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

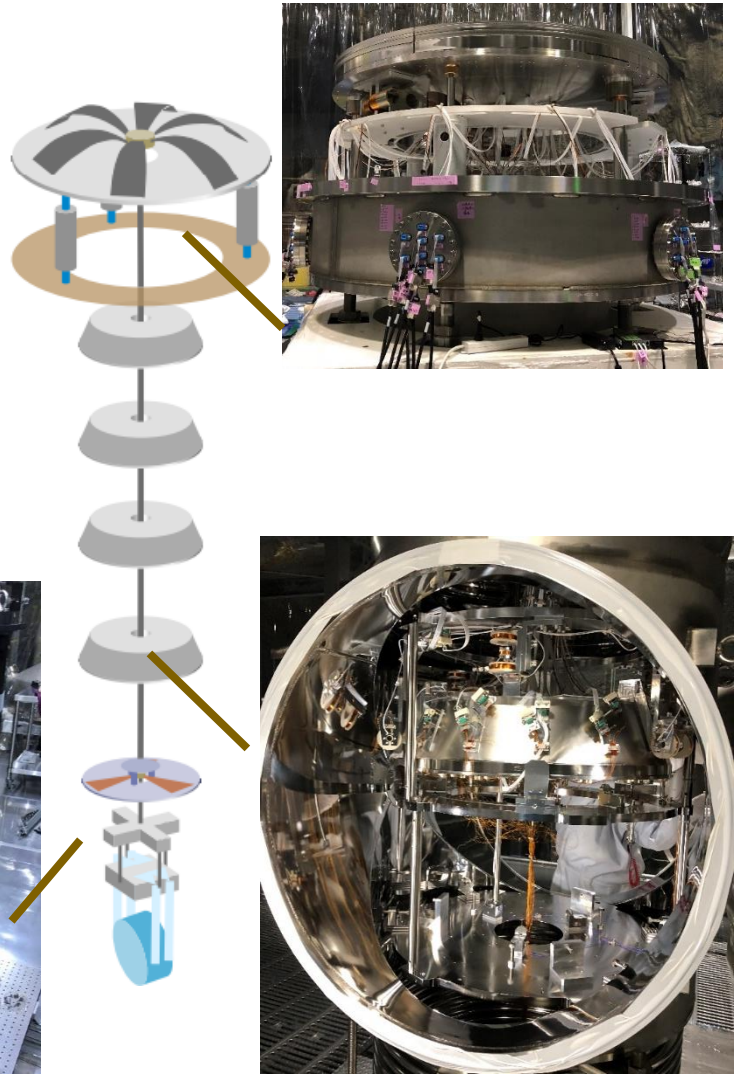
藤井善範

東京大学 理学系研究科 天文学専攻 博士課程2年
国立天文台 重力波プロジェクト推進室

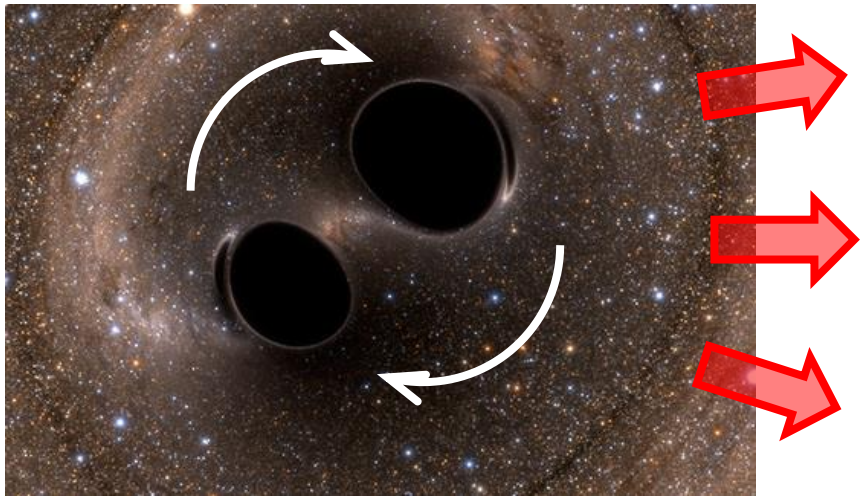
高橋竜太郎, L. Trozzo, 正田亜八香, 阿久津智忠, 佐藤直久, 石崎秀晴, E. N. T. SanMartin, M. Barton, 平田直篤, 麻生洋一, R. Flaminio(国立天文台), 奥富弘基(総研大), F. P. E. Arellano, 宮本昂拓, 牛場崇文, 三代浩世希, 山本尚弘, 宮川治, 上泉眞裕, (東大宇宙線研), 和泉究(宇宙研), 都丸隆行(高エネ研), on behalf of the KAGRA collaboration

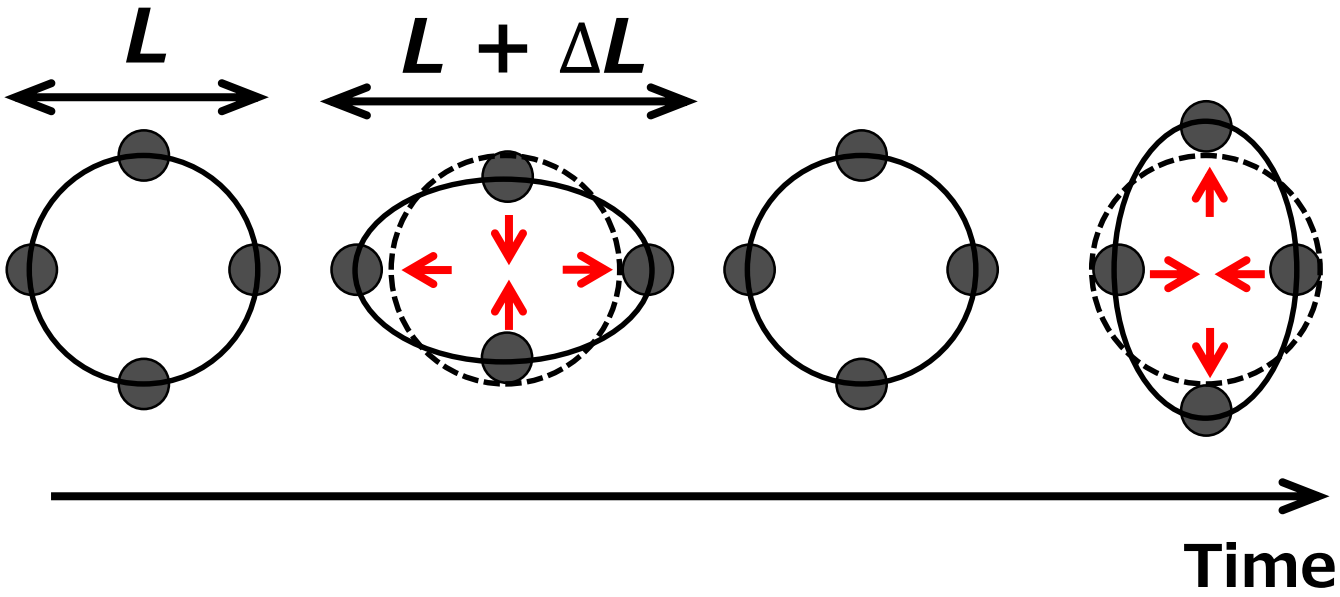
大型重力波望遠鏡 KAGRA における防振装置のための制御系の開発

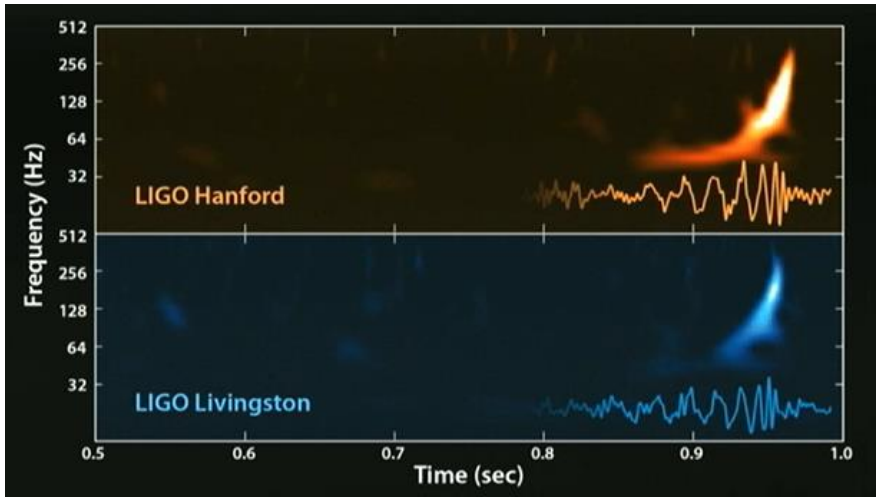
内容： メイン鏡用の防振装置の制御系の実装状況と、そのパフォーマンスのまとめ



重力波?







- 2015.9.14 初検出!
- BBH, BNS 検出!

→ **新しい天文学!**

大型重力波望遠鏡 KAGRA

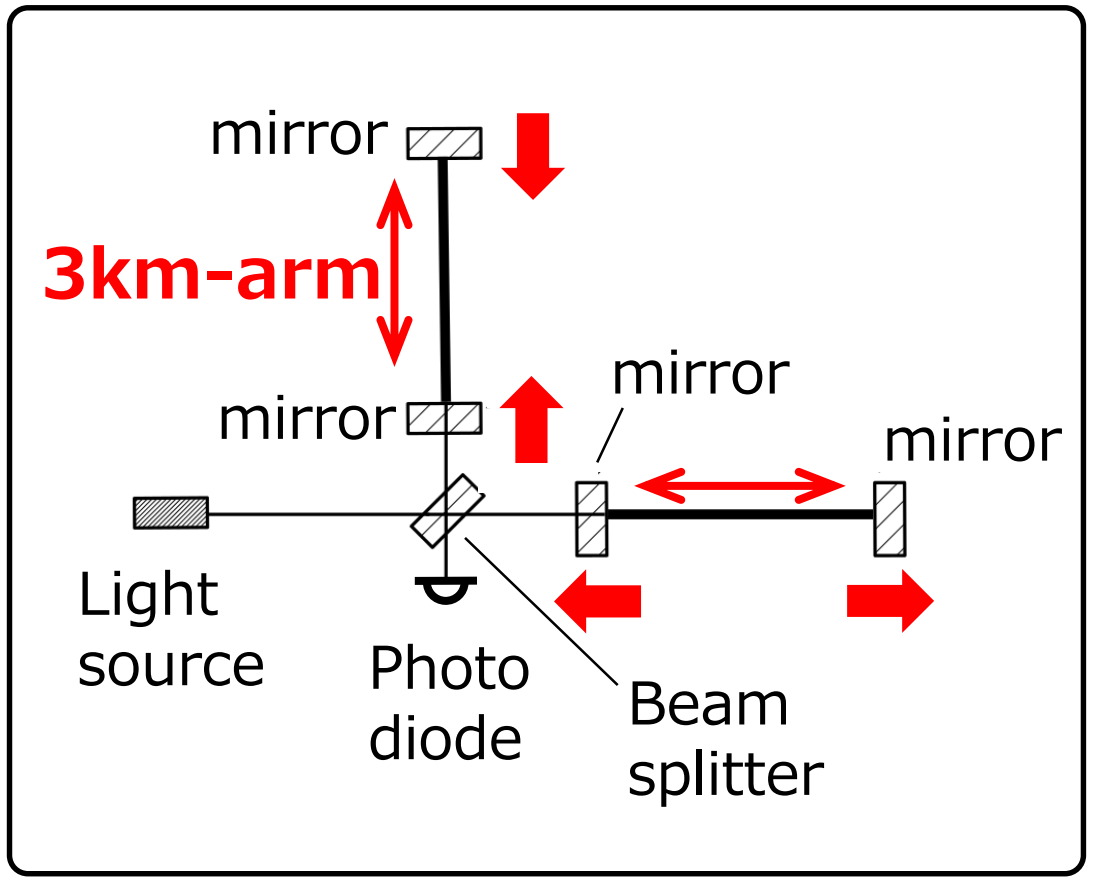
(From JGW-G1909822)

直近の目標:
LIGO/Virgo - O3への参加

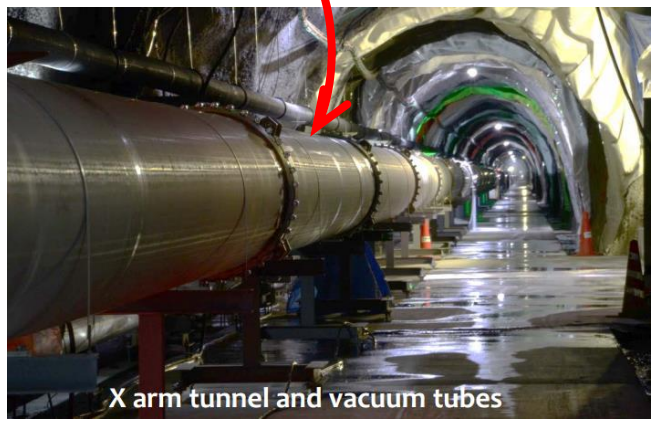
主な進捗:
- サファイアミラーの完成
- 防振システムの組立て完了
- 3km共振器の制御

など他

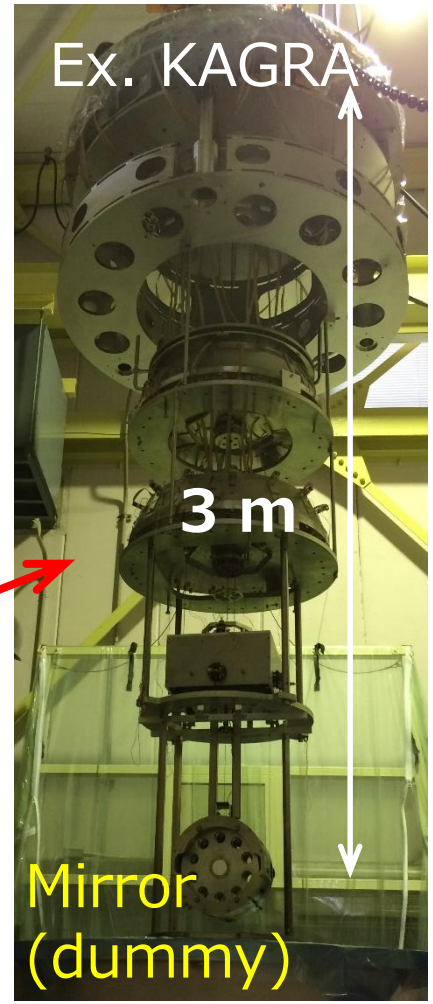
重力波検出器と、サスペンション



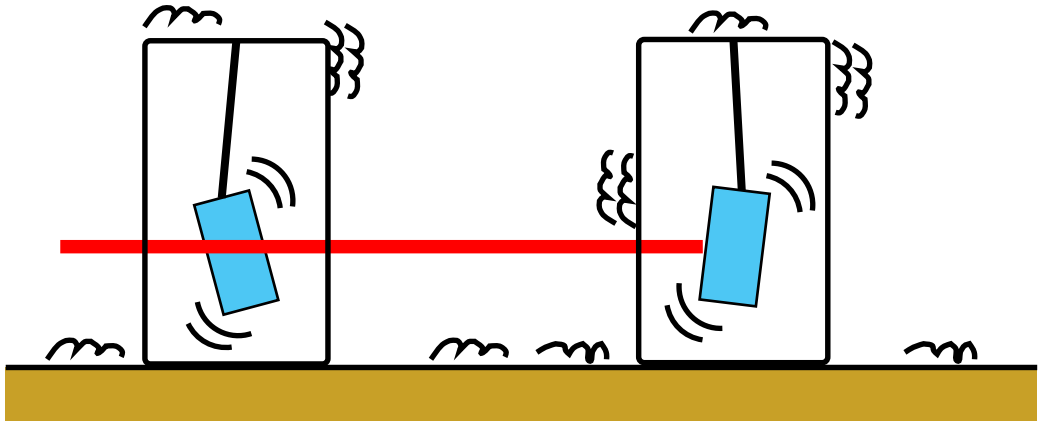
1) Michelson-based interferometer
2) Fabry-Perot cavities
3) 3km-arm

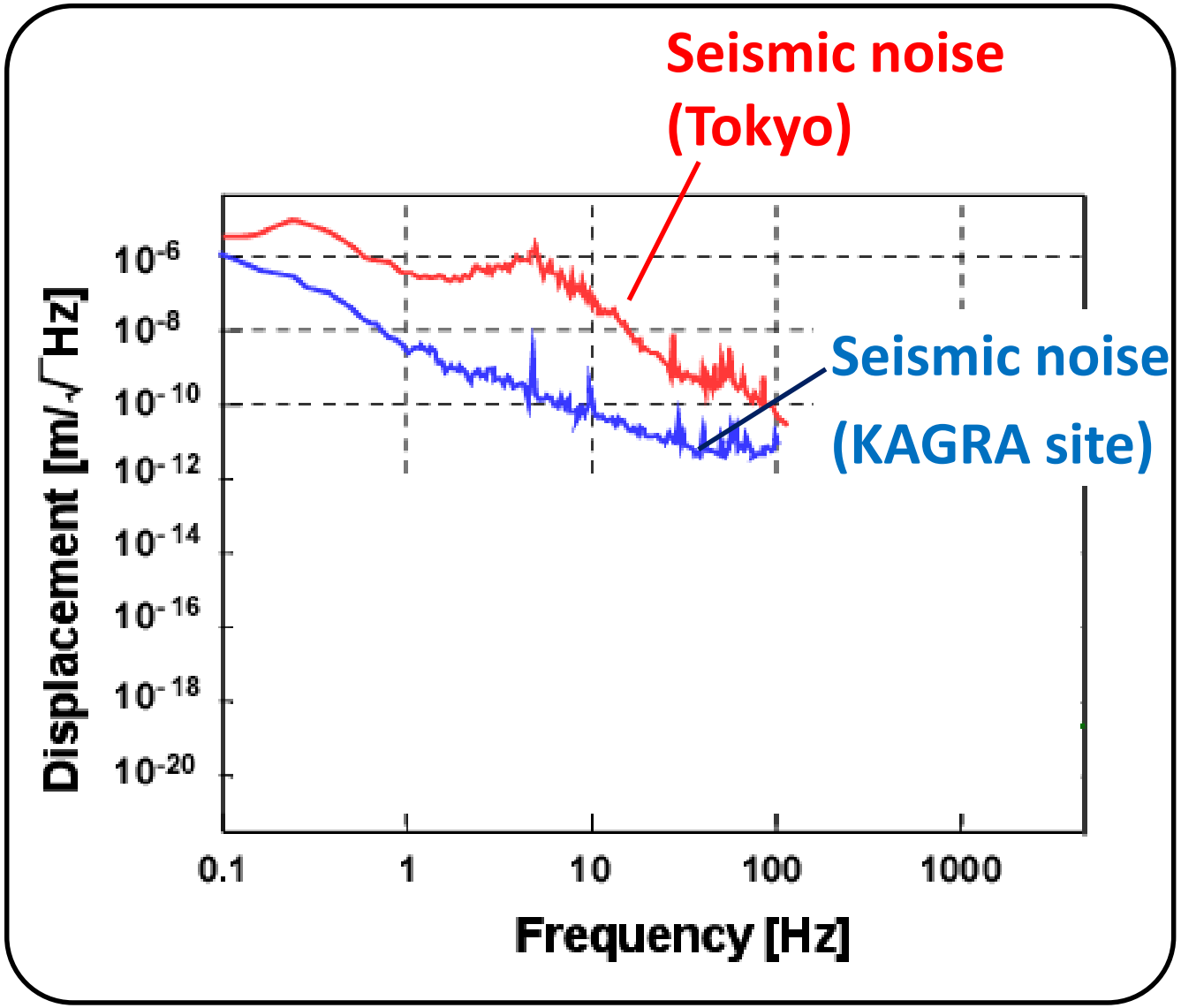


4) Suspended core optics

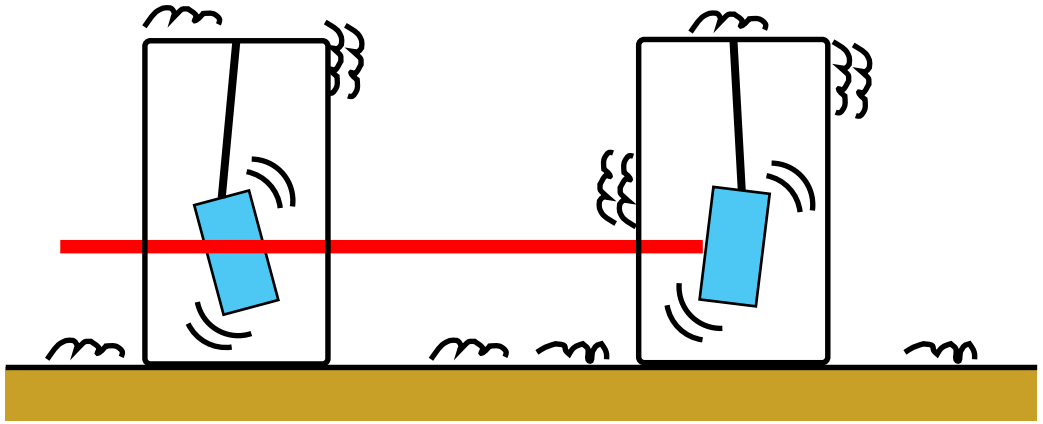


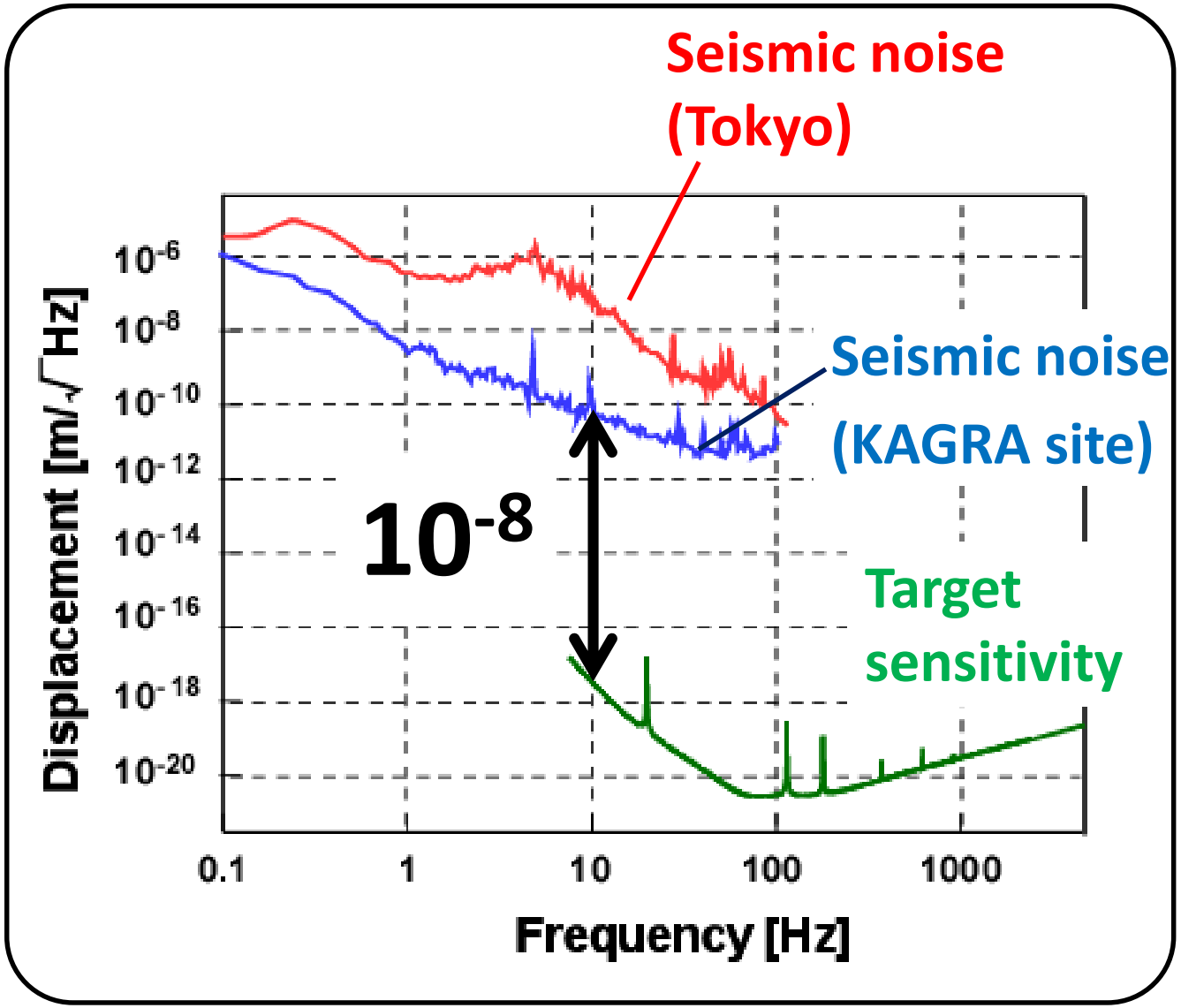
地面振動雑音



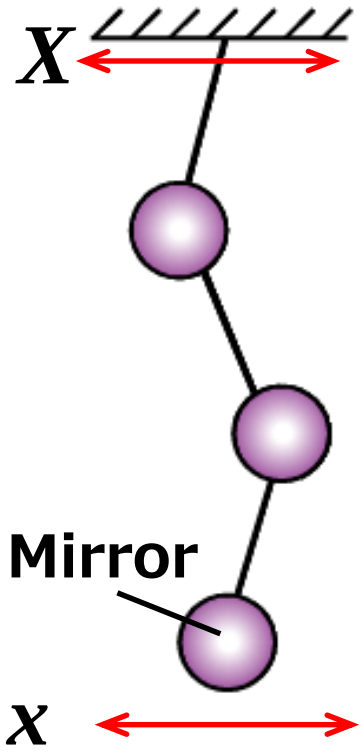

Seismic noise
(Tokyo)
Seismic noise
(KAGRA site)
Displacement [m/√Hz]
10-6
10-8
10-10
10-12
10-14
10-16
10-18
10-20
0.1
1
10
100
1000
Frequency [Hz]

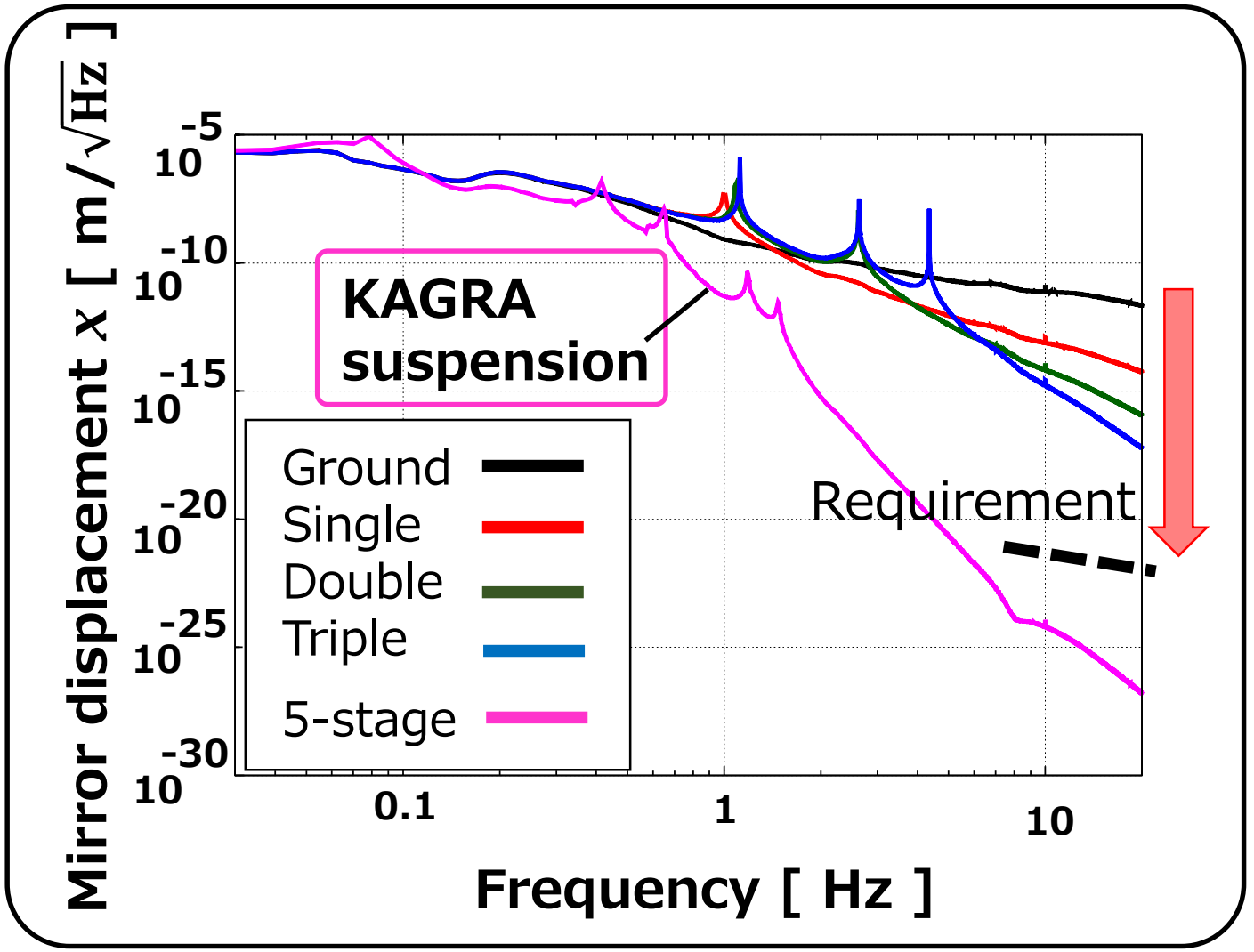
地面振動雑音



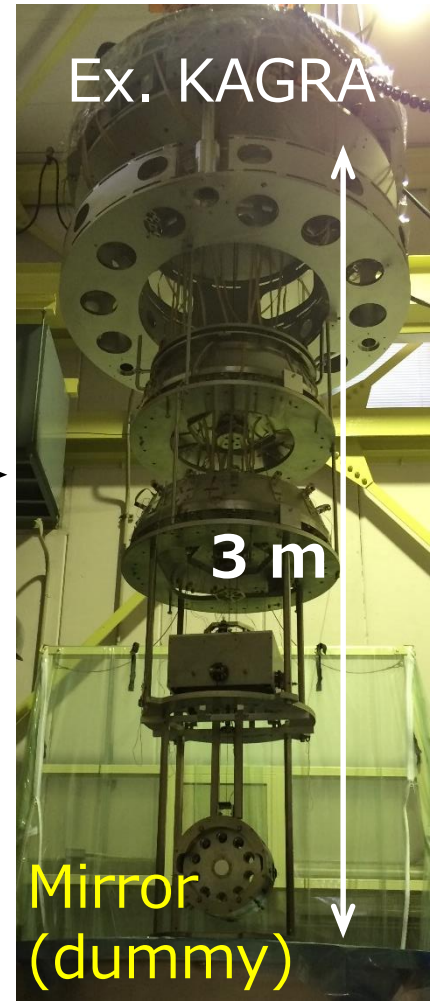

Seismic noise
(Tokyo)
Seismic noise
(KAGRA site)
Target
sensitivity
10^{-8}
Displacement [m/√Hz]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
0.1
1
10
100
1000
Frequency [Hz]

Seismic attenuation





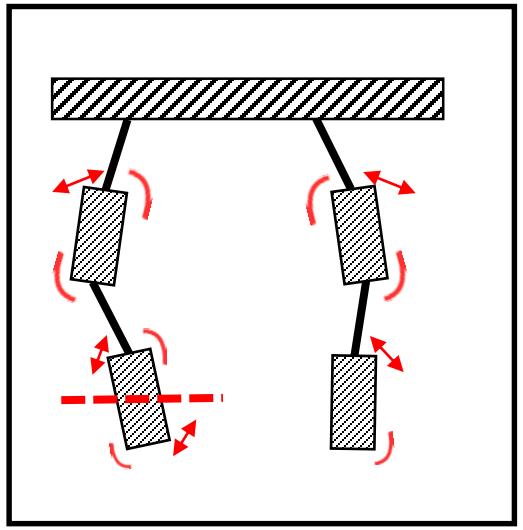
(BS/SRs-suspension case)



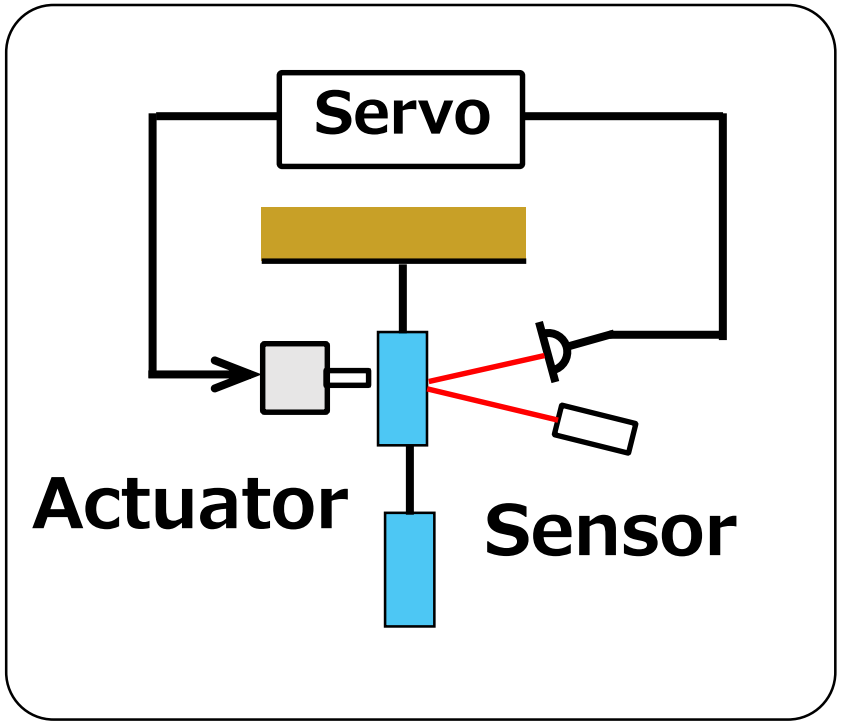
Resonance damping

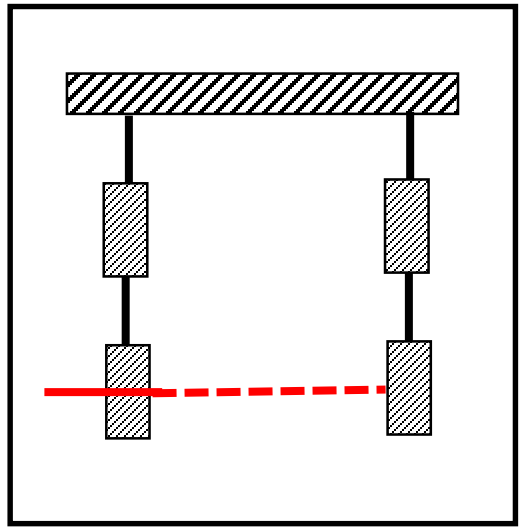
→ *Active control*

制御雑音を小さく保ちつつ
揺れ(RMS)を抑える。



Starting interferometer operation

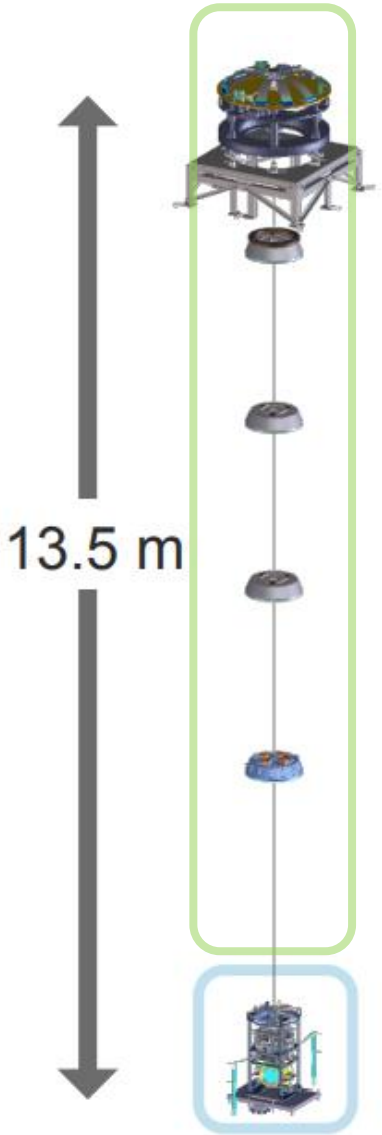


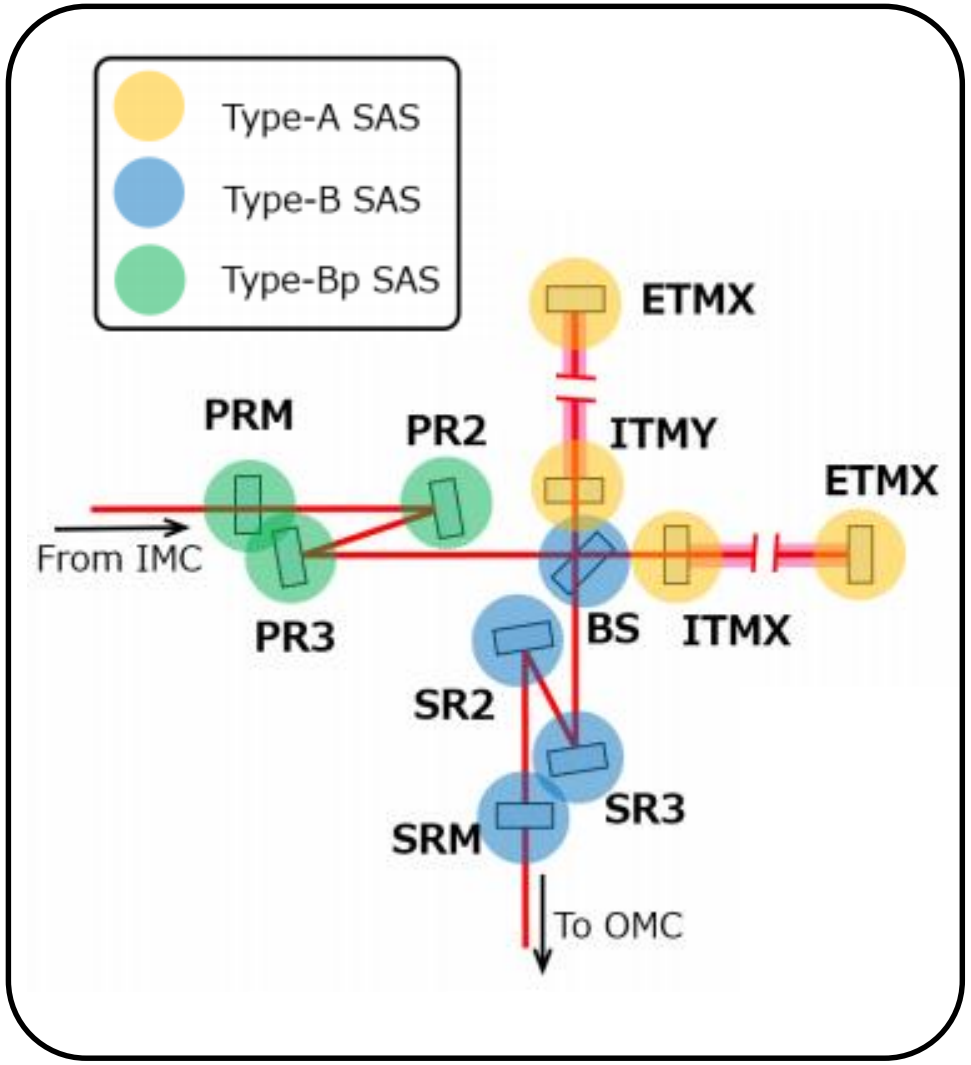


Stable interferometer operation

メイン鏡用の防振装置

メイン鏡用の防振装置

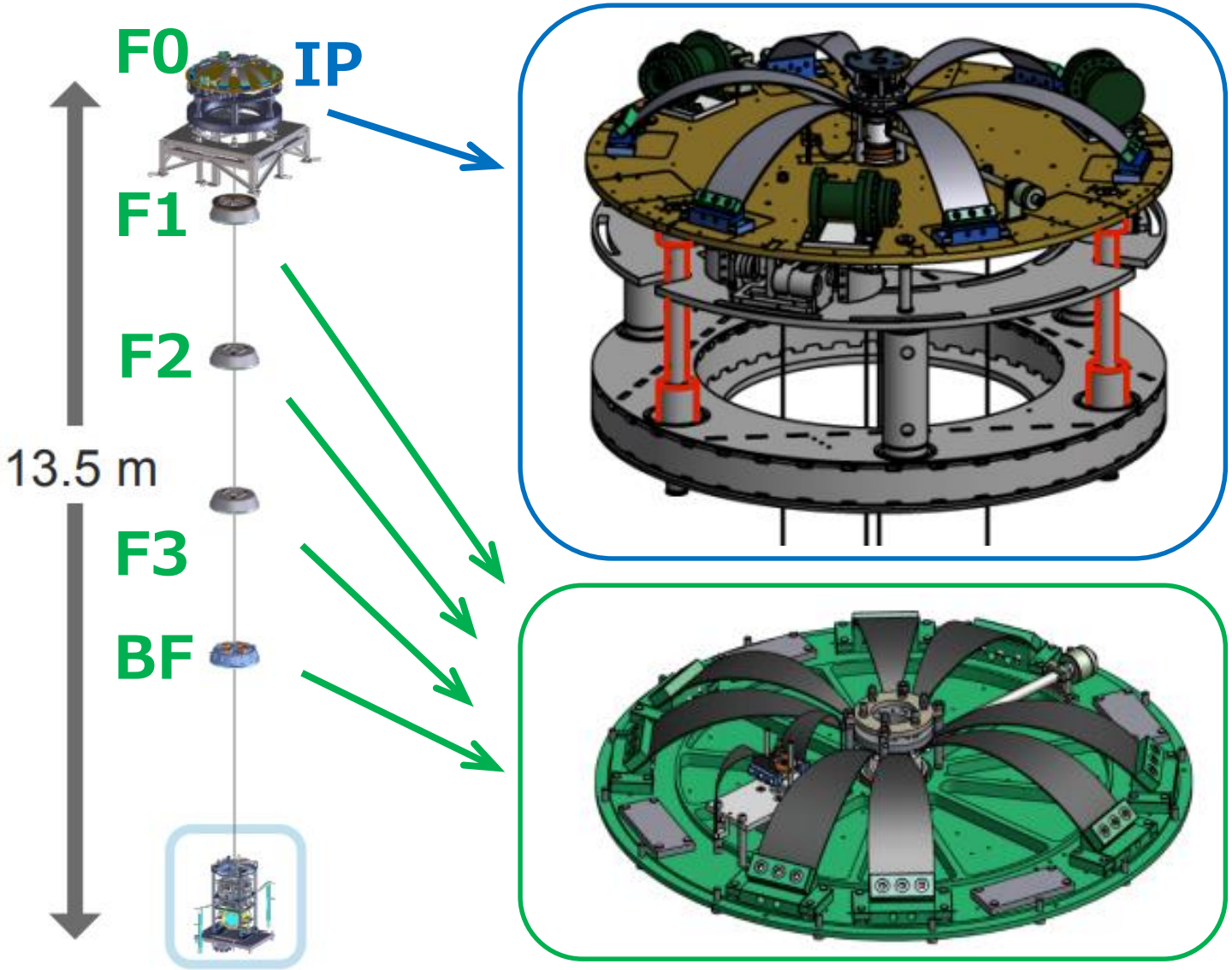




- Upper 5 stages:
  room-temperature

- Lower 4 stages:
  cryogenic-temperature

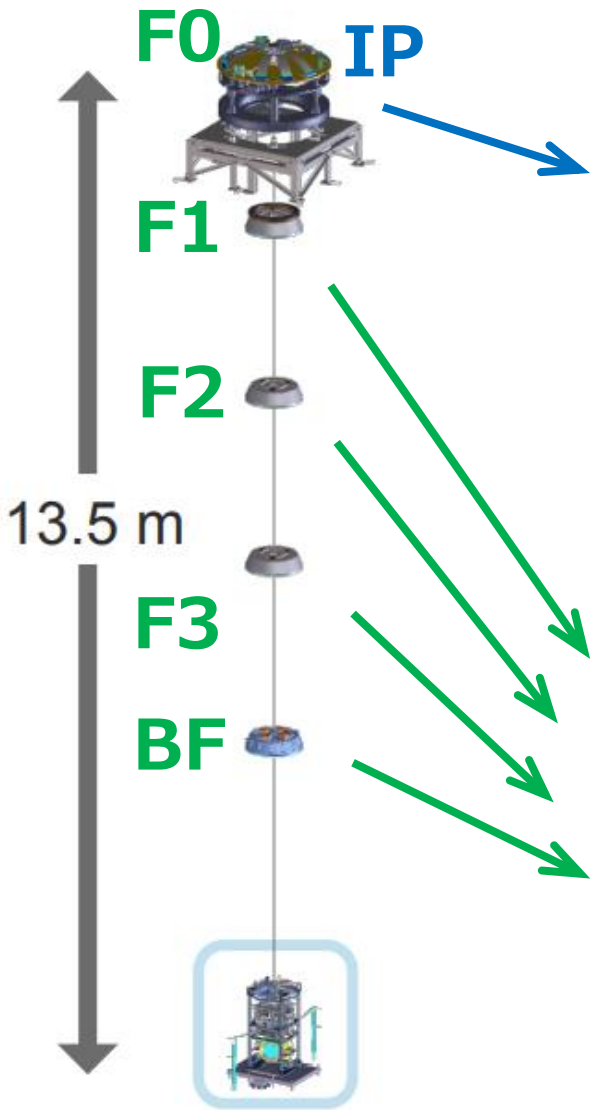
メイン鏡用の防振装置

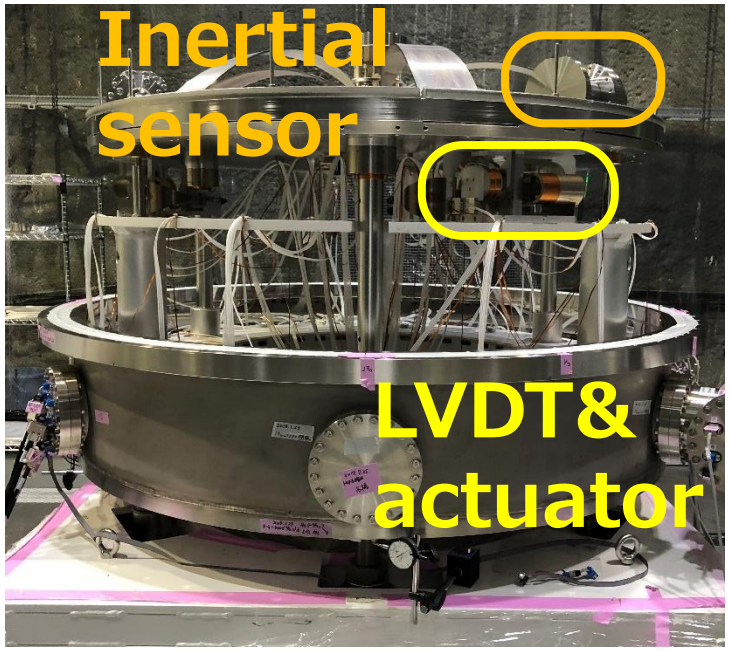


INVERTED PENDULUM
(~ 70 mHz)

GEOMETRIC-ANTI SPRING
(~ 0.4 Hz)

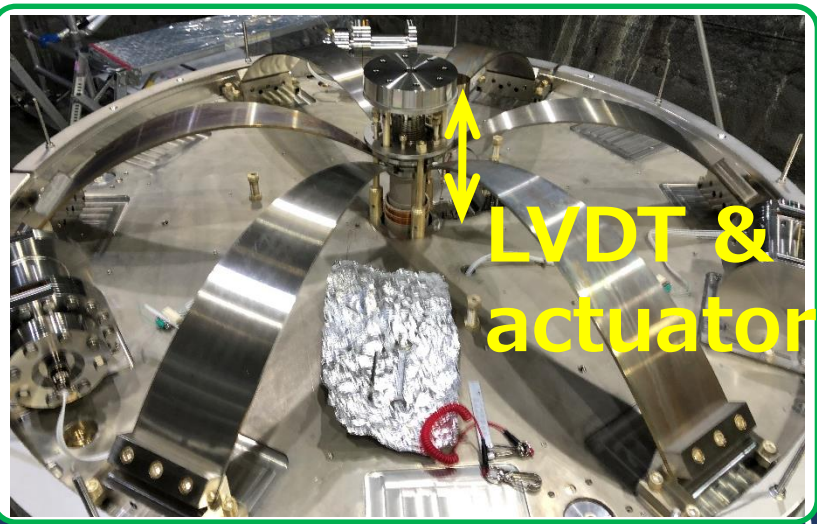
メイン鏡用の防振装置





Inverted Pendulum

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

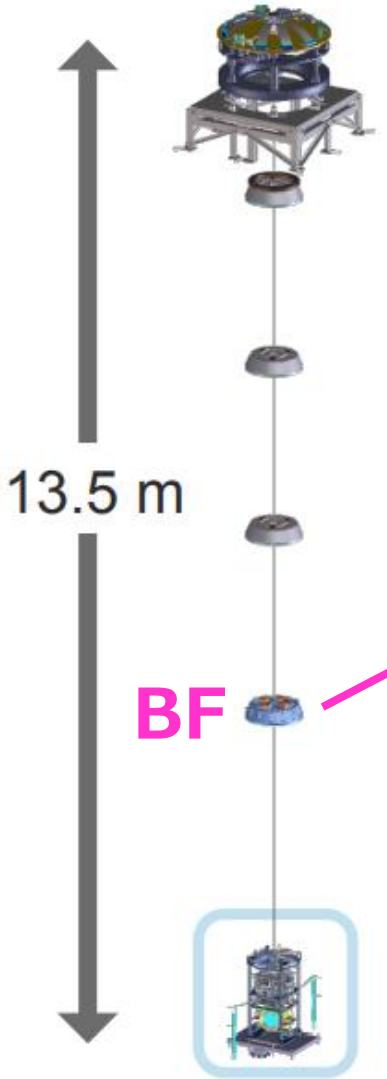


Geometric-Anti Spring

with 1 vertical
LVDT & actuator unit

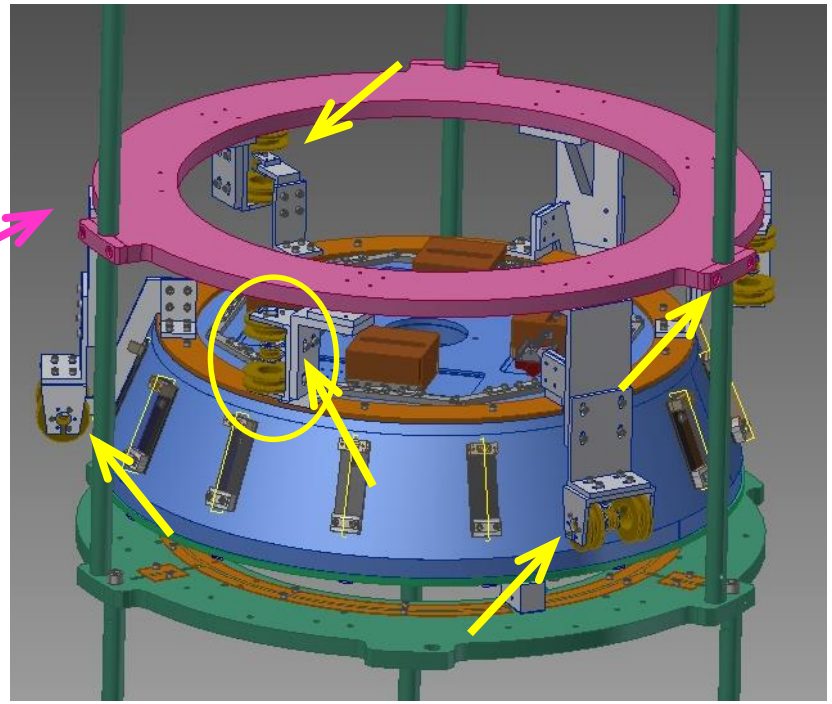
メイン鏡用の防振装置

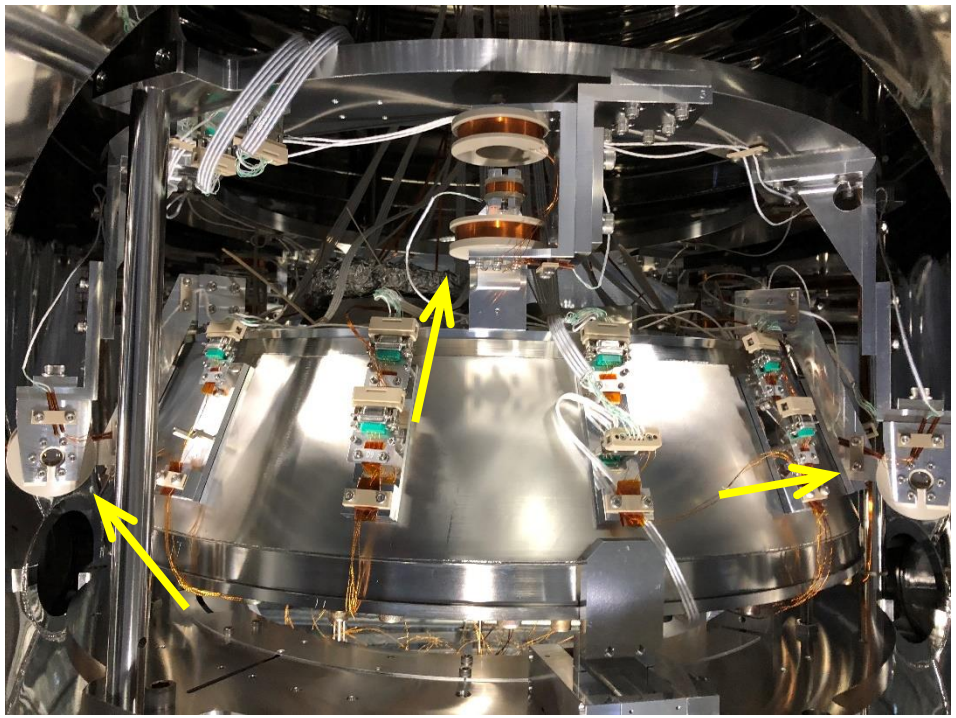
(イタリアのグループの協力のもと開発)



BOTTOM-FILTER DAMPER

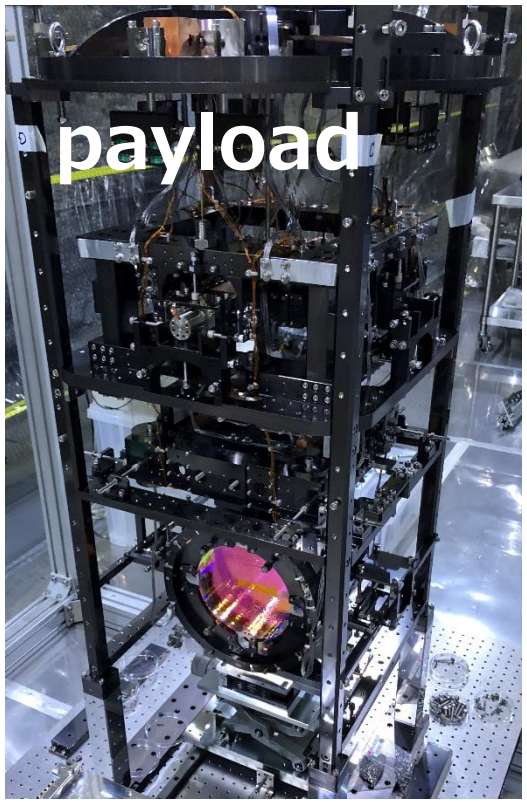
with 3 horizontal & 3 vertical LVDT & actuator units



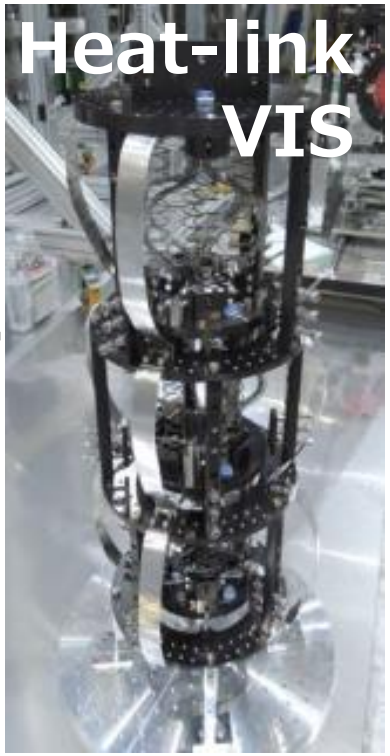


メイン鏡用の防振装置

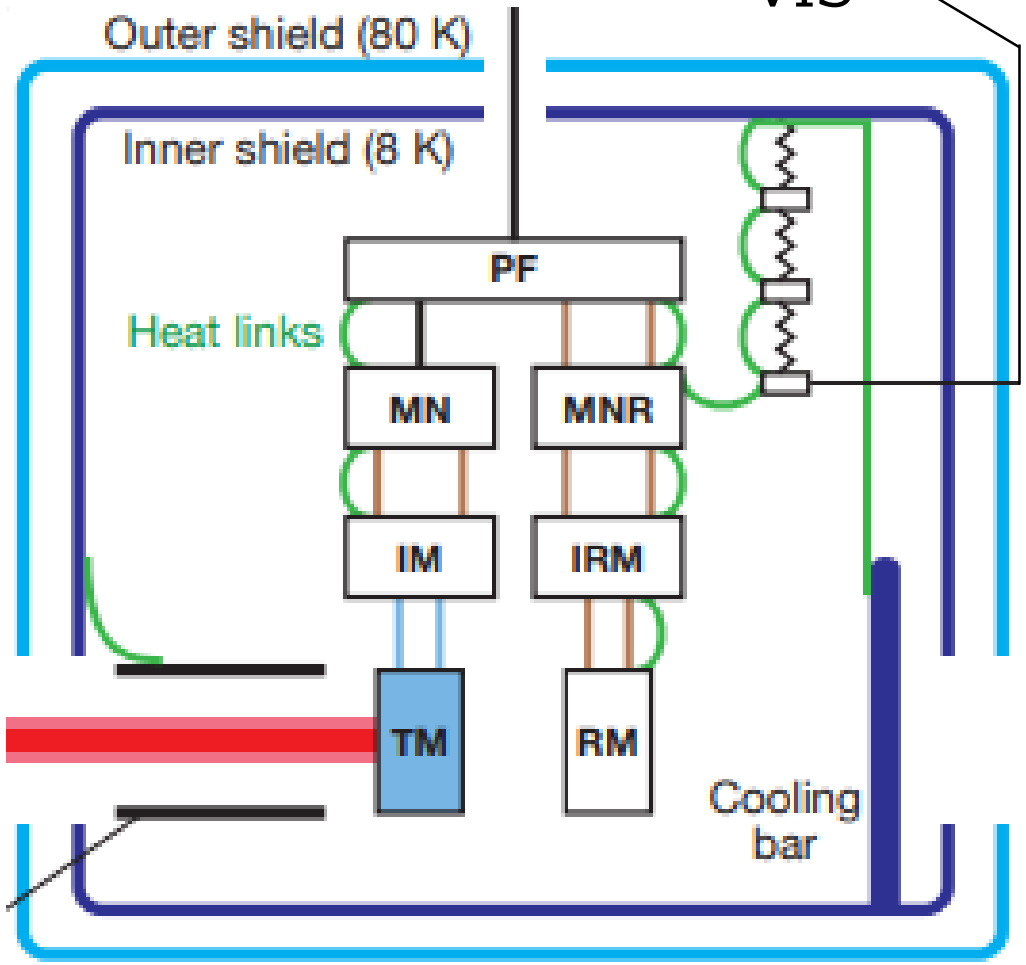
クライオスタットの中



+



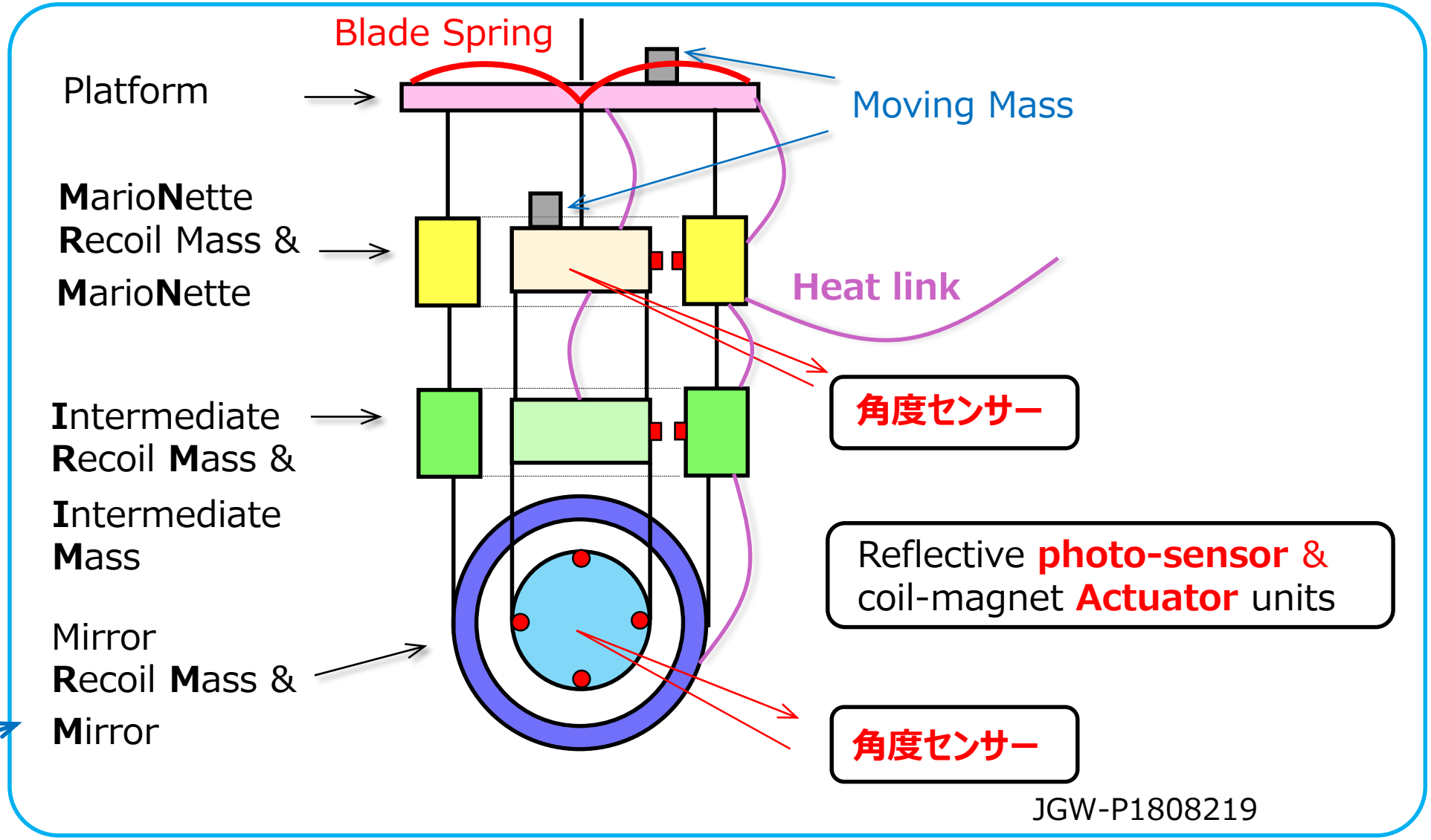
(+ Wide-angle baffle)



JGW-P1809347

メイン鏡用の防振装置

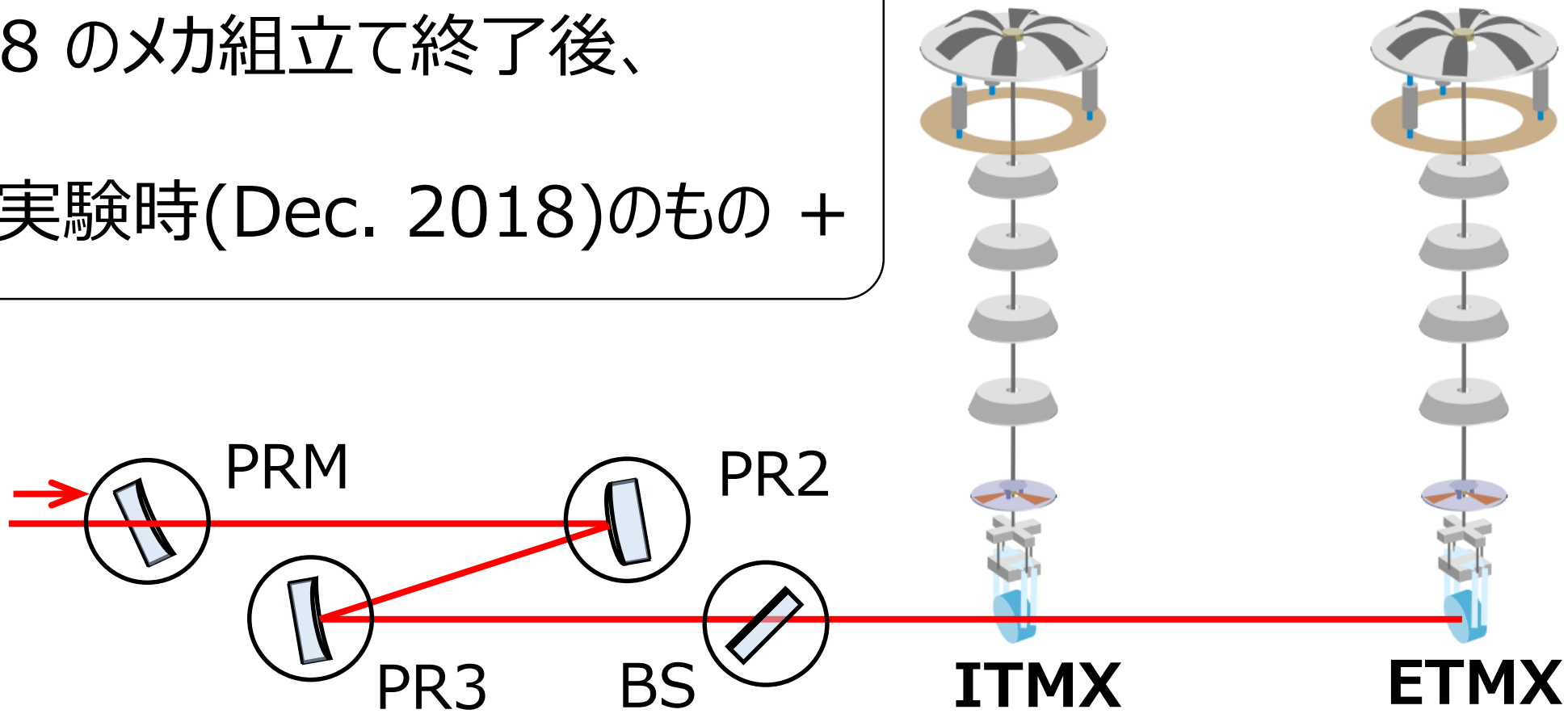

13.5 m


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

制御系の実装状況

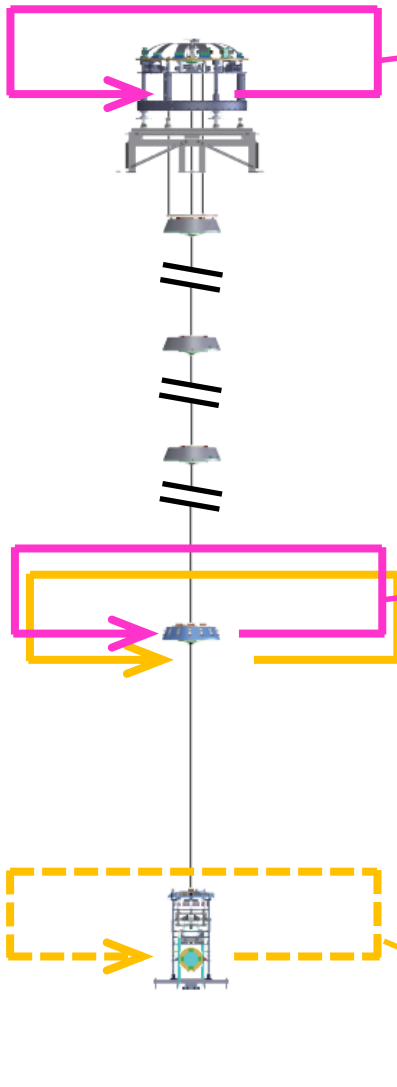
~Aug. 2018 のメカ組立て終了後、

主にX-arm 実験時(Dec. 2018)のもの +



With 変位センサー, [for damping]

IP



DC+Damp

For L / T / Yaw

BF-damper

DC+Damp

For Yaw

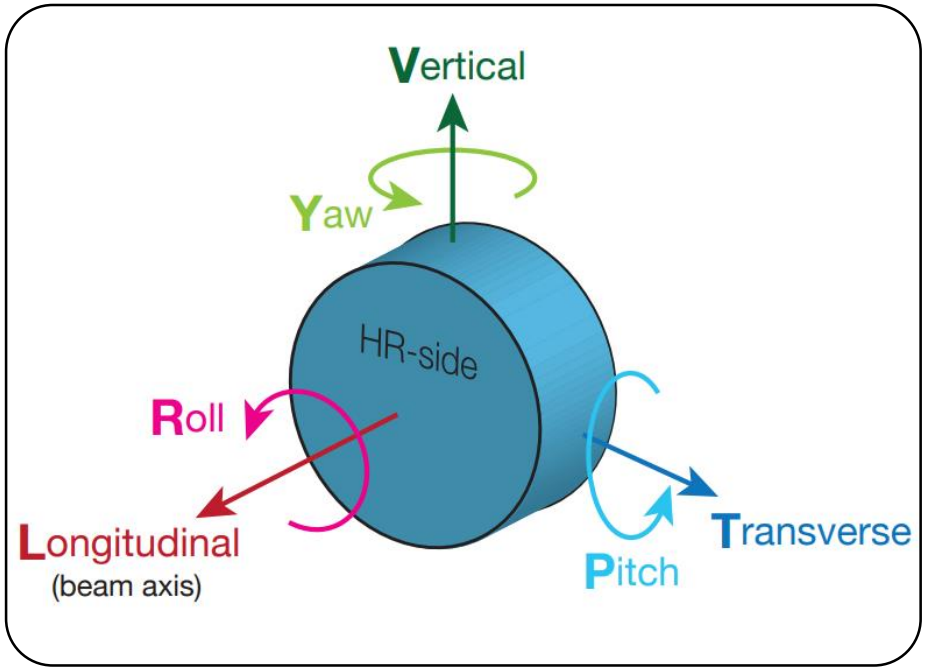
For L / T

Damp

(TMoplev)

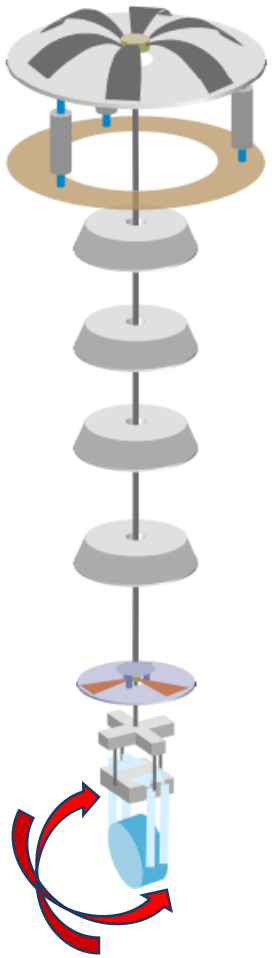
Damp

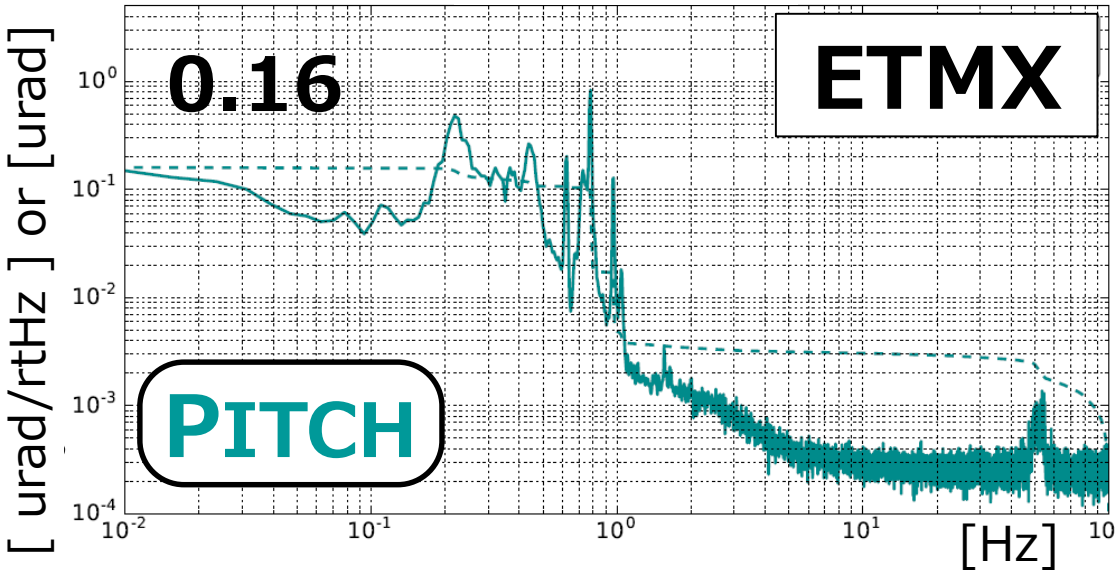
For P / Y

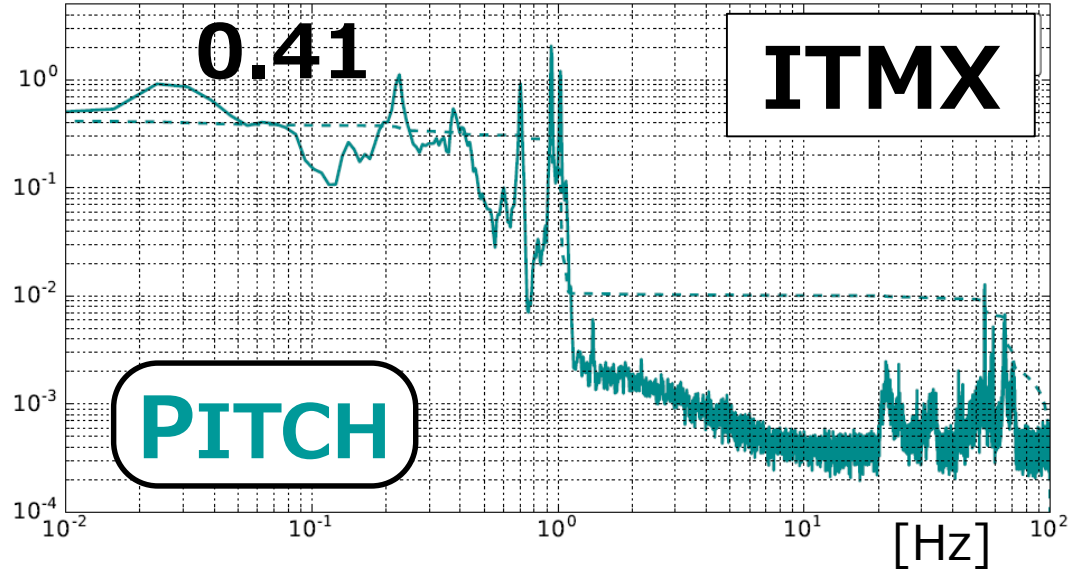


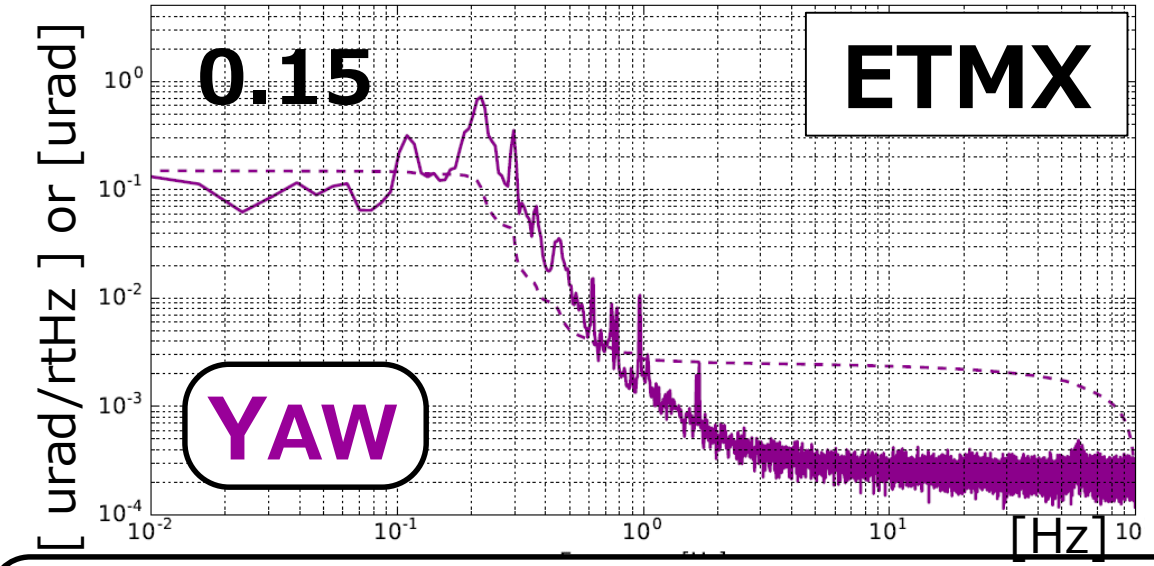
With 変位センサー, [residuals]

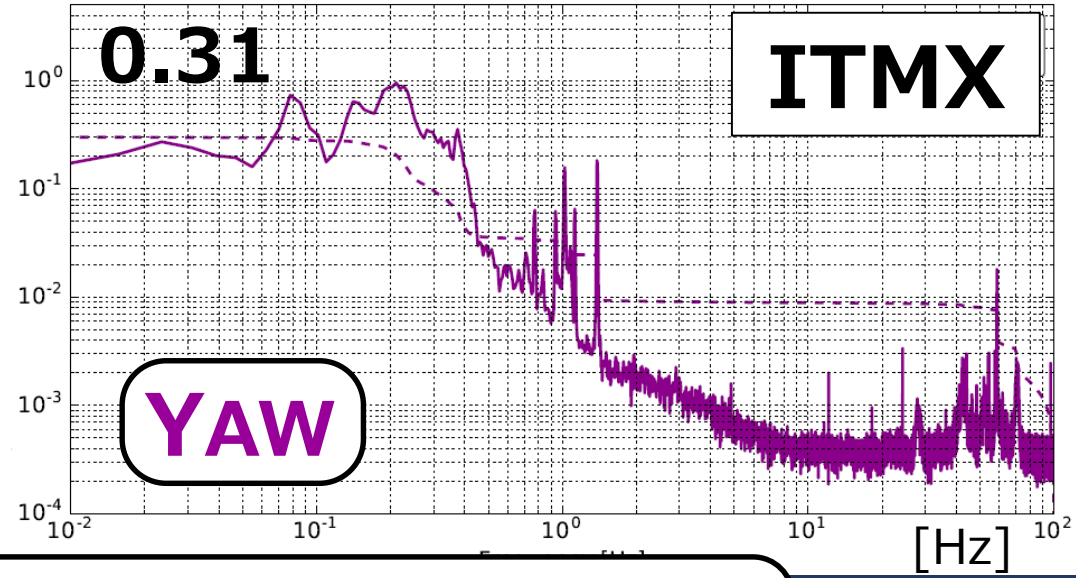
最終的な目標: < 0.2urad







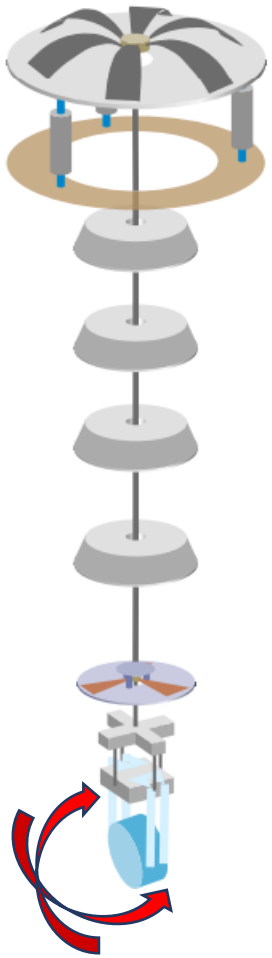


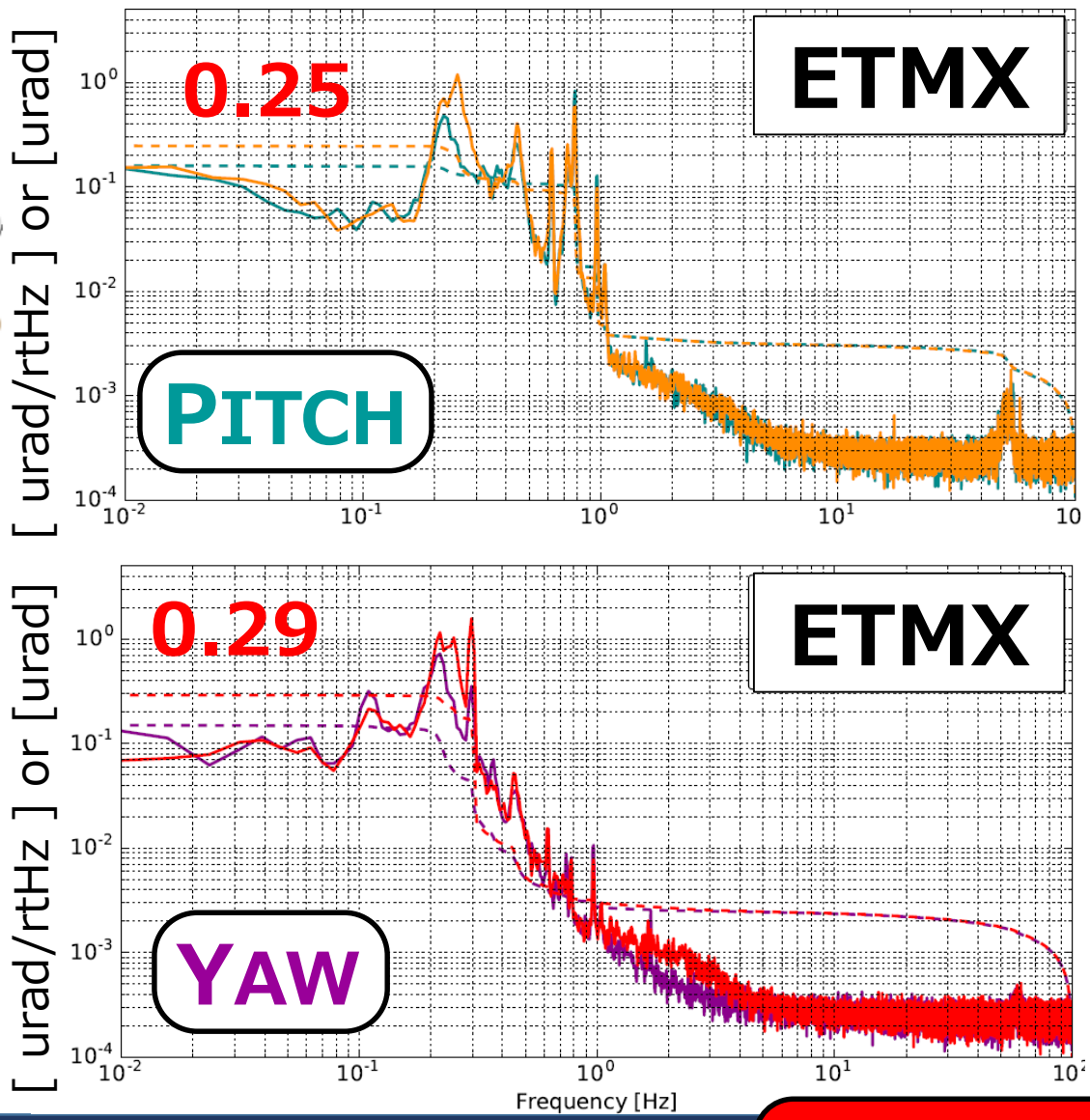


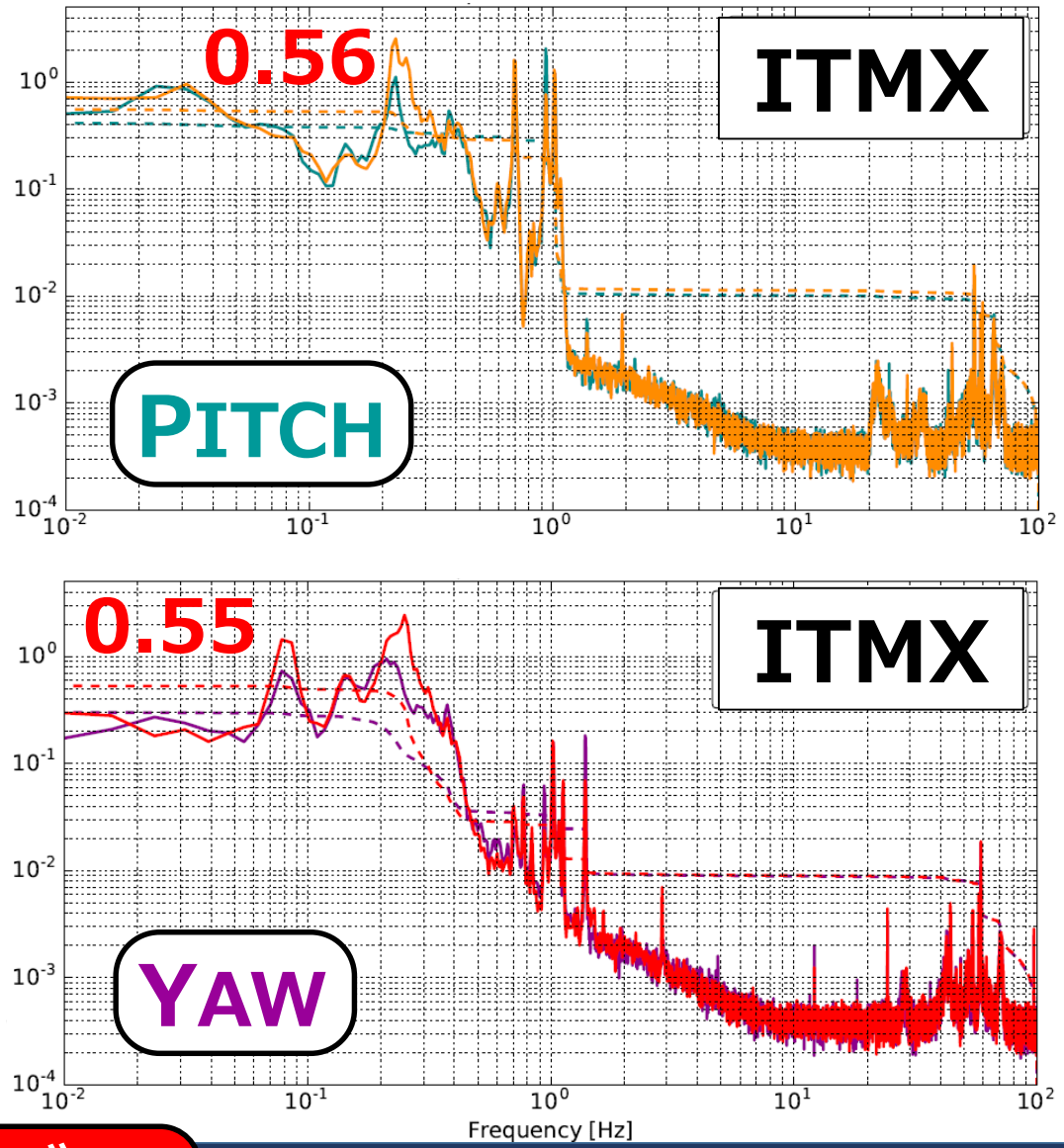
X-arm Locked. Thanks to Kamioka environment.

With 変位センサー, [residuals]

悪天候だと



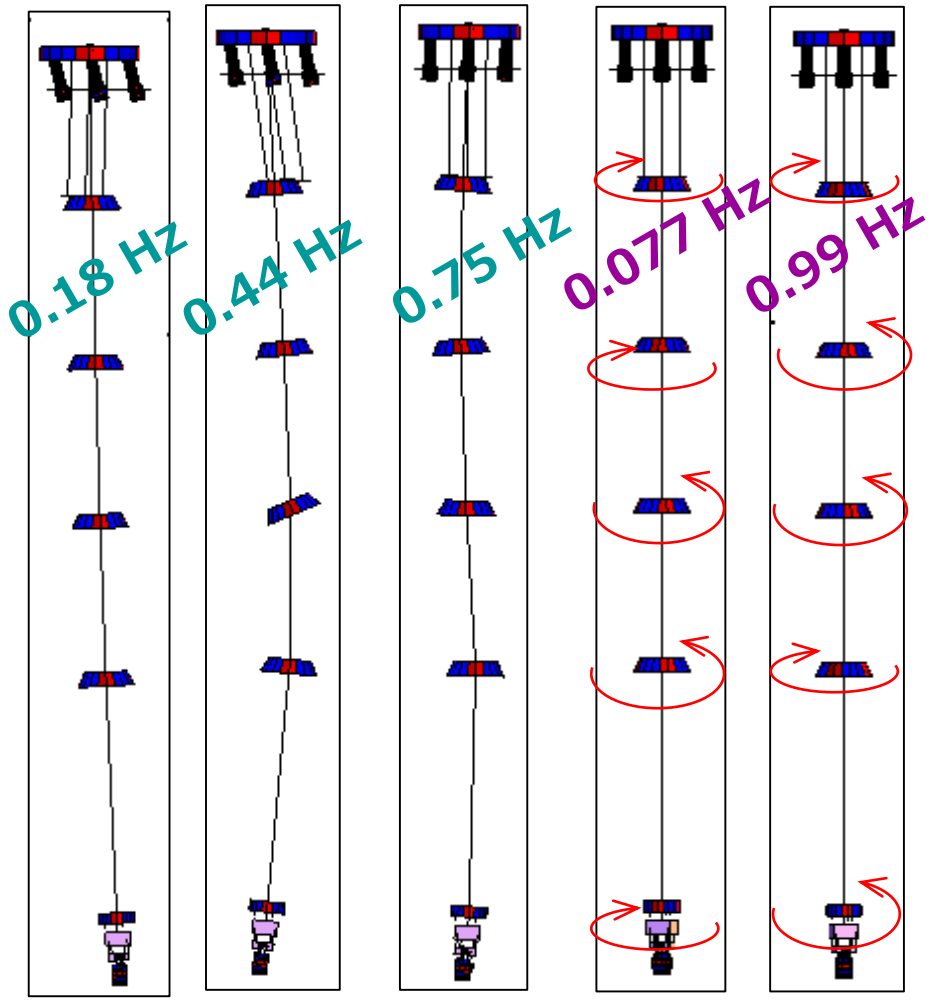


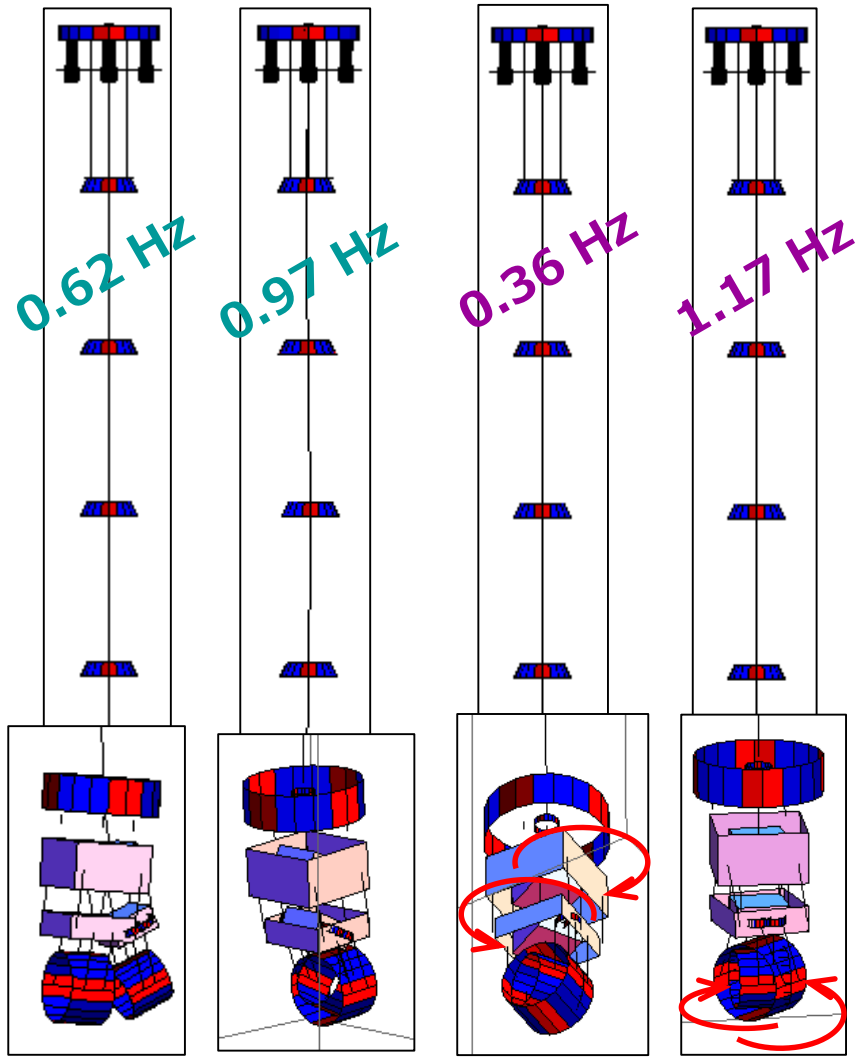


Lock できず..

Candidate (main) resonant modes?

Preliminary



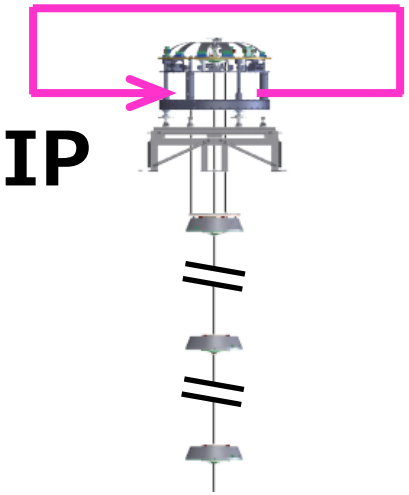


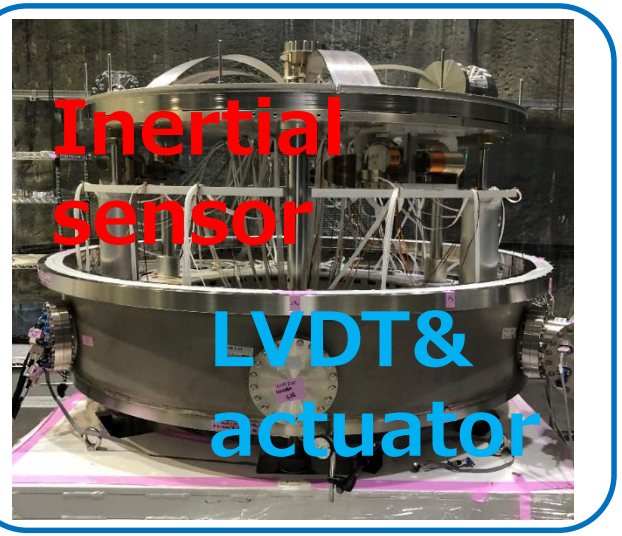
→ damping at tower-part

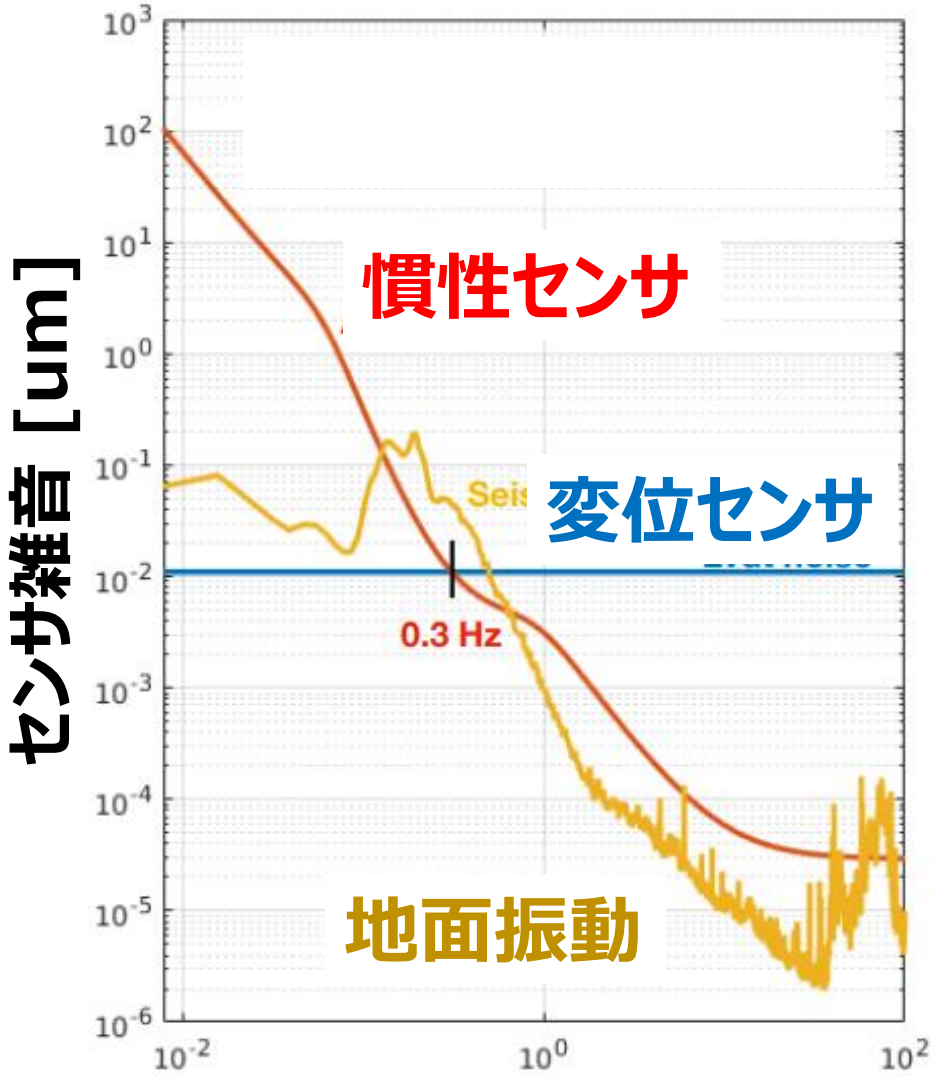
→ damping at payload

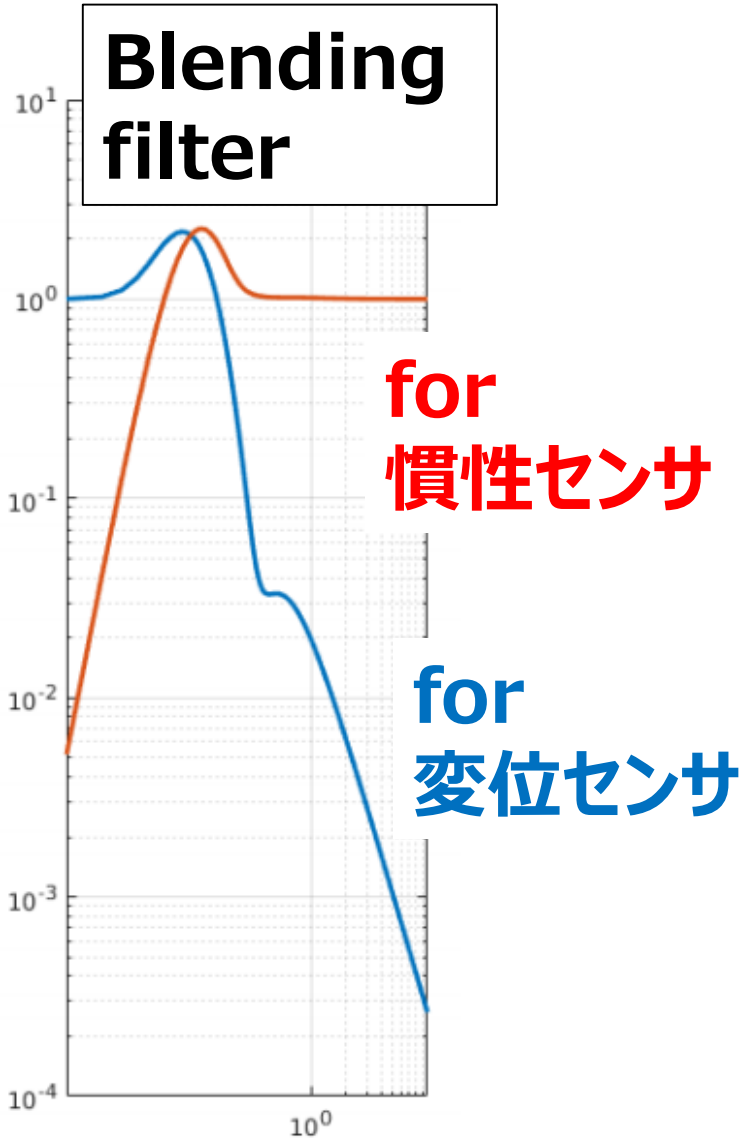
Sensor blending & inertial damping

(From JGW-G1909932)



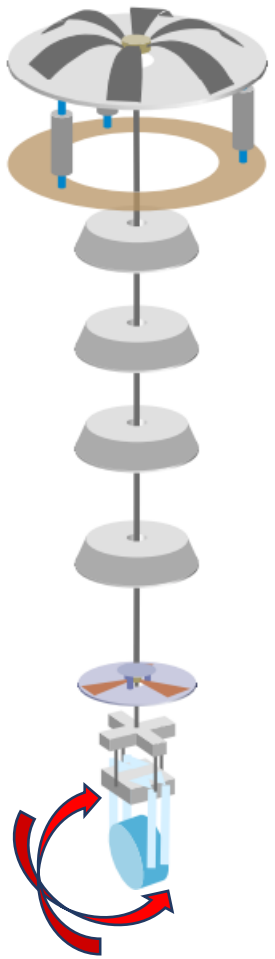


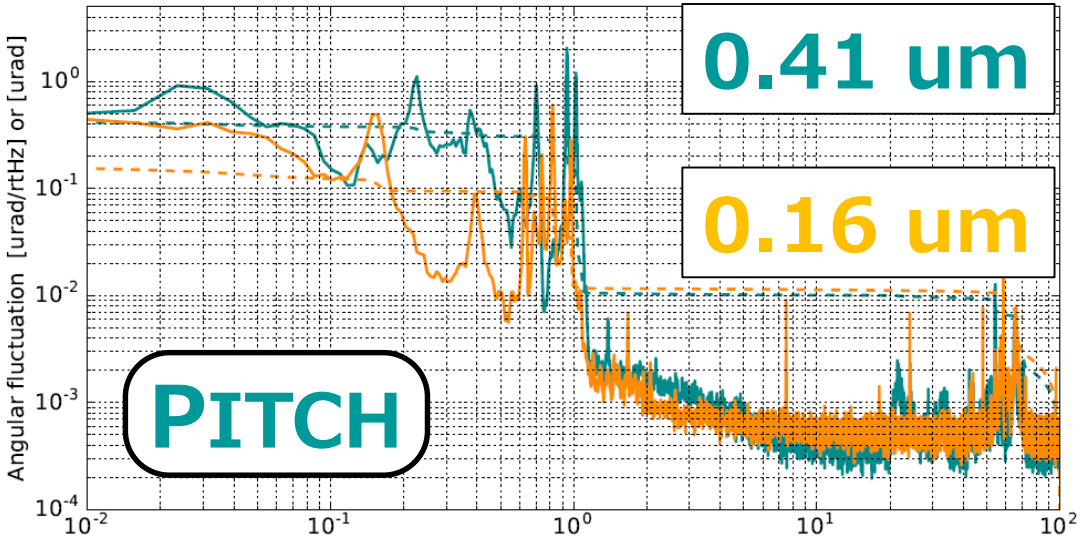




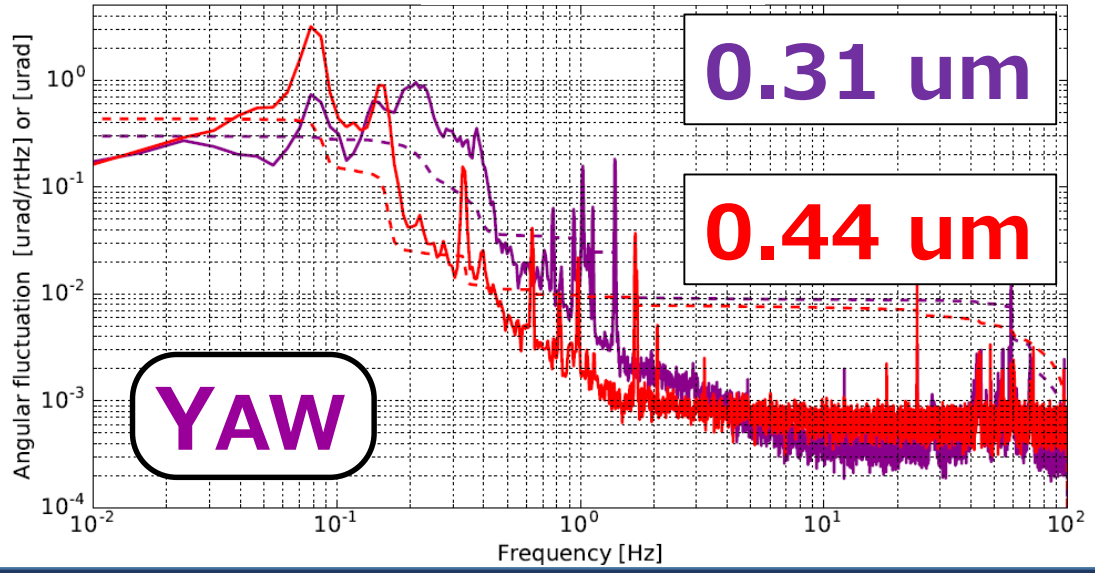
Sensor blending & inertial damping

ITMX



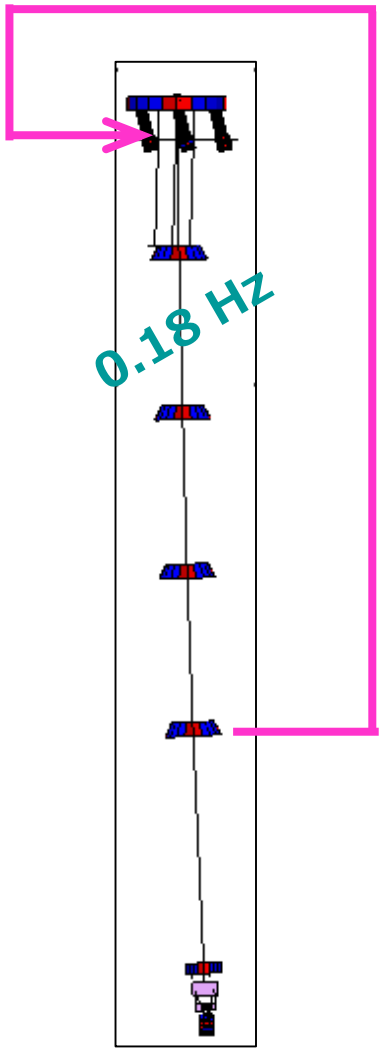


w/ inertial damping



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。

まとめ:

-- 変位センサを用いた、シンプルなダンピングコントロールは実装済み。
  -- 片腕(Xarm)のロックは成功
    ただし、
    → ダンプしきれていないモードあり。
    → 地面振動が活発(悪天候時など)だと、鏡の揺れが大きすぎる。ロック不可。

-- Inertial damping at IP stage の実装試験中
  → 実効的な揺れ(RMS)をまだ抑える必要あり、の様子。

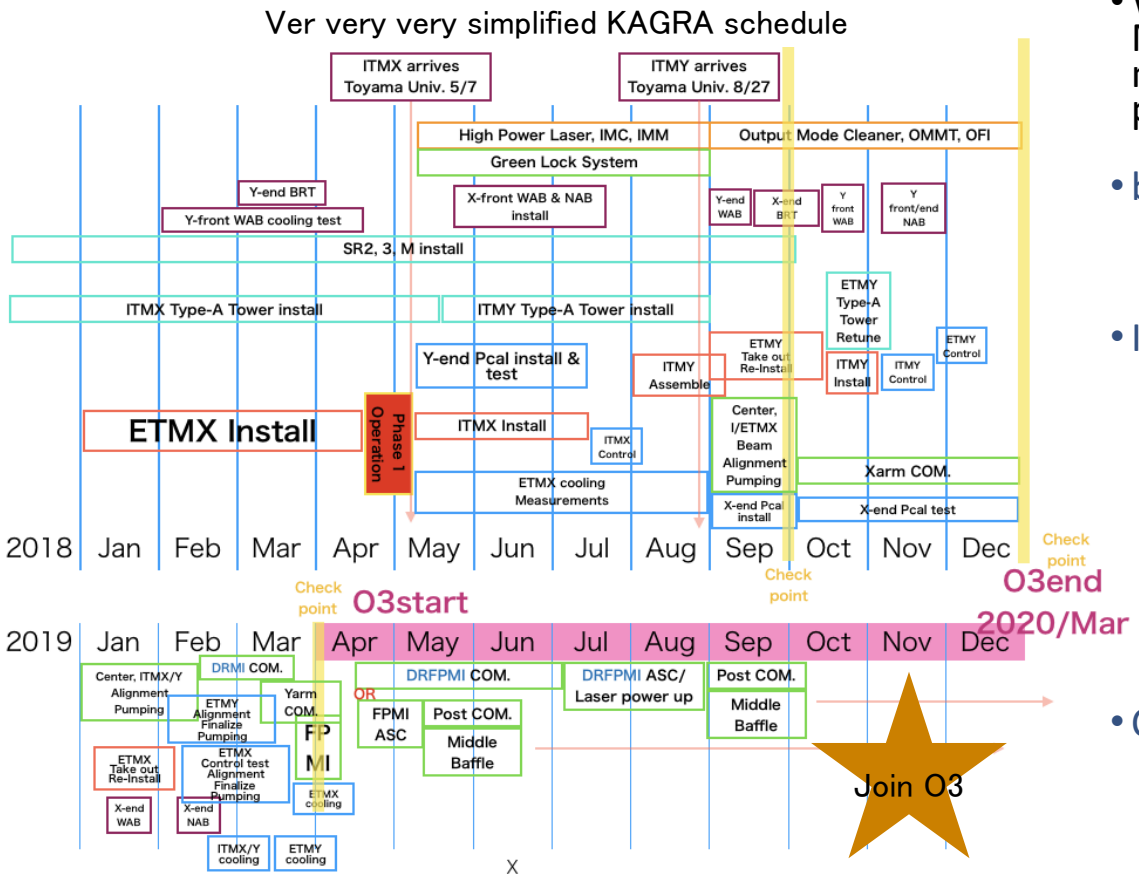
今後:

- ☐ フィルタの改良 / ループの追加 etc.
- ☐ feed-forward を用いた地面振動subtraction

Backup

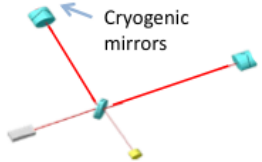
(From JGW-G1909942)

Progress in FY2018



- We have completed bKAGRA Phase1 in May 2018. After then, we conducted many things to join O3 as early as possible.

- bKAGRA Phase1
  - 3km Cryogenic Michelson Interferometer

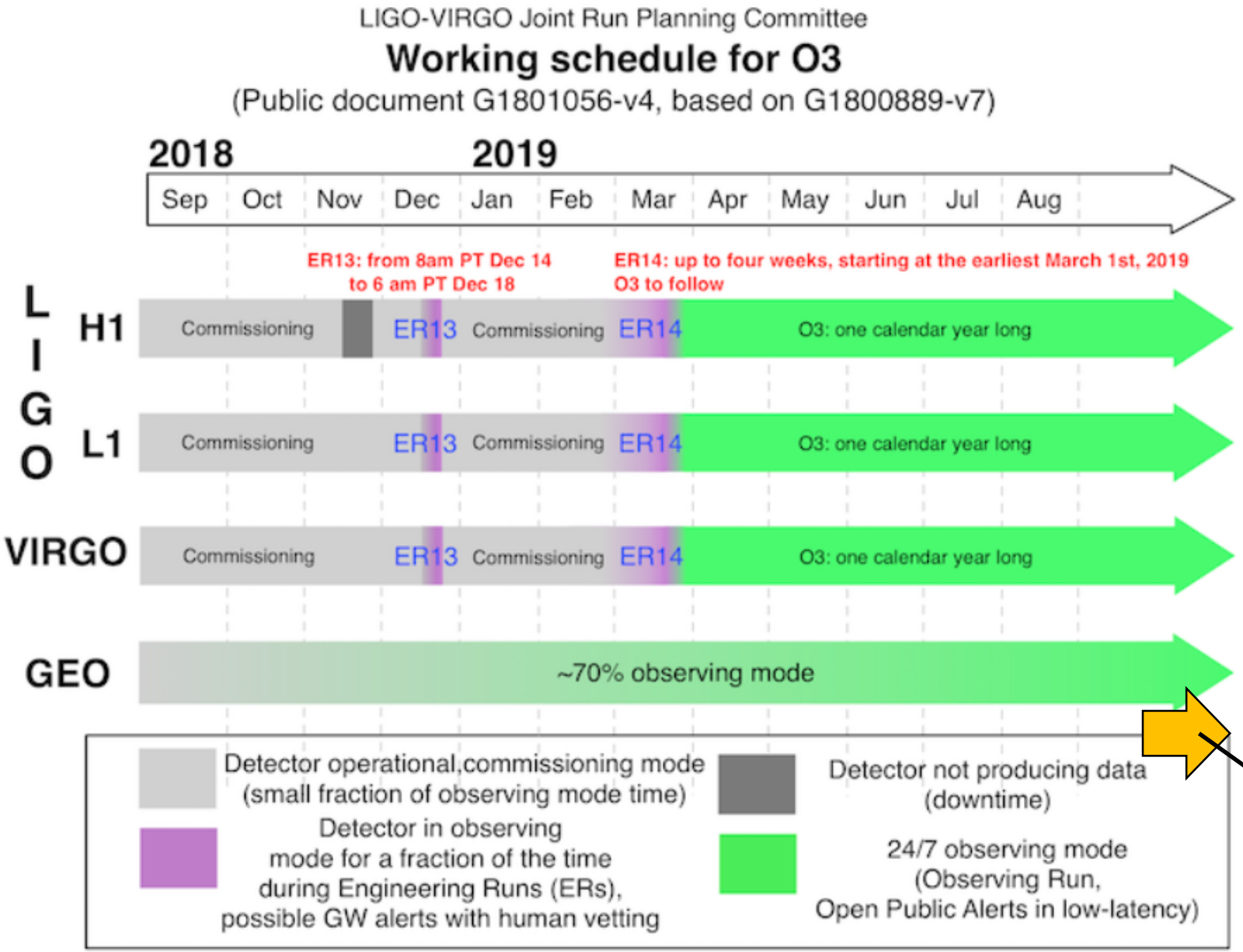


- Installation …Done!!
  - High power laser
  - Green lock system
  - Sapphire test masses
  - Calibration system
  - All other optics
  - Output optics
  - Optical baffles
  - Transmission beam monitor system

- Commissioning
  - X-arm 3km Fabry-Perot cavity (done)
  - DRMI (on going now)
  - Y-arm 3km Fabry-Perot cavity (start soon)
  - FPMI (start in March)
  - DRFPMI (After FPMI)

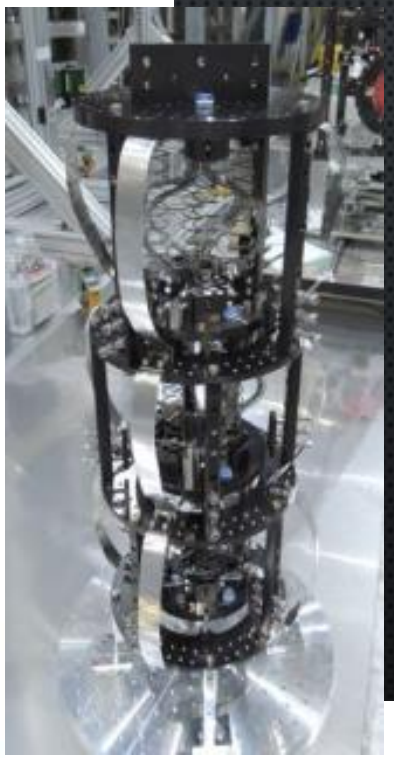
We have done on schedule!!

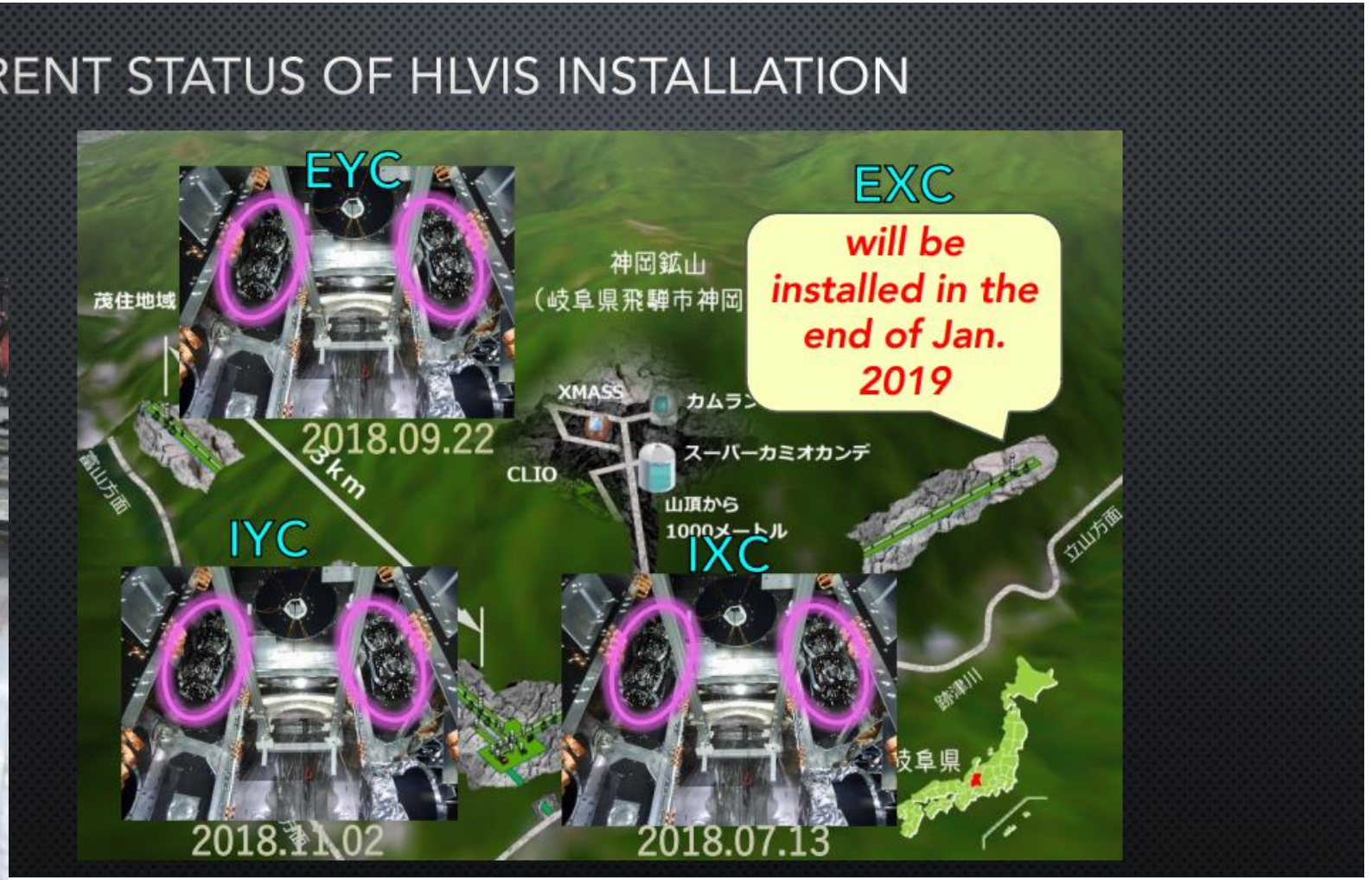
宇宙線研 内山氏より



KAGRAのO3
参加時期(予定)

Type-A suspensions?





JGW-P1809382

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.

Then, mechanical installation status

for O3-observation

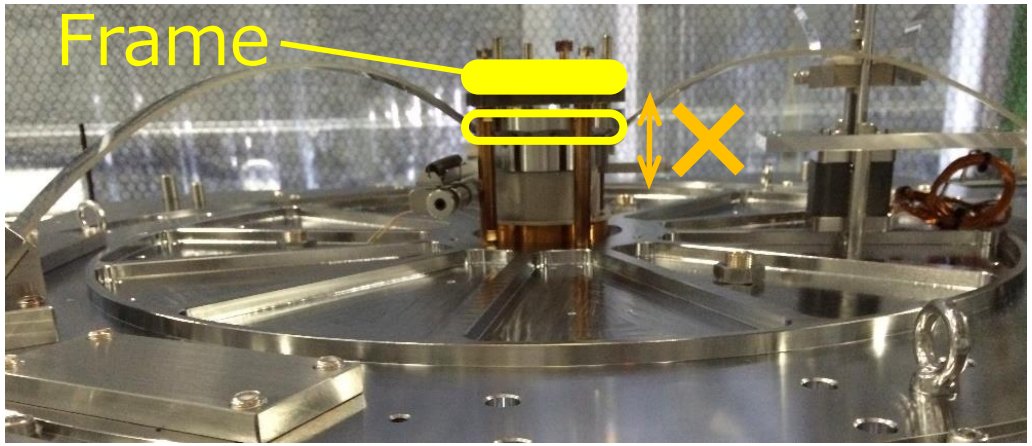
Mechanical installation has done! For all 4 of them!

Mechanical installation has done! HOWEVER ..

ETMX & ETMY:

for ETMX - F2 GAS
for ETMY - F1 & F2 GAS

Hitting,, ~No oscillation

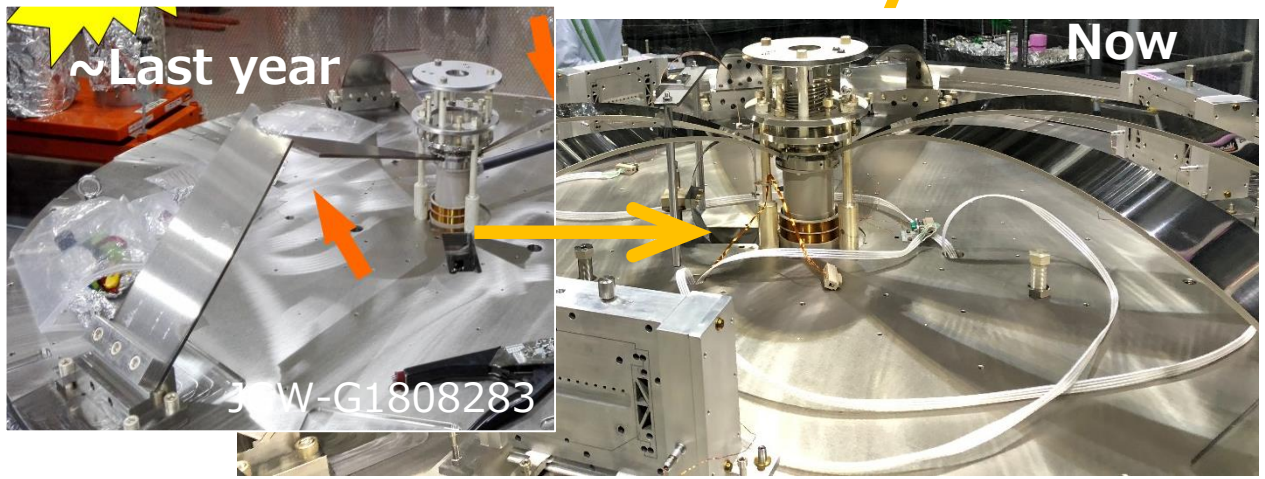


Mass tuning, necessary
but no accessibility.

ITMX & ITMY:

for ITMX / ITMY – F0 GAS

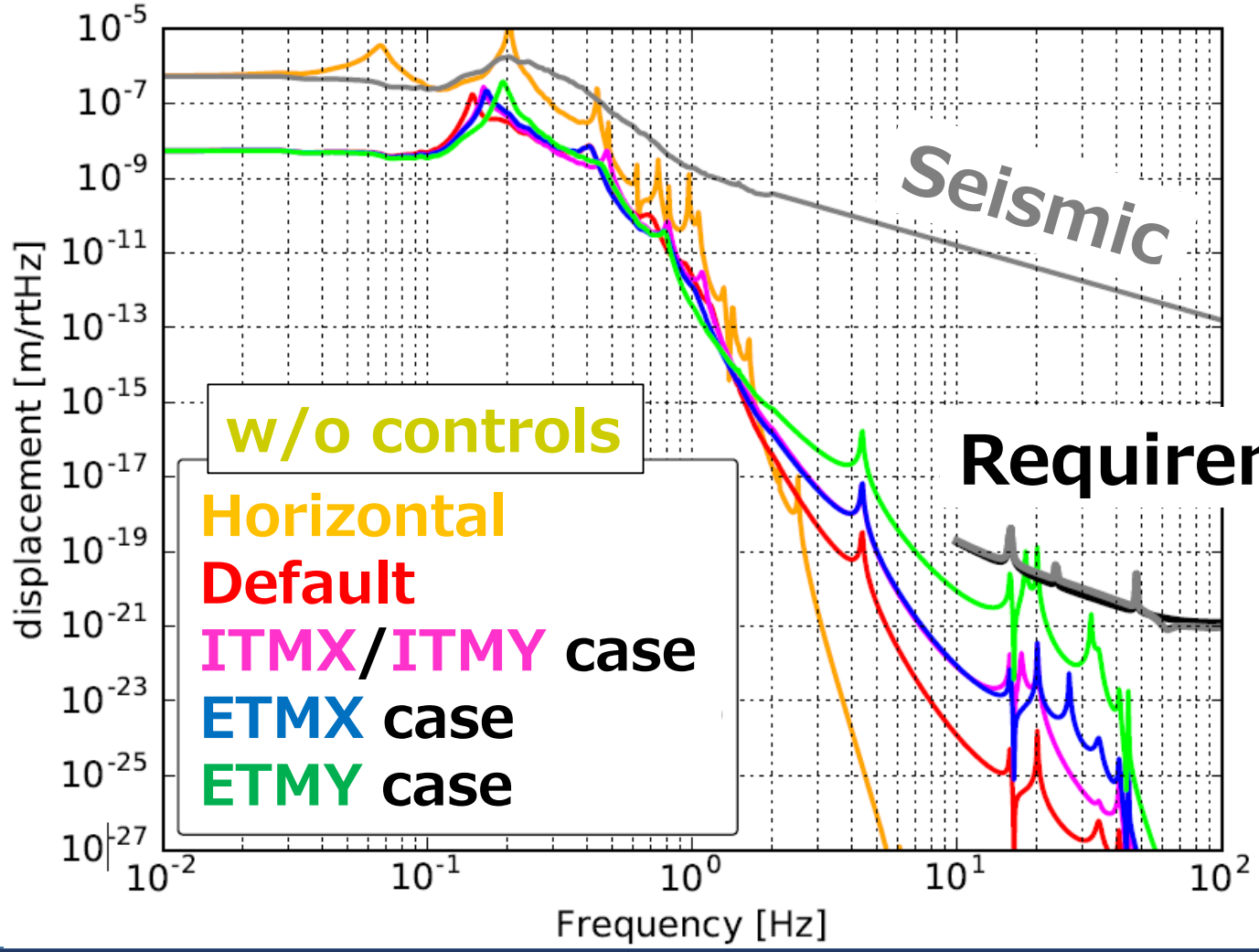
**Newly made blades
could not hold the system..**



Blade replacement, necessary
but time consuming (etc).

Mechanical installation has done! HOWEVER ..

According to a simulation, assuming 1% coupling,



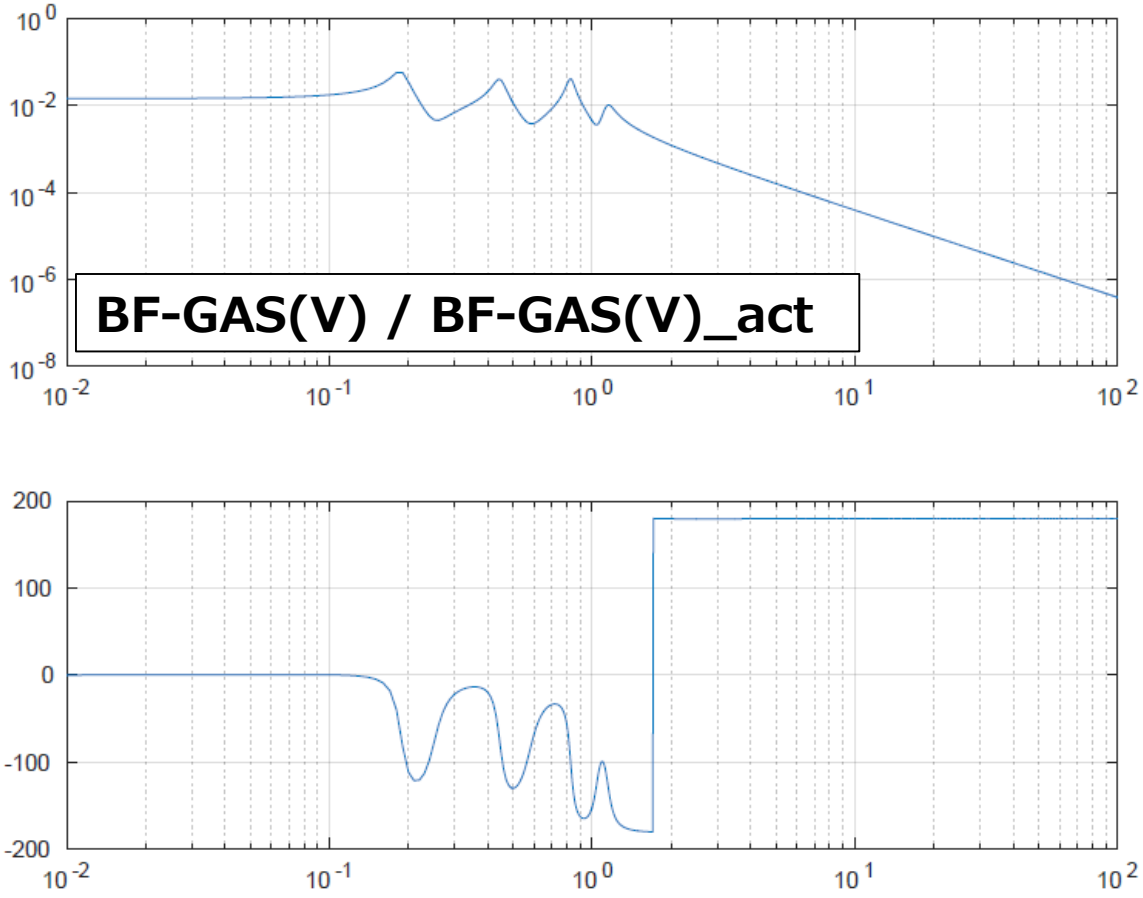
"acceptable
for the O3-run"

(should be)

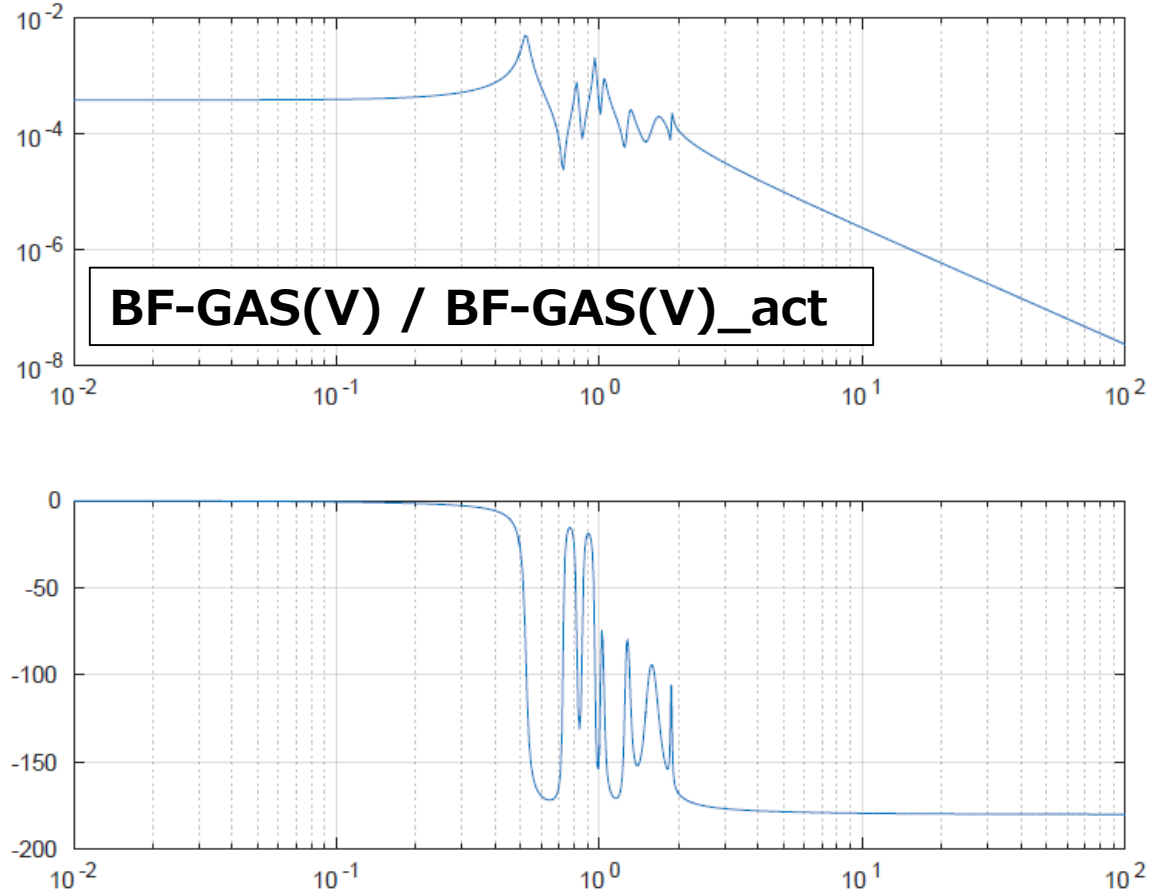
Note:
-- Modeled w/o Heat-links
-- params are not tuned.

Vertical transfer functions (fitted)

ETMX



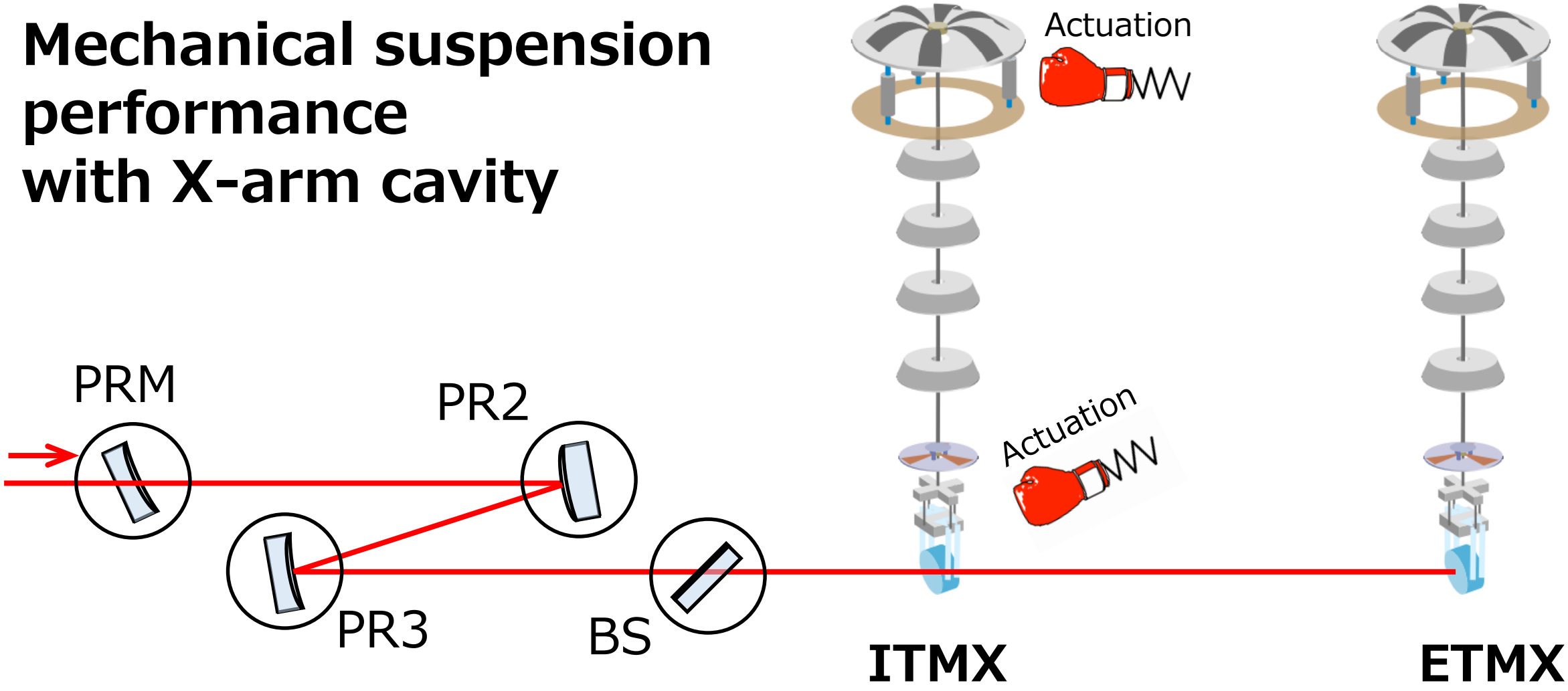
ITMX



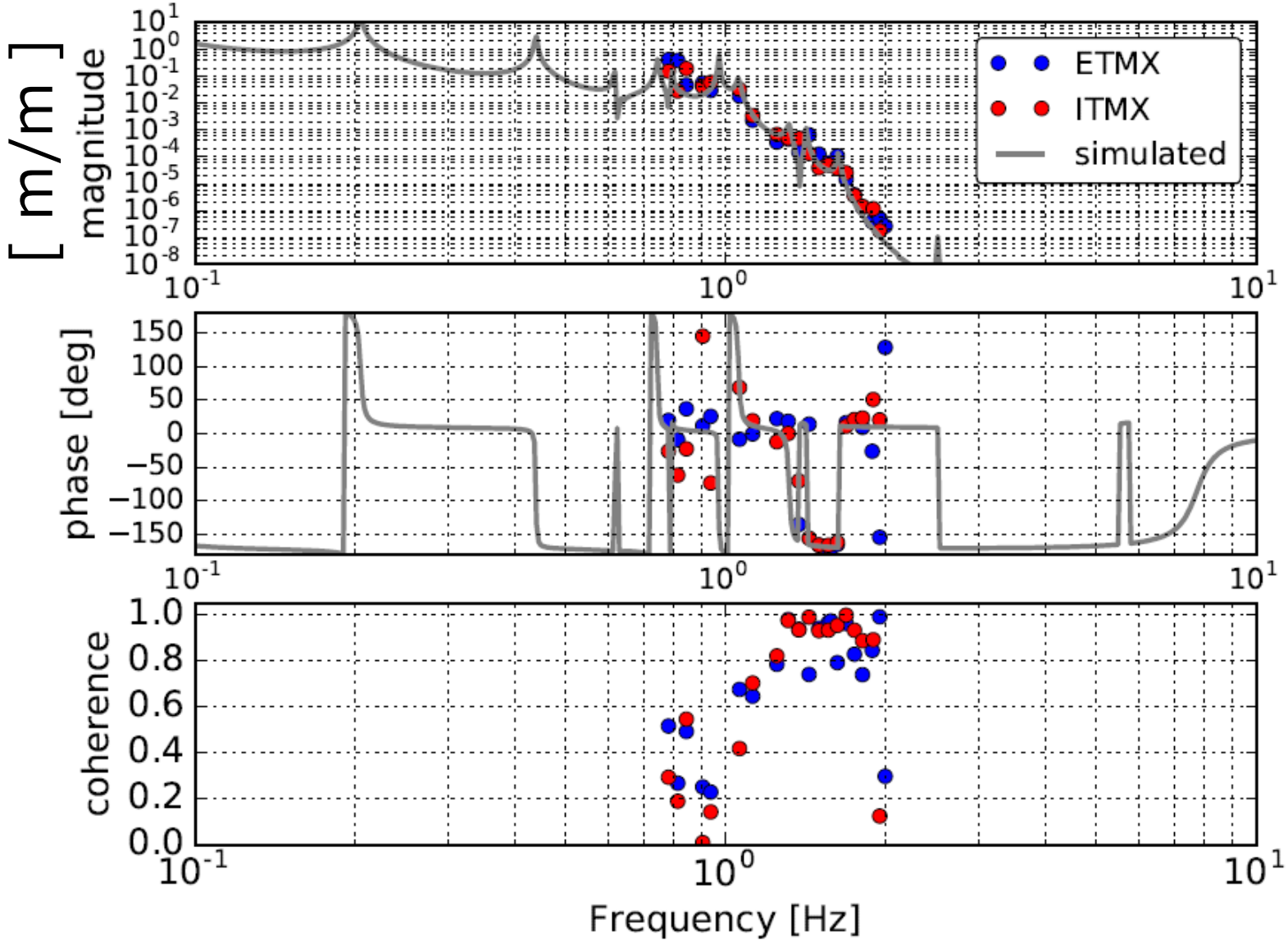
Verification of suspension performance

Measurement:

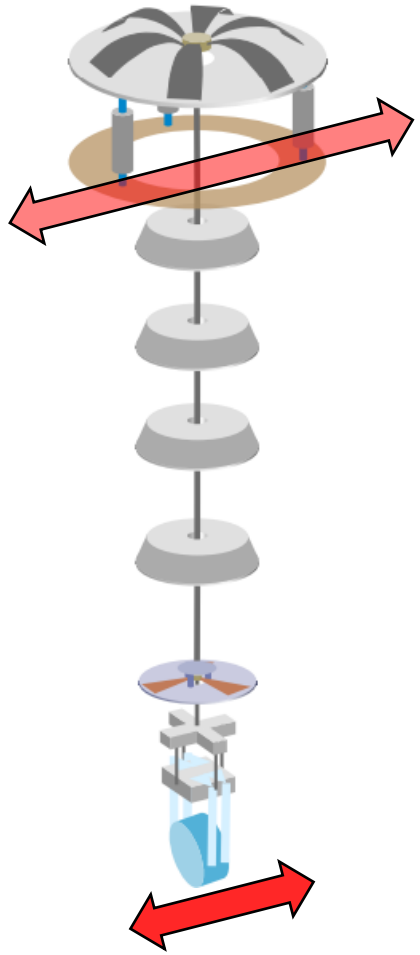
Mechanical suspension performance with X-arm cavity



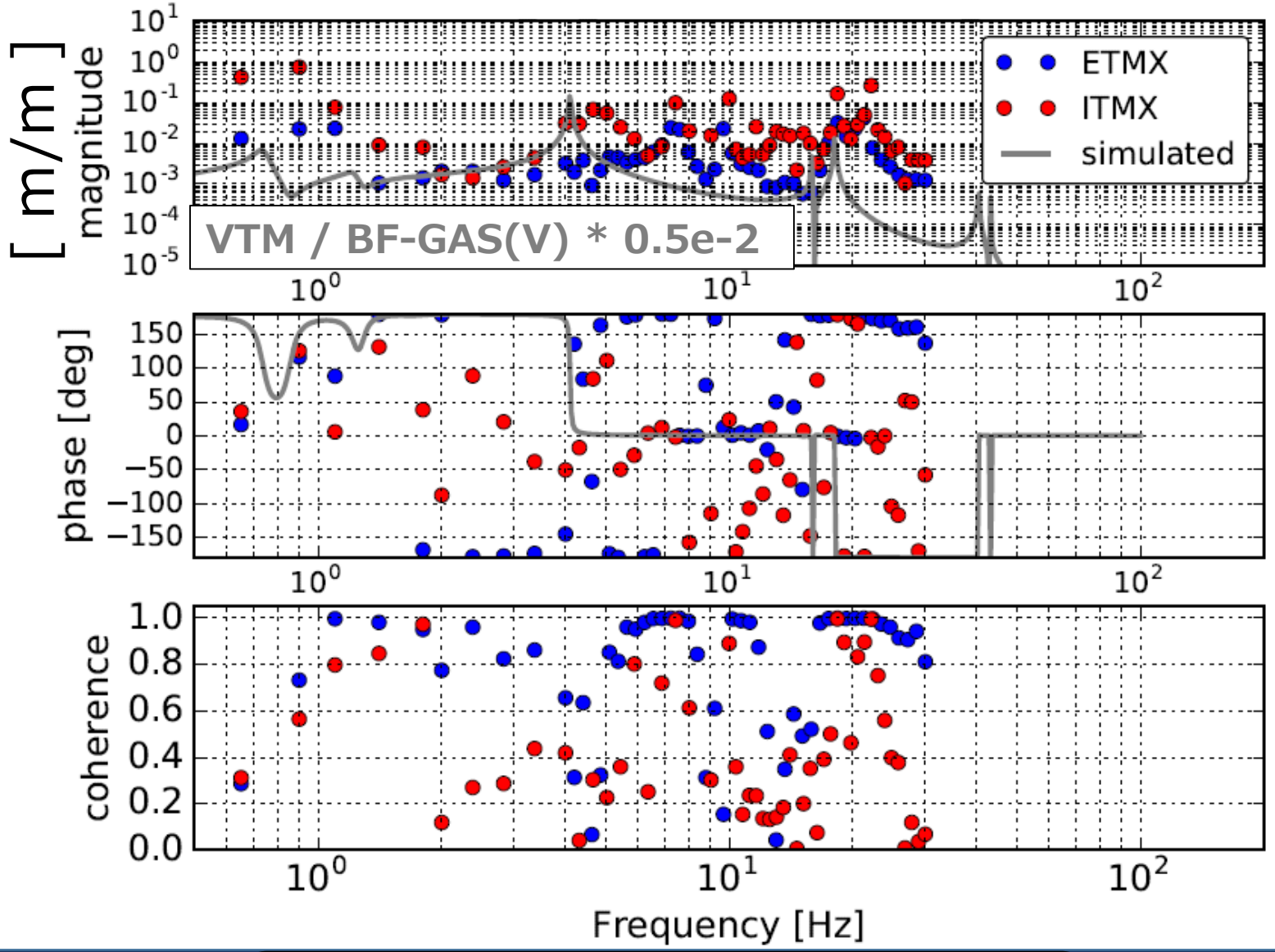
Vibration isolation ratio, [Good news!]



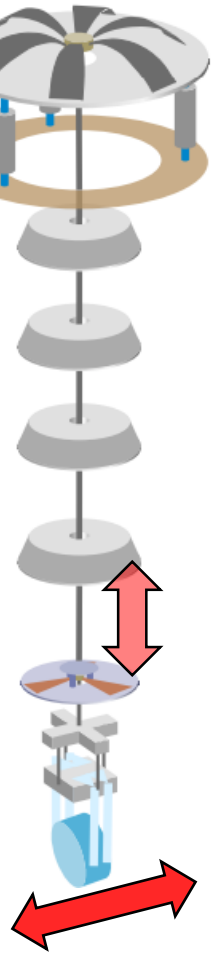
From ground to TM



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

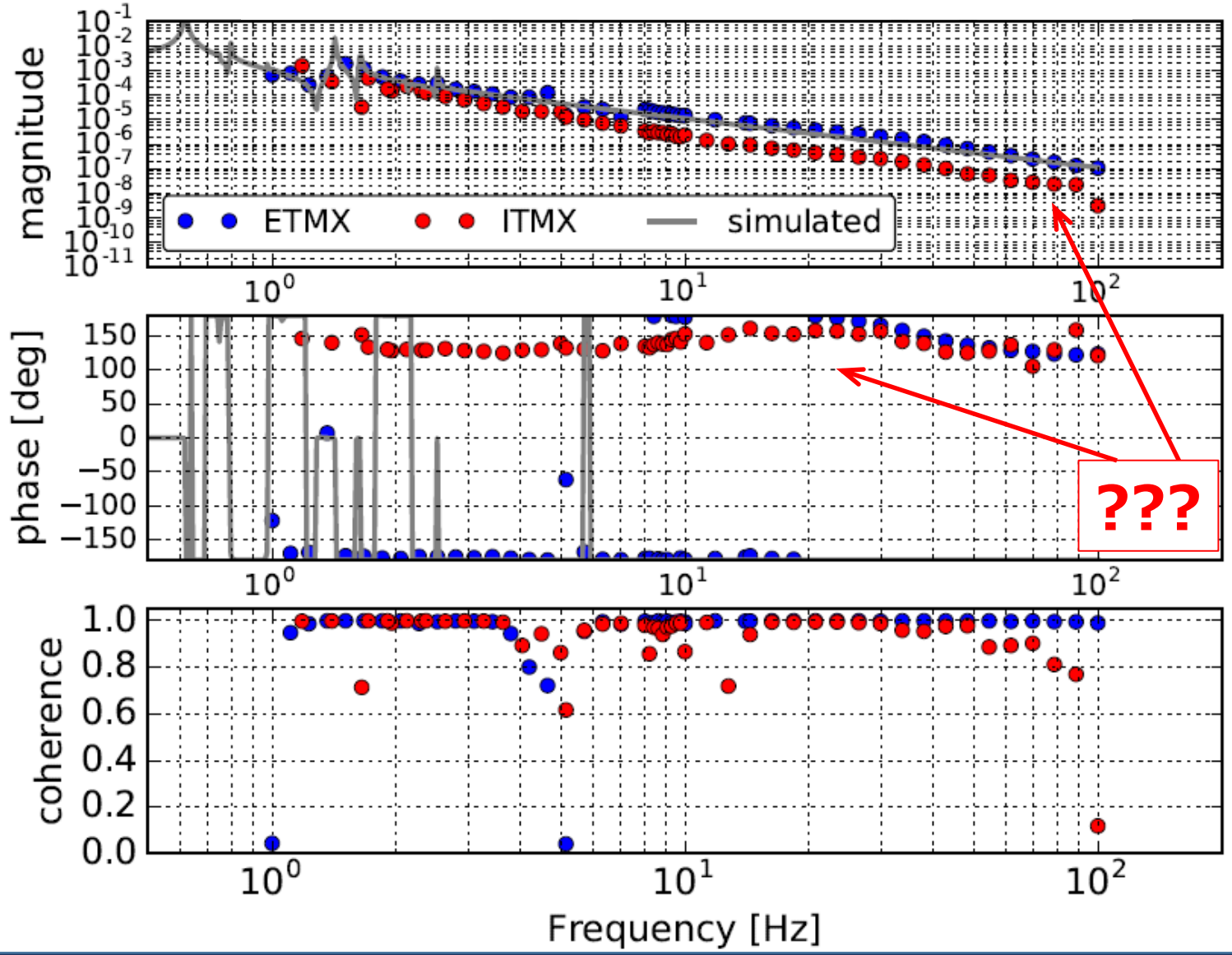


From BF-GAS to TM

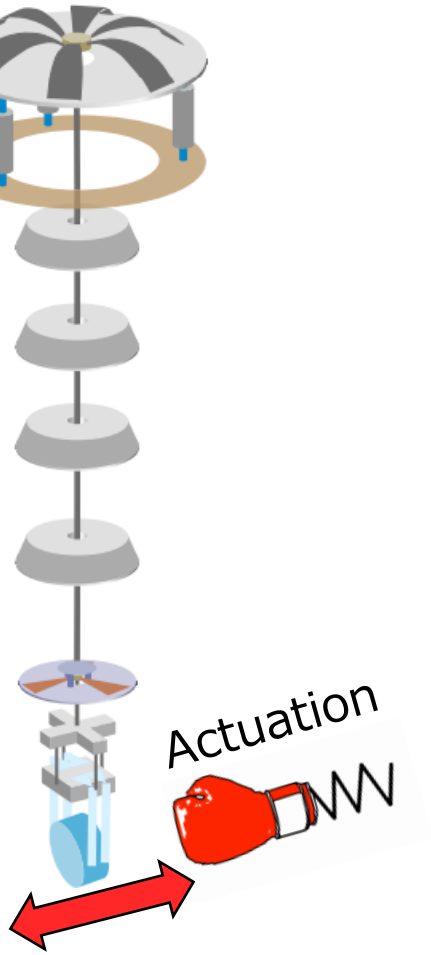


Real was not so simple..

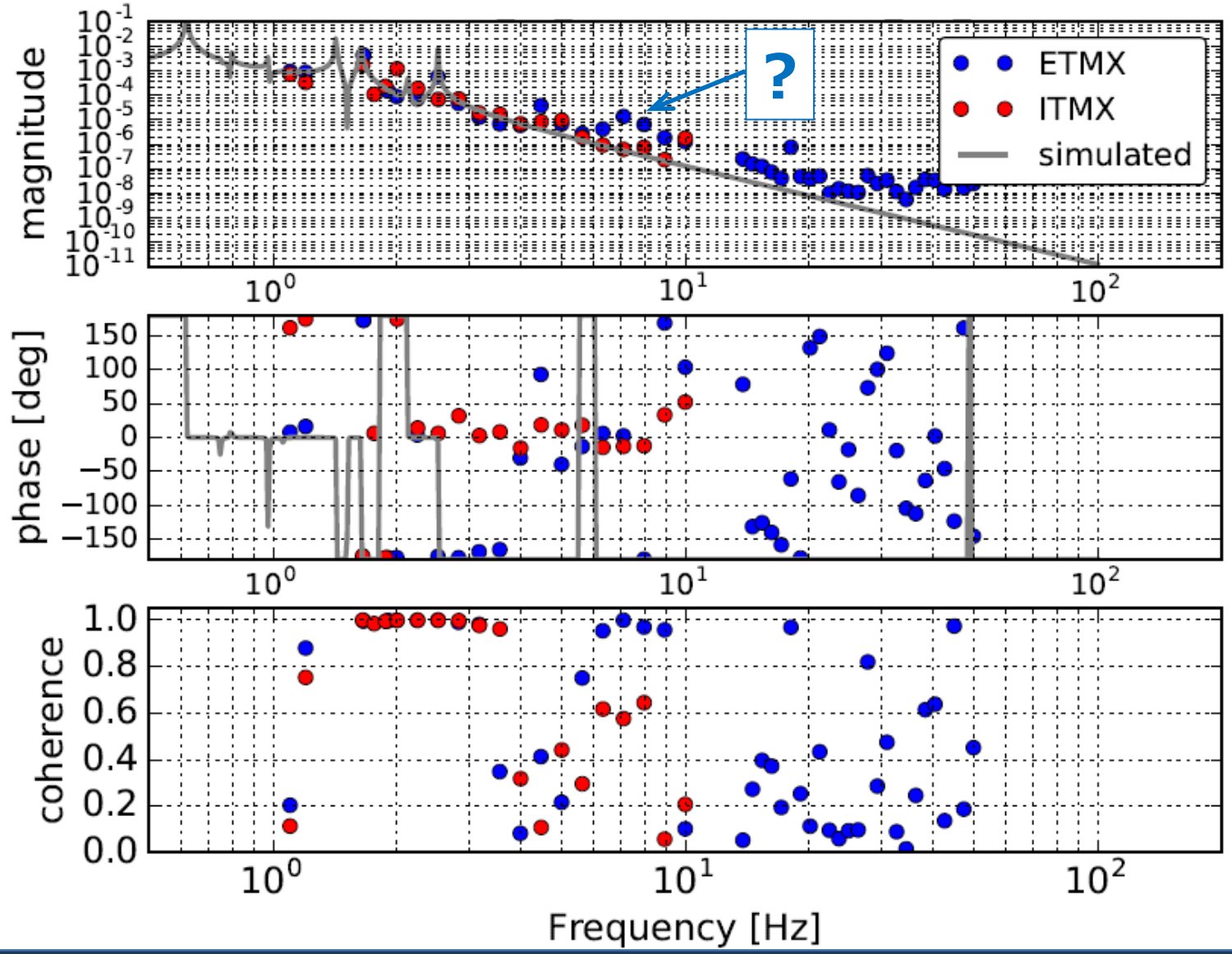
Force transfer functions



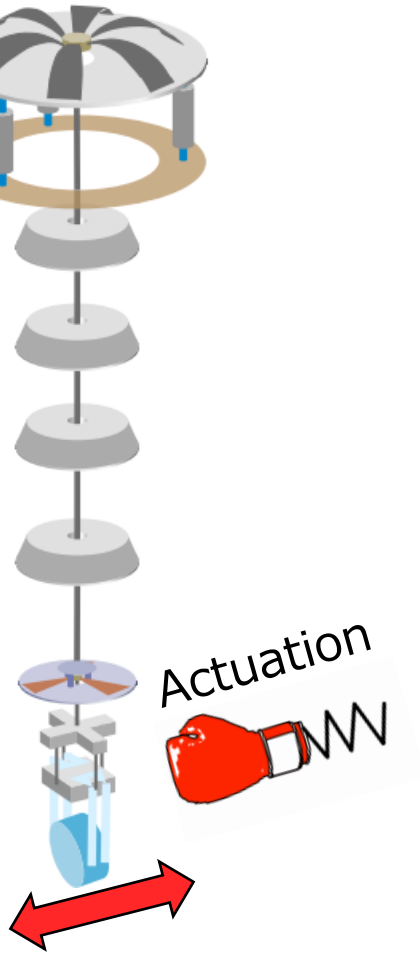
From (TM-RM)-act to TM



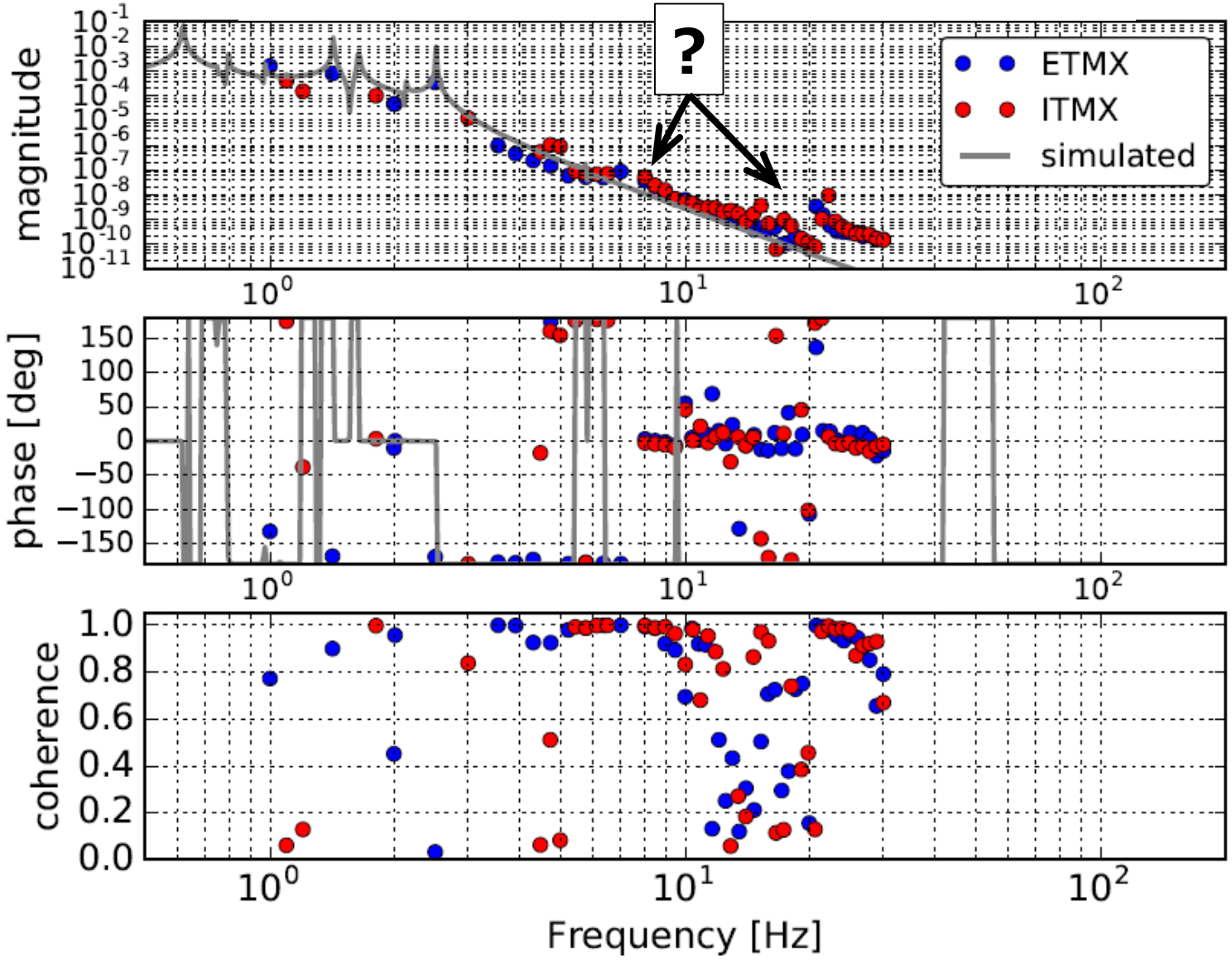
Force transfer functions



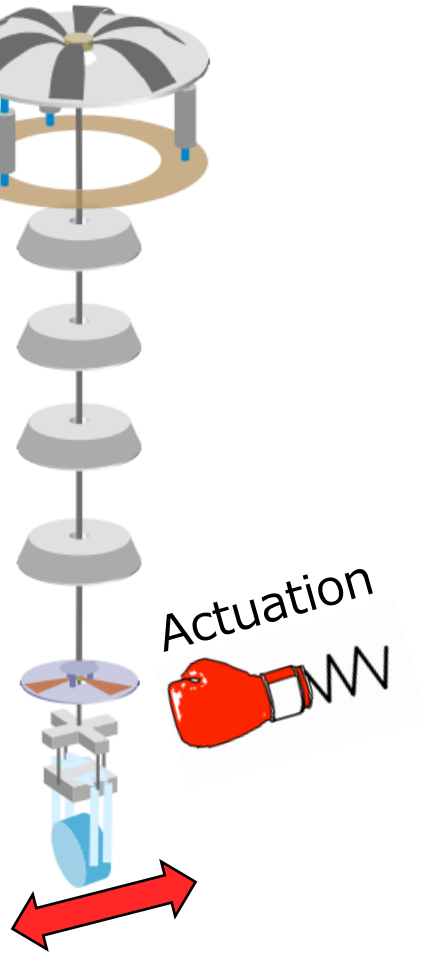
From (IM-IMR)-act to TM



Force transfer functions



From (MN-MNR)-act to TM



Note: Measurement of mechanical suspension performance with X-arm cavity

Excitation point:

Excited stage name	Degree of freedom
TM	L
	P
IM	L
	V
MN	L
BF	GAS
	(L)
IP	L

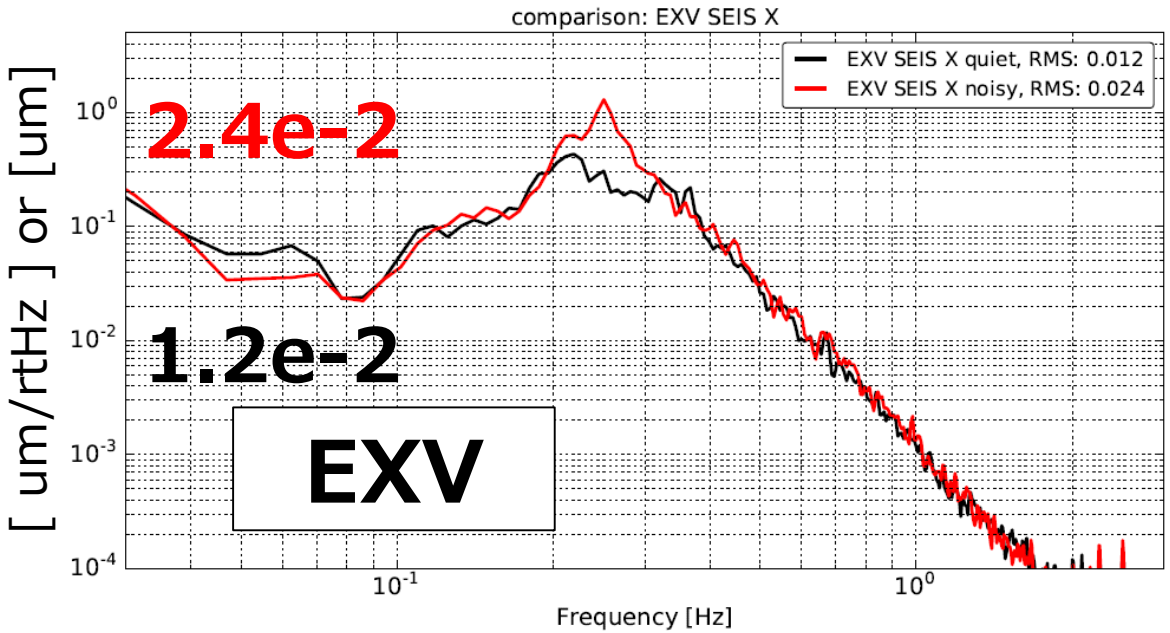
Sensing point:

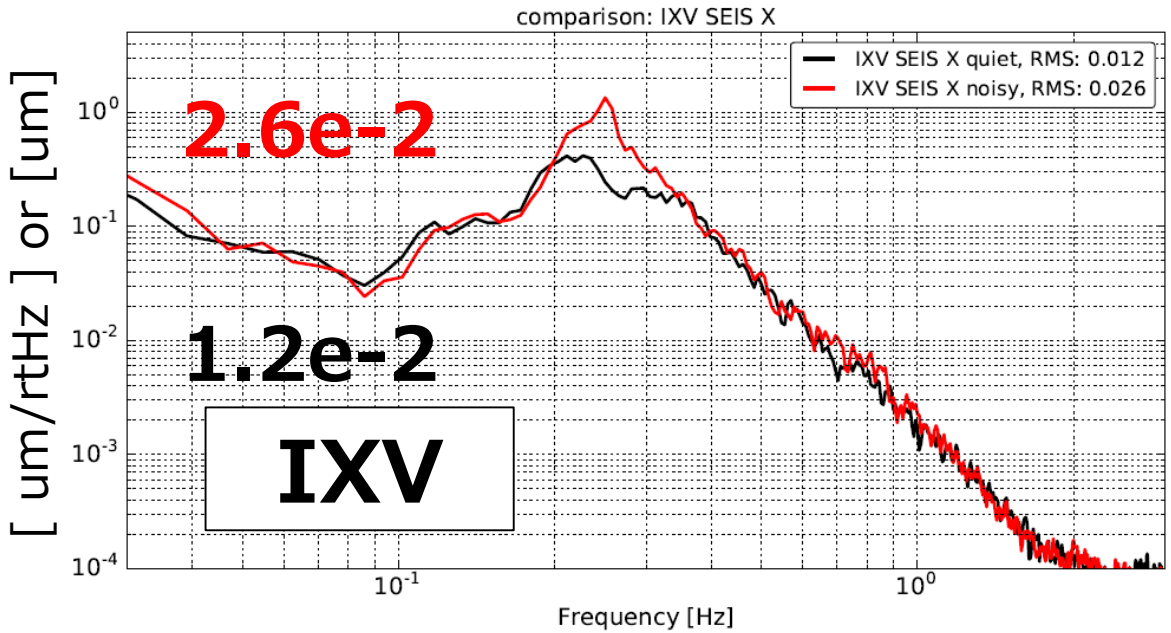
All the local sensors for ETMX and ITMX

(*1) Some resonances have to be identified, as shown in the above.
(*2) measurement files are stored under */users/VISsvn/* though, Not much organized well now.. please let me know if you want to have them ASAP.

With displacement sensors, [residuals] In bad weather

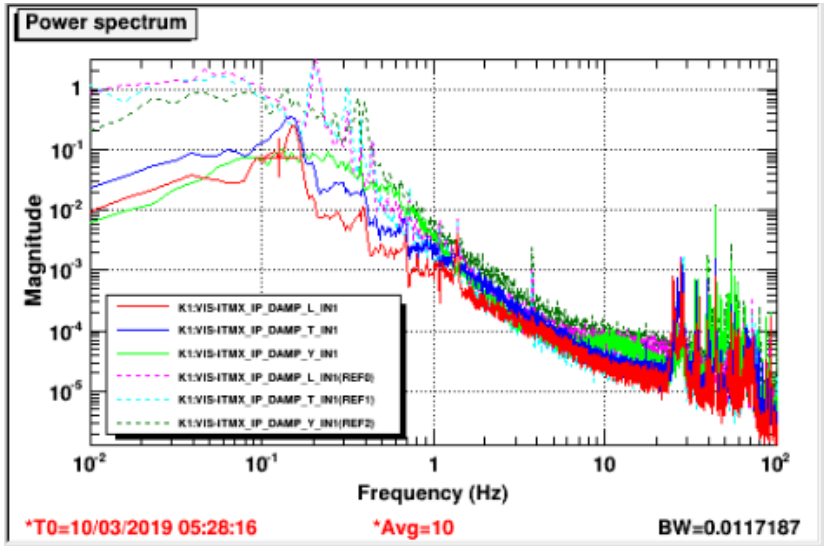
Seismic motion when the weather was normal/bad
(From page #16)

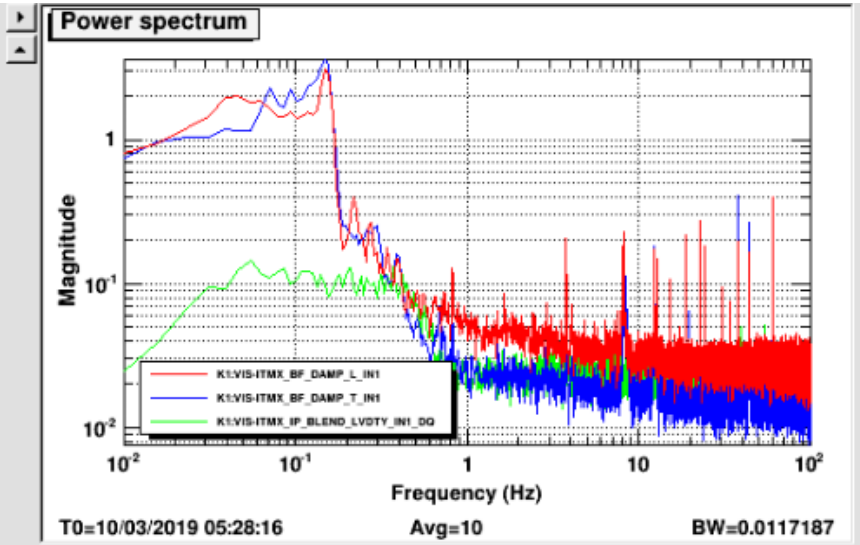


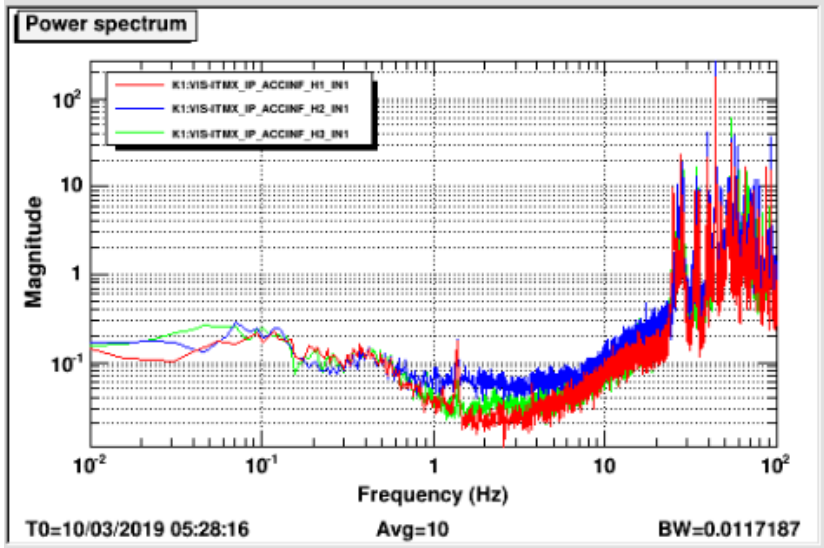


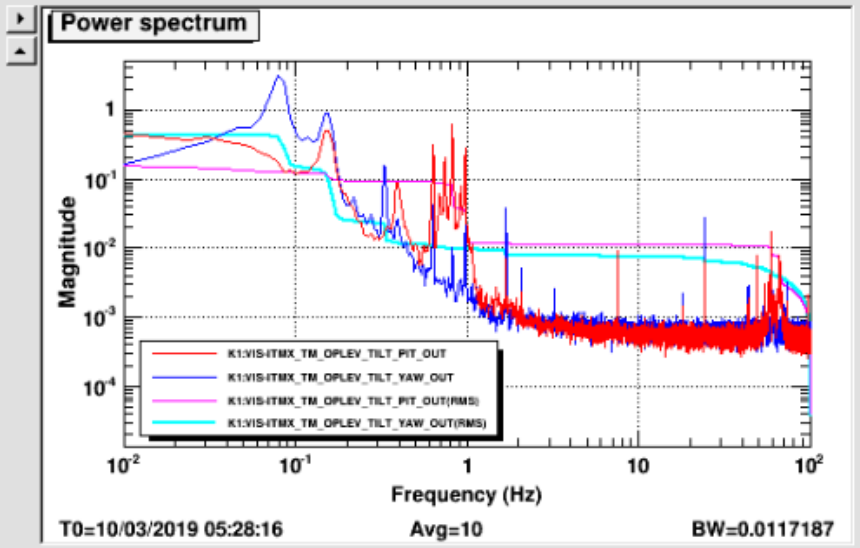
NOT locked..

Sensor blending & inertial damping



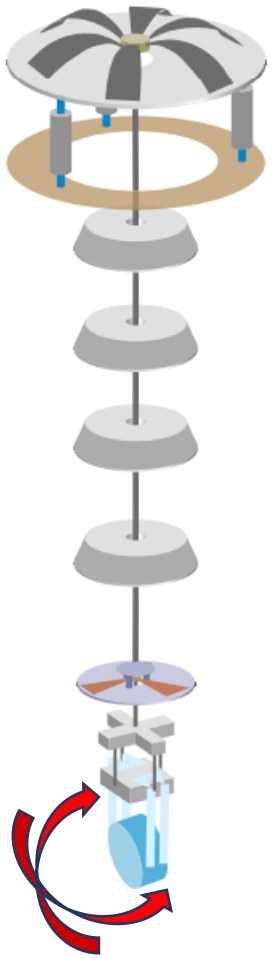


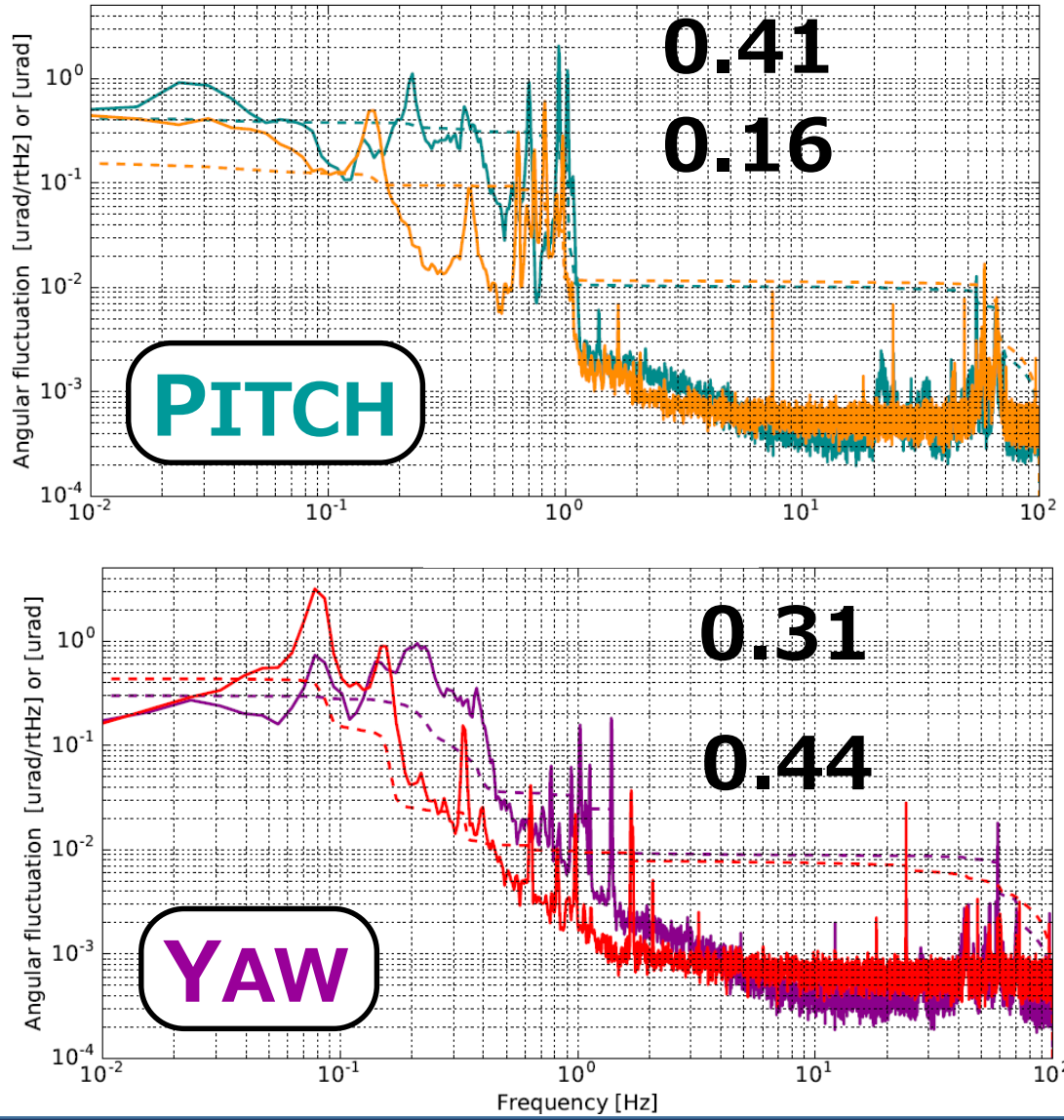




on March 10th, 2019

Sensor blending & inertial damping

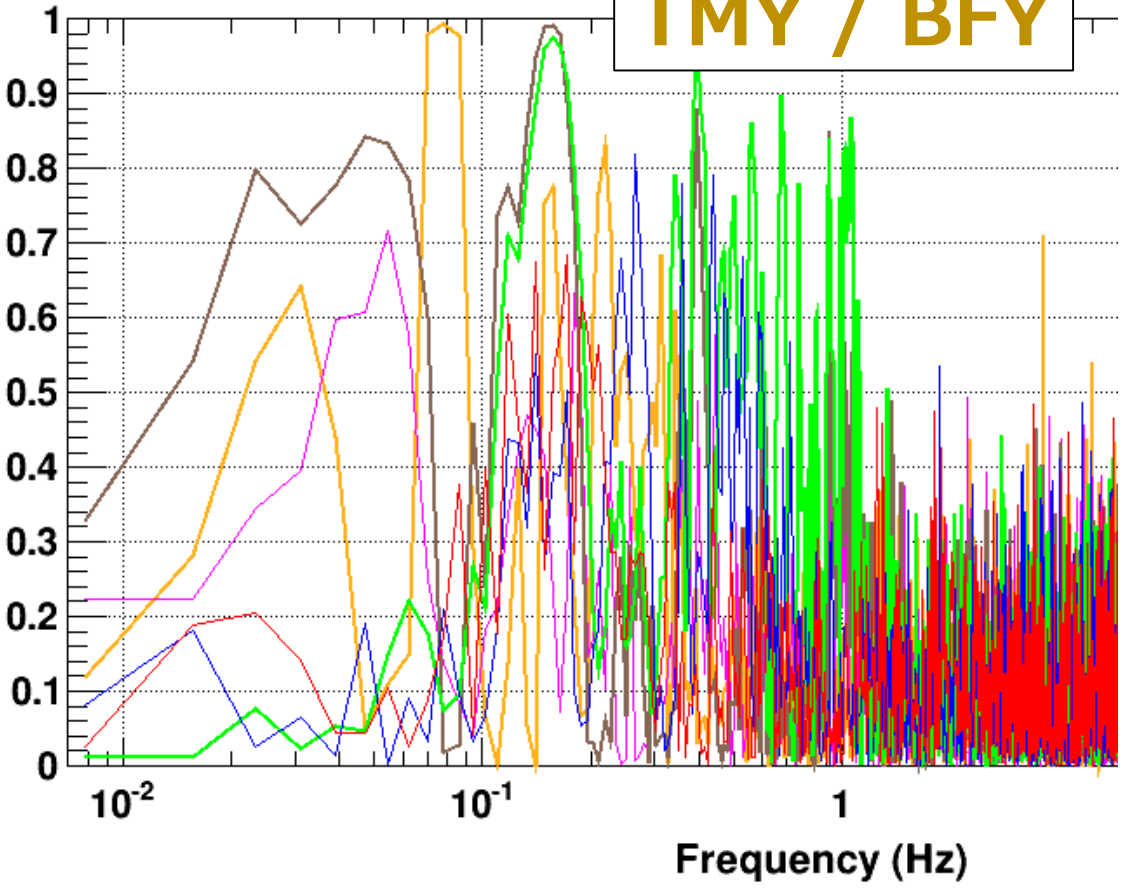




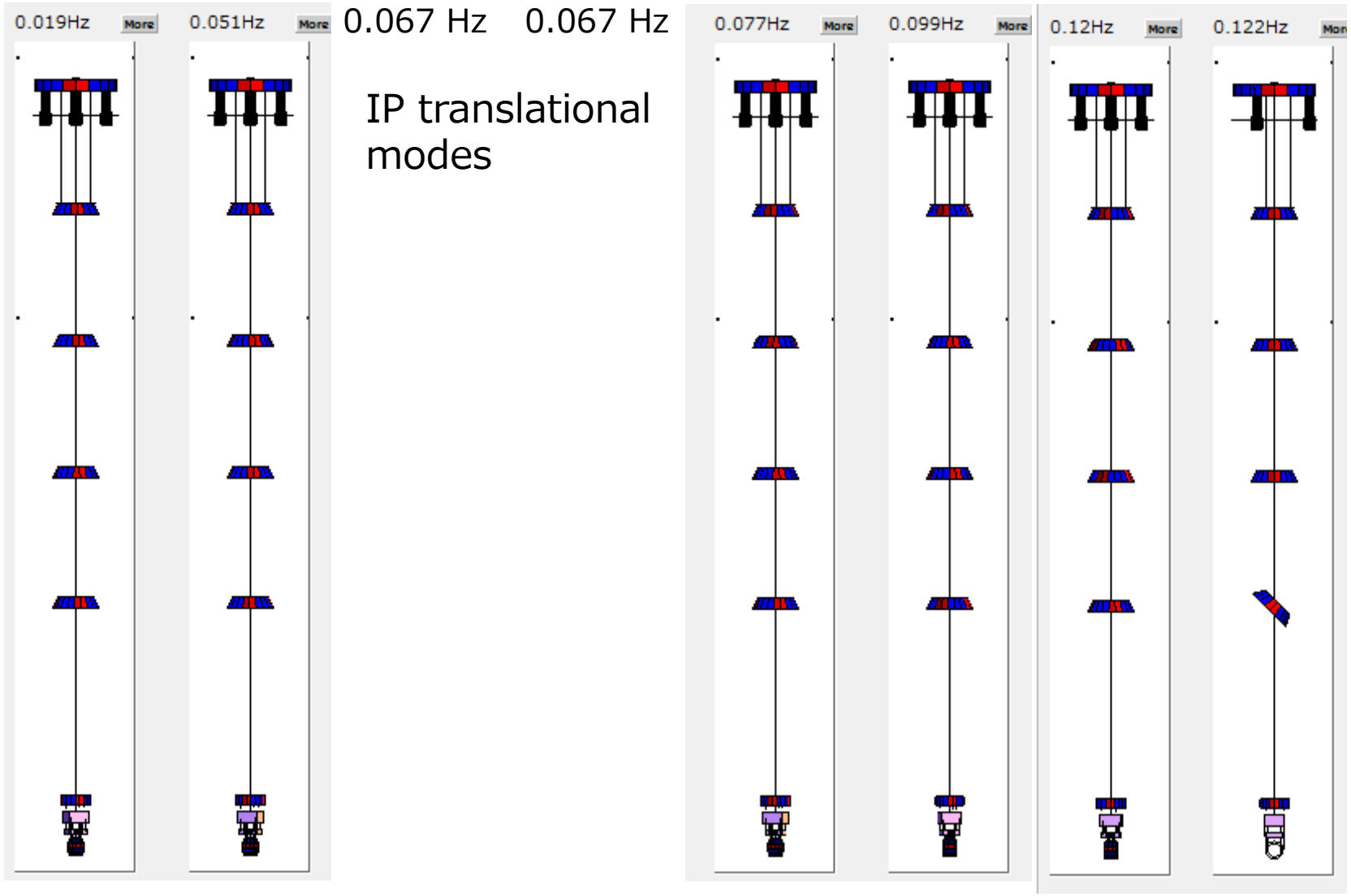
TMP / IPL

TMY / IPL

TMY / BFY



#1 #2 #3 #4 #5 #6 #7 #8



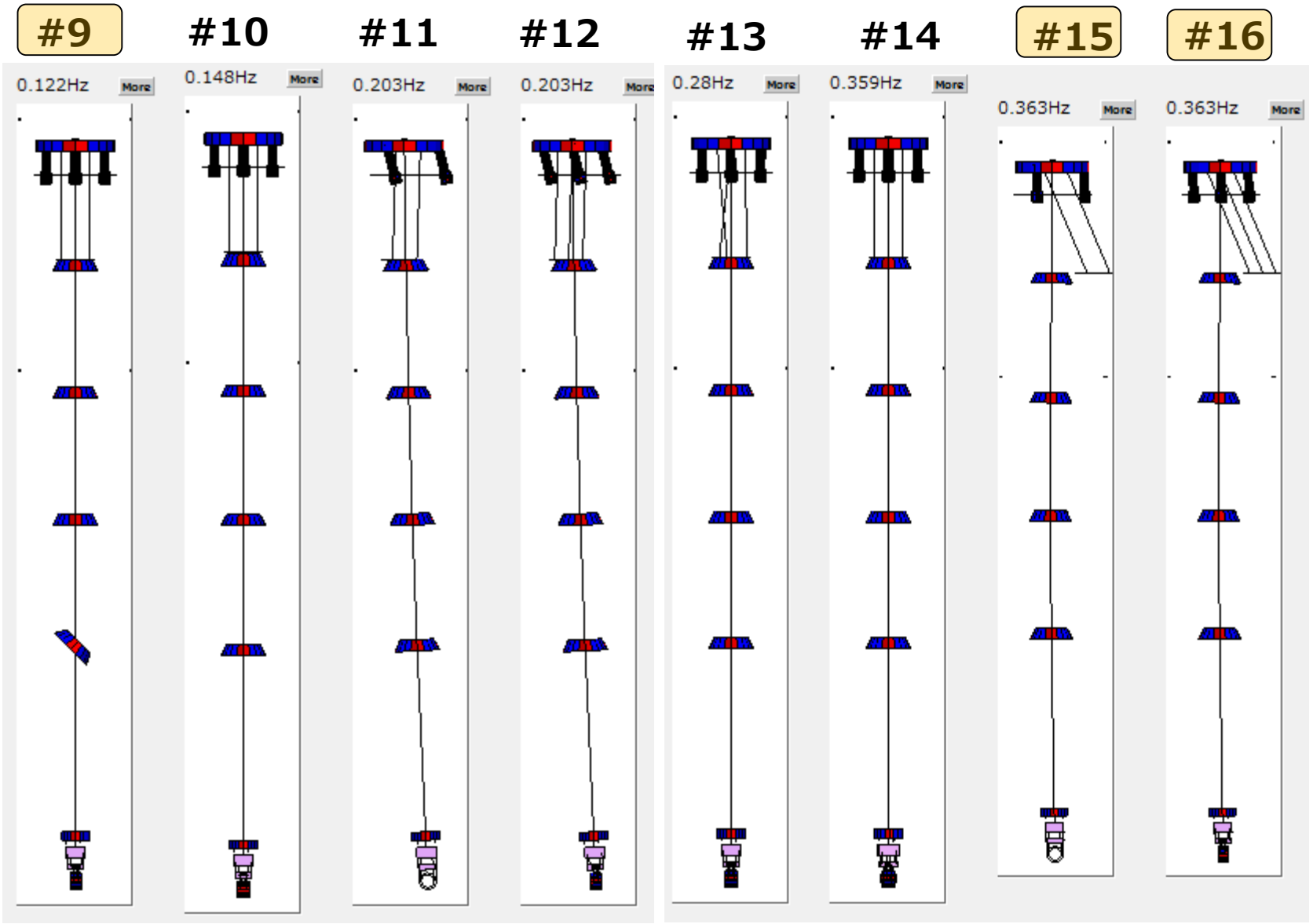
IP translational modes

Type-A SAS,

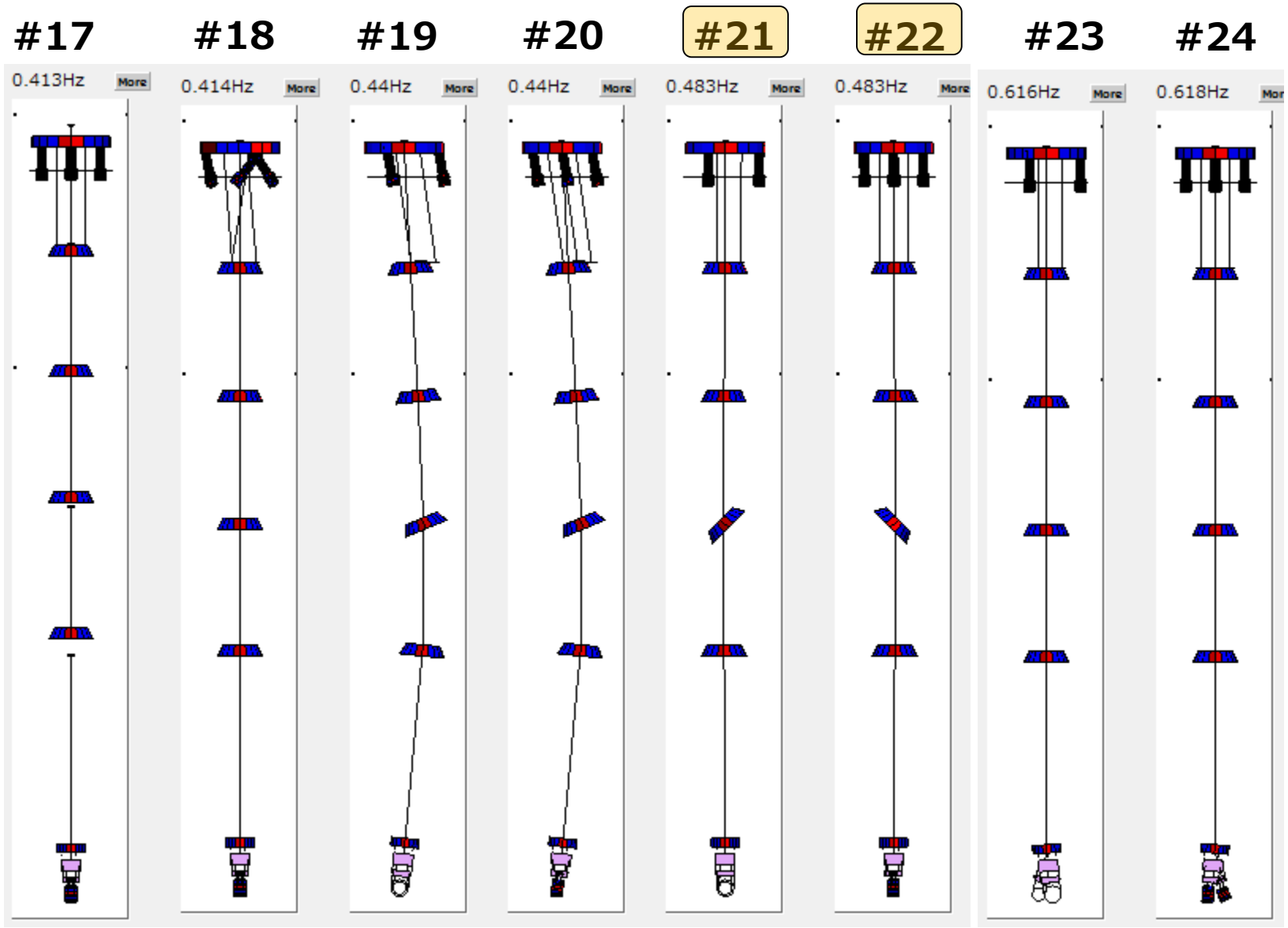
‘TyrpeA180429_20K’

Eigen mode: 75 modes

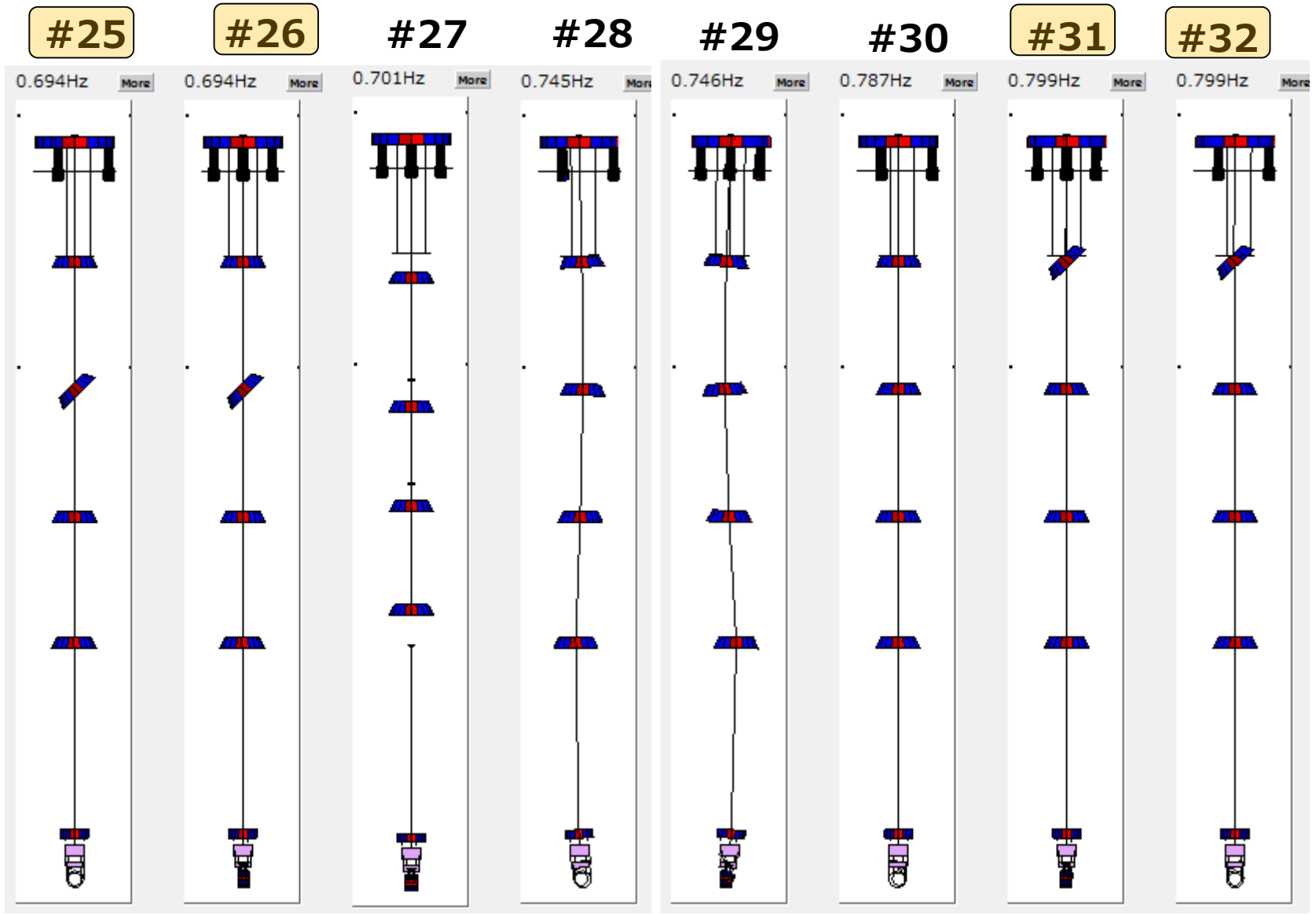
Less interest now



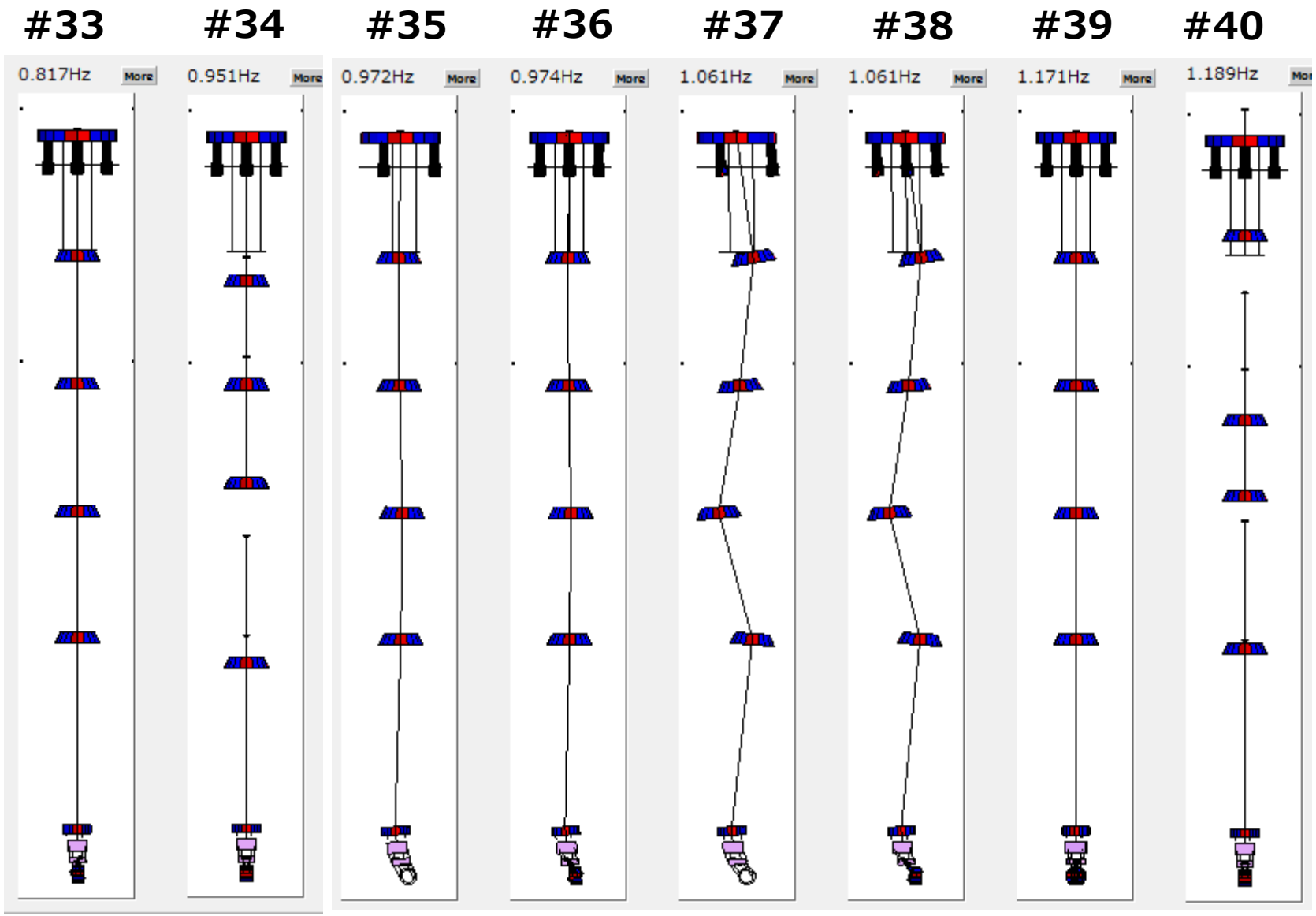
Less interest now



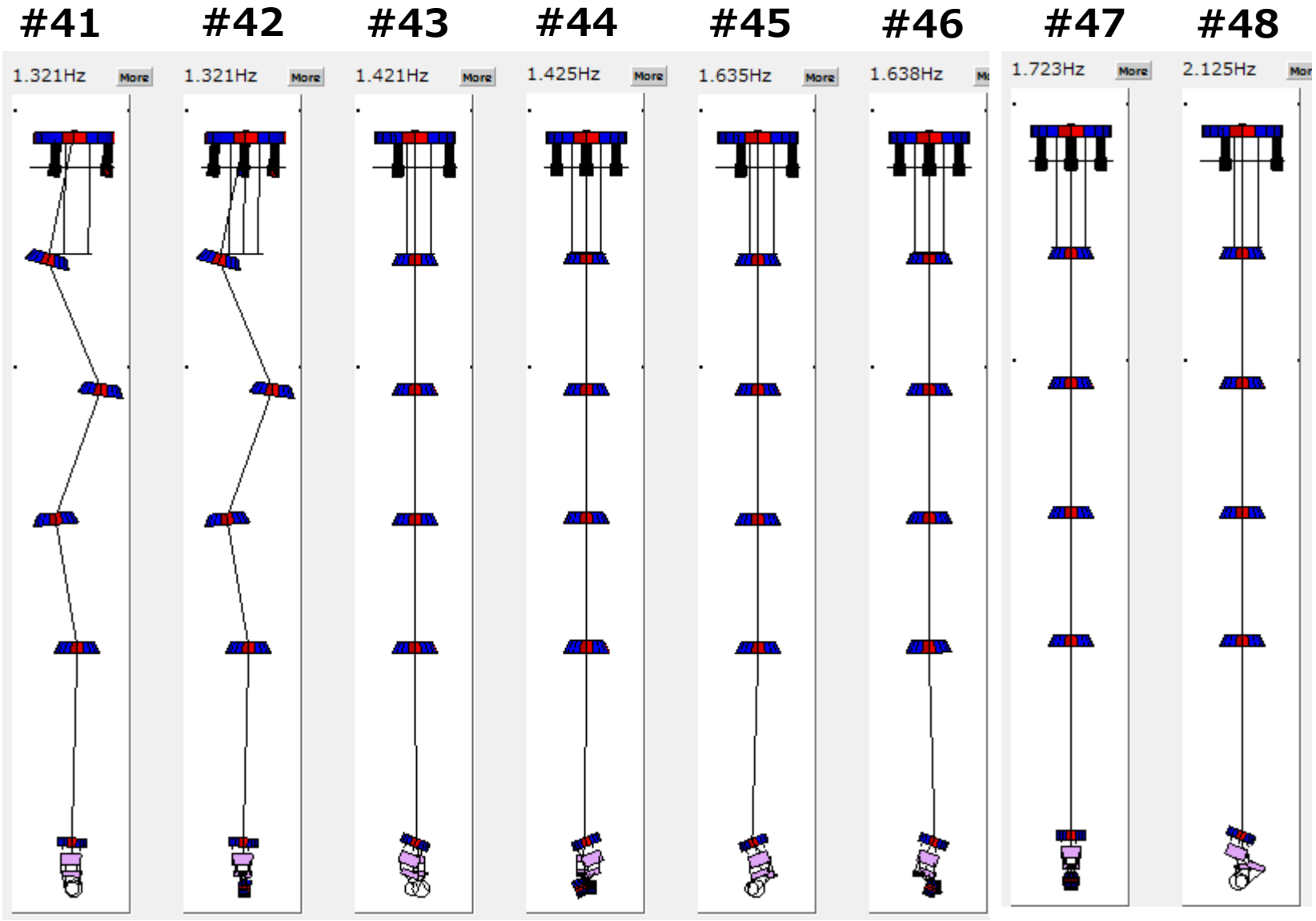
Less interest now



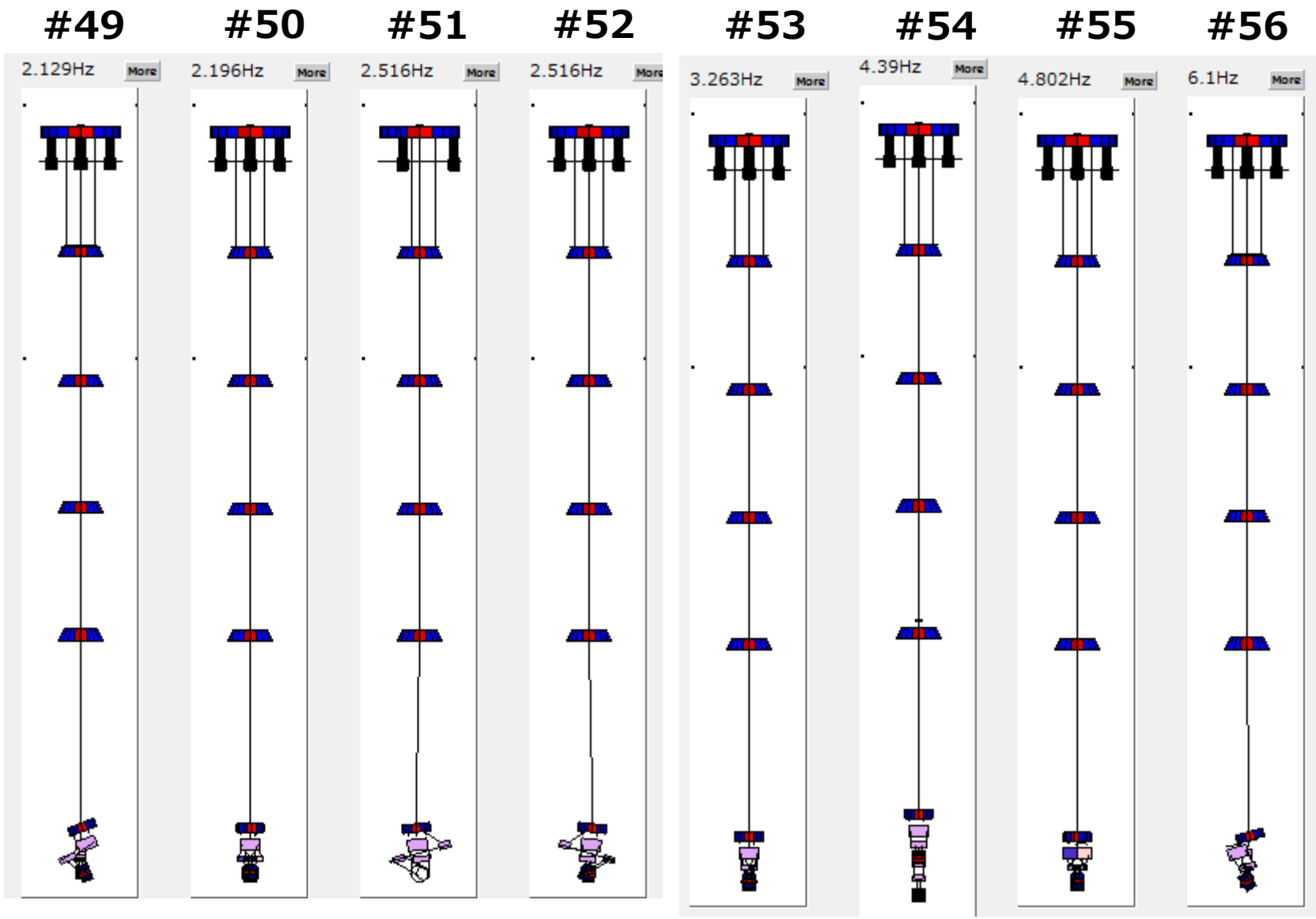
Less interest now



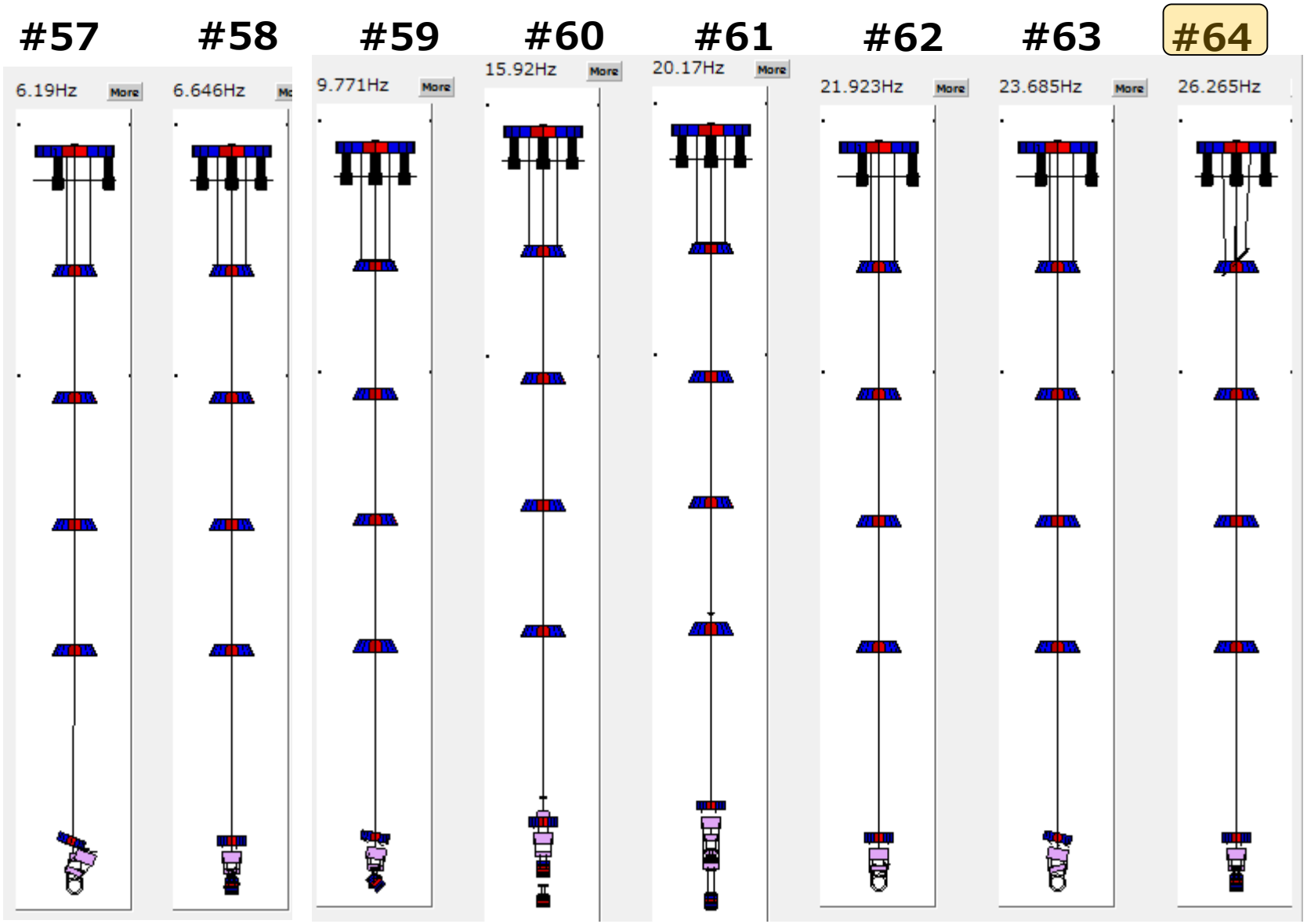
Less interest now



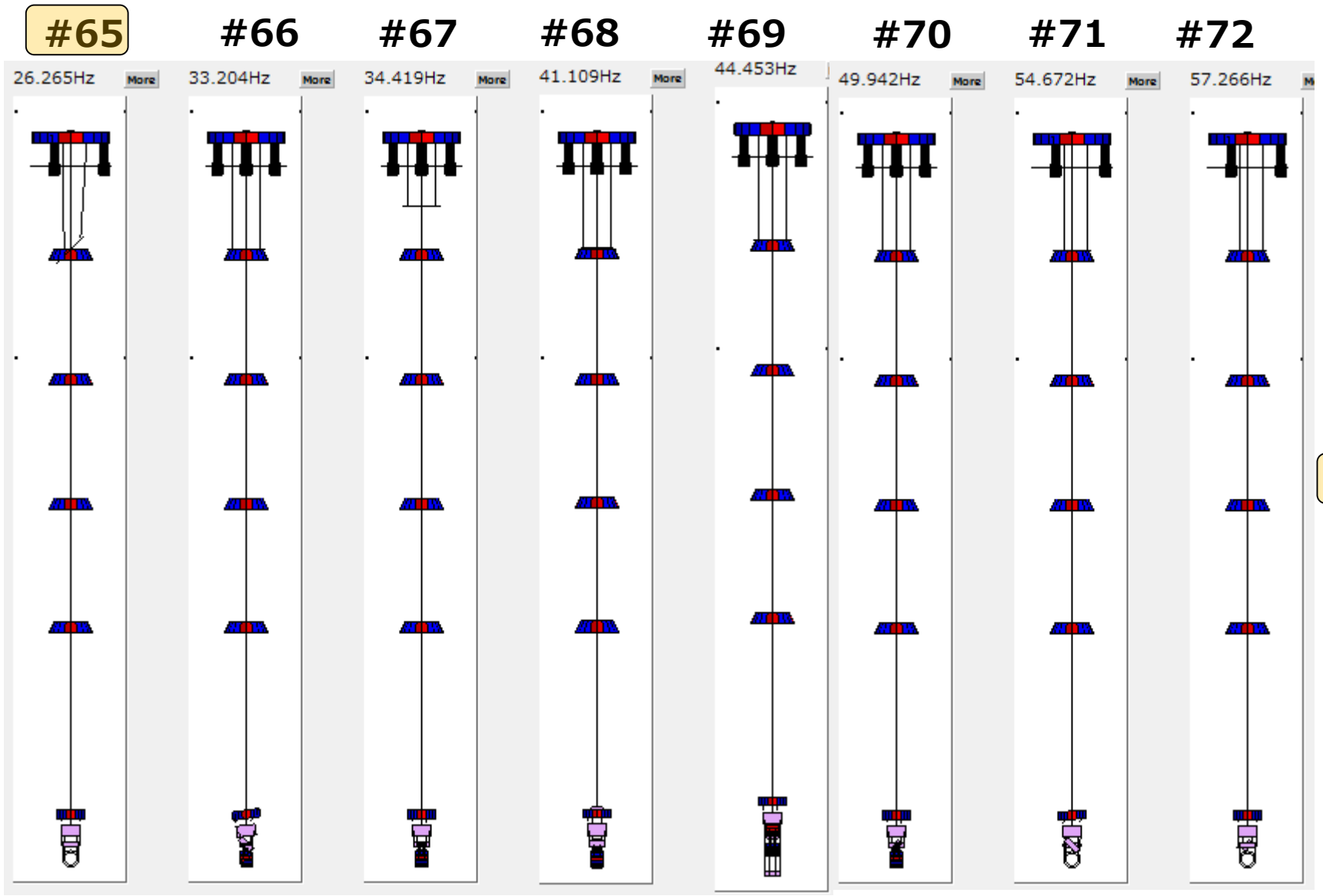
Less interest now



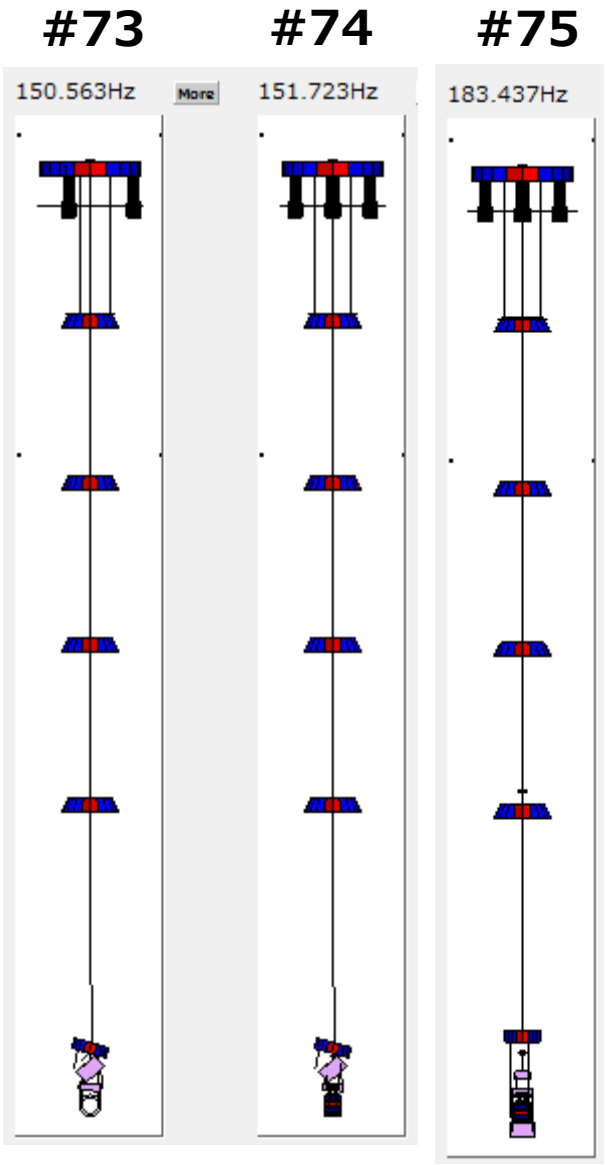
Less interest now



Less interest now



Less interest now



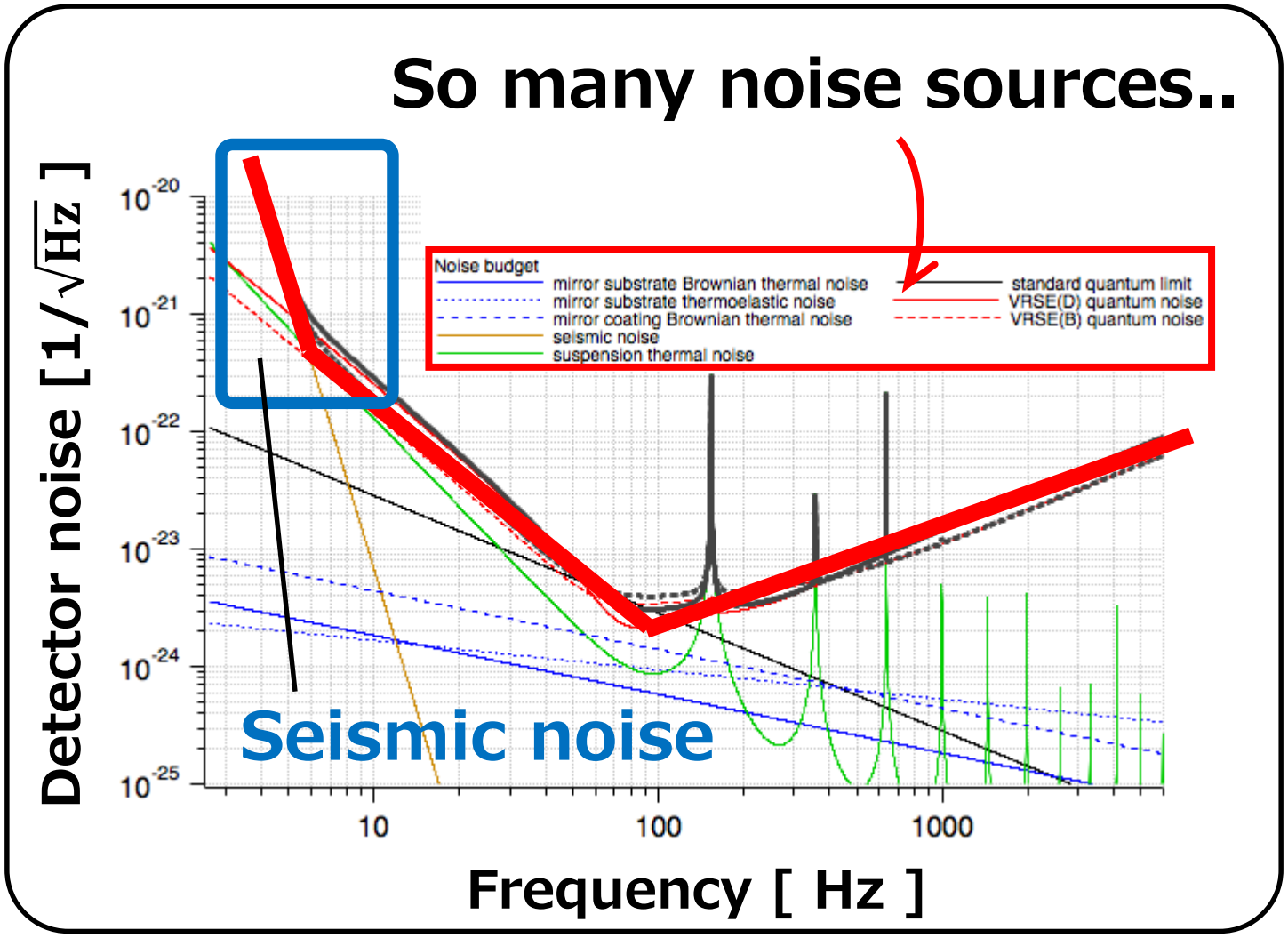
Less interest now

Detector noise

- Quantum noise
- Thermal noise
  …
- **Seismic noise**

mirror oscillation

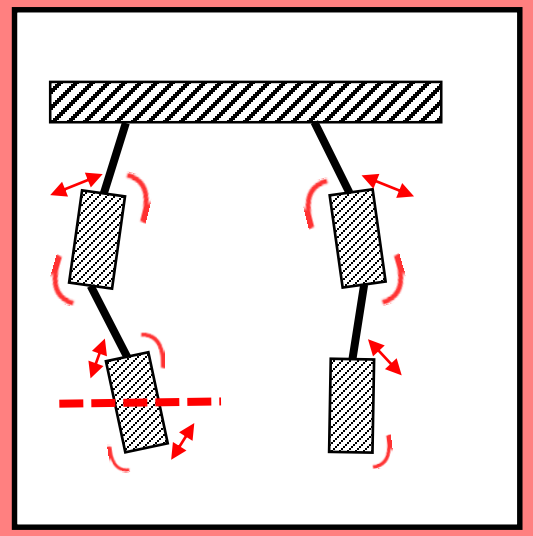
→ Necessary to suppress



In case of KAGRA

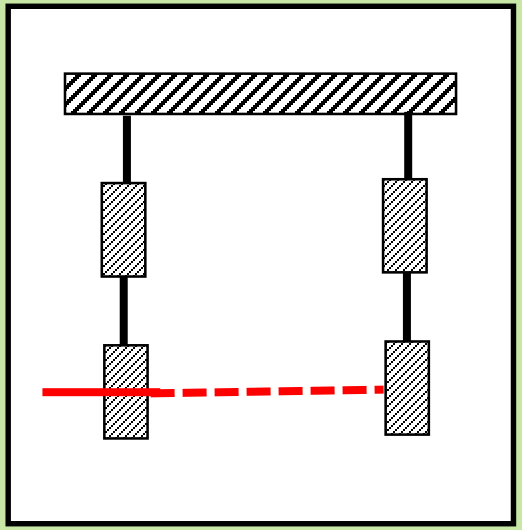
Designing active control system / Control phase

1. Calm-down phase



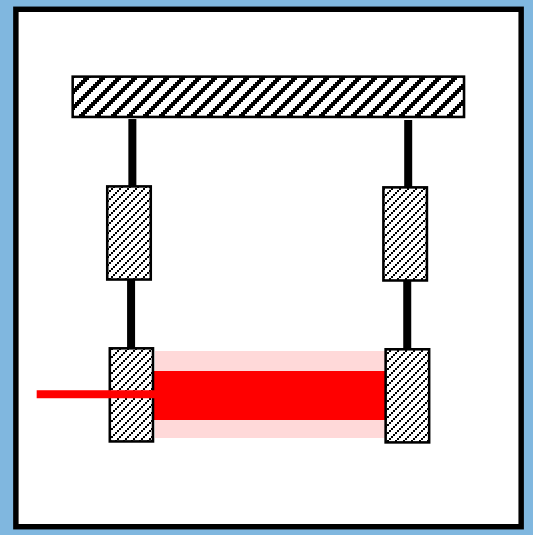
Suppress
large disturbance

2. Lock-acquisition phase



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

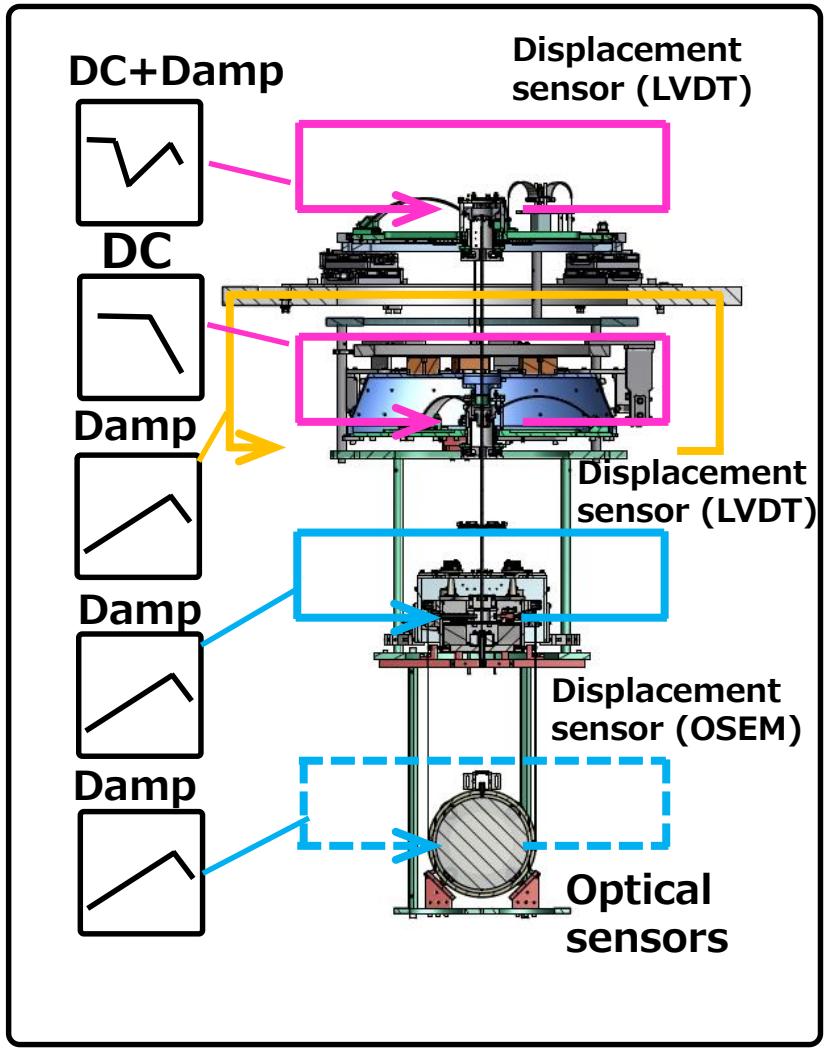
3. Observation phase



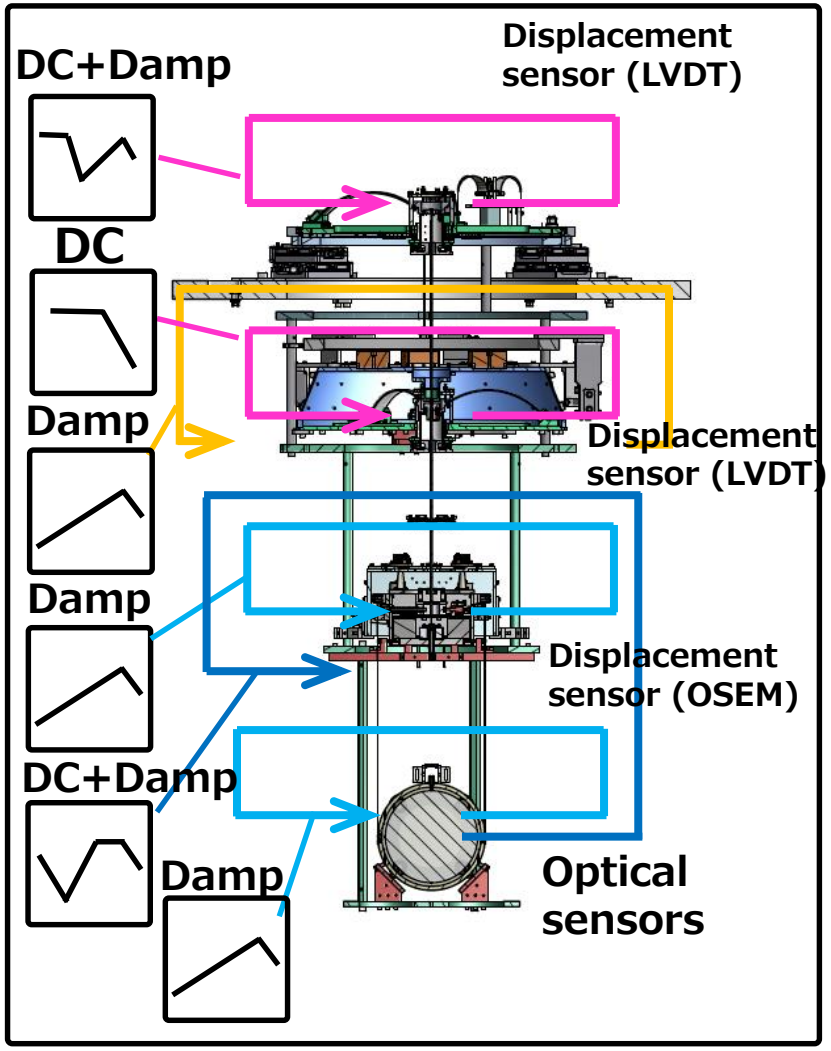
Keep position
with low noise
control

Designing active control system / ex. Type-Bp SAS

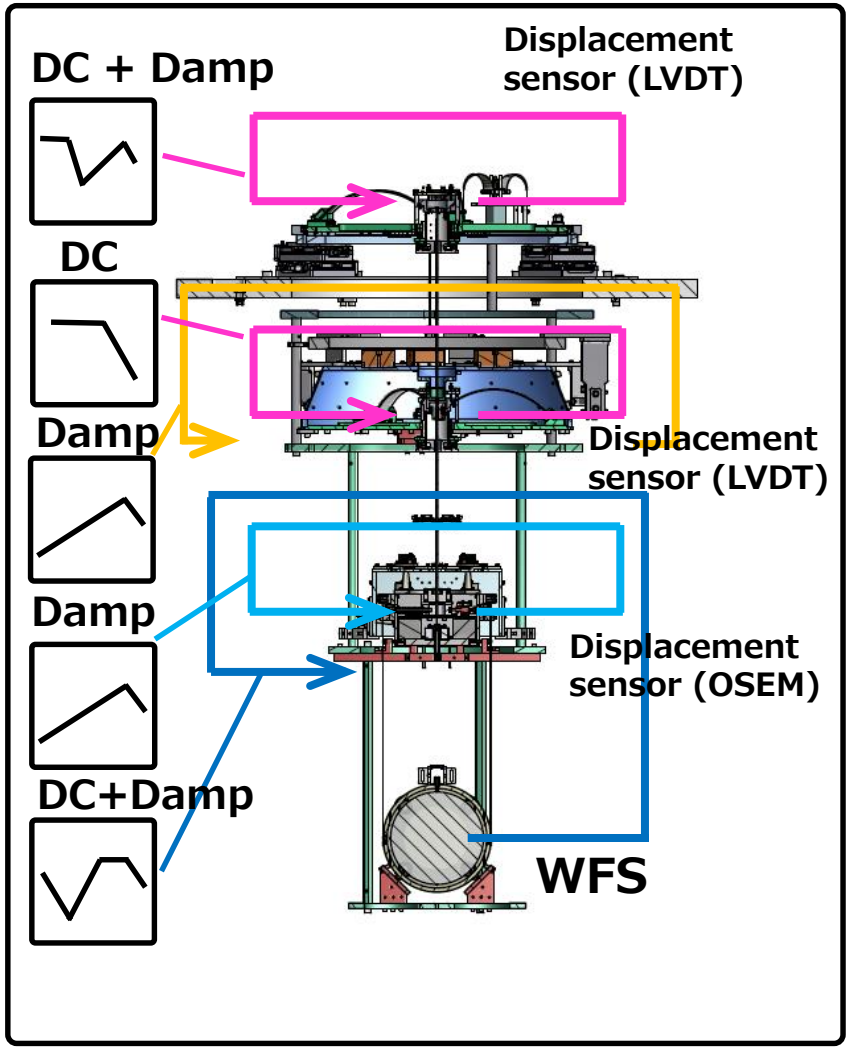
1. Calm-down phase



2. Lock-acquisition phase

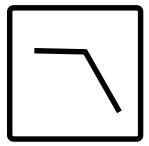


3. Observation phase

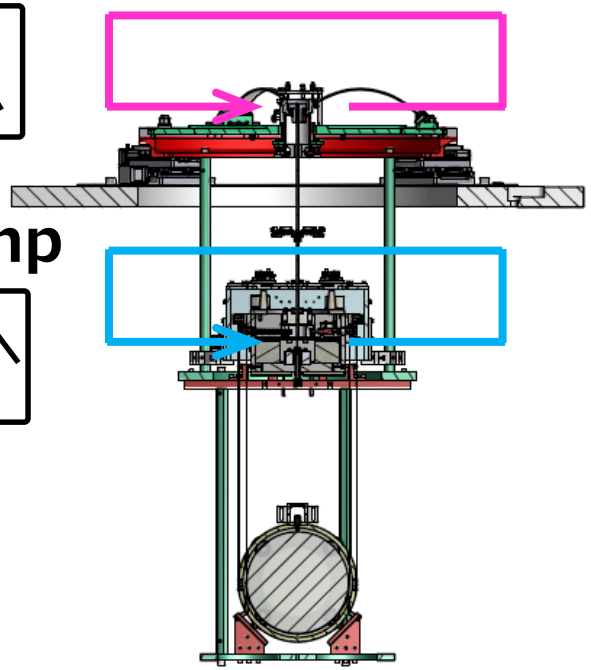


2. Decay time measurement

DC

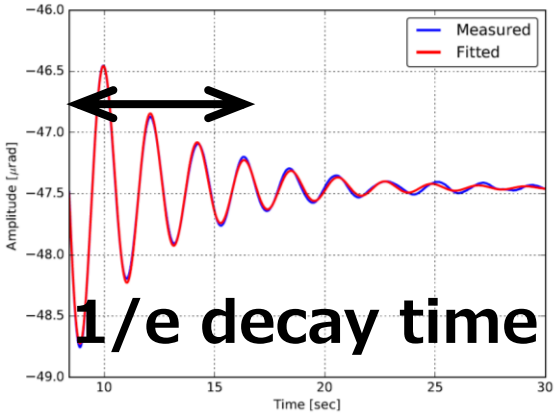


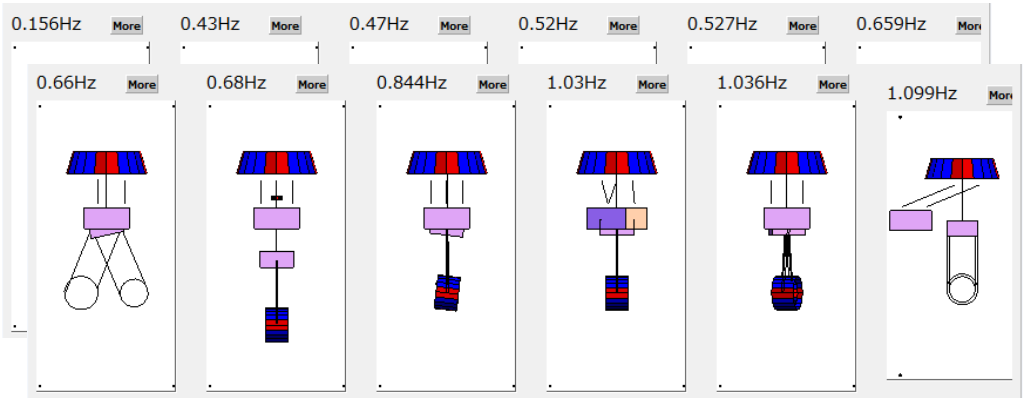
Damp



(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.