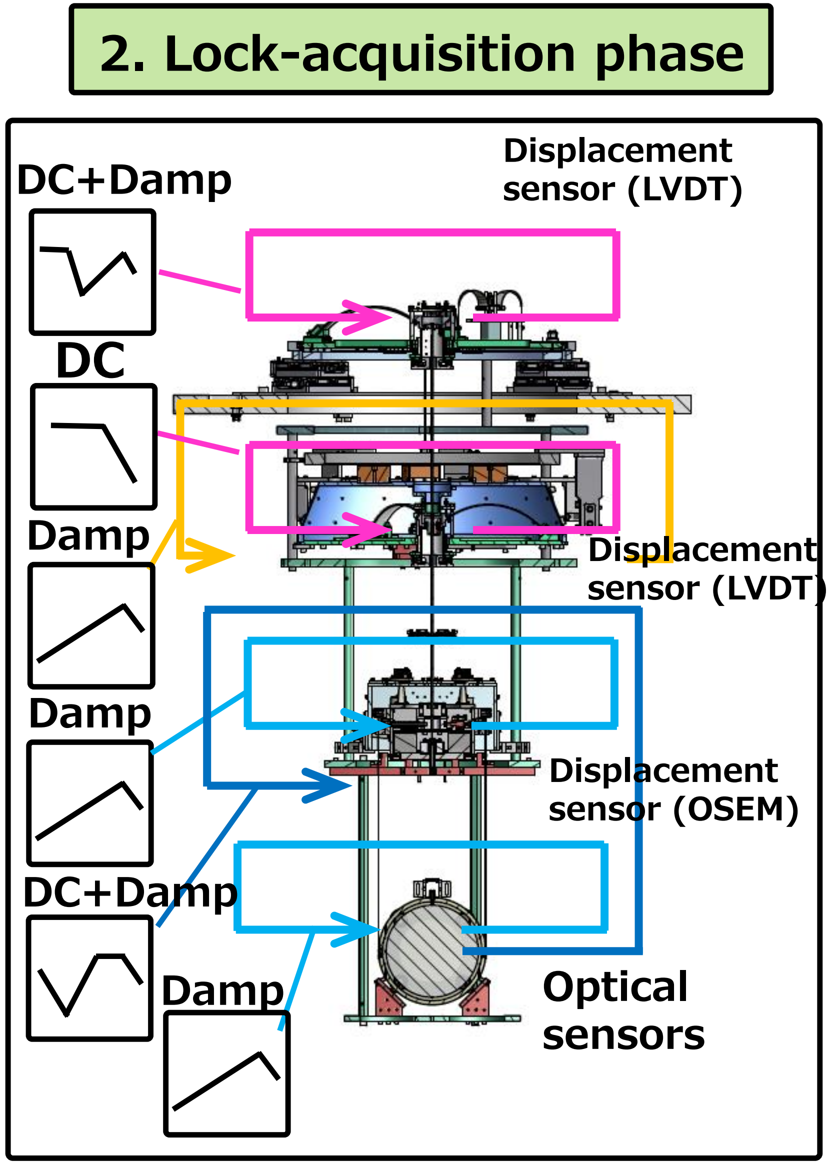
So many noise sources..

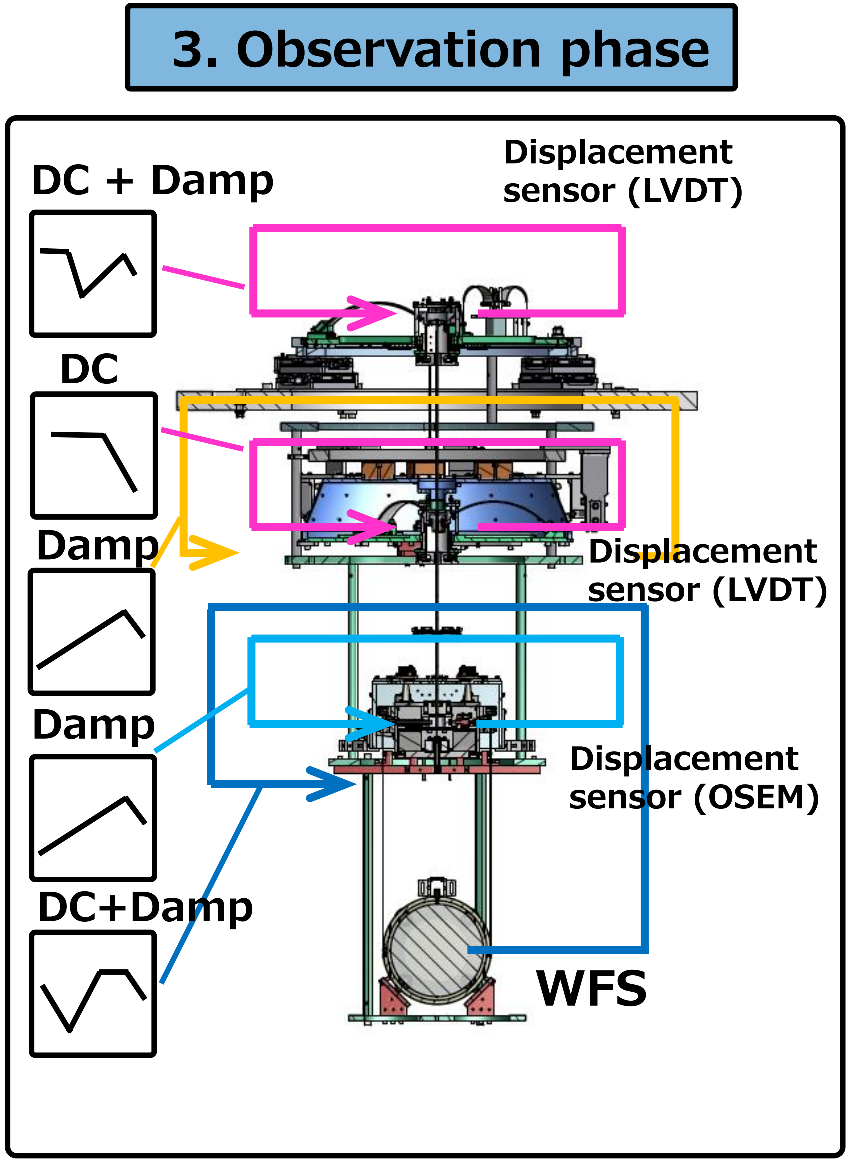


In case of KAGRA

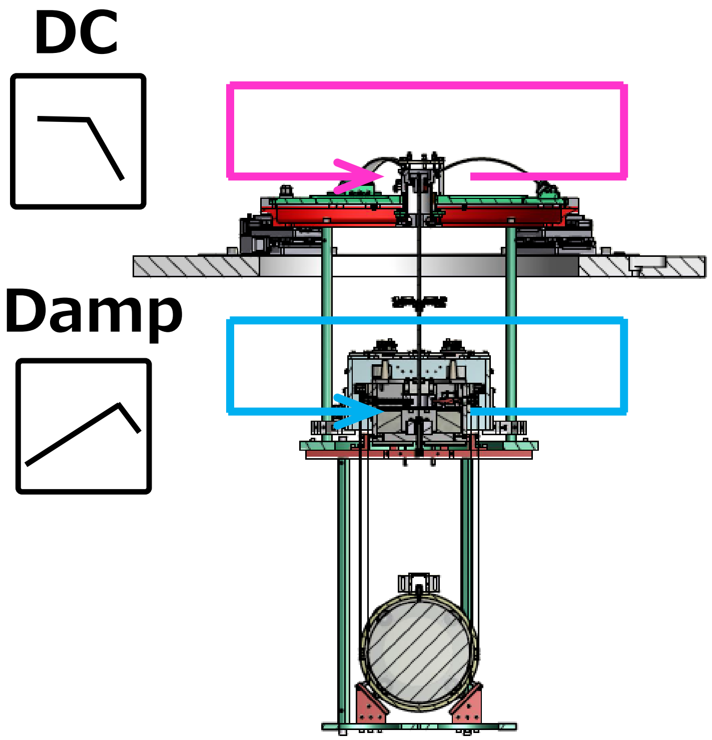
Designing active control system / ex. Type-Bp SAS





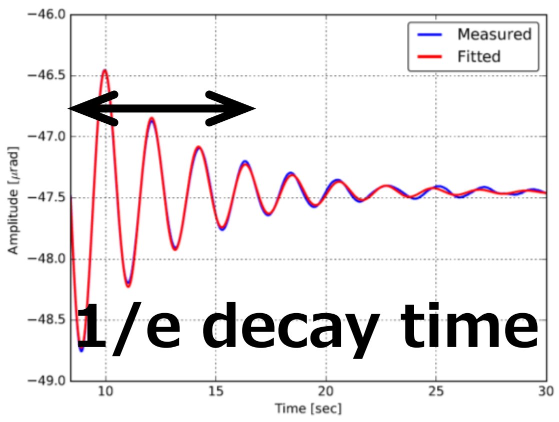


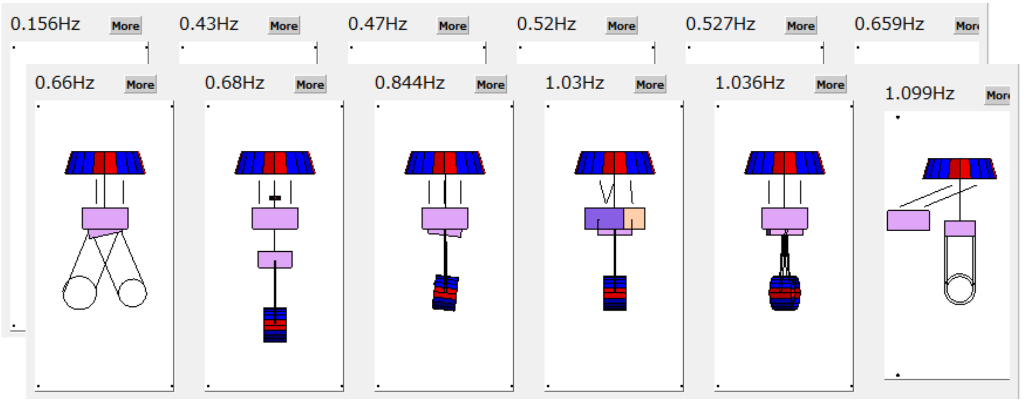
2. Decay time measurement



(Example)

For damping resonances





For the resonant modes
which disturb the lock acquisition.

→ We have to measure the decay time constants
w/ and w/o damping controls,
in order to verify the damping control performance,
FOR ALL THE TYPE-A/B/Bp SUSPENSIONS.