# Vibration isolation for the KAGRA beam splitter and signal recycling optics

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ICRR, THE UNIVERSITY OF TOKYO

# Outline

- About KAGRA: cryogenic payload, underground location and types of suspensions.
- Description of the Type B suspension: mechanics.
- Type B suspension model prediction: control loop noise within the interferometer observation band.
- Future work
- Conclusions

# Acknowledgment


- **Core Type B team:** Mark Barton (leader), Fabian Peña Arellano, Naoatsu Hirata.
- **Other VIS members:** Ryutaro Takahashi (VIS leader), Yoshinori Fujii, Yoichi Aso (manager), Koki Okutomi, Ayaka Shoda, Naoisha Sato, Hideharu Ishisaki, Lucia Trozzo.
- **Previous members:** Enzo Tapia San Martin, Takanori Sekiguchi, Naoko Ohishi, Daisuke Tatsumi, Riccardo De Salvo.
- **Others:** Raffaele Flaminio, Akutsu, Tomotada Akutsu, Simon Zeidler.
- **Students:** Yuhang Zhao, Kazuya Yokogawa, Yuya Kuwahara, Yingtang Liu, Toshiya Yoshioka, Perry Forsyth, Panwei Huang, Rikako Hatoya, Terrence Tsang, Ryohei Kozu.

# References

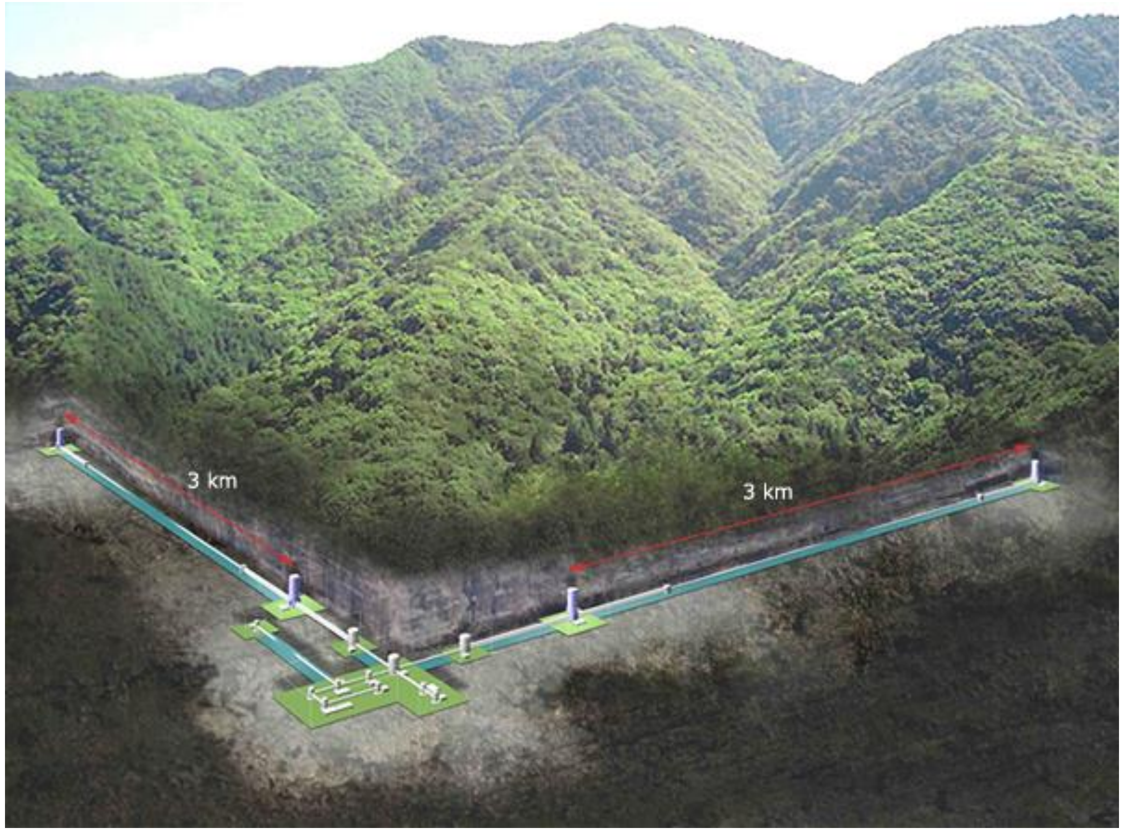

- Akiyama et al. "**Vibration isolation system with a compact damping system for power recycling mirrors of KAGRA**." Classical and Quantum Gravity, 12 April 2019, **36** 095015.
- Fabián Peña Arellano et al. "**Characterization of the room temperature payload prototype for the cryogenic interferometric gravitational wave detector KAGRA.**" Review of Scientific Instruments, **87**, 034501 (2016).
- T. Sekiguchi, **"A study of low frequency vibration isolation system for large scale gravitational wave detectors,"** PhD thesis, University of Tokyo, 2016.
- K. Okutomi, **"Development of a 13.5-meter-tall Vibration Isolation System for the Main Mirrors in KAGRA, "** PhD thesis, The Graduate University of Advances Studies, 2019.
- Mark Beker, **"Low frequency sensitivity of next generation gravitational wave detectors,"** PhD thesis, Nikhef, 2013.
- Matheus Blom, **"Seismic attenuation for Advanced Virgo: vibration isolation for the external injection bench,"** PhD thesis, Nikhef, 2015.
- Alexander Wanner, **"Seismic Attenuation System (AEI-SAS) for the AEI 10 m Prototype,"** PhD thesis, Leibniz Universität Hannover, 2013.

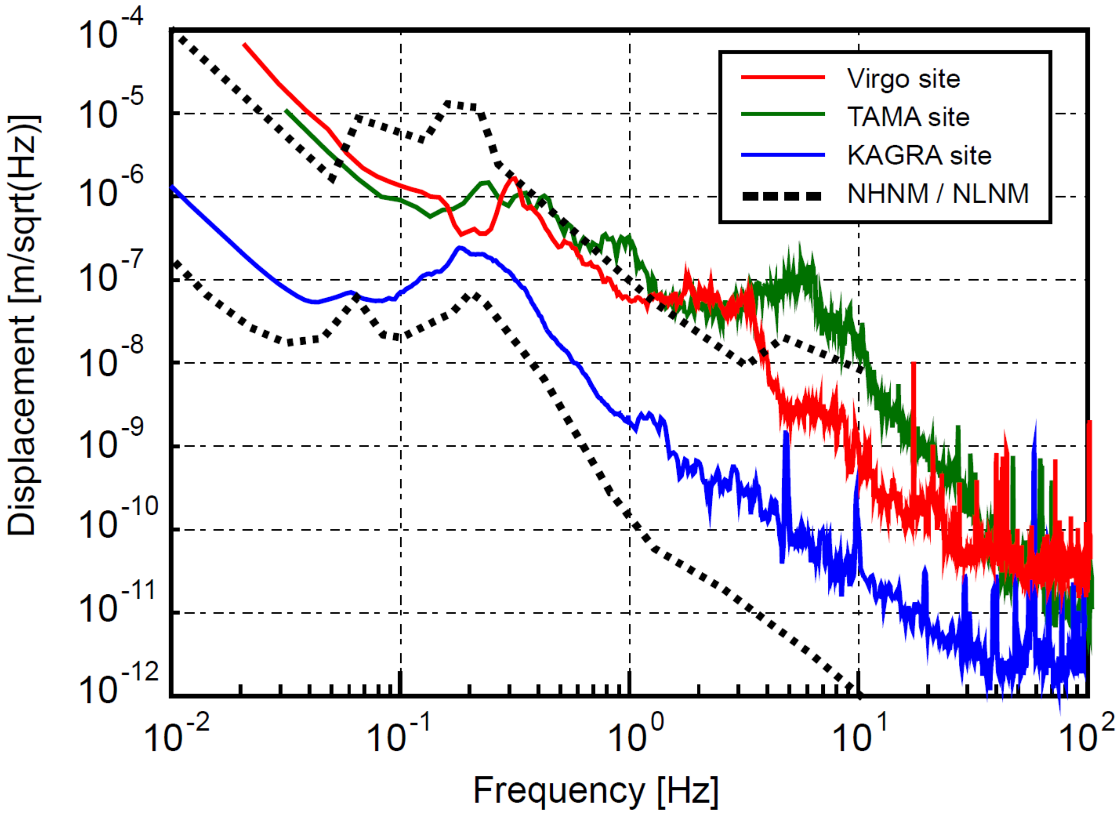
# Introduction

WHAT KAGRA IS

# KAGRA is an underground detector

Depending in the frequency between 10 and 100 times reduction between TAMA and KAGRA sites

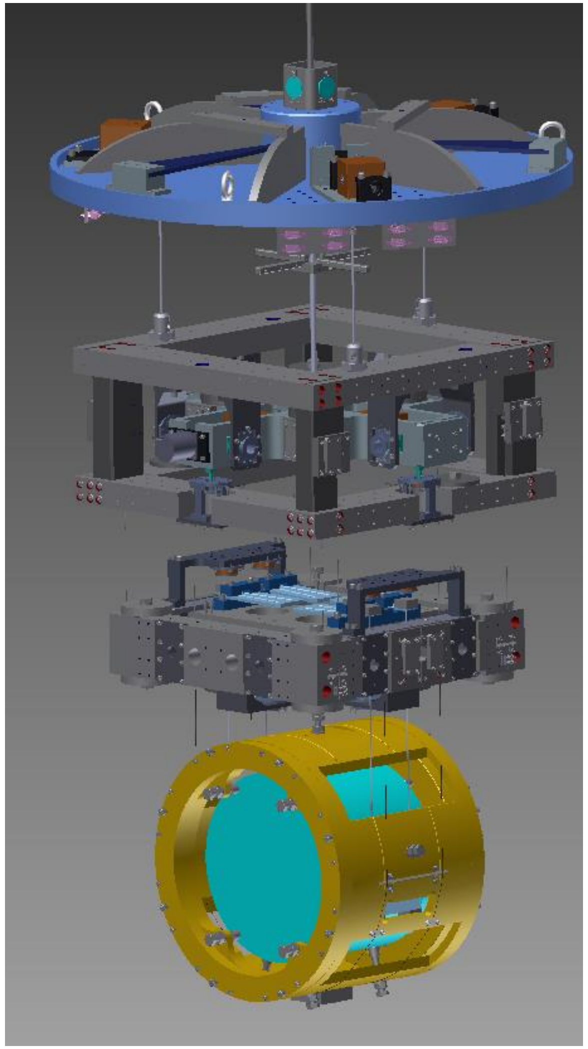



Plot by Takanori Sekiguchi

# KAGRA is a cryogenic detector (1)

- **Sapphire mirrors**
- **Cooled down to 20 K**
- **Mass of 200 kg**



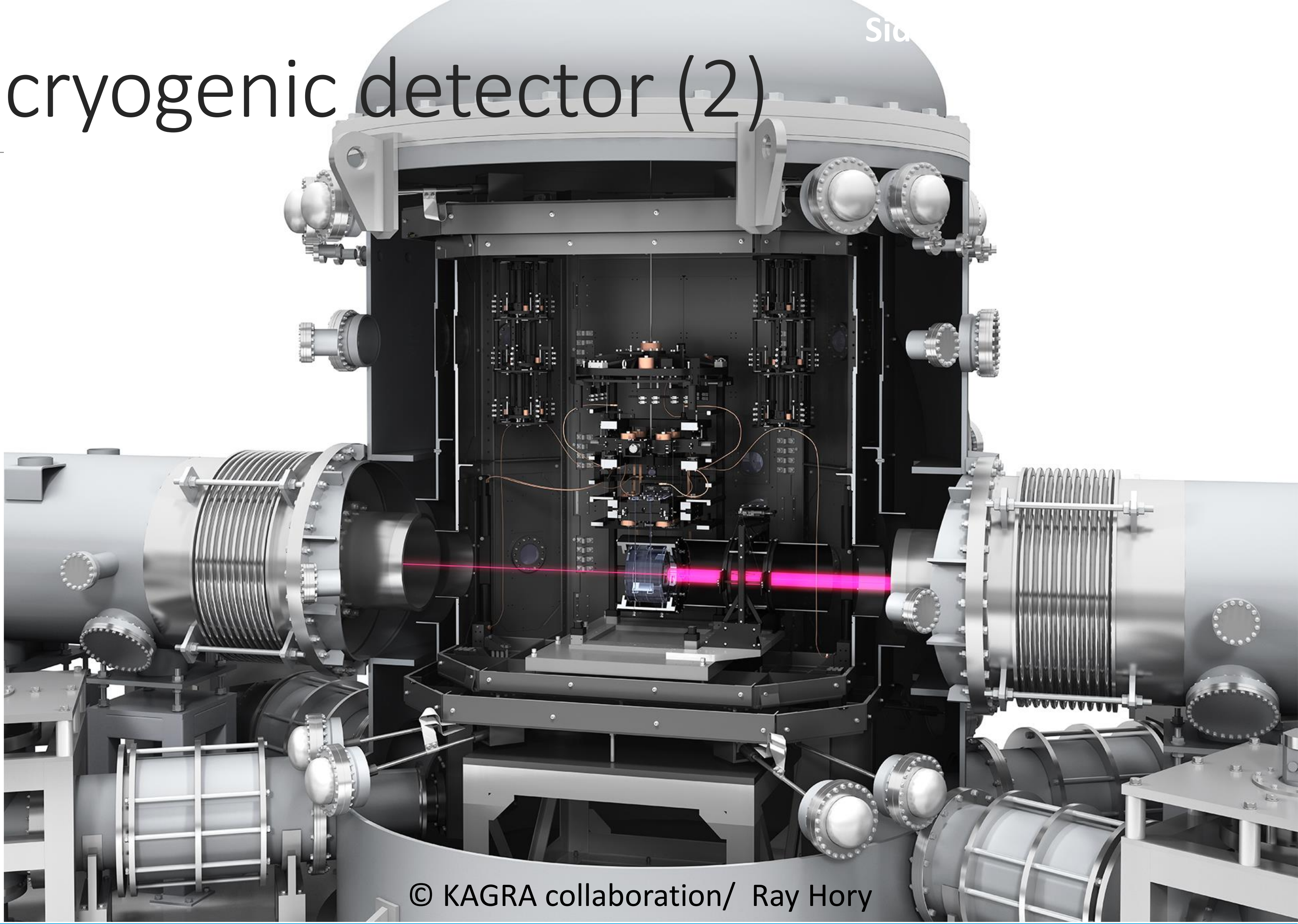
Drawing by A. Hawigara

Photo by Tomotada Akutsu

Don’t expect a tropical place like Natal!

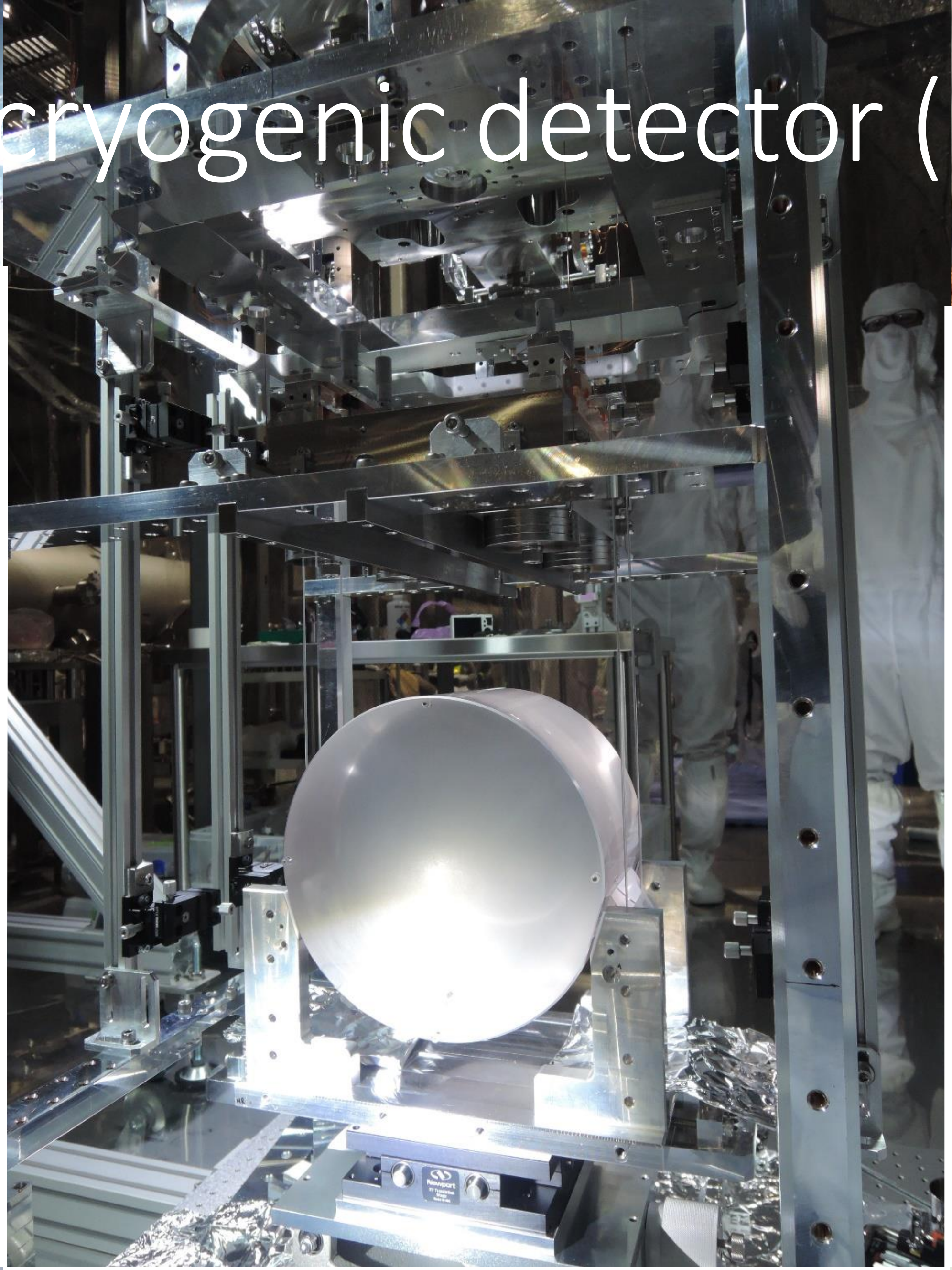
# KAGRA is a cryogenic detector (2)

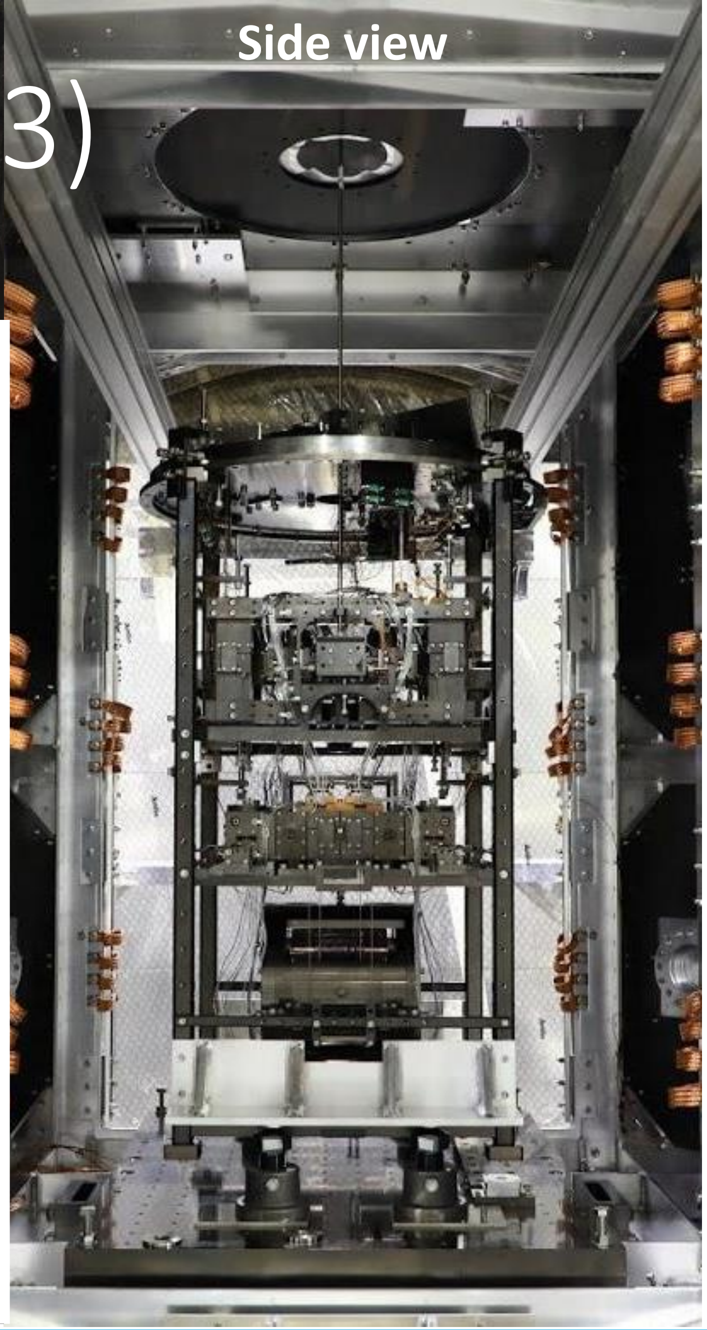
- Sapphire mirrors
- Cooled down to 20 K
- Mass of 200 kg



© KAGRA collaboration/  Ray Hory

# KAGRA is a cryogenic detector (3)

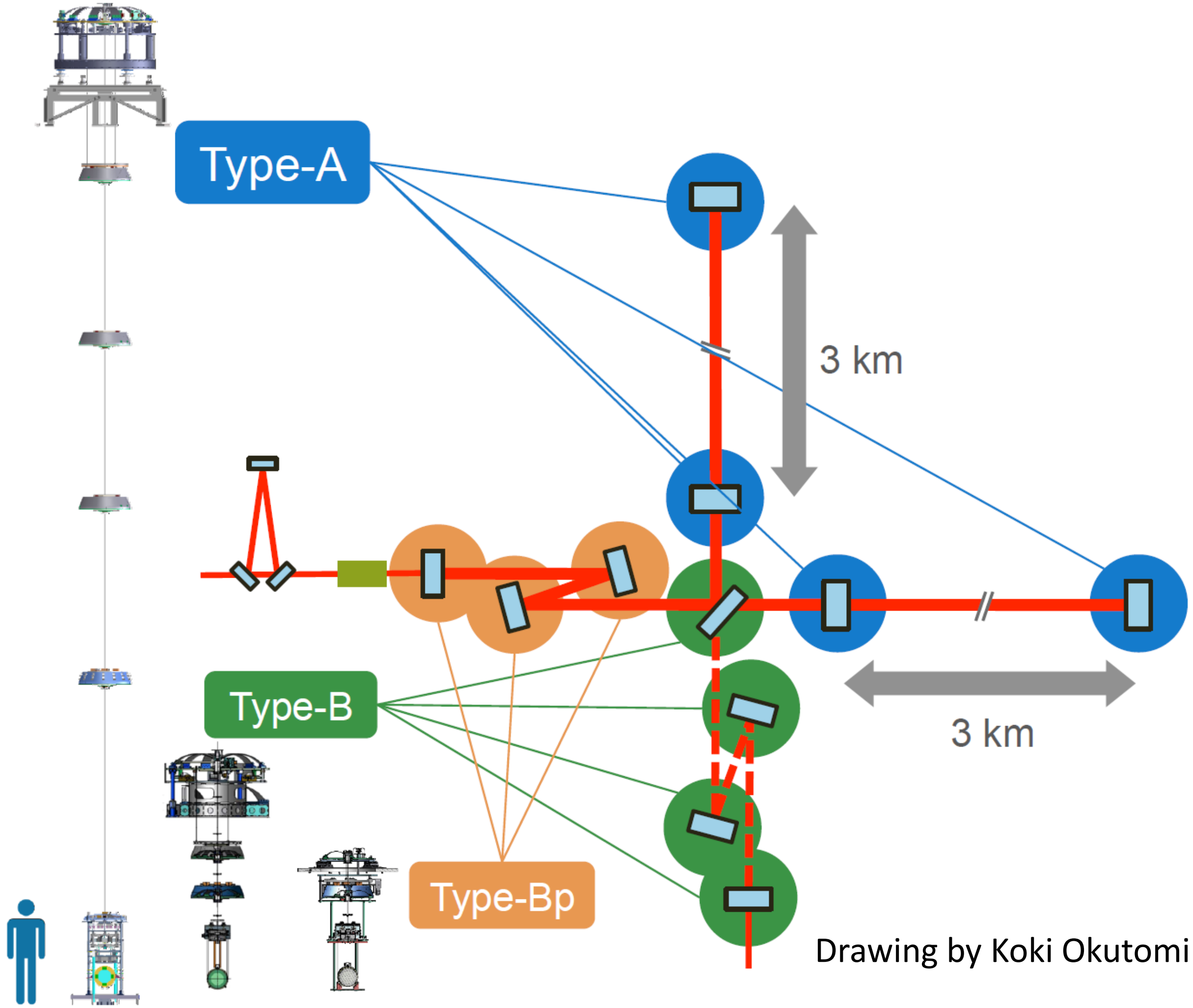





Photos: Rahul Kumar and Higiwara.

# Suspensions for the main interferometer mirrors (1)

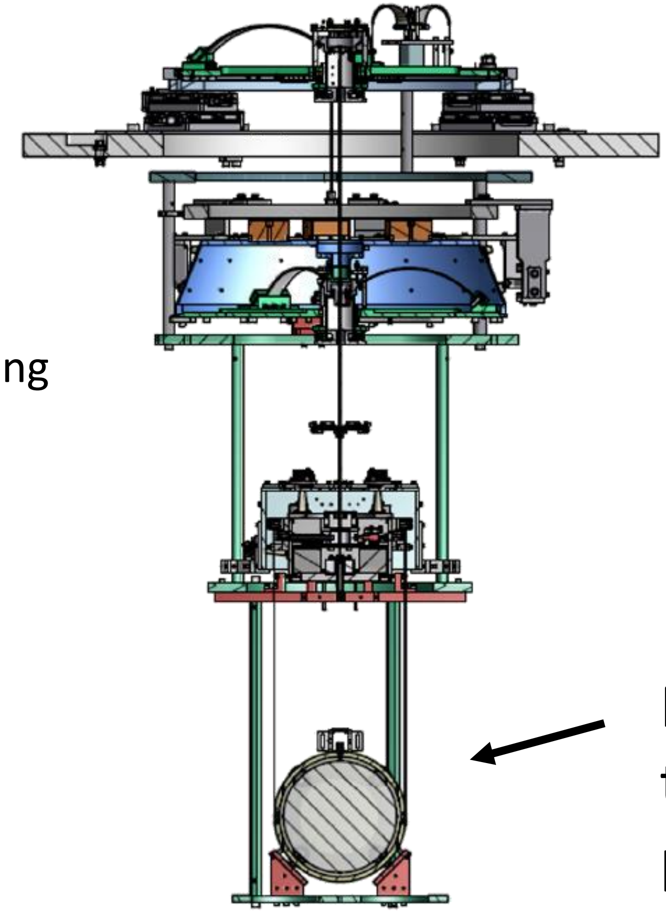
- 4 × Type A for the Test Masses sensitive to GW.
- 4 × Type B for the beam splitter and signal recycling mirrors.
- 3 × Type Bp for the power recycling mirrors.



# Suspensions for the main interferometer mirrors (2)

Type Bp

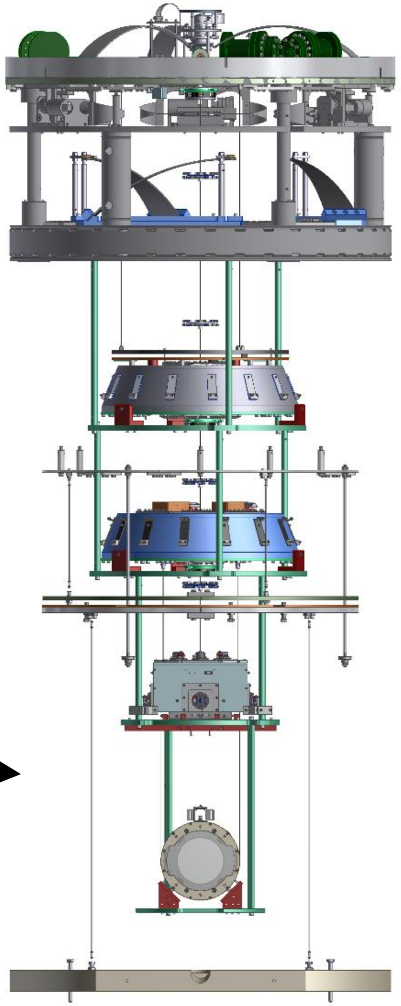
Power recycling mirrors



Type B

Beam splitter and signal recycling mirrors

Room temperature payload



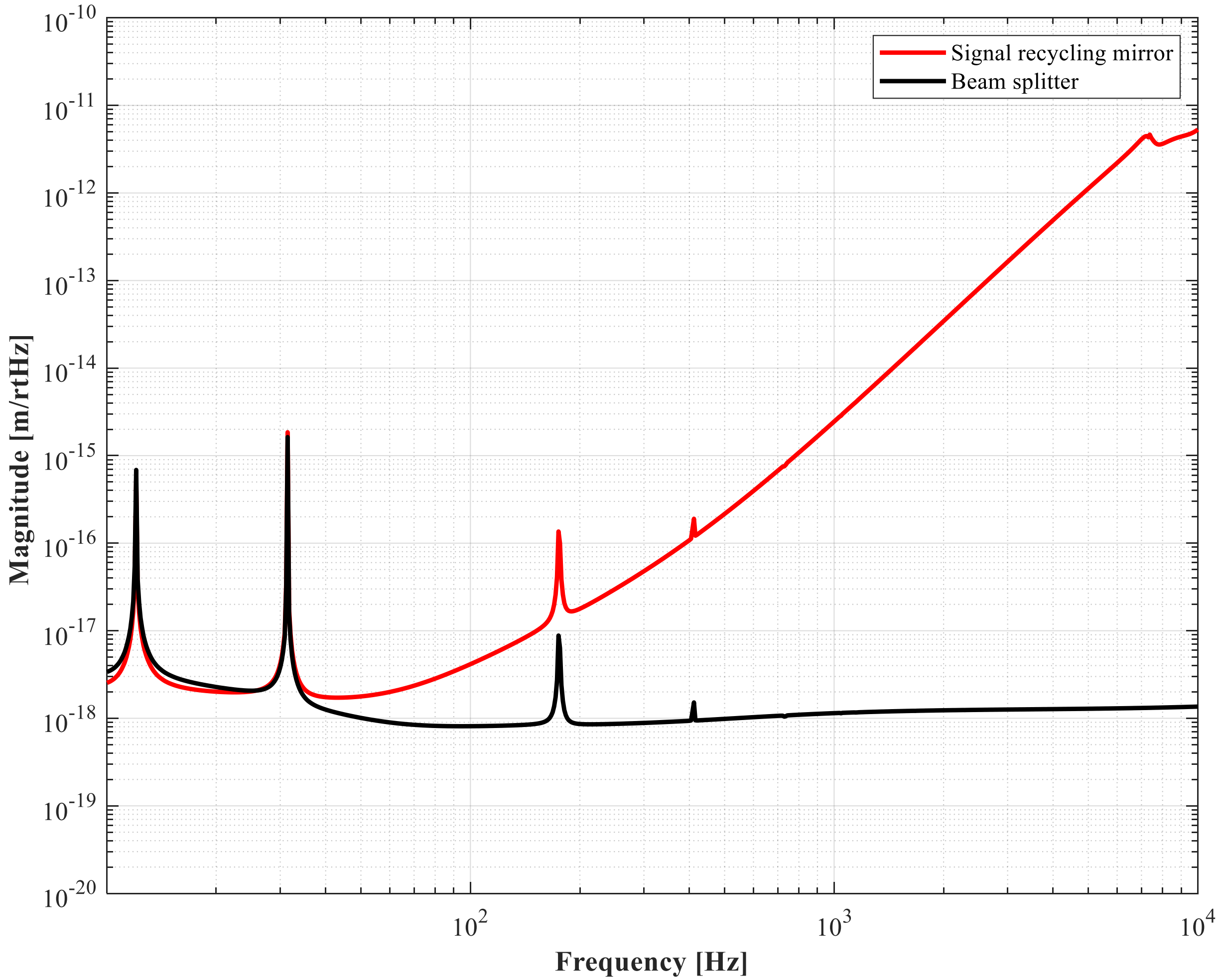
Type A

Test masses

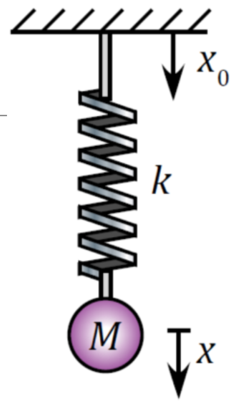
Cryogenic payload

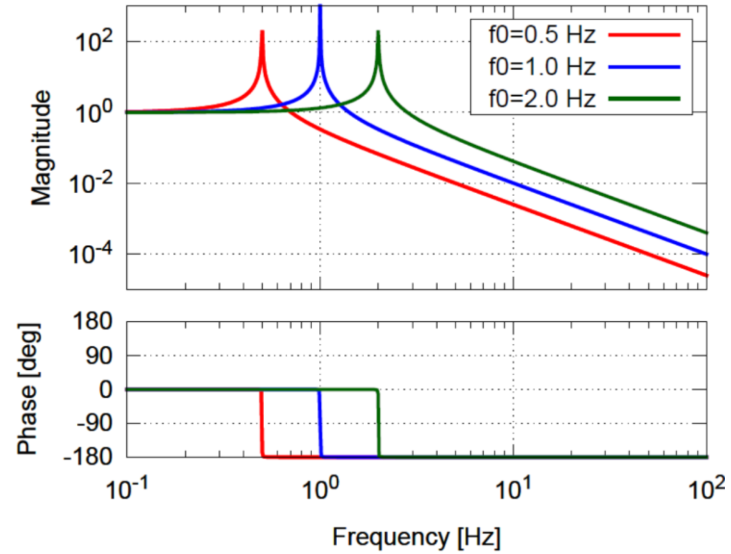
# Aim of requirements

- At high frequencies above and at 10 Hz: to achieve the interferometer target sensitivity.
  - Beam splitter: **3.39 × $10^{-18}$ m/√Hz at 10 Hz**.
  - Signal recycling mirror: **2.54 × $10^{-18}$ m/√Hz at 10 Hz**.
- At low frequencies:
  - Lock acquisition: **v = 0.5 µm/s (integrated RMS)**.
  - Interferometer stable operation: pitch and yaw **1 µm RMS** displacement.
  - Quick recovery after losing the interferometer lock (e.g. due to an earthquake): time constant upon damping of less than **60 seconds**.
  - Enzo Tapia will talk about the performance at low frequencies.



# Passive vibration isolation




A simple example:

$$M\ddot{x} = -k(x - x_0)$$

$x$: position of the load.

$x_0$: position of the ground.

$M$: mass of the load.

$k$: stiffness of the spring.

$$\omega_0 = \sqrt{\frac{k}{M}}$$

The solution in frequency domain yields the transfer function:

$$H(\omega) \equiv \frac{\tilde{x}(\omega)}{\tilde{x}_0(\omega)} = \frac{1}{1 - (\omega/\omega_0)^2}$$

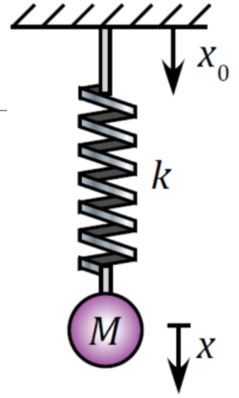
Above the resonant frequency the vibrations are filtered.

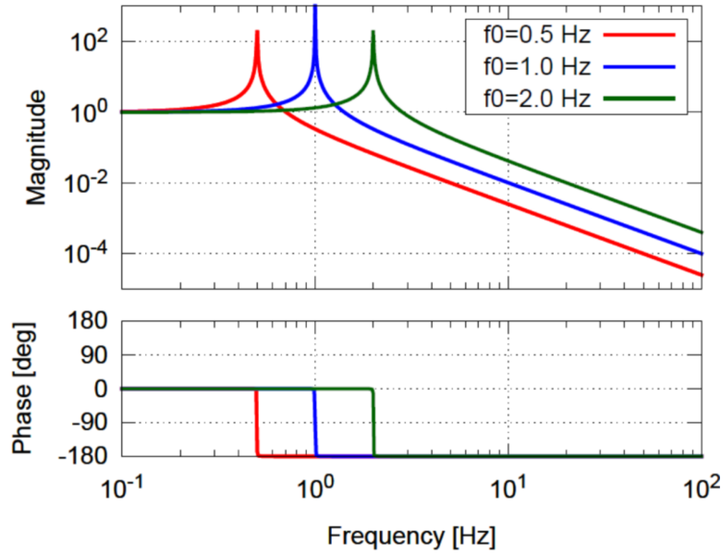
**Challenge: support a heavy load (100s of kg) with a very soft system (low resonant frequency).**

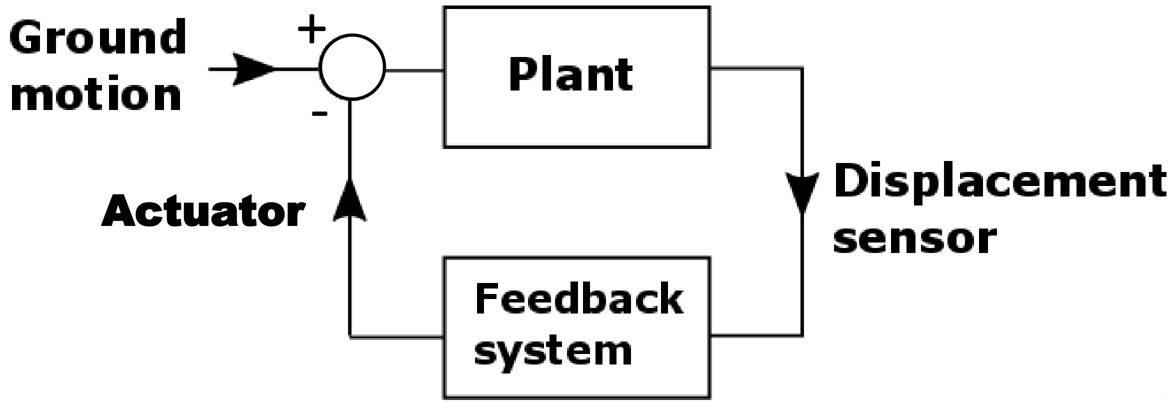
T. Sekiguchi, **"A study of low frequency vibration isolation system for large scale gravitational wave detectors,"** Ph.D. thesis, University of Tokyo, 2016.

# Active vibration isolation

- The system still has  resonant movement that has to be damped
- We need to damp resonant motion to keep stability of the optical system.



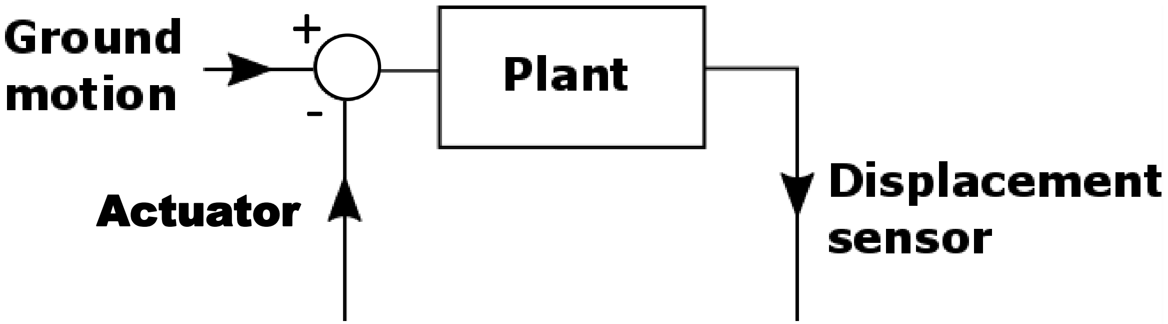




- Geophones for velocity.
- Shadow sensors for displacement.
- Inductive sensors for displacement.

T. Sekiguchi, **“A study of low frequency vibration isolation system for large scale gravitational wave detectors,”** Ph.D. thesis, University of Tokyo, 2016.

# Transfer functions

- Other type of transfer functions are measured with the control loop open.
- We move the system according to a prescription and sense its response.




We use them for

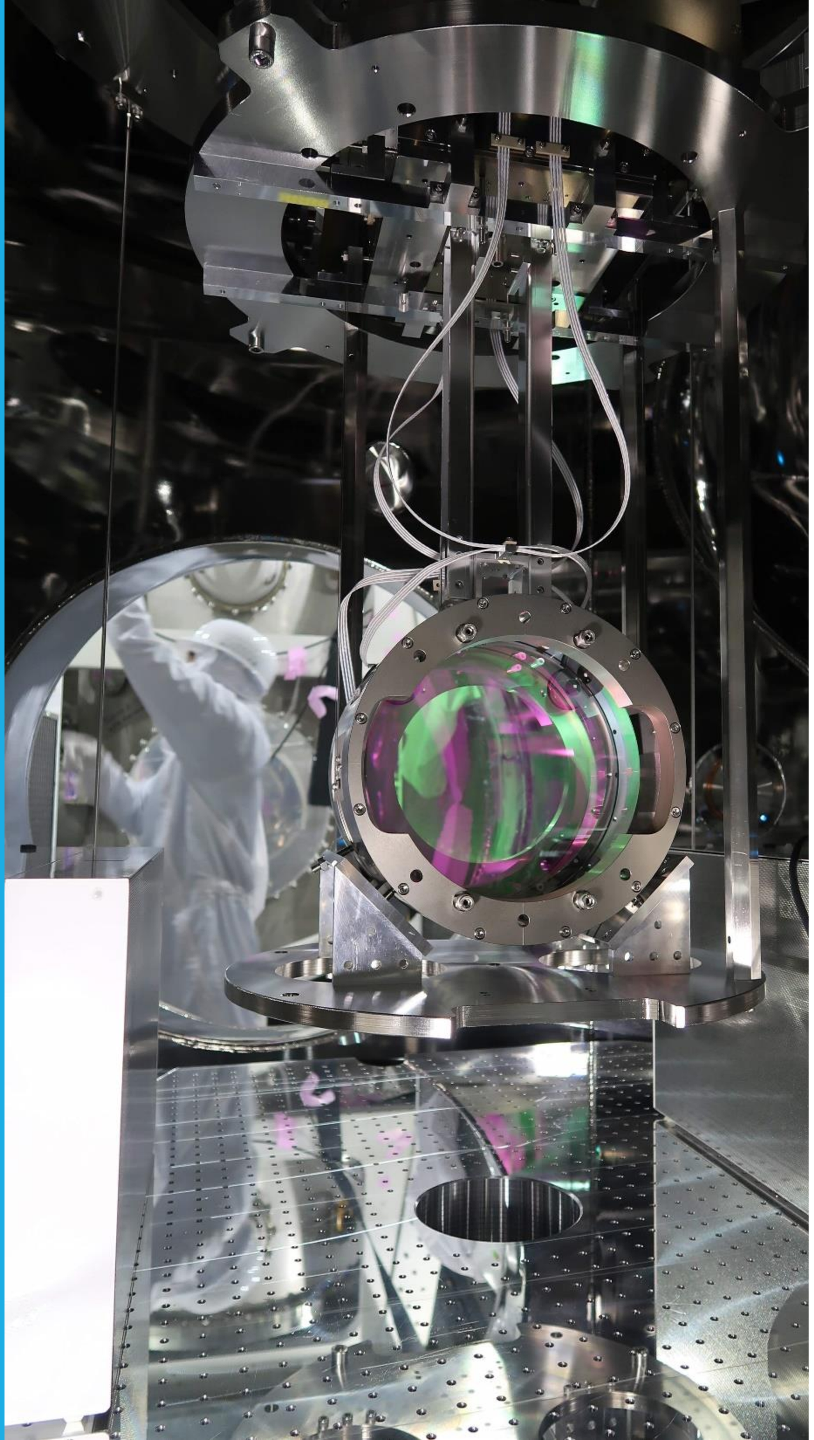
- Assessing the health of the system
  - Otherwise freely hanging components are touching each other.
  - Misconnected or disconnected cables
  - Errors in the software
- Designing controls filters offline.

# Description of the Type B suspension

Room temperature

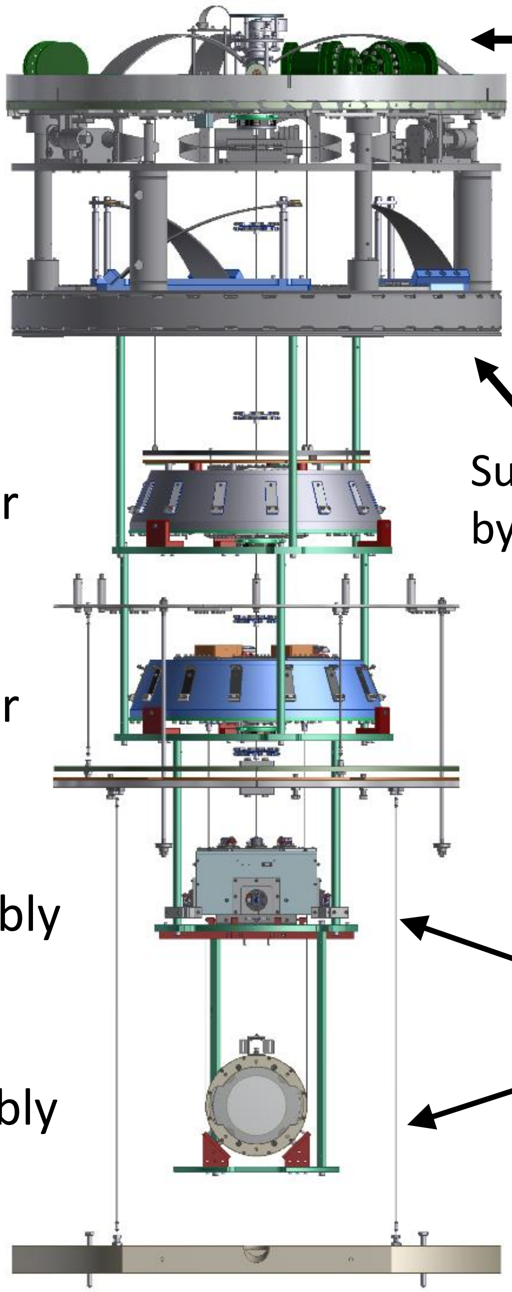
Beam splitter

Three signal recycling mirrors



# Overview of the suspension

- Quadruple pendulum.
- A pre-isolator:
  - Inverted pendulum horizontal isolation.
  - GAS filter for vertical isolation.
- A chain with 3 × GAS filters for vertical isolation.
- Magnetic damper.
- Payload:
  - Marionette and its recoil body.
  - Optic and its recoil body.
- Sensors and actuators.
- Optical lever.
- Suspended optical table.



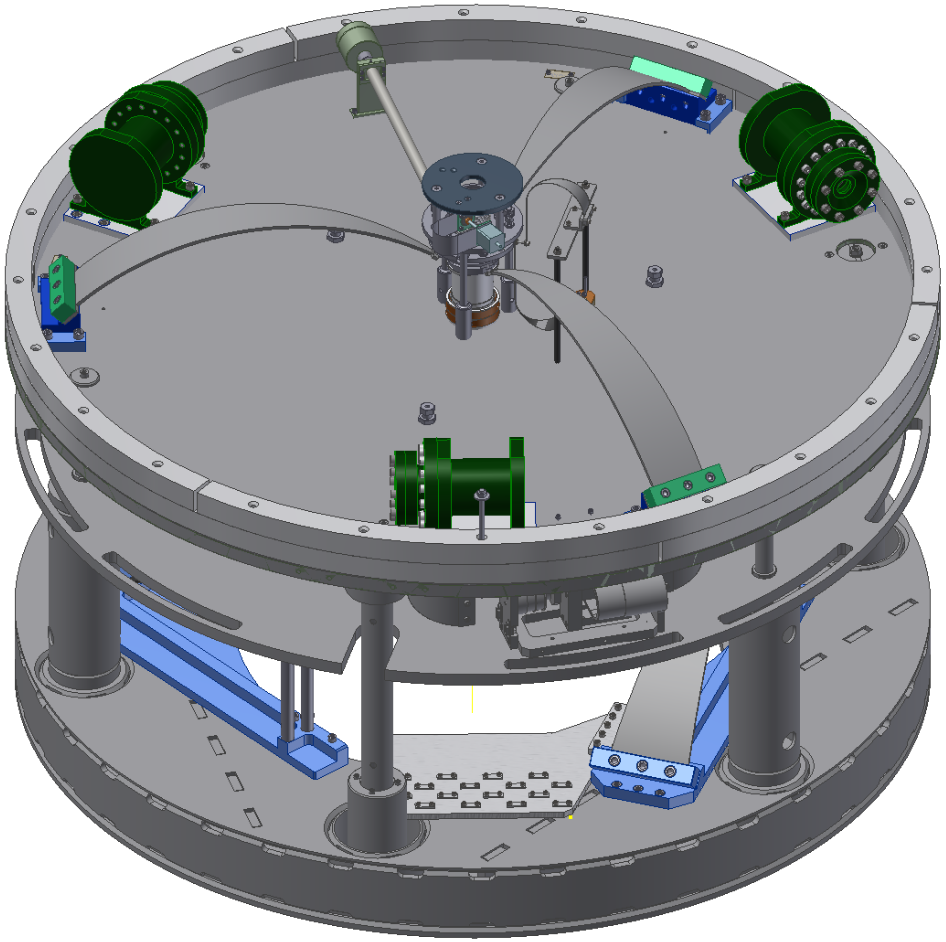
# Basic elements of the pre-isolator

## Inverted pendulum for horizontal isolation

- 3 × IP legs
- 3 × Geophones for inertial damping.
- 3 × LVDTs for position measurement.
- 3 × Coil-magnet actuators.
- 3 × Horizontal mechanical actuators.

## Geometric anti-spring filter for vertical isolation

- Three maraging steel blades.
- 1 × LVDT for position measurement.
- 1 × Coil-magnet actuator.
- 1 × Vertical mechanical actuator (fishing rod).
- 1 × Yaw mechanical actuator.

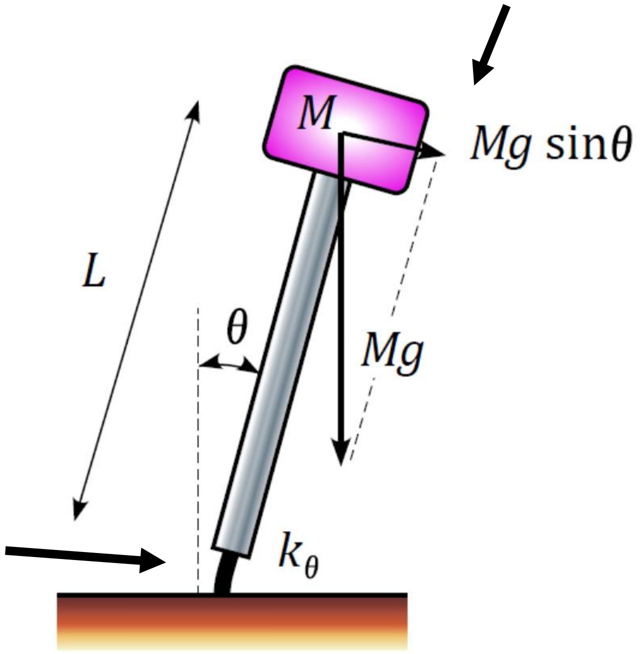


SR pre-isolator

# Inverted pendulum: horizontal isolation

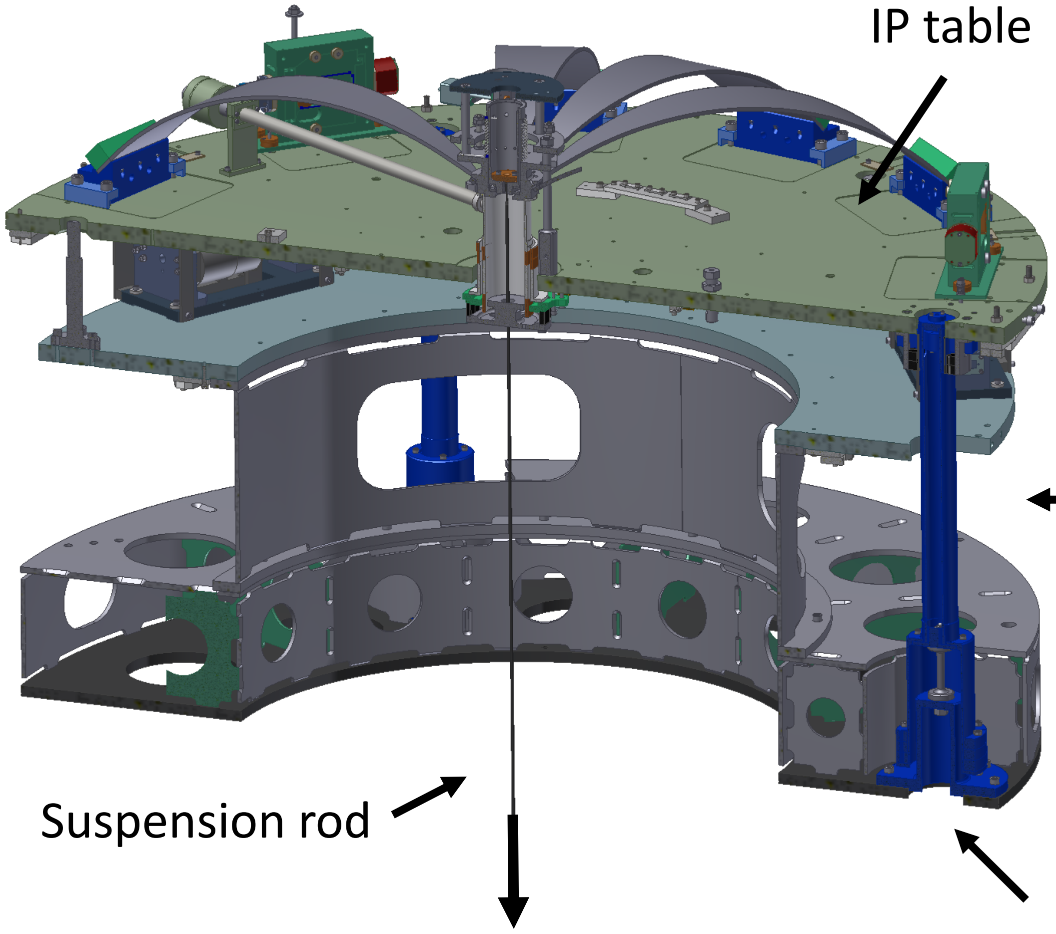
- It filters horizontal vibrations.
- A stiff flexure provides a restoring force for the heavy load.
- When the IP is out of equilibrium the weight of the load produces the anti-spring effect making the system softer.

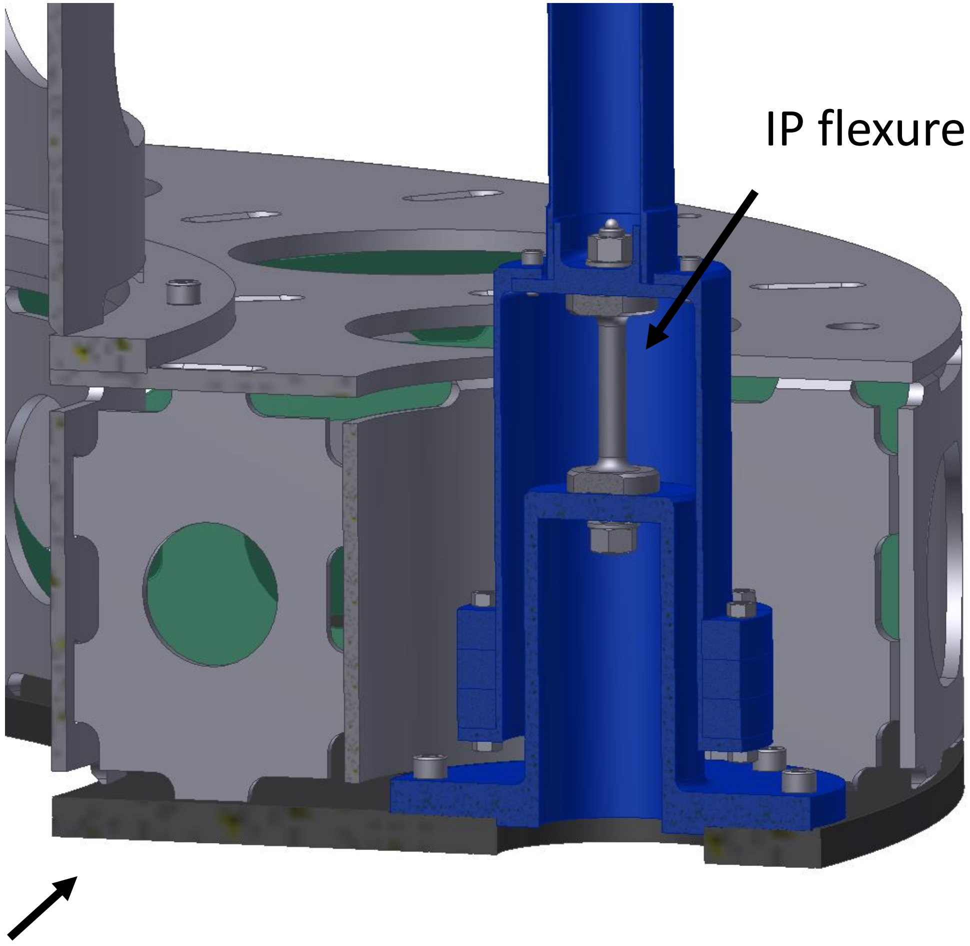
The weight pulls the load away from equilibrium




T. Sekiguchi, **"A study of low frequency vibration isolation system for large scale gravitational wave detectors,"** Ph.D. thesis, University of Tokyo, 2016.

# Inverted pendulum components (1)



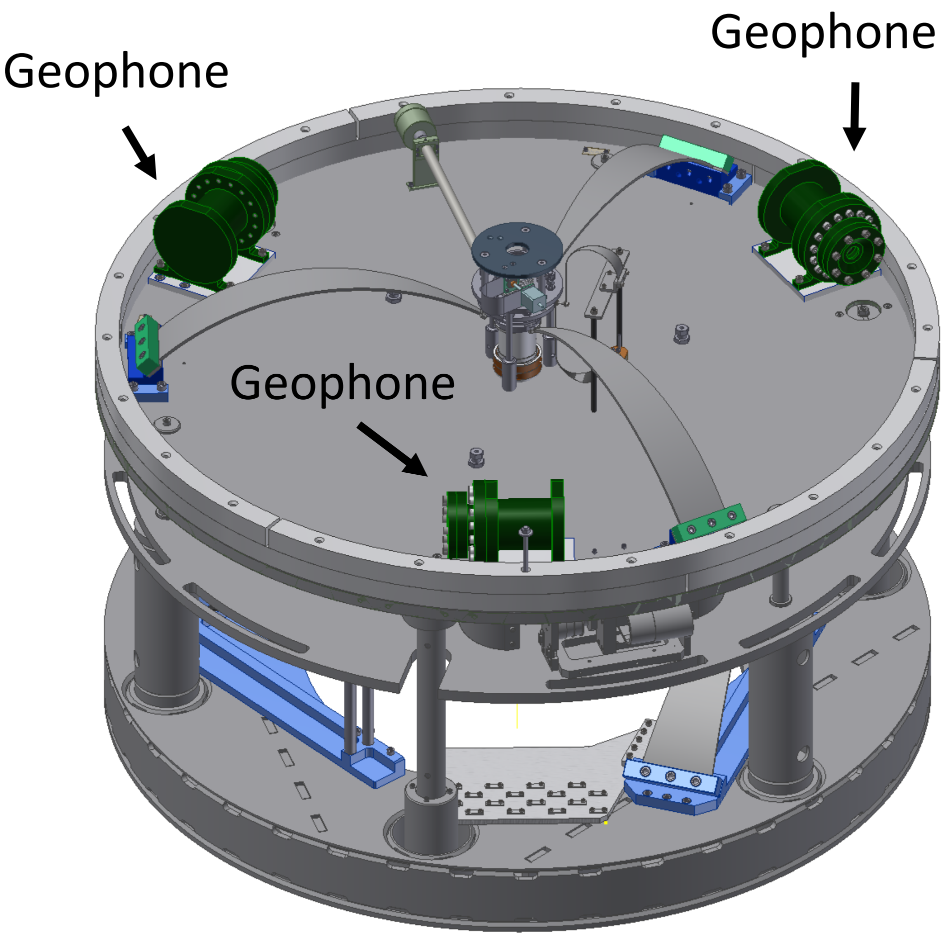

Base supported by the ground

BS pre-isolator

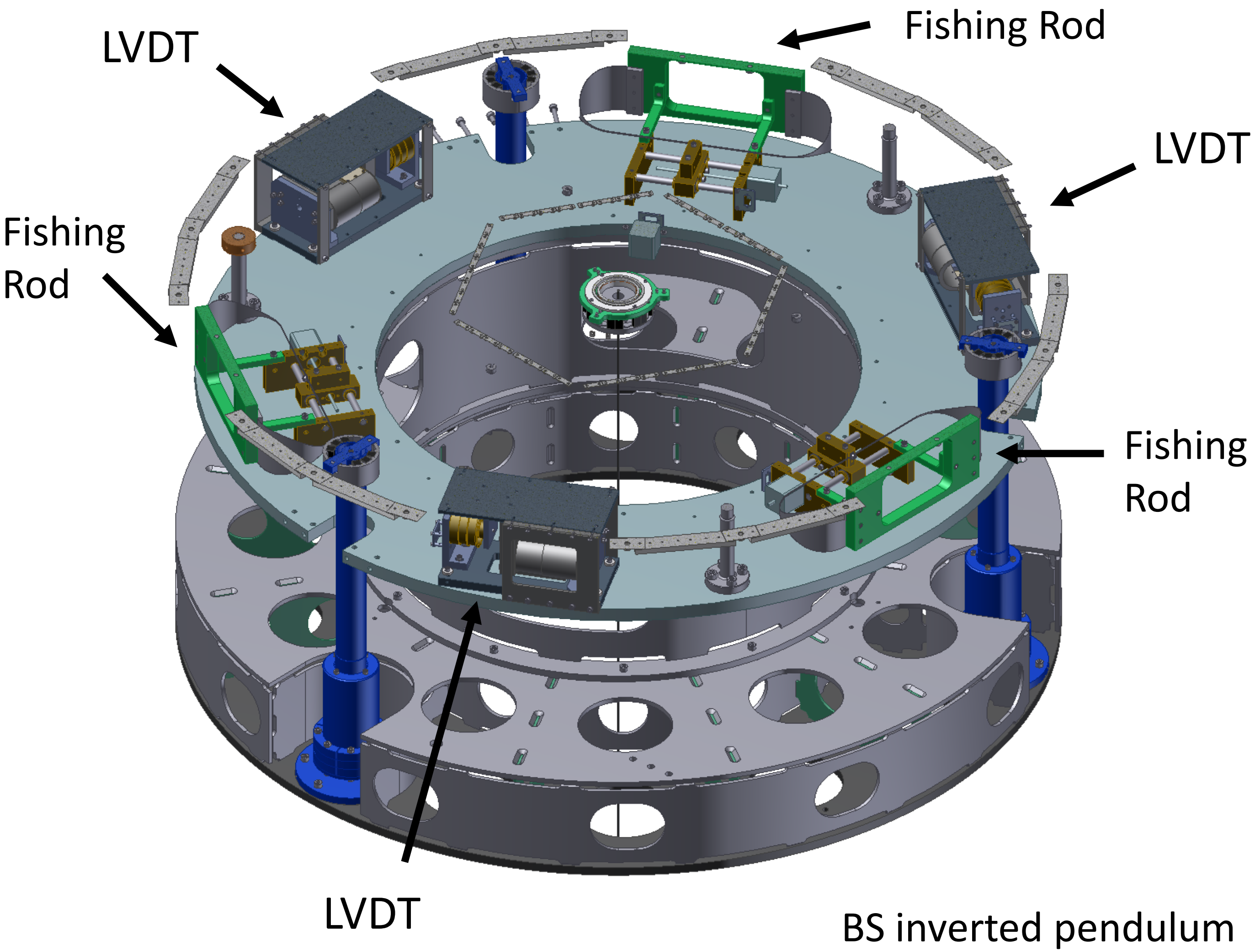
248 kgf

The flexure is ~ ∅10.6 mm

# Inverted pendulum components (2)



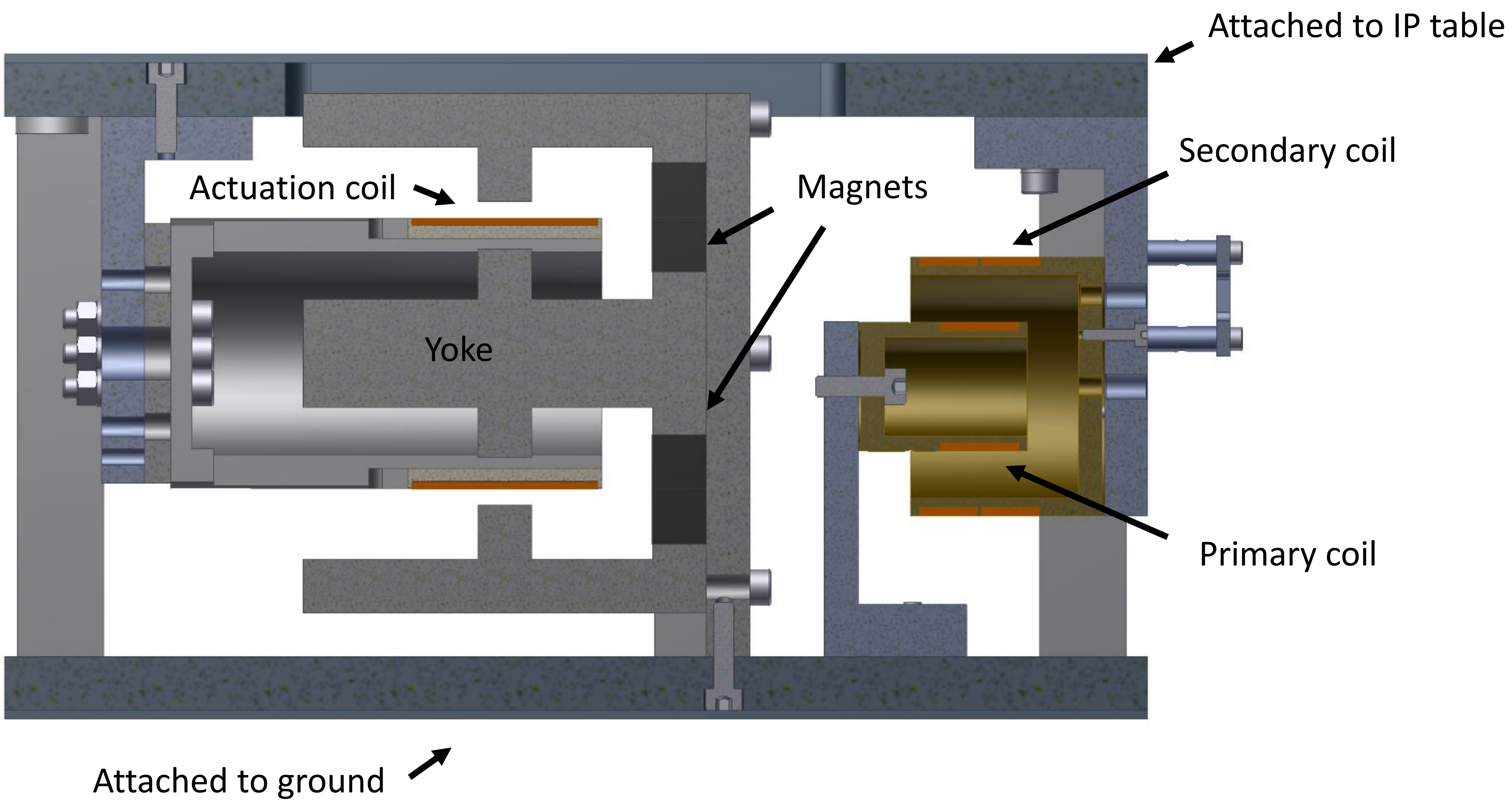

SR inverted pendulum



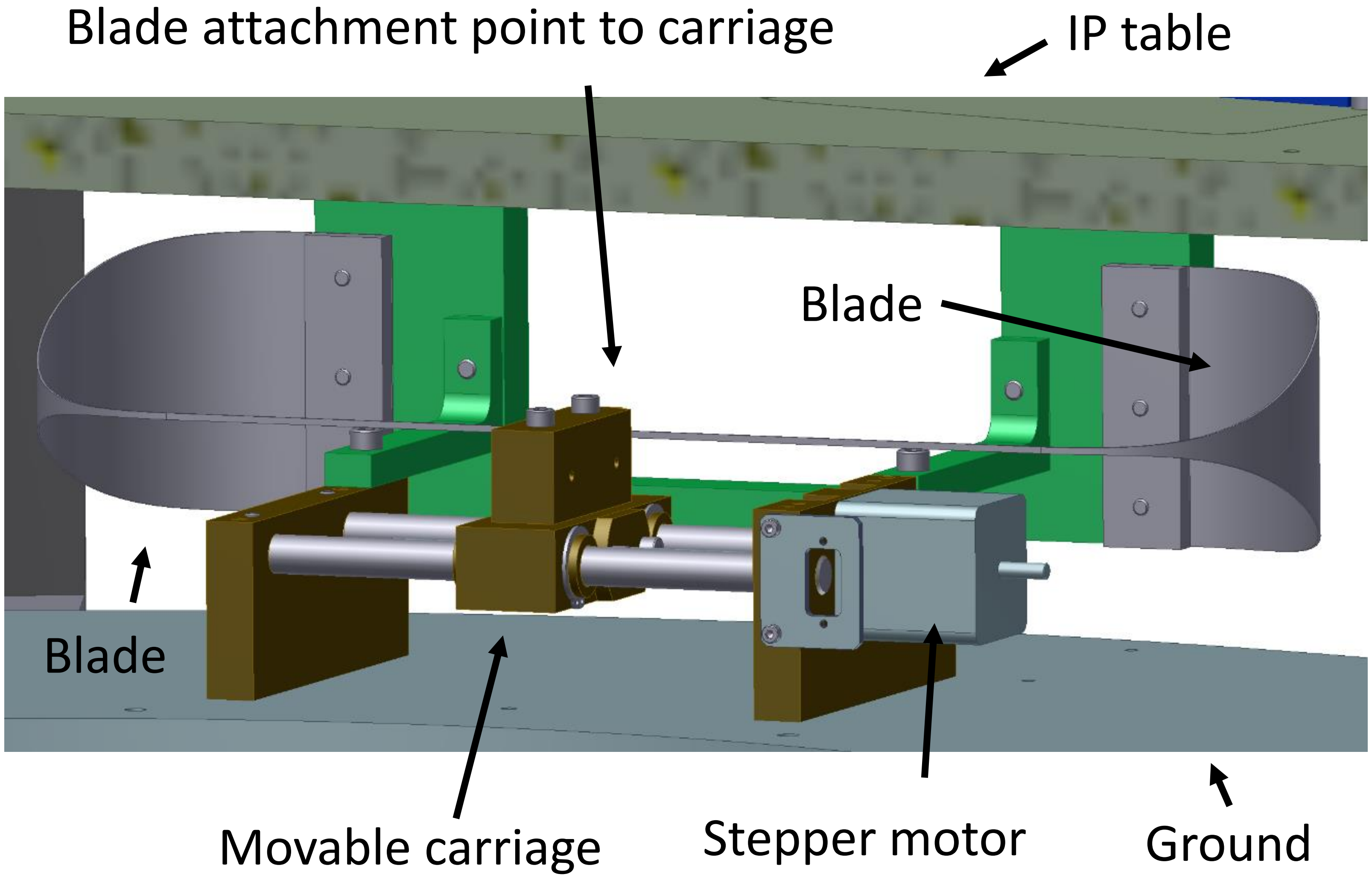

BS inverted pendulum

# LVDTs and coil-magnet actuators at the IP

(Linear Variable Displacement Transducer
or any of the other 3 different names)



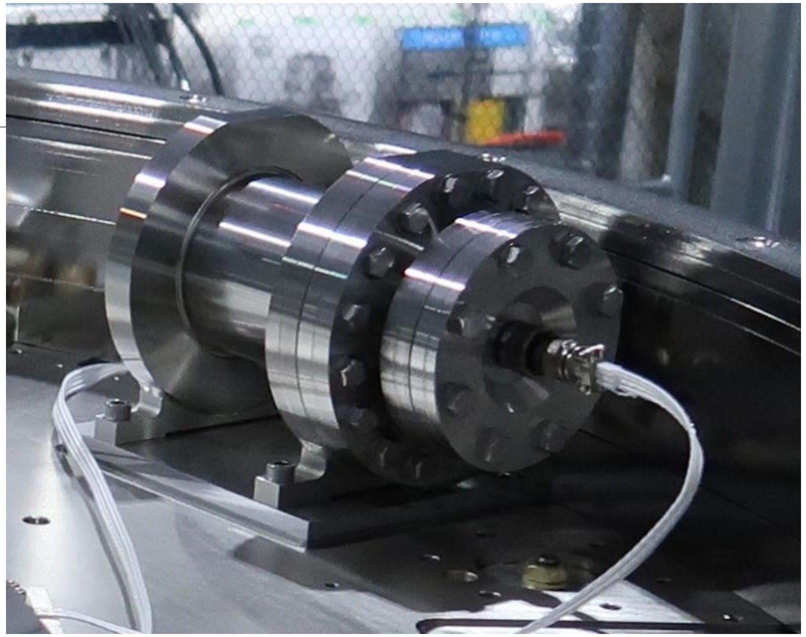
# Horizontal fishing rods at the IP

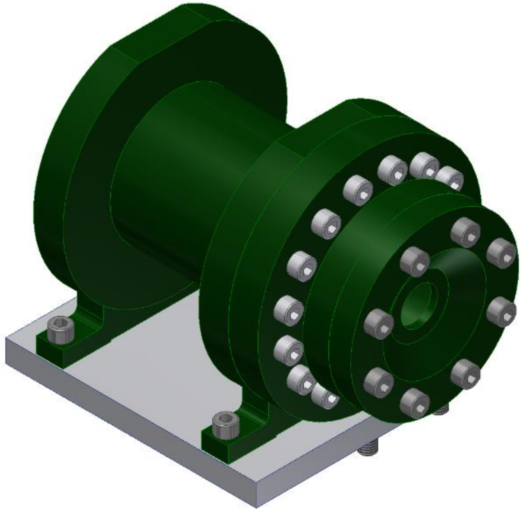



- We can adjust the IP position within several 10s of μm and μrad of the desired position.
- Then we use the coil magnet actuators.

# Geophones

- They provide an output proportional to velocity.
- The aim of using the geophones is to damp the micro-seismic peak at around 200 mHz.
- The geophones and the LVDTs are combined into a single sensor using a blending filter:
  - LVDT for position control at low frequencies (aiming at lower than 90 mHz.)
  - Geophones for the micro-seismic peak at 0.2 Hz.
- They are inside a hermetically sealed pod in air.

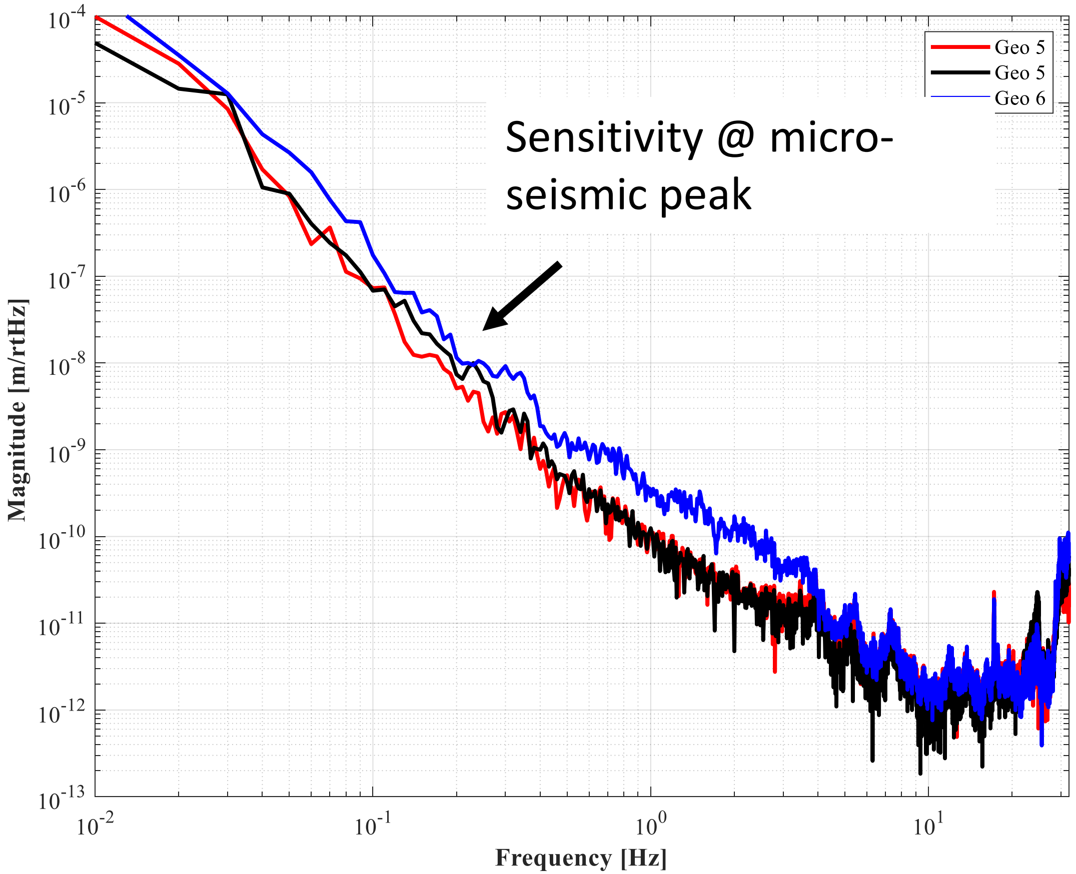




# Geophone sensitivity

The noise is measured in sets of three geophones by estimating the correlated and uncorrelated components of their signals.

- Correlated component: ground vibrations at the measurement site.
- Uncorrelated components: the noise of each geophone.




Sleeman et al. **Three channel correlation analysis: a new technique to measure instrumental noise in digitalizer and seismometers.** Bulletin of the Seismological Society of America, vol. 96, issue 1, pp. 258-271

Measured by Yoshinori Fujii

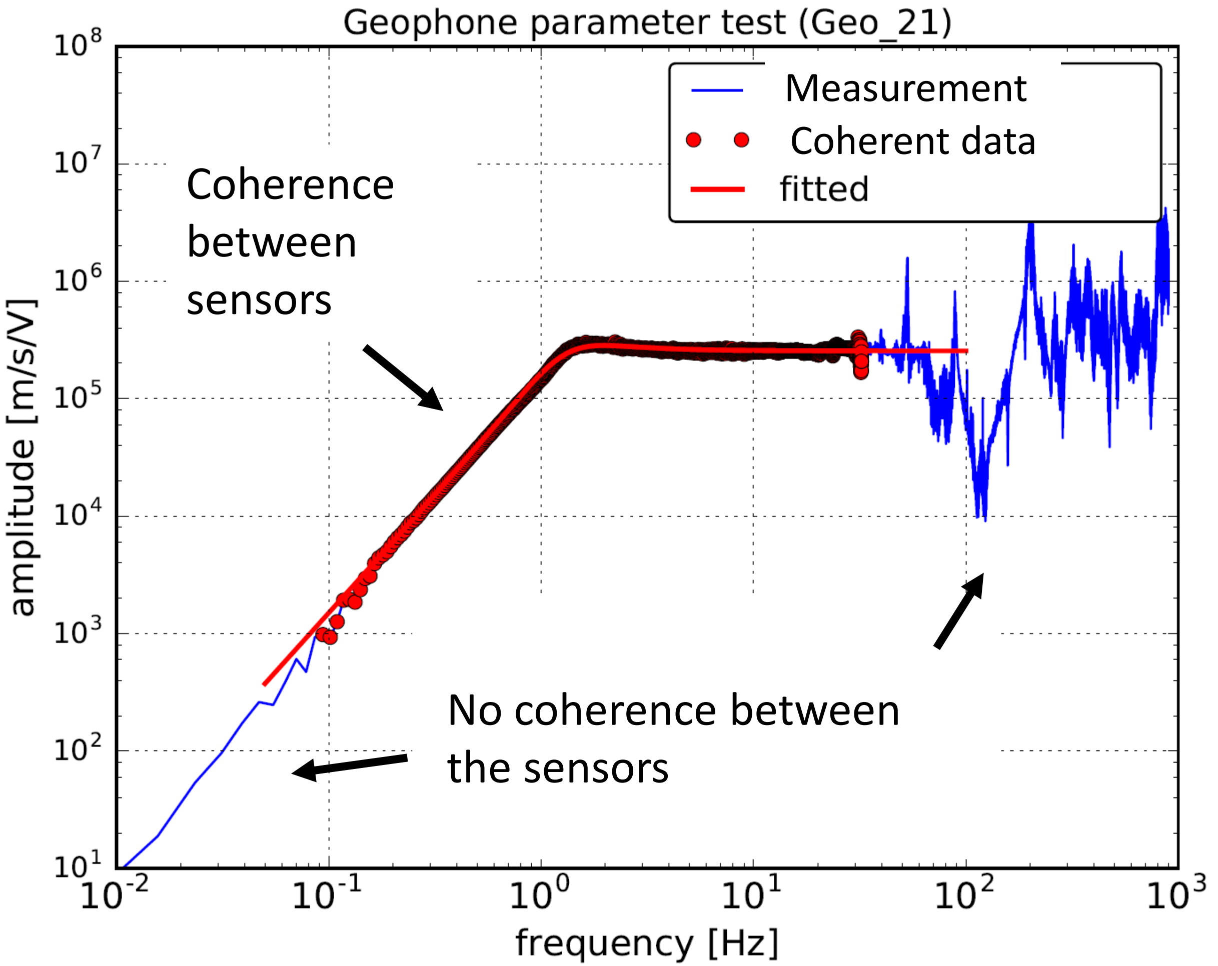
# Geophones calibration

- Geophone respond to ground velocity:

$$H_{GEO}(\omega) = \frac{G_e \omega^2}{\omega_0^2 + 2i\eta\omega\omega_0 - \omega^2}$$

$G_e$: constant [V/m/s].
$\eta$: intrinsic damping ratio.
$\omega_0$: resonant frequency [rad/s].

- They are calibrated using a reference device.

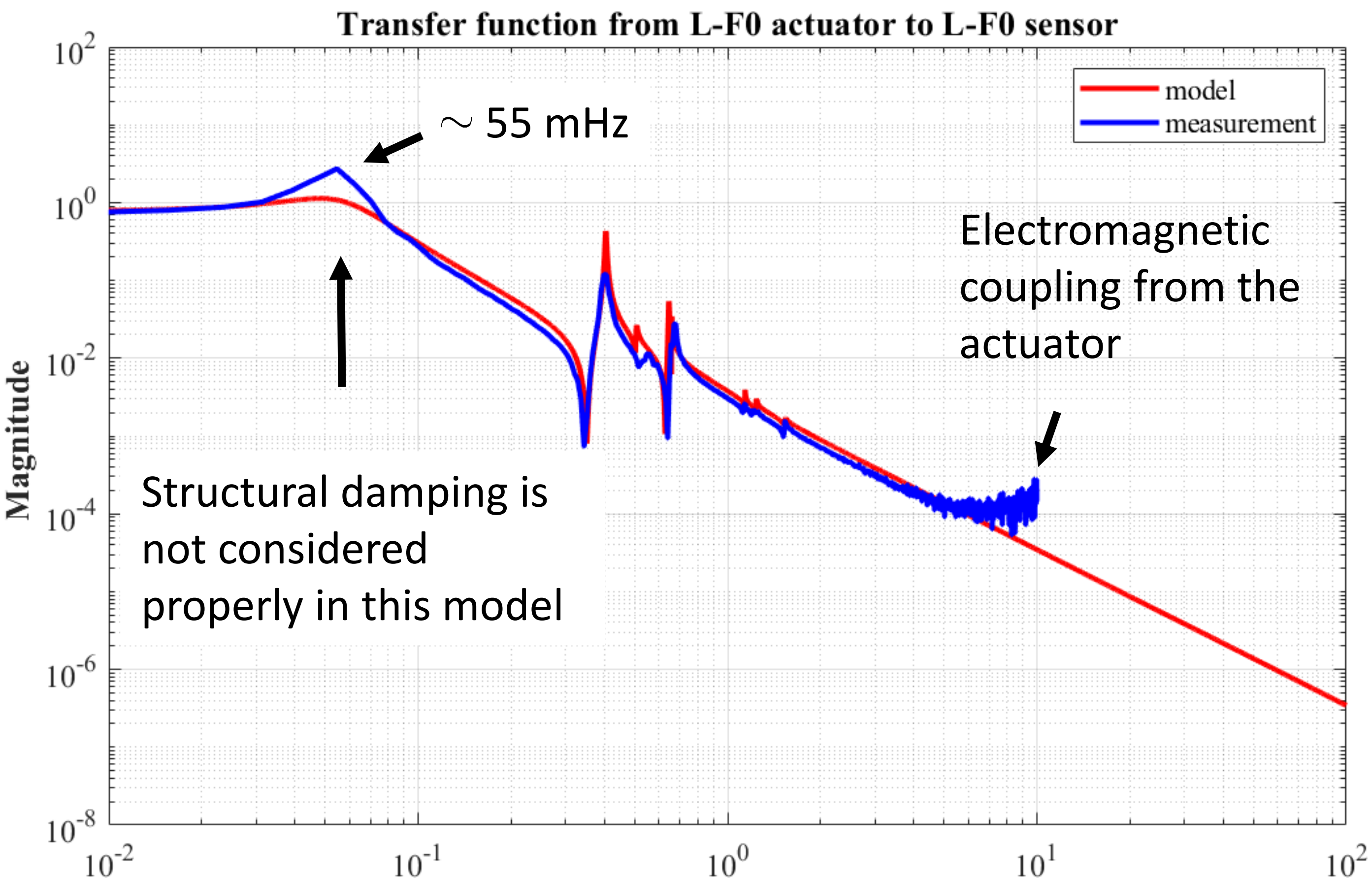


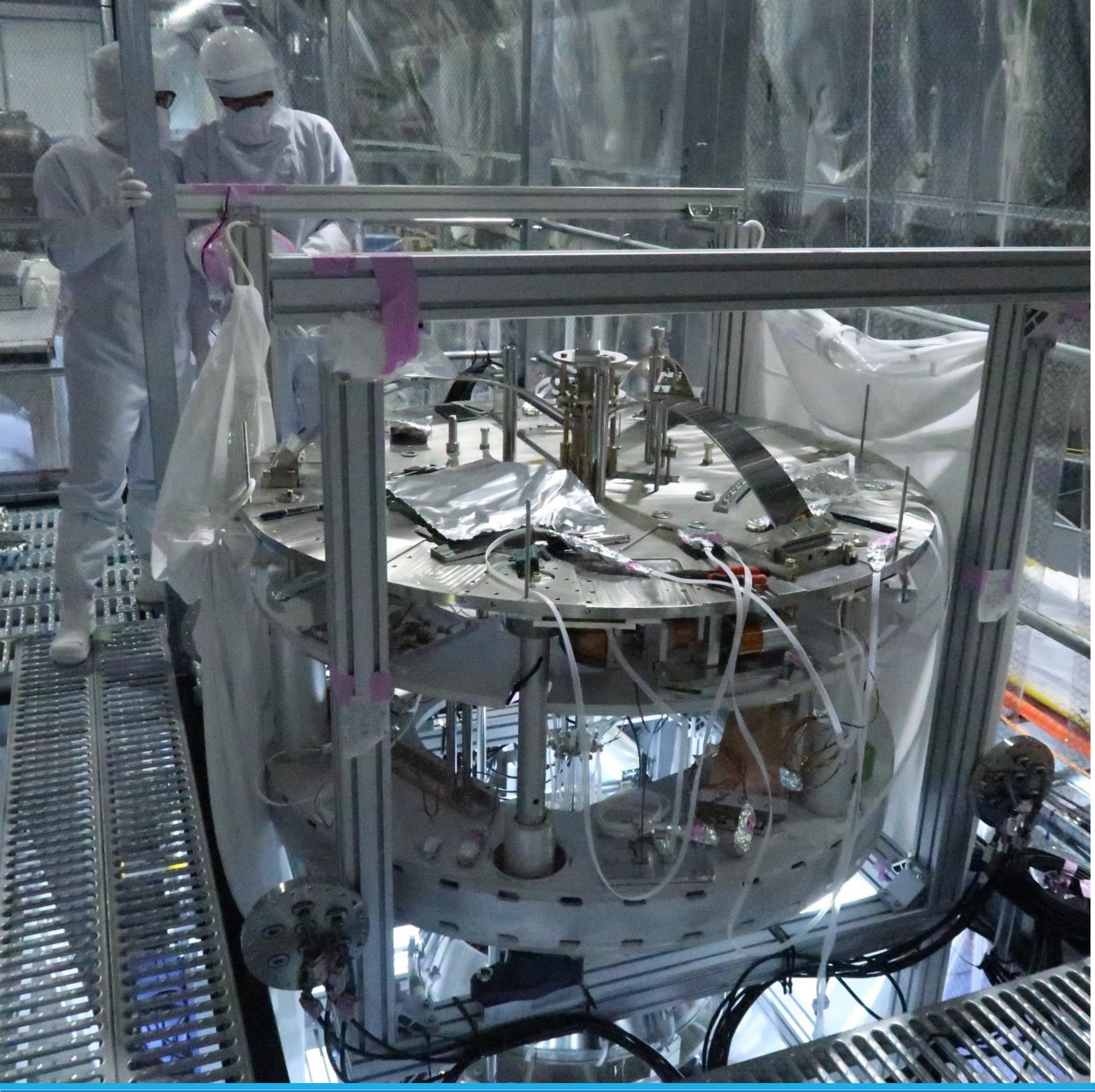
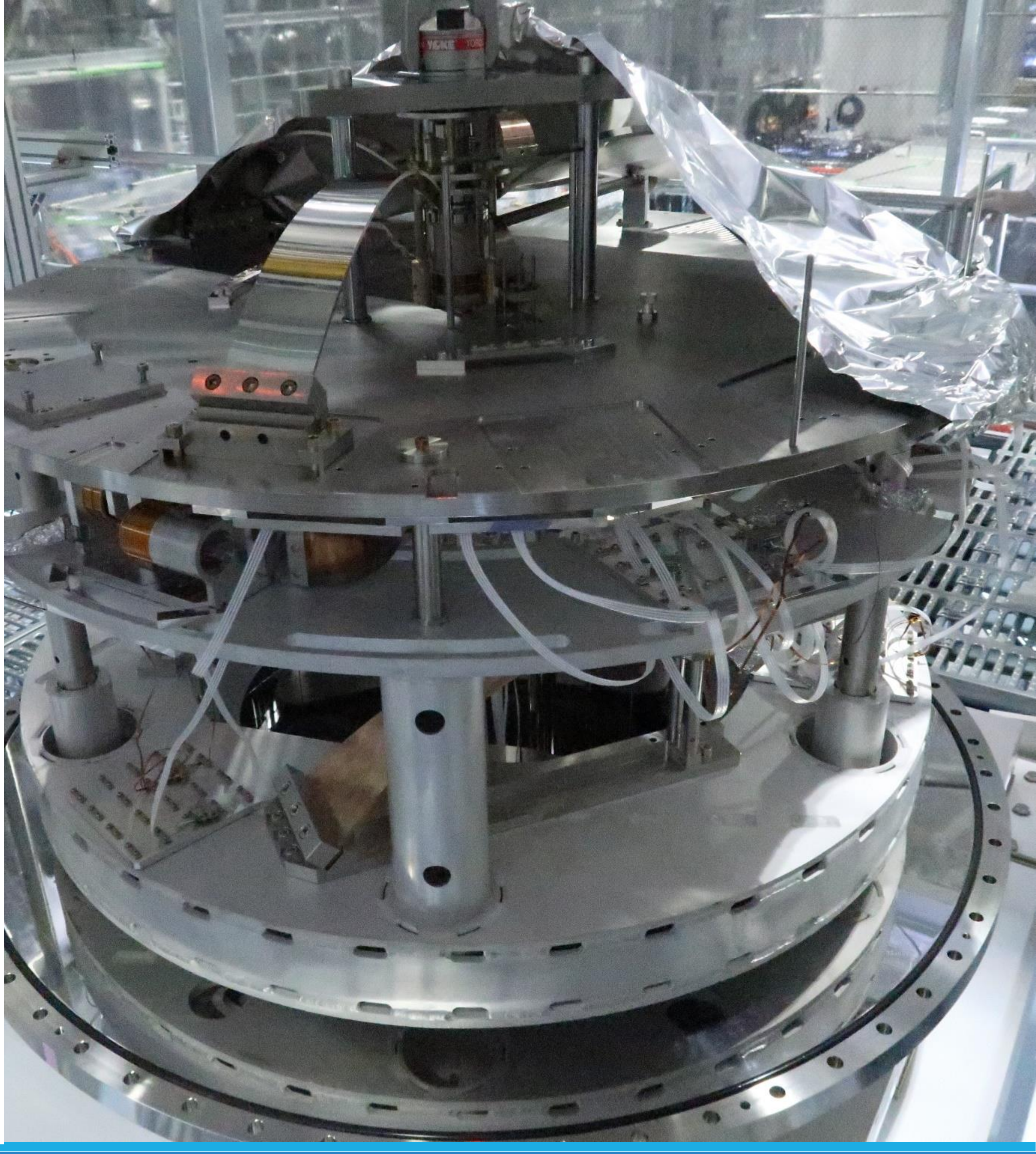

Measured by Yoshinori Fujii

# Inverted pendulum properties

Resonant frequencies for the SR2 IP:

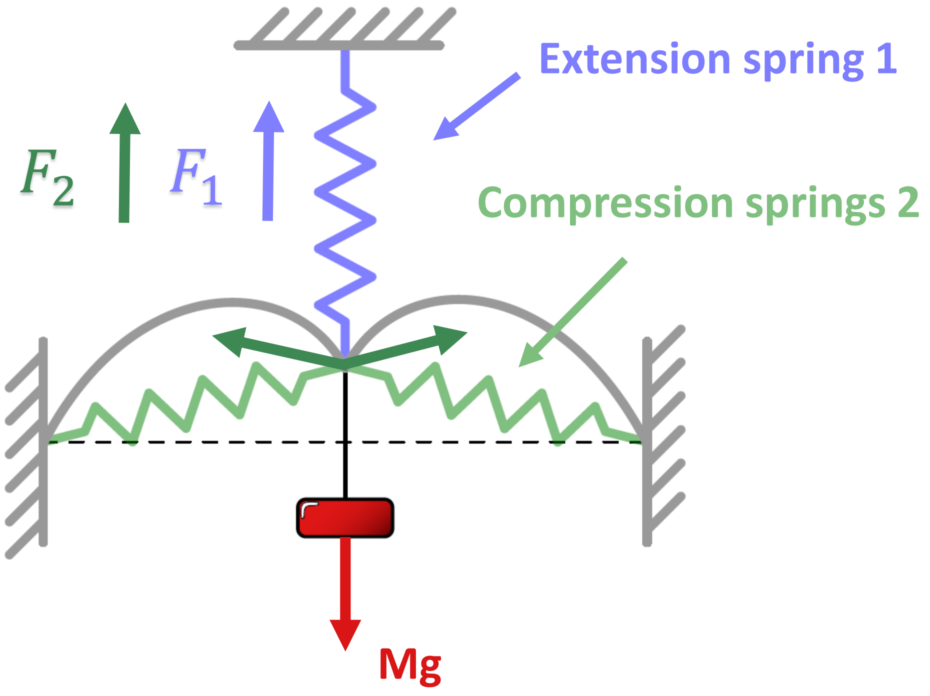
- Longitudinal: ∼ 55 mHz.
- Transverse: ∼ 55 mHz.
- Yaw: ∼ 300 mHz.



# Geometric anti-spring

- It filters vertical vibrations.
- The extension spring is very stiff so it can support a heavy load.
- The compression springs push the load away from the equilibrium position as the load moves: the system becomes softer.

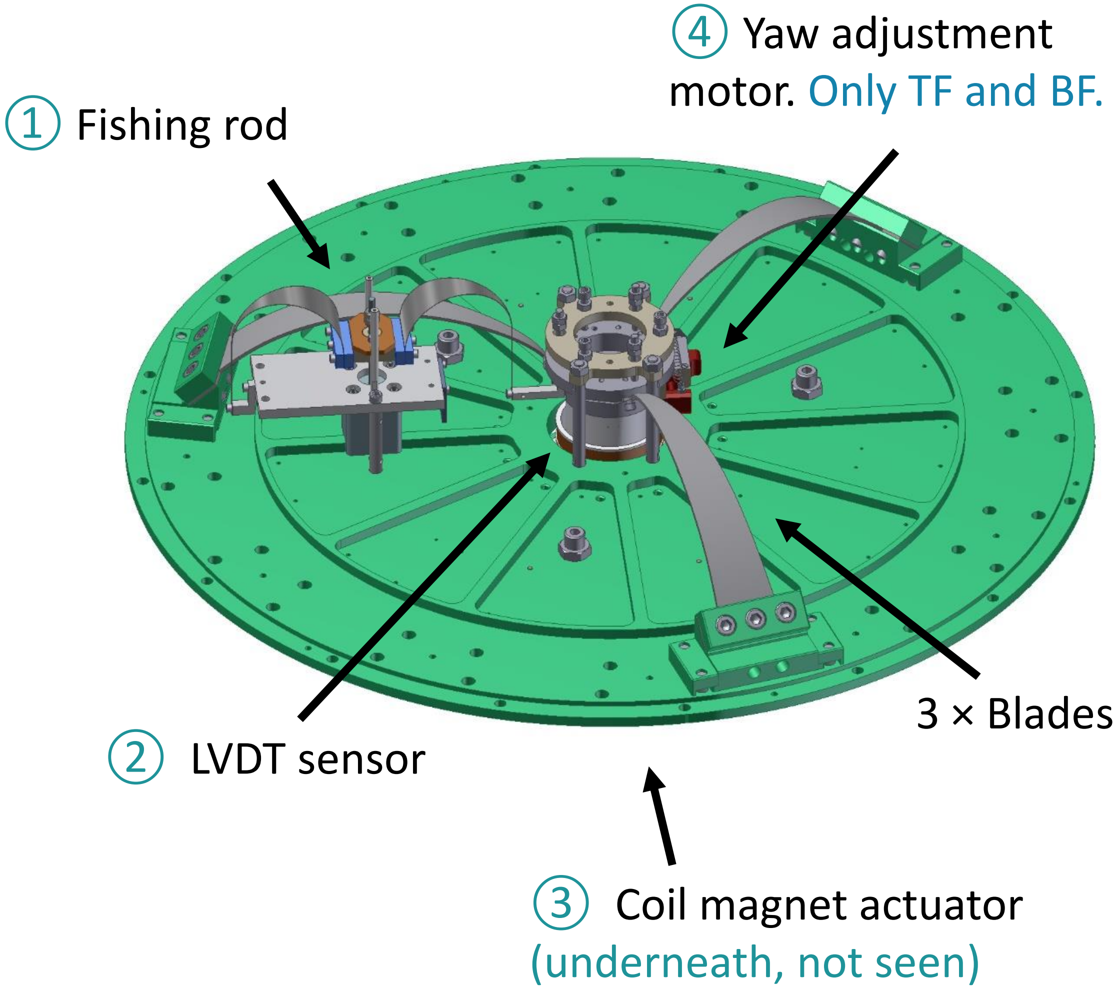



Original drawing by Alexander Wanner

# GAS filters in the Type B suspension

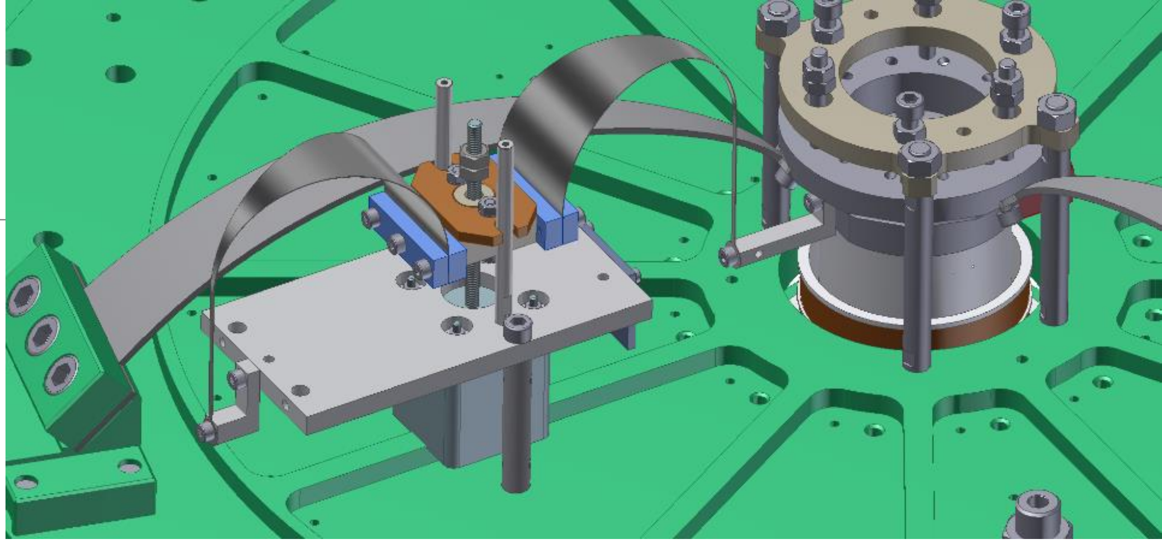
Similarities and differences:

- All of them have fishing rod actuators. ①
- All of them have LVDT displacement sensors. ②
- All of them have coil-magnet actuators. ③
- Yaw adjustment motor: Top Filter and Bottom filter. ④
- Magnetic damper ring: only Standard Filter.
- The Intermediate Recoil Mass (IRM) hangs directly from the Bottom Filter base plate. (It will be shown later.)
- The Bottom Filter has tilt mechanism to finely adjust the position of the IRM. (Not shown.)

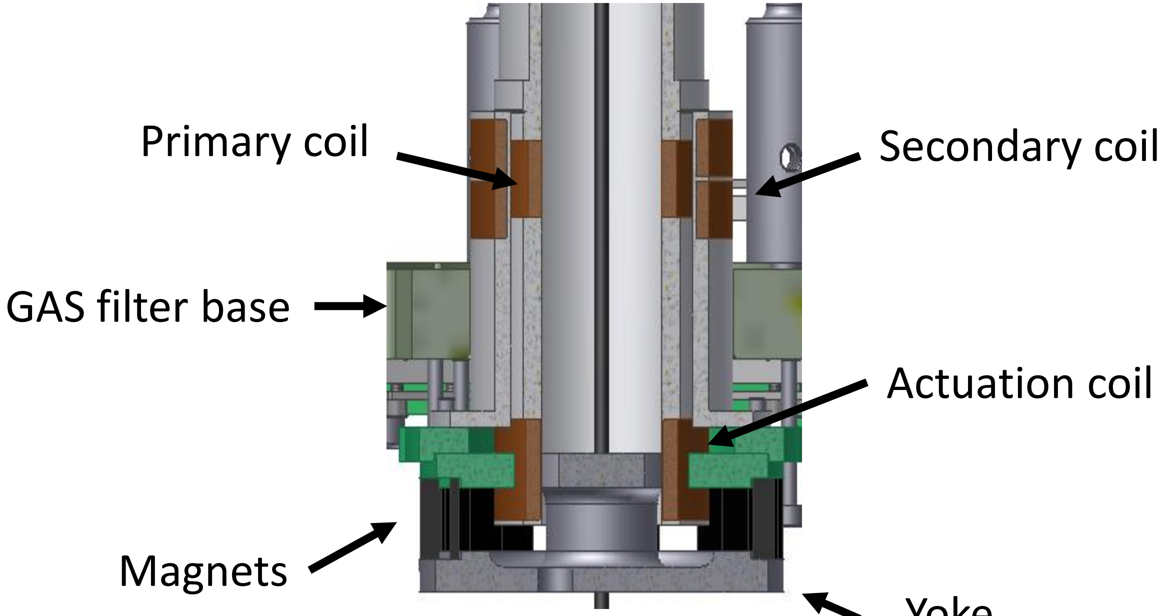


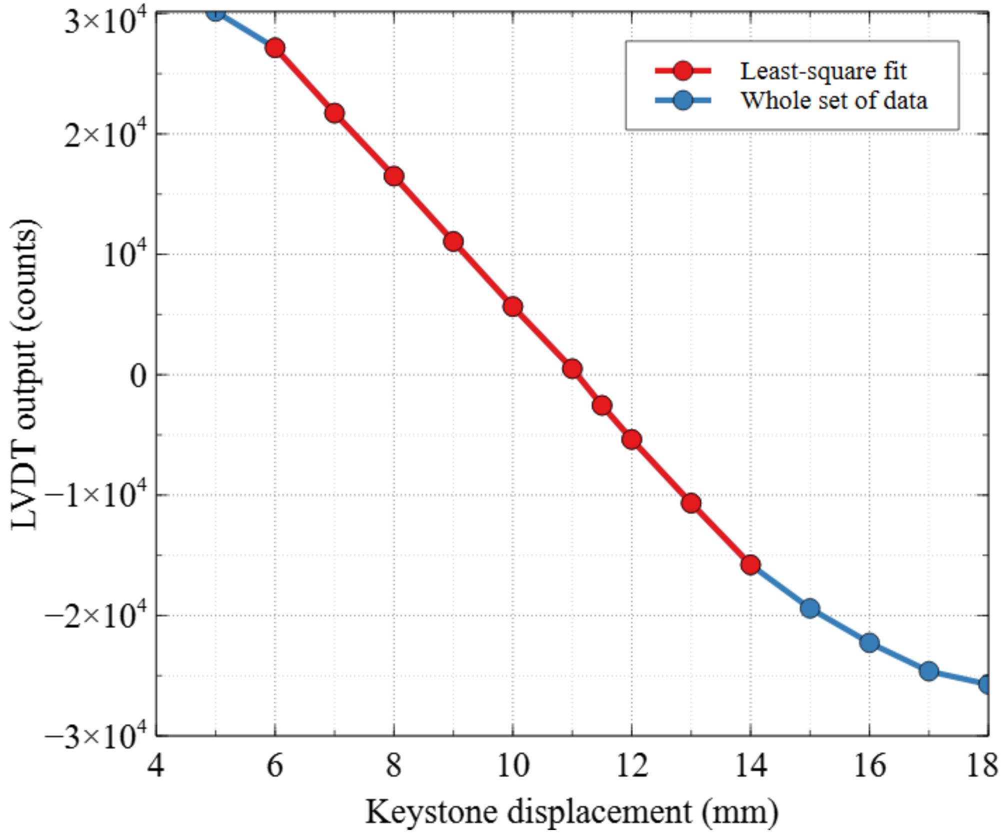
# Fishing rods

- Its aim to finely adjust the position of the load:
  - We need to set the optic at the correct height.
  - The keystone has to be at the right height.
- We usually have to move it by tens of microns at the time and then use the coil magnet actuator to take it to the desired position.
- **This is not used in the control loop.**



# LVDT calibration



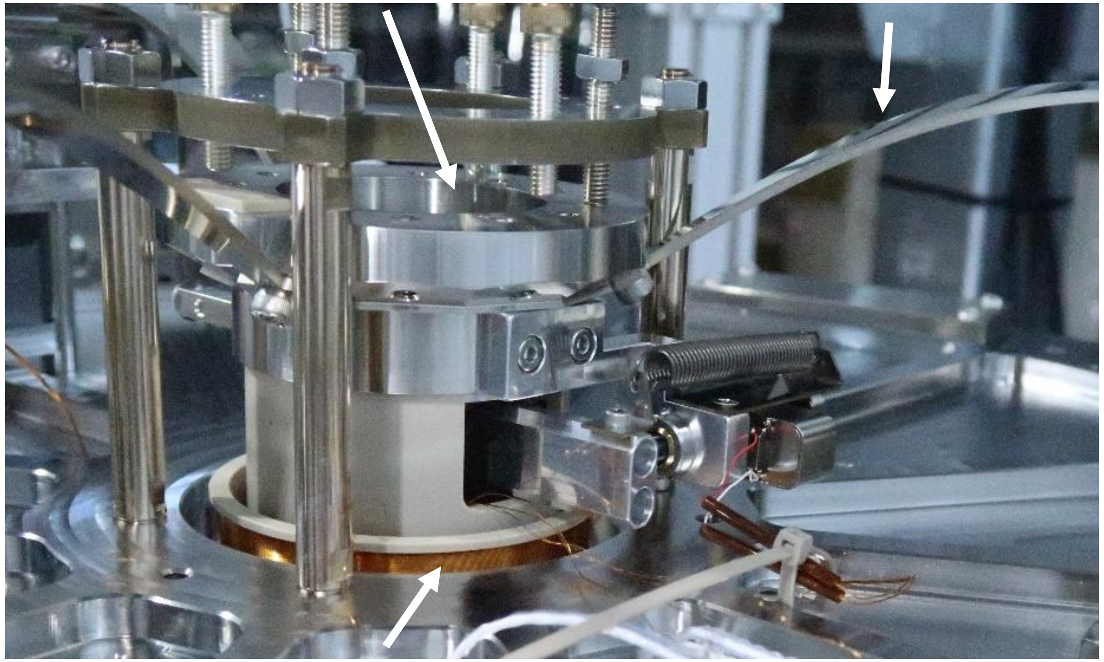

- Example: F0 LVDT in SRM
- Calibration factor example: -0.185 μm/count.
- Linear range: 8 mm.

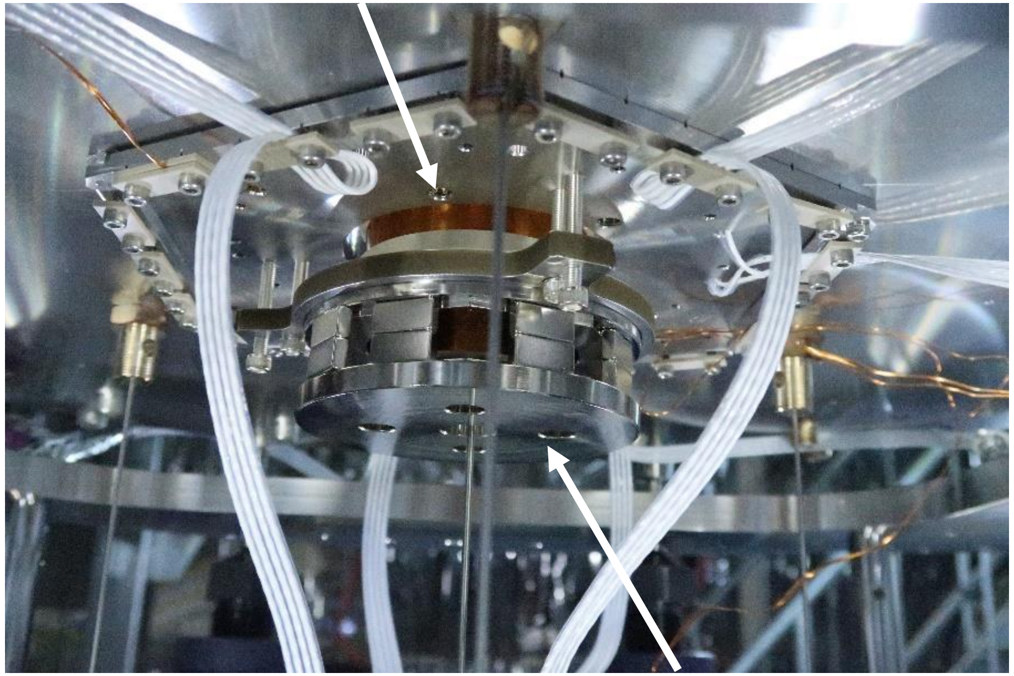
# LVDT and coil-magnet actuators

Keystone

Blade

Actuation coil





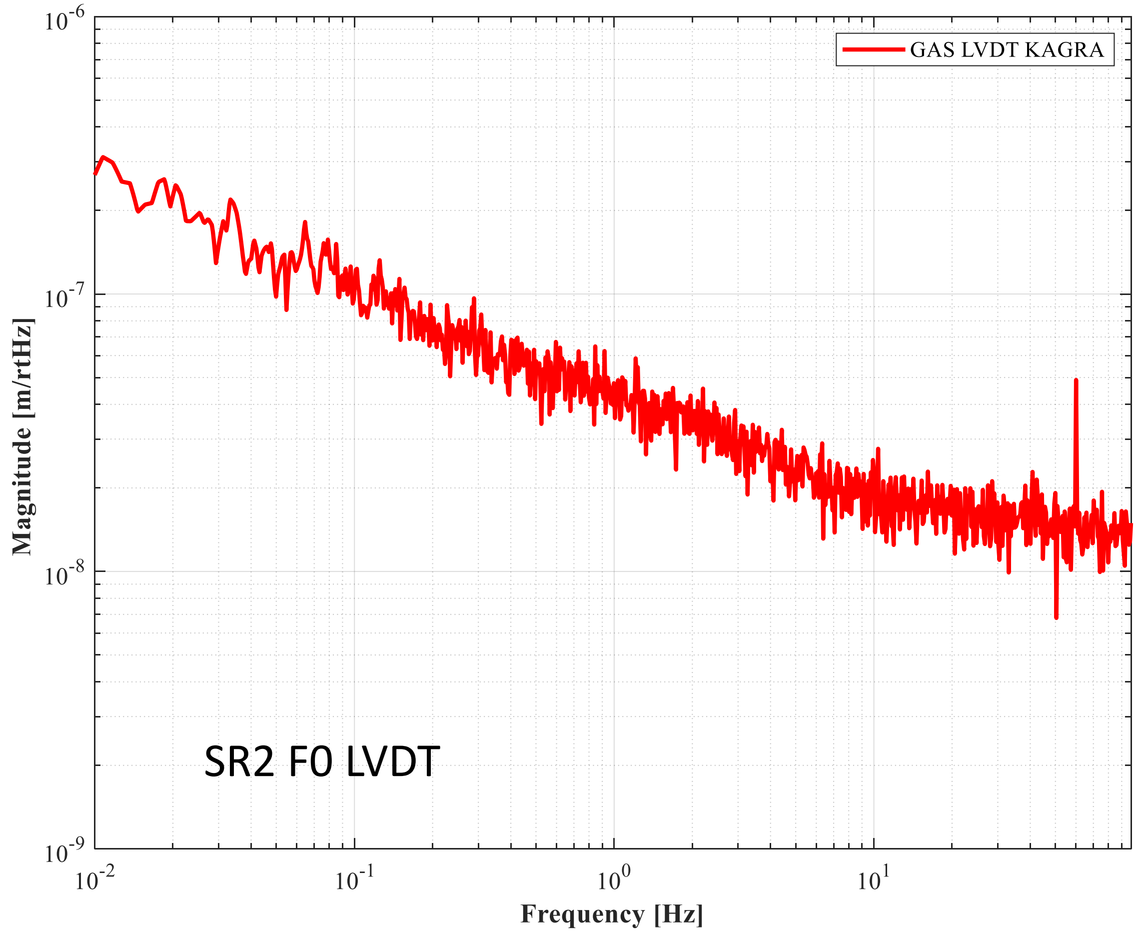
LVDT secondary coil

Yoke

Suspension rod at the centre of coils

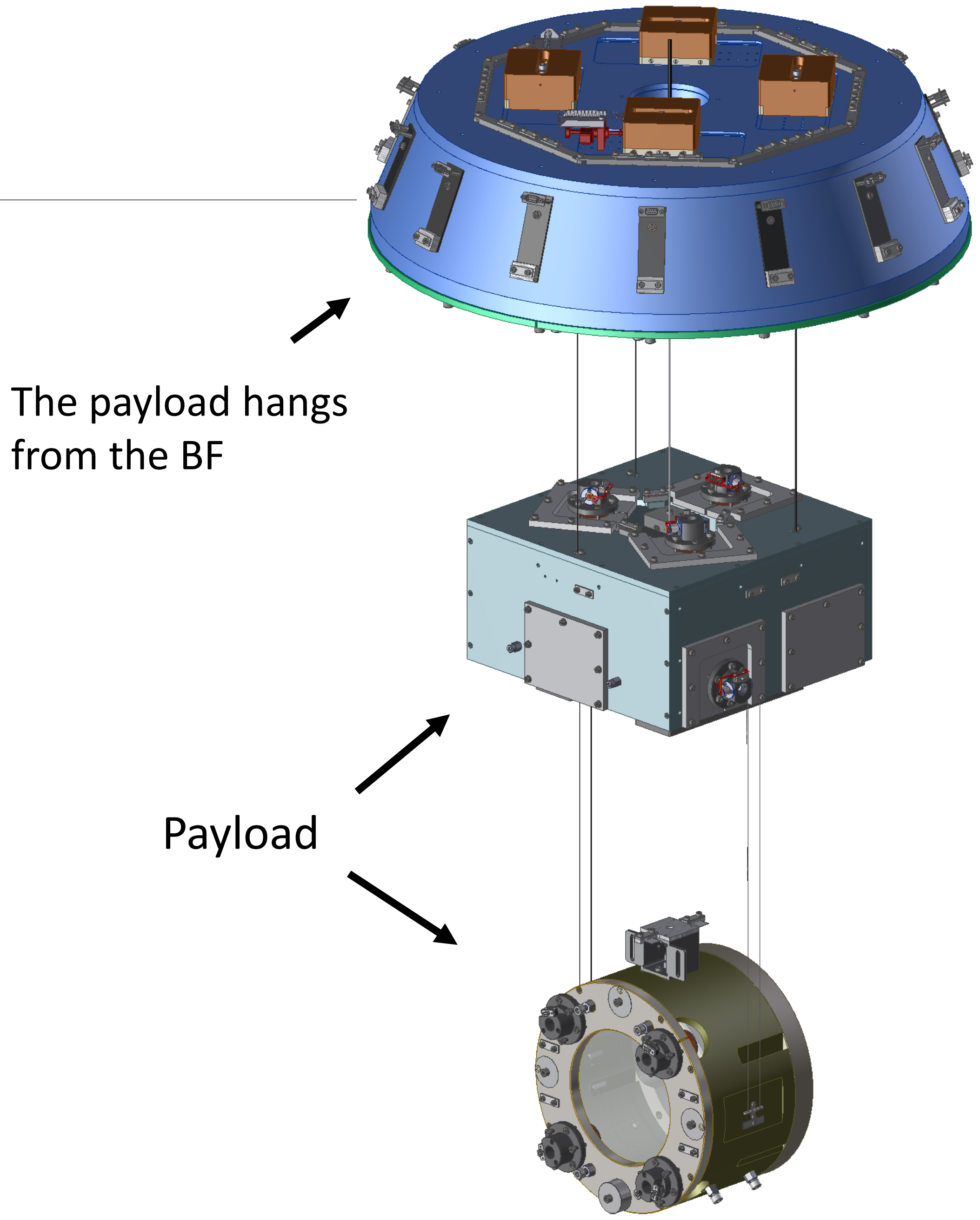
# LVDT sensitivity

- It was measured by locking the LVDT.
- At 1 Hz: 0.04 µm/√Hz.
- At 10 Hz: 0.02 µm/√Hz.
- Integrated RMS: typical values from 0.1 to 0.5  µm.



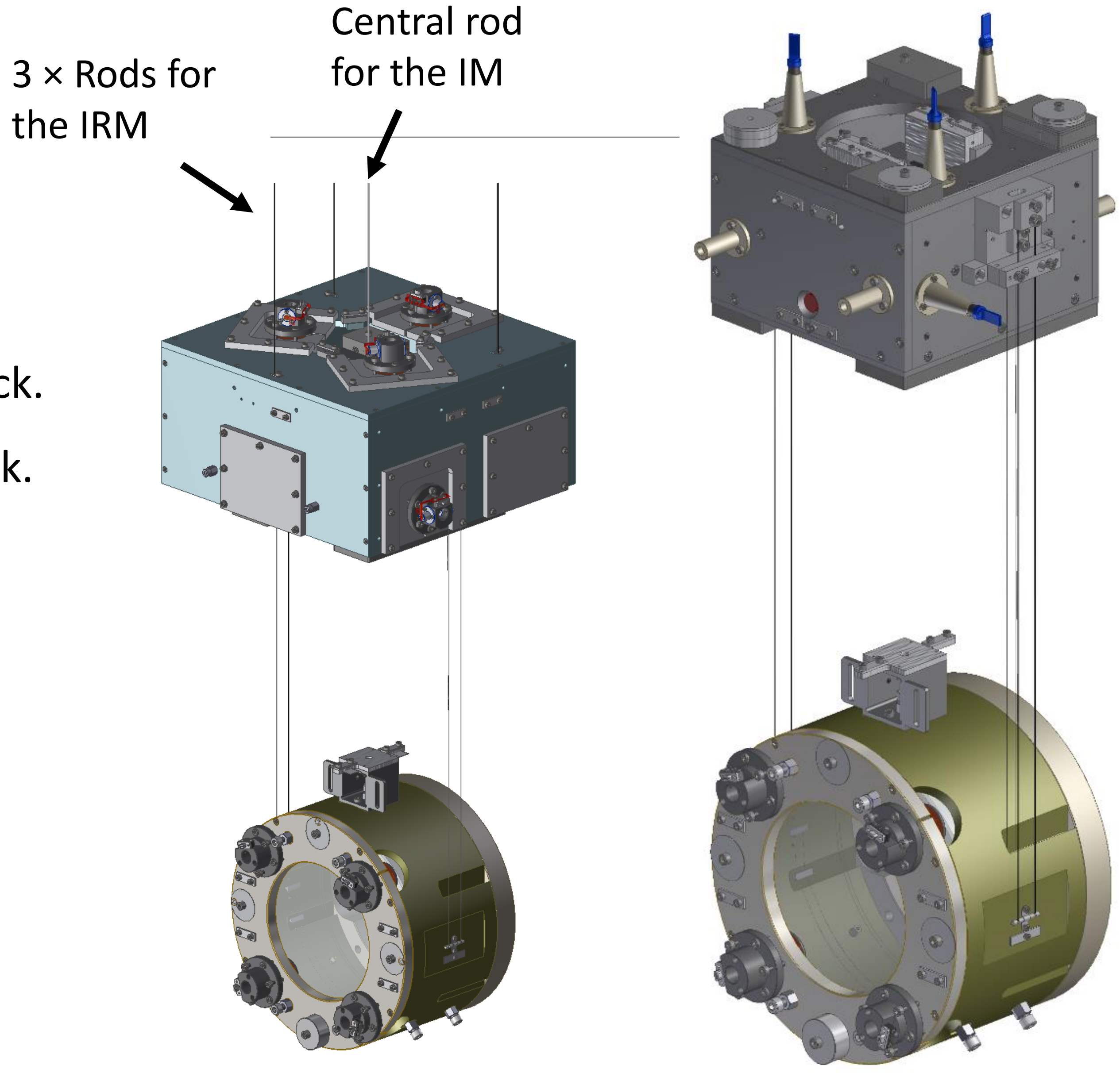
# The payload (1)

- Optic:
  - it has magnets for applying forces with coils.
  - It has primary and secondary wire breakers.
- Recoil Mass: it holds coil for applying forces onto the optic.
- Intermediate Mass (IM)
  - It holds the optic and the Recoil Mass with wires.
  - It serves as a marionette for roll and pitch.
  - Yaw is adjusted with either the Bottom Filter or Top Filter.
  - It has OSEMS to actively damp the resonant modes of the payload itself.
- Intermediate Recoil Mass:
  - Holds the OSEMs.
  - Hangs from the BF with three suspension rods.
- Oplev on the ground for measuring pitch, yaw and longitudinal.

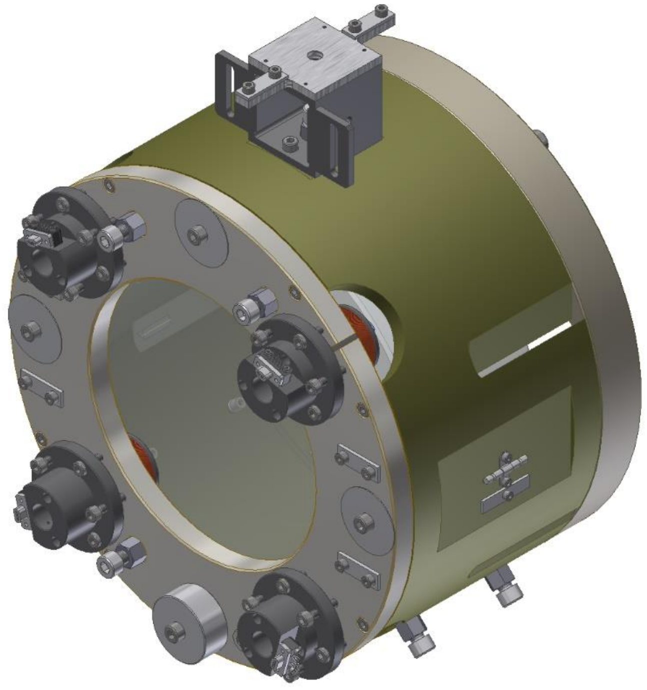


# The payload (2)

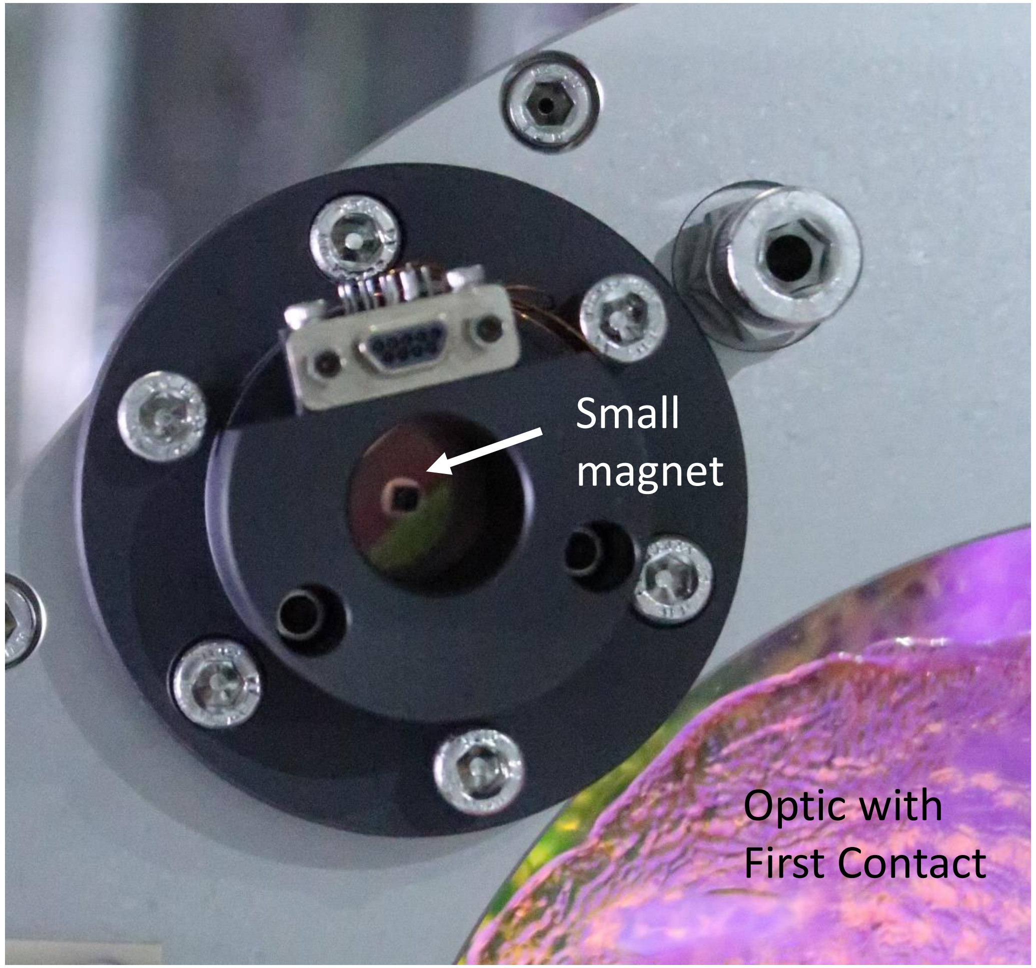
- IRM: 3 × 2 mm maraging rod.
- IM: 1 × 2 mm maraging rod (neck).
- Optic:  2 × loops of piano wire 200 µm thick.
- RM: 2 × loops of tungsten wire 650 µm tick.
- IRM: aluminium, 8.9 kg.
- IM: aluminium and stainless, 26.2 kg.
- Optic: fused silica, 10.2 kg.
- RM: titanium, 12.0 kg.



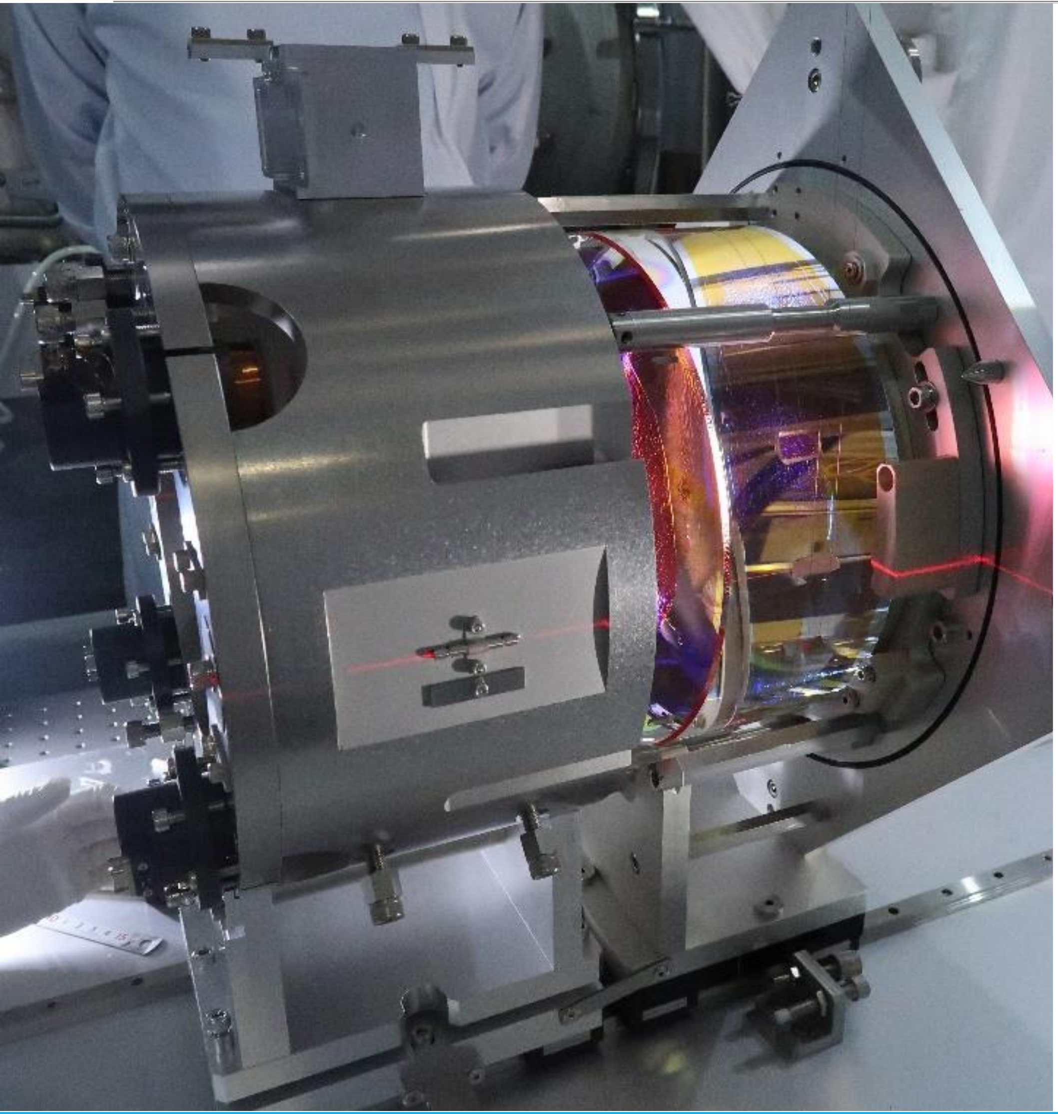
# The Optic and the Recoil Mass (1)



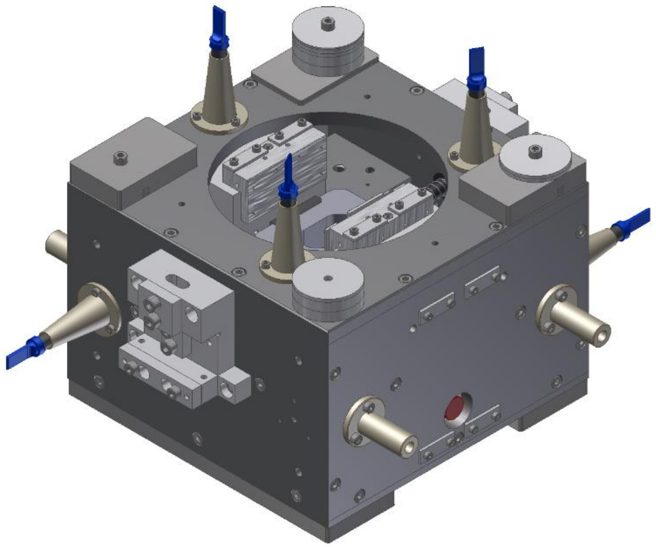
The centres of mass of the optic and RM coincide, nominally.

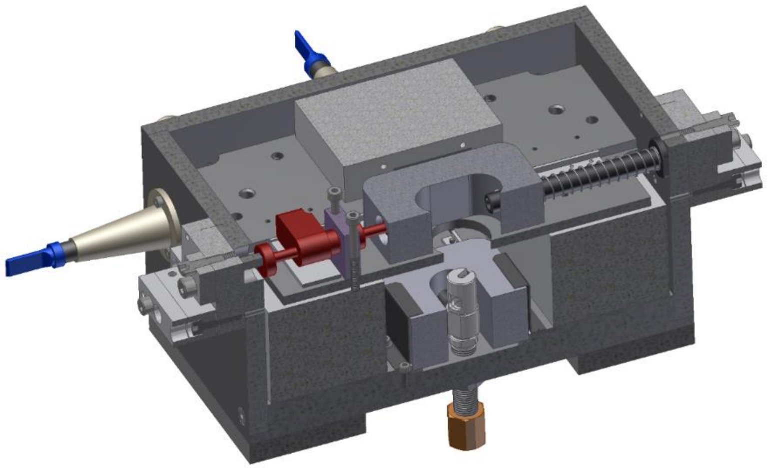


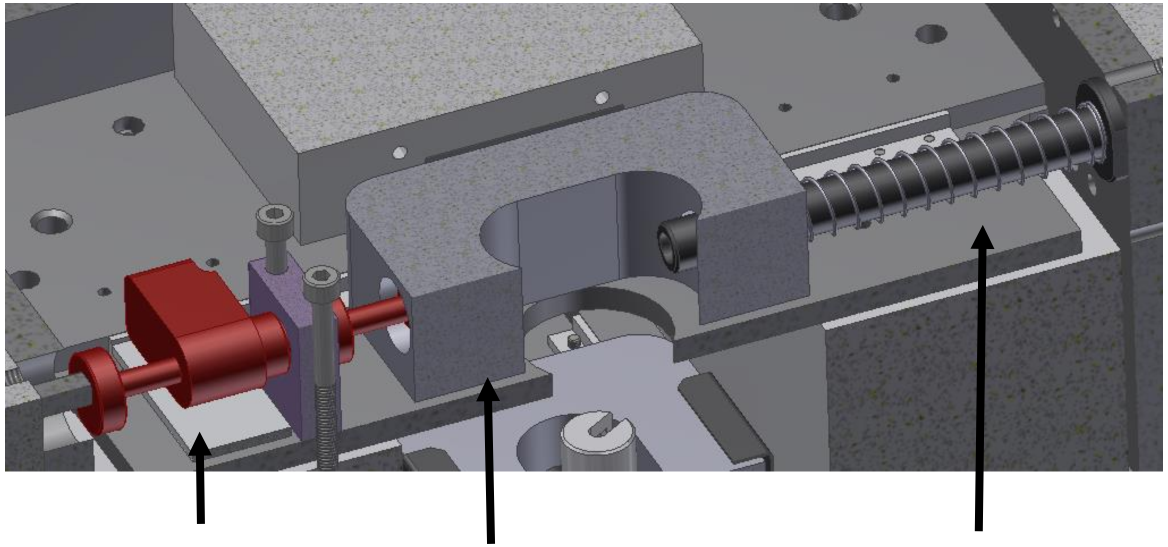
# The Optic and the Recoil Mass (2)



# The Intermediate Mass marionette (1)

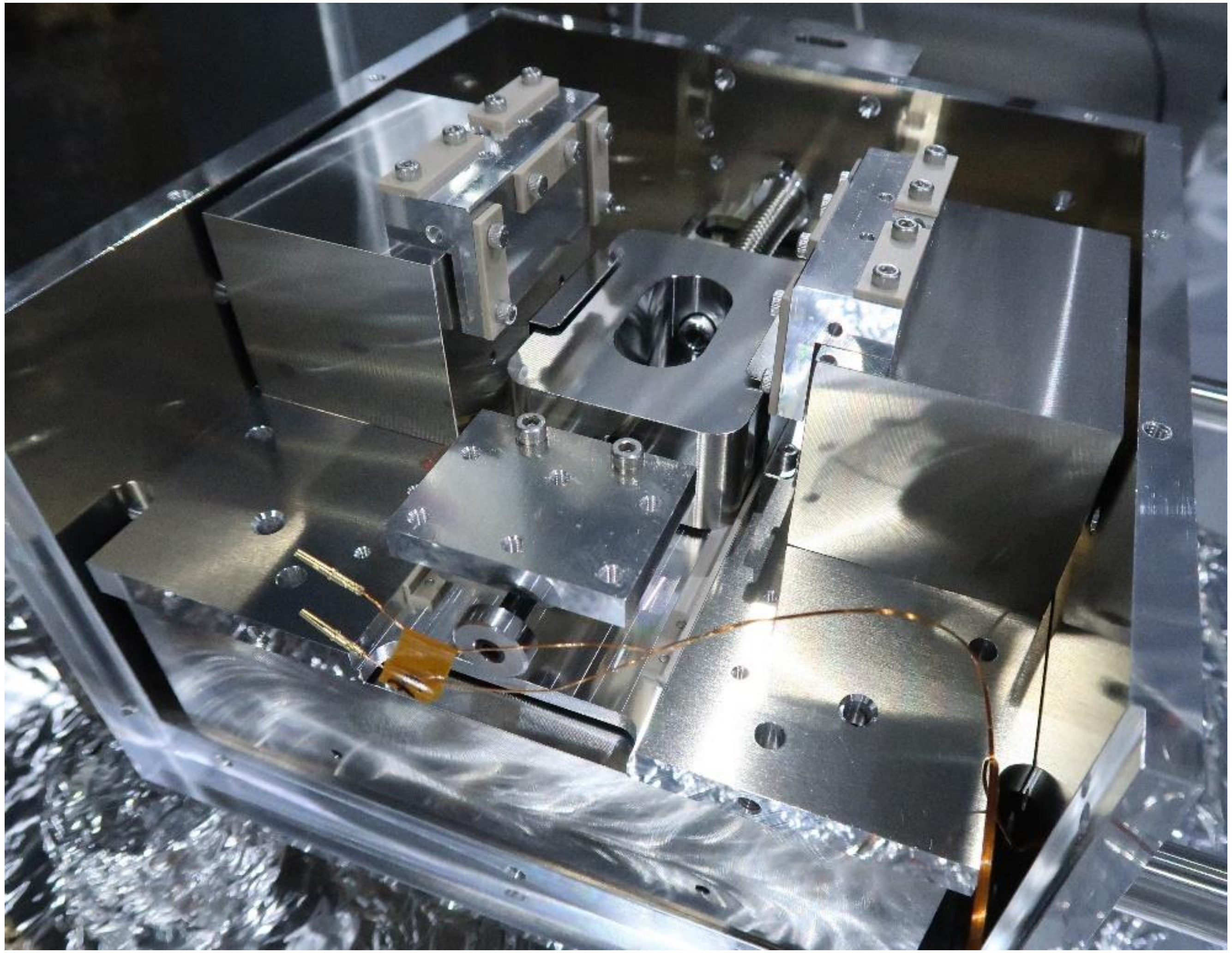




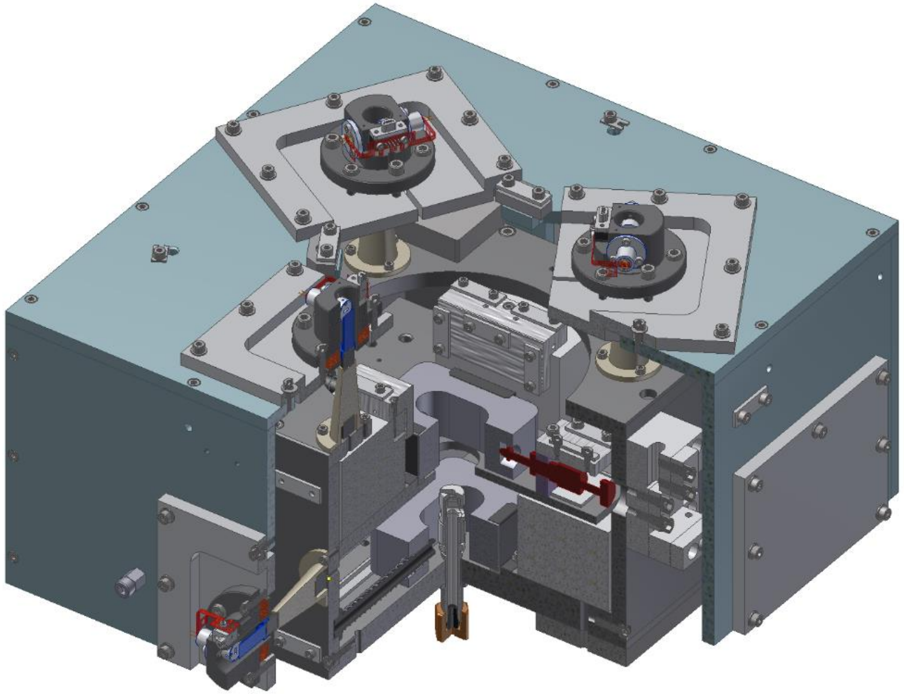


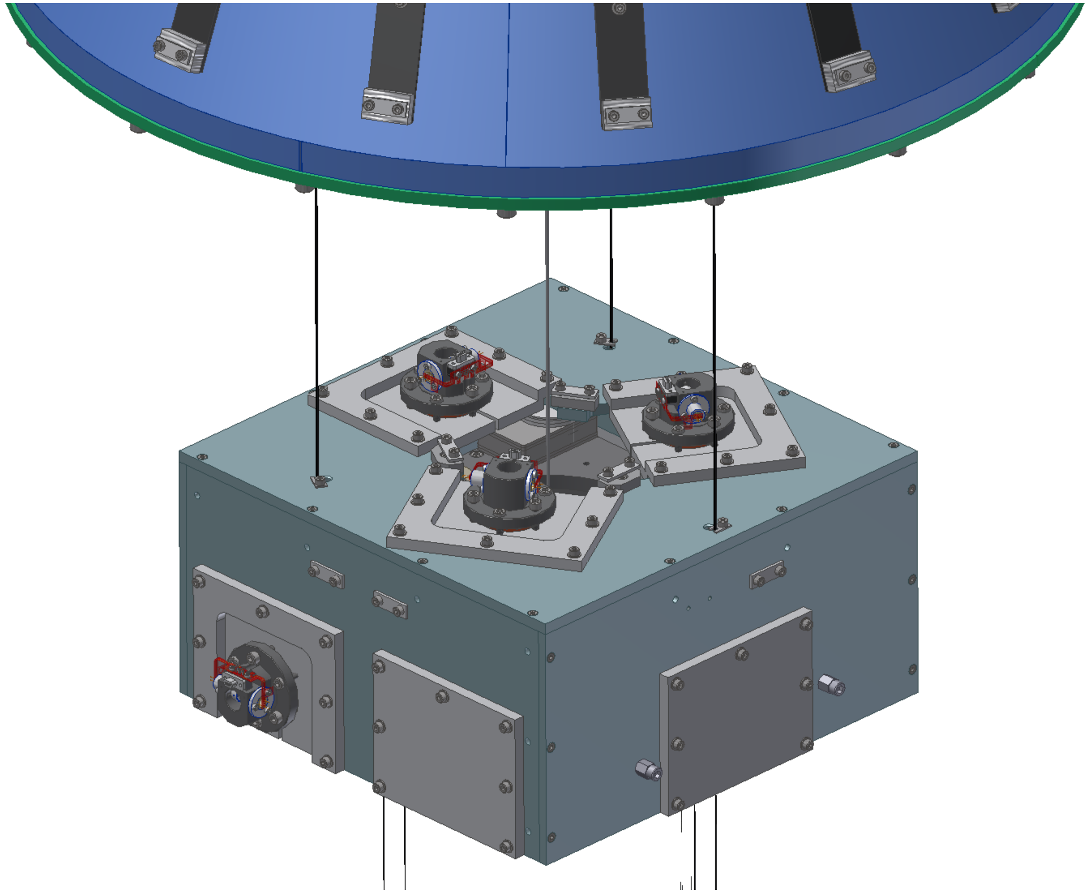

- We can tilt the marionette in roll and pitch by changing the position of its centre of mass with sliding masses within.
- We tend to adjust within a few µrad from desired position and then use coil magnet actuation.

# The Intermediate Mass marionette (2)



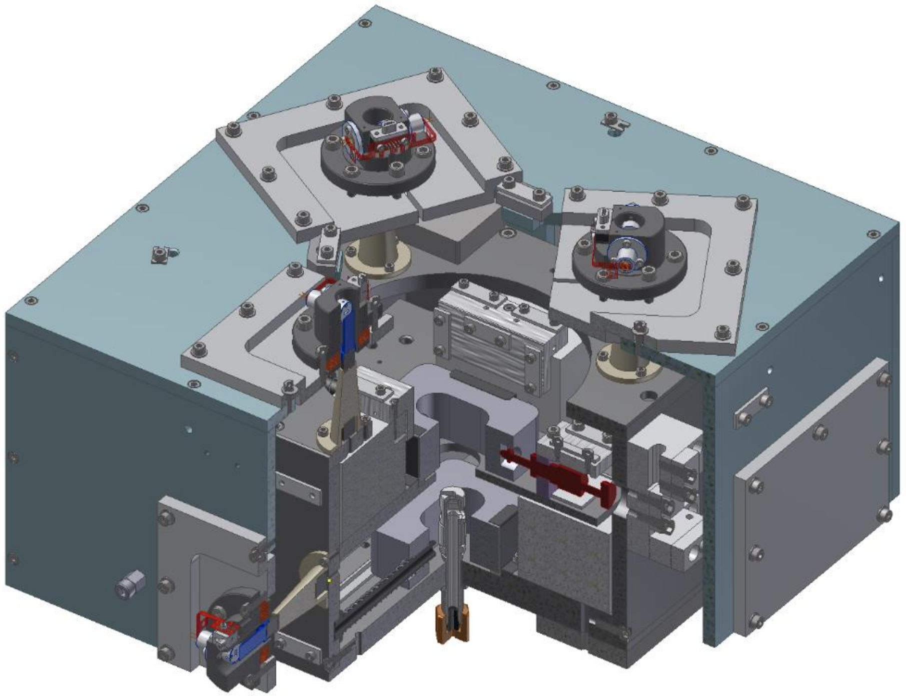
# Intermediate Recoil Mass

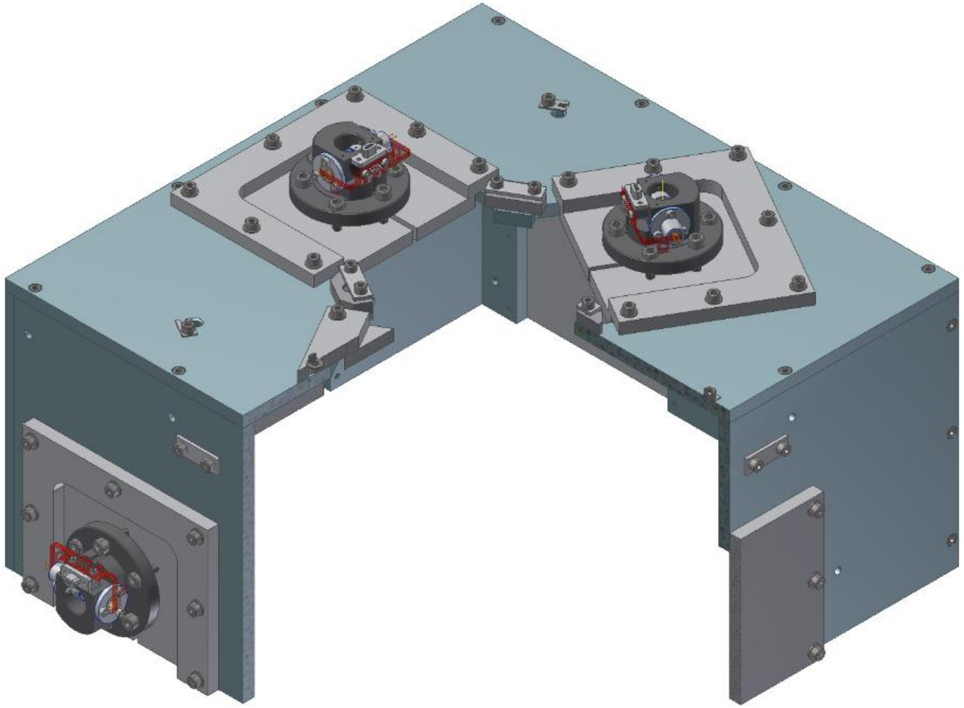




- The RM is a box  opened a the bottom.
- It holds the OSEMs.
- It hangs from the BF

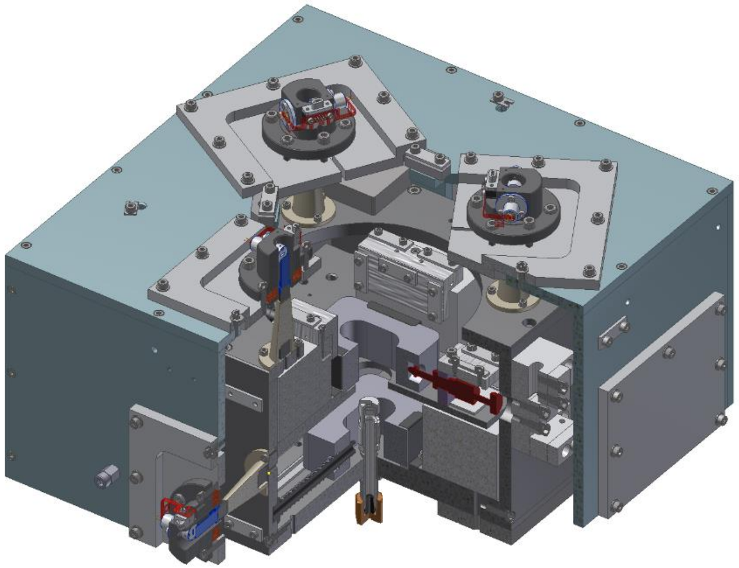
# Intermediate Recoil Mass

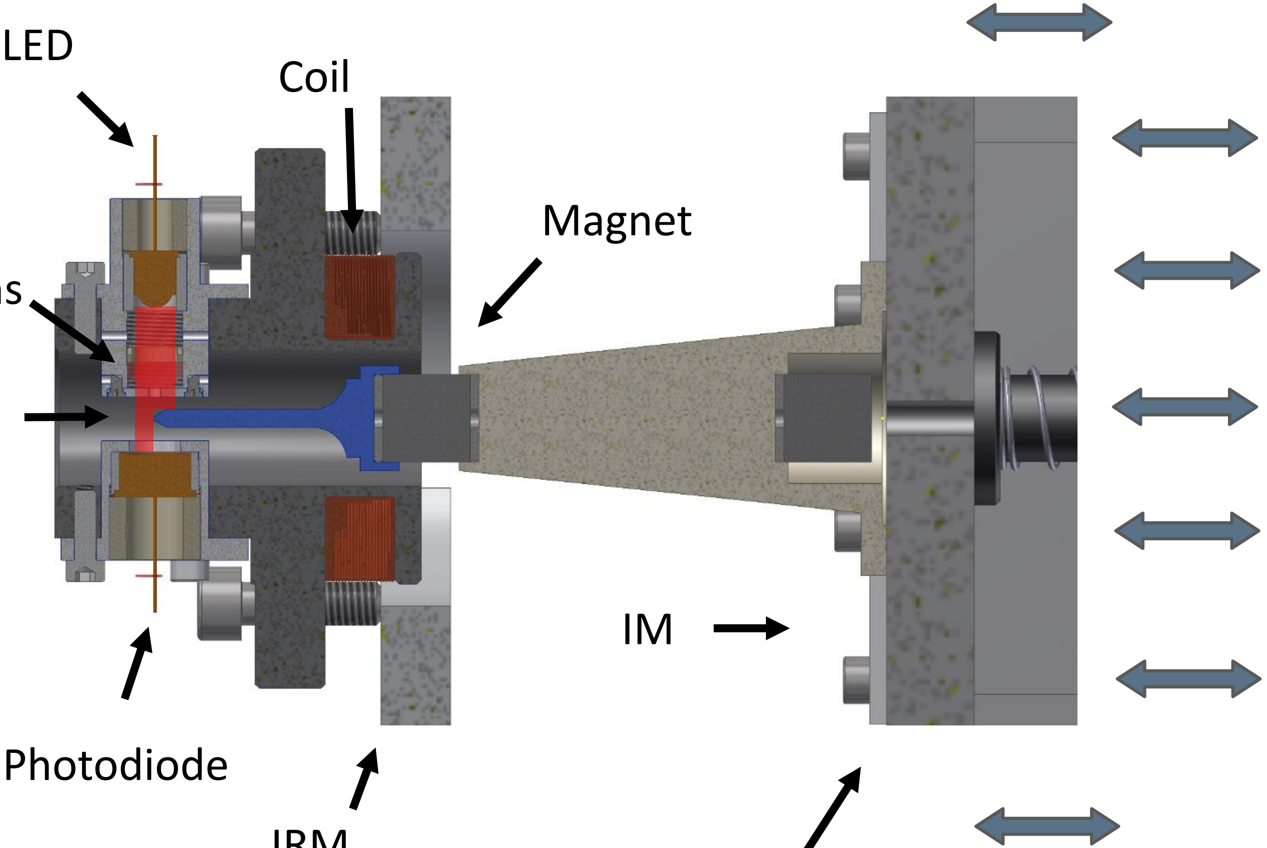




- The RM is a box  opened a the bottom.
- It holds the OSEMs.
- It hangs from the BF

# OSEM: Optical Sensor and Electromagnetic Actuator



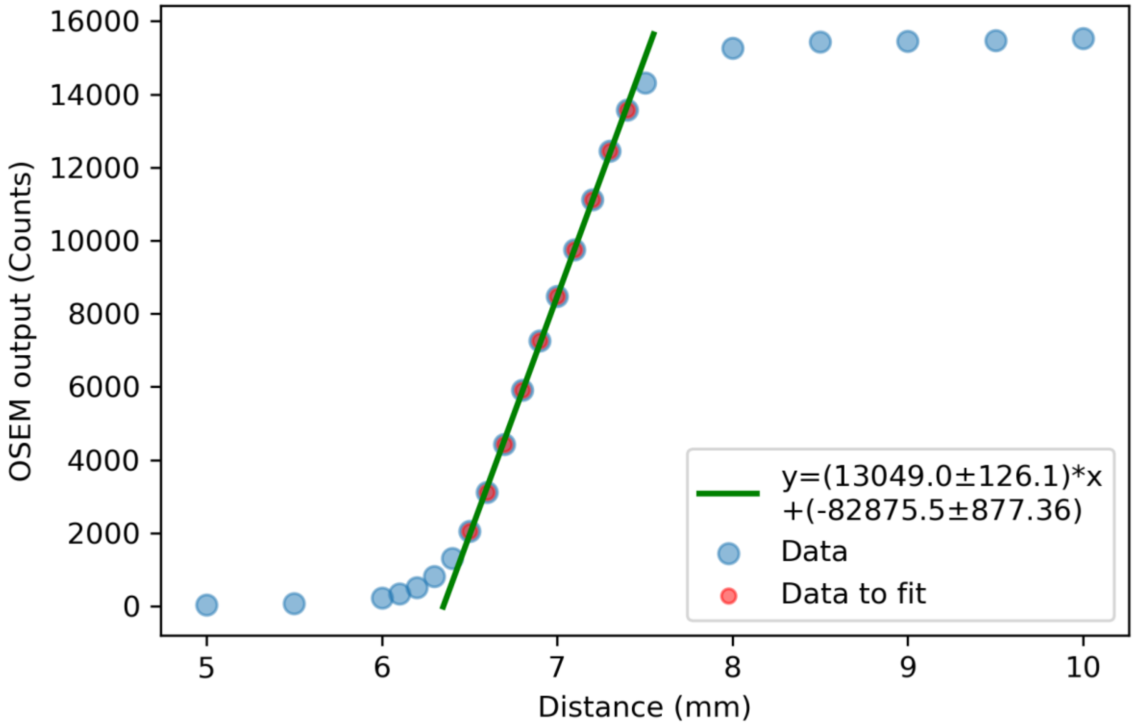


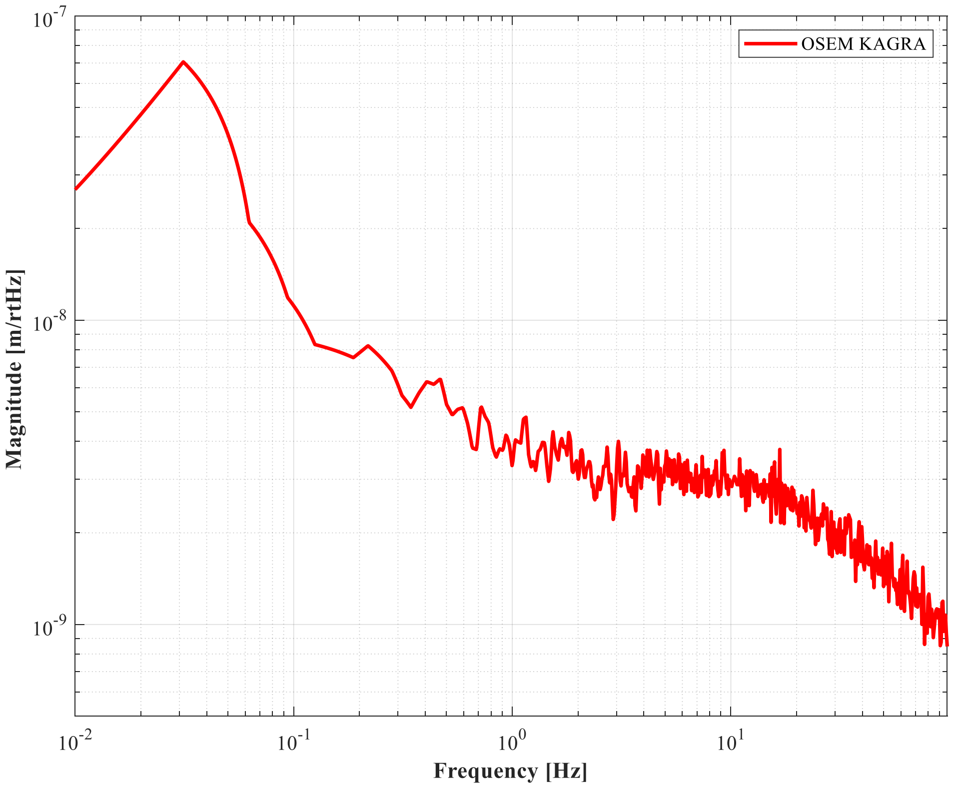

- The position sensor is a shadow sensor.
- It has a coil magnet-actuator.
- Mounted on IRM.
- 6 × OSEMs for 6 DoF: L, T, V, R, P and Y.

When the IM moves the flag changes the amount of light reaching the photodiode.

# OSEM calibration and sensitivity

- Calibration factor: 2.89 mV/µm
- Linear range: 0.9 mm



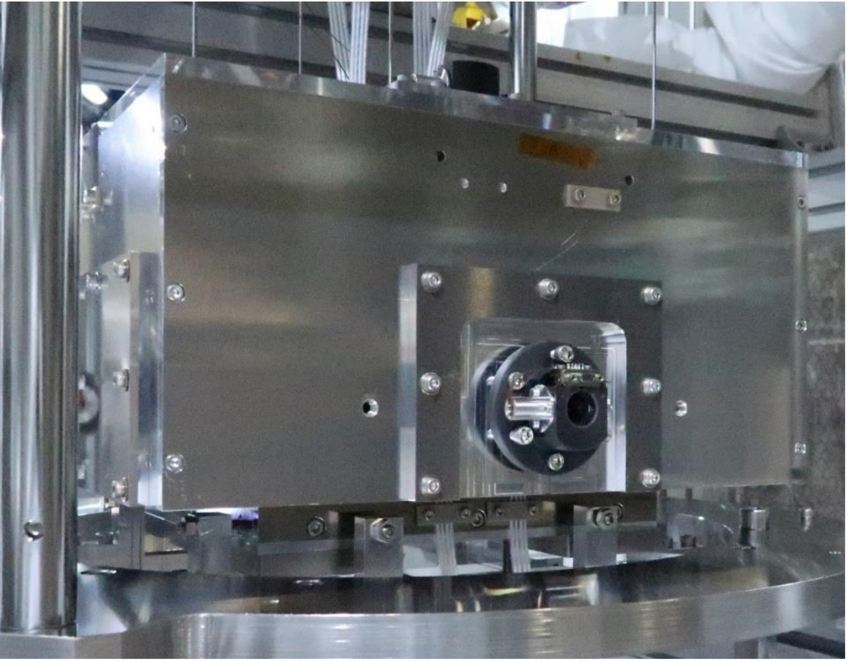
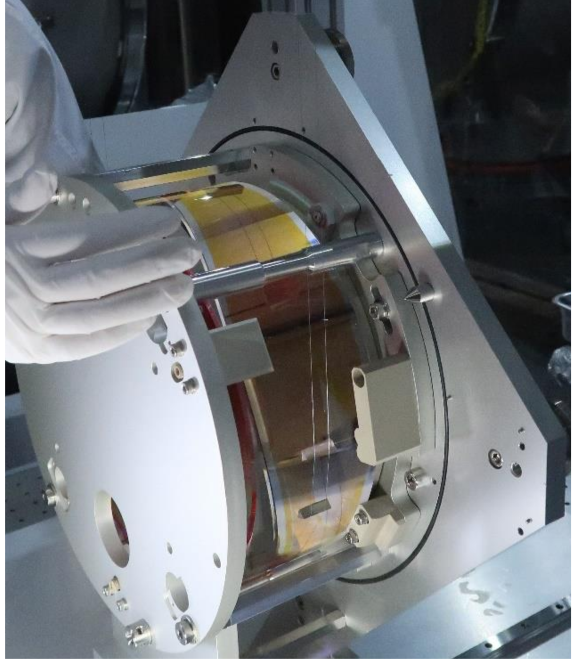
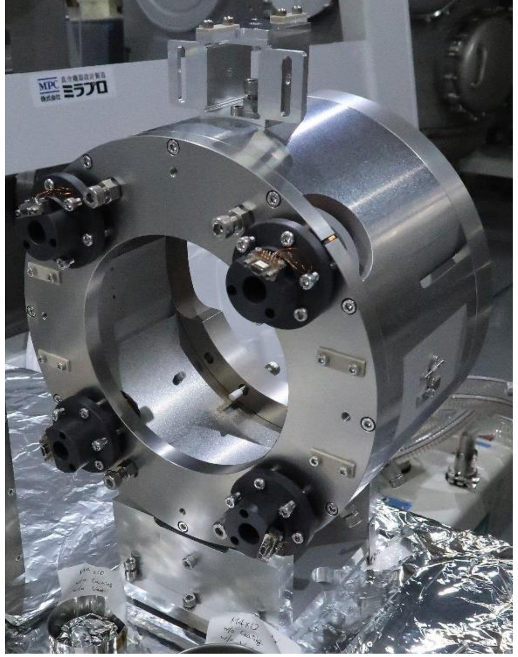
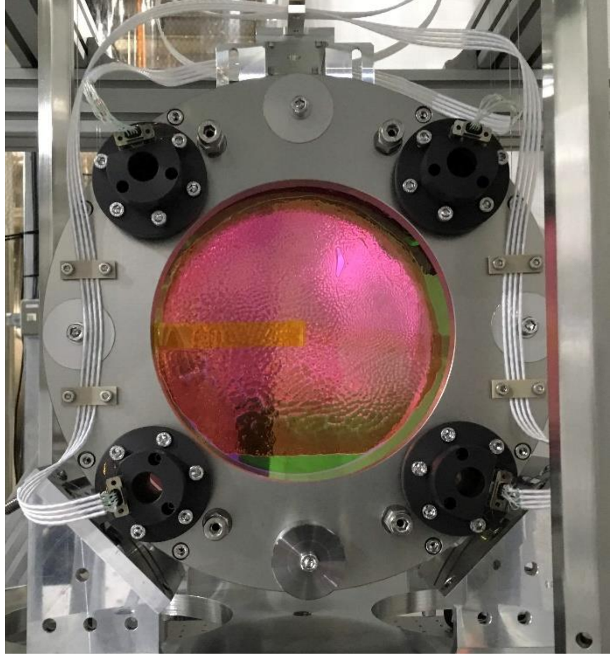
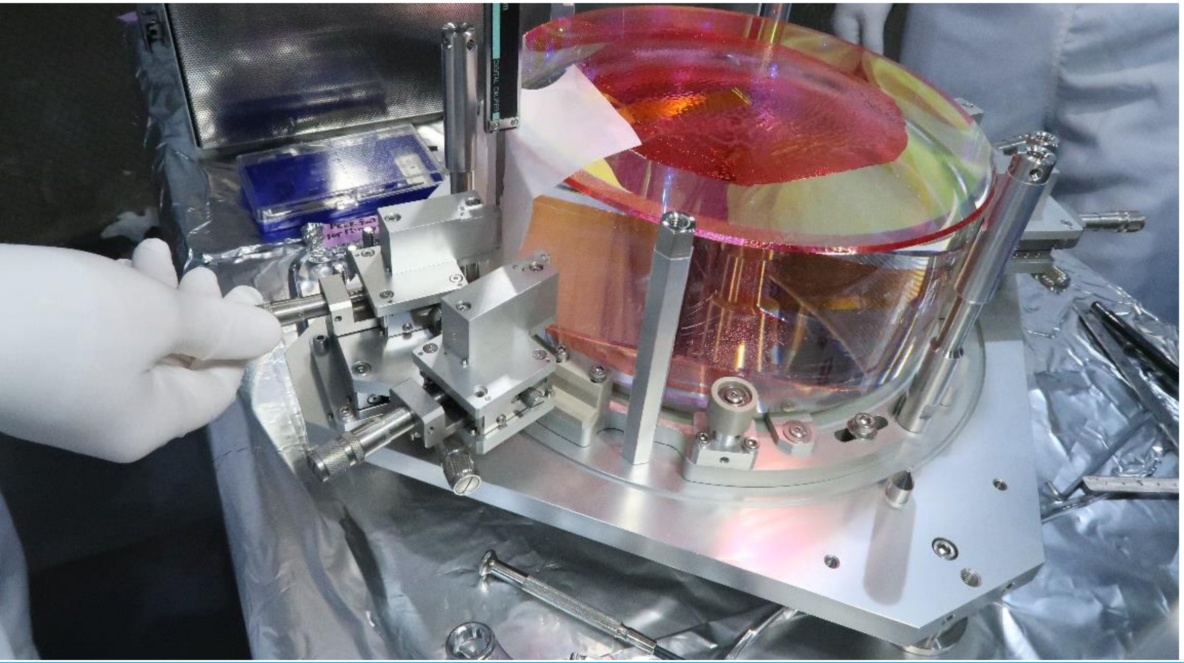



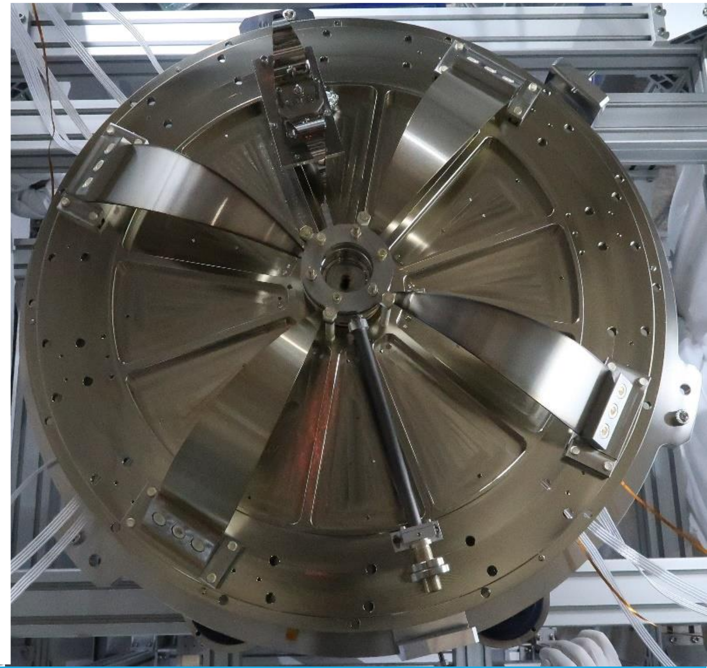

Measured by Panwei

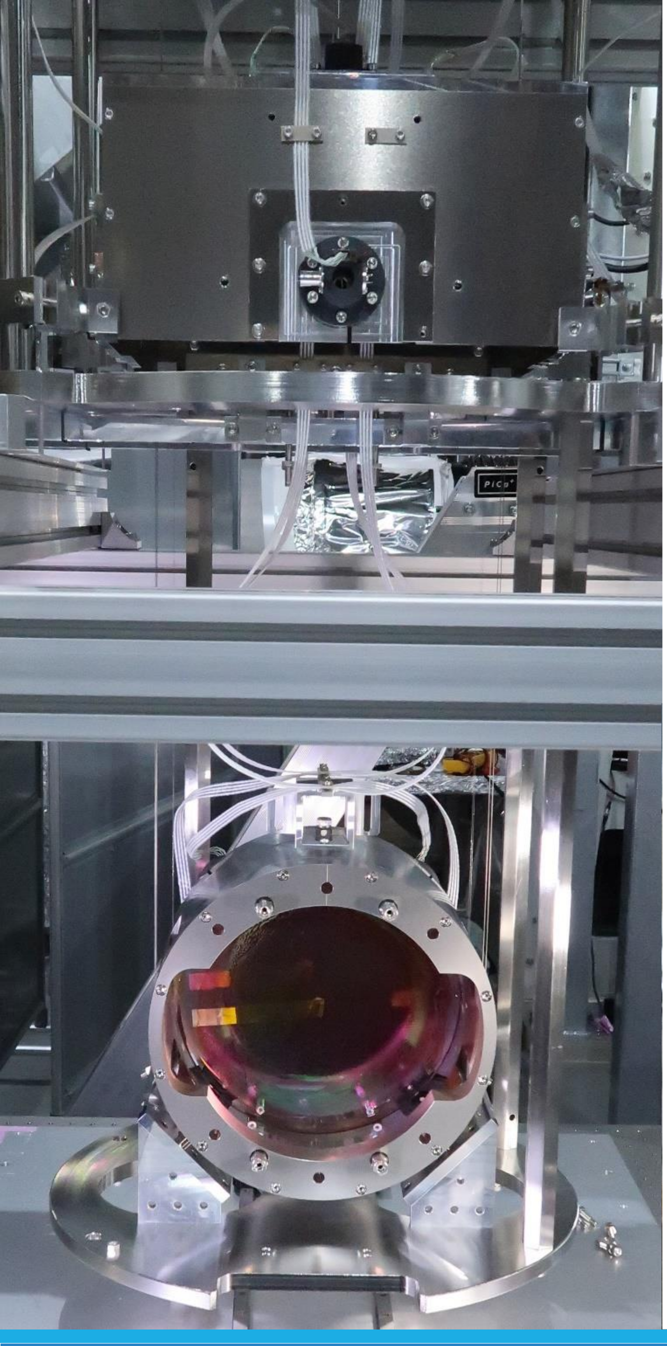
# A quick graphical tour to assembly

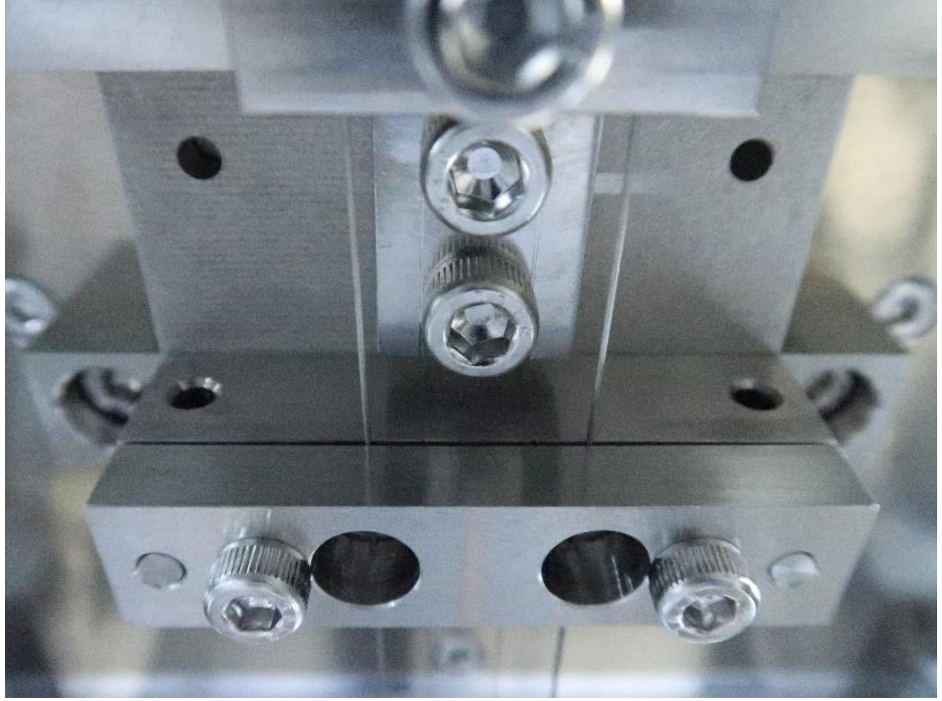
Just a few pictures

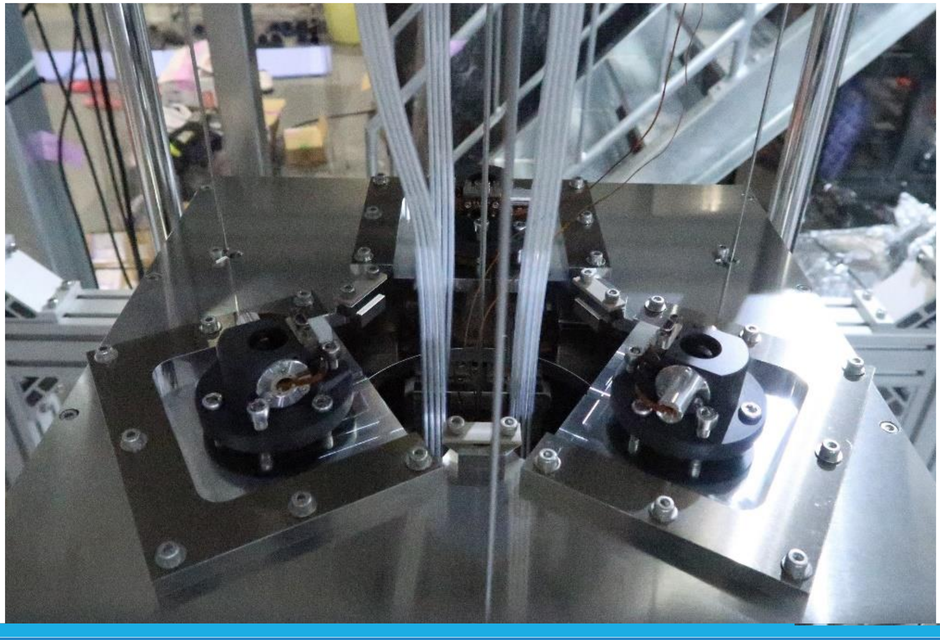
12 of June 2019

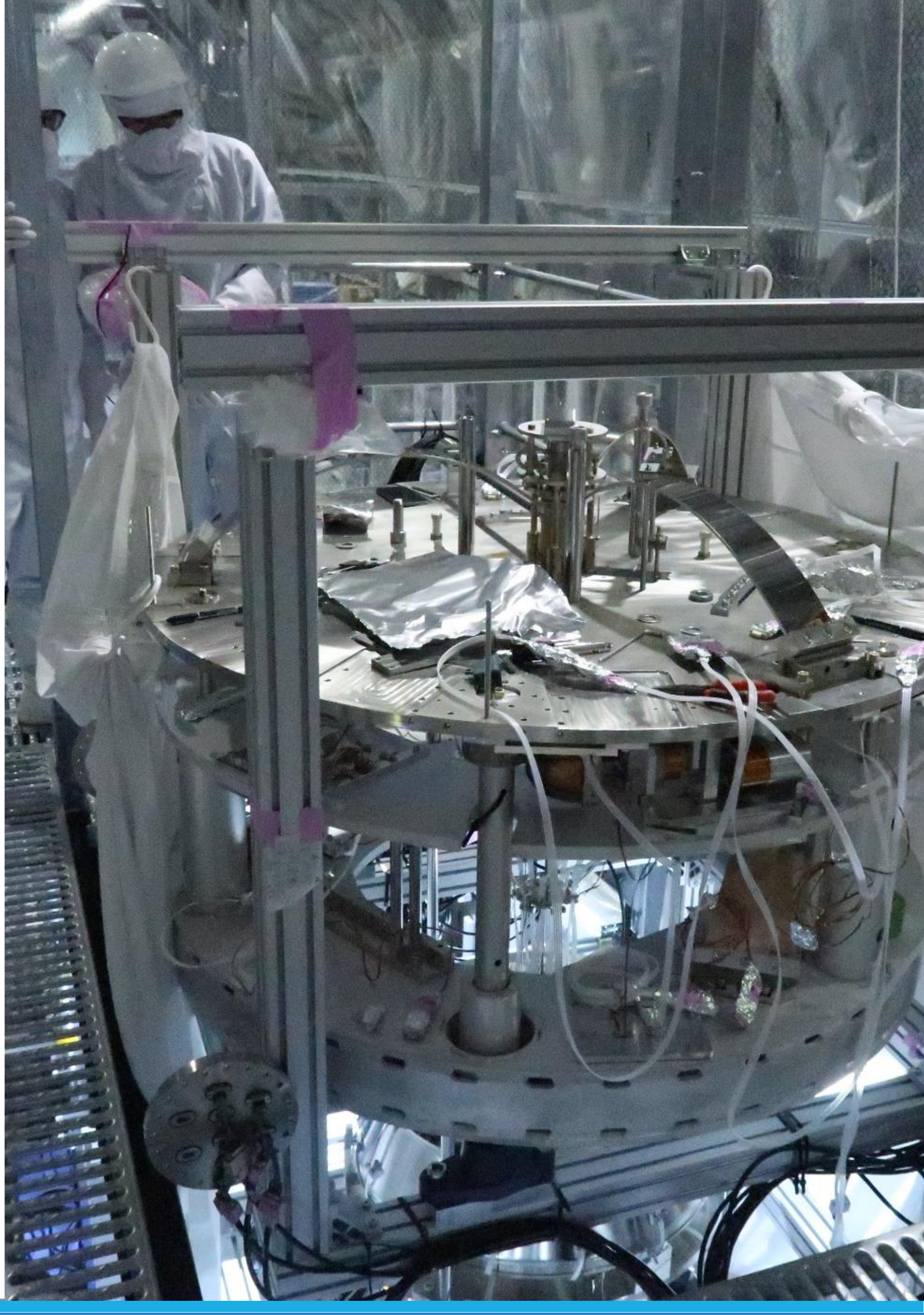










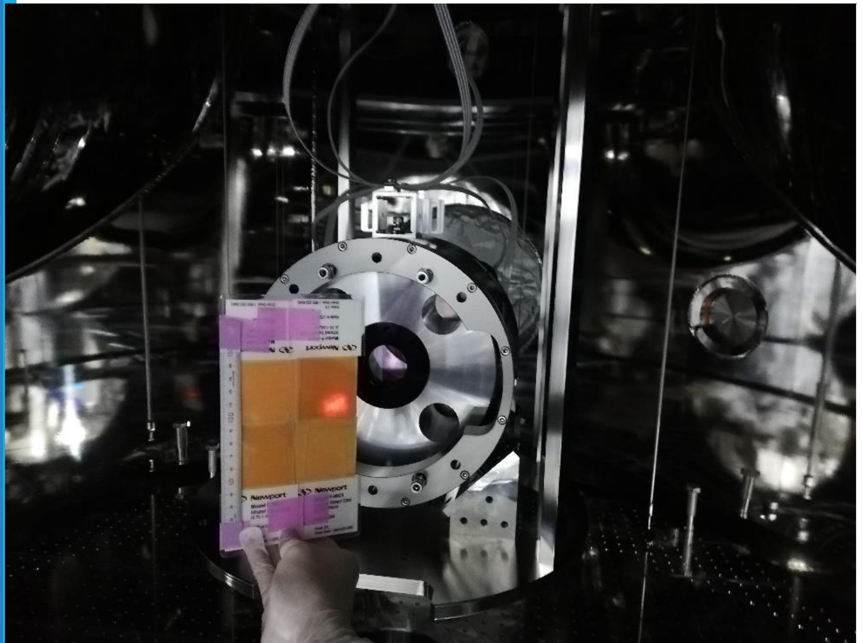




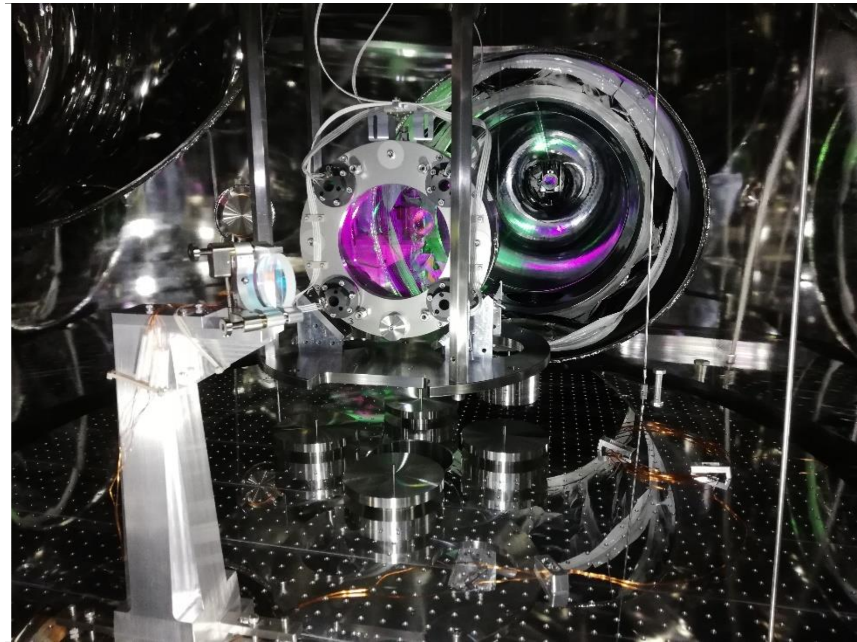


# Some measurements, simulation and status.

- How does the system behave at low frequencies? Enzo has an answer!
- What does the suspension model predict within the interferometer observation band above 10 Hz?



SRM with interference pattern



SR2 with SR3 far away along the pipe

# Tools for simulation

## SUMCOM: free hanging suspension

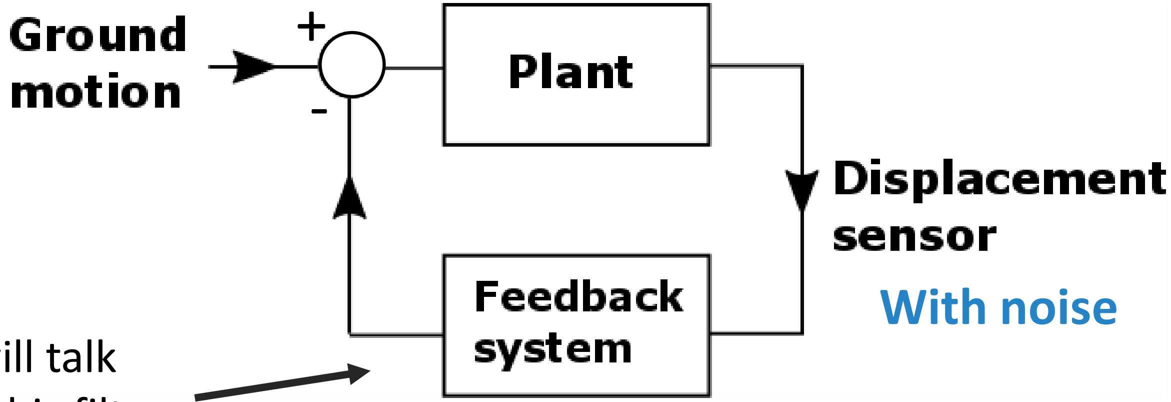
- Mathematica.
- Transfer function and list of resonant modes.
- It's capable of taking into account structural damping using complex numbers.
- Control system simulation has not being implemented.
- It provides a graphical representation of the resonant modes.

## Control system simulation

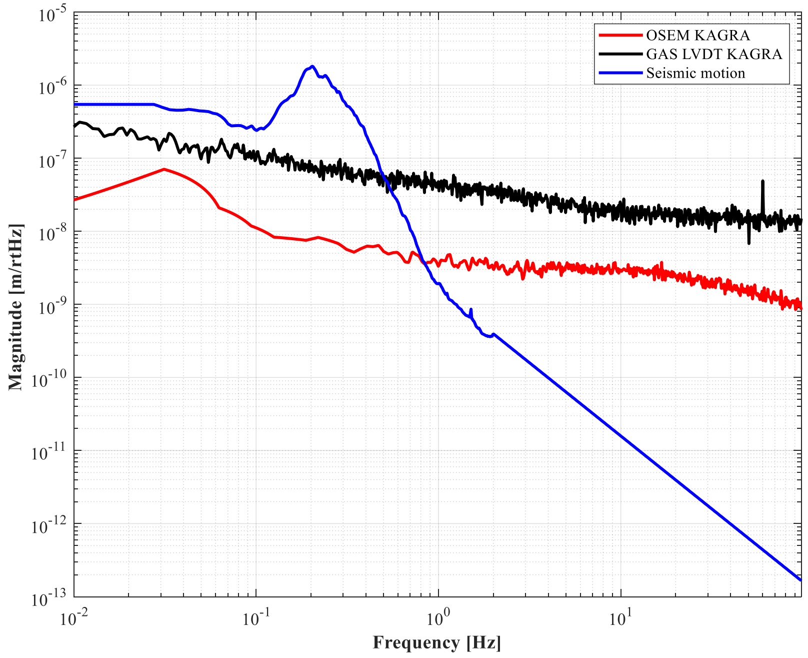
- Matlab/Simulink.
- Transfer function and list of resonant modes.
- Only viscous damping is available.
- It's used to assess the sensor noise fed back into the system.
- Control filter design above 10 Hz.

Software written by Takanori Sekiguchi

# Noise in sensors and the control loop

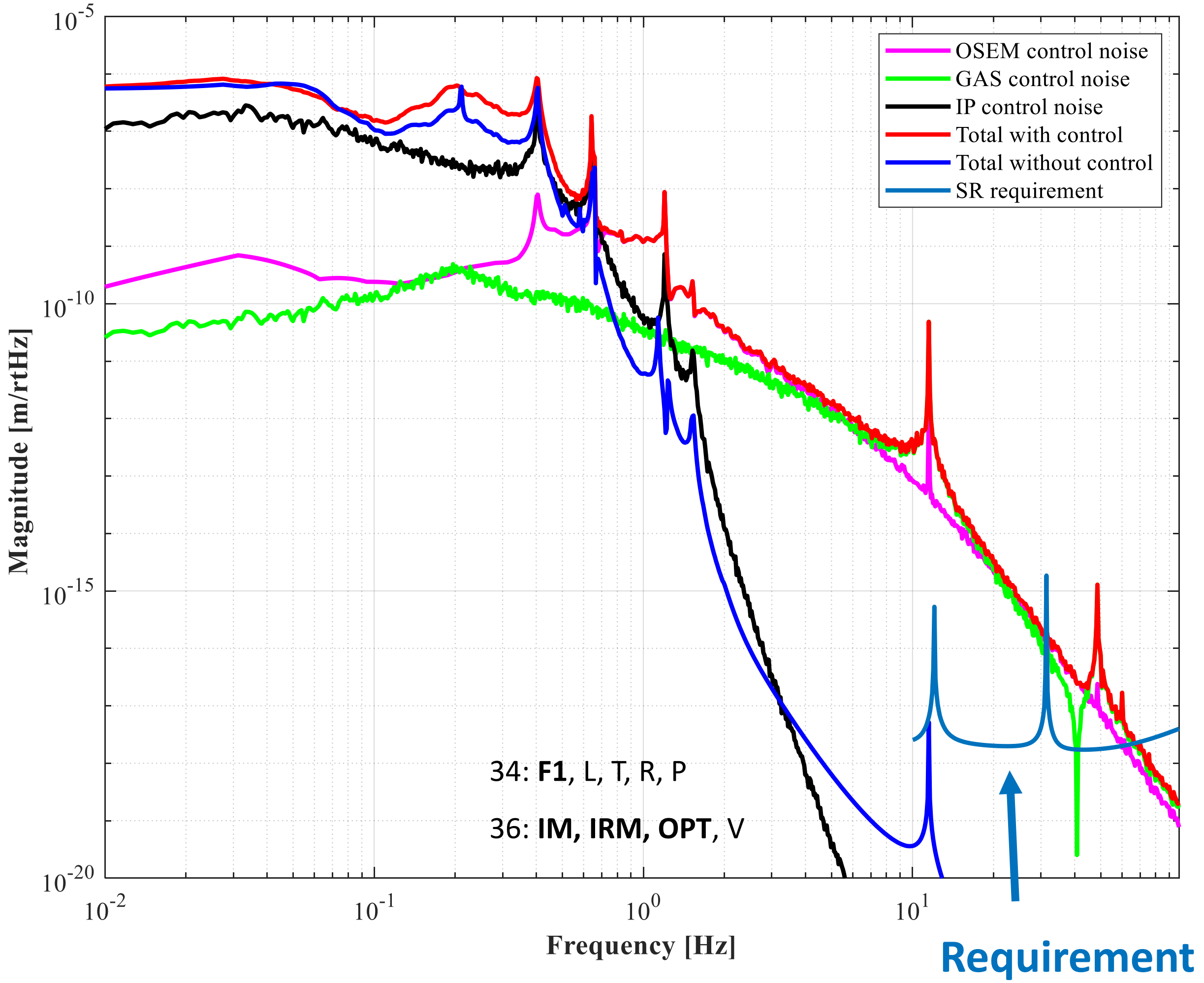



Enzo will talk
about this filters



# Current status: residual motion within the observation band

- We have calculated the motion of the optic to be too large within the observation frequency band.
- The GAS LVDT noise fed back by the control loop is too high. Control filters still have to be rolled-off above resonant frequencies and below 10 Hz.
- Inertial damping not implemented yet.
- The calculation assumes 1% coupling from the vertical to the horizontal degree of freedom.
- The OSEMs are expected to be off during observation. Angular control will be transferred to the main interferometer which uses wavefront sensors.

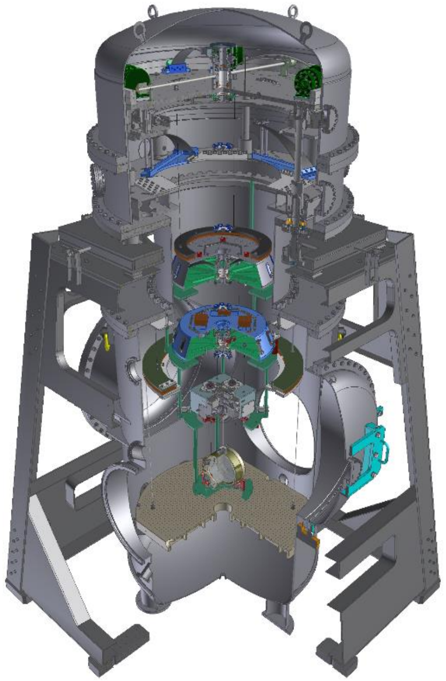


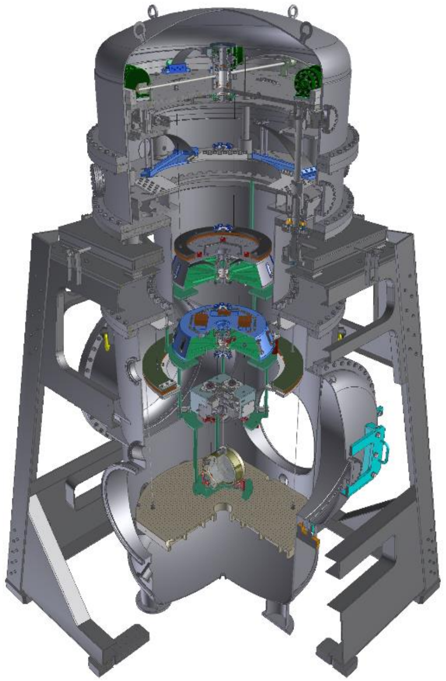
# Immediate future work

- We will attempt to take advantage of the common mode rejection there may be among suspensions.
- Characterization within the interferometer observation band.

# Common mode rejection (1)

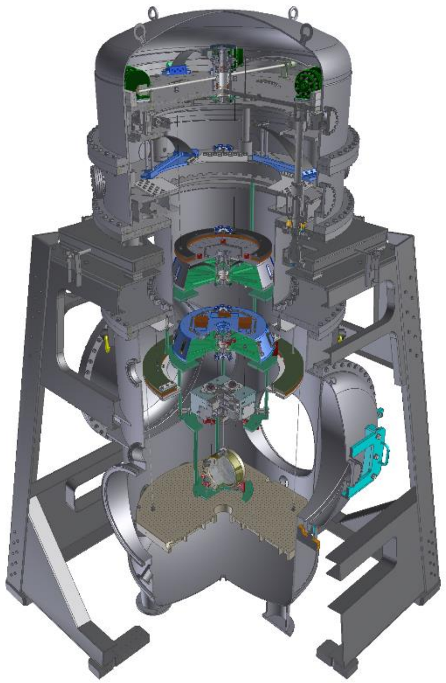
- In general, the suspensions move in dissimilar ways.
- In principle, in order to keep the mirrors as still as possible with respect to each other, perturbations have to be damped locally at each suspension.

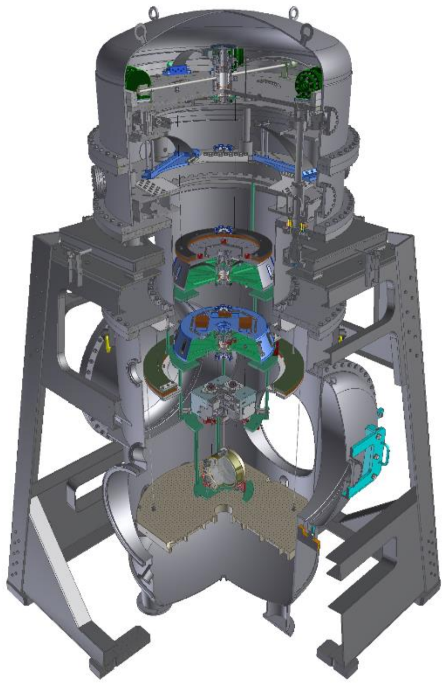




# Common mode rejection (2)

- Nevertheless, we found evidence that in the central room the suspensions move together to a *certain extent*.
- We would like to explore how to use this common mode movement in order to design a suitable control strategy.

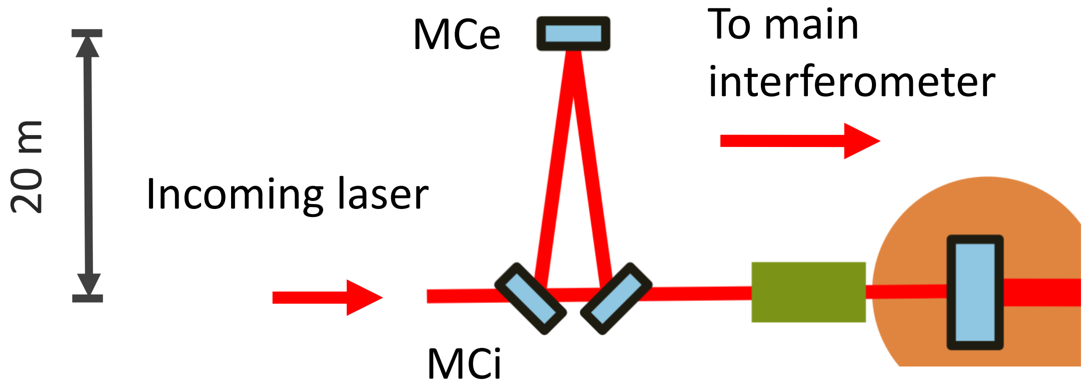


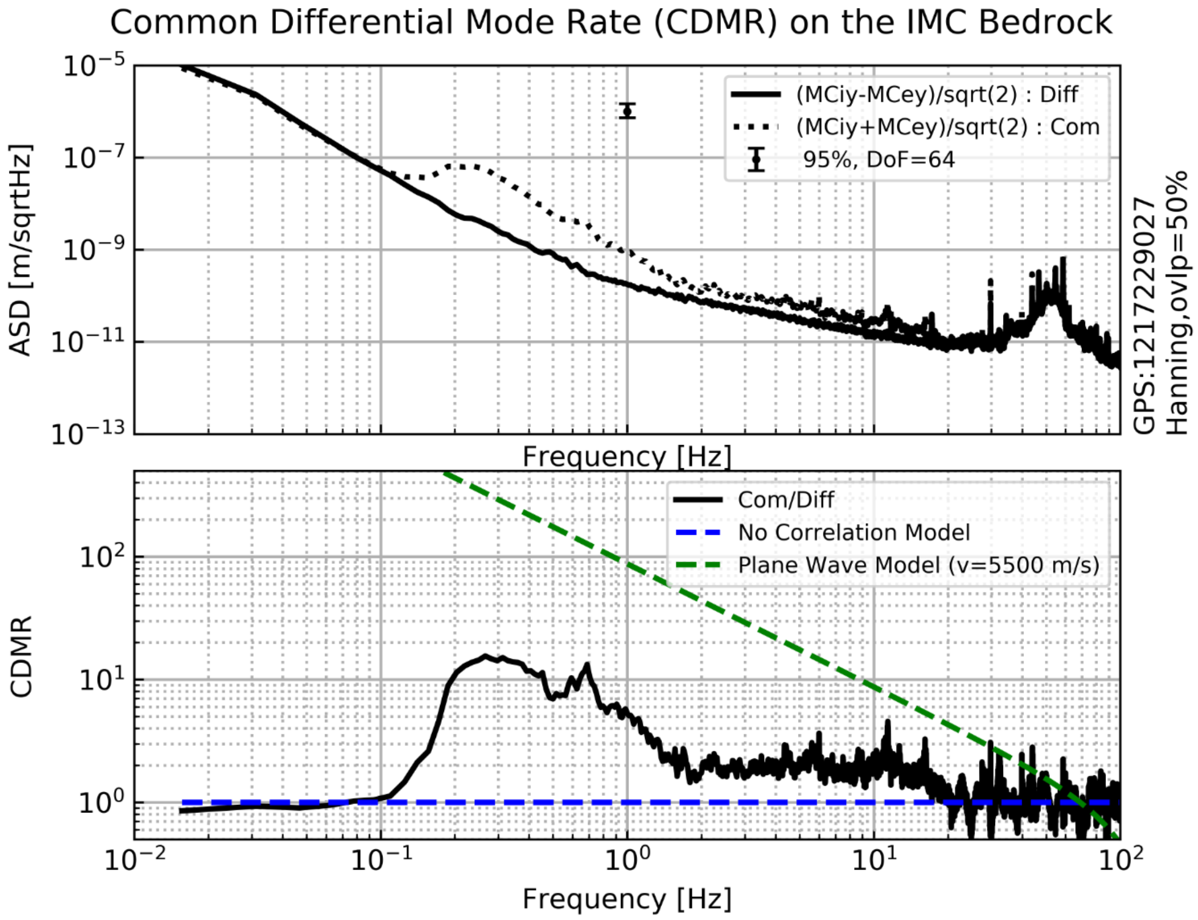


# Common mode rejection evidence

Common and differential seismic motion was measured in the Input Mode Cleaner area:

- Below 20 Hz down to almost 0.150 Hz the common mode is larger than the differential mode.
- A *very simple preliminary* model of the a plane wave traveling along the length of the IMC tunnel does not agree with the measurement.
- More work is necessary.

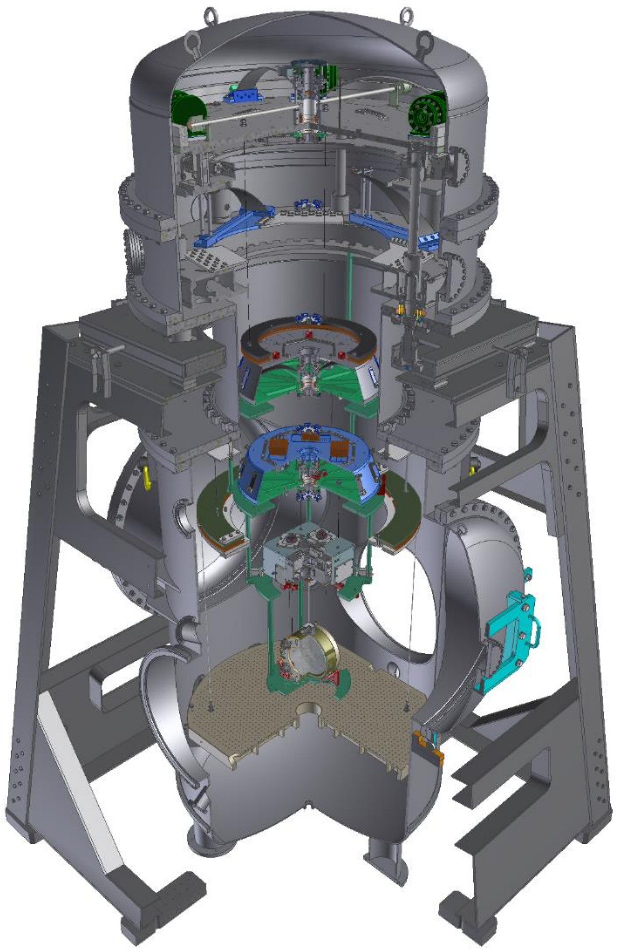



Measurement and calculation by Kousei Miyo

# Dual recycling Michelson Interferometer

- We'll use the DRMI as a displacement sensor for characterization.
- Measure residual motion.
- Decide whether to use inertial damping or common-mode rejection.
- We'll use the back reflections of the input Test Masses.
- The PR cavity will be used for laser frequency stabilization.
- We aim to shake the IP and measure geophone output and interferometer output.



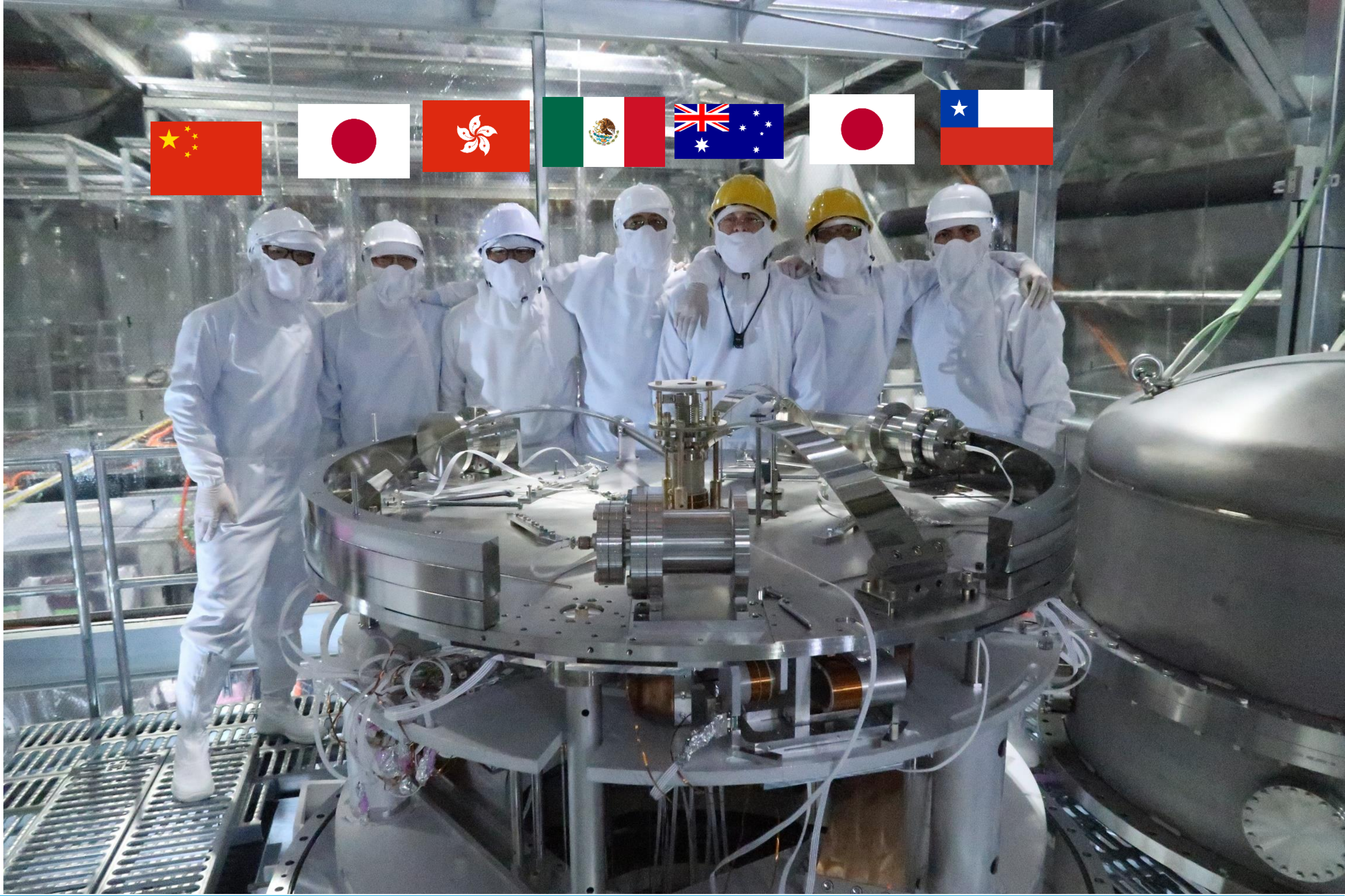
# Summary

- We have built four Type B suspensions for the beam splitter and signal recycling mirrors.
  - Passive vibration isolation: IP and three GAS filters.
  - Active vibration isolation: LVDTs, OSEMS and coil-magnet actuators.
  - Payload comprises a marionette, the optic and their recoil masses.
- More work is required to meet the requirement of at 10 Hz, namely, to roll-off the GAS control filters.
- We aim to characterize the system by shaking the IP table and measuring transfer function from geophones to interferometer output.
- We want to explore ways of using common mode rejection in order to design a suitable control strategy.

# KAGRA is an international collaboration

This version of the Type B team has members from:

- Australia
- Mexico
- Japan
- Chile
- Hong Kong
- China

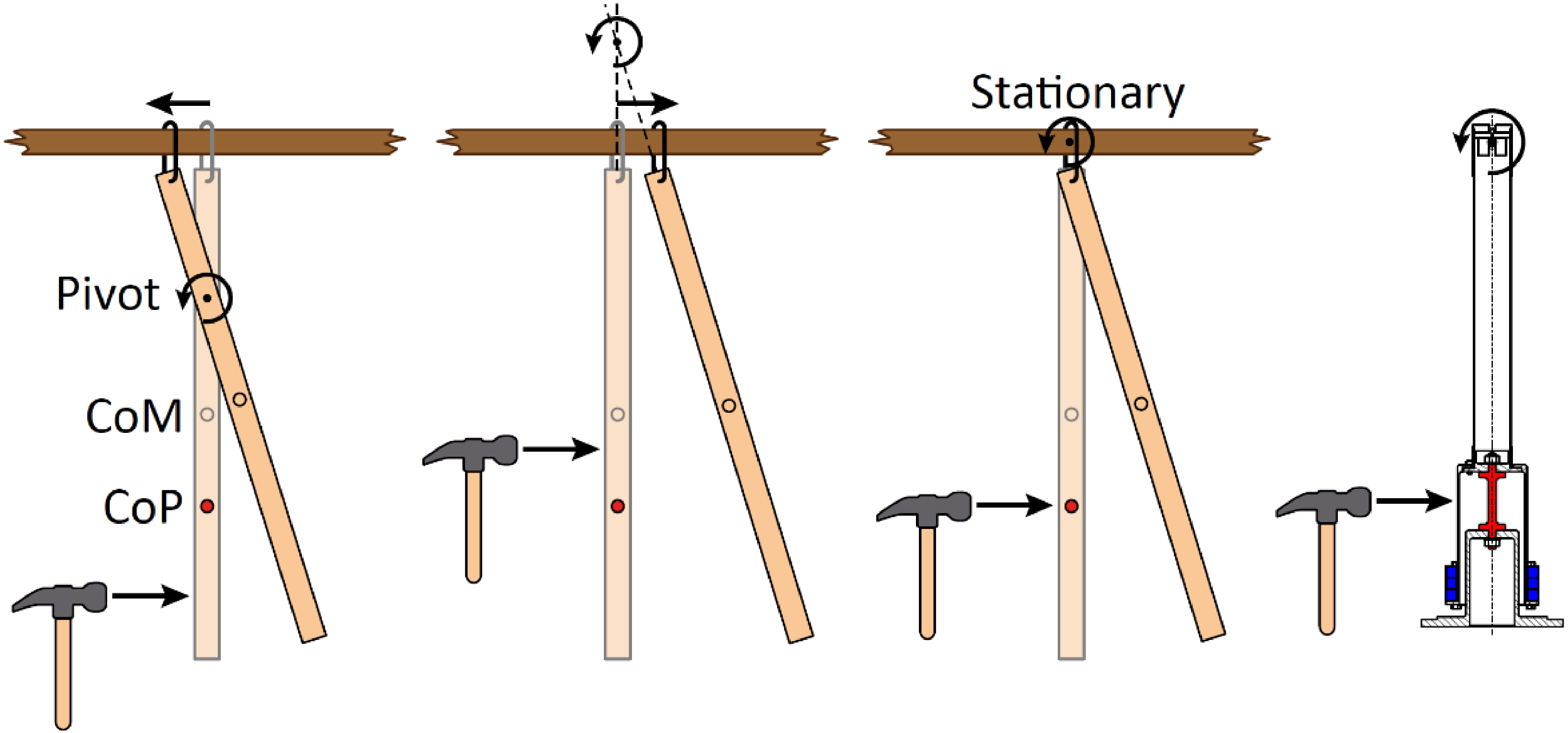


# Temperature and GAS filters

| | | | | |
|---|---|---|---|---|
| K | L | M | N | O |
| **Beam splitter** | | | | |
| **Filter** | **Frequency (Hz)** | **klog** | **Drift (mm/C°)** | **Total drift (mm)** |
| BF | 0.448 | 3385 | -0.314475604 | -0.597503647 |
| F1 | 0.425 | 3376 | -0.349433974 | -0.66392455 |
| F0 | 0.209 | 3385 | -1.444942001 | -2.745389801 |

| | | | | |
|---|---|---|---|---|
| E | F | G | H | I |
| **SRM** | | | | |
| **Filter** | **Frequency (Hz)** | **klog** | **Drift per degree (mm/C°)** | **Total drift (mm)** |
| BF | 0.45 | 6886 | -0.311686477 | -0.592204306 |
| F1 | 0.38 | 6886 | -0.437094955 | -0.830480415 |
| F0 | 0.56 | 6886 | -0.201264386 | -0.382402334 |

# Centre of percussion effect



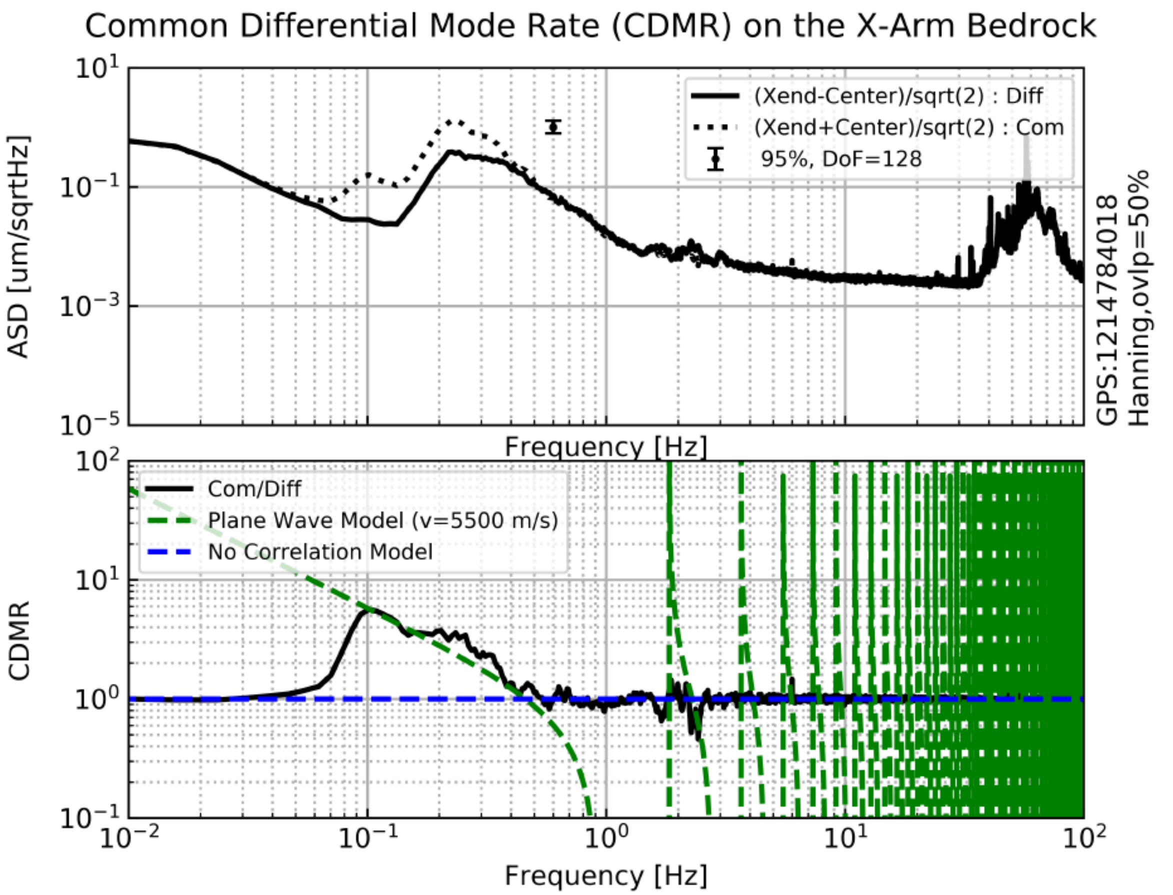

Drawing by Alexander Wanner

# Common mode rejection evidence

The seismic noise common and differential modes were measured between the X end and the central room using seismometers:

- Below 0.4 Hz down to about 0.06 Hz the common mode is larger than the differential mode.
- A *very simple preliminary* model of the a plane p-wave traveling along the length of the X arm agrees with the measurement.
- More work is necessary.

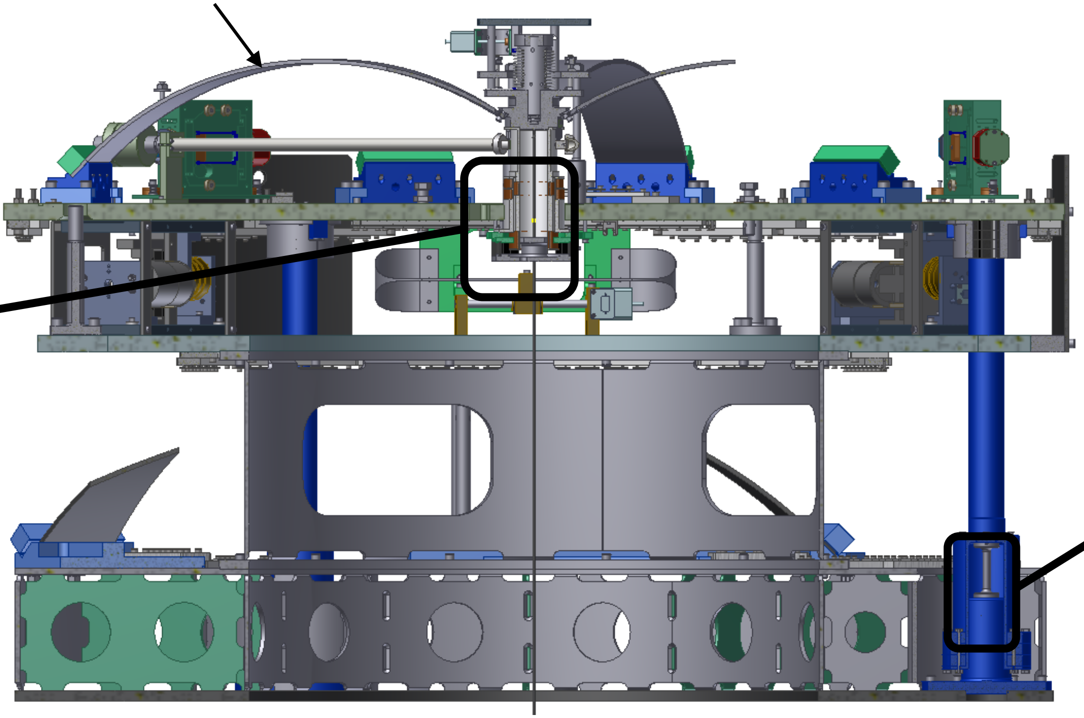
Measurement and calculation by Kouseki Miyo

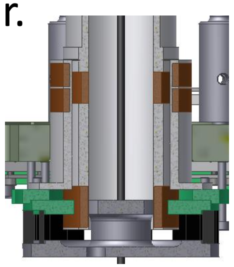


# Inverted pendulum and top filter (1)

GAS blade springs

LVDT and coil-magnet
Actuator.





Inverted
pendulum
flexure