

# 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)

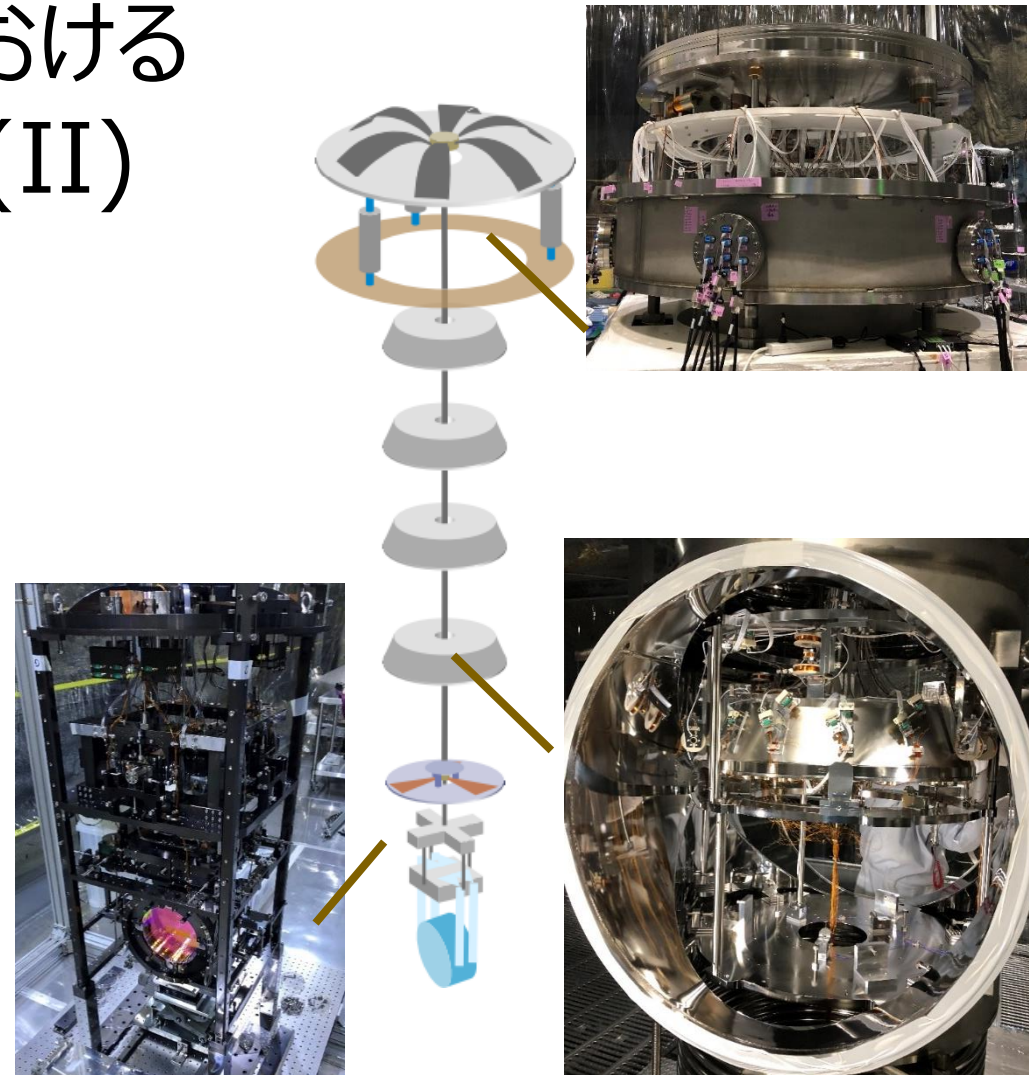
藤井善範

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

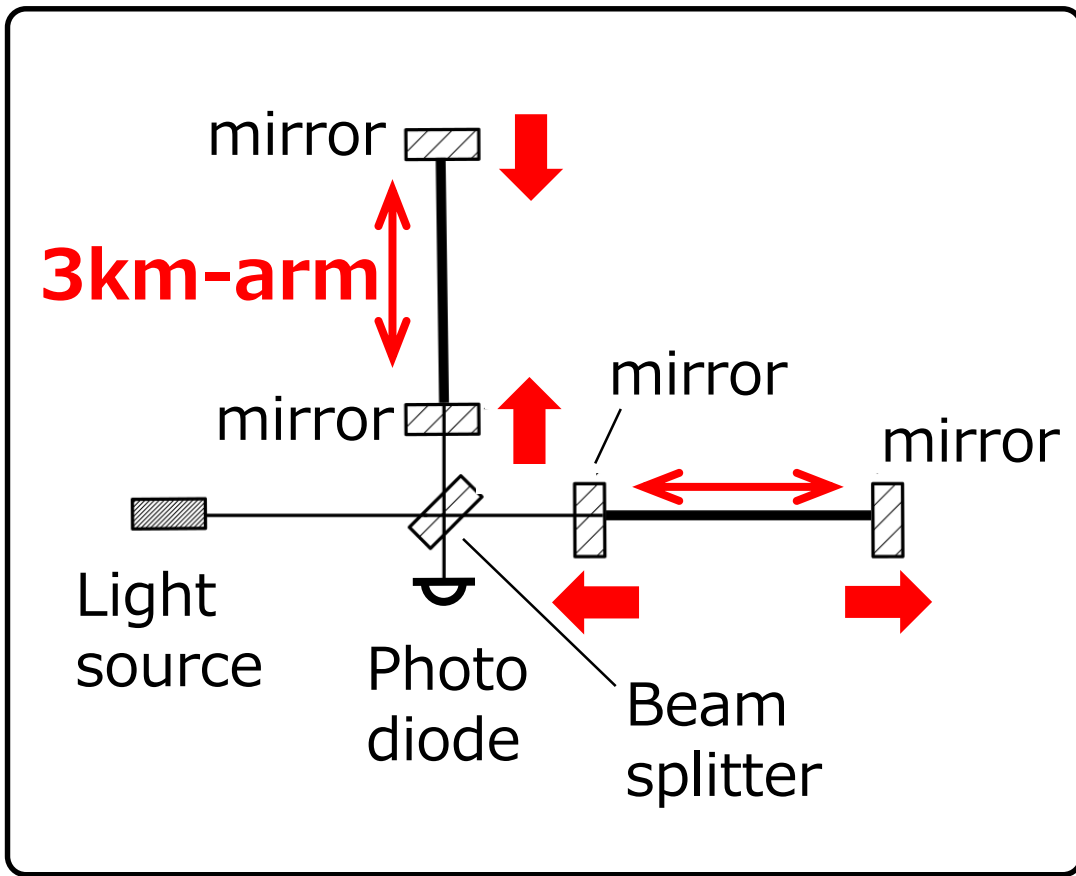
高橋竜太郎, L. Trozzo, 正田亜八香, 阿久津智忠, 佐藤直久, 石崎秀晴, E. N. T. SanMartin,  
M. Barton, 平田直篤, 麻生洋一, 都丸隆行, R. Flaminio(国立天文台), 奥富弘基,  
F. P. E. Arellano, 宮本昂拓, 牛場崇文, 三代浩世希, 山本尚弘, 宮川治,  
上泉眞裕, (東大宇宙線研), 和泉究(宇宙研),  
on behalf of the KAGRA collaboration

# 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)

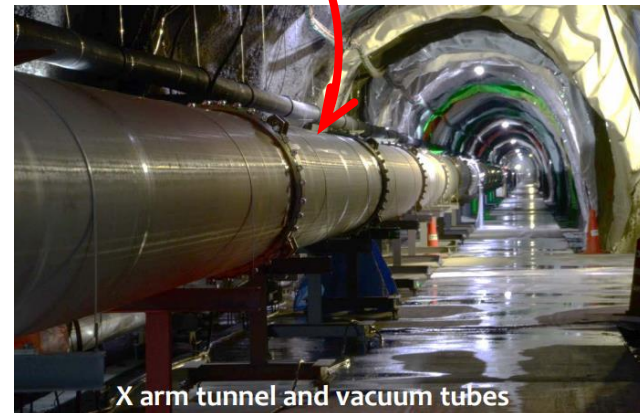
**内容：** メイン鏡用の防振装置の  
地面振動流入の抑制の  
制御系の開発状況



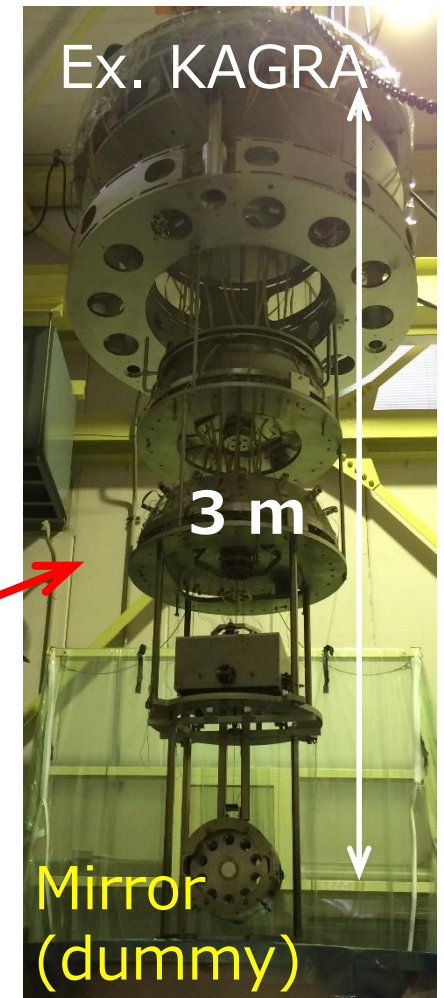
# 重力波検出器と、サスペンション



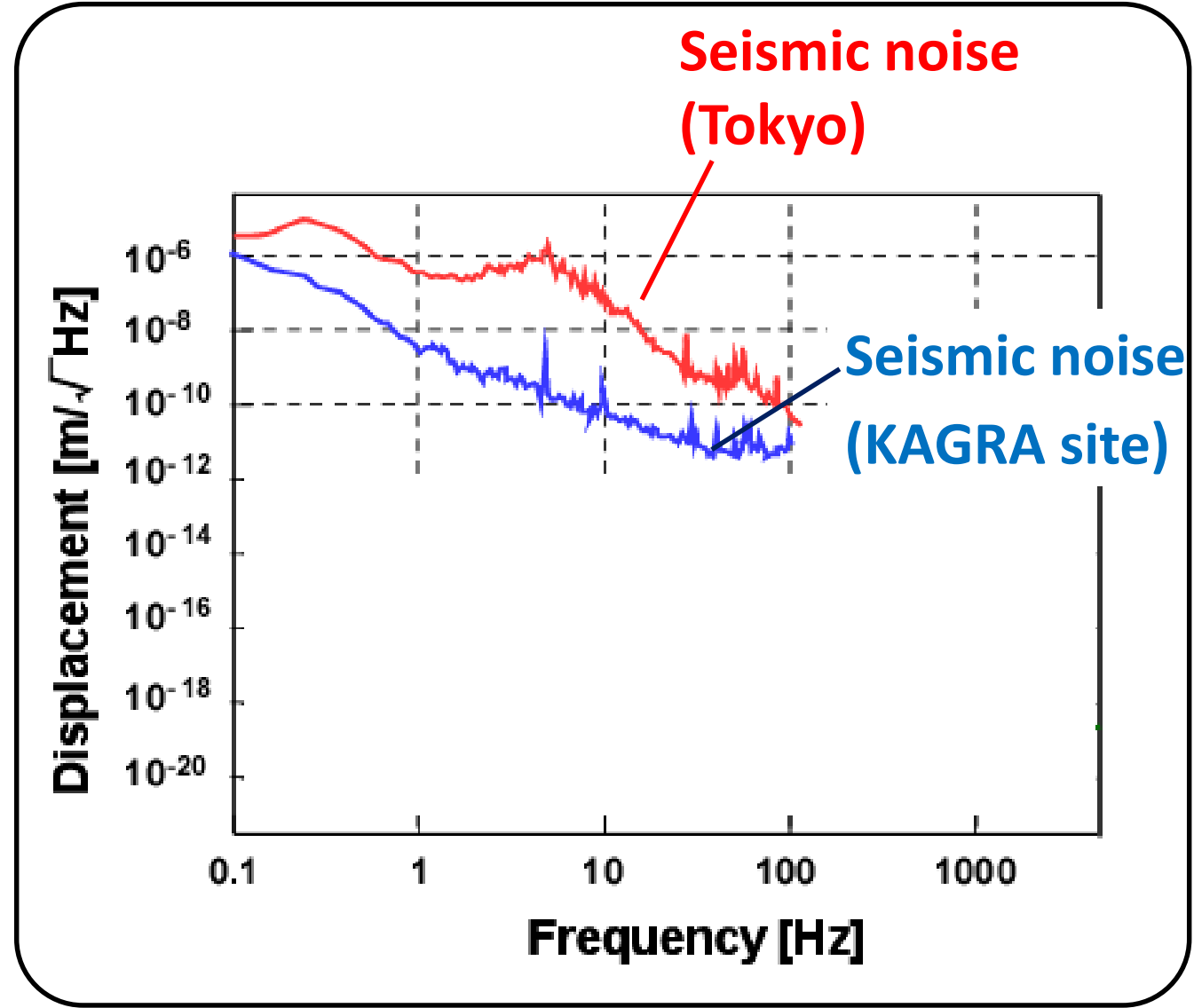
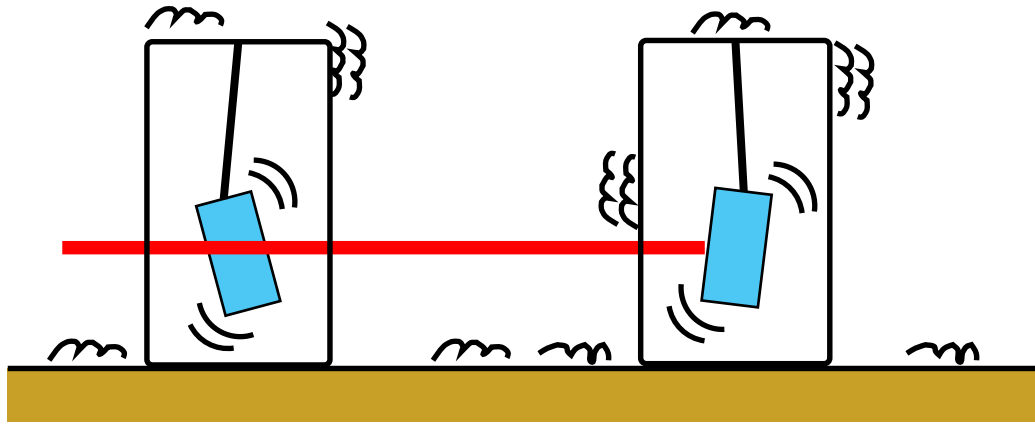
- 1) Michelson-based interferometer
- 2) Fabry-Perot cavities
- 3) 3km-arm



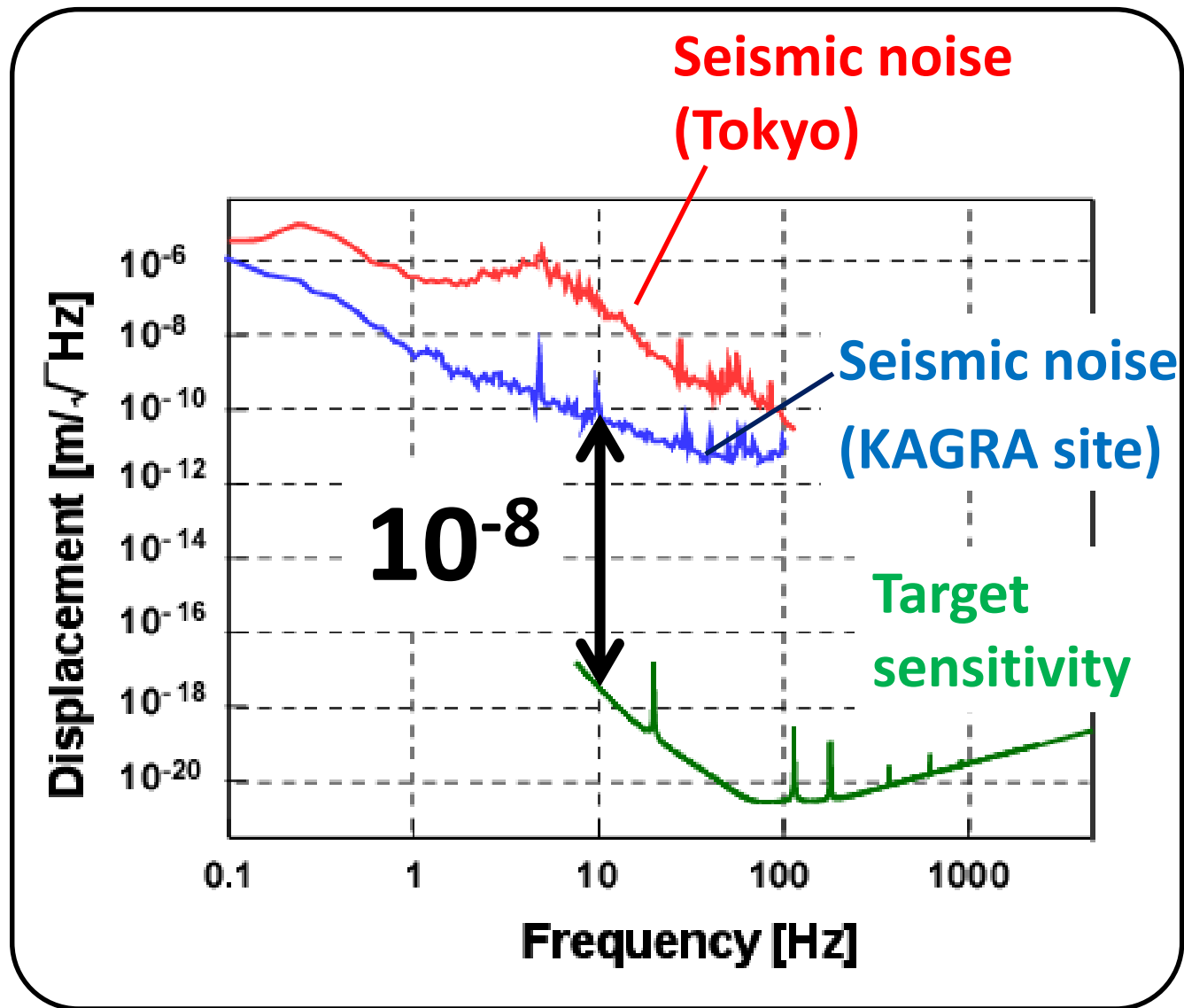
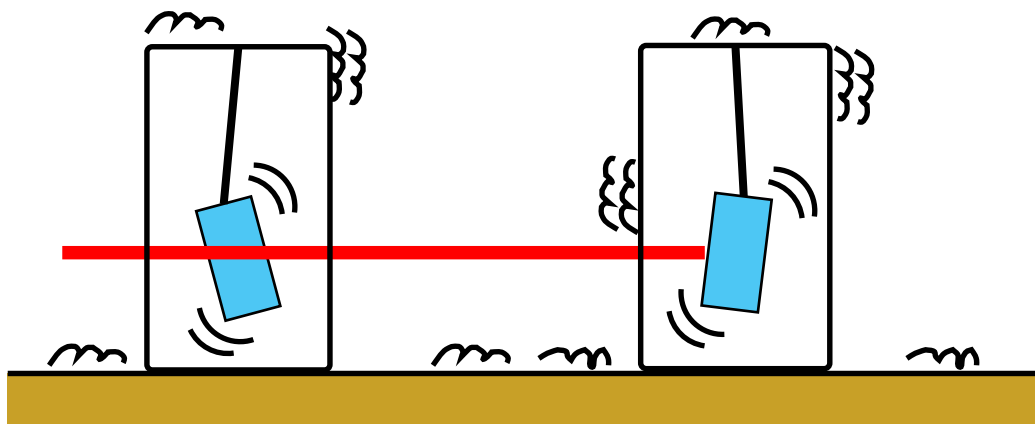
- 4) Suspended core optics



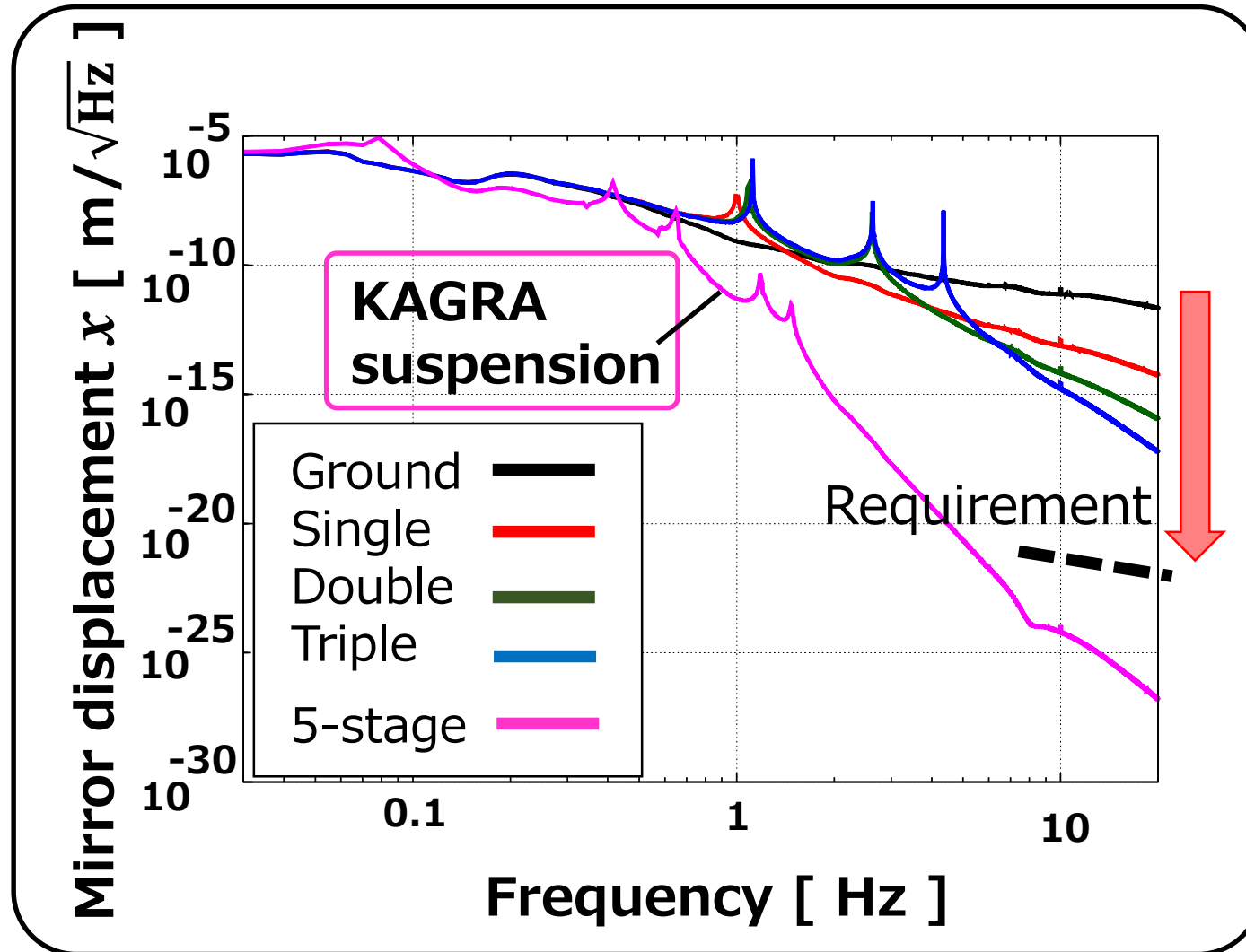
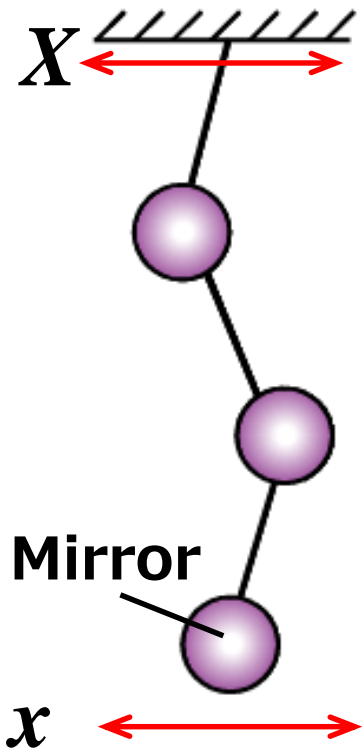
# 地面振動雑音



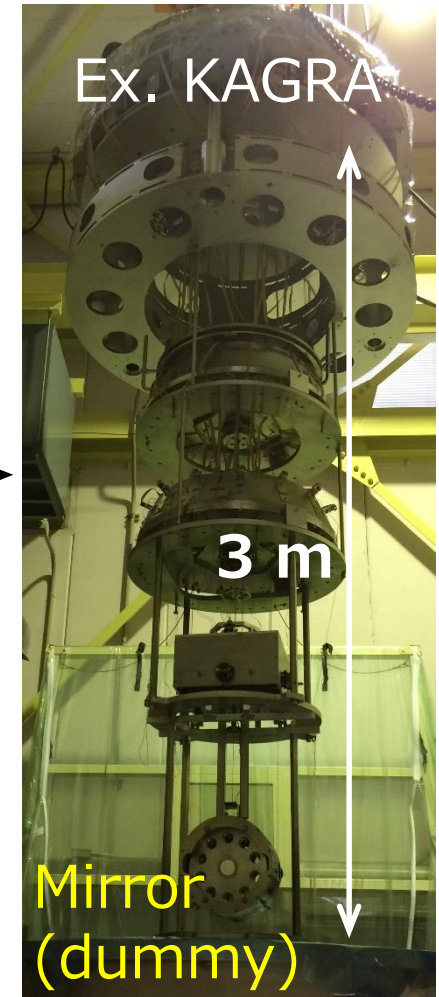
# 地面振動雑音



# 地面振動雑音の低減 → 振り子

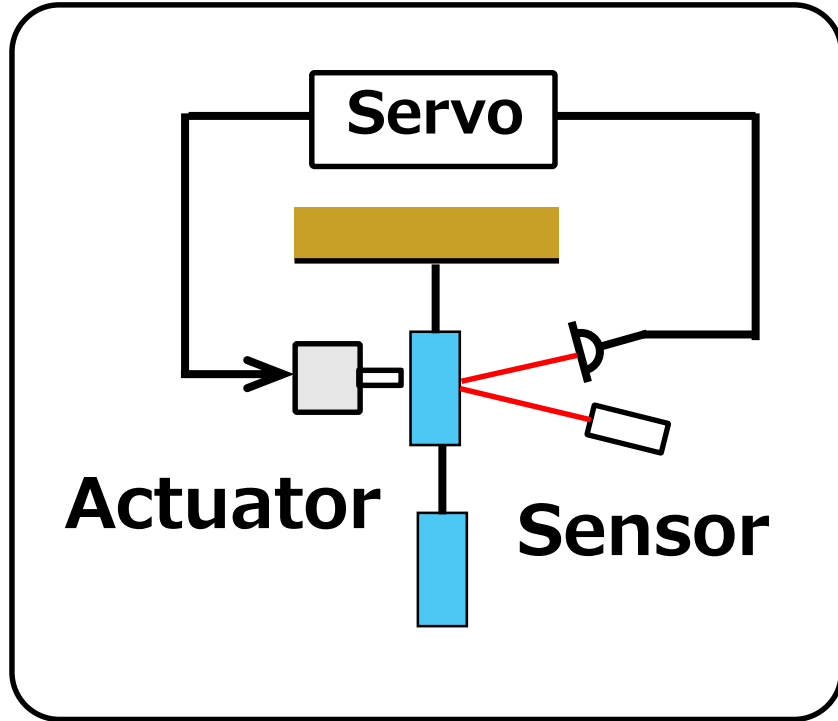


(BS/SRs-suspension case)

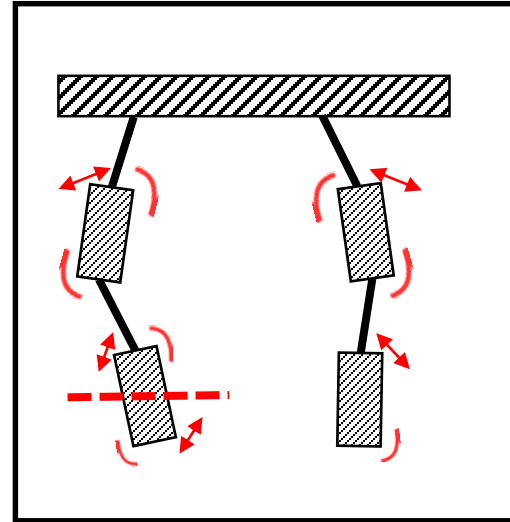


# 共振のダンピング

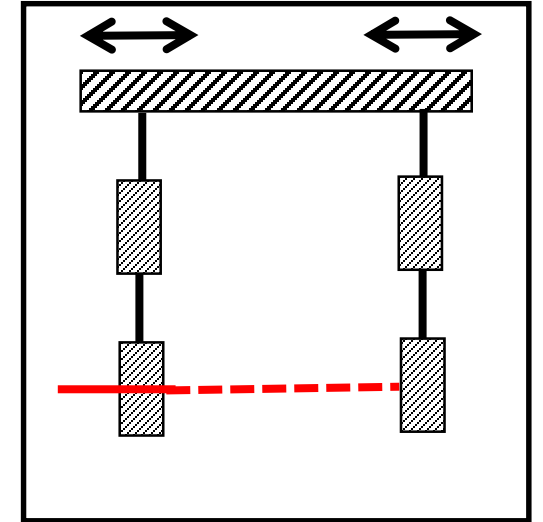
## → アクティブ制御



~~interferometer operation~~



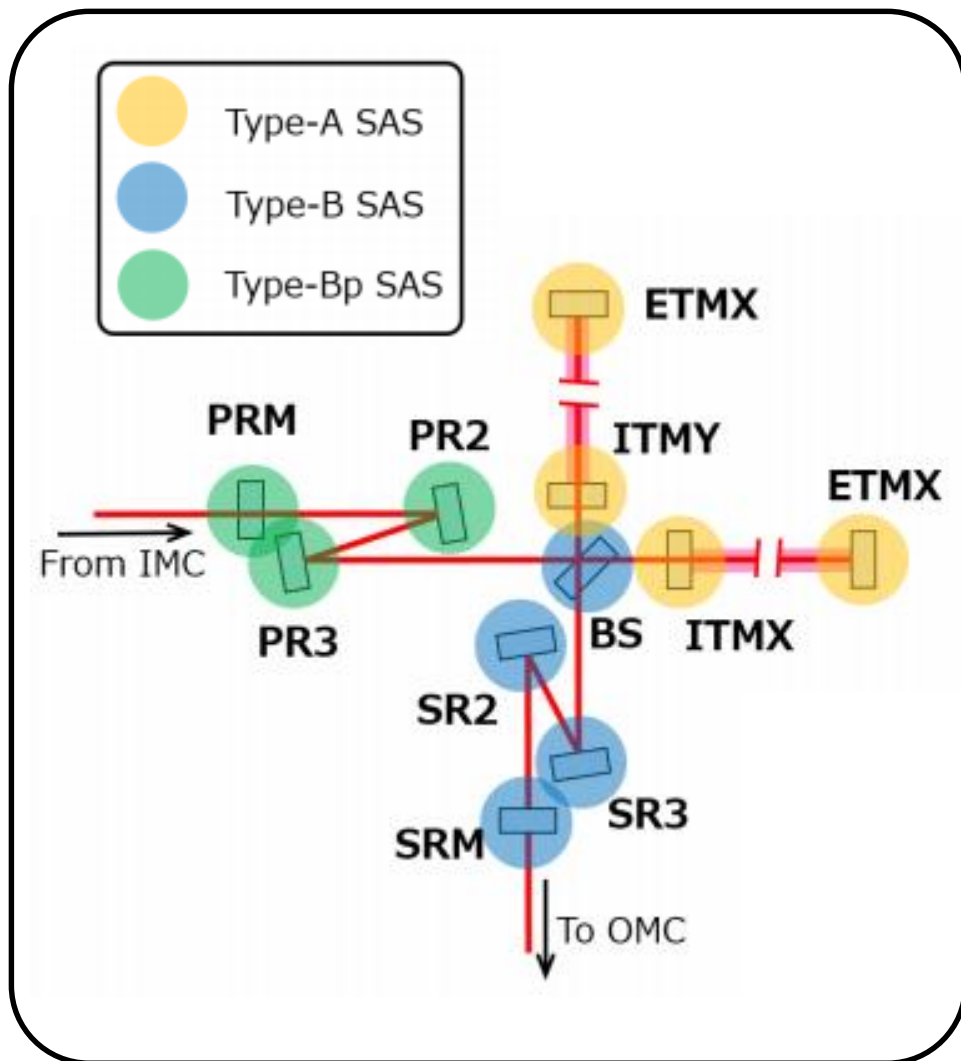
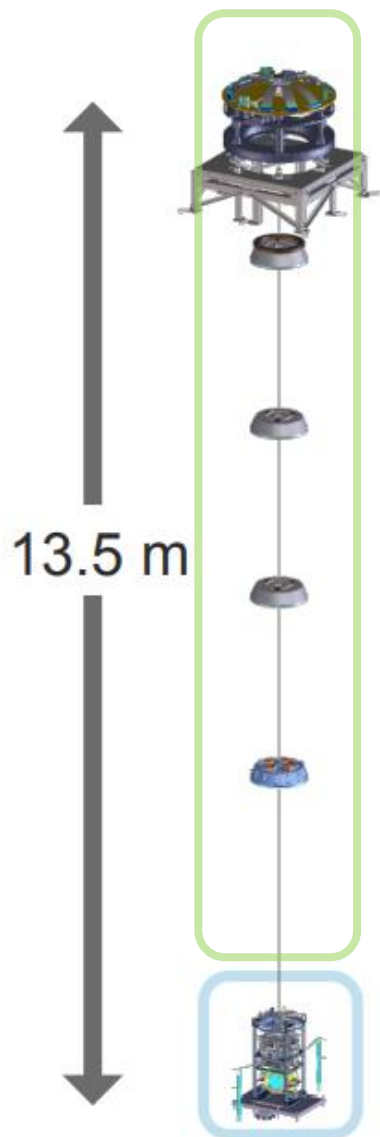
Stable operation



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

# メイン鏡用の防振装置

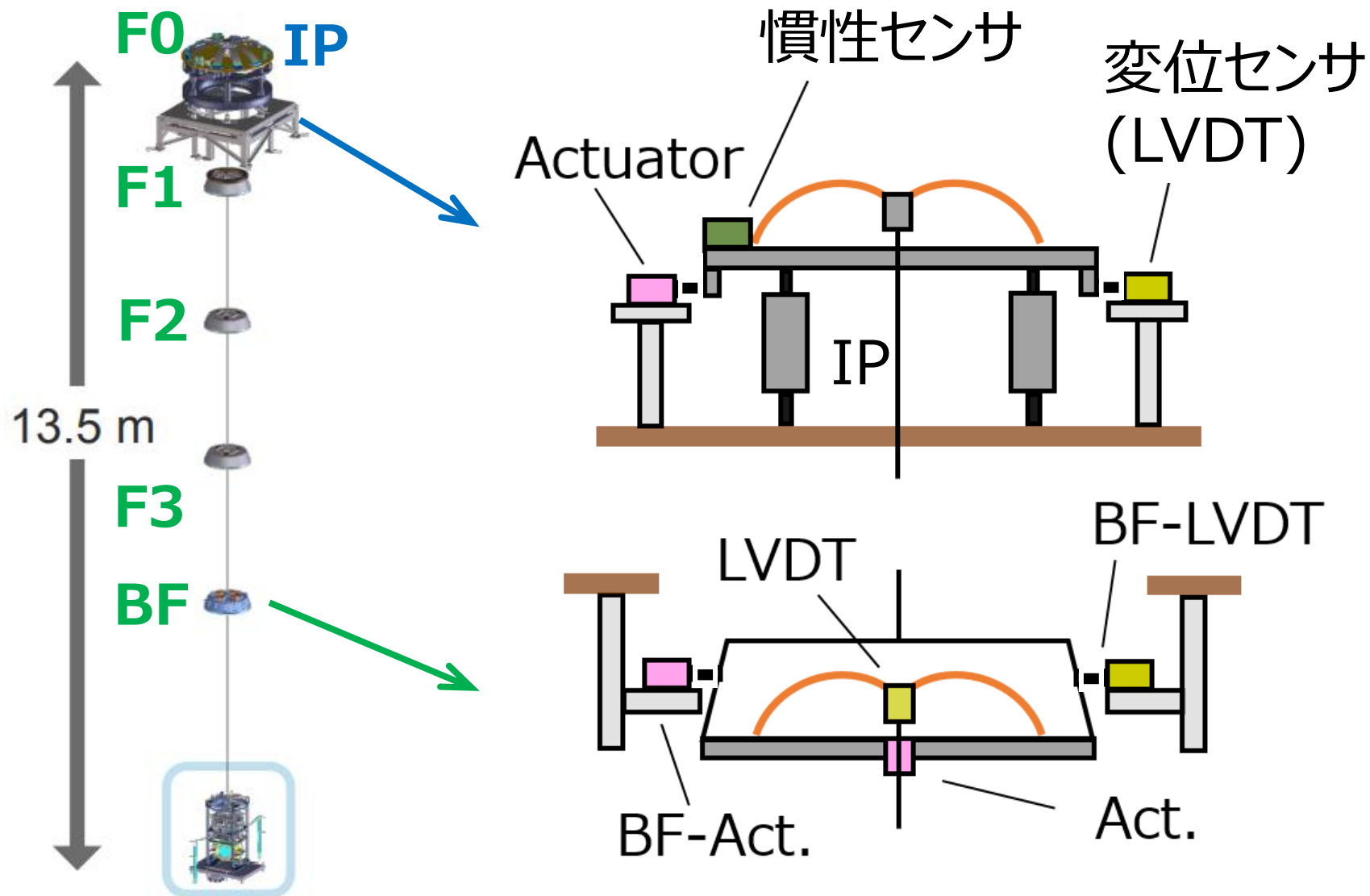


- Upper 5 stages: room-temperature
- Lower 4 stages: cryogenic-temperature

メカものは全て  
インストール済み



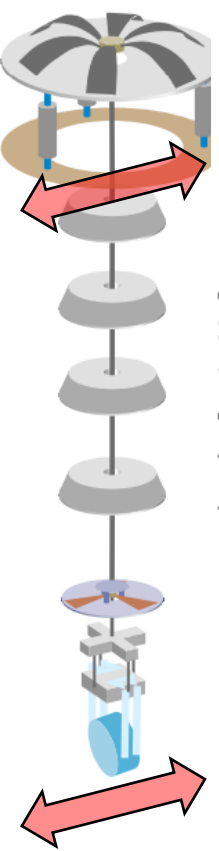
# メイン鏡用の防振装置



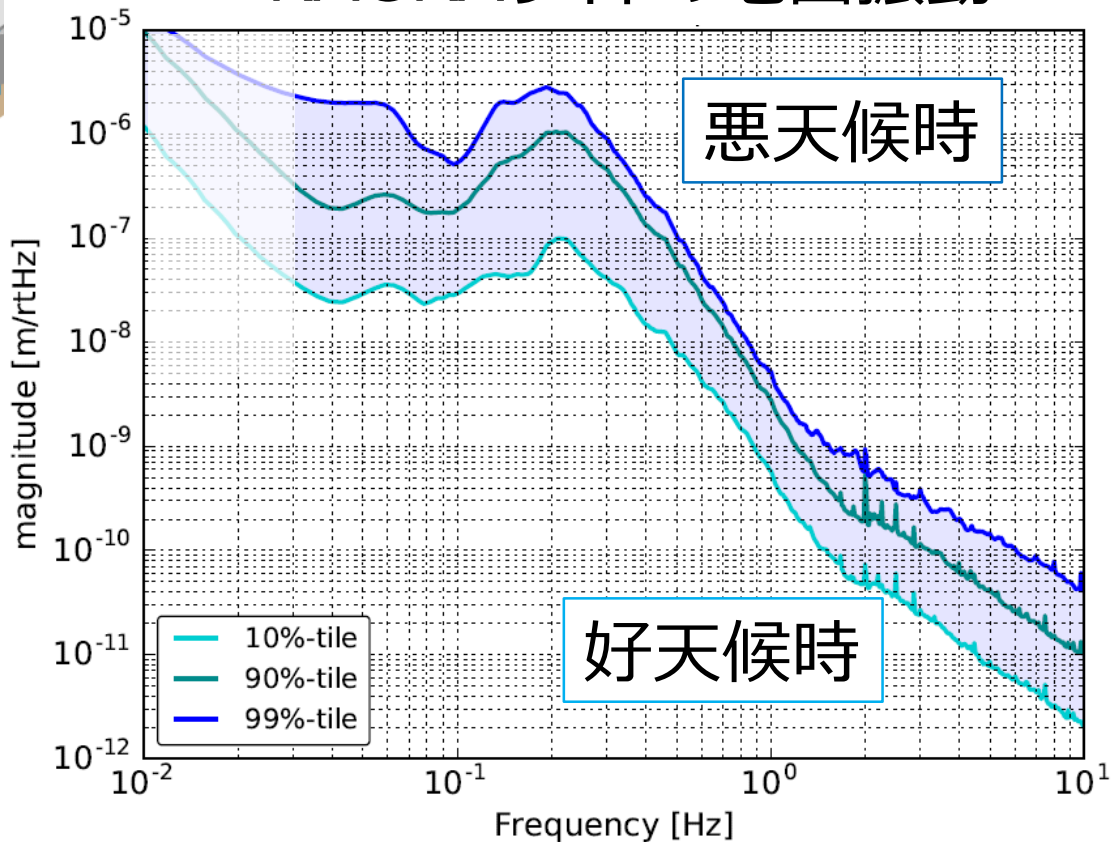
倒立振り子  
IP:  $\sim 70$  mHz

幾何反バネ フィルタ  
F0 - BF:  $\sim 0.4$  Hz

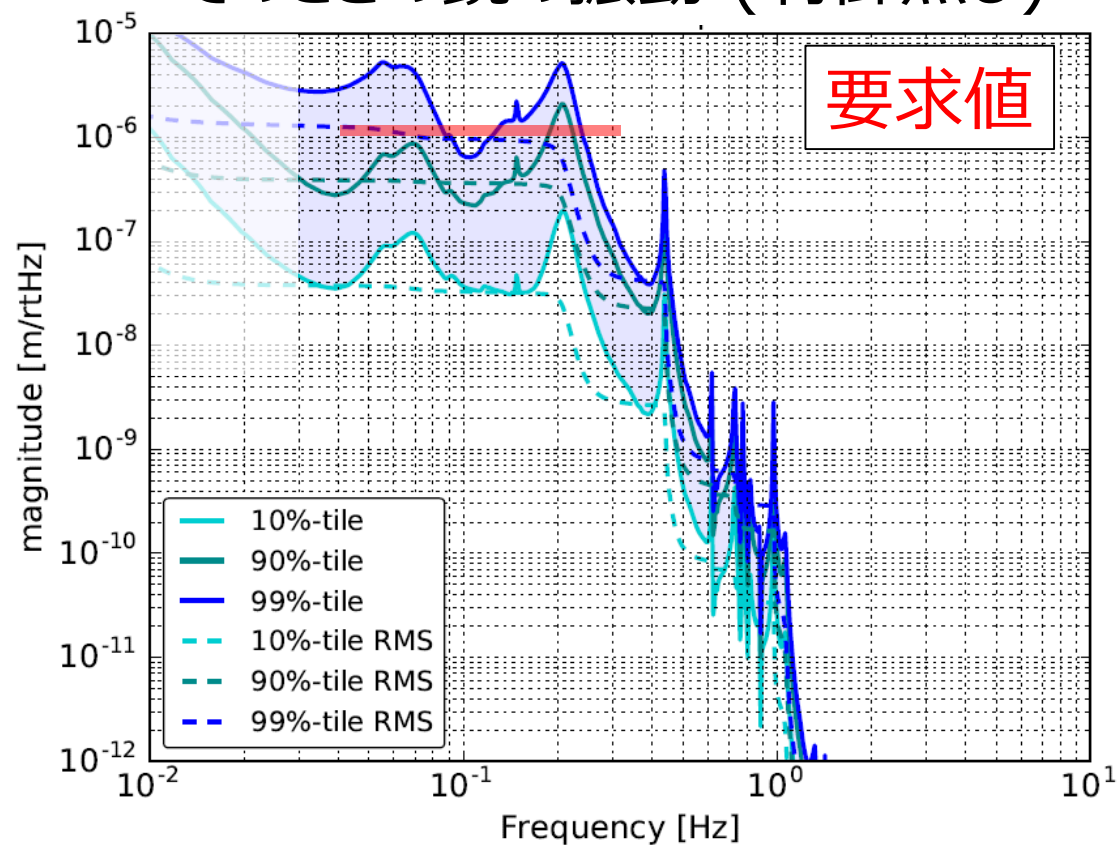
# 神岡での地面振動レベルと、サスペンションの応答



## KAGRAサイトの地面振動



## そのときの鏡の振動 (制御無し)



# 神岡での地面振動レベルと、サスペンションの応答

- RMSの寄与が大  
→ 抑制が必要

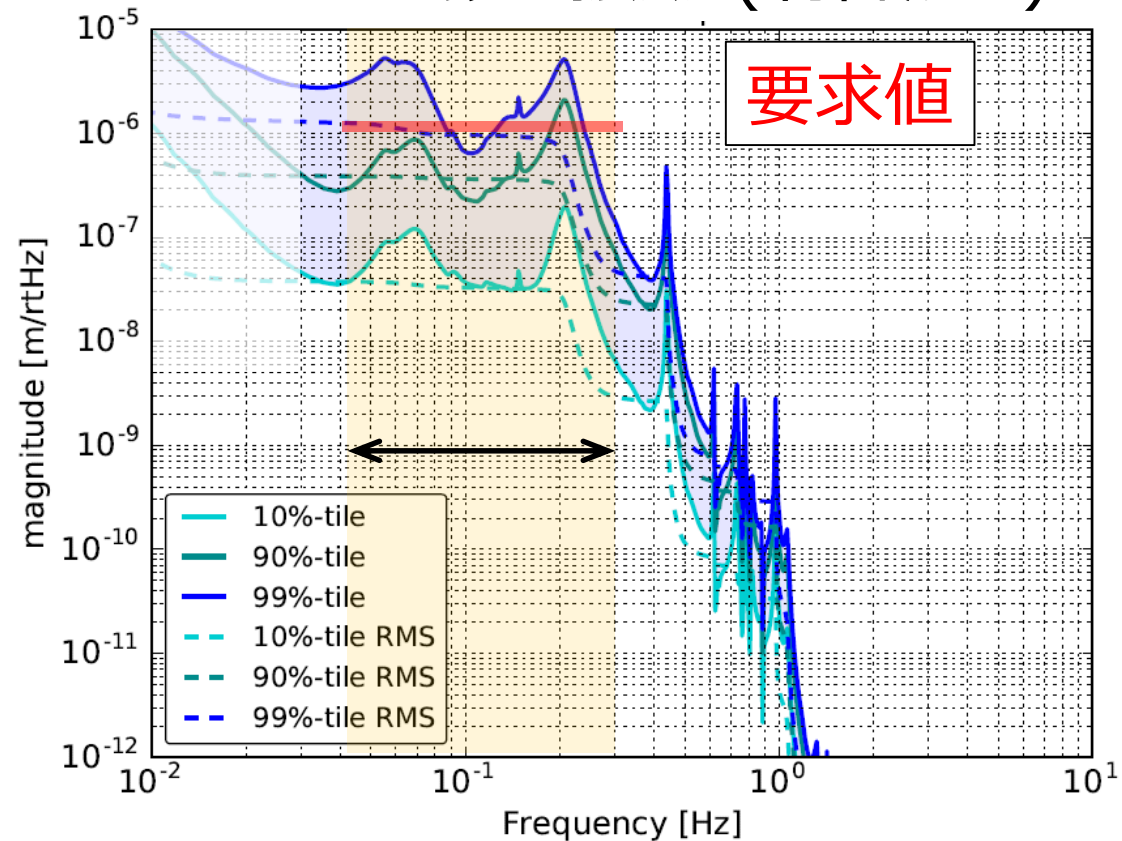
-- 好天候時  
→ 要求値を満たせる

-- 悪天候時(特に冬場)  
→ 要対処 at 上段

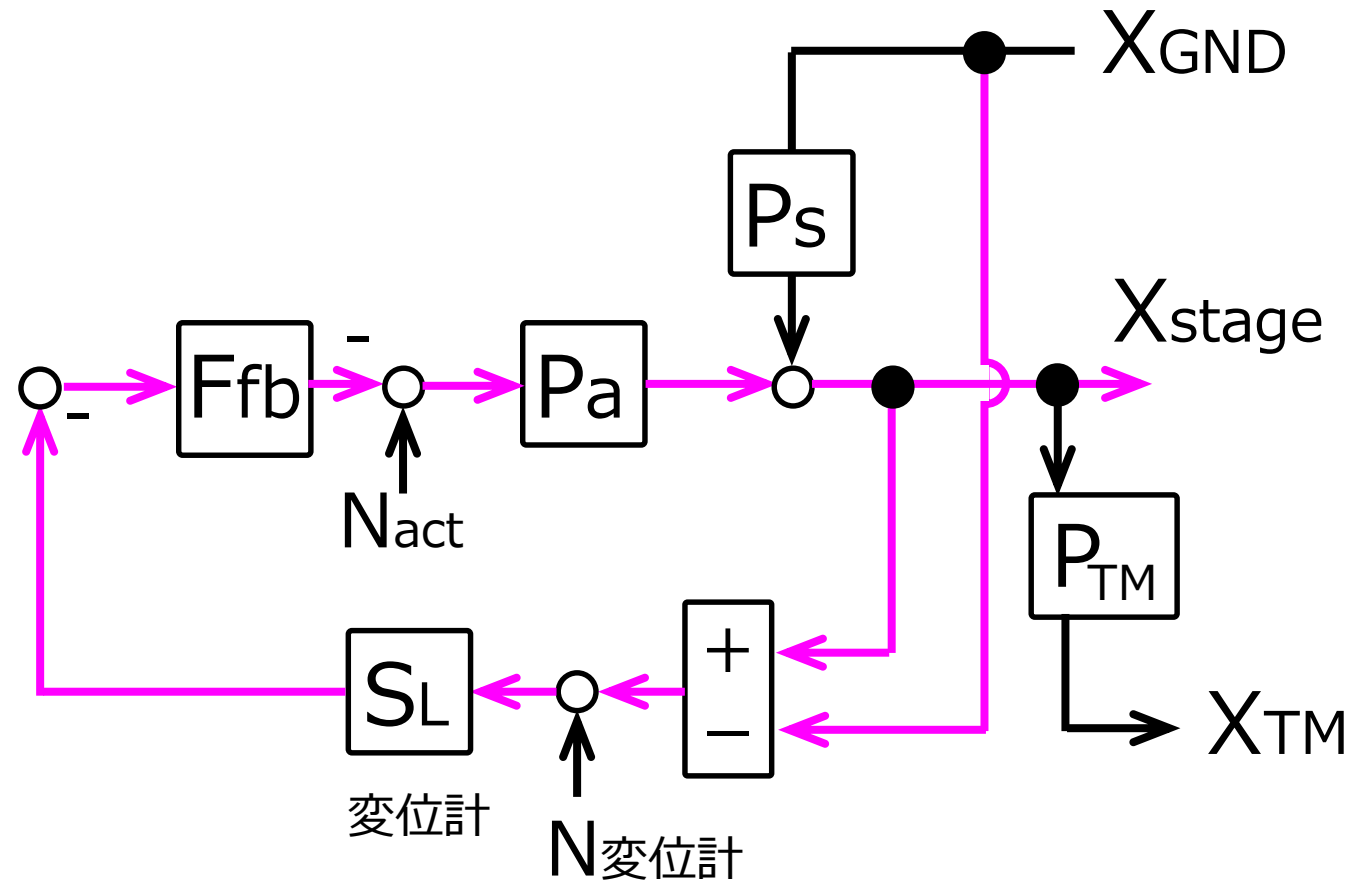
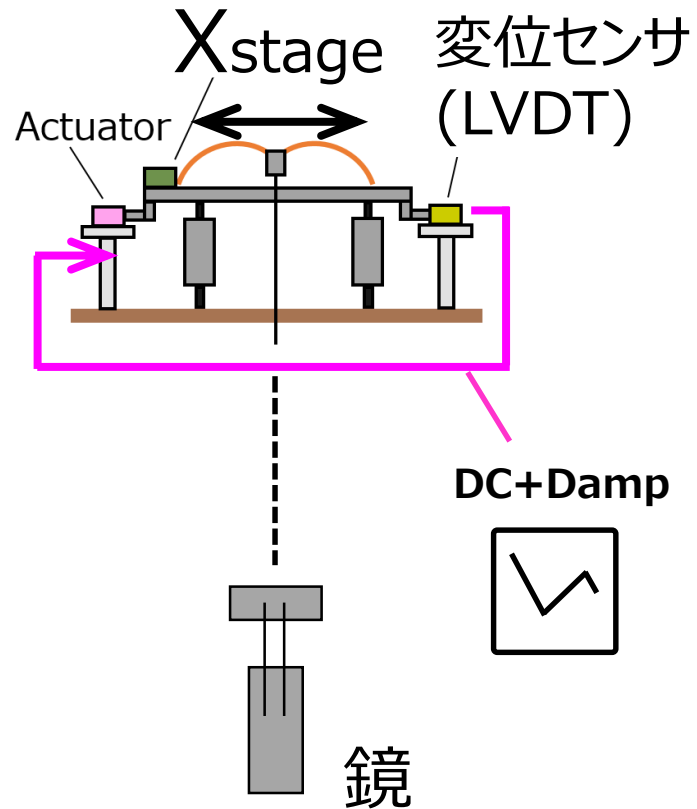


0.2 Hz  
mode

そのときの鏡の振動 (制御無し)



# 今回考える制御系 (Lのみ):

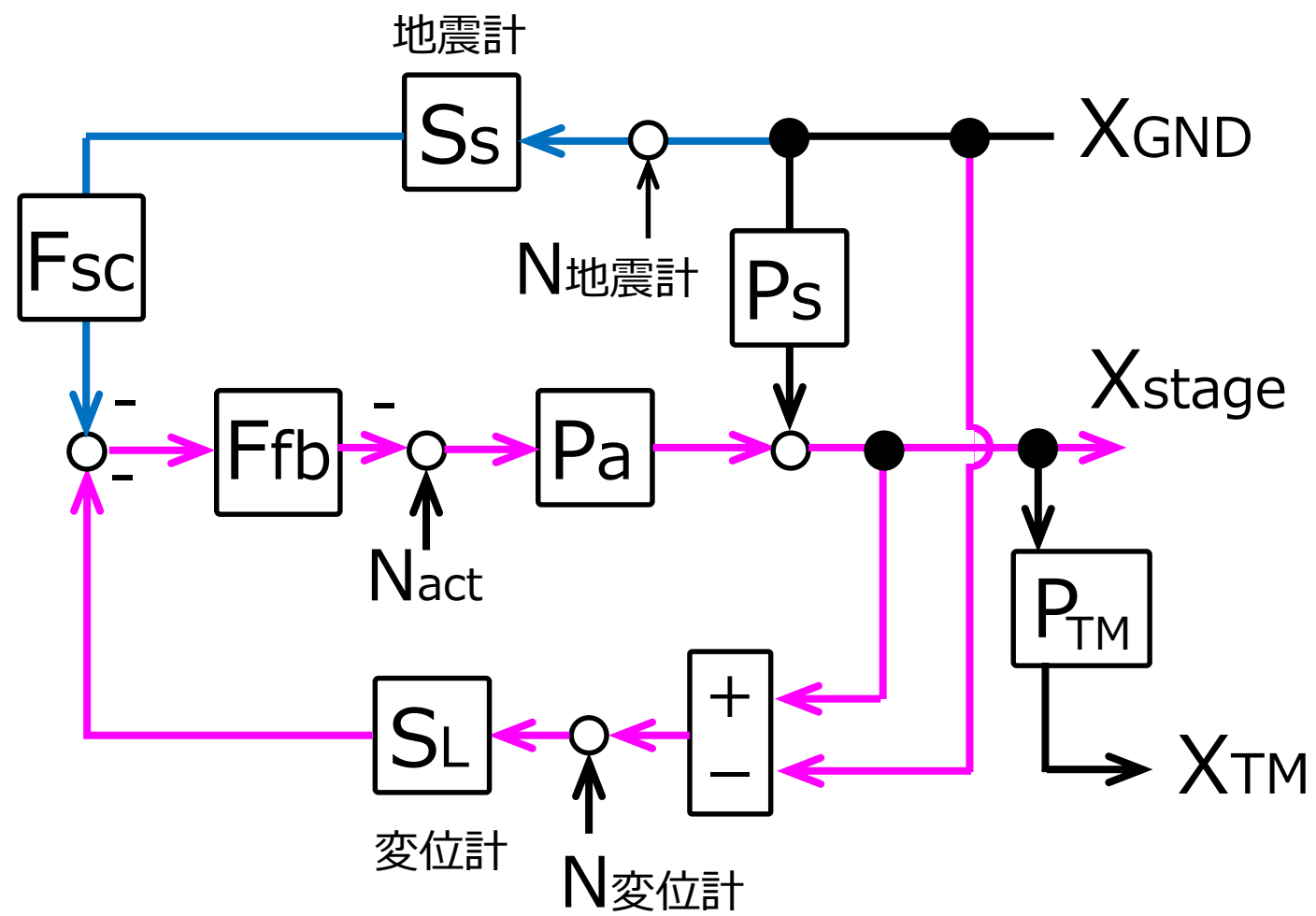
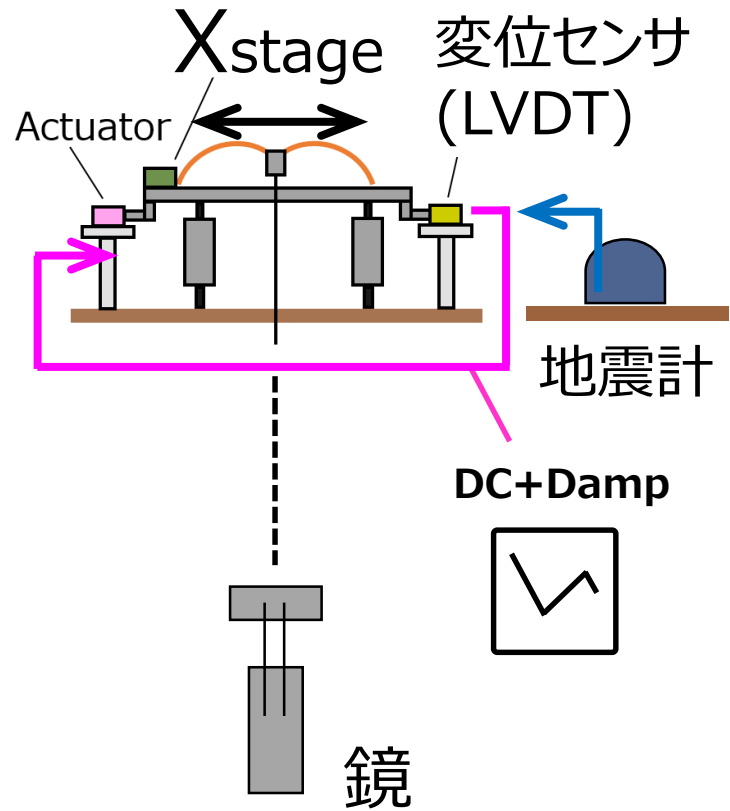


変位計:

$(X_{stage} - X_{GND})$   
で制御

$X_{stage} \sim X_{GND}$   
地面程度は揺れる

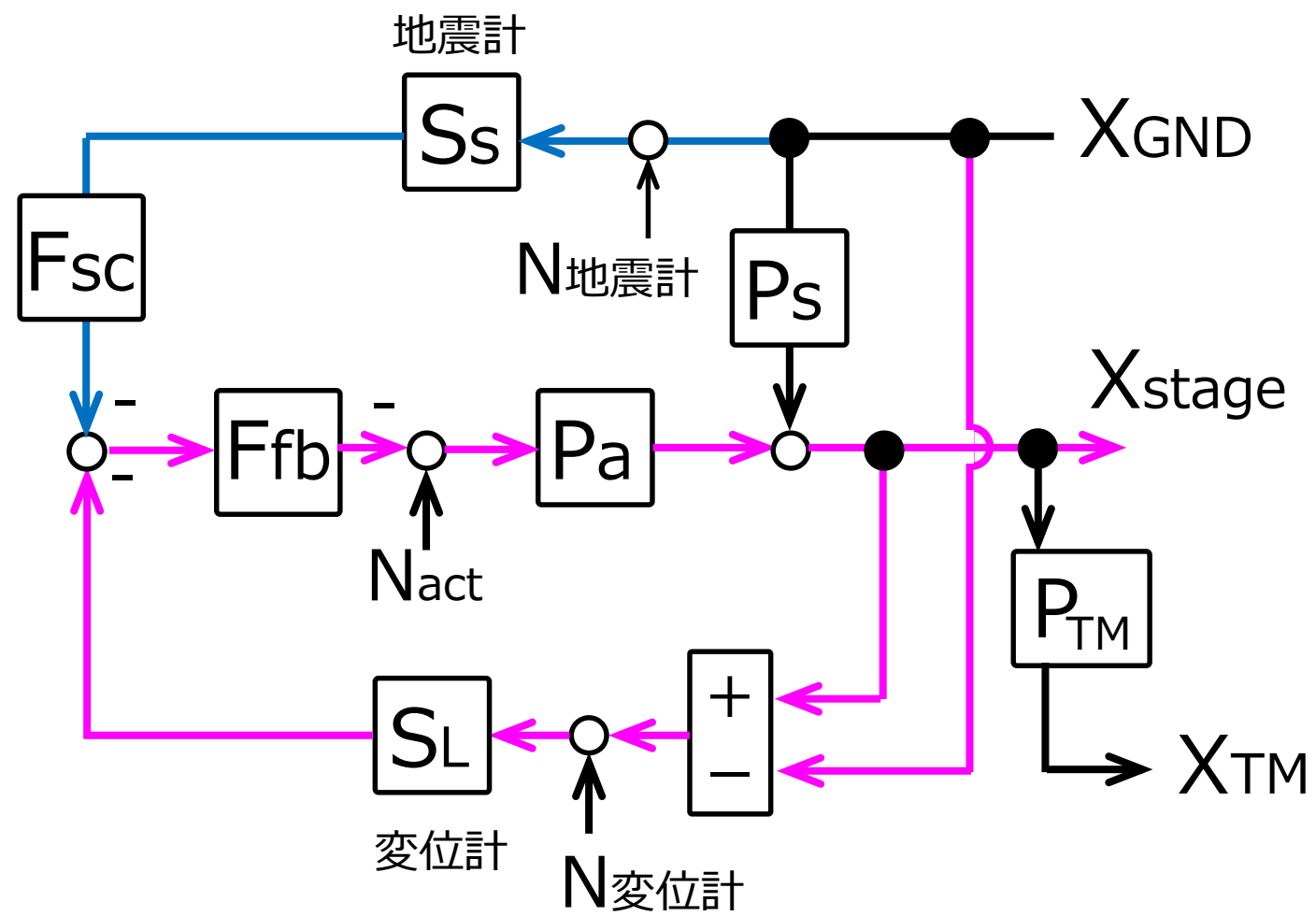
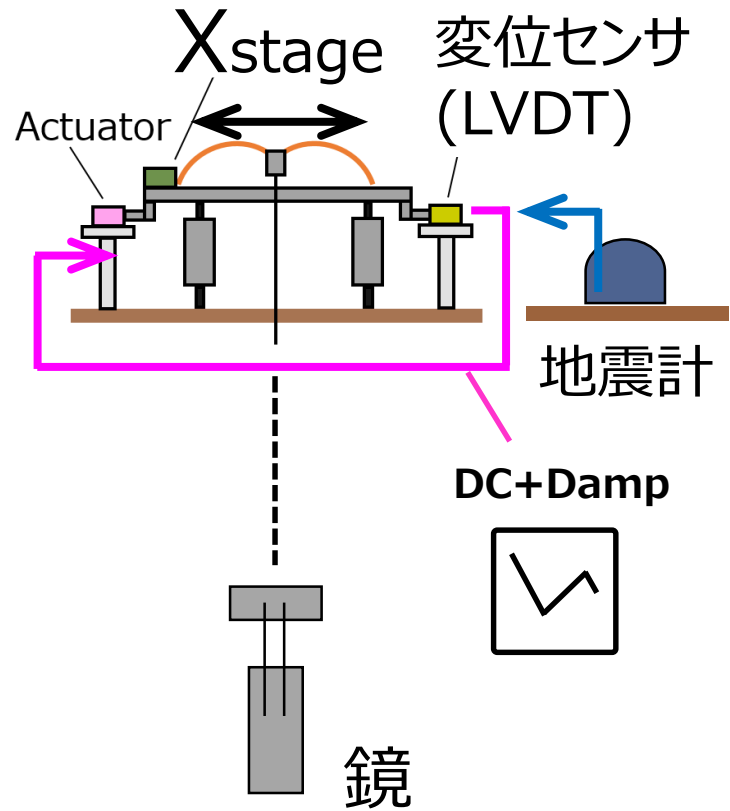
# 今回考える制御系 (Lのみ):




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

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

# 今回考える制御系 (Lのみ):

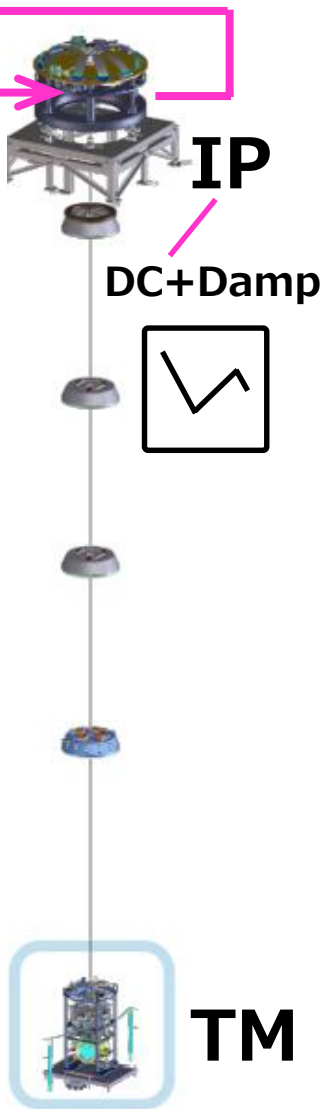


$F_{sc} = S_L/S_s$  にて :

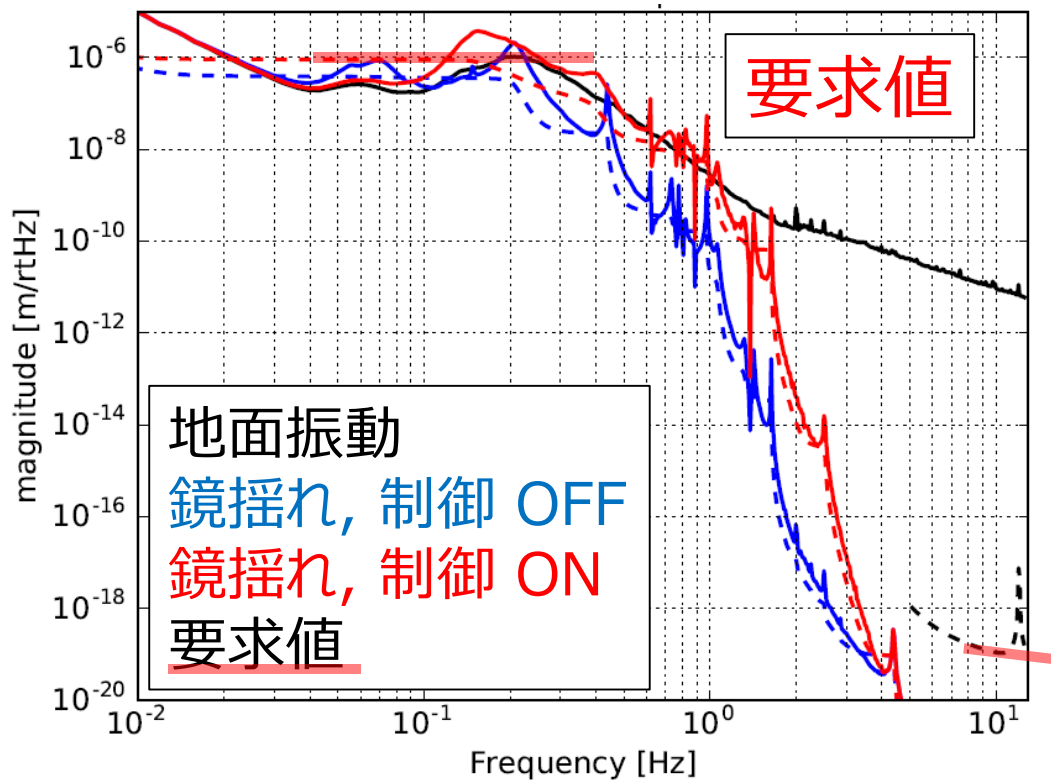
$$X_{stage} = \frac{1}{1 + G} \left[ G \left( 1 - F_{sc} \frac{S_s}{S_L} \right) + P_s \right] X_{GND}$$

変位計経由の地面振動流入 カット → Sensor correction

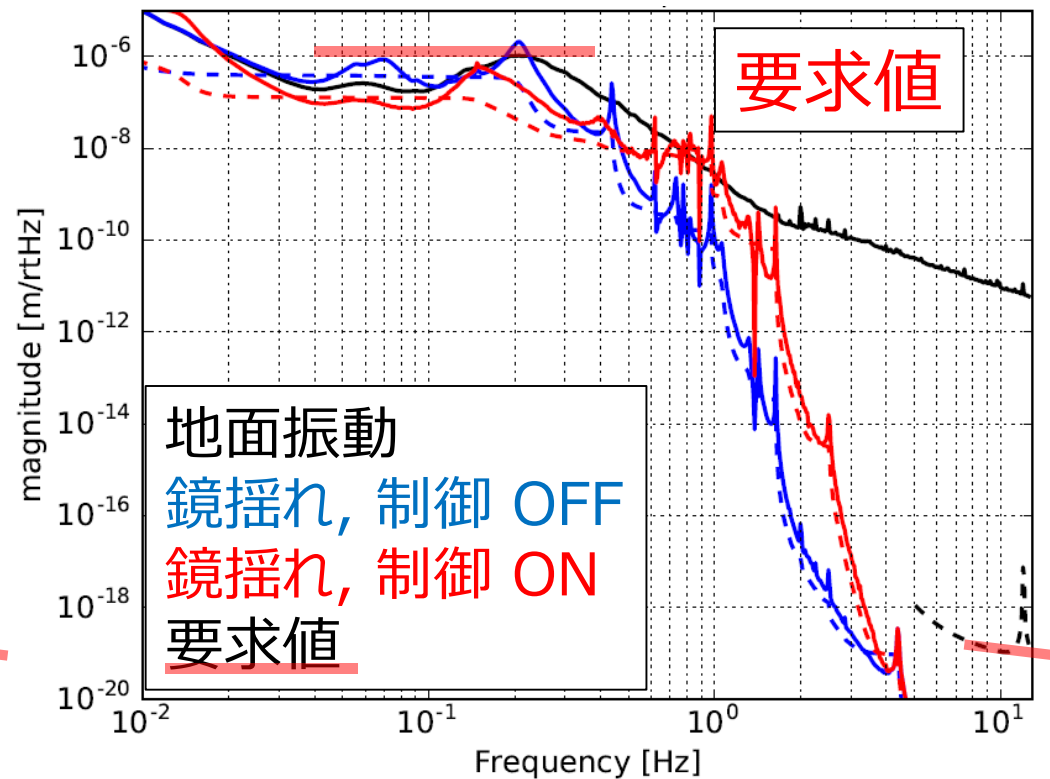
# シミュレーション: 90%tile 地面振動を仮定のときの、鏡揺れ



## Sensor correction OFF

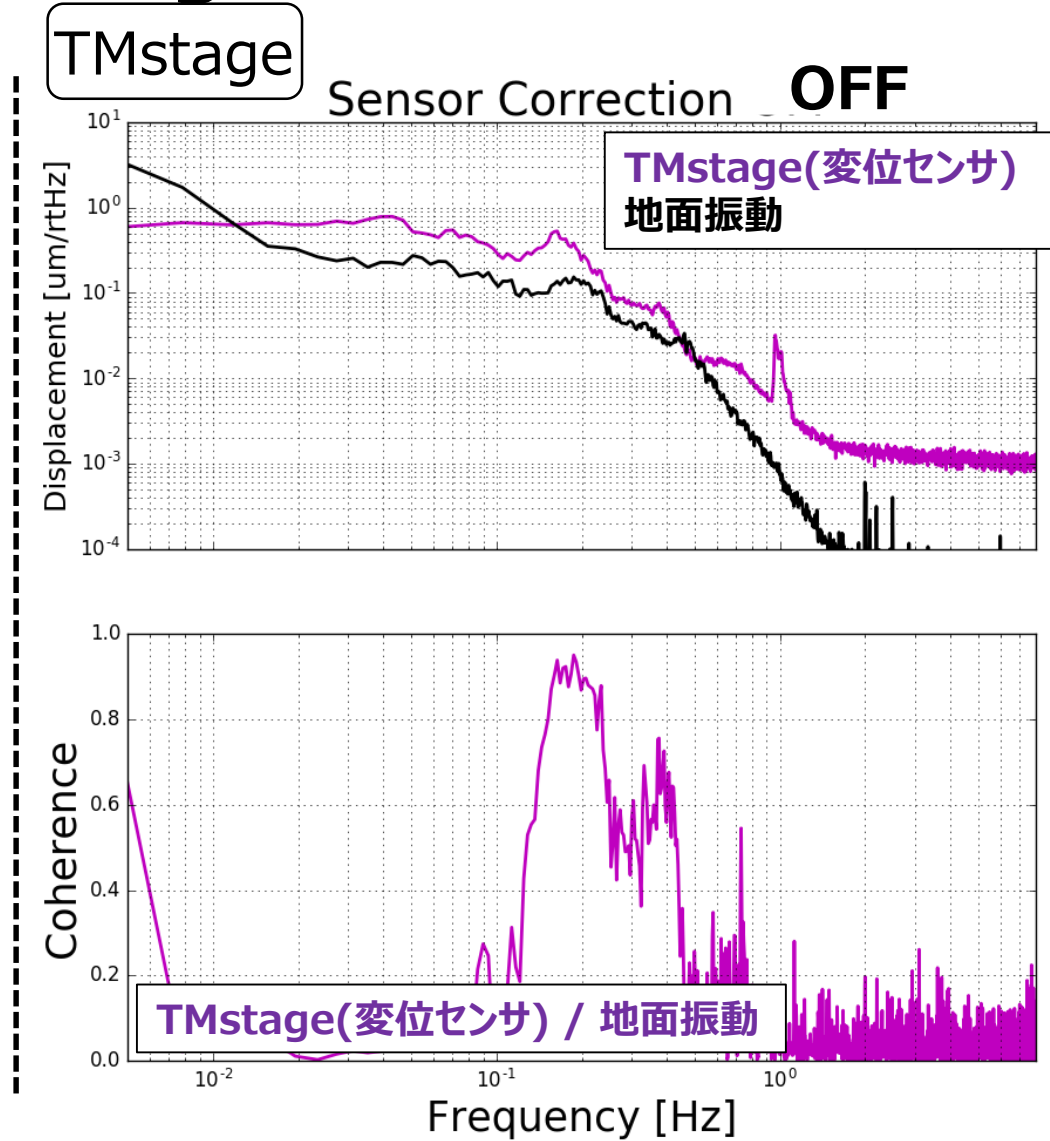
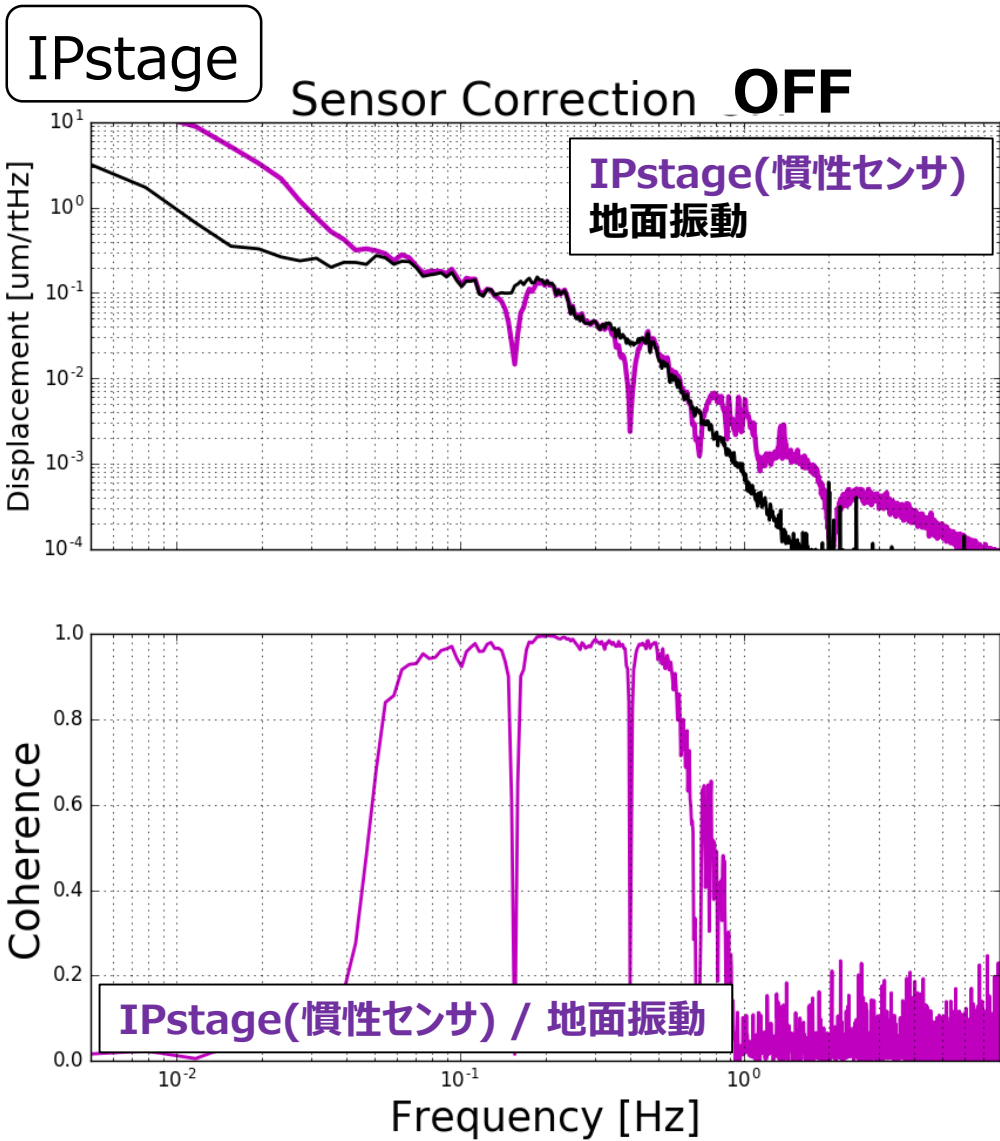
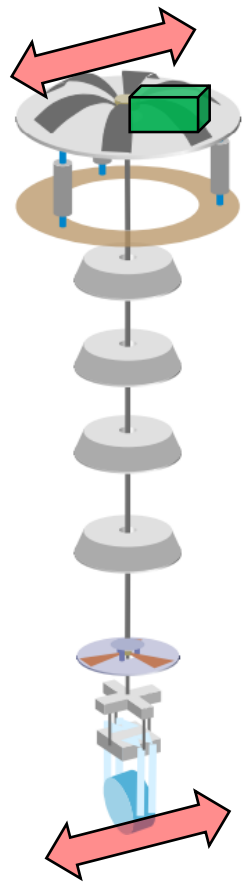


## Sensor correction ON



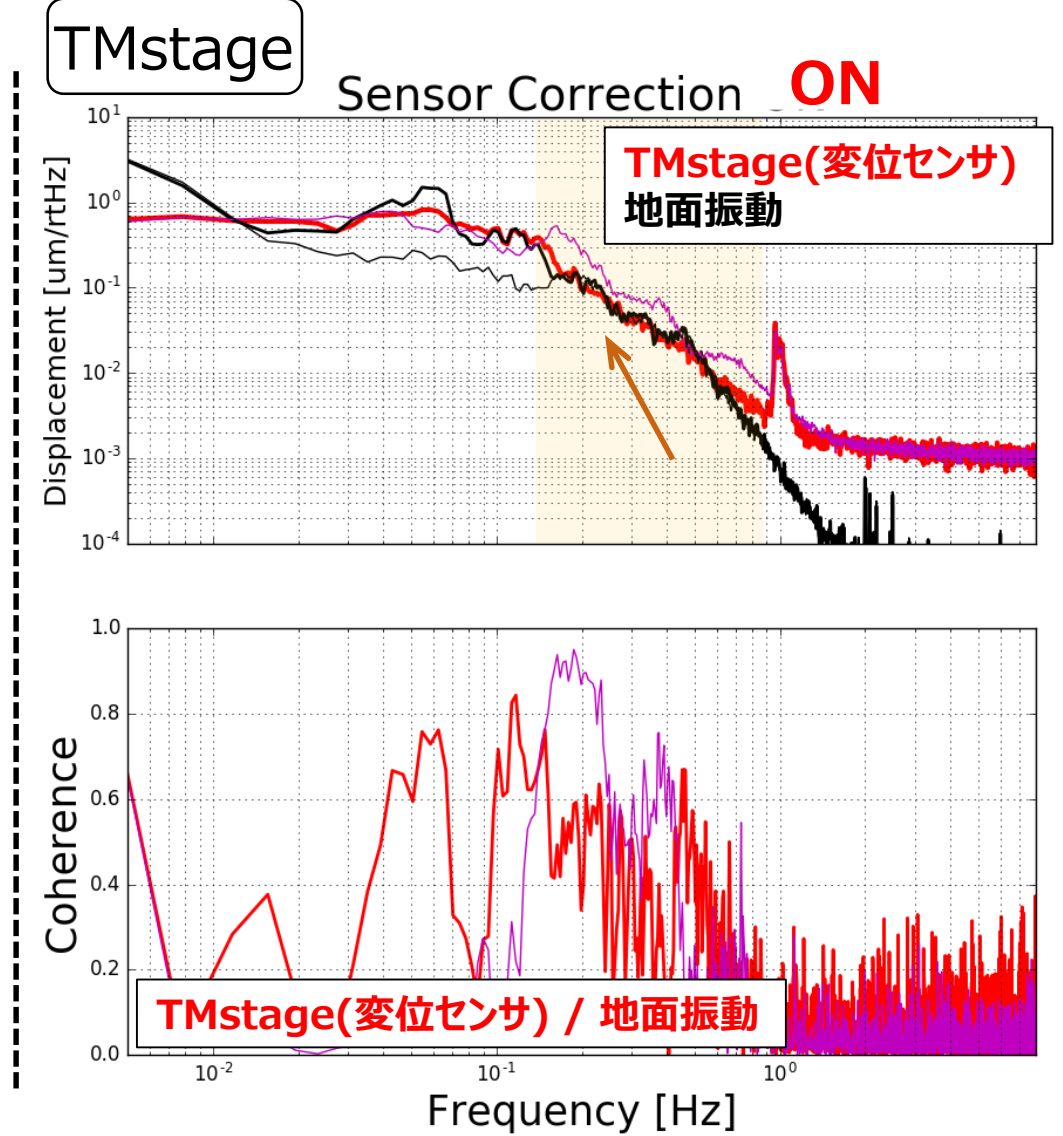
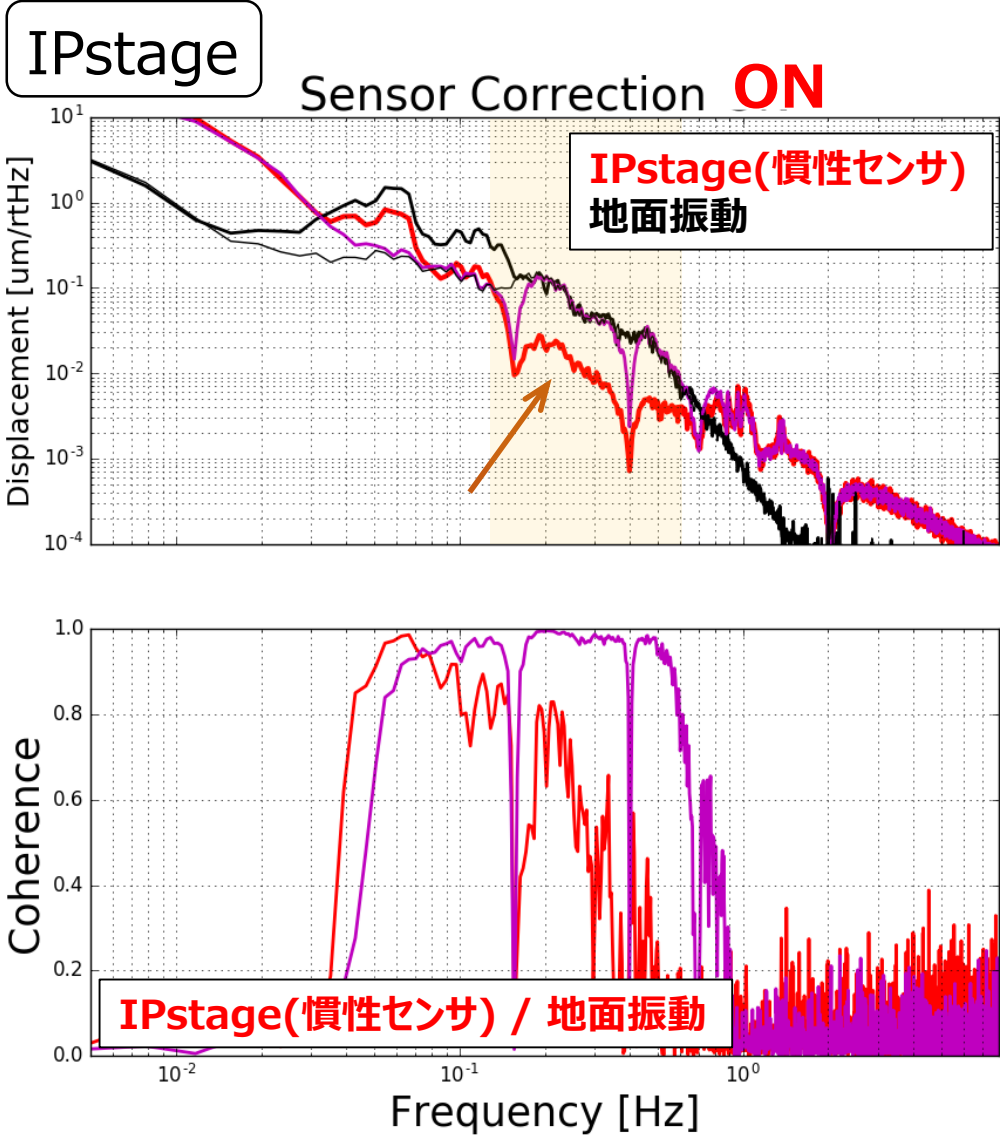
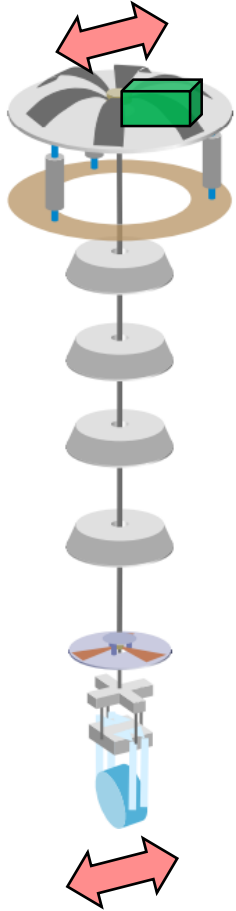
→ Sensor correction を用いて、要求値を満たせる。

# テスト実装: 1つのサスペンションのIP-stageに実装





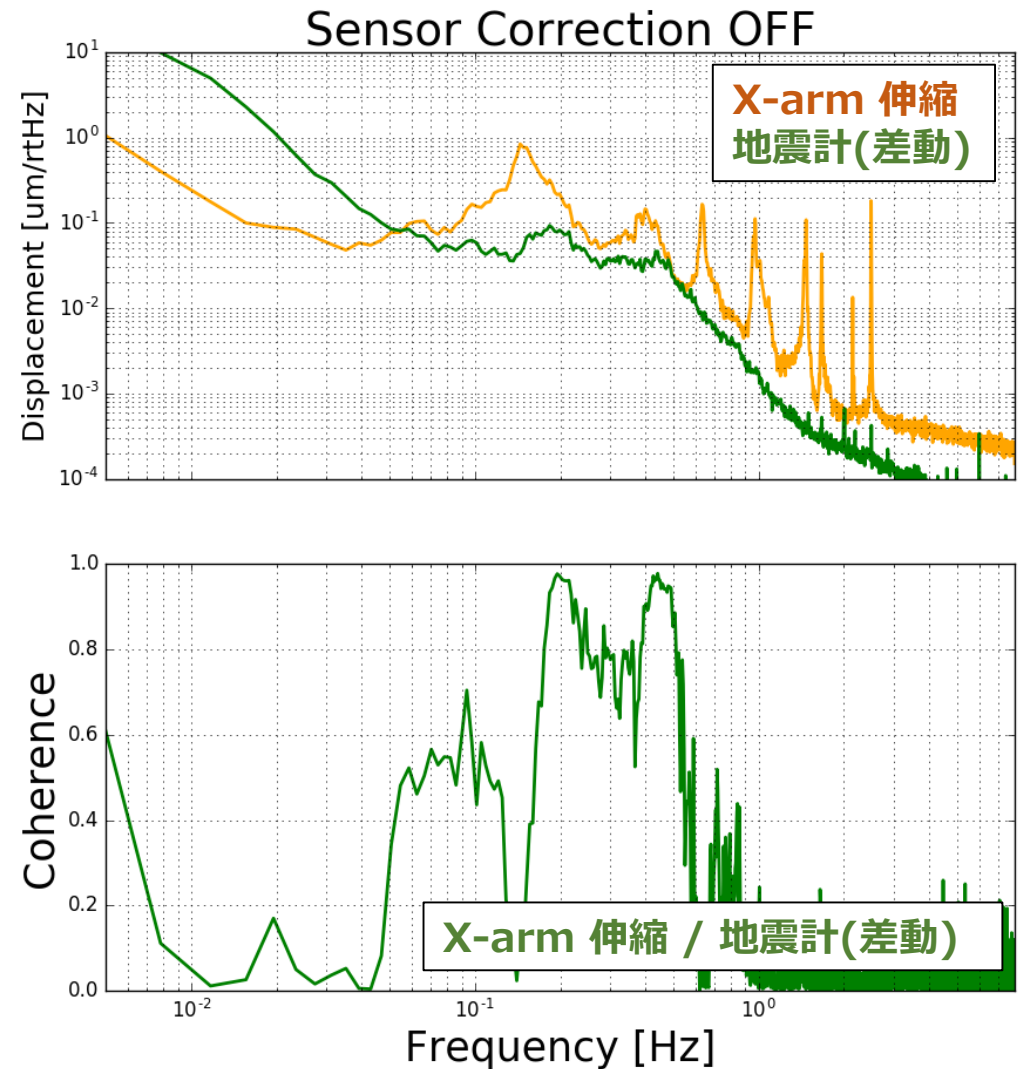
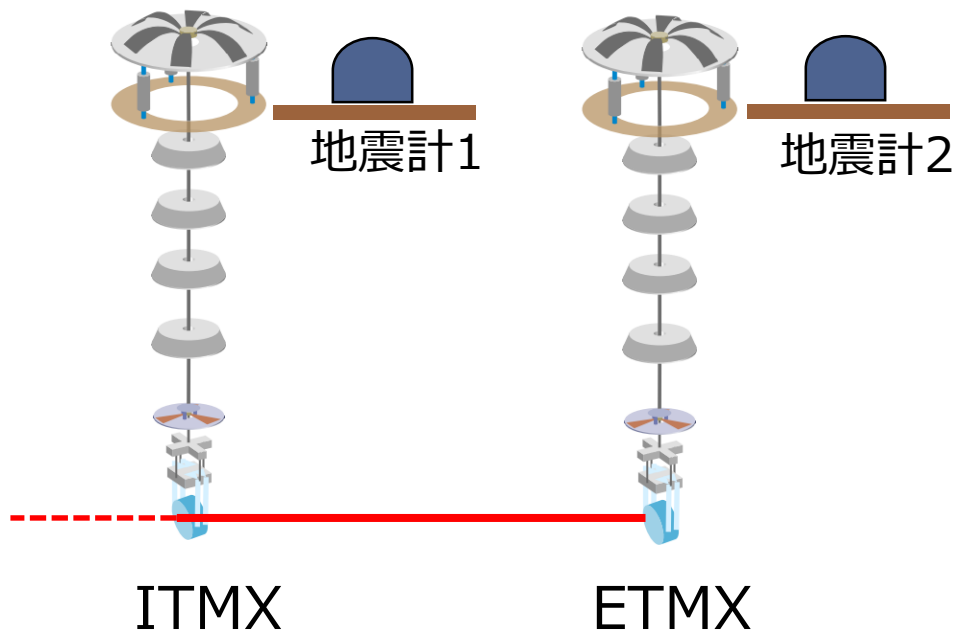
# テスト実装: 1つのサスペンションのIP-stageに実装



ASJ → SC worked at 0.15 ~ 0.7Hz. jji

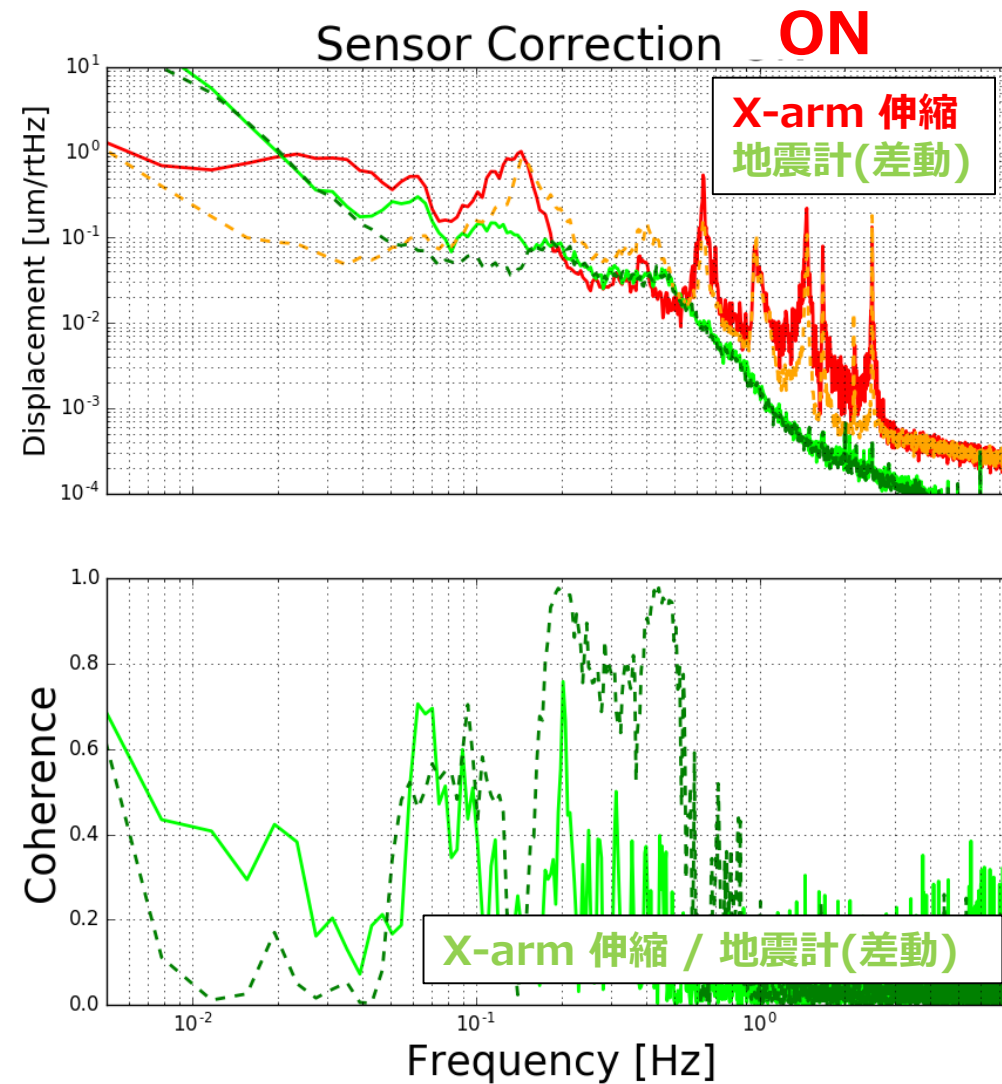
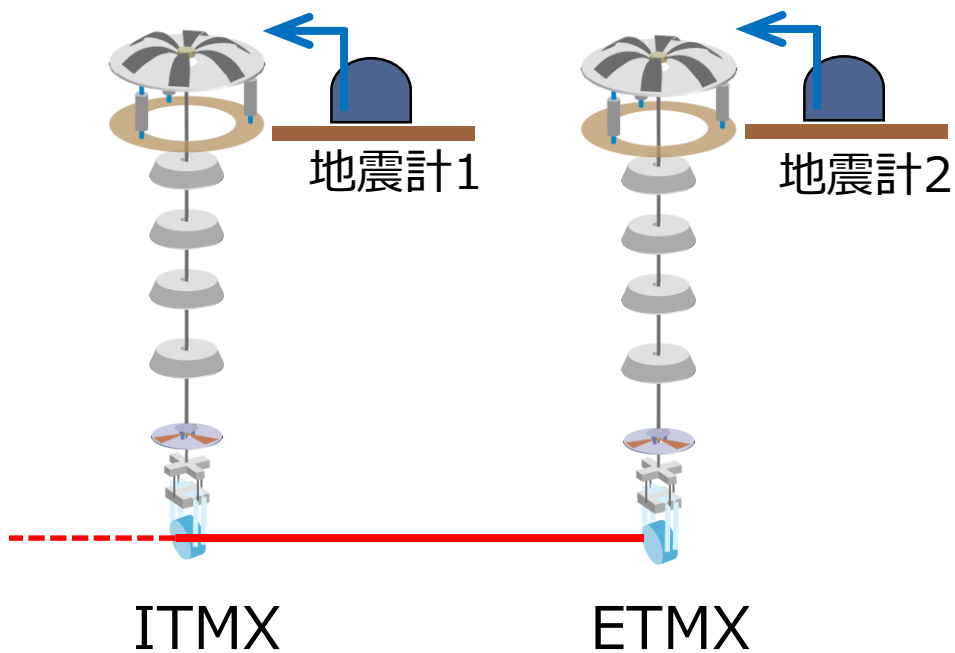
# テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

- 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



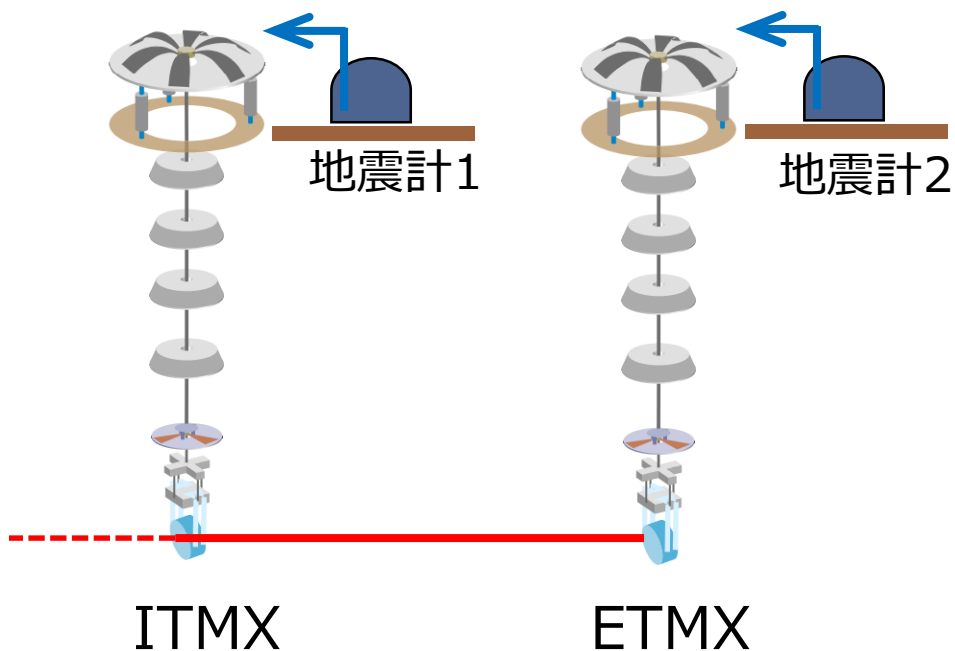
# テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

→ 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

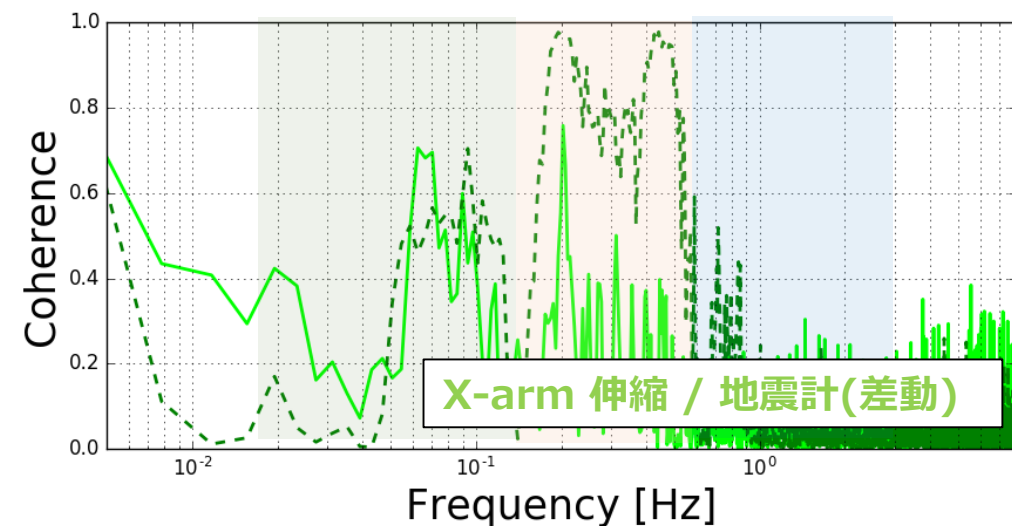
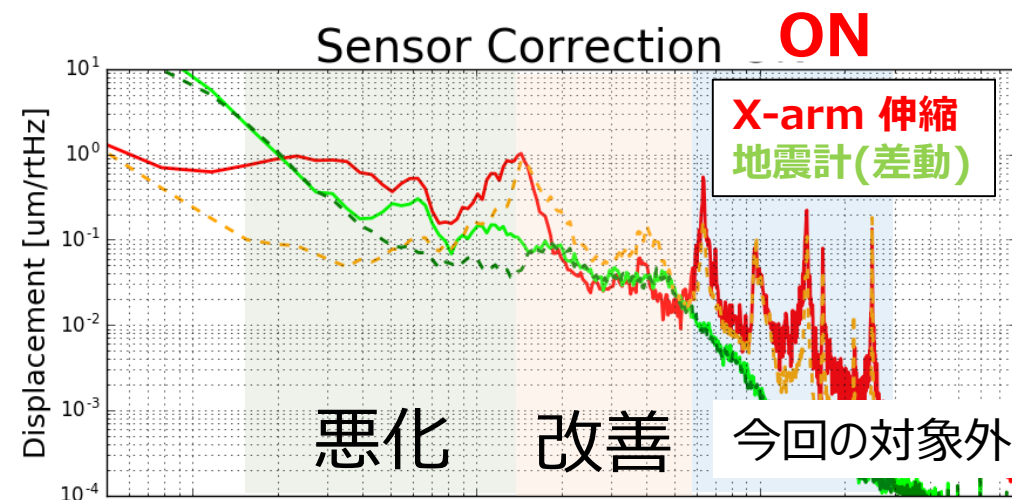


-- SC worked at 0.15 ~ 0.6Hz.

-- 低周波: 悪化

→ SC filterからの地震計の雑音の流入ほか

→ To be investigated.



## まとめ:

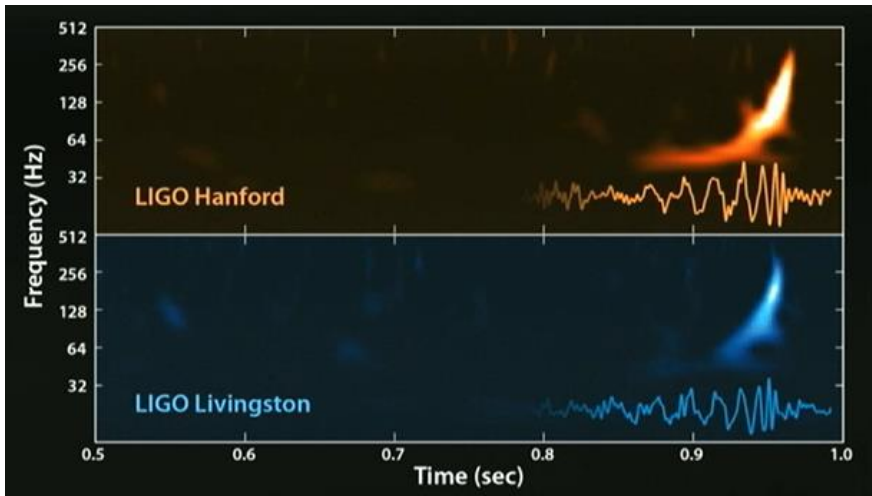
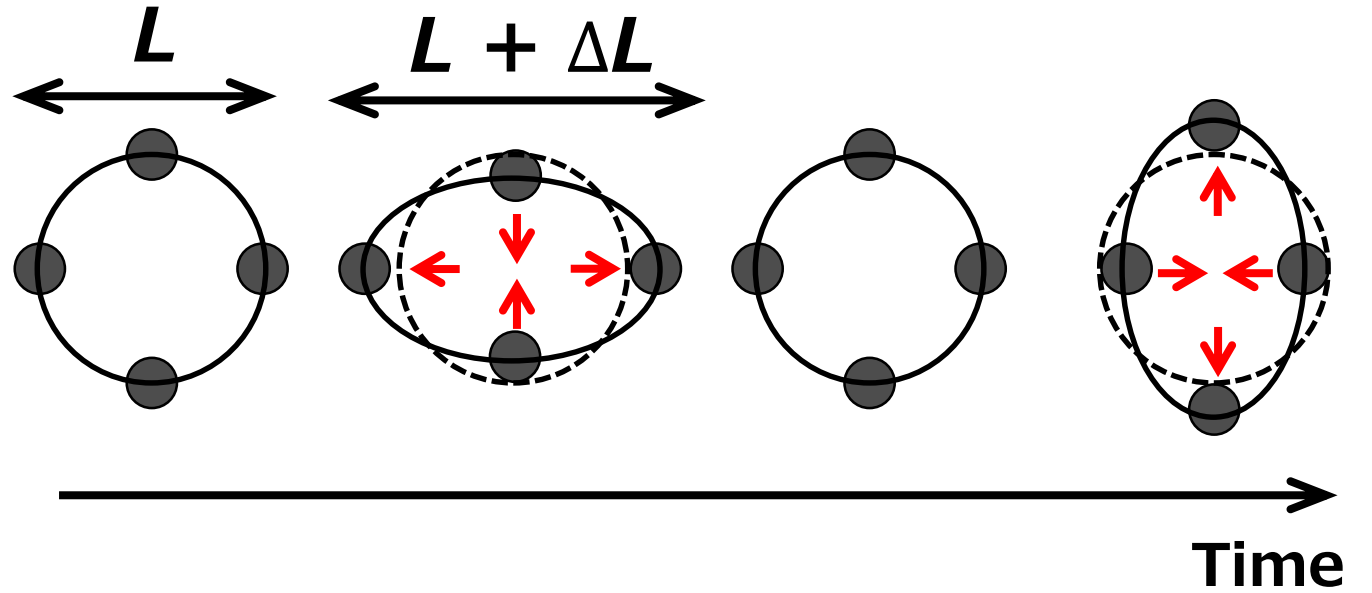
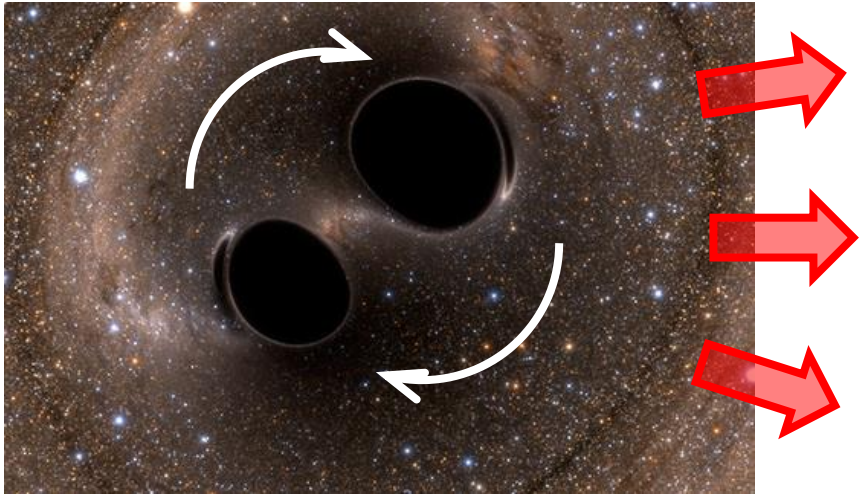
- 変位センサと、地面に置いた地震計とを用いて、鏡のRMS揺れを抑える制御系を作成し、試験的に実装した。
- local / global とともに 0.15 ~ 0.6 Hzでは、振動は低減されが、  
< 0.15 Hz では悪化(の様子)  
とくにRMS の改善なし  
→ (今回の試験の)低周波帯での性能: 要 調査

## 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

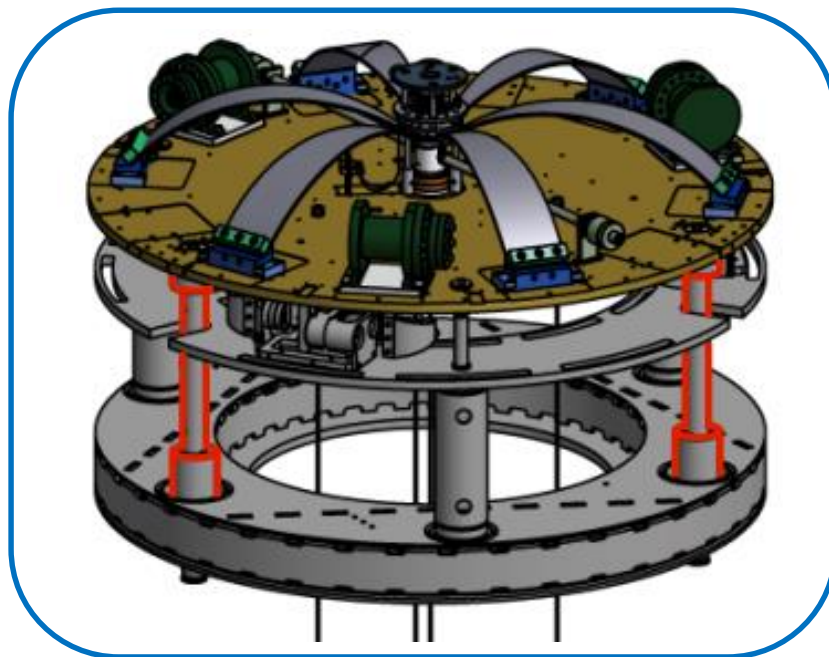
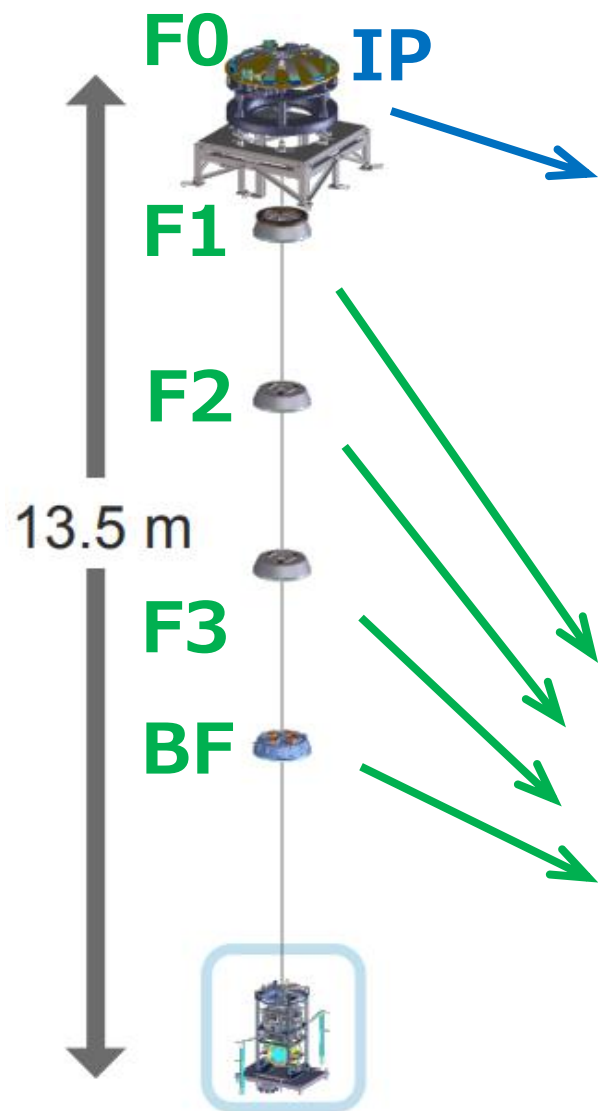
# 重力波?



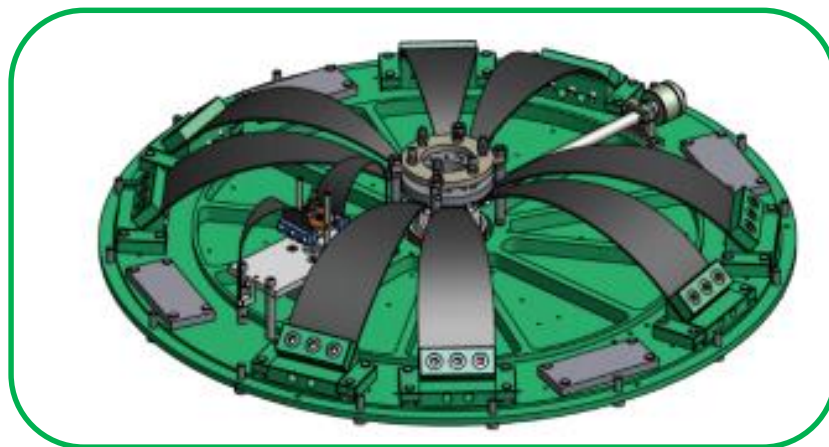
- 2015.9.14 初検出!
- BBH, BNS 検出!

→ 新しい天文学!

# メイン鏡用の防振装置



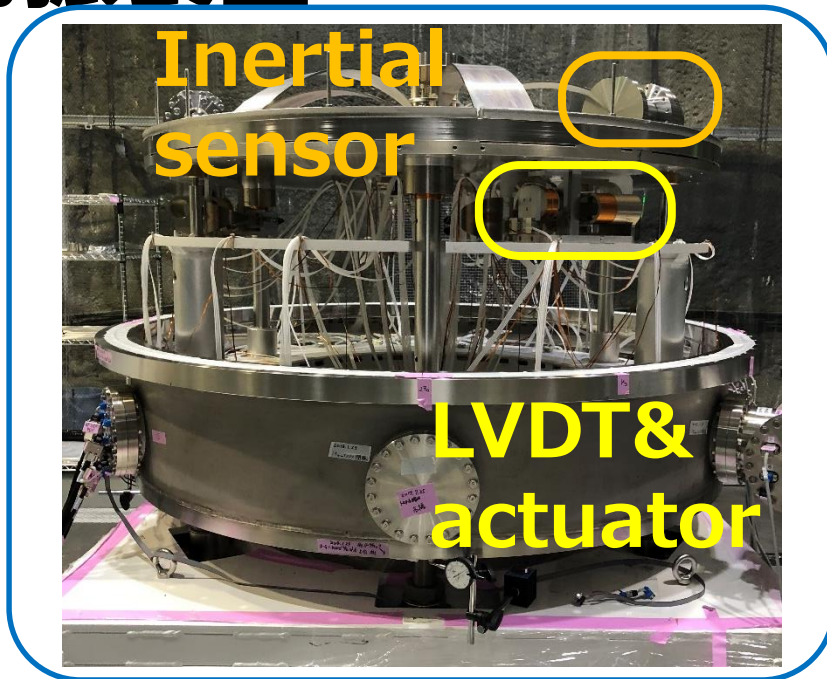
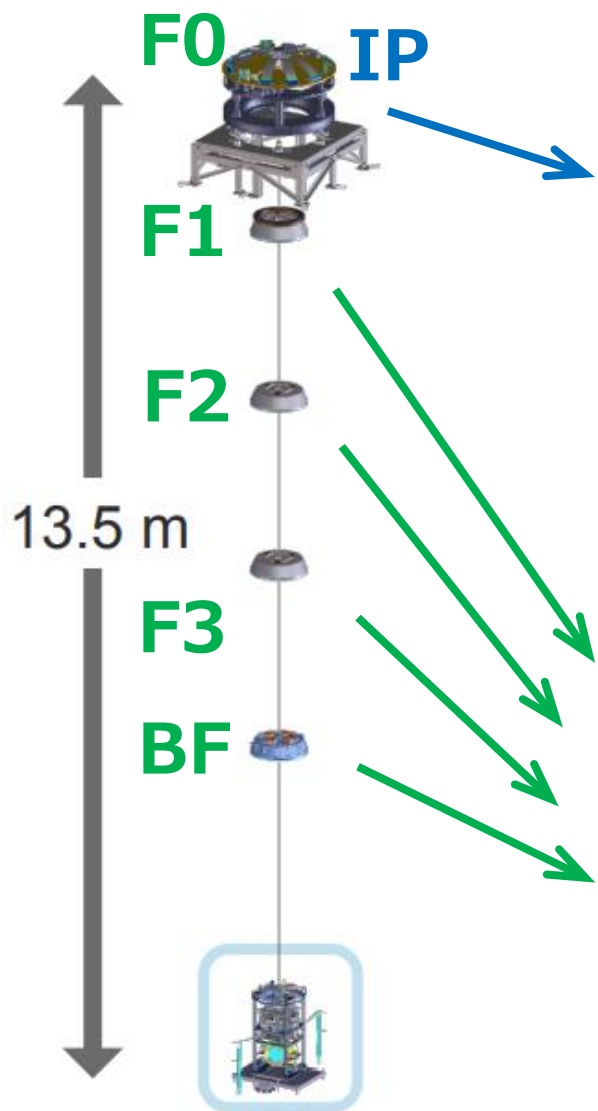
INVERTED PENDULUM  
( $\sim 70$  mHz)



GEOMETRIC-ANTI SPRING  
( $\sim 0.4$  Hz)



# メイン鏡用の防振装置



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



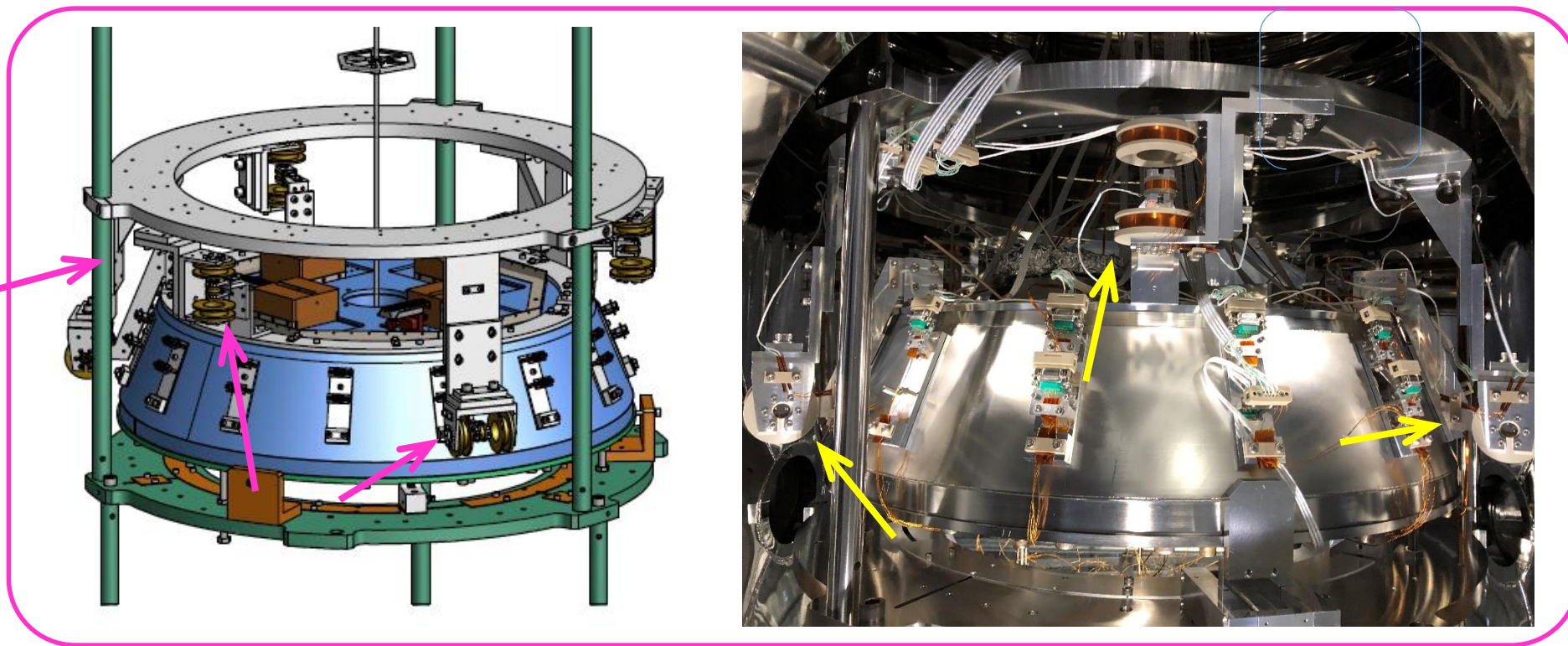
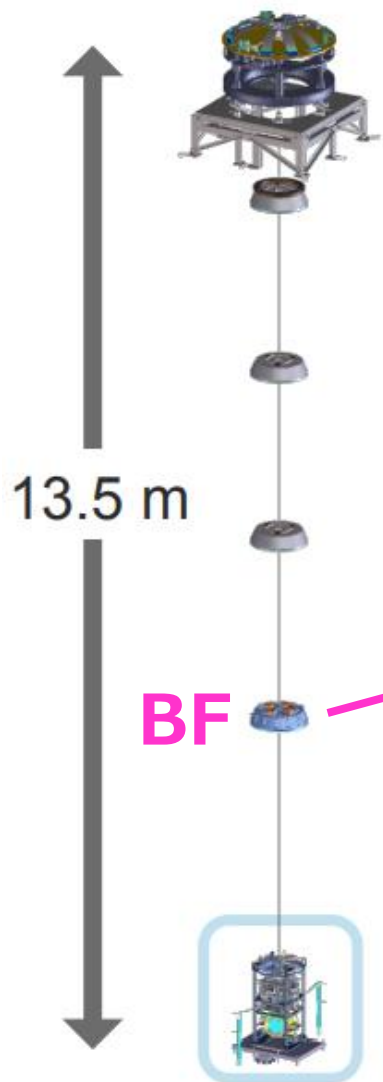
GEOMETRIC-ANTI SPRING  
with 1 vertical  
LVDT & actuator unit

# 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)

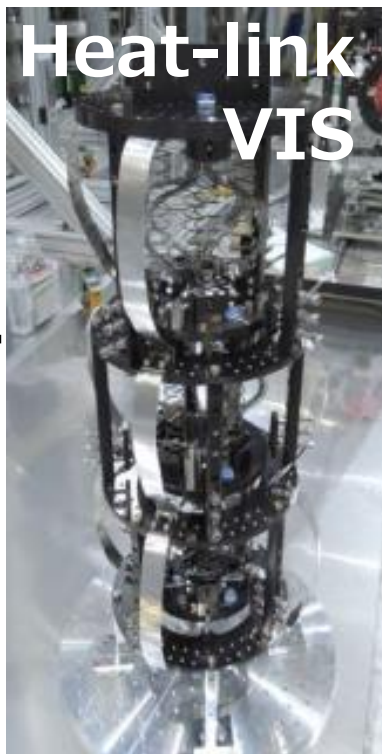
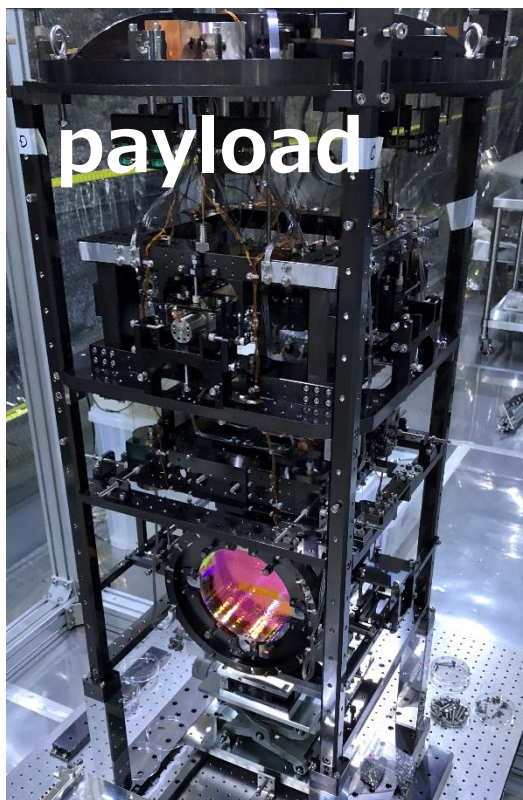
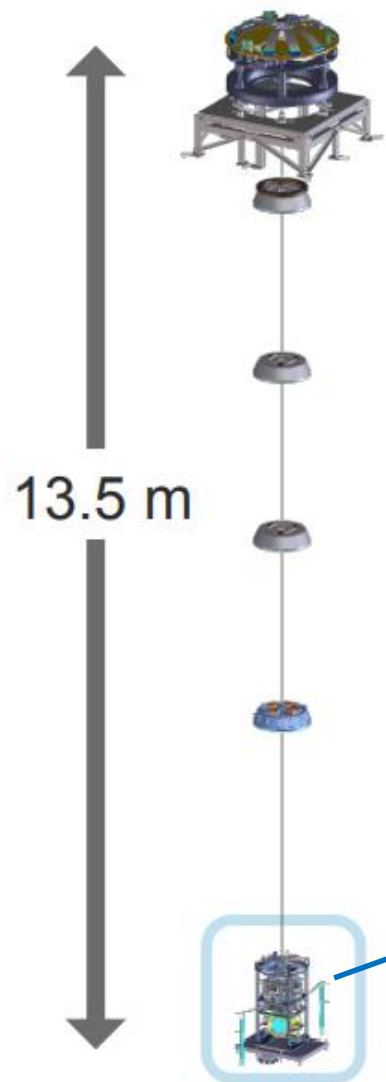
## BOTTOM-FILTER DAMPER

with 3 horizontal & 3 vertical LVDT & actuator units

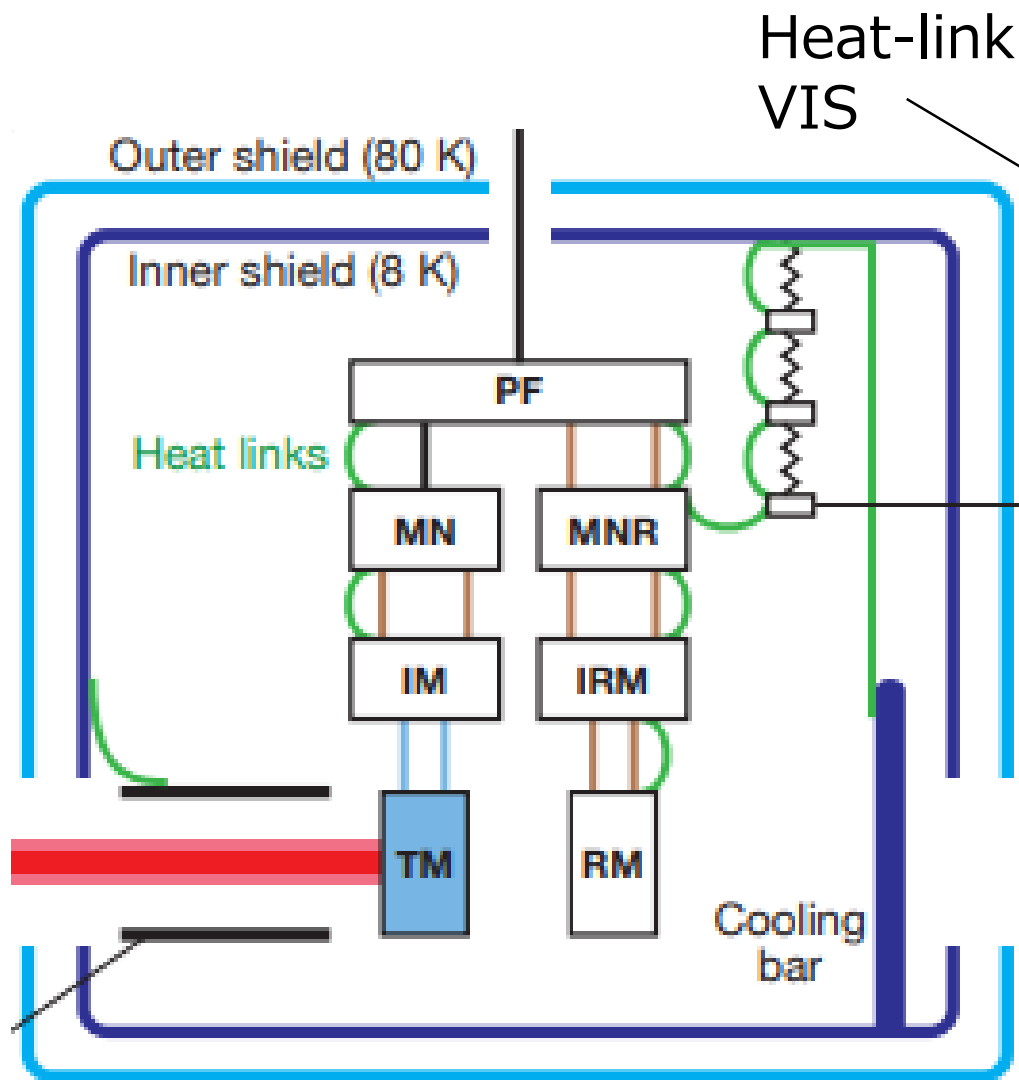


# メイン鏡用の防振装置

## クライオスタットの中

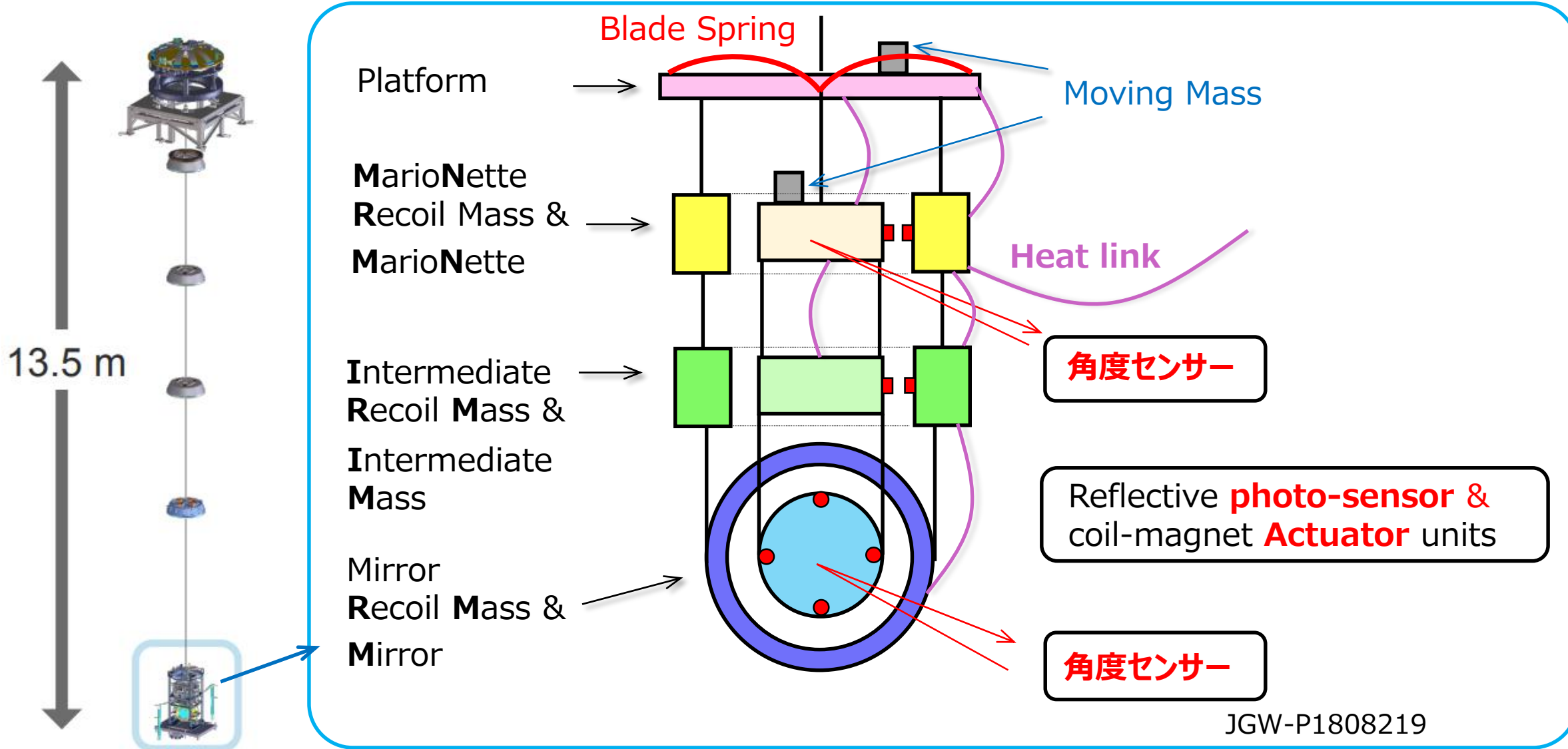


(+ Wide-angle baffle)

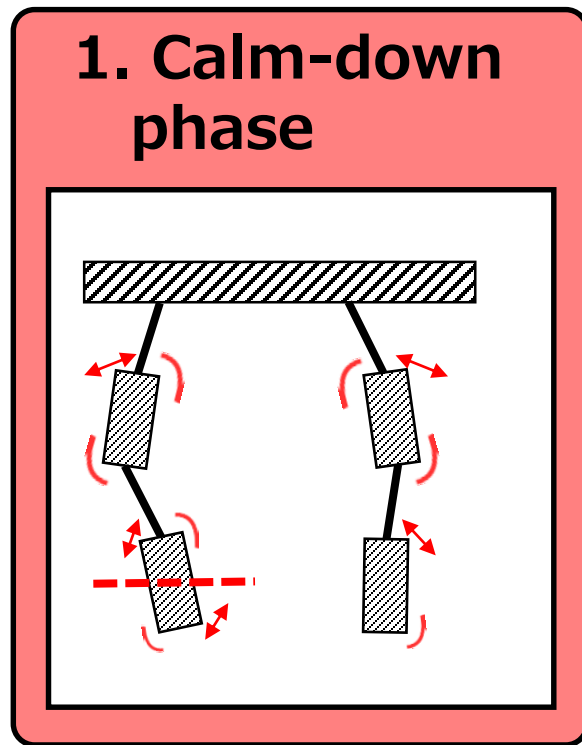


JGW-P1809347

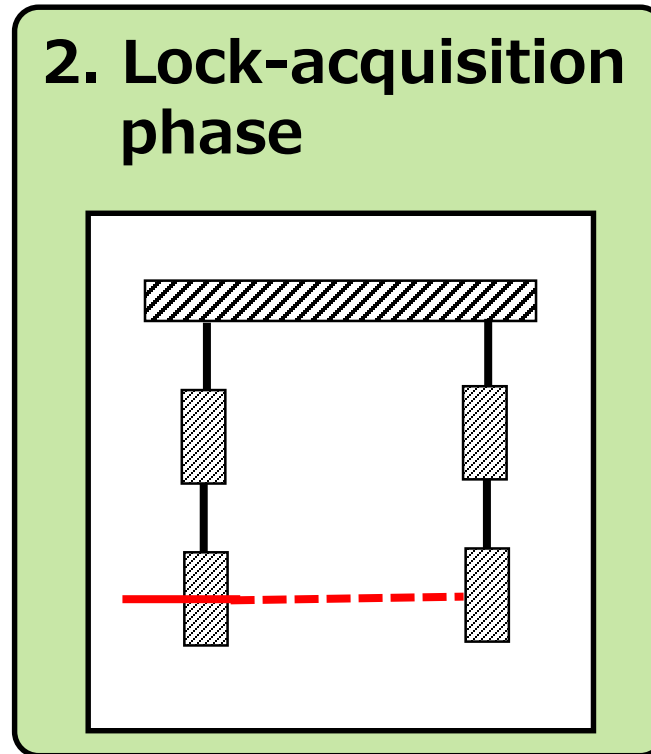
# メイン鏡用の防振装置



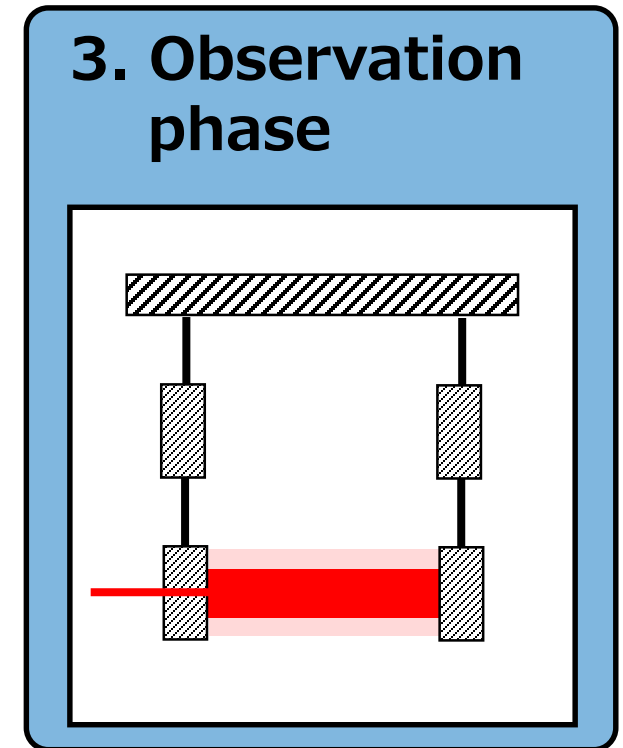
# Designing active control system / Control phase



Suppress  
large disturbance

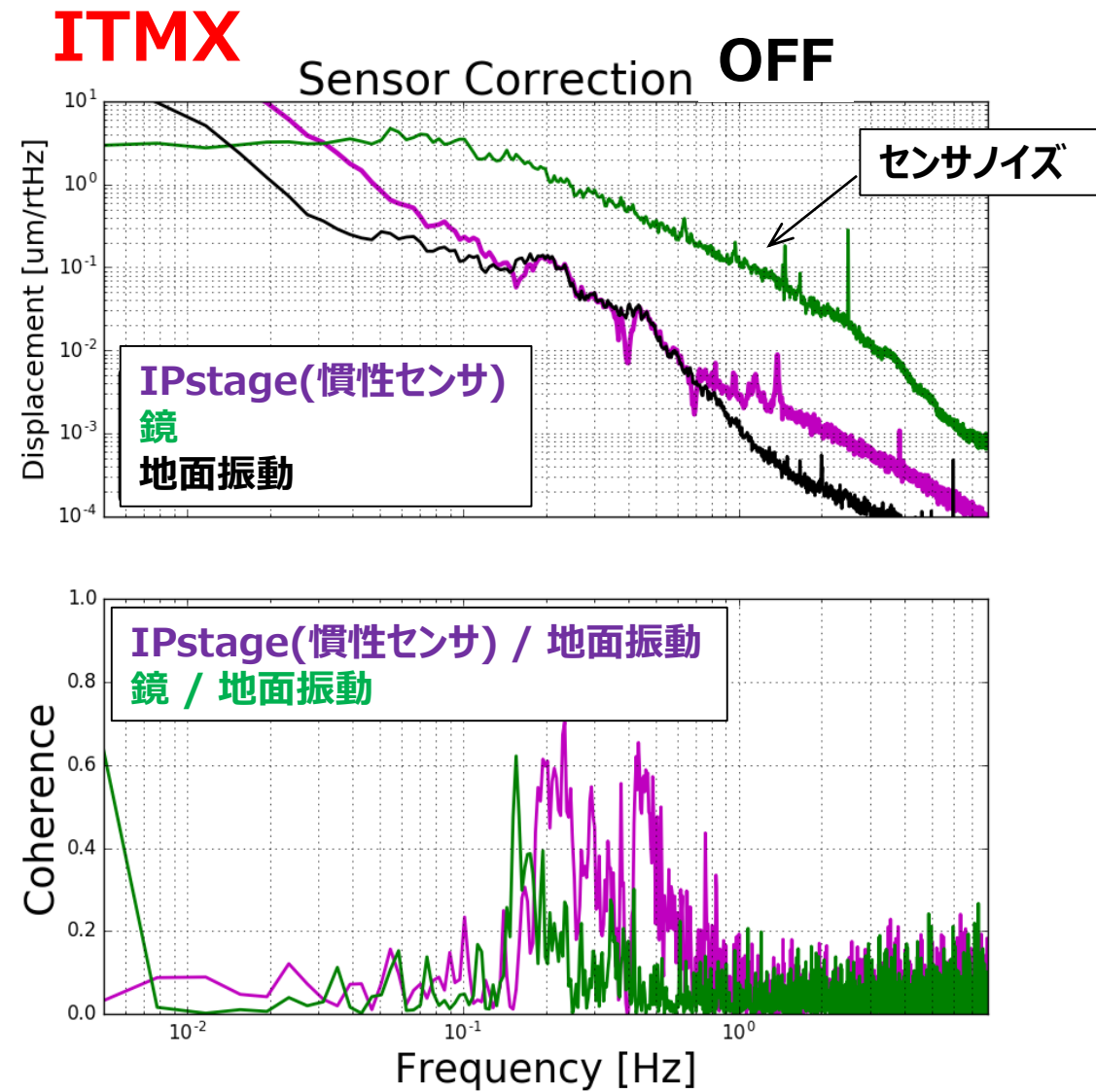
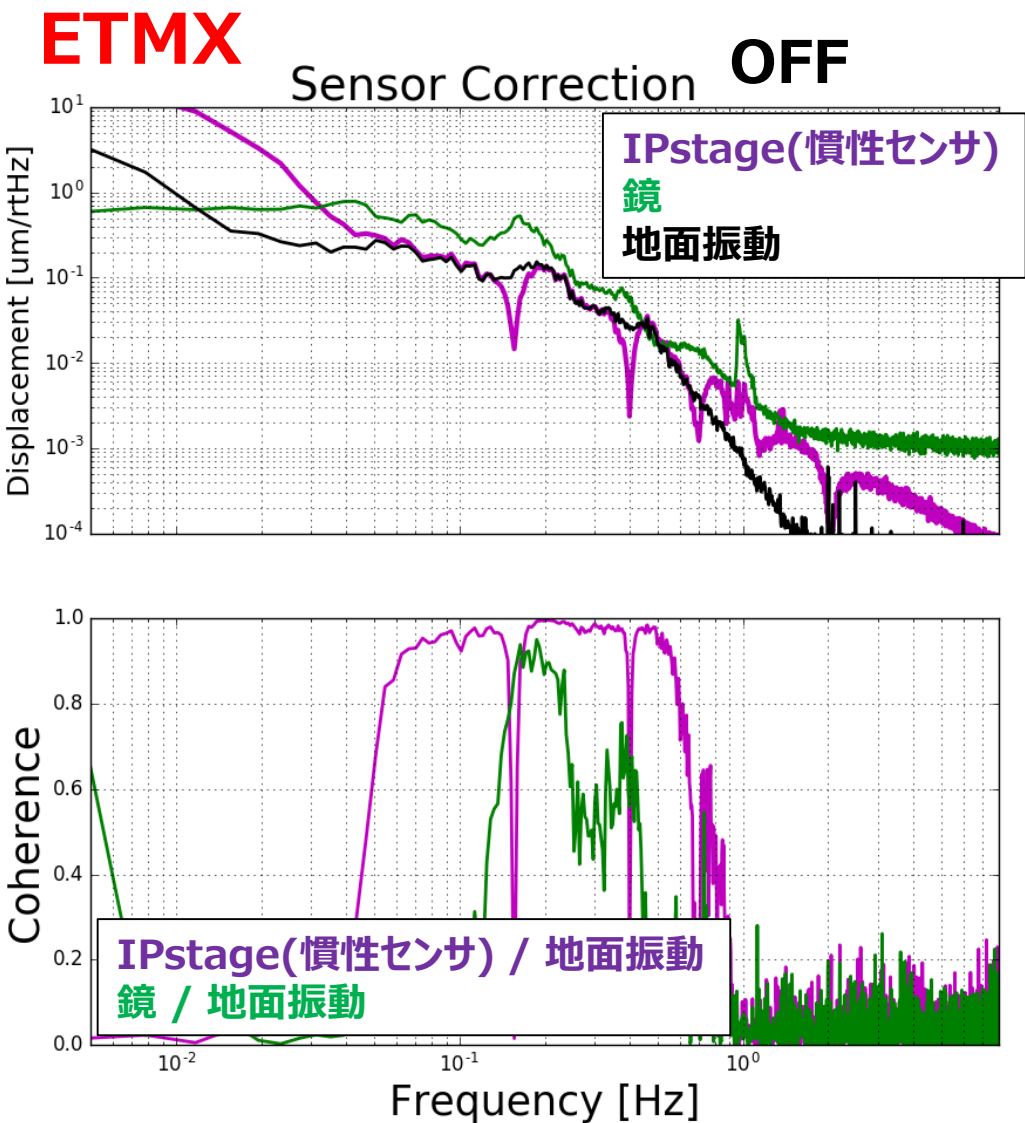
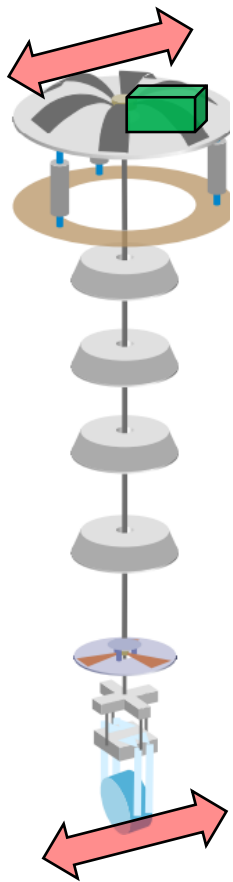


Reduce RMS velocity  
RMS angle  
(**R**oot-**M**ean-**S**quare)

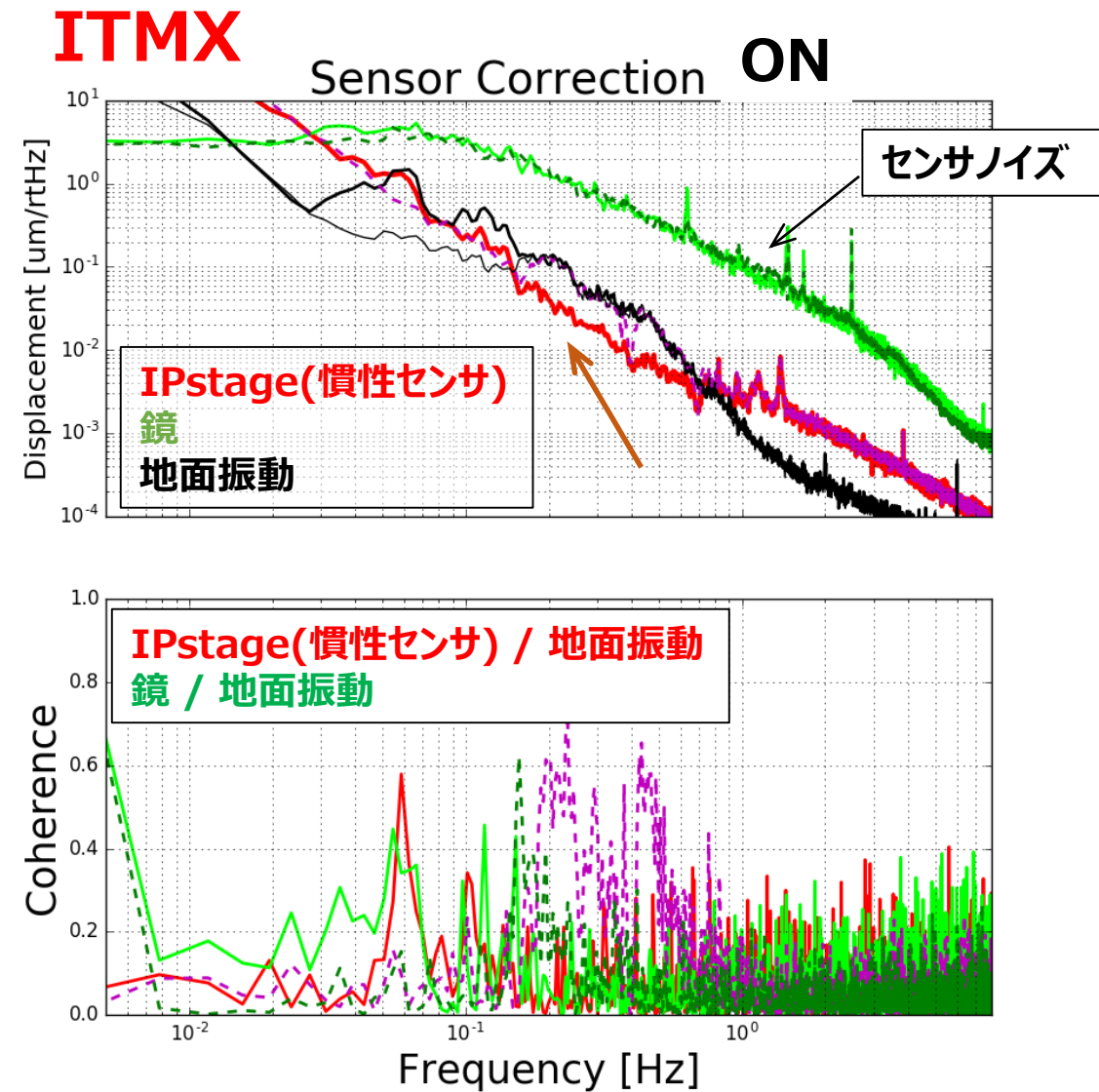
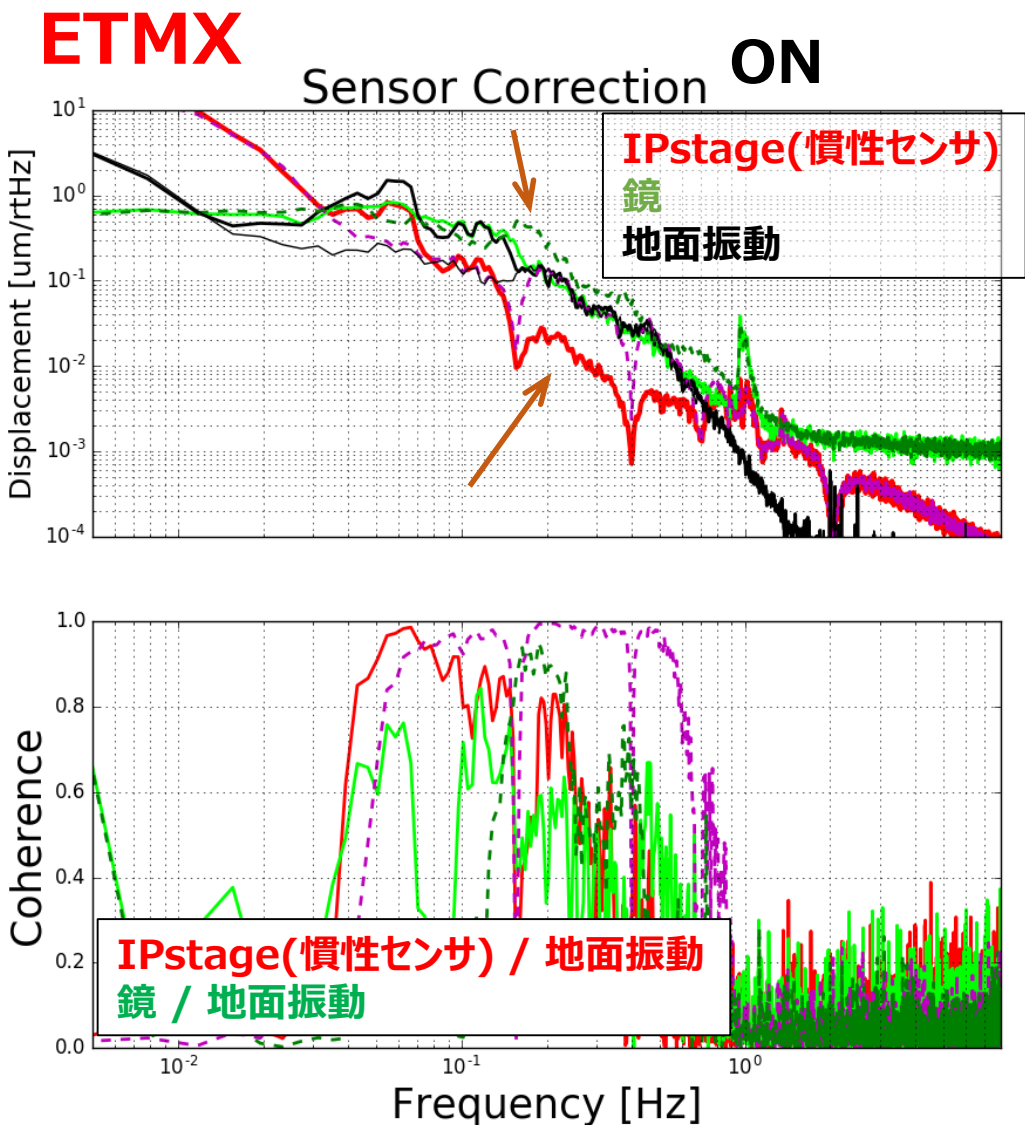
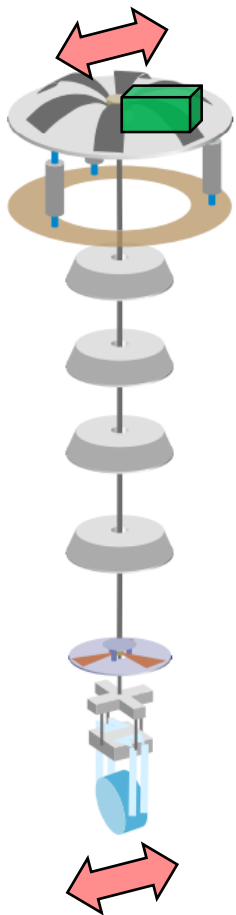


Keep position  
with low noise  
control

# 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



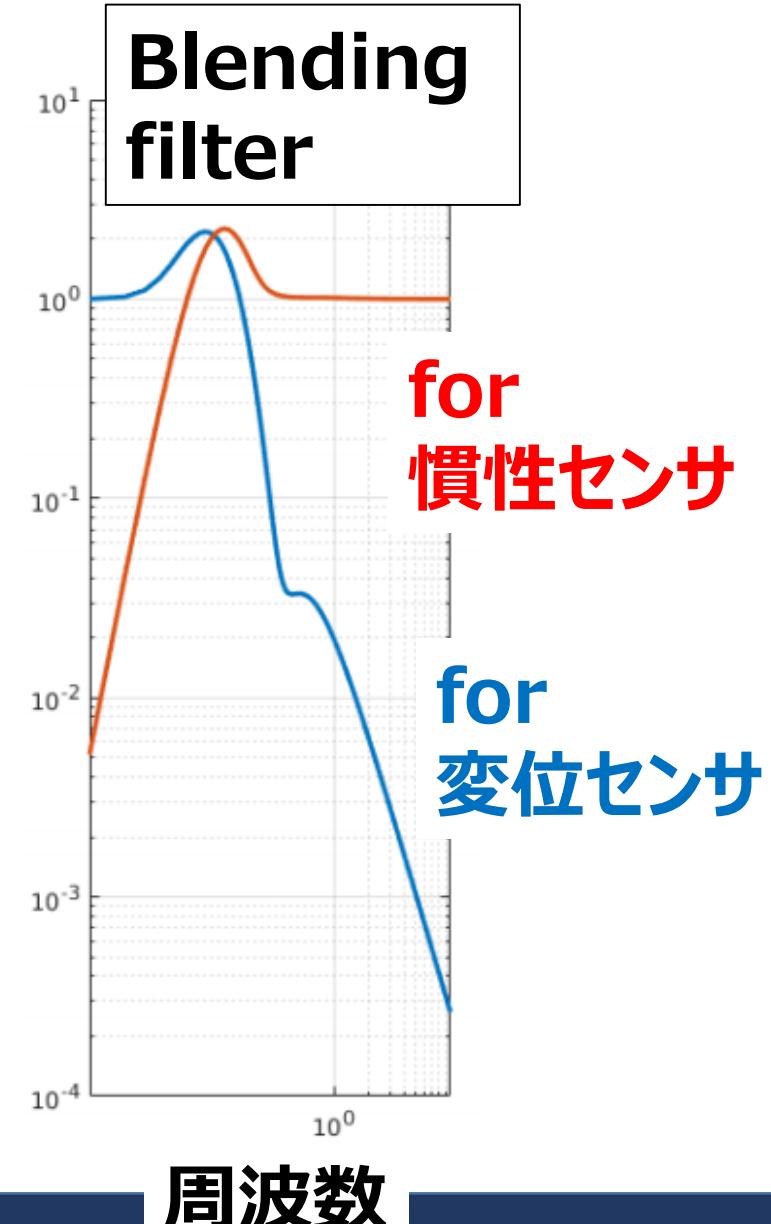
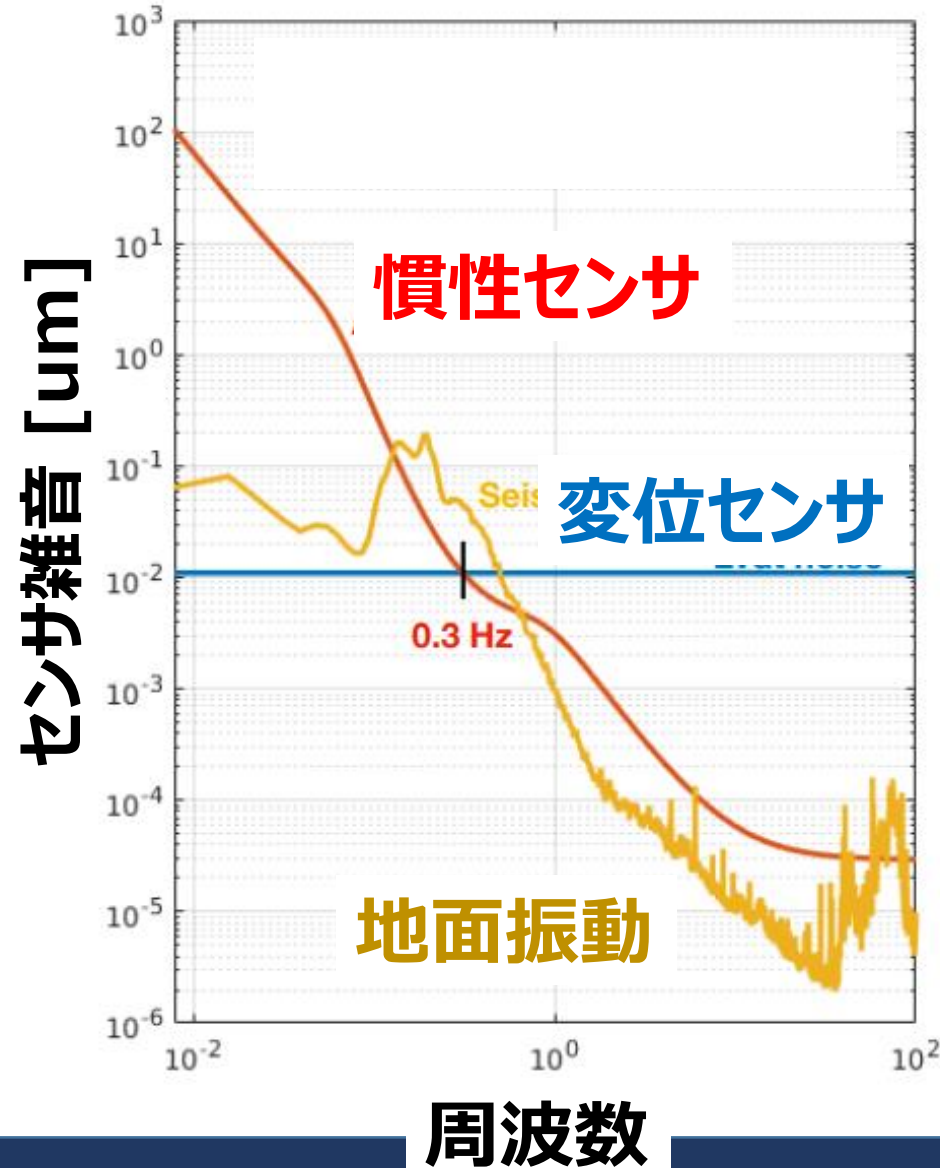
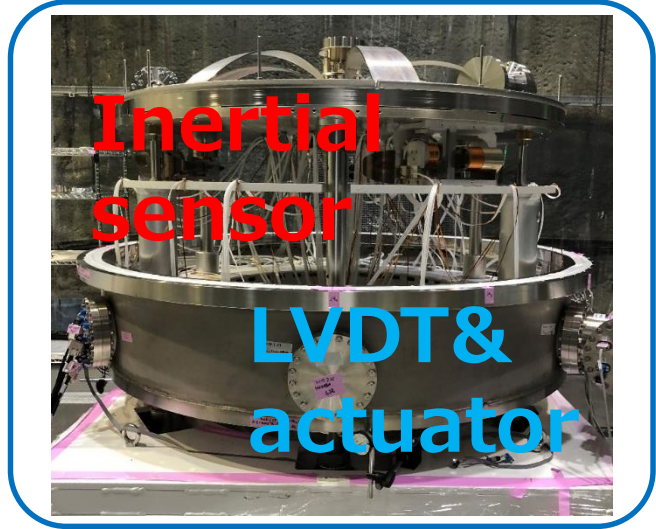
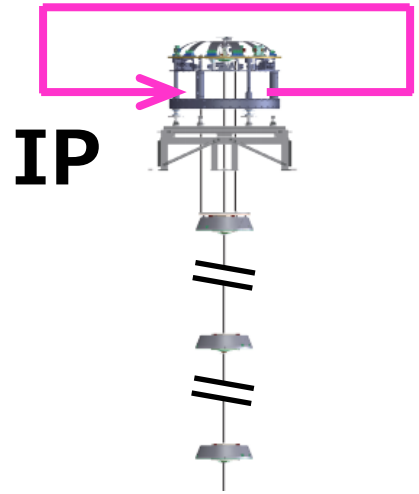
# テスト実装: 2つのサスペンションのIP-stageに実装、localで見ると



→ 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。

# Sensor blending & inertial damping

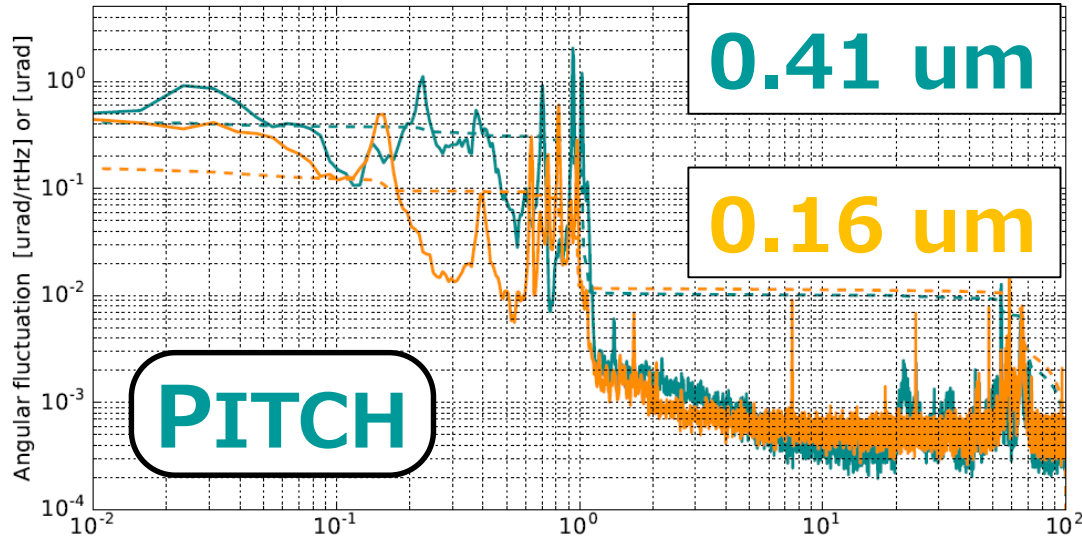
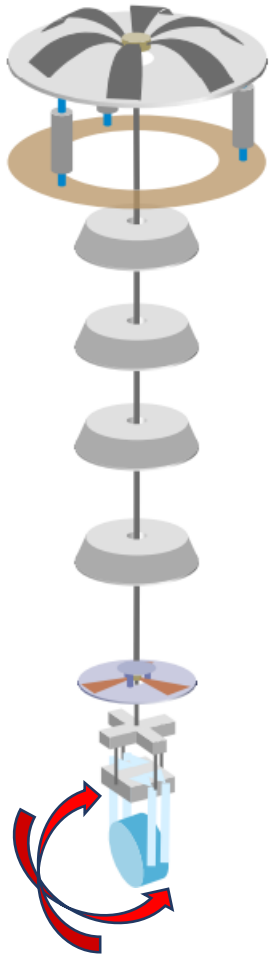
(From JGW-G1909932)



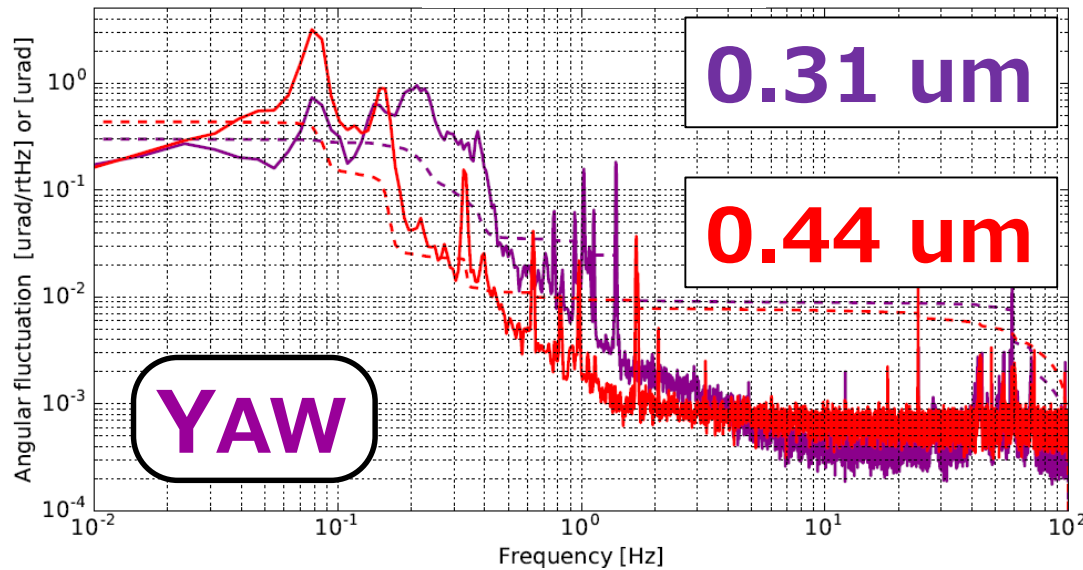


# Sensor blending & inertial damping

ITMX

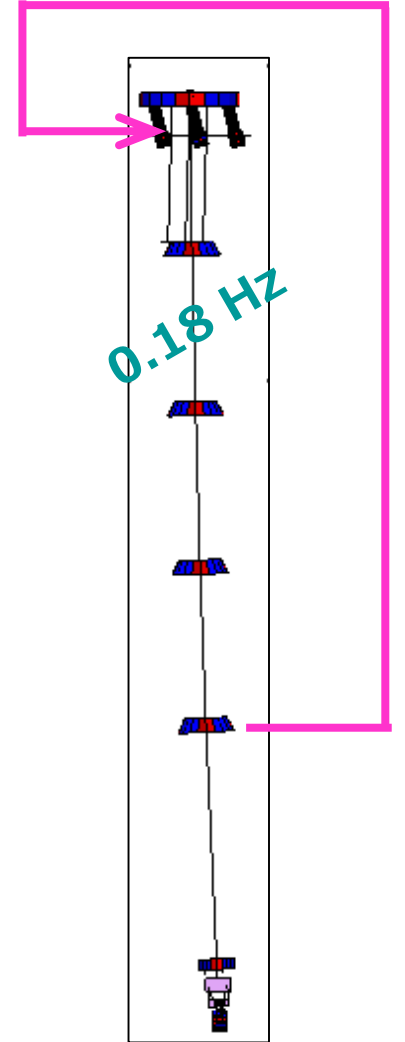


w/ inertial damping



w/ inertial damping

Next



(\*)異なる日の測定。ただし地面振動レベルは同程度。

# 大型重力波望遠鏡 KAGRA

Toyama Bay  
Toyama City

## KAGRA in Kamioka, Japan



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

(From JGW-G1909822)

Feb 14th, 2019

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Image © 2013 DigitalGlobe  
© JGW-G1909822  
Data Japan Hydrographic Association

Google earth

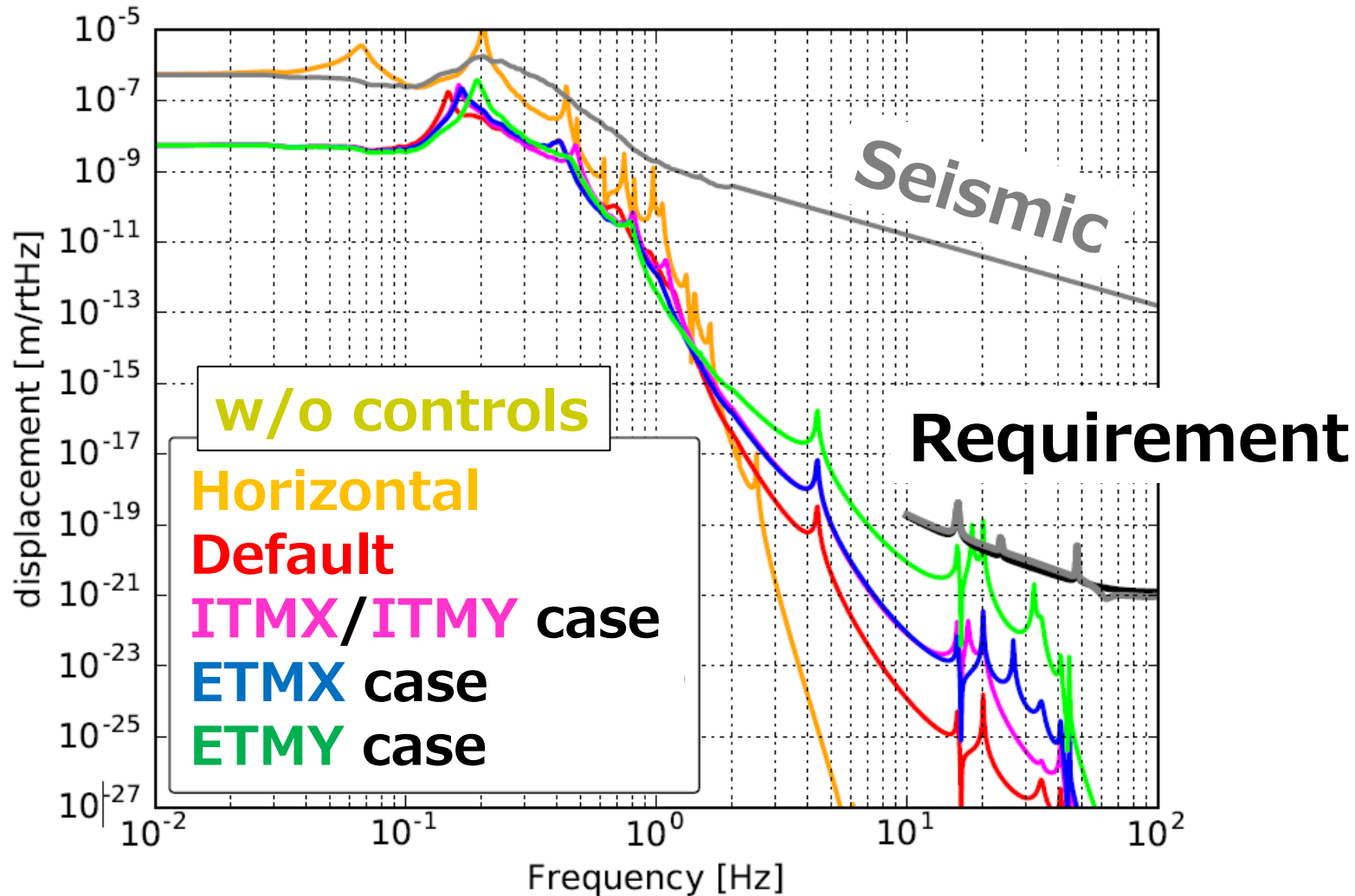
# Requirements, Type-A suspensions

<b>Calm-down phase</b>		
Item	Requirement	For/Determined by
1/e modal decay time	< 1 min	Quick recovery
RMS displacement (L)	< 50 $\mu\text{m}$	Smooth transition to next phase
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 50 $\mu\text{m}$	Smooth transition to next phase
<b>Lock acquisition phase</b>		
Item	Requirement	For/Determined by
RMS velocity (L)	< 240 $\mu\text{m/s}$	Auxiliary laser locking
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 880 nrad	Optical gain degradation < 5%
<b>Observation phase</b>		
Item	Requirement	For/Determined by
Displacement noise (L) @ 10 Hz	< $8 \times 10^{-20}$ m/Hz <sup>1/2</sup>	Sensitivity
Displacement noise (V) @ 10 Hz	< $8 \times 10^{-18}$ m/Hz <sup>1/2</sup>	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  $\mu\text{m}$  and 50  $\mu\text{rad}$ , 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,



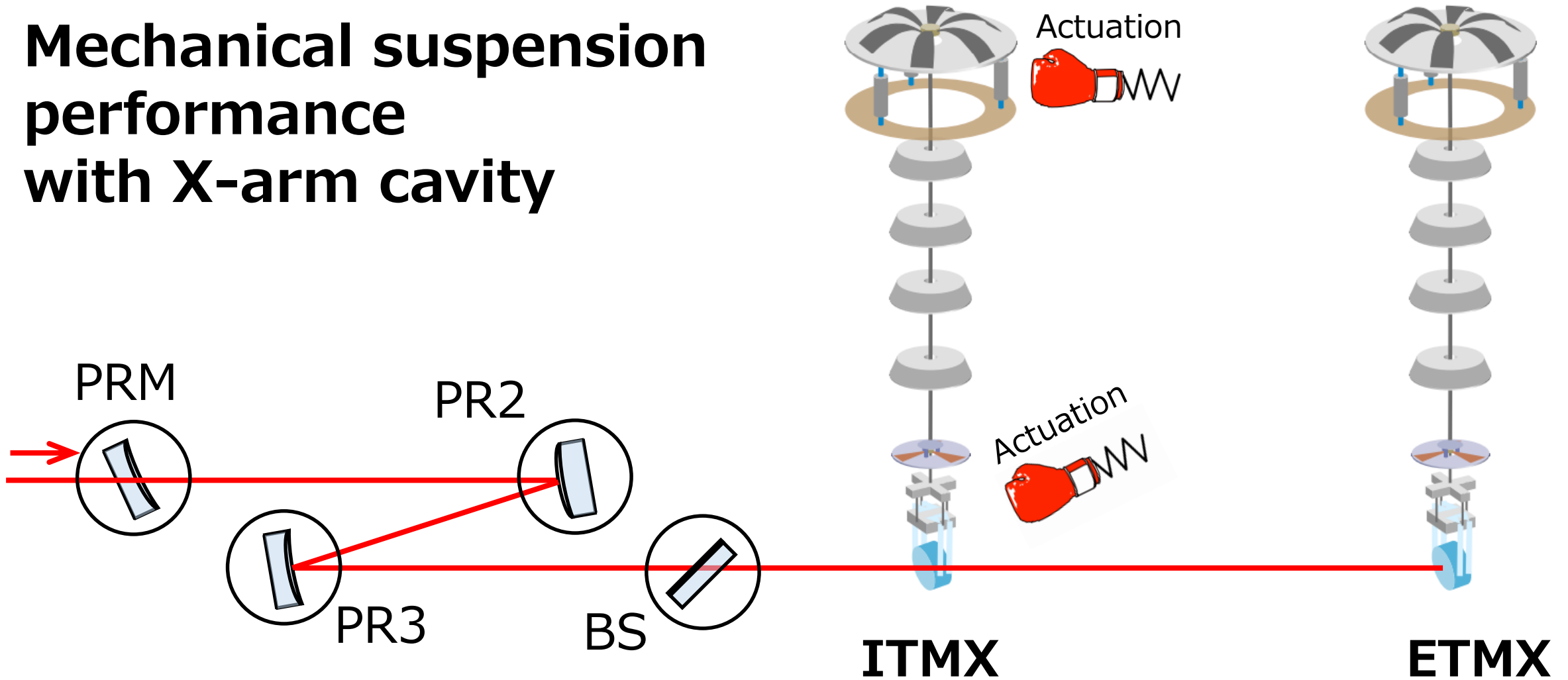
“acceptable for the O3-run”  
(should be)

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

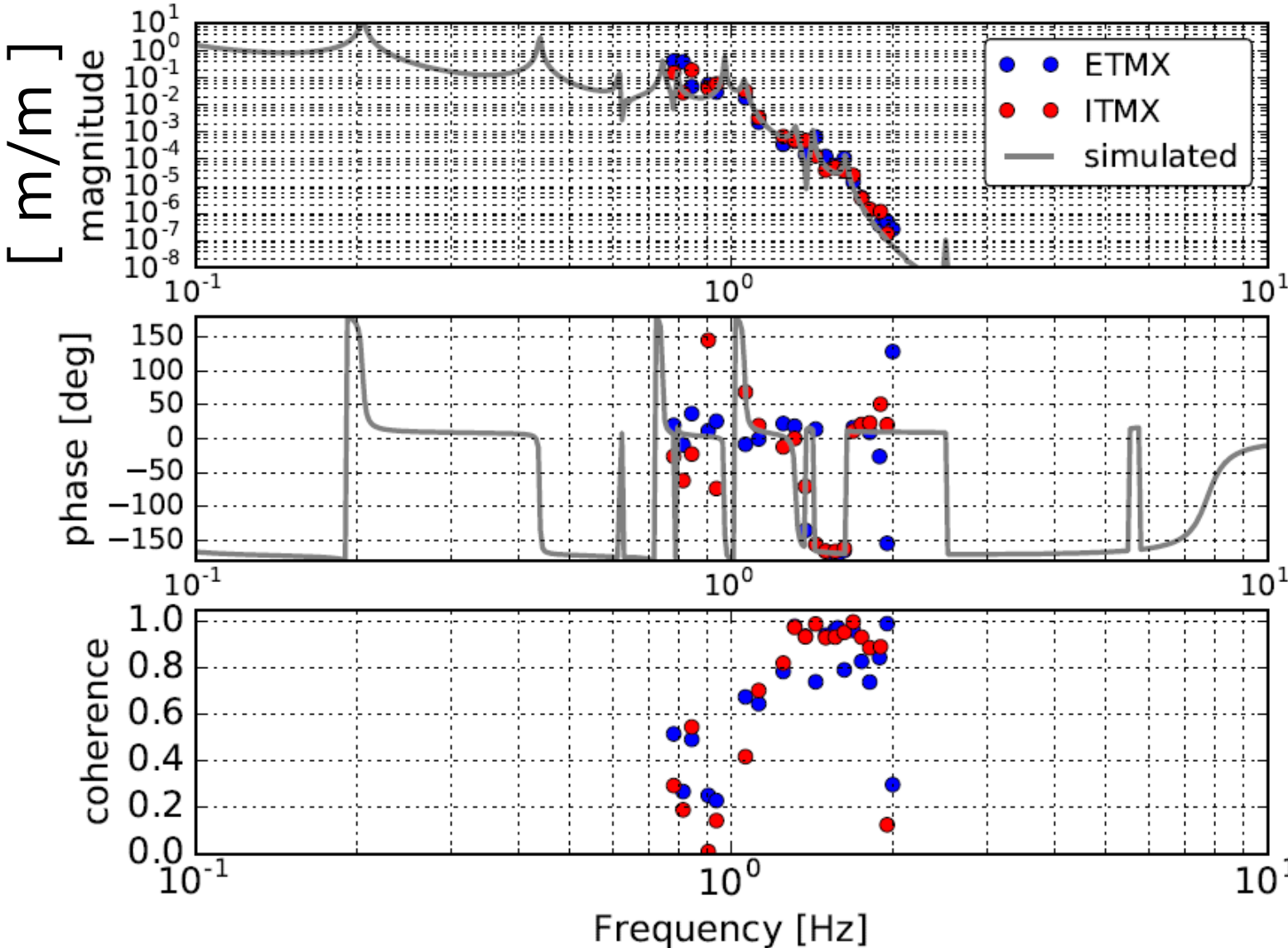
# Verification of suspension performance

# Measurement:

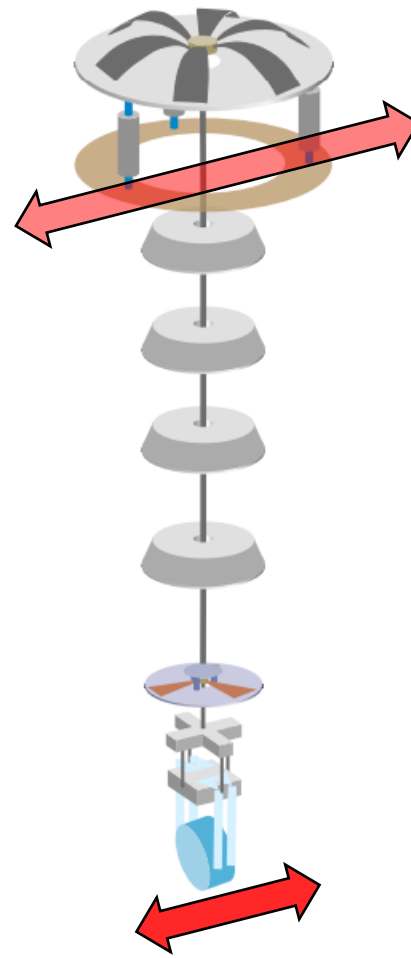
## Mechanical suspension performance with X-arm cavity



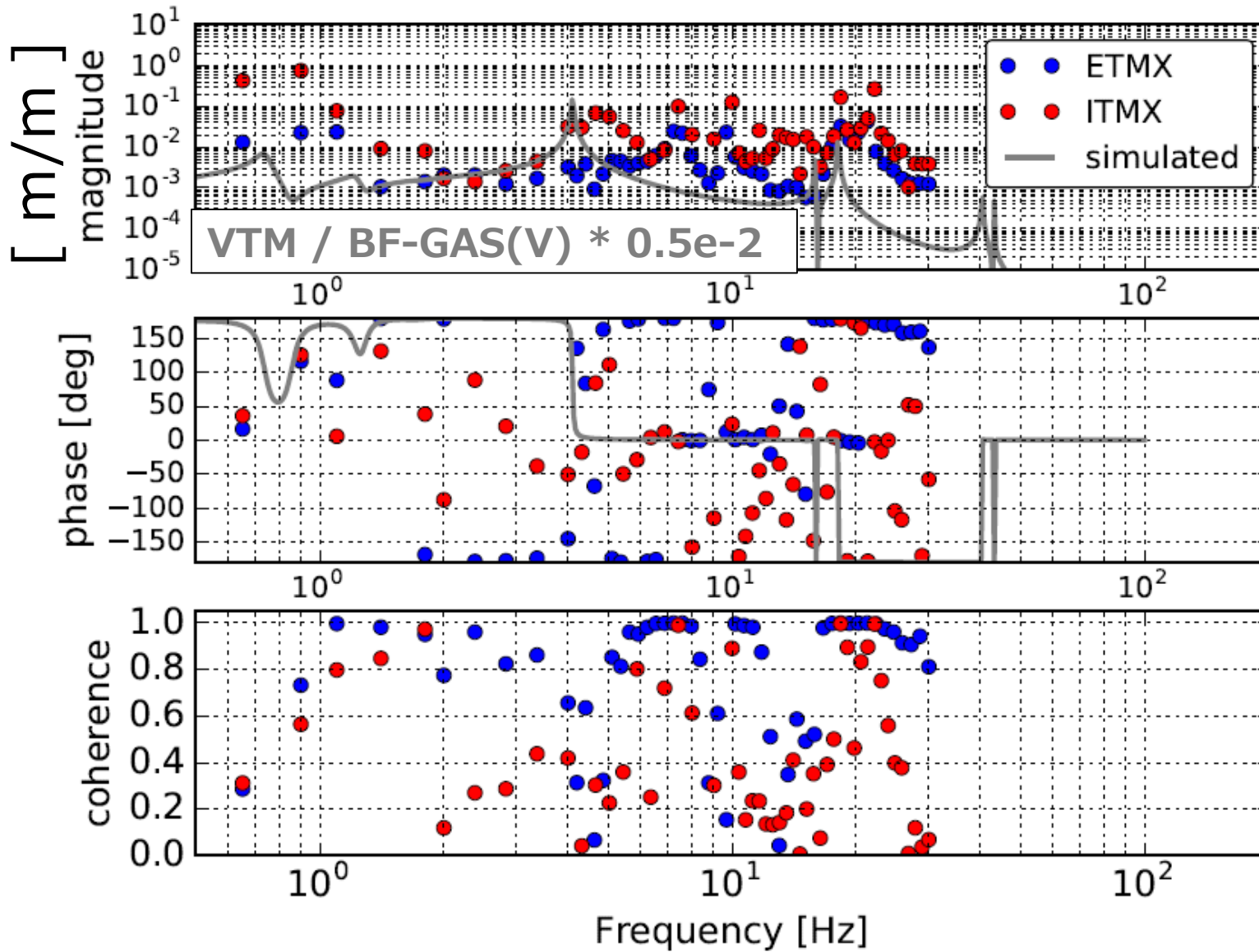
# Vibration isolation ratio, [ Good news! ]



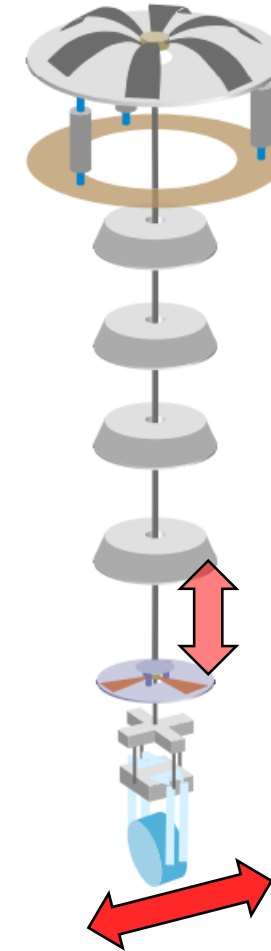
From ground to TM



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



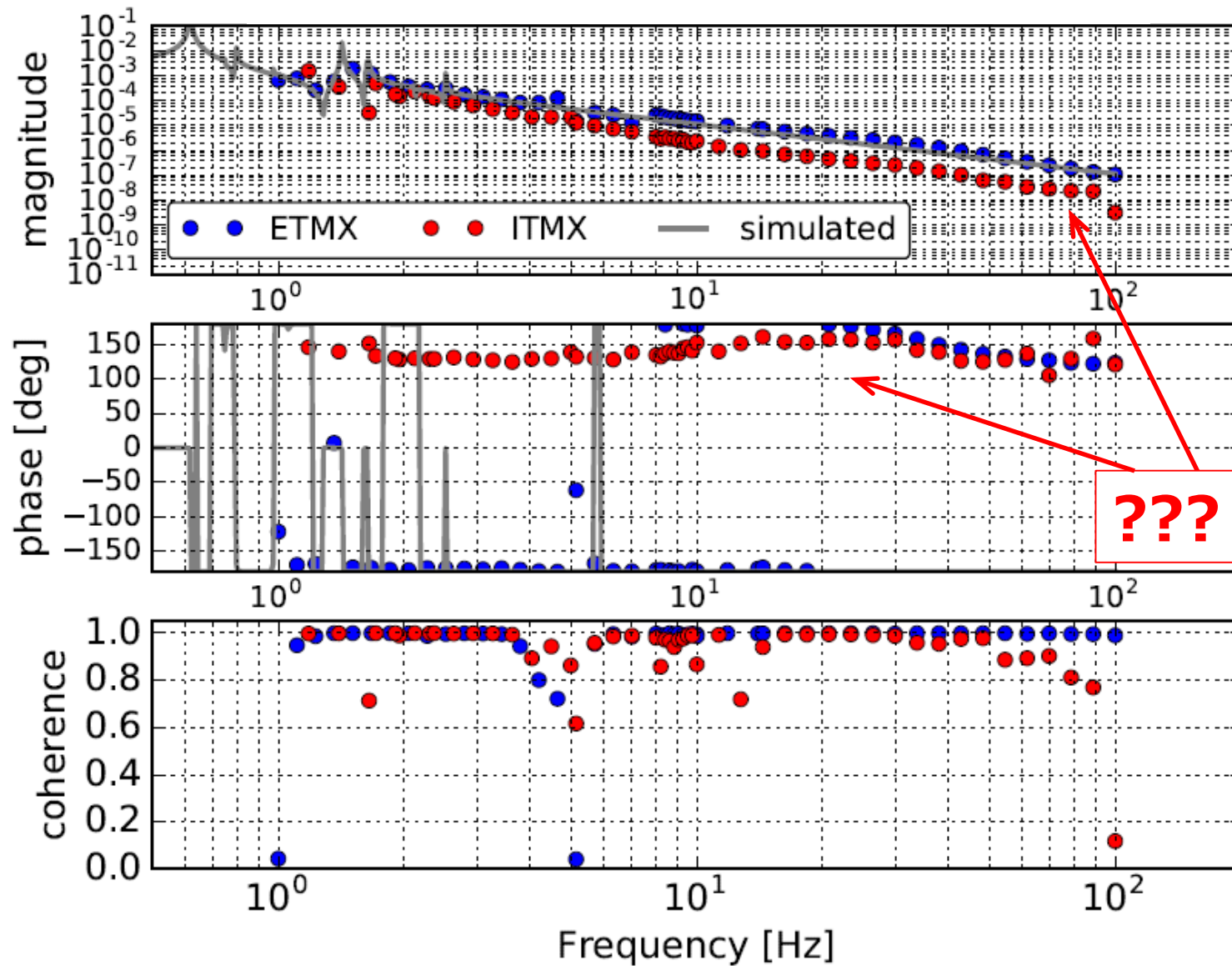
From BF-GAS to TM



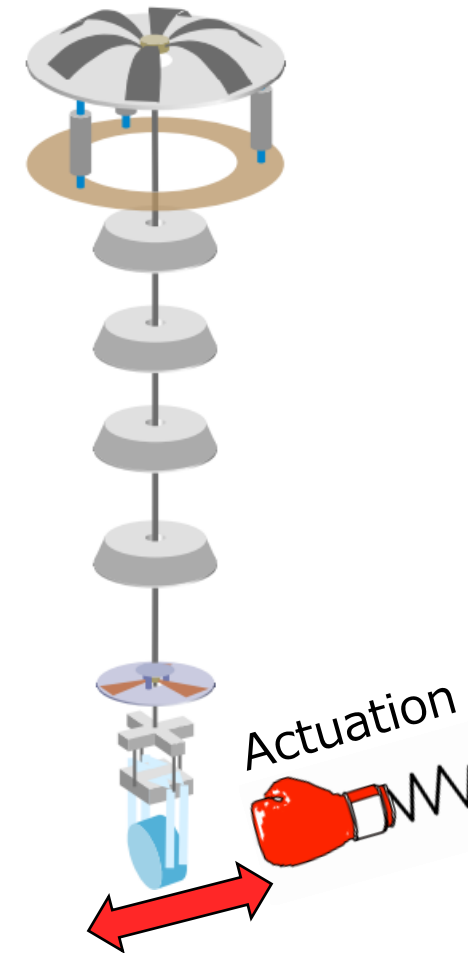
**Real was not so simple..**



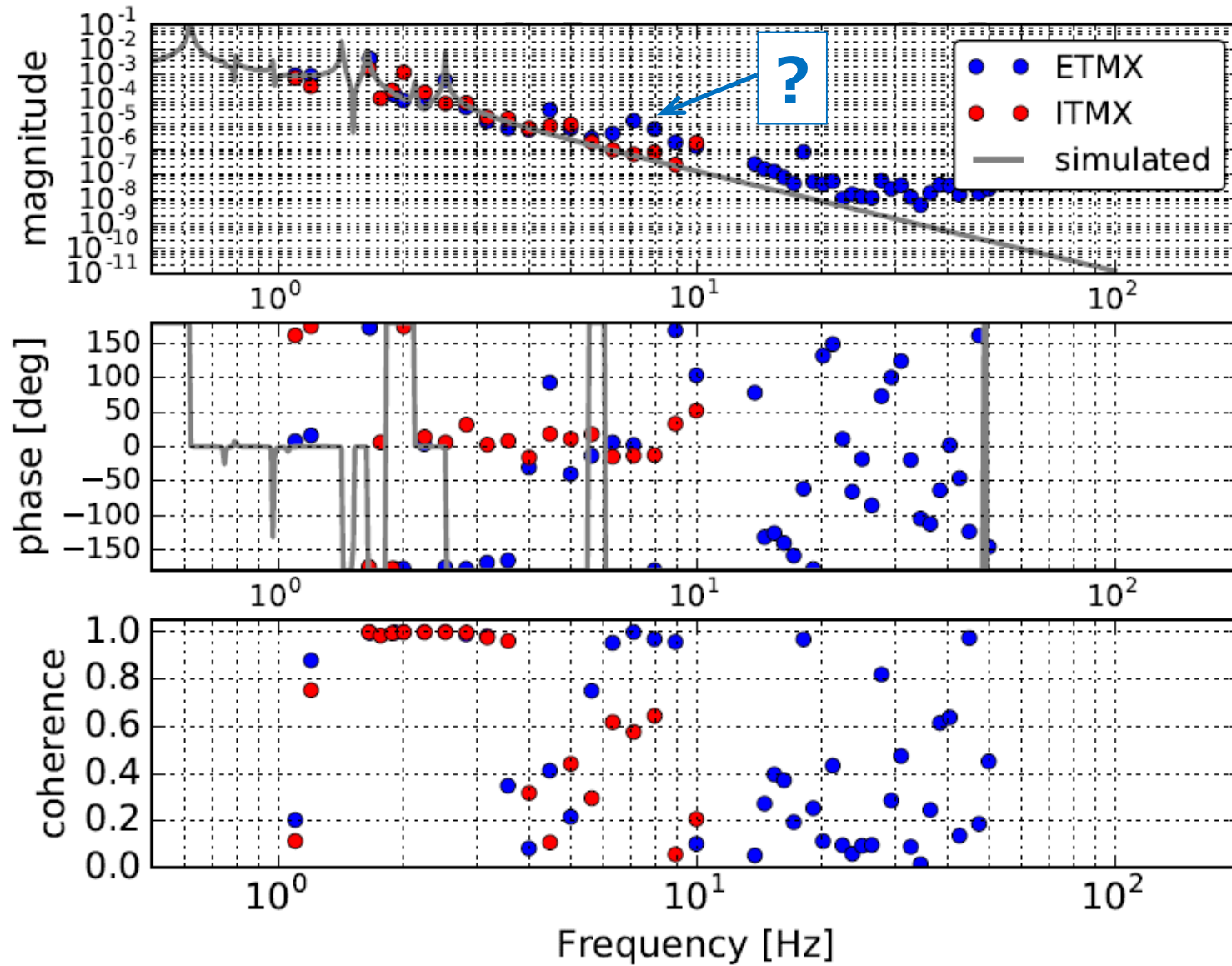
# Force transfer functions



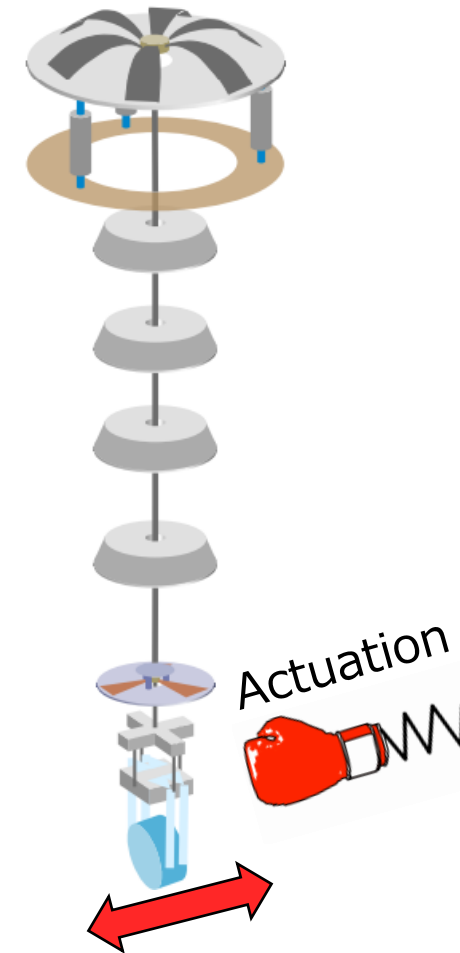
From (TM-RM)-act  
to TM



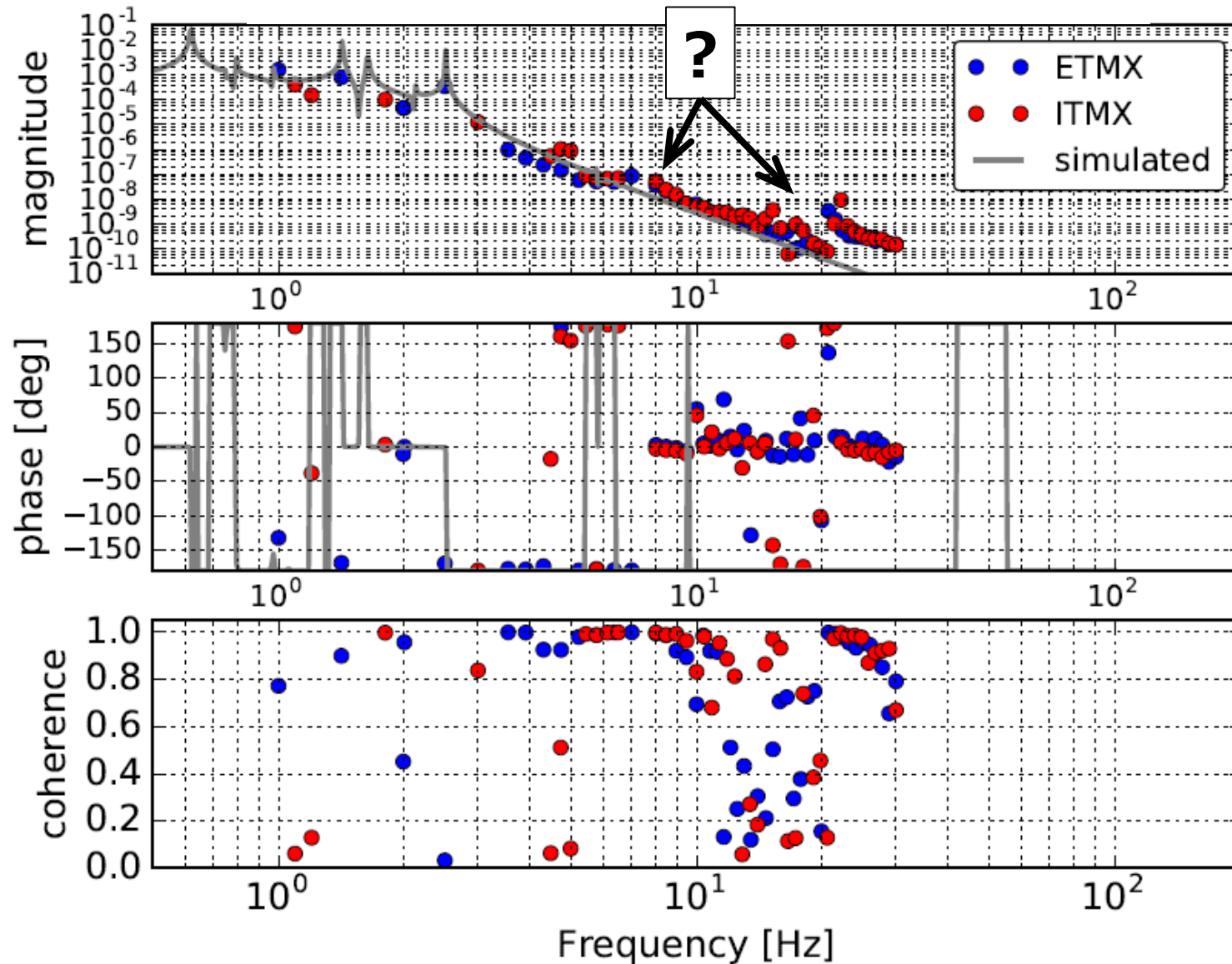
# Force transfer functions



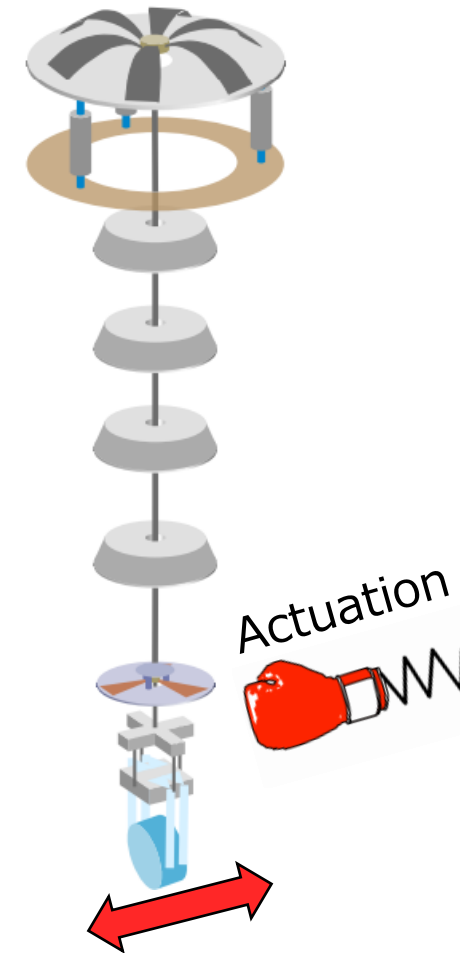
From (IM-IMR)-act  
to TM

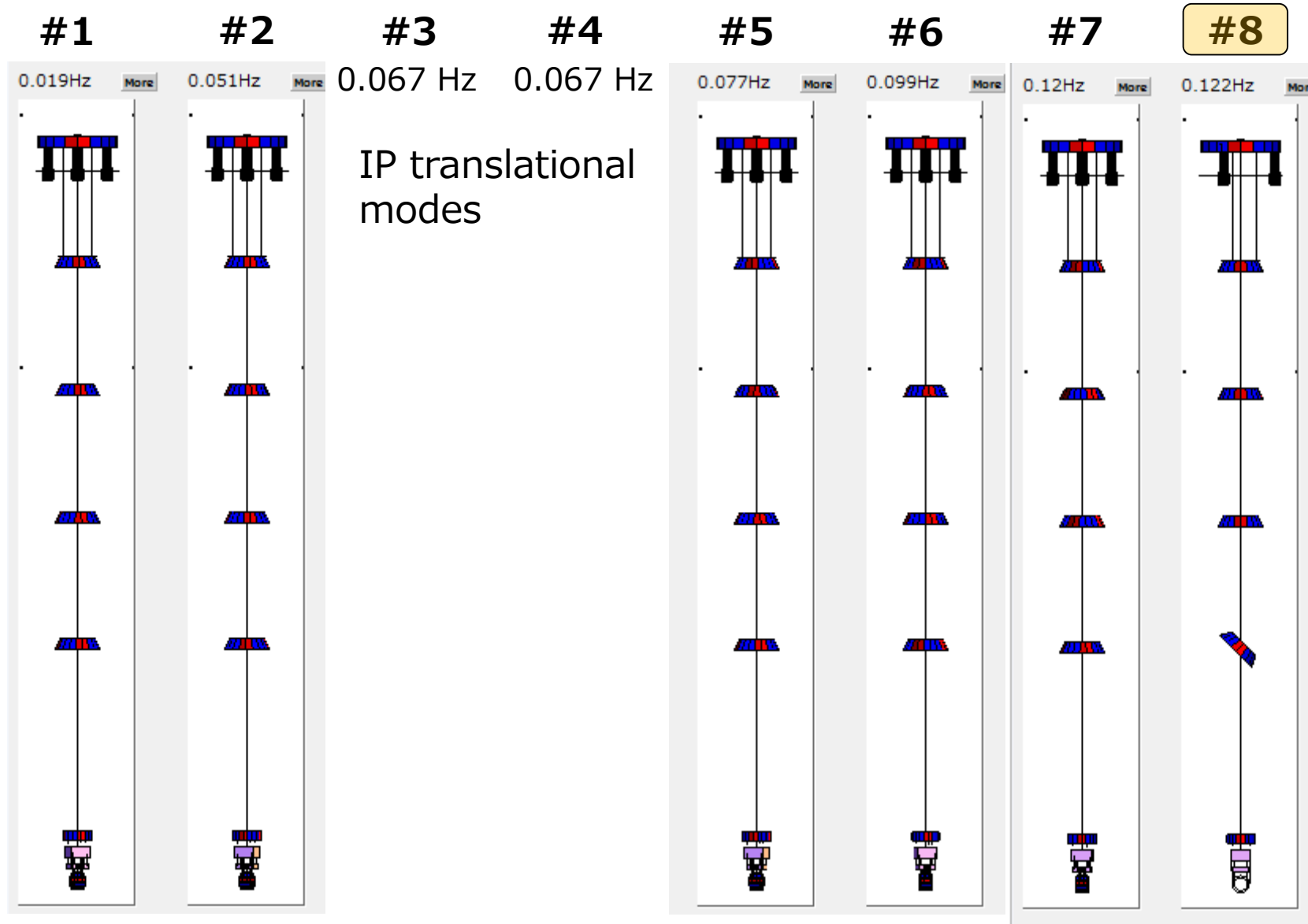


# Force transfer functions



From (MN-MNR)-act  
to TM



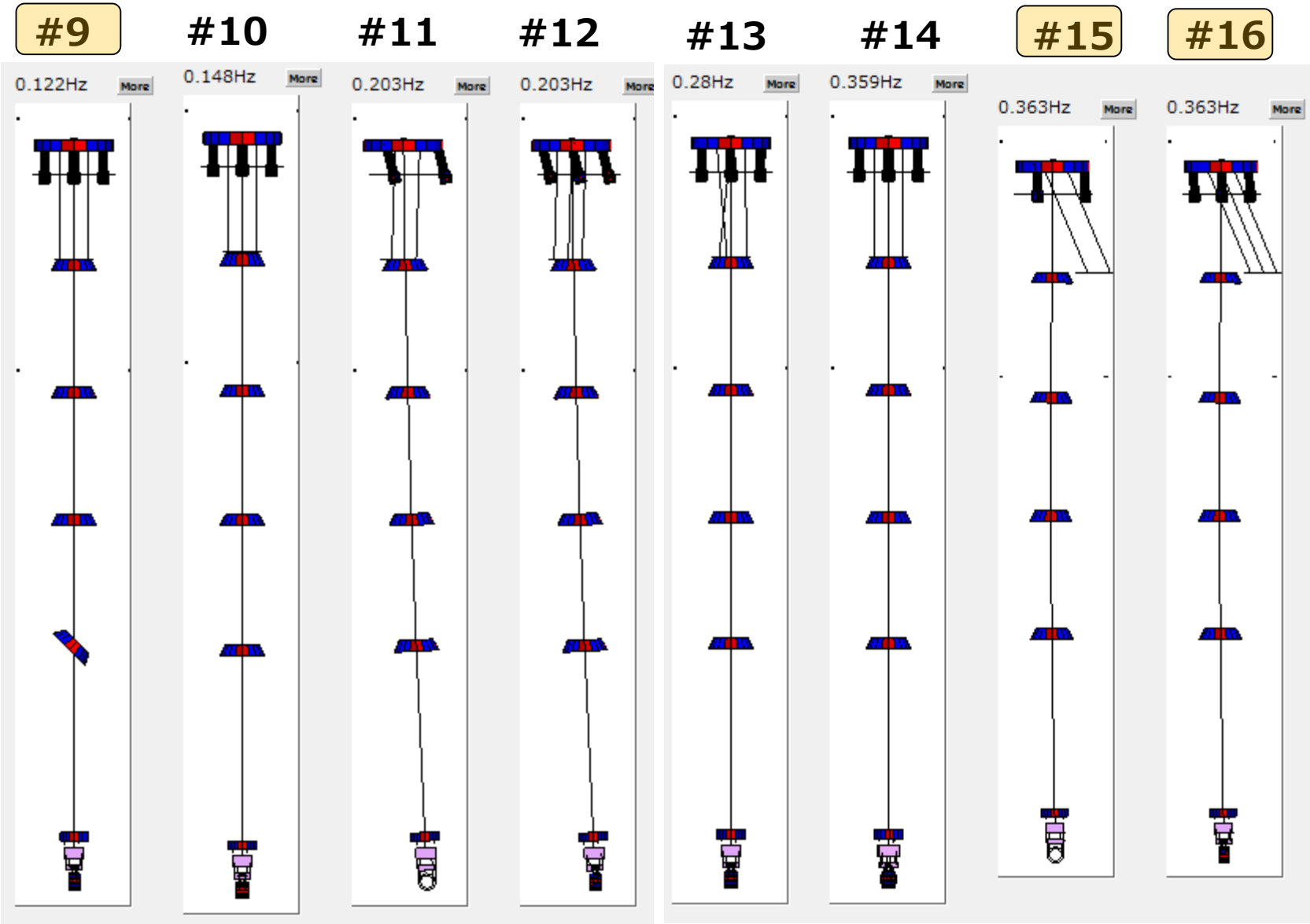


Type-A SAS,

'TypeA180429\_20K'

Eigen mode: 75 modes

#8 Less interest now



#9 Less interest now

#17

#18

#19

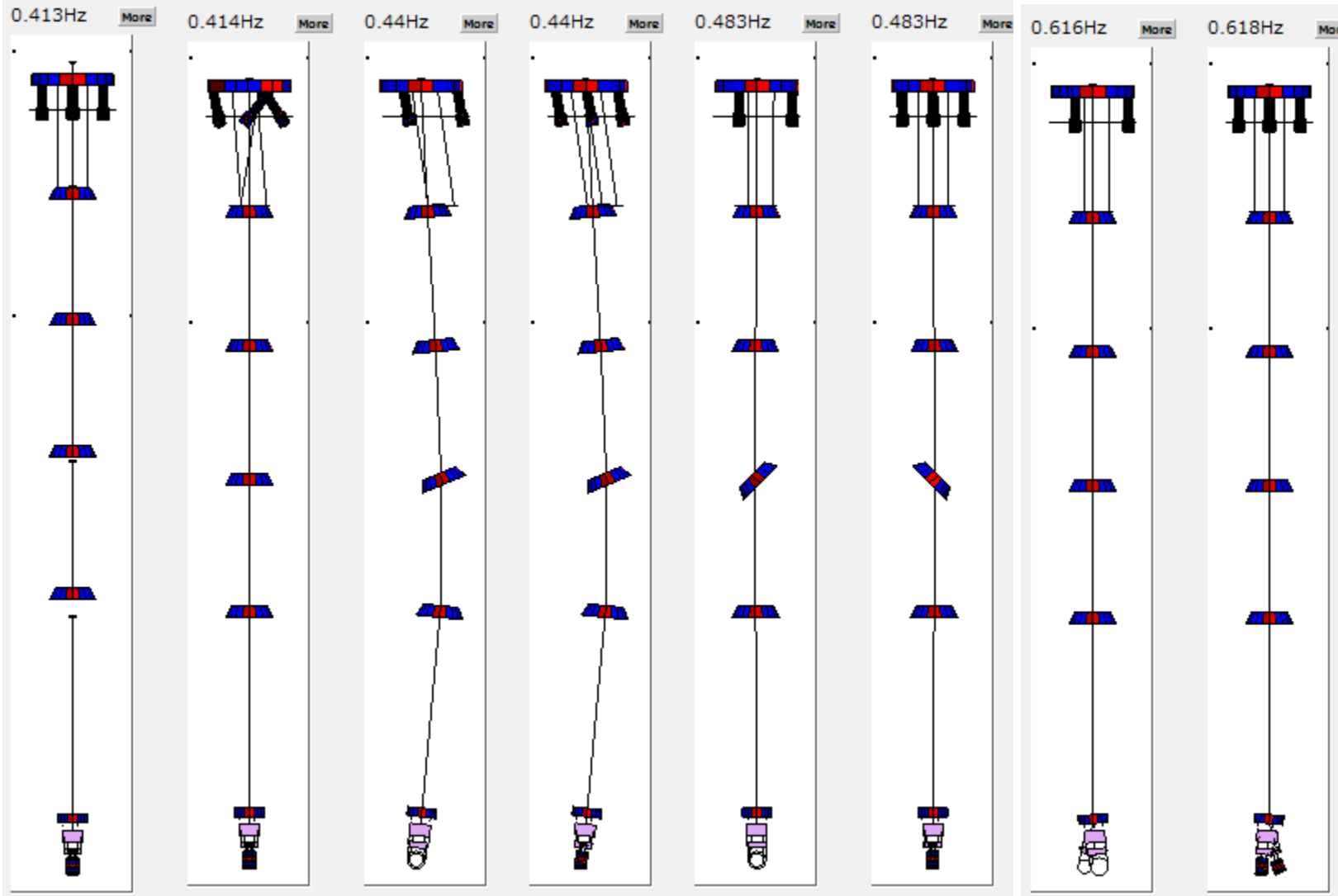
#20

#21

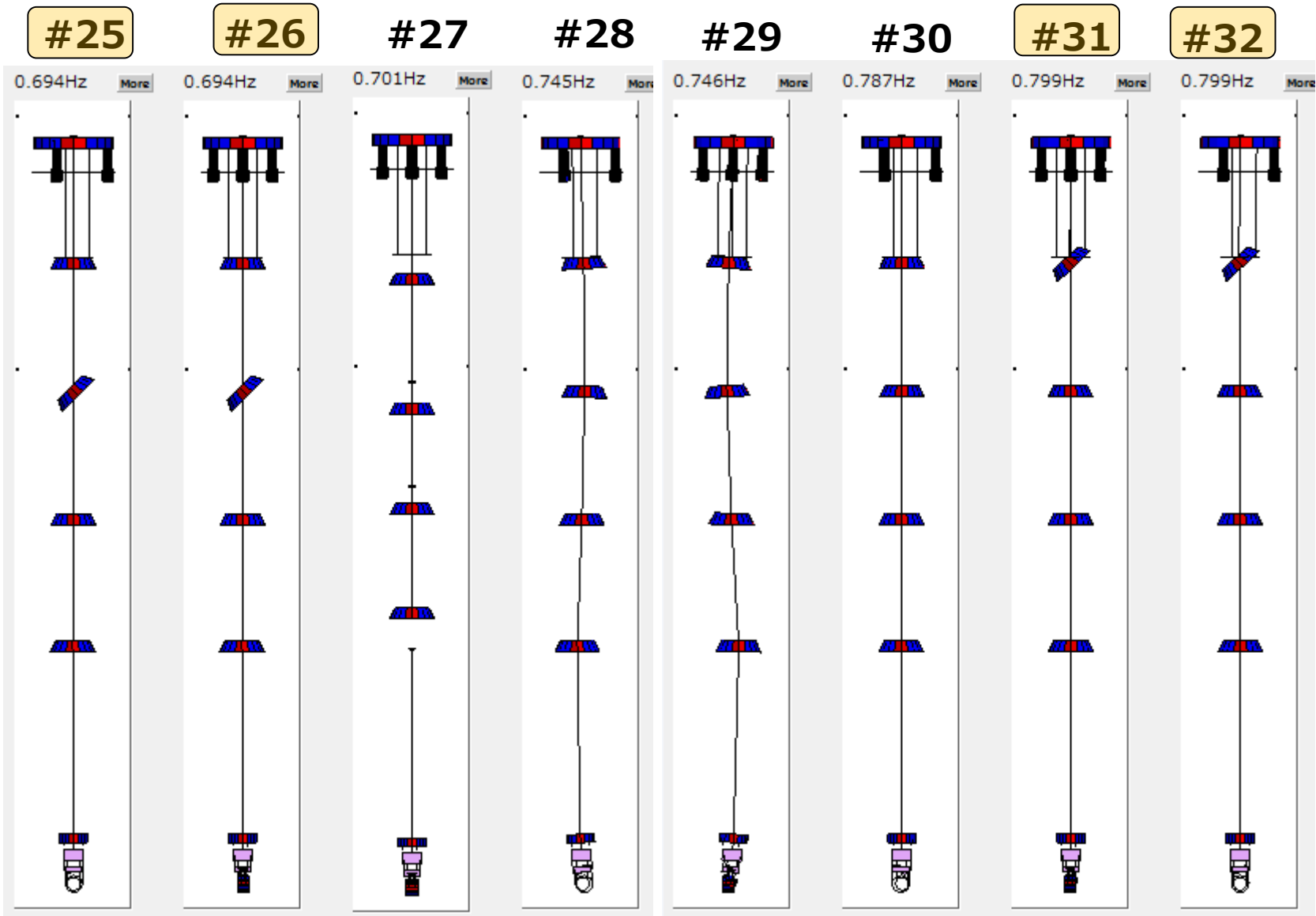
#22

#23

#24



Less interest now



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

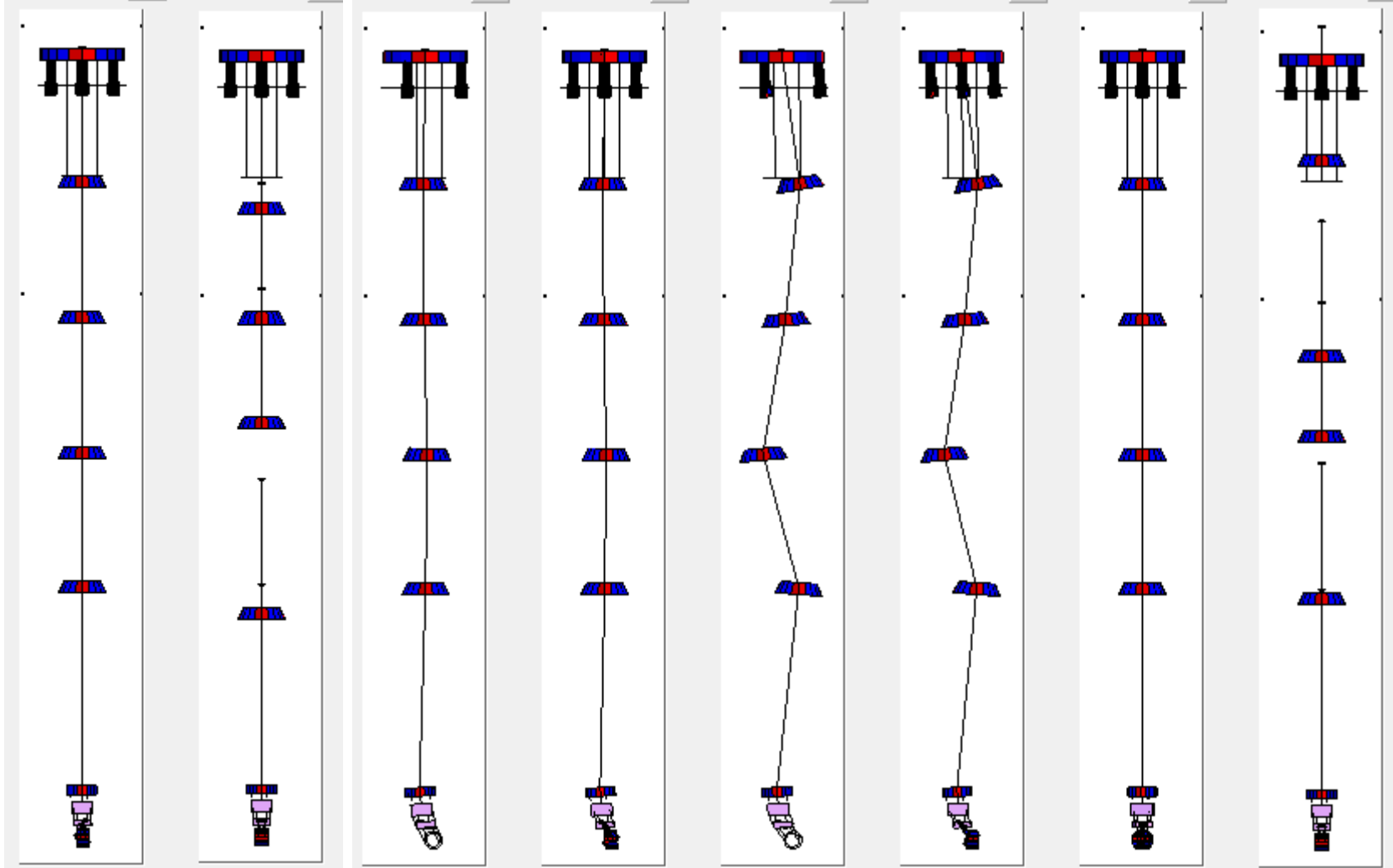
More

1.171Hz

More

1.189Hz

More



 Less interest now



#41

#42

#43

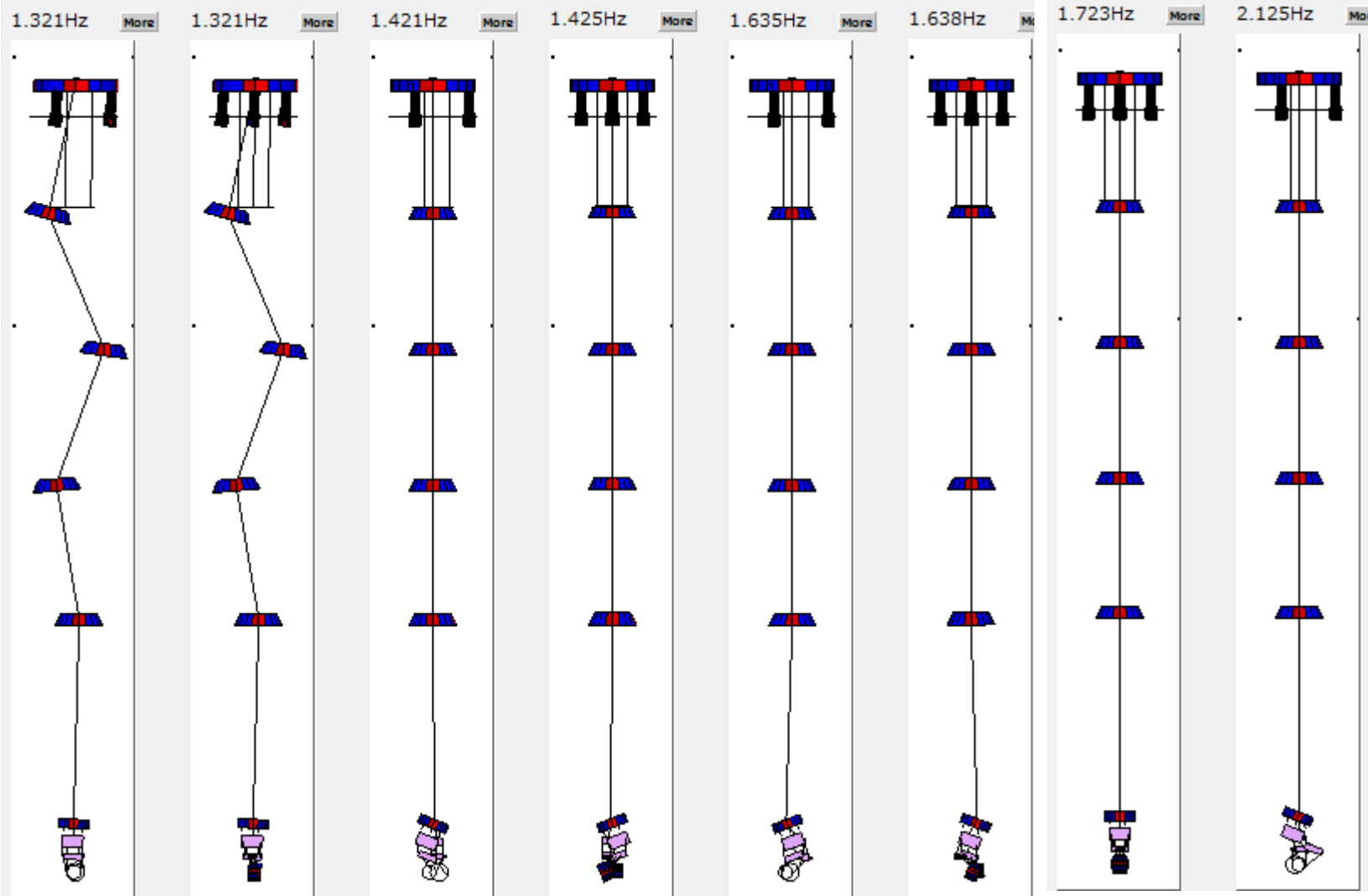
#44

#45

#46

#47

#48



 Less interest now

#49

#50

#51

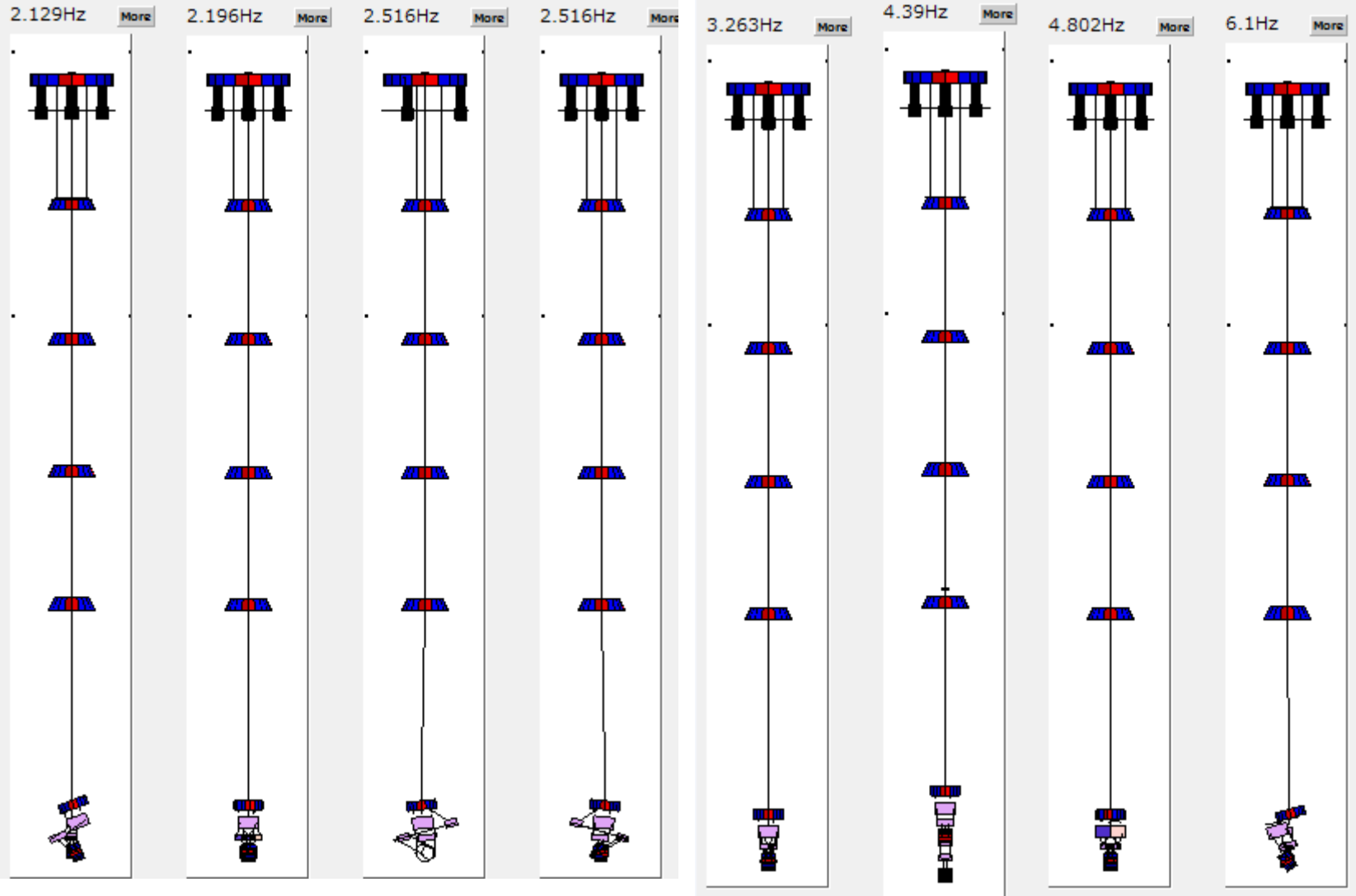
#52

#53

#54

#55

#56



 Less interest now

#57

#58

#59

#60

#61

#62

#63

#64

6.19Hz

6.646Hz

9.771Hz

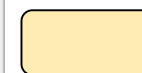
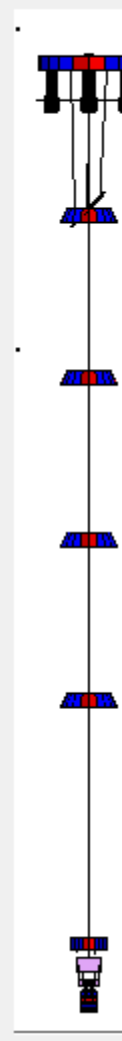
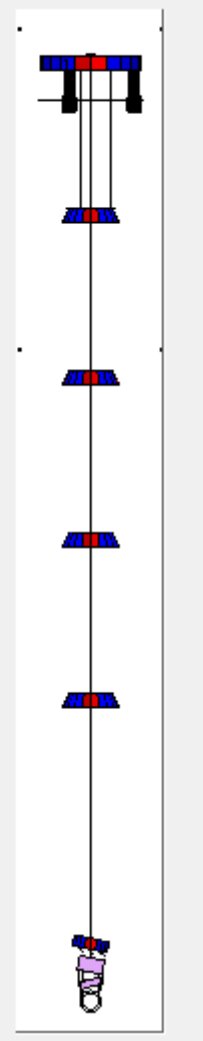
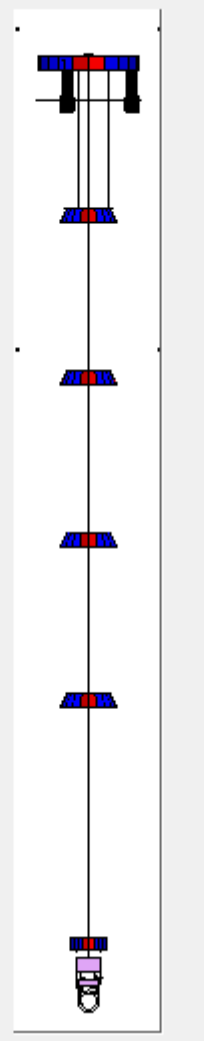
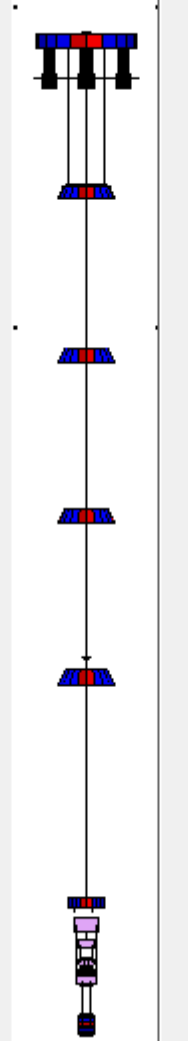
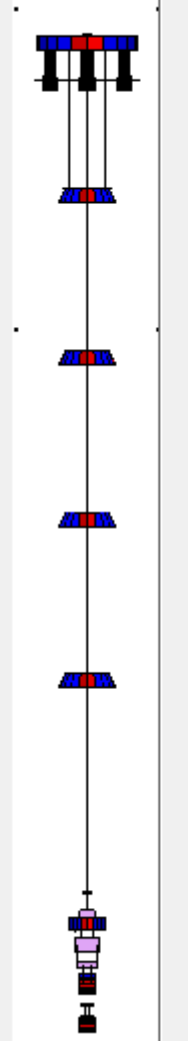
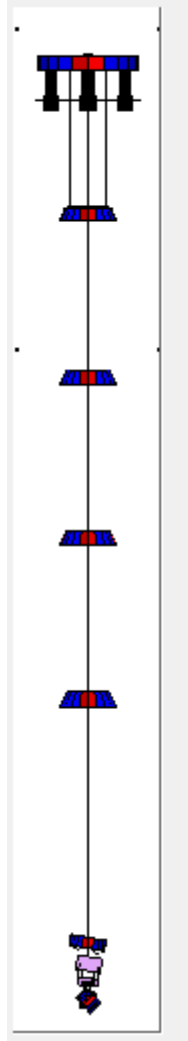
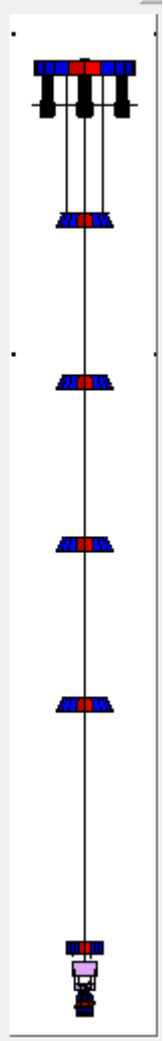
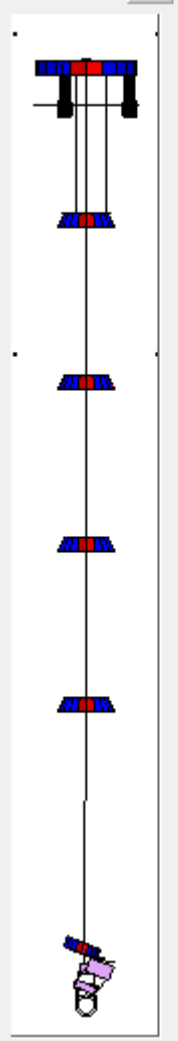
15.92Hz

20.17Hz

21.923Hz

23.685Hz

26.265Hz



Less interest now

#65

#66

#67

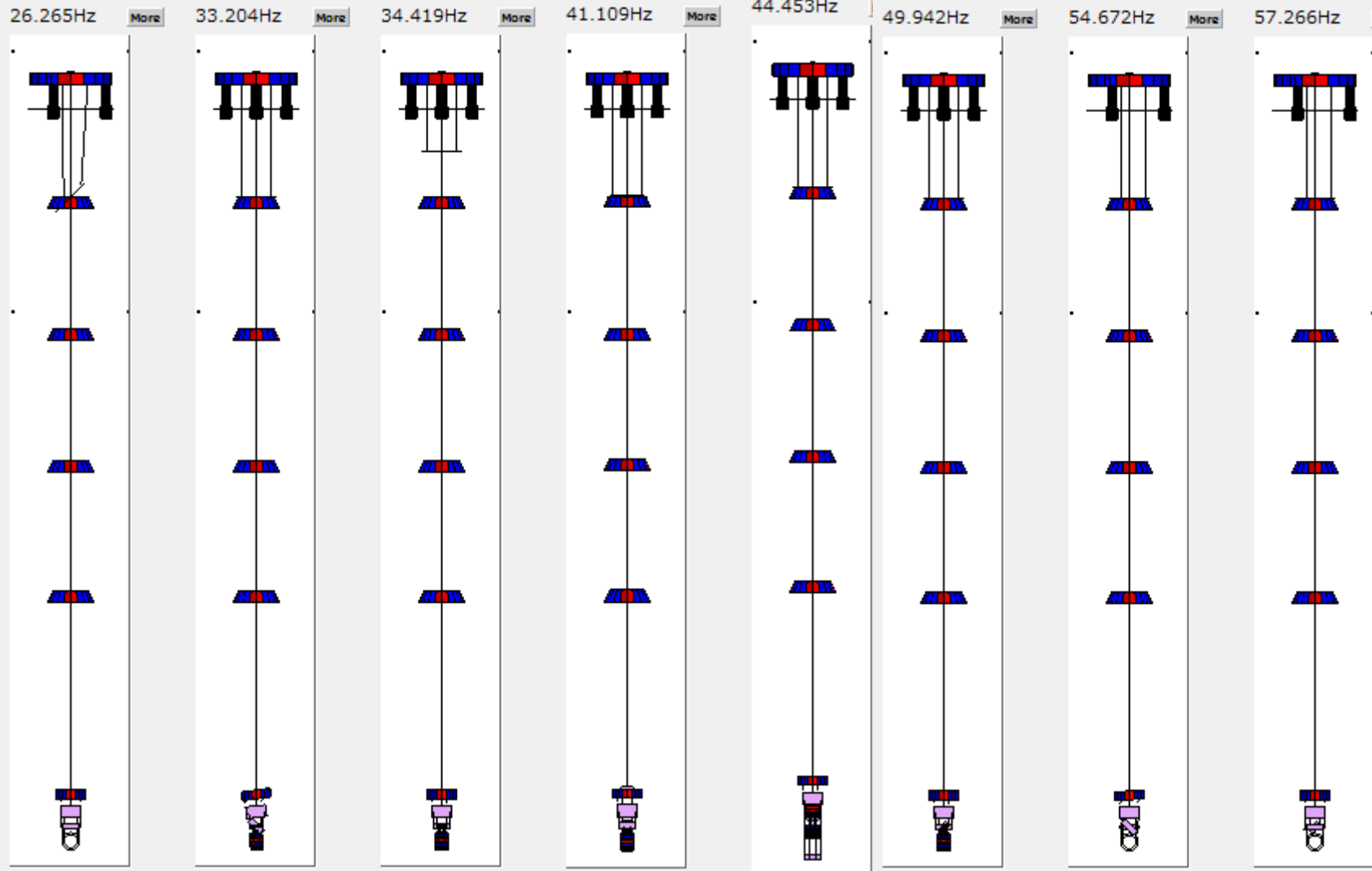
#68

#69

#70

#71

#72



 Less interest now

#73

#74

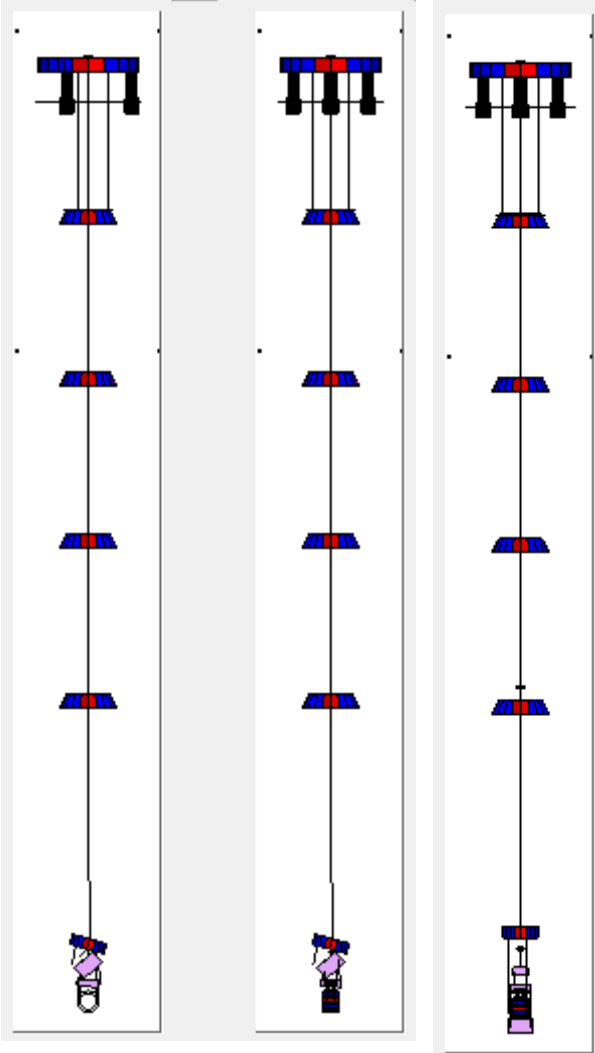
#75

150.563Hz

More

151.723Hz

183.437Hz



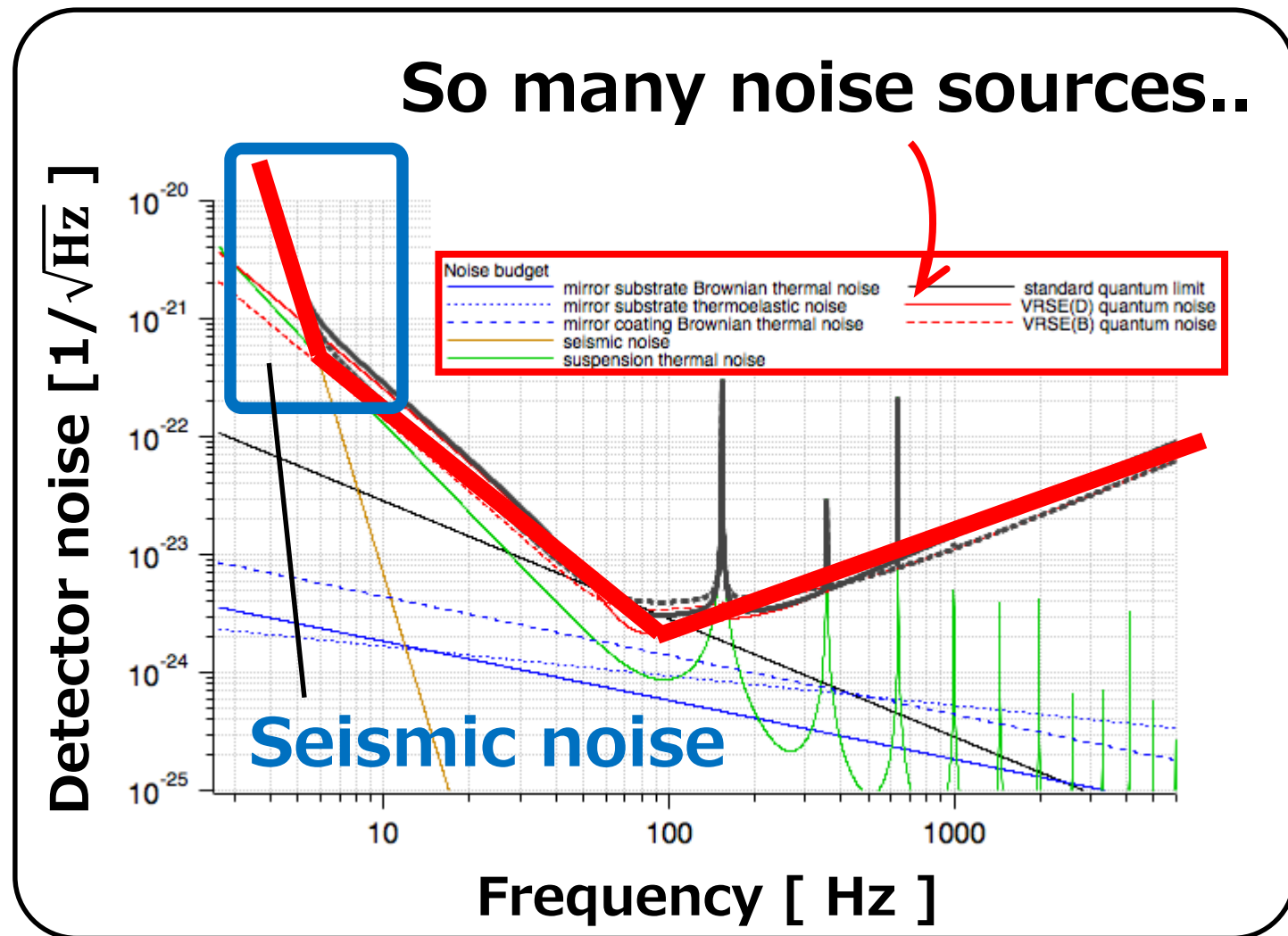
 Less interest now

# Detector noise

- Quantum noise
- Thermal noise
- ...
- **Seismic noise**

**mirror oscillation**

→ Necessary to suppress



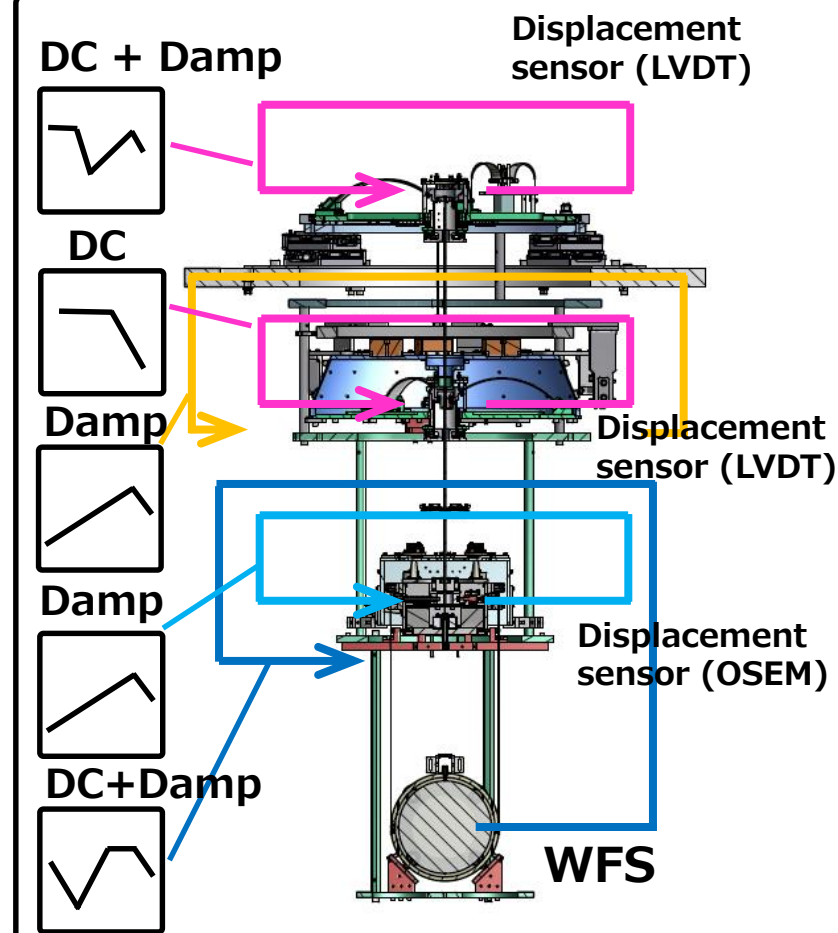
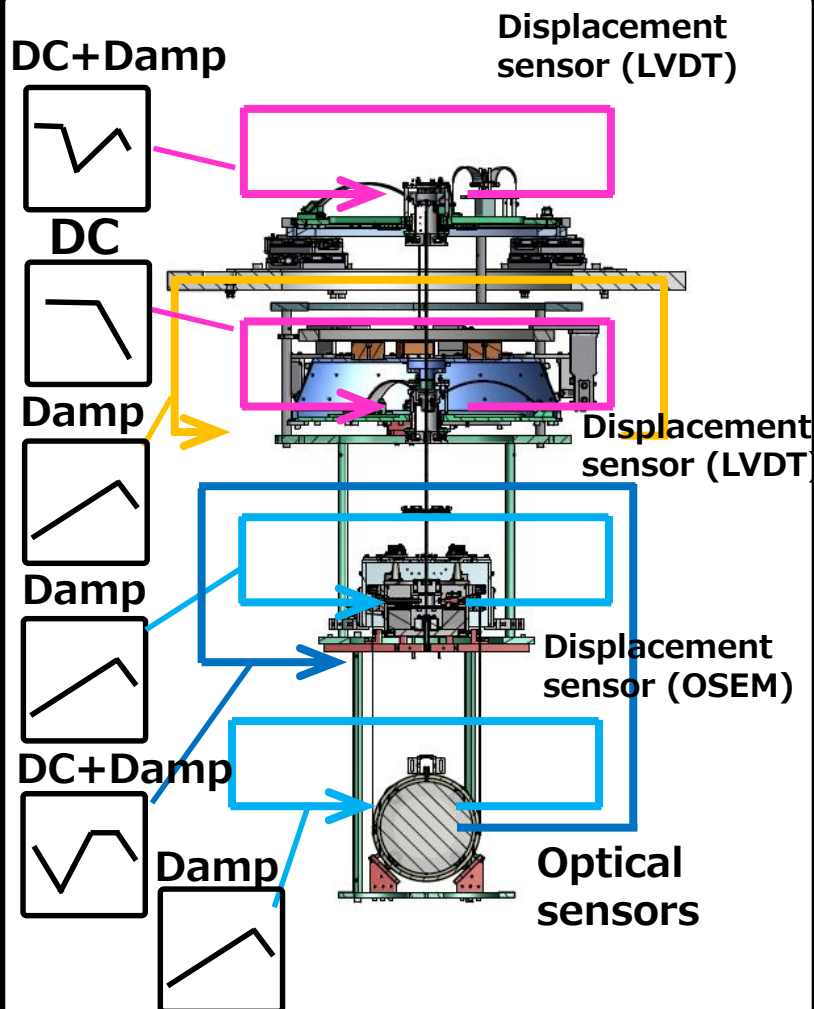
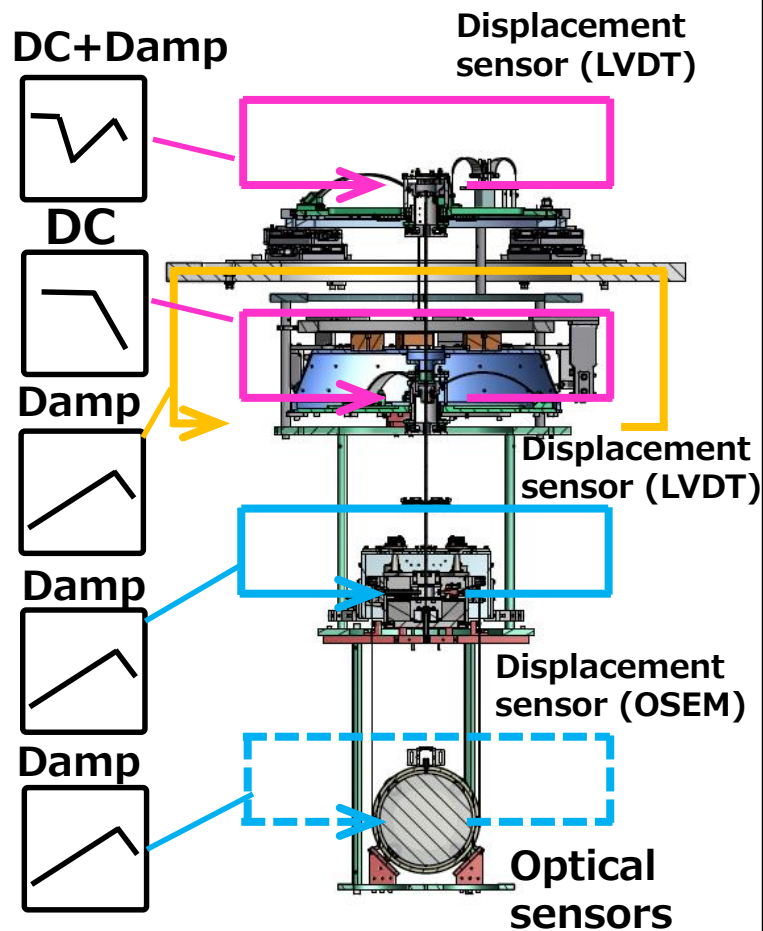
In case of KAGRA

# Designing active control system / ex. Type-Bp SAS

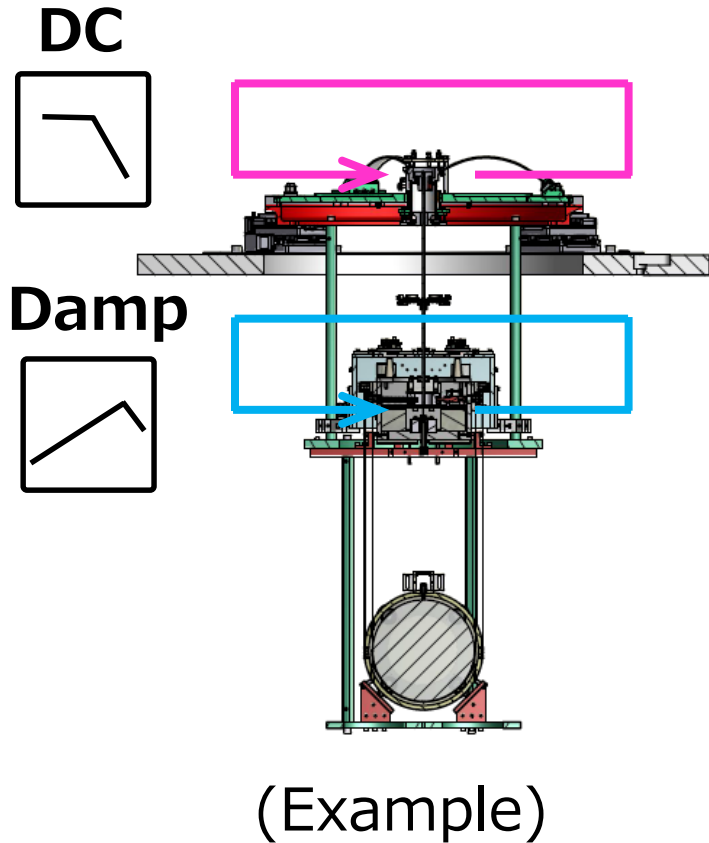
## 1. Calm-down phase

## 2. Lock-acquisition phase

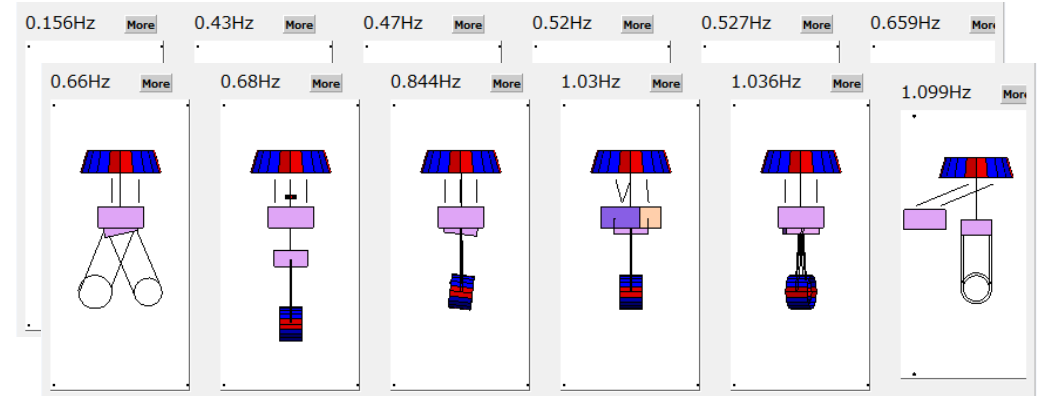
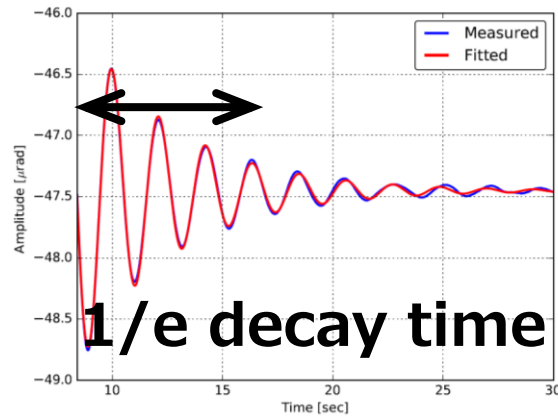
## 3. Observation phase



# 2. Decay time measurement



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.