VIBRATION ISOLATION SYSTEM FOR THE CRYOGENIC MIRRORS IN KAGRA

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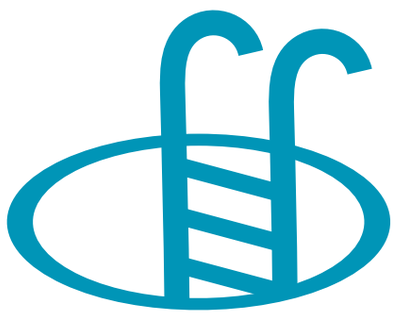
CONTENTS

- Vibration isolation system for KAGRA
- Type-A suspension: overview
- Characterization and control test


KAGRA

KAGRA FEATURES



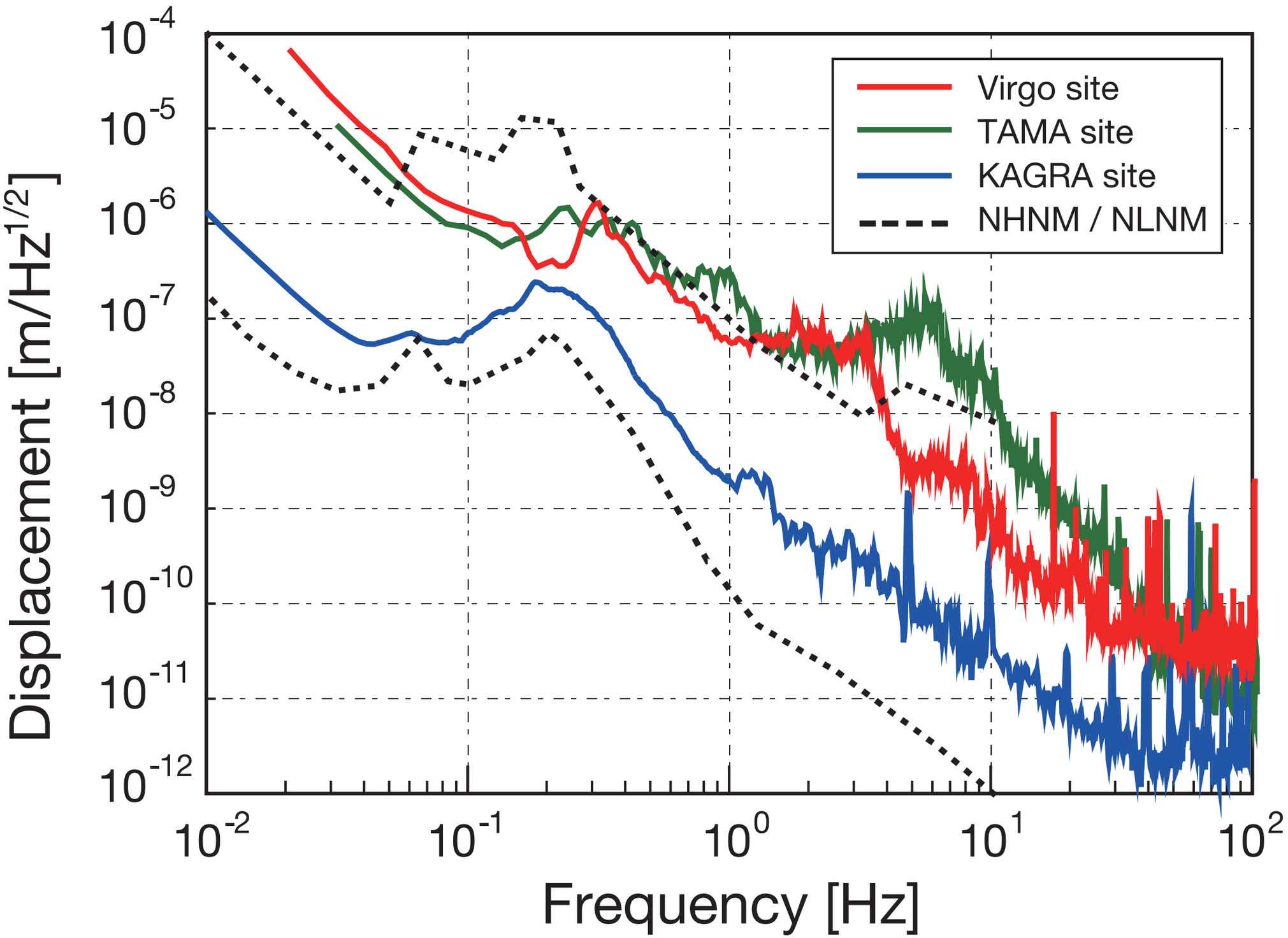
UNDERGROUND

Smaller seismic noise
~ 1-2 orders of magnitude
in ~1-100 Hz

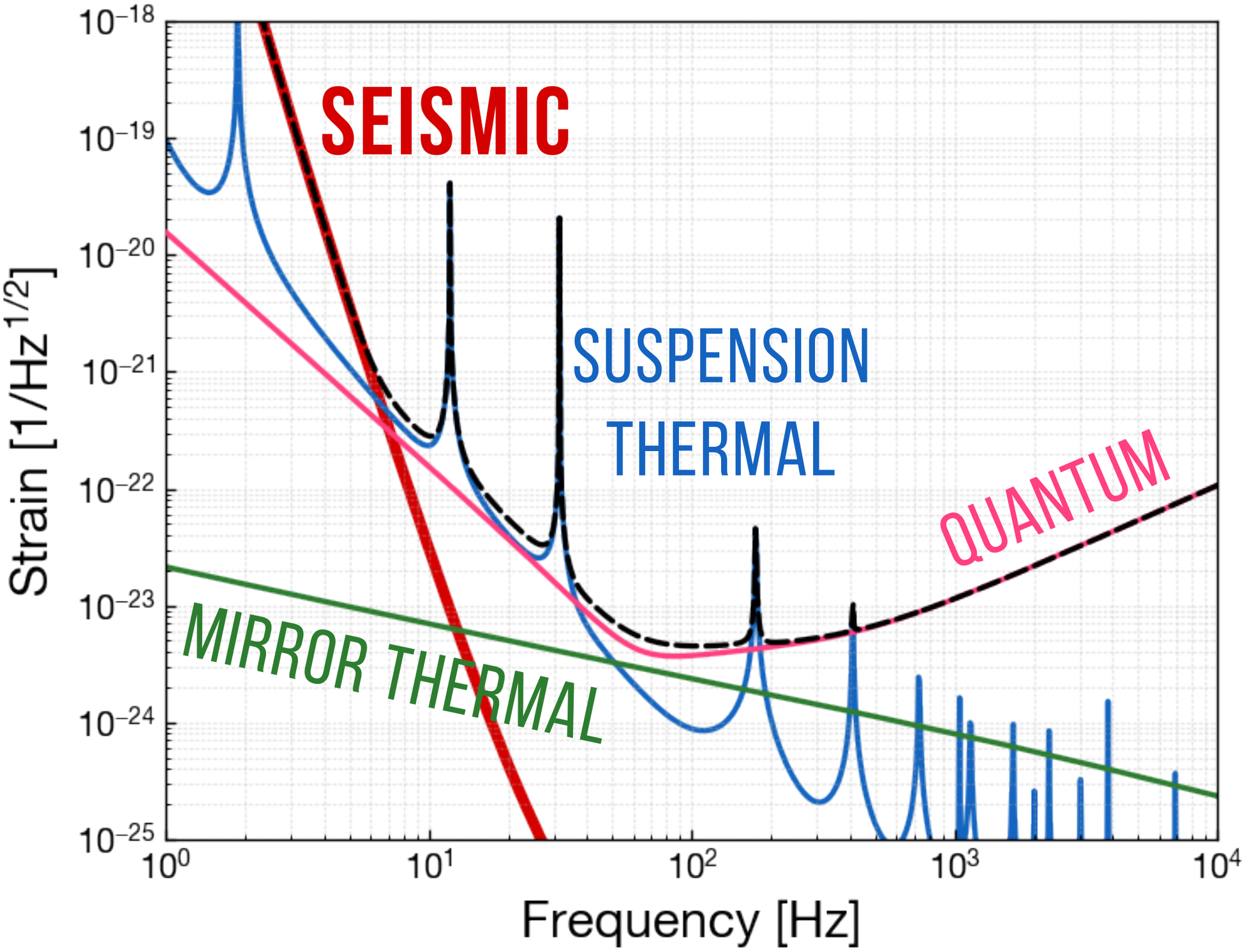
CRYOGENIC

Smaller thermal noise
Many potential benefits

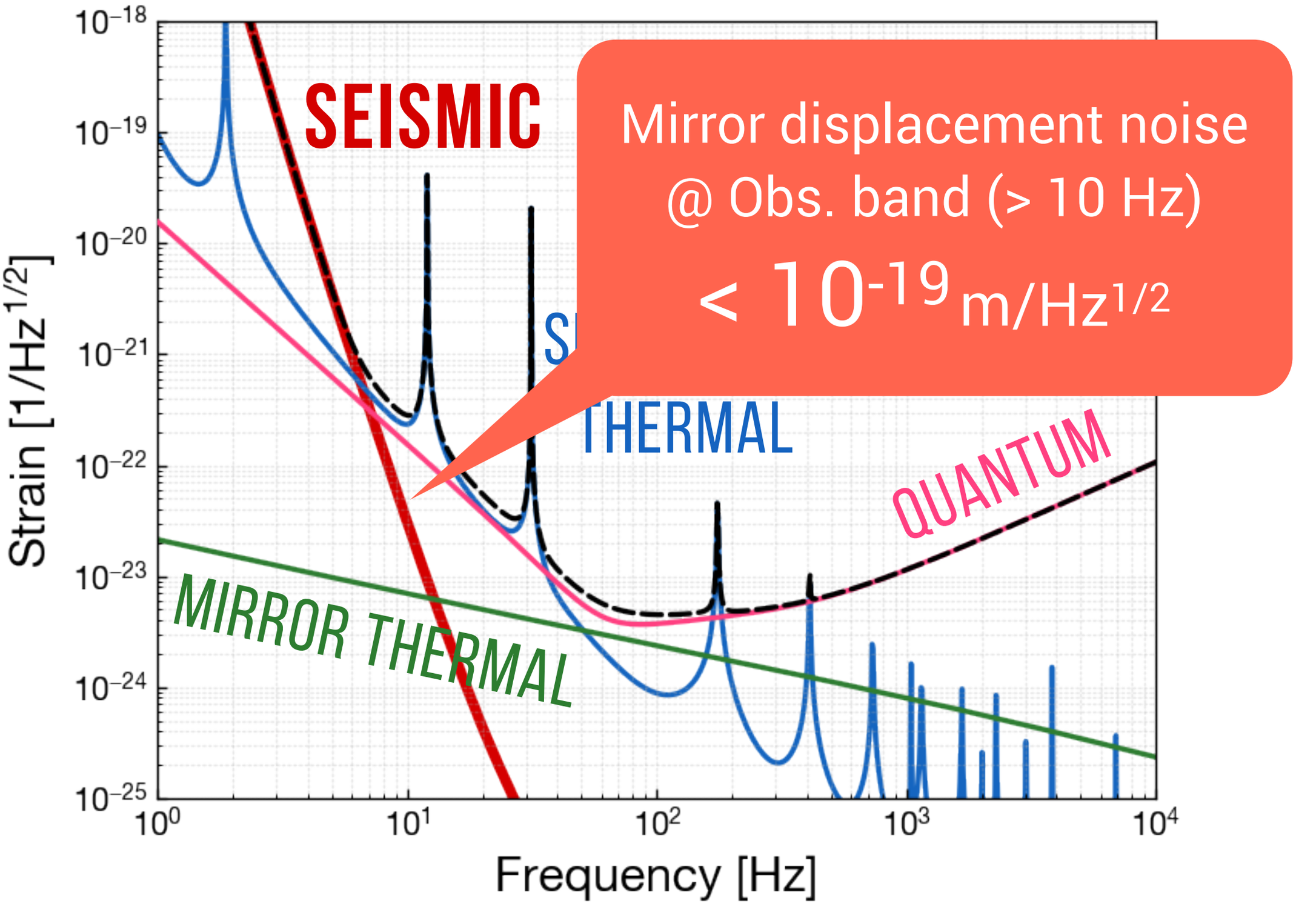
SEISMIC NOISE



SENSITIVITY



SENSITIVITY

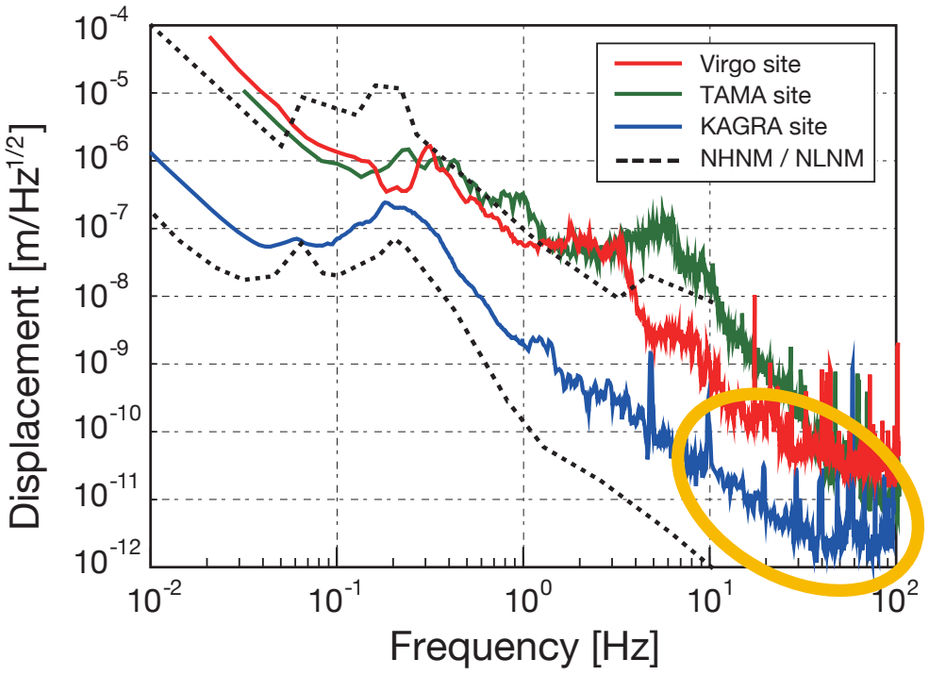


Mirror displacement noise
@ Obs. band (> 10 Hz)

$< 10^{-19}$ m/Hz$^{1/2}$

VIBRATION ISOLATION

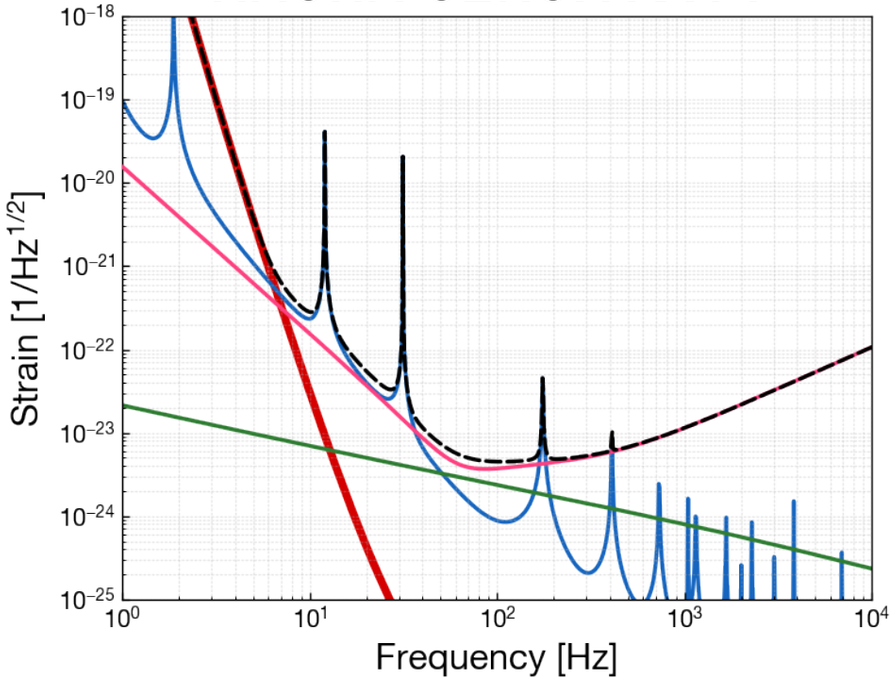
SEISMIC SPECTRUM



Seismic noise

10^{-10} m/Hz$^{1/2}$

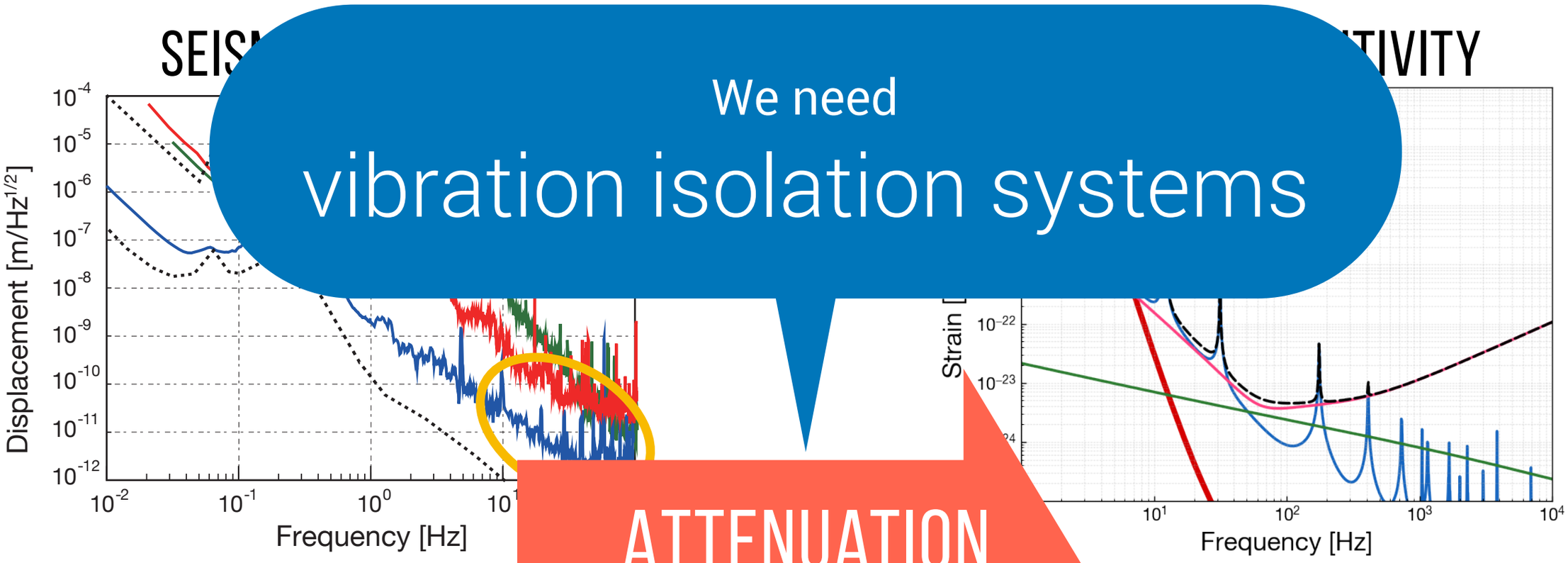
KAGRA SENSITIVITY



Mirror displacement requirement @ > 10 Hz

10^{-19} m/Hz$^{1/2}$

VIBRATION ISOLATION



We need

vibration isolation systems

ATTENUATION FACTOR:

< 10^{-9}

Seismic noise

10^{-10} m/Hz$^{1/2}$

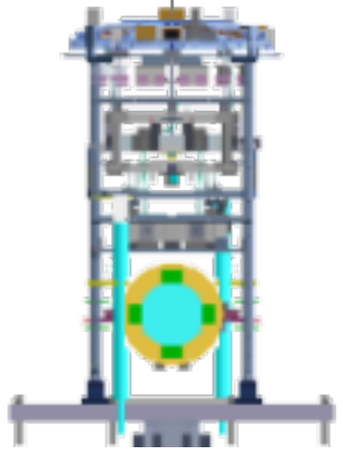
or displacement

irement @ > 10 Hz

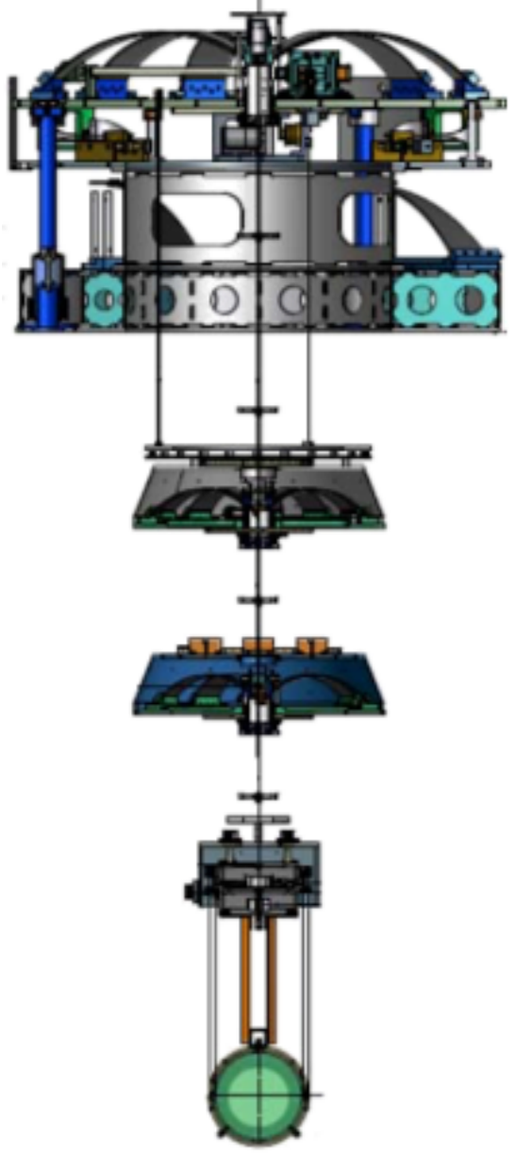
10^{-19} m/Hz$^{1/2}$

VIBRATION ISOLATION SYSTEMS IN KAGRA

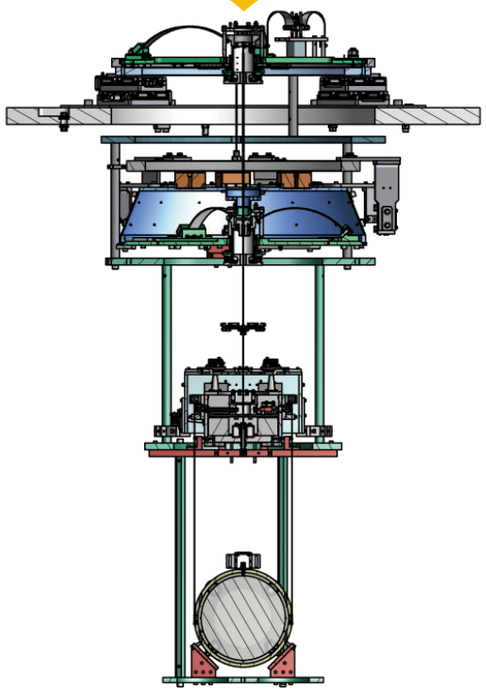
TYPE-A



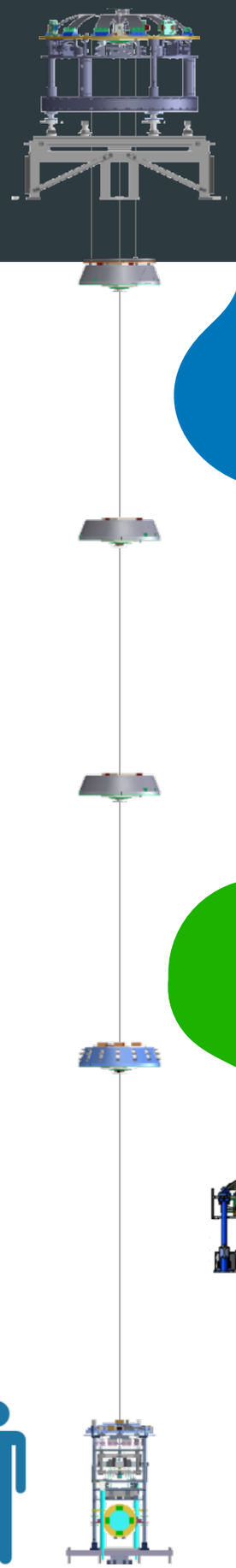
TYPE-B

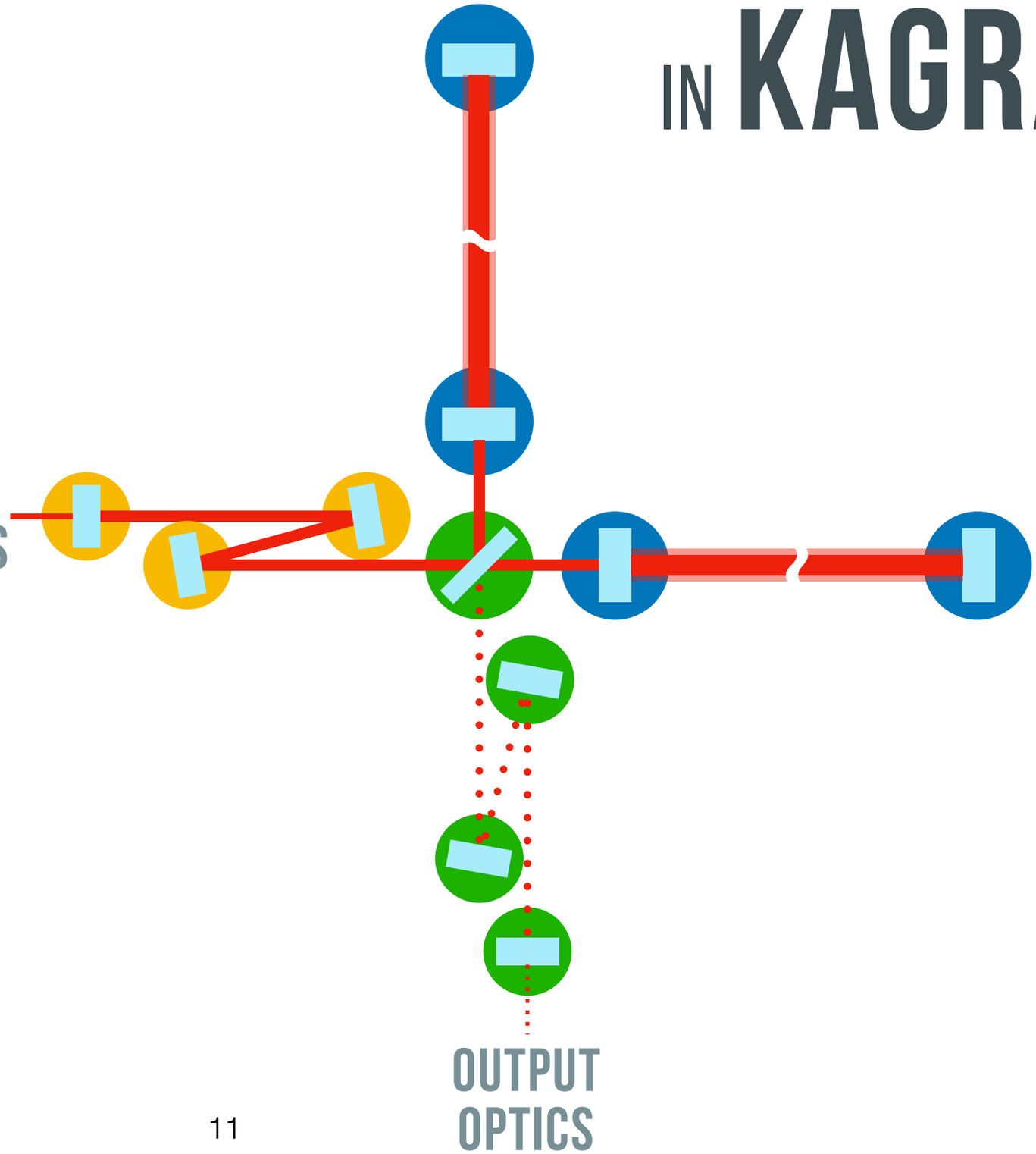


TYPE-BP

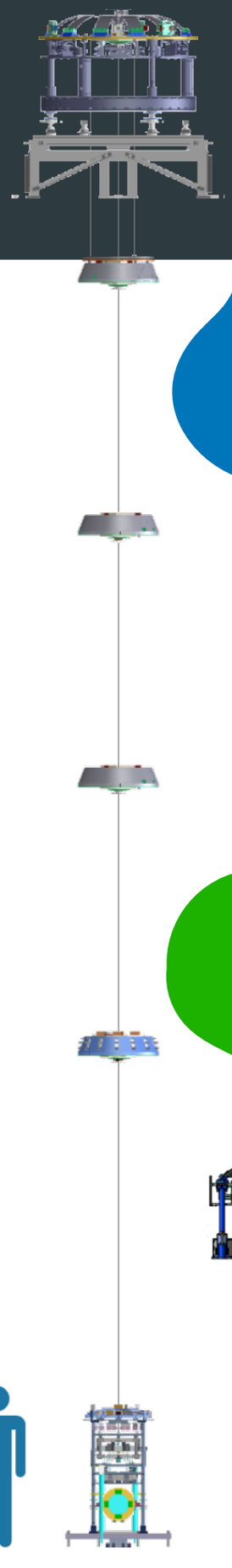


VIBRATION ISOLATION SYSTEMS IN KAGRA

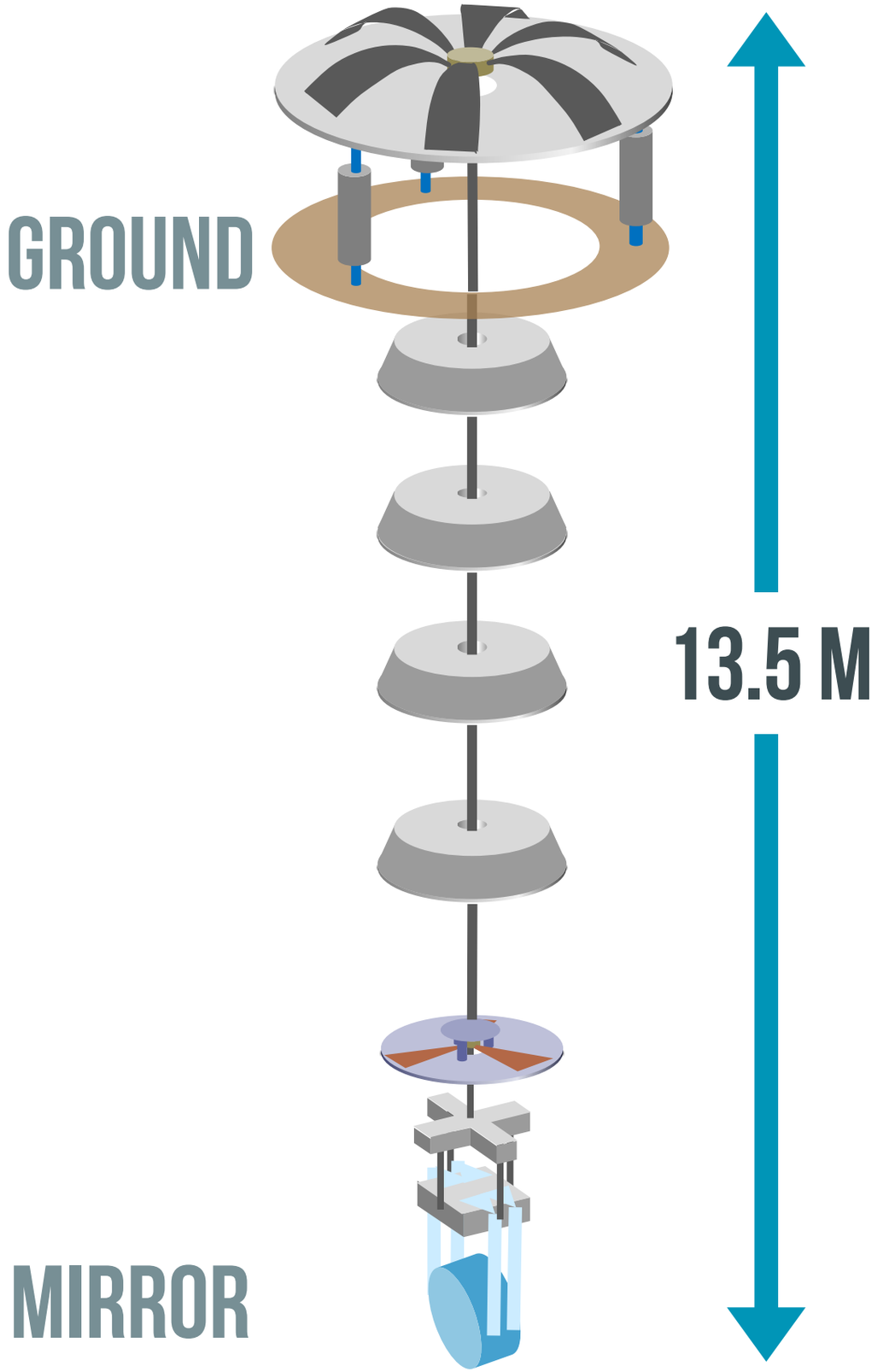




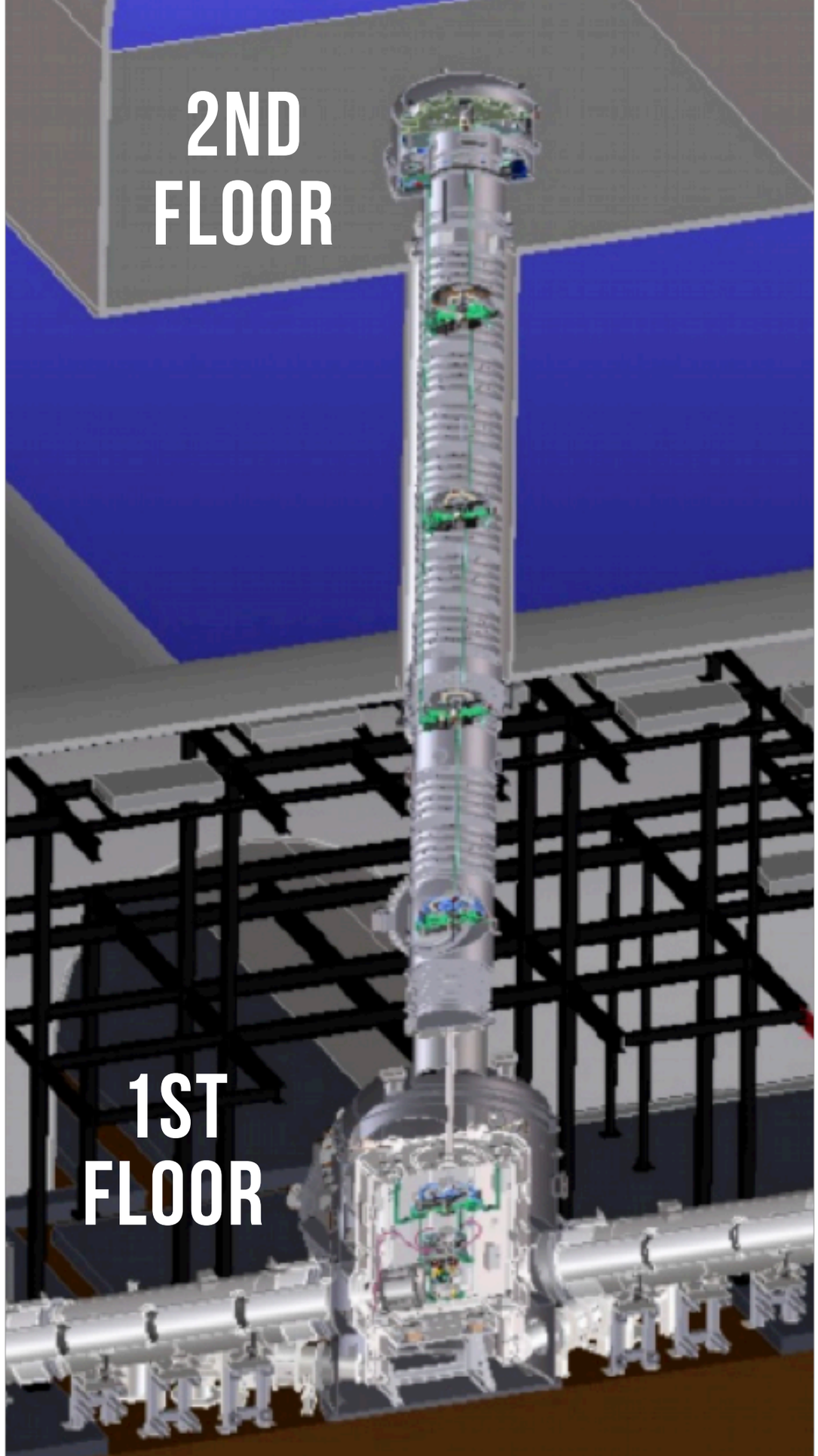
VIBRATION ISOLATION SYSTEMS IN KAGRA



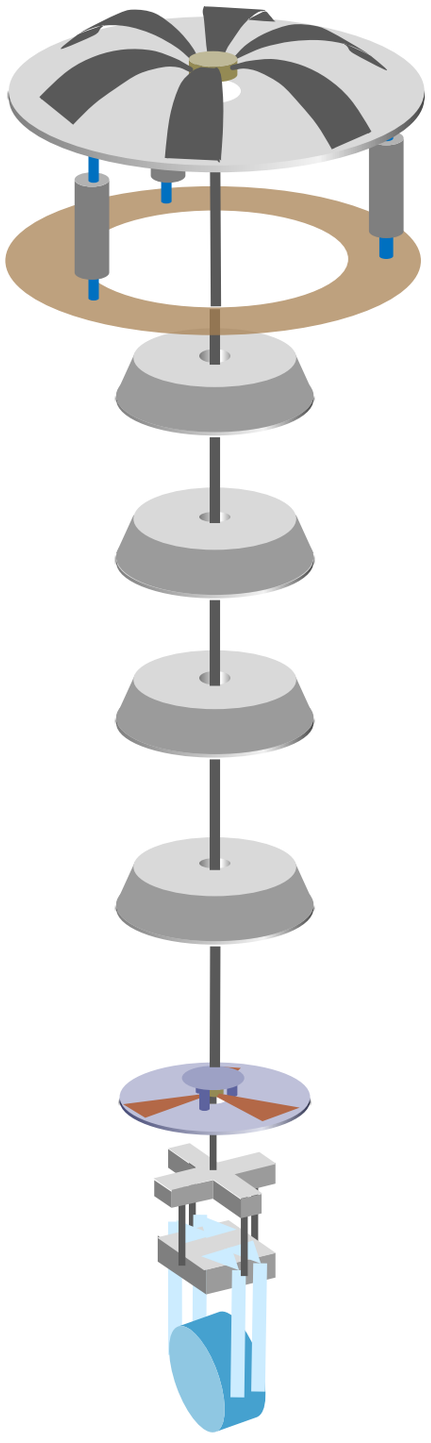
TYPE-A SUSPENSION



TYPE-A SUSPENSION



OVERVIEW



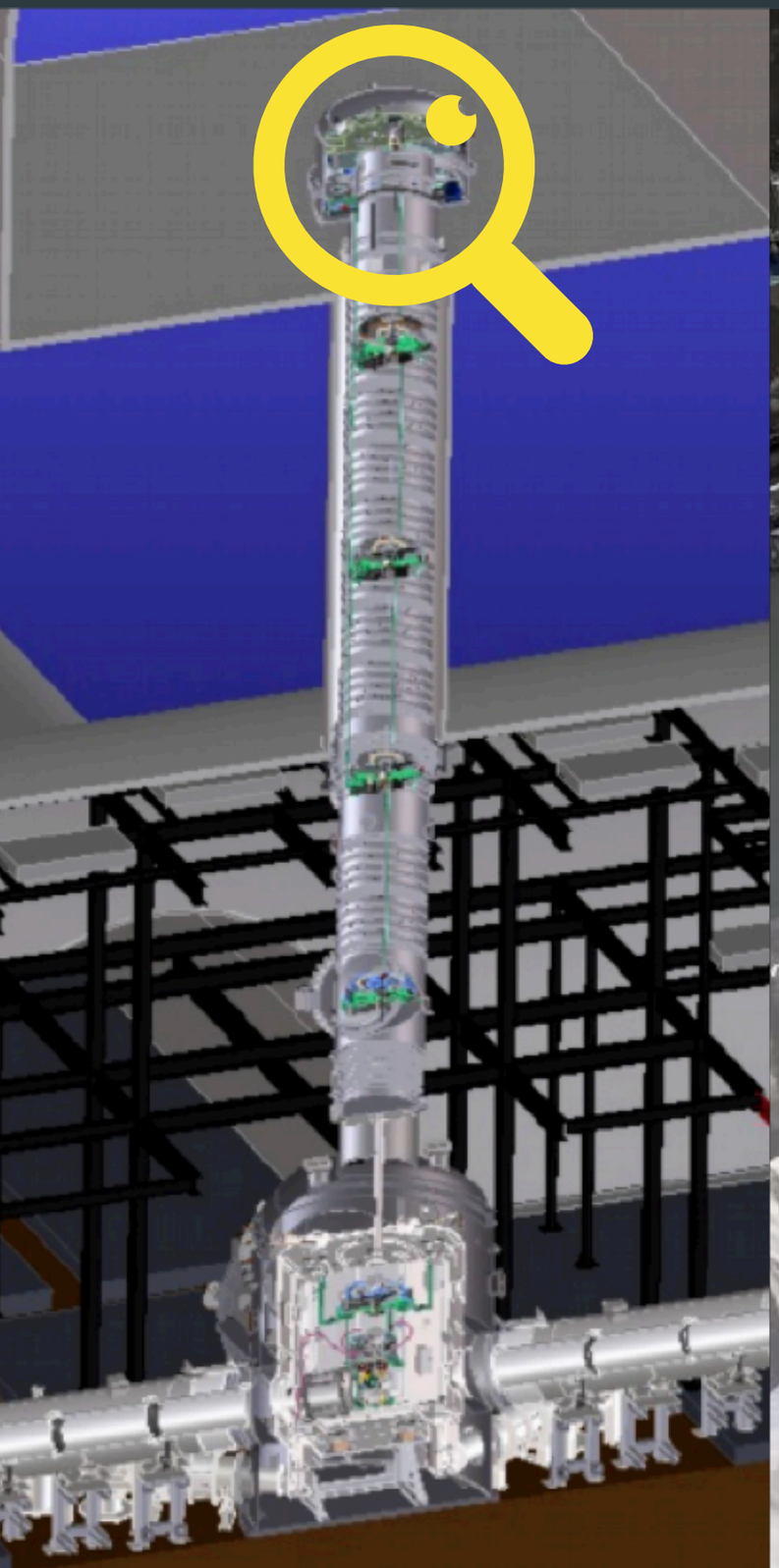
TOWER

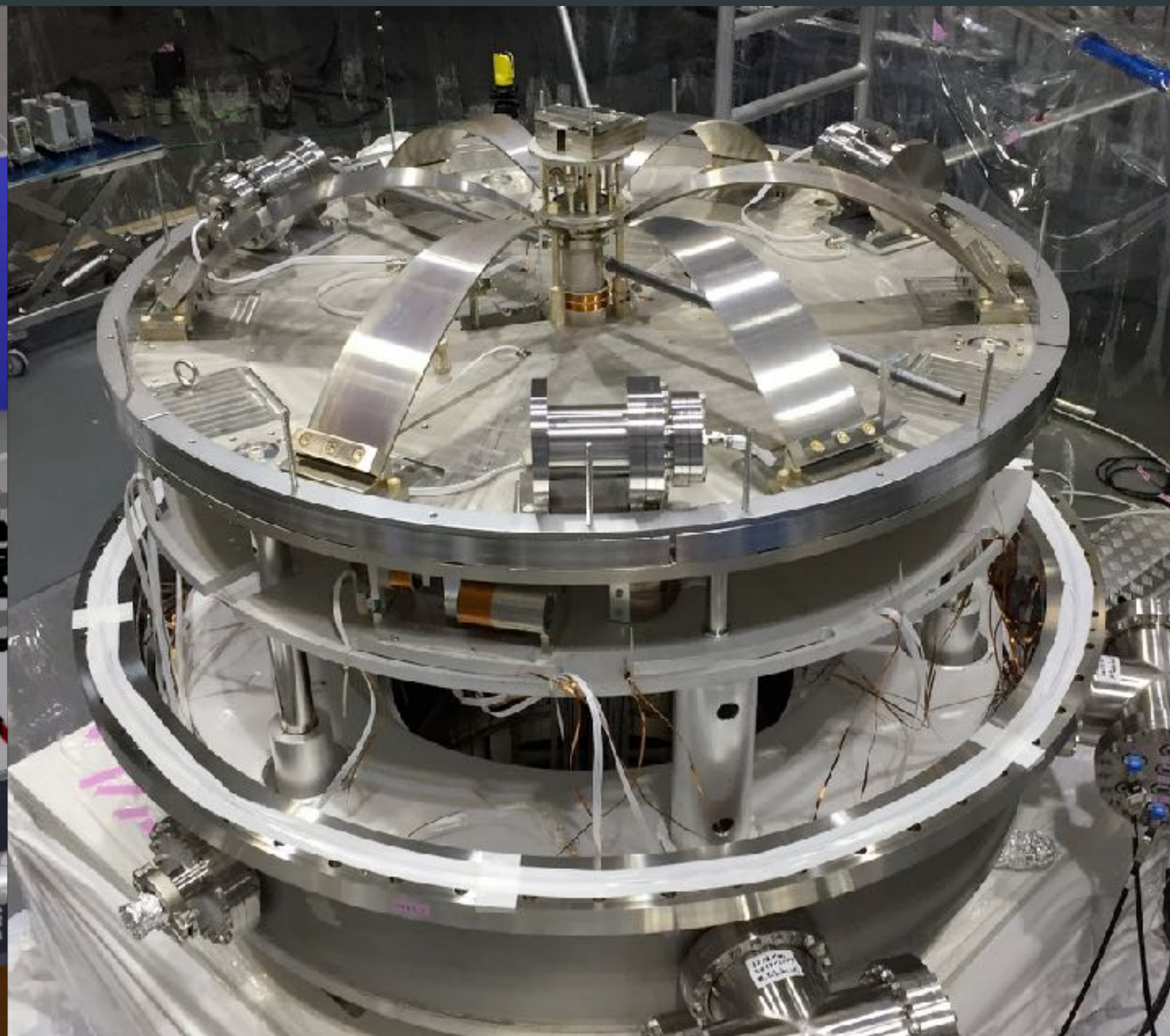
- Top 5 stages of low frequency oscillators
- **Inverted pendulum**: ~ 70 mHz in horizontal
- **Geometric Anti-Spring (GAS) filter**:
  ~ 300 mHz in vertical

CRYOGENIC PAYLOAD

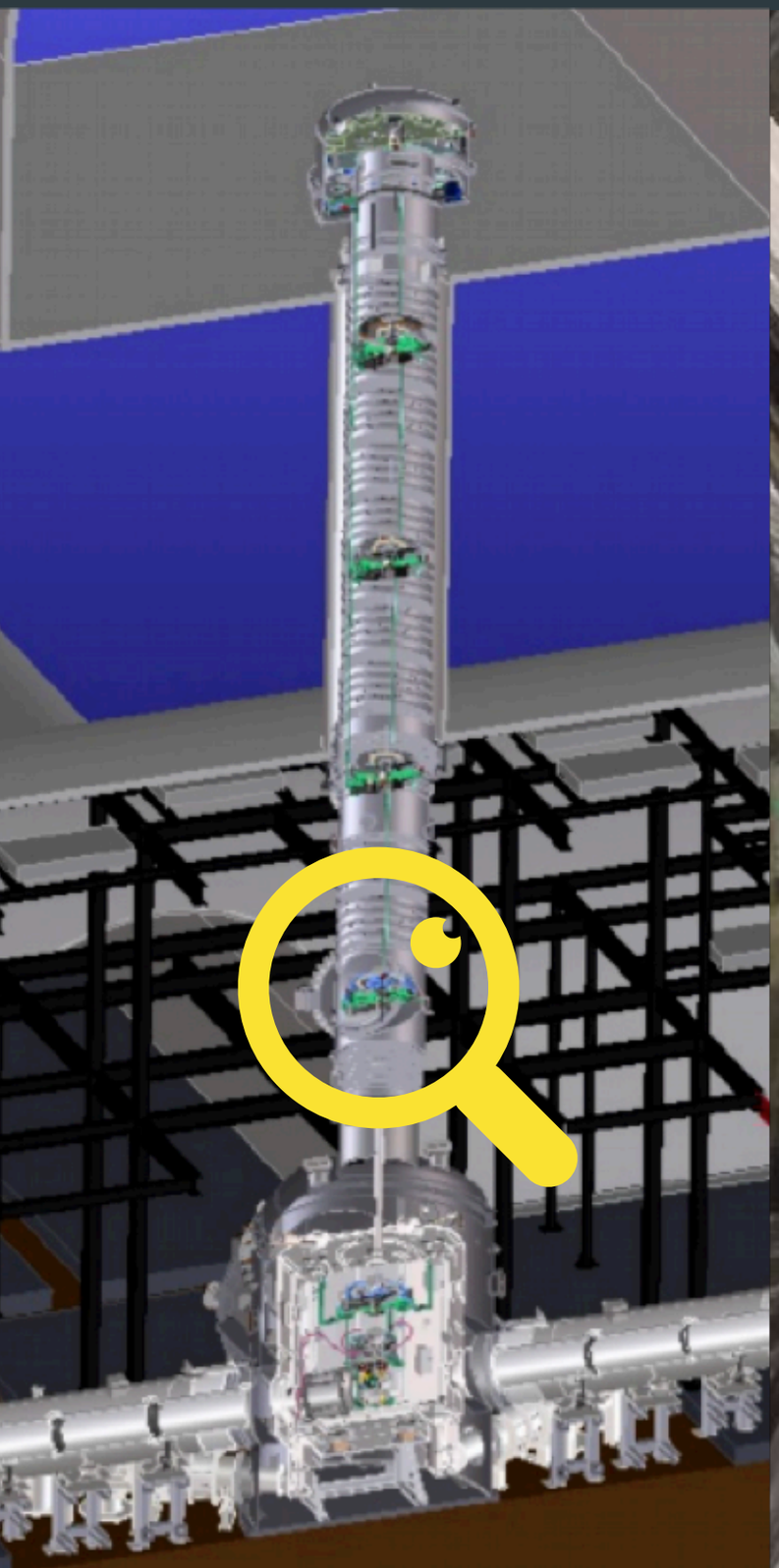
- Bottom 4 stages in cryogenics (~ 20 K)
- **Sapphire mirror**: 22.5 kg (ears included)

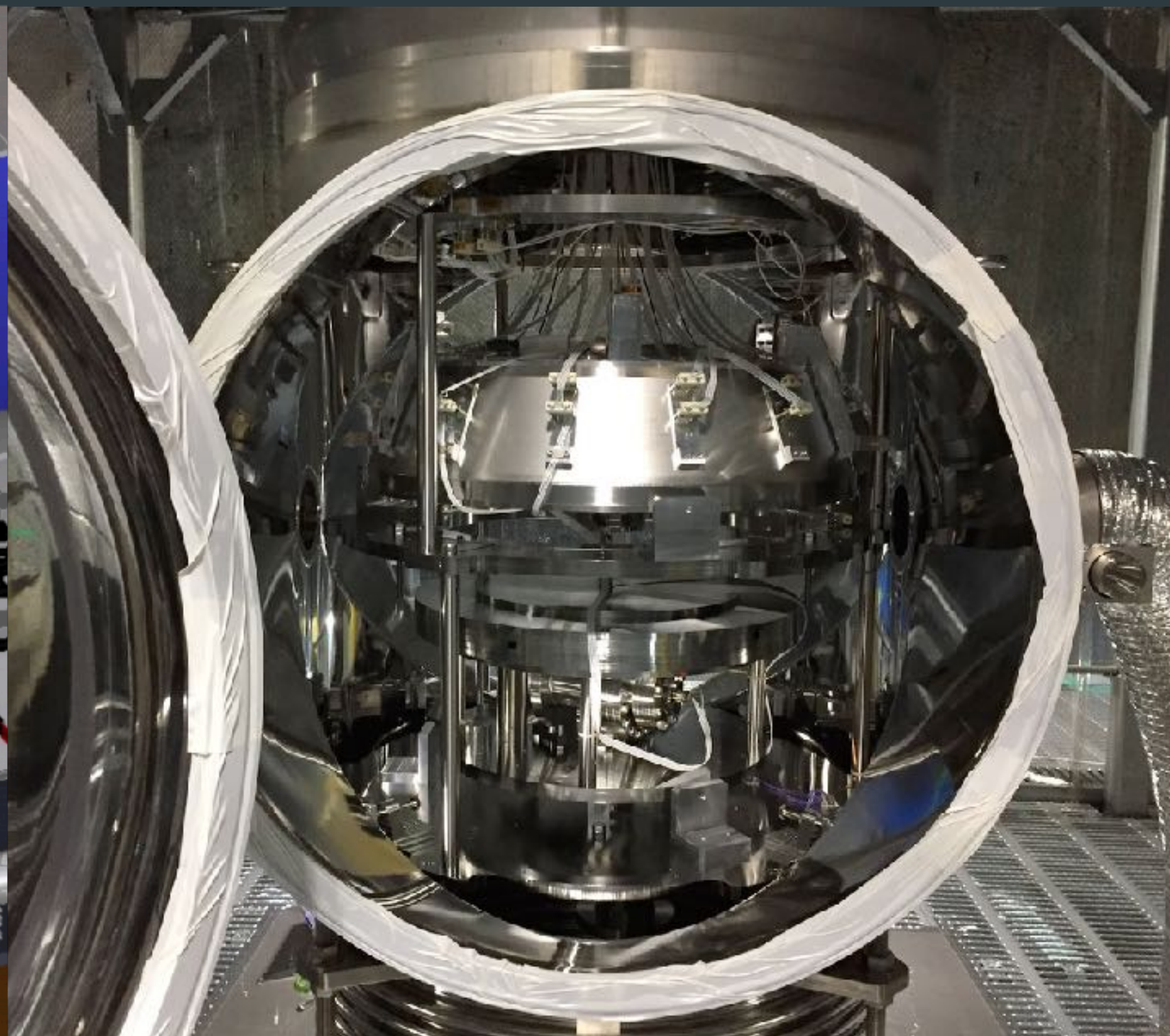
PRE-ISOLATOR





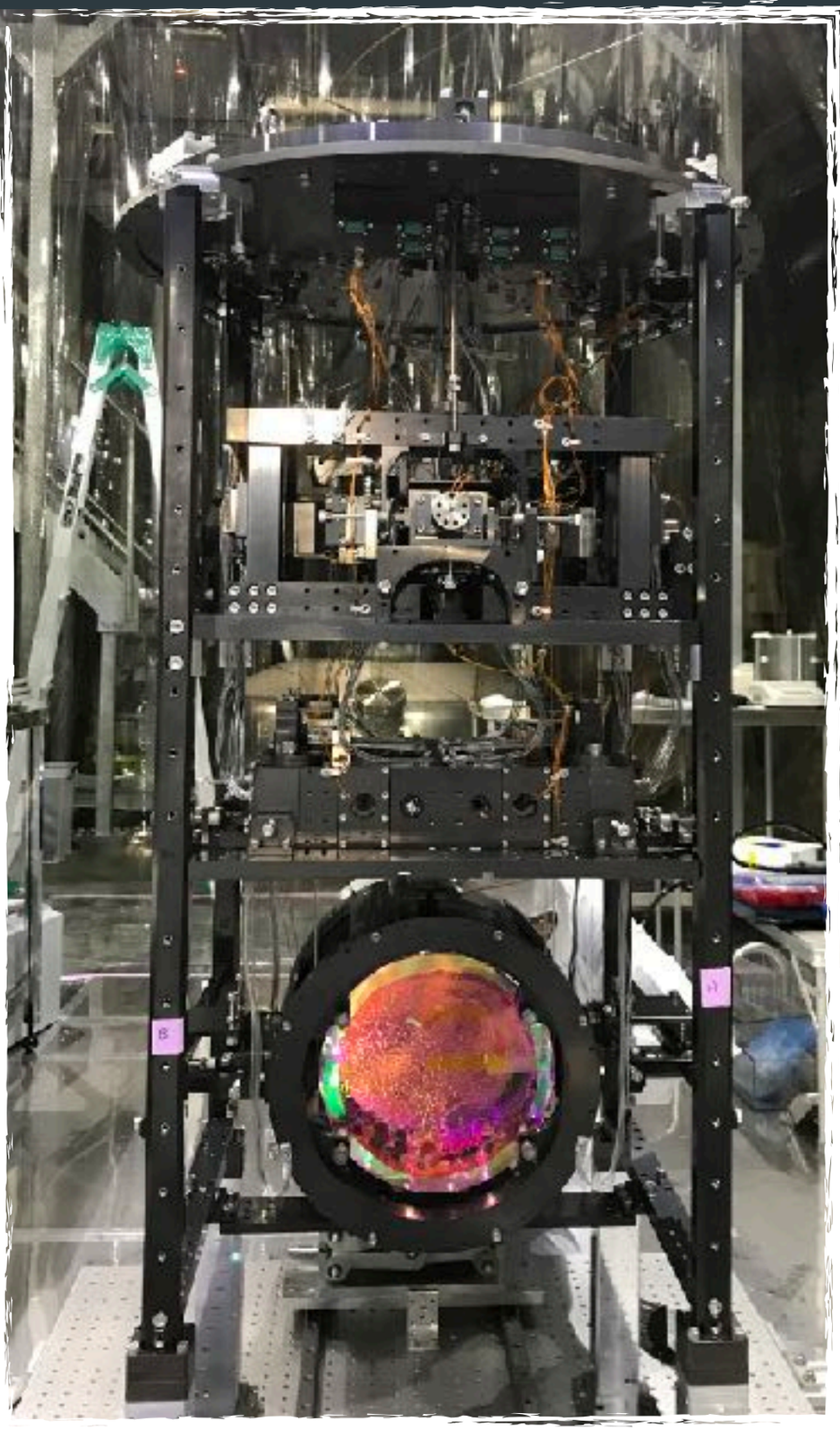
BOTTOM FILTER

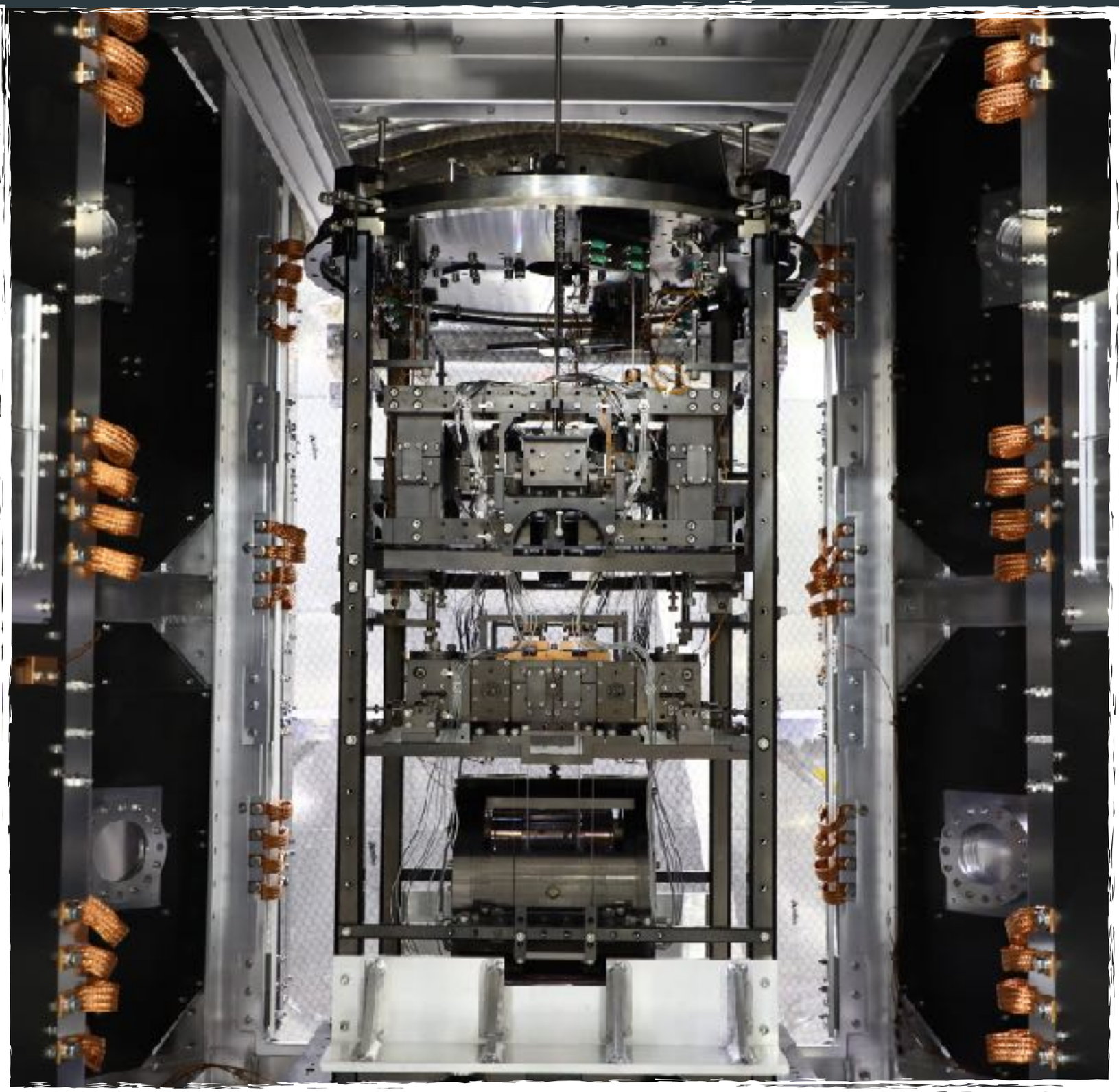




CRYOGENIC PAYLOAD

CRYOGENIC PAYLOAD





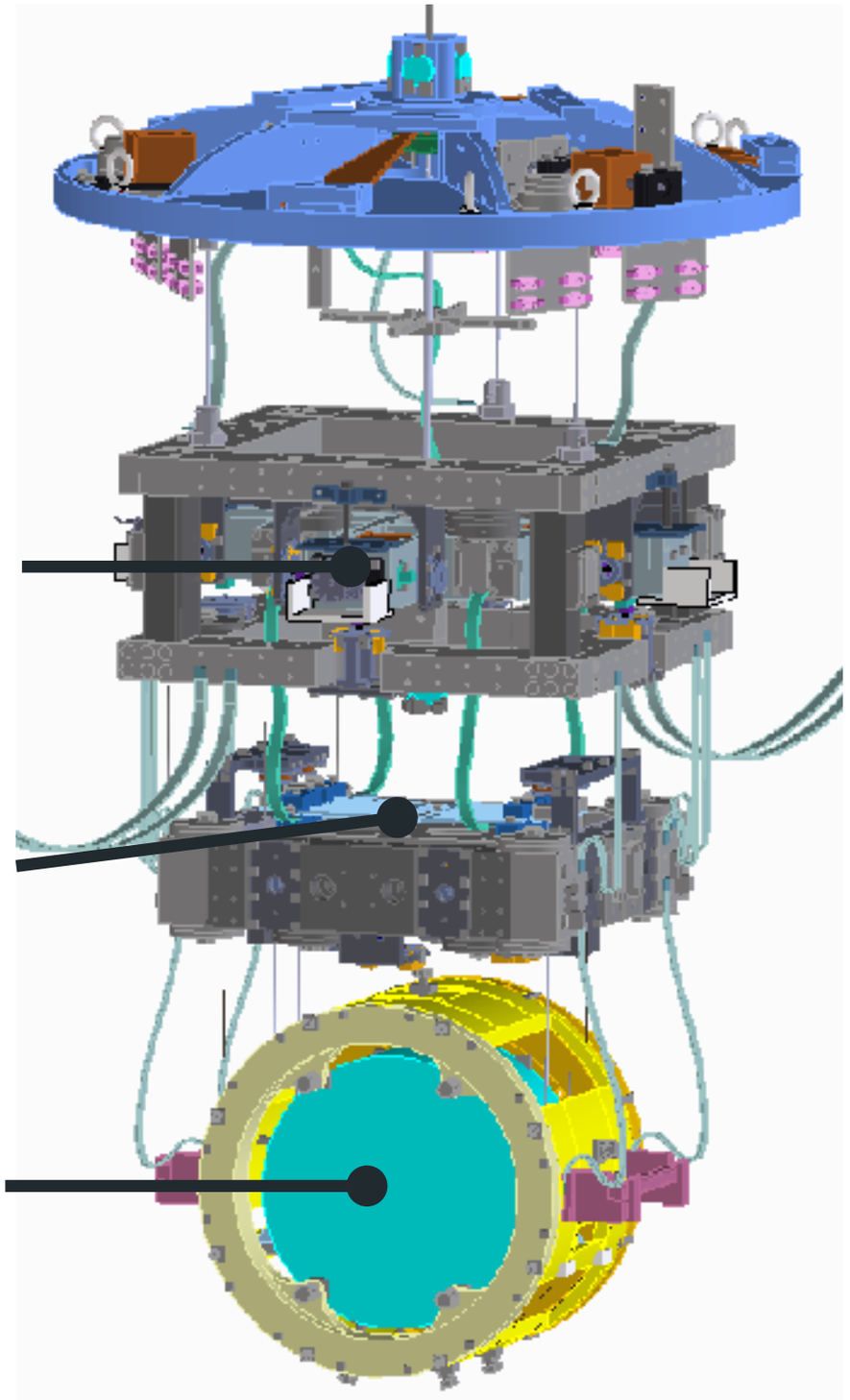
PAYLOAD COMPONENTS

Platform
(PF)

Marionette
(MN)

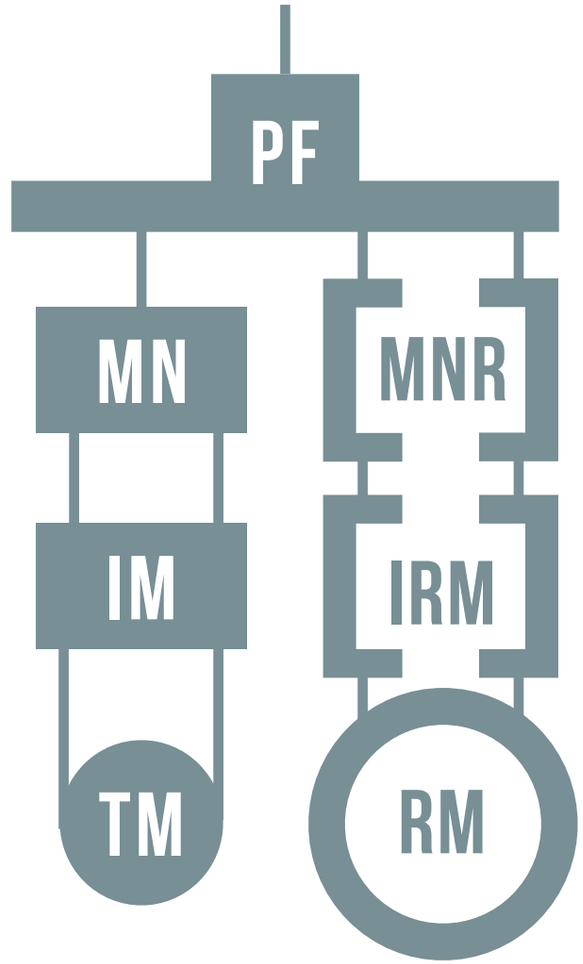
Intermediate Mass
(IM)

Test Mass
(TM)

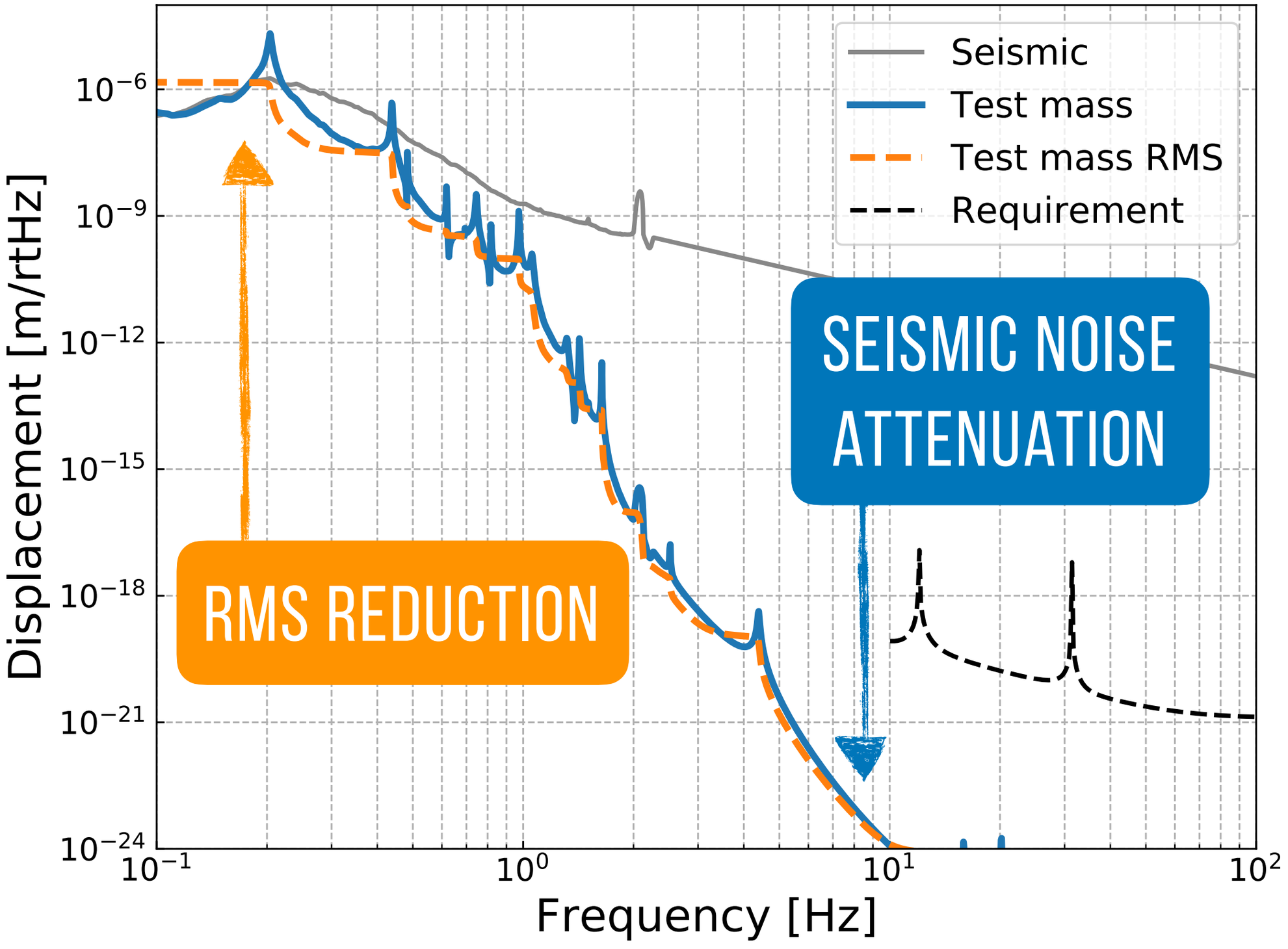


TOTAL WEIGHT ~ 200 KG

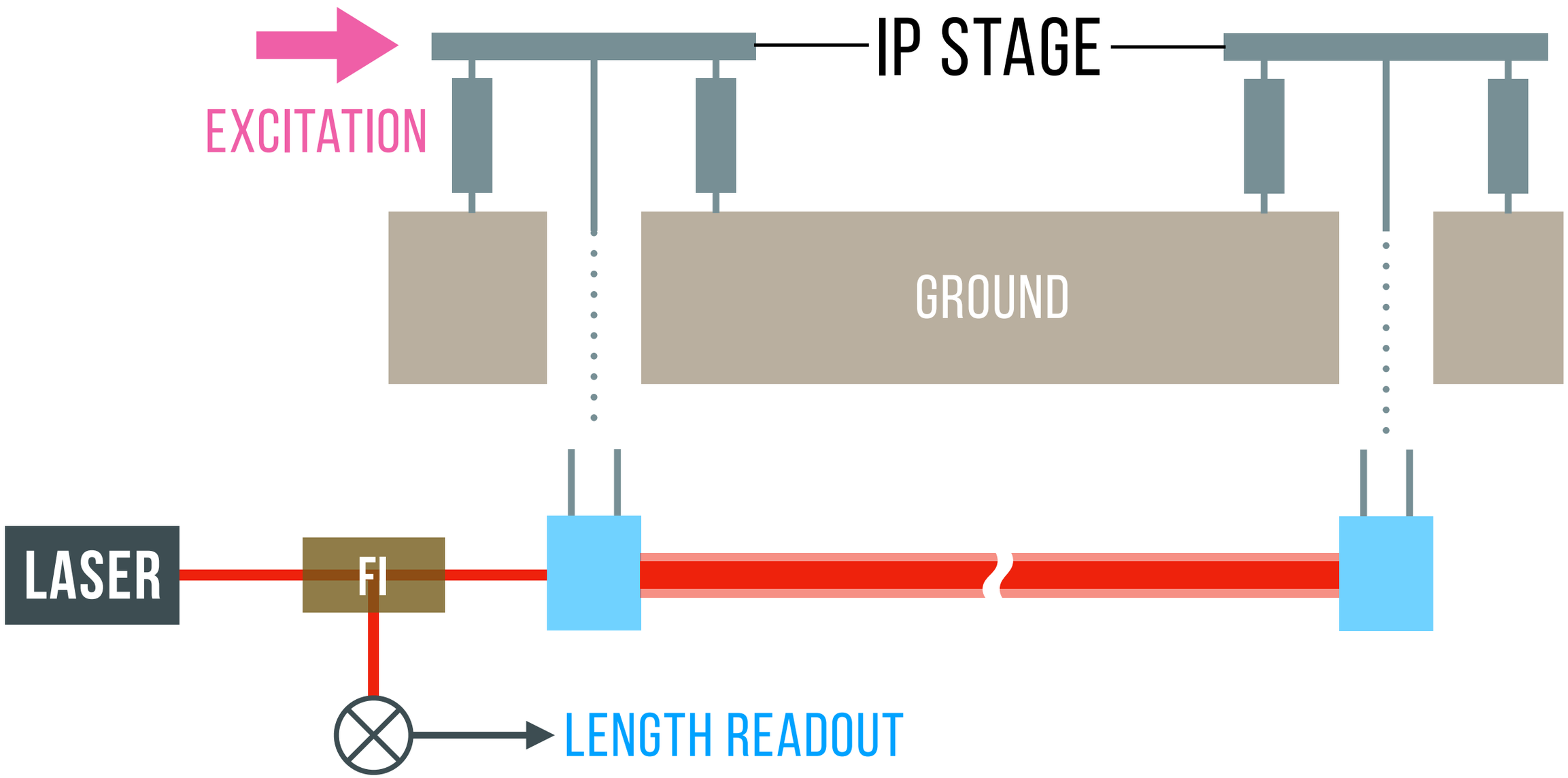
PARALLEL CHAIN



SUSPENSION'S ROLL

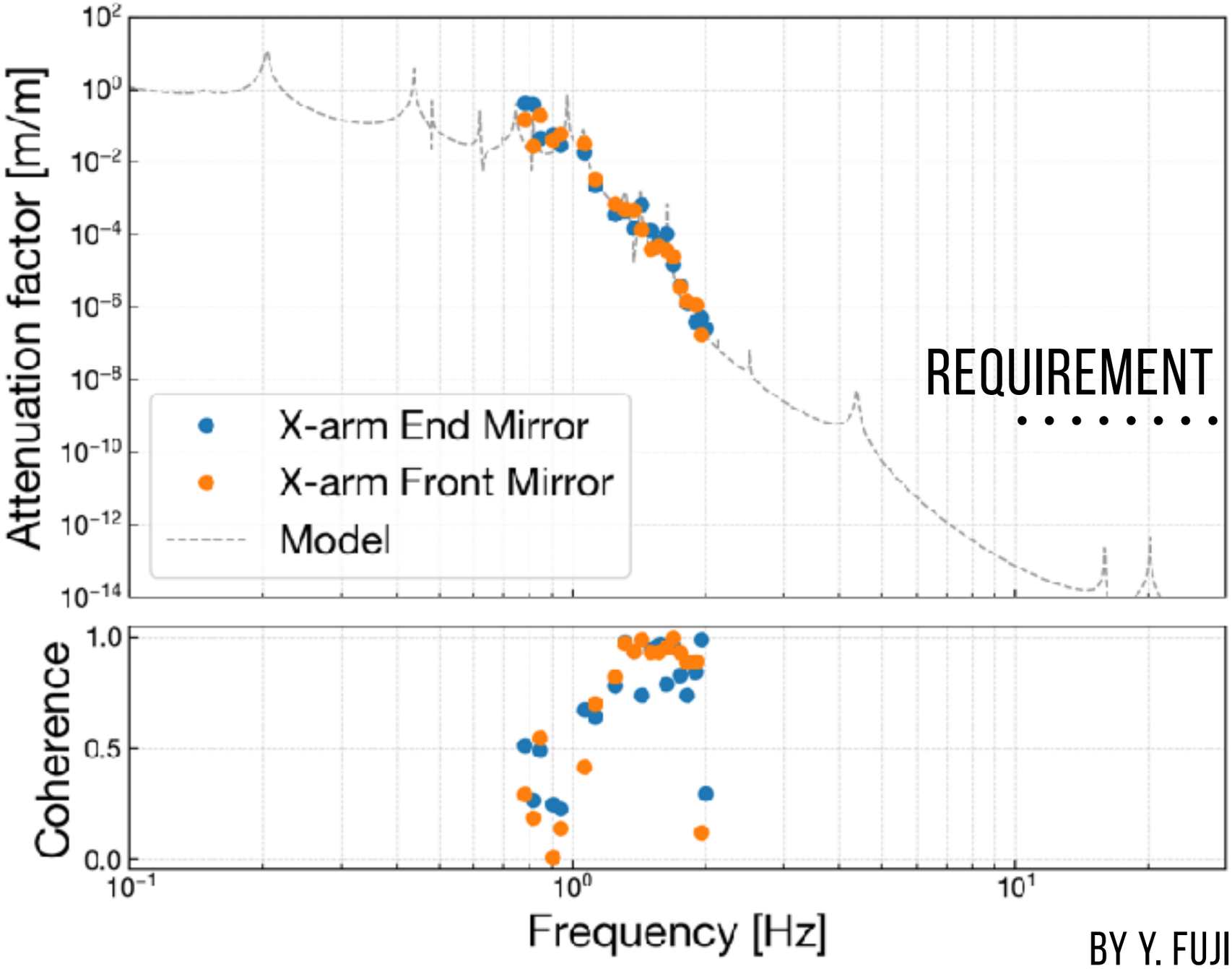


1. Seismic Attenuation Measurement



$$\left(\text{Attenuation factor}\right) = \underbrace{\left(\text{Ground-IP Transmissivity}\right)}_{\text{Model estimation}} \times \underbrace{\left(\text{IP-Mirror Transmissivity}\right)}_{\text{Measurement}}$$

RESULT



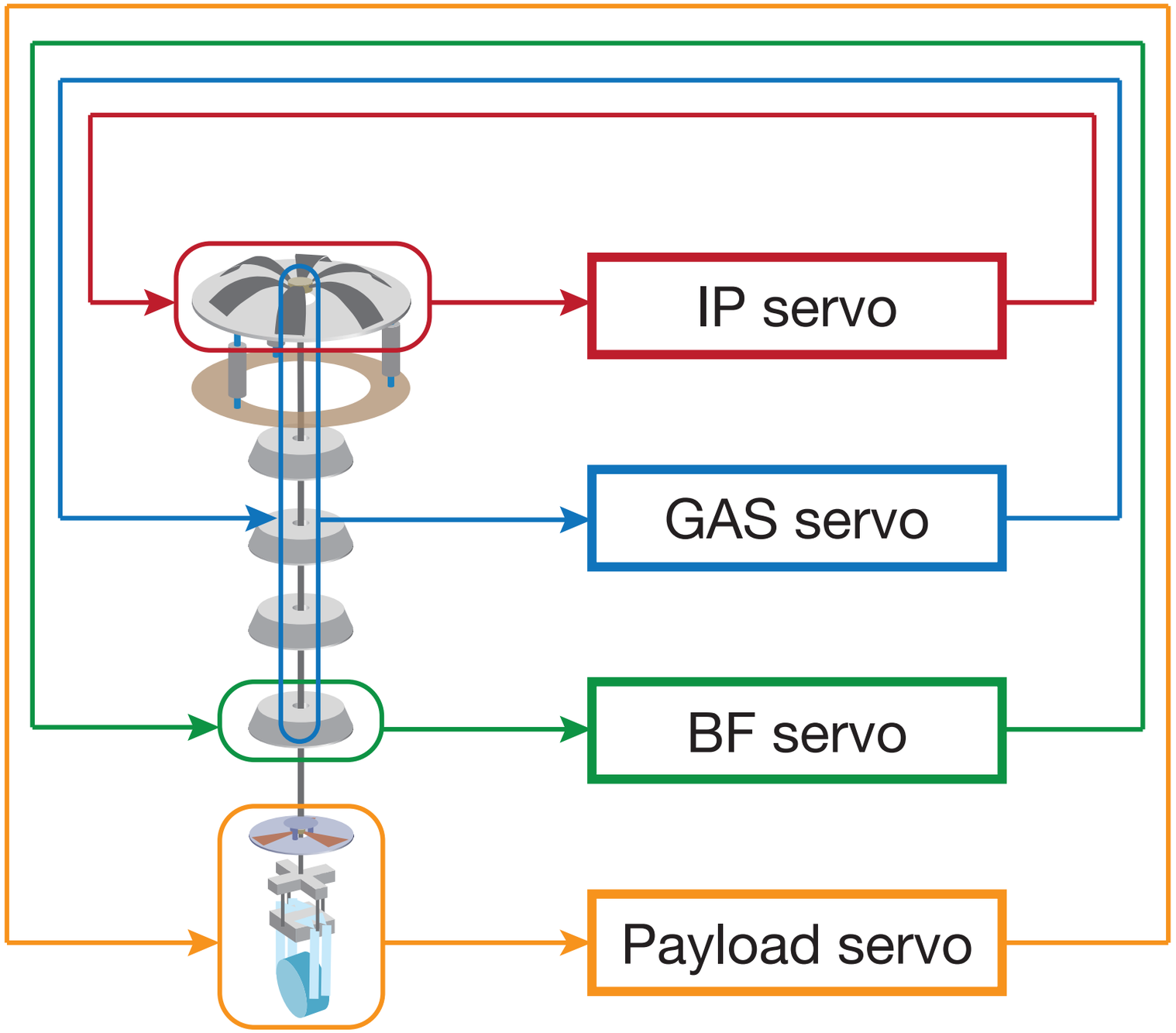
BY Y. FUJII

Single-arm Measurement

- Good agreement with model prediction
- Data in observational band not obtained

▶ Further measurement with advanced interferometer configuration

2. RMS Suppression Control



Tower

IP GAS BF

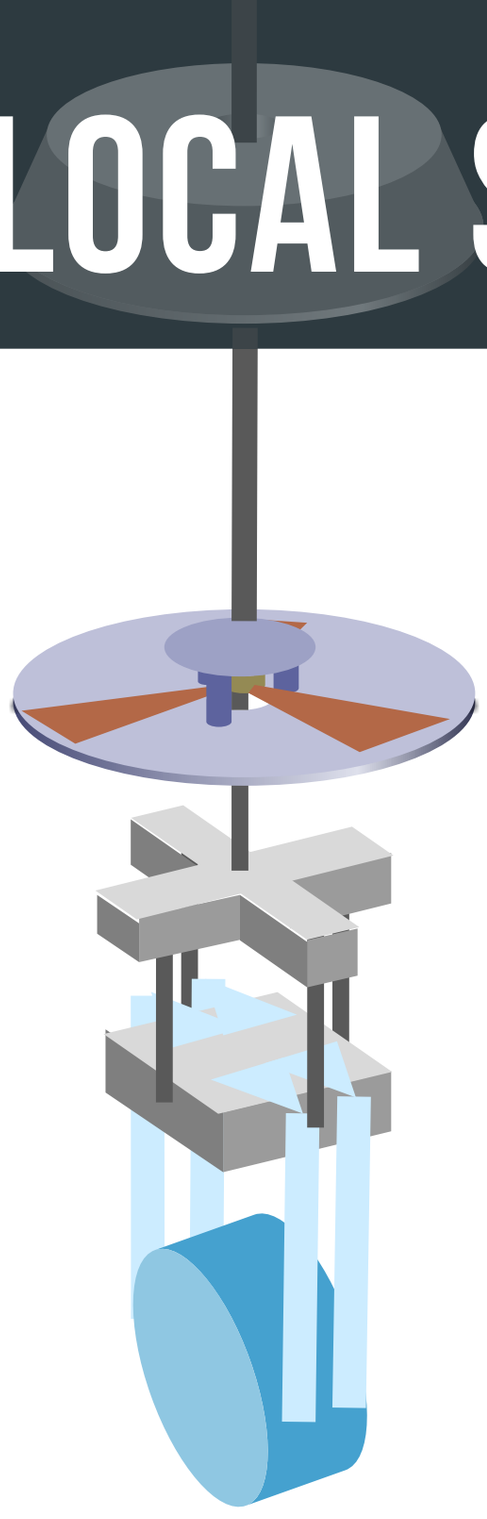
Peak damping + DC position control in low frequency (< 1 Hz)

Payload

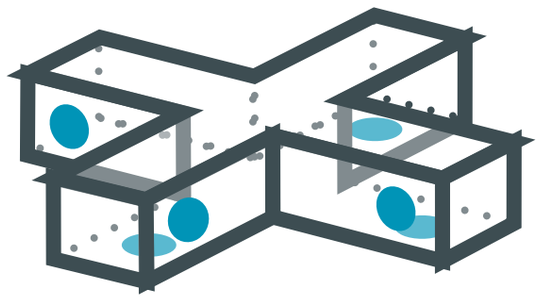
Payload

Peak damping + Angular RMS suppression in low~in-band frequency (> 0.1 Hz)

LOCAL SENSORS - PAYLOAD

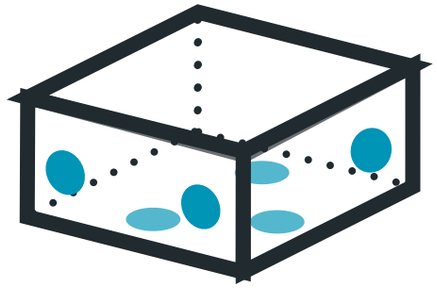


MN



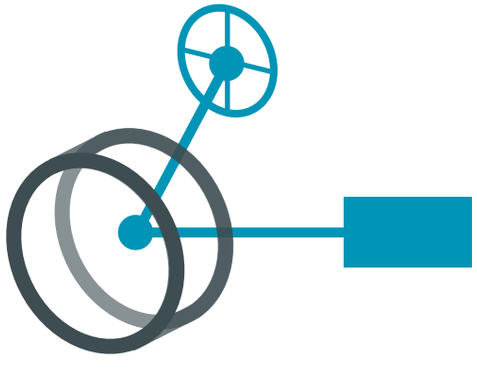
- Photo-sensor
  MN-MNR displacement
- Optical Lever
  MN angles w.r.t. ground

IM



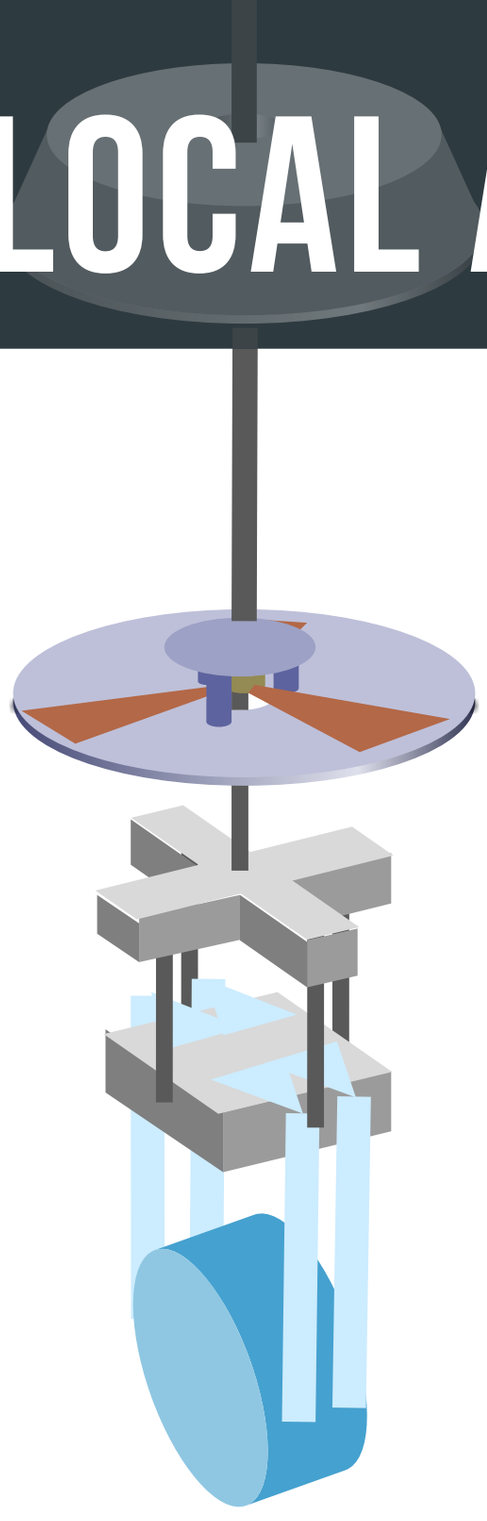
- Photo-sensor
  IM-IRM displacement

TM

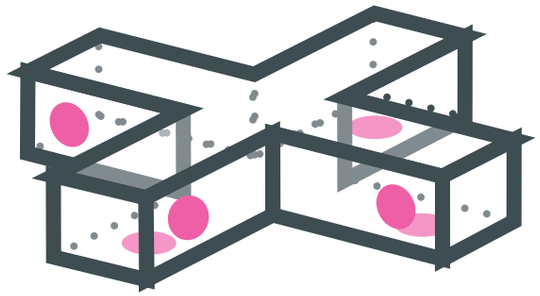


- Optical Lever
  TM-ground in (L, P, Y)

LOCAL ACTUATORS - PAYLOAD



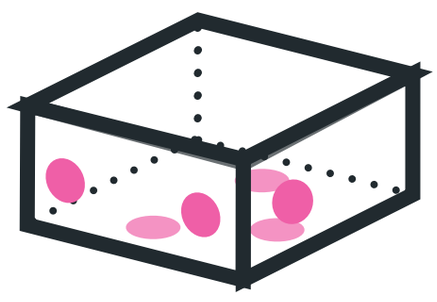
MN



OSEM-type actuator

MN-MNR relative force

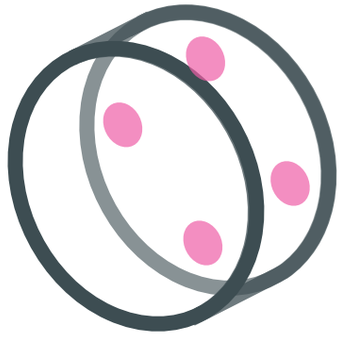
IM



Coil-magnet actuator

IM-IRM relative force

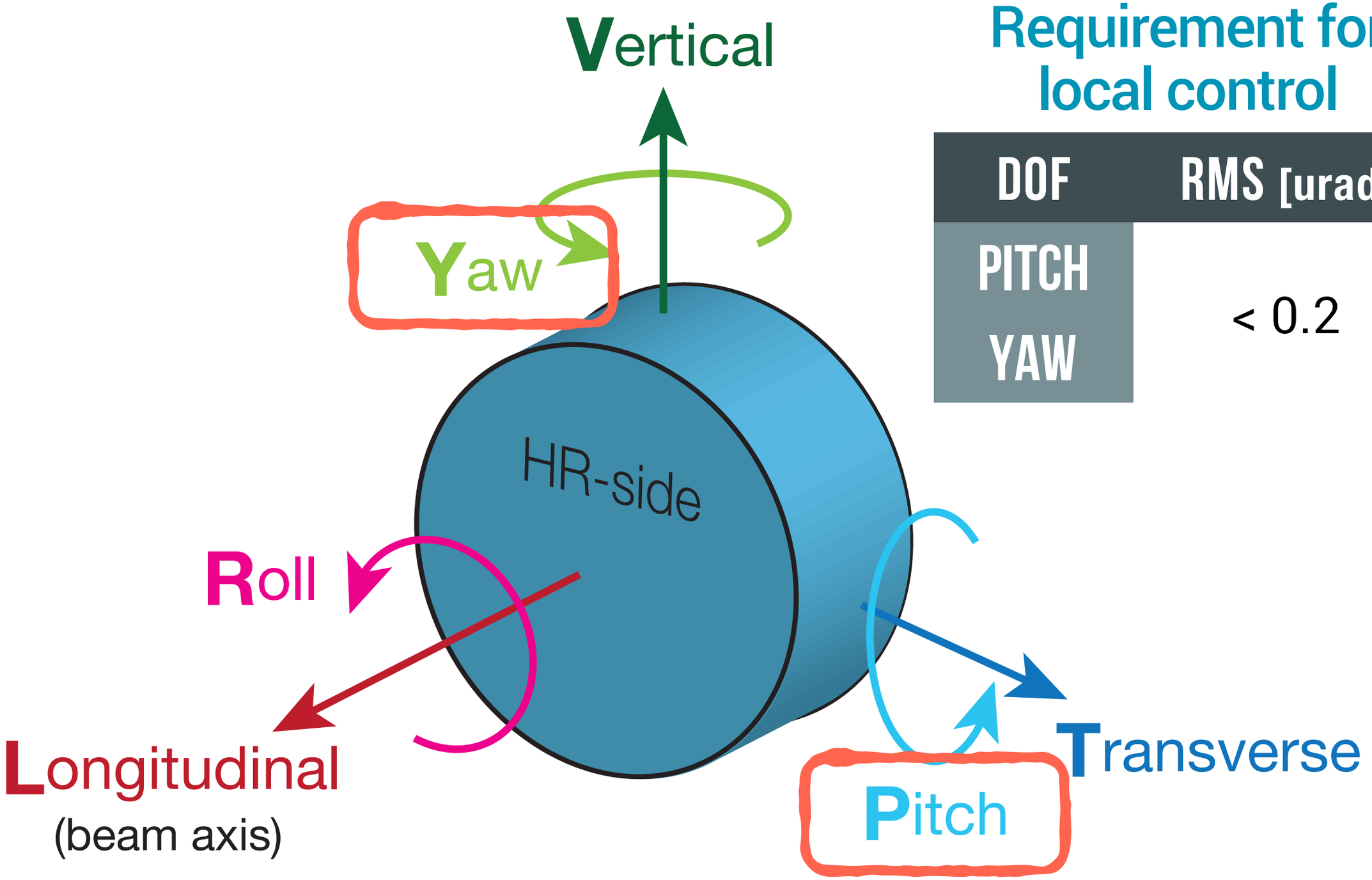
TM



Coil-magnet actuator

TM-RM relative force in (L, P, Y)

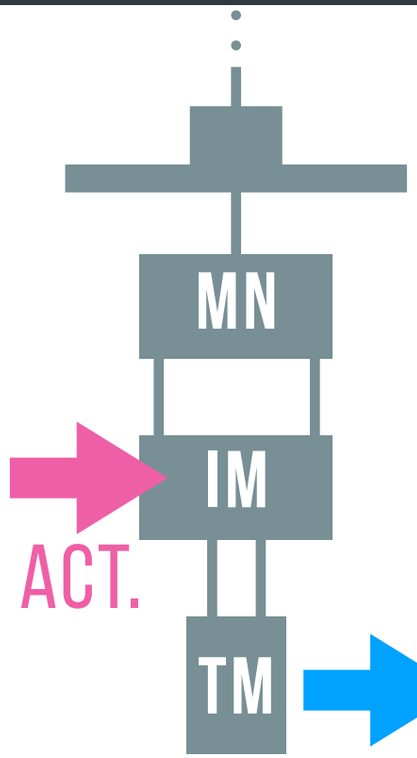
ALIGNMENT CONTROL



Requirement for local control

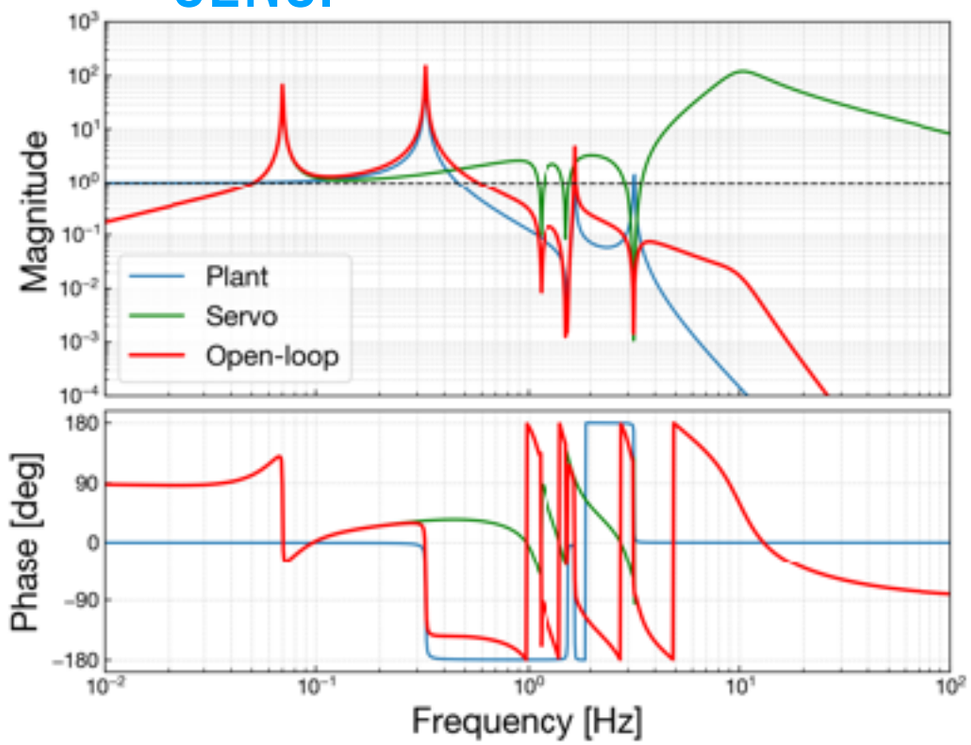
DOF	RMS [urad]
PITCH	< 0.2
YAW	

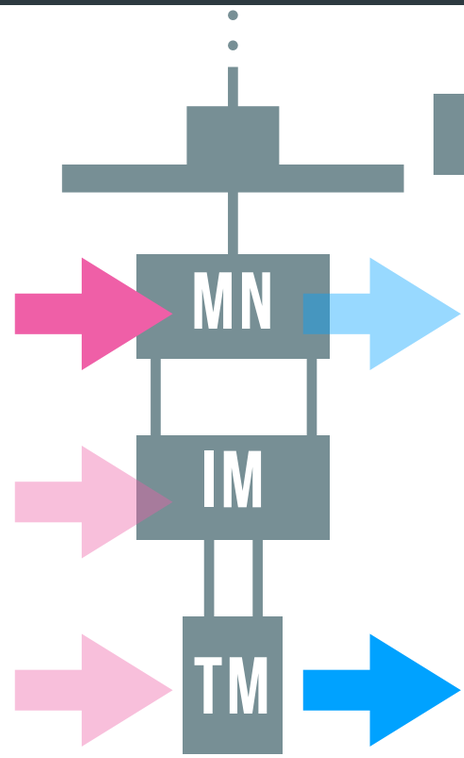
PAYLOAD CONTROL STRATEGY



Broadband feedback

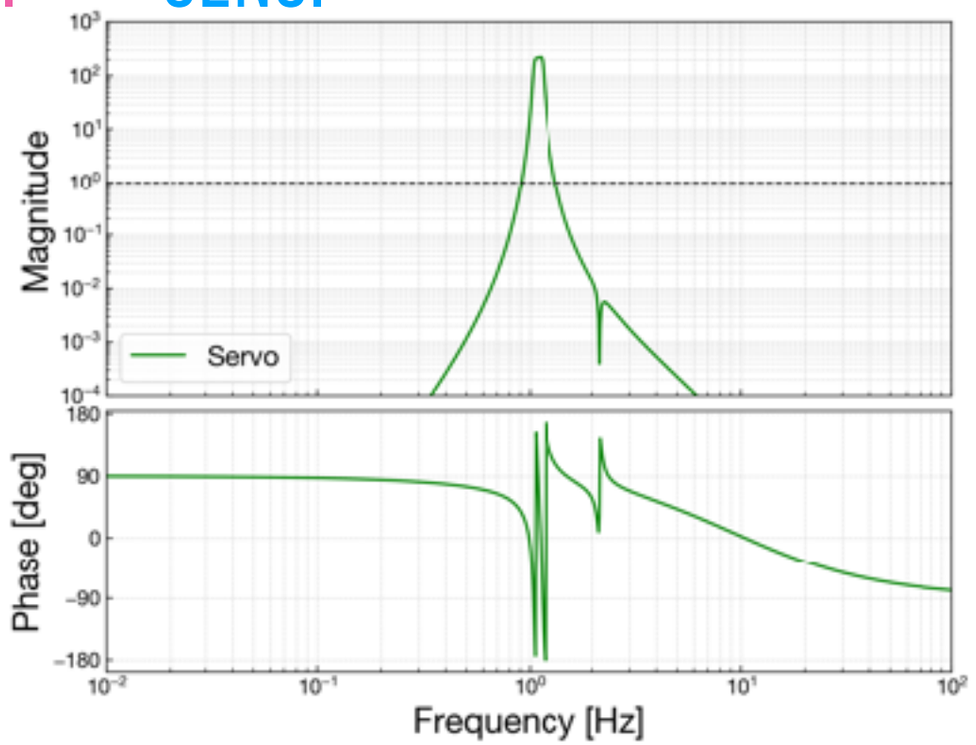
Utilizing intrinsic mechanical peaks.





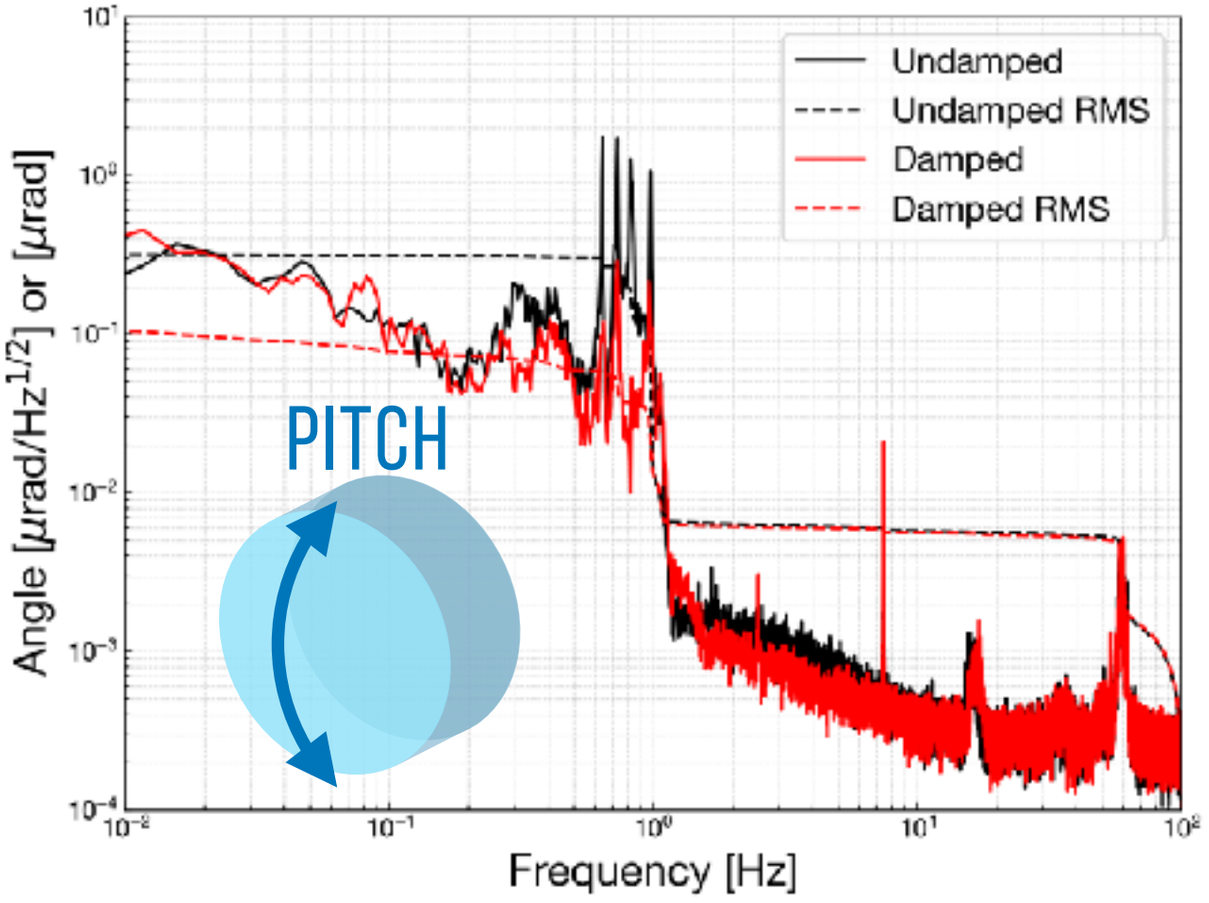
Generic Band-pass feedback

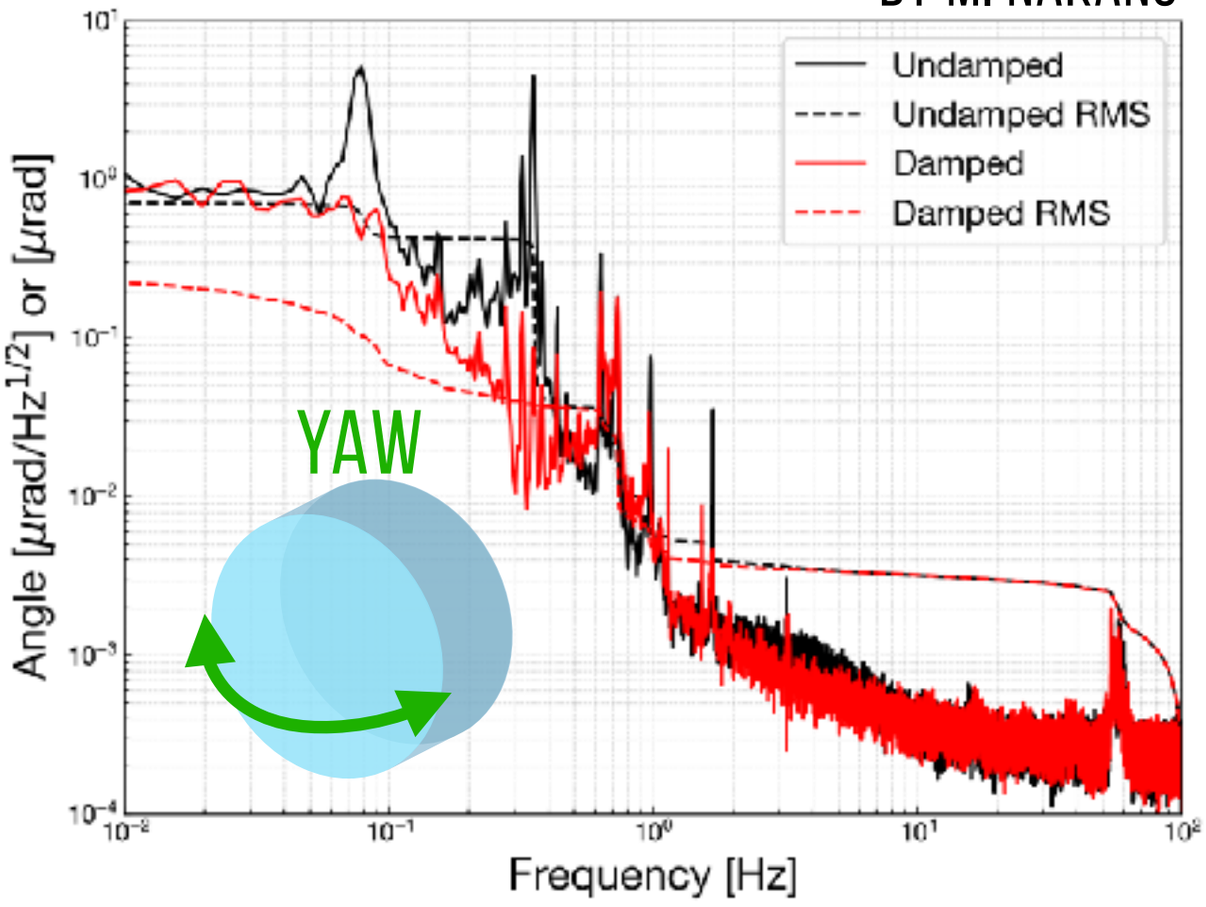
Selective paths for specific peak damping when excited



CURRENT RESULT

BY M. NAKANO





DOF	RMS [urad]	REQ. [urad]
PITCH	✅ 0.103	< 0.2
YAW	(✅) 0.220	

- Local control ▸ ~ ✅ OK
- Next step:
  - ▸ Global alignment control
  - ▸ (P, Y) RMS < ~ 10 nrad

SUMMARY

Type-A suspension

All the 4 suspensions are under commissioning with the interferometer

Vibration isolation performance

Good agreement with the model prediction,
further characterization being prepared

RMS suppression control

Local control requirements being satisfied, further works ongoing for global alignment sensing control

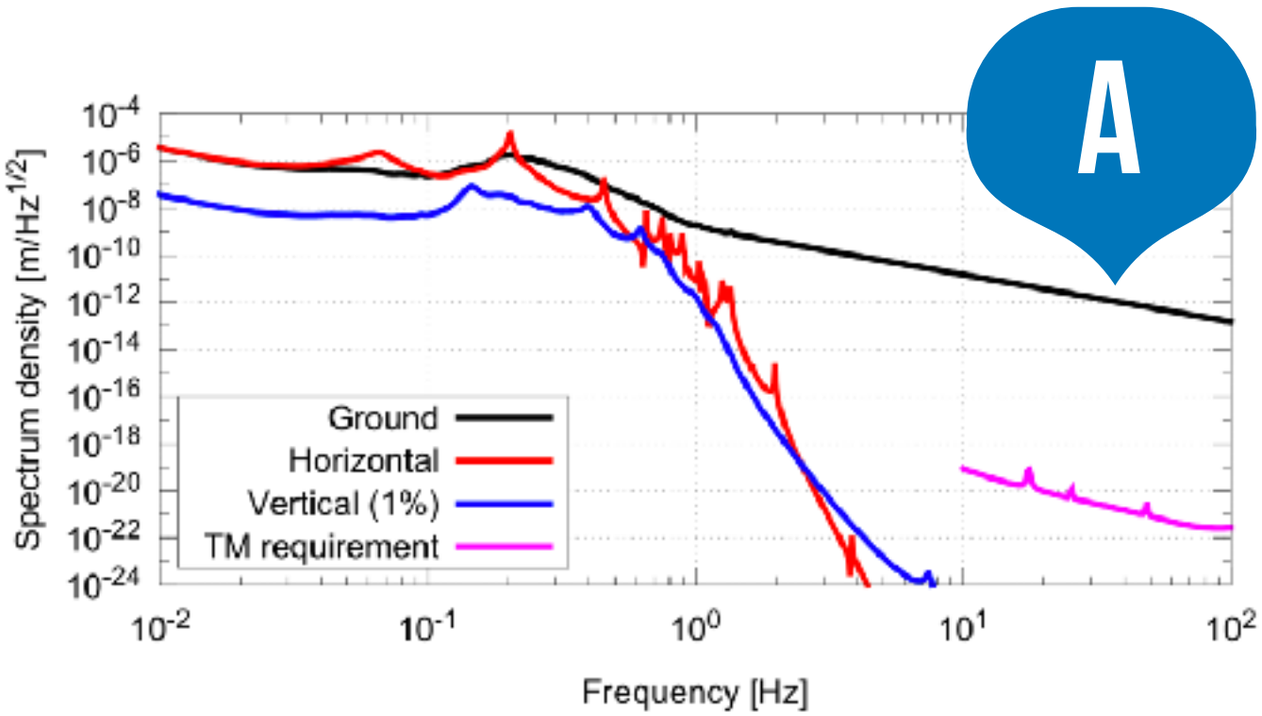
KAGRA COMING SOON!

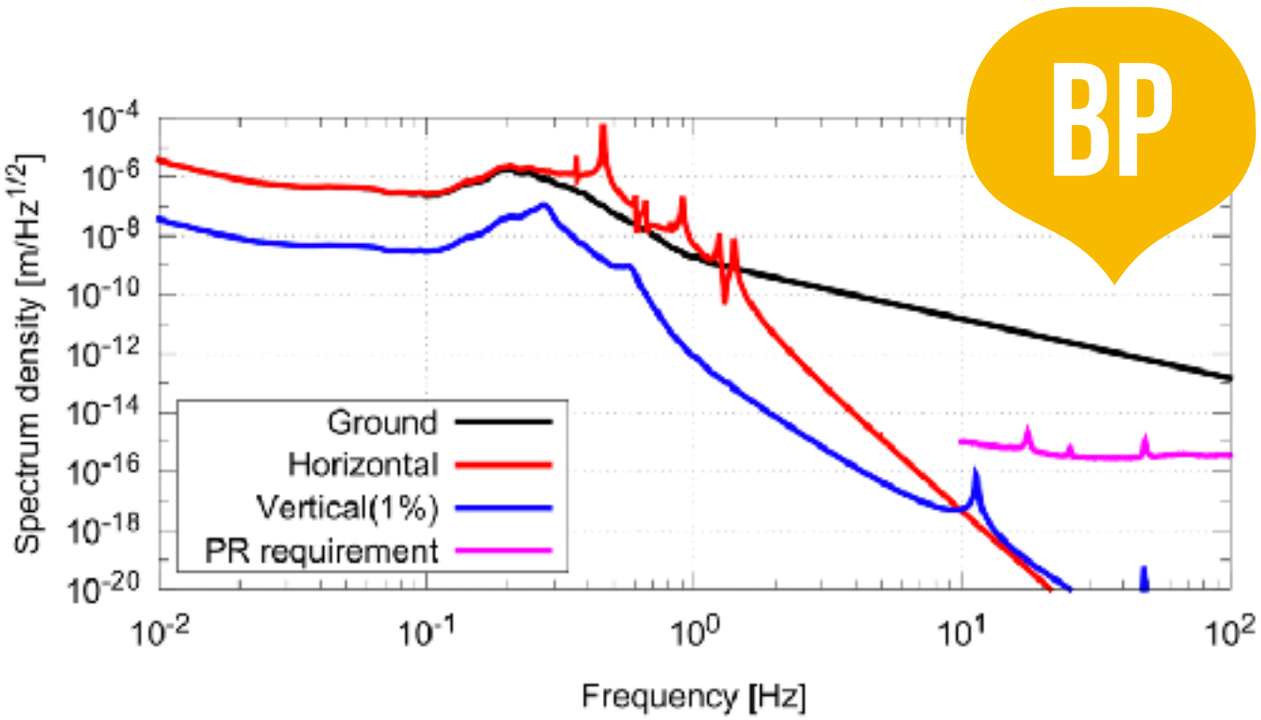
BACKUP SLIDES

COMPONENTS

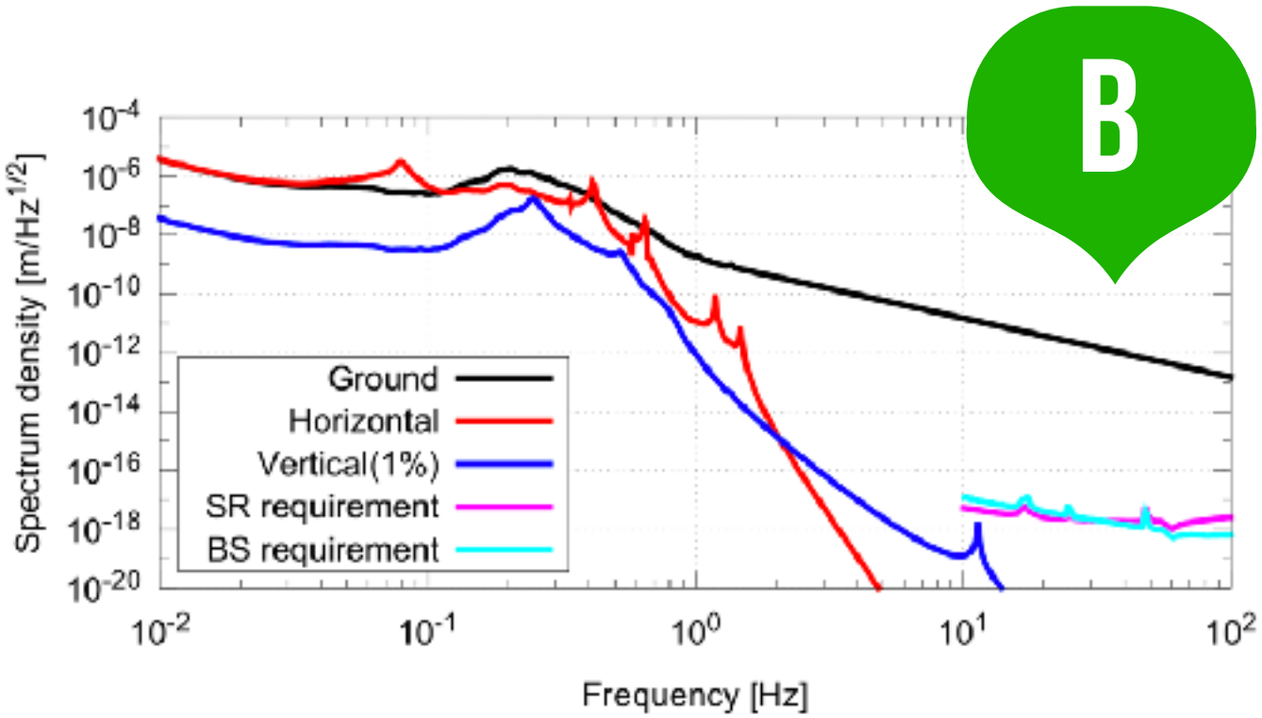
TYPE-A	TYPE-B	TYPE-BP
9 stages	5 stages	3 stages
Inverted Pendulum	Inverted Pendulum	–
GAS Filter x5	GAS Filter x3	GAS Filter x2
Payload: Cryogenic	Room-temperature	Room-temperature
For 4 TMs	For BS and 3 SRs	For 3 PRs

PERFORMANCE



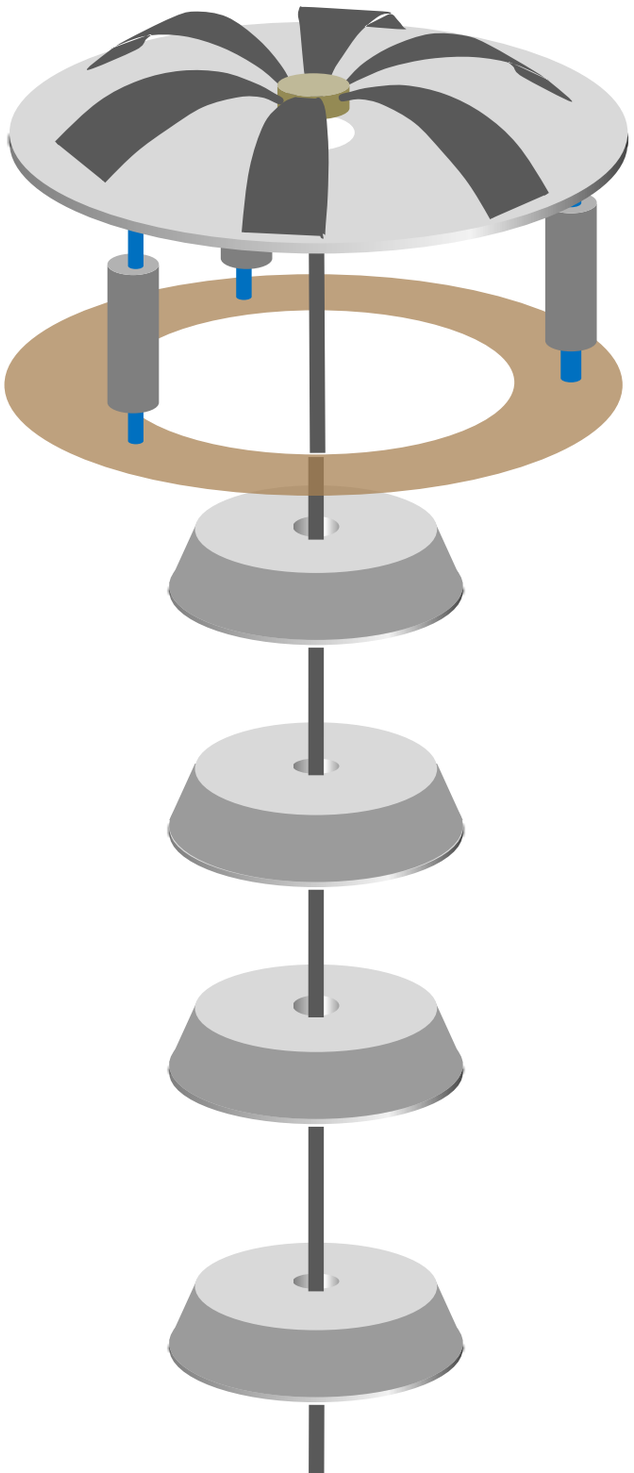


cf.T. Sekiguchi, PhD thesis (2014)



- Both horizontal and vertical motions contribute the displacement noise

TOWER



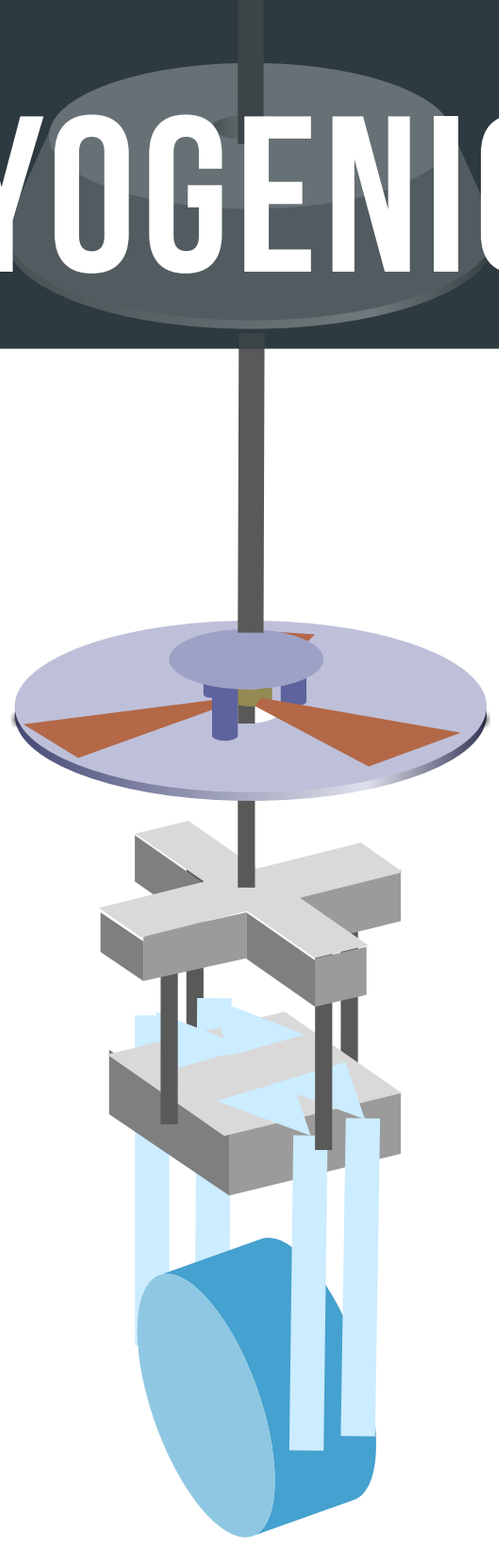
PRE-ISOLATION STAGE

- Inverted pendulum legs
- **Horizontal** resonance ~ 70 mHz

MECHANICAL FILTER CHAIN

- 5 geometric anti-springs
- **Vertical** resonance ~ 300 mHz

CRYOGENIC PAYLOAD



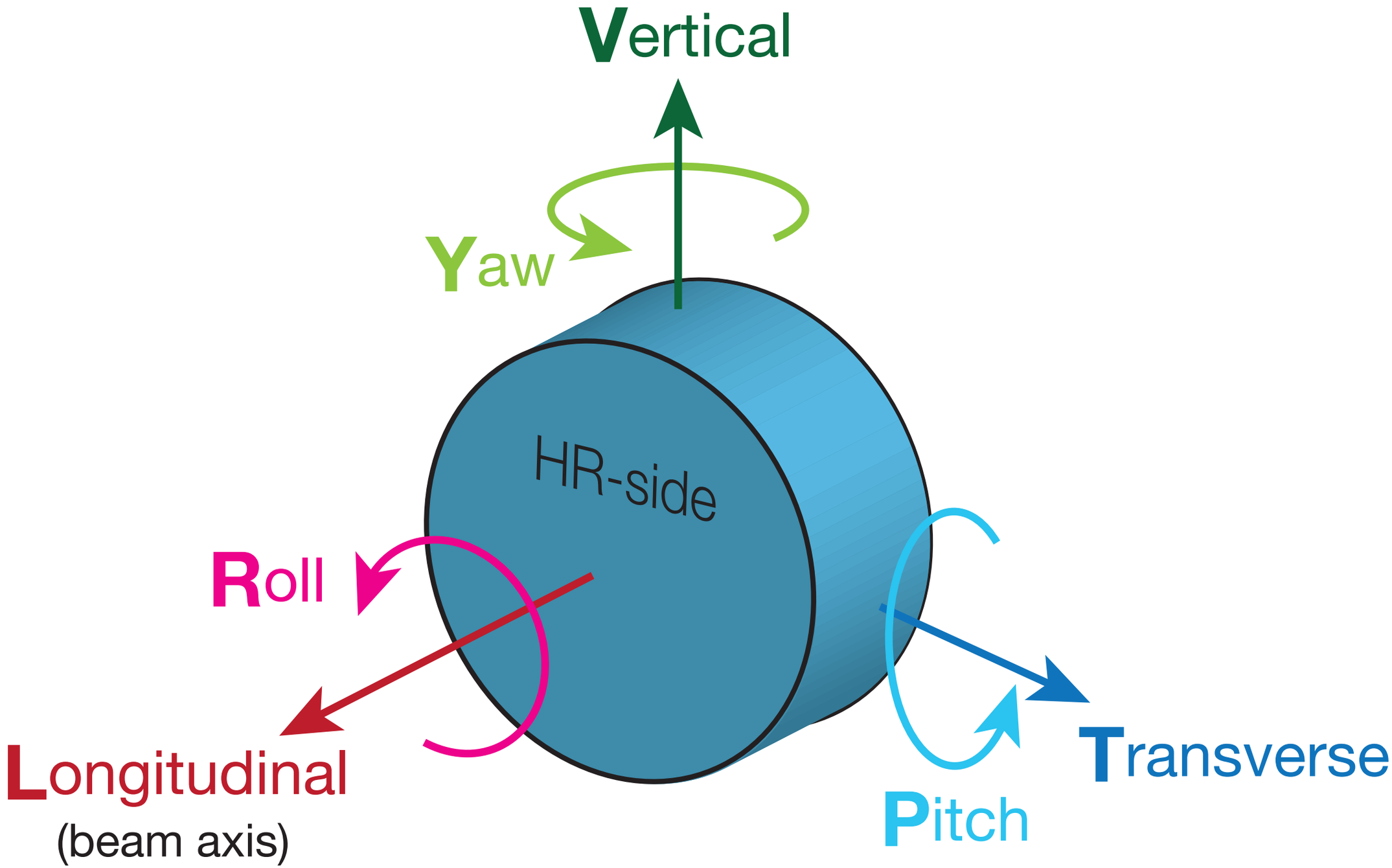
RADIATION + CONDUCTIVE COOLING

- Black coated surface
- Pure aluminum heat links

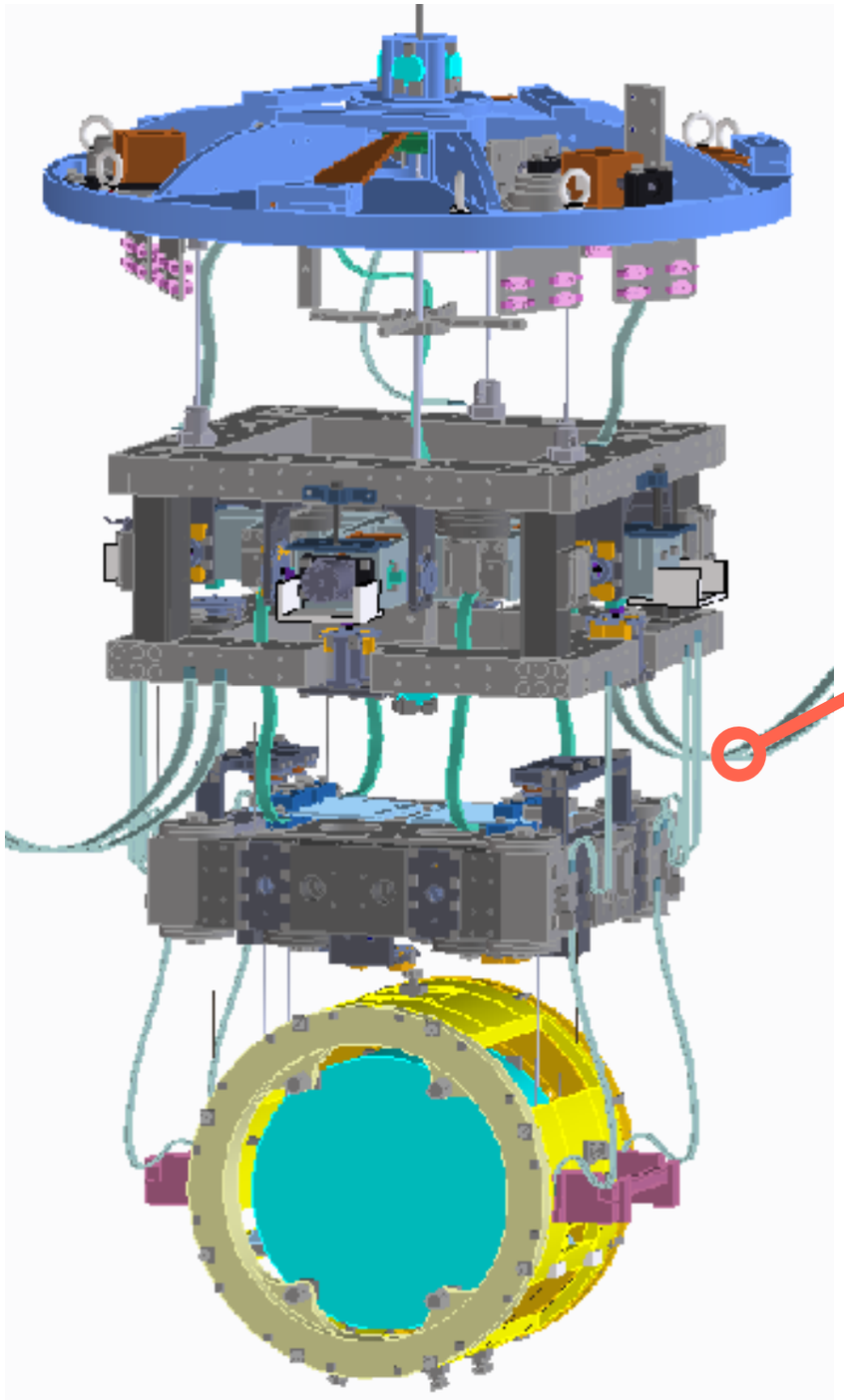
SAPPHIRE TEST MASS & FIBERS

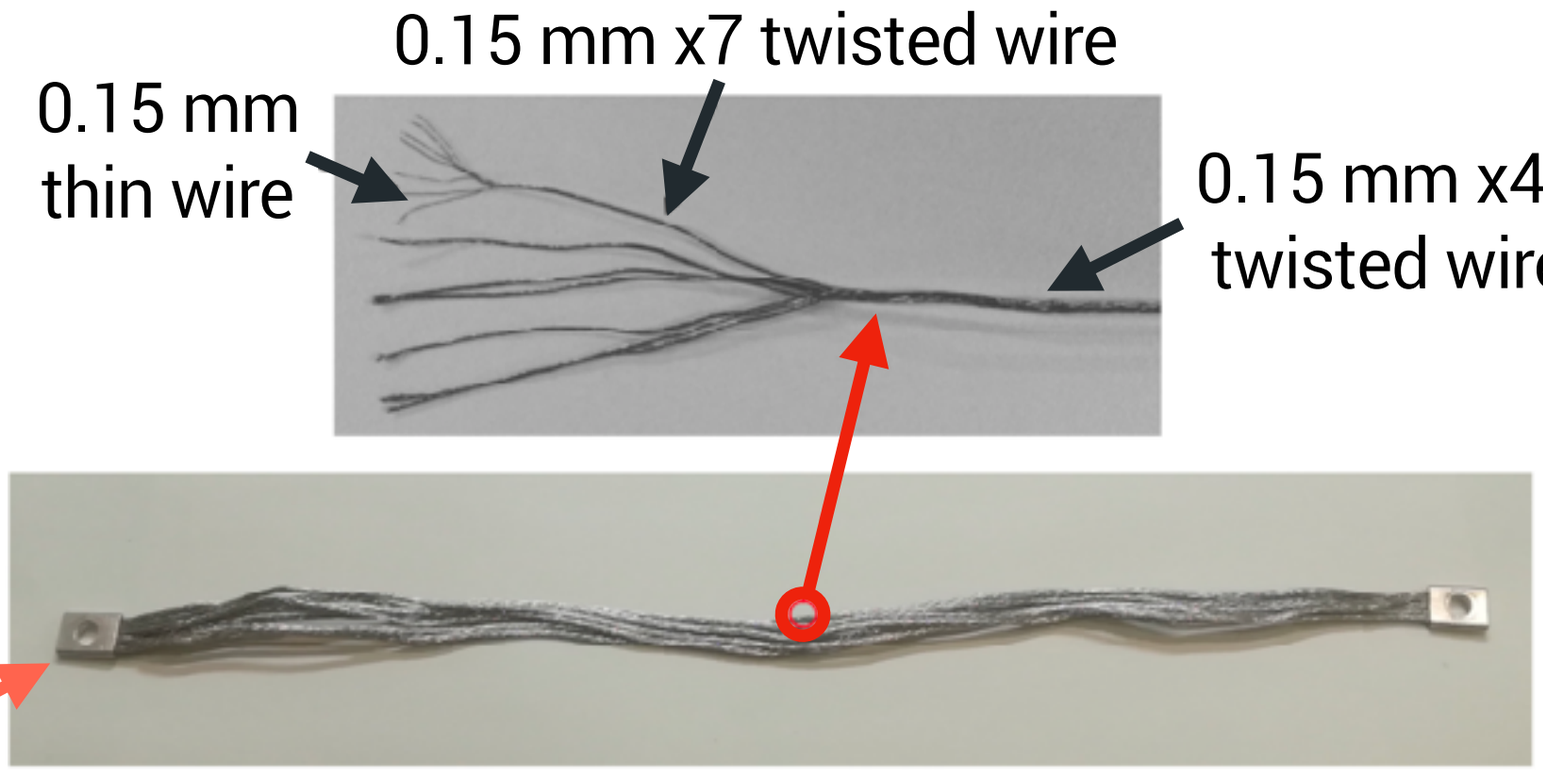
- Weight: 22.5 kg (ears included)
- Hydro-catalysis bonding

DEGREES OF FREEDOM



HEAT LINK





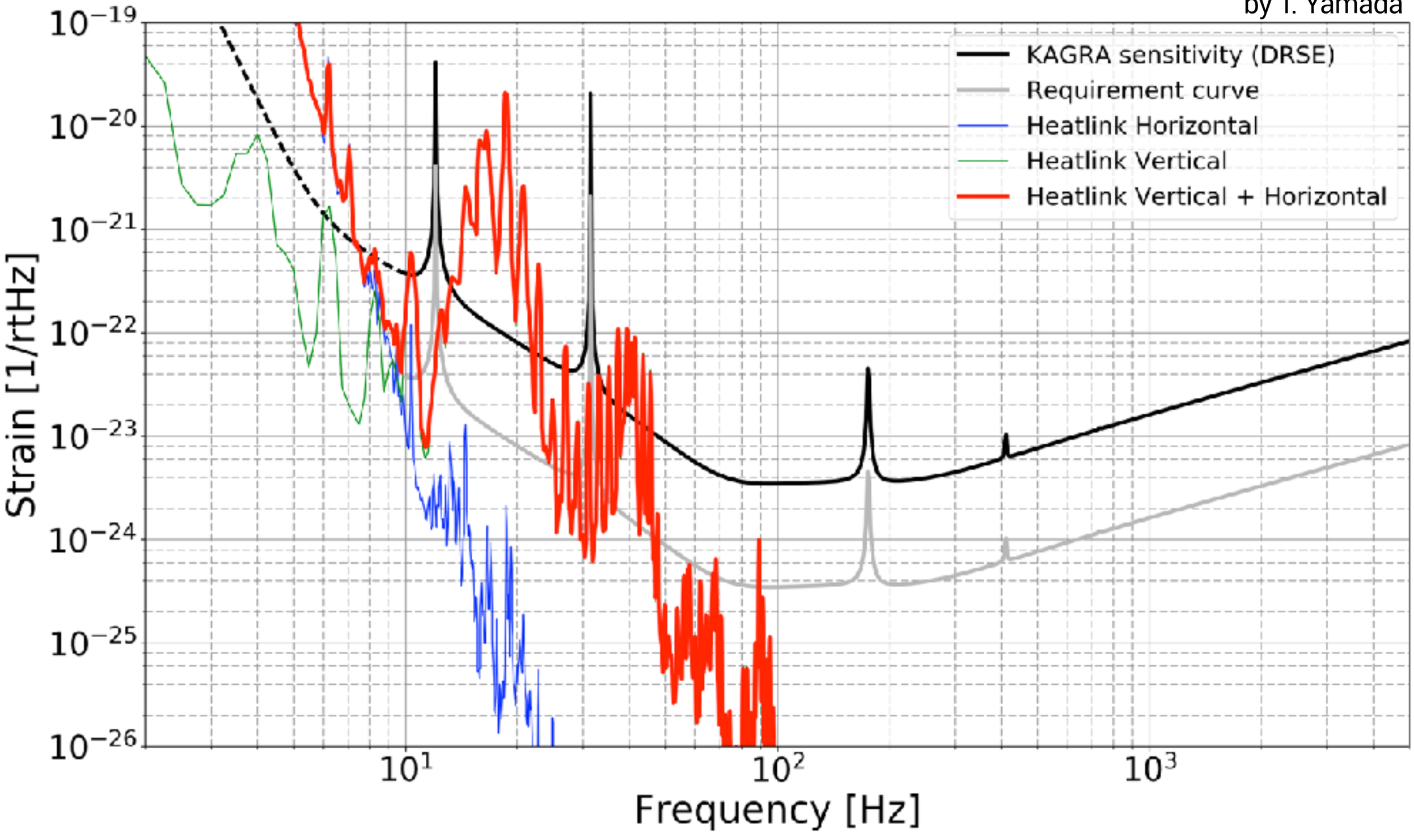
0.15 mm x49 twisted wire x7 in parallel

- 6N (99.9999%) aluminum wire
- High conductivity ~ 18.5 kW/m/K
- Low stiffness: $k_{\mathrm{strand}} = \frac{1}{43} k_{\mathrm{single}}$

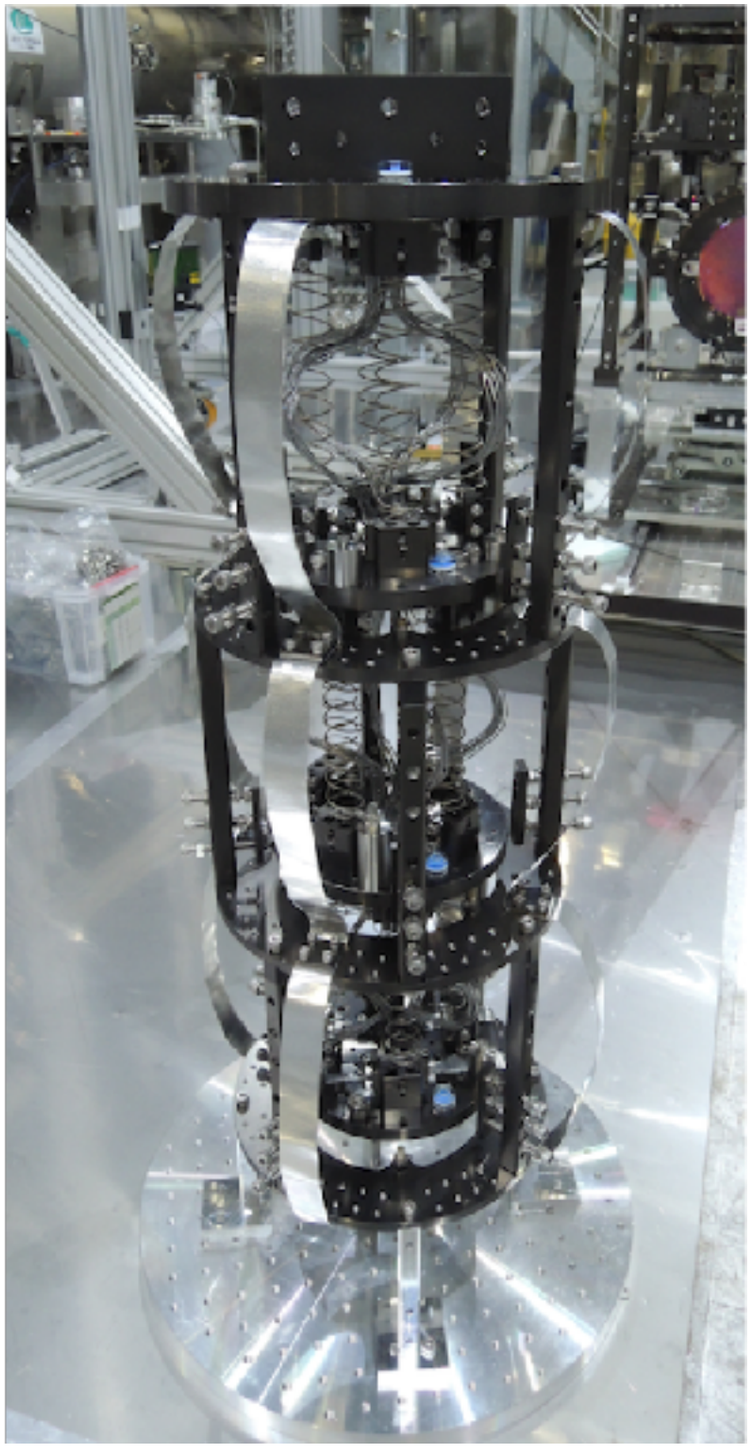
cf. T. Yamada Master Thesis (2018)

HEAT LINK INDUCES VIBRATION

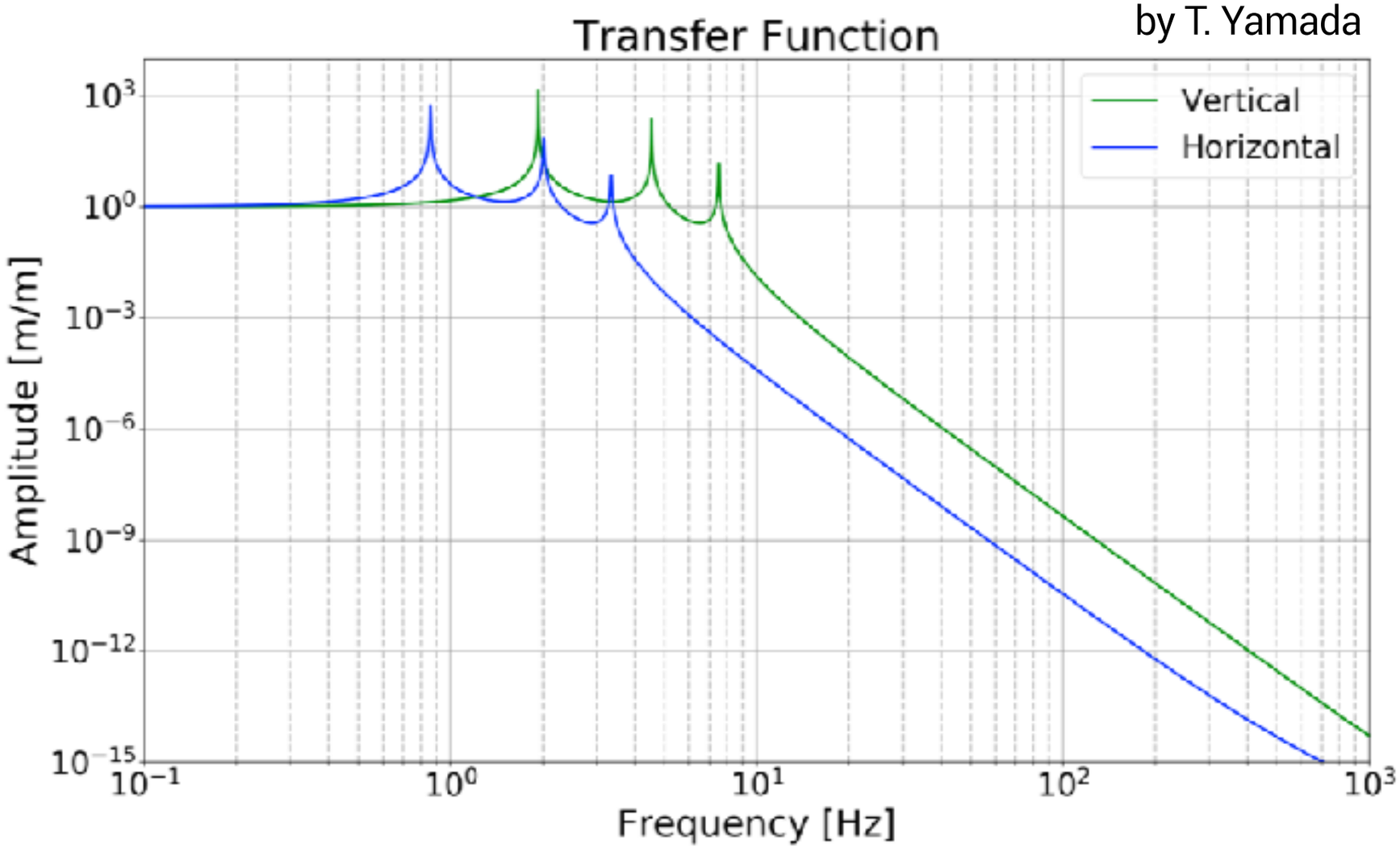
by T. Yamada



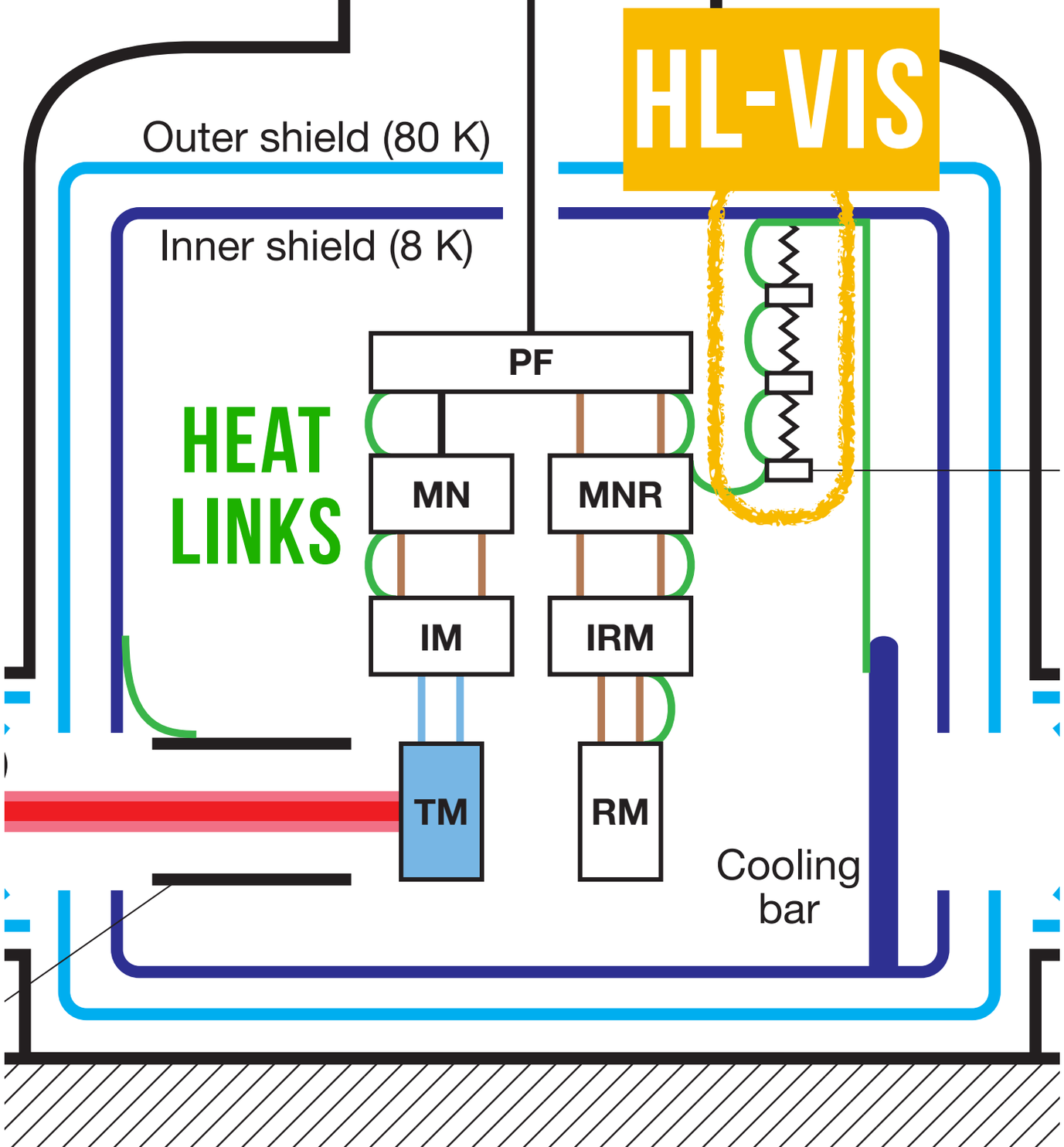
Heat Link Vibration Isolation System

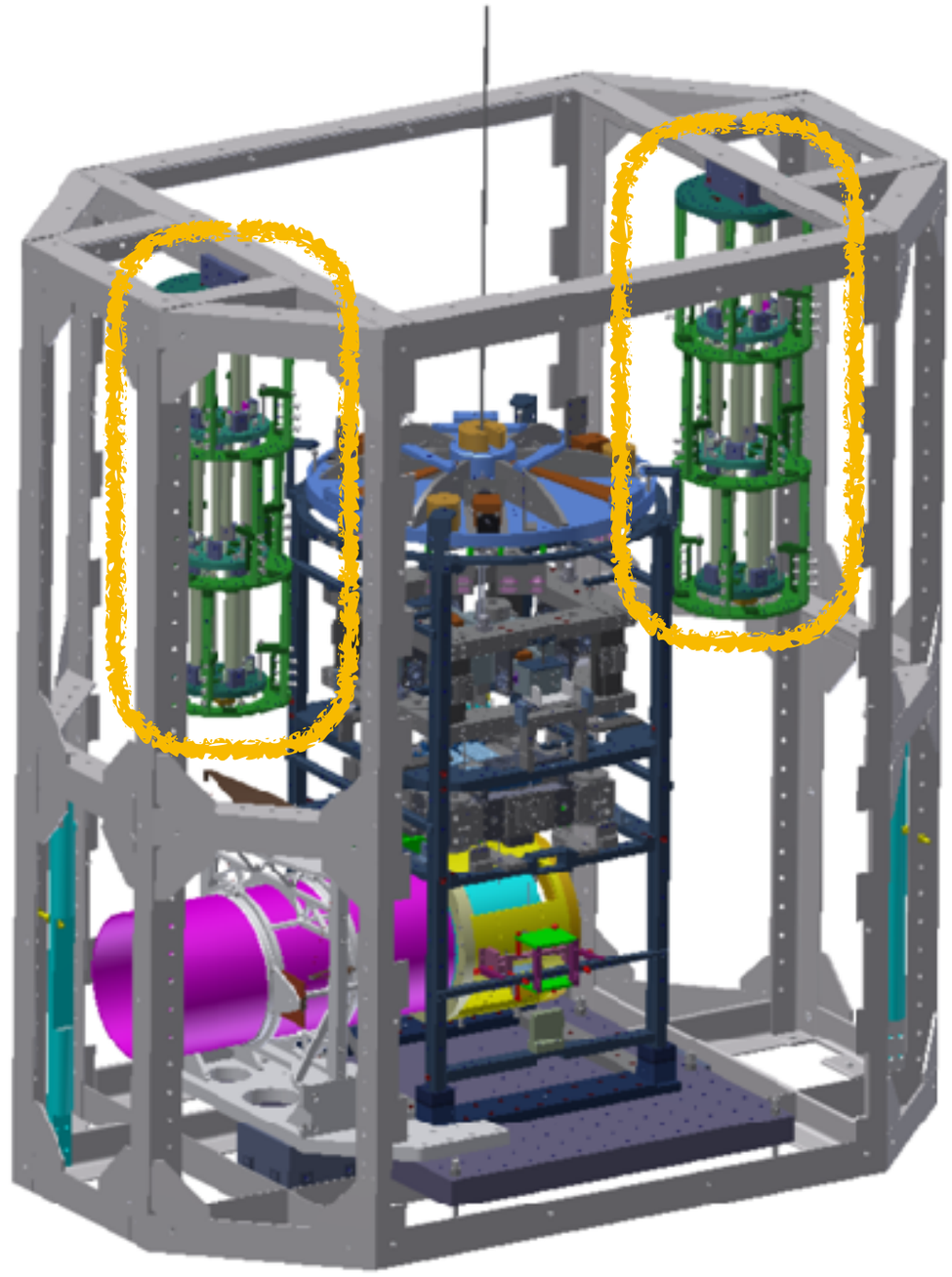


by T. Yamada



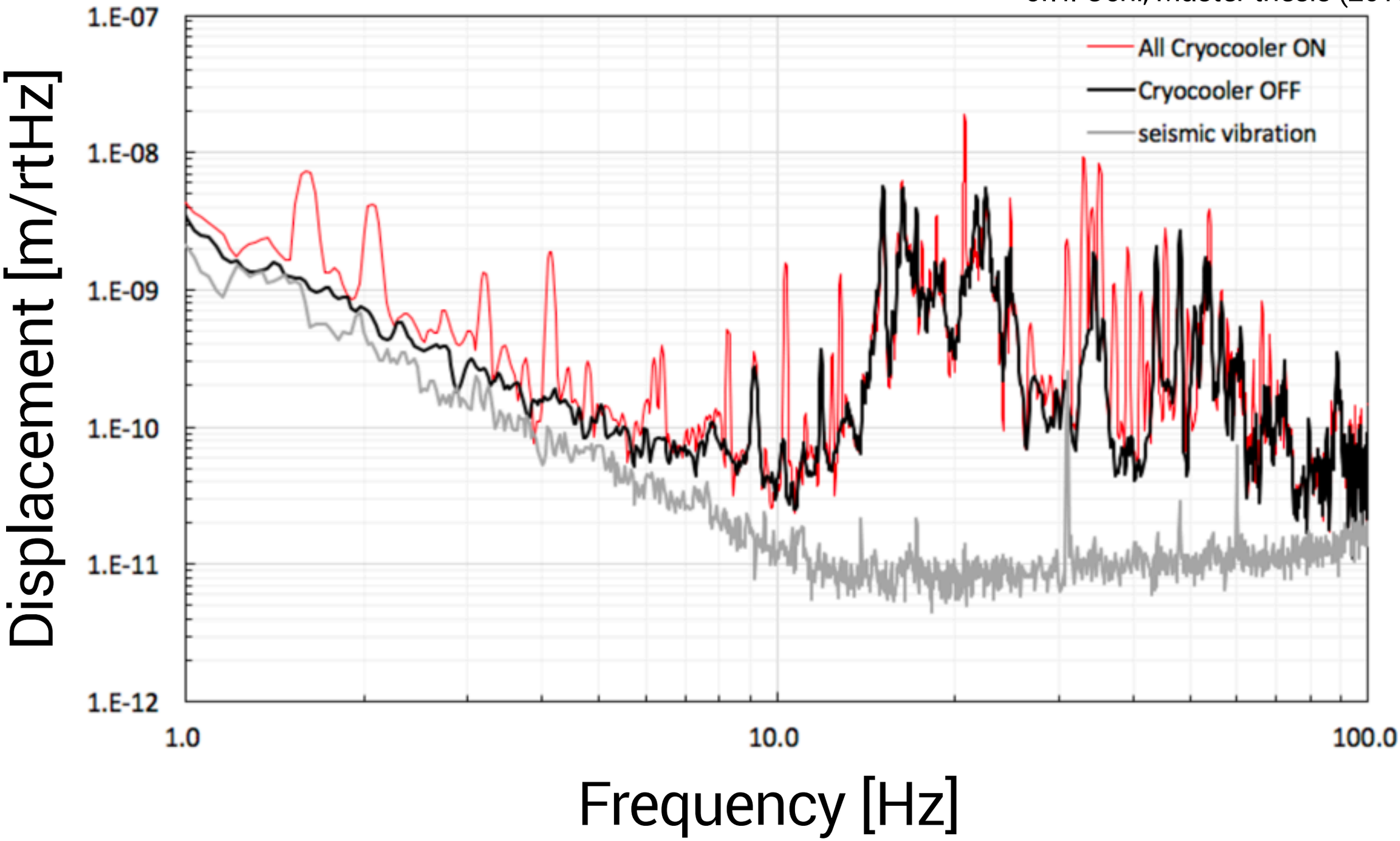
Heat Link Vibration Isolation System





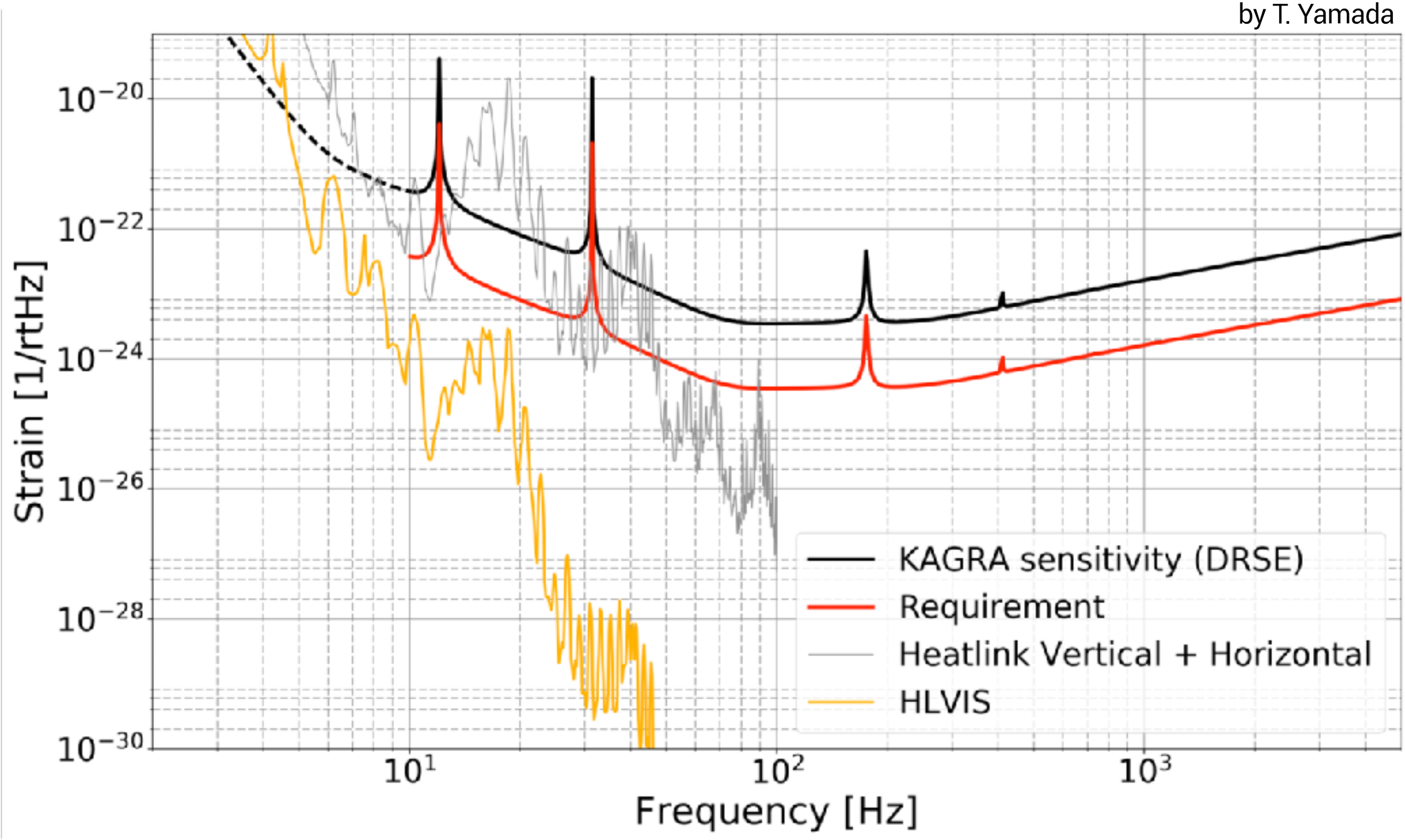
VIBRATION IN THE CRYOSTAT

cf.T. Ochi, Master thesis (2018)

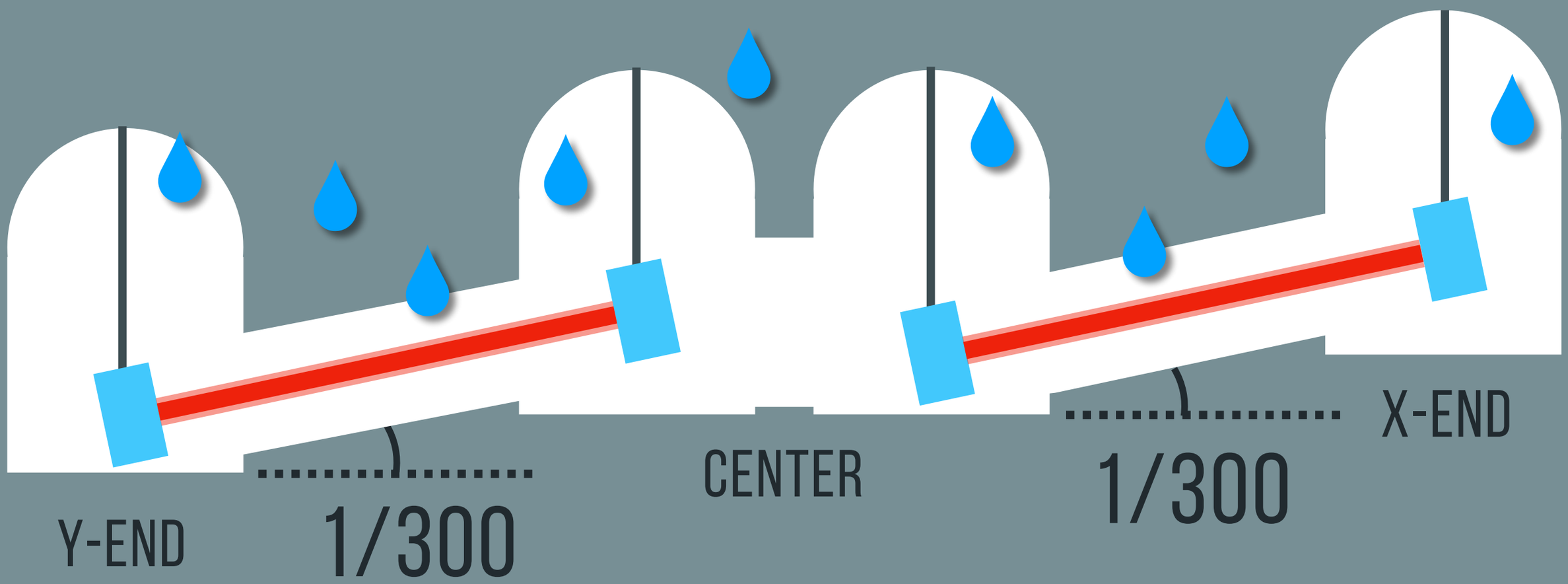


HL-VIS DESIGN PERFORMANCE

by T. Yamada



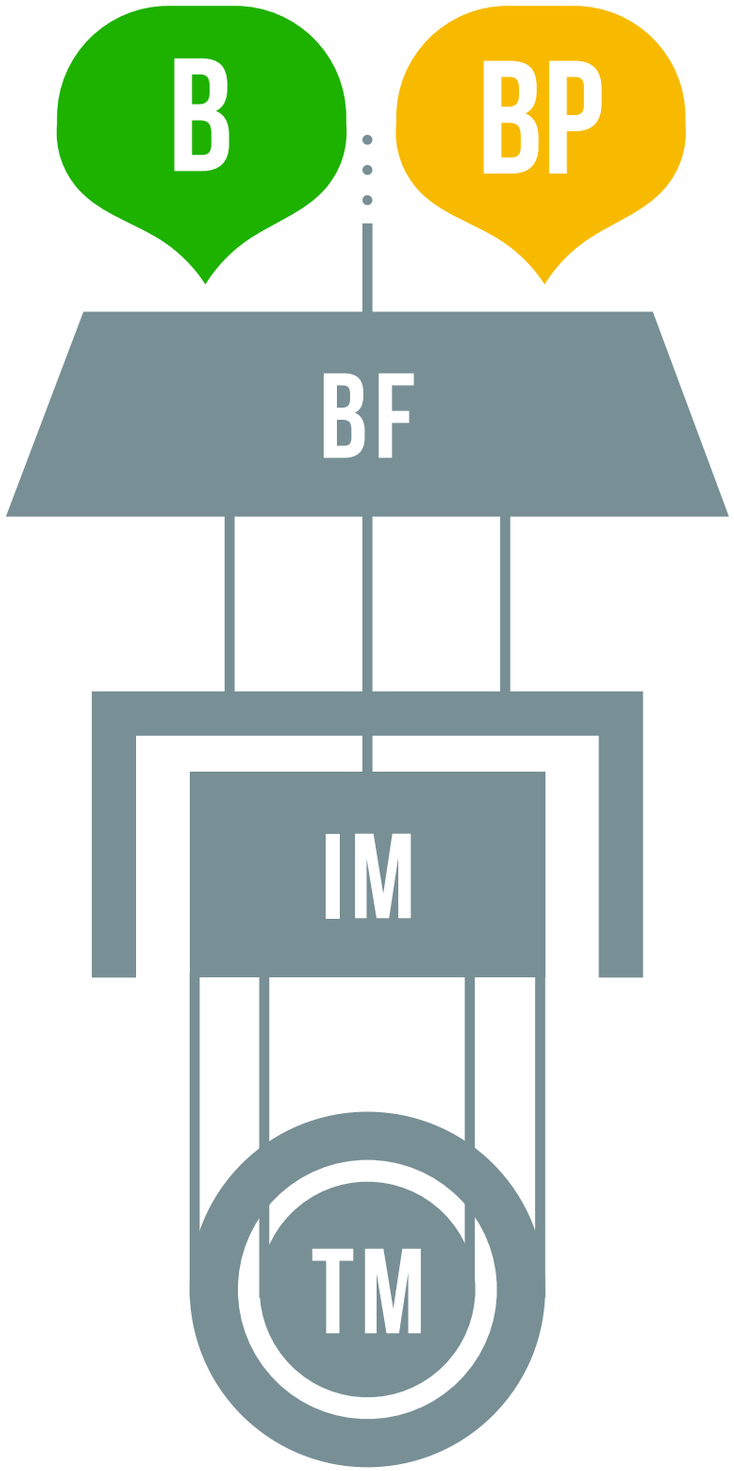
VERTICAL-TO-LONGITUDINAL COUPLING

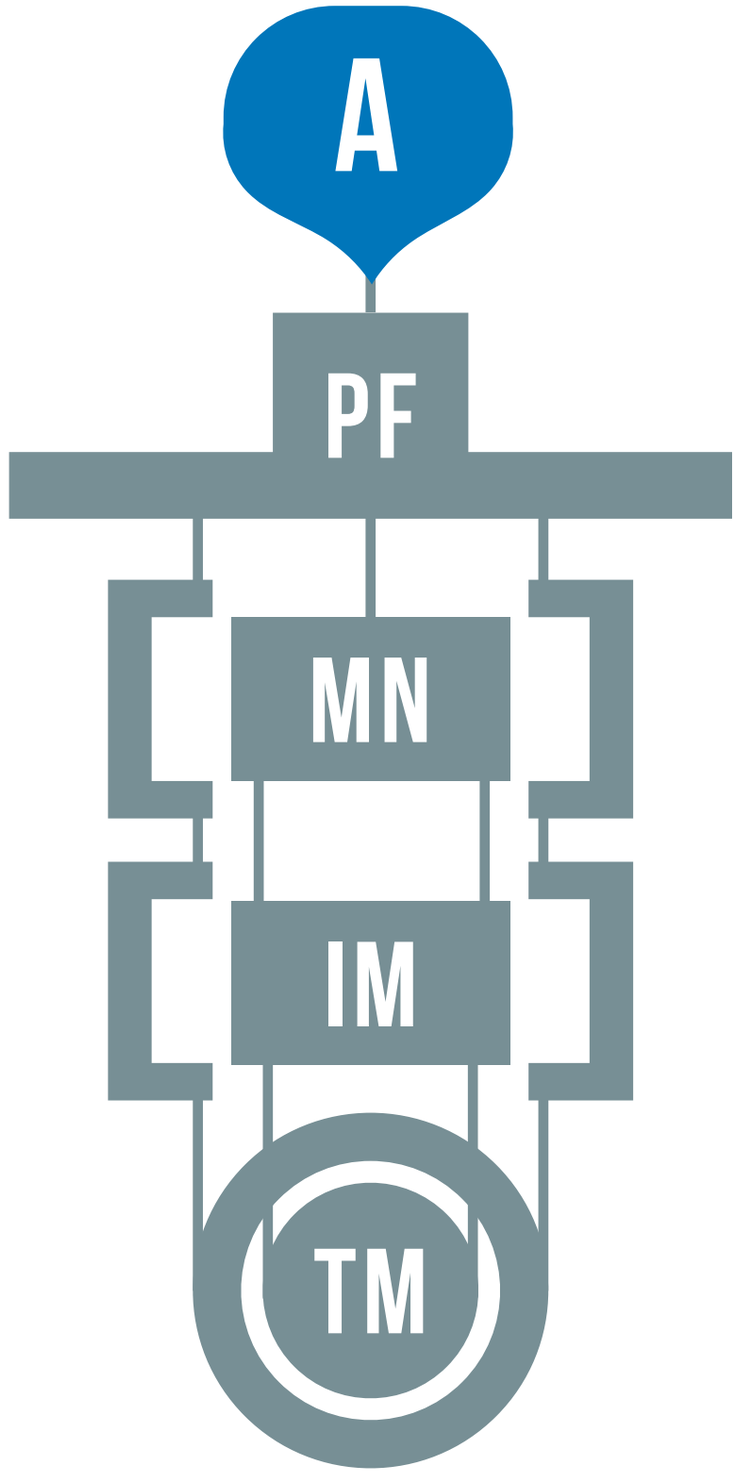


$$\frac{\text{(Longitudinal)}}{\text{(Vertical)}} \lesssim 1\%$$

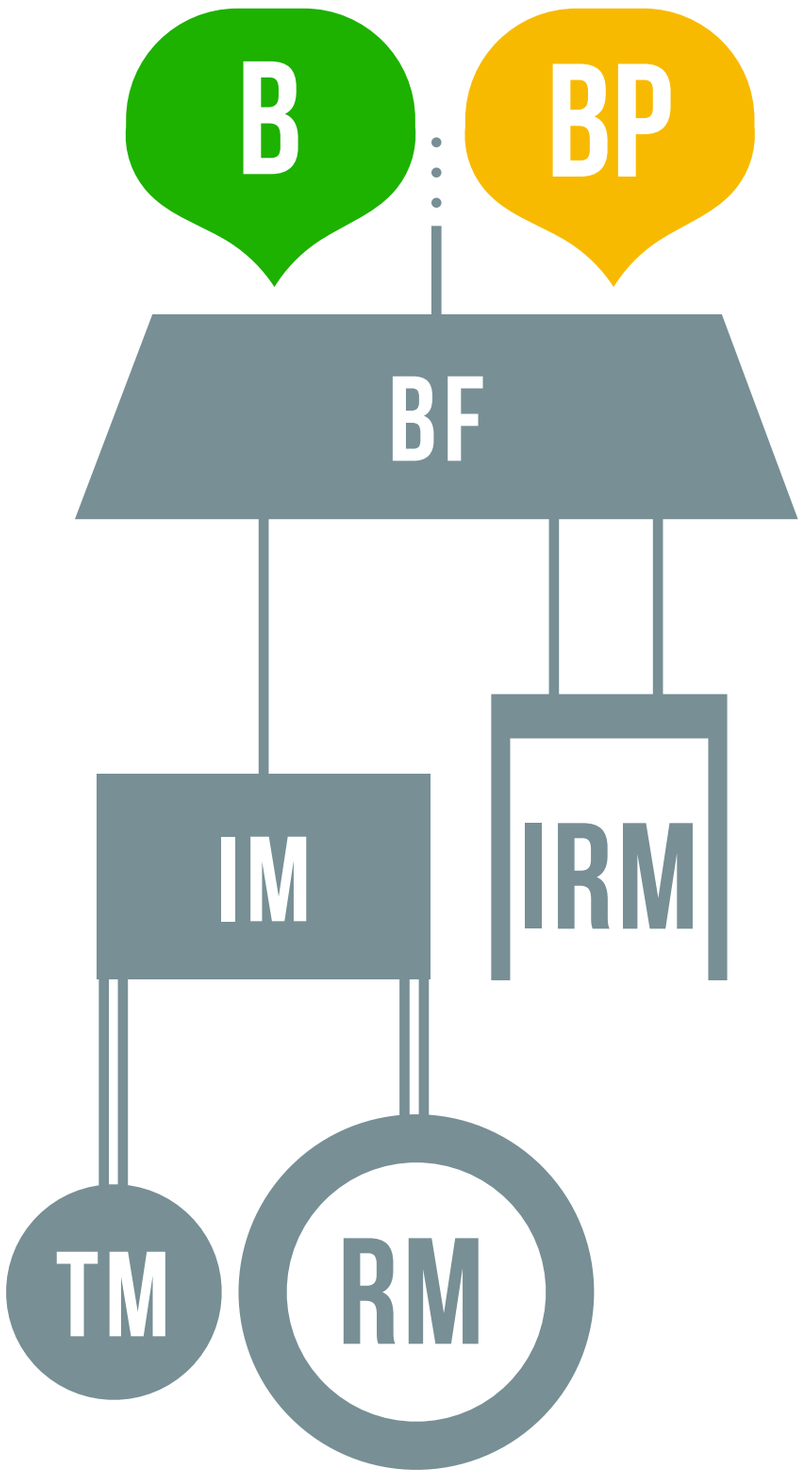
VERTICAL-TO-LONGITUDINAL COUPLING

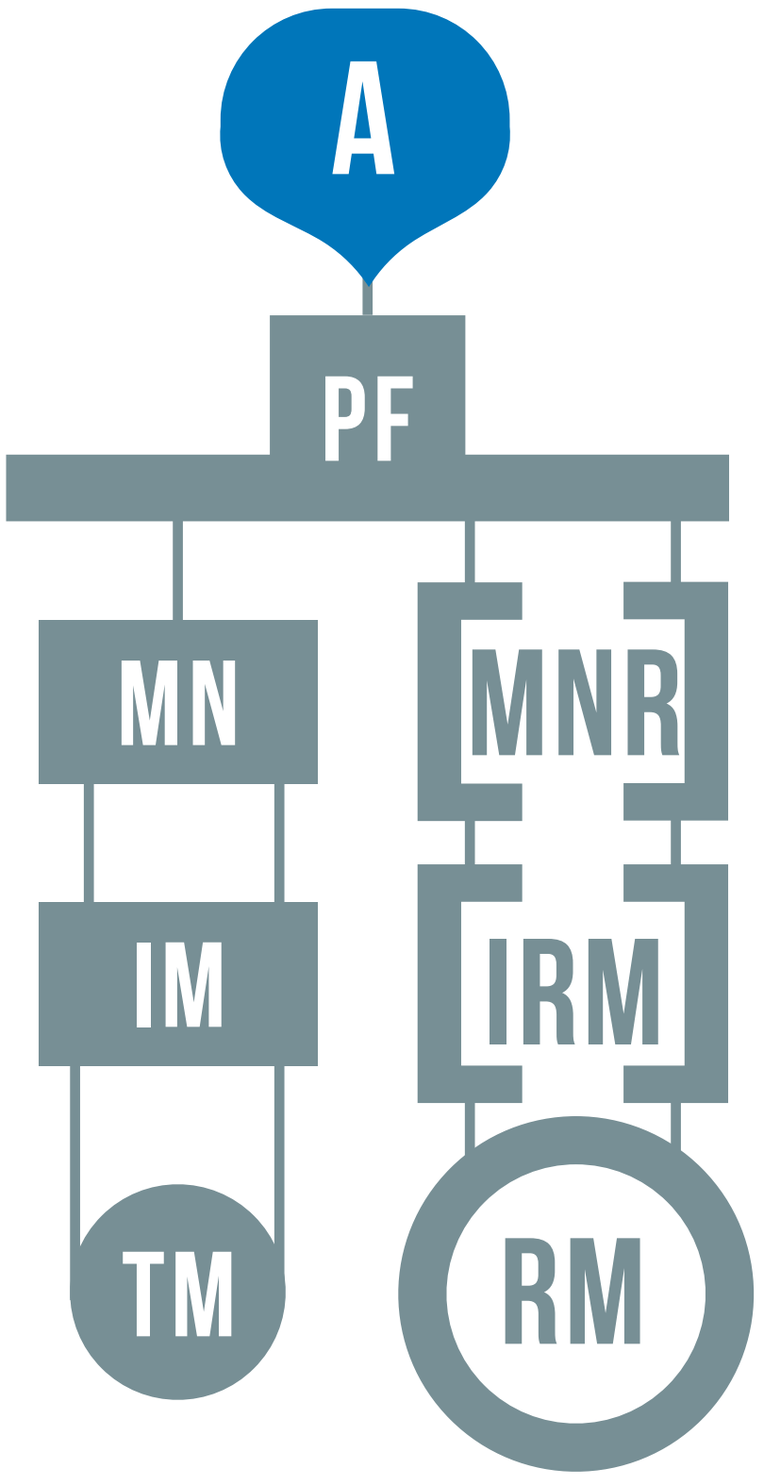
PAYLOAD STRUCTURE



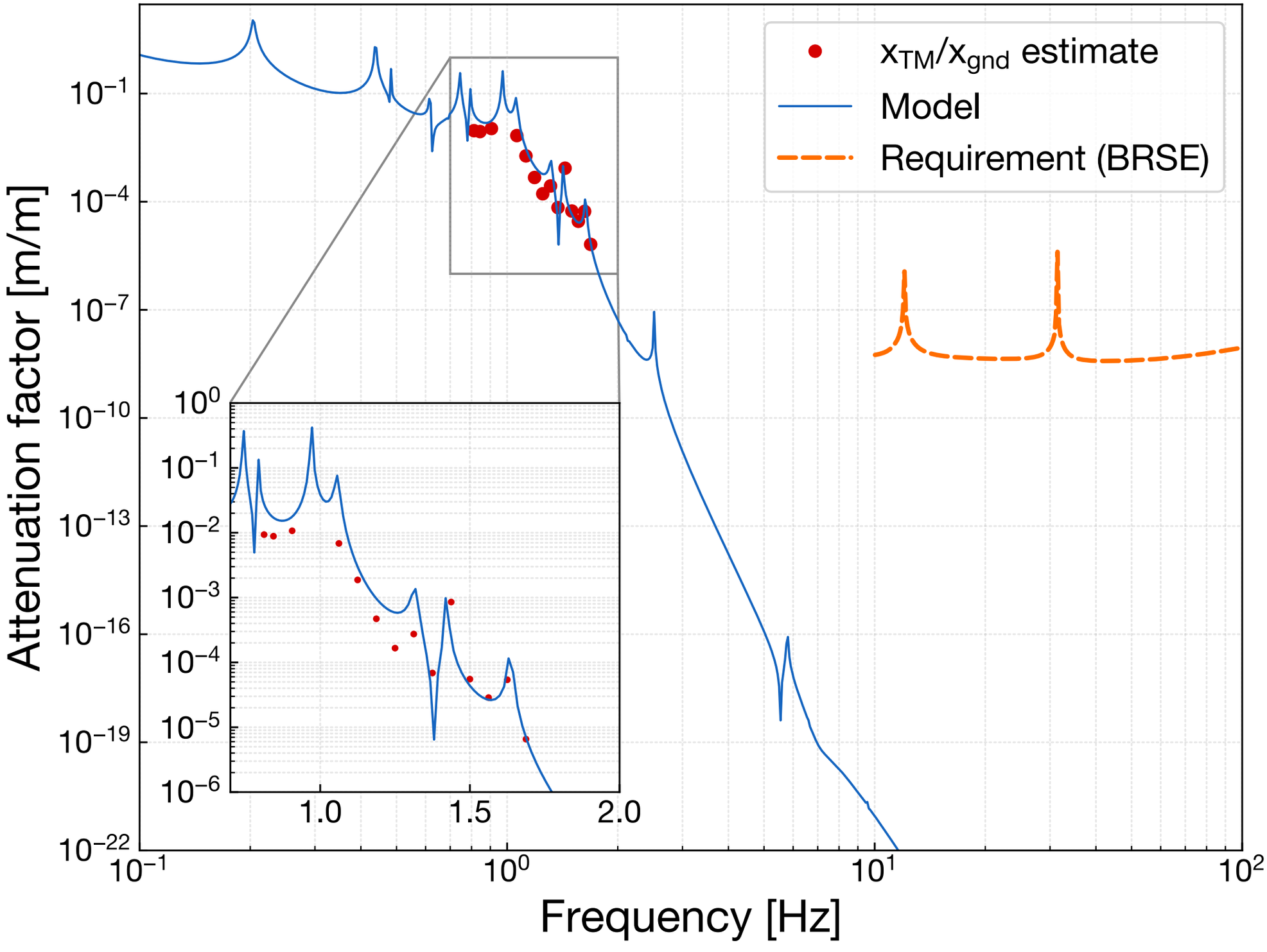


PAYLOAD STRUCTURE

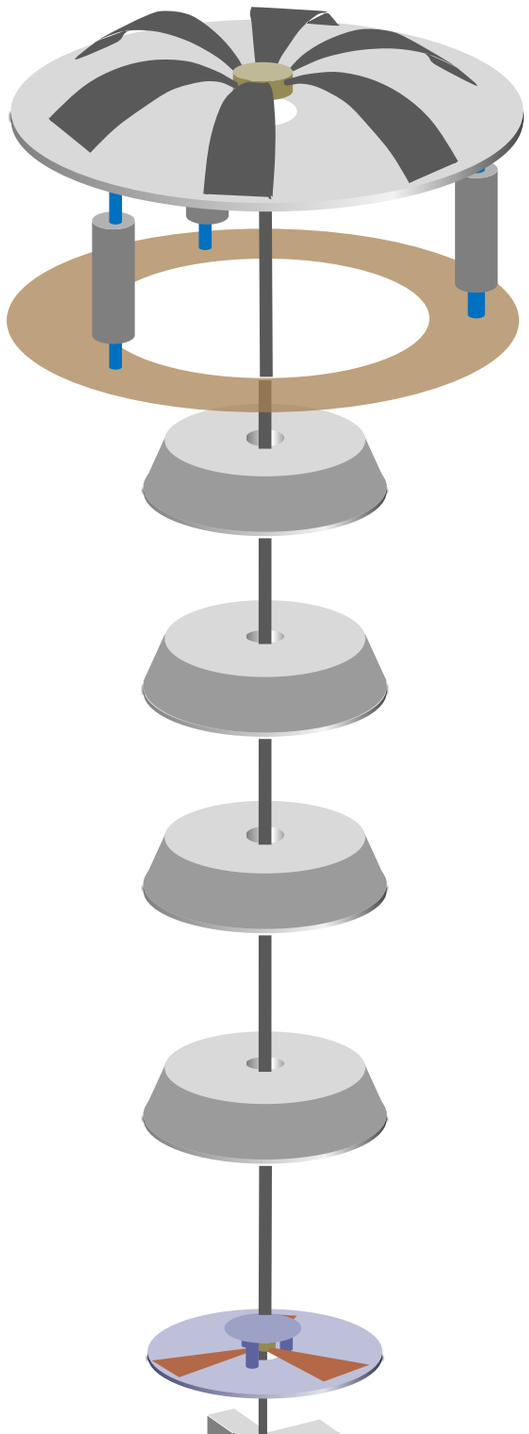




Vibration Isolation Ratio MEASUREMENT



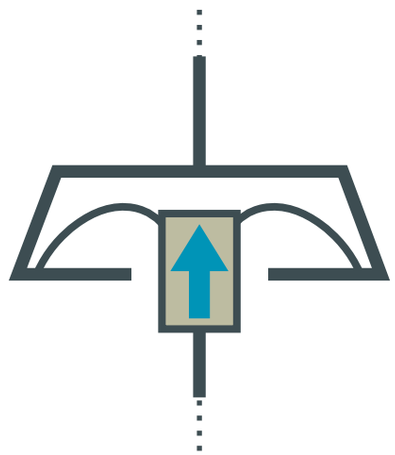
LOCAL SENSORS - TOWER



IP

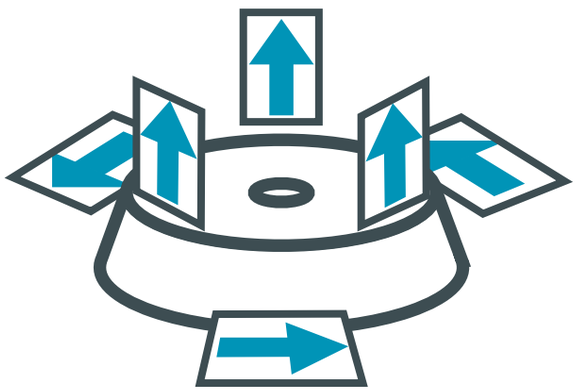
- LVDT
  IP-ground displacement
- Geophone
  IP inertial velocity

GAS



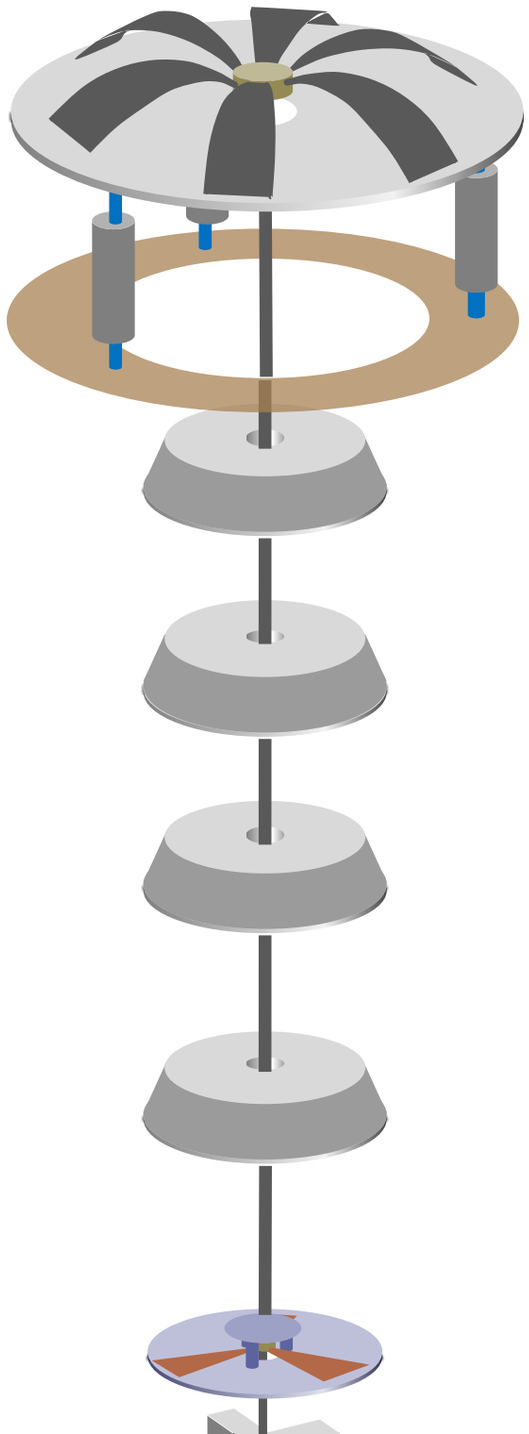
- LVDT
  keystone-body displacement

BF

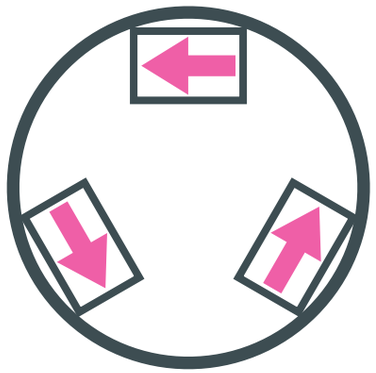


- LVDT
  BF-frame displacement

LOCAL ACTUATORS - TOWER



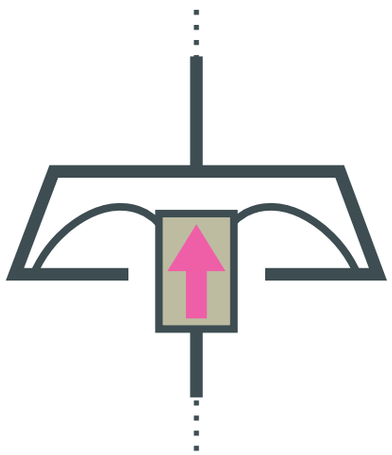
IP



Voice coil actuator

IP-ground force

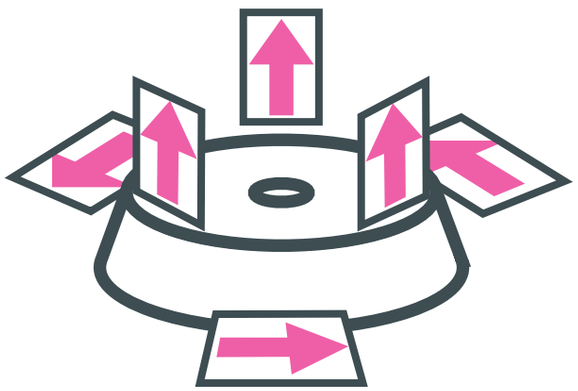
GAS



Voice coil actuator

keystone-body force

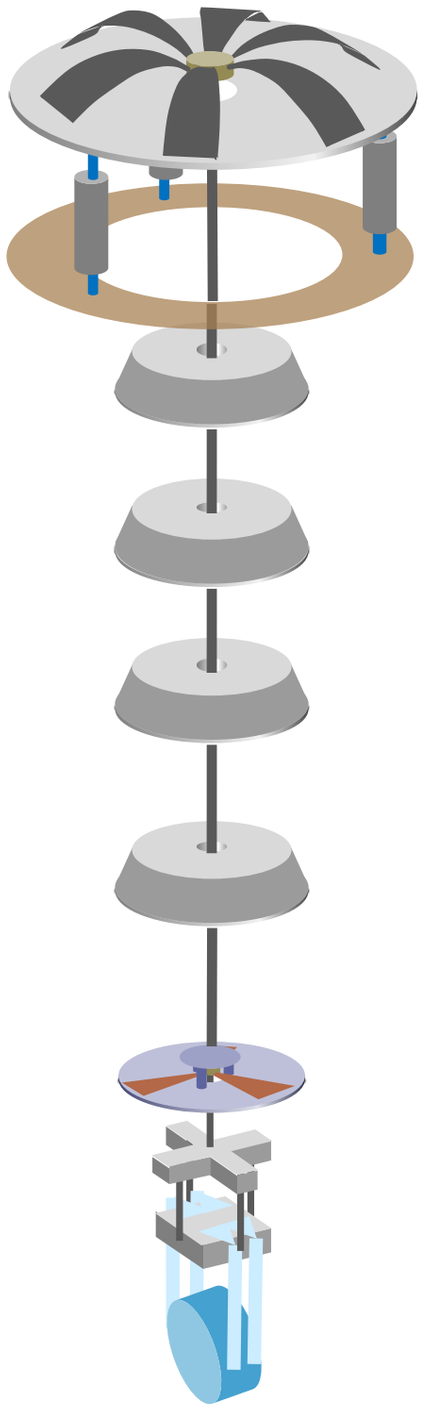
BF



Coil-magnet actuator

BF-frame force

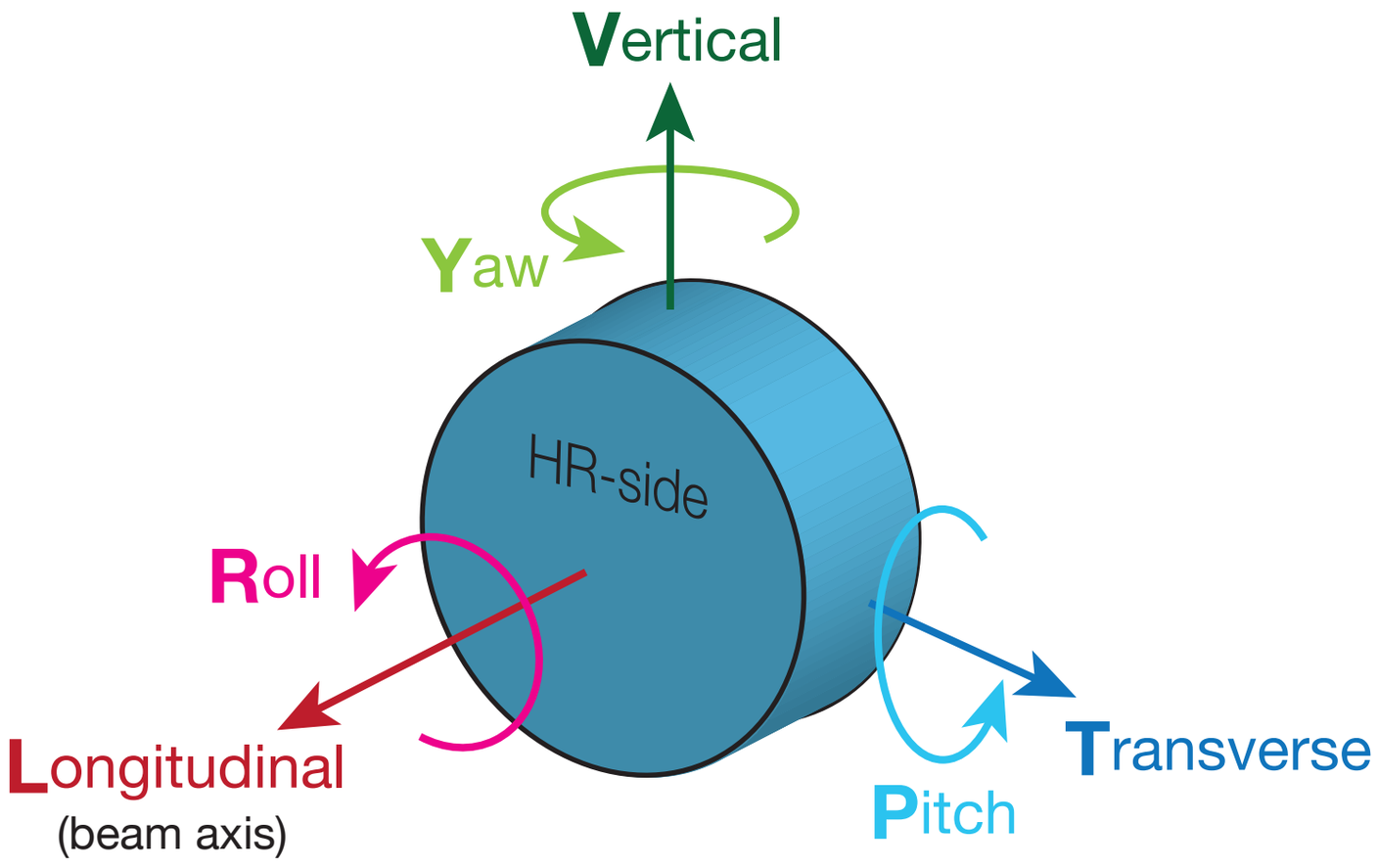
TORSION MODE DAMPING



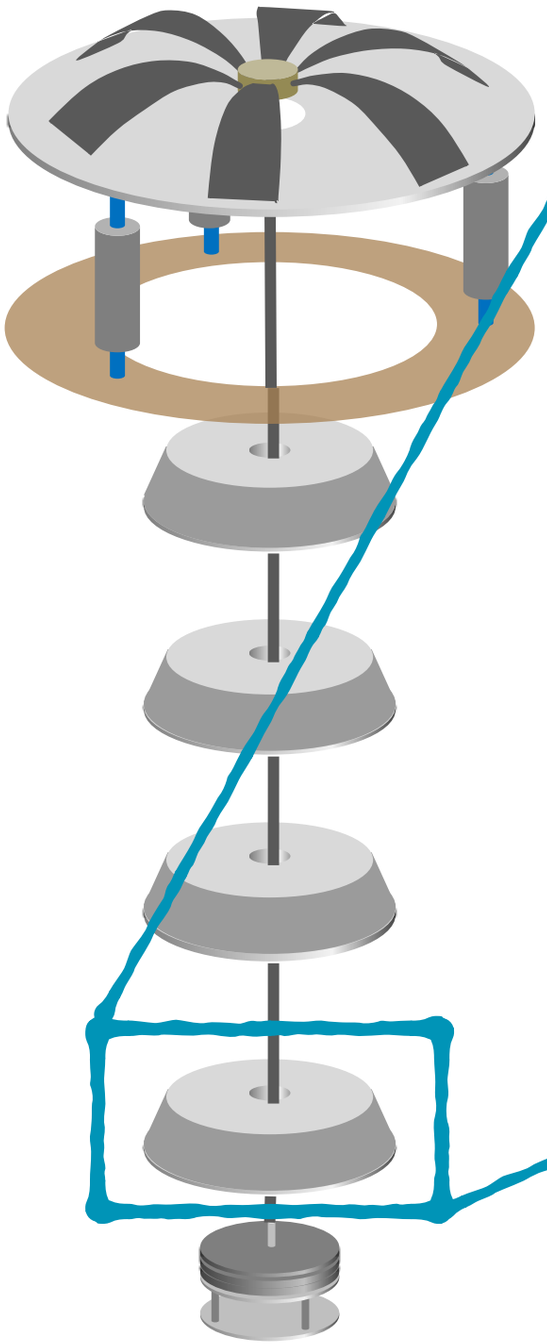
SINGLE WIRE CONNECTION

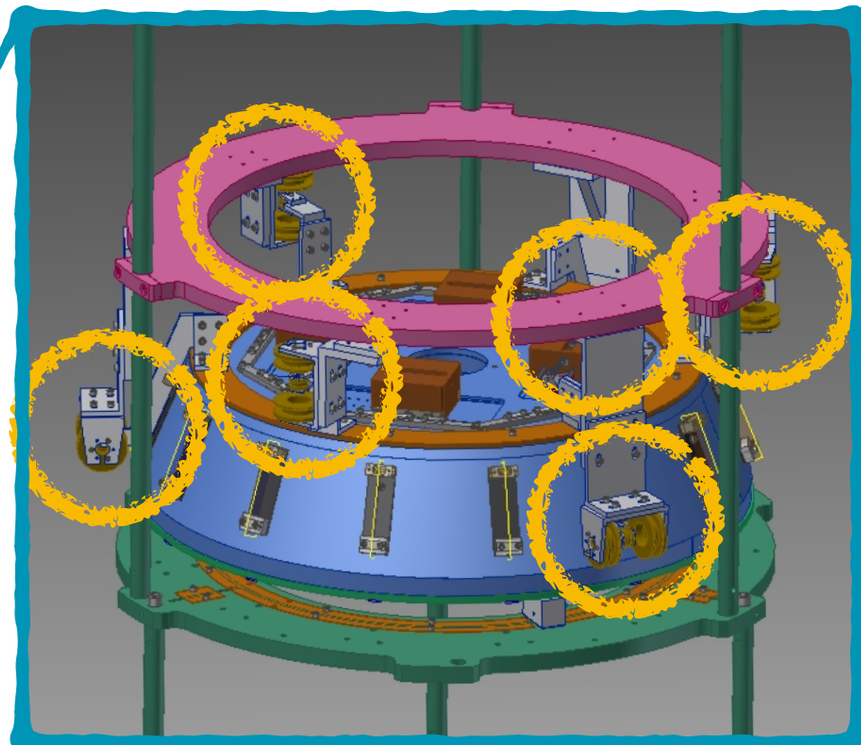
Requirements

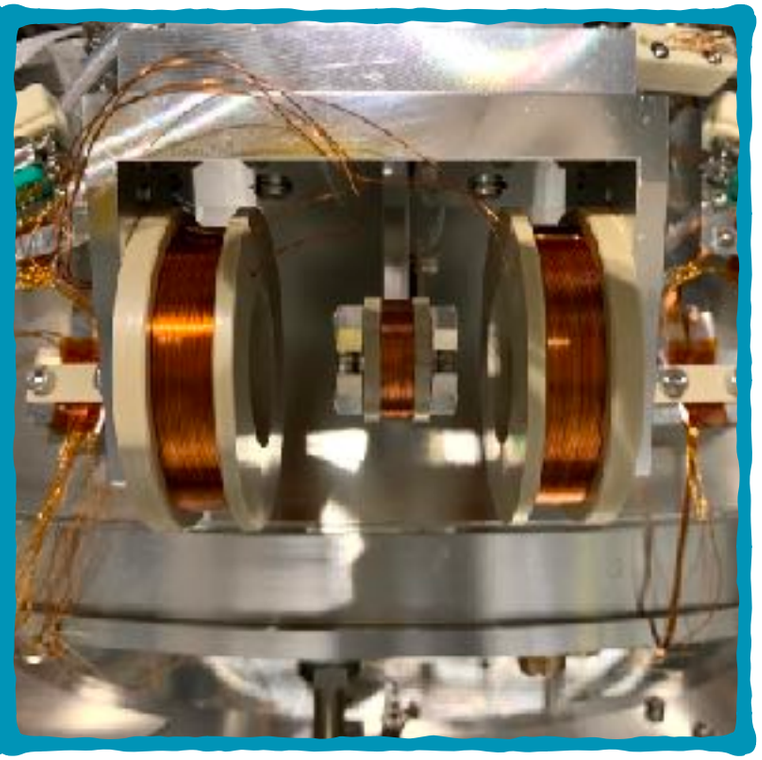
- Yaw RMS at TM < **0.88 urad**
- Mode decay time < **60 sec.**



BF DAMPER

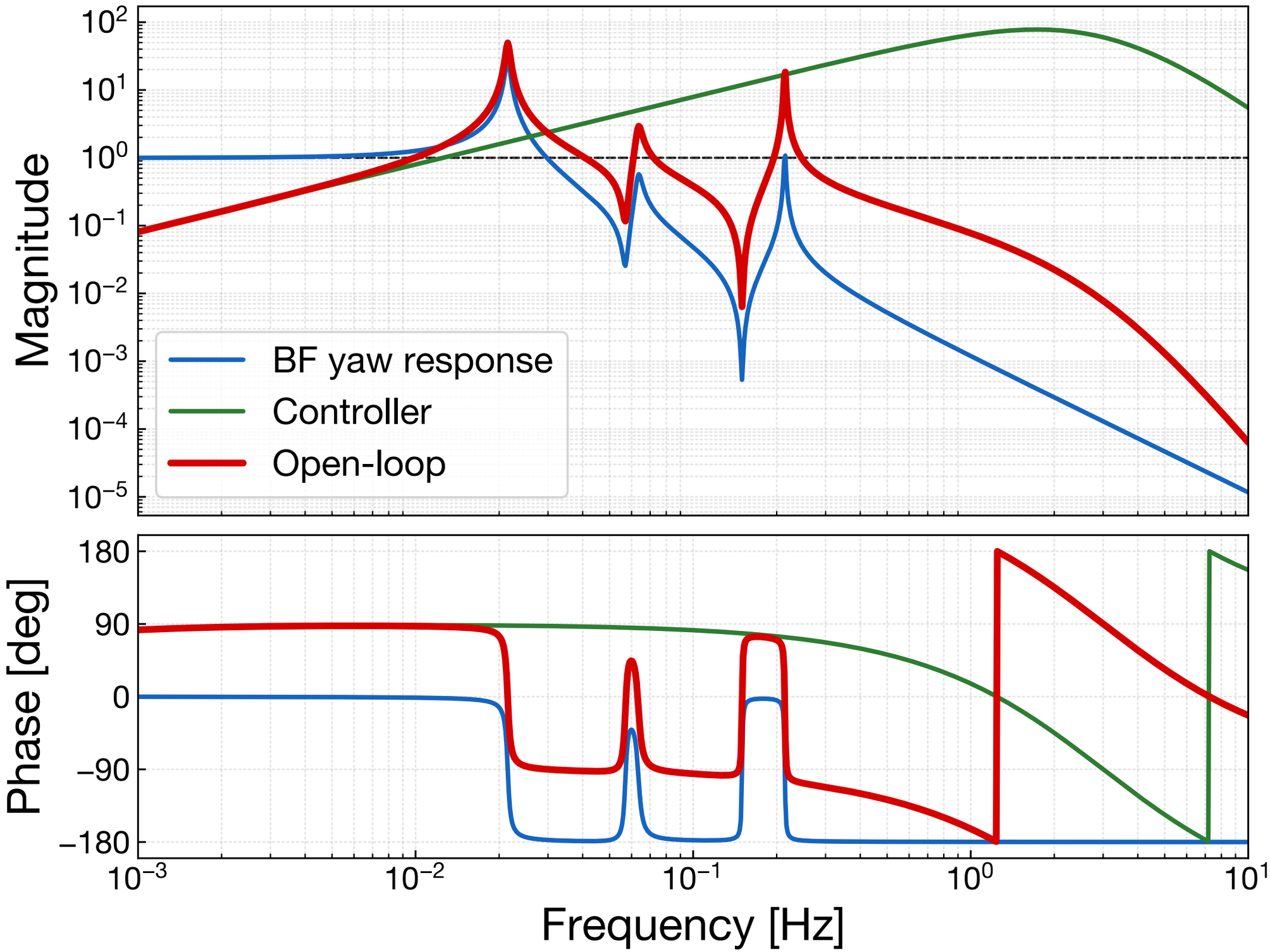




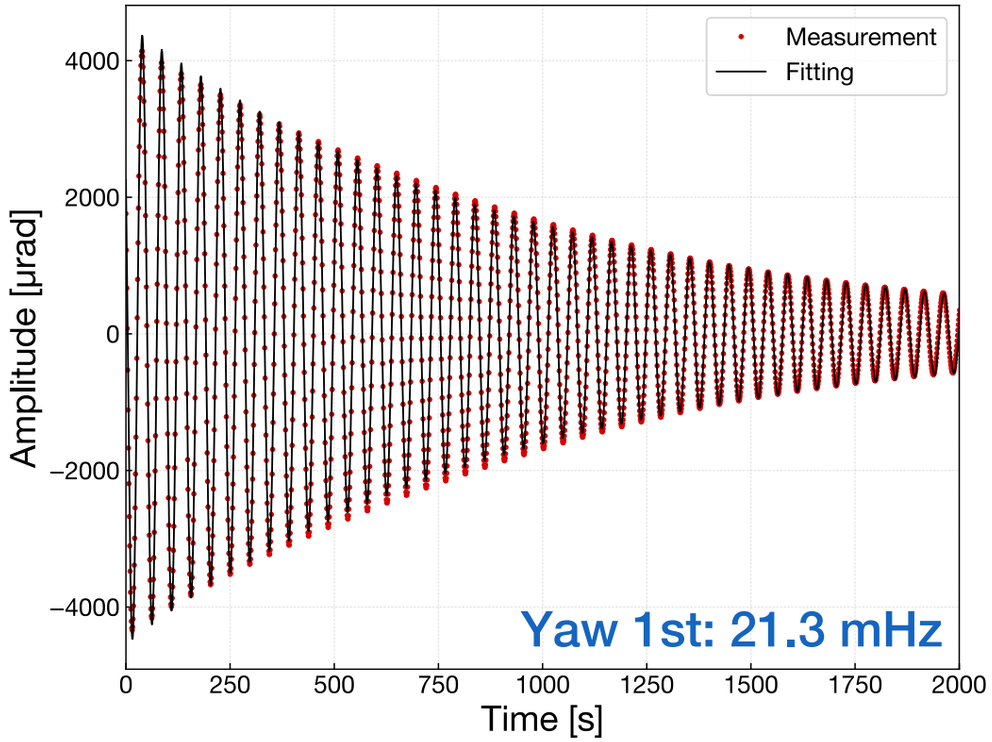


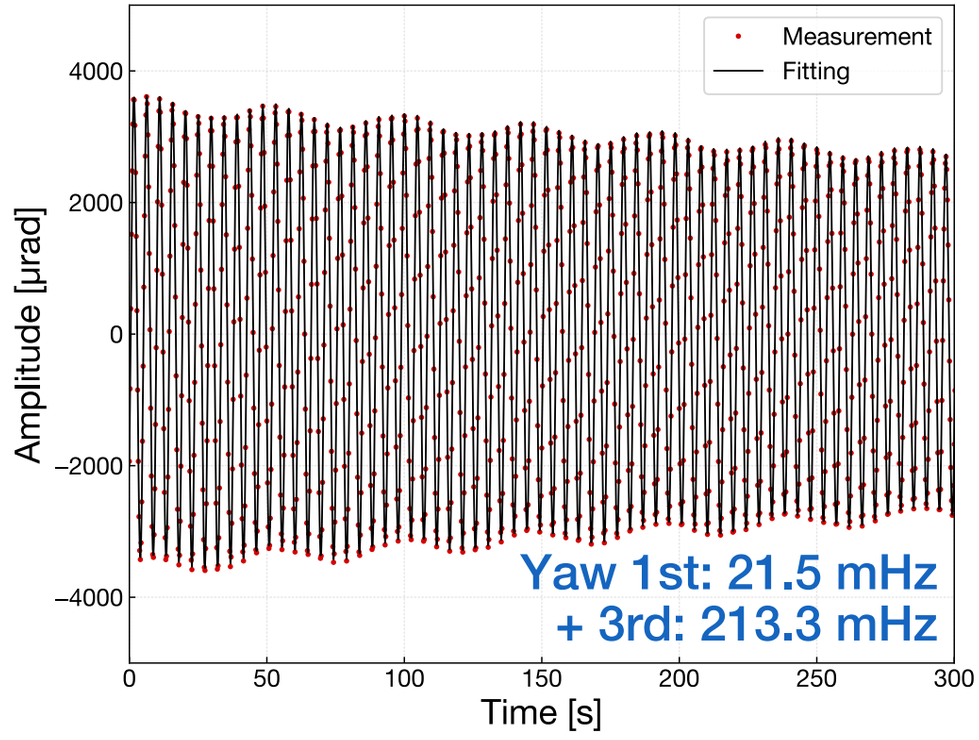
- LVDT + Coil-magnet actuator unit
- 6 DoFs sensing & actuation w.r.t. the ground

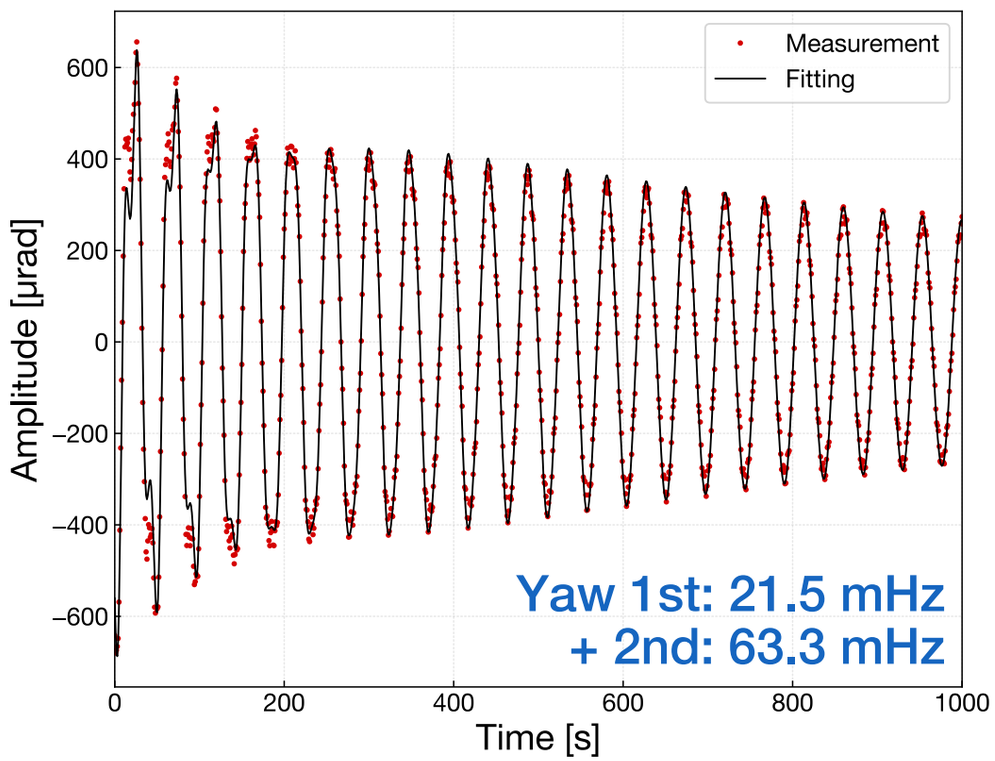
DAMPING LOOP



DECAY TIME MEASUREMENT

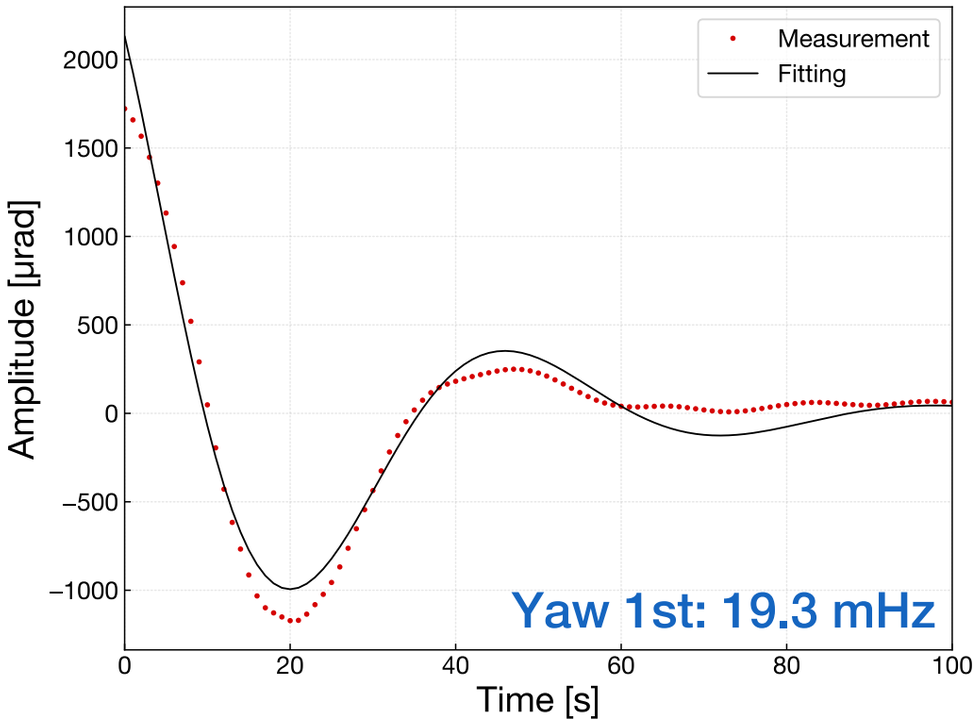


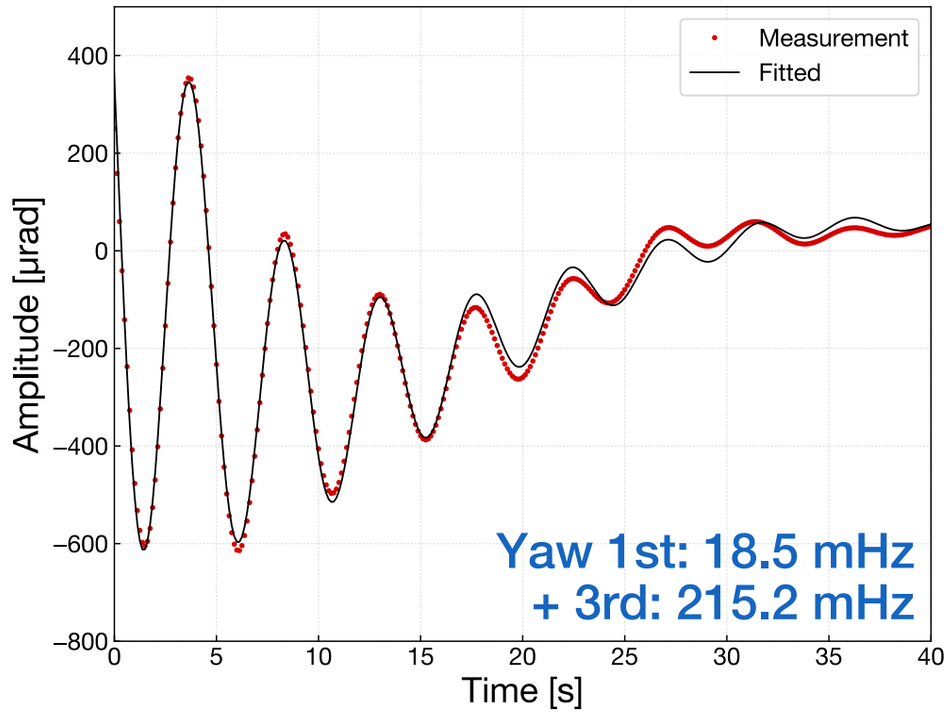


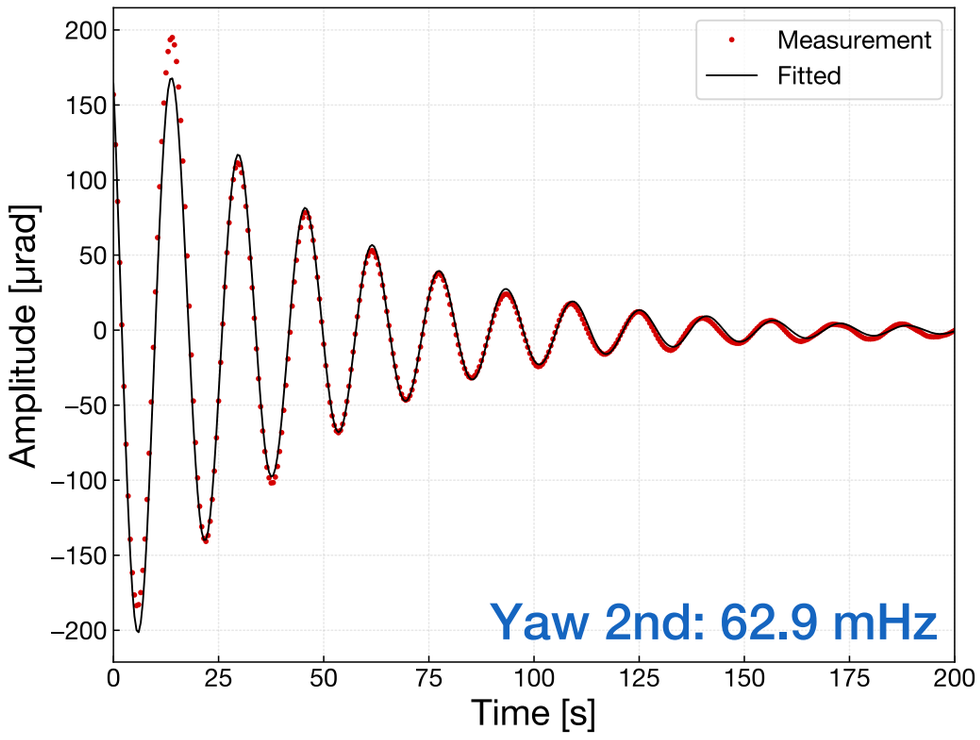


MODE	DECAY TIME
#1	961.4 sec.
#2	158.6 sec.
#3	1155.5 sec.

DECAY TIME MEASUREMENT

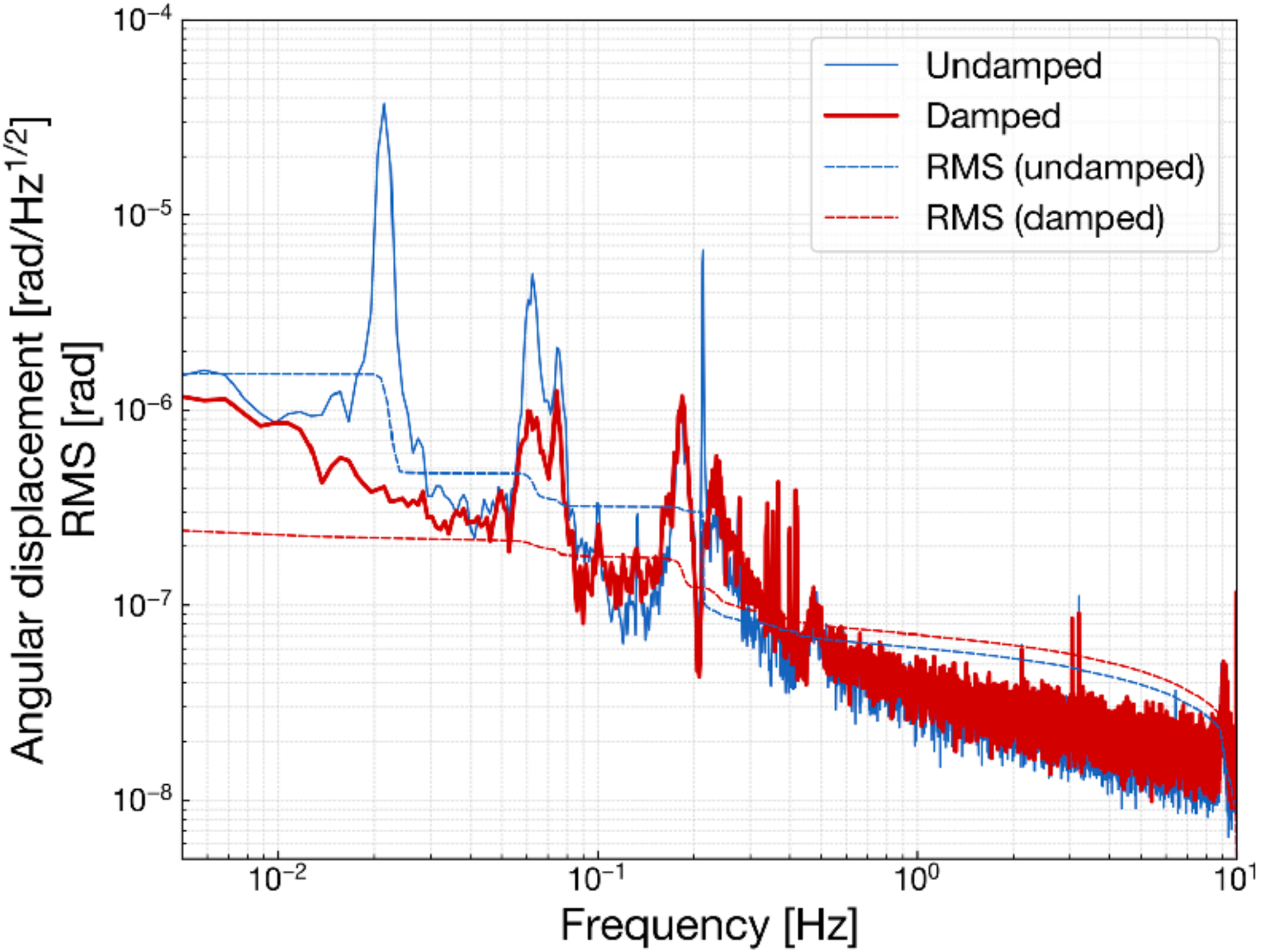




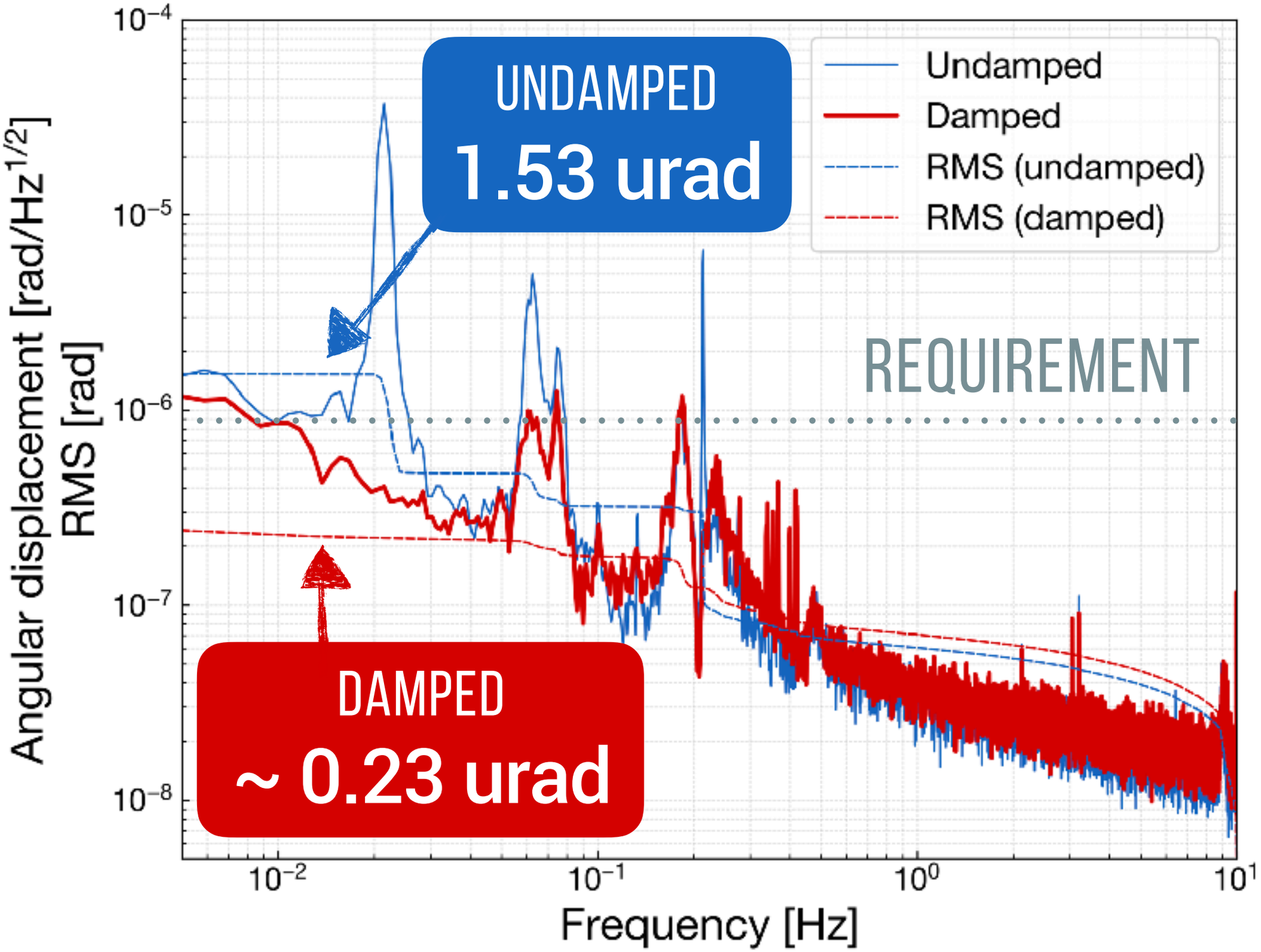


MODE	DAMPED DECAY TIME
#1	24.8 sec.
#2	43.9 sec.
#3	9.5 sec.

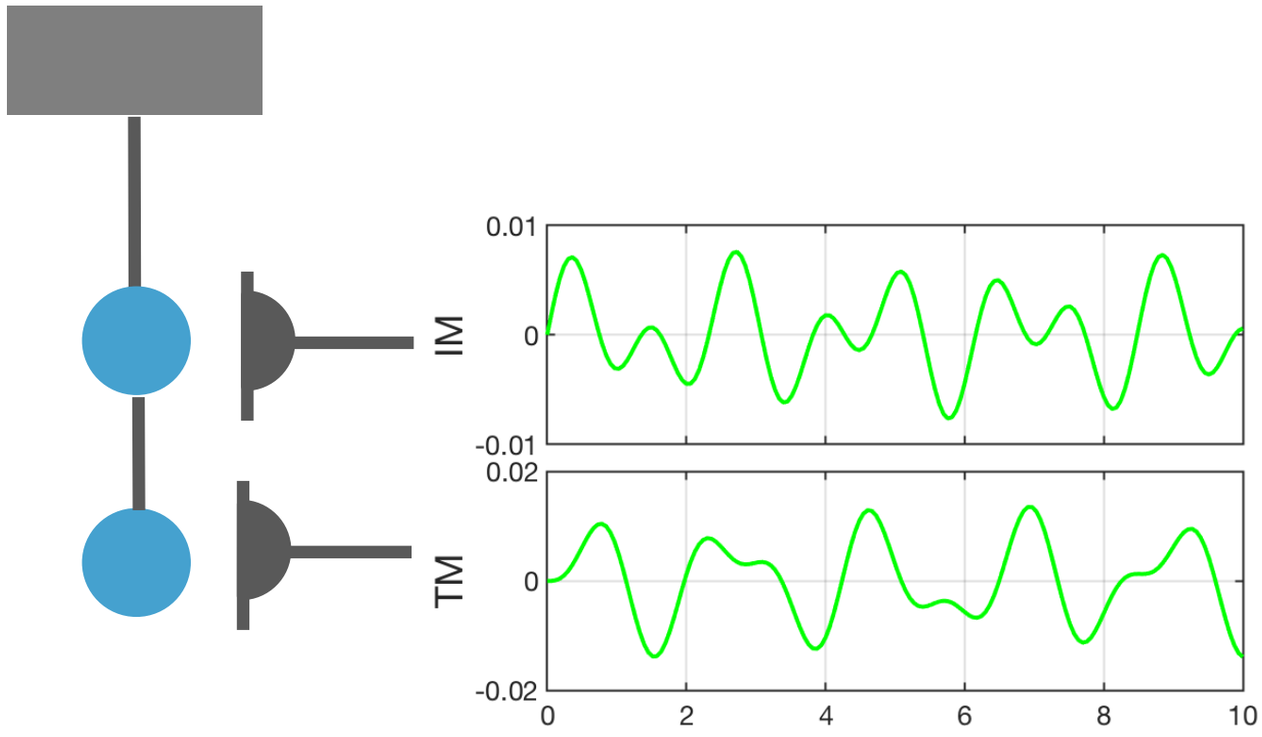
YAW MODE DAMPING

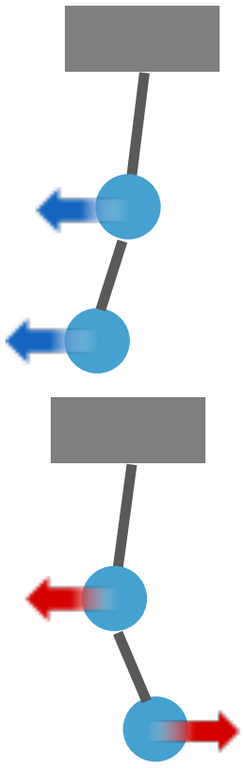


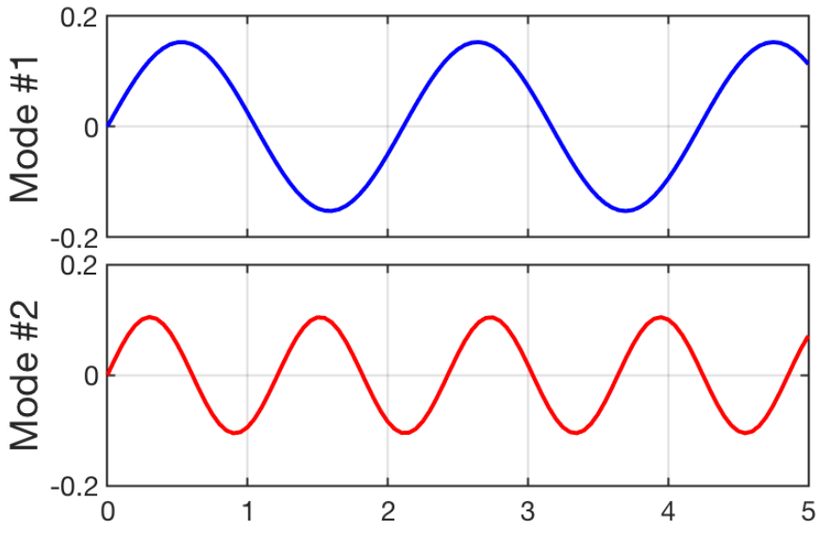
YAW MODE DAMPING



MODAL DAMPING





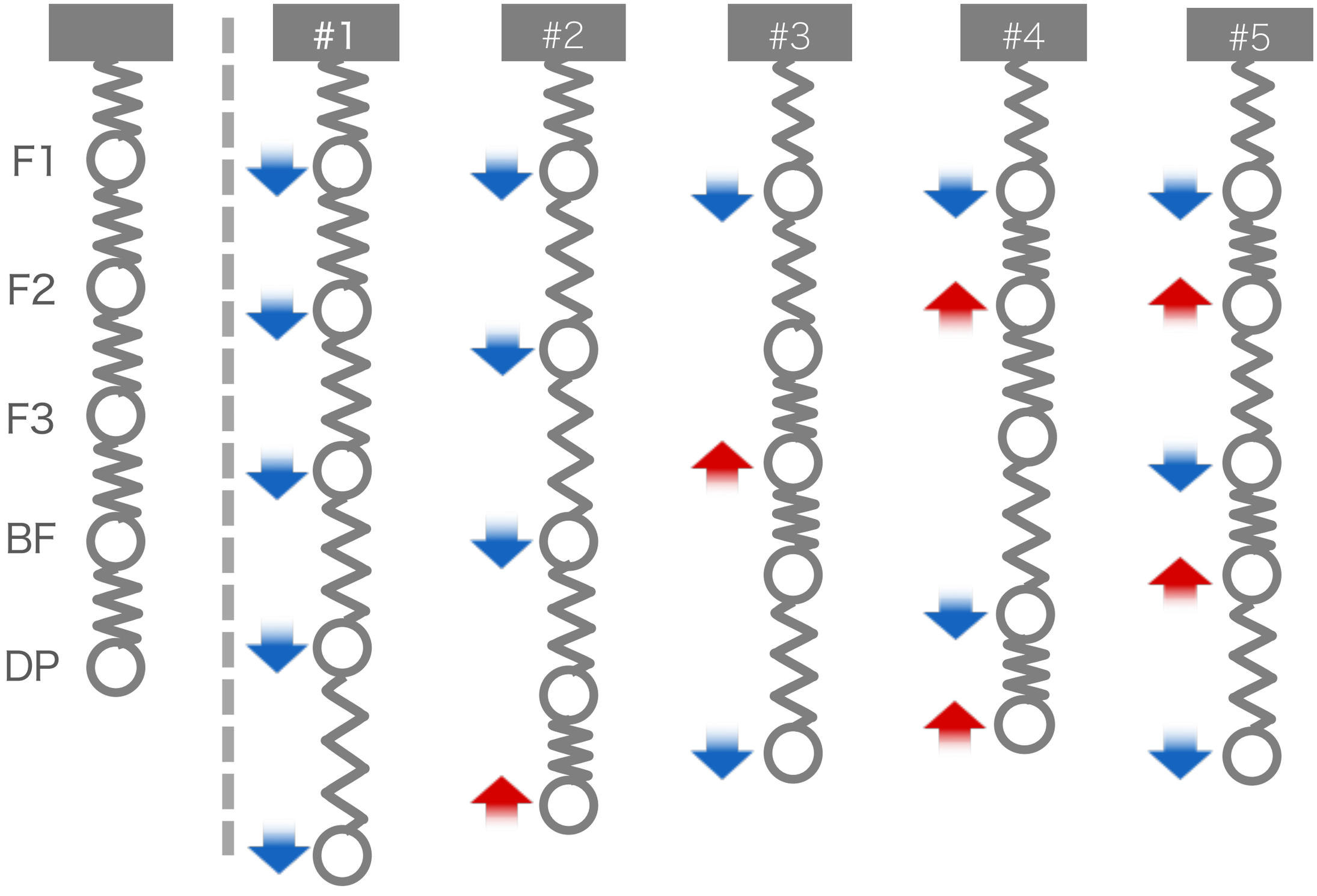


STAGE-BASIS

MODAL-BASIS

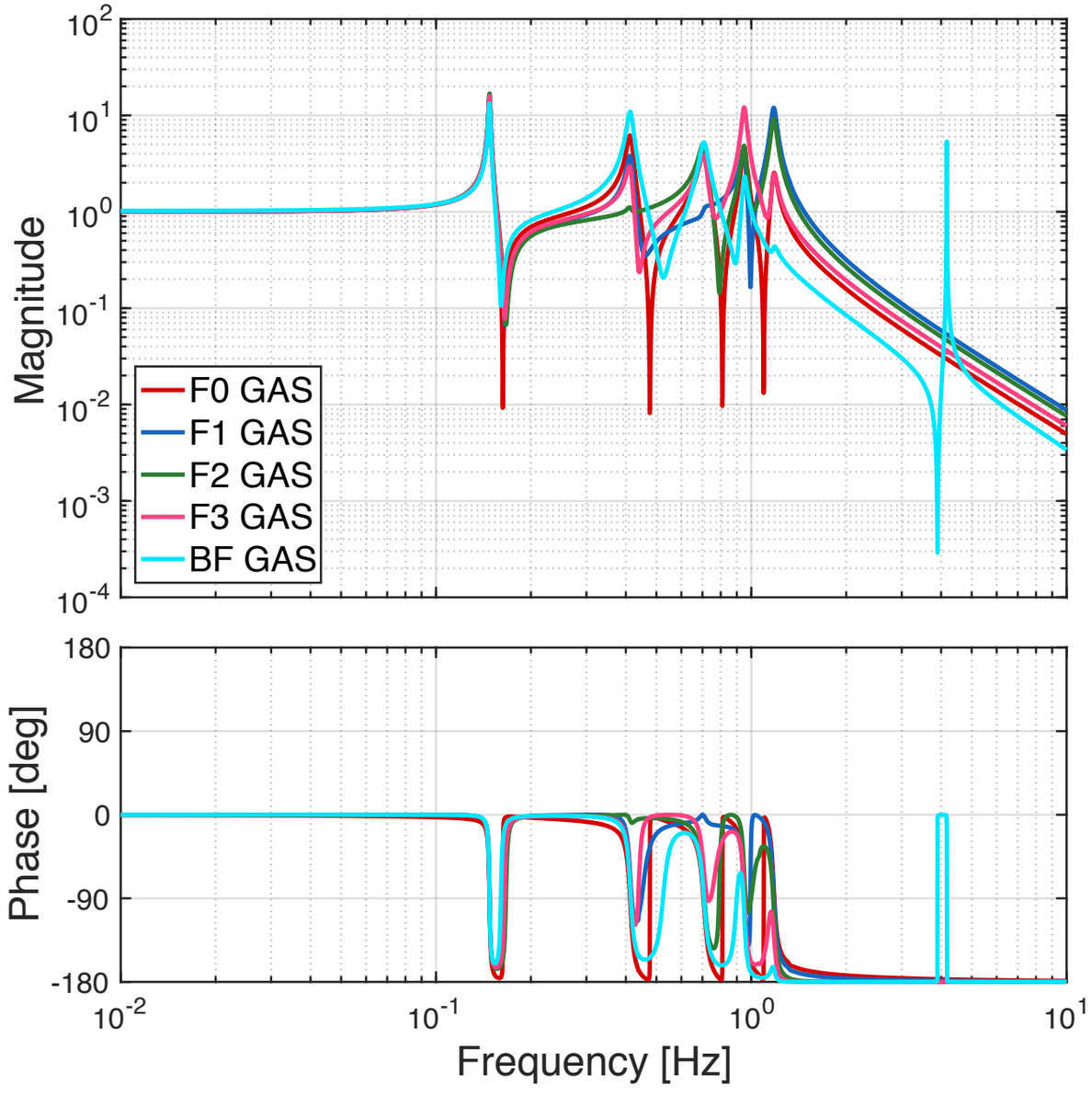
- Decouples sensor signals into modal amplitudes

VERTICAL MODES

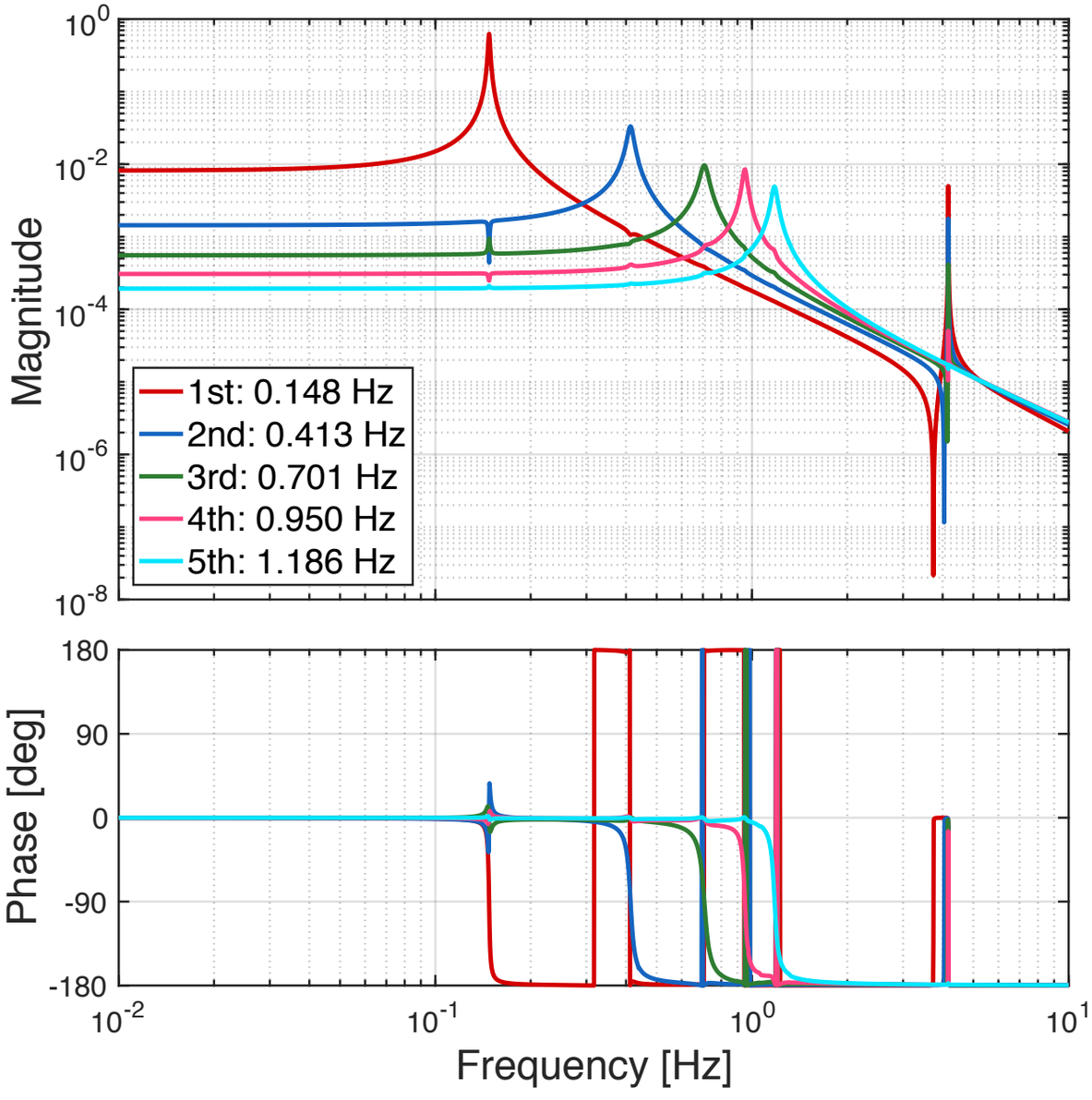


GAS FILTER RESPONSE (1)

MODEL PREDICTION



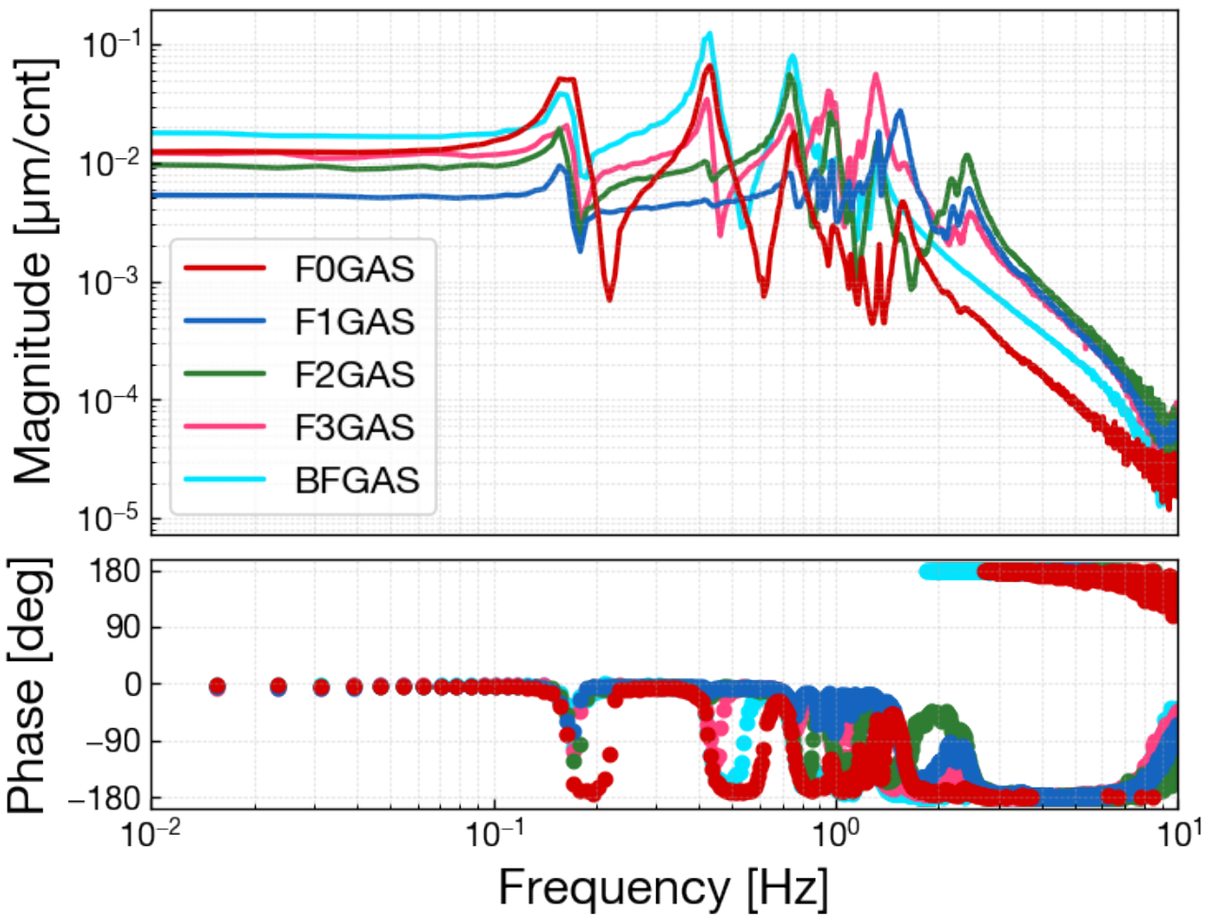
STAGE-BASIS



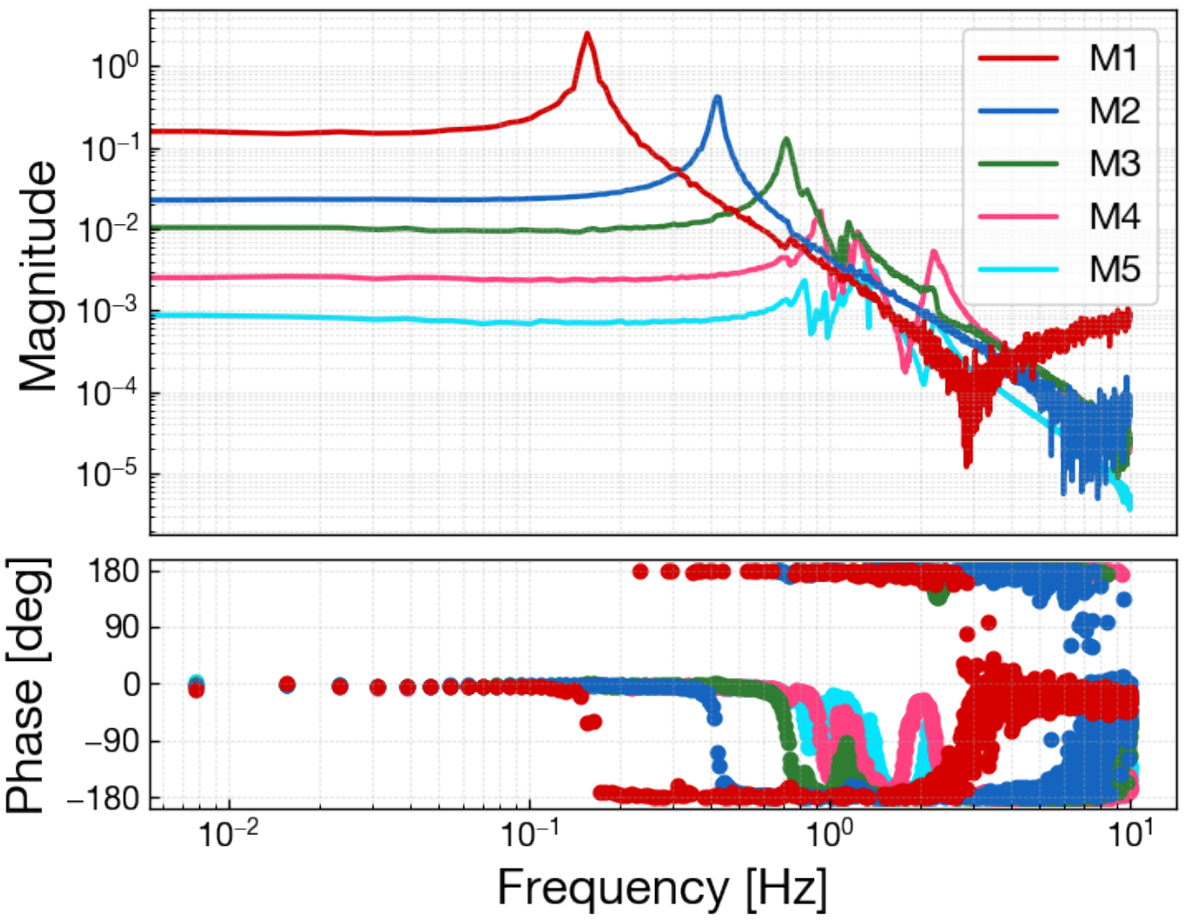
MODAL-BASIS

GAS FILTER RESPONSE (2)

MEASUREMENT RESULT



STAGE-BASIS

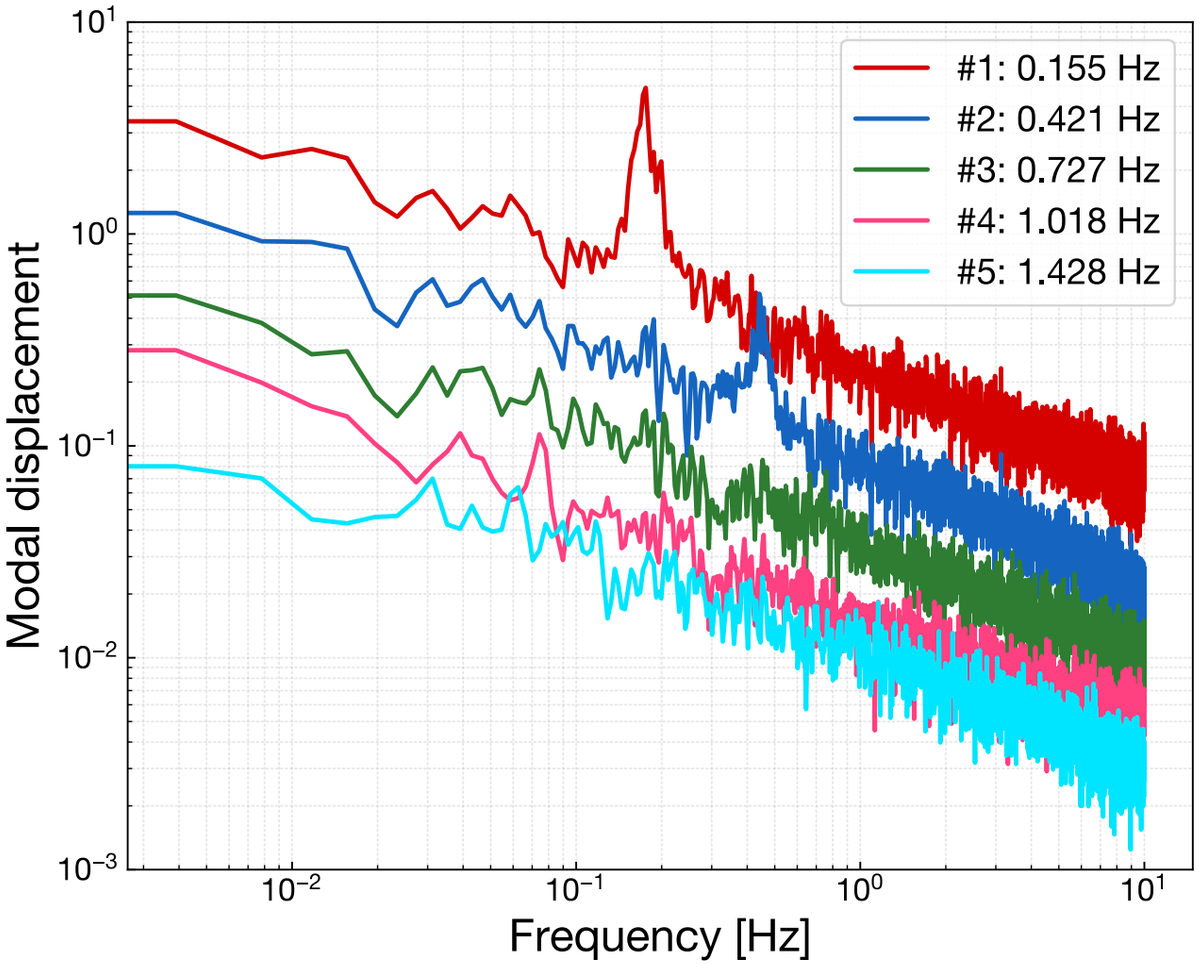


MODAL-BASIS

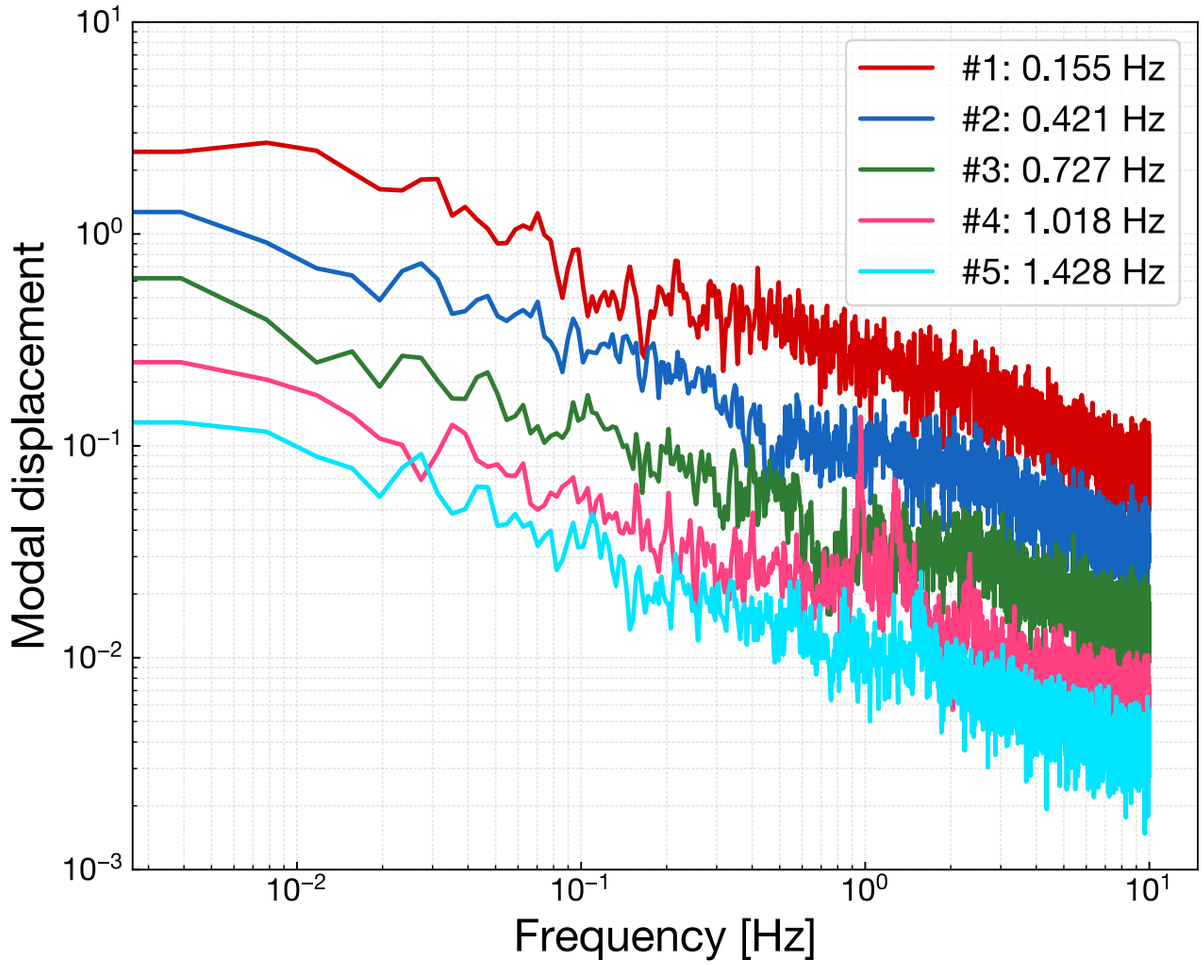
- Modal responses can make the filter design simple

MODAL SPECTRUM

MEASUREMENT RESULT

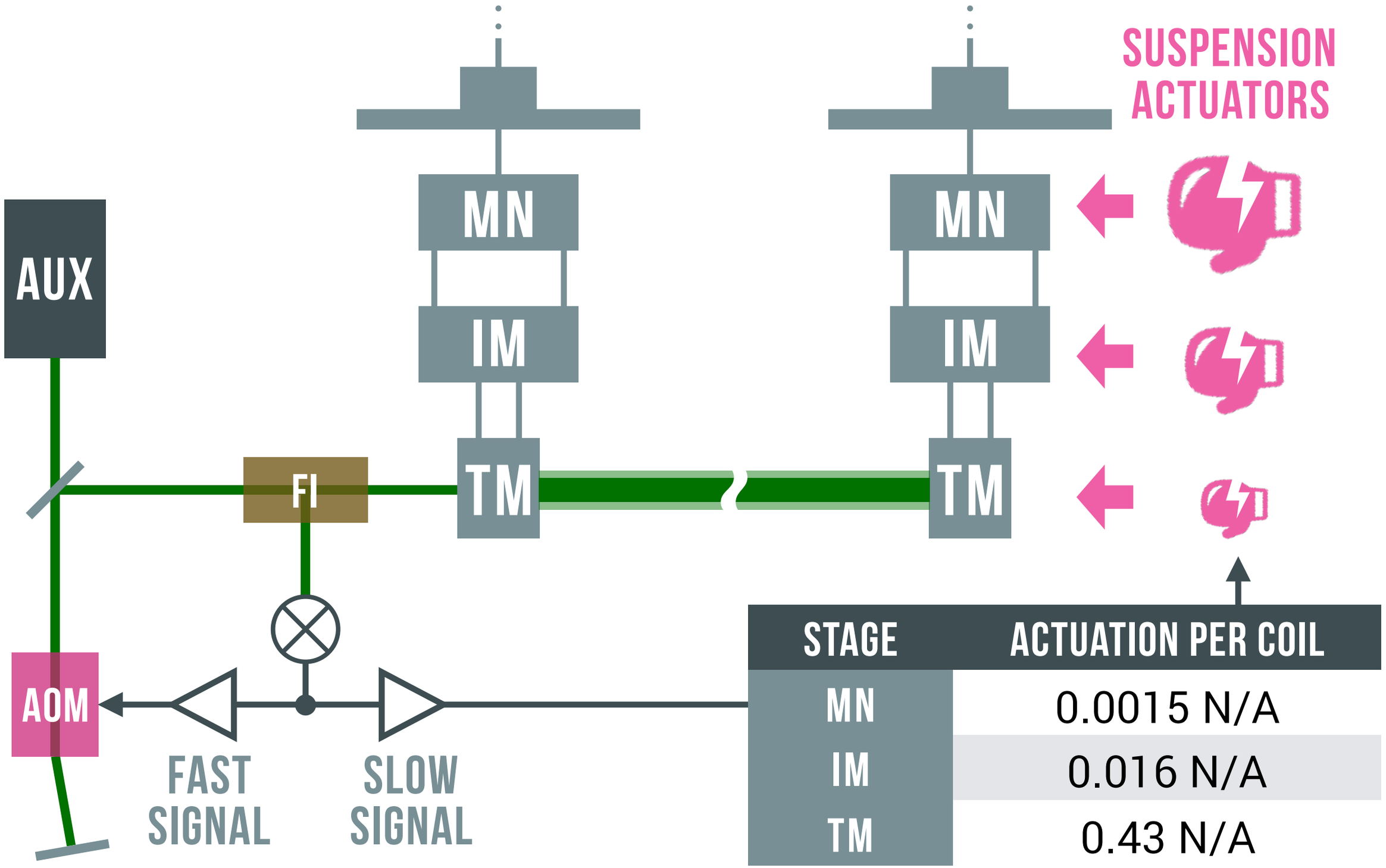


UNDAMPED



1ST & 2ND MODE DAMPED

HIERARCHICAL CONTROL



STAGE	ACTUATION PER COIL
MN	0.0015 N/A
IM	0.016 N/A
TM	0.43 N/A