VIBRATION ISOLATION SYSTEM FOR THE CRYOGENIC TEST MASSES IN KAGRA

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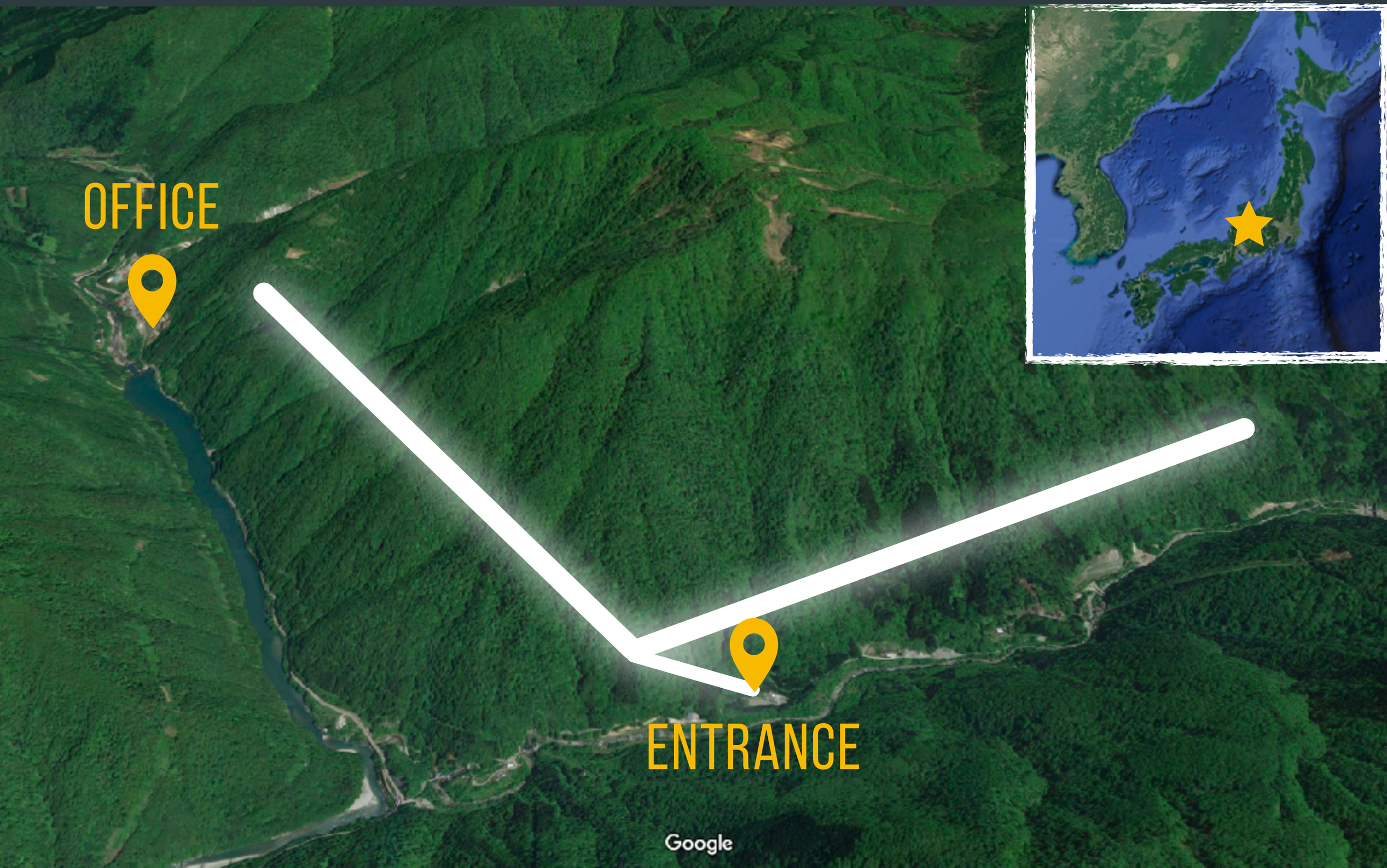
CONTENTS

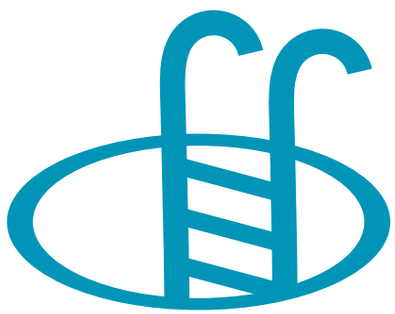
- Vibration isolation systems in KAGRA
- Type-A suspension
- Topics of the suspension control


KAGRA

WHERE ARE WE?



KAGRA FEATURES



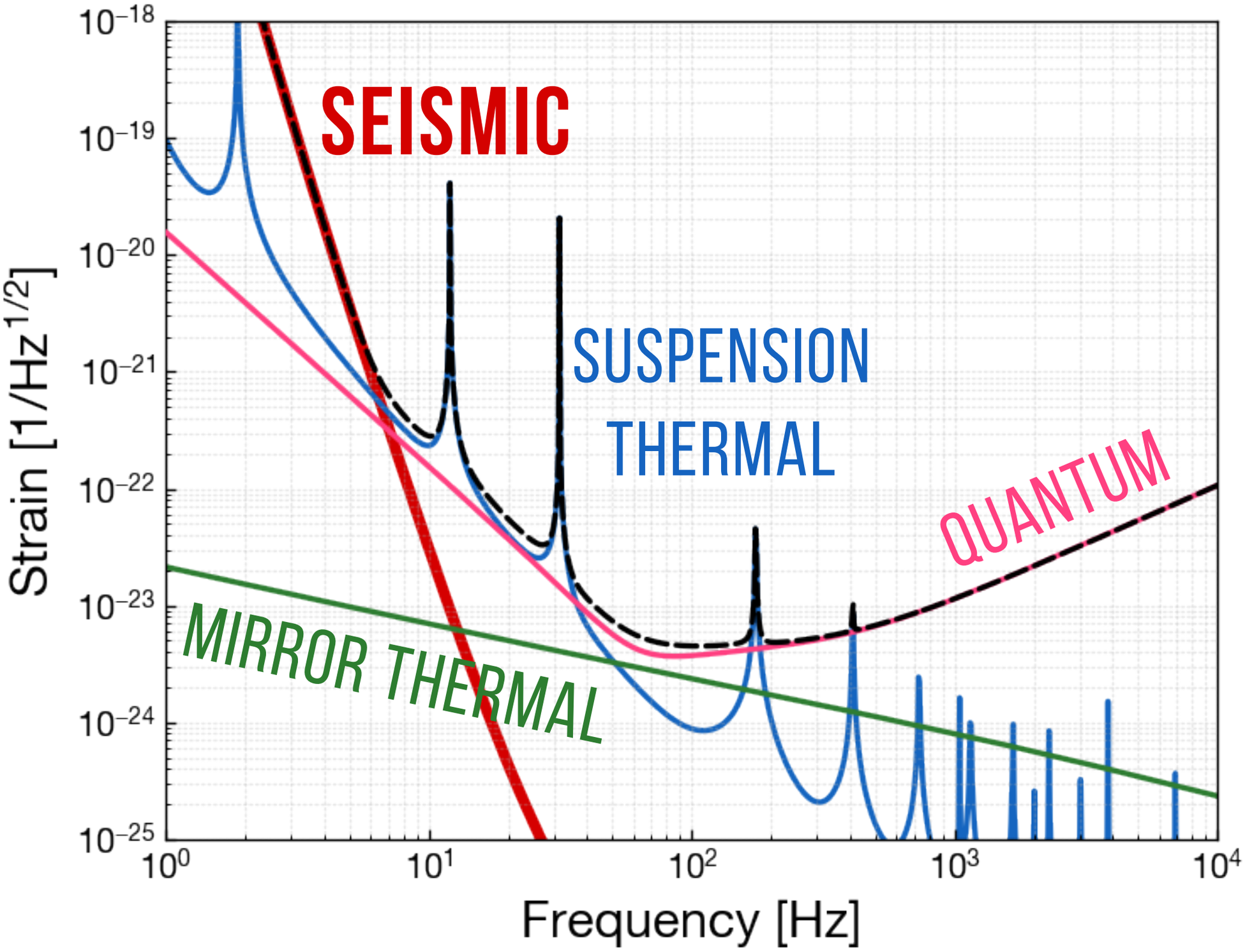
UNDERGROUND

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

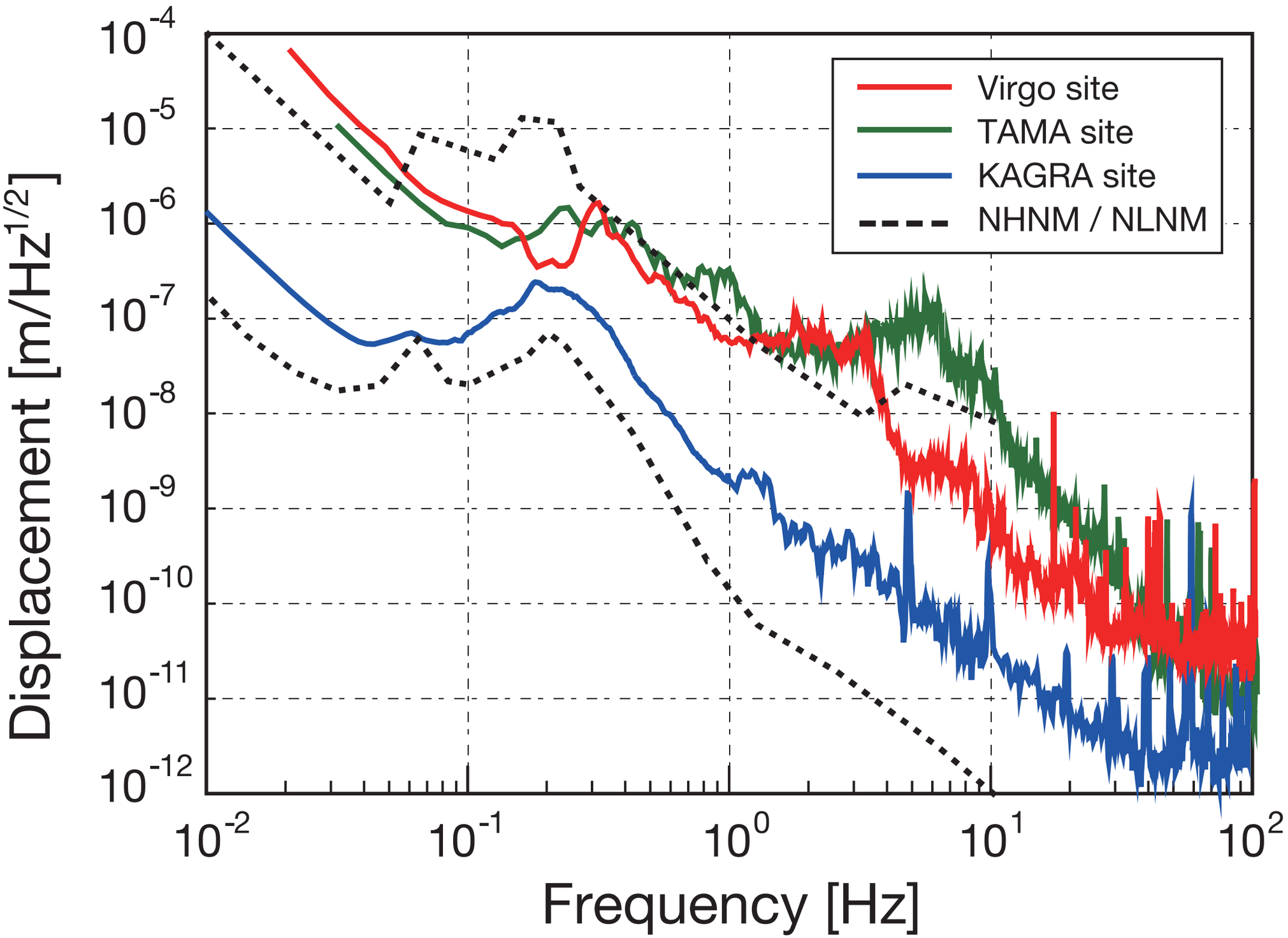
CRYOGENIC

Smaller thermal noise
Many potential benefits

SENSITIVITY

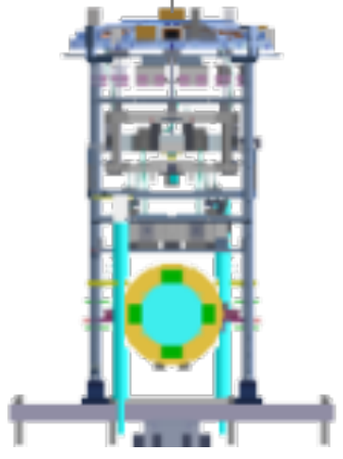


SEISMIC NOISE

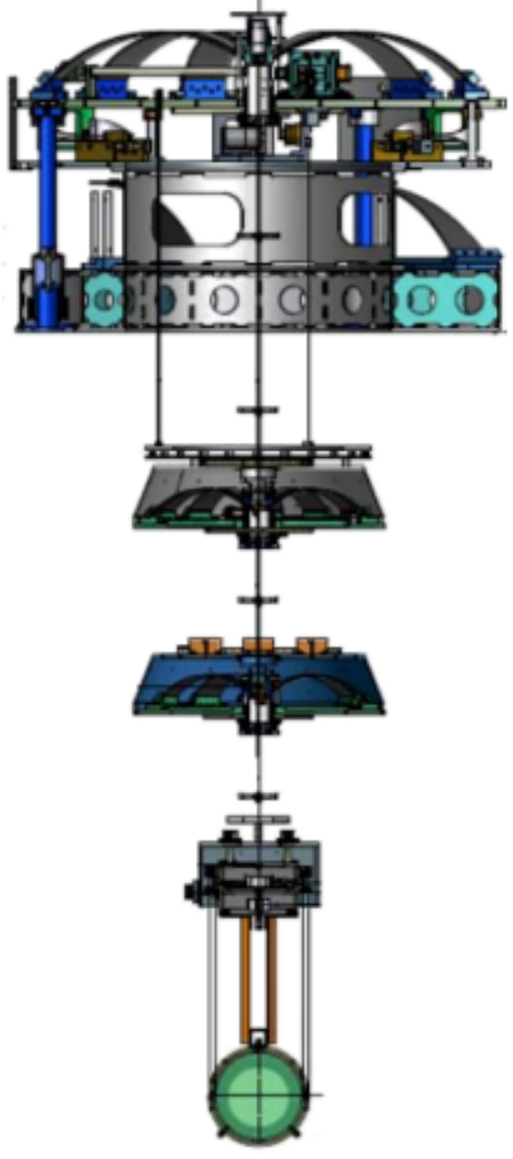


VIBRATION ISOLATION SYSTEMS IN KAGRA

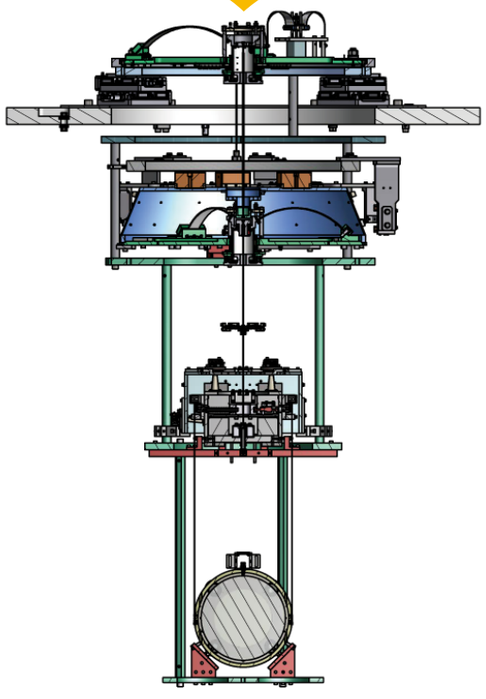
TYPE-A



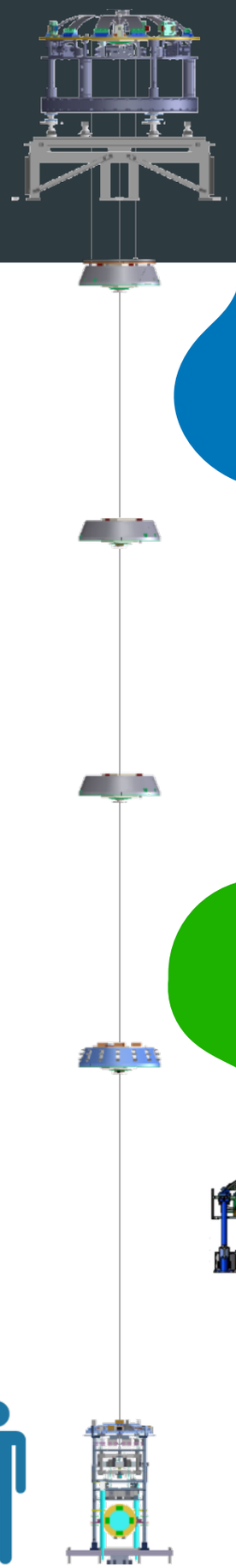
TYPE-B

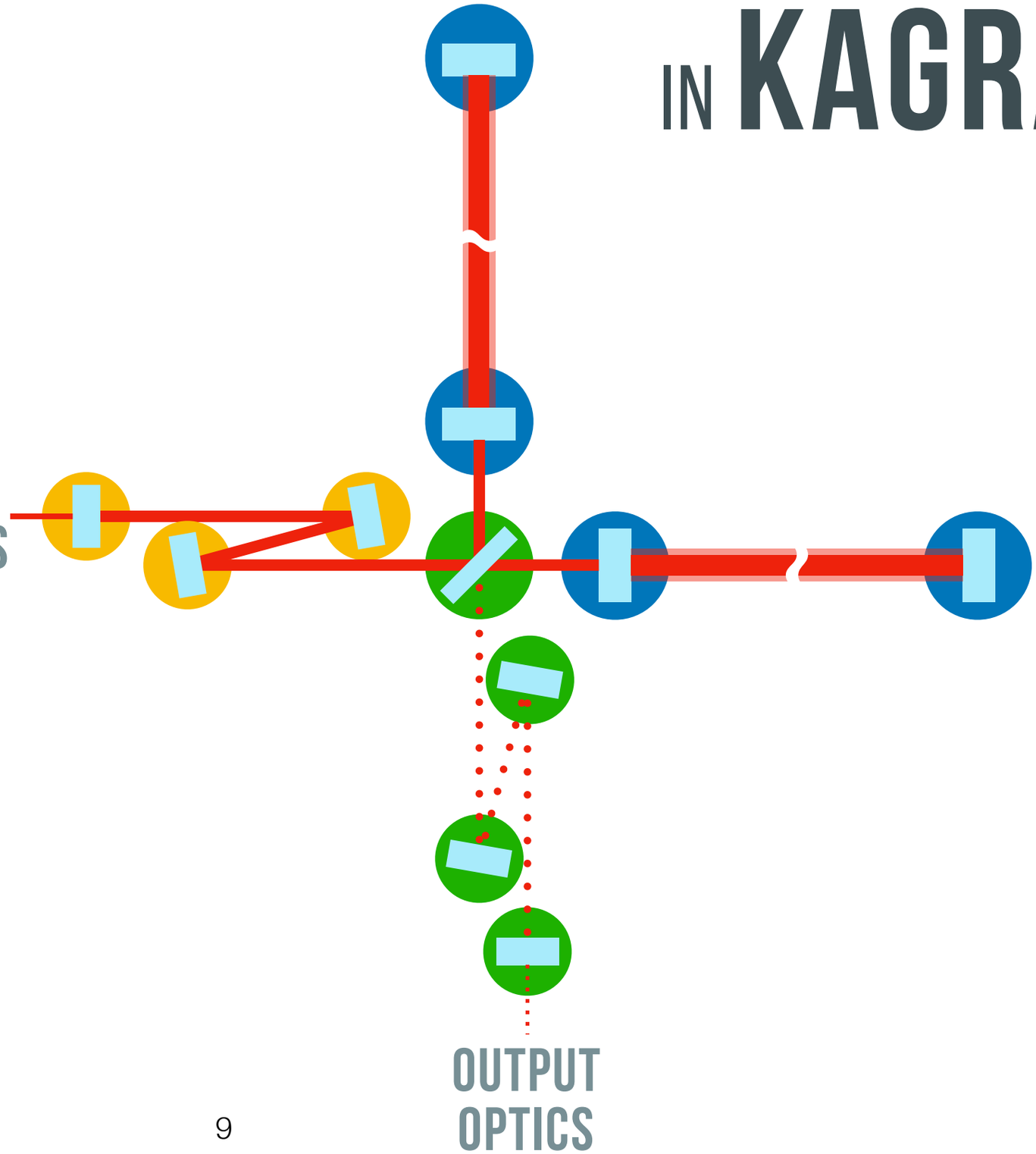


TYPE-BP

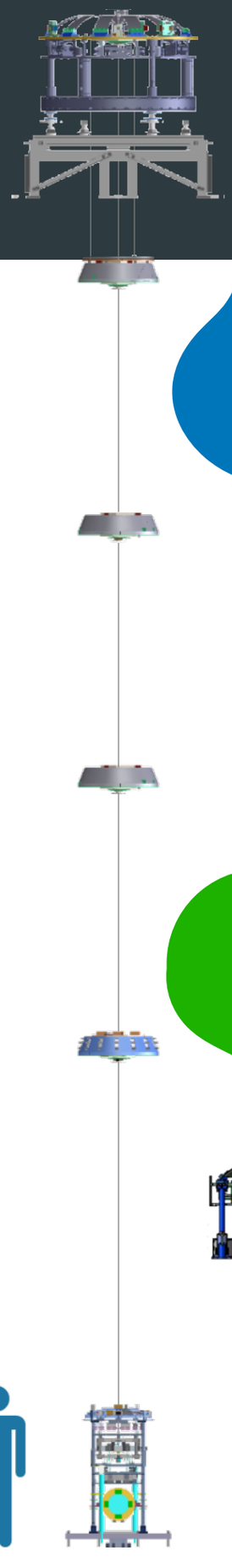


VIBRATION ISOLATION SYSTEMS IN KAGRA





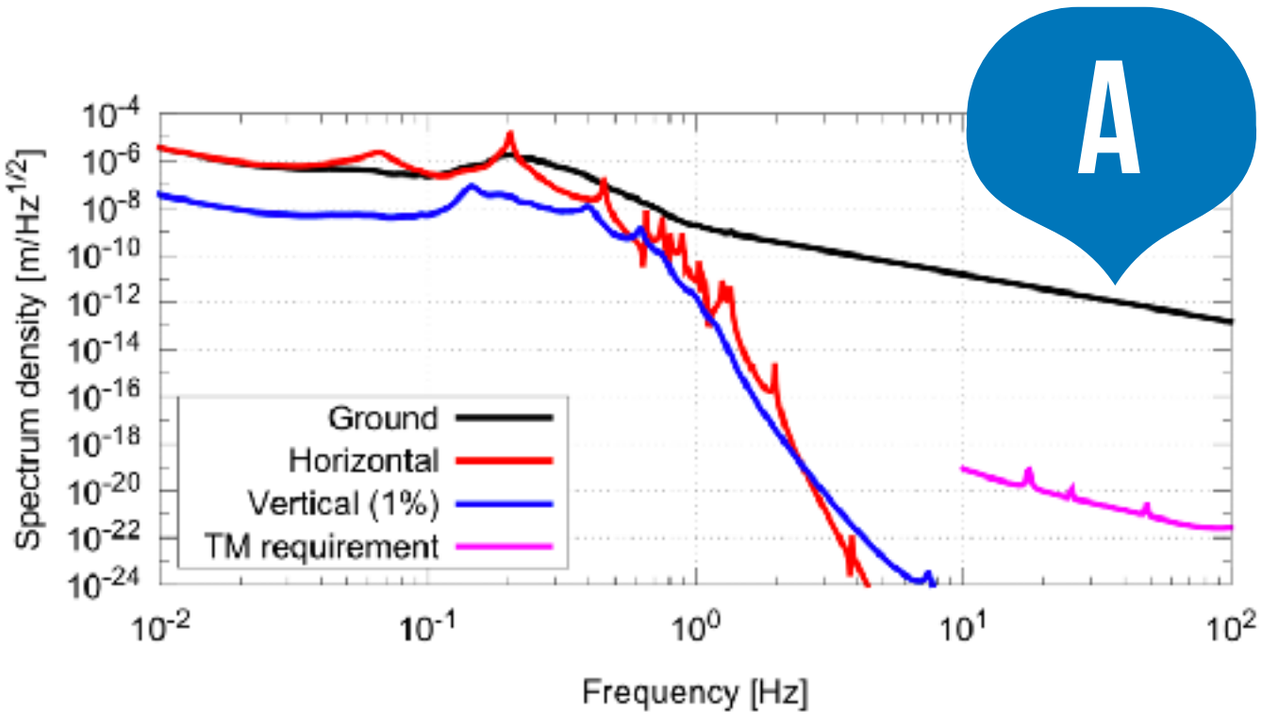
VIBRATION ISOLATION SYSTEMS IN KAGRA

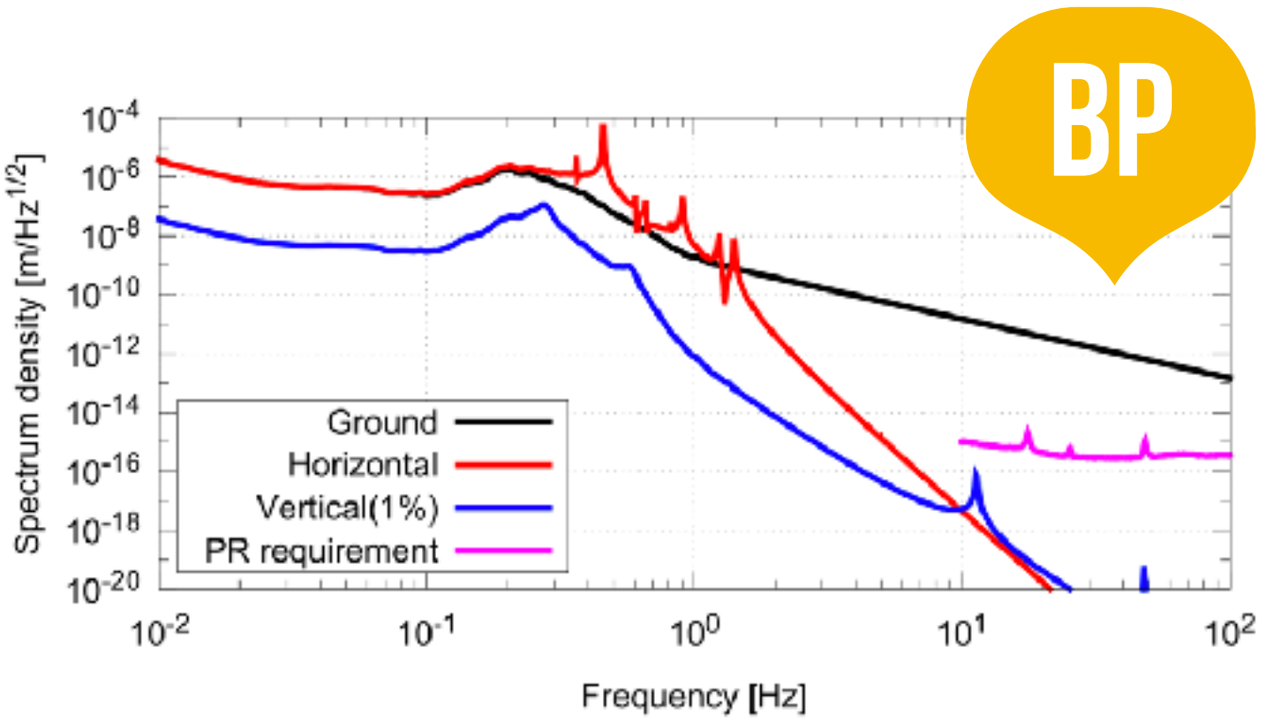


COMPONENTS

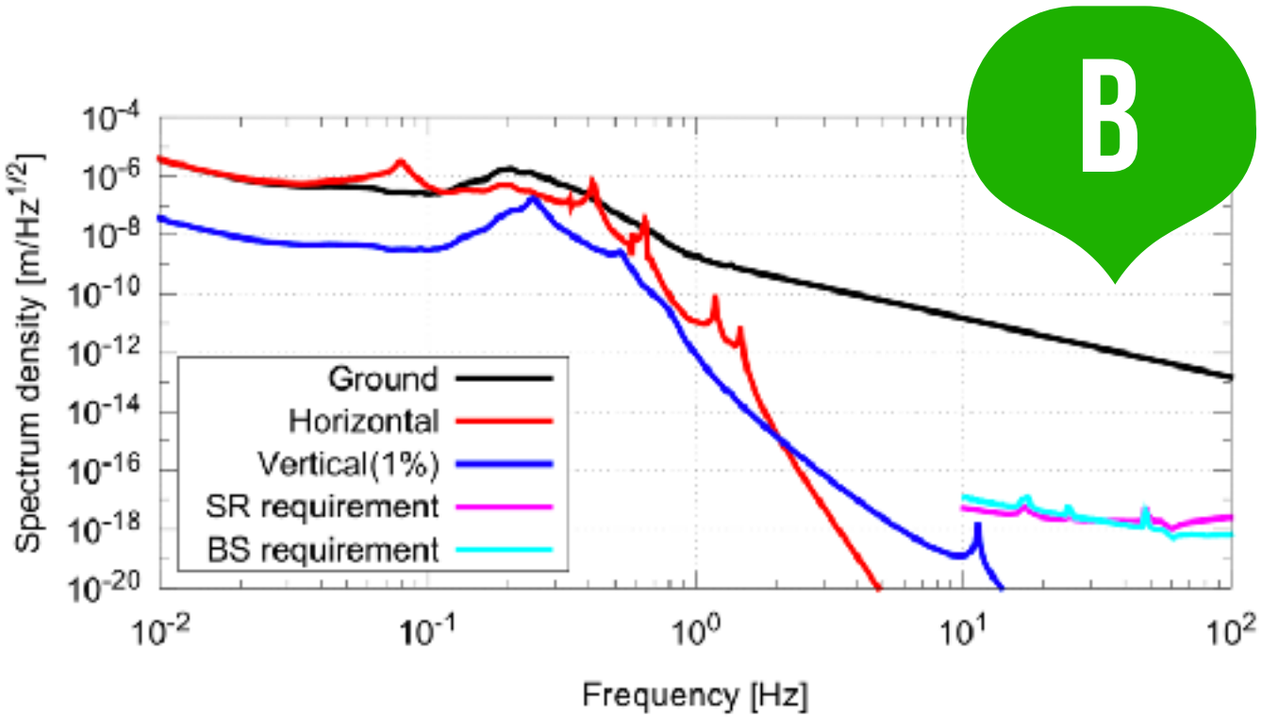
TYPE-A	TYPE-B	TYPE-BP
9 stages	5 stages	3 stages
Inverted Pendulum	Inverted Pendulum	–
GAS Filter x5	GAS Filter x3	GAS Filter x2
Payload: Cryogenic	Room-temperature	Room-temperature
For 4 TMs	For BS and 3 SRs	For 3 PRs

PERFORMANCE



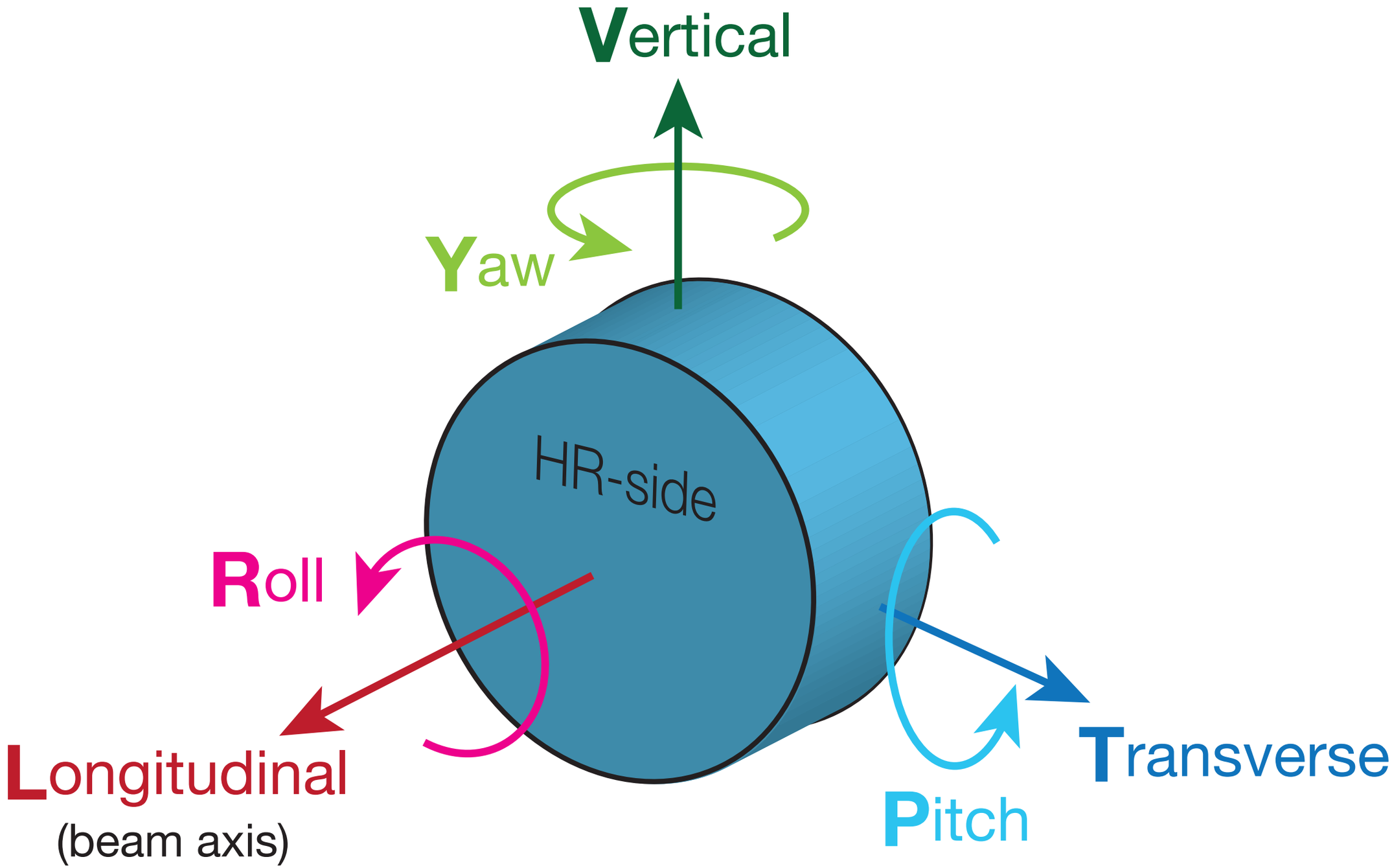


cf.T. Sekiguchi, PhD thesis (2014)

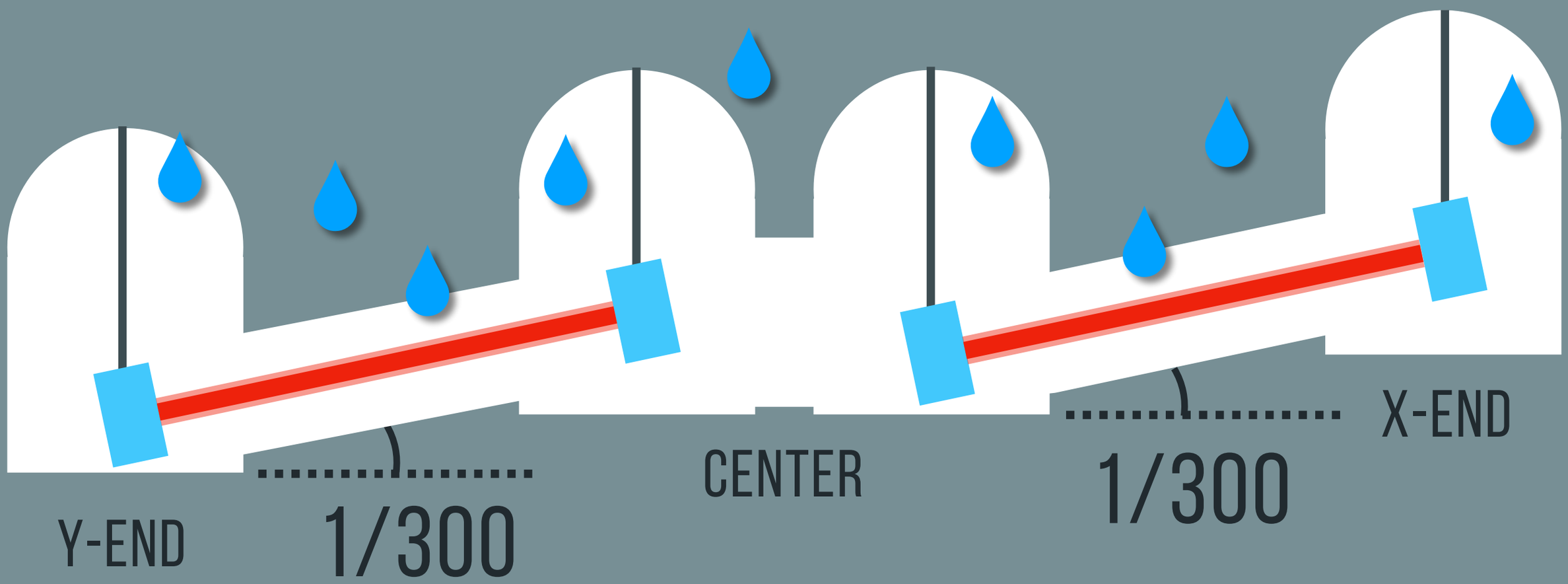


- Both horizontal and vertical motions contribute the displacement noise

DEGREES OF FREEDOM



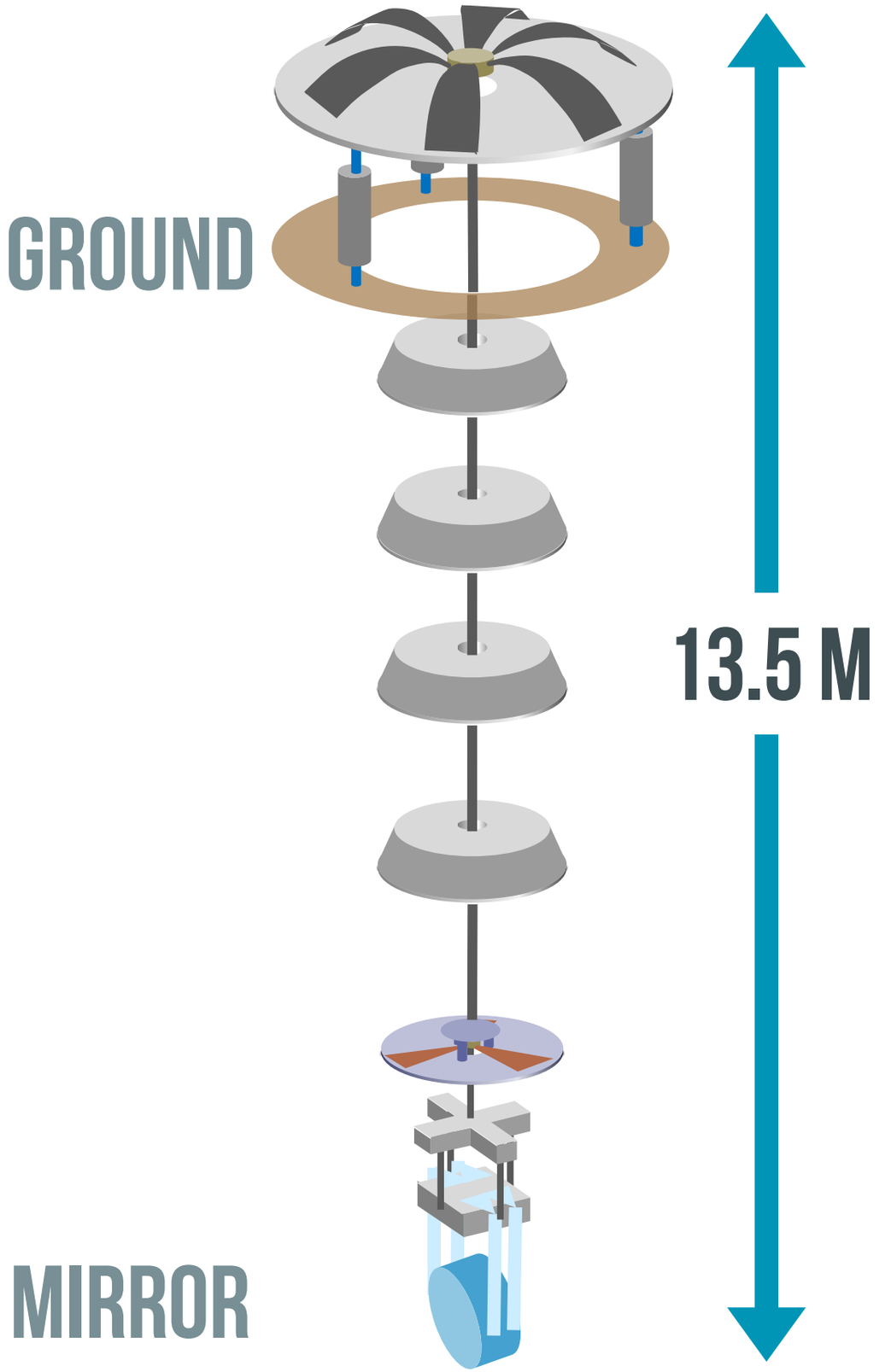
VERTICAL-TO-LONGITUDINAL COUPLING



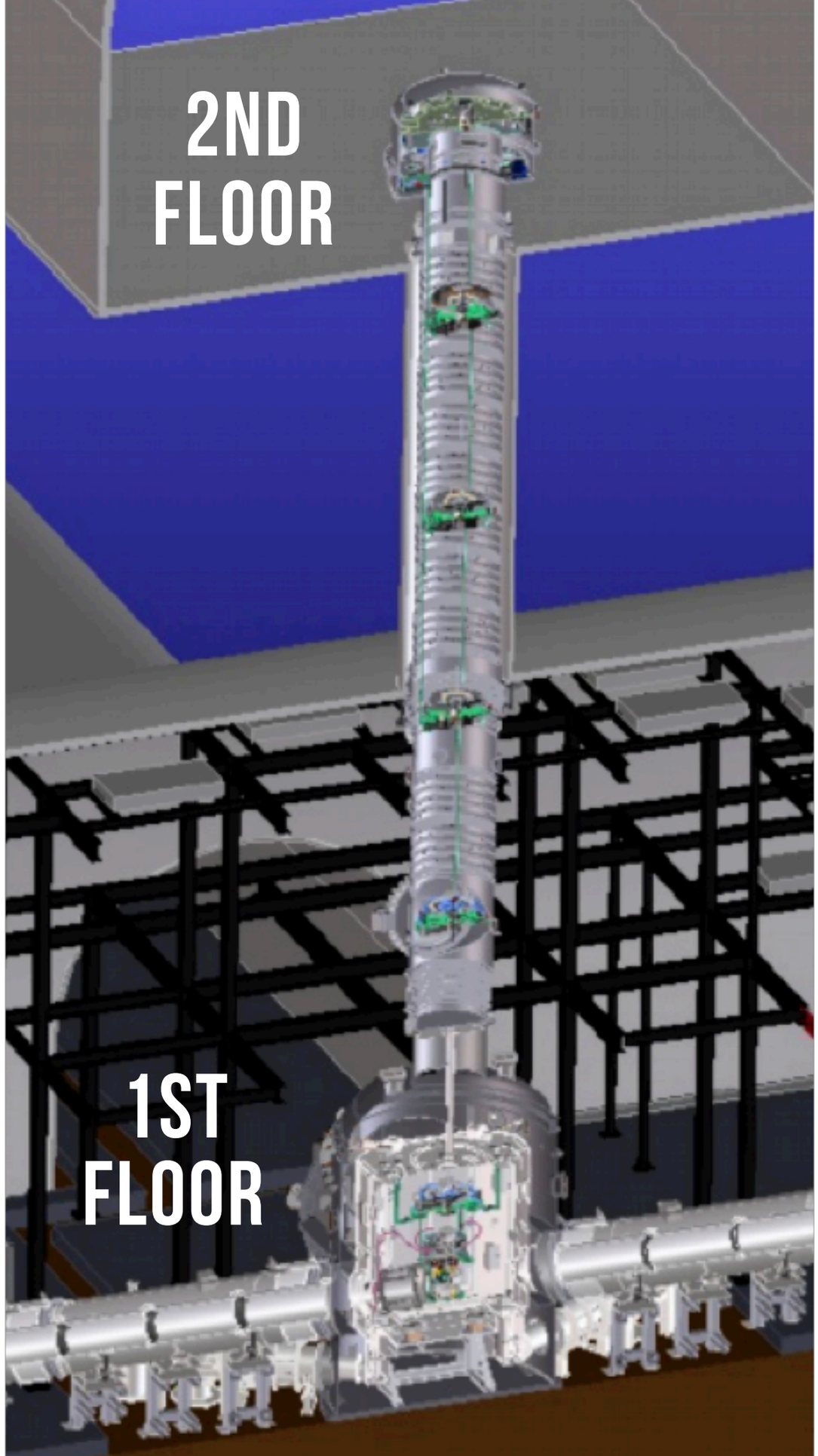
$$\frac{\text{(Longitudinal)}}{\text{(Vertical)}} \lesssim 1\%$$

VERTICAL-TO-LONGITUDINAL COUPLING

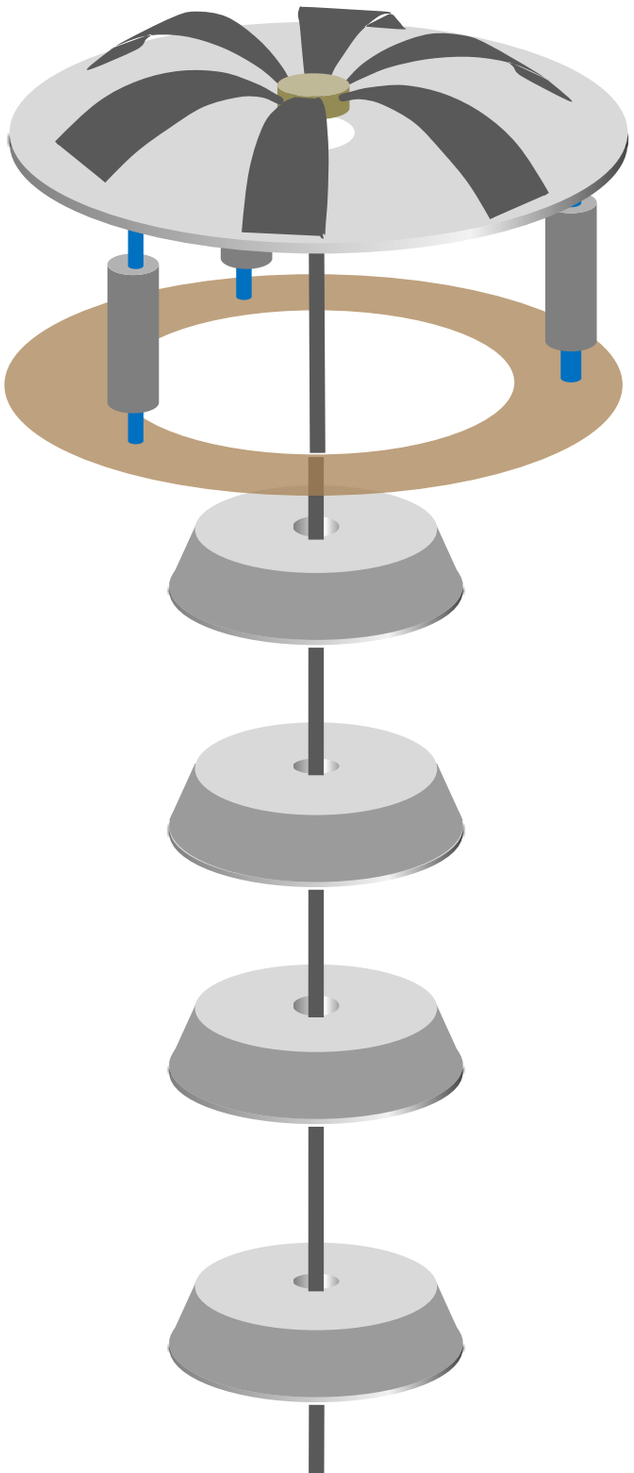
TYPE-A SUSPENSION



TYPE-A SUSPENSION



TOWER



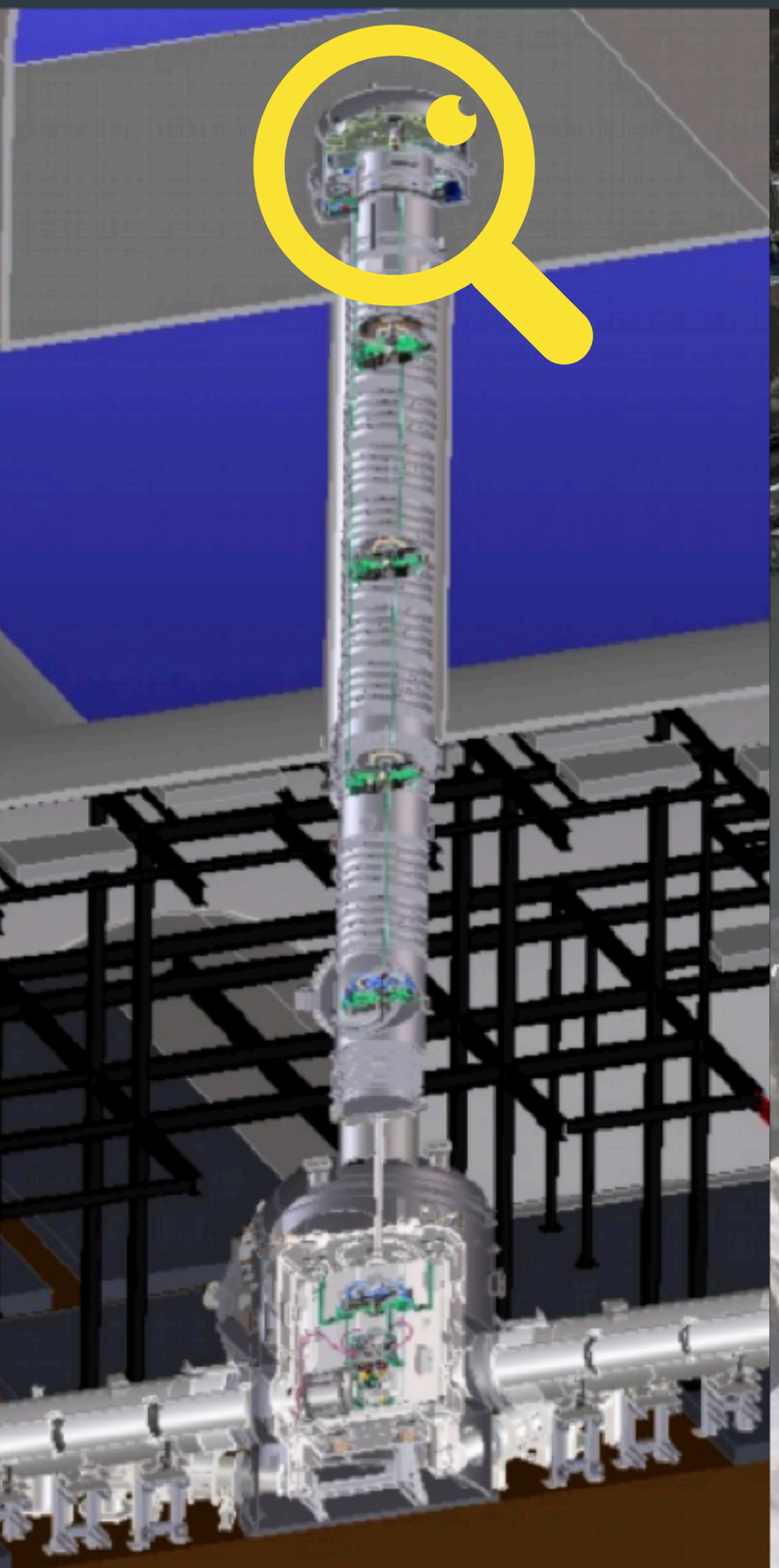
PRE-ISOLATION STAGE

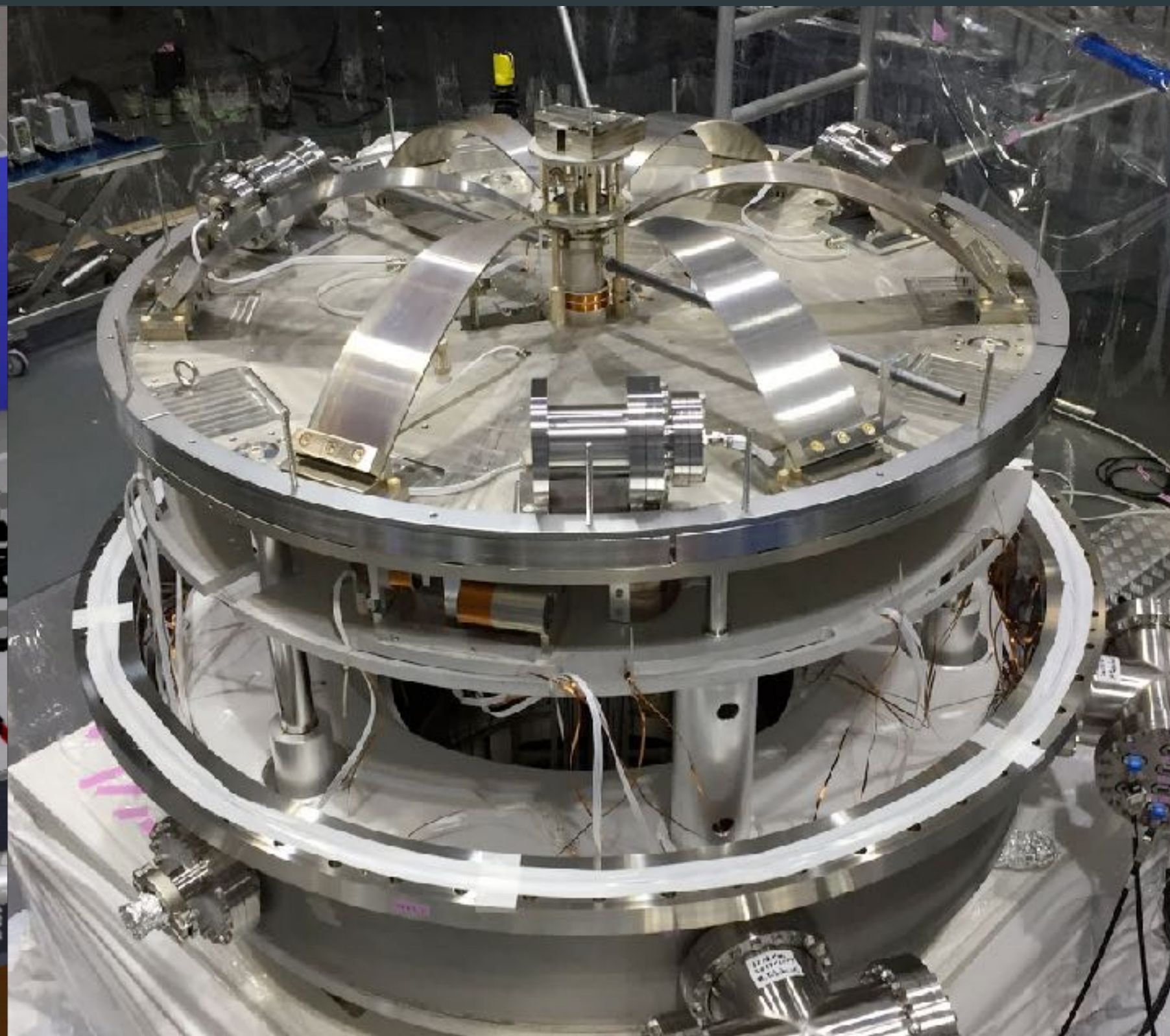
- Inverted pendulum legs
- **Horizontal** resonance ~ 70 mHz

MECHANICAL FILTER CHAIN

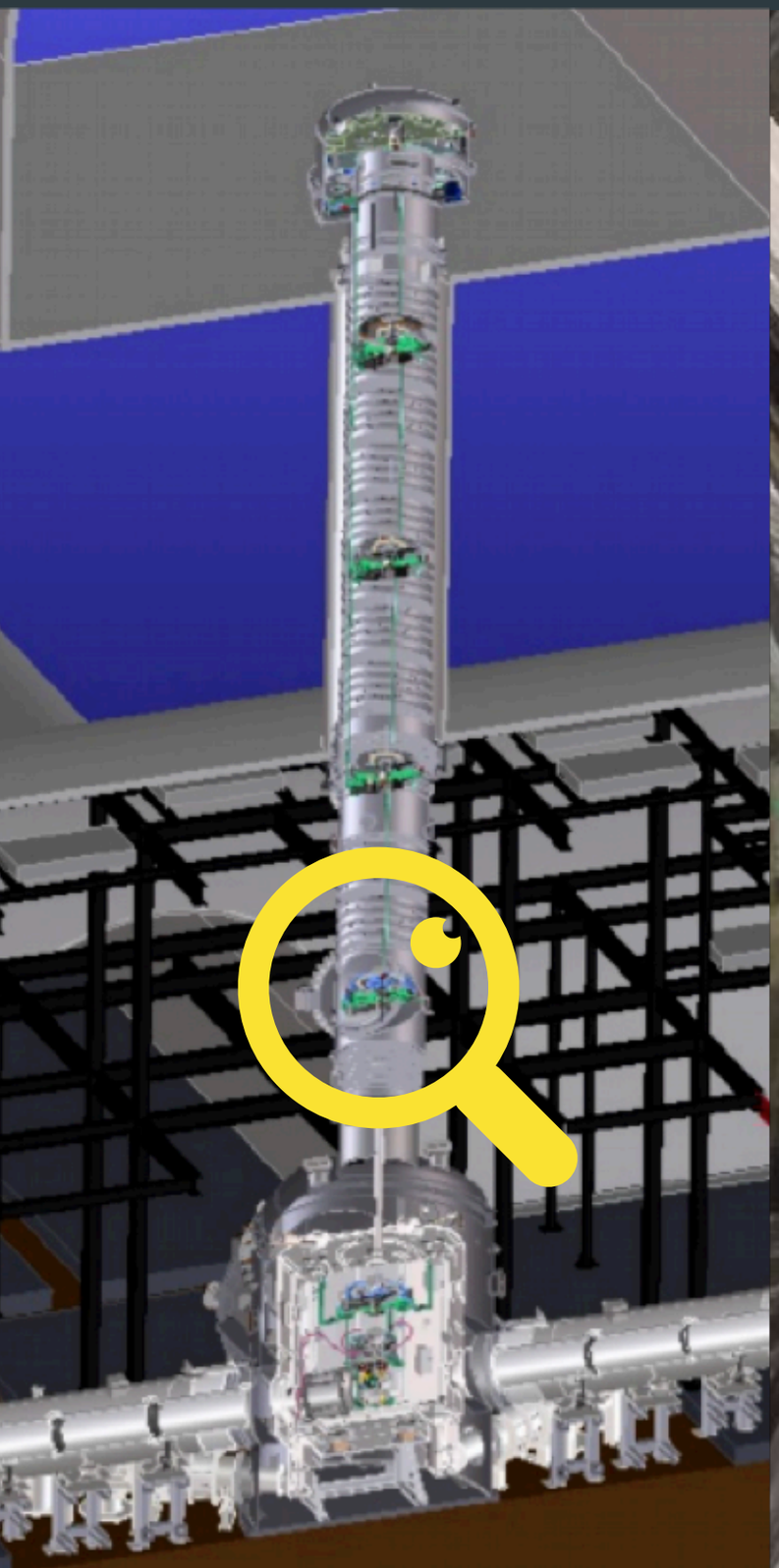
- 5 geometric anti-springs
- **Vertical** resonance ~ 300 mHz

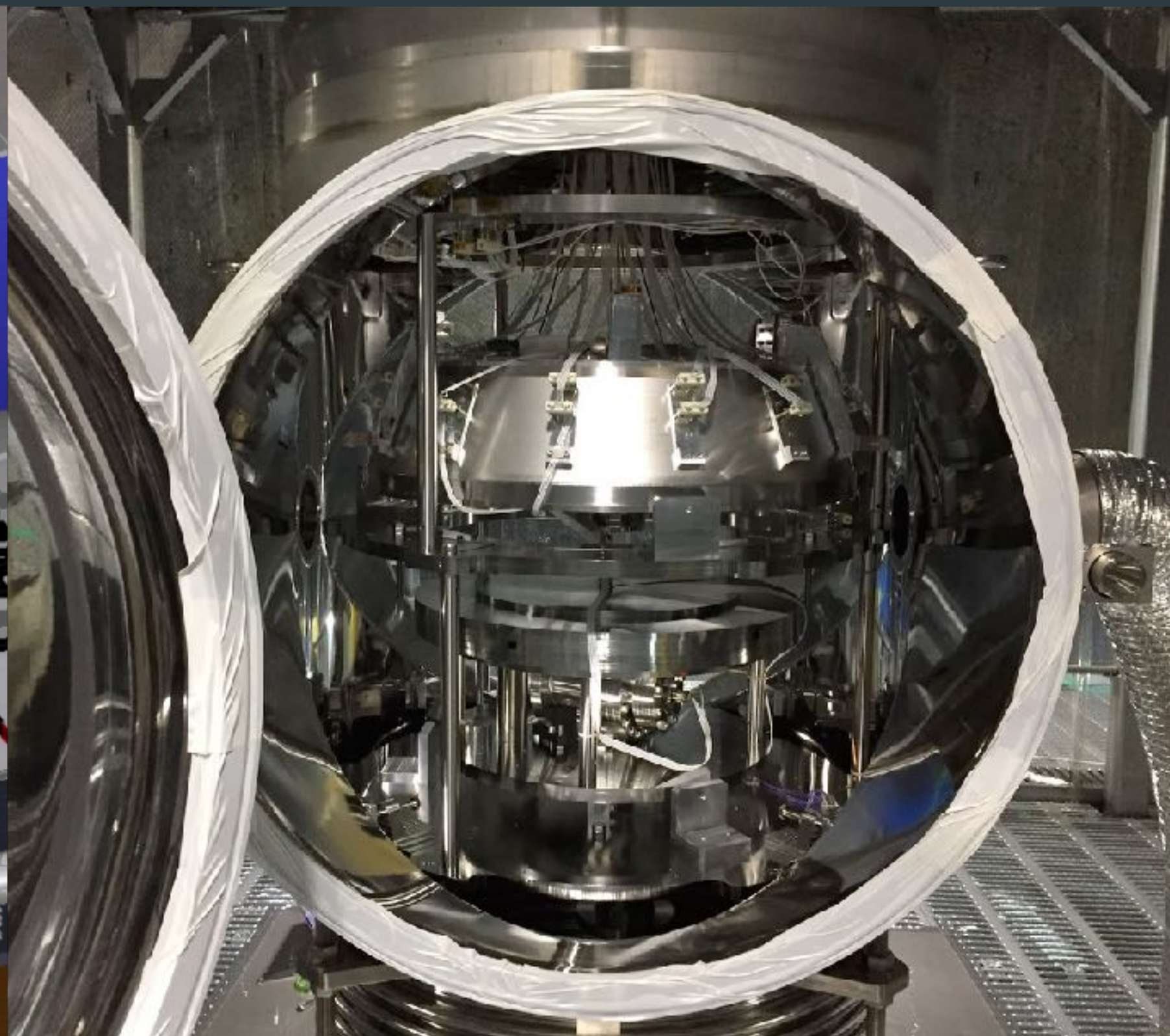
PRE-ISOLATOR



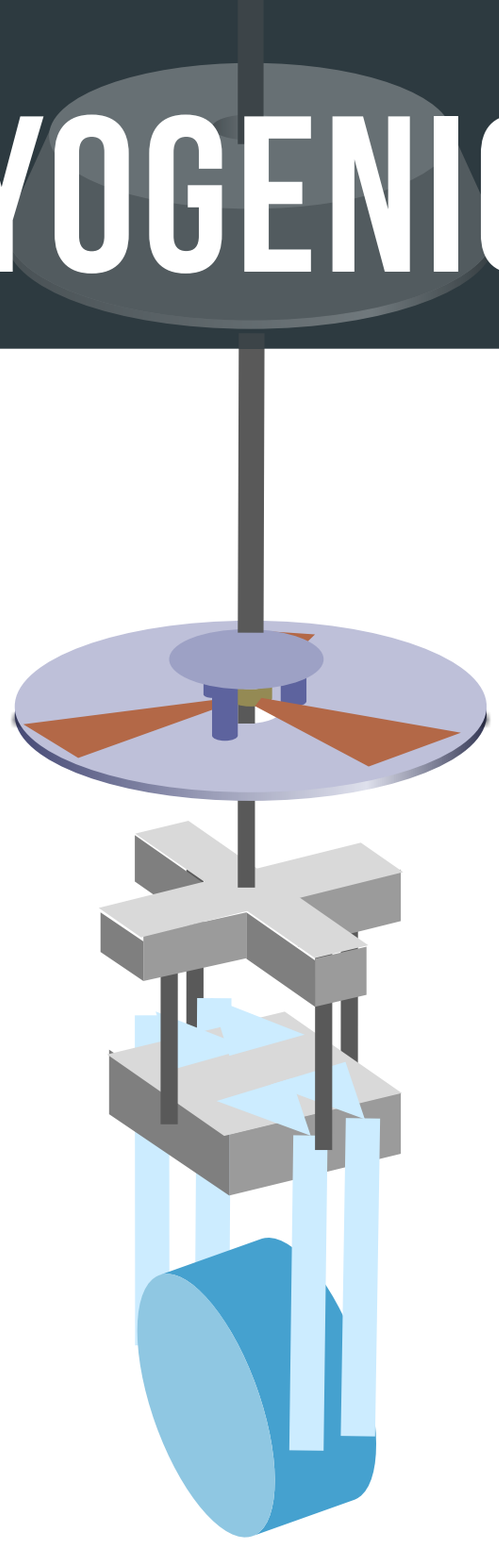


BOTTOM FILTER





CRYOGENIC PAYLOAD



RADIATION + CONDUCTIVE COOLING

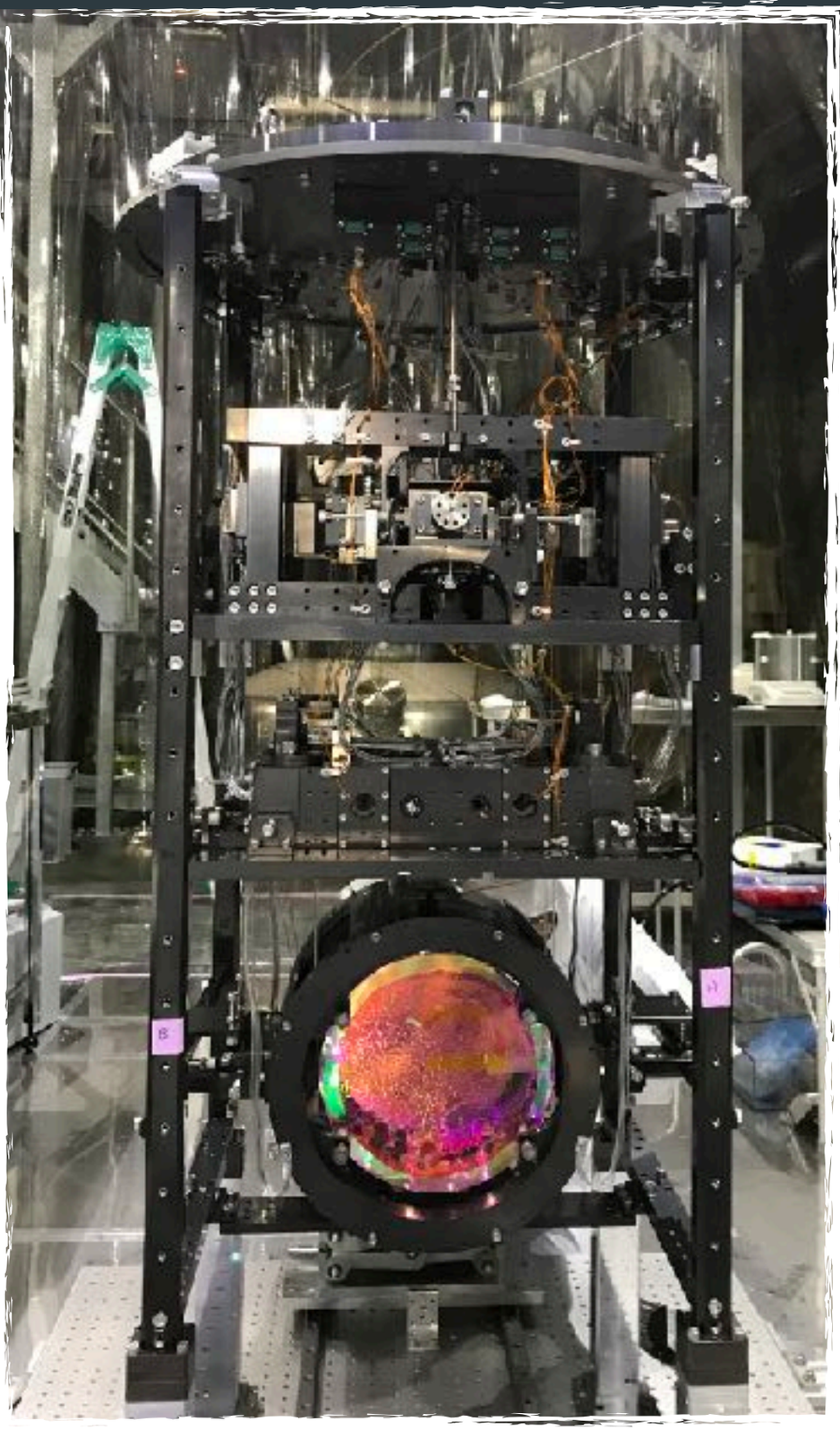
- Black coated surface
- Pure aluminum heat links

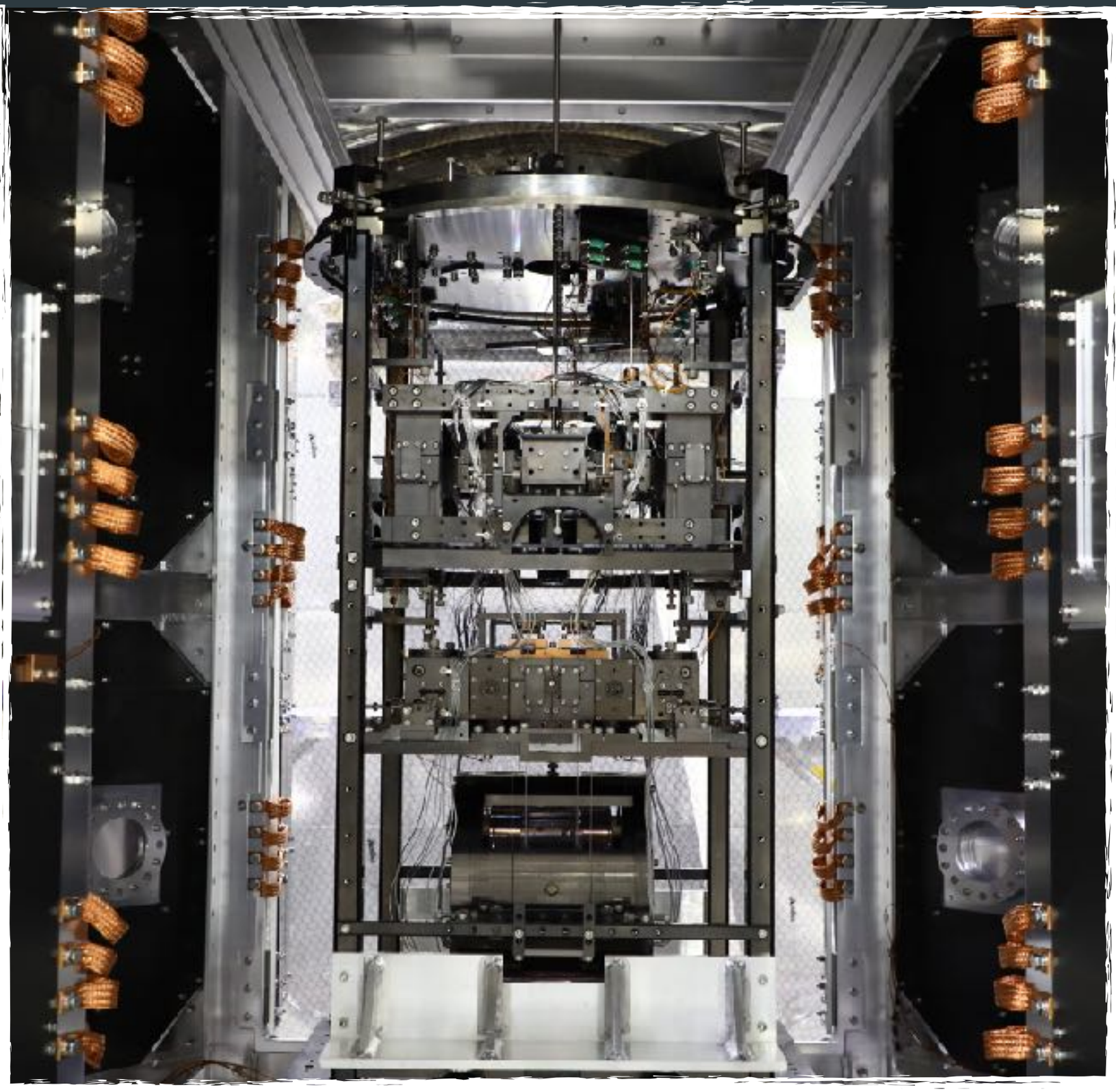
SAPPHIRE TEST MASS & FIBERS

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

CRYOGENIC PAYLOAD

CRYOGENIC PAYLOAD





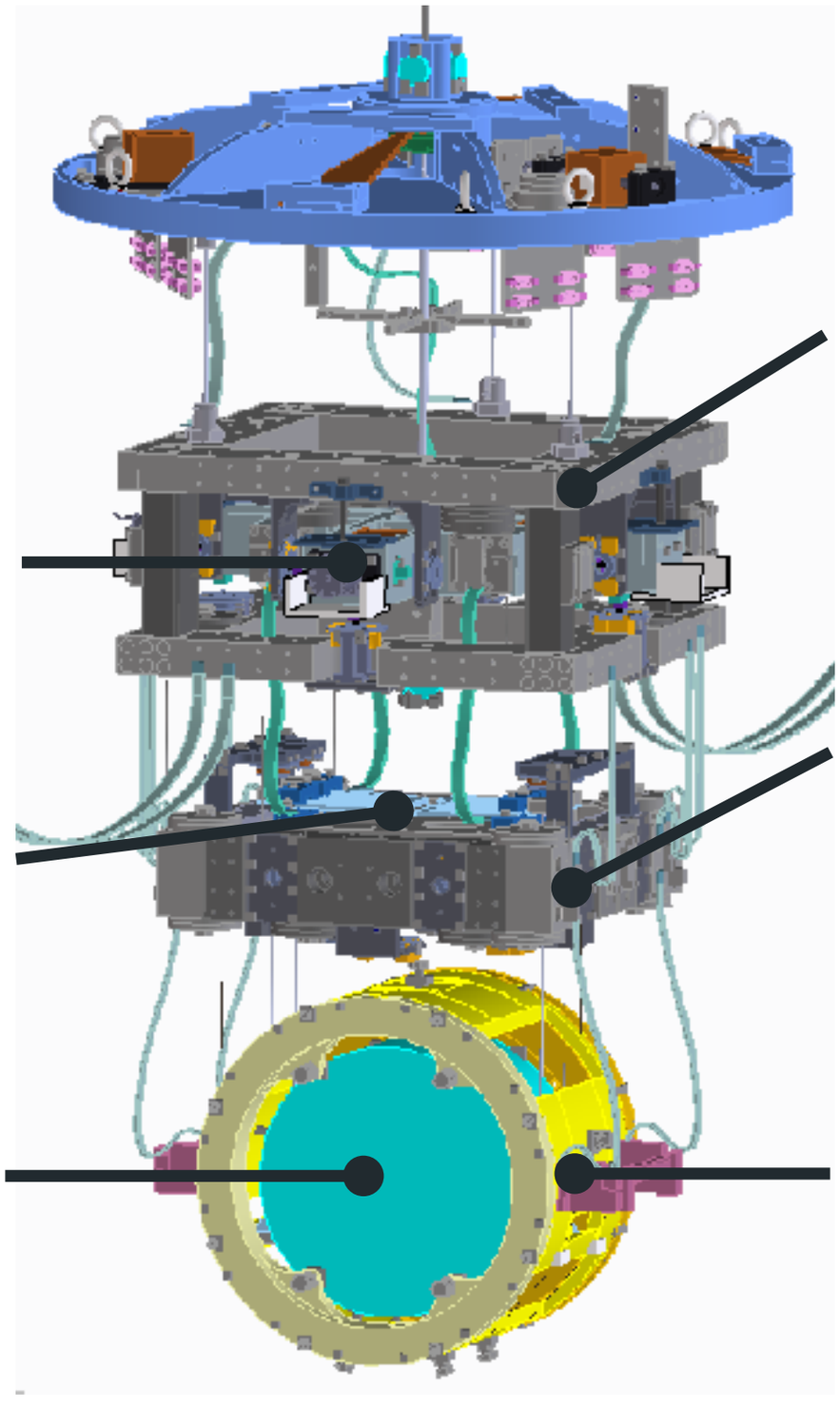
PAYLOAD COMPONENTS

Platform **(PF)**

Marionette **(MN)**

Intermediate Mass **(IM)**

Test Mass **(TM)**



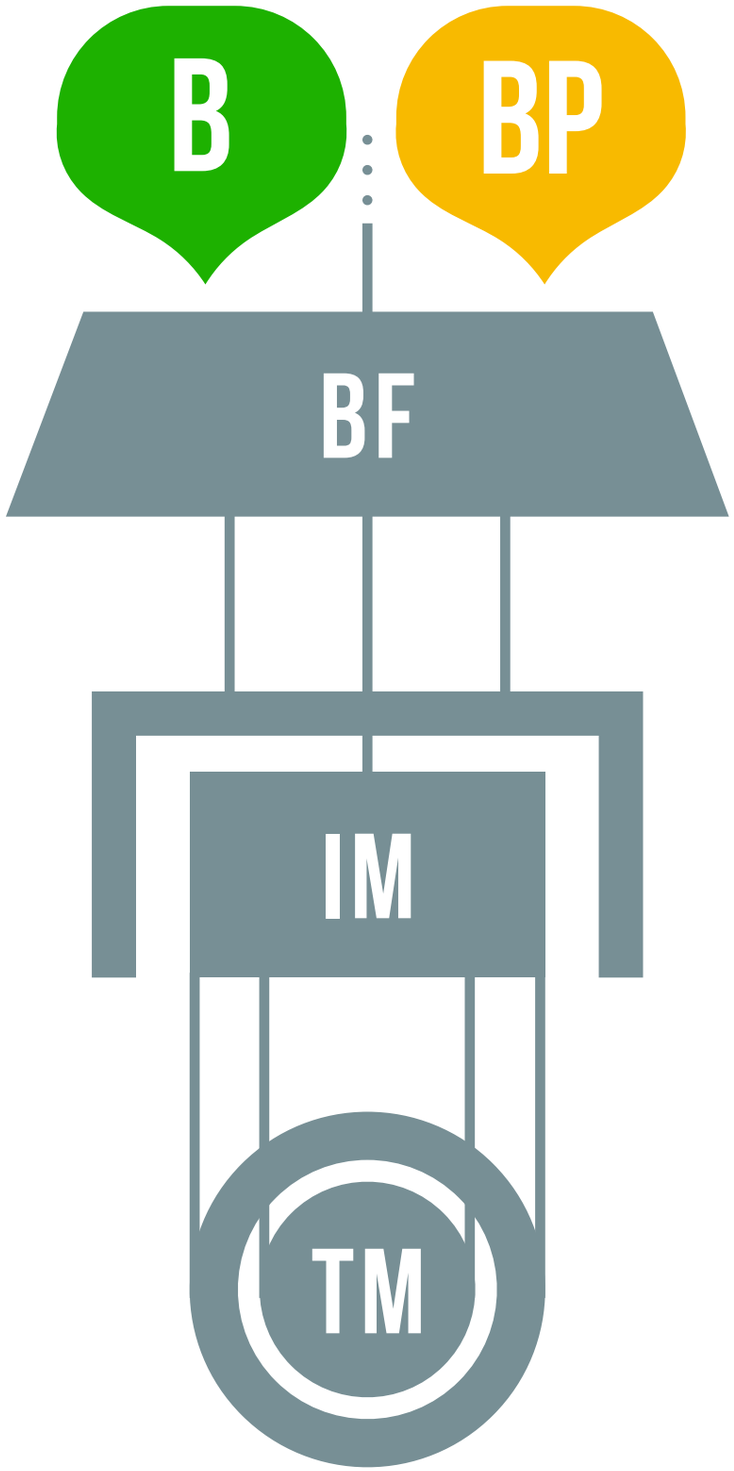
TOTAL WEIGHT ~ 200 KG

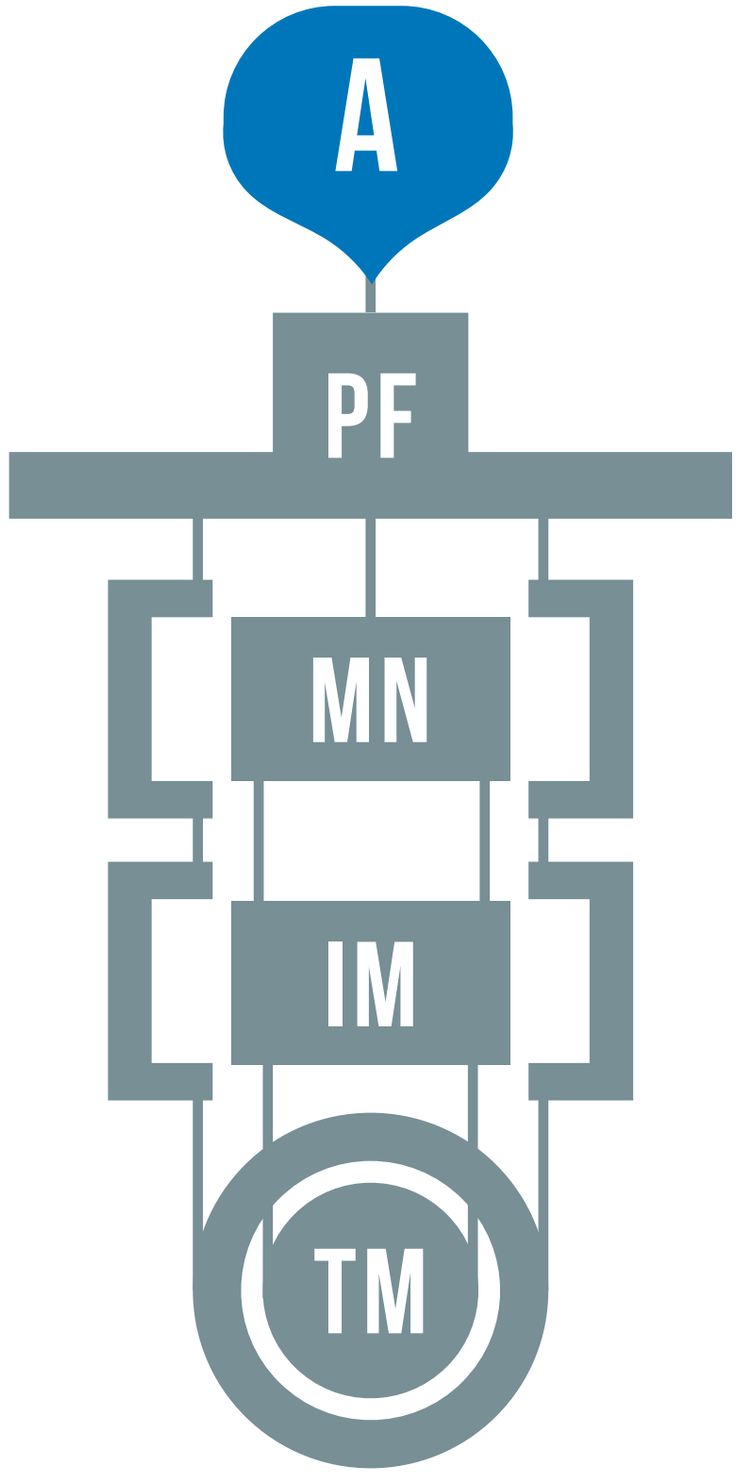
Marionette Recoil Mass **(MNR)**

Intermediate Recoil Mass **(IRM)**

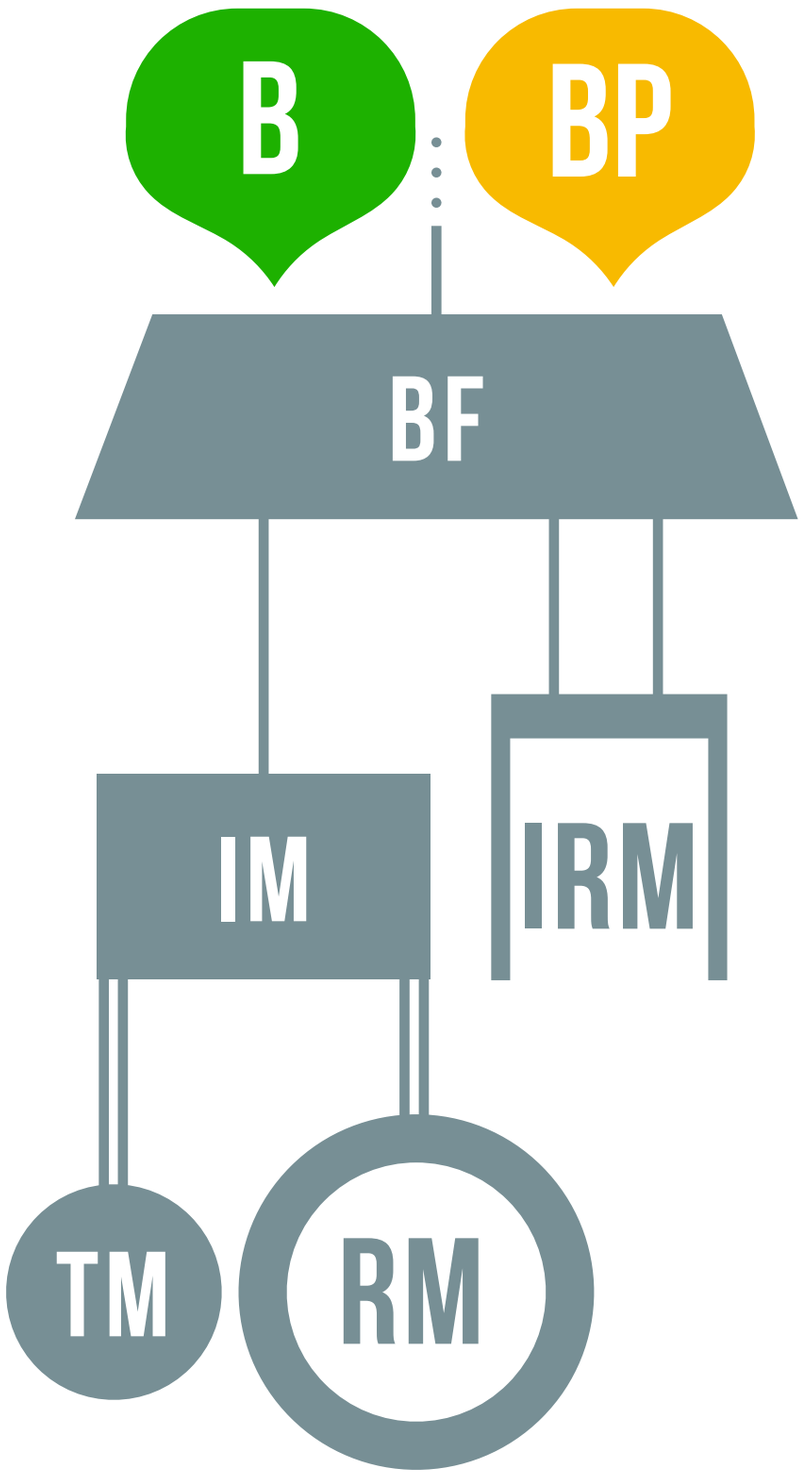
Recoil Mass **(RM)**

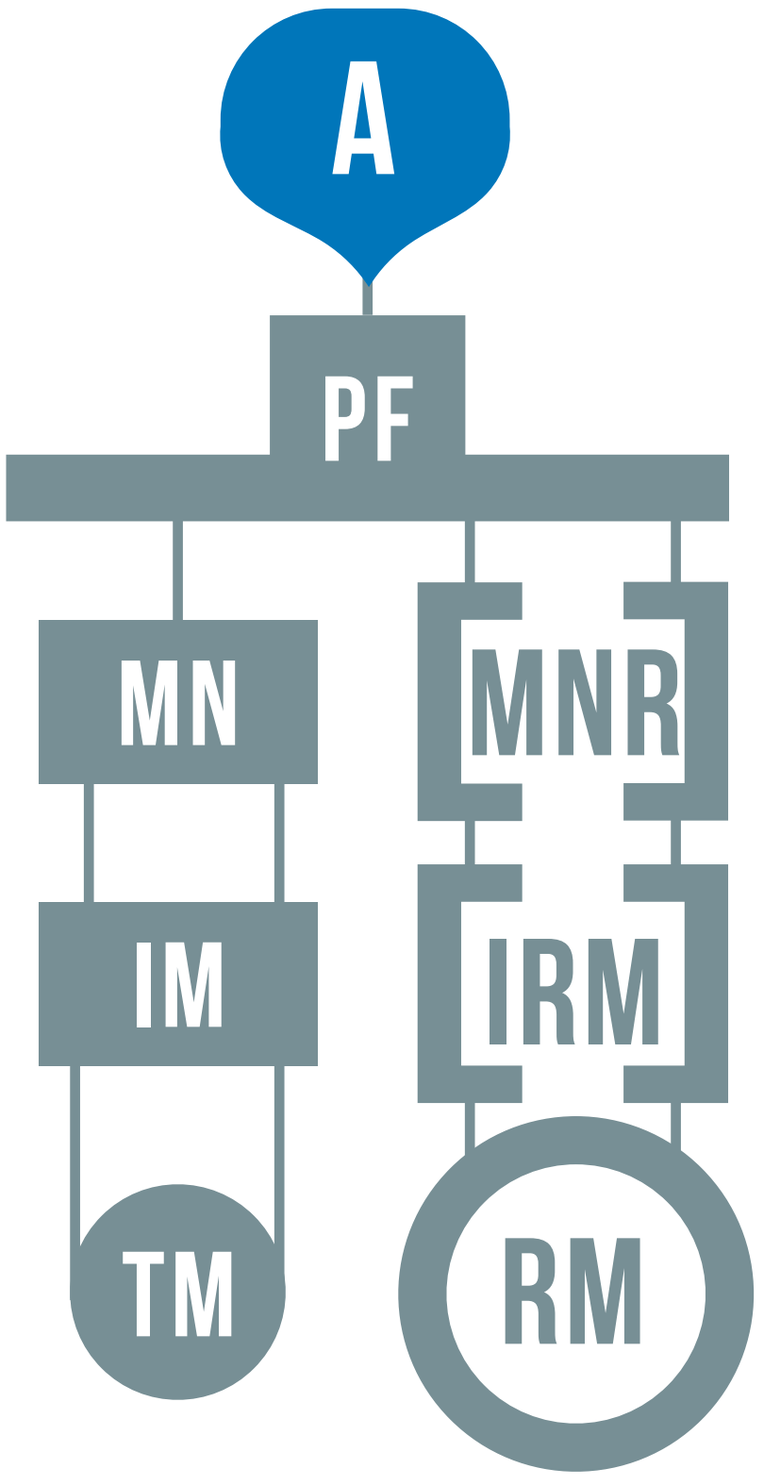
PAYLOAD STRUCTURE



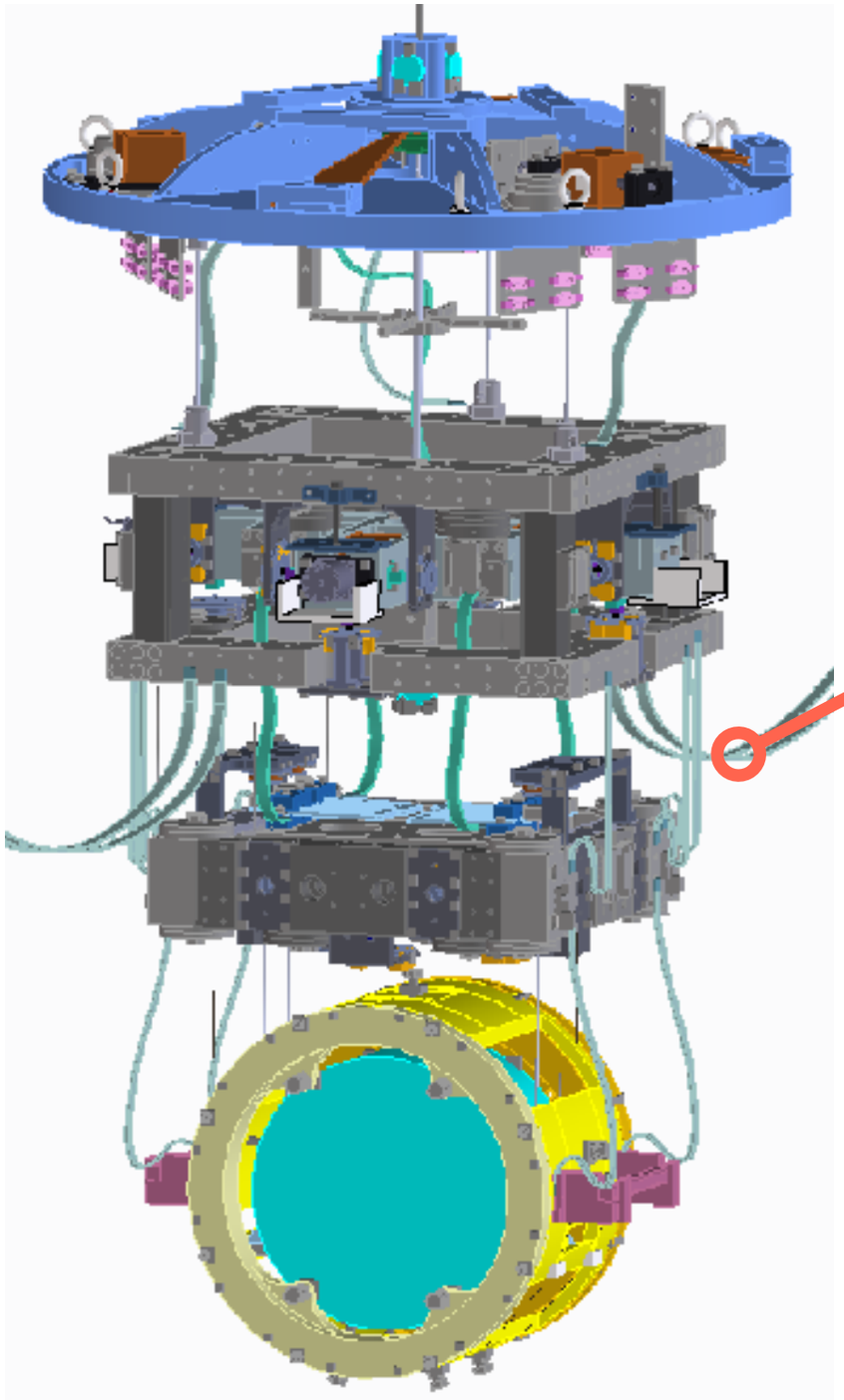


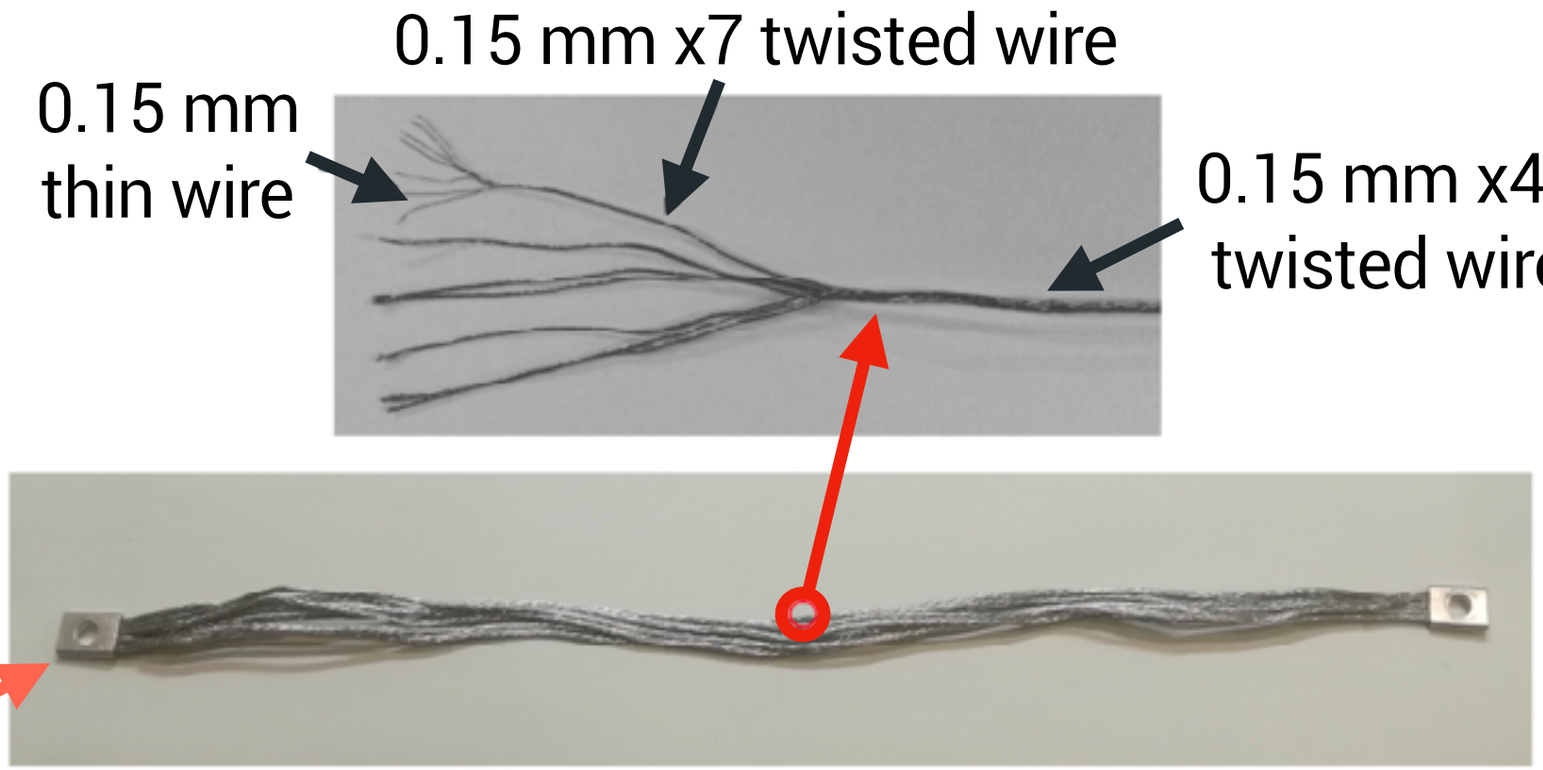
PAYLOAD STRUCTURE





HEAT LINK





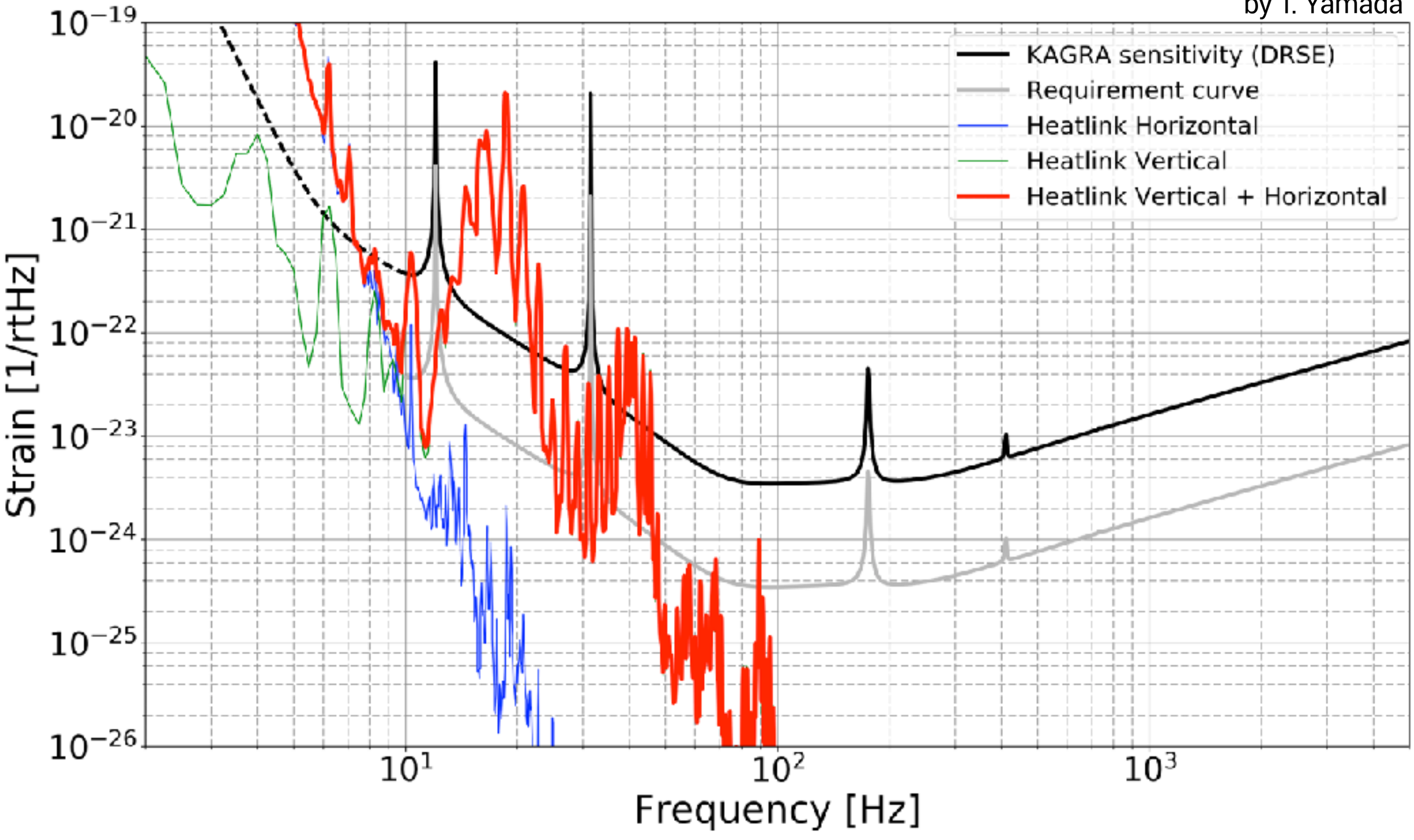
0.15 mm x49 twisted wire x7 in parallel

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

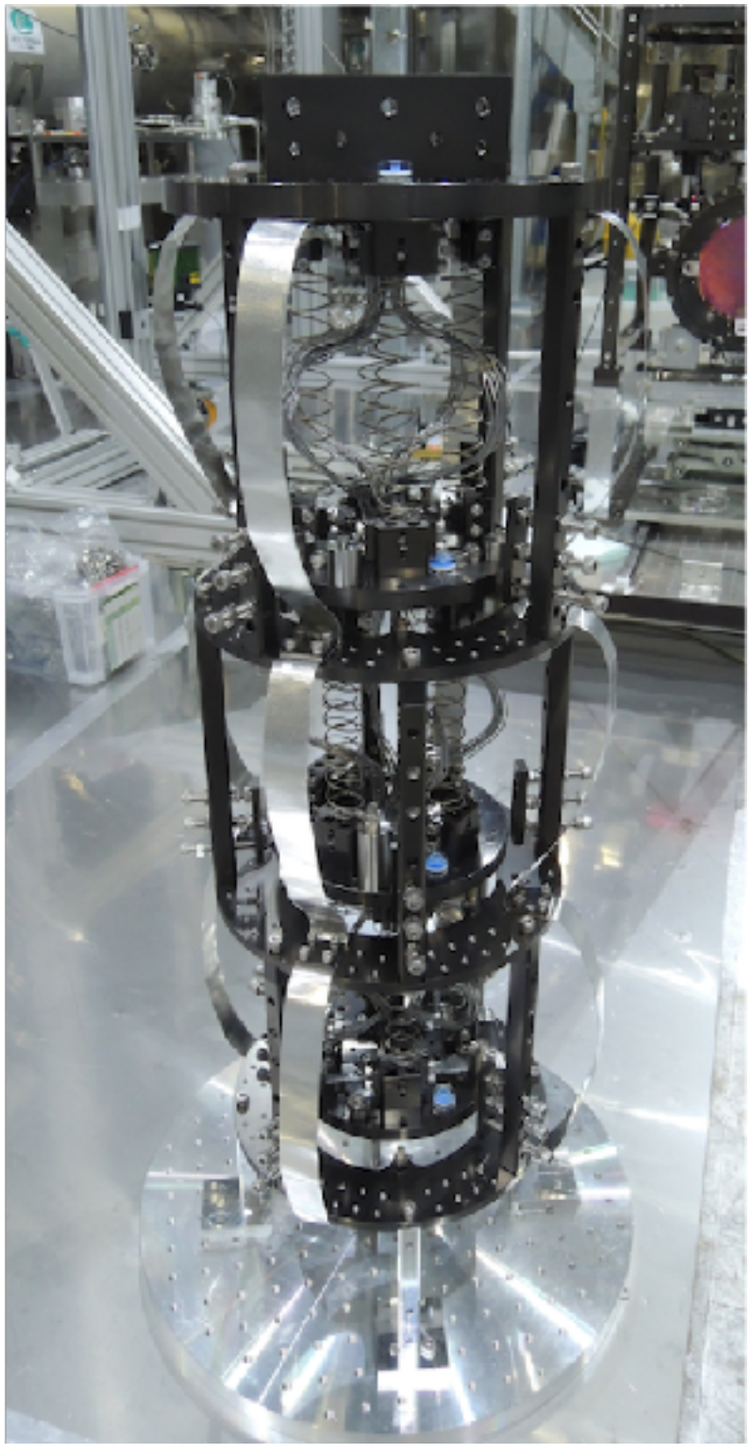
cf. T. Yamada Master Thesis (2018)

HEAT LINK INDUCES VIBRATION

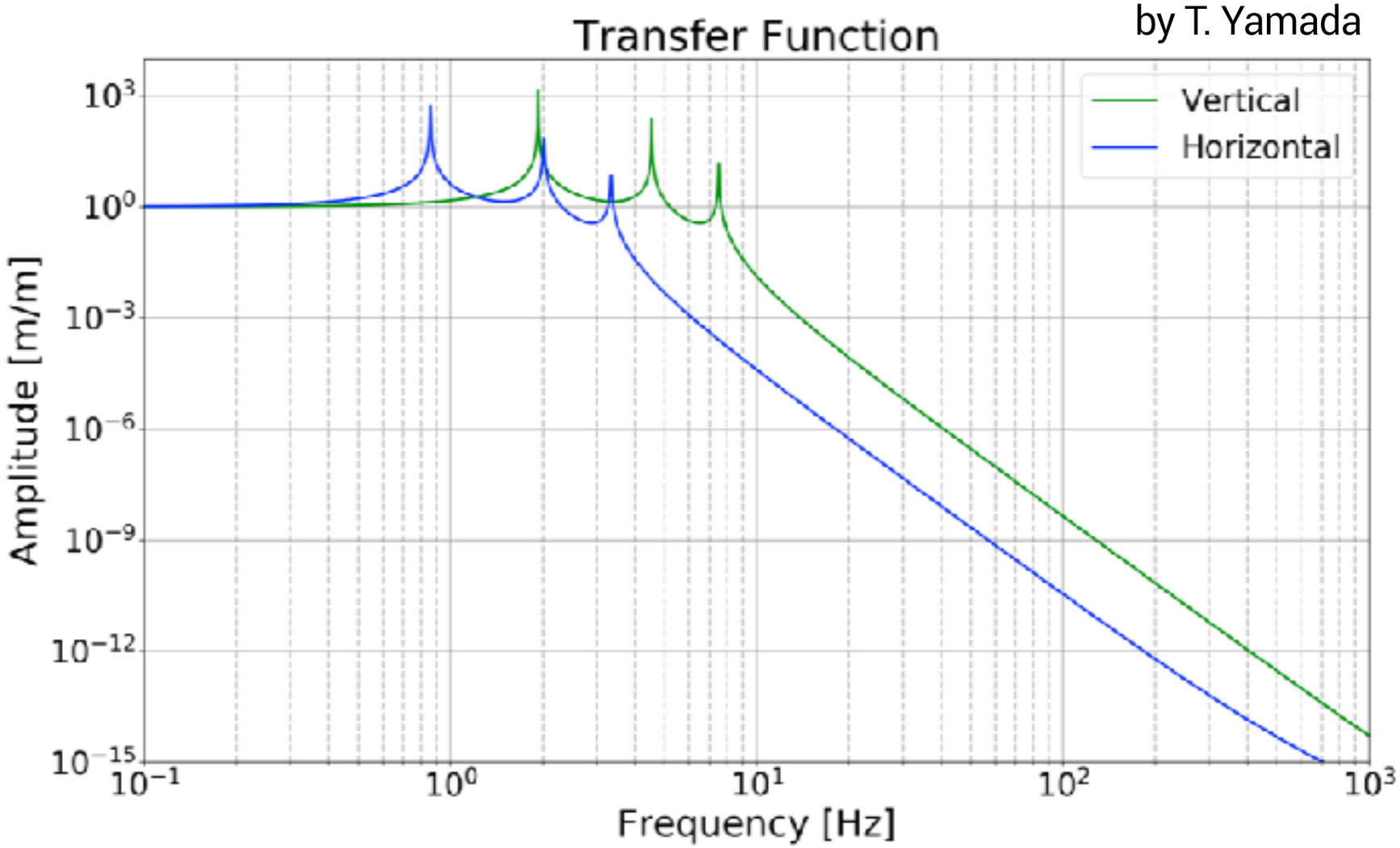
by T. Yamada



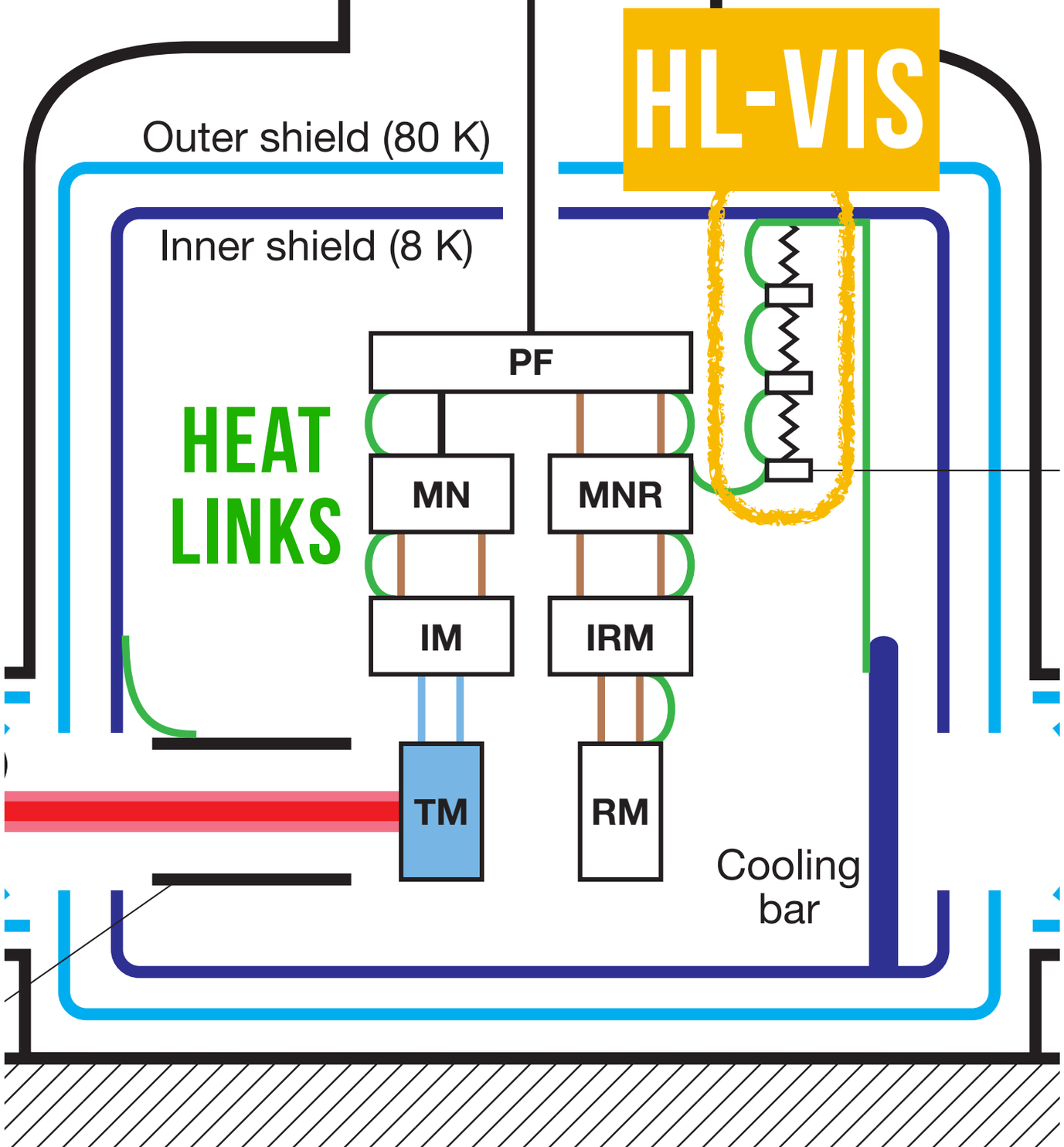
Heat Link Vibration Isolation System

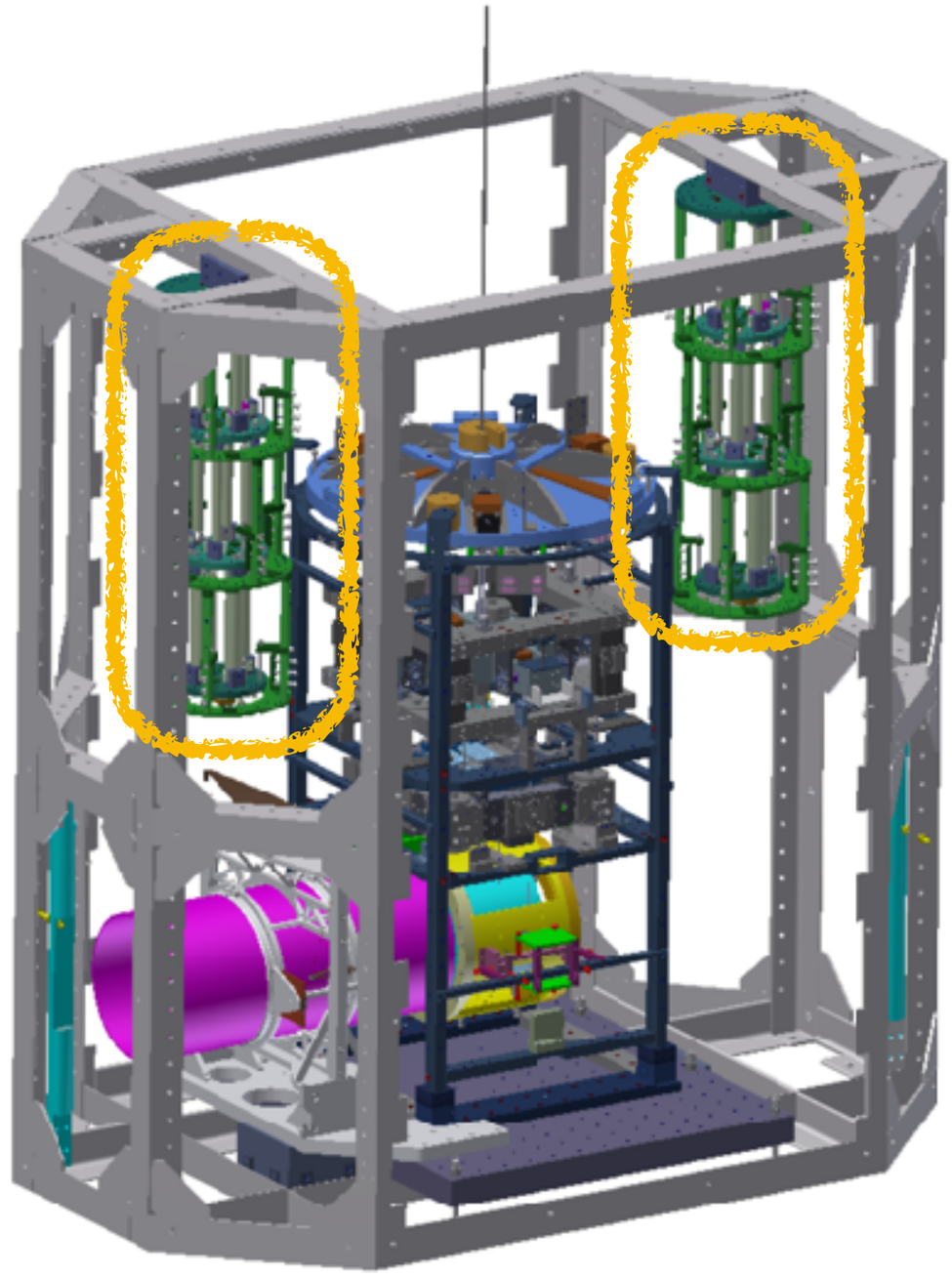


by T. Yamada



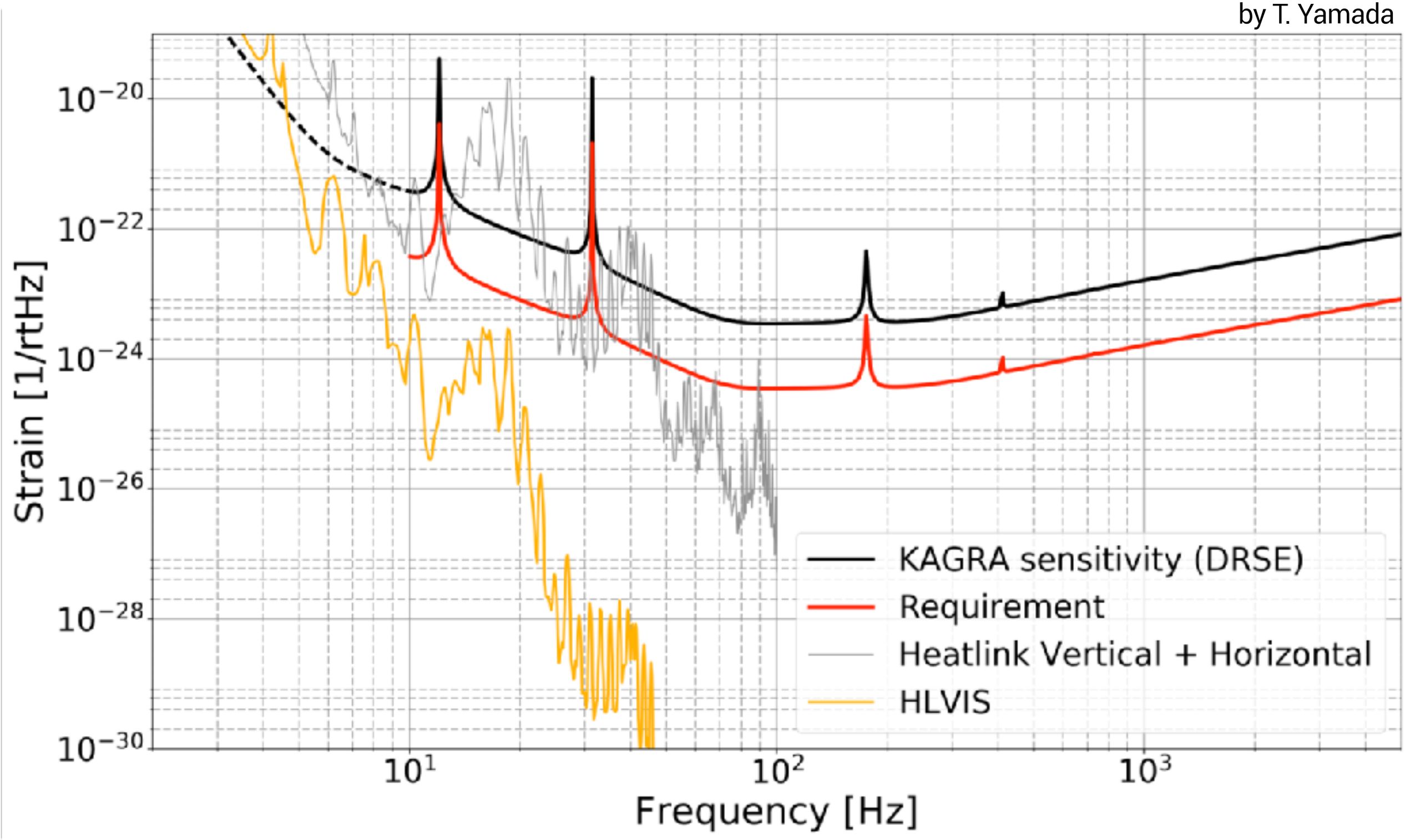
Heat Link Vibration Isolation System



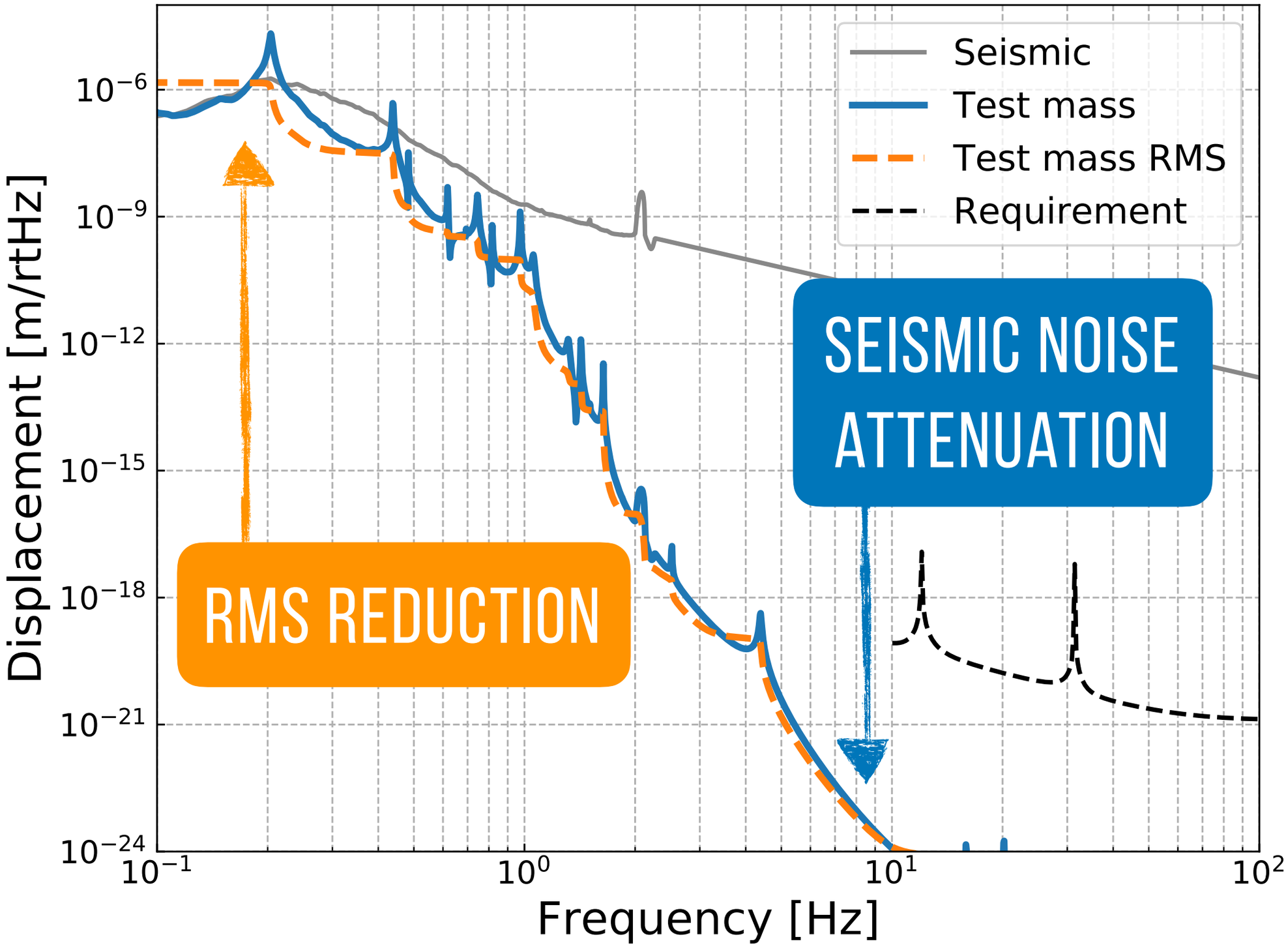


HL-VIS DESIGN PERFORMANCE

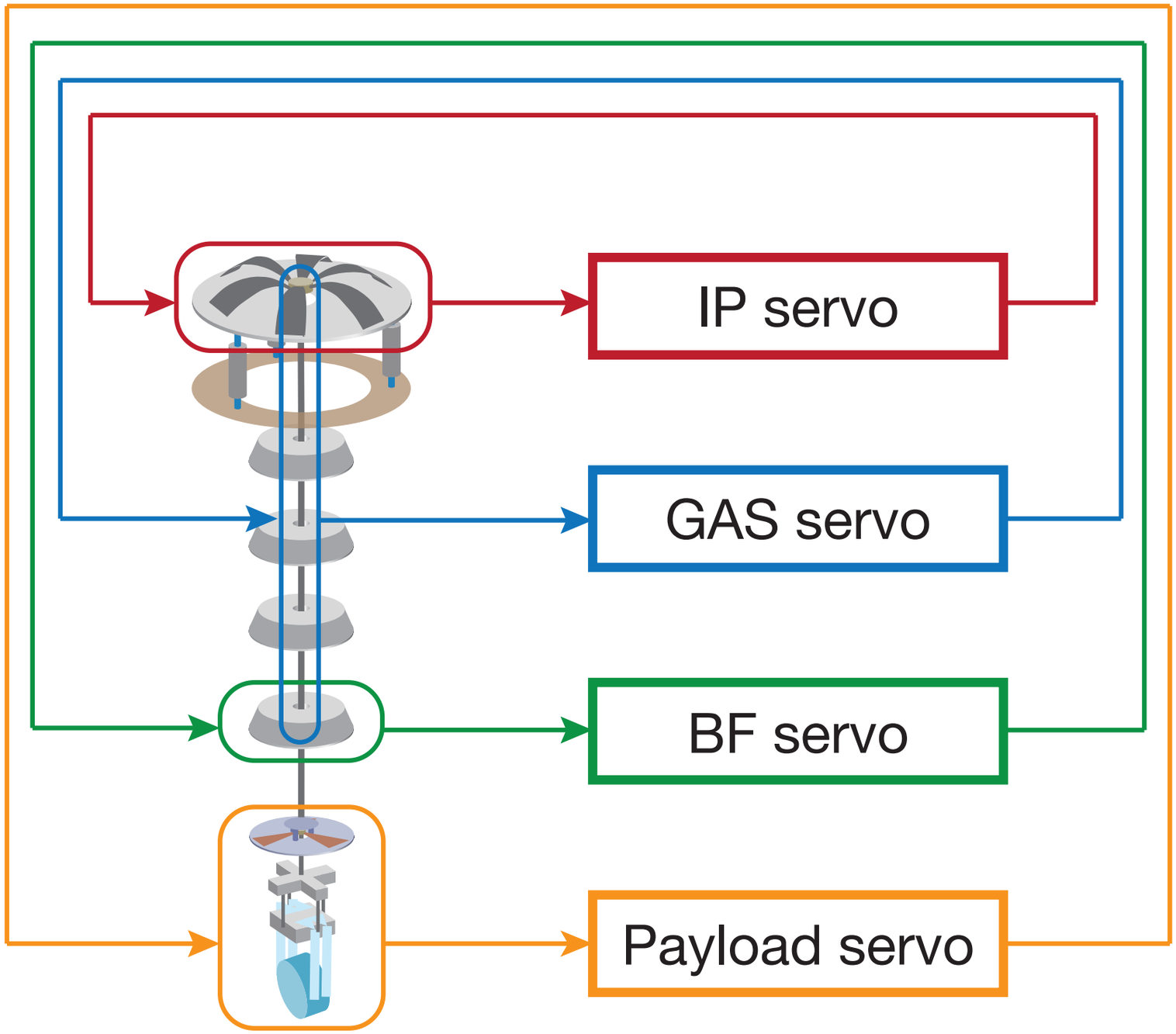
by T. Yamada



SUSPENSION'S ROLL

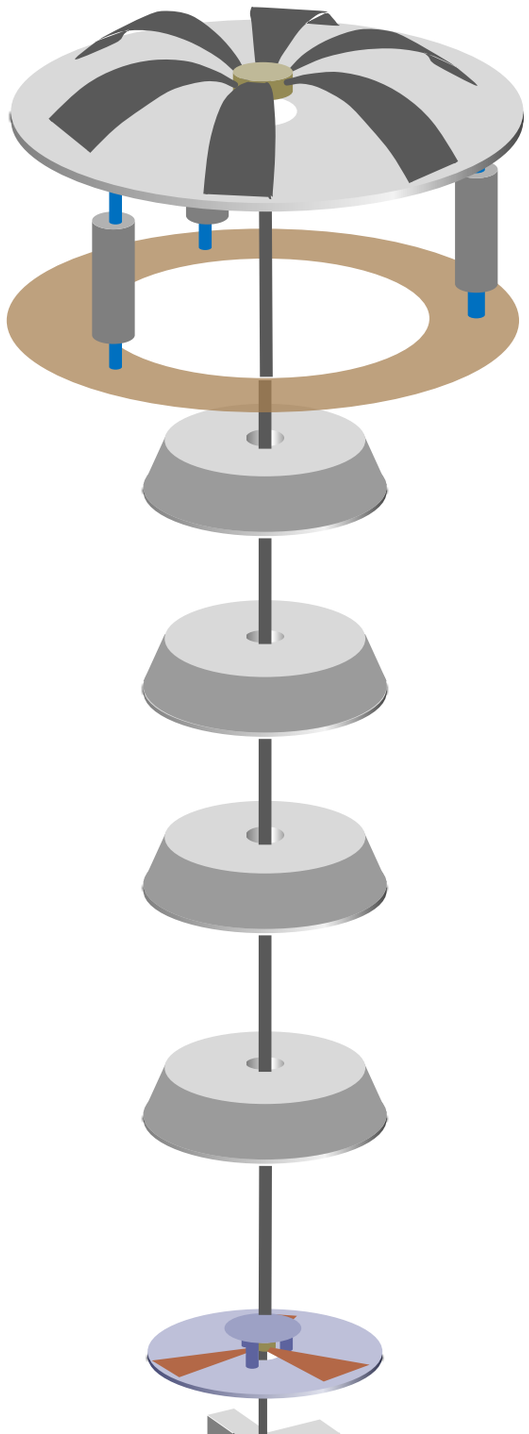


CONTROL SCHEMATICS



- **IP**
  Horizontal 3 DoFs
- **GAS**
  Vertical DoF x 5 stages
- **BF**
  6 DoFs w.r.t the ground
  (Torsion mode damping)
- **Payload**
  Relative DoFs w.r.t.
  the recoil chain

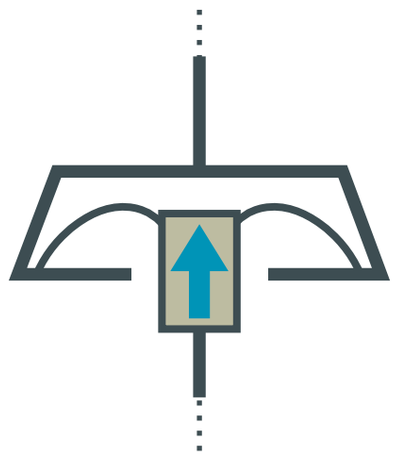
LOCAL SENSORS - TOWER



IP

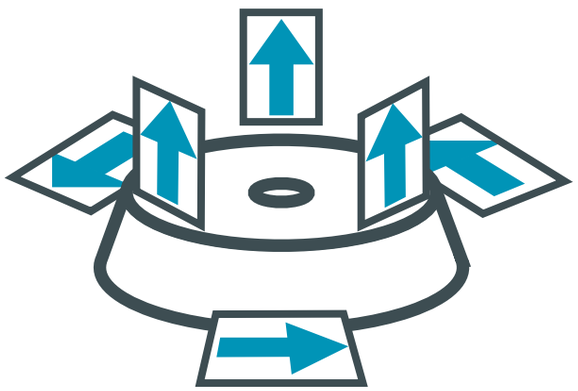
- LVDT
  IP-ground displacement
- Geophone
  IP inertial velocity

GAS



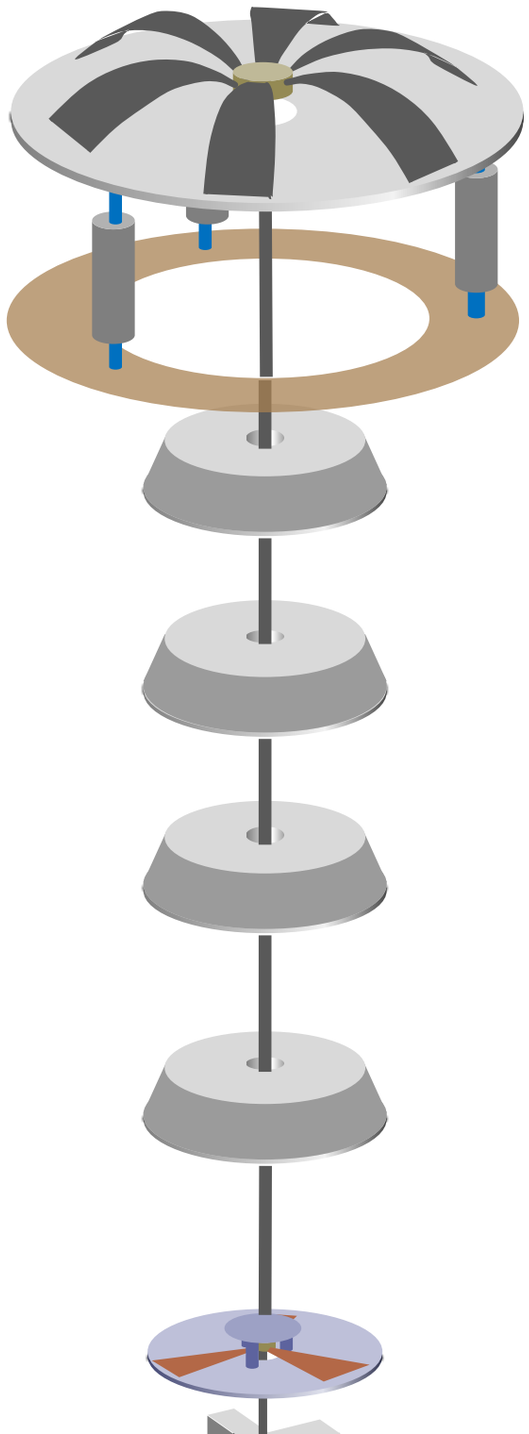
- LVDT
  keystone-body displacement

BF

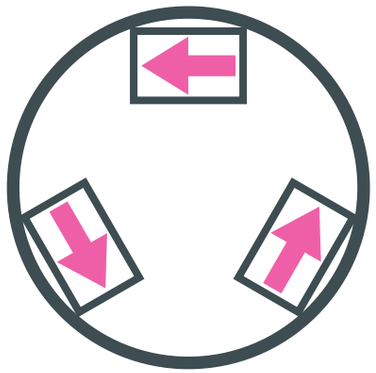


- LVDT
  BF-frame displacement

LOCAL ACTUATORS - TOWER



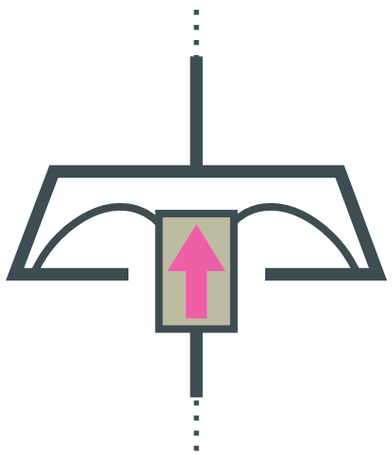
IP



Voice coil actuator

IP-ground force

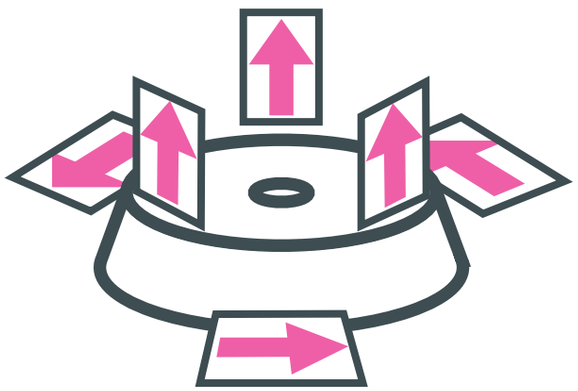
GAS



Voice coil actuator

keystone-body force

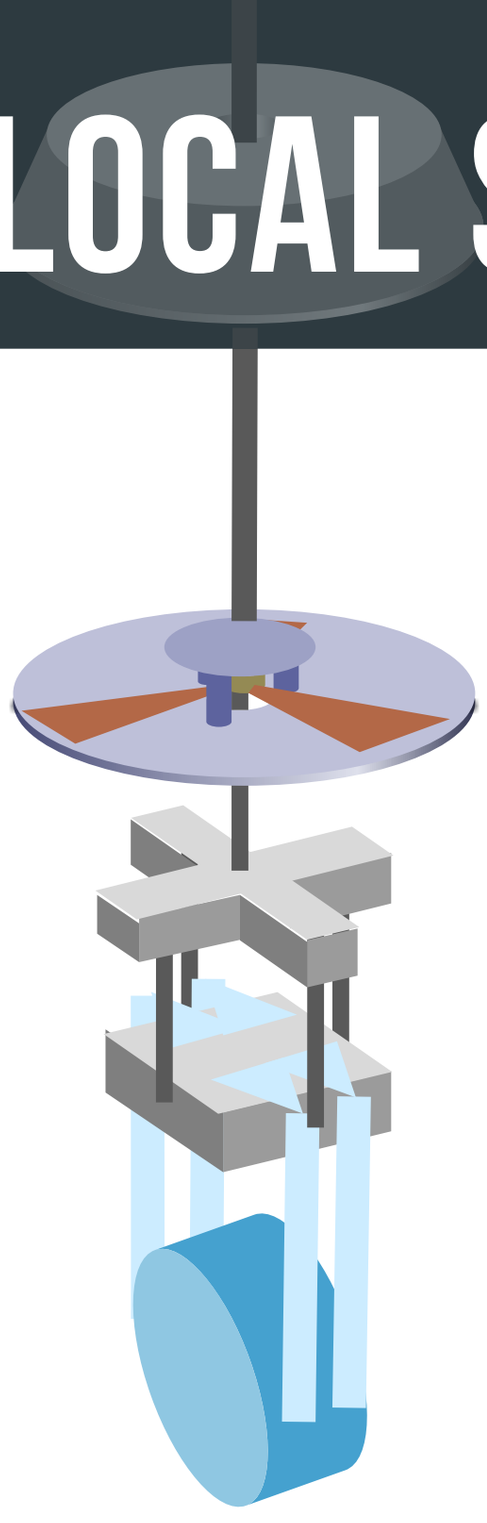
BF



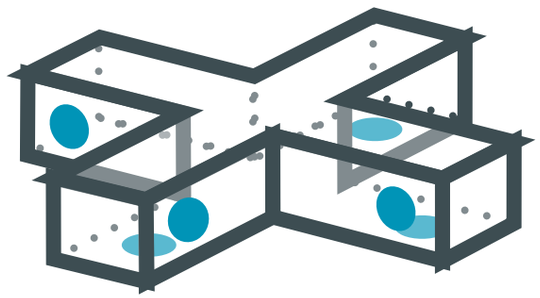
Coil-magnet actuator

BF-frame force

LOCAL SENSORS - PAYLOAD

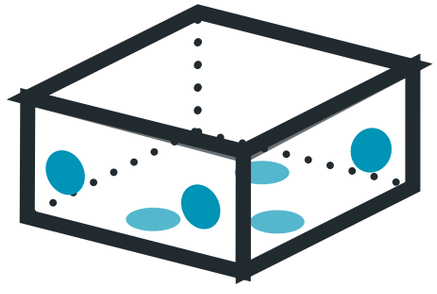


MN



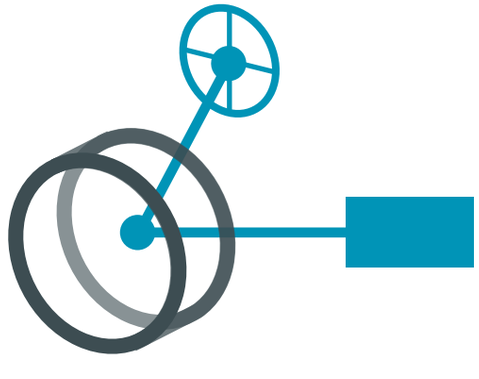
- Photo-sensor
  MN-MNR displacement
- Optical Lever
  MN angles w.r.t. ground

IM



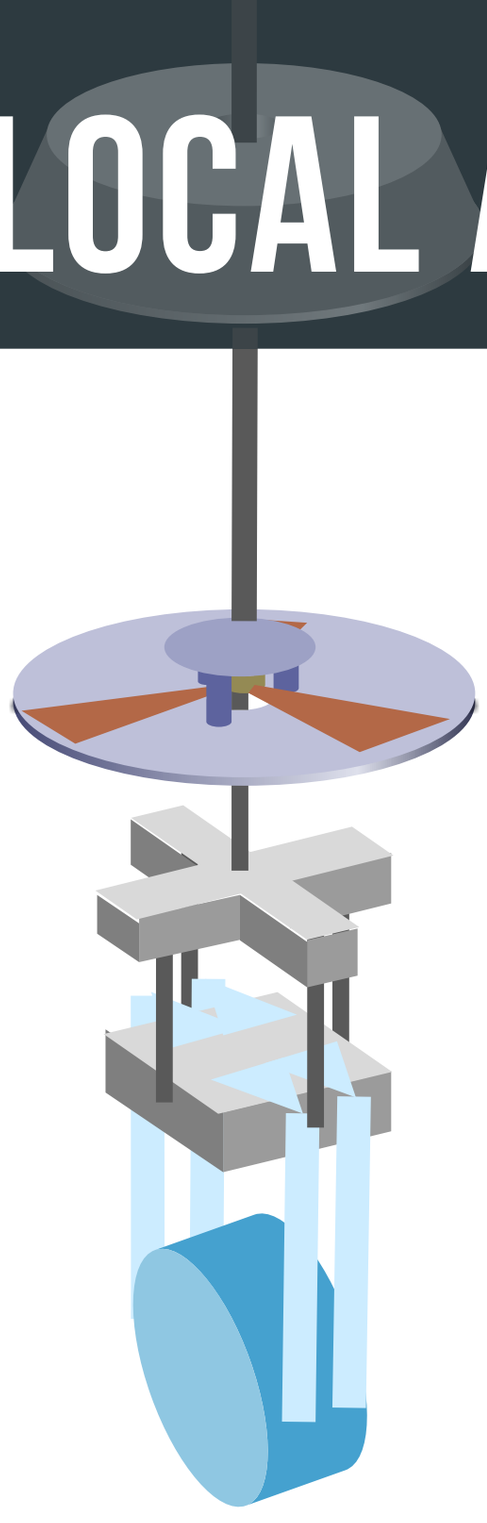
- Photo-sensor
  IM-IRM displacement

TM

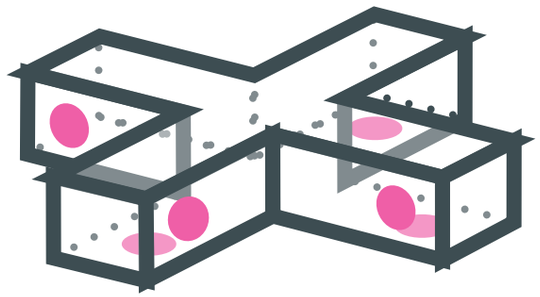


- Optical Lever
  TM-ground in (L, P, Y)

LOCAL ACTUATORS - PAYLOAD

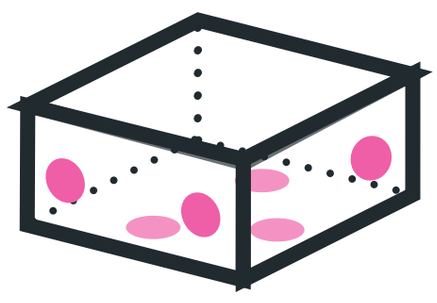


MN



OSEM-type actuator
MN-MNR relative force

IM



OSEM-type actuator
IM-IRM relative force

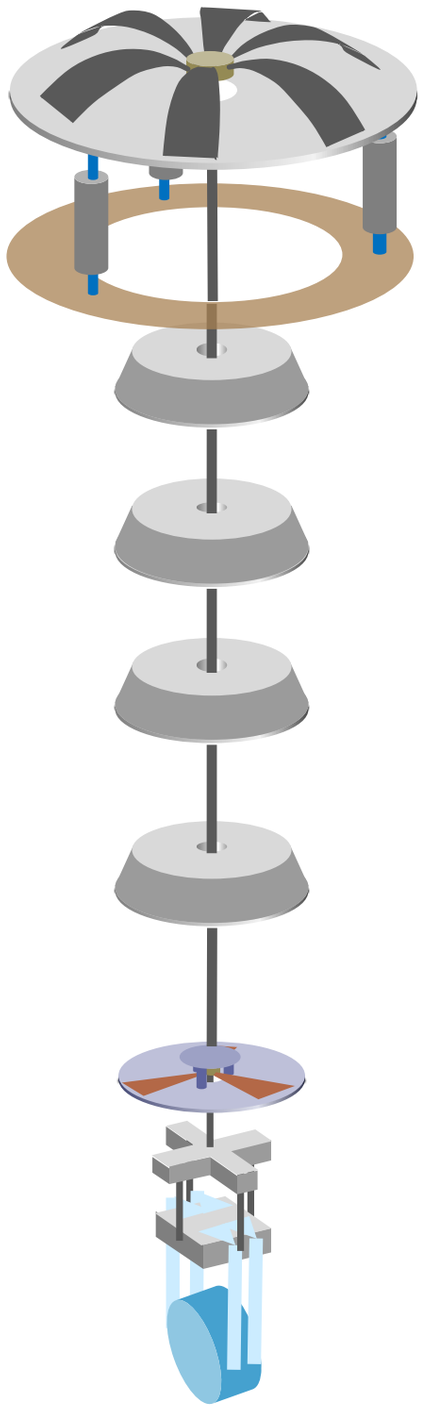
TM

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

TOPICS OF THE SUSPENSION CONTROL

- Torsion mode damping
- Modal damping of the GAS vertical chain
- Hierarchical control

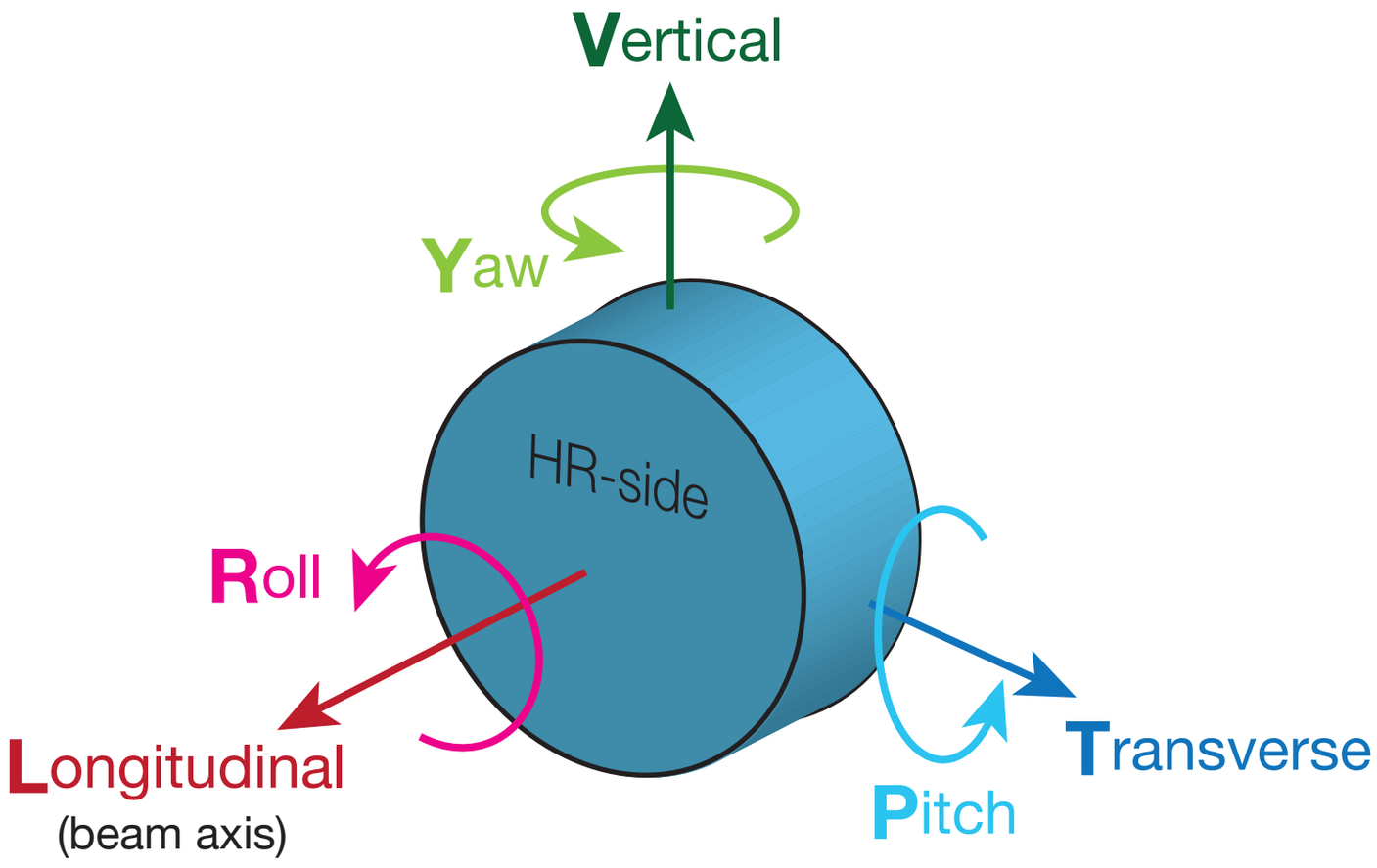
TORSION MODE DAMPING



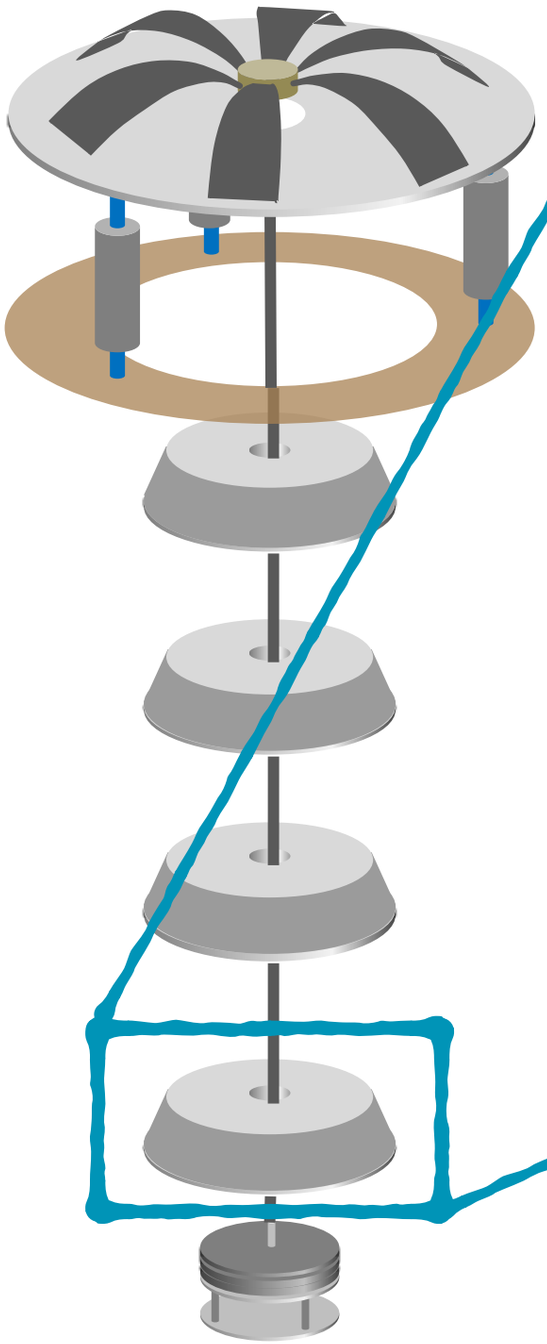
SINGLE WIRE CONNECTION

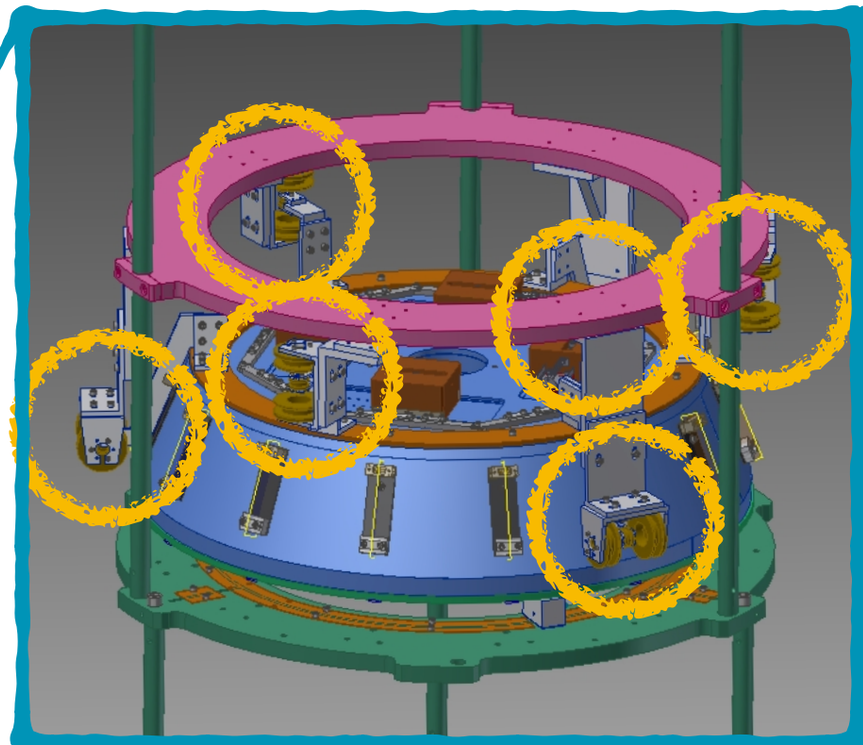
Requirements

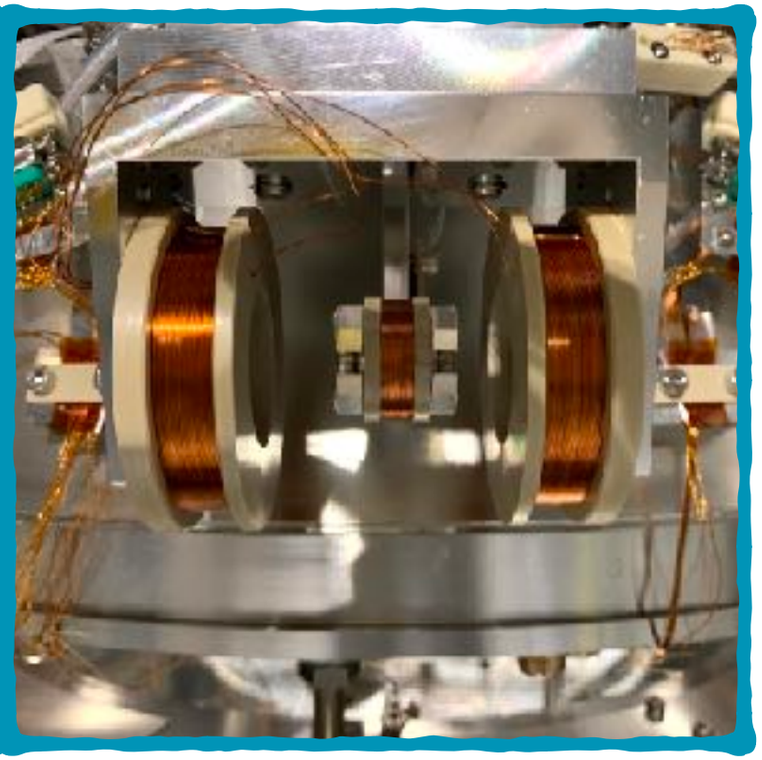
- Yaw RMS at TM < **0.88 urad**
- Mode decay time < **60 sec.**



BF DAMPER

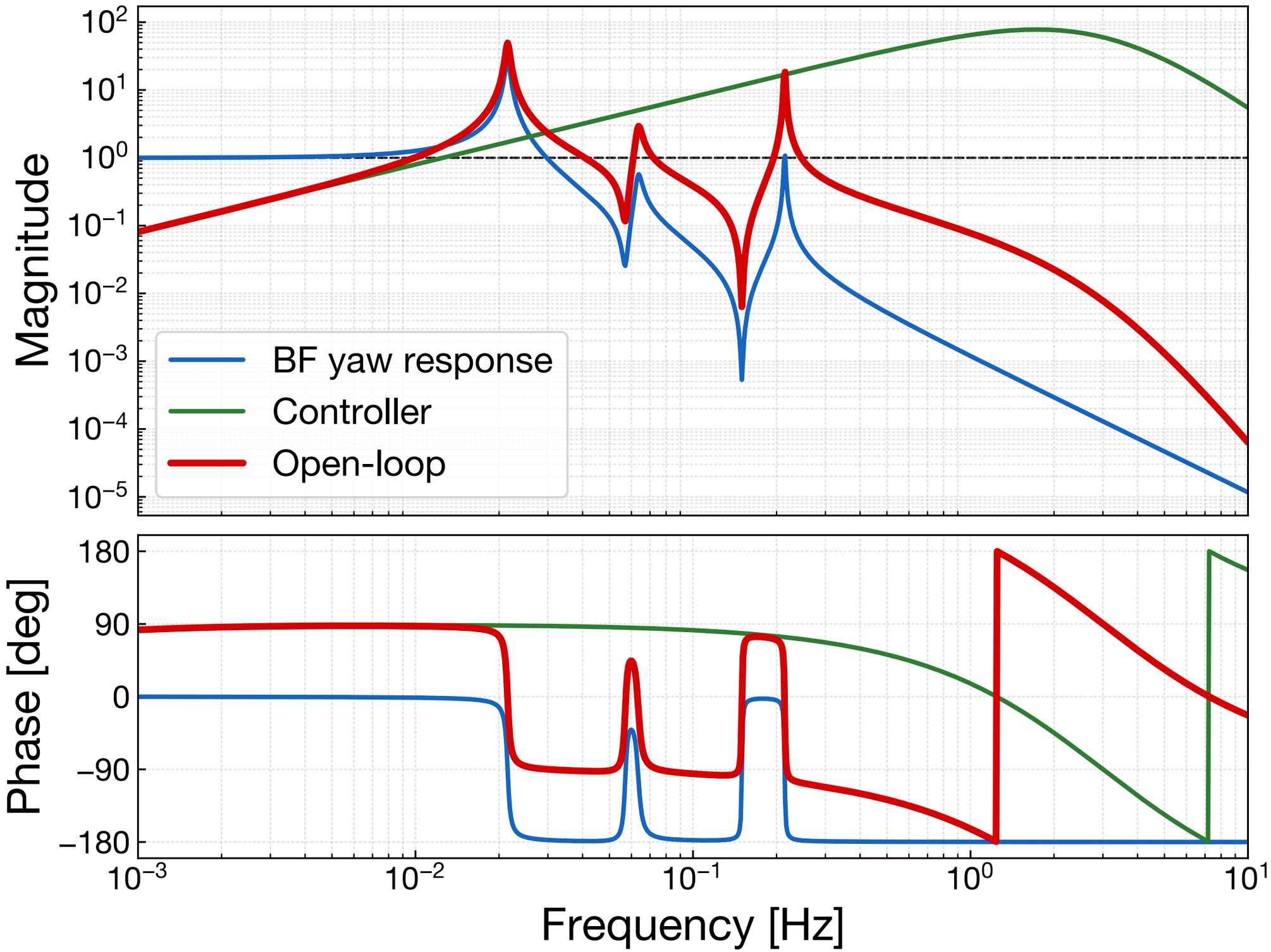




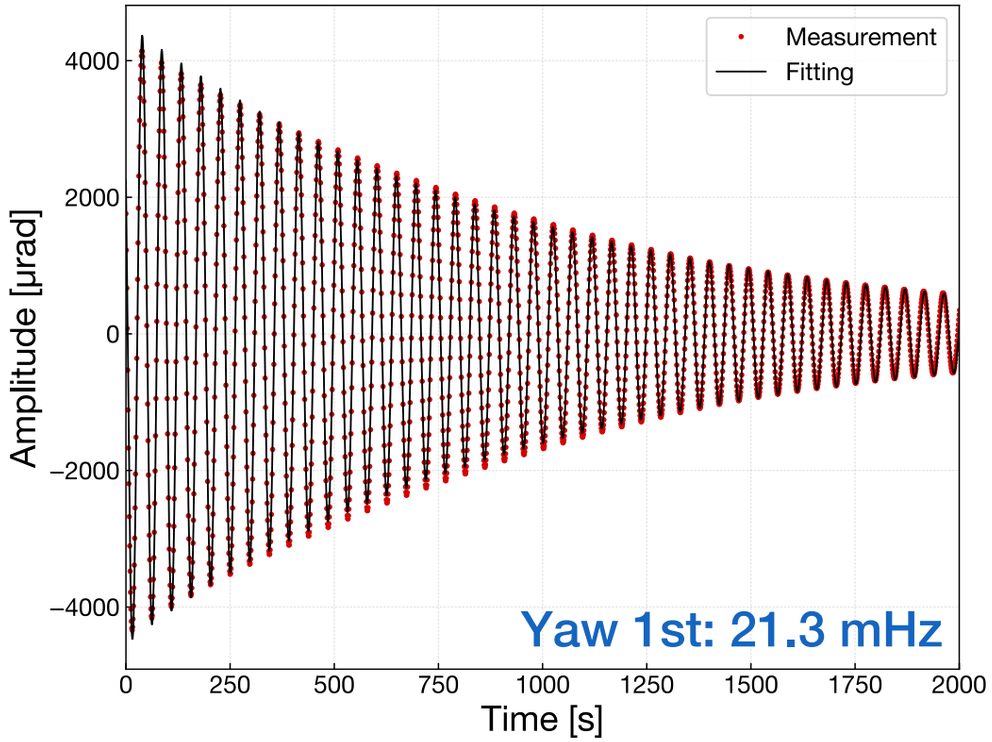


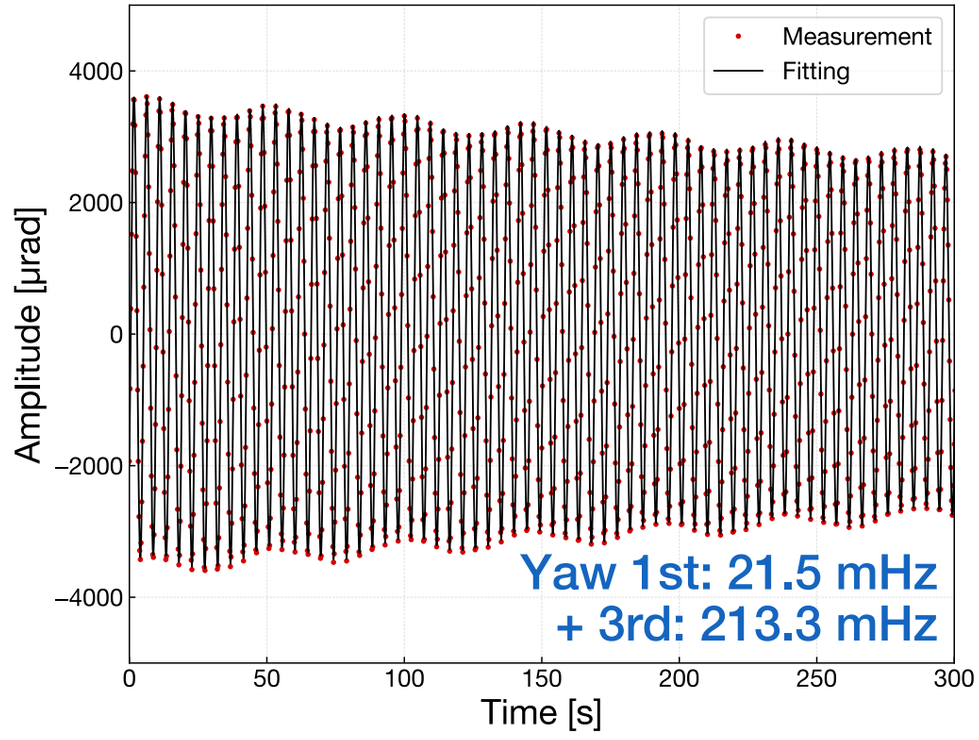
- LVDT + Coil-magnet actuator unit
- 6 DoFs sensing & actuation w.r.t. the ground

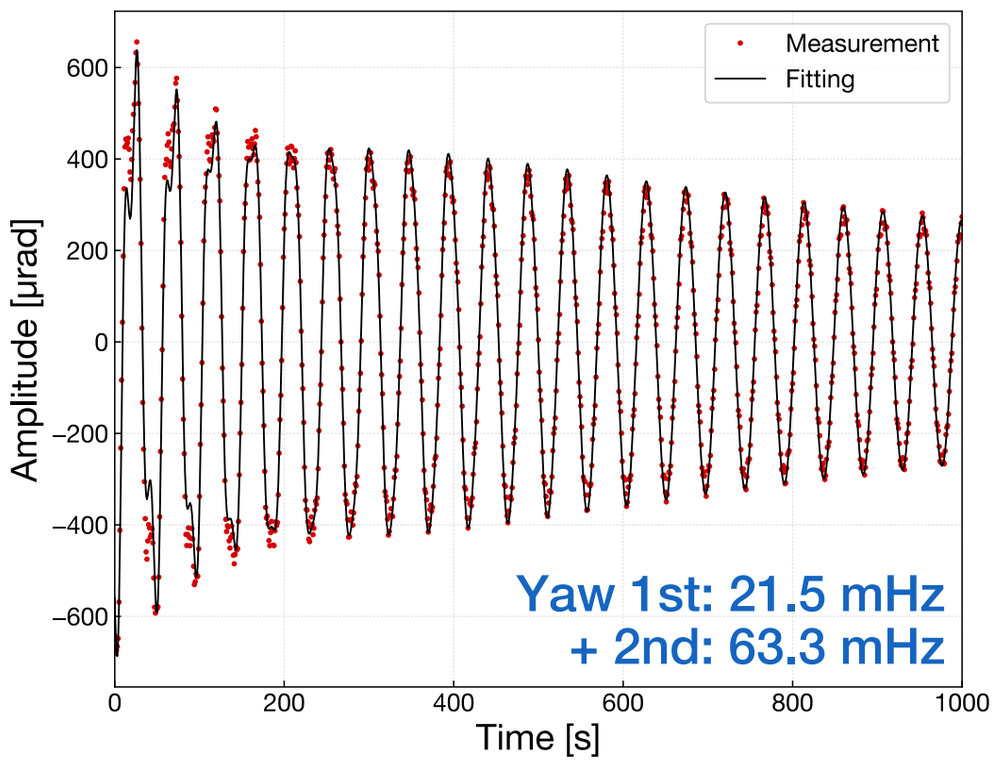
DAMPING LOOP



DECAY TIME MEASUREMENT

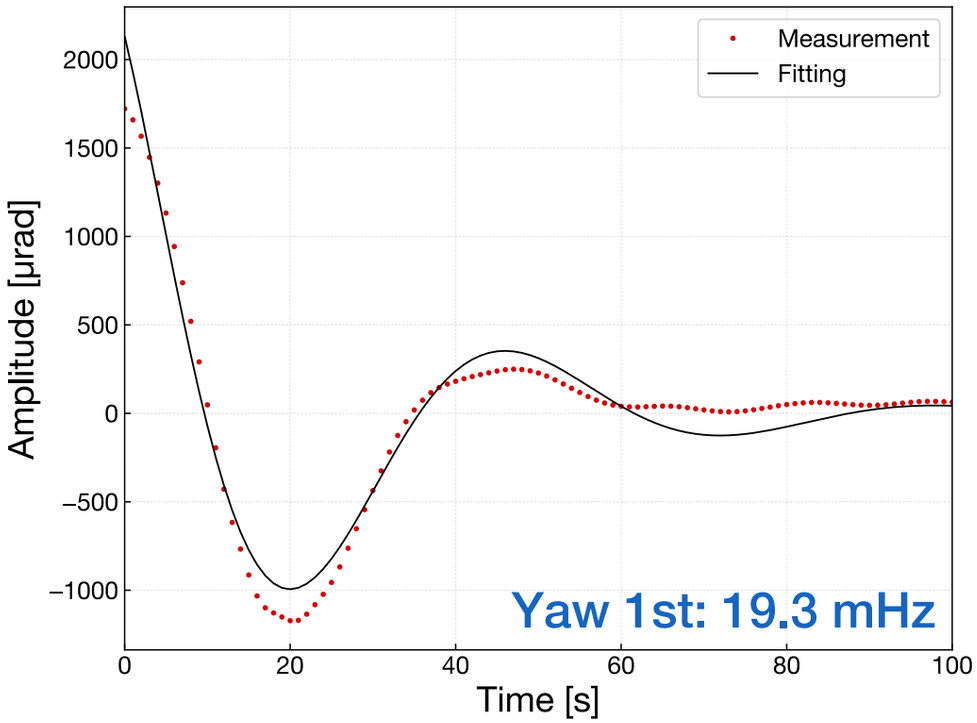


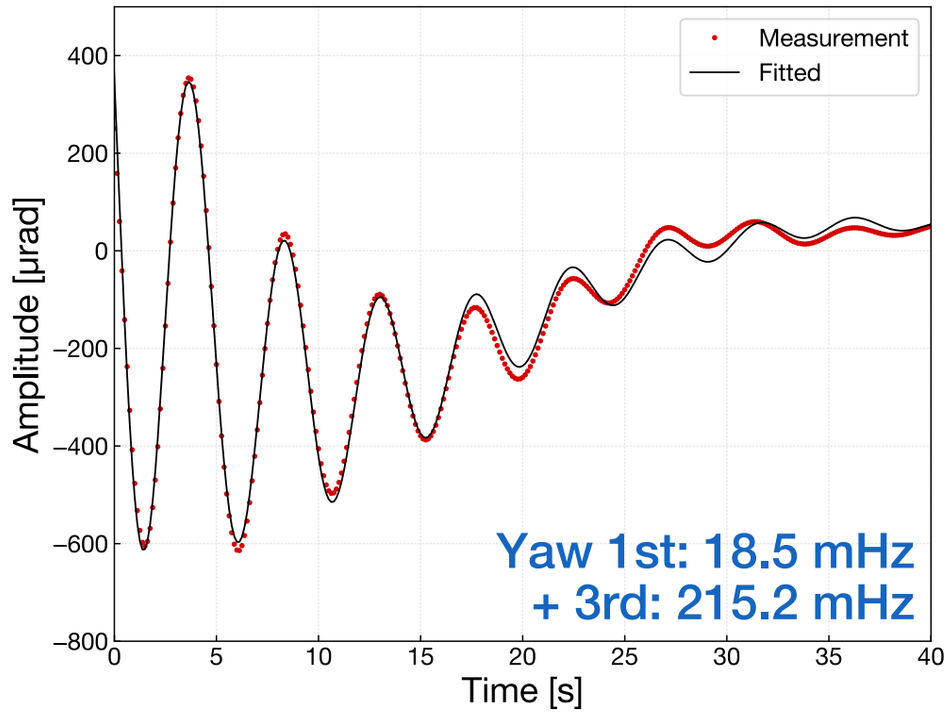


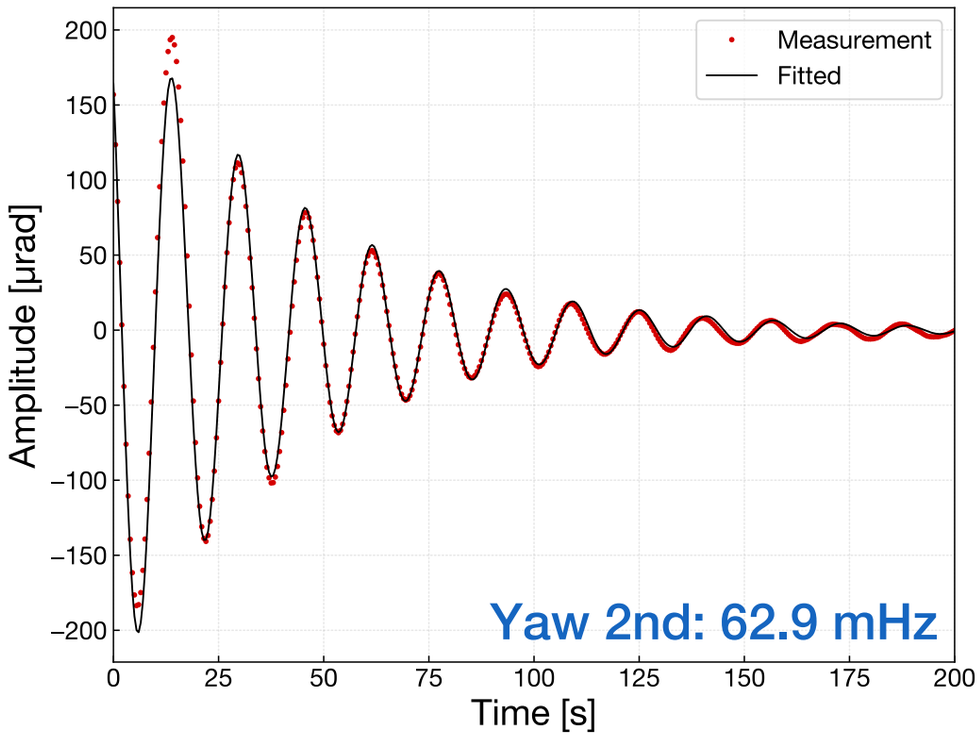


MODE	DECAY TIME
#1	961.4 sec.
#2	158.6 sec.
#3	1155.5 sec.

DECAY TIME MEASUREMENT

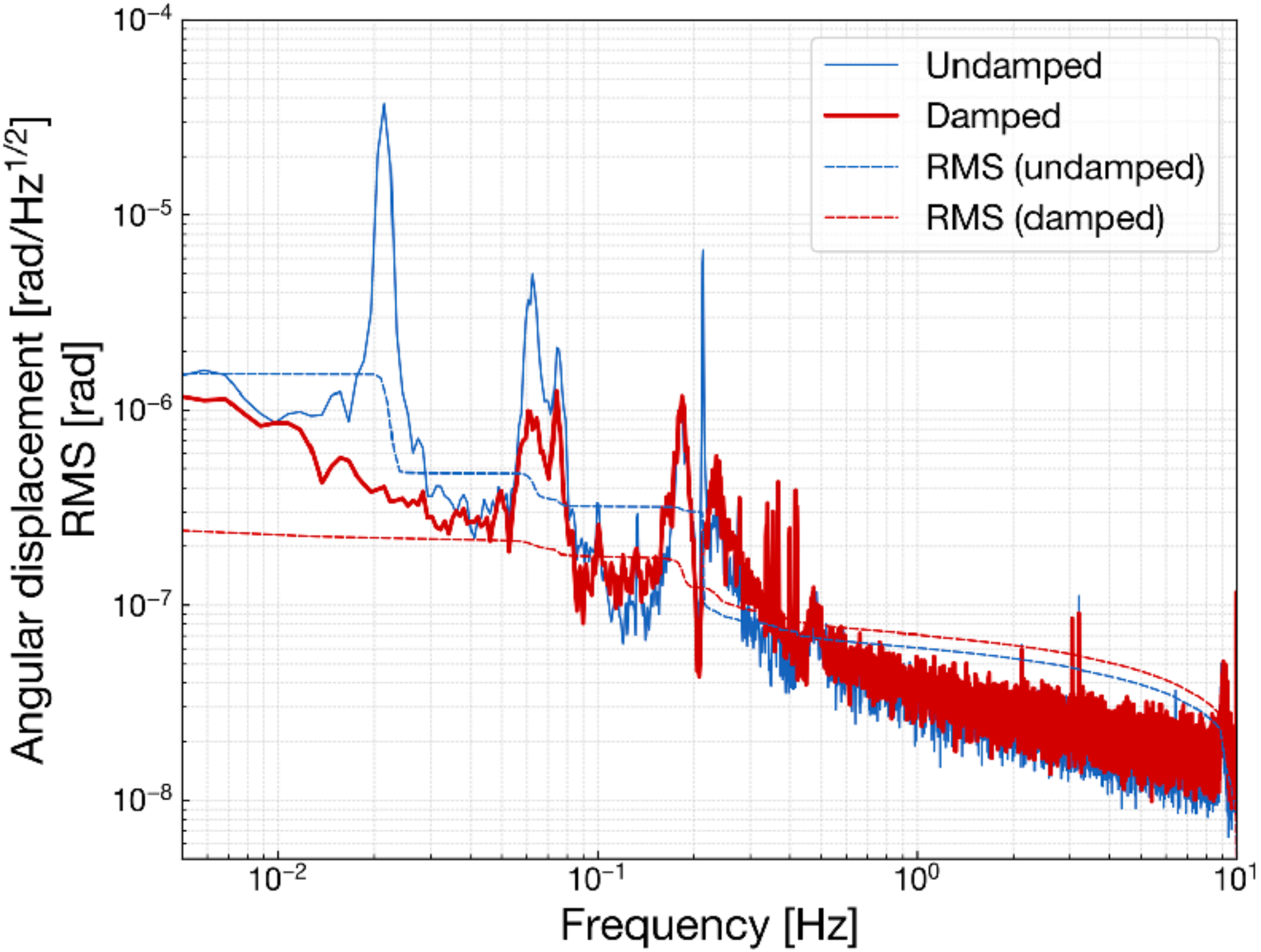




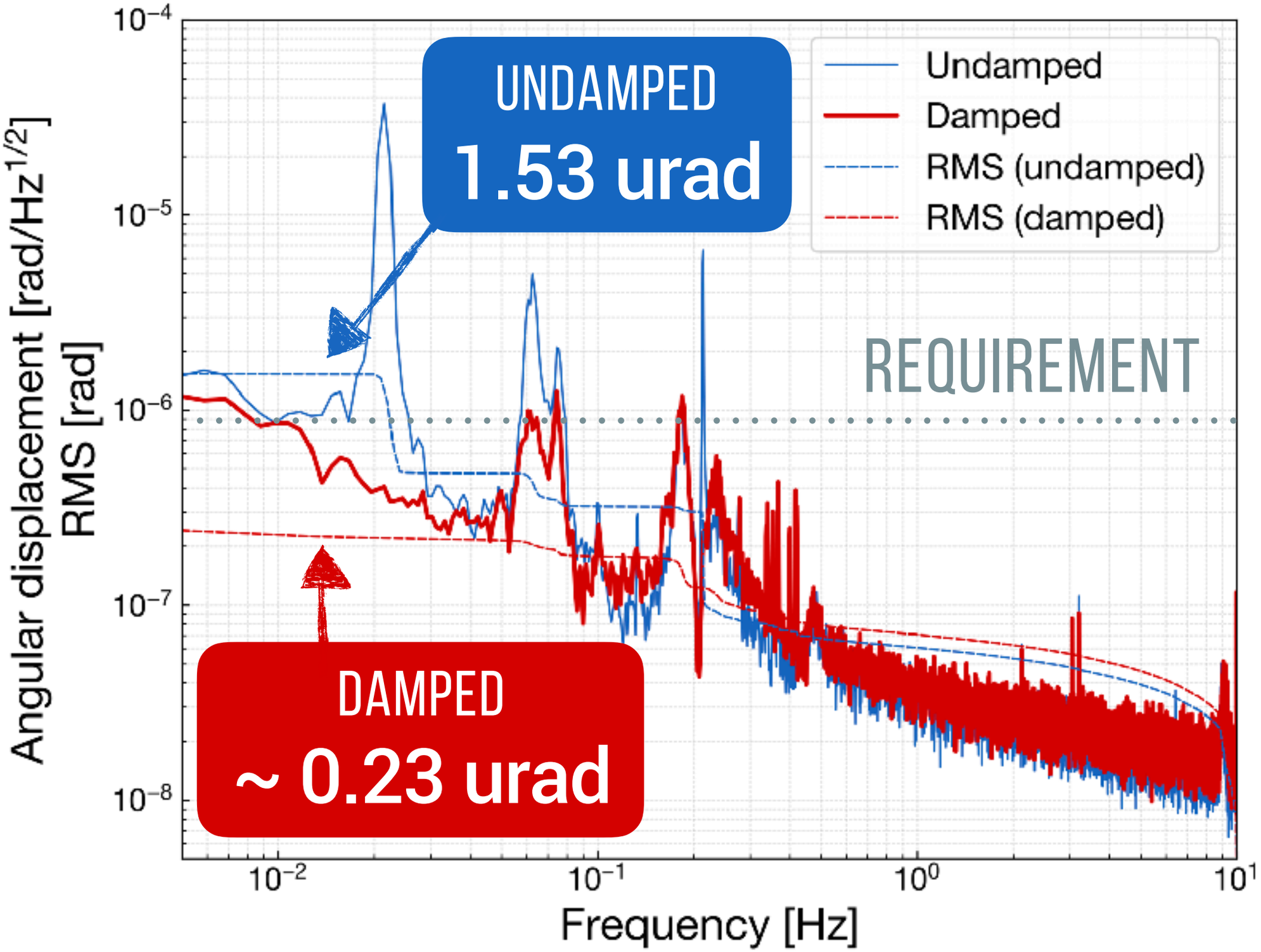


MODE	DAMPED DECAY TIME
#1	24.8 sec.
#2	43.9 sec.
#3	9.5 sec.

YAW MODE DAMPING



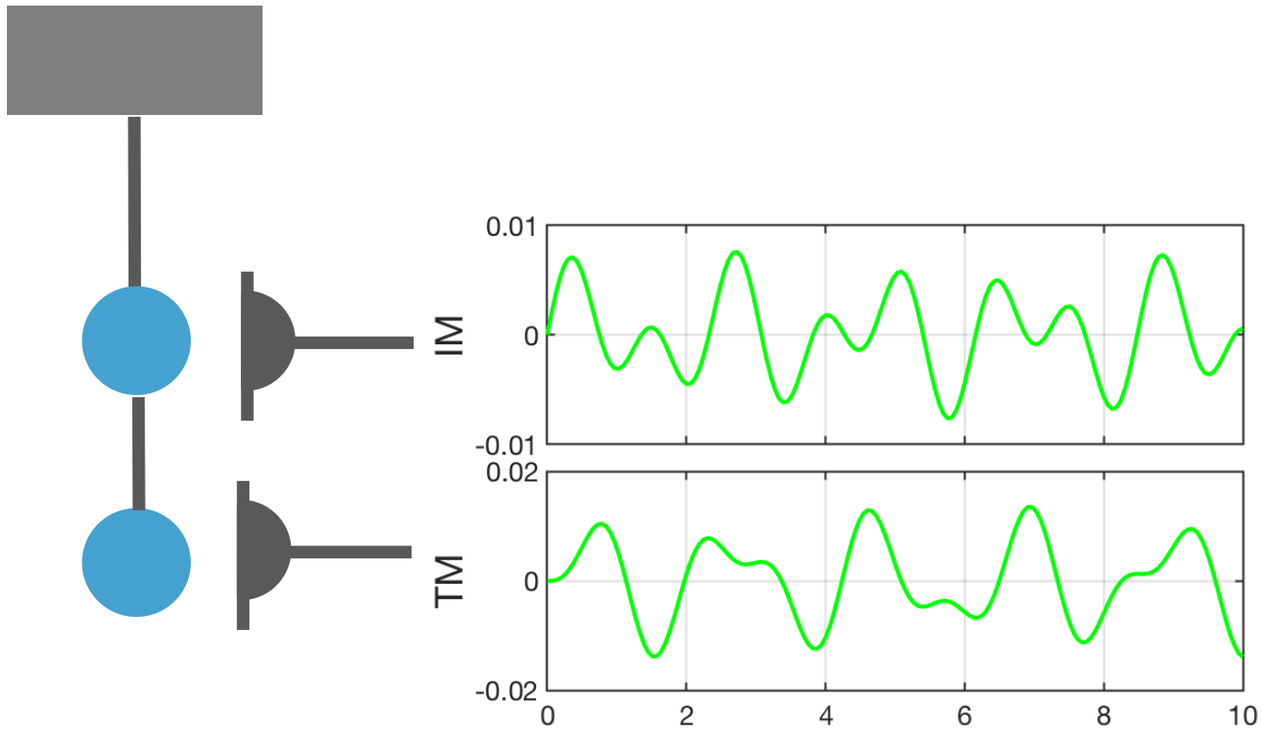
YAW MODE DAMPING

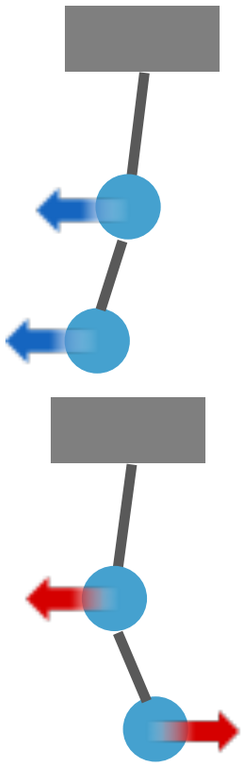


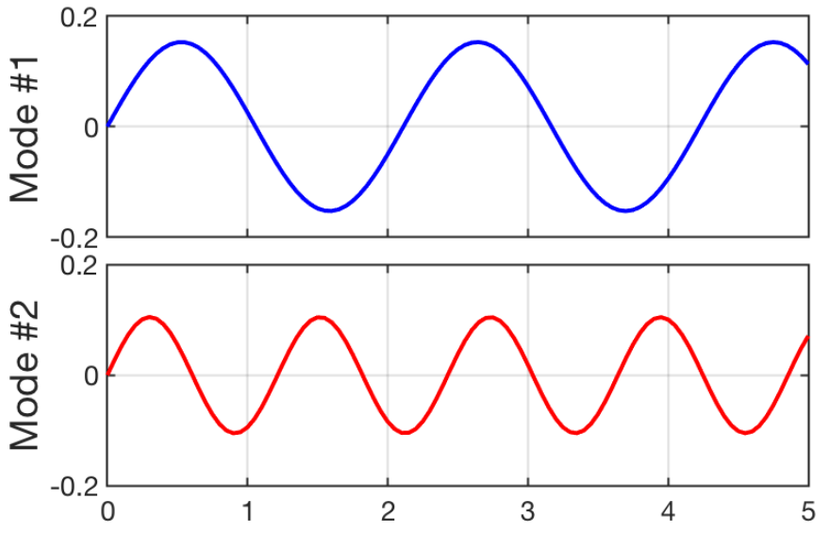
TOPICS OF THE SUSPENSION CONTROL

- Torsion mode damping
- **Modal damping of the GAS vertical chain**
- Hierarchical control

MODAL DAMPING





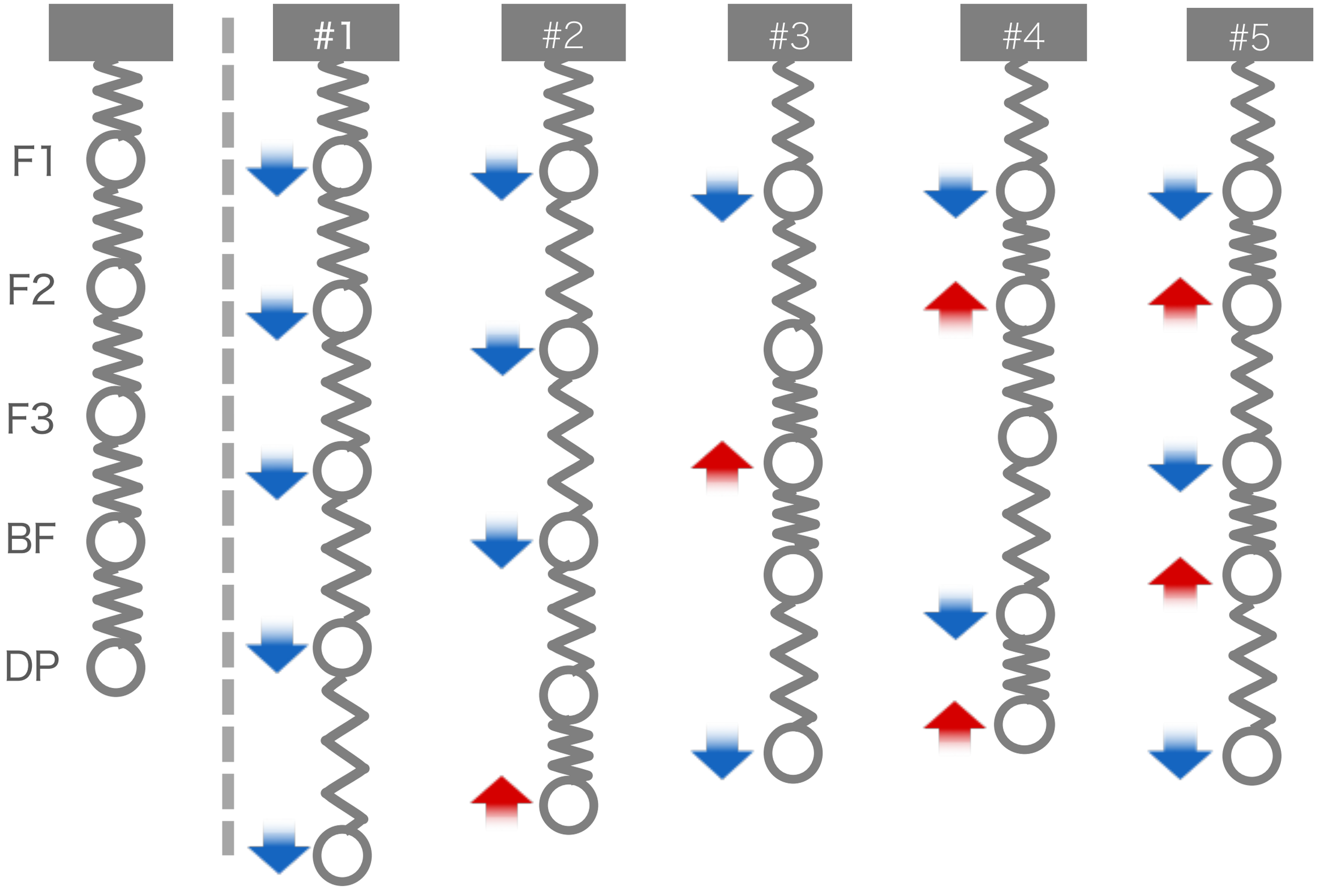


STAGE-BASIS

MODAL-BASIS

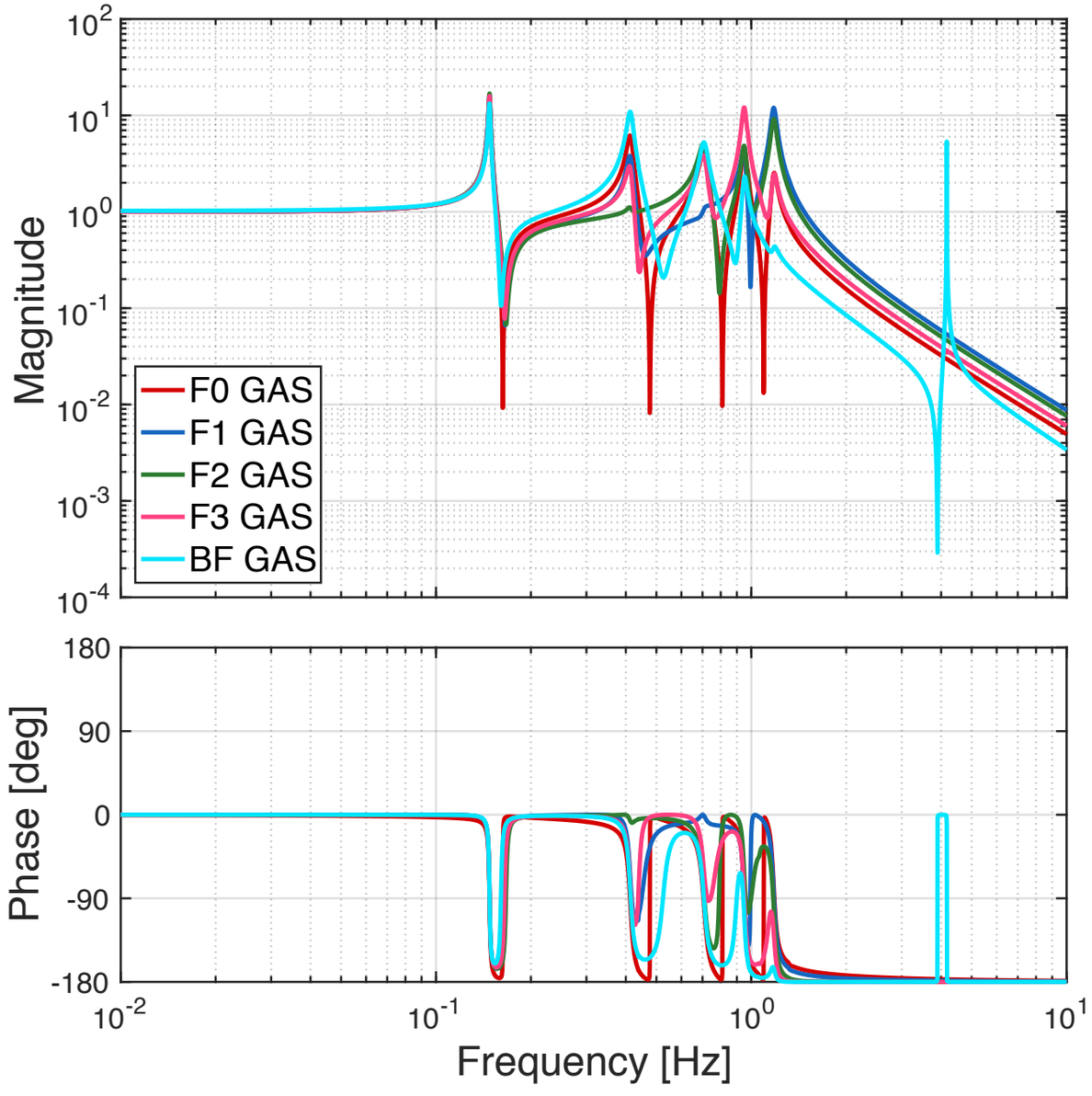
- Decouples sensor signals into modal amplitudes

VERTICAL MODES

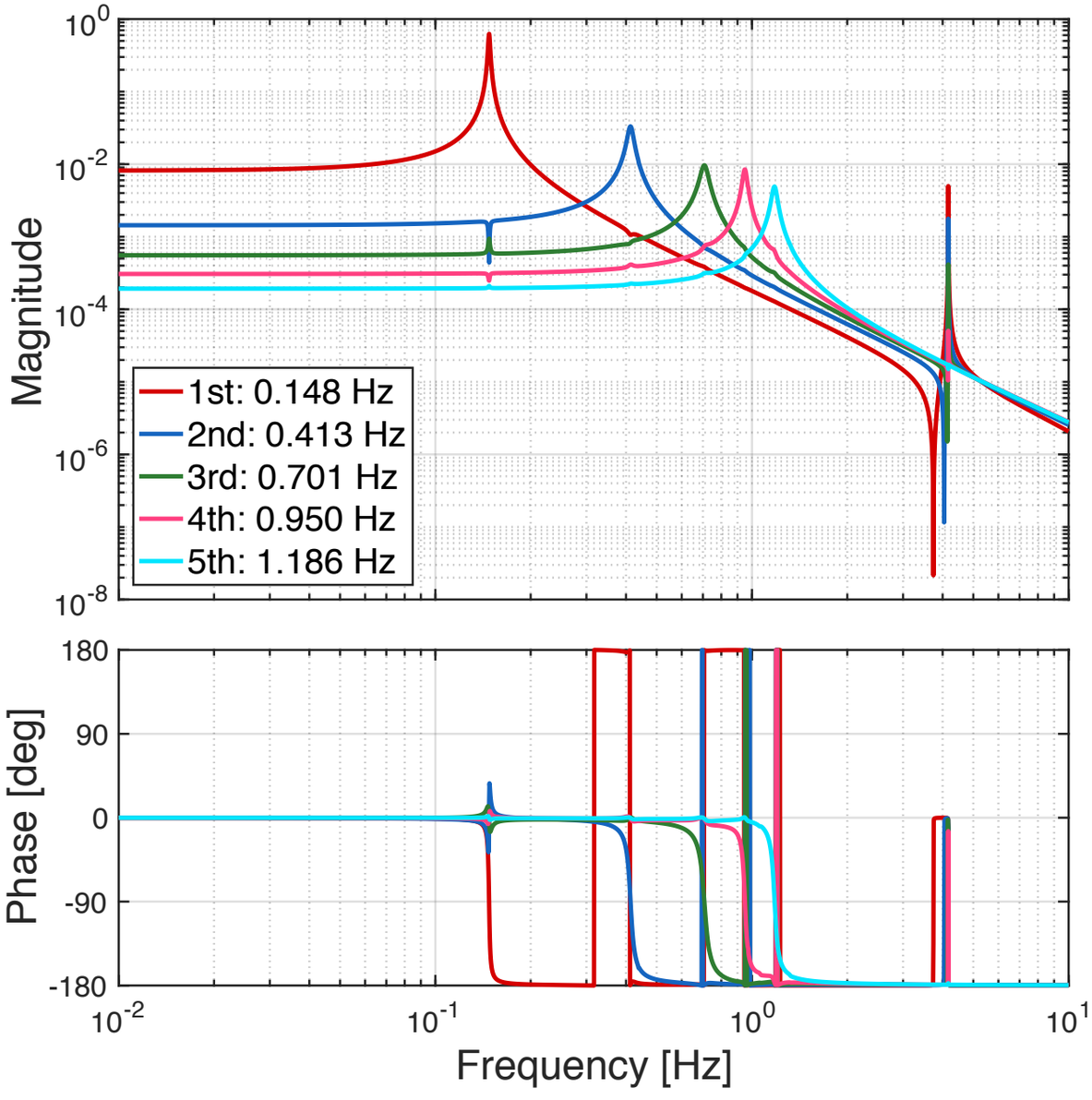


GAS FILTER RESPONSE (1)

MODEL PREDICTION



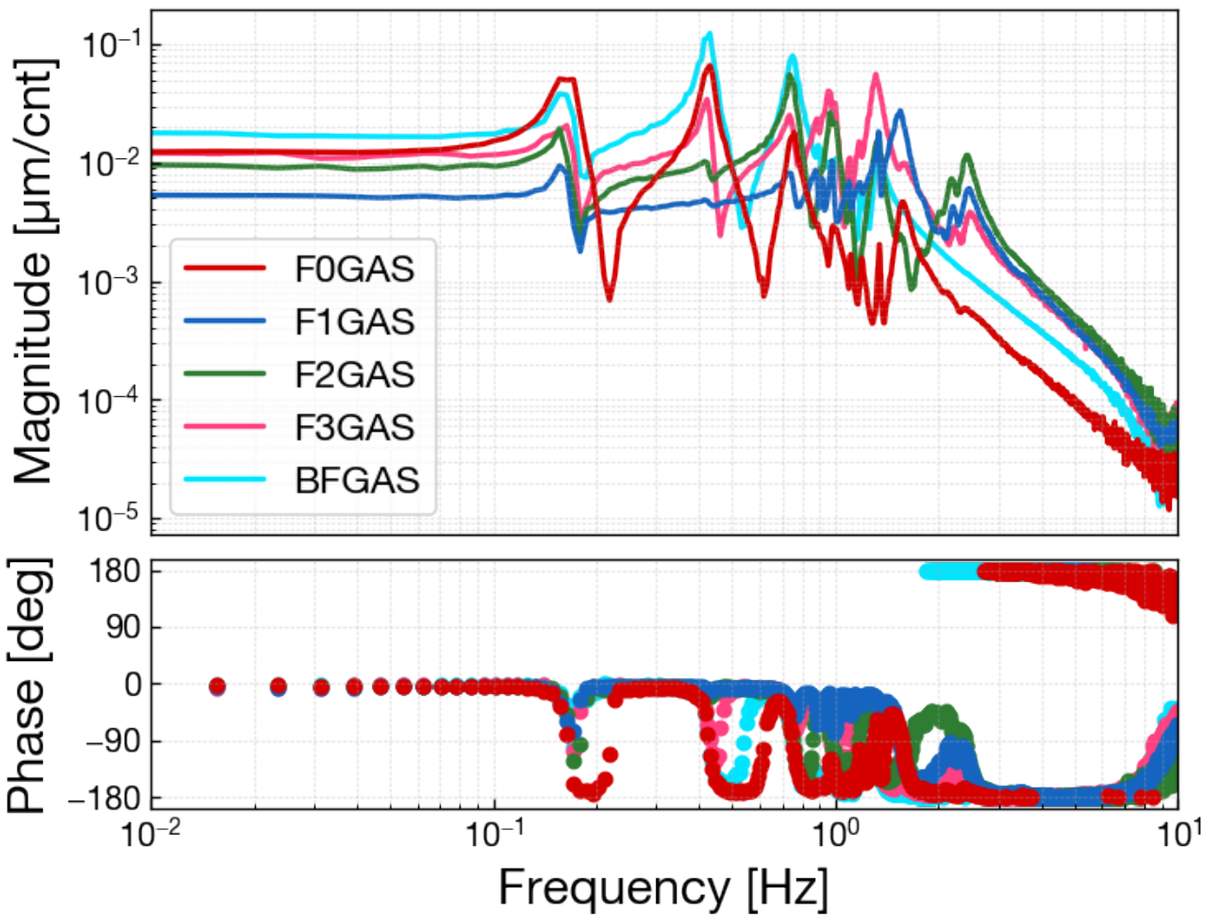
STAGE-BASIS



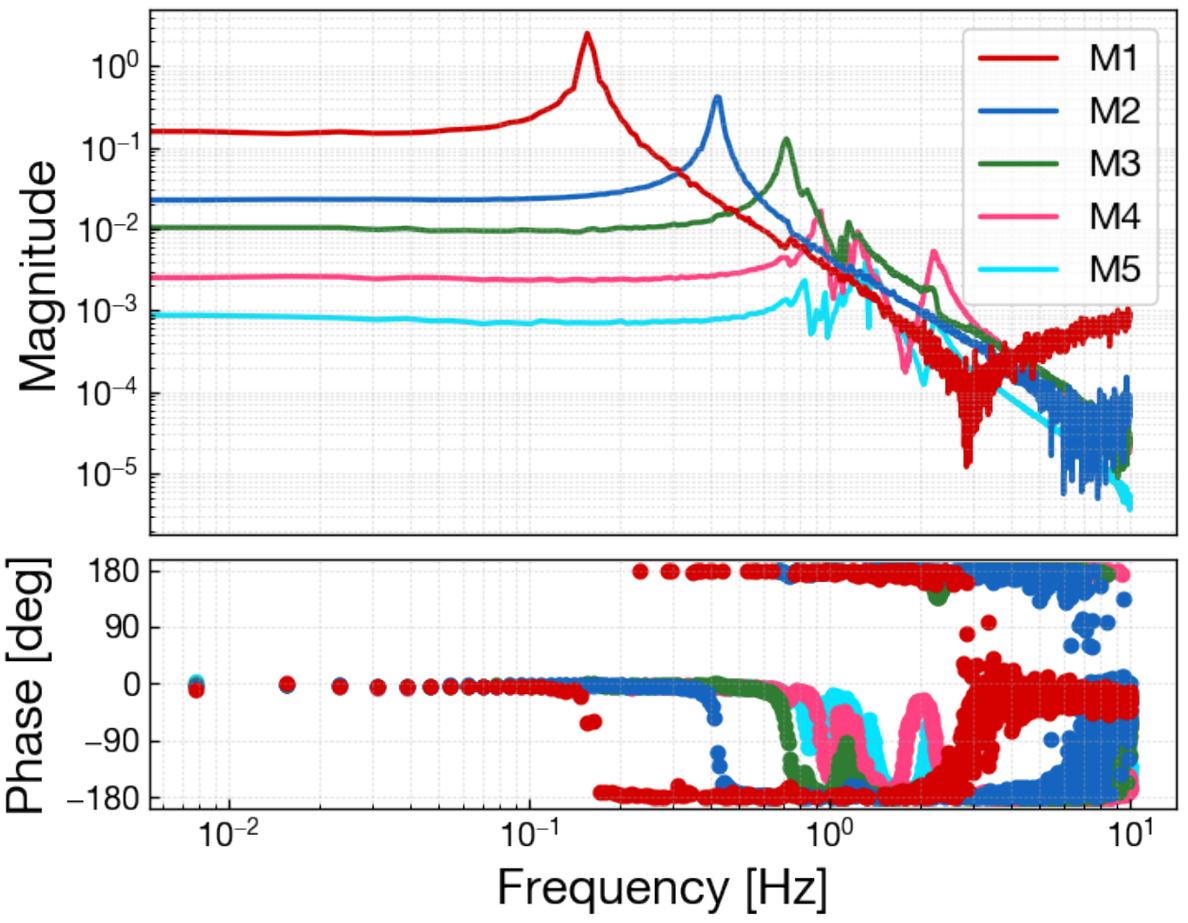
MODAL-BASIS

GAS FILTER RESPONSE (2)

MEASUREMENT RESULT



STAGE-BASIS

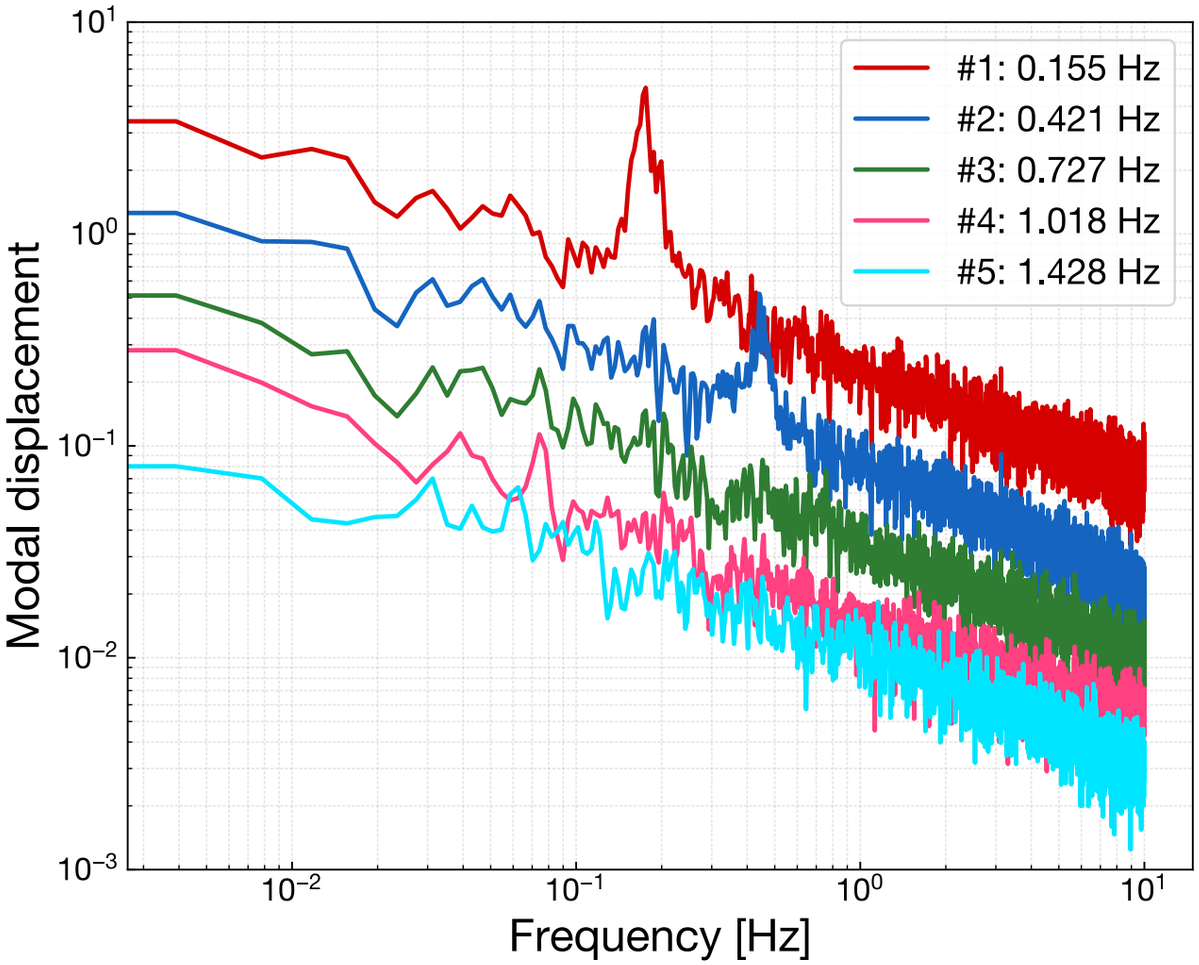


MODAL-BASIS

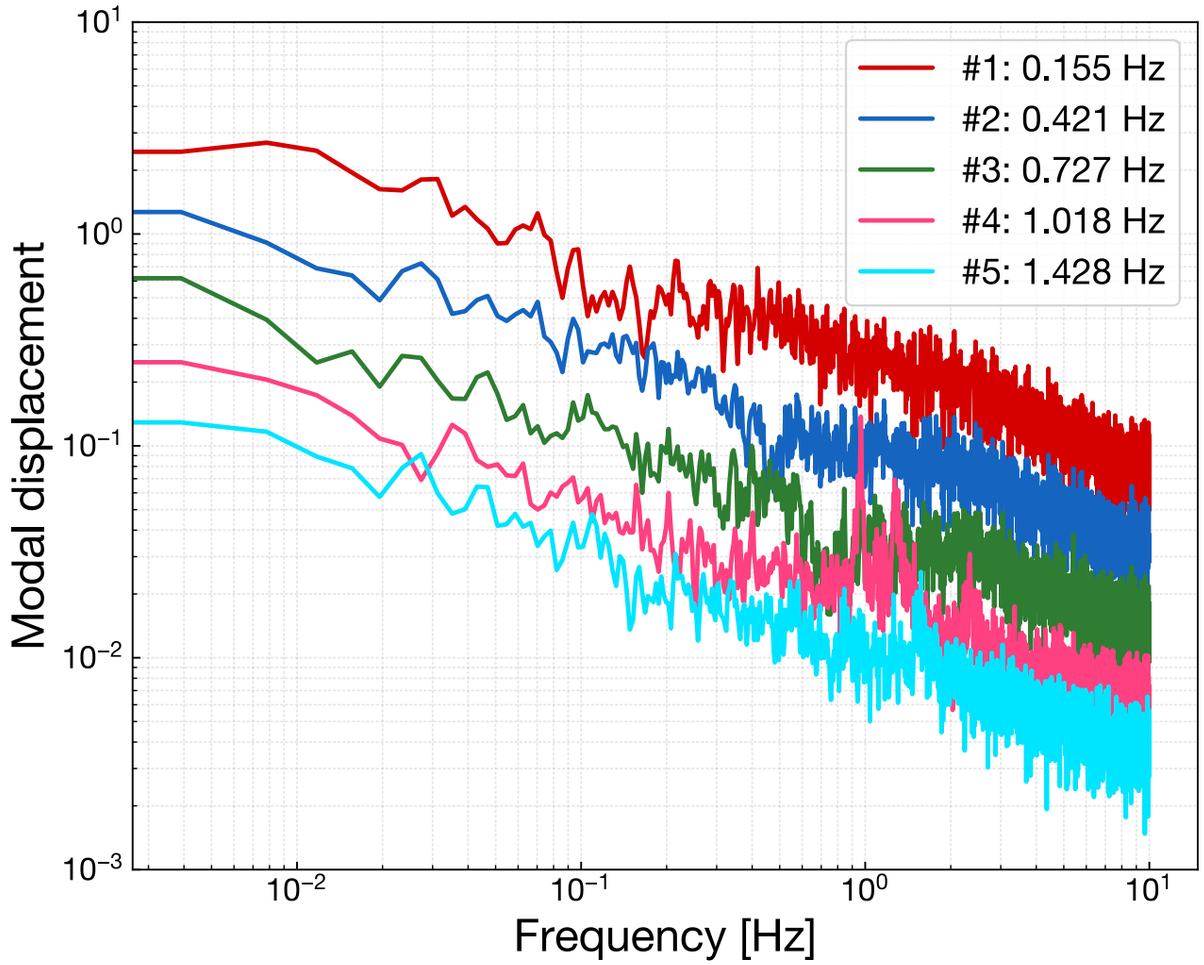
- Modal responses can make the filter design simple

MODAL SPECTRUM

MEASUREMENT RESULT



UNDAMPED

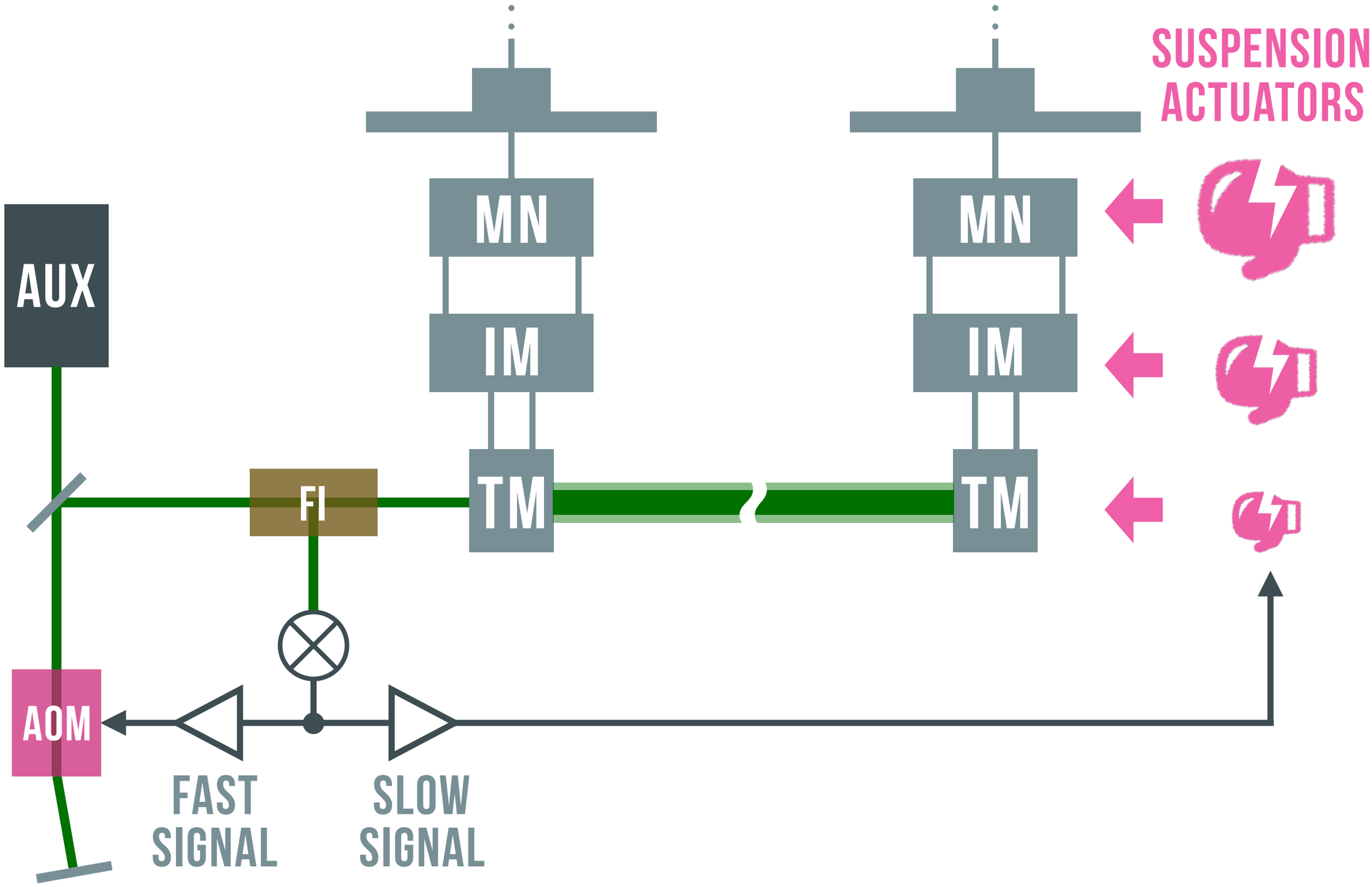


1ST & 2ND MODE DAMPED

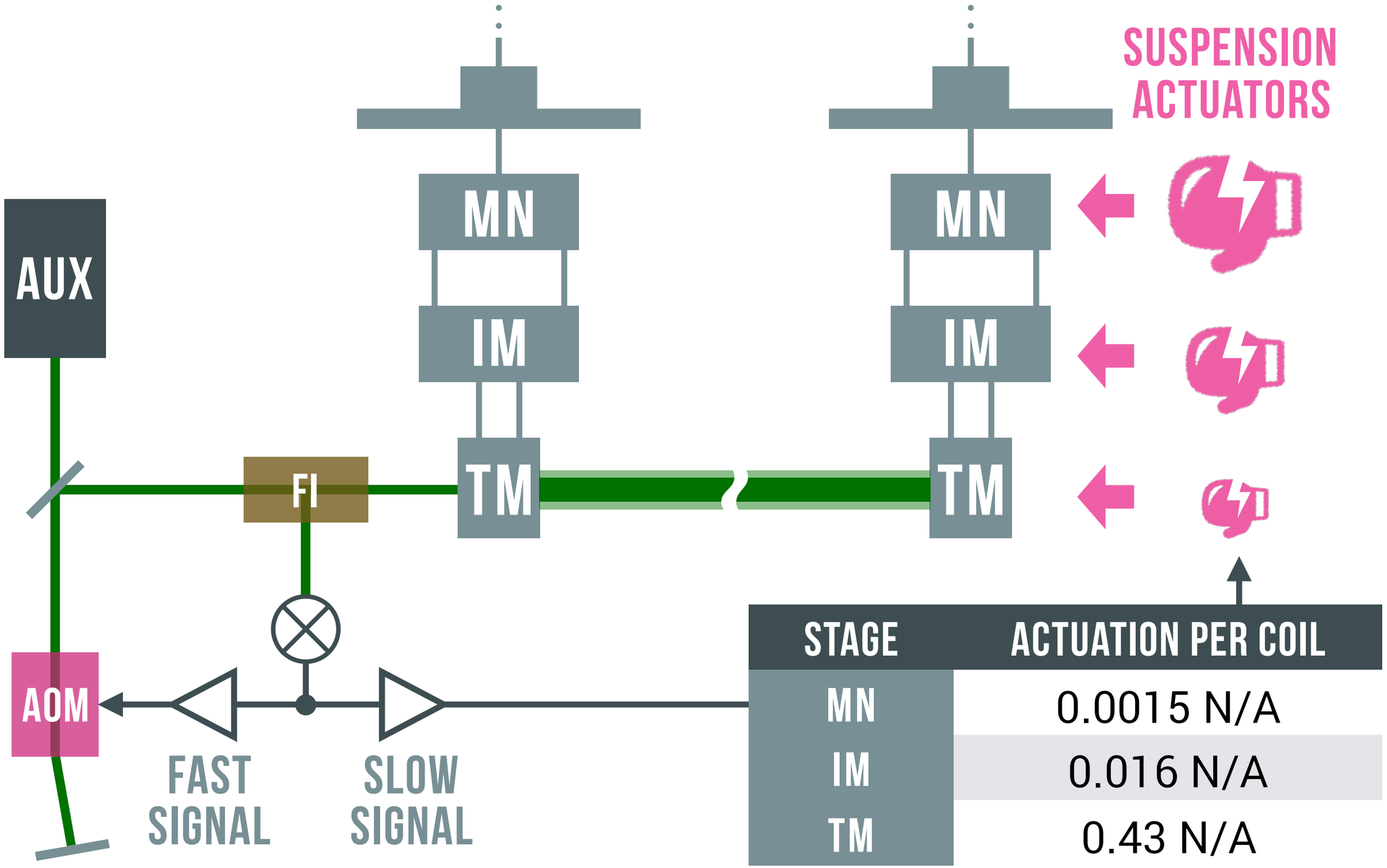
TOPICS OF THE SUSPENSION CONTROL

- Torsion mode damping
- Modal damping of the GAS vertical chain
- Hierarchical control

HIERARCHICAL CONTROL



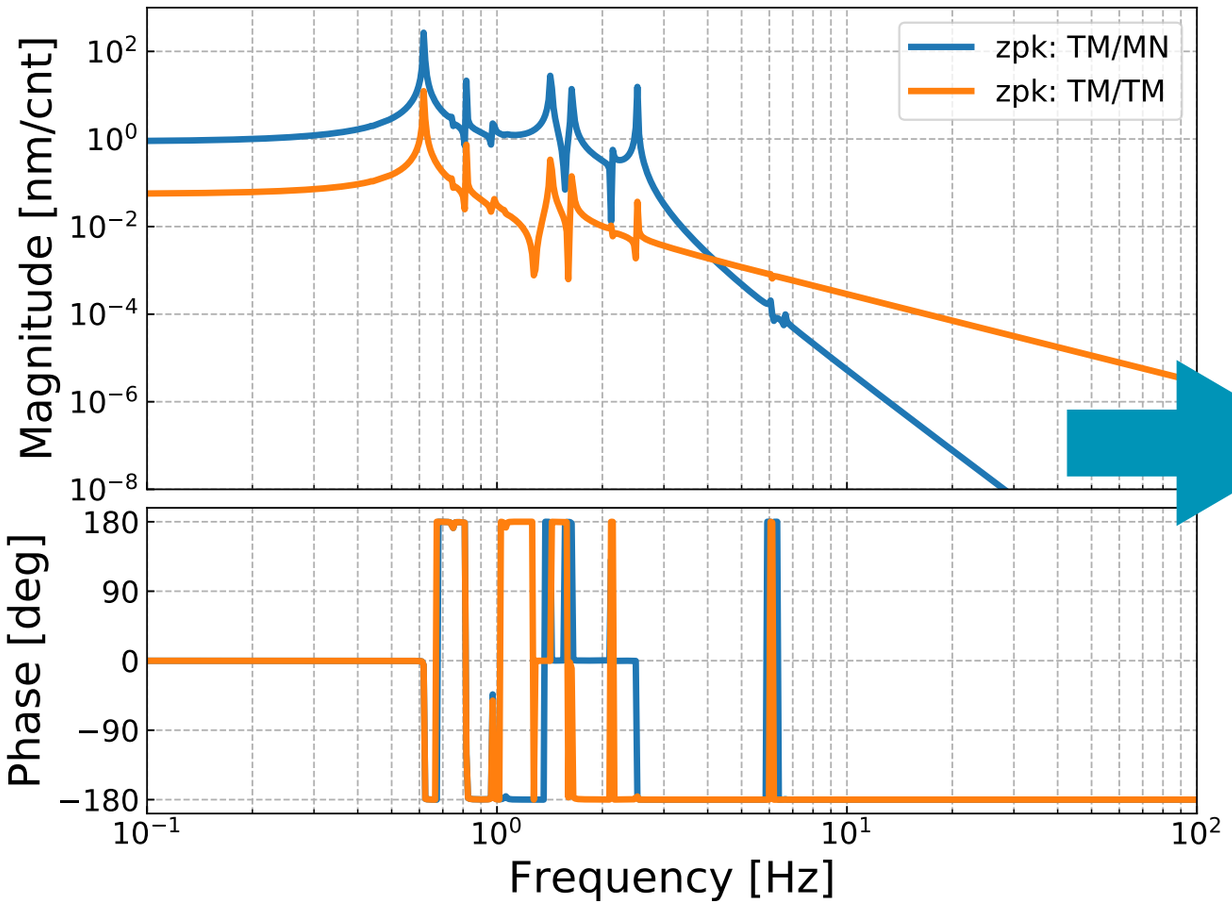
HIERARCHICAL CONTROL

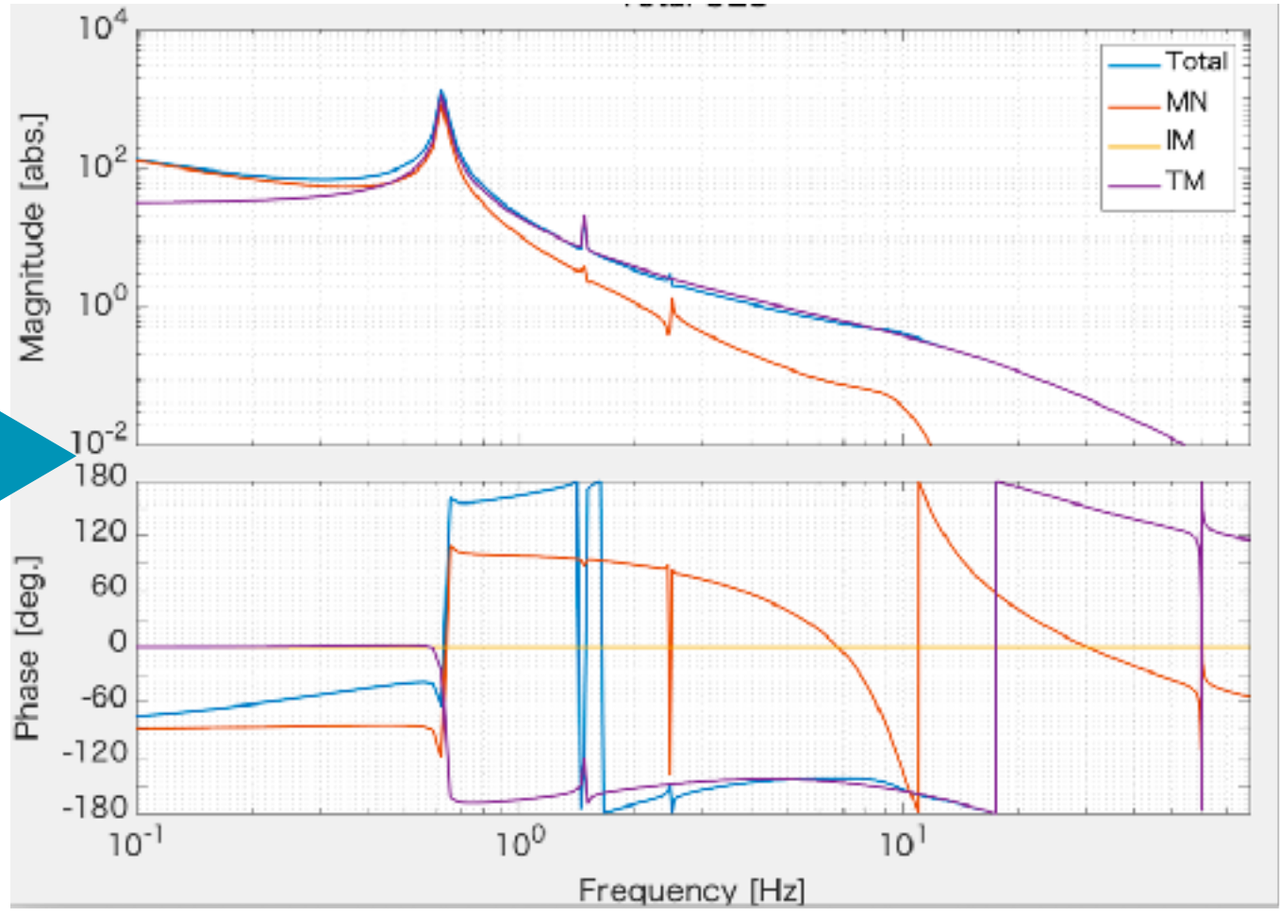


STAGE	ACTUATION PER COIL
MN	0.0015 N/A
IM	0.016 N/A
TM	0.43 N/A

FOR THE FIRST MASS LOCK

by M. Nakano



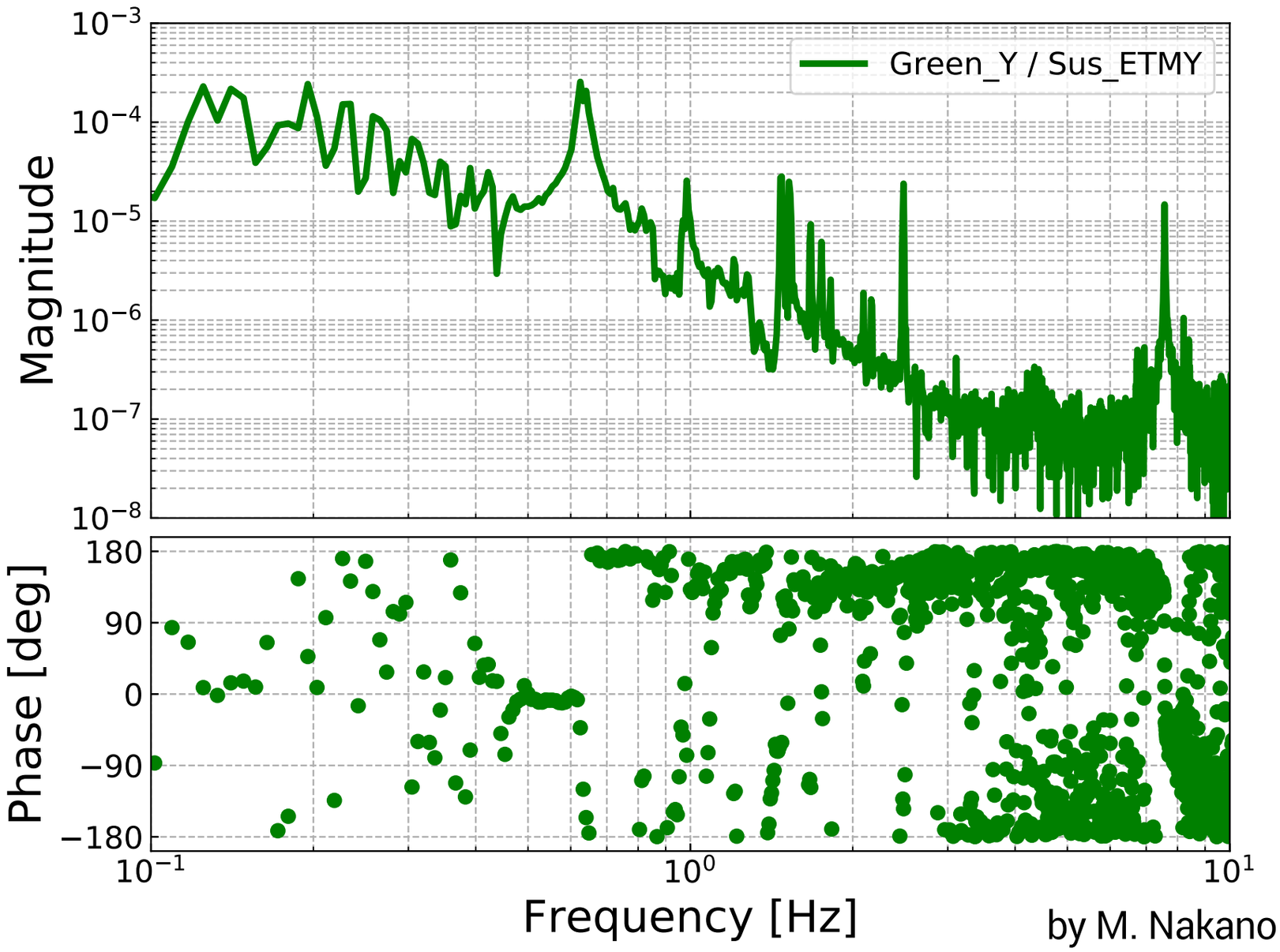


SUSPENSION RESPONSE

LOOP DESIGN

- X-arm: frequency reference, Y-arm: mass lock loop

CURRENT PROGRESS



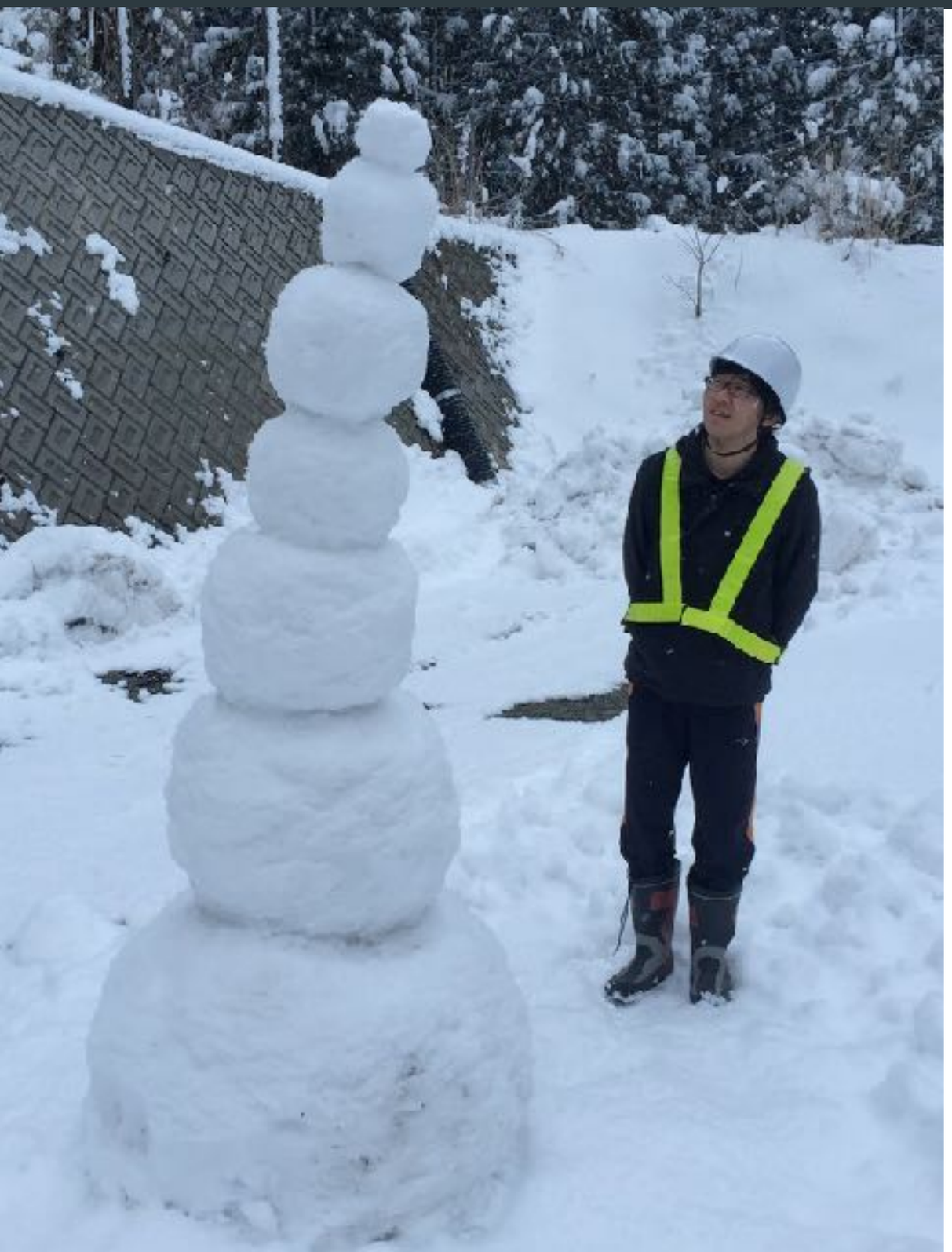
- Hierarchical filters for the suspension actuator have been designed to achieve the mass lock

MANY TO-DO

- Sensor & actuator diagonalization
- Inertial damping
- Decay time measurements
- Automation of the control transition (Guardian)
- Control loop optimization
- Global IP control

etc...

SUMMARY



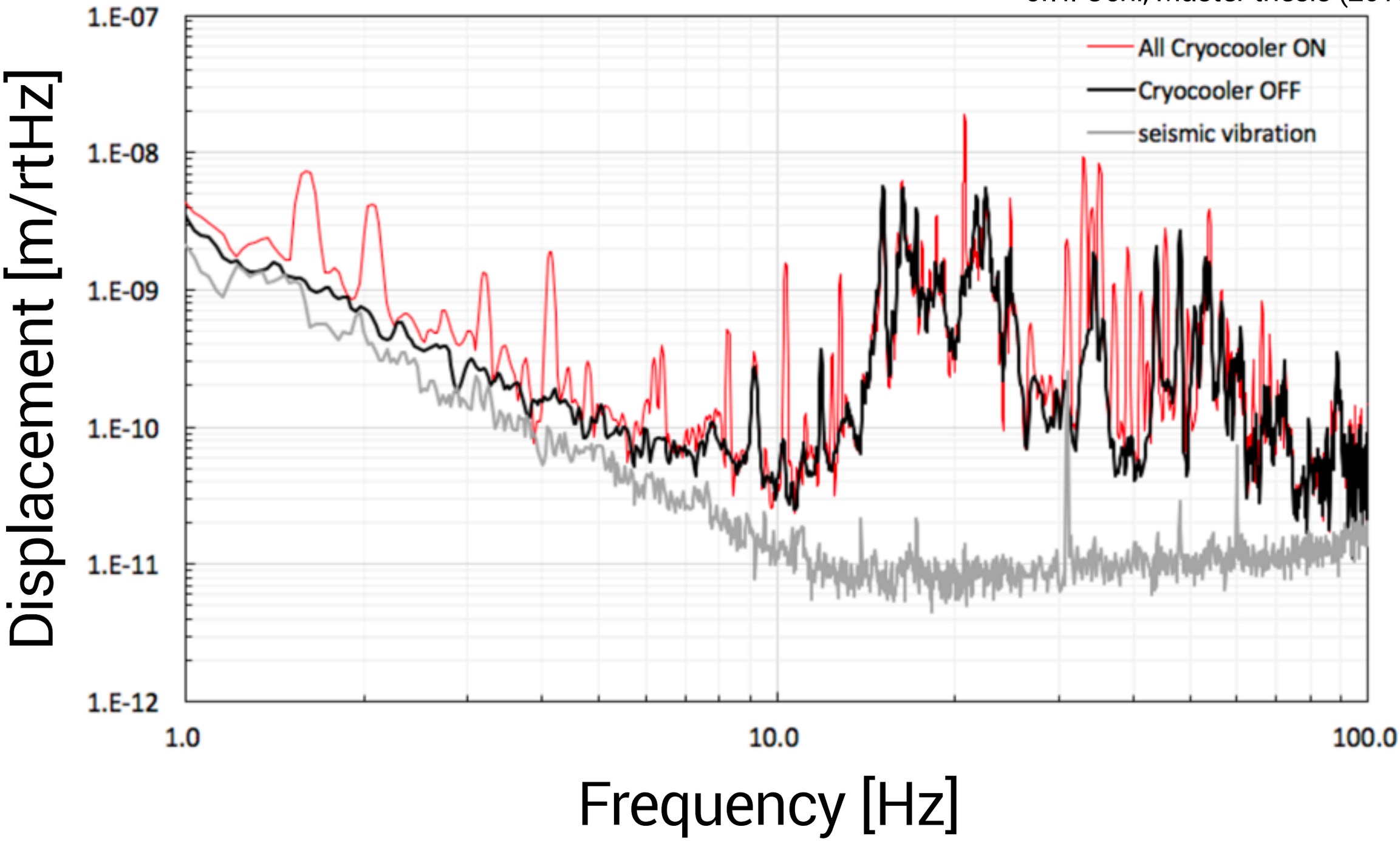
- **Type-A suspension**
  All the 4 suspensions are cooled down and under commissioning.
- **Measurements**
  Characterization and local control are challenging but exciting.
- **Commissioning work is ongoing toward O3**

KAGRA COMING SOON!

BACKUP SLIDES

VIBRATION IN THE CRYOSTAT

cf.T. Ochi, Master thesis (2018)



Vibration Isolation Ratio MEASUREMENT