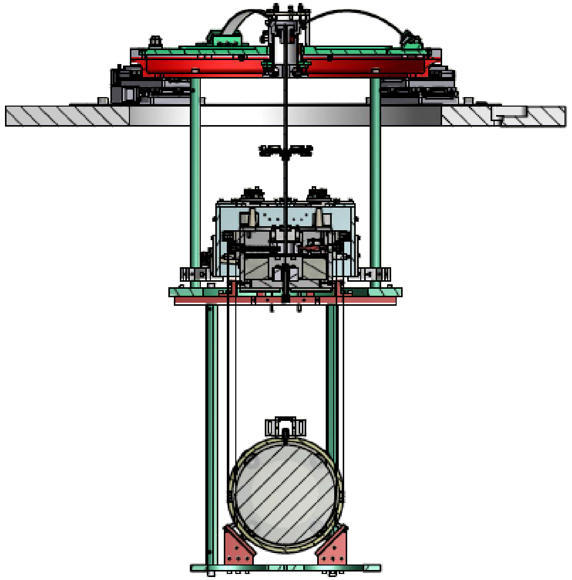
Development of
Power Recycling Seismic Attenuation System for KAGRA

Yoshinori Fujii



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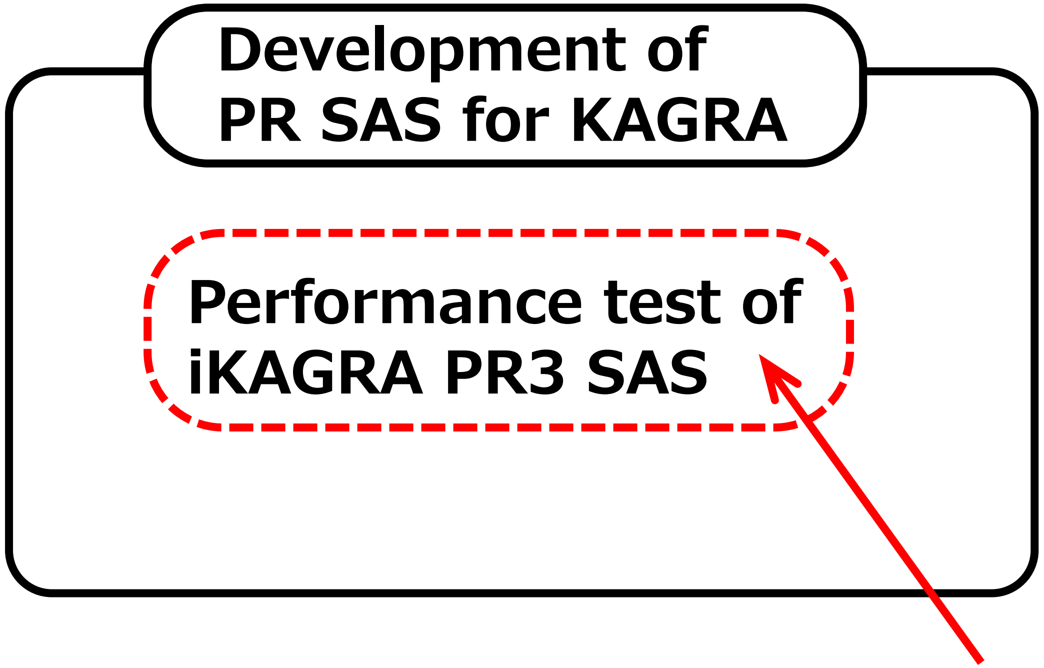
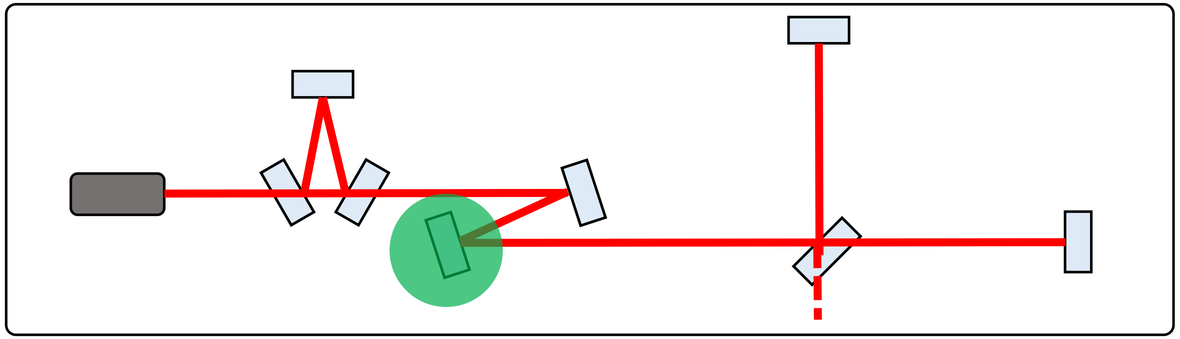
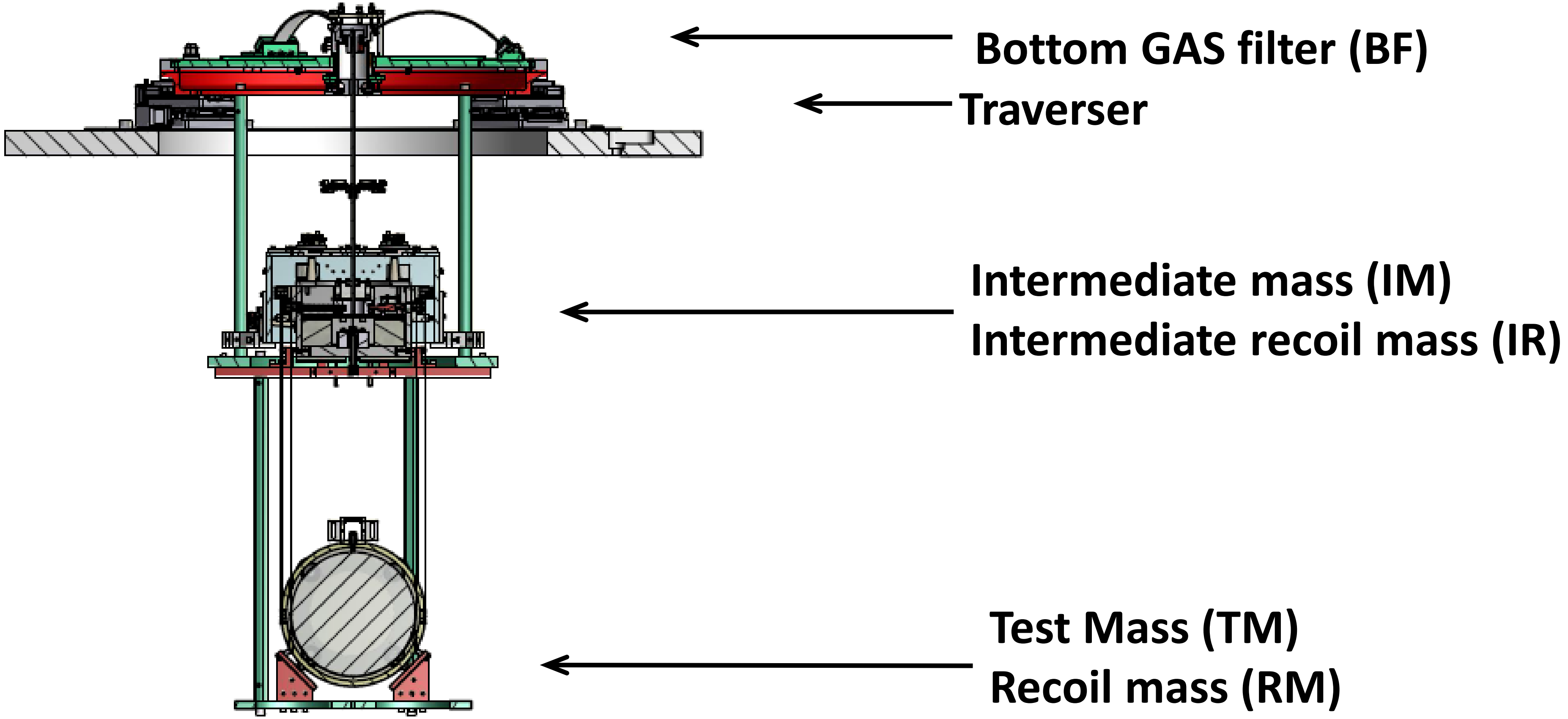


1. Introduction

iKAGRA PR3 SAS (= Type-Bpp SAS)

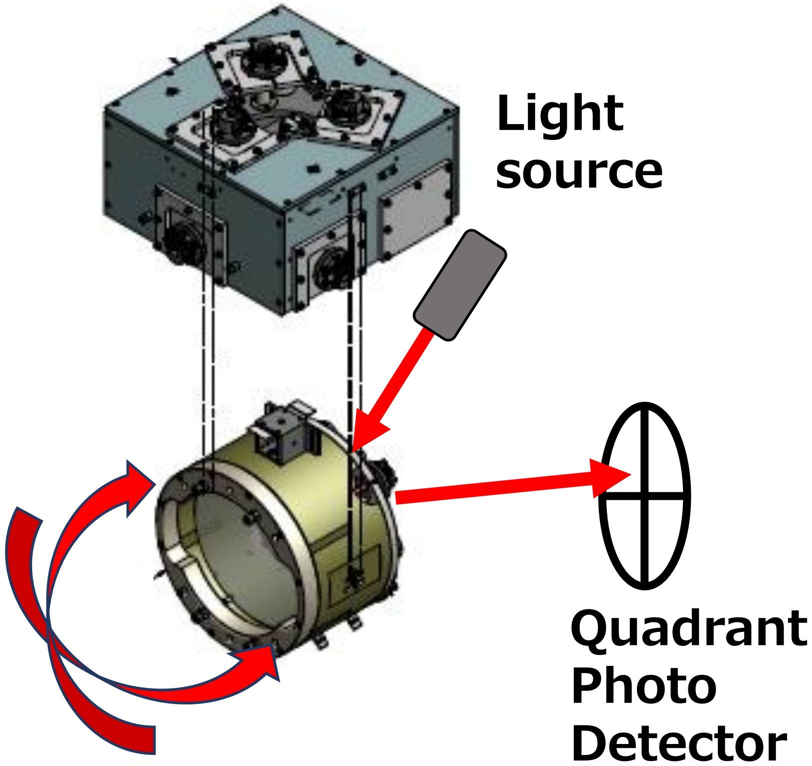




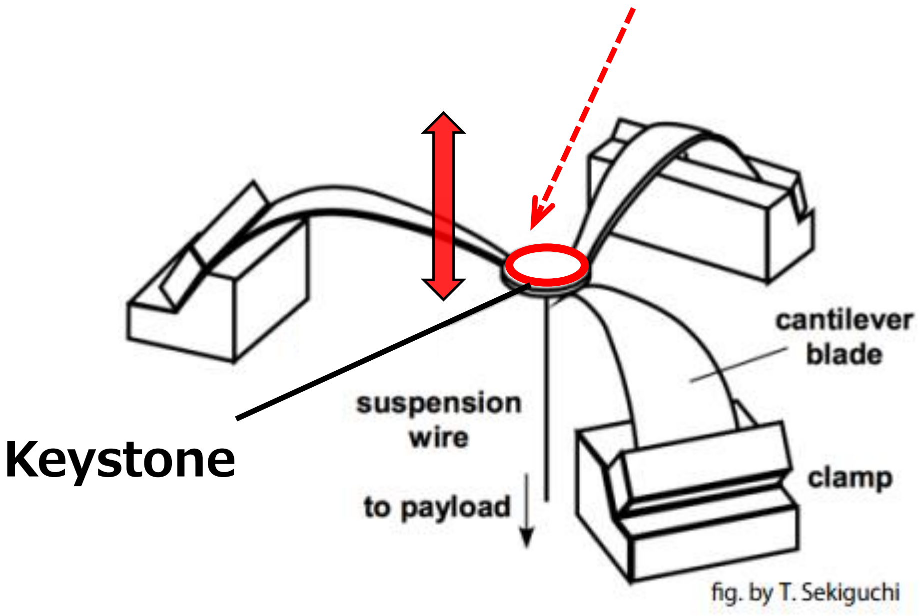
Sensors & actuators for active control (in iKAGRA)

Optical Lever

→ senses angular motion of the optic



Linear Variable Differential Transducer

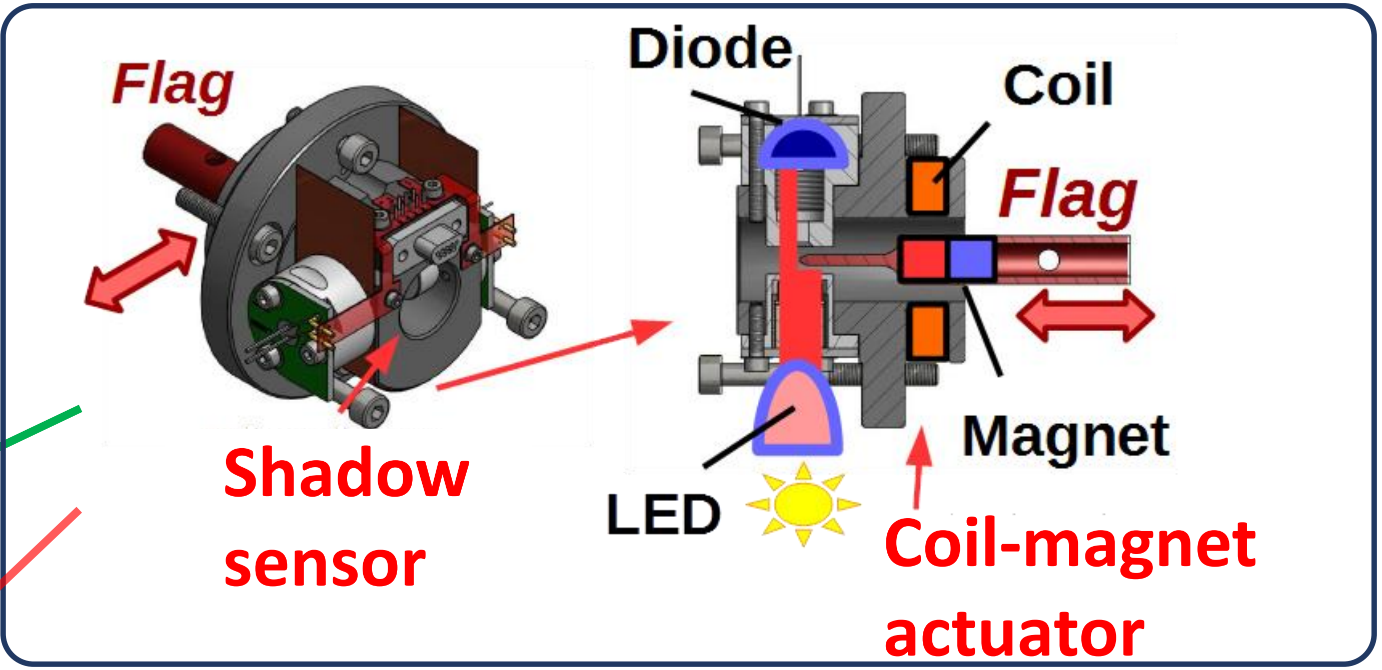


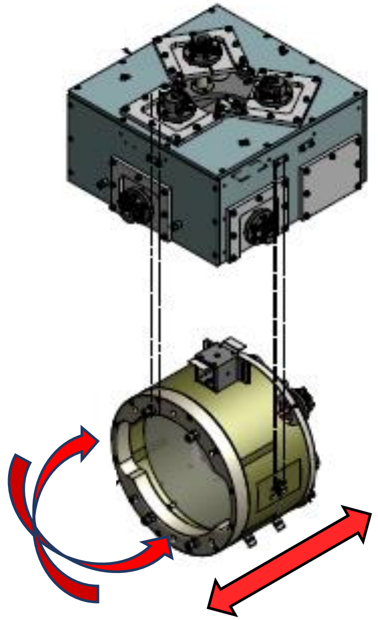
→ senses & actuates position of keystone

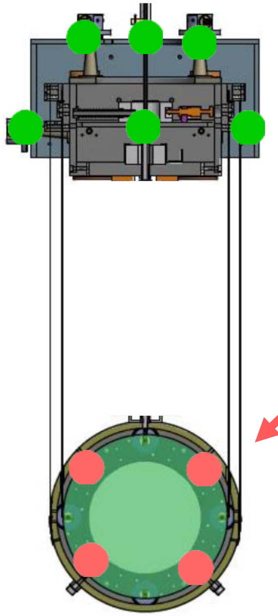
Sensors & actuators for active control (in iKAGRA)

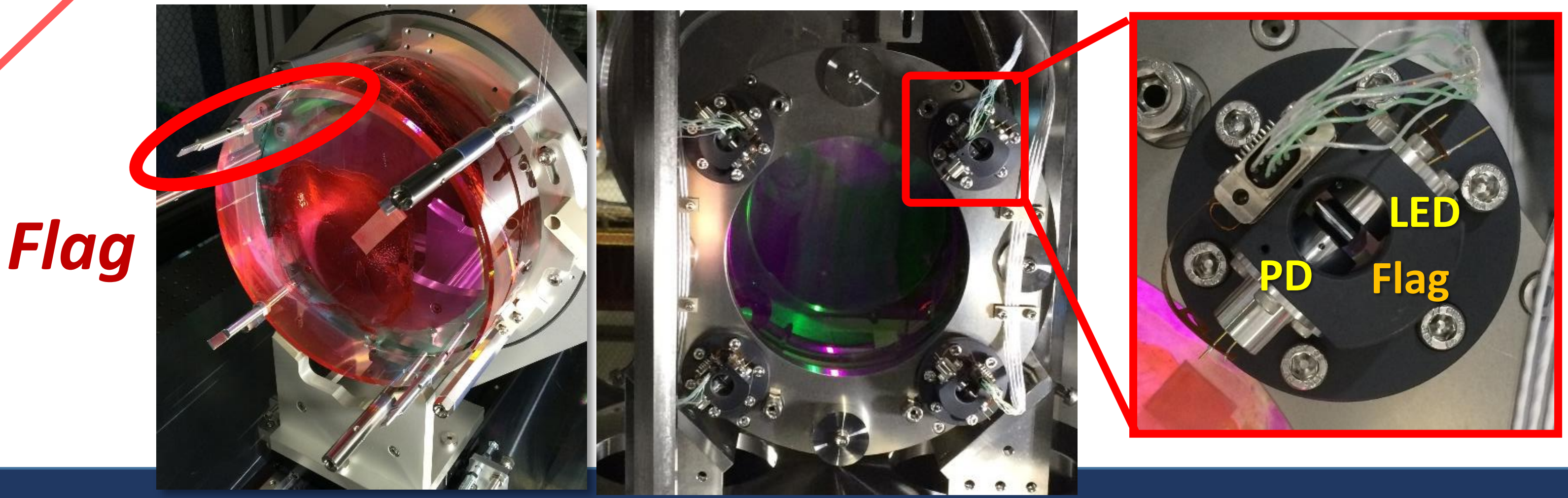
Optical Sensor and
Electro-Magnetic actuator (OSEM)

→ senses & actuates relative position of mass and recoil mass





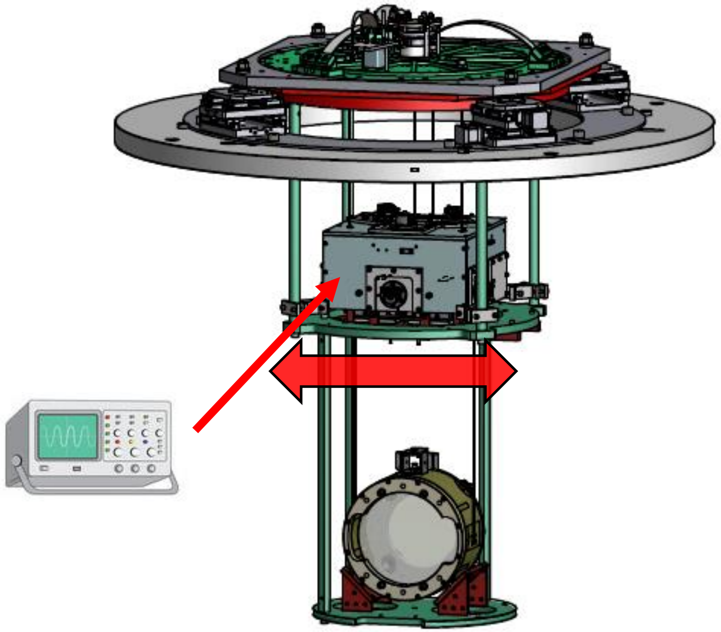


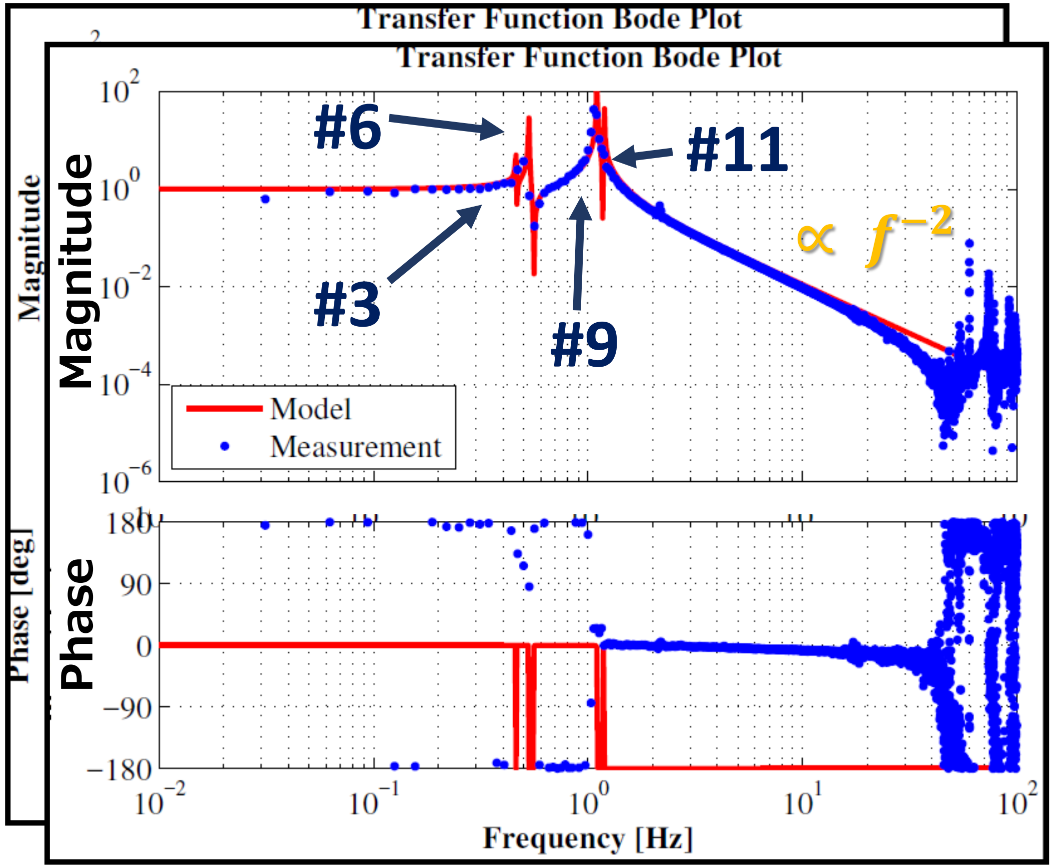


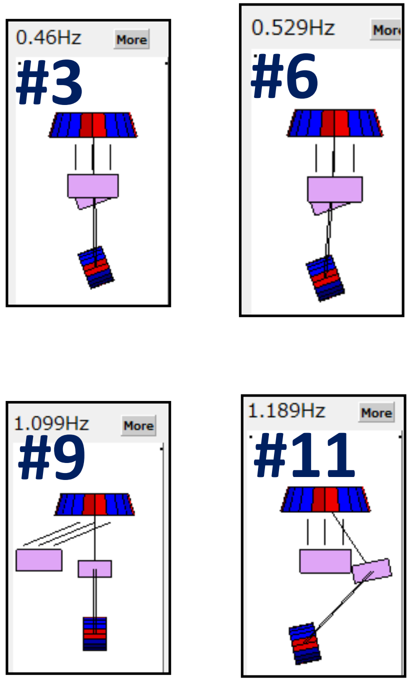
Assembly

October 2015 - February 2016 (test hanging & installation at Kamioka)

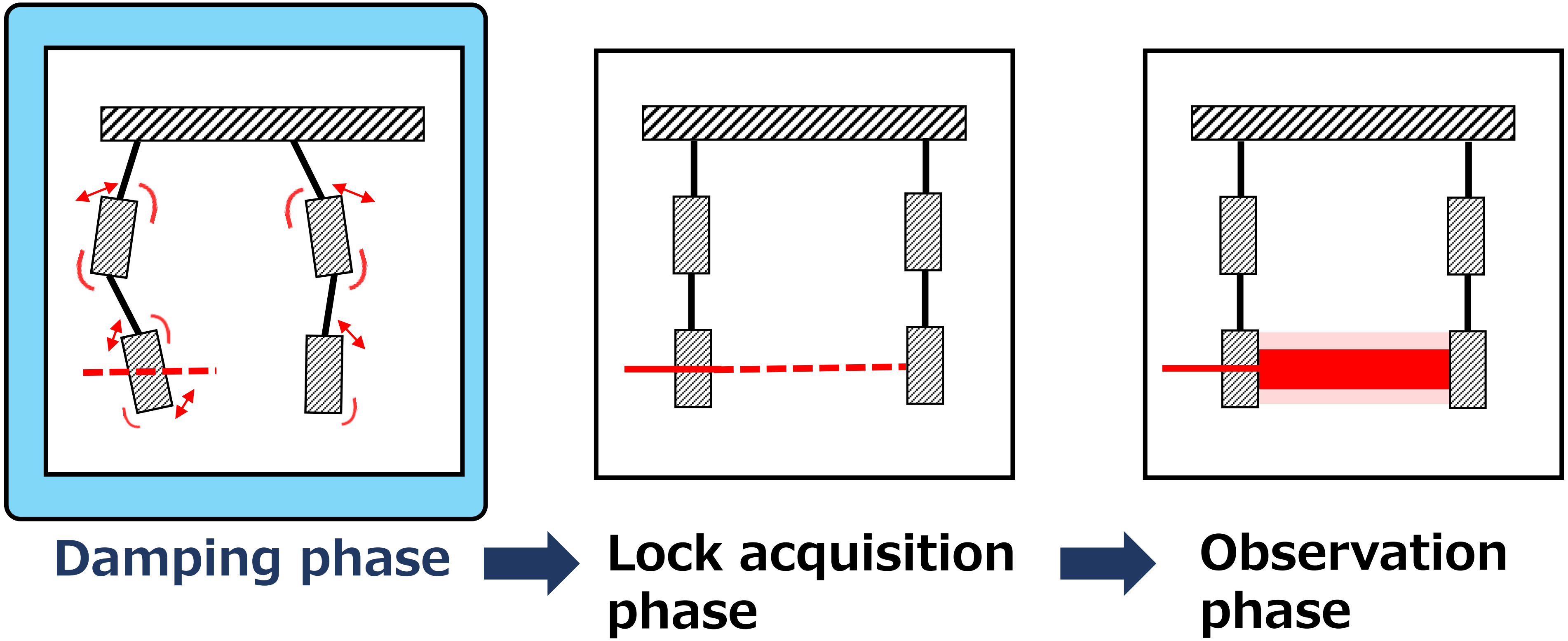
Frequency response is get along with the simulation?





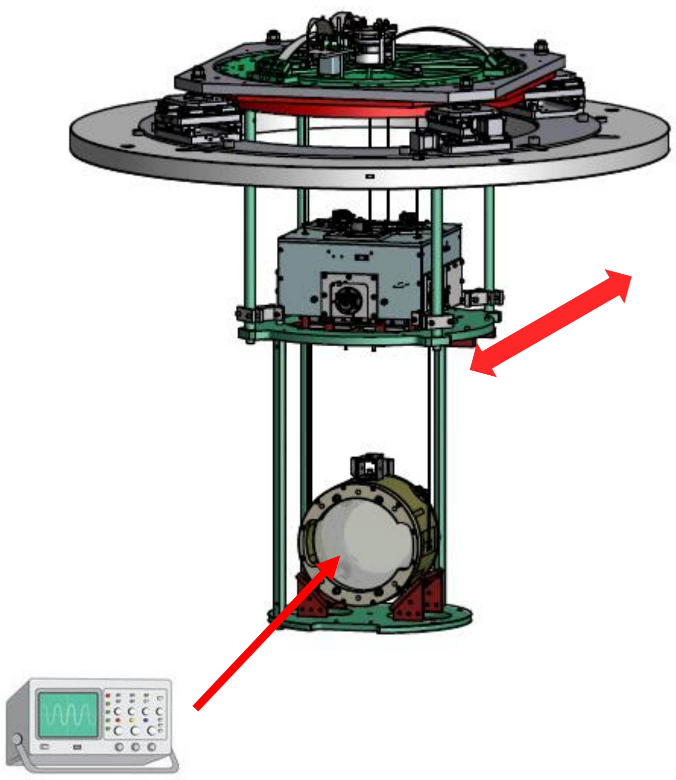


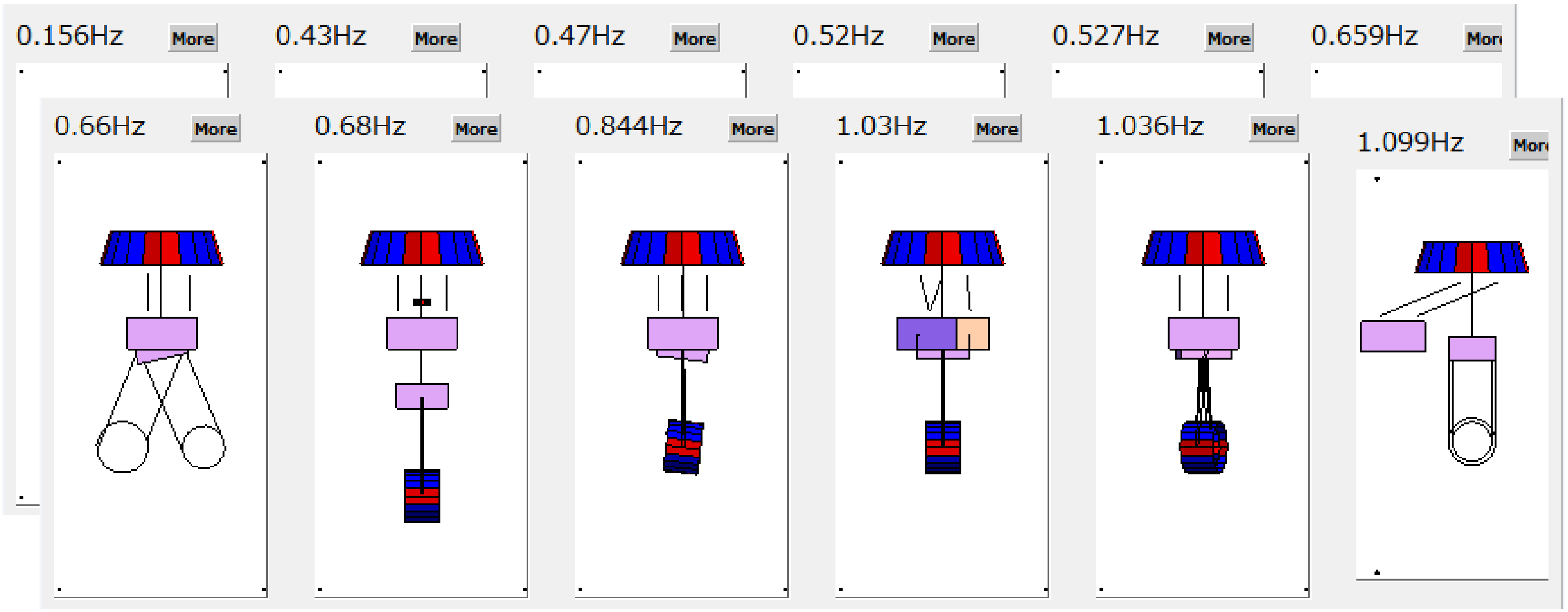
2. Performance test (measured on 23-25, May, 2016)



2-1. Damping performance test

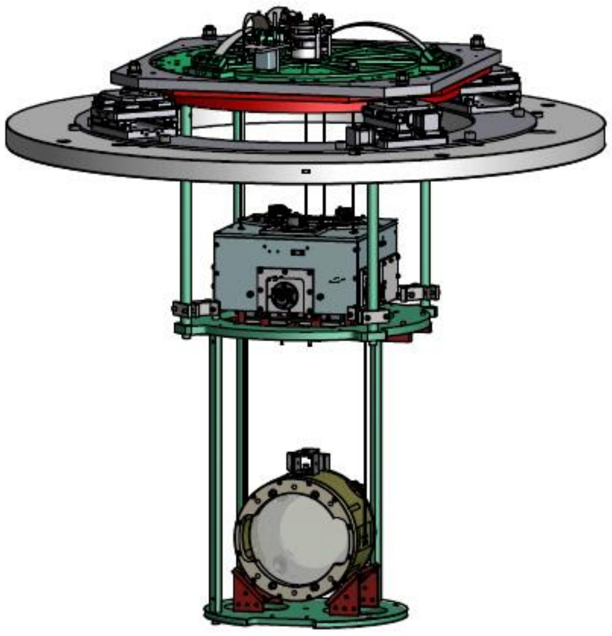
All the resonances can be damped within a short time with active control ?

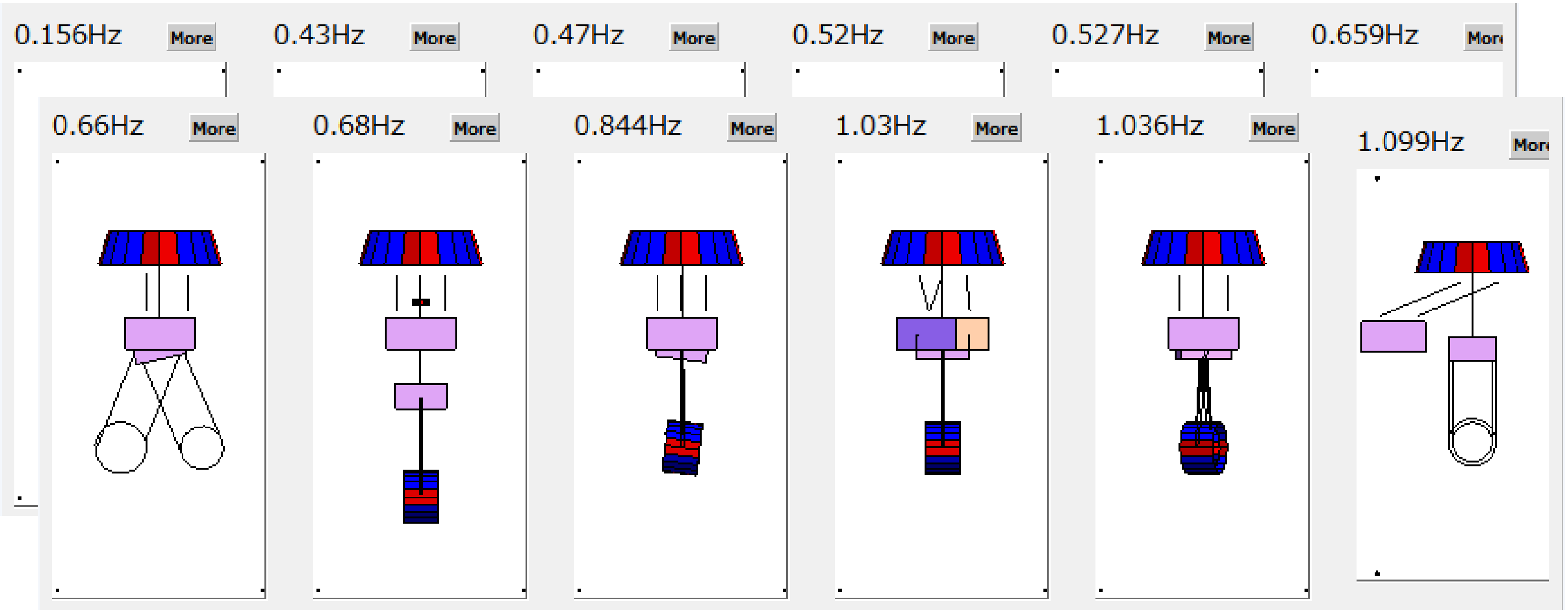




2-1. Damping performance test

All the resonances can be damped within a short time with active control ?

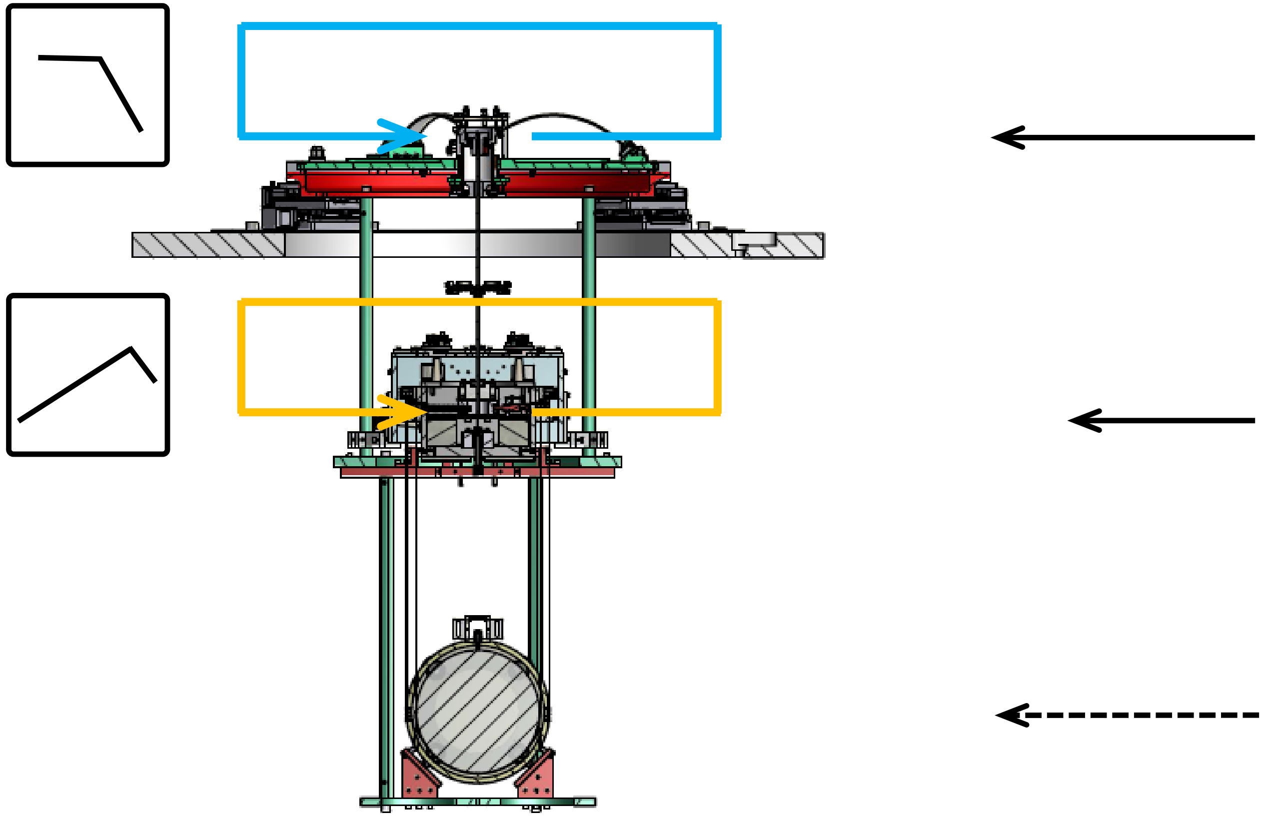




Resonances to be taken care (< 20 Hz) → 19 modes

Requirement in this test : 1/e decay time < 1 min.

Implemented control loops

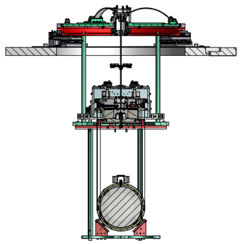


GAS :
DC control, with LVDT

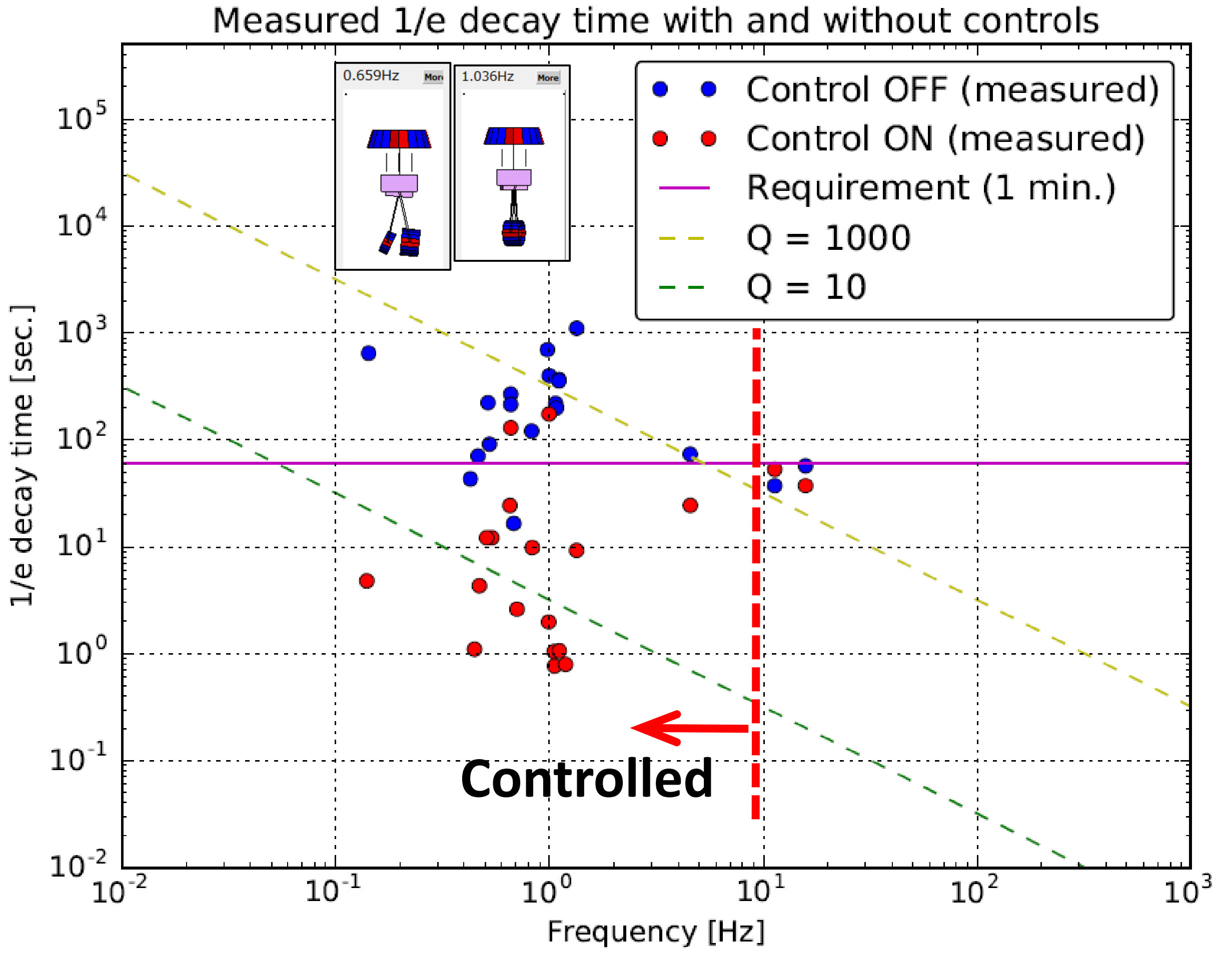
IM – IR :
Damping control, with OSEMs
(~ 10 Hz cutoff)

TM – RM :
Freely suspended

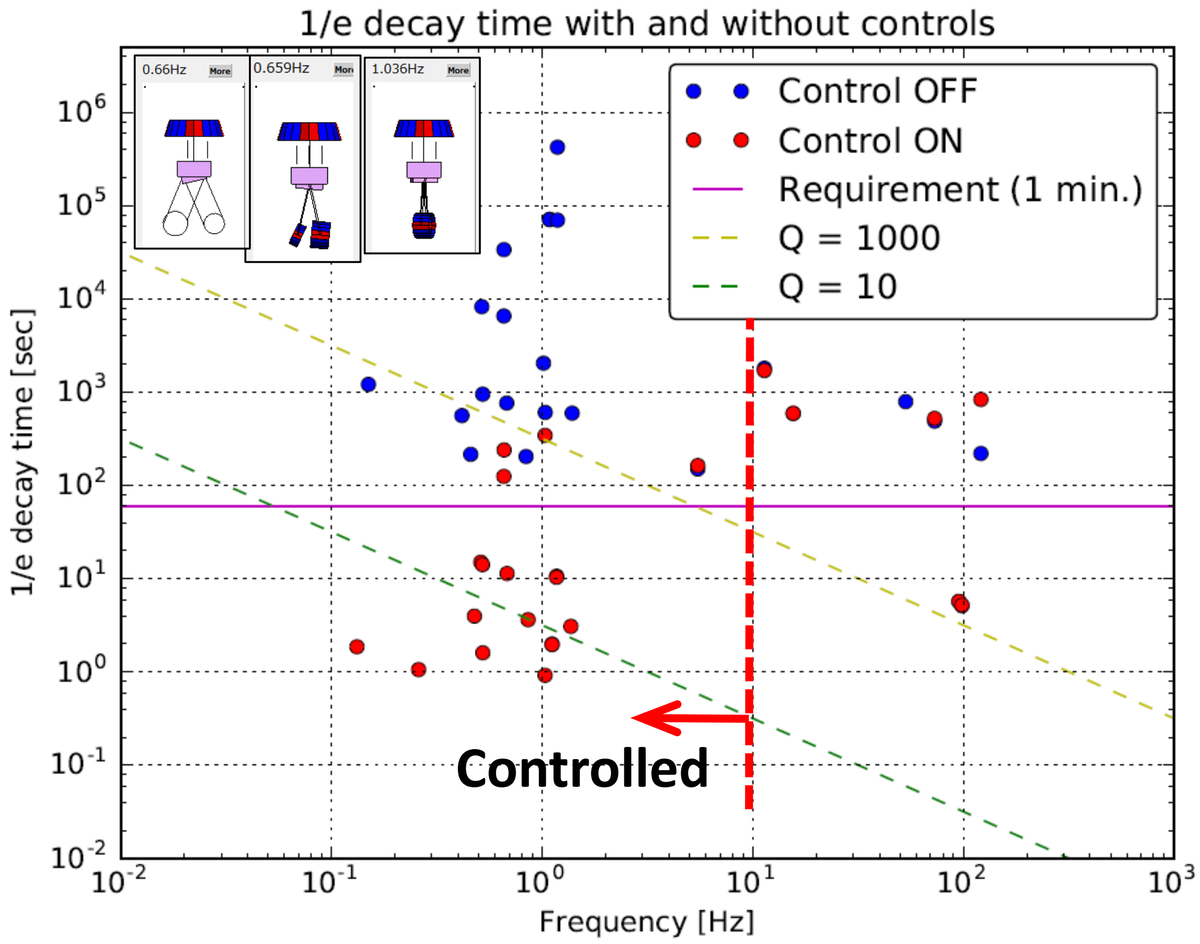
Measured damping time: Control ON vs. Control OFF



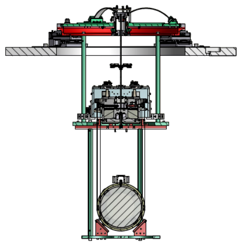
Measured



Model



Measured damping time: Control ON vs. Control OFF

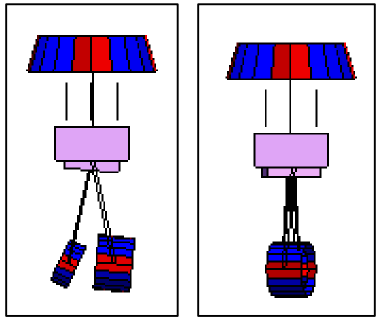


1. Simulation tends to tell larger natural Q factors than the actual ones.

→ Actual feedback filters can be different from the simulated ones, due to actual Q factors.

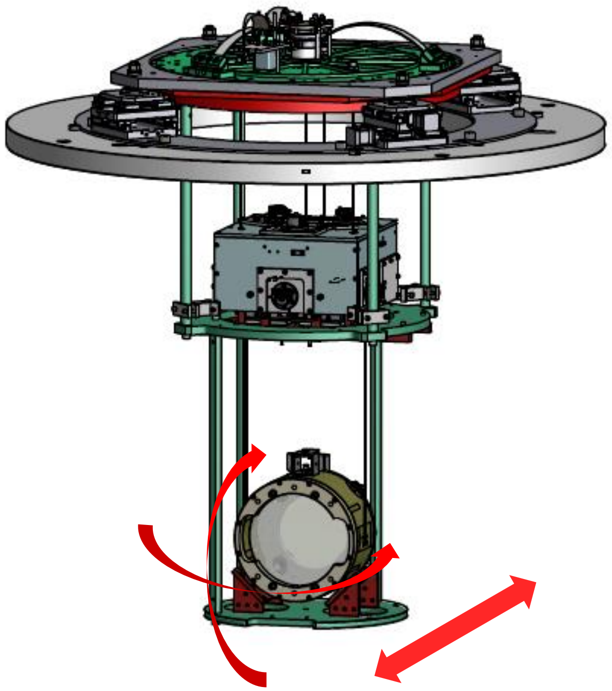
→ notch? cut-off frequency? ..
→ Filter tuning at the site would be needed.

2. To damp optic & recoil mass motion, sensing the optic motion is needed.



→ Is oplev available, even just after large disturbances ?
(now investigating oplev's behavior after earthquakes.)

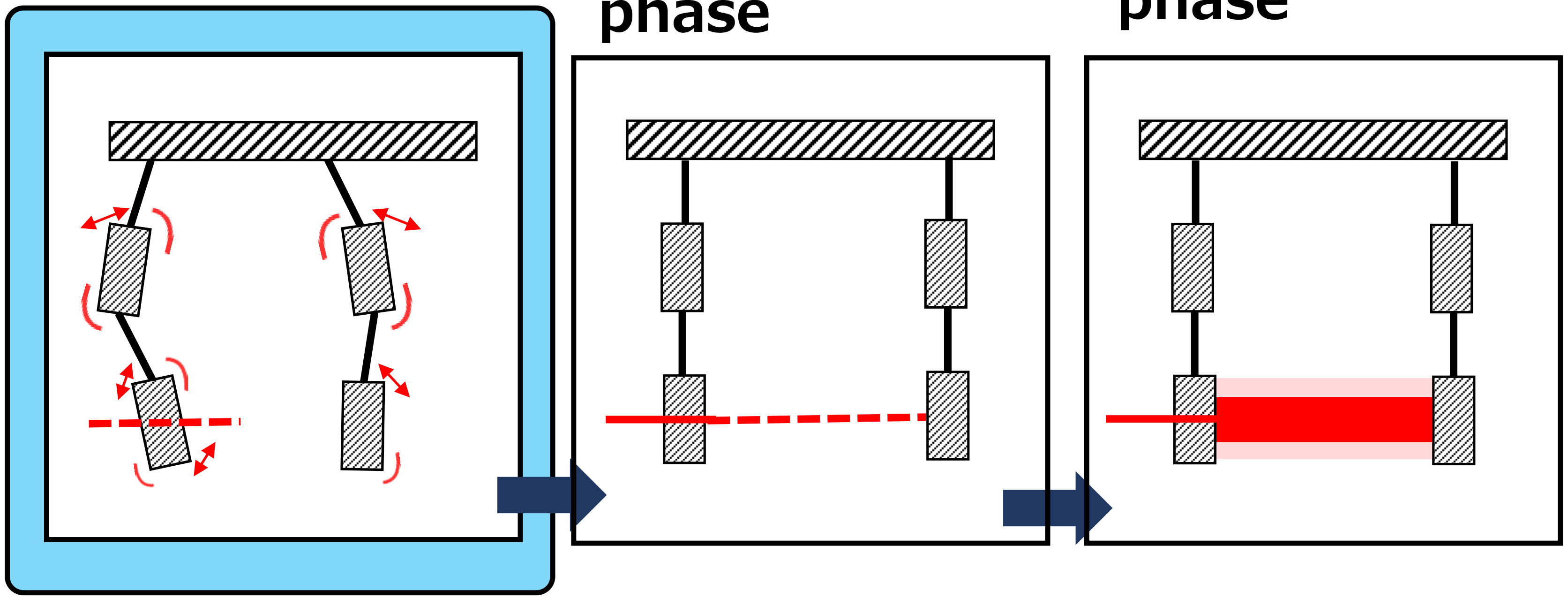
2-2. Residual vibration



Damping phase

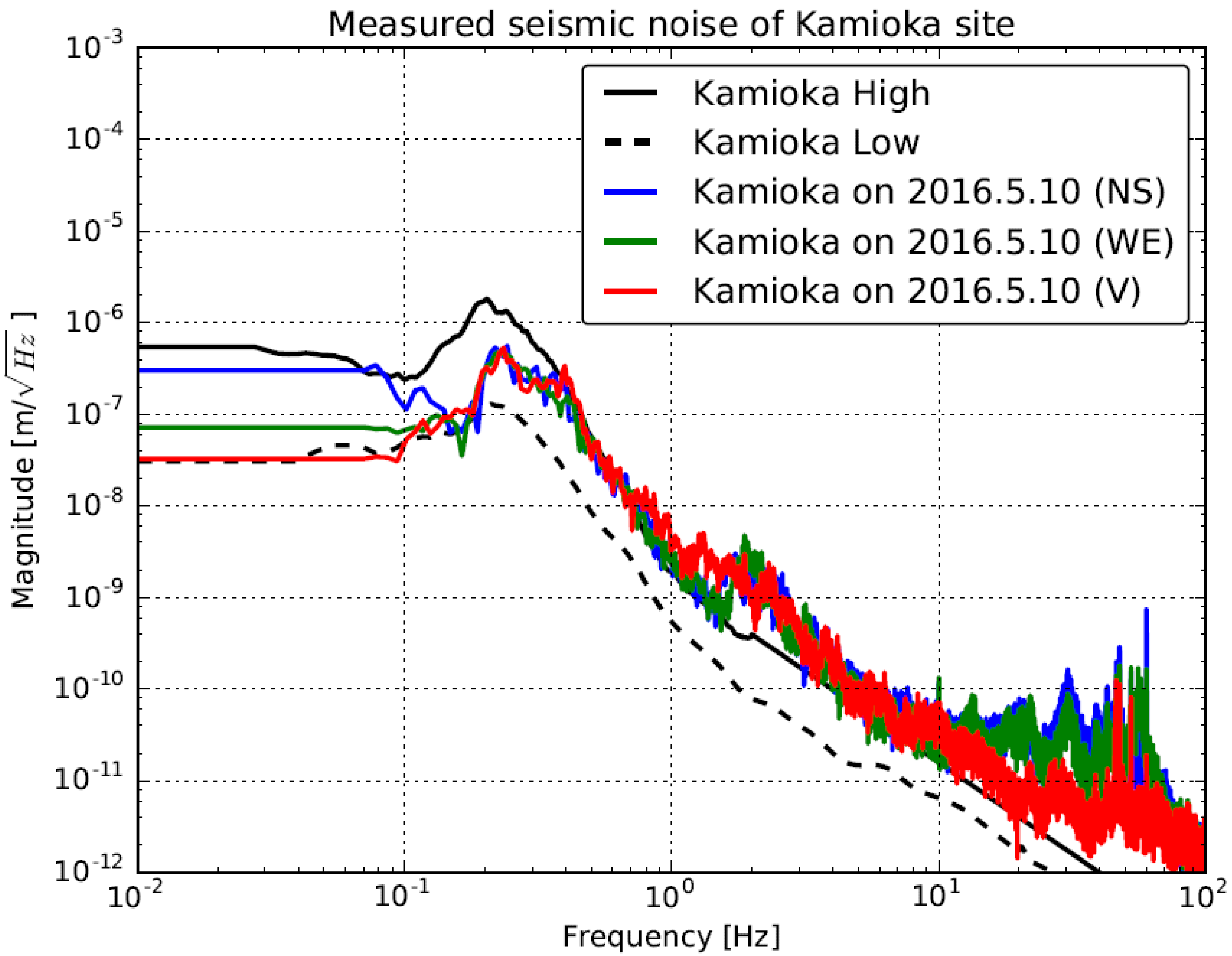
Lock acquisition phase

Observation phase



Model vs. Measurement

Seismic noise of Kamioka (on 2016.5.10)

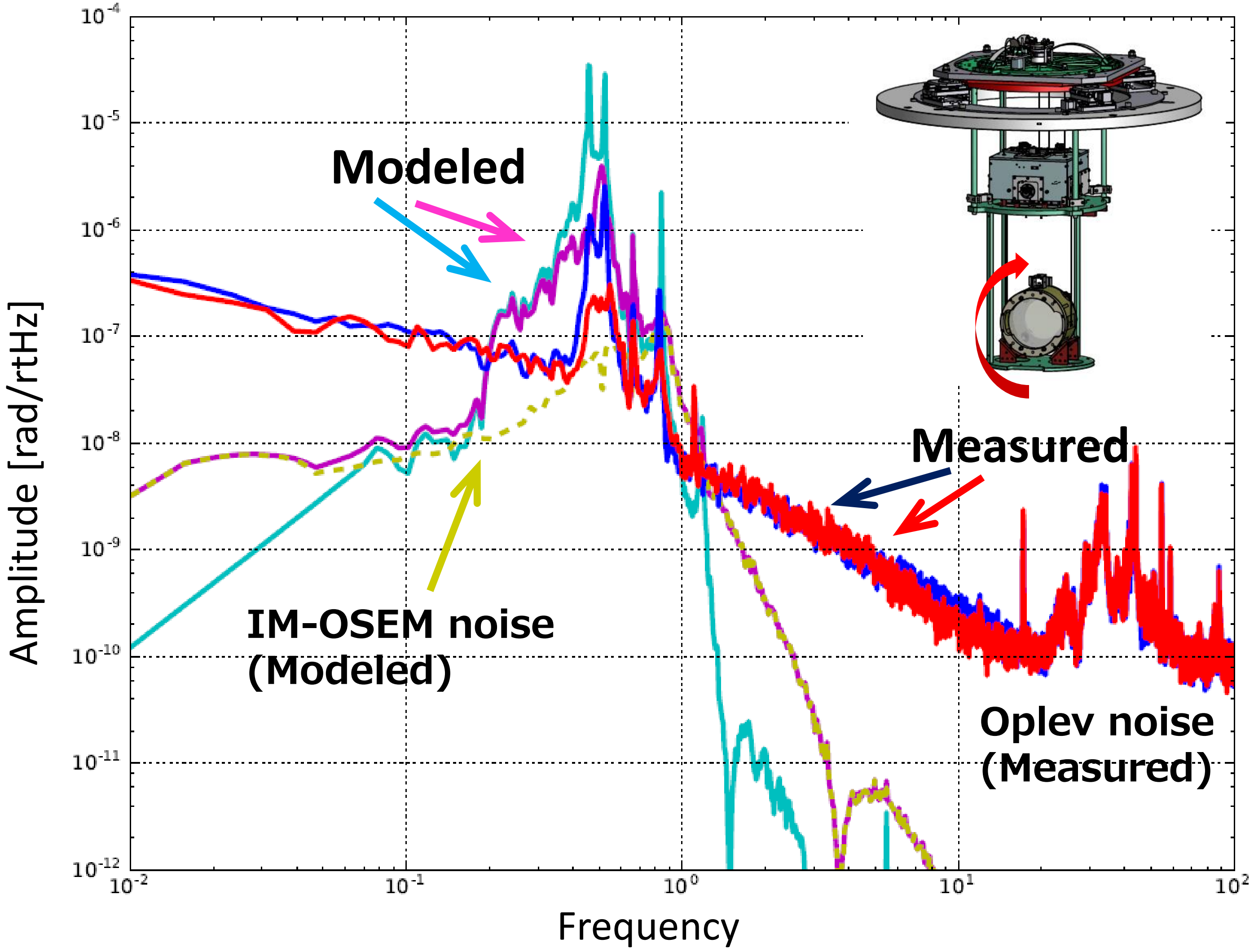


In following calculation, seismic noise measured on 2016.5.10 is considered (blue one).

Measurement was done on 2016.5.24.

Angular fluctuation of the optic (Pitch)

Model (based on20 16.5.10) vs. Measured (on 2016.5.24)



○ Resonance frequency

× 0.2 ~ 0.4 Hz structure

→ depends on seismic noise

× Q factor (without control)

→ lack of modeling

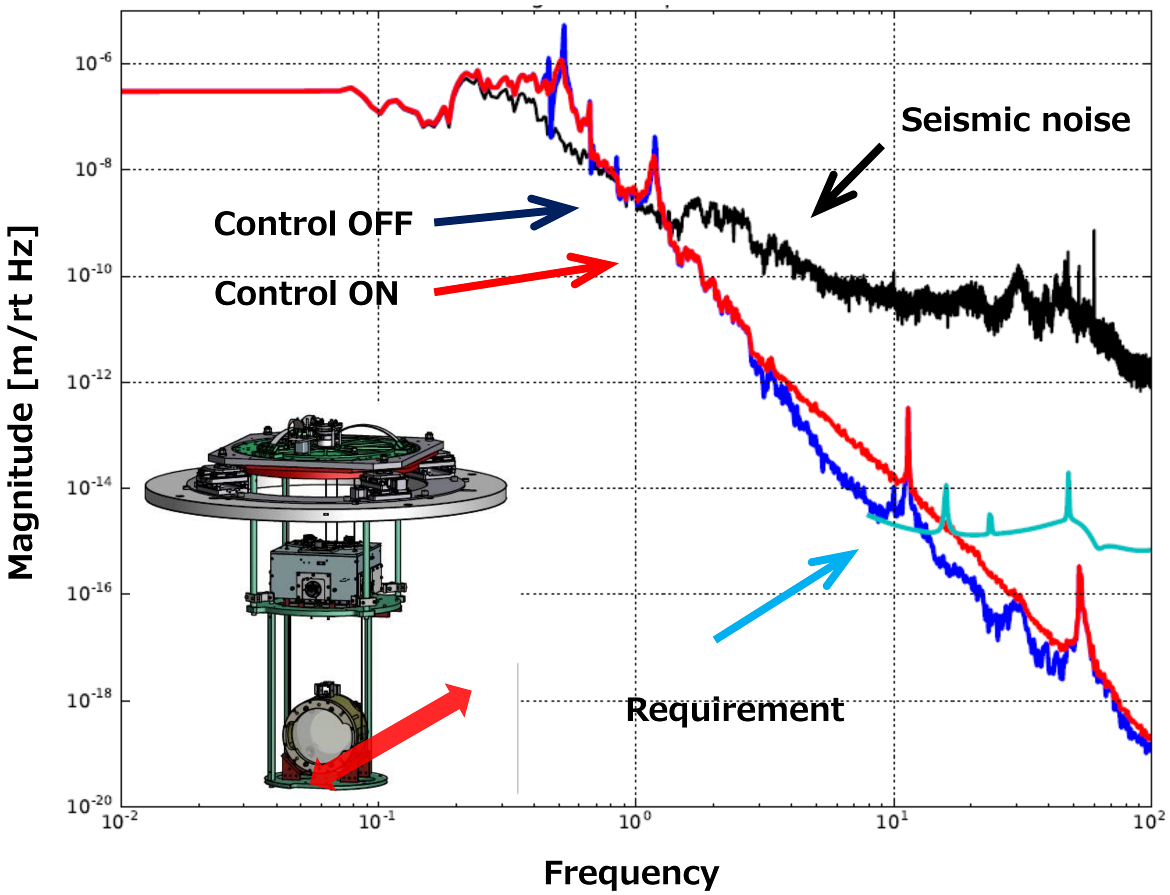
→ At least, about RMS,
Simulation > actual behavior

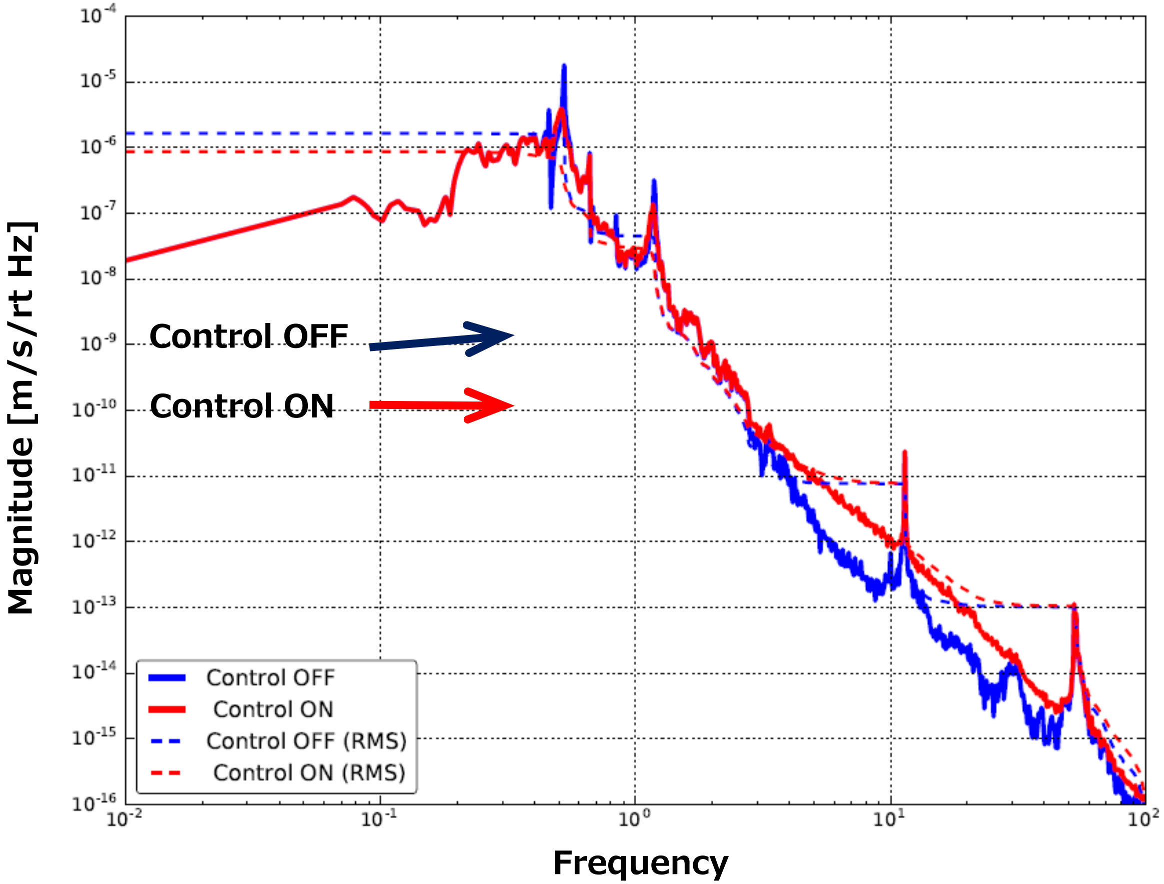
RMS values

Control OFF (Model) : 4.4 um
Control ON (Model) : 0.7 um

Control OFF (Measured) : 0.37 um
Control ON (Measured) : 0.10 um

Expected fluctuation of the optic

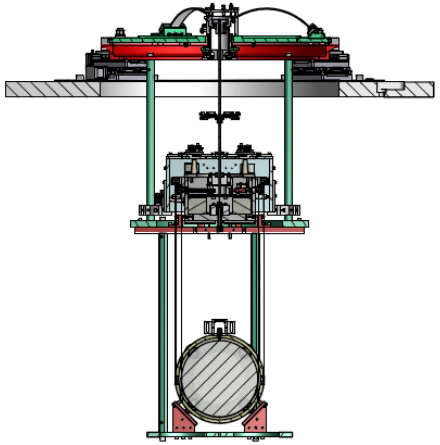




Control OFF : 0.5 um (RMS)
Control ON : 0.3 um (RMS)

Control OFF : 1.7 um/s
Control ON : 0.8 um/s

2. performance test



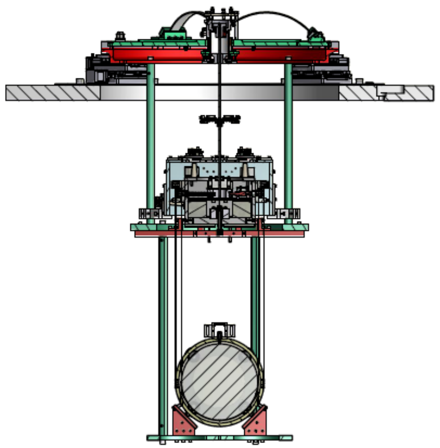
Measurement vs. Model

1. Actual Q factors < predicted Q factors (of free swinging)
   → Some simulated servo filters can be modified at the site.
2. Sensing TM motion is needed, in damping phase.
   → should be investigated if oplev is available in the damping phase.
3. Resonance peak → model describes the actual behavior.
4. Simulated RMS > Actual RMS.

Using more sensors would be useful for more detailed characterization.
(Seismometers, length sensor for Longitudinal motion of the optic, etc ..)

“iKAGRA data”, which I’d like to include:

→ Data for characterization of the iKAGRA PR3 SAS.

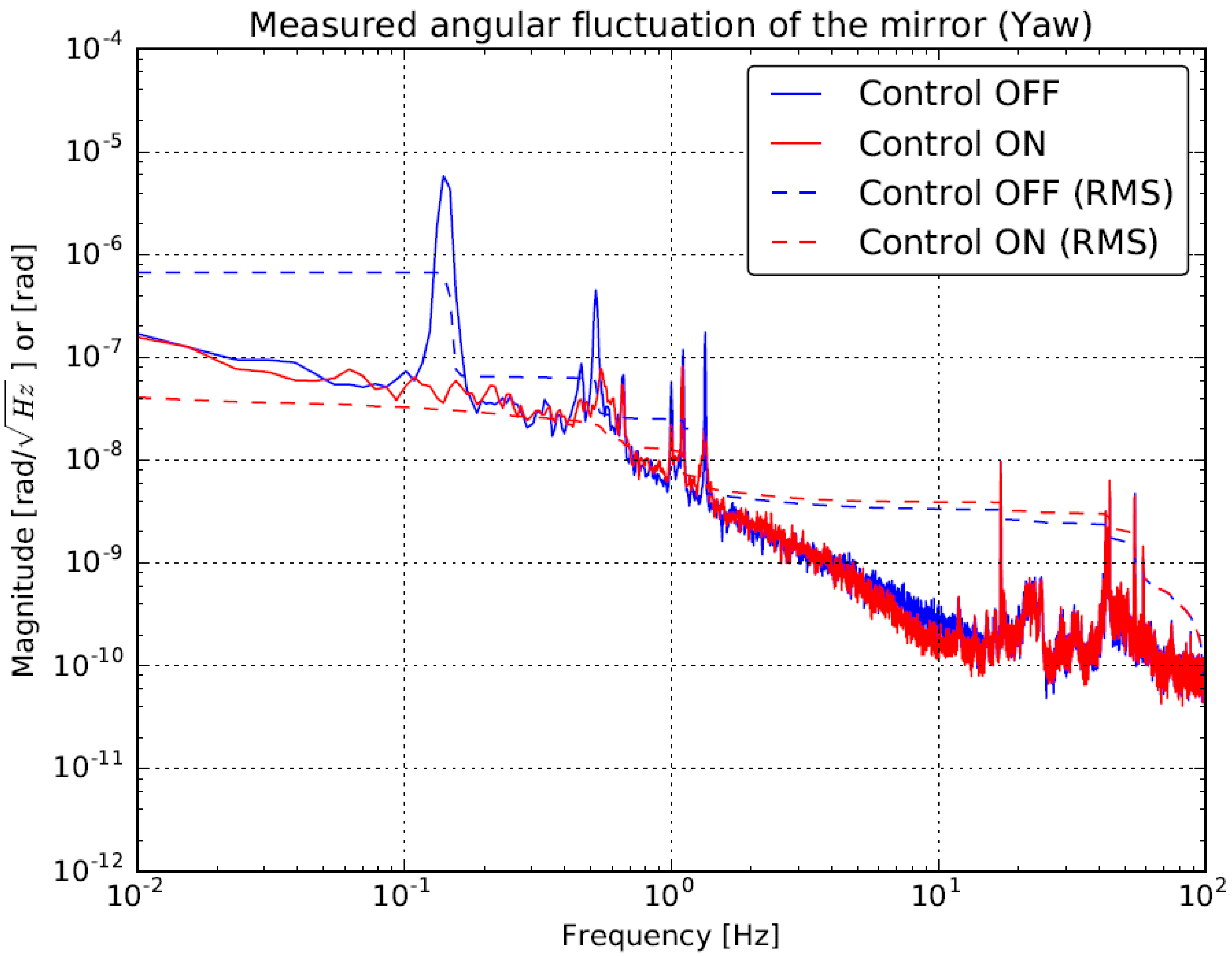


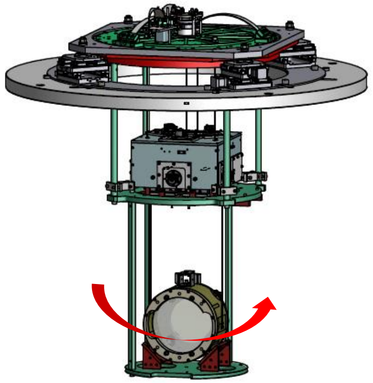
Back up

Other Type-Bpp measurement

Angular fluctuation of the mirror (Yaw)

Measured



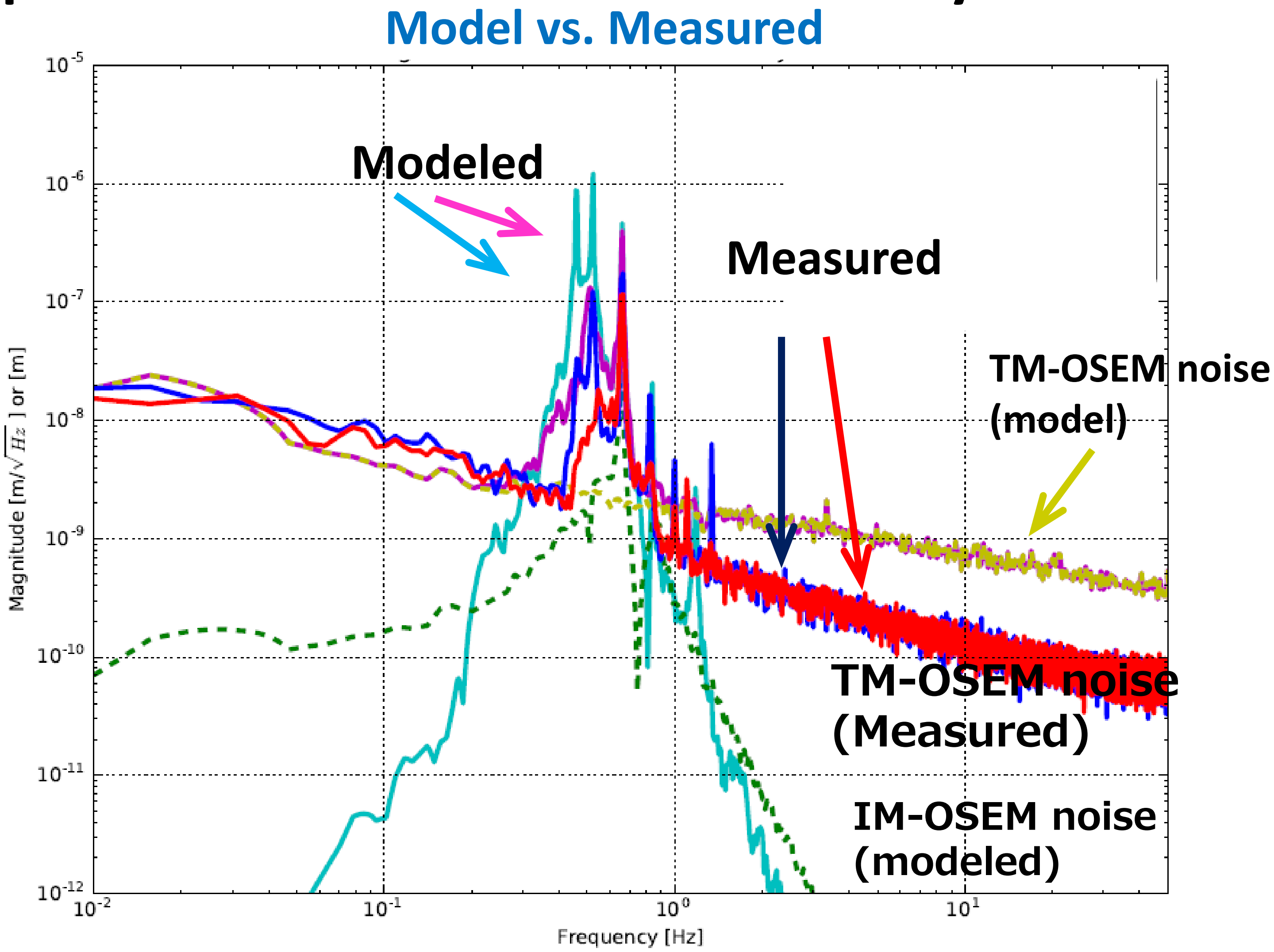


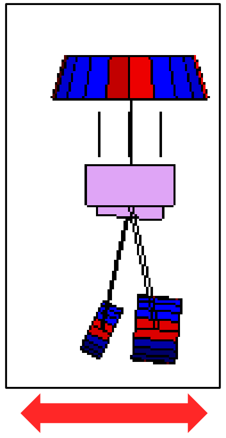
RMS values

Control OFF (Model) : --- urad
Control ON (Model) : --- urad

Control OFF (Measured) : 0.63 urad
Control ON (Measured) : 0.040 urad

Displacement fluctuation measured by TM-OSEM (Longitudinal)





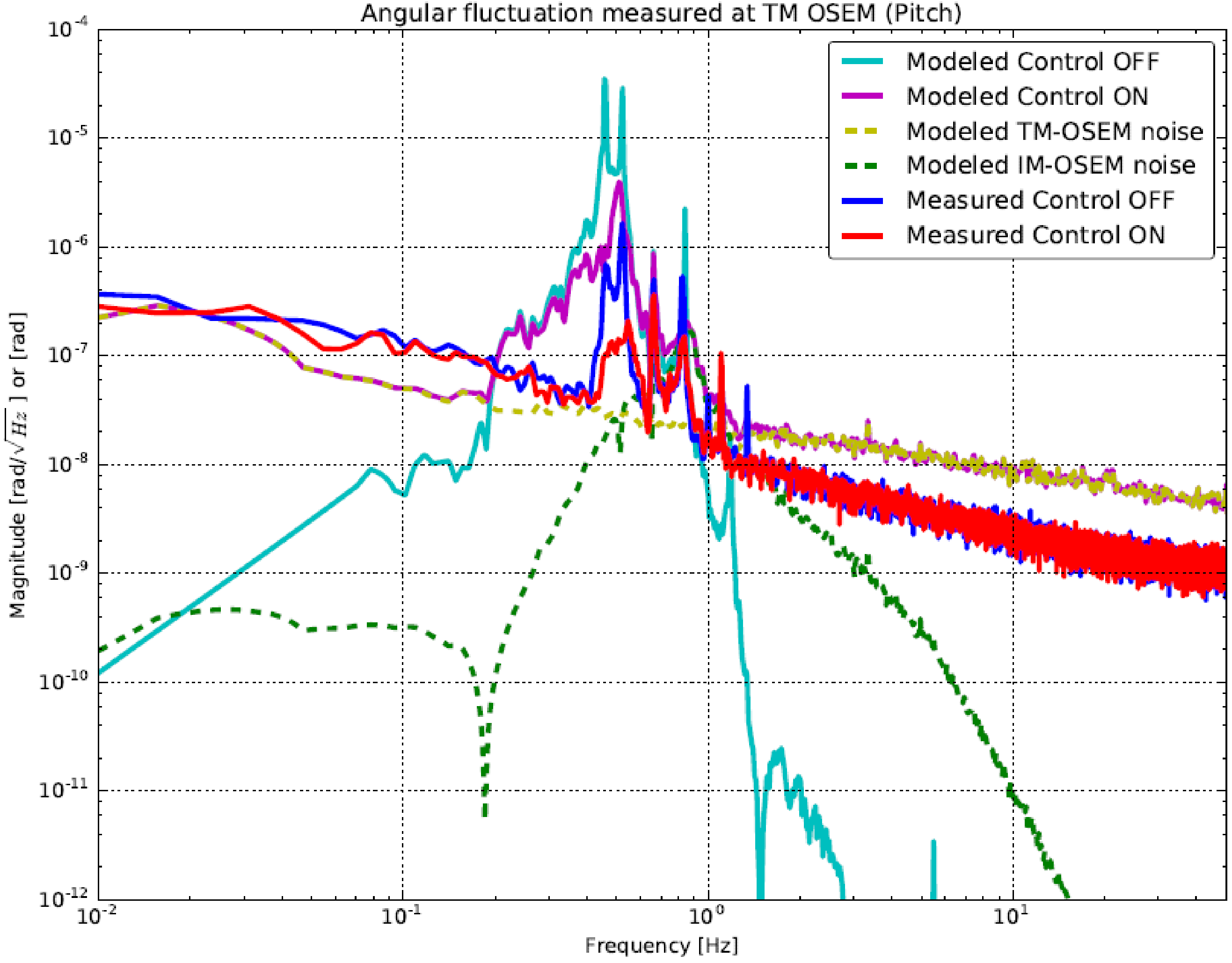
RMS values

Control OFF (Model) : 0.27 um
Control ON (Model) : 0.049 um

Control OFF (Measured) : 0.027 um
Control ON (Measured) : 0.016 um

Angular fluctuation measured by TM-OSEM (Pitch)

Model vs. Measured



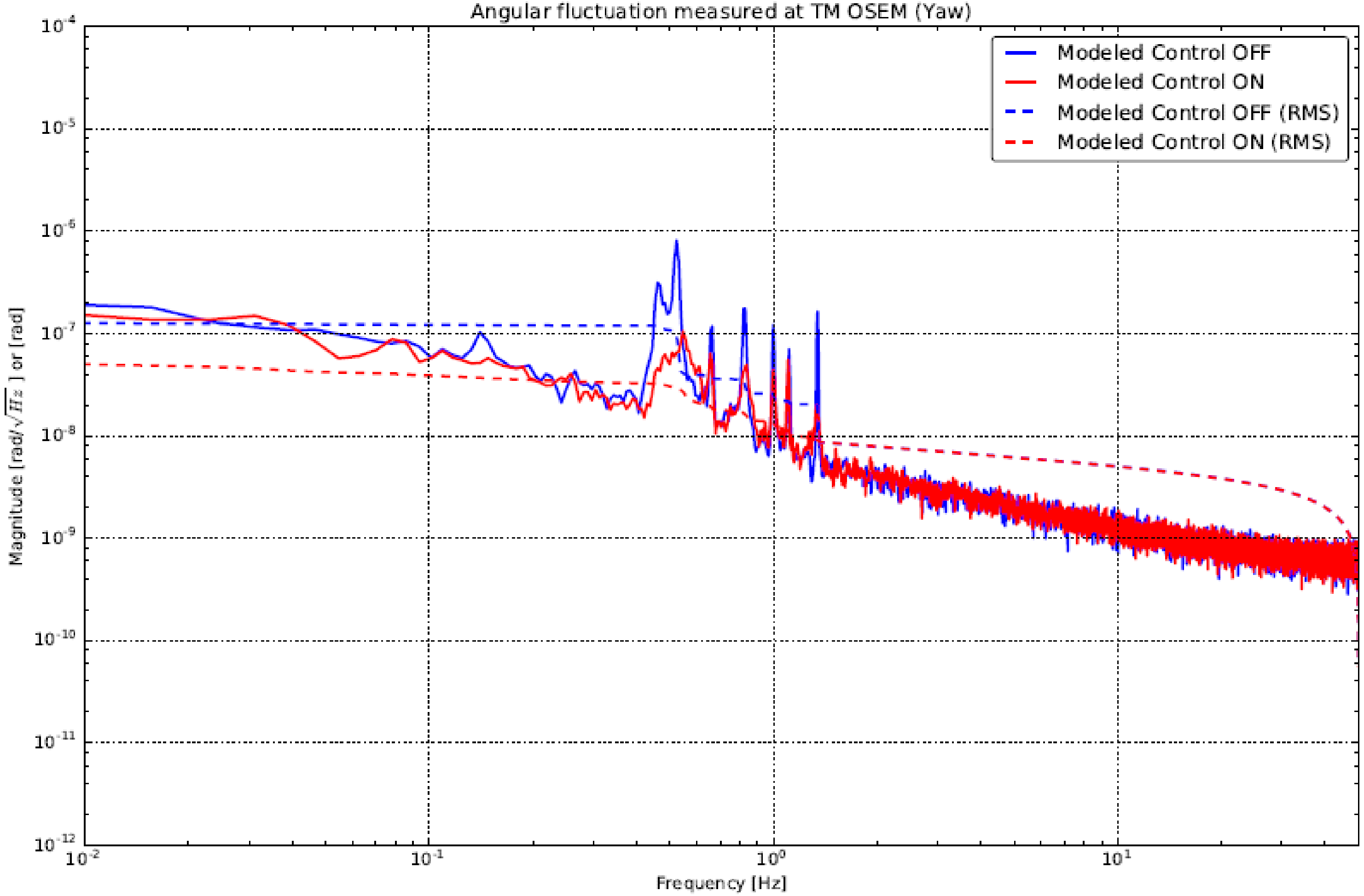
RMS values

Control OFF (Model) : 7.2 urad
Control ON (Model) : 1.1 urad

Control OFF (Measured) : 0.29 urad
Control ON (Measured) : 0.11 urad

Angular fluctuation measured by TM-OSEM (Yaw)

Measured

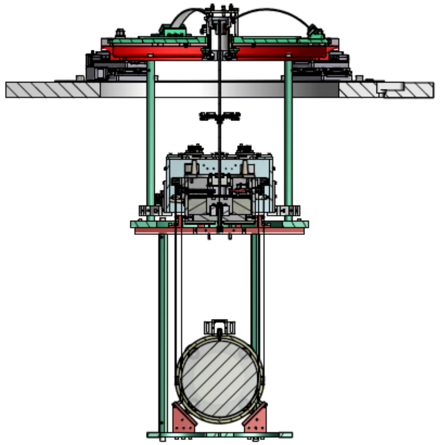


RMS values

Control OFF (Model) : ---
Control ON (Model) : ---

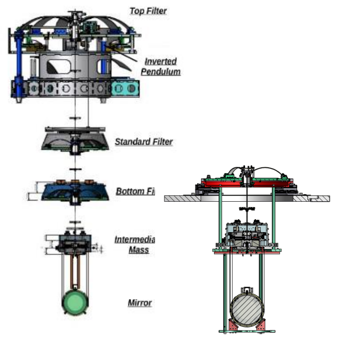
Control OFF (Measured) : 0.13 urad
Control ON (Measured) : 0.052 urad

2-3. Type-Bpp at Kamioka
vs. Type-B1proto at Tokyo Mitaka

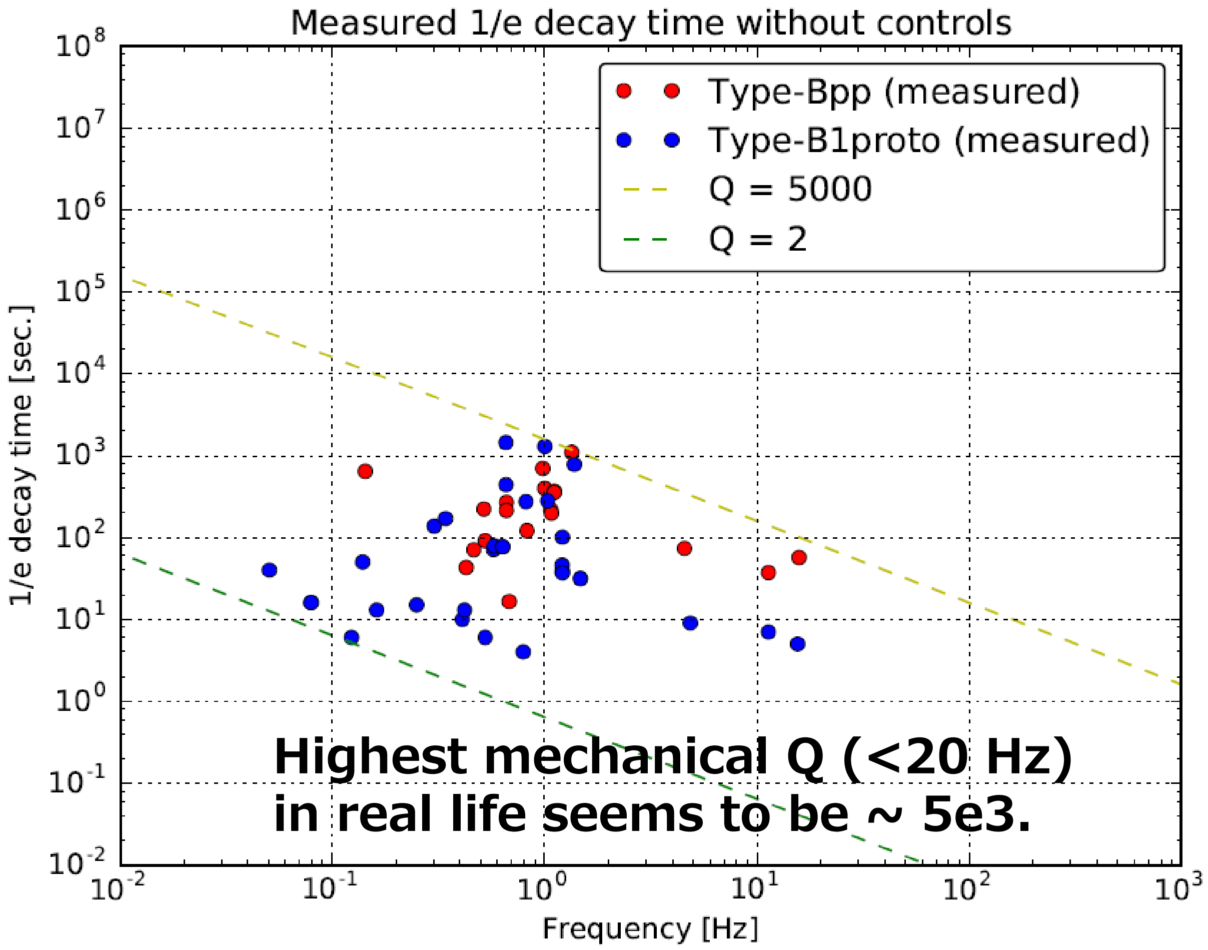


vs.

Mechanical Q factor of free swinging : Type-B1proto vs. Type-Bpp

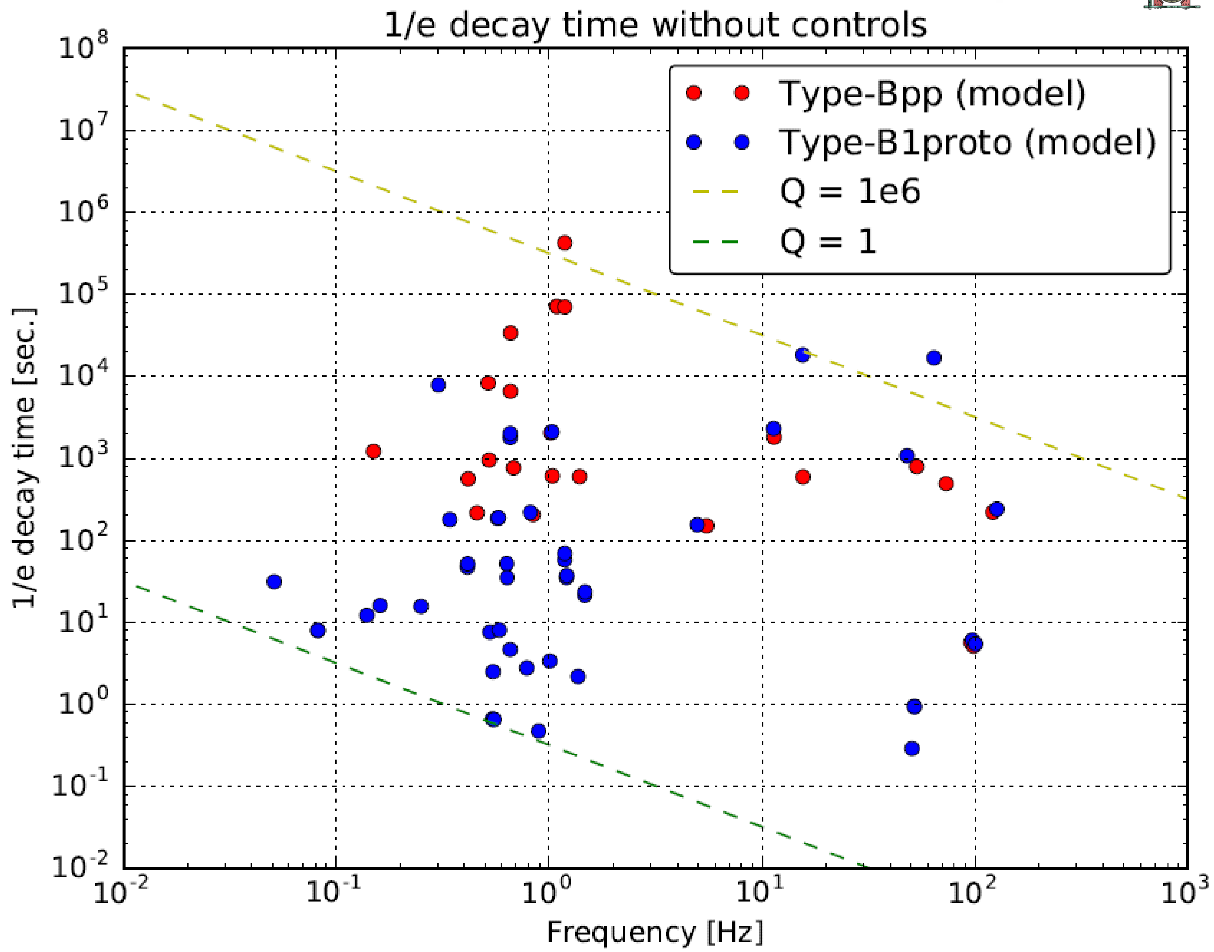


Measured

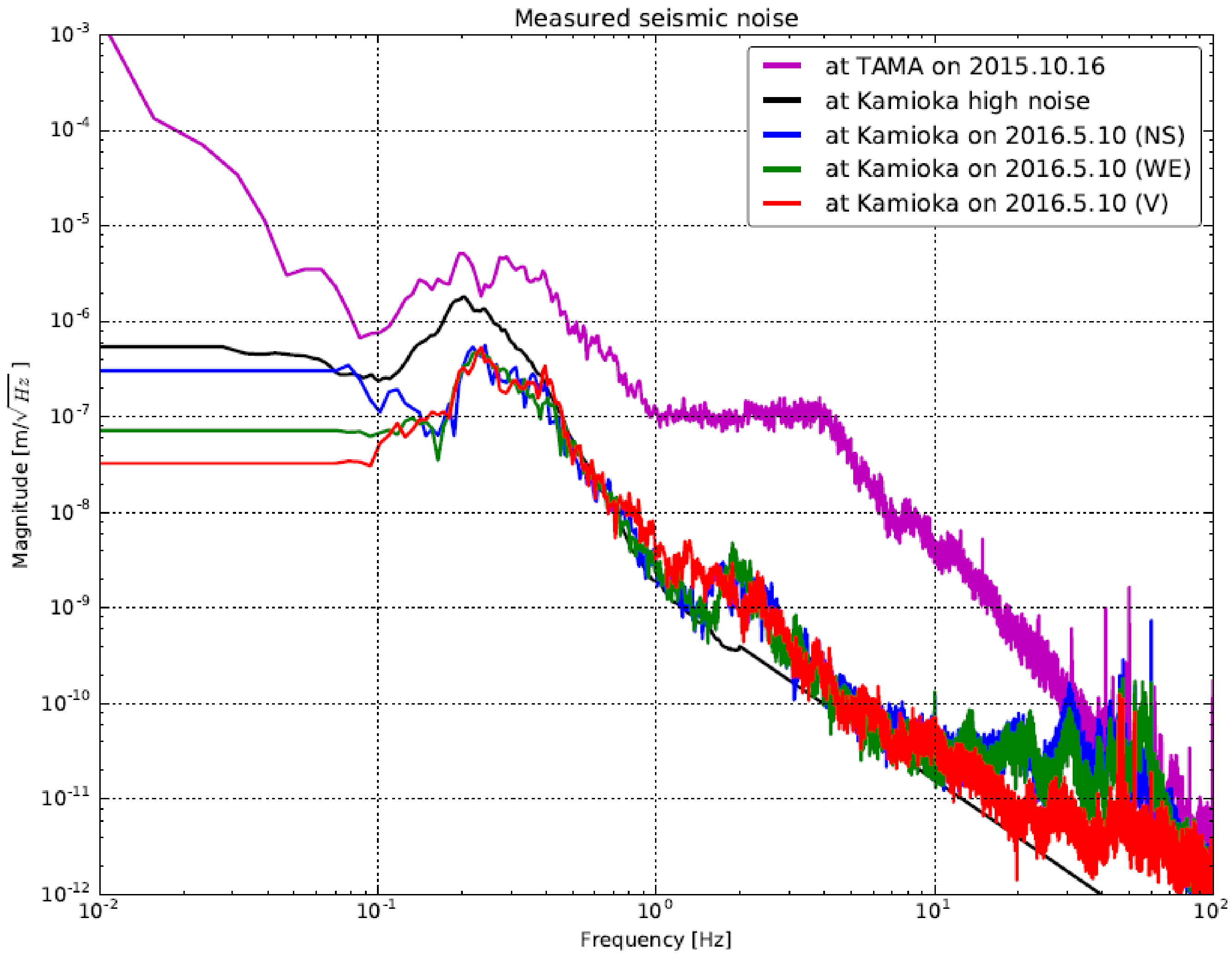


Highest mechanical Q (<20 Hz) in real life seems to be ~ 5e3.

Model

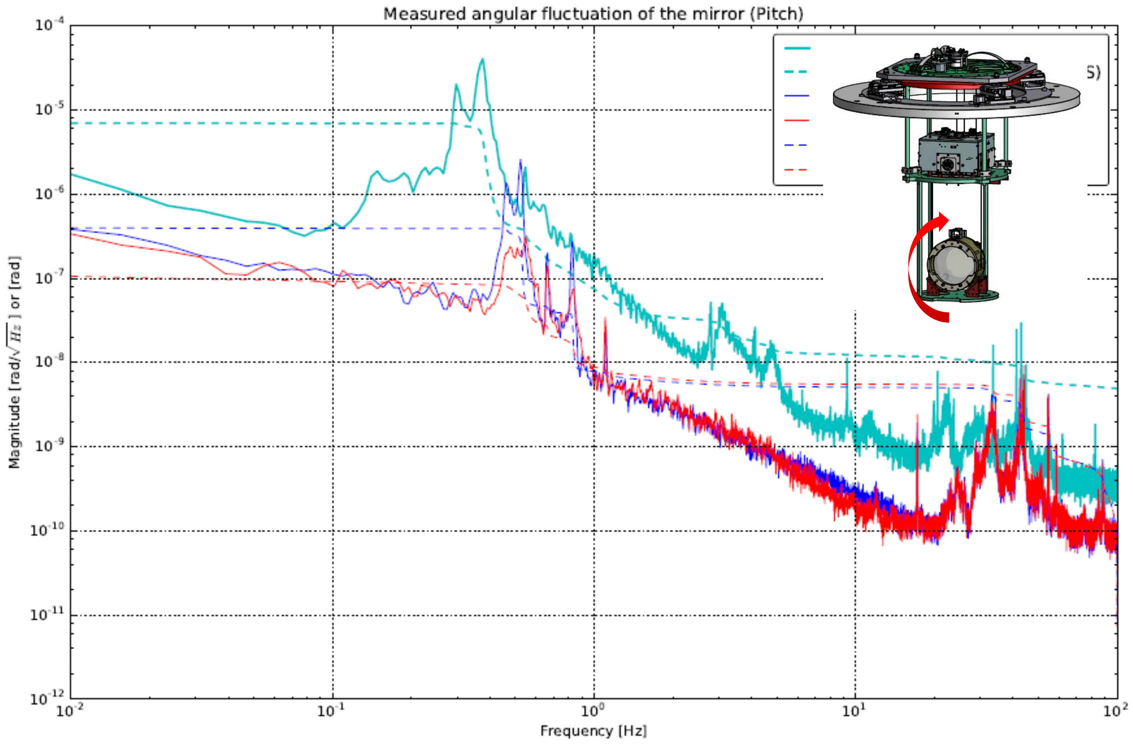


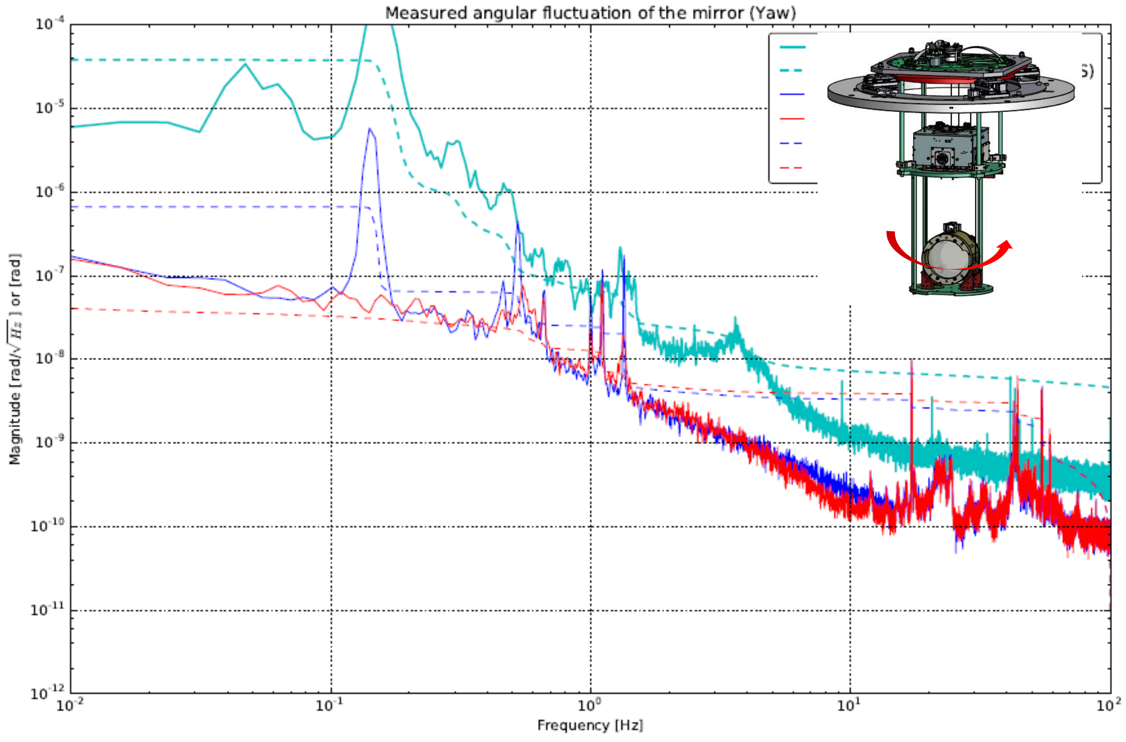
Seismic noise : Kamioka vs. TAMA



Seismic noise of Kamioka on 2016.5.10 was smaller than that of Tokyo, by ~ one order of magnitude at 1 Hz, by ~ two order of magnitude at 10 Hz.

Angular fluctuation of the mirror (Type-B1proto vs. type-Bpp)





RMS values

Control OFF (TypeB1proto) : 7.0 urad

Control OFF (Measured) : 0.37 urad

Control ON (Measured) : 0.10 urad

RMS values

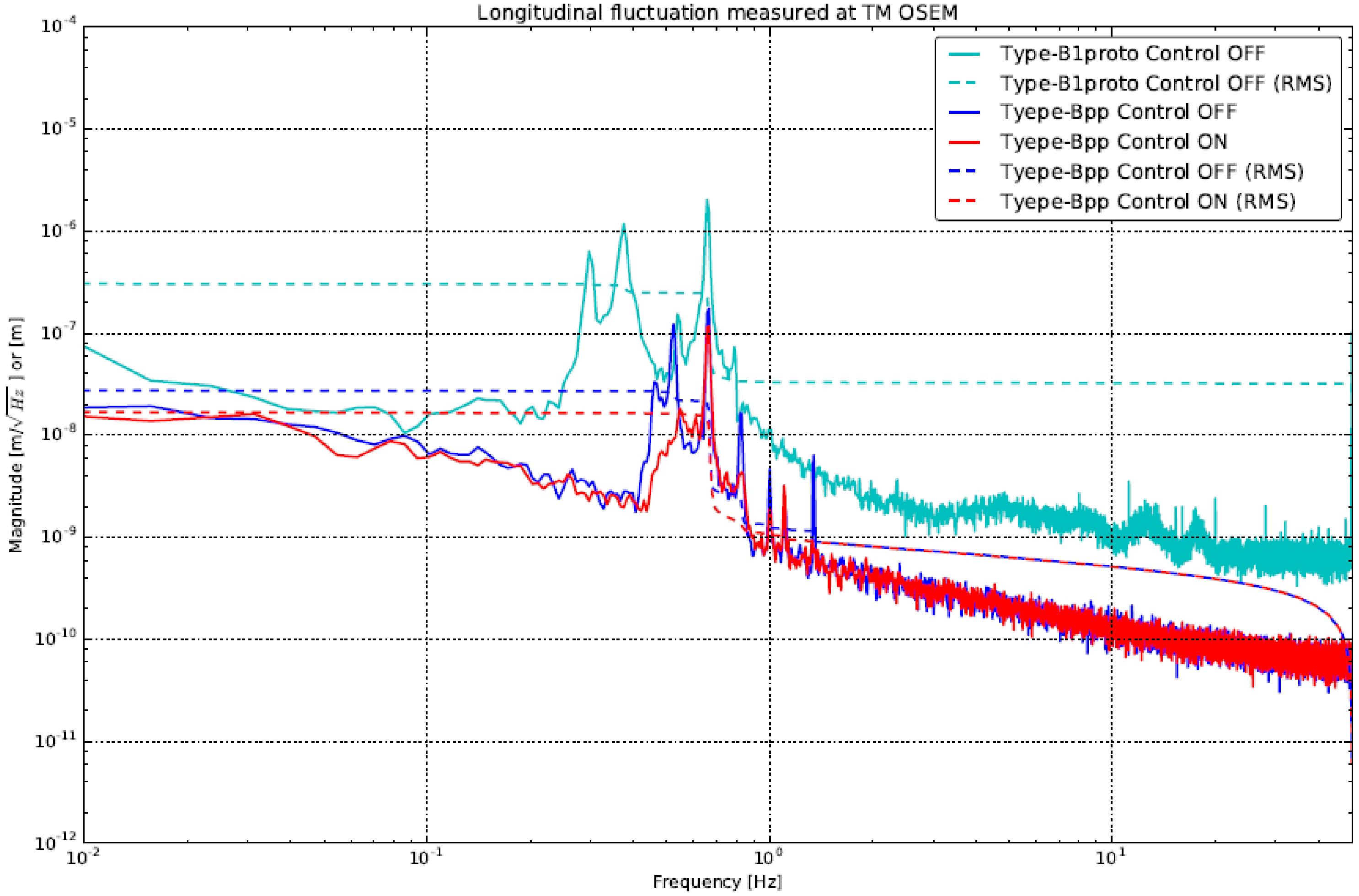
Control OFF (TypeB1proto) : 37 urad

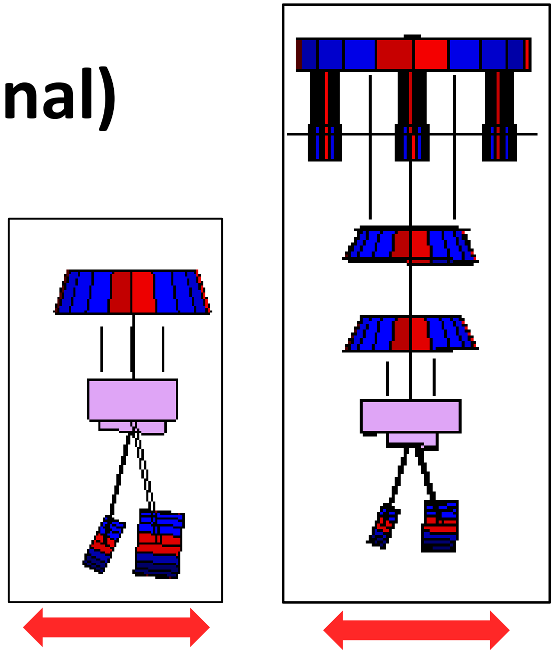
Control OFF (Measured) : 0.63 urad

Control ON (Measured) : 0.040 urad

Displacement fluctuation measured by TM-OSEM (Longitudinal)

Type-B1proto vs. type-Bpp





RMS values

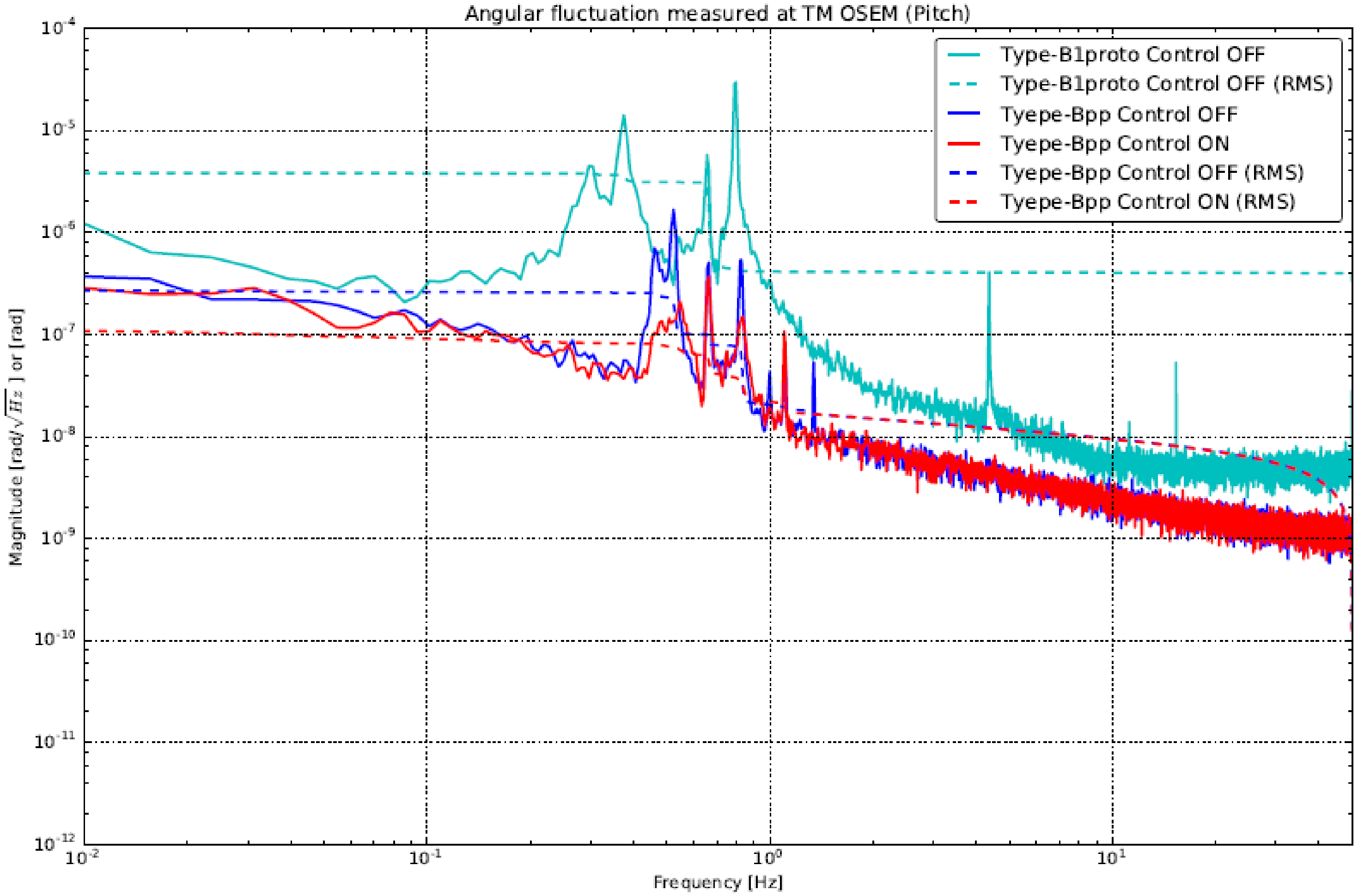
Control OFF (TypeB1proto) : 0.31 um

Control OFF (Measured) : 0.027 um

Control ON (Measured) : 0.016 um

0.3 Hz → 0.4 Hz : Caused by the suspension point difference of the IM

Angular fluctuation measured by TM-OSEM (Pitch)
Type-B1proto vs. type-Bpp



RMS values

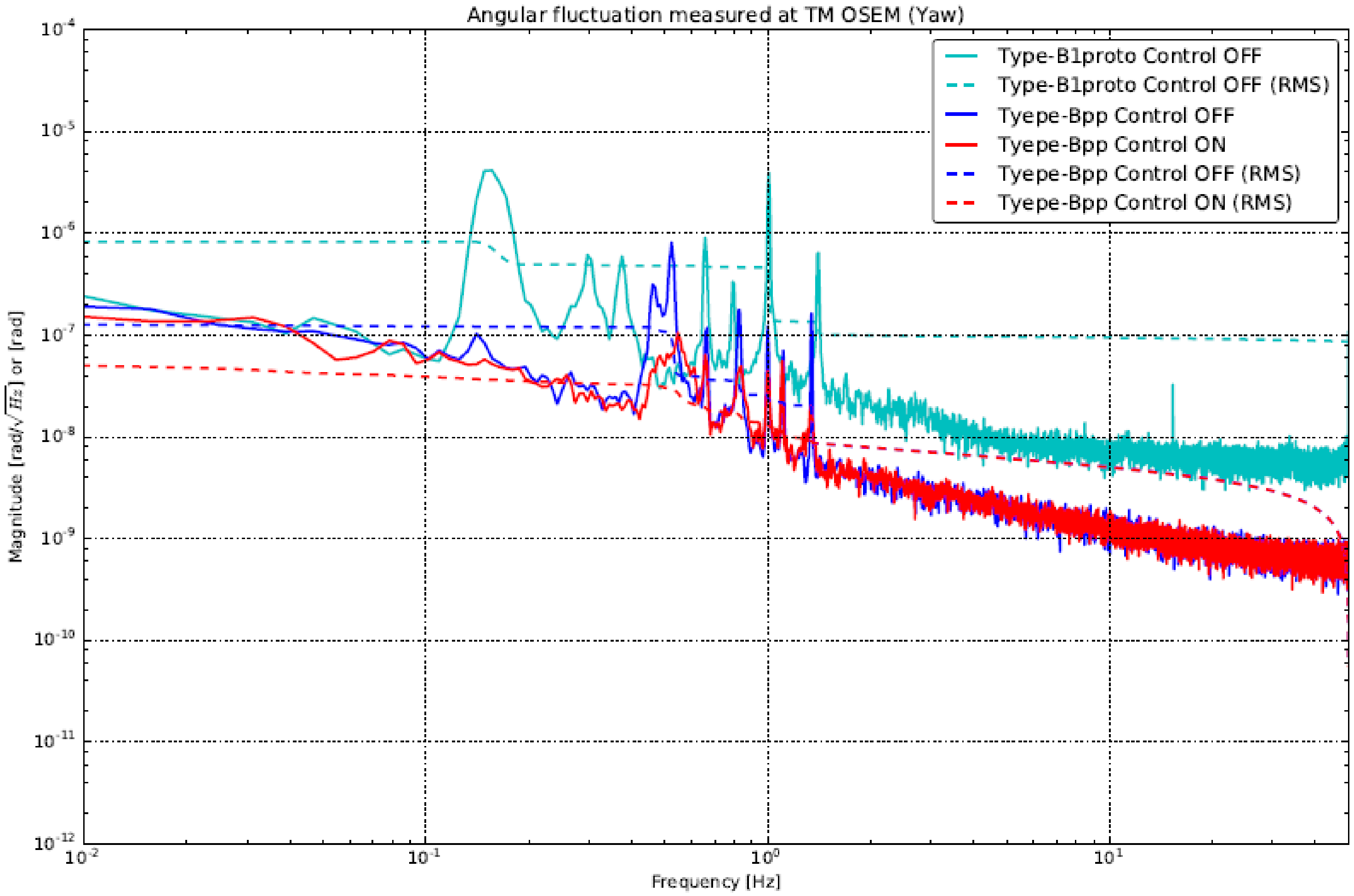
Control OFF (TypeB1proto) : 4.0 urad

Control OFF (Measured) : 0.29 urad

Control ON (Measured) : 0.11 urad

0.3 Hz → 0.4 Hz : Caused by the suspension point difference of the IM

Angular fluctuation measured by TM-OSEM (Yaw)
Type-B1proto vs. type-Bpp



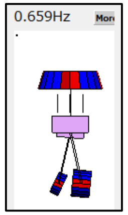
RMS values

Control OFF (TypeB1proto) : 0.83 urad

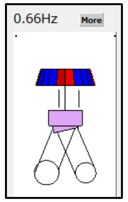
Control OFF (Measured) : 0.13 urad

Control ON (Measured) : 0.052 urad

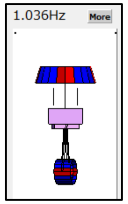
No-controlled damping time comparison



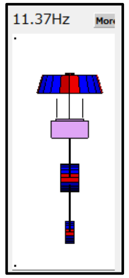
LRM – LTM	0.65 Hz	Measured *t* [s]	Modeled *t* [s]
typeB1proto		1448	1790
typeBpp		268	6585



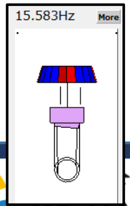
TRM – TTM	0.65 Hz	Measured *t* [s]	Modeled *t* [s]
typeB1proto		442	2009
typeBpp		214	33905



YRM – YTM	1.00 Hz	Measured *t* [s]	Modeled *t* [s]
typeB1proto		1295	2101
typeBpp		398	608



VRM	11.5 Hz	Measured *t* [s]	Modeled *t* [s]
typeB1proto		7	2305
typeBpp		37	1812



RTM	15.8 Hz	Measured *t* [s]	Modeled *t* [s]
typeB1proto		5	18266
typeBpp		57	593

Can be suffered from the aluminum sheet.

3. Summary

Performance test of iKAGRA PR3 SAS at Kamioka

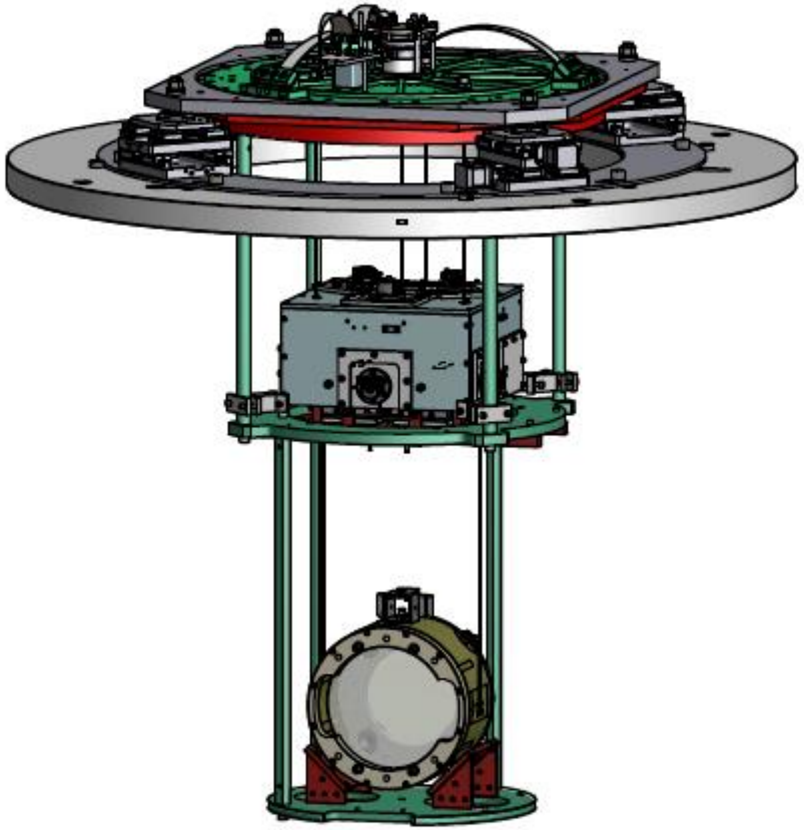
The differences of p.22 can come from difference of

1. Seismic noise
2. Suspension points
3. circuits, power supply,.. etc.

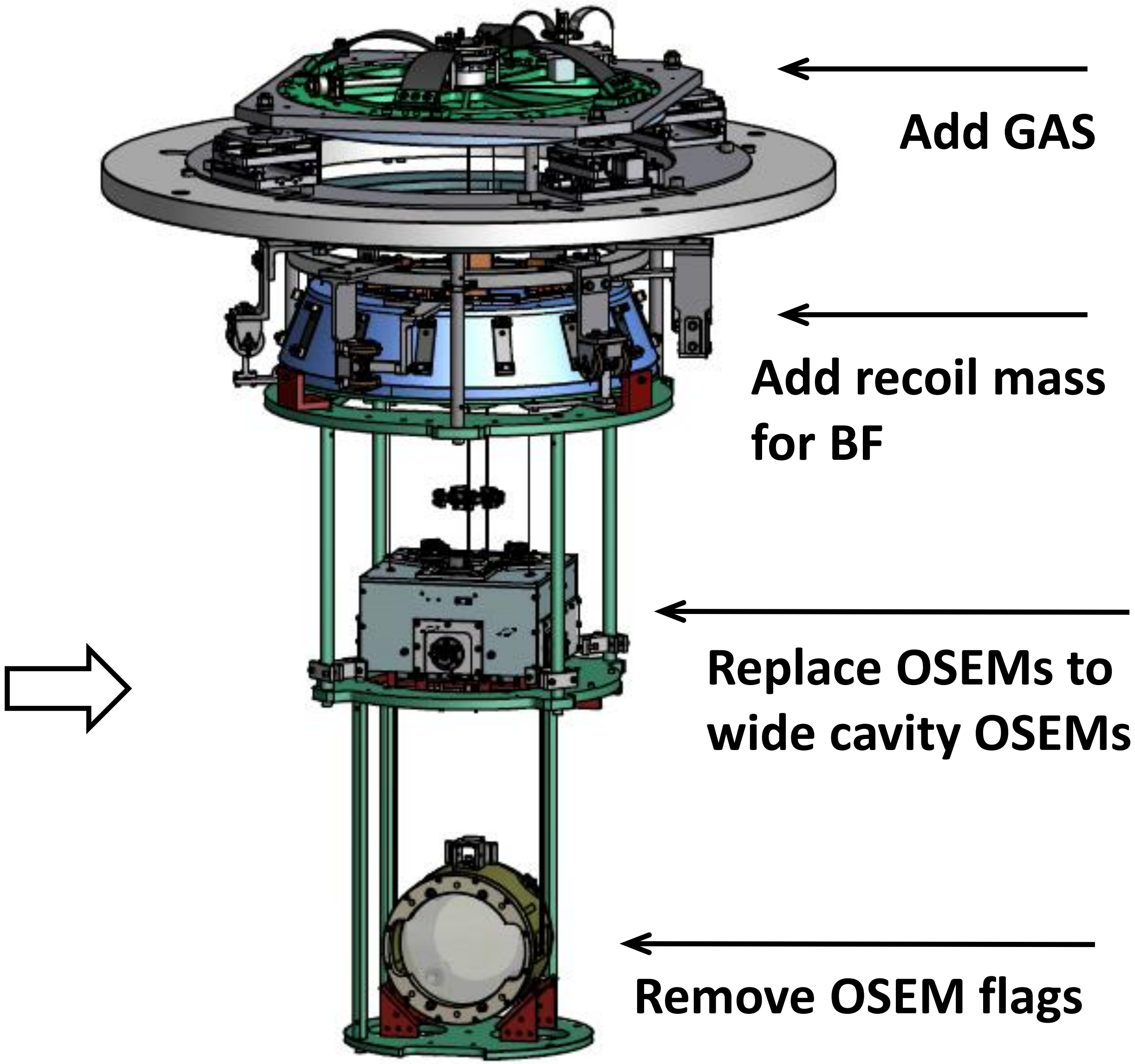
Contents

4. Introduction

bKAGRA PR SAS (= Type-Bp SAS)

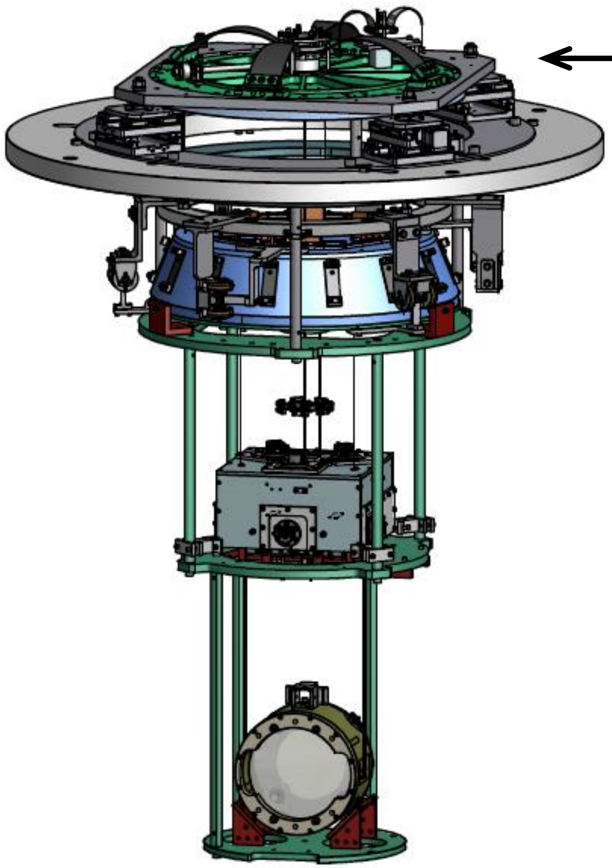


Type-Bpp SAS



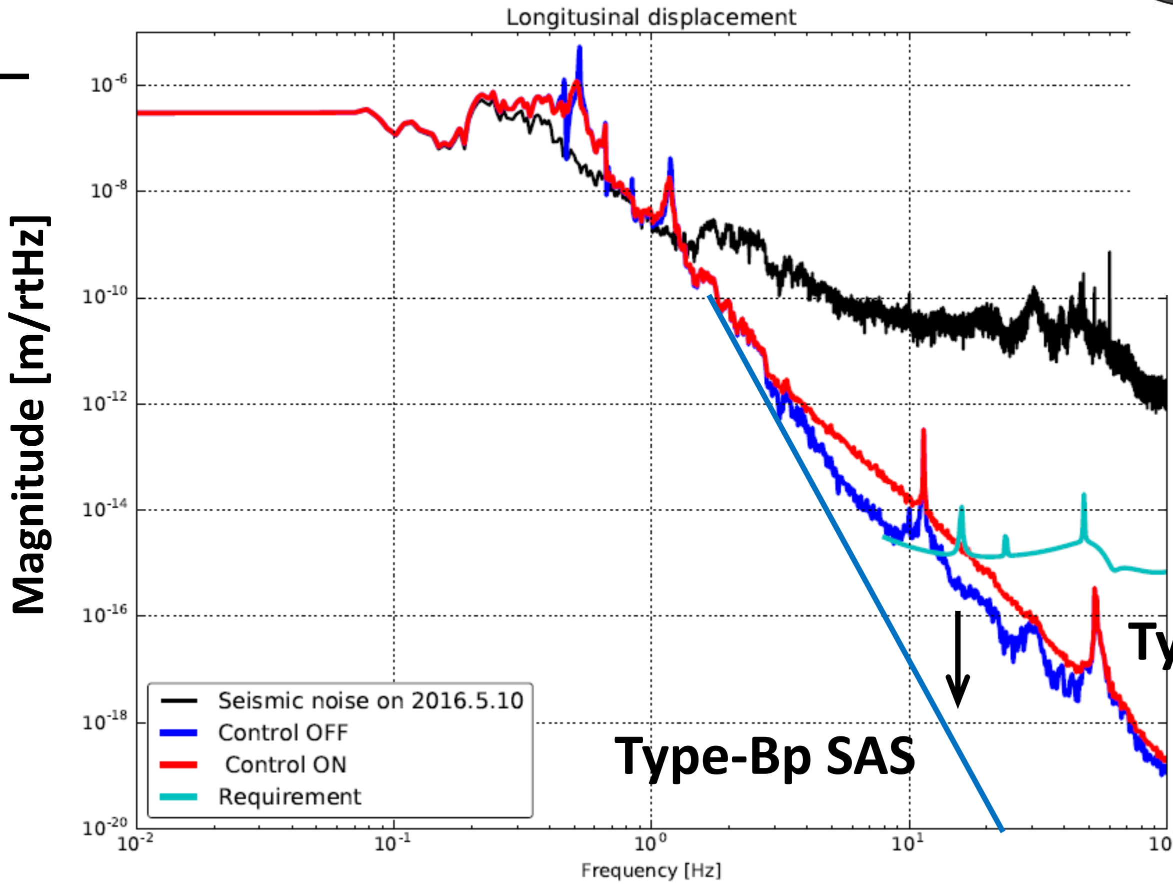
Type-Bp SAS

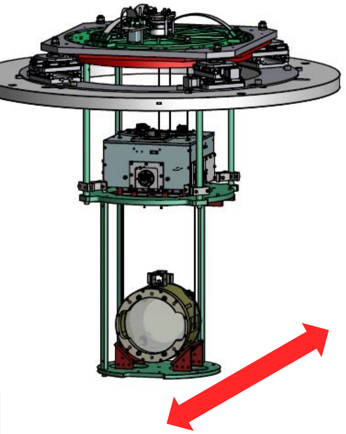
Modification



Type-Bp SAS

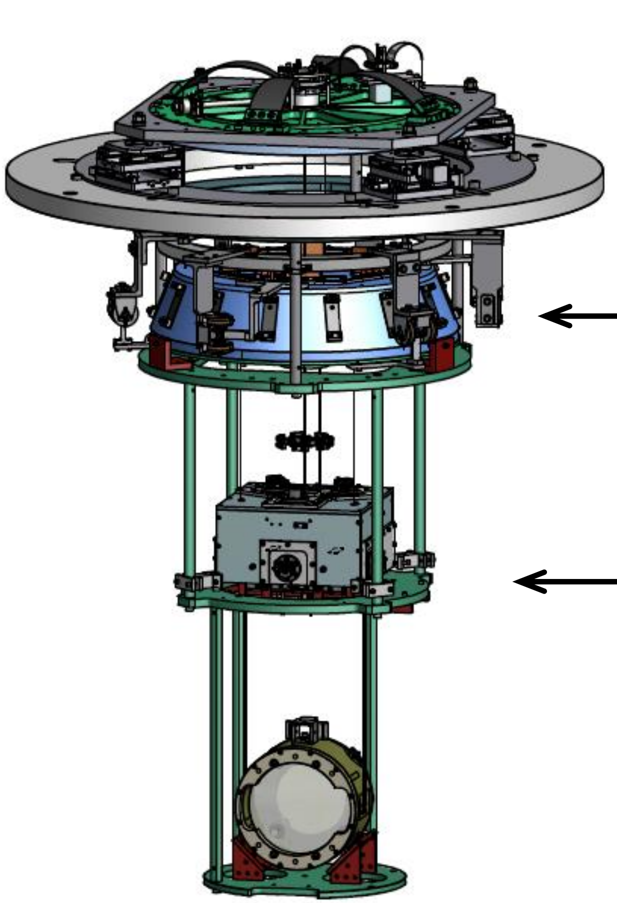
Standard GAS filter





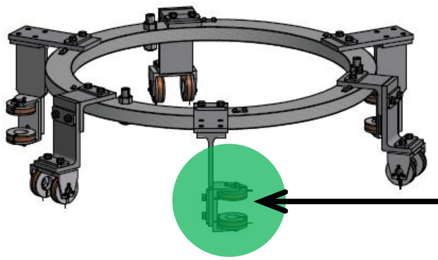
Purpose : improve vibration isolation performance.

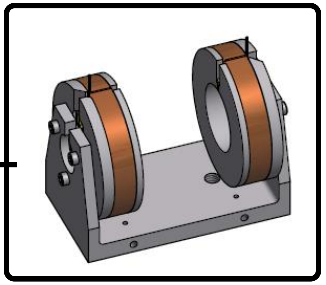
Modification

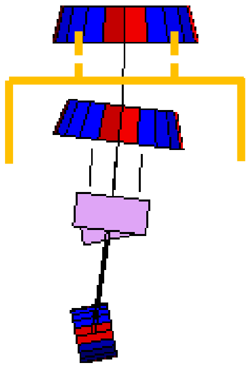


Type-Bp SAS

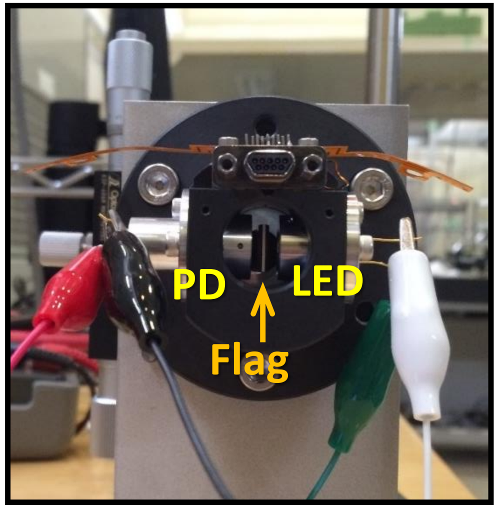
Bottom filter recoil mass

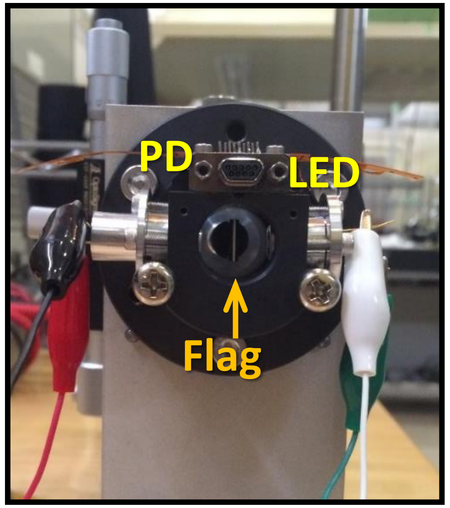






Purpose : damp the whole chain pendulum mode

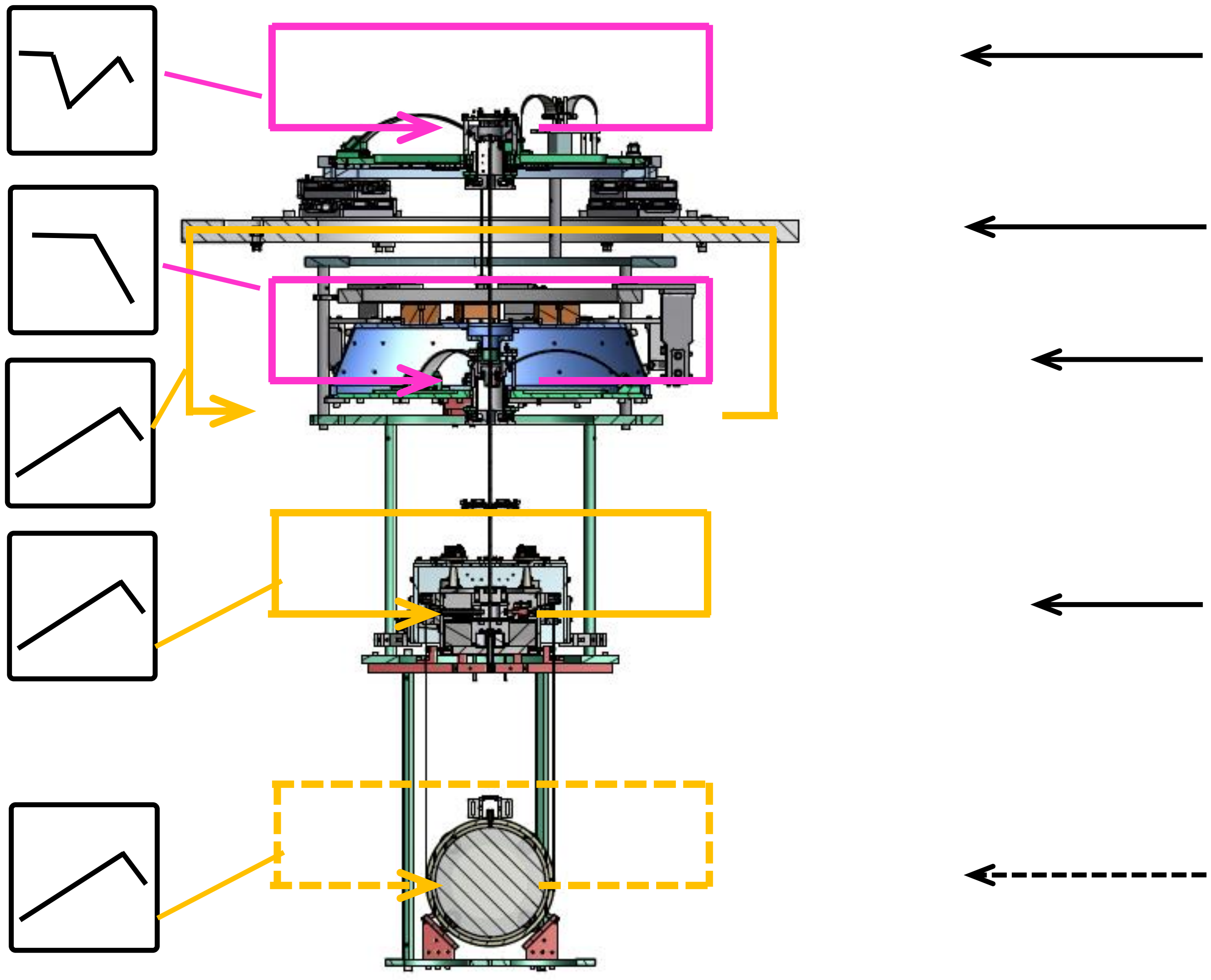




Purpose : reduce risk of breaking OSEM flags

Controllability of Type-Bp SAS

Control loops in damping phase



SF - GAS:
DC +damping control, with LVDT

BF - GAS:
DC control, with LVDT

BF – BR :
Damping control, with small LVDT

IM – IR :
Damping control, with OSEM

TM – RM :
(Damping control, with Oplev & OSEM) actuators

Requirements for control

Making servo filters for the each phase

1. Damping phase →
2. Lock-acquisition phase
3. Observation phase

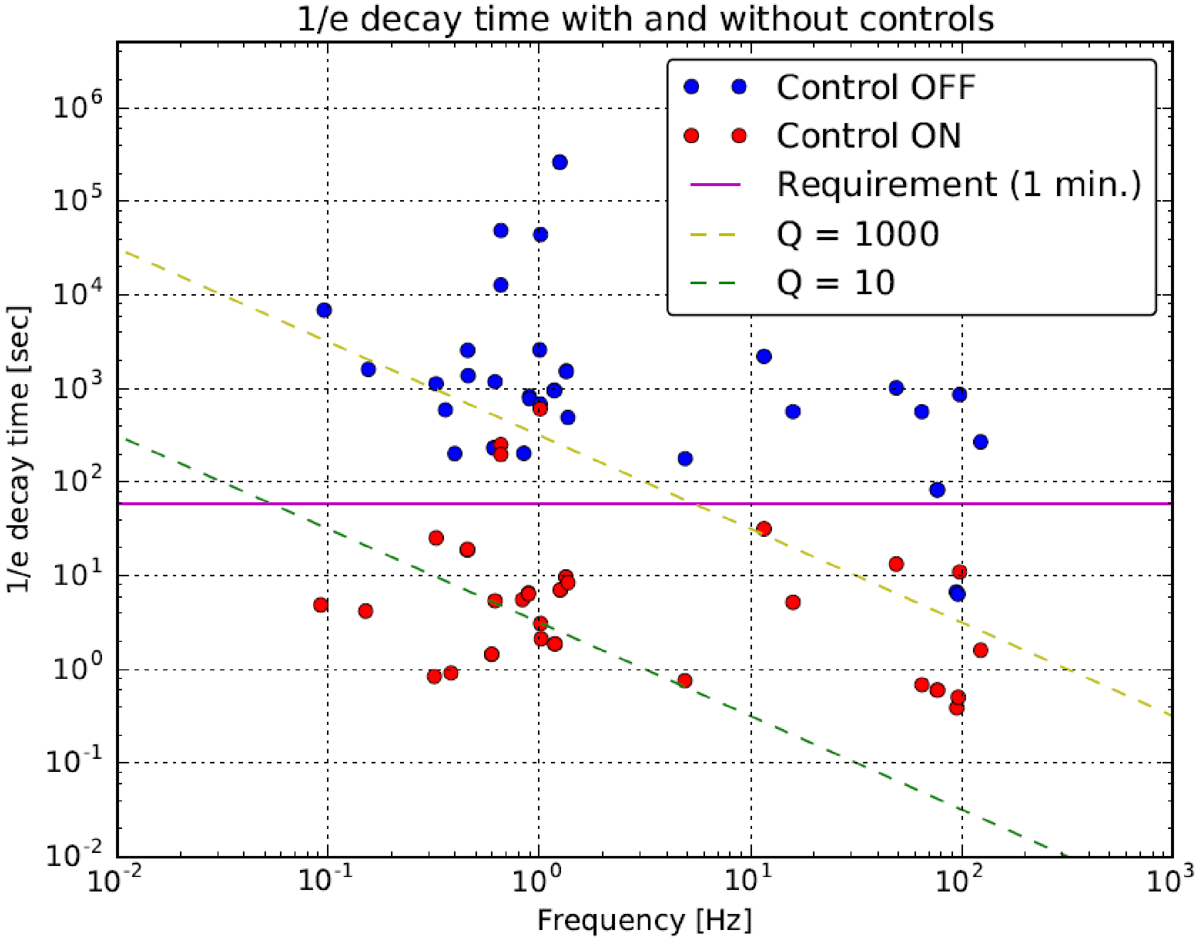
Damping

Requirement

1. Damping time < 1min.
2. RMS displacement (L) < 50 um
3. RMS displacement (T, V) < 1 mm
4. RMS displacement (P, Y) < 50 urad

Simulated damping time: Control ON vs. Control OFF

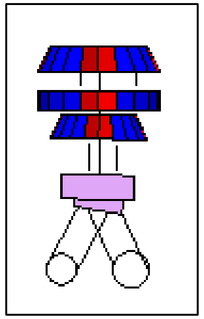
Model



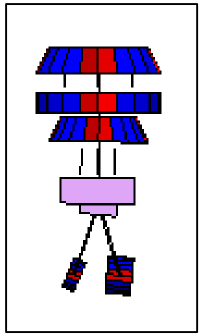
GAS : DC

IM : Damping (IMOSEM→ IMOSEM)

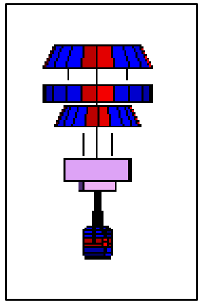
If oplev is not available…



252 sec



198 sec

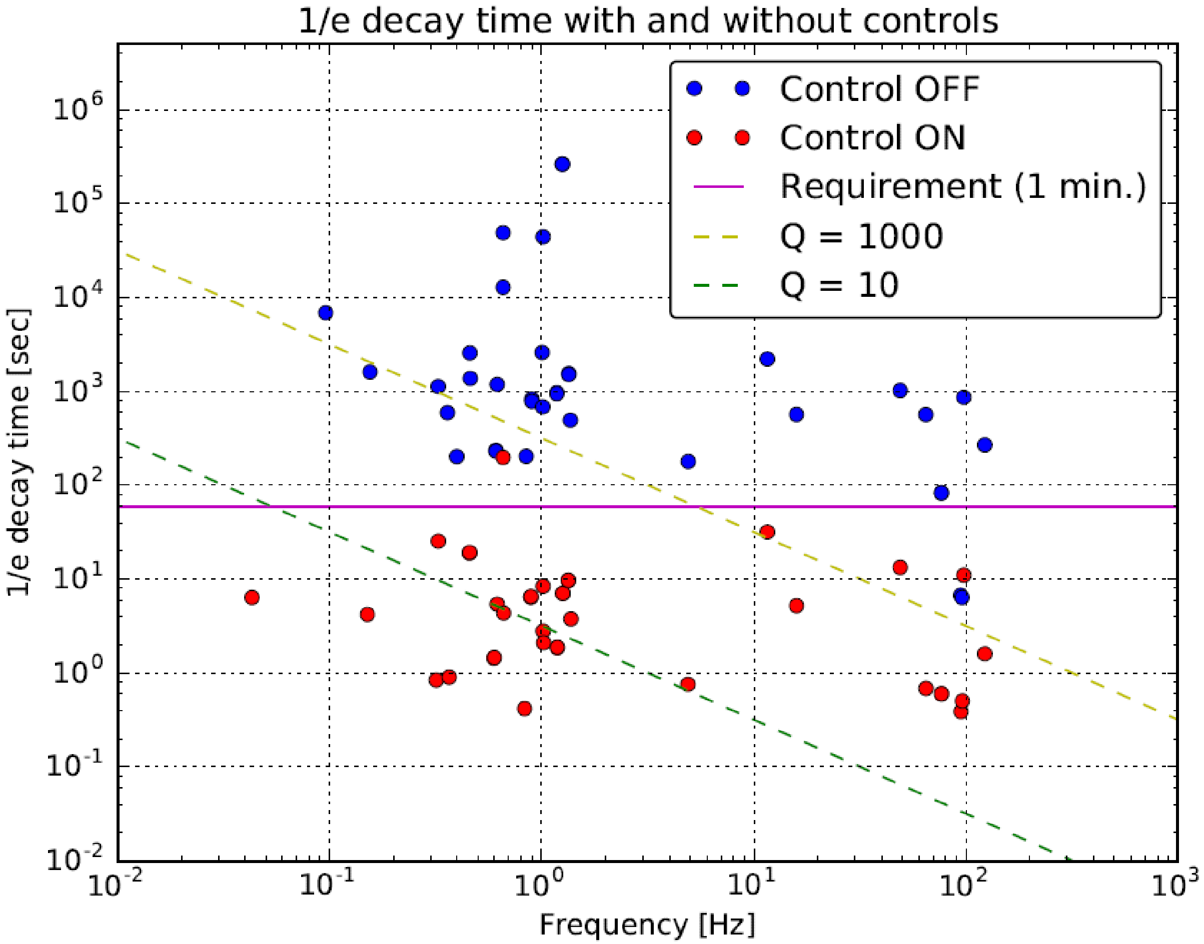


609 sec

To be investigated :
if oplev is available just after large disturbance.

Simulated damping time: Control ON vs. Control OFF

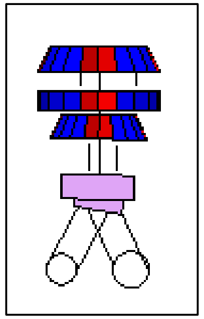
Model



GAS : DC

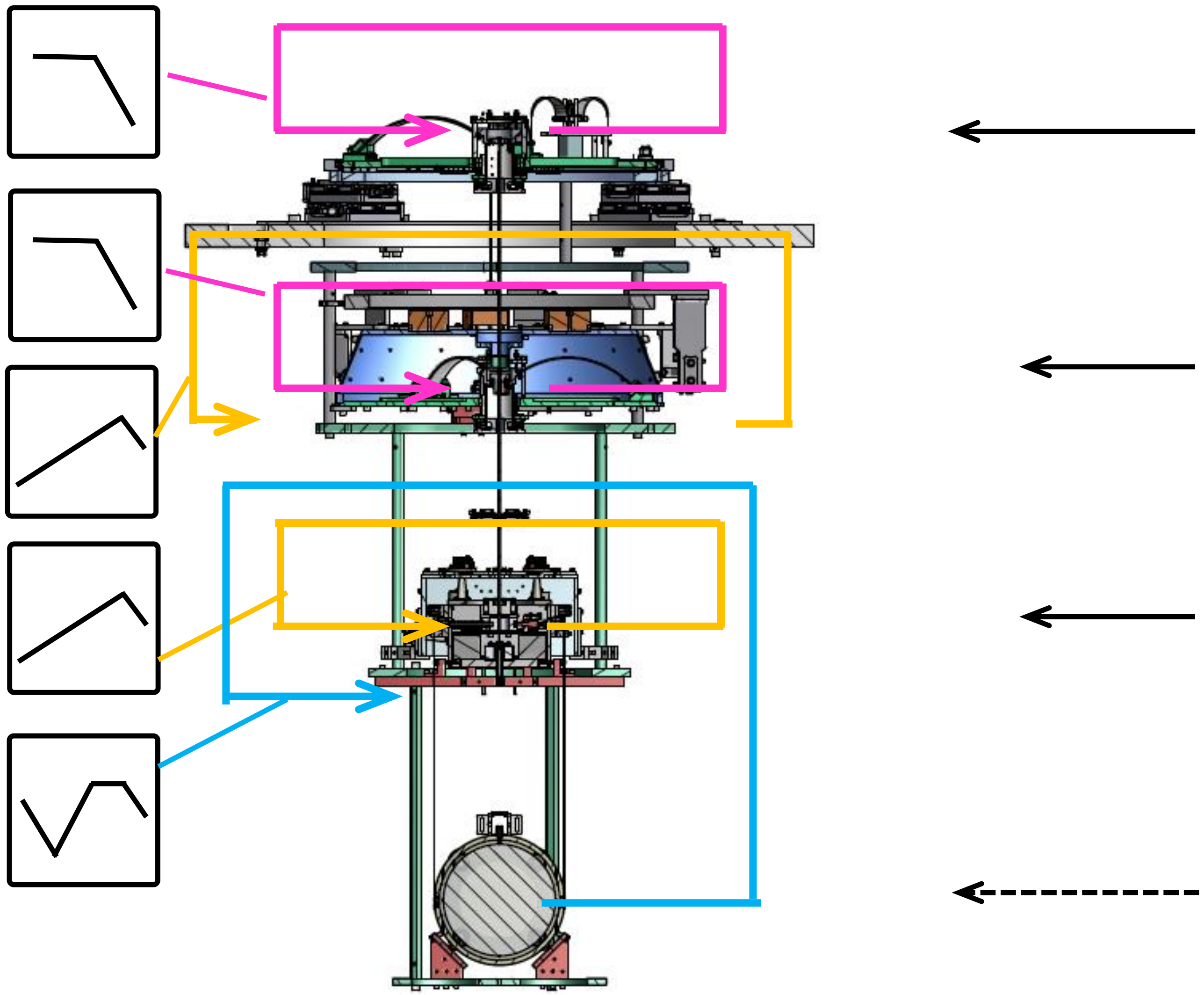
IM : Damping (IMOSEM→ IMOSEM)

TM : Damping (TMoplev → TMOSEM)



198 sec

Control loops in lock-acquisition phase



GAS :
DC control, with LVDT

BF – BR :
Damping control, with small LVDT

IM – IR :
Damping control, with OSEM
(only L, T, V, R)

TM – IM :
DC
+ damping control, with oplev & IM OSEM actuator

(Servo_lock5)

Requirements for control

＊＊(下)から計算すると、要求値は
～ 7, 8 um/sec 程度だったので、
ひとまず5um/sec に設定した。

Making servo filters for the each phase

1. Damping phase →
2. Lock-acquisition phase
3. Observation phase
4.

Requirement
1. RMS velocity (L) < 5 um/sec.
2. RMS displacement (T, V) < 1 mm
3. RMS displacement (P, Y) < 2 urad

＊＊

$$\text{(Maximum power of actuator)} \times \frac{d_{FWHW}}{\text{RMS velocity}} > M \times \text{(RMS velocity)}$$

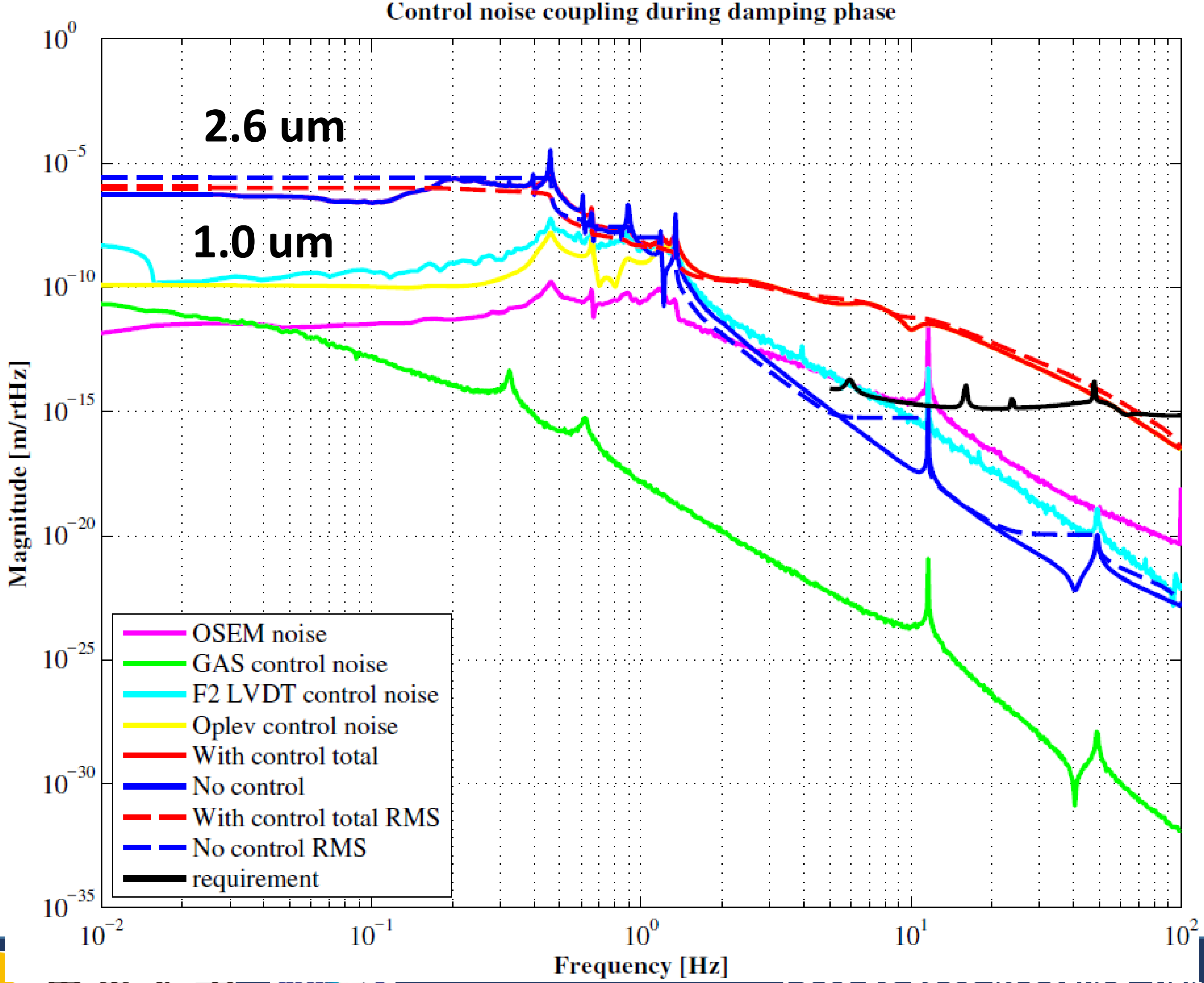
4* 0.129 N/A * 136e-3 A　　532 nm/57　　10 kg

→ RMS velocity < 8.1 um/sec

http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/KAGRA/Subgroups/VIS/ActuatorDesign

Longitudinal displacement fluctuation with “KamiokaHighNoise”

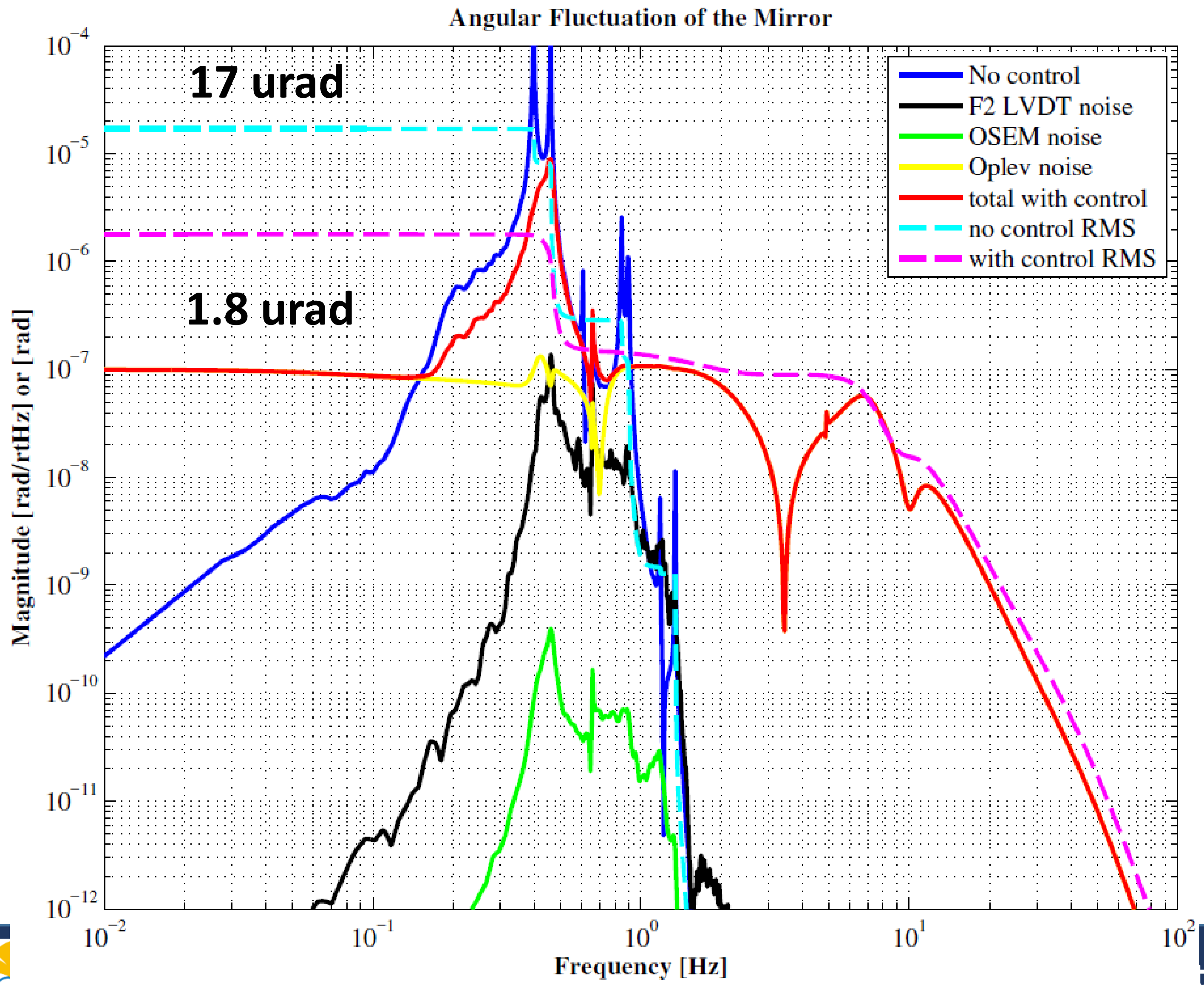
Model



Angular fluctuation (Pitch)

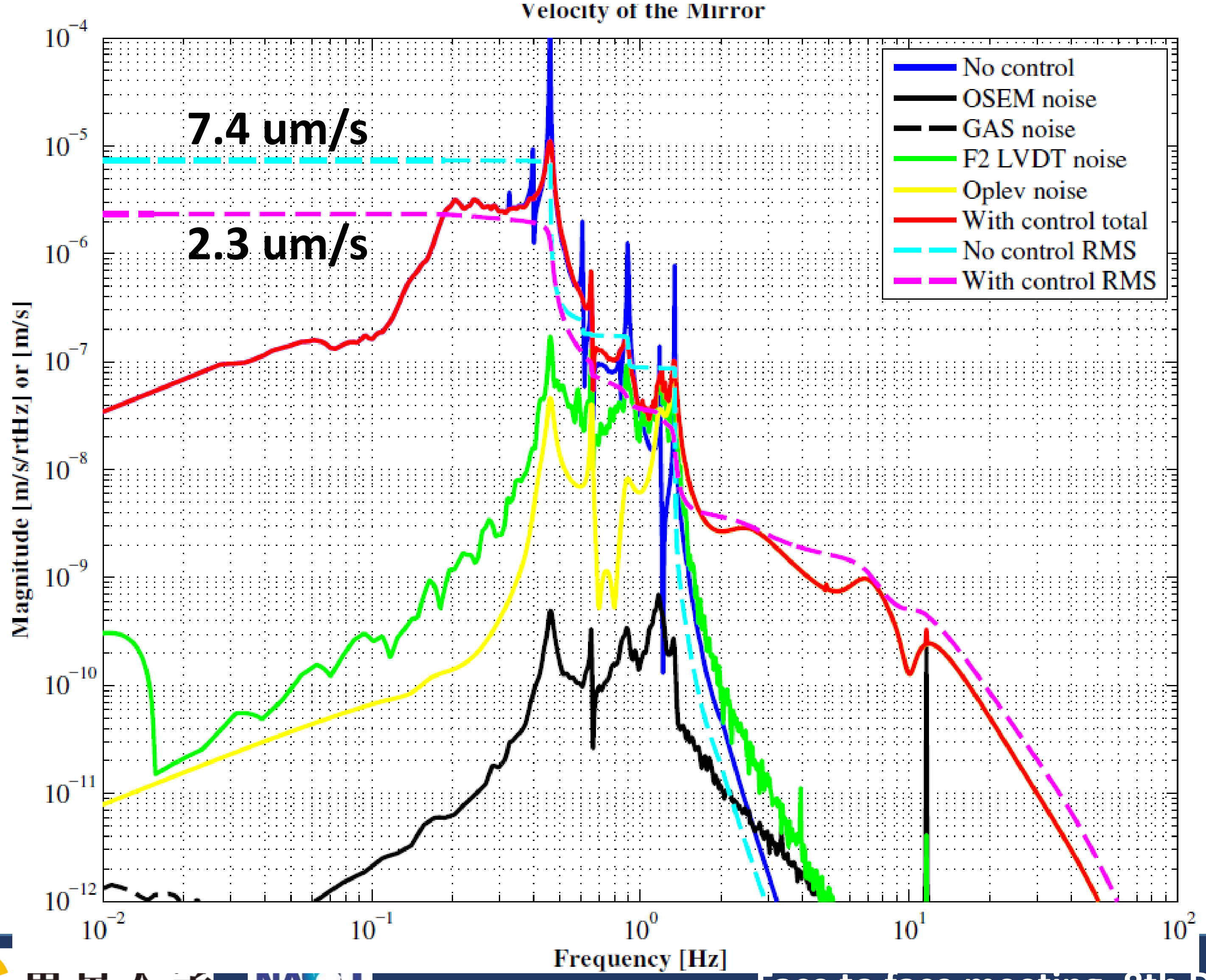
With “KamiokaHighNoise”

Model

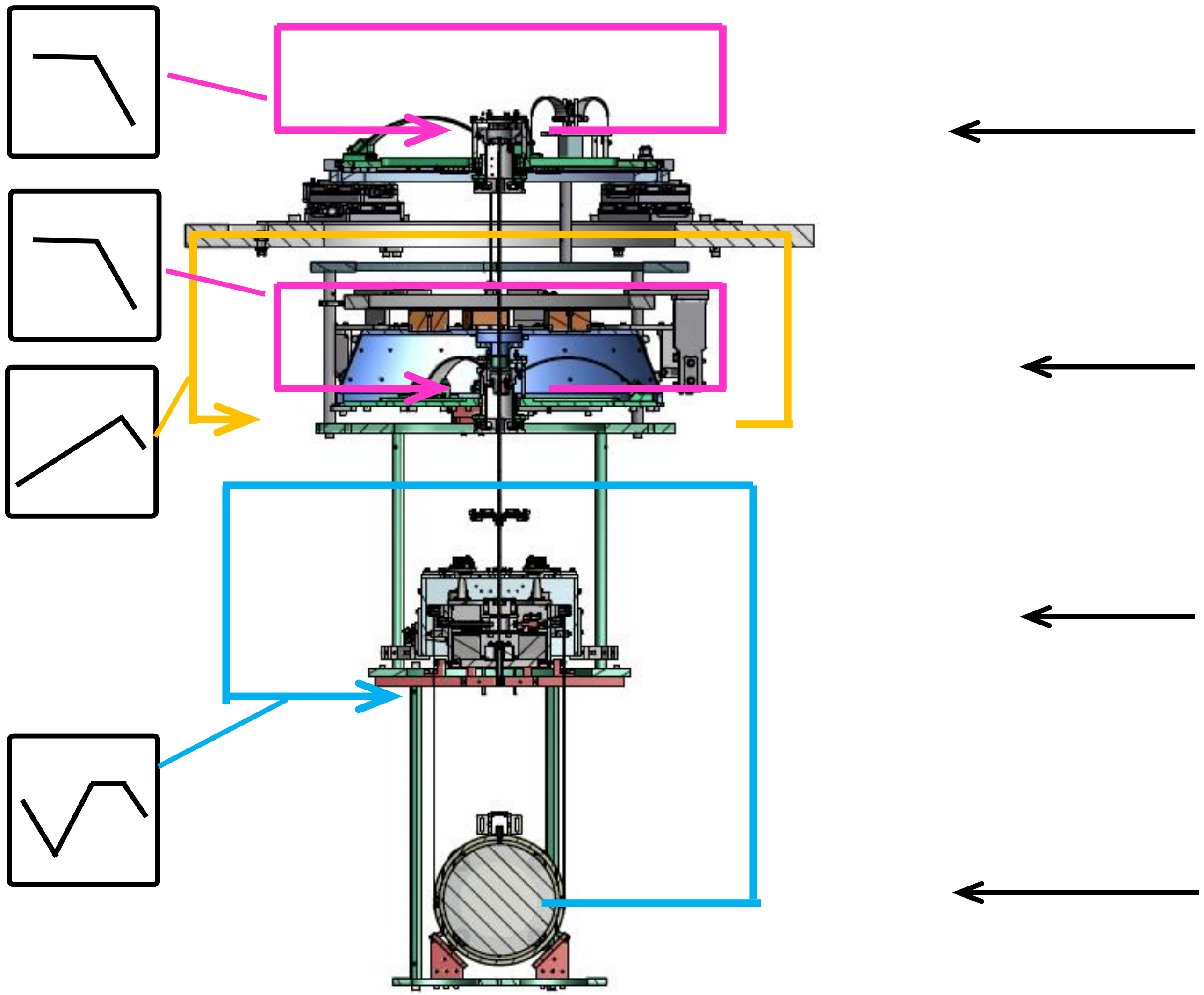


Longitudinal velocity fluctuation with “KamiokaHighNoise”

Model



Control loops in observation phase



GAS :
DC control, with LVDT

BF – BR :
Damping control, with small LVDT

IM – IR :
No control,

TM – IM :
DC
+ damping control, with WFS & IM OSEM actuator

(Servo_obs3)

Requirements for control

Making servo filters for the each phase

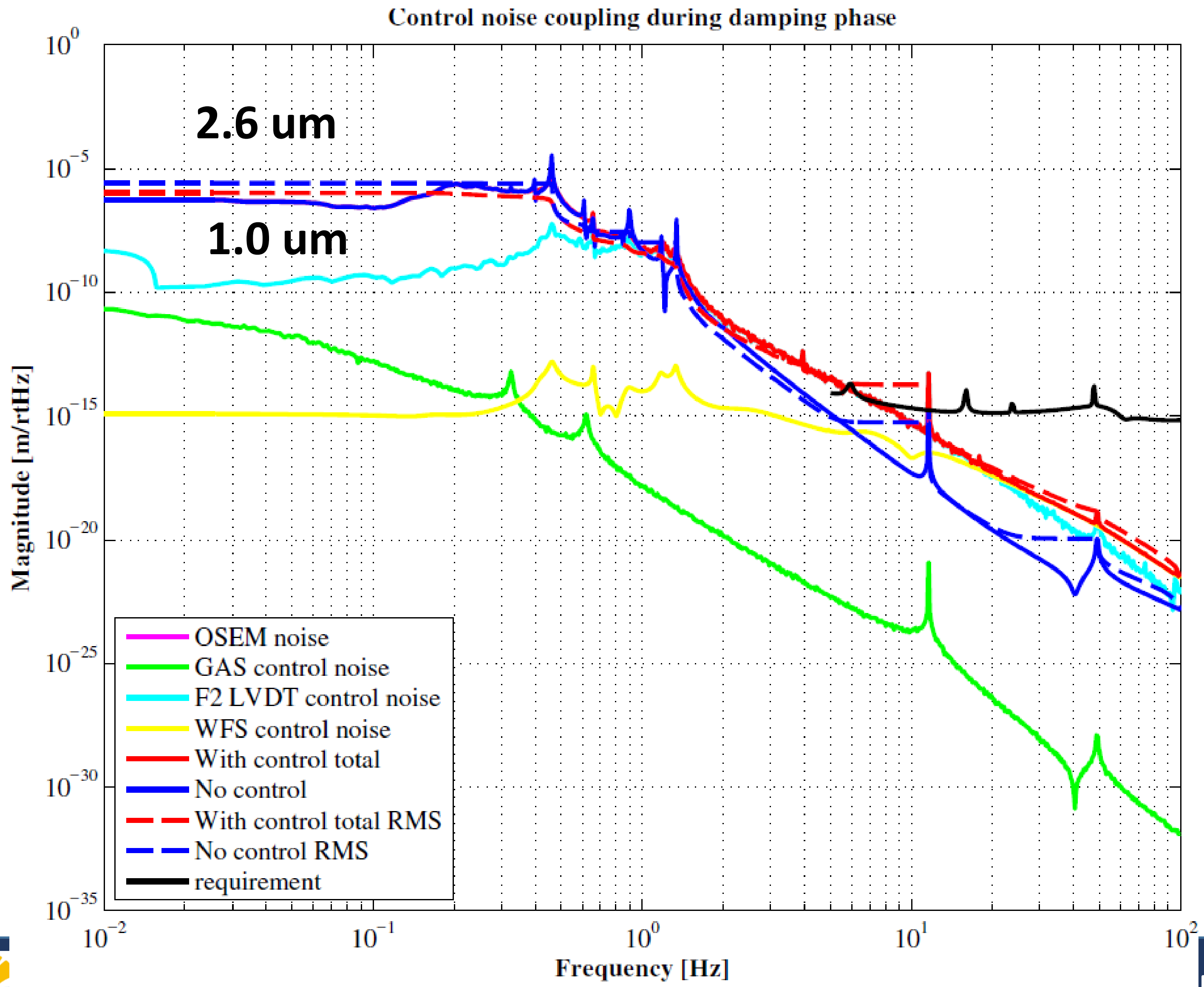
1. Damping phase →
2. Lock-acquisition phase
3. Observation phase
4.

Requirement

1. Displacement (L) < 1e-15 m at 10 Hz
2. RMS displacement (L) < 70 um
3. RMS displacement (T, V) < 1 mm
4. RMS displacement (P, Y) < 2 urad

Longitudinal displacement fluctuation With “KamiokaHighNoise”

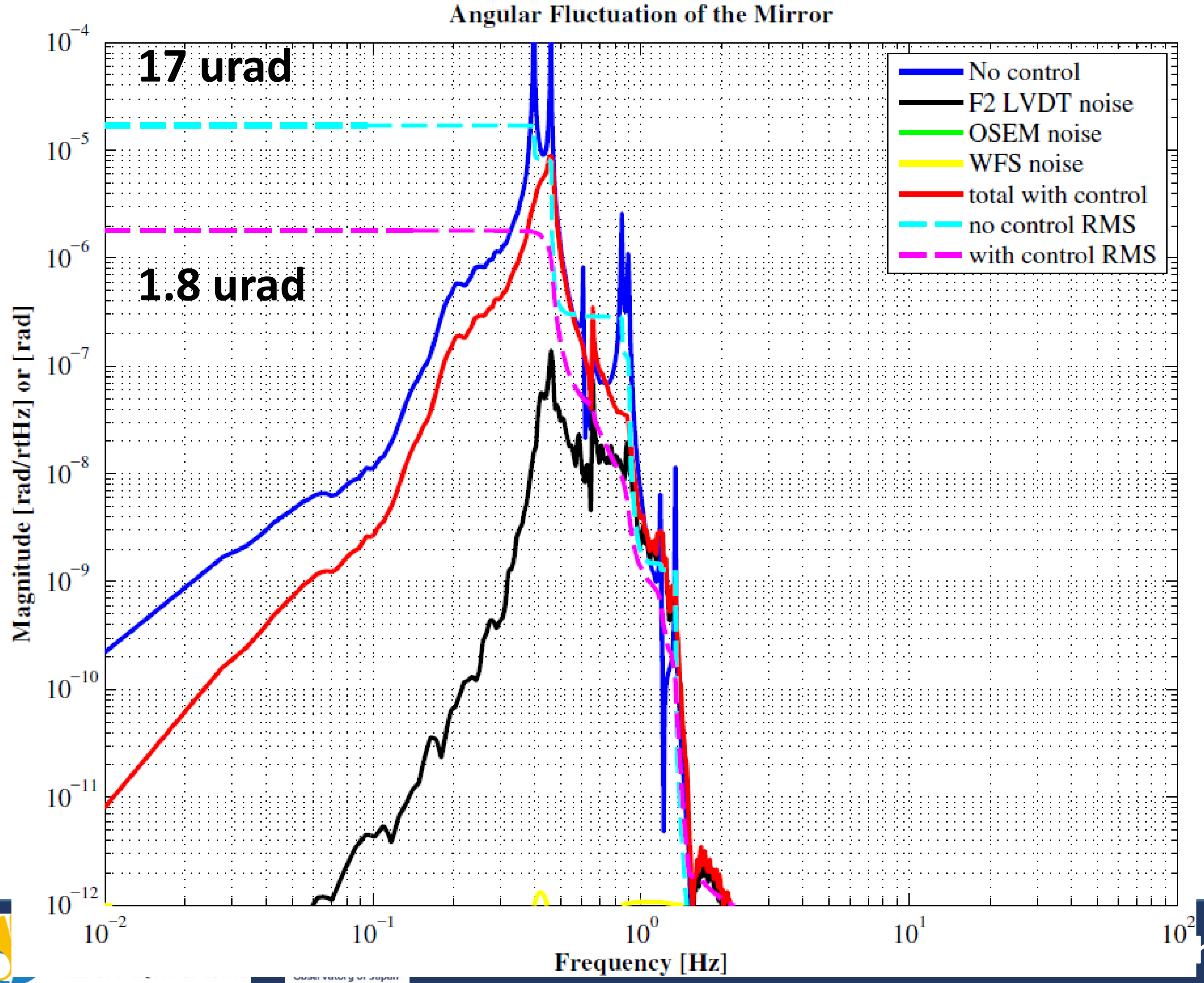
Model



Angular fluctuation (Pitch)

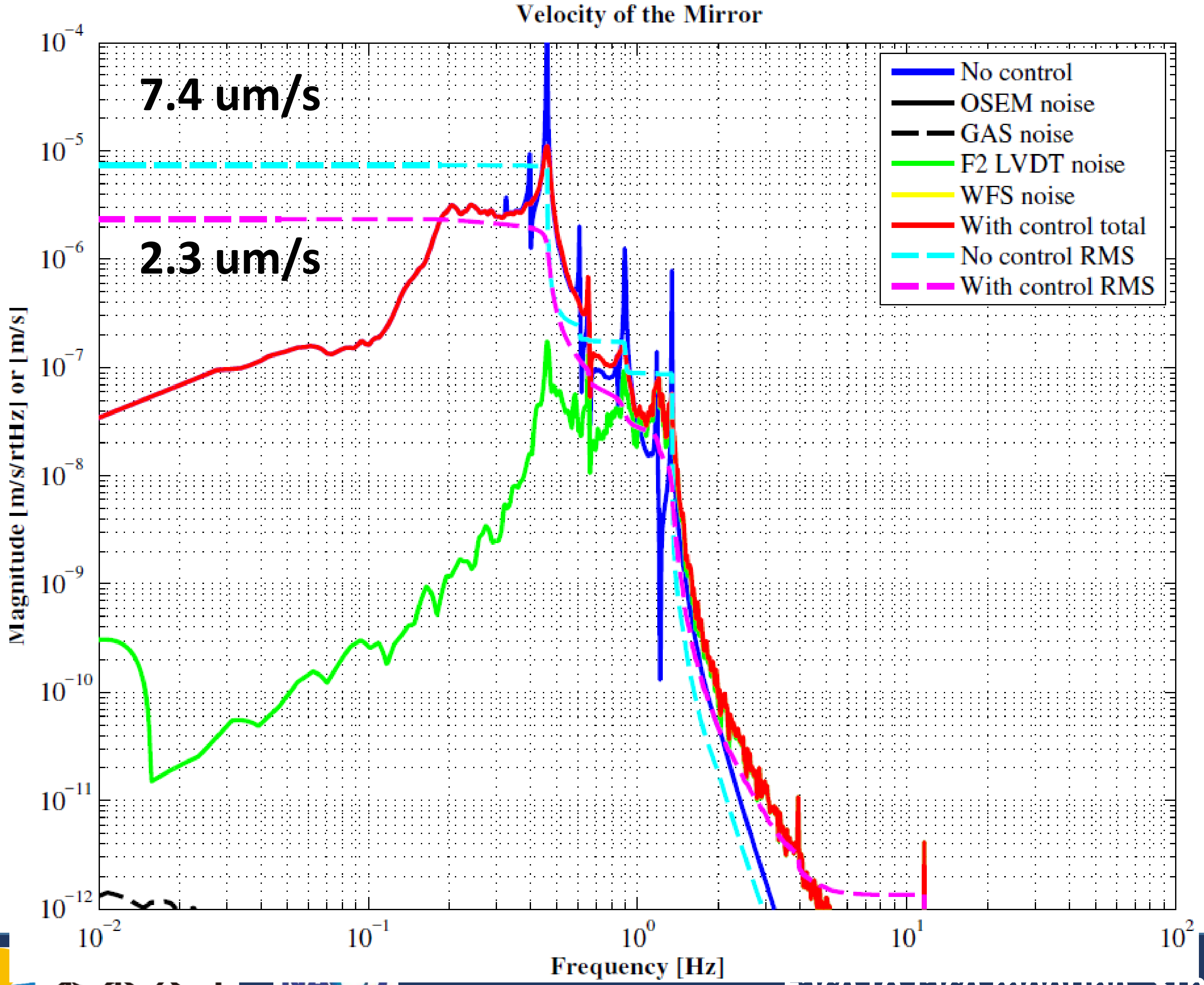
With "KamiokaHighNoise"

Model

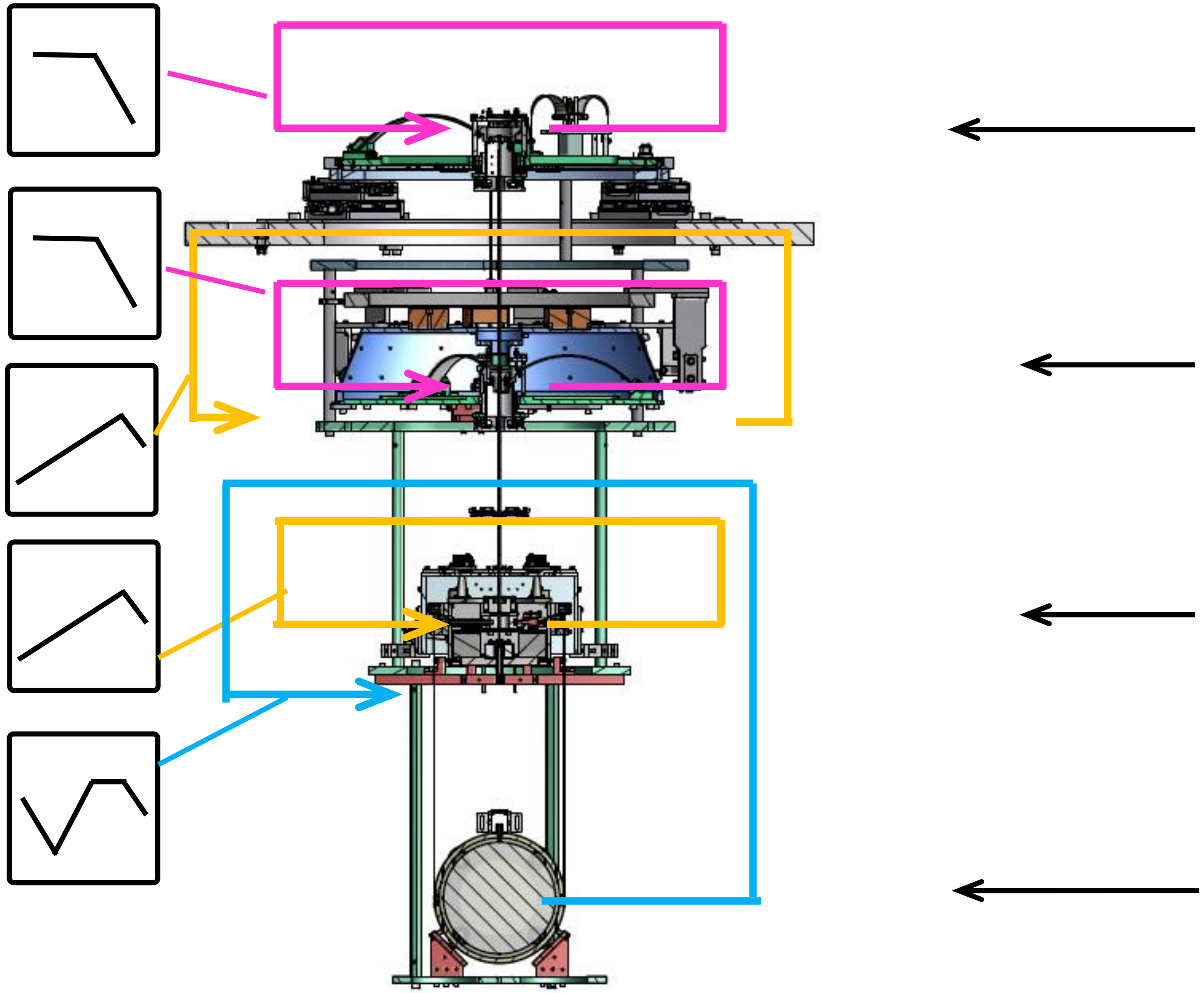


Longitudinal velocity fluctuation

Model



Control loops in observation phase with IM-OSEMs (another option)



GAS :
DC control, with LVDT

BF – BR :
Damping control, with small LVDT

IM – IR :
Damping control, with OSEM
(only L, T, R)

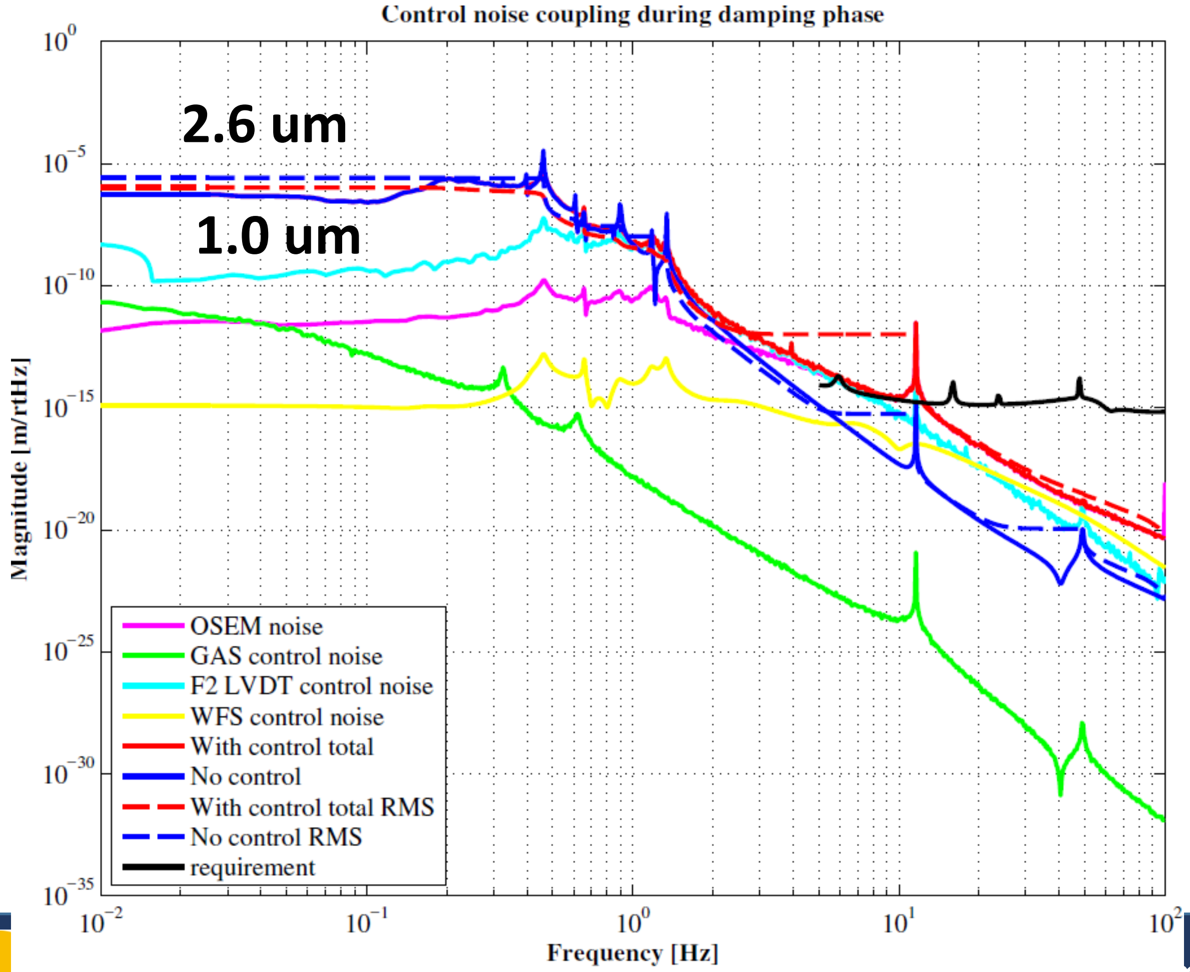
TM – IM :
DC
+ damping control, with WFS & IM OSEM actuator

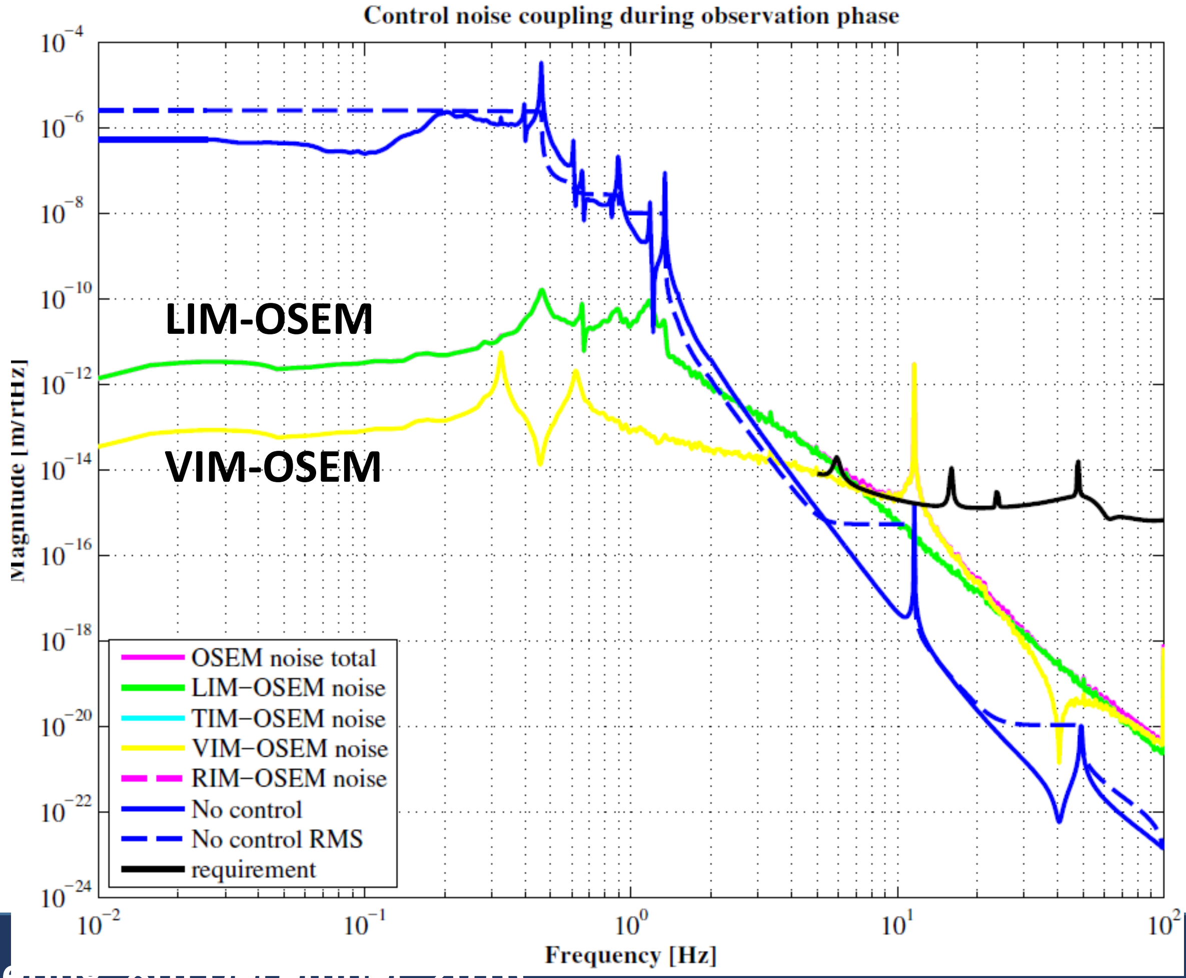
(Servo_obs5)

Longitudinal displacement fluctuation   With “KamiokaHighNoise”

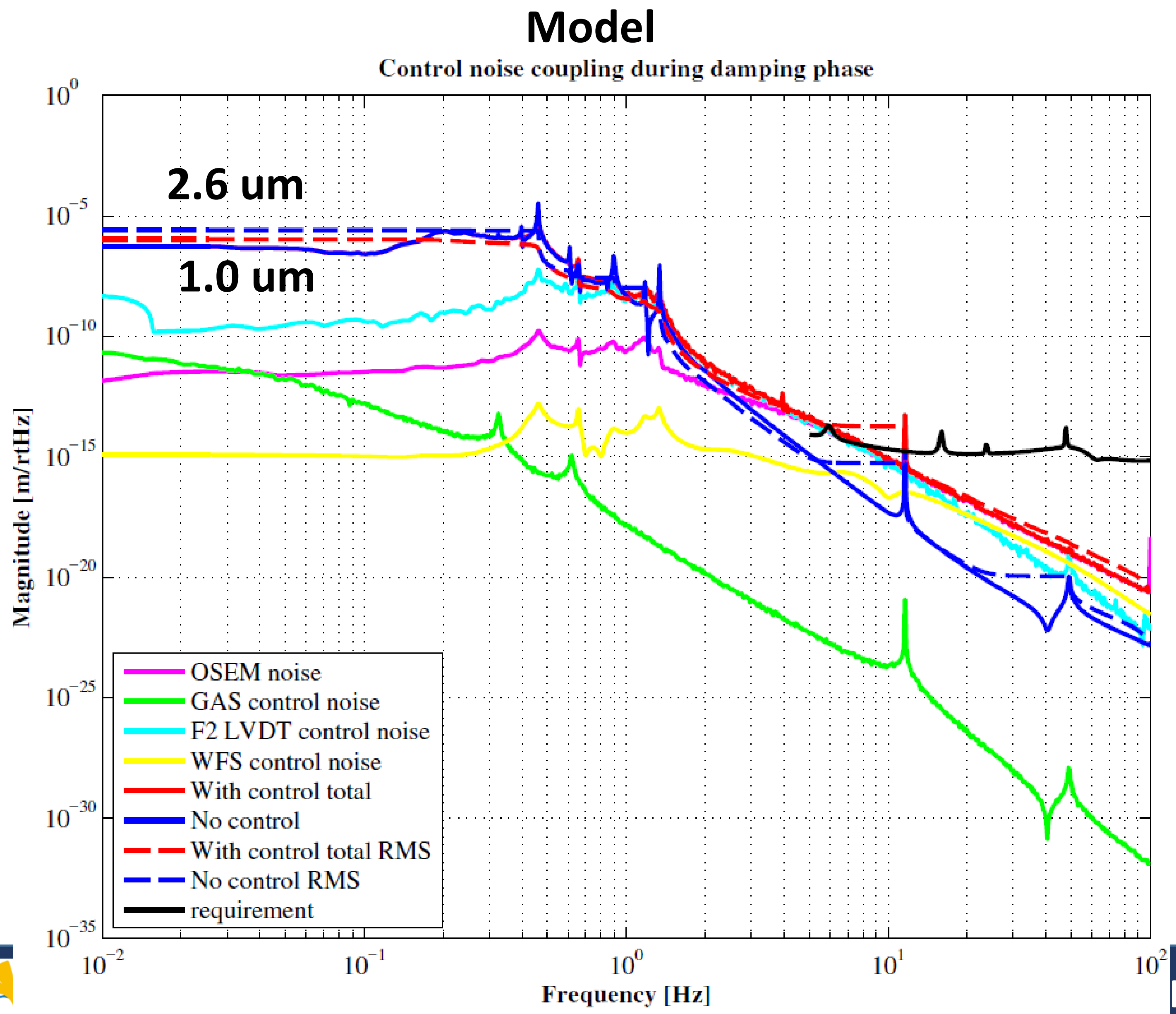
IM – IR : If IM-OSEM damping controls are ON (for L, T, V, R DoF)

Model





Longitudinal displacement fluctuation   With "KamiokaHighNoise"

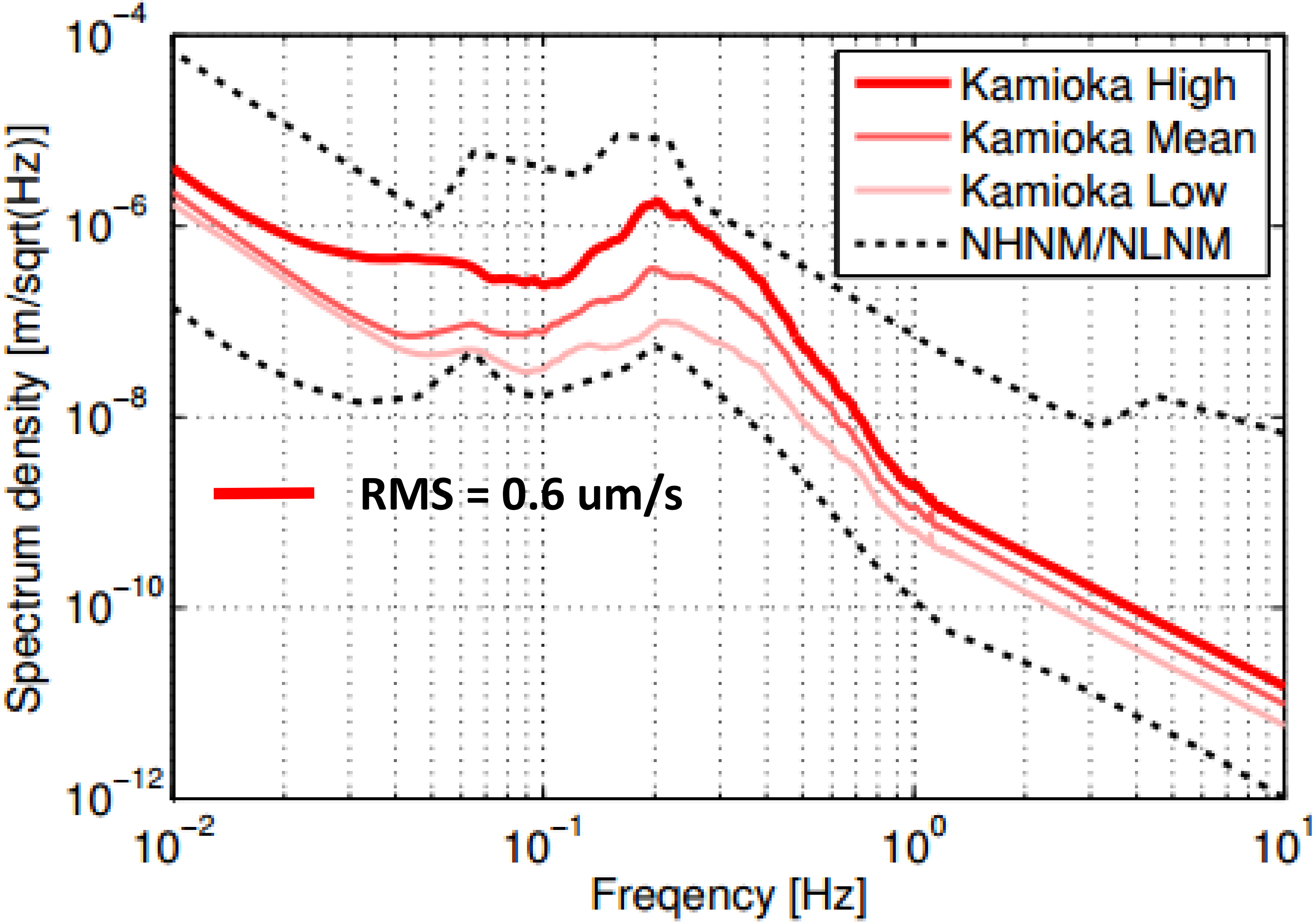


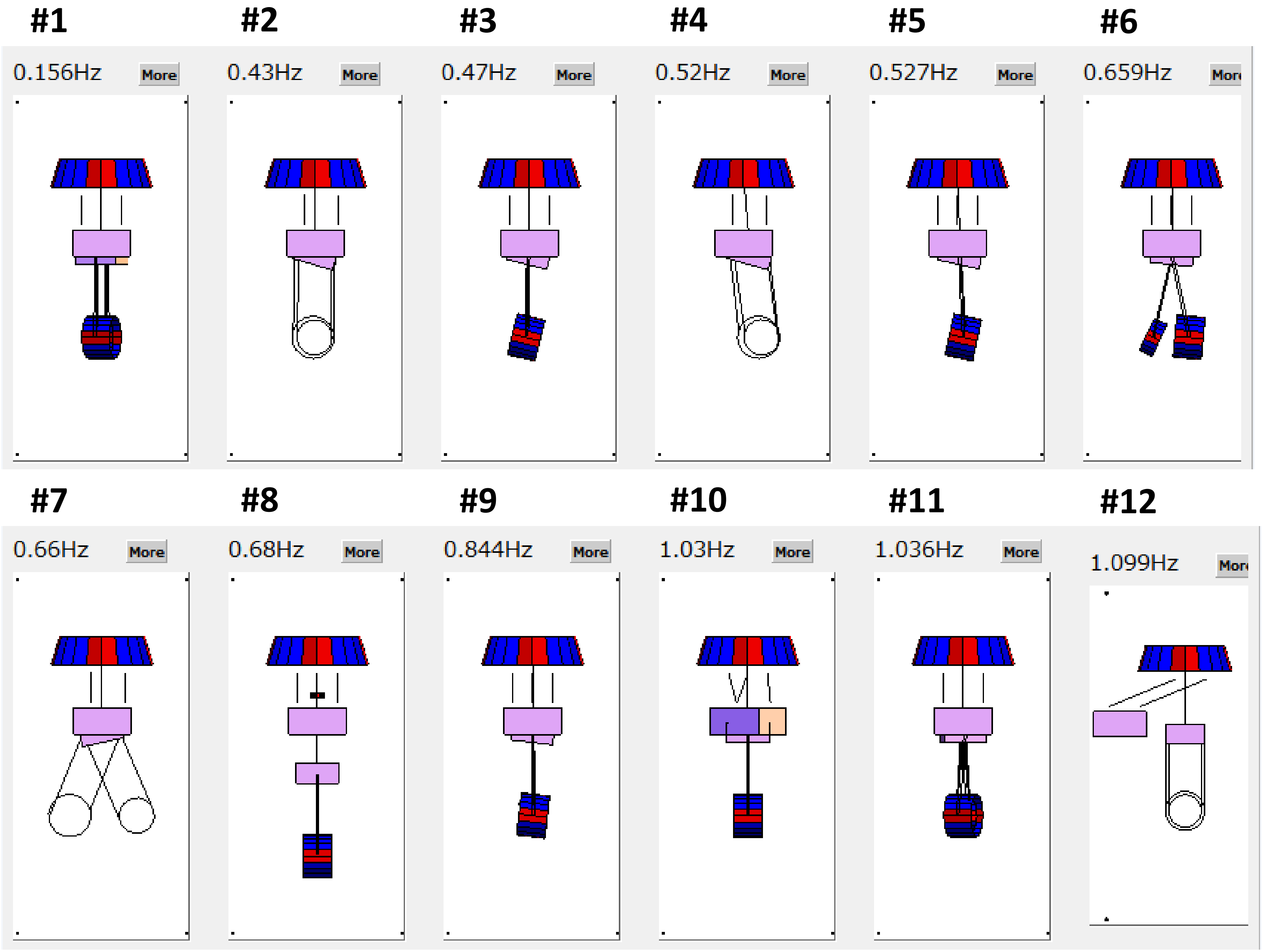
IM – IR :

If IM-OSEM damping controls are ON (for L, T, R DoF)

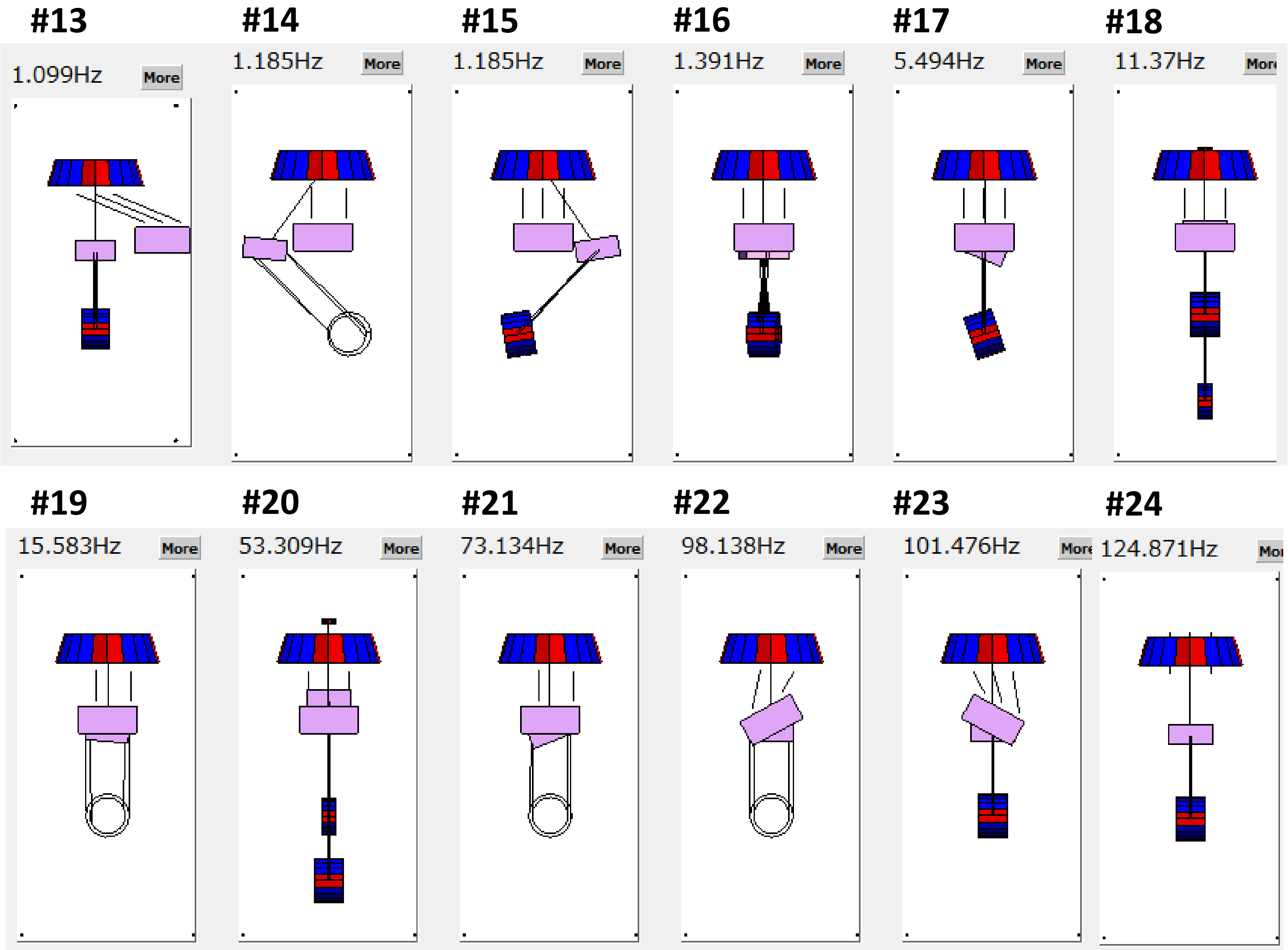
Using OSEM would be available only for type-Bp SAS though, maybe..

Assumed longitudinal seismic noise

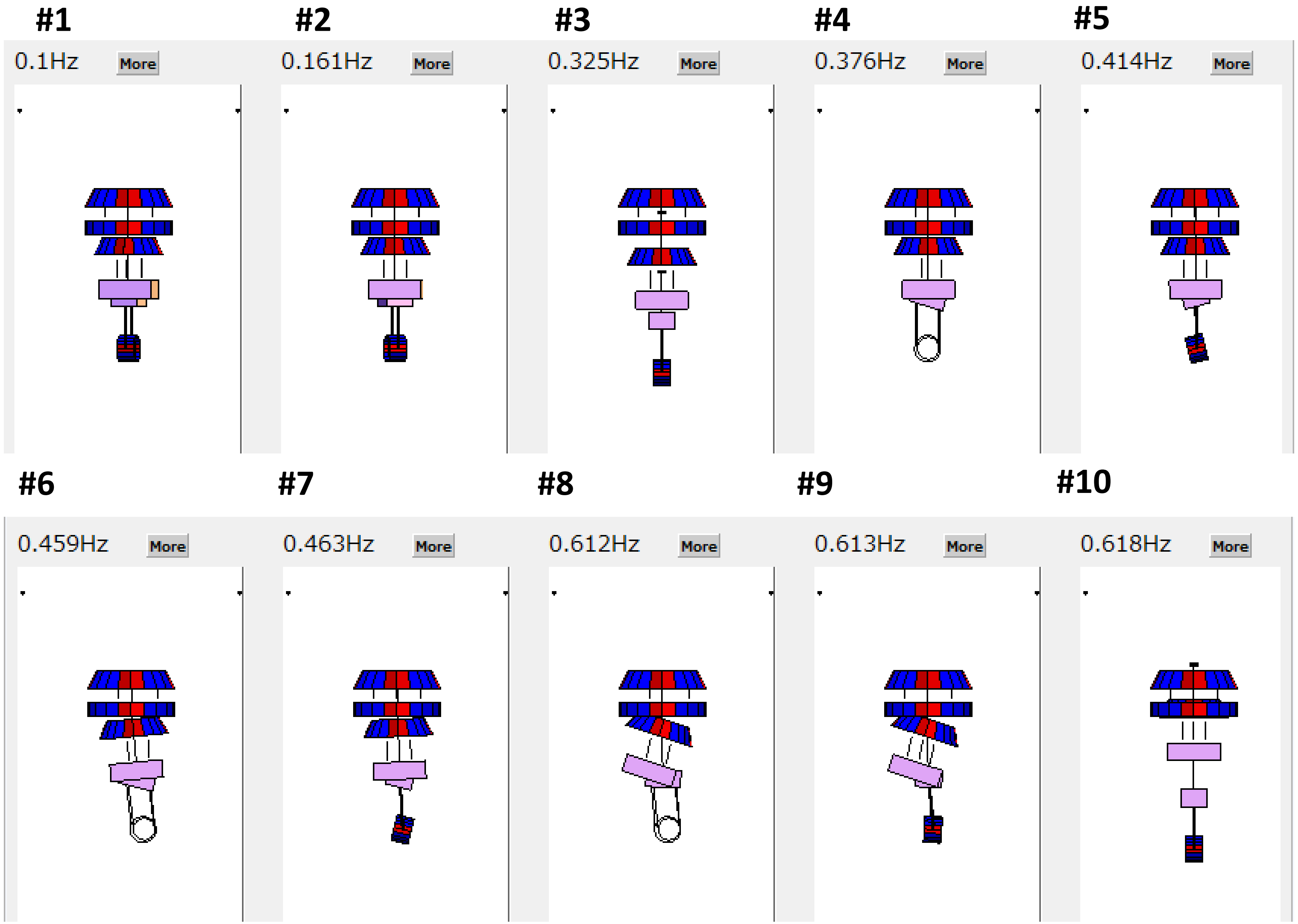


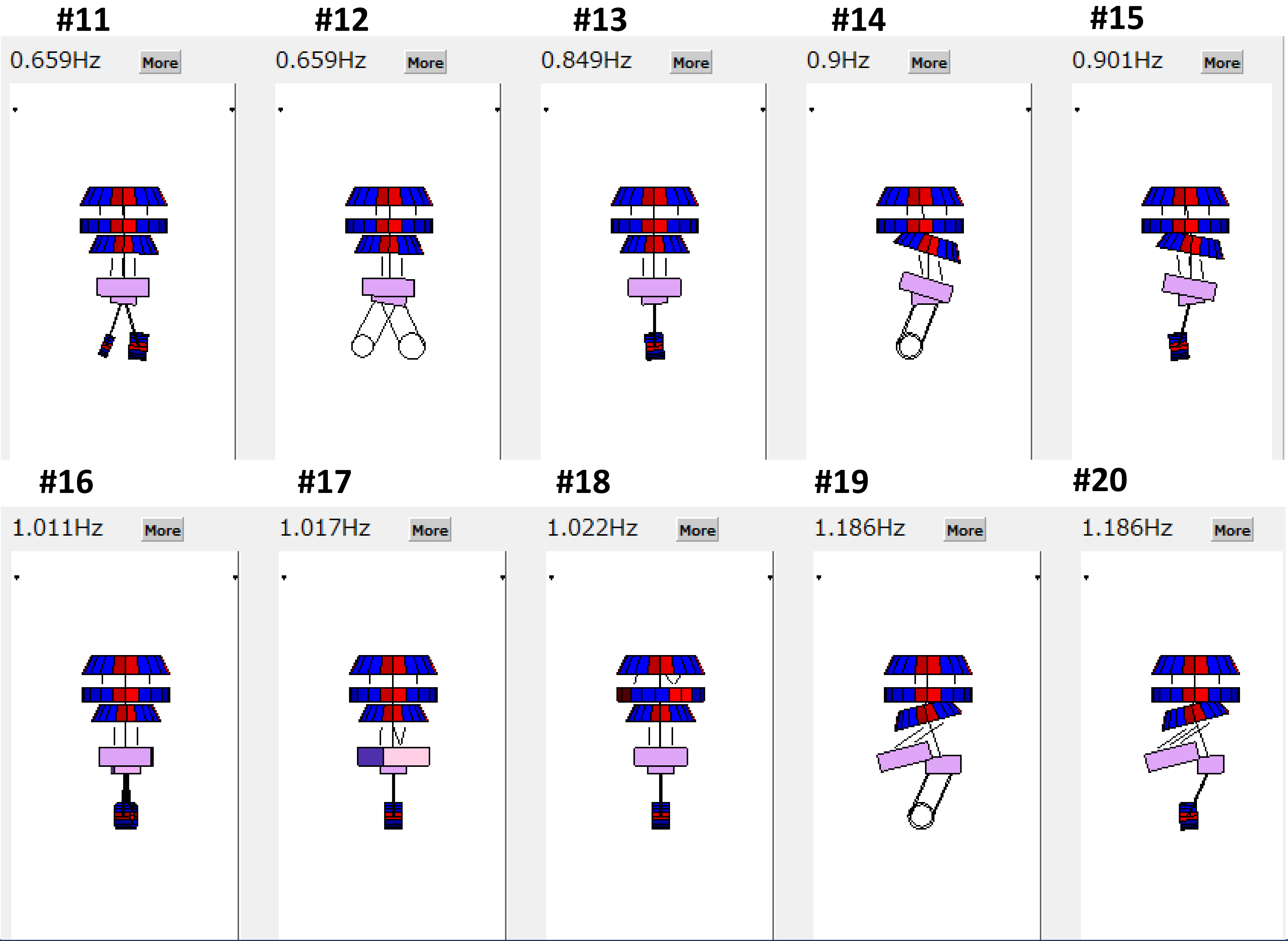


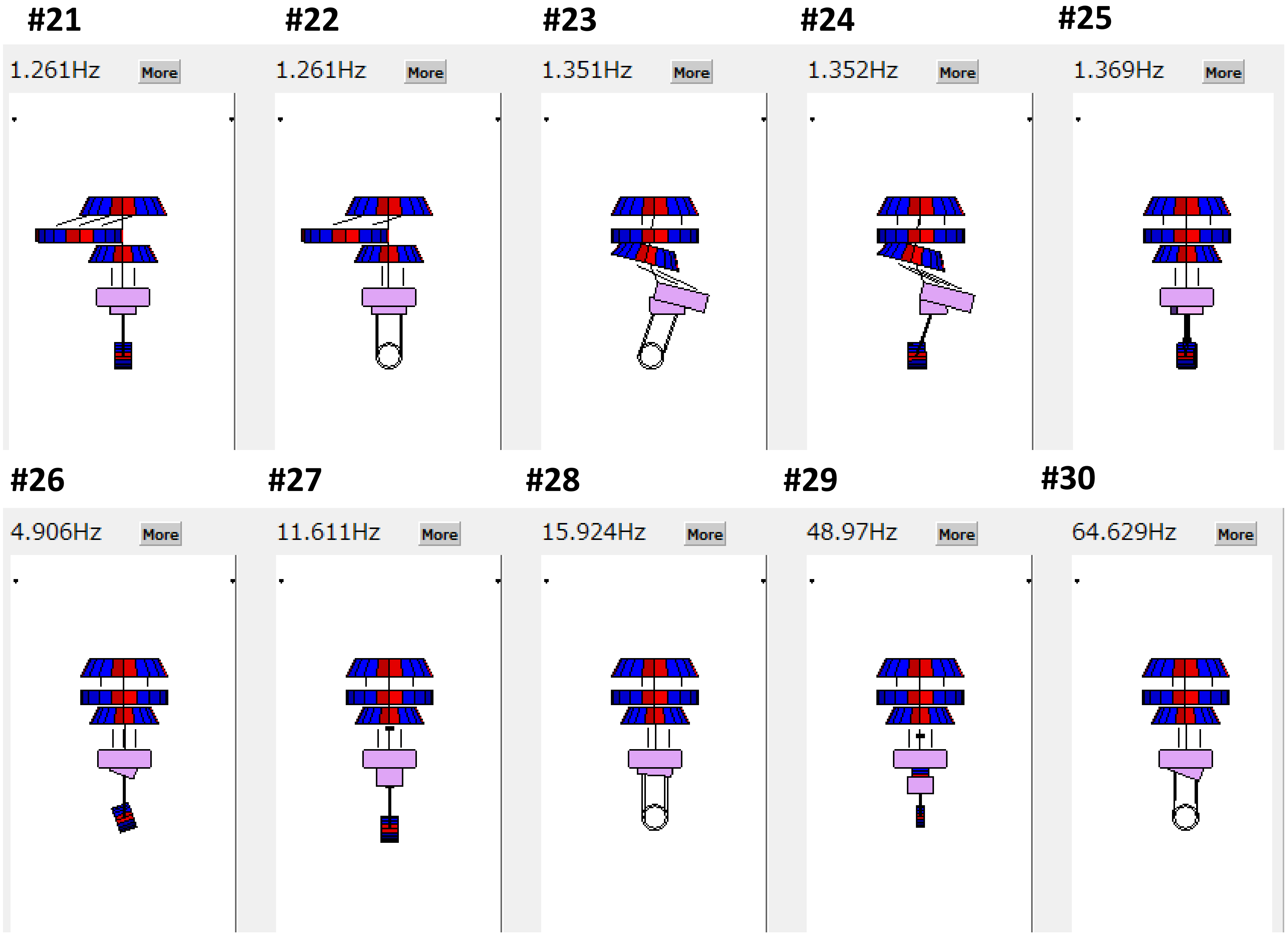
TypeBpp SAS
Eigen mode List : 24 modes


#13
1.099Hz
More
#14
1.185Hz
More
#15
1.185Hz
More
#16
1.391Hz
More
#17
5.494Hz
More
#18
11.37Hz
#19
15.583Hz
More
#20
53.309Hz
More
#21
73.134Hz
More
#22
98.138Hz
More
#23
101.476Hz
#24
124.871Hz

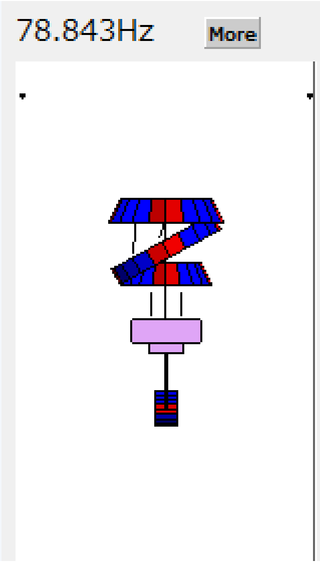
TypeBp SAS
Eigen mode List : 36 modes



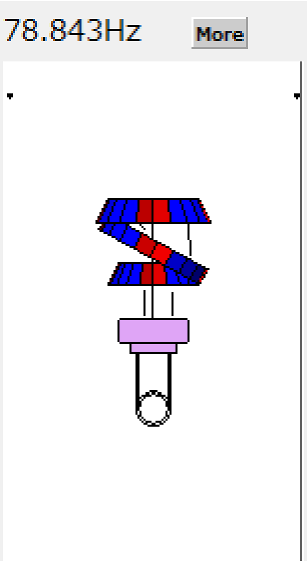

#11
0.659Hz
More
#12
0.659Hz
More
#13
0.849Hz
More
#14
0.9Hz
More
#15
0.901Hz
More
#16
1.011Hz
More
#17
1.017Hz
More
#18
1.022Hz
More
#19
1.186Hz
More
#20
1.186Hz
More


#21
1.261Hz More
#22
1.261Hz More
#23
1.351Hz More
#24
1.352Hz More
#25
1.369Hz More
#26
4.906Hz More
#27
11.611Hz More
#28
15.924Hz More
#29
48.97Hz More
#30
64.629Hz More

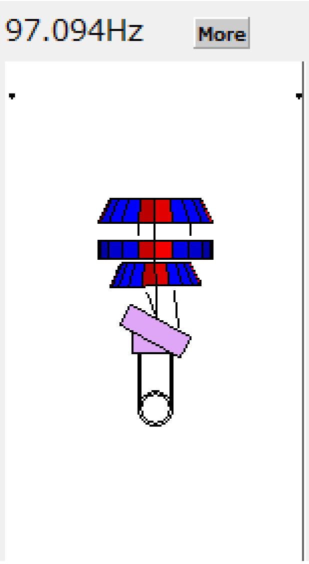
#31



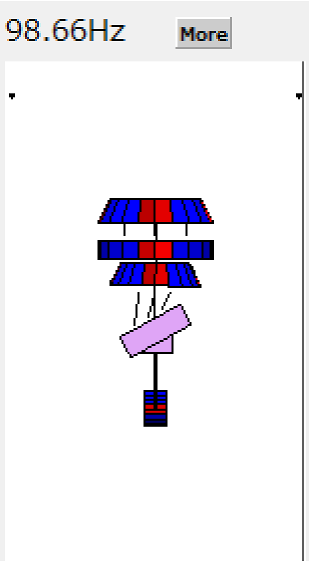
#32



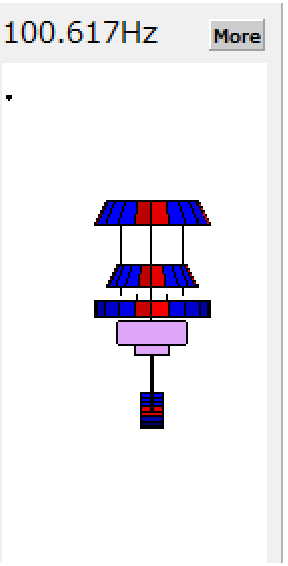
#33



#34



#35



#36