

KAGRA腕共振器のための 9段防振懸架システムの制御

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KAGRAコラボレーション^E

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山本尚弘, 阿久津智忠^B, 麻生洋一^B, 都丸隆行^B,
KAGRAコラボレーション^E

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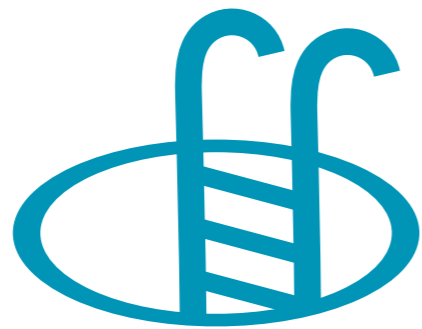
- KAGRA防振懸架システム
- Type-A suspension
- 性能評価と制御の実装

The logo for KAERA features the word in a bold, black, sans-serif font. The letter 'A' is replaced by a blue circle containing a white stylized 'E' shape. The logo is set against a white, torn-paper-like background with a blue circular outline.

KAERA



KAGRAの特徴



地下環境

~ 1-2 桁小さい地面振動

@ ~1-100 Hz

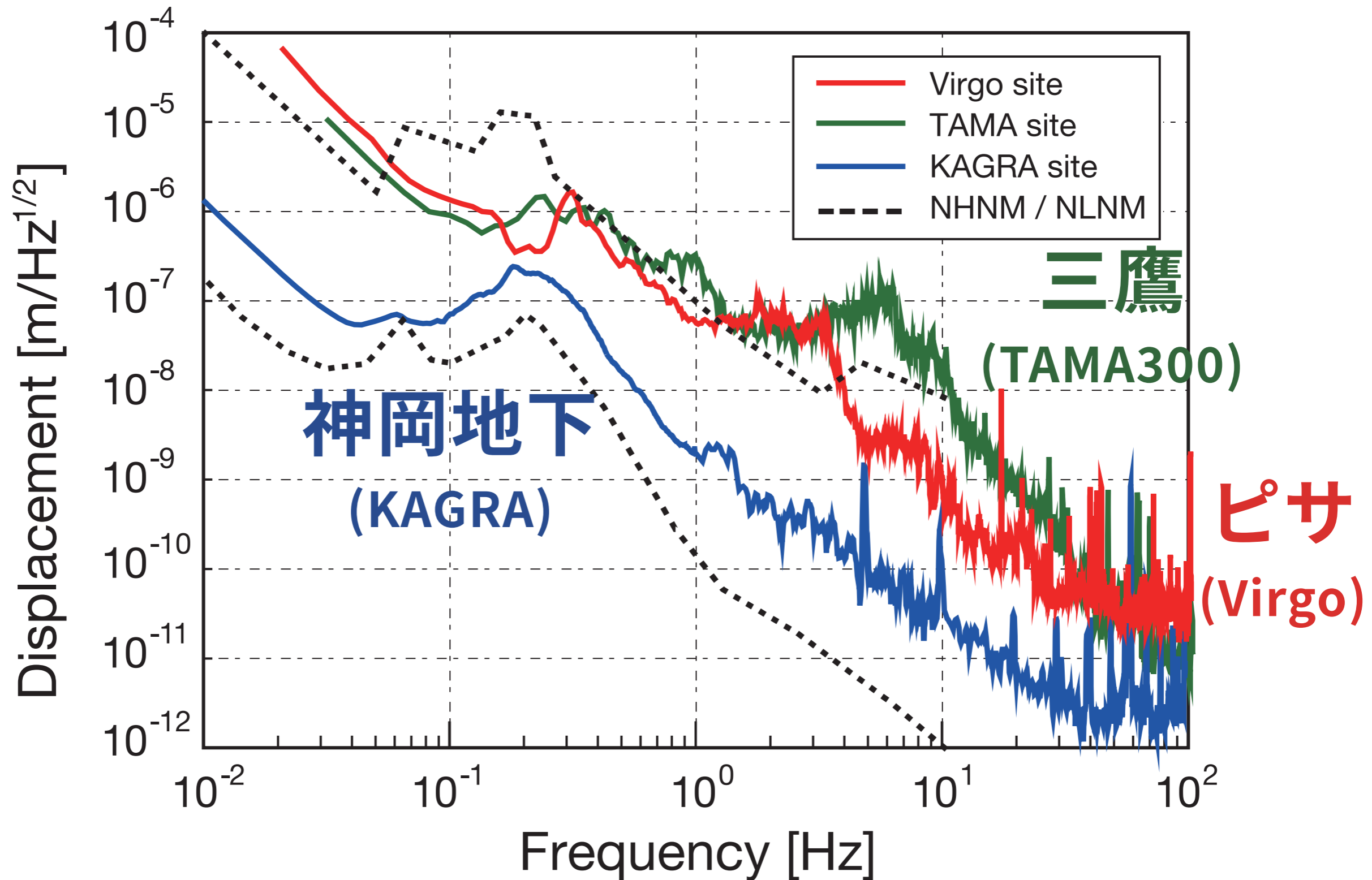


低温鏡

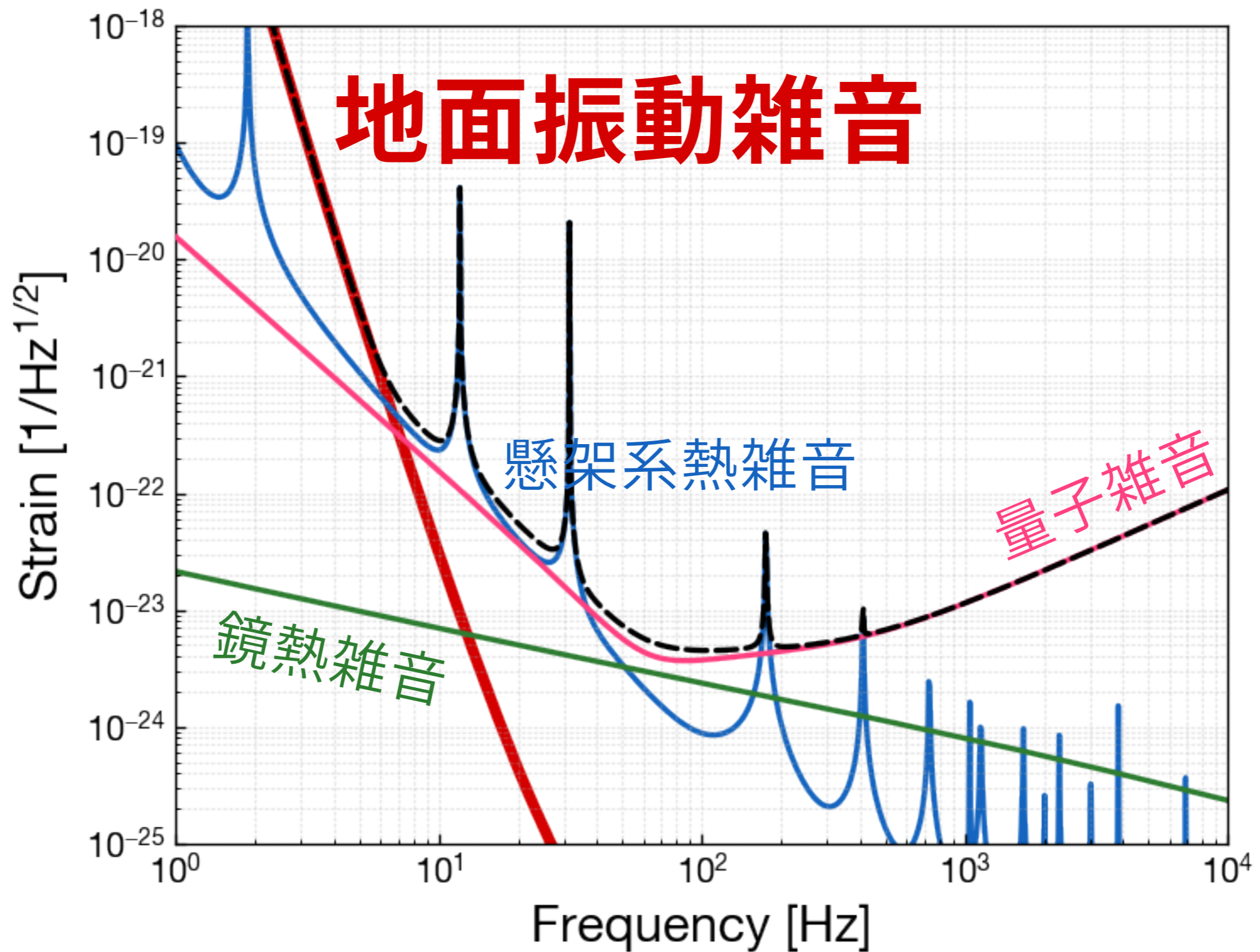
熱雑音低減

さまざまな利点

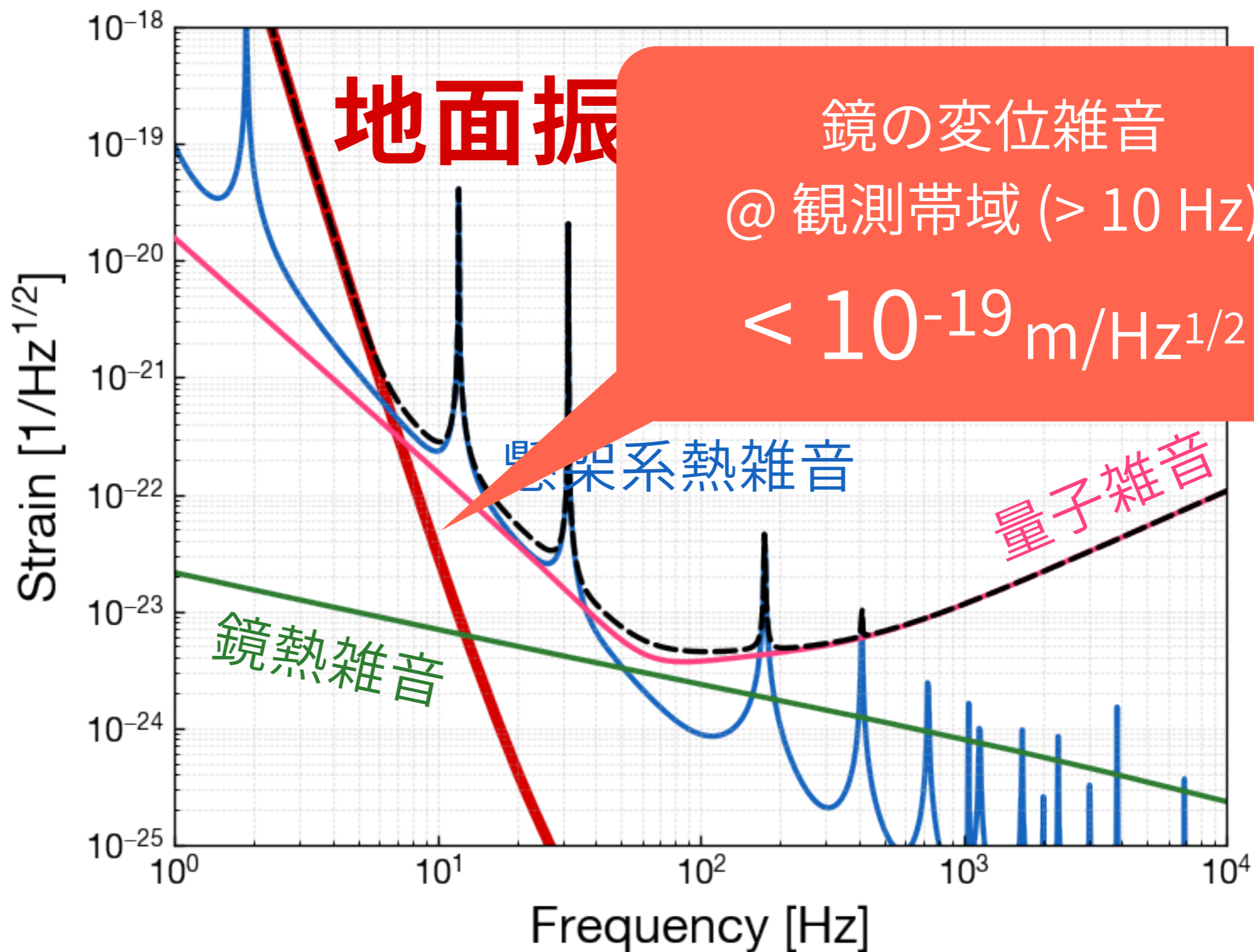
地下の地面振動



KAGRA感度曲線

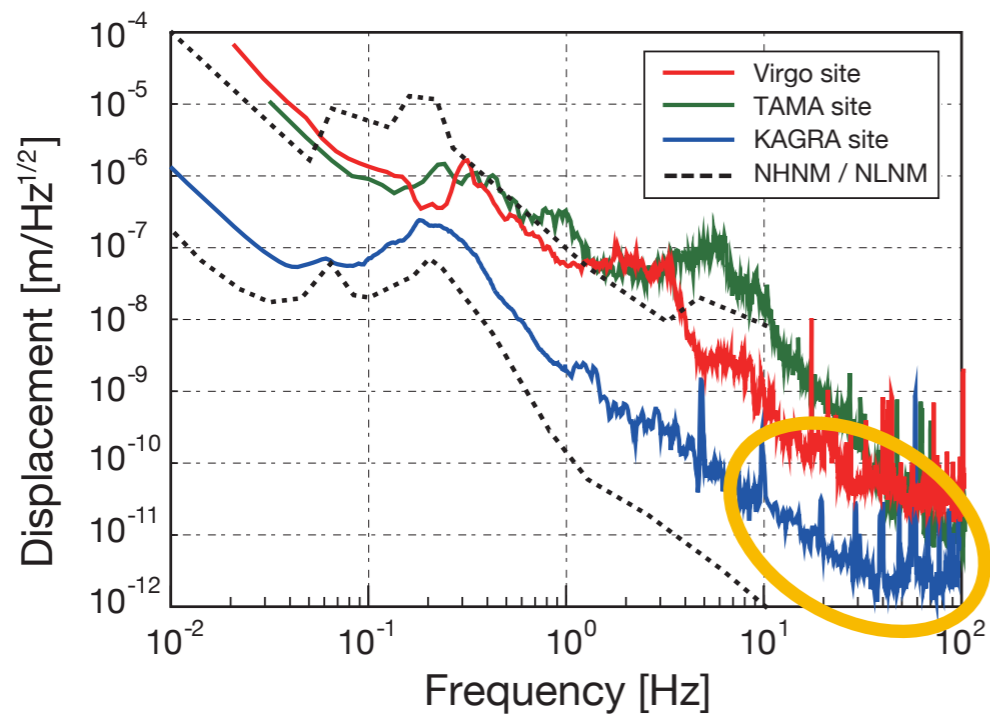


KAGRA感度曲線



鏡の防振

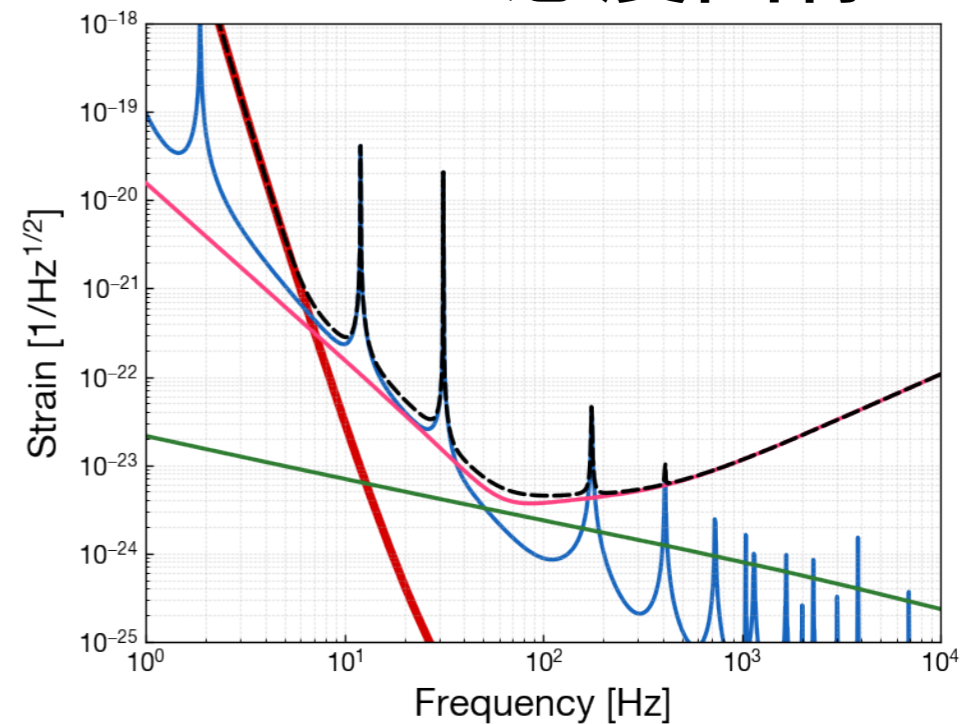
地面振動



地面振動

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

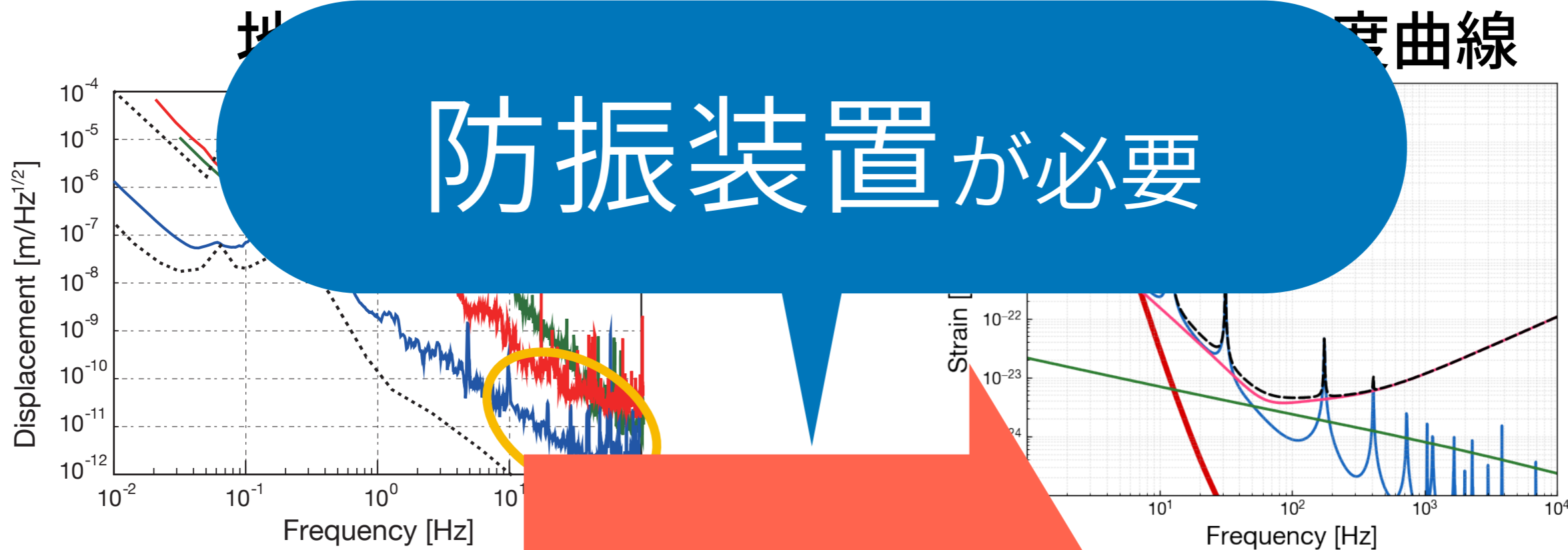
KAGRA感度曲線



鏡変位雑音の要求値
($> 10 \text{ Hz}$)

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

鏡の防振



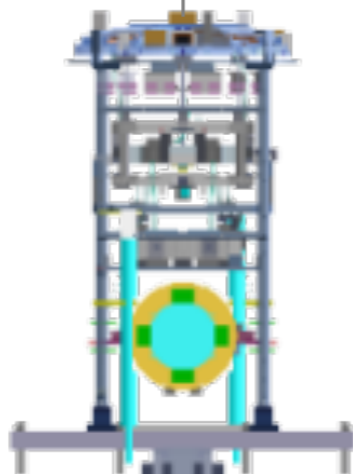
$10^{-10} \text{ m}/\text{Hz}^{1/2}$

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

変位雑音の要求値
($> 10 \text{ Hz}$)

Vibration Isolation Systems

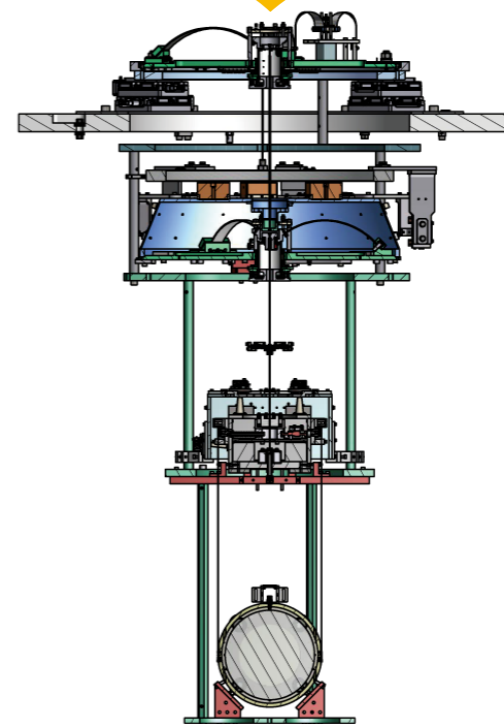
TYPE-A



TYPE-B

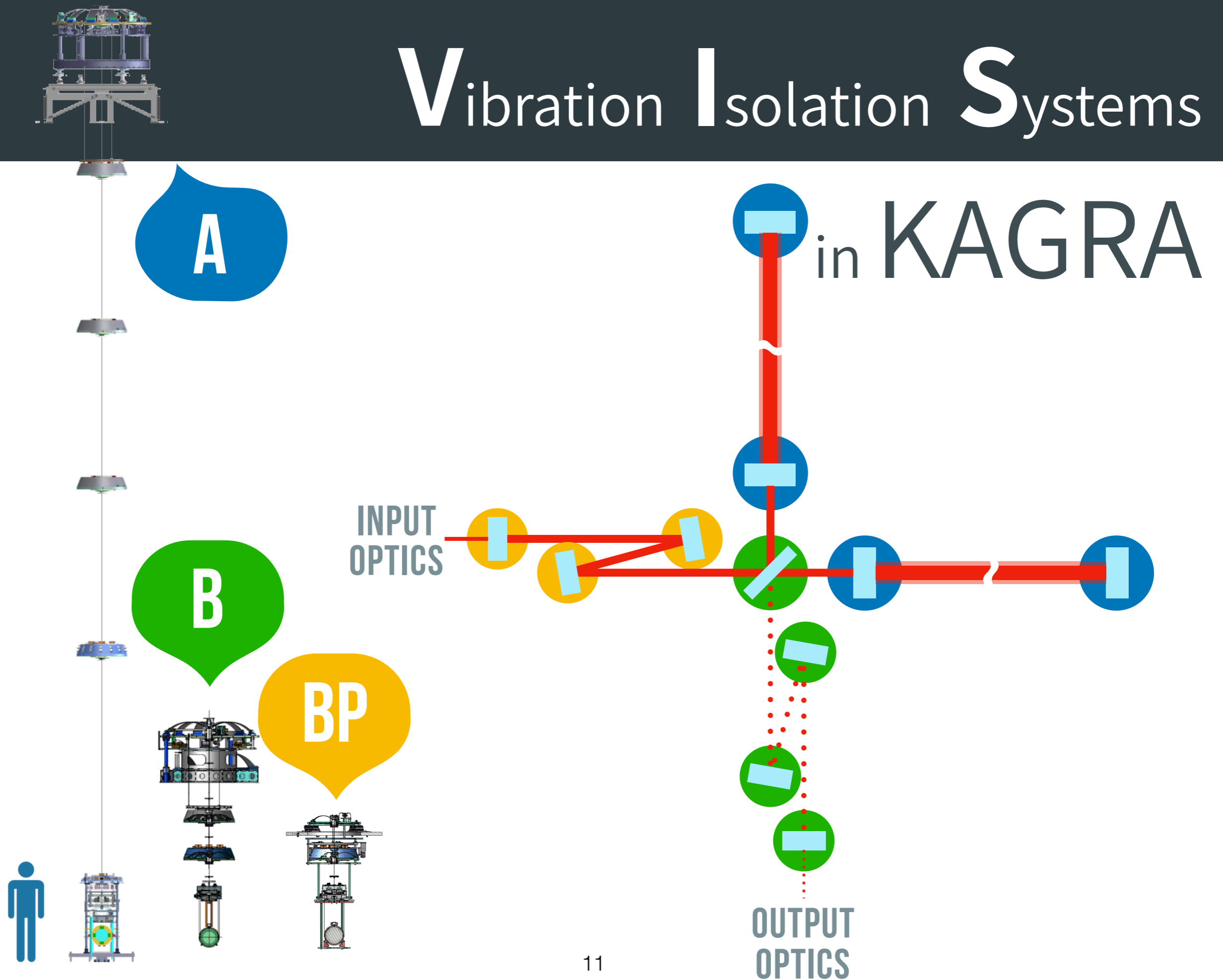


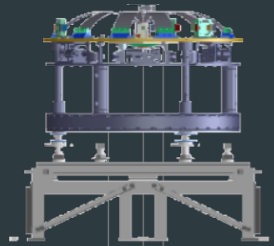
TYPE-BP



in KAGRA

Vibration Isolation Systems





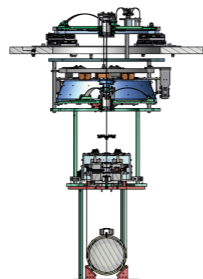
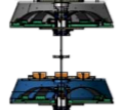
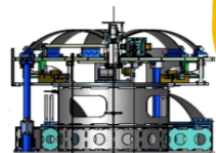
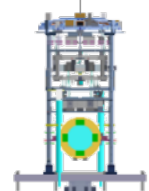
Vibration Isolation Systems

A

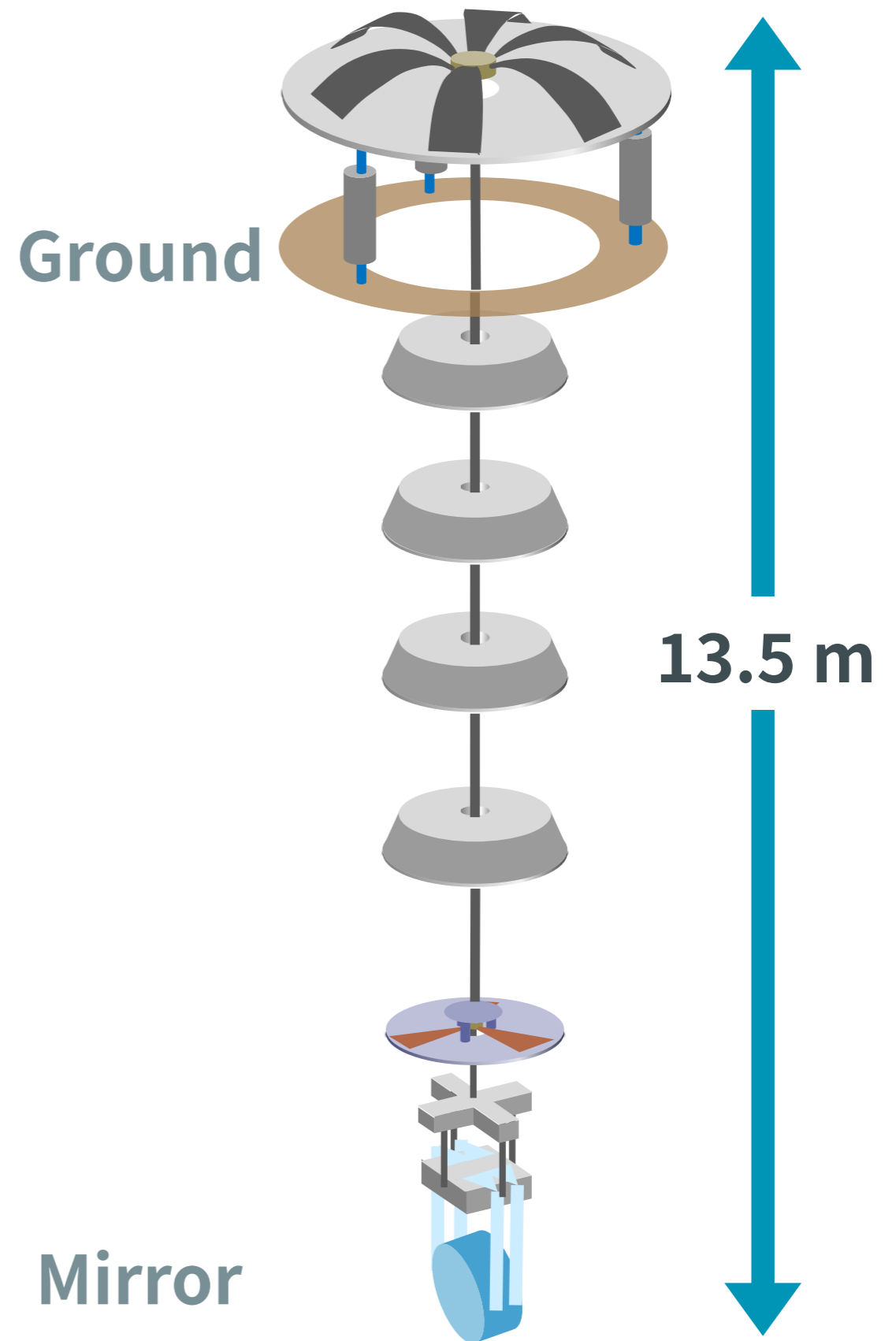
in KAGRA

B

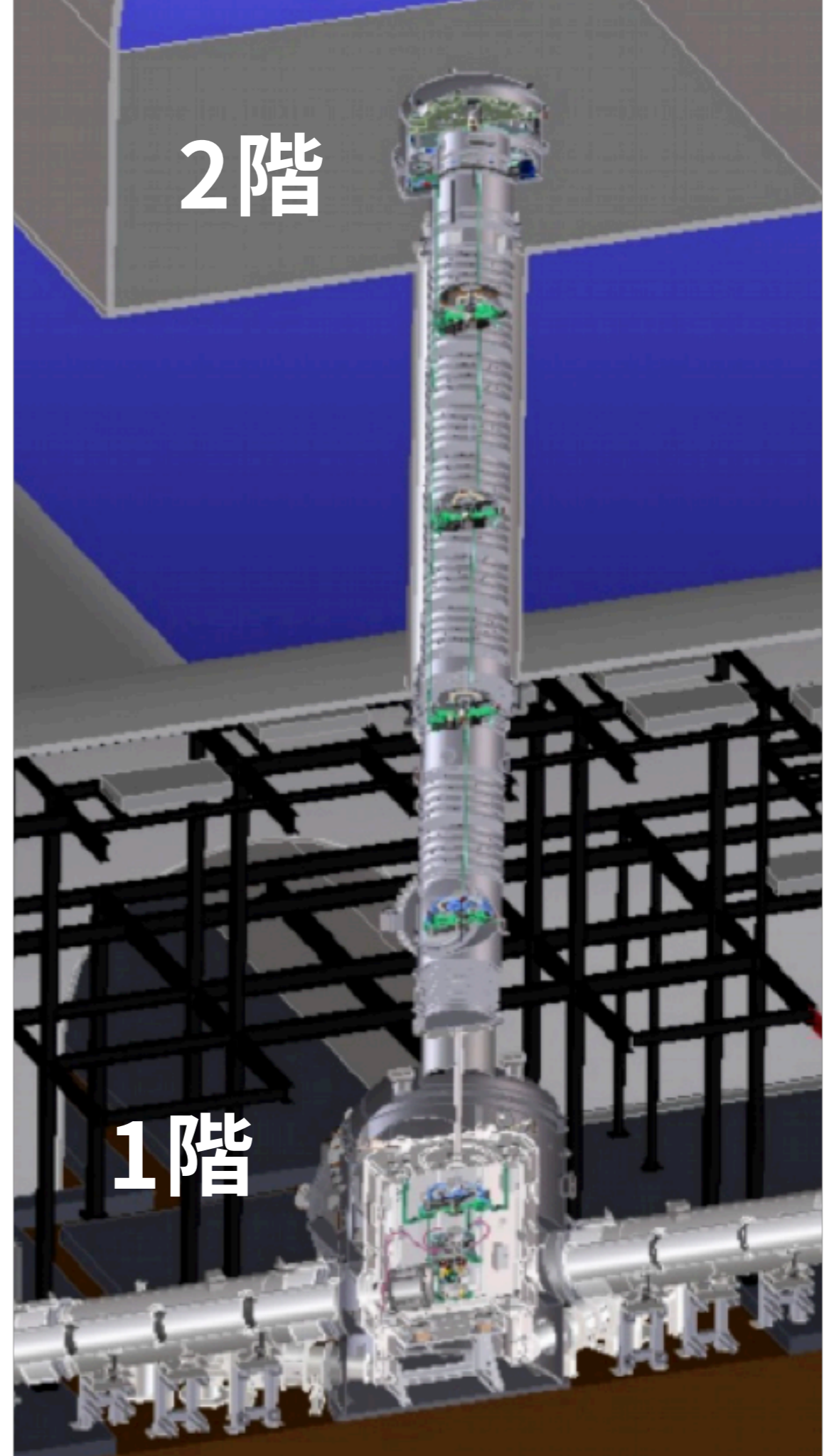
BP



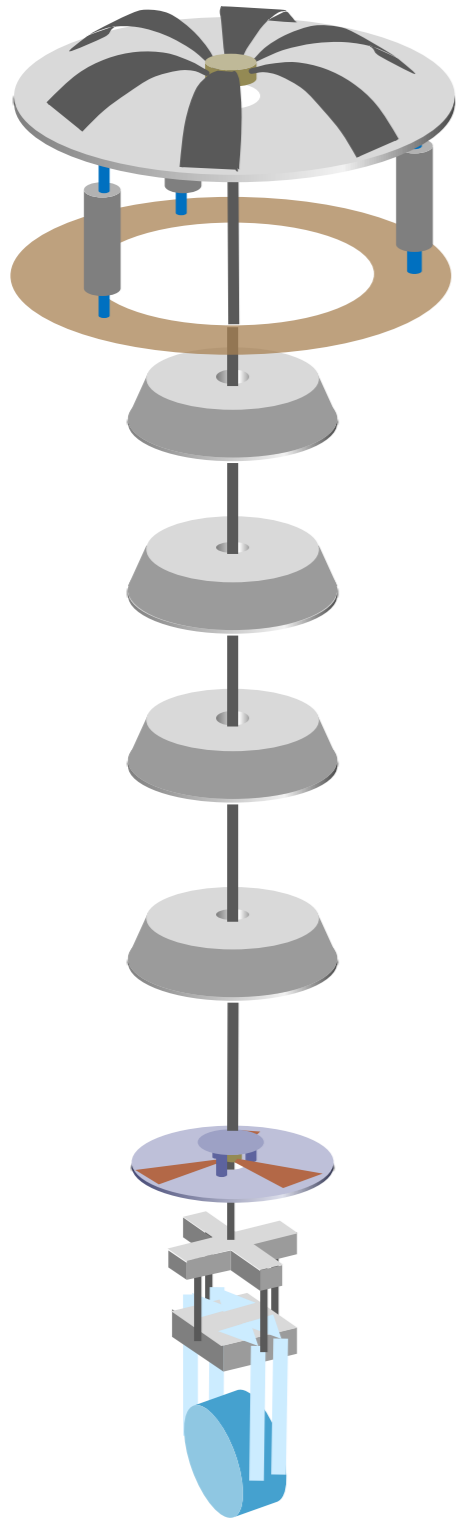
Type-A Suspension



Type-A Suspension



Type-A Suspension



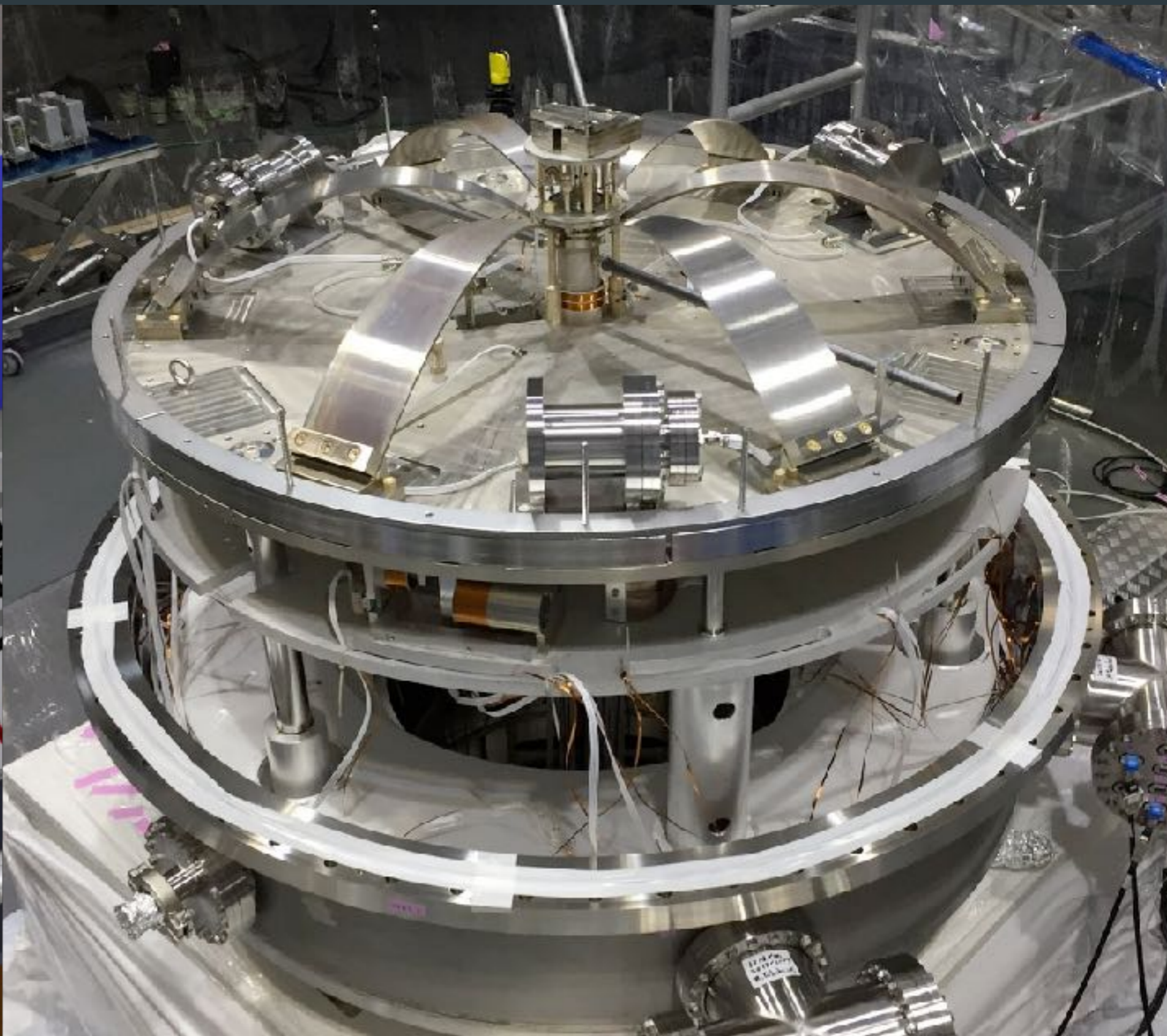
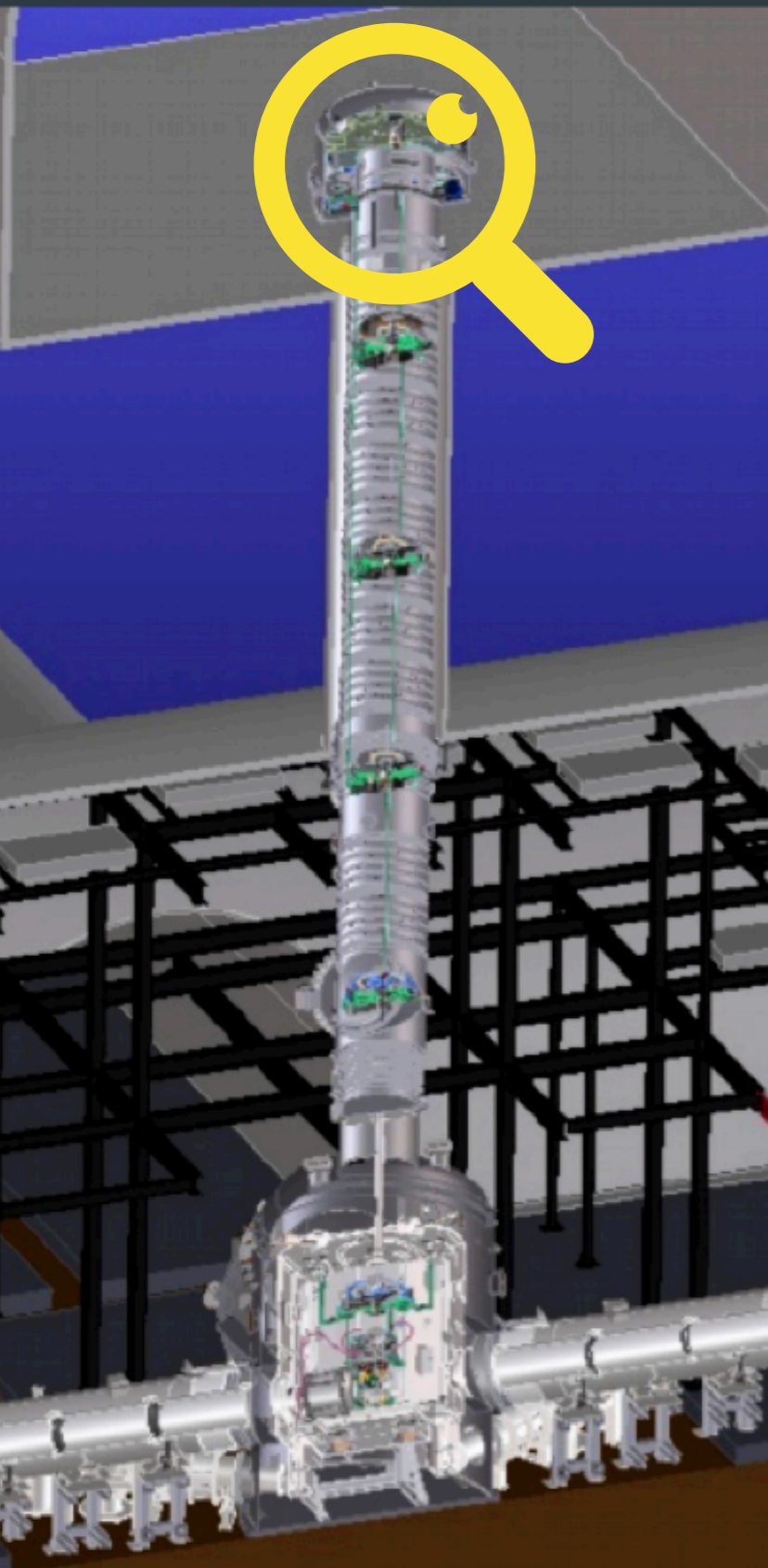
タワー

- 上5段、低周波振動子からなる常温部
- **倒立振子 (IP)**: 水平方向の共振 ~ 70 mHz
- **Geometric Anti-Spring (GAS) フィルタ**: 垂直方向の共振 ~ 300 mHz

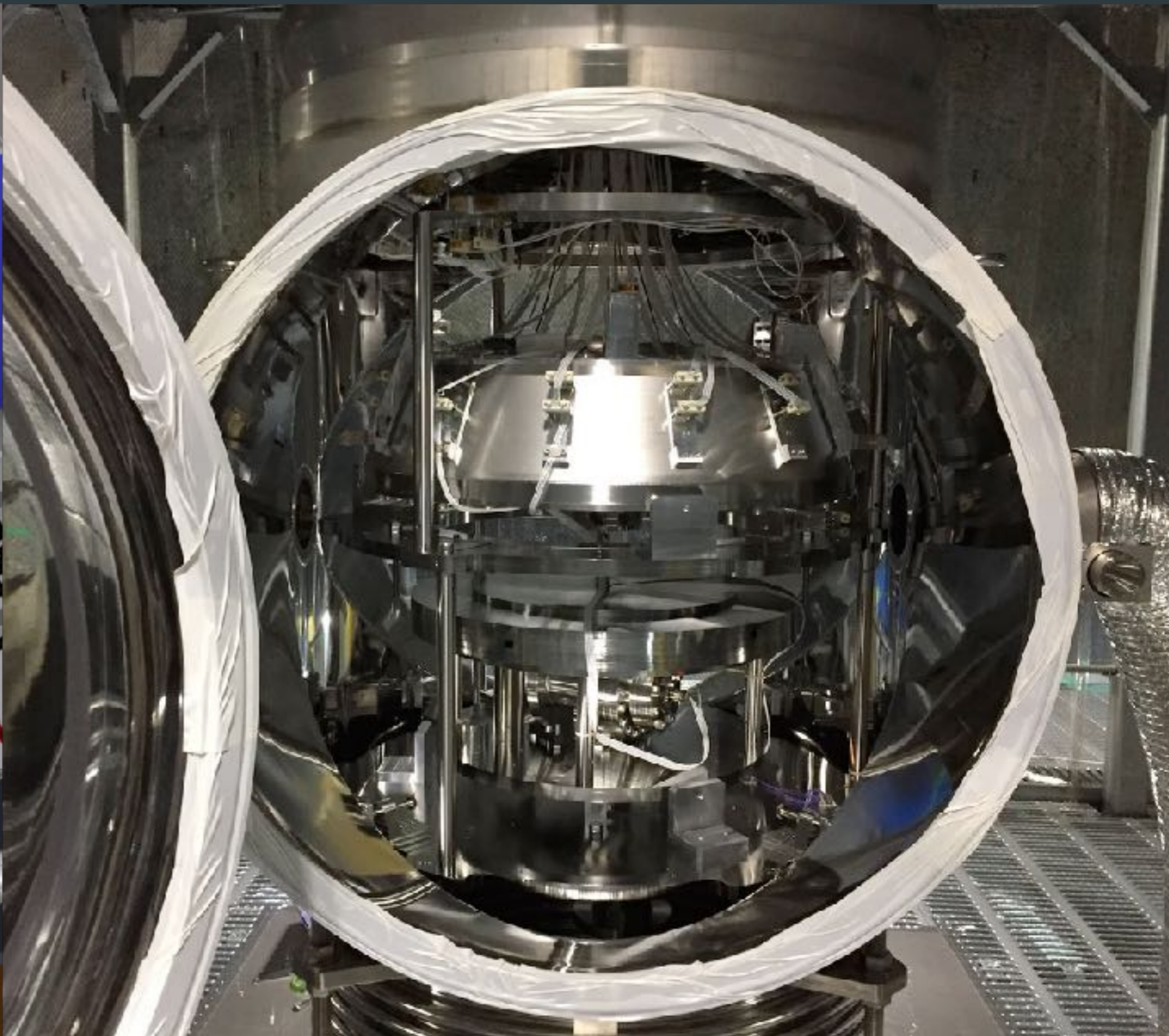
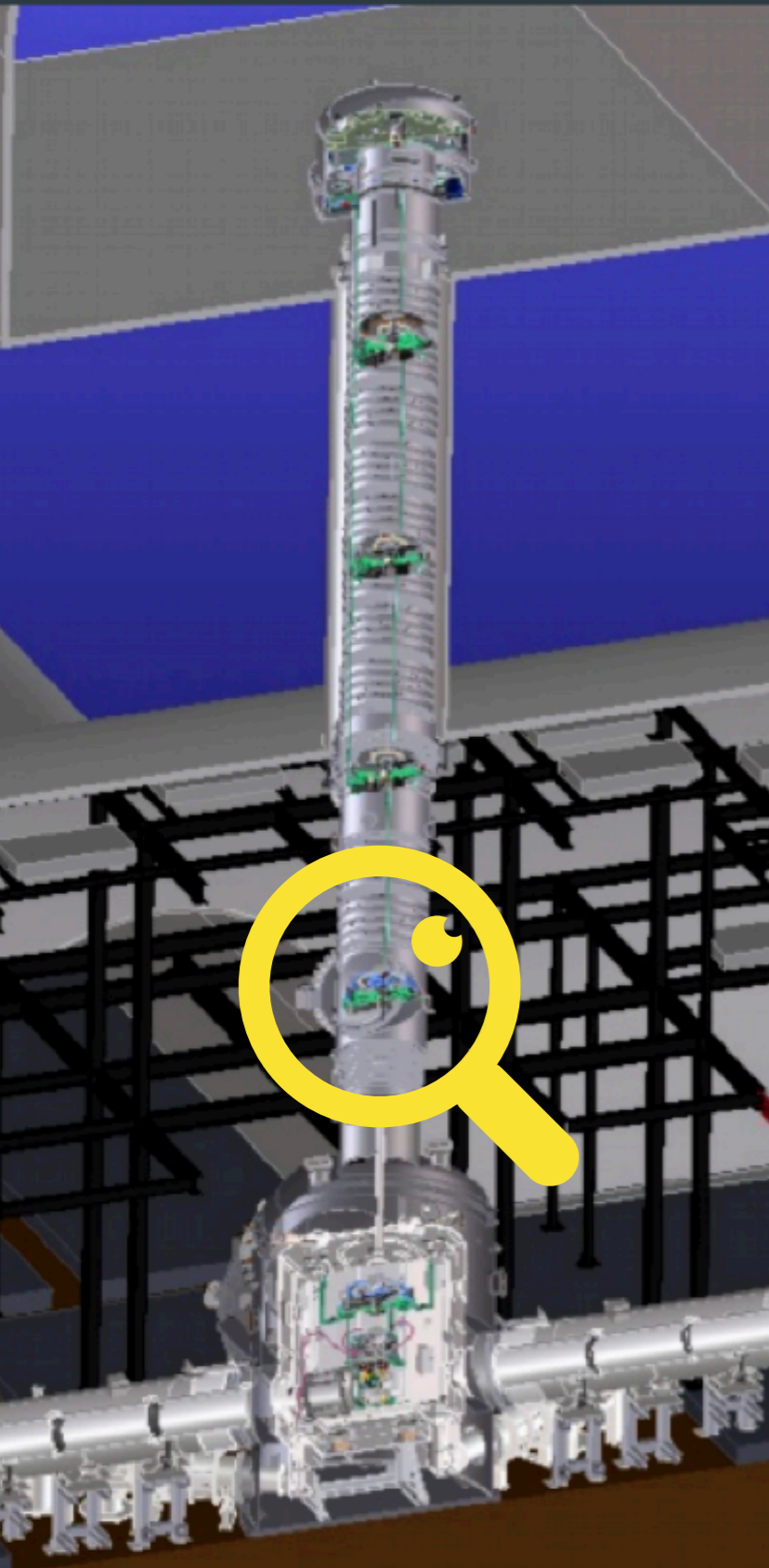
低温ペイロード

- 下4段、低温部 (~ 20 K)
- **サファイア鏡**: 22.5 kg (ファイバ接着用耳含む)

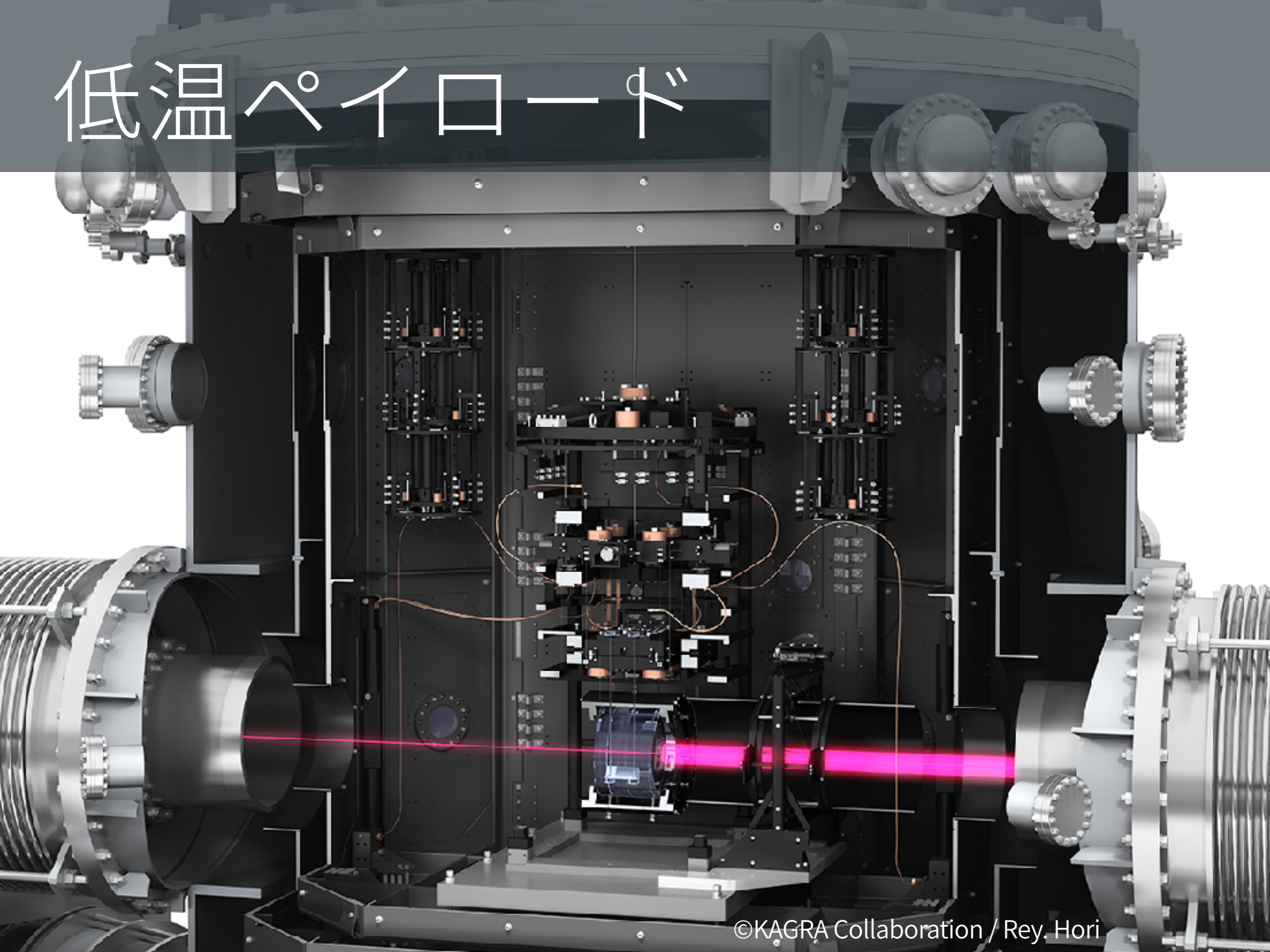
Pre-Isolator



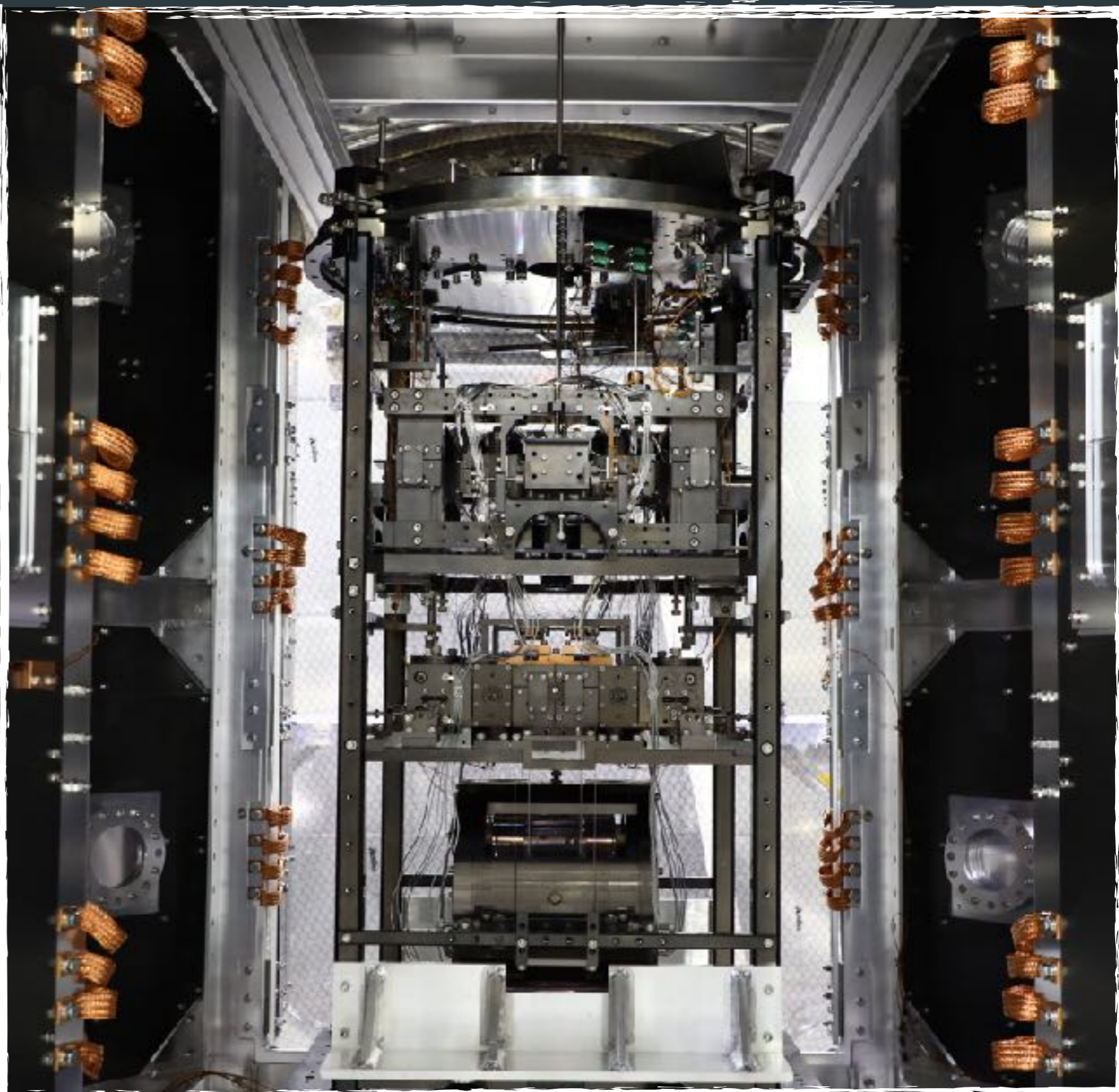
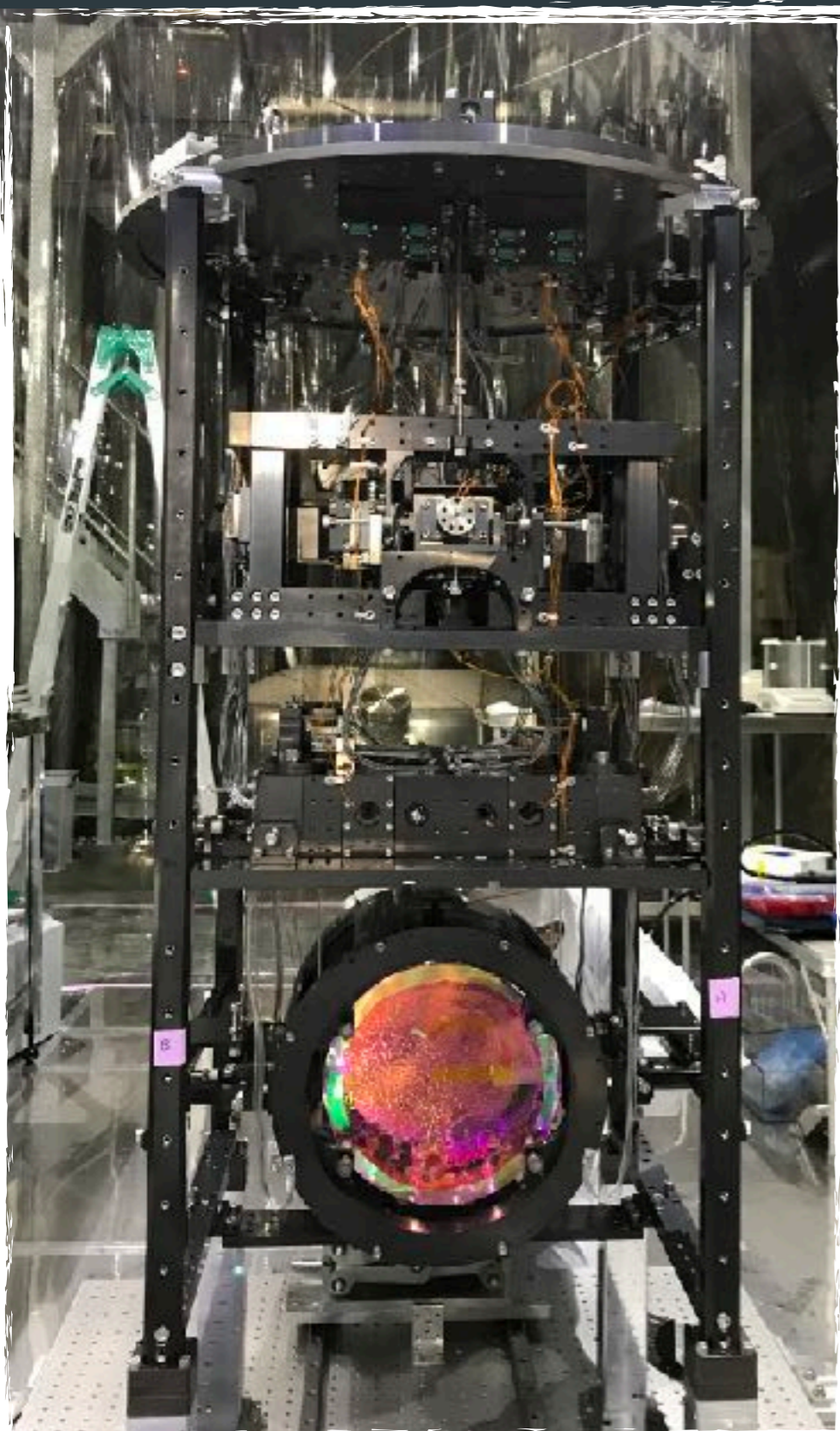
Bottom Filter



低温ペイロード



低温ペイロード



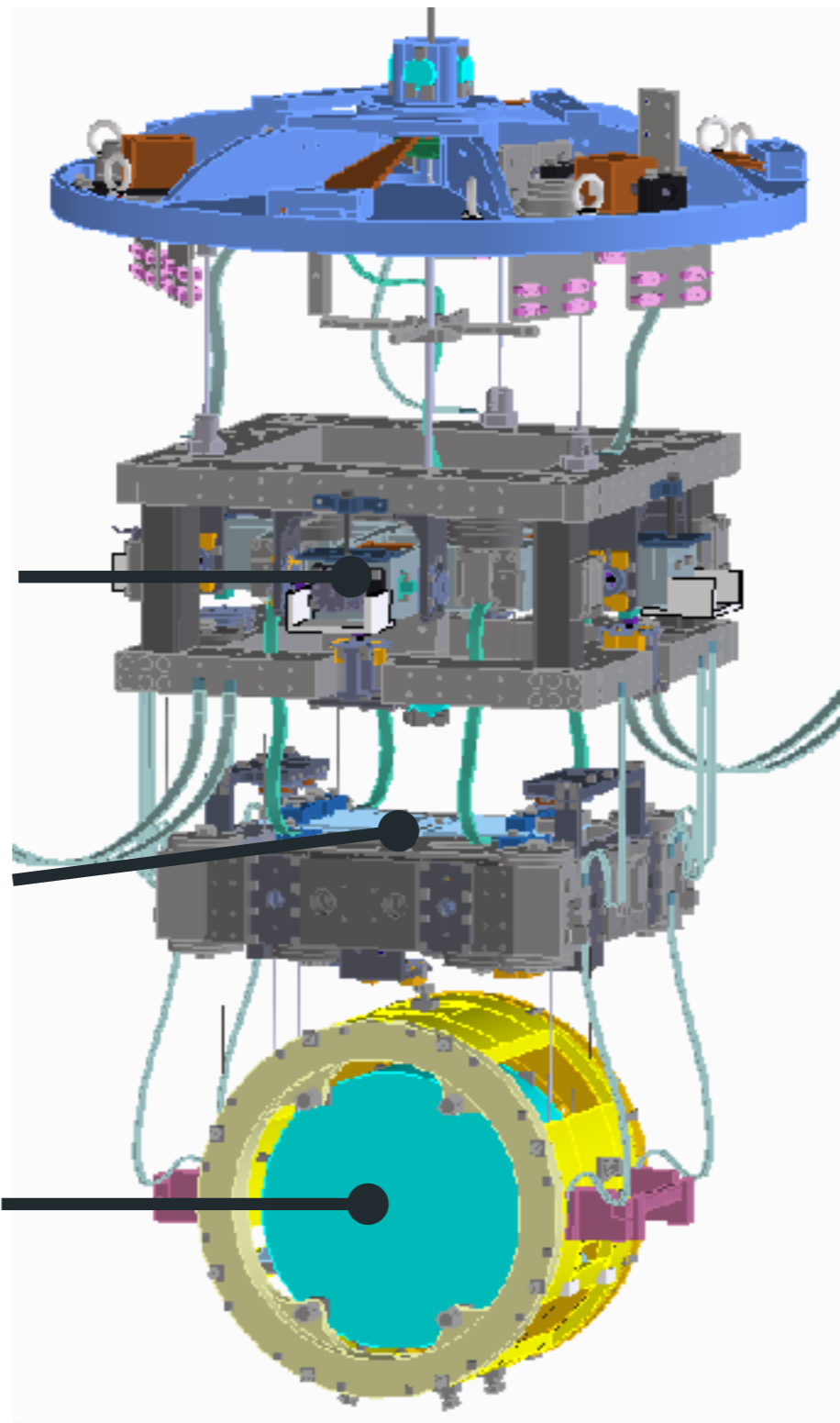
低温ペイロード構成

プラットフォーム
(PF)

マリオネット
(MN)

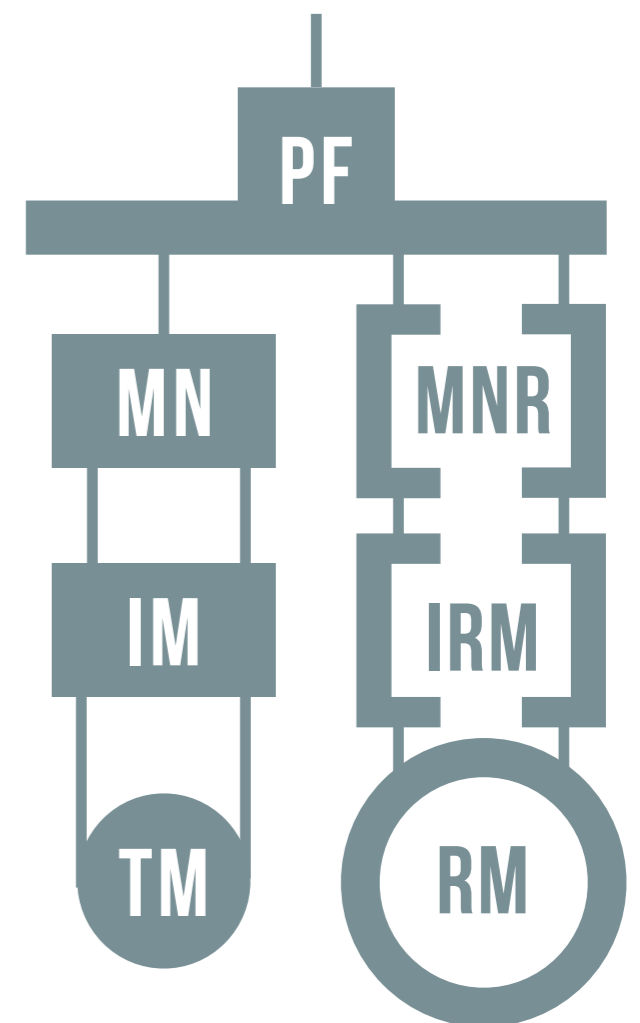
中段マス
(IM)

テストマス
(TM)

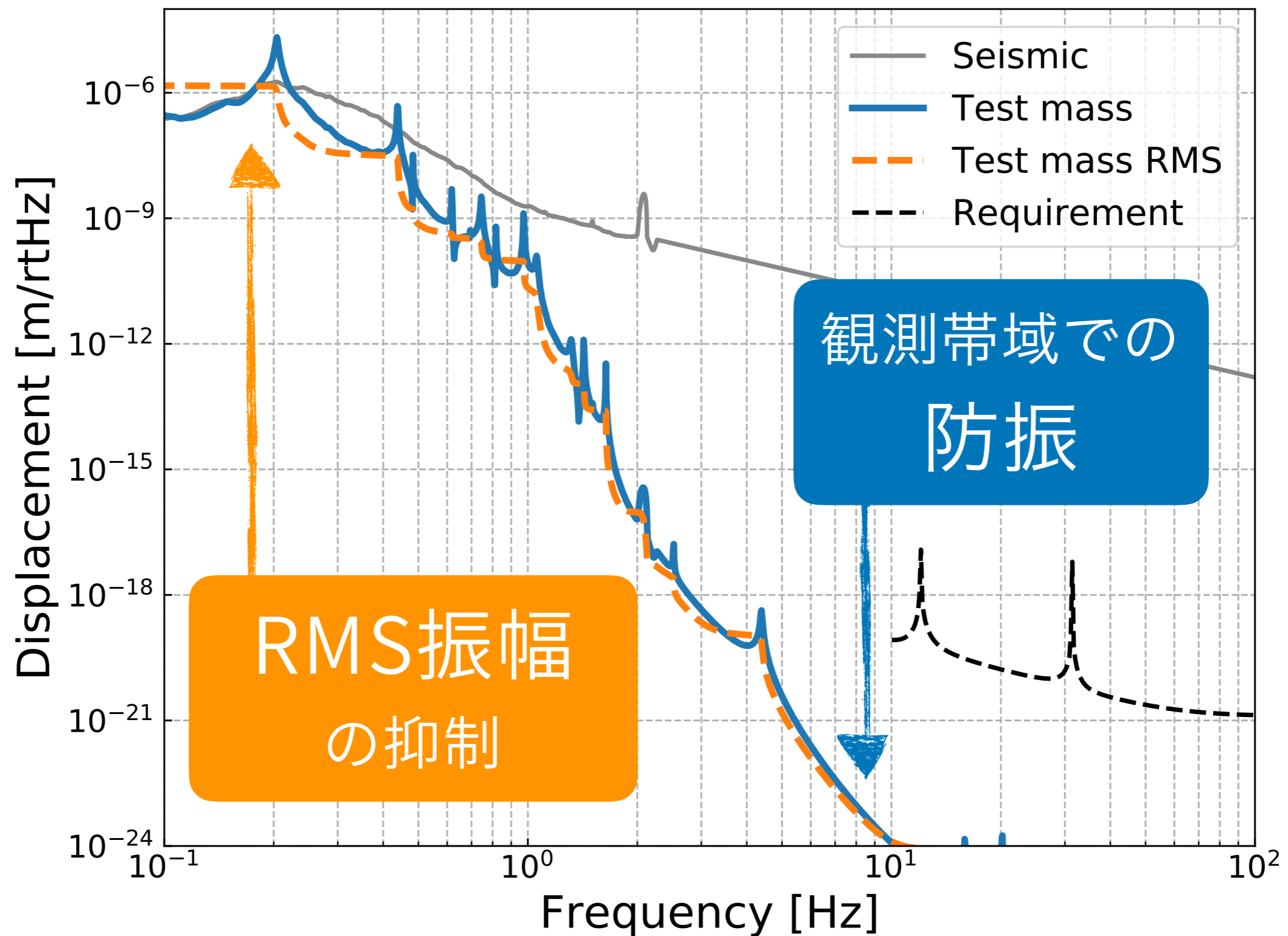


総重量 ~ 200 kg

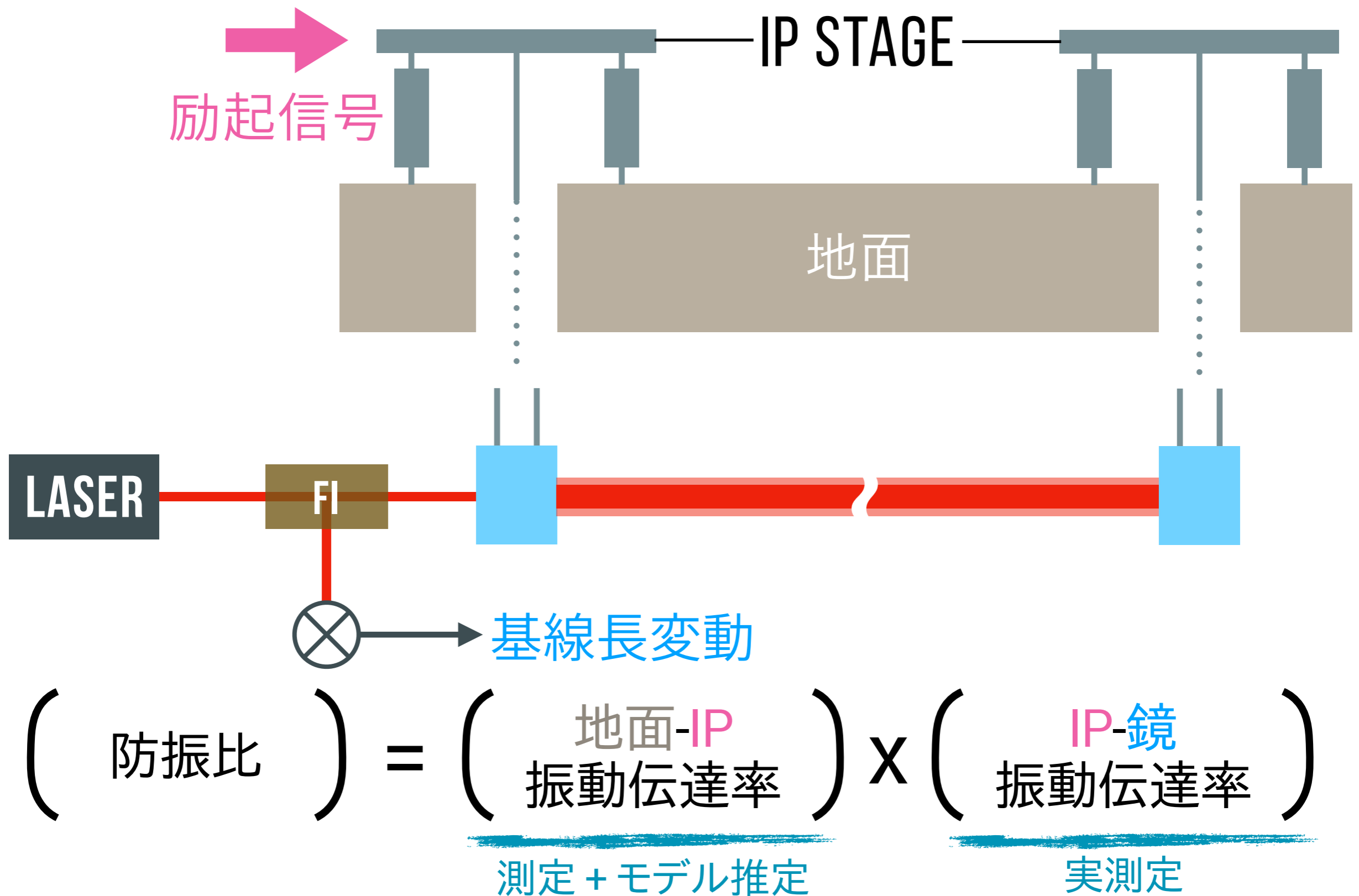
反跳マスと並行懸架



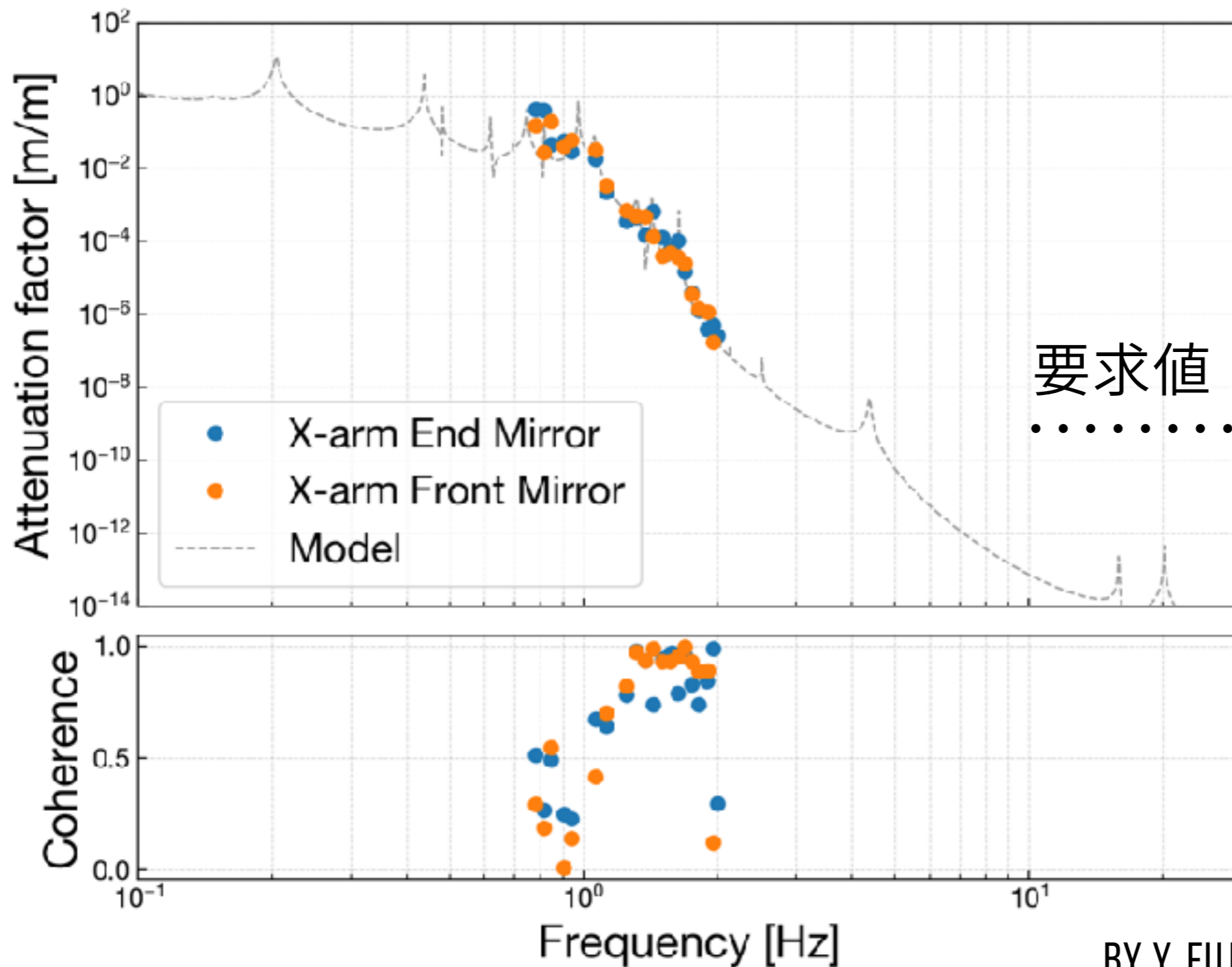
懸架システムの役割



1. 防振比の測定



測定結果

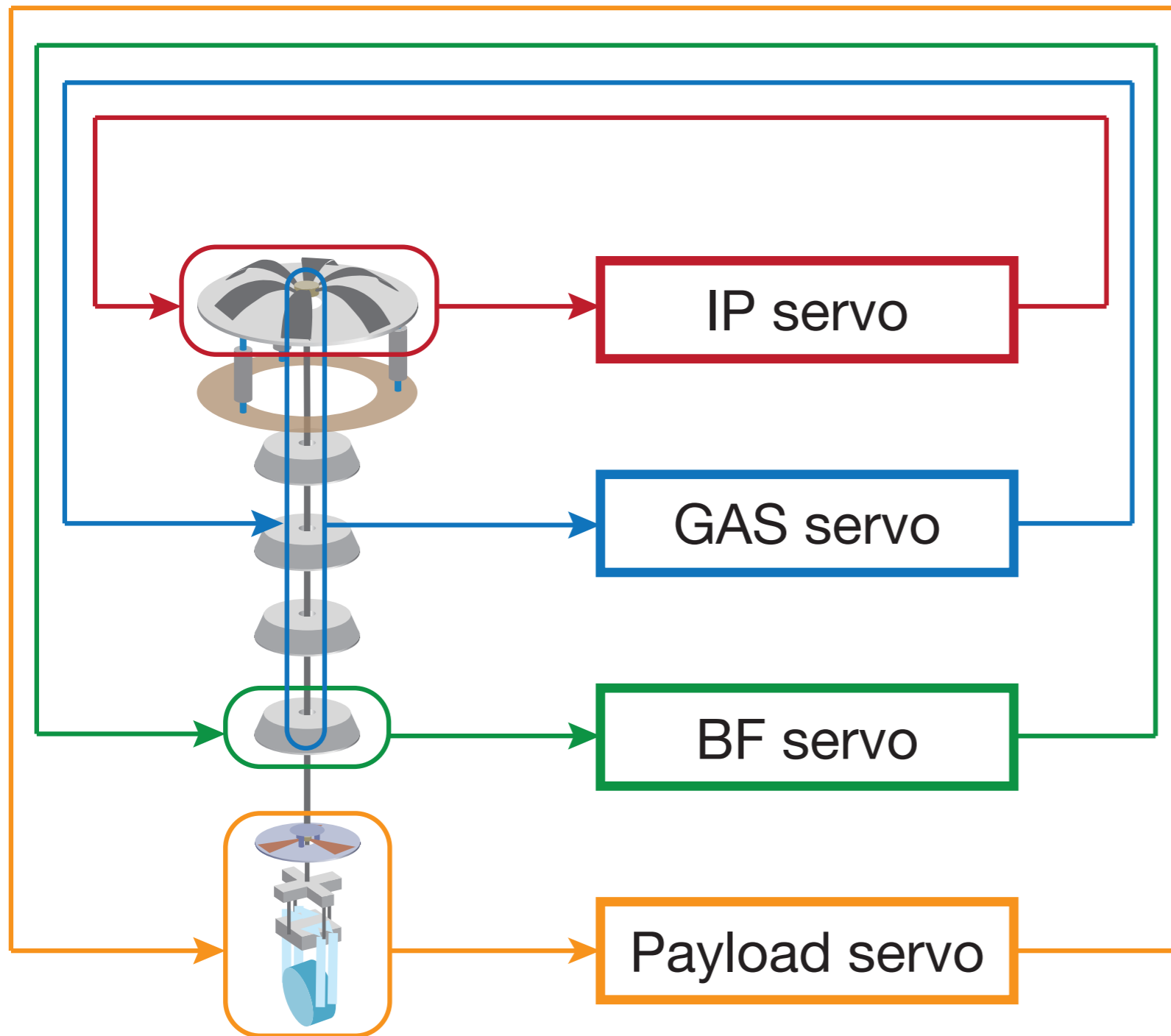


■ 単一腕共振器での測定

- モデル予測とはよく一致（特に > 1 Hz）

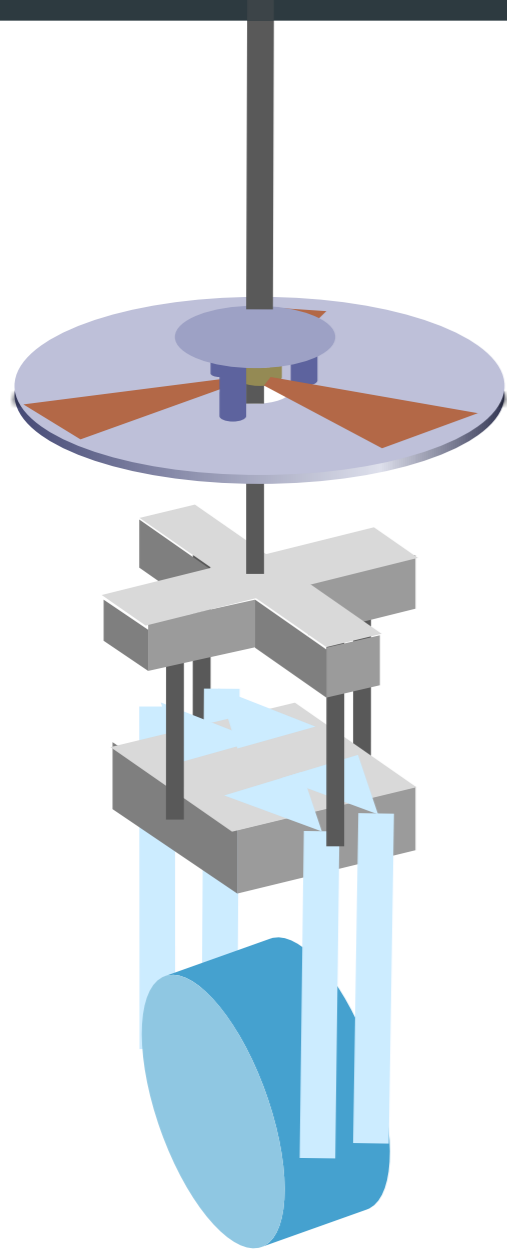
▶ 観測帯域での評価は干渉計の自由度を増やして行う

2. RMS抑制のためのローカル制御

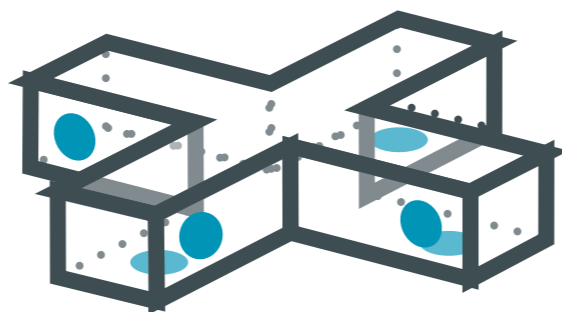


- タワー
 - IP ■ GAS ■ BF
 - 共振の能動減衰 + DC位置制御 (< 1 Hz)
- ペイロード ■ Payload
- 共振の能動減衰 + 角度揺れ抑制制御 (> 0.1 Hz)

センサー - ペイロード



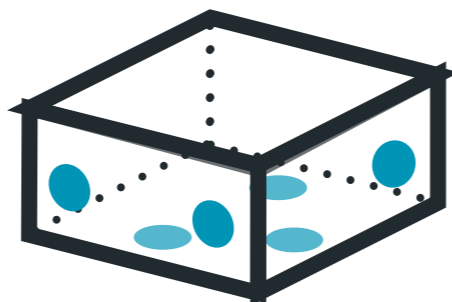
MN



■ 反射型フォトセンサ
MN-MNR 間の相対変位

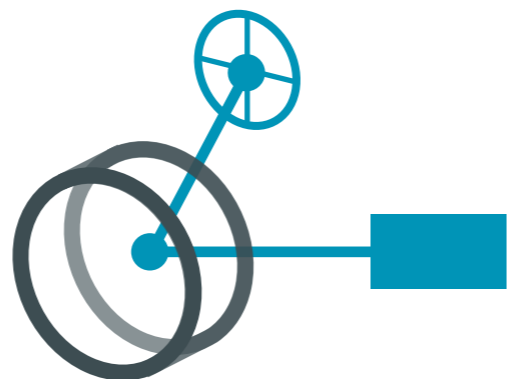
■ 光てこ
MNの地面に対する角度

IM



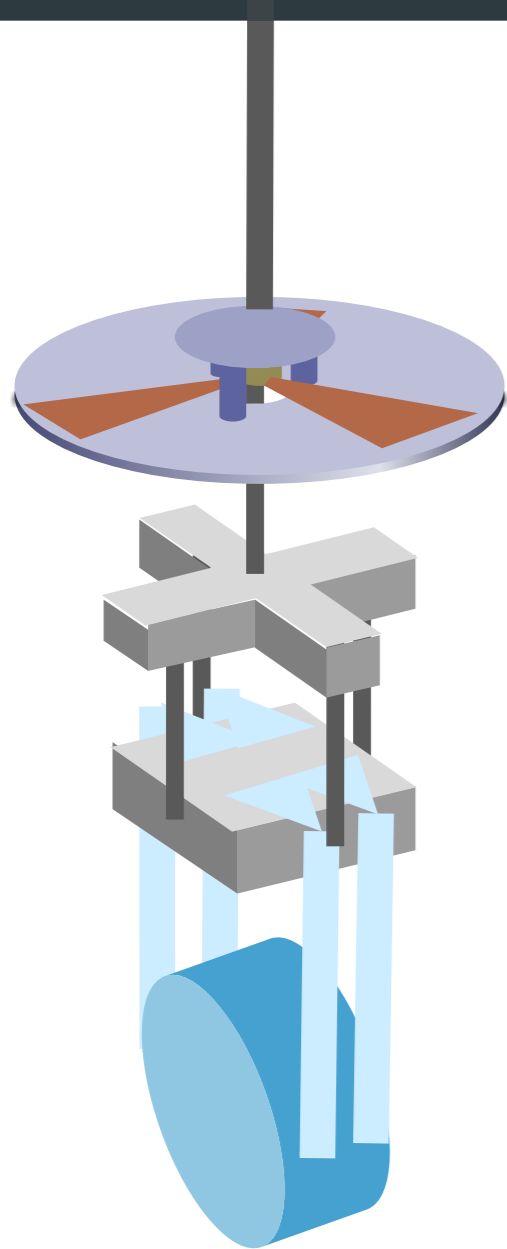
■ 反射型フォトセンサ
IM-IRM 間の相対変位

TM

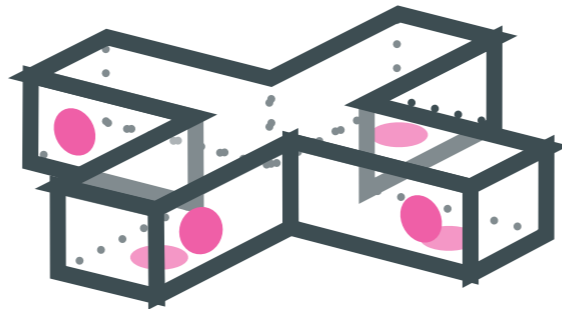


■ 光てこ
TMの地面に対する変位 (L, P, Y)

アクチュエータ - ペイロード

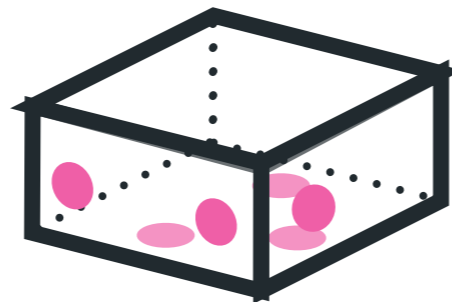


MN



■ コイルマグネットアクチュエータ
MN-MNR 間の相対6自由度

IM



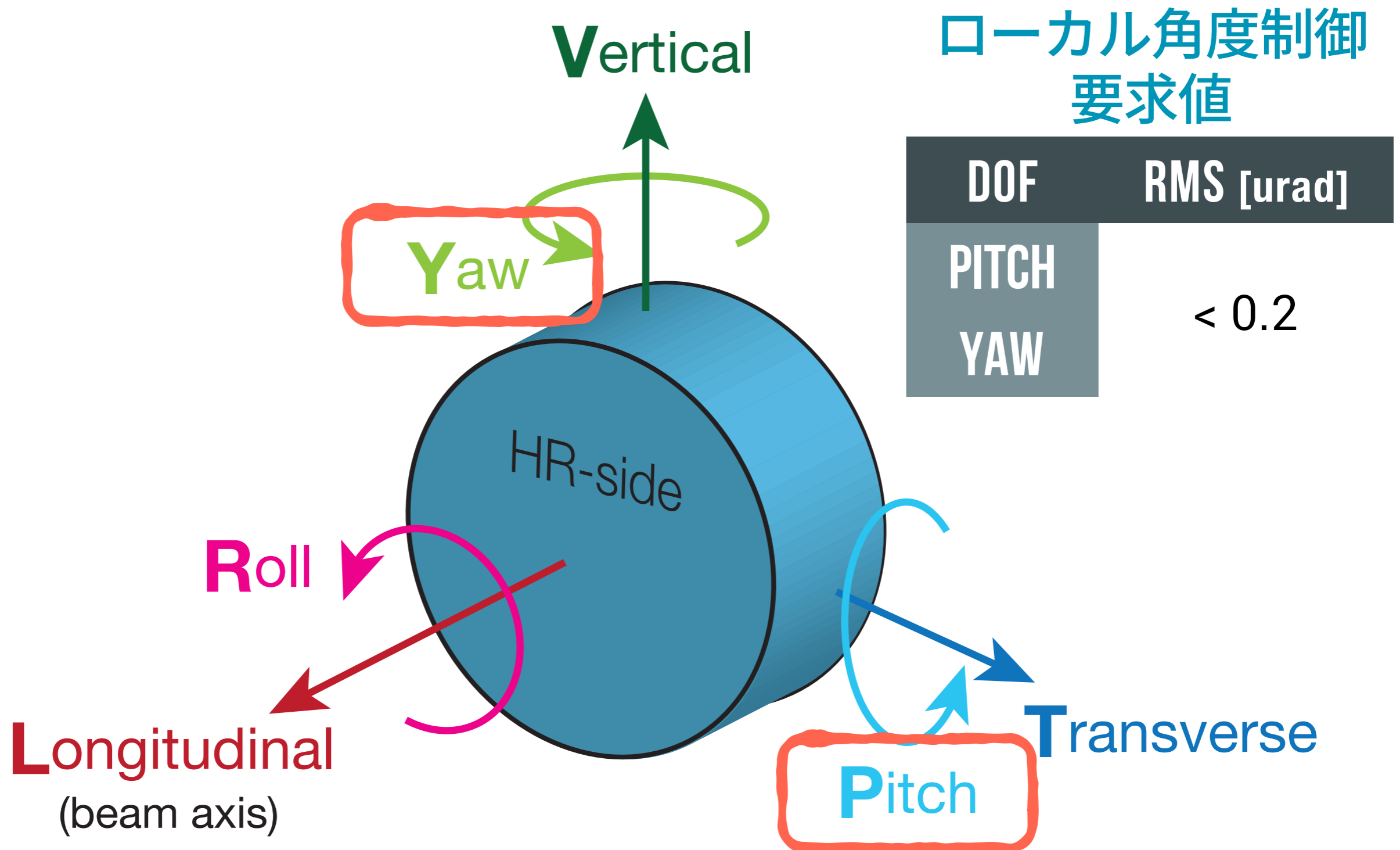
■ コイルマグネットアクチュエータ
IM-IRM 間の相対6自由度

TM

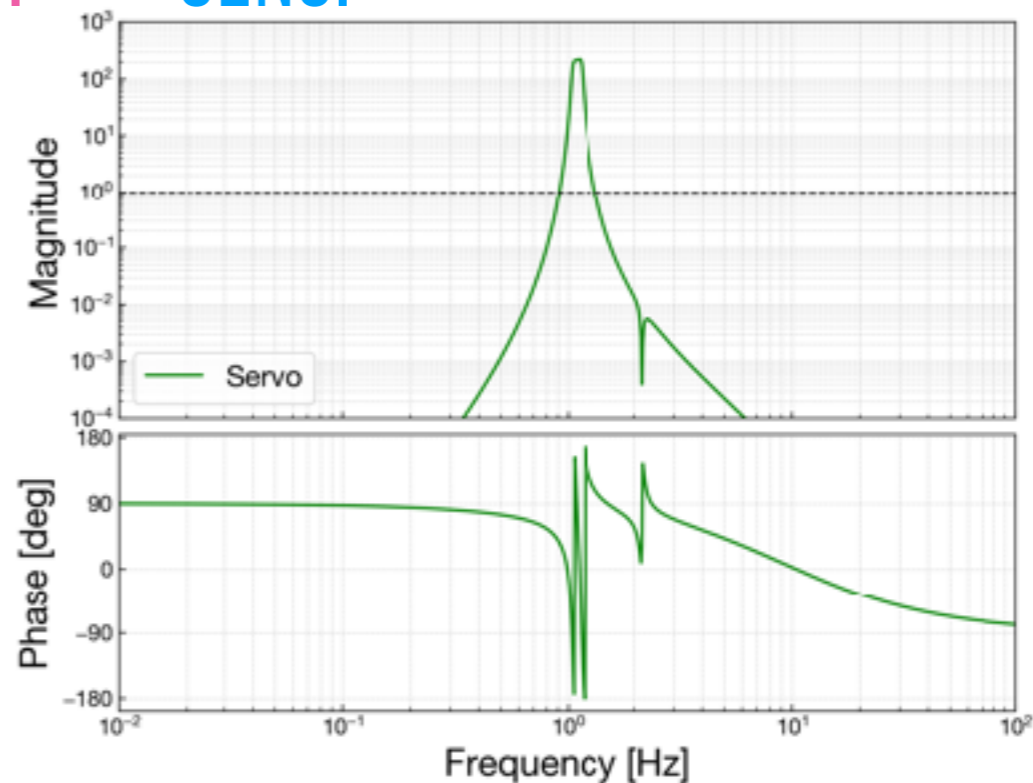
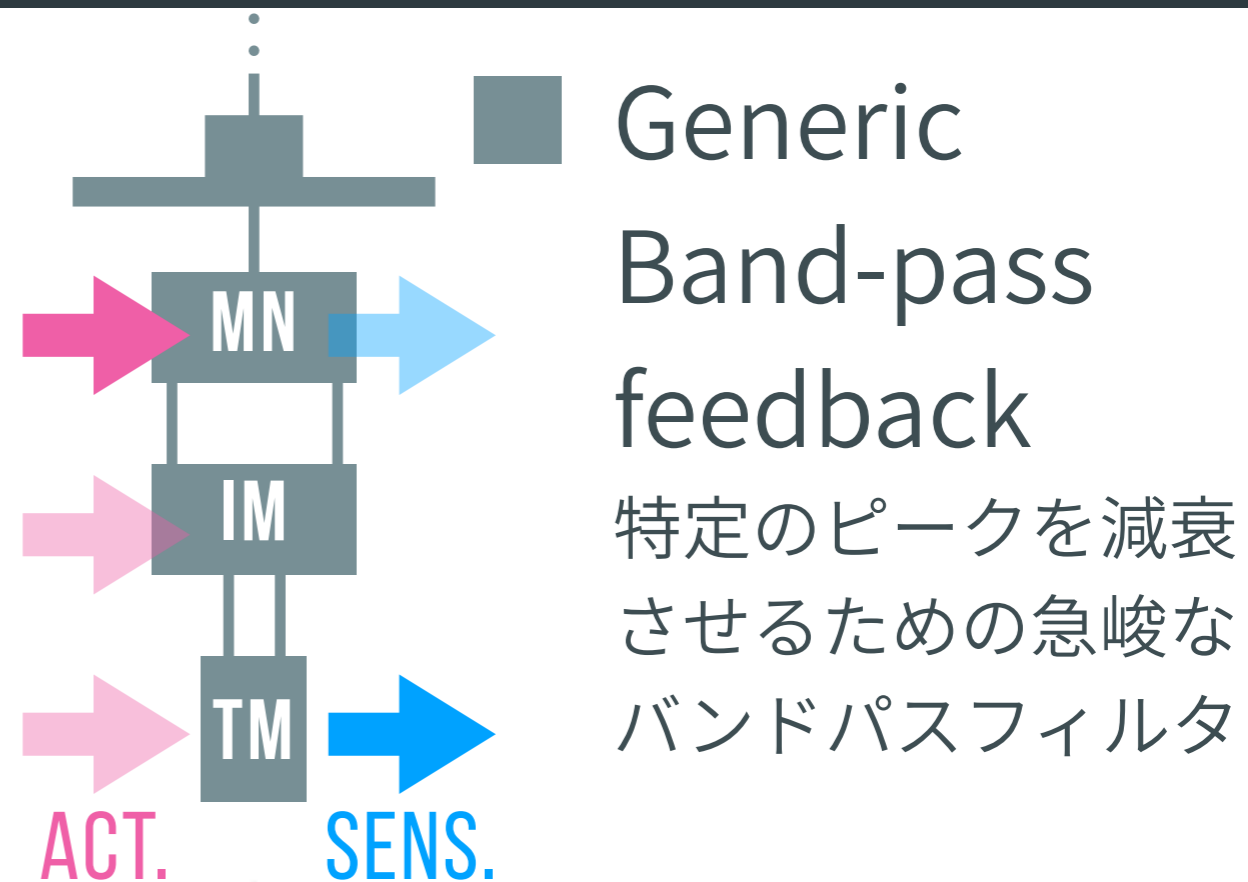
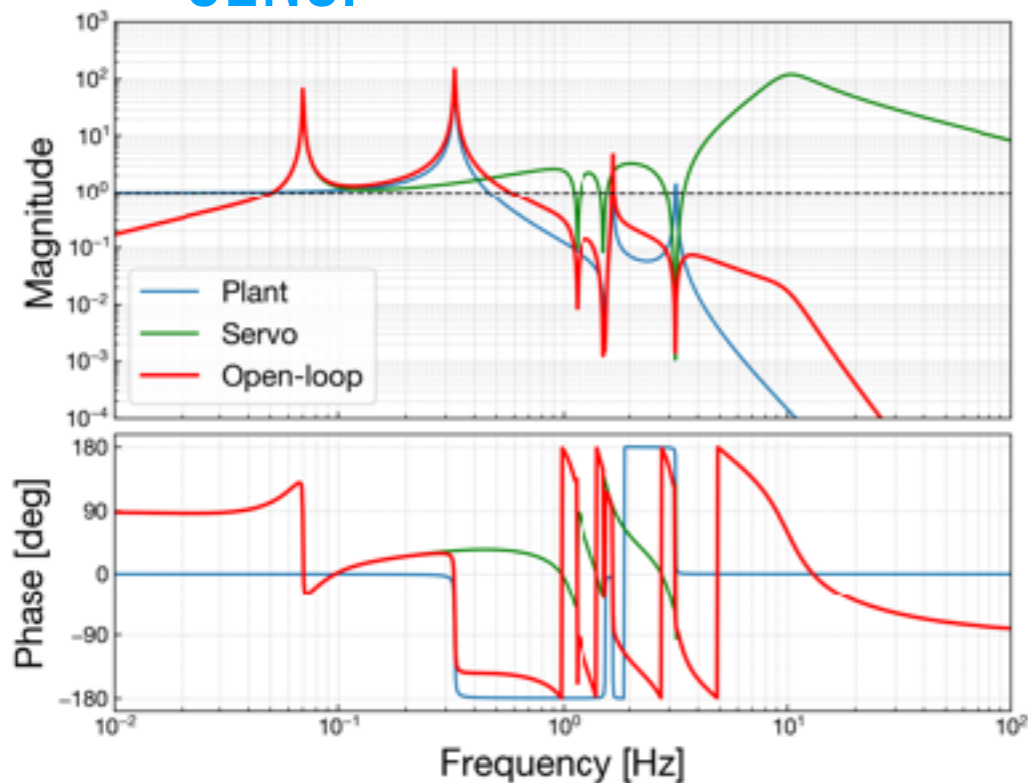
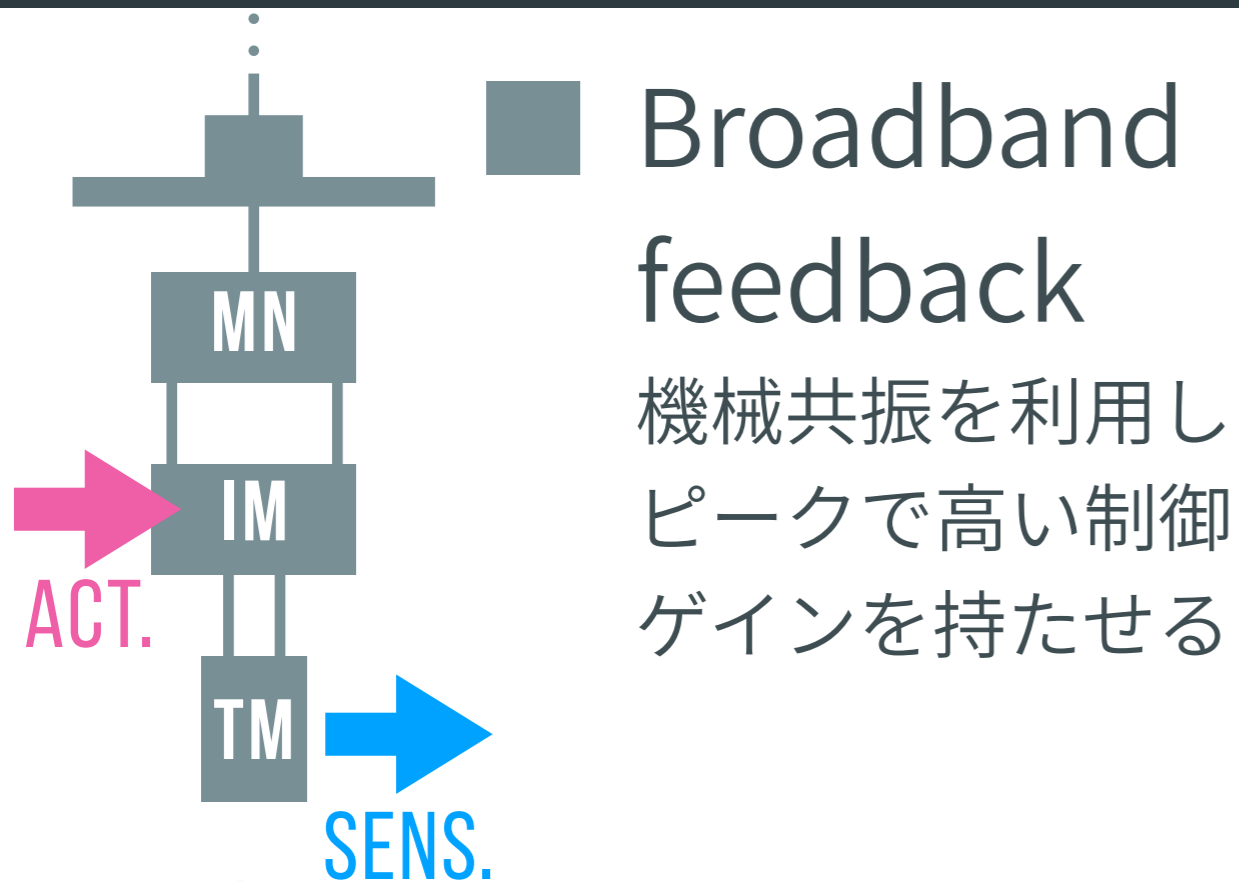


■ コイルマグネットアクチュエータ
TM-RM 間の相対3自由度 (L, P, Y)

角度制御

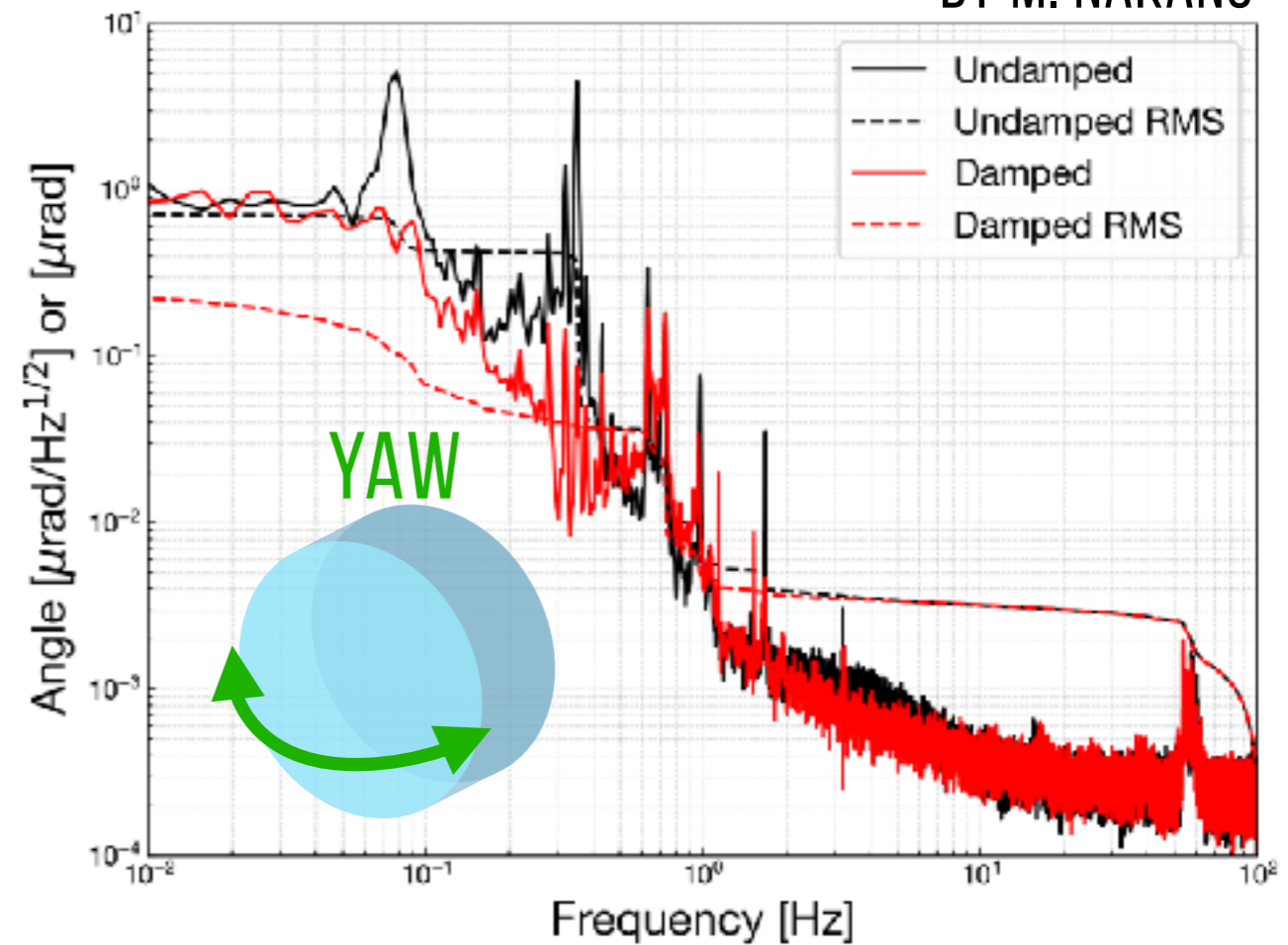
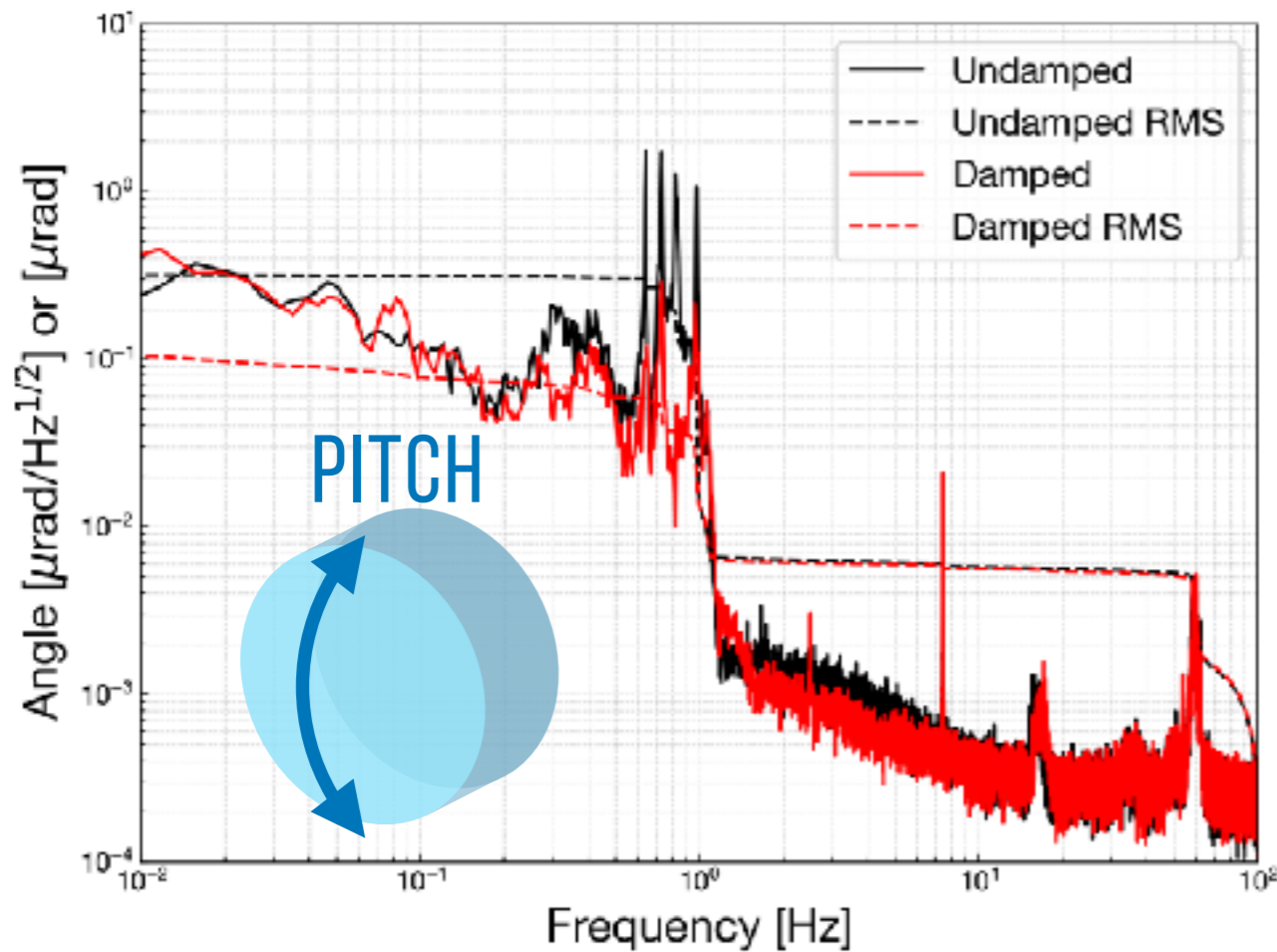


ペイロード制御



現状

BY M. NAKANO



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

ローカル制御 ▶ ~ ✓ OK

Next step:

▶ グローバル角度制御

▶ (P, Y) RMS < ~ 10 nrad

まとめ

■ Type-A suspension

全4台が干渉計とのコミッショニング中

■ 防振性能の評価

モデル予測とよく一致している
観測帯域での評価は今後の課題

■ RMS抑制のためのローカル制御

ローカル制御における要求値は概ね満たしている
グローバル角度制御に向けて準備中

KAGRA COMING SOON!





BACKUP SLIDES

Components

TYPE-A

9 stages

Inverted Pendulum

GAS Filter x5

Payload: Cryogenic

For 4 TMs

TYPE-B

5 stages

Inverted Pendulum

GAS Filter x3

Room-temperature

For BS and 3 SRs

TYPE-BP

3 stages

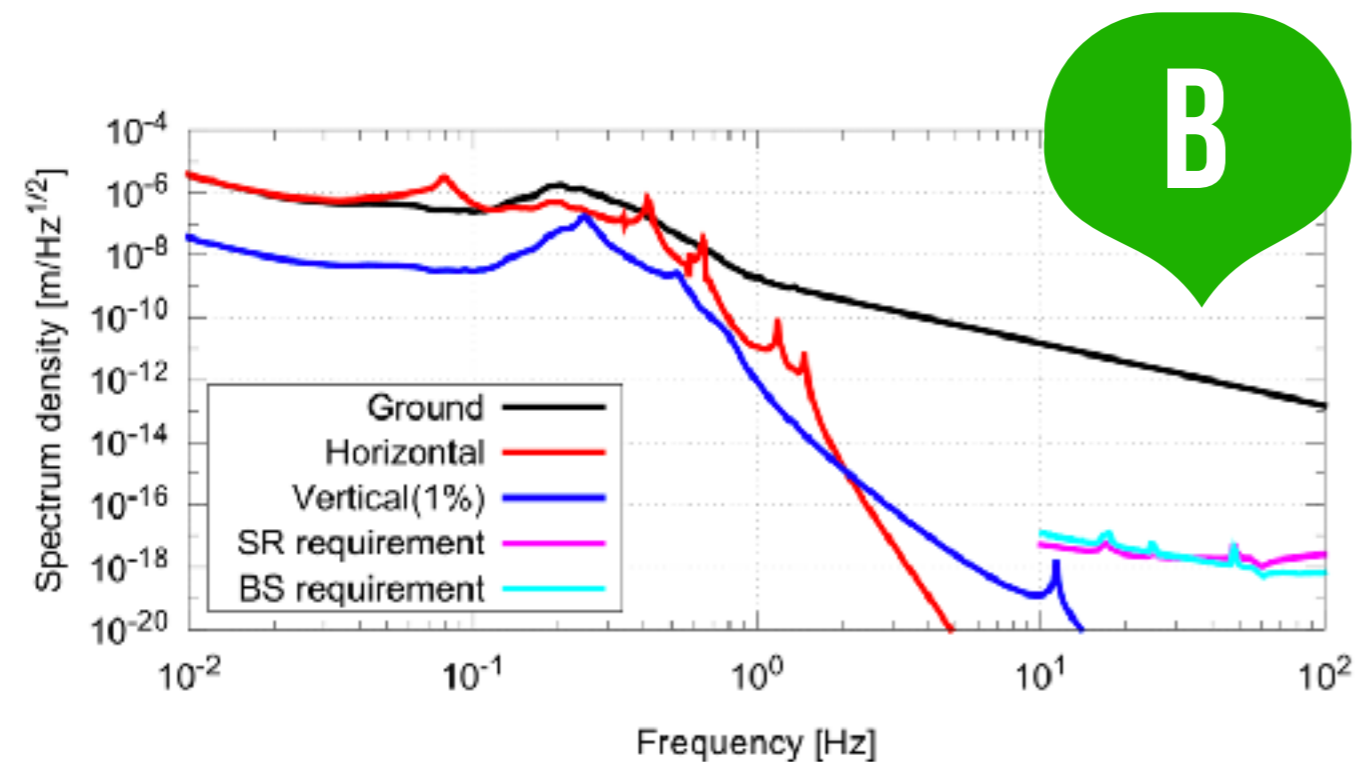
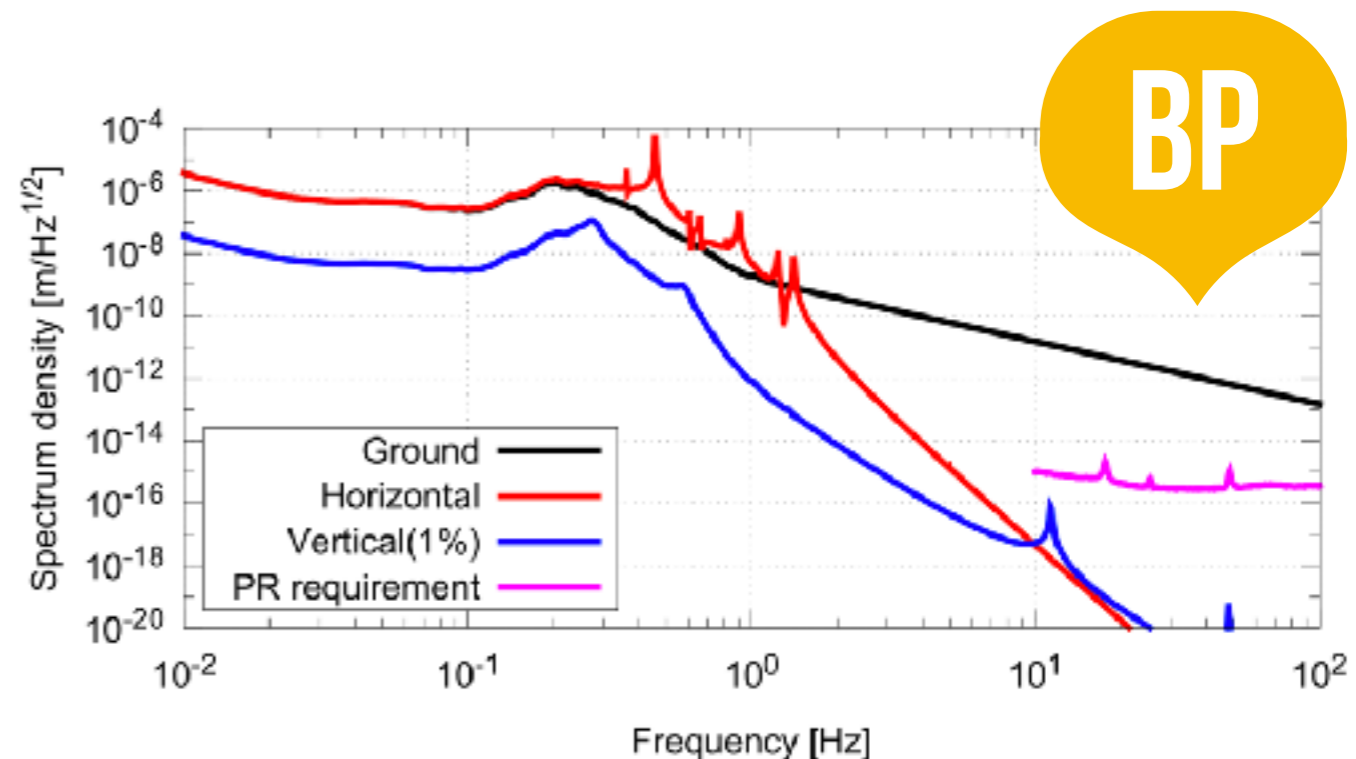
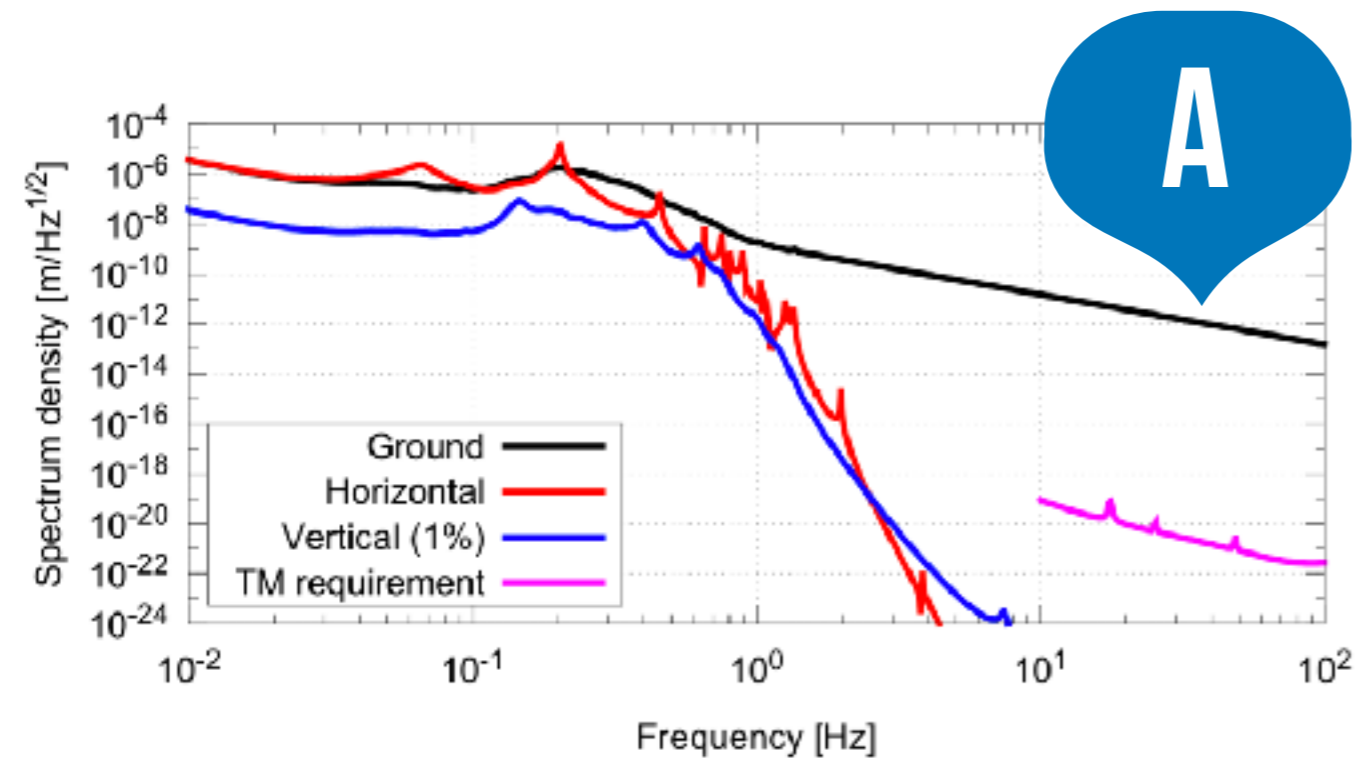
–

GAS Filter x2

Room-temperature

For 3 PRs

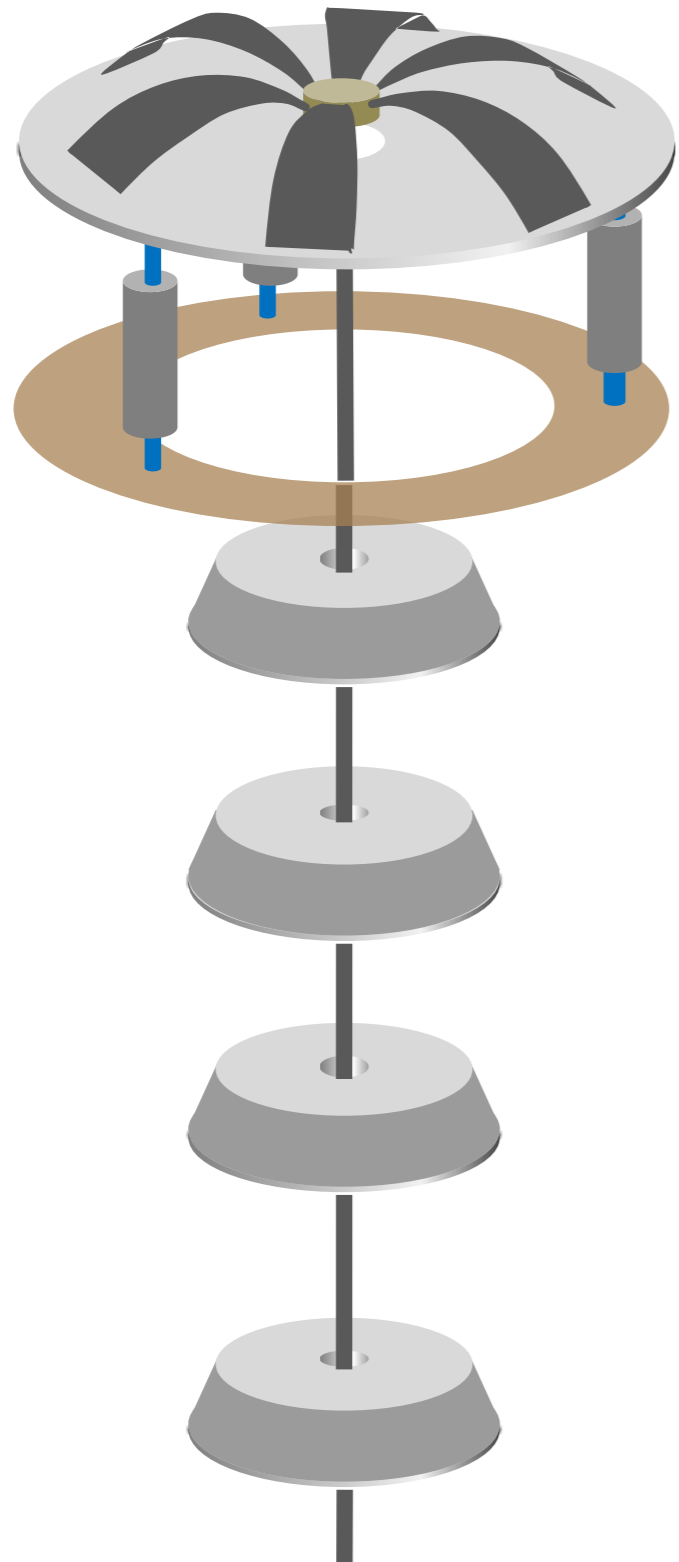
Performance



cf. T. Sekiguchi, PhD thesis (2014)

■ Both **horizontal** and **vertical** motions contribute the displacement noise

Tower



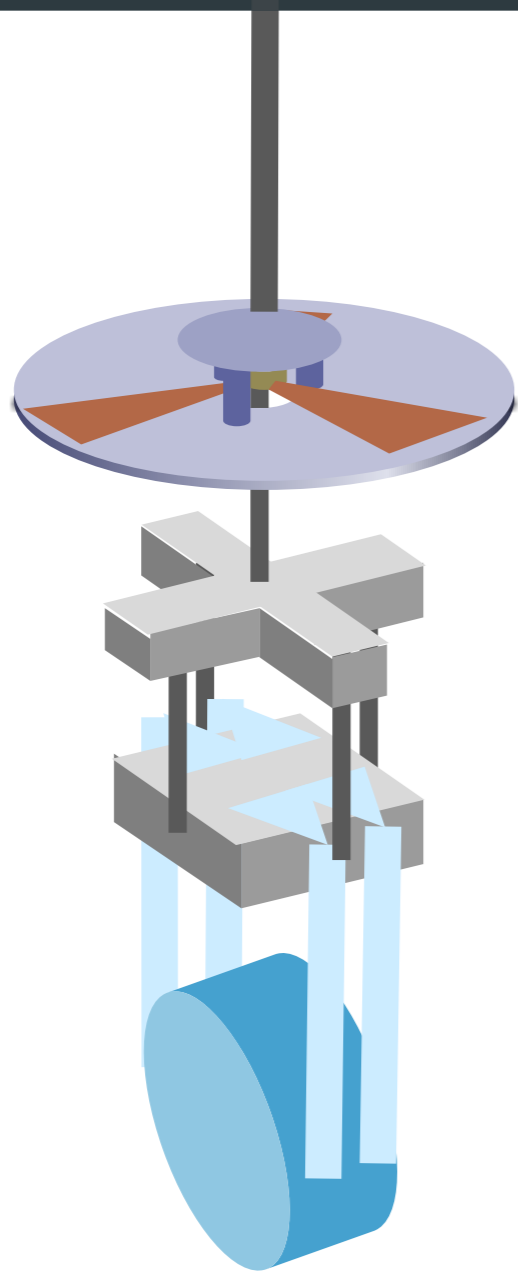
PRE-ISOLATION STAGE

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

MECHANICAL FILTER CHAIN

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

CRYOGENIC Payload



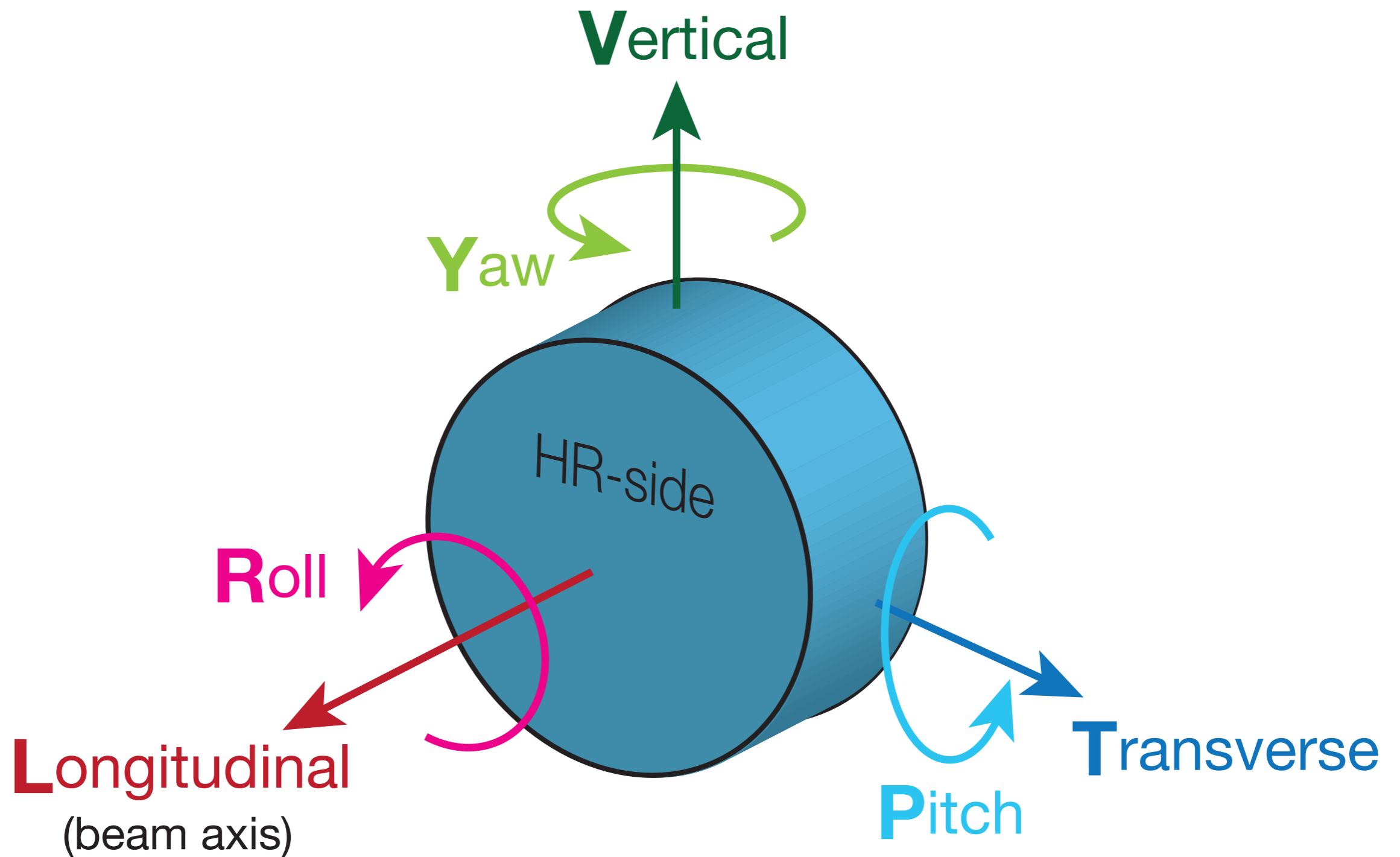
RADIATION + CONDUCTIVE COOLING

- Black coated surface
- Pure aluminum heat links

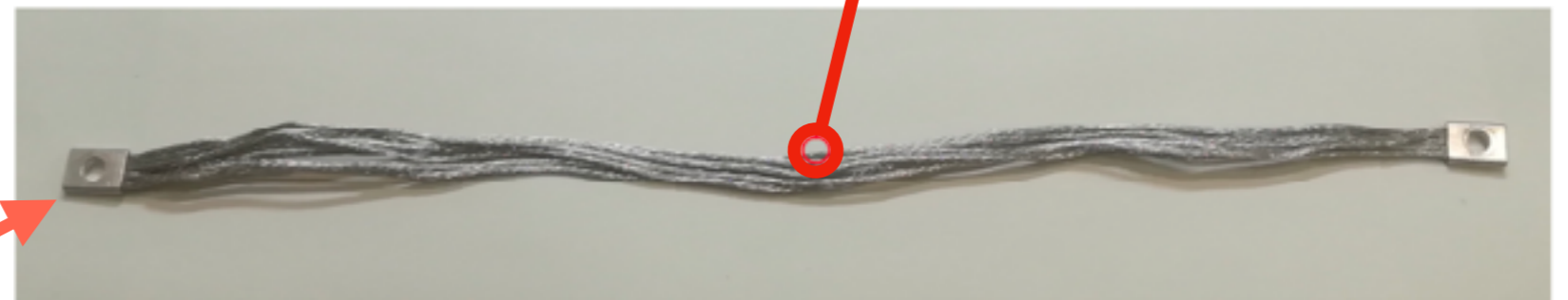
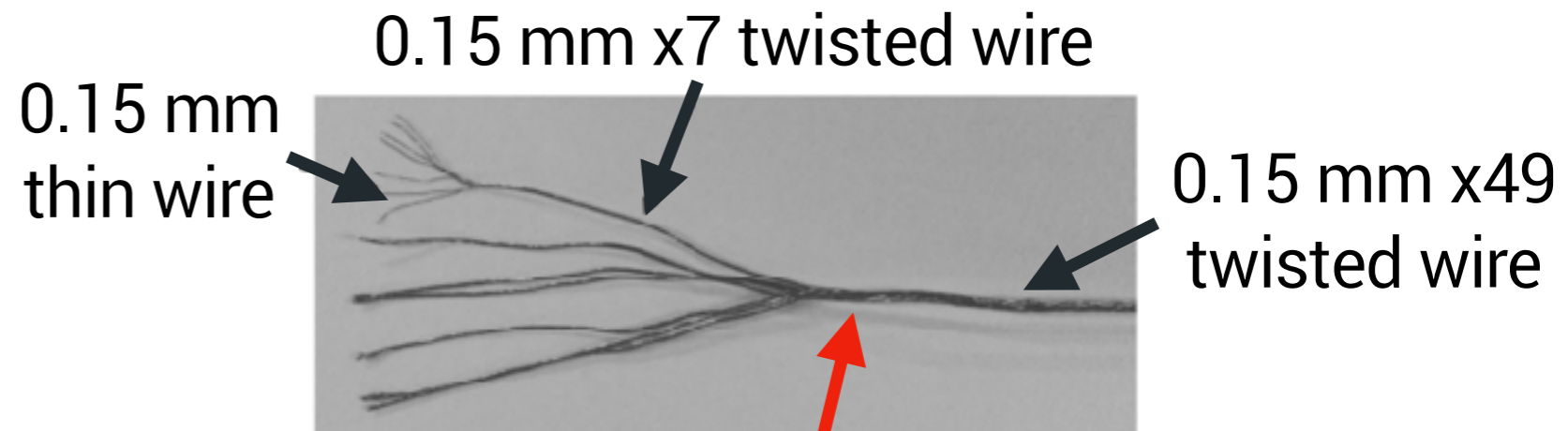
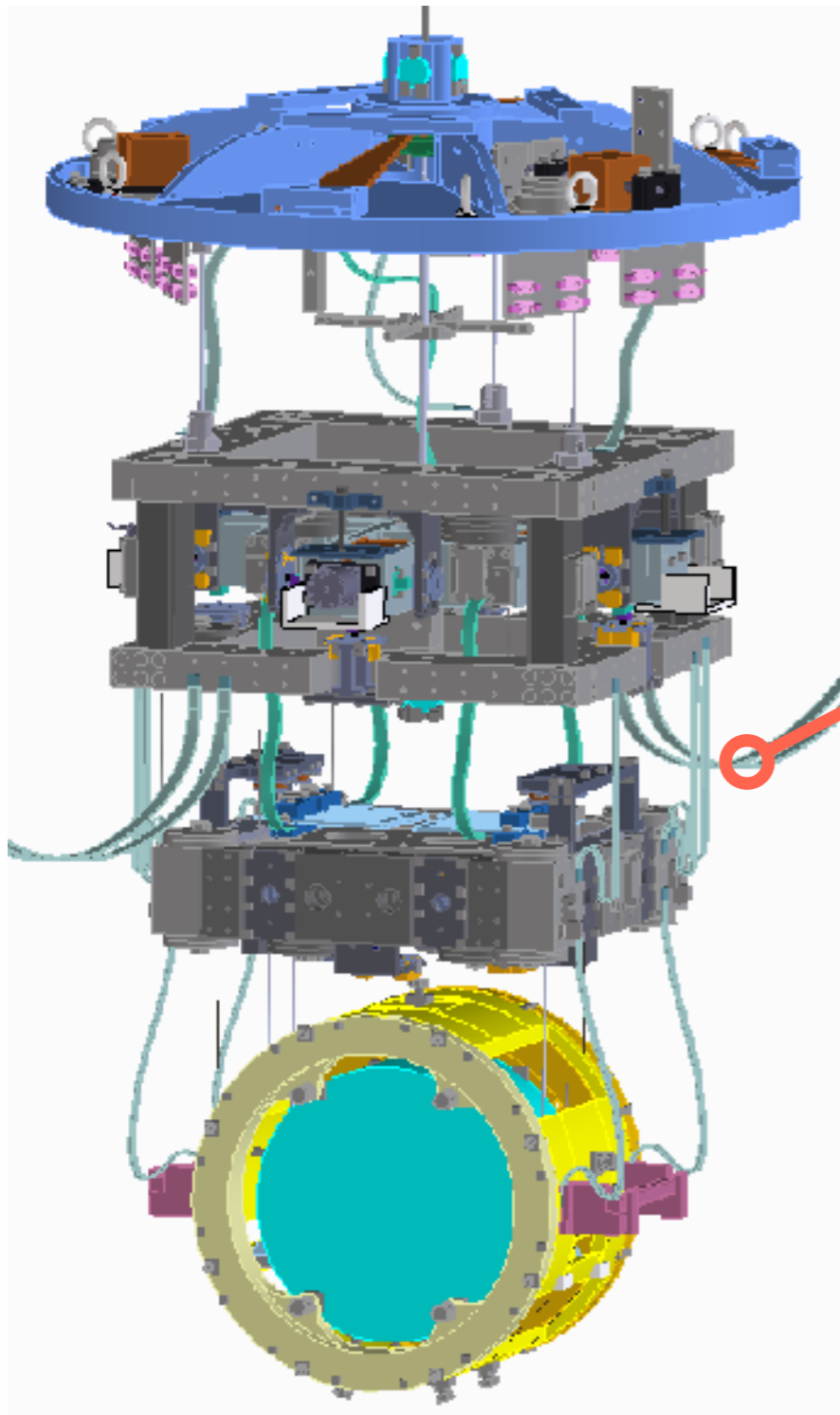
SAPPHIRE TEST MASS & FIBERS

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

Degrees of Freedom



Heat Link



0.15 mm x49 twisted wire x7 in parallel

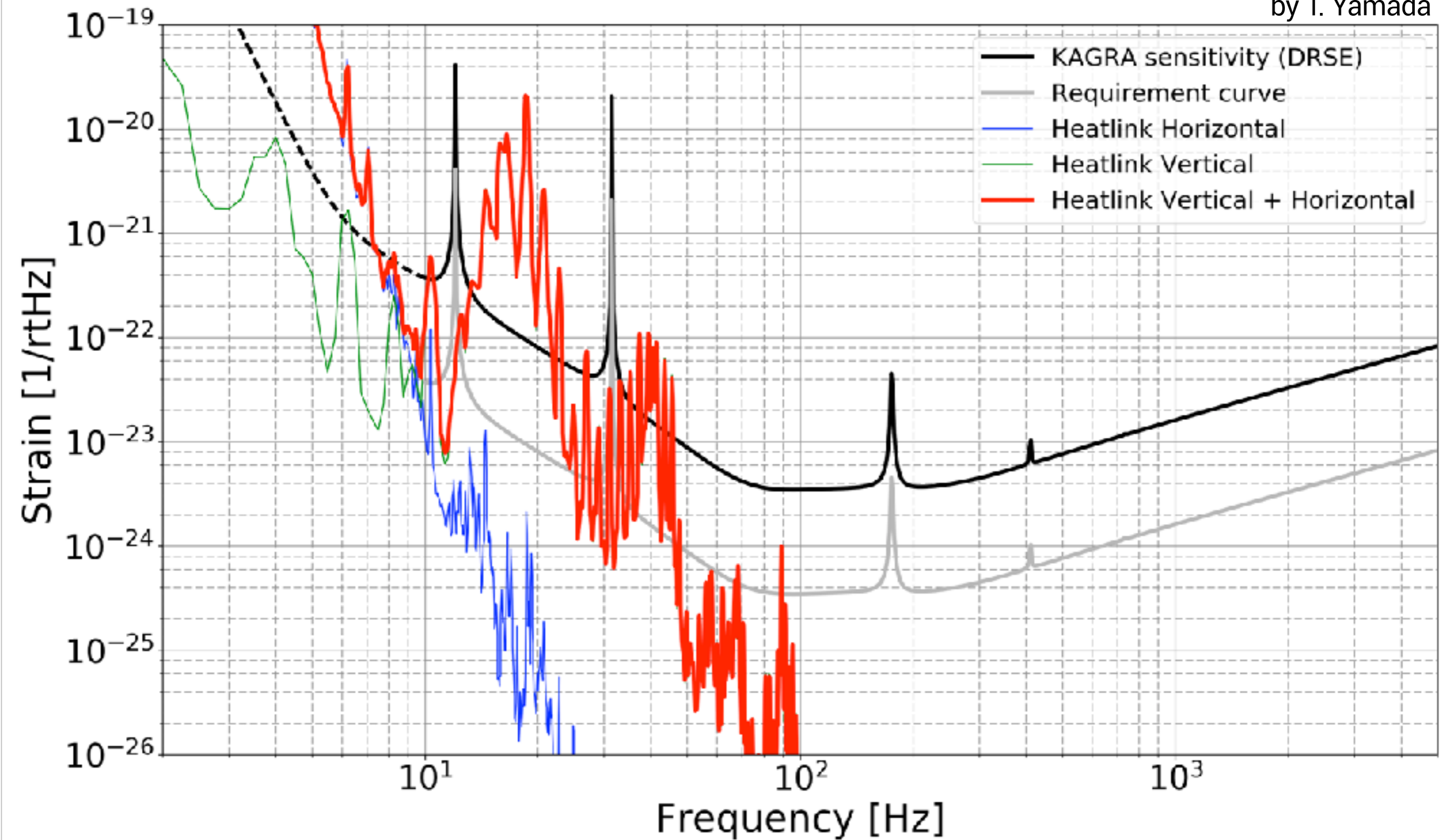
■ 6N (99.9999%) aluminum wire

■ High conductivity ~ 18.5 kW/m/K

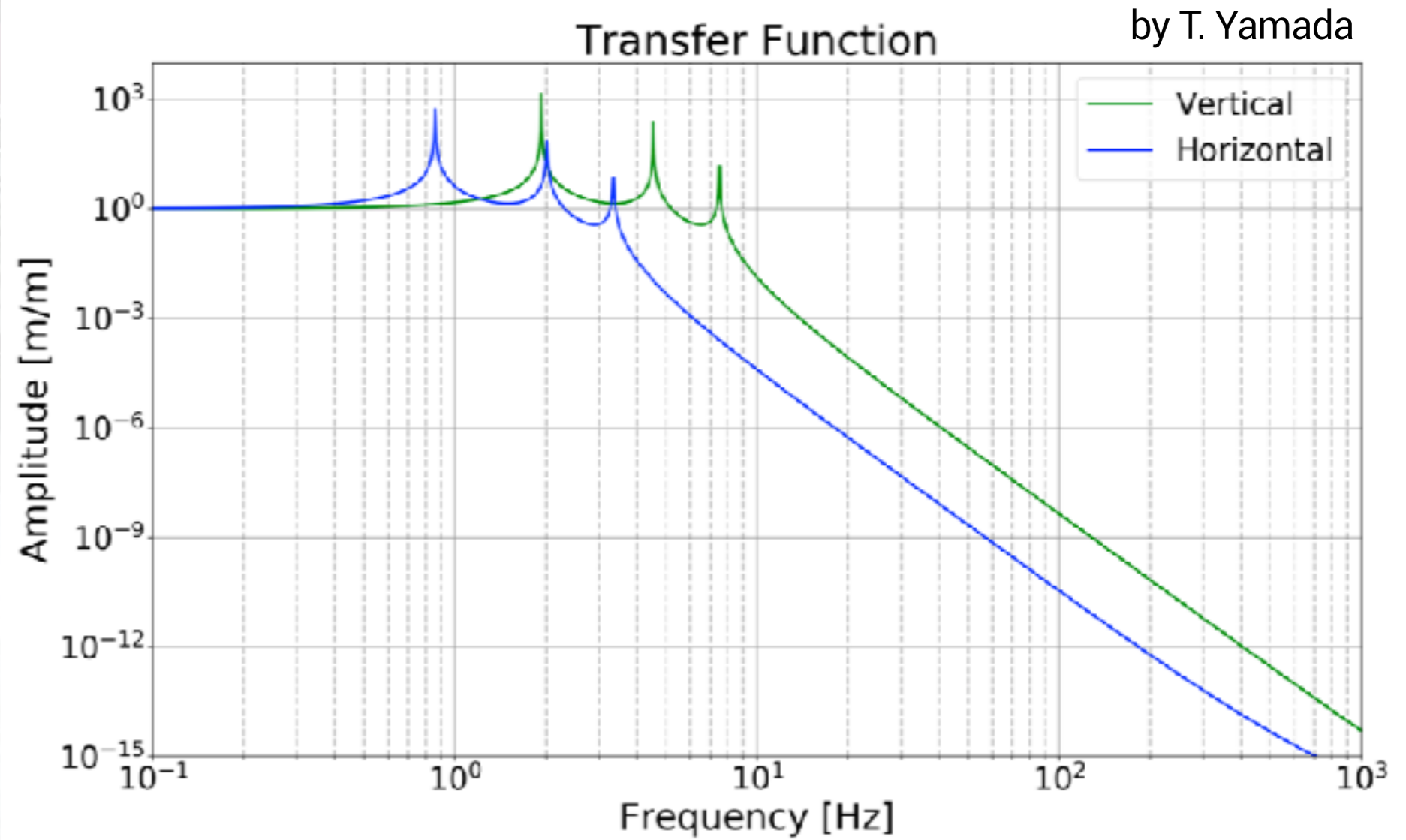
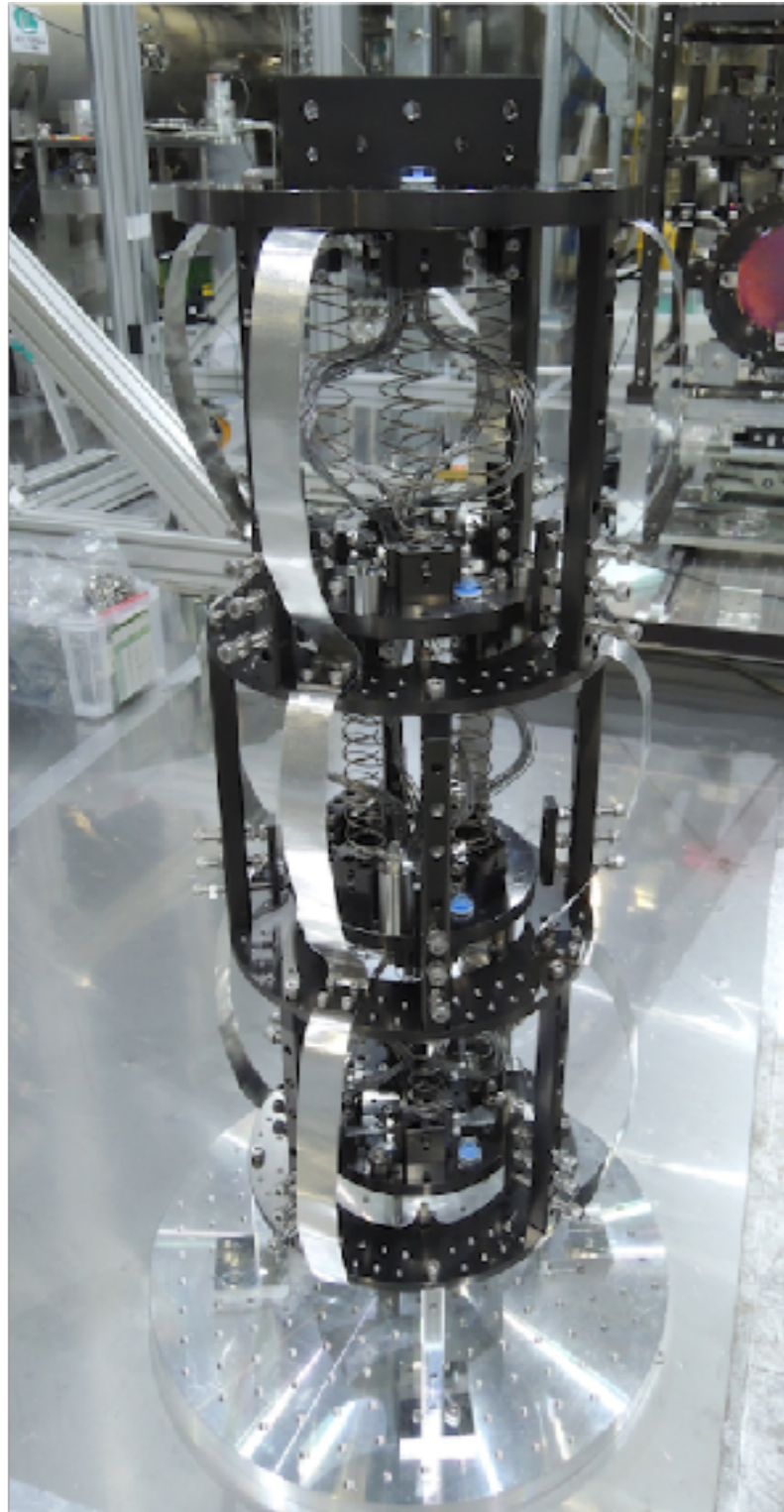
Low stiffness: $k_{\text{strand}} = \frac{1}{43} k_{\text{single}}$

Heat Link INDUCES Vibration

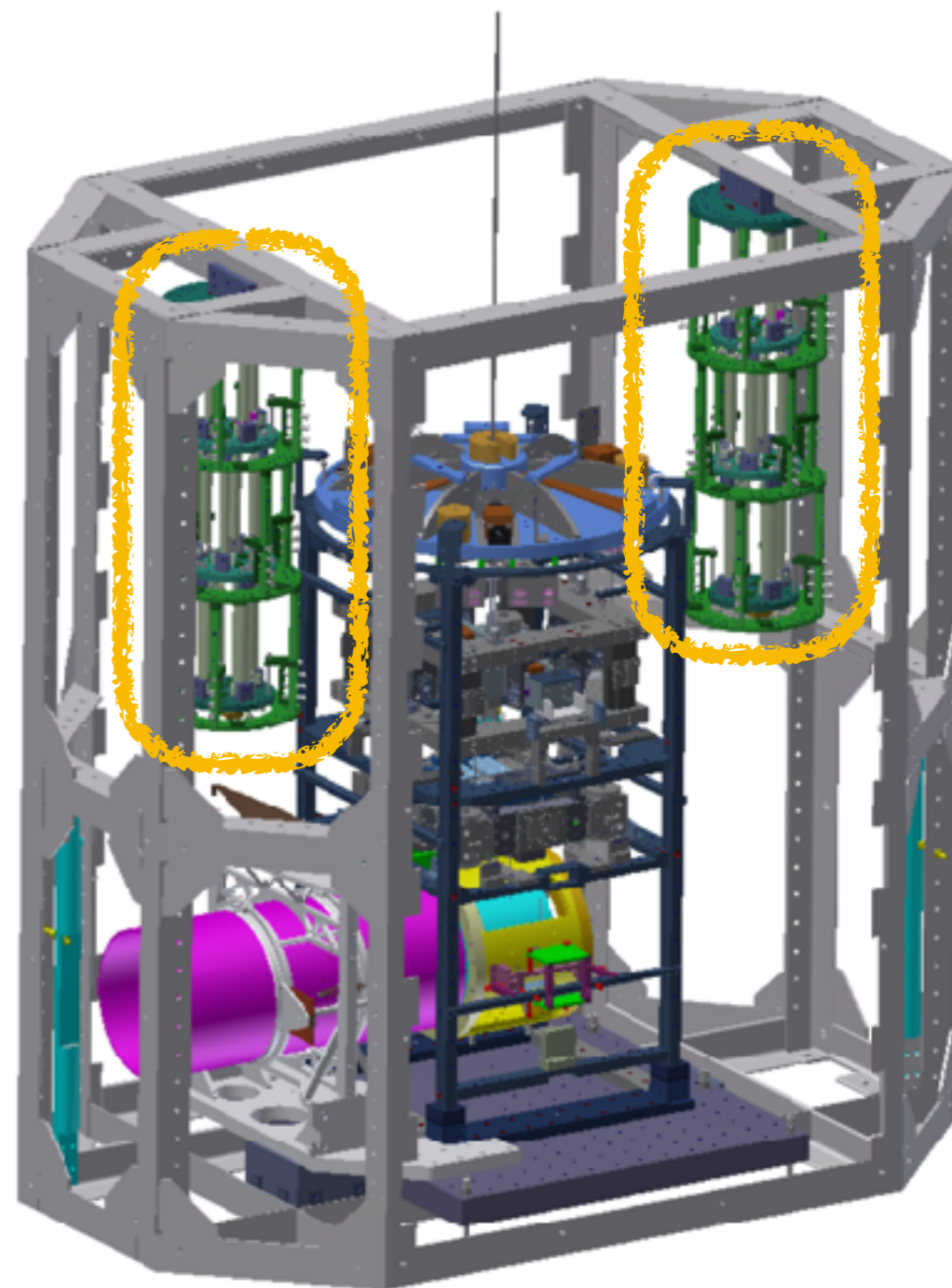
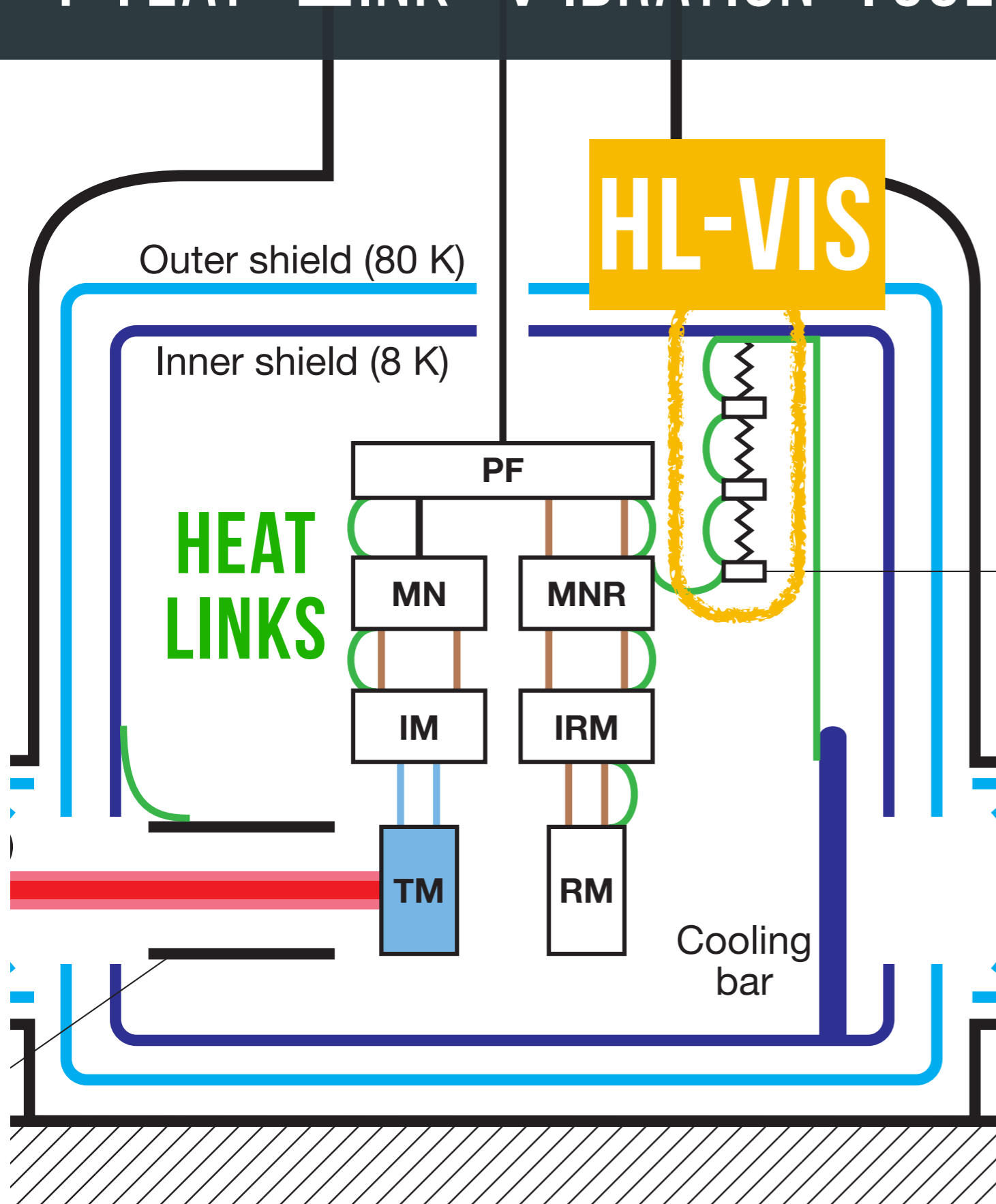
by T. Yamada



HEAT LINK VIBRATION ISOLATION SYSTEM

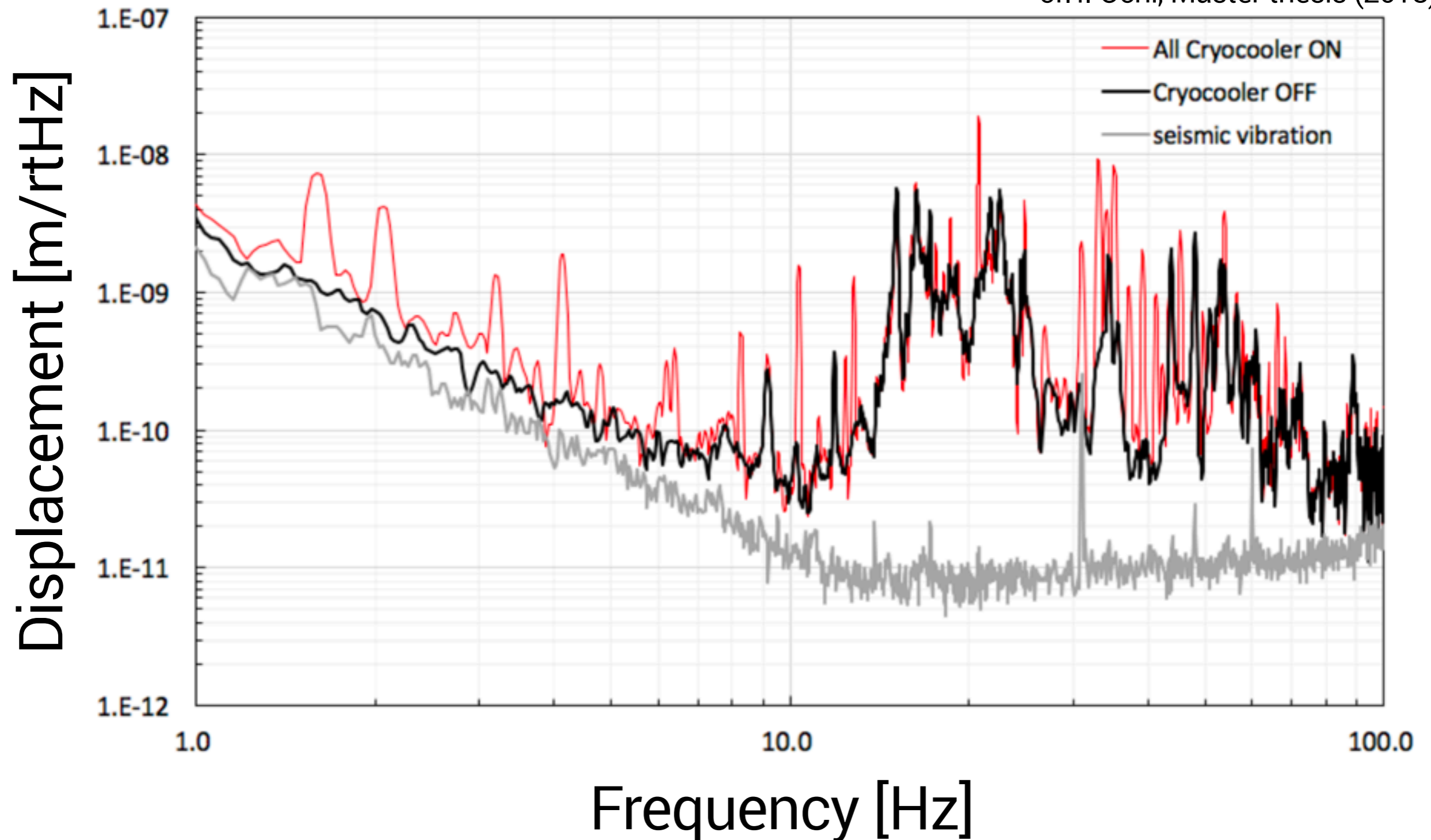


HEAT LINK VIBRATION ISOLATION SYSTEM



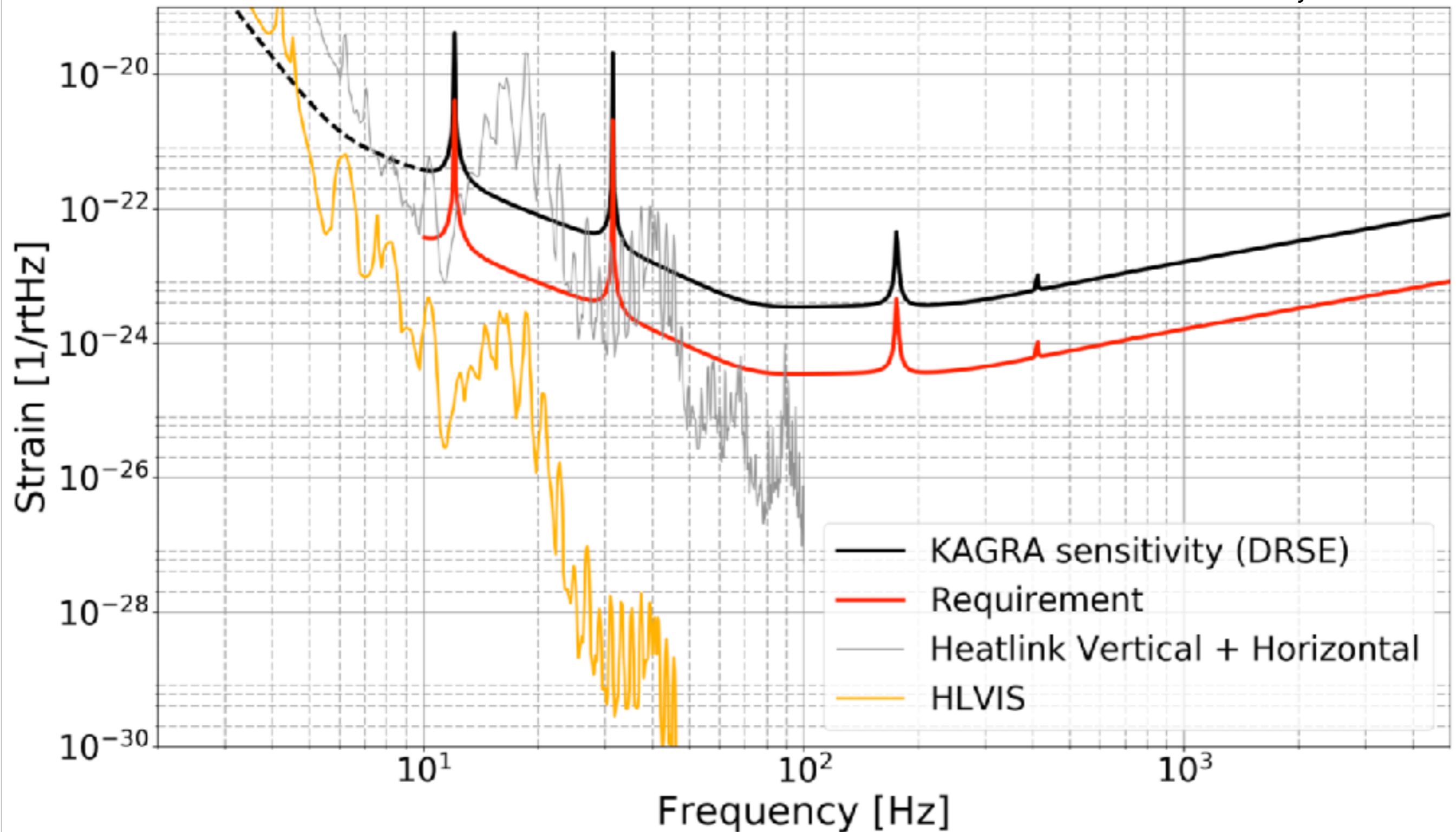
Vibration IN THE Cryostat

cf.T. Ochi, Master thesis (2018)

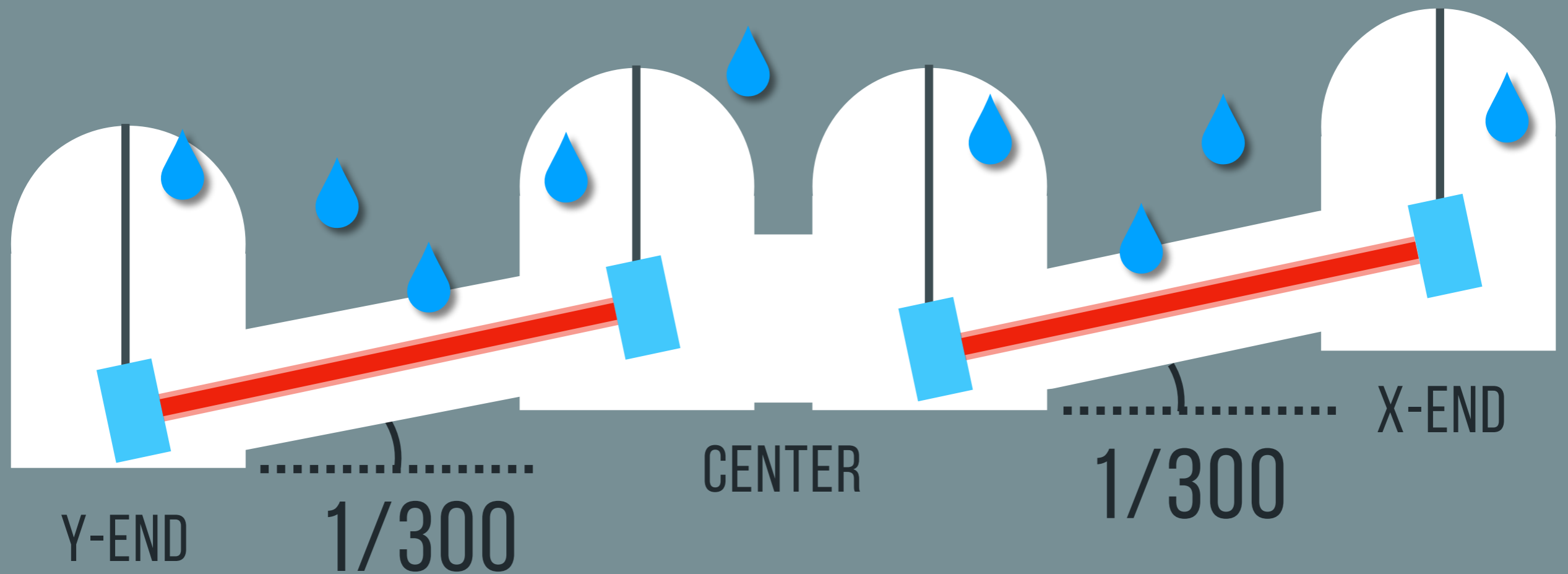


HL-VIS Design Performance

by T. Yamada



VERTICAL-TO-LONGITUDINAL Coupling



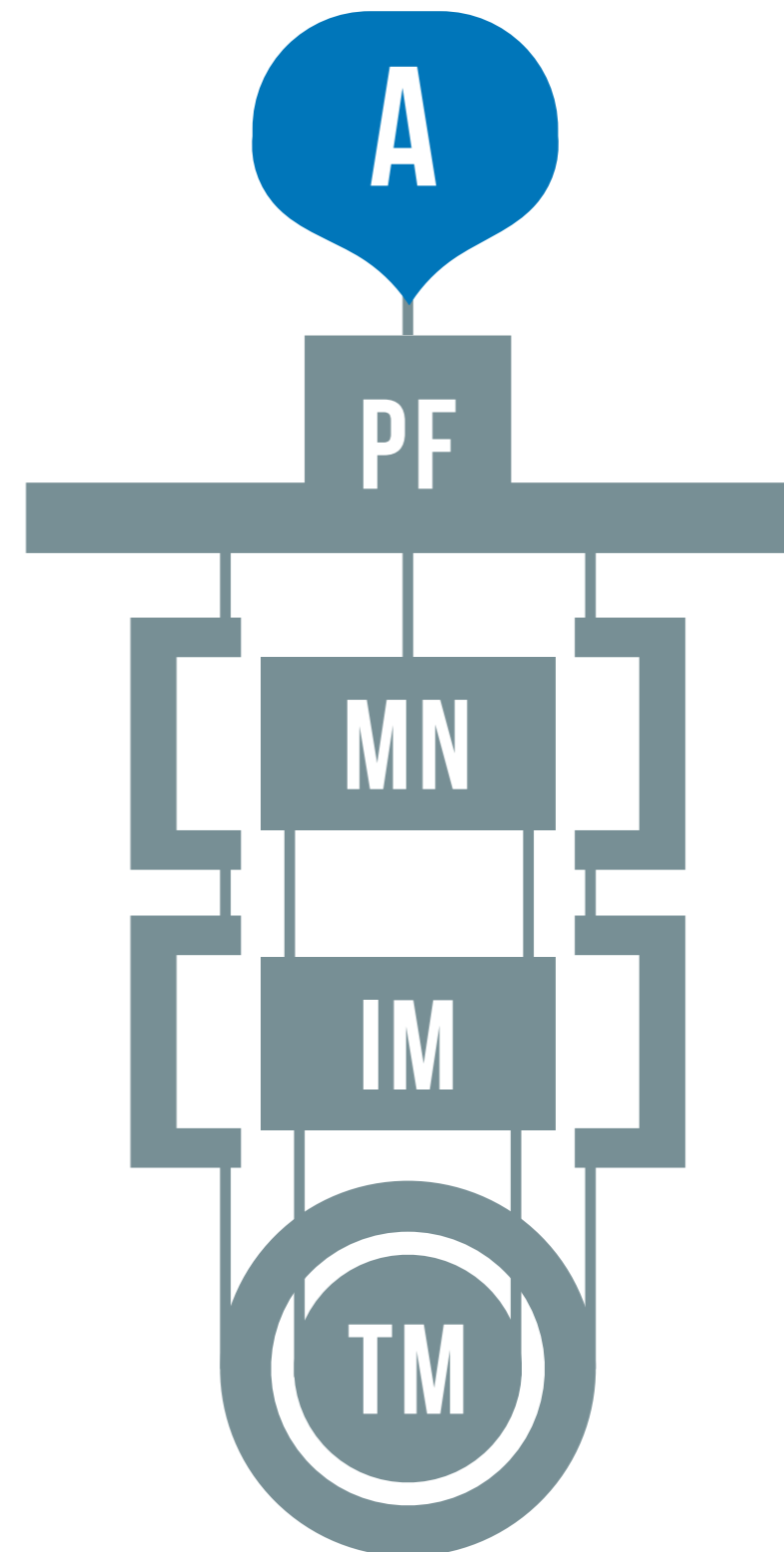
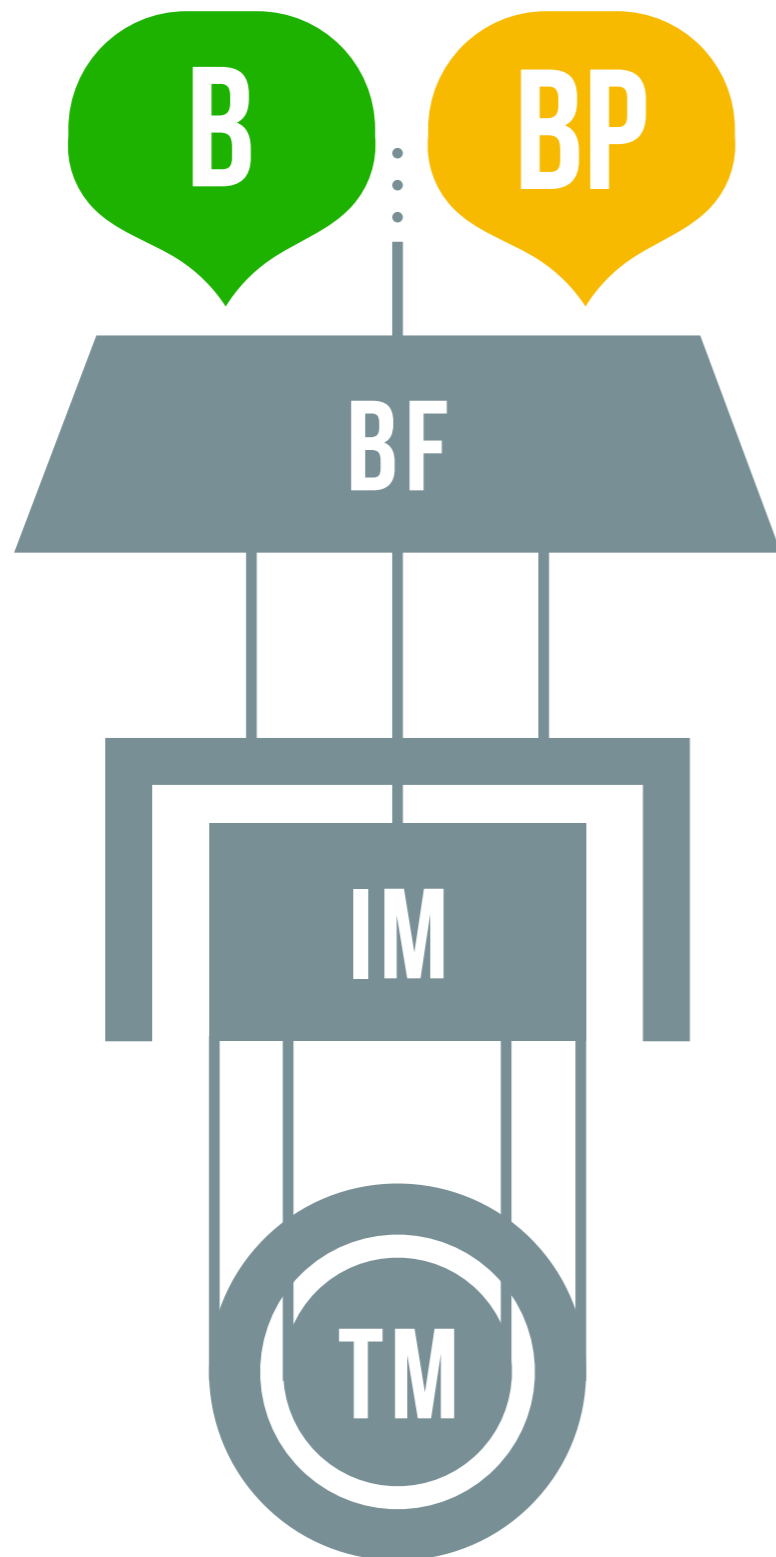
$$\frac{\text{(Longitudinal)}}{\text{(Vertical)}} \lesssim 1\%$$

VERTICAL-TO-LONGITUDINAL Coupling

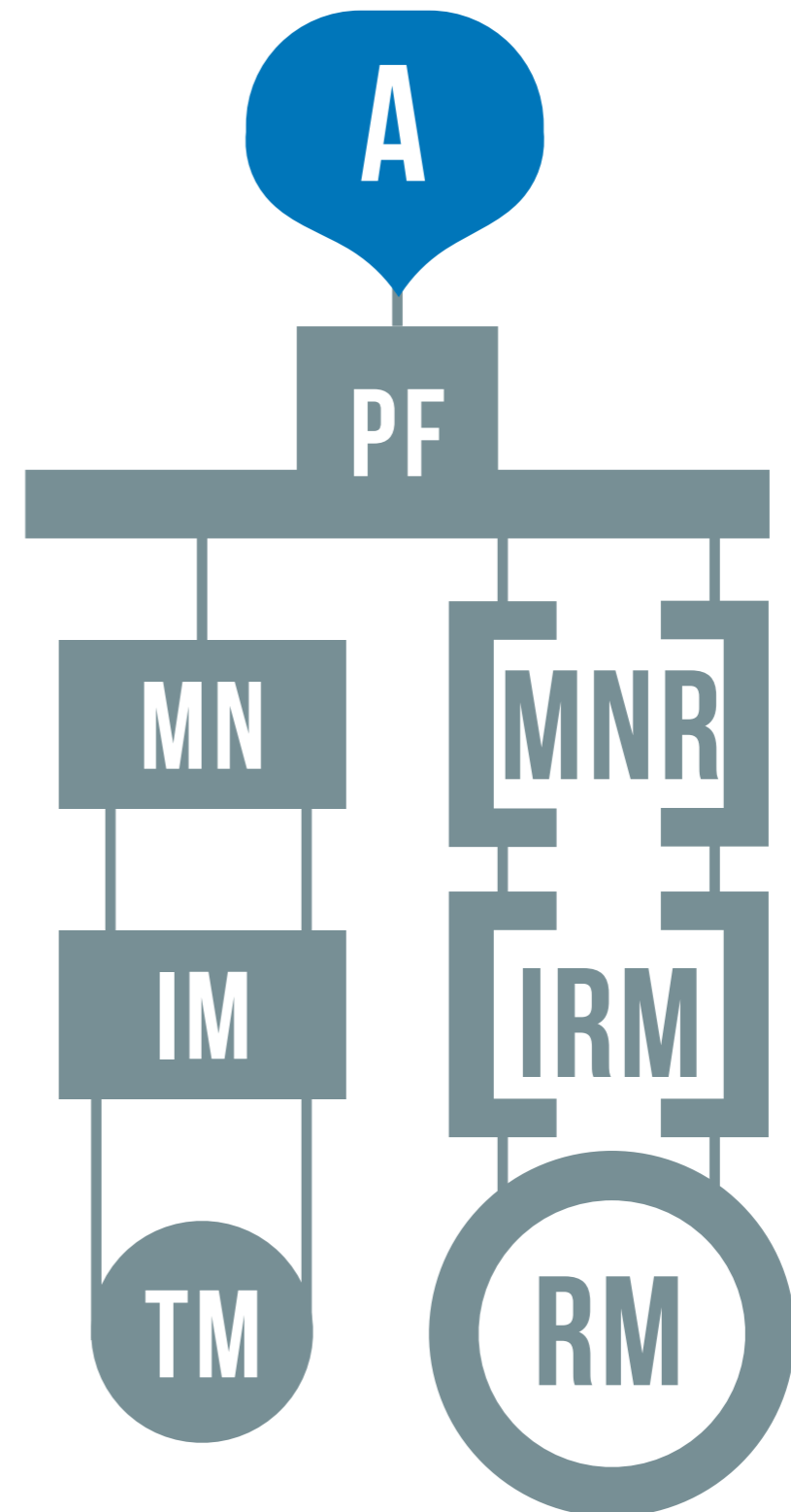
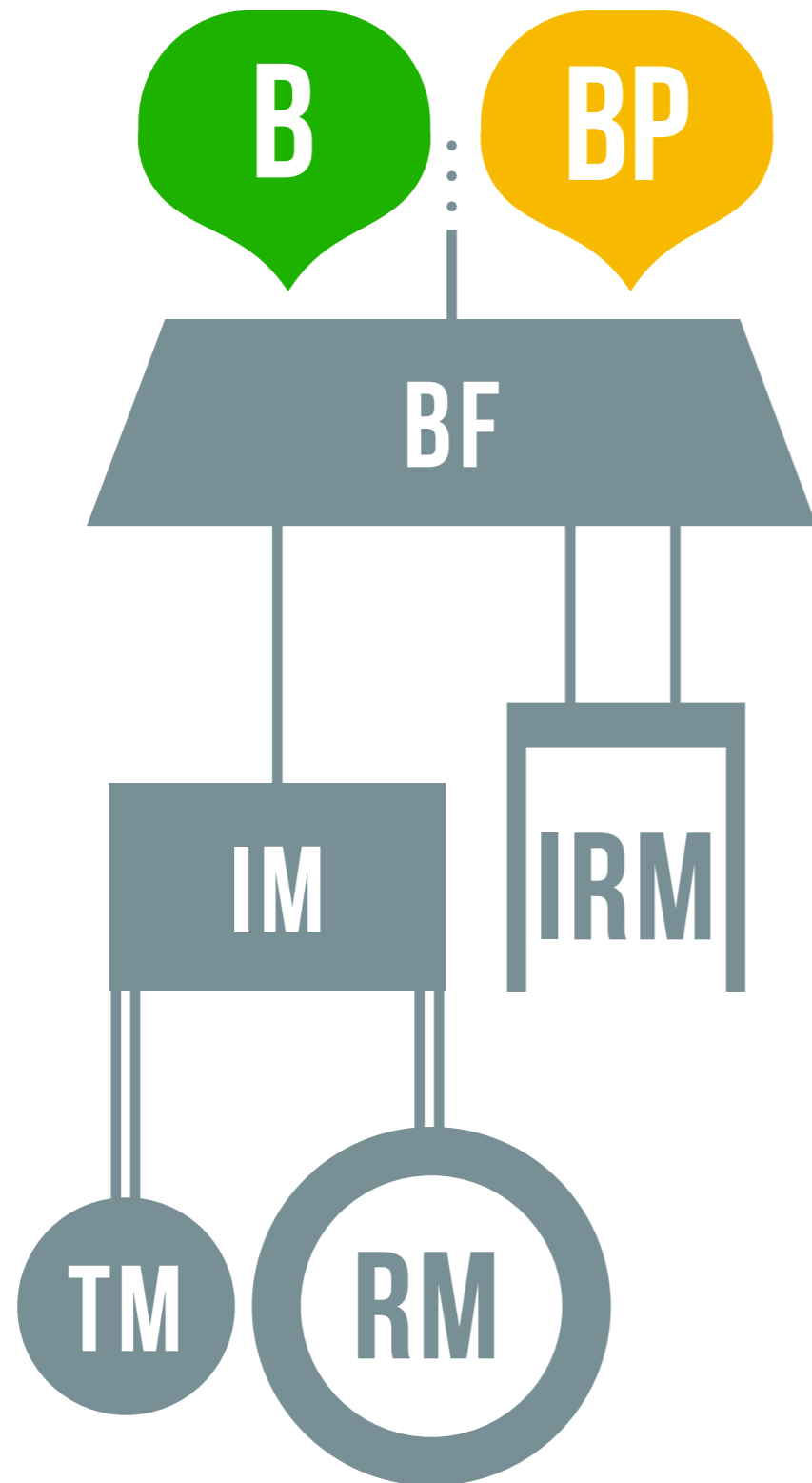


2017.04.11

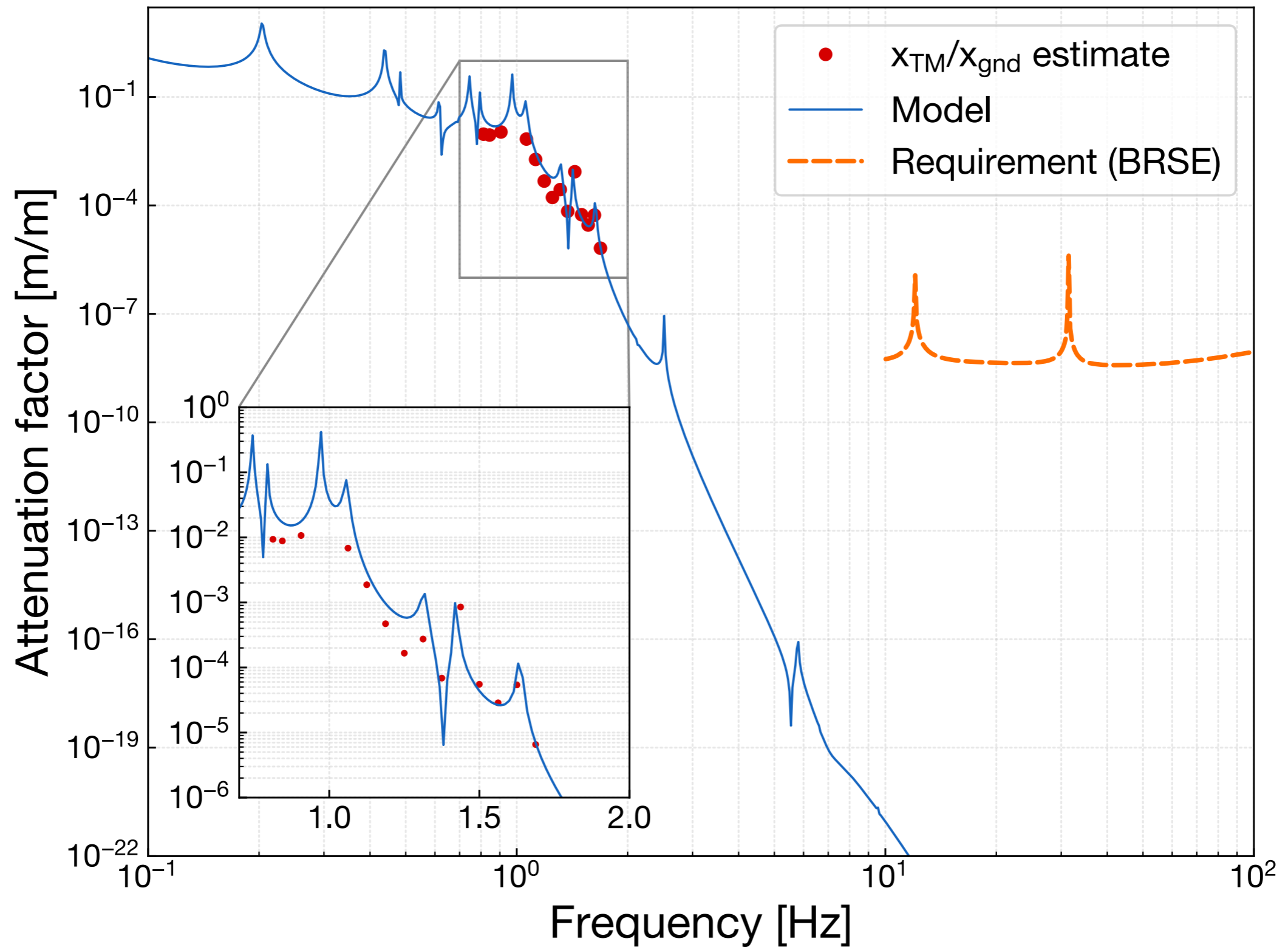
Payload Structure



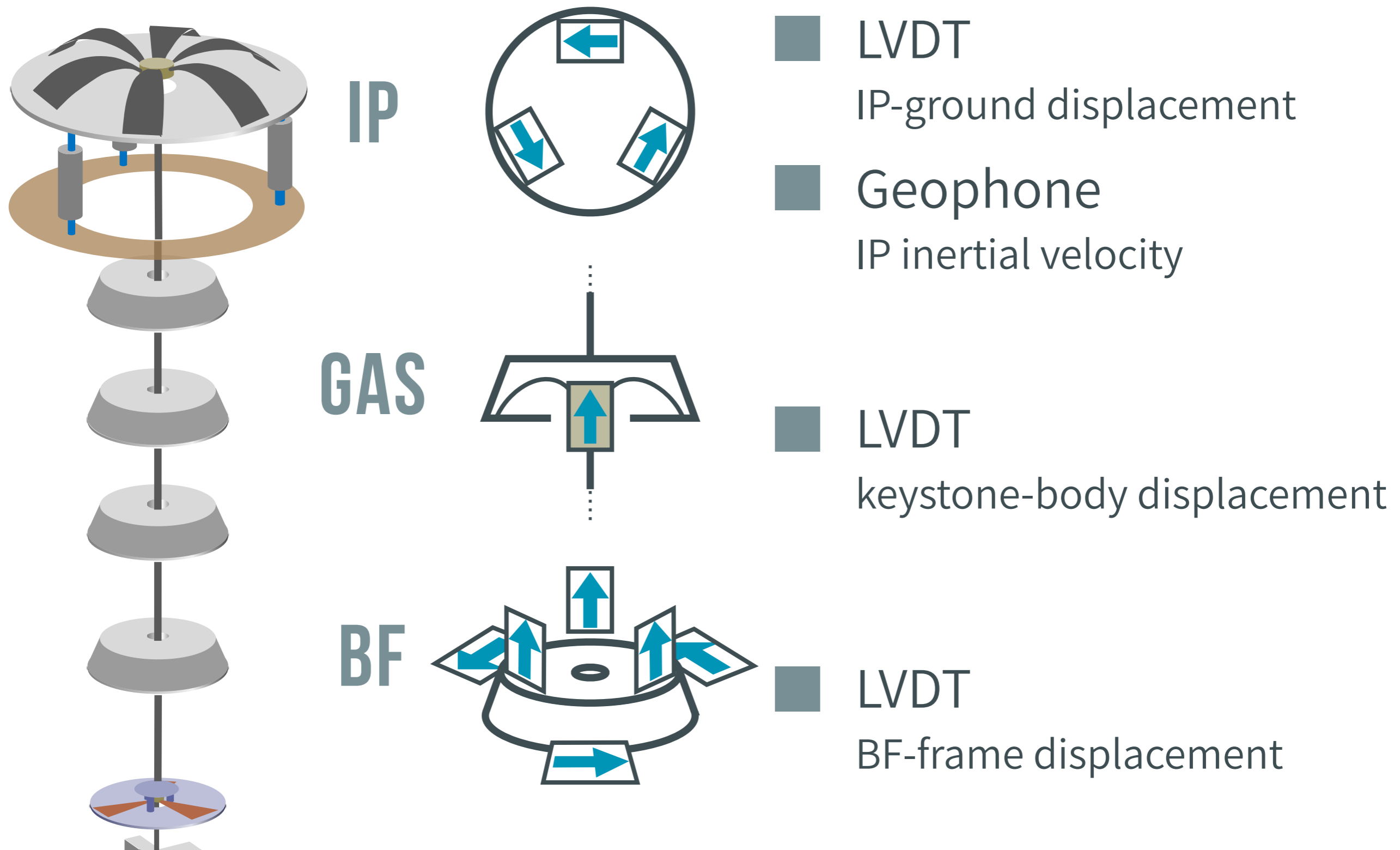
Payload Structure



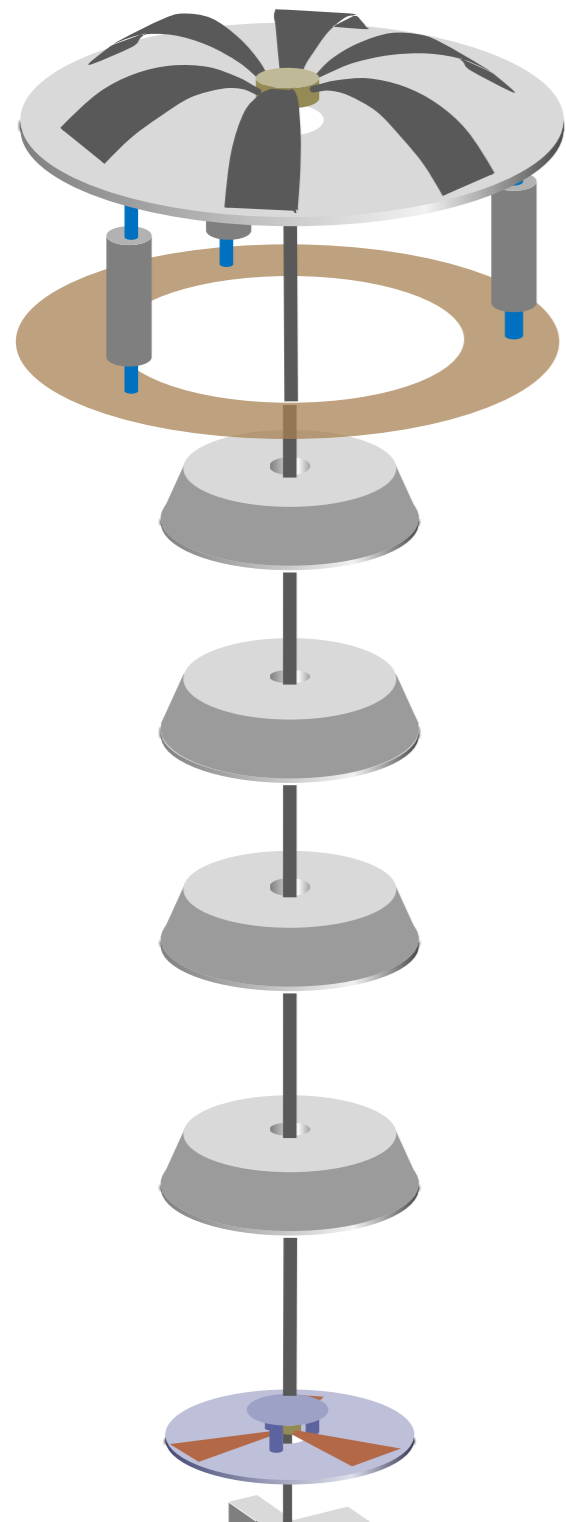
VIBRATION ISOLATION RATIO Measurement



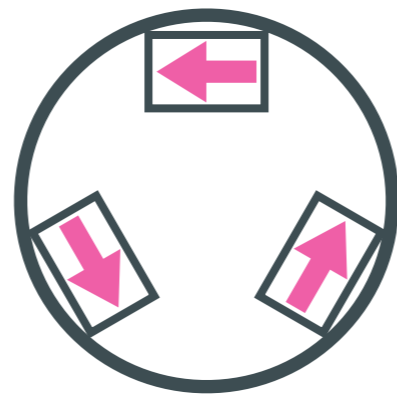
Local Sensors - Tower



Local Actuators - Tower

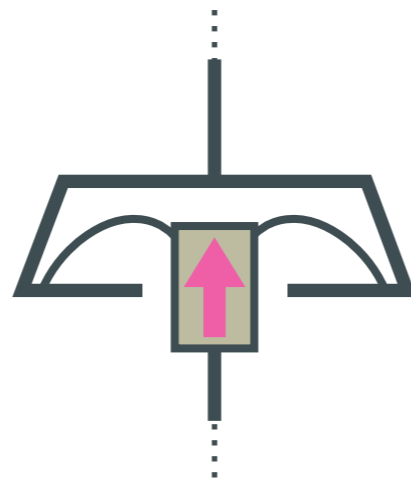


IP



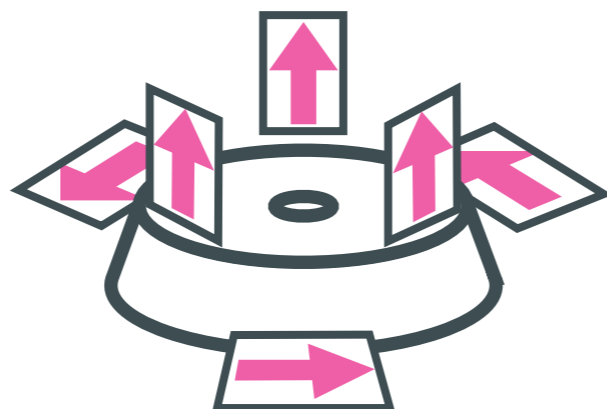
■ Voice coil actuator
IP-ground force

GAS



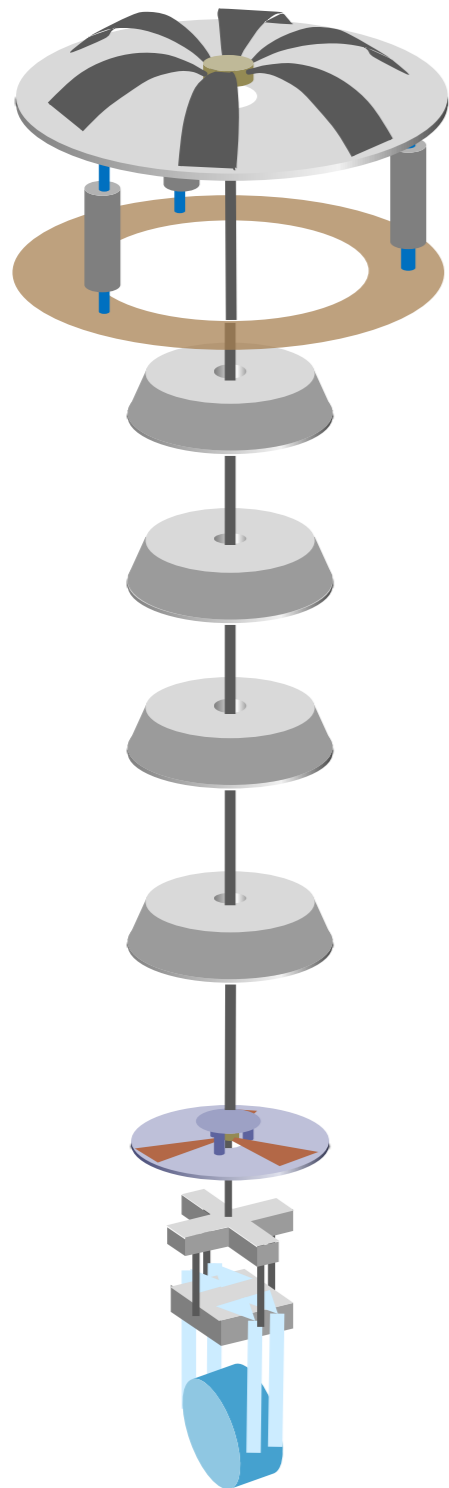
■ Voice coil actuator
keystone-body force

BF



■ Coil-magnet actuator
BF-frame force

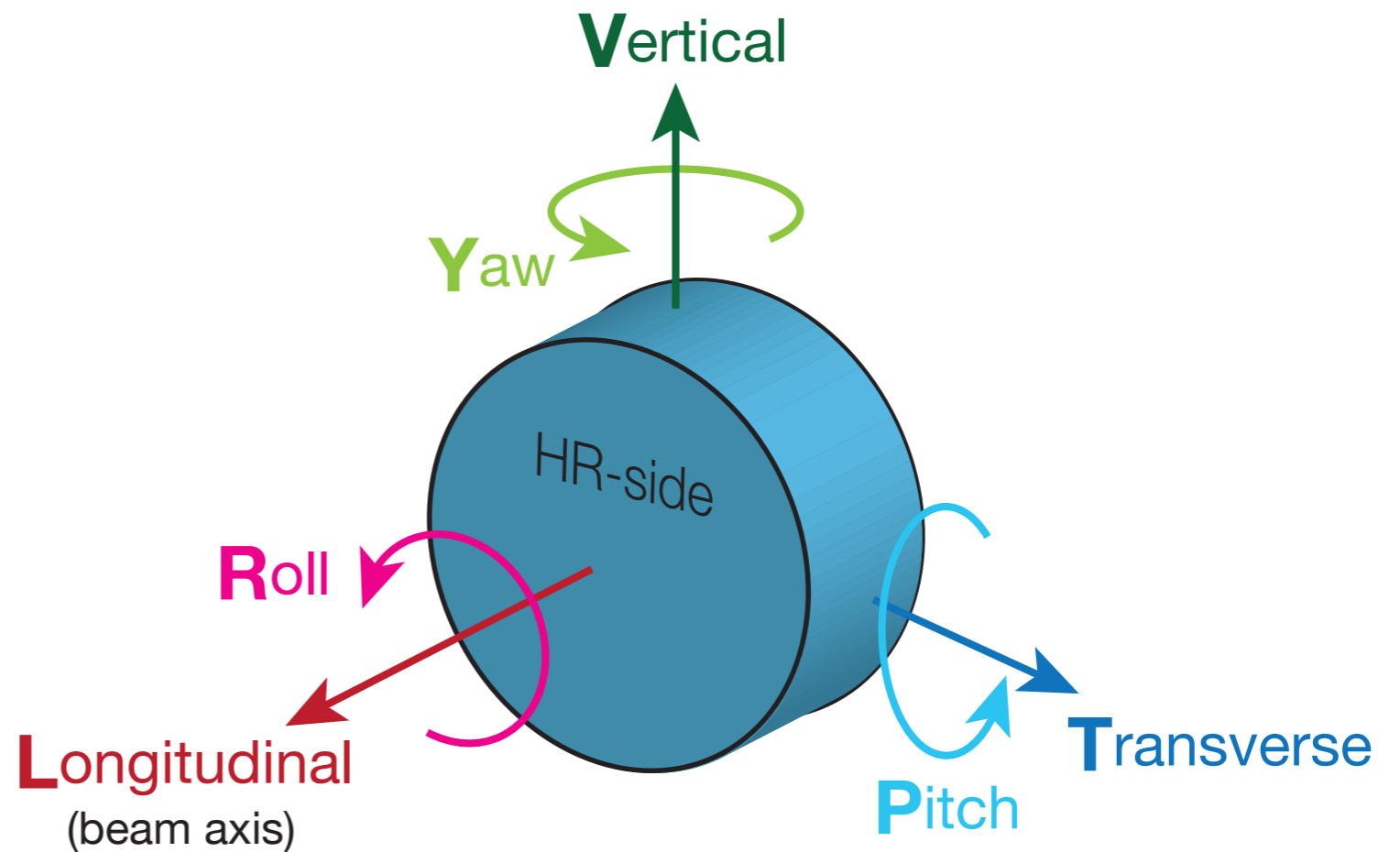
Torsion Mode Damping



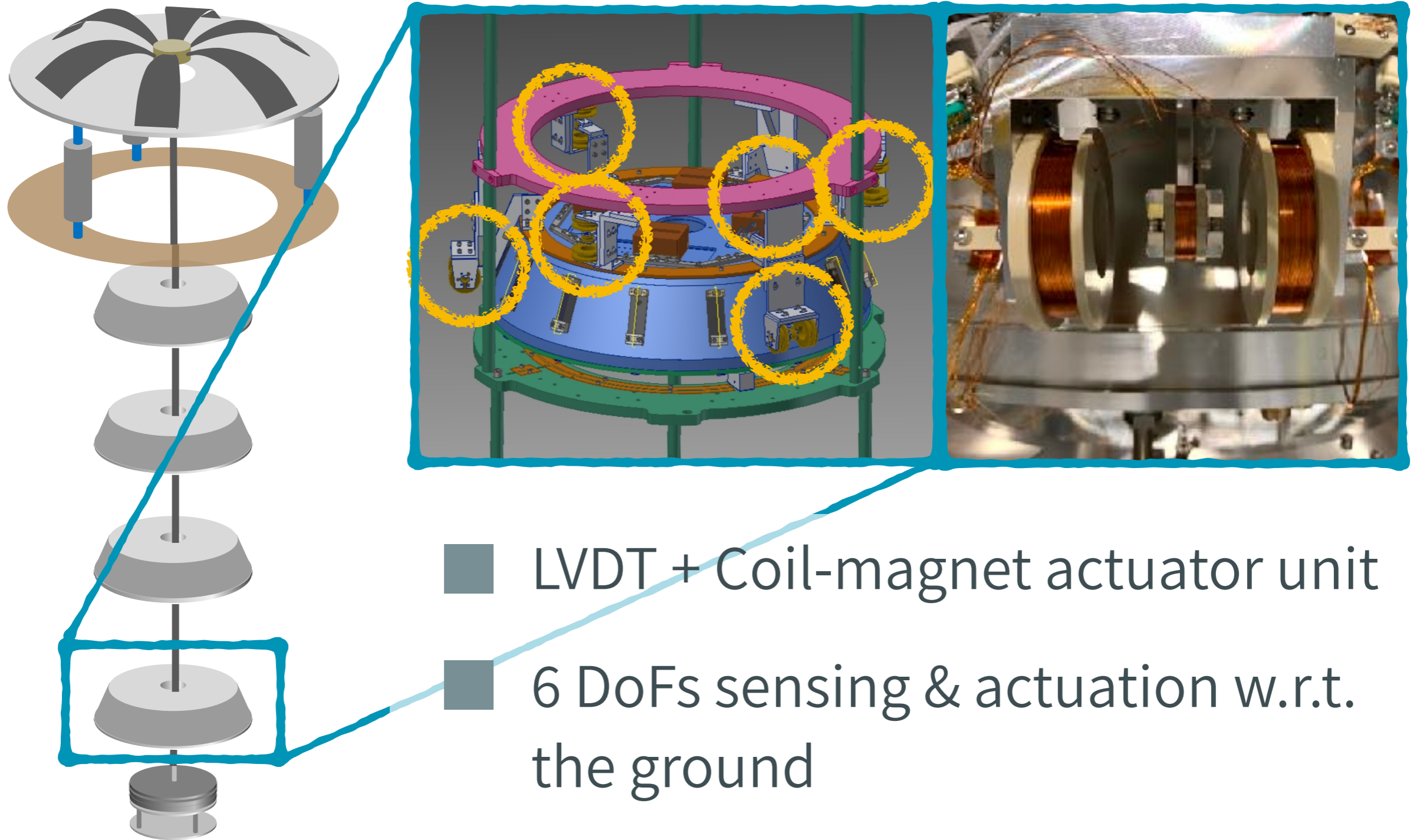
SINGLE WIRE CONNECTION

Requirements

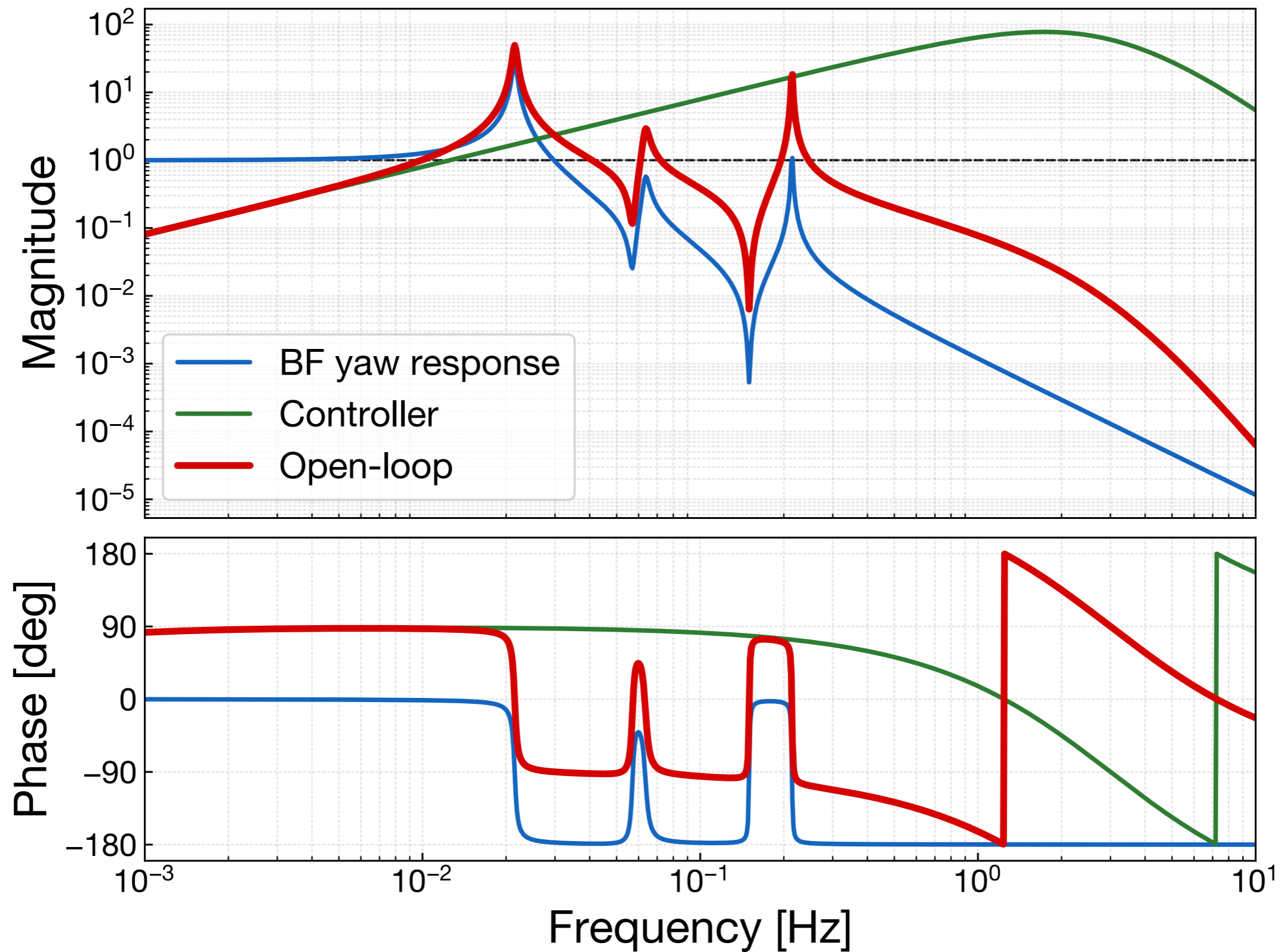
- Yaw RMS at TM < **0.88 urad**
- Mode decay time < **60 sec.**



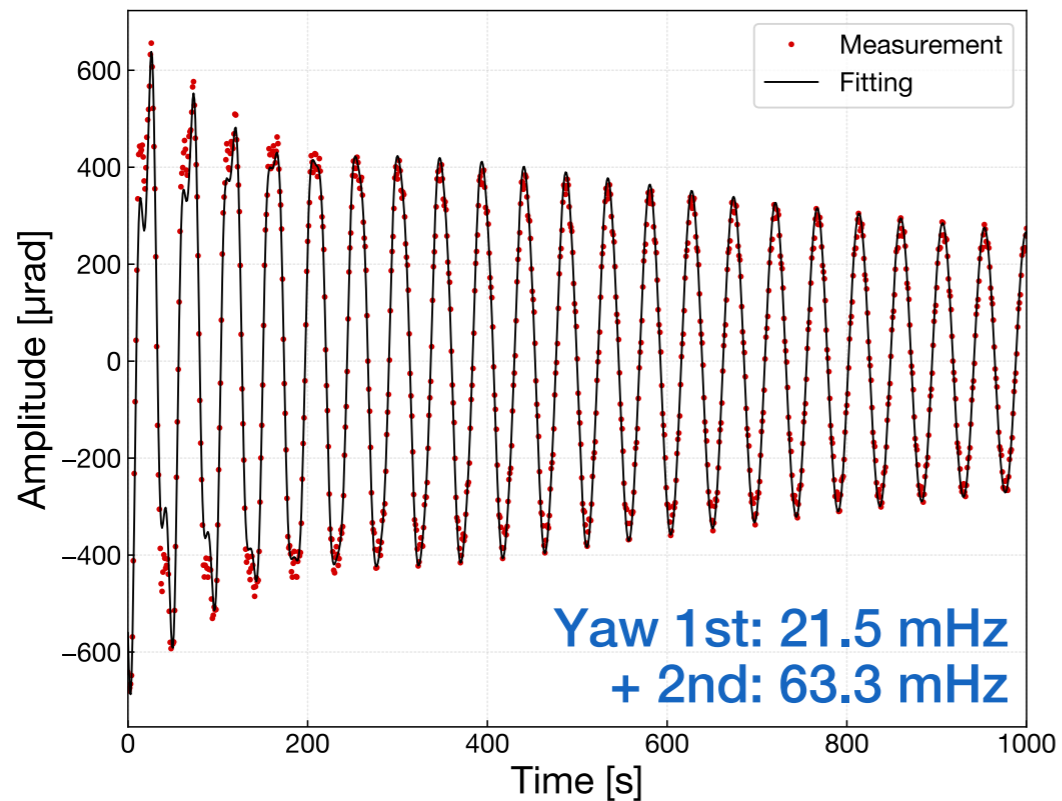
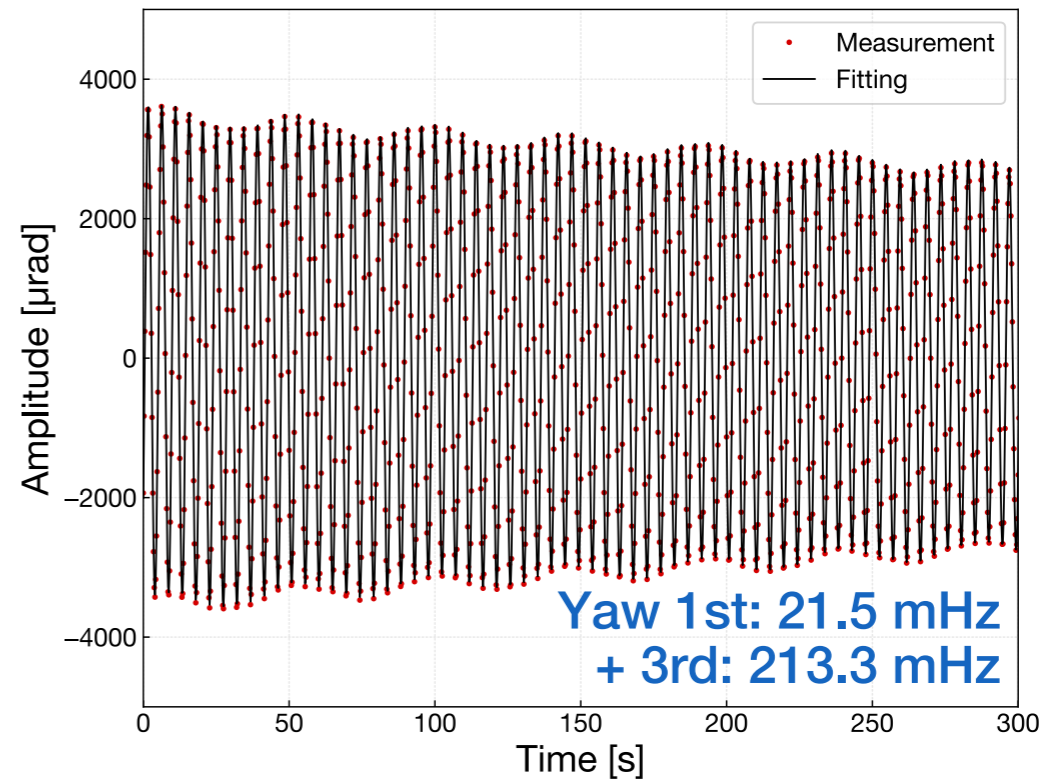
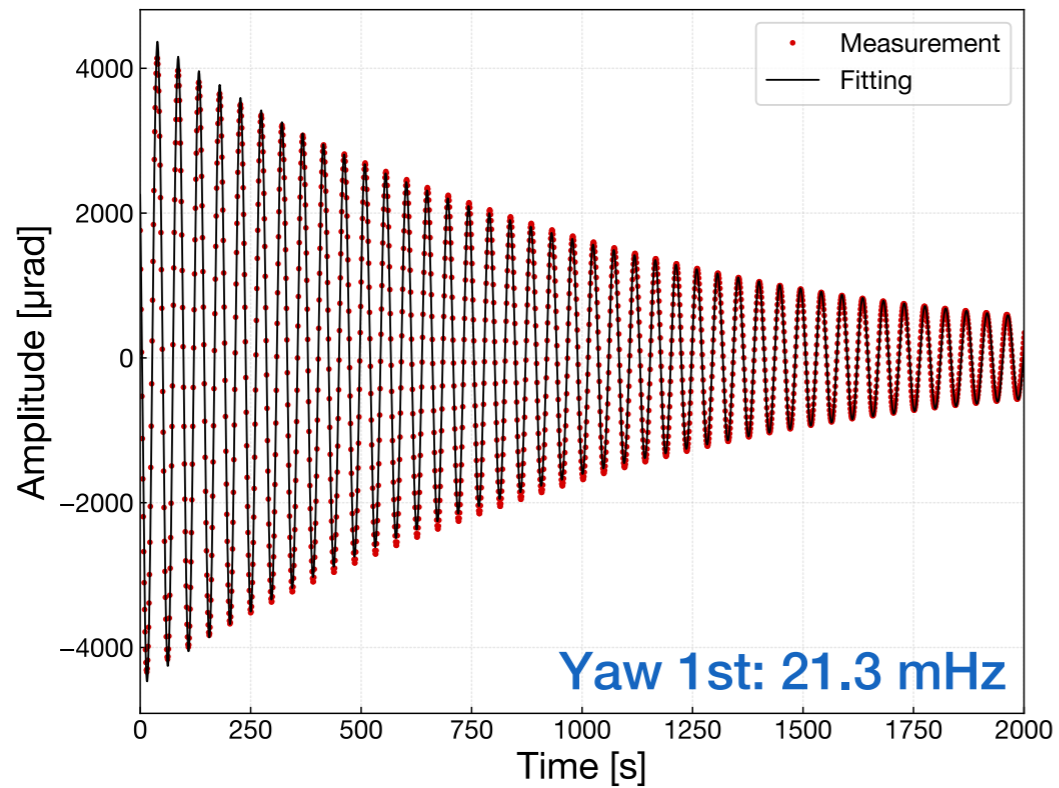
BF Damper



Damping Loop



Decay Time Measurement



MODE

DECAY TIME

#1

961.4 sec.

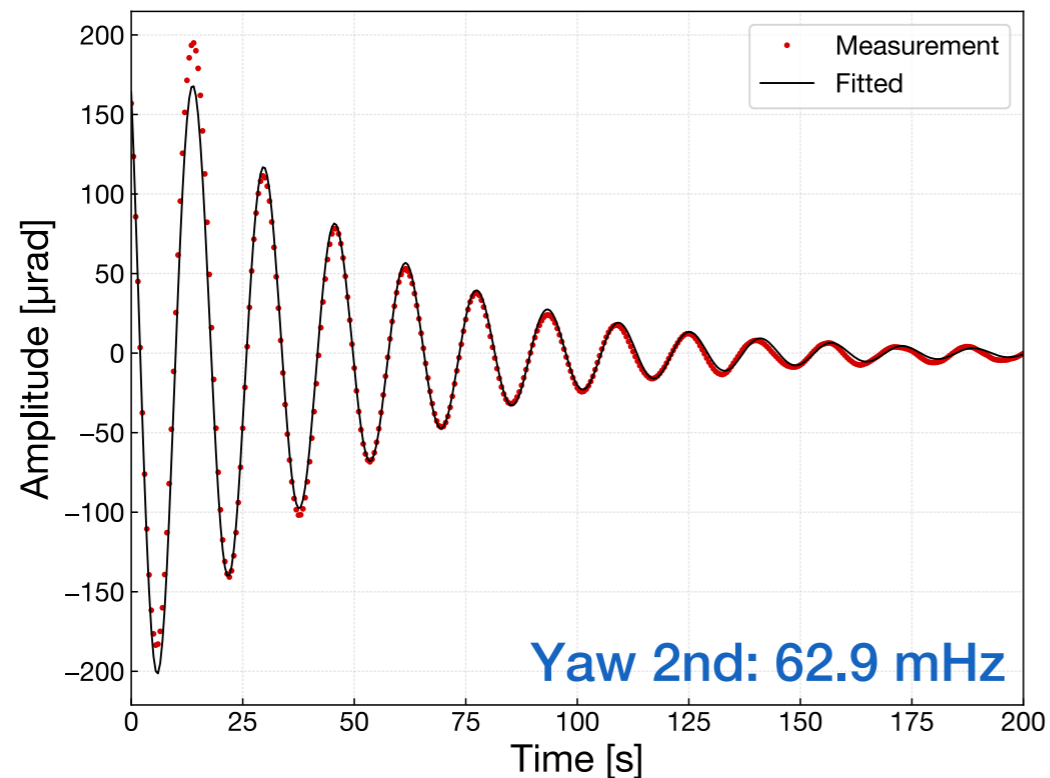
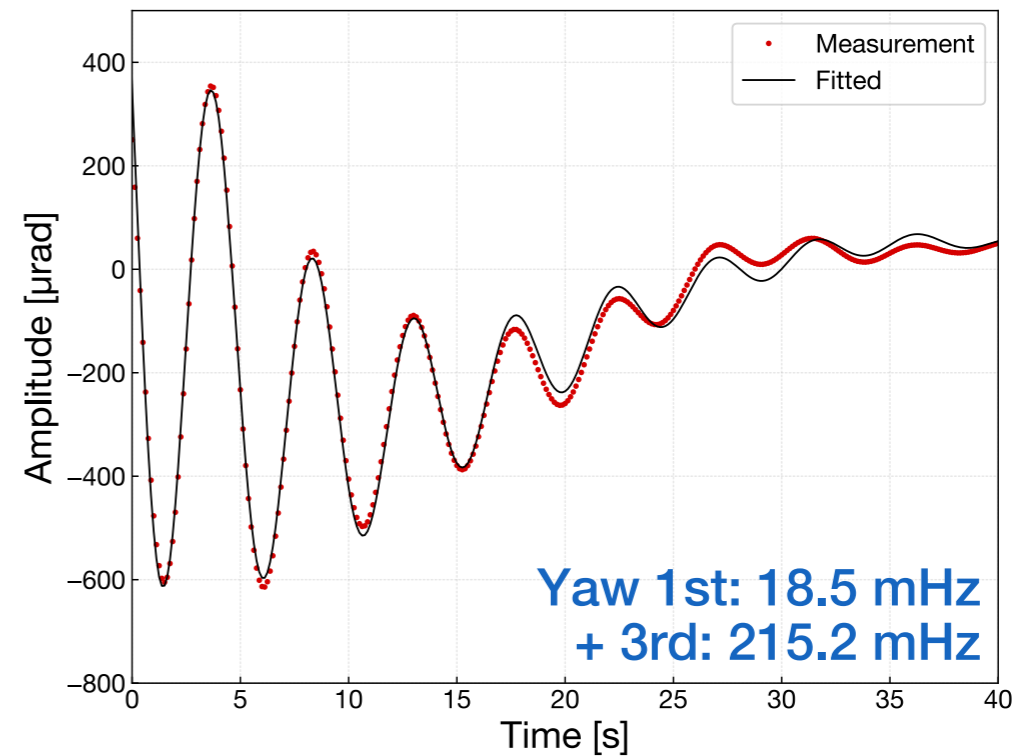
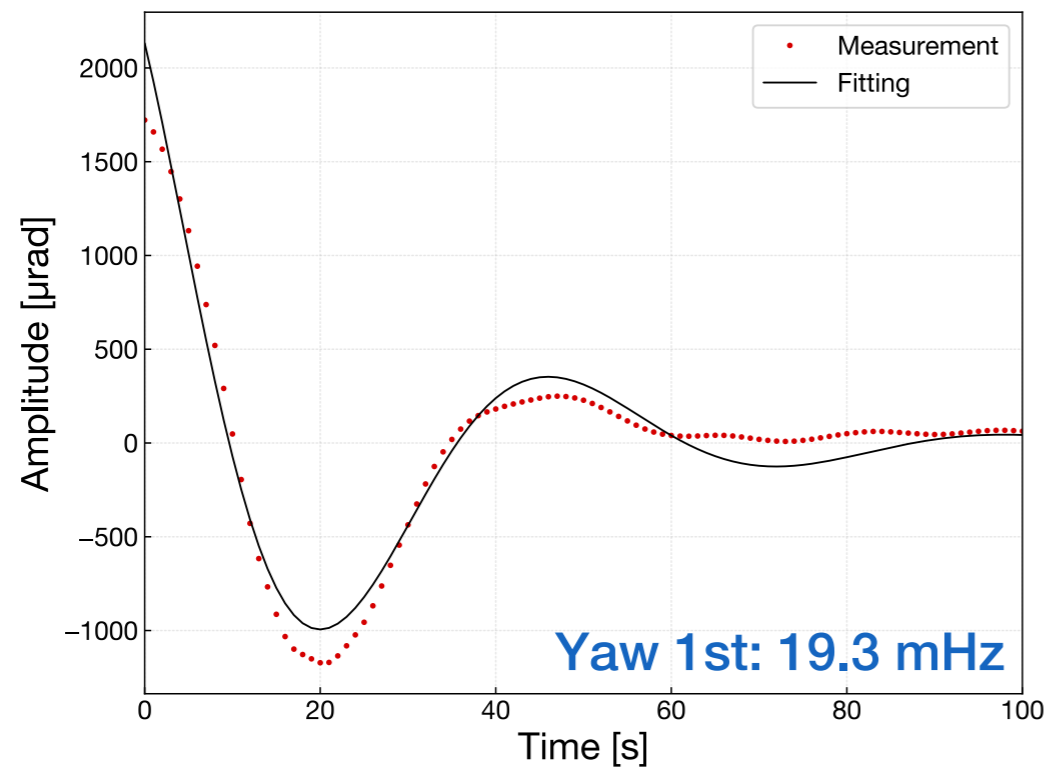
#2

158.6 sec.

#3

1155.5 sec.

Decay Time Measurement



MODE

DAMPED DECAY TIME

#1

24.8 sec.

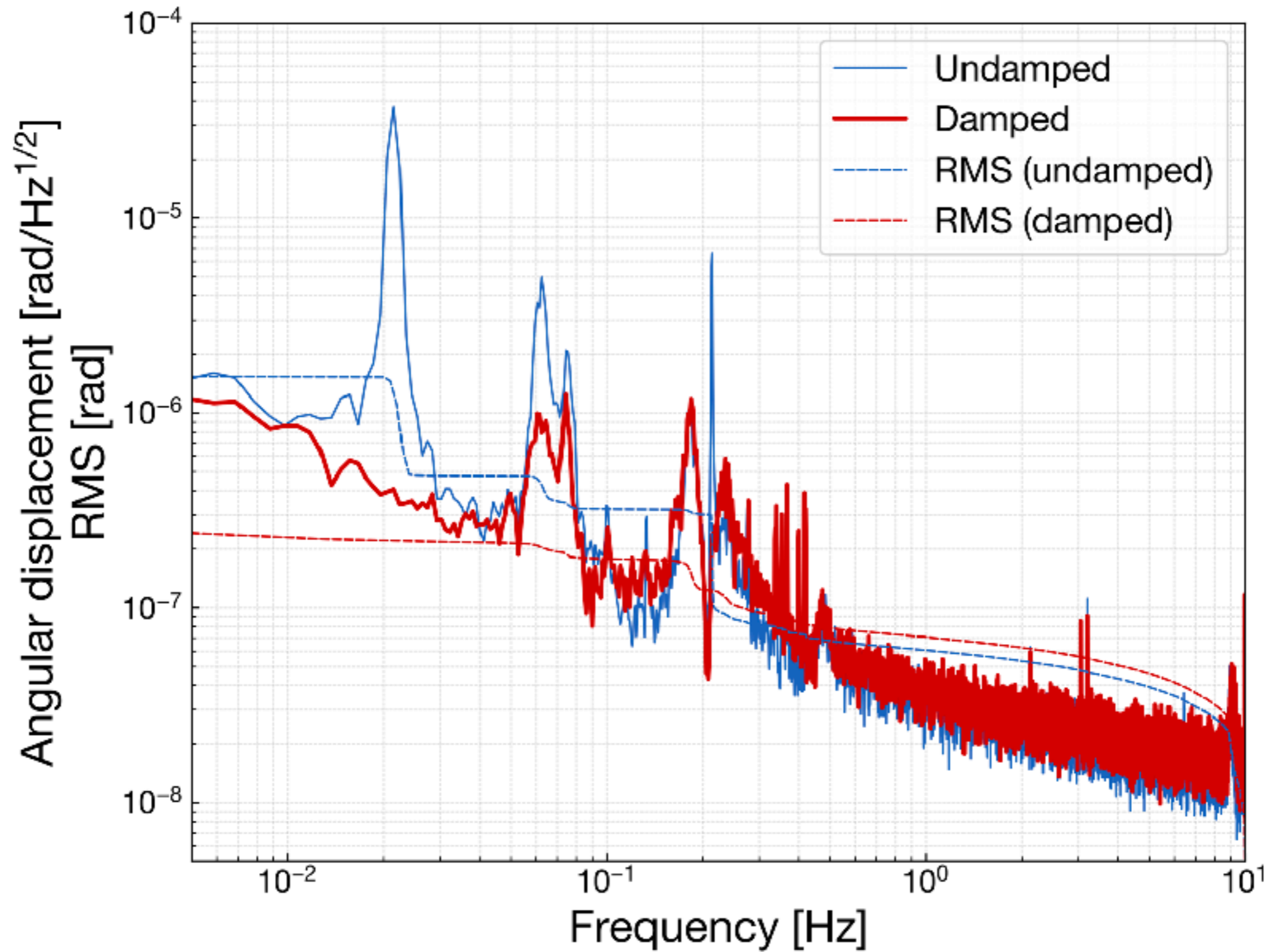
#2

43.9 sec.

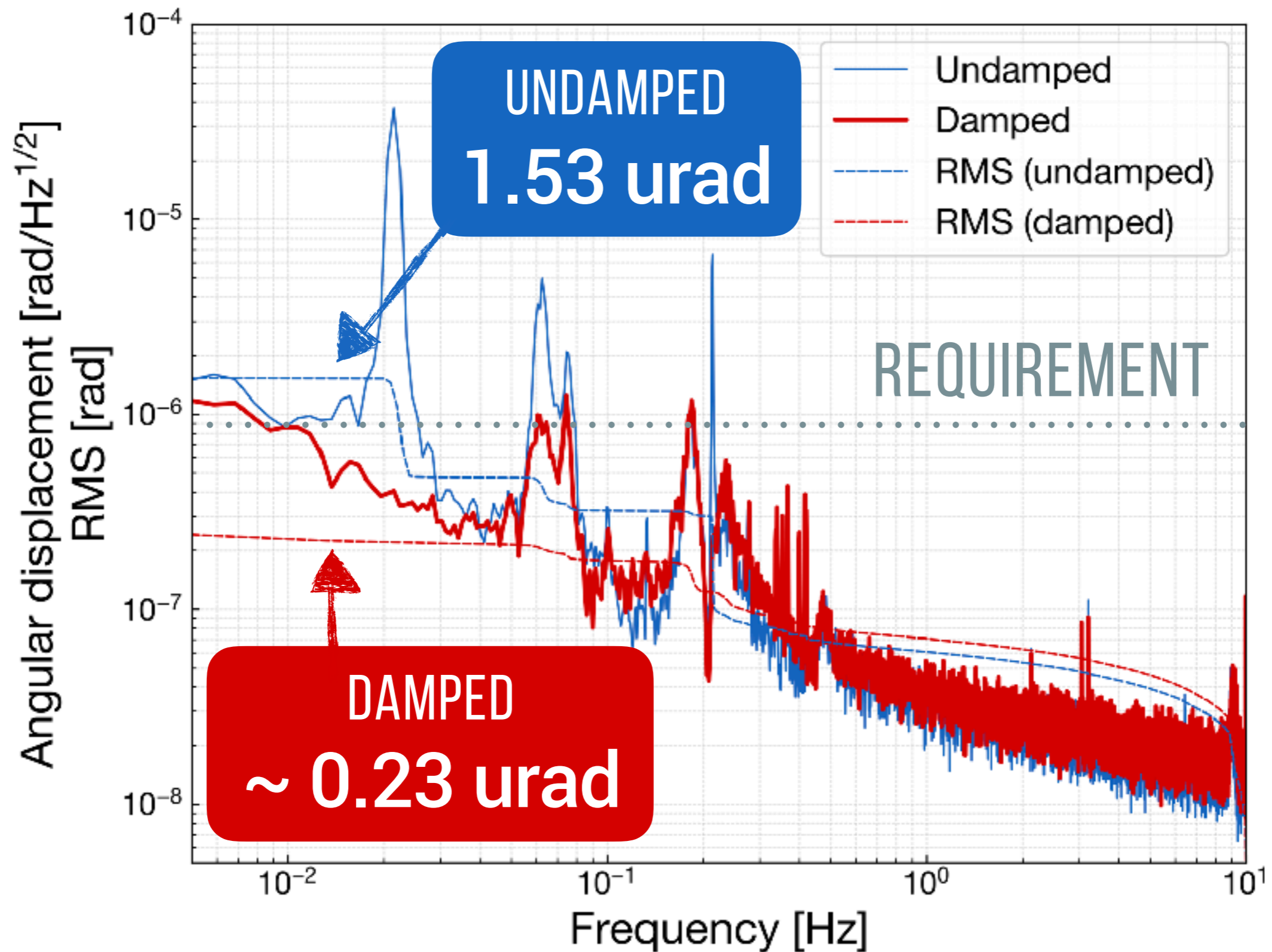
#3

9.5 sec.

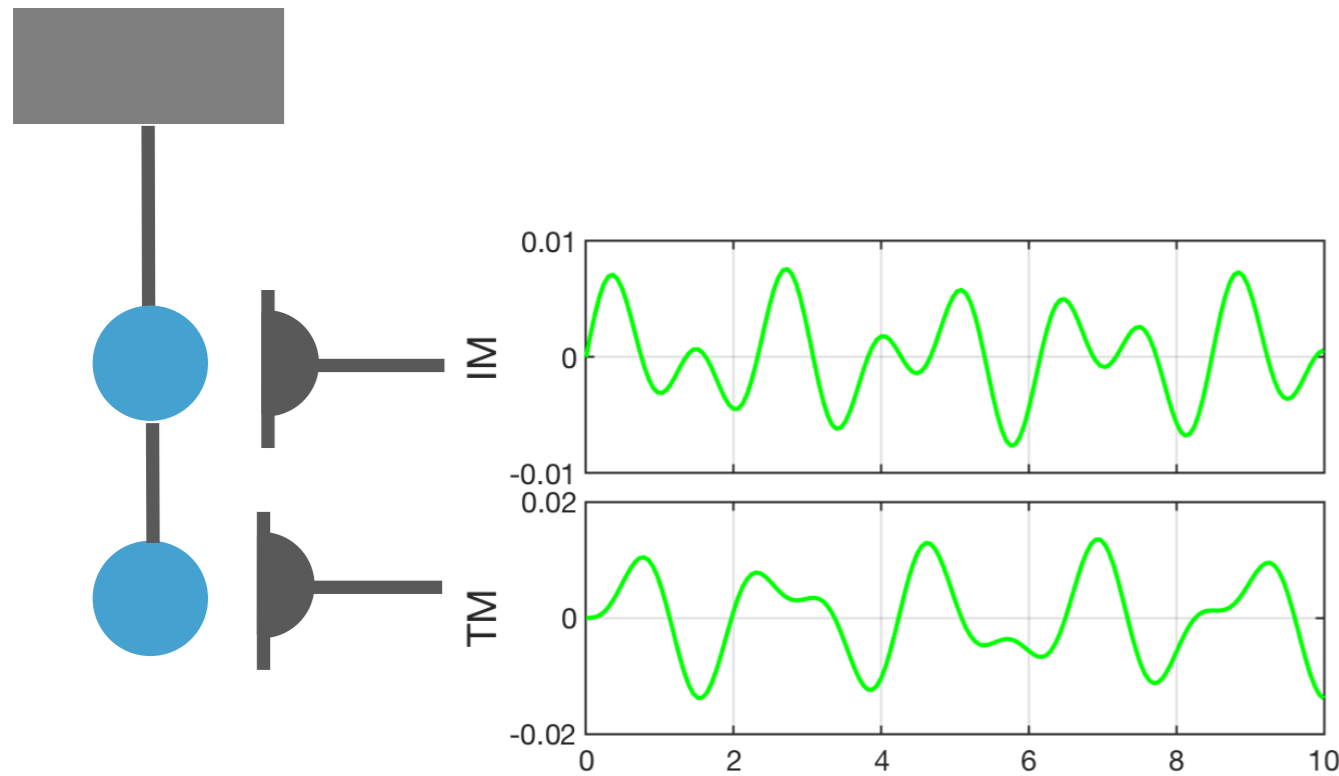
Yaw Mode Damping



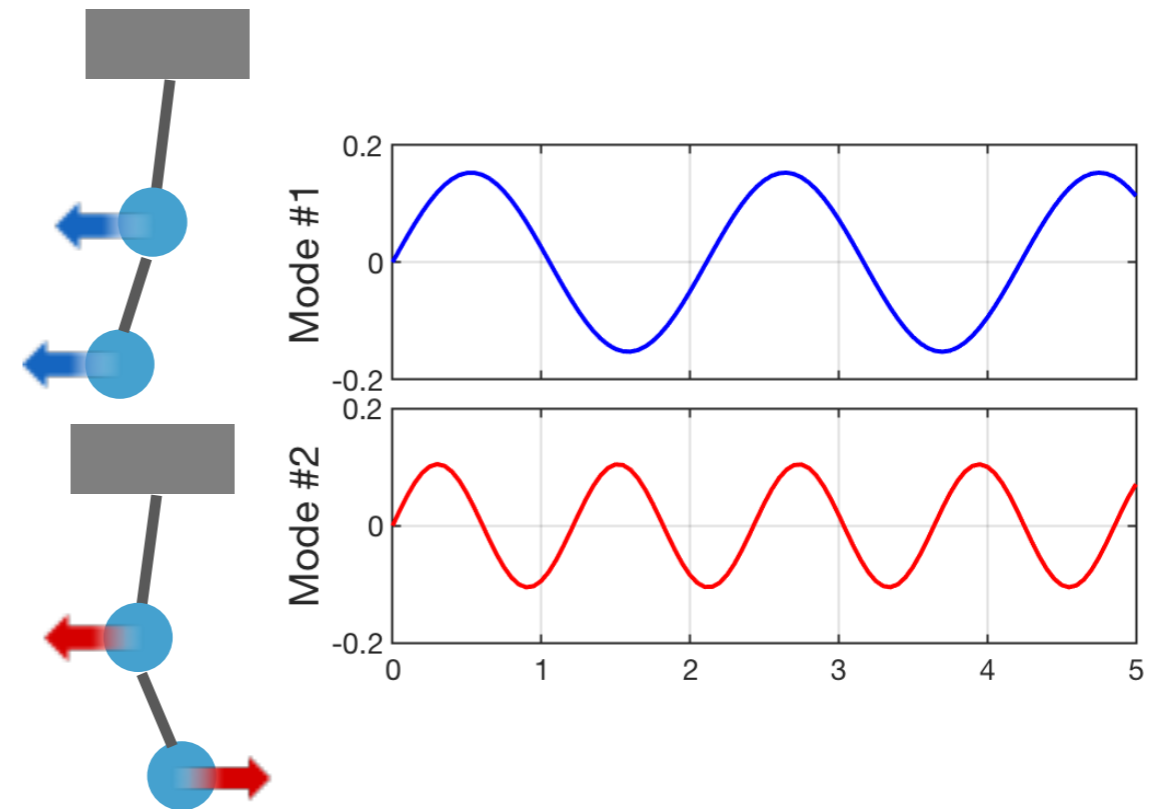
Yaw Mode Damping



Modal Damping



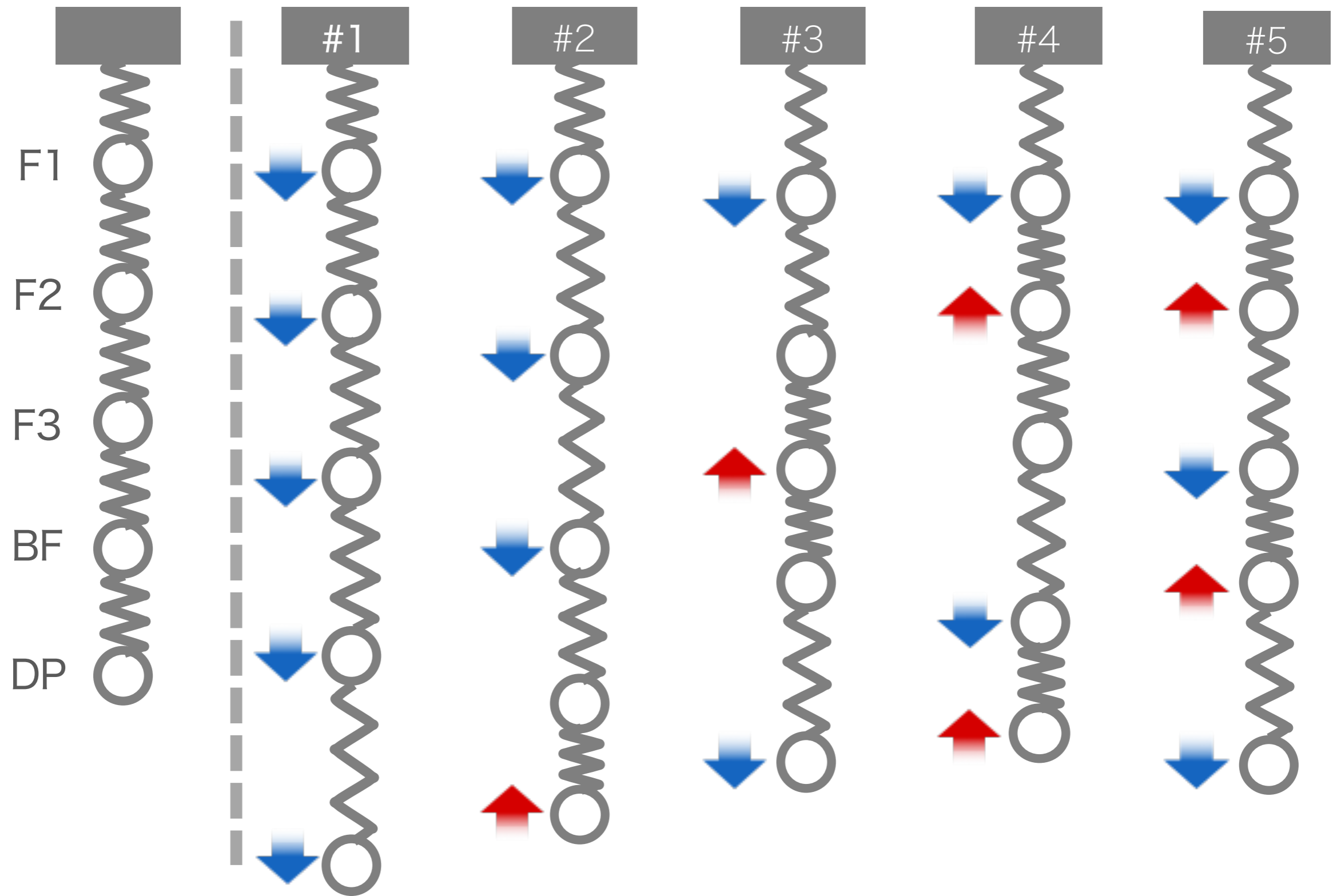
STAGE-BASIS



MODAL-BASIS

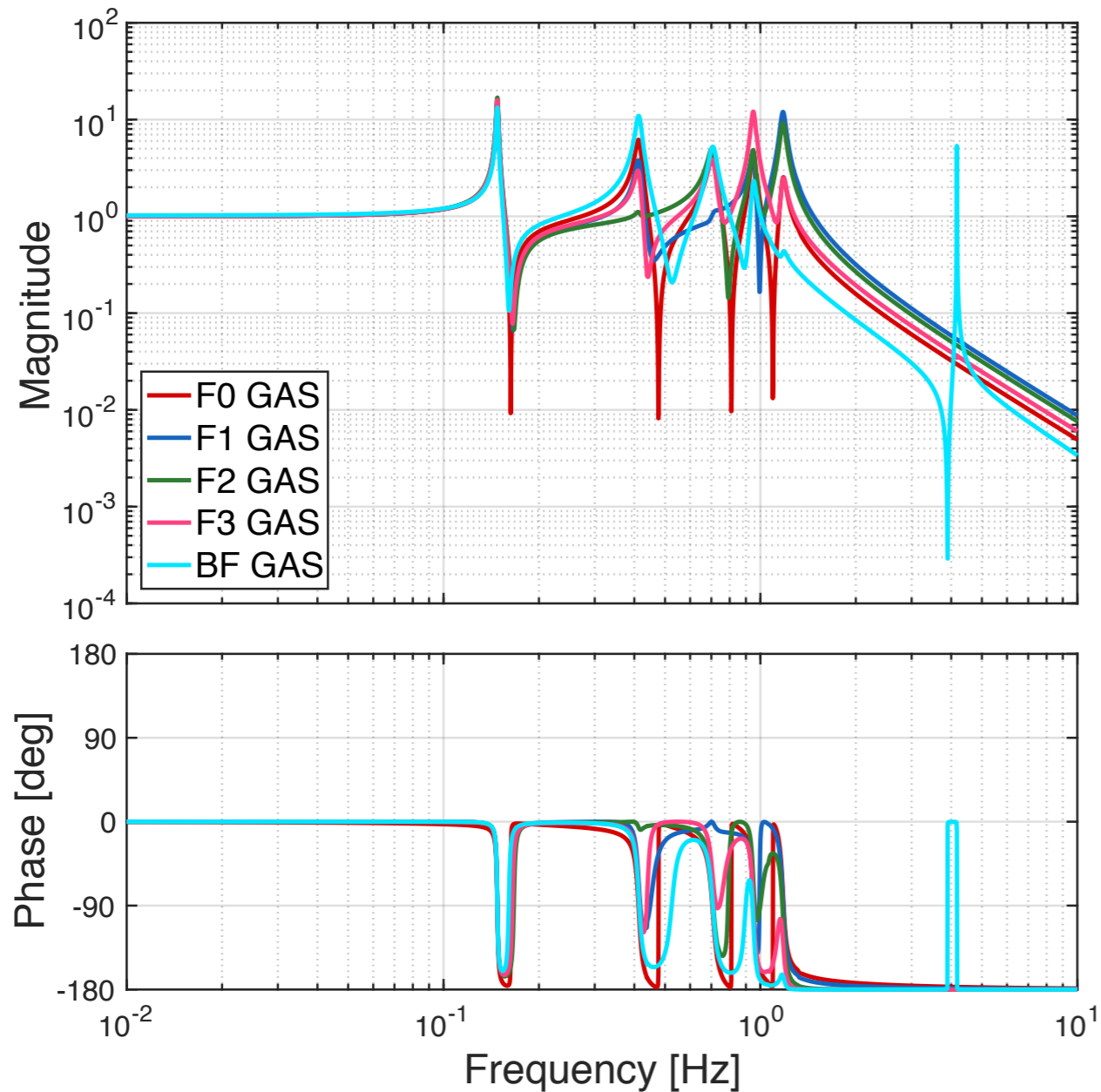
- Decouples sensor signals into modal amplitudes

Vertical Modes

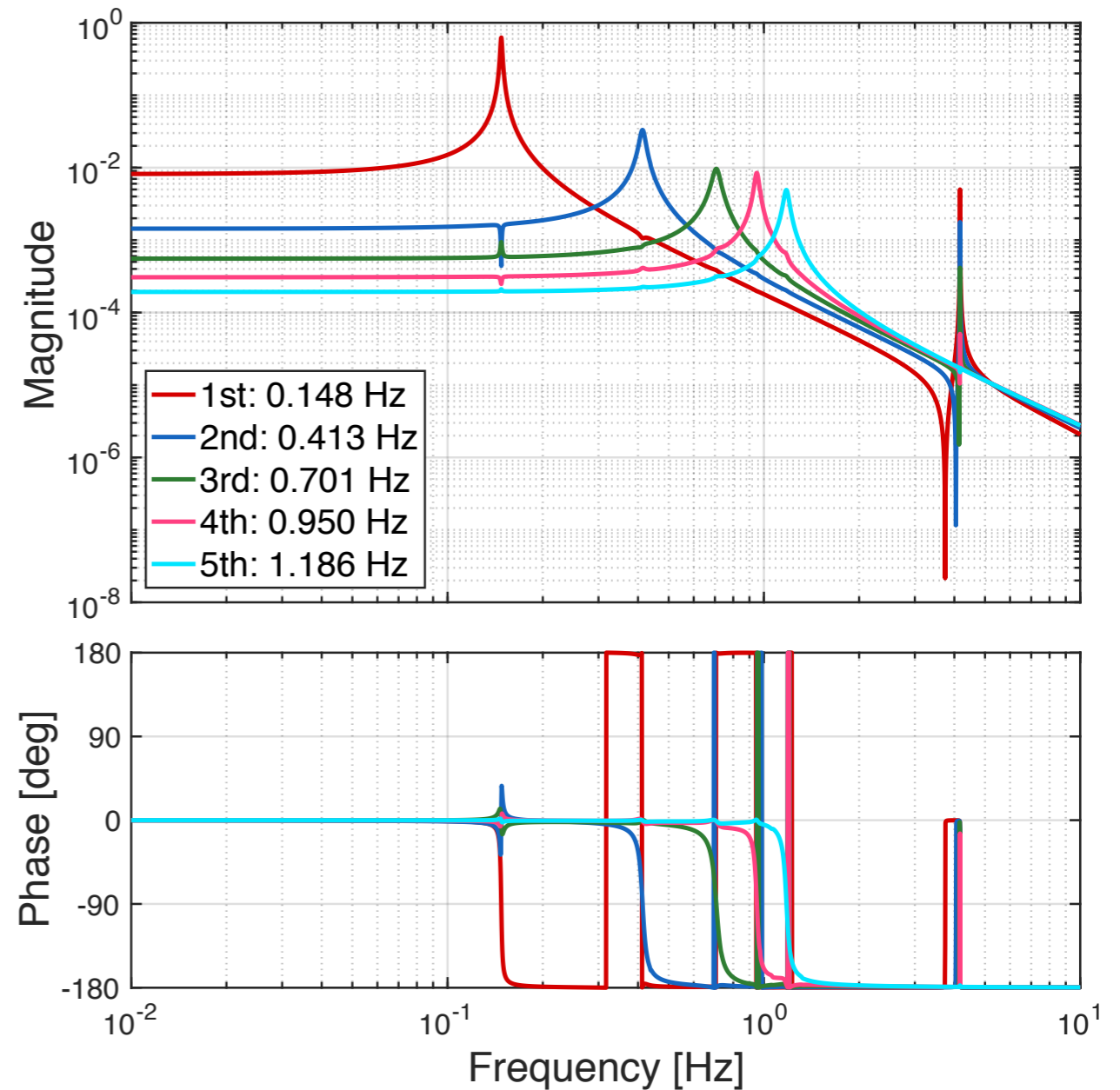


GAS Filter Response (1)

MODEL PREDICTION



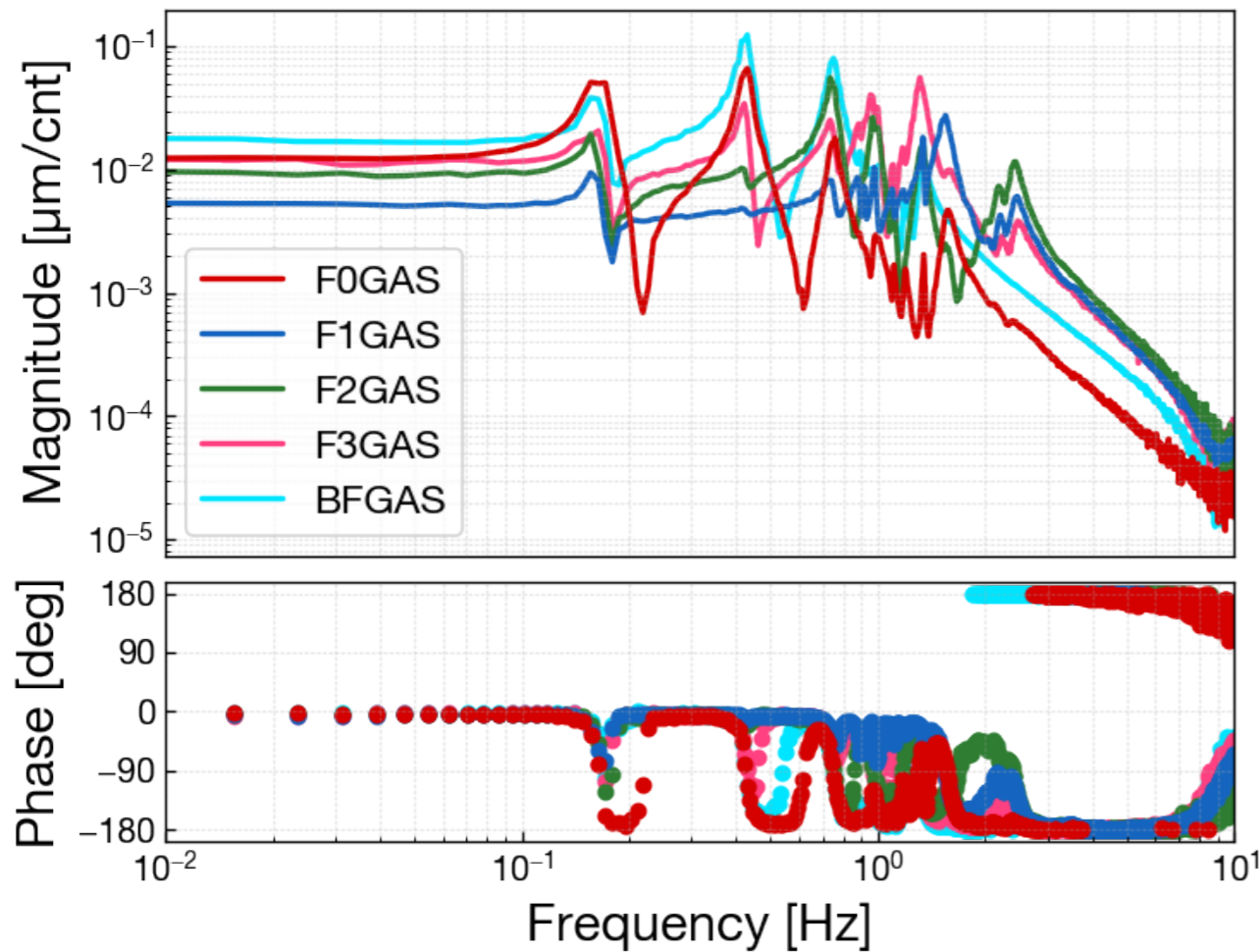
STAGE-BASIS



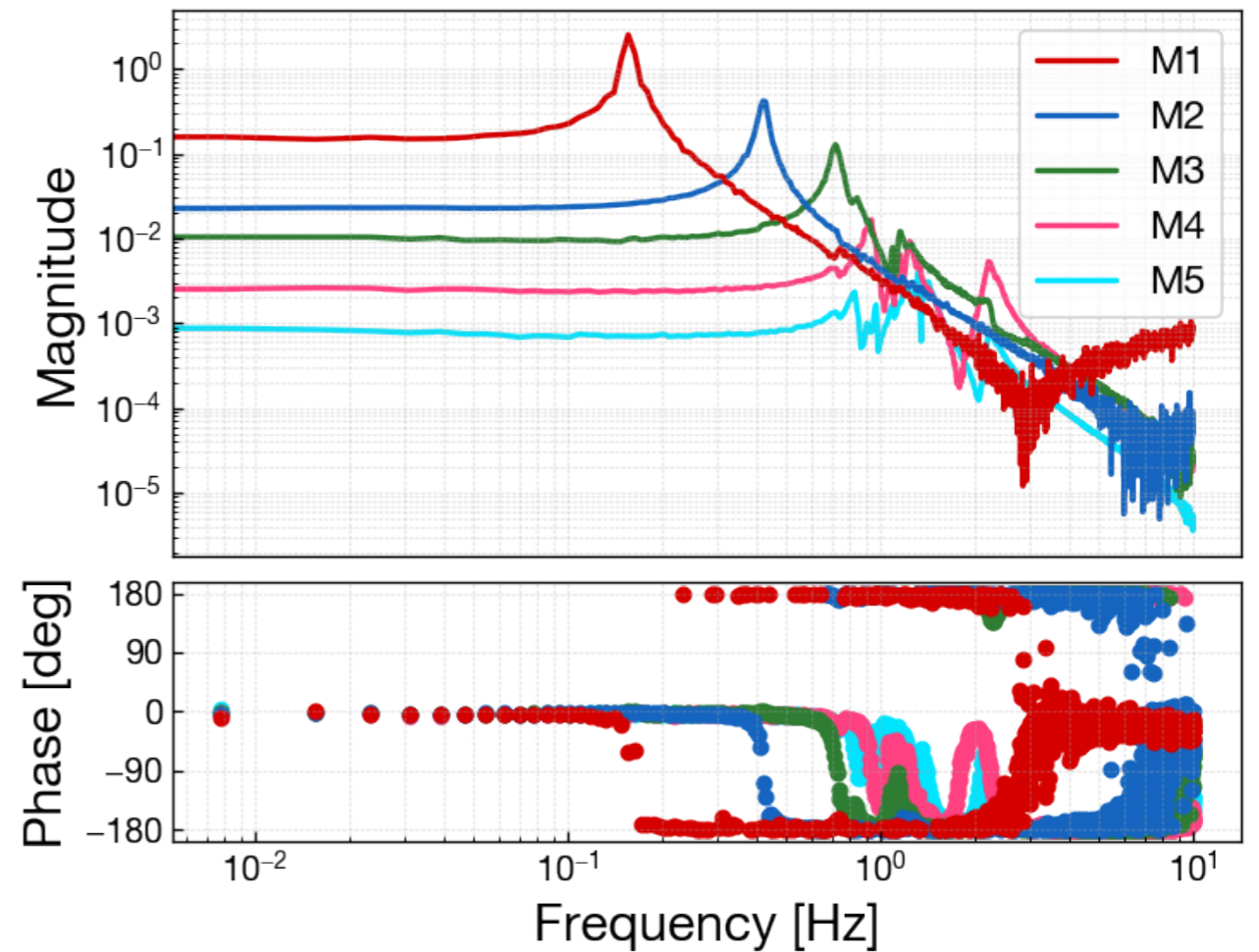
MODAL-BASIS

Gas Filter Response (2)

MEASUREMENT RESULT



STAGE-BASIS

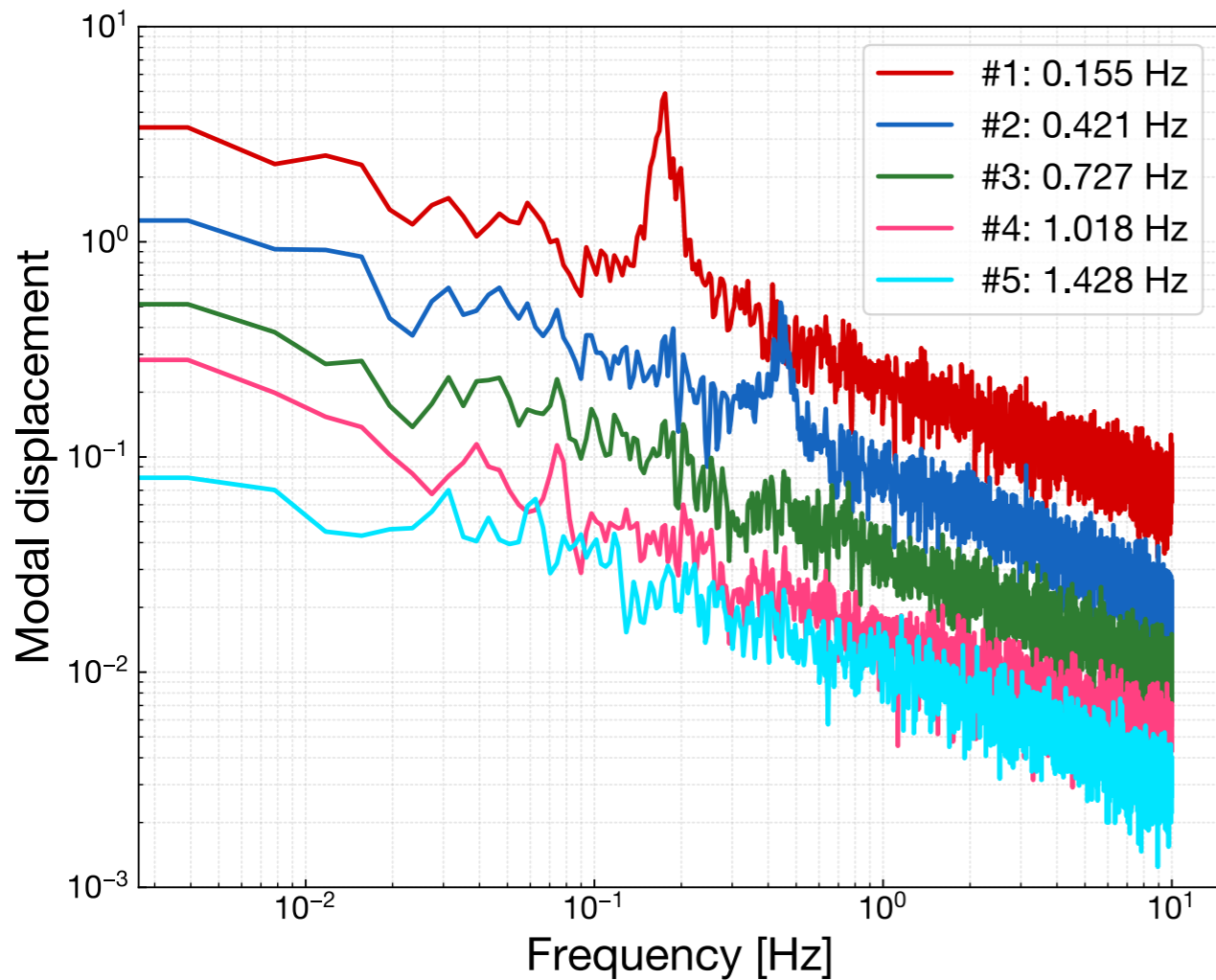


MODAL-BASIS

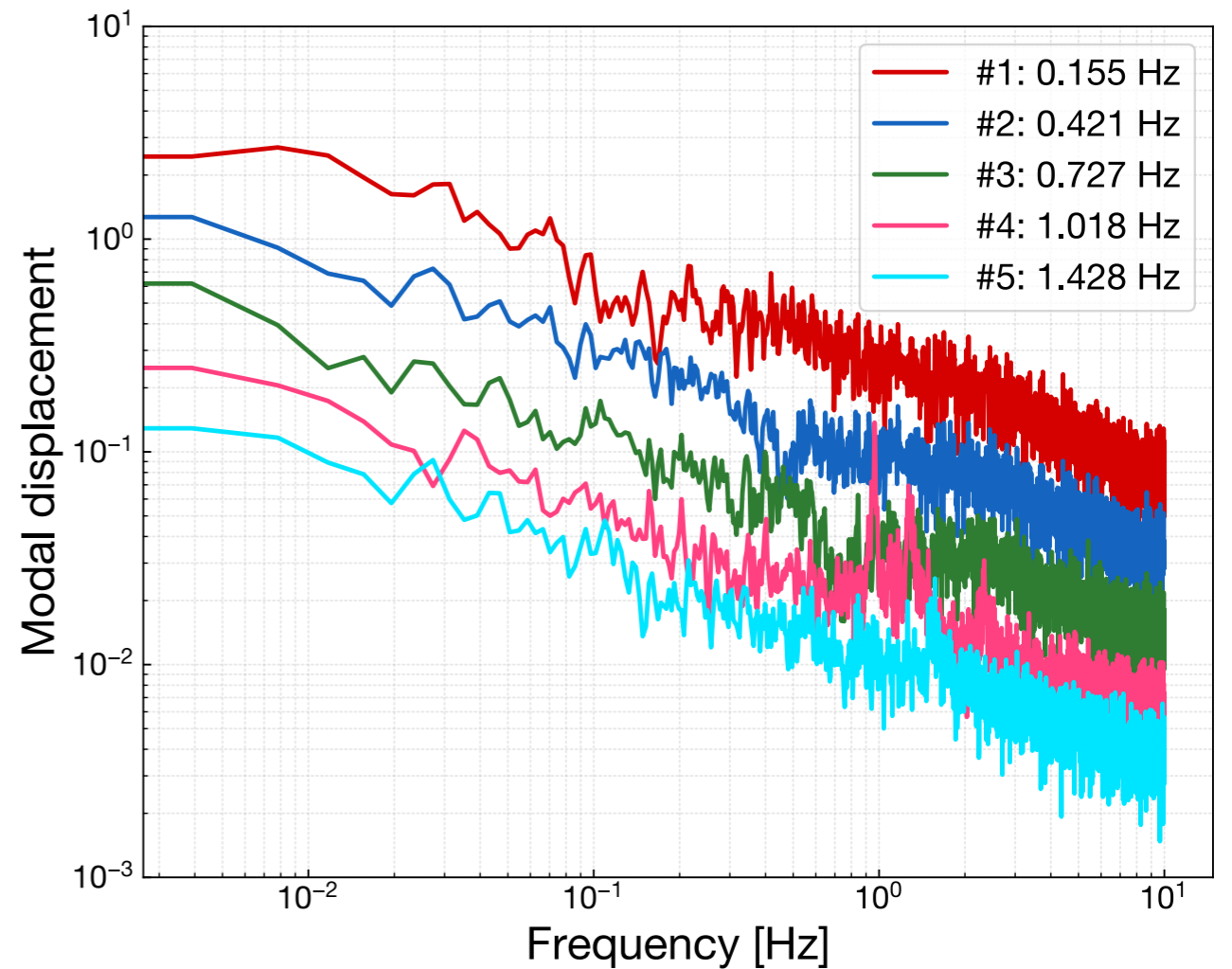
■ Modal responses can make the filter design simple

Modal Spectrum

MEASUREMENT RESULT



UNDAMPED



1ST & 2ND MODE DAMPED

Hierarchical Control

