Cryogenic Coating Thermal Noise direct measurement

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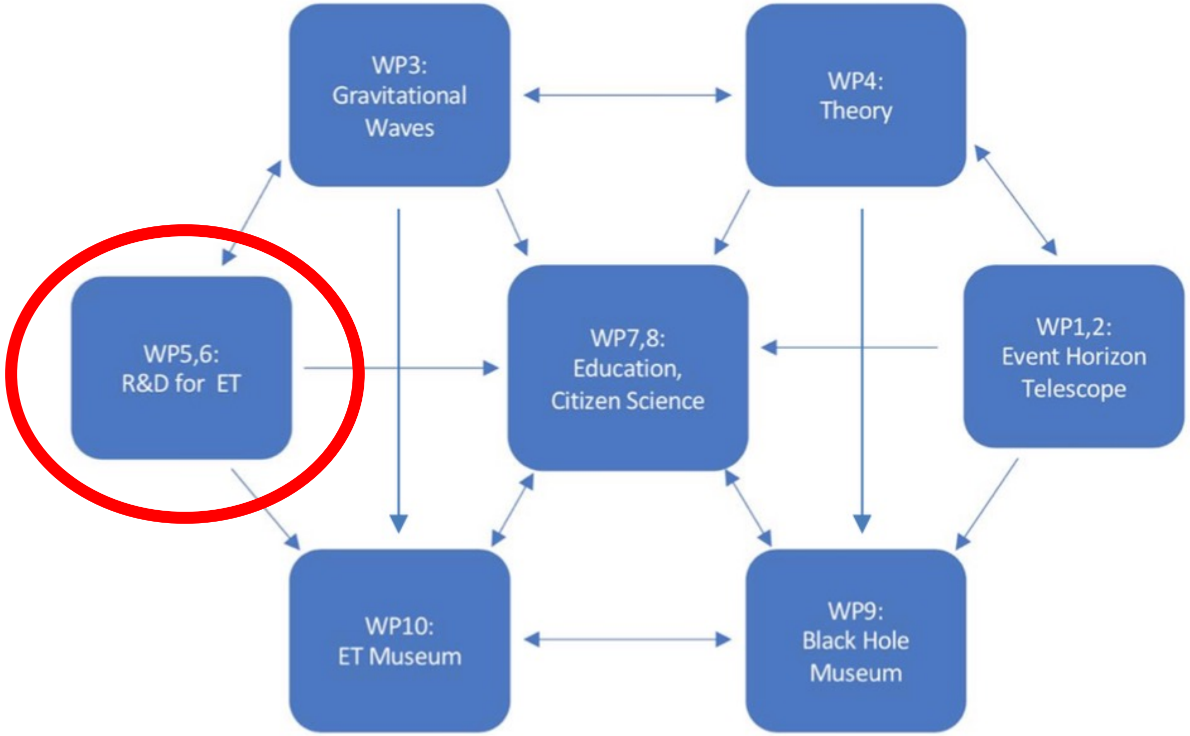
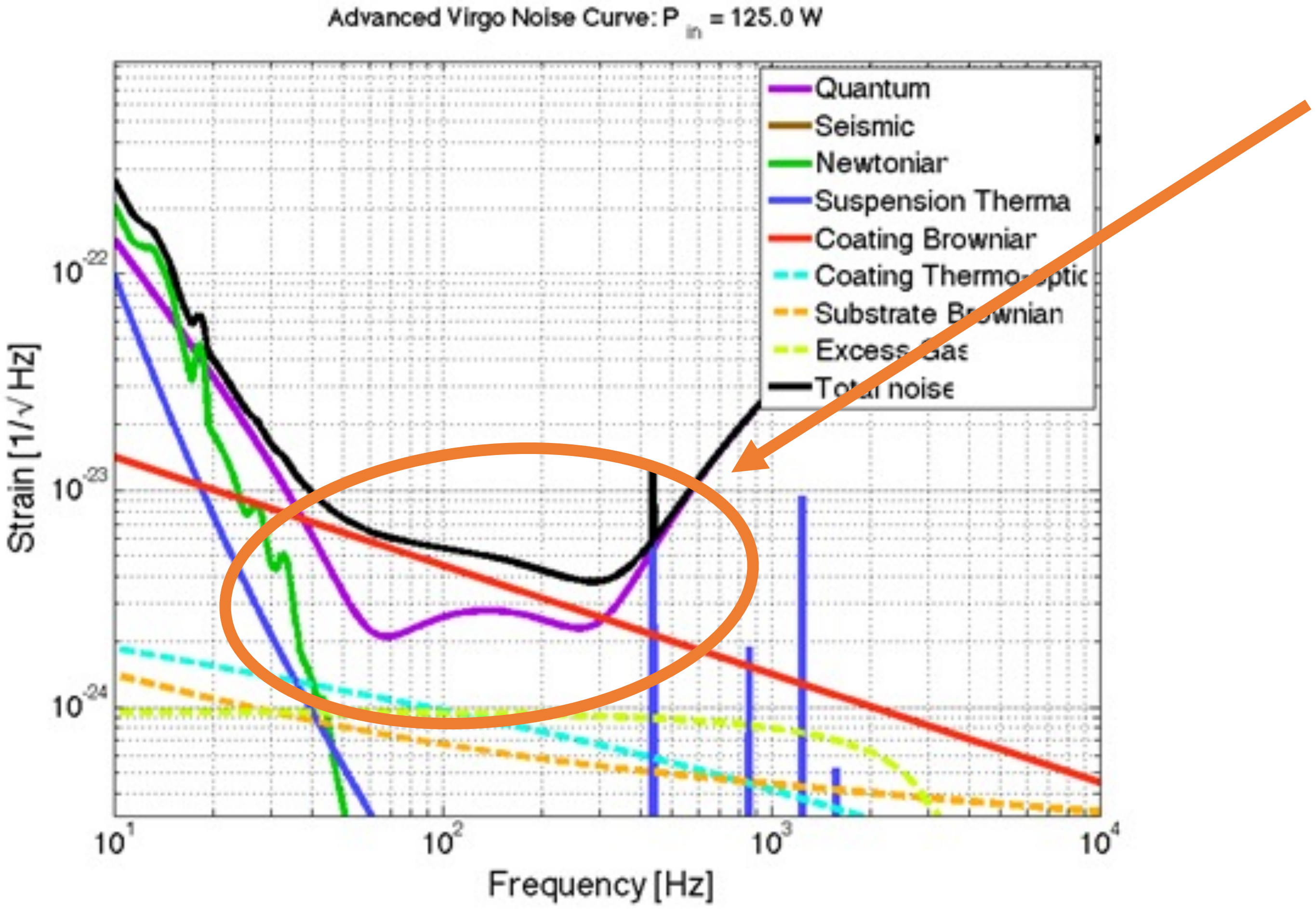
Dutch Black Hole Consortium · Nikhef · UM · University of Twente | MESA+ Institute · EMS

Dutch Black Hole Consortium

A group of 30+ scientists, carrying out an interdisciplinary black hole research program throughout the Netherlands: https://www.dbhc.nl/



Sensitivity of Gravitational Wave Detectors



Mid-range Frequencies:

Sensitivity limited by mirror coating thermal noise

$$x_c^2(\omega) = \frac{4k_BT}{\omega}\frac{1-\sigma^2}{\sqrt{\pi}E_0 w}\phi_{eff,c}(\omega)$$

- directly proportional to material properties (E_0, σ, $\phi_{eff,c}$)
- inversely proportional to the beam spot size on the mirror (w)
- directly proportional to temperature (T)

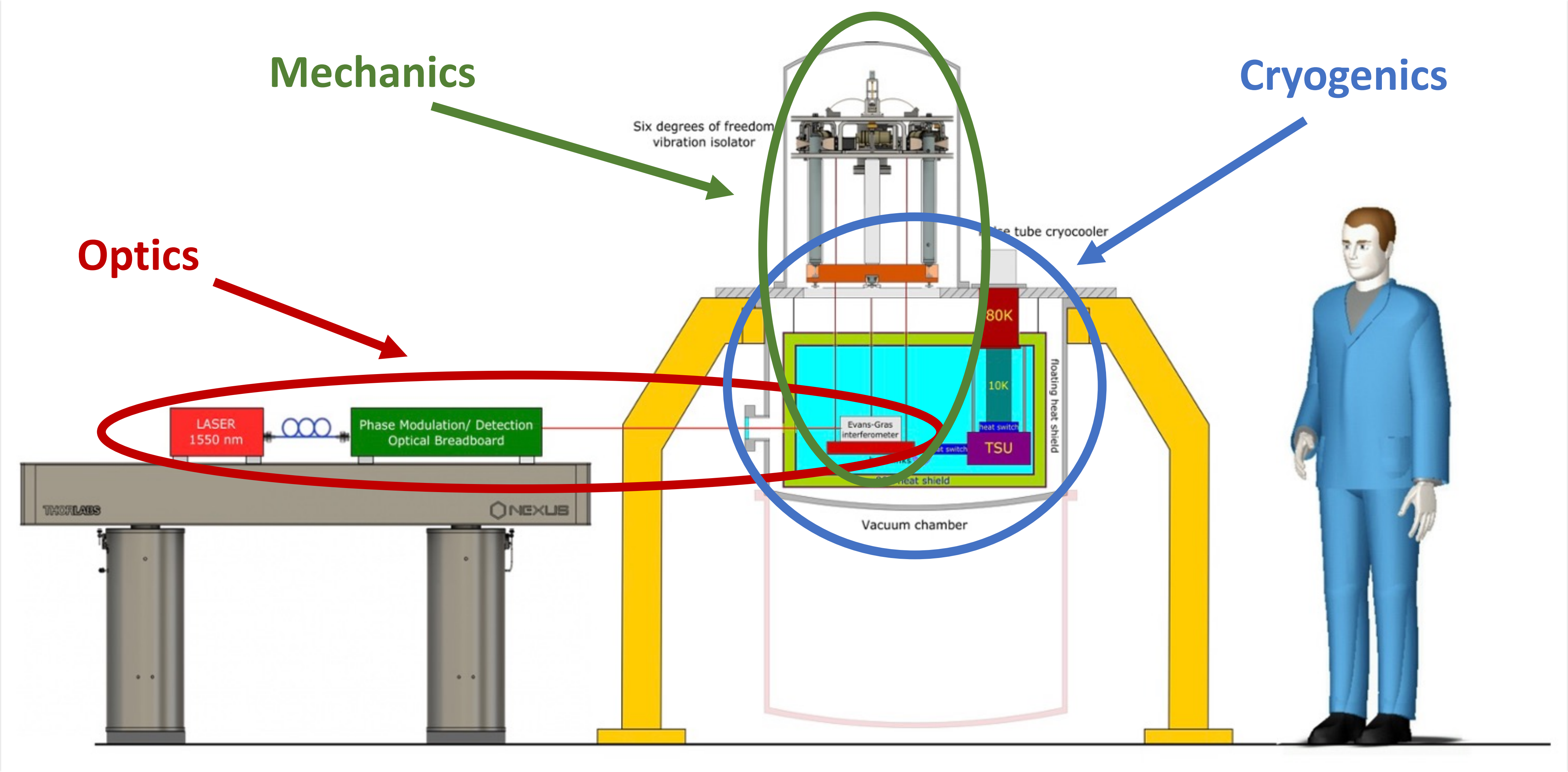
Different technique to reduce the thermal noise impact -> decrease the working temperature -> new material needed for coating

Motivations & Goals

- TN of new coatings directly measured using an interferometric method in a cryogenic environment to select the material to be used in the third-generation detectors;
- A low noise fast turnaround cryogenic test bench essential to characterize new sensors and actuators compatible with low temperature environment.
- R&D on new low noise technology is of wide interest -> Liquid free low noise cryogenics more and more required in many fields of fundamental physics.

➡ Cryogenic test bench with ~ 10^{-13} m / sqrt (Hz) residual motion above 30 Hz

Motivations & Goals



A flexible test facility available to anyone (not just in the GW collaboration) who needs it

Three main work packages

- Cryogenic Technology (Koen)
- Seismic Attenuation System (Enrico)
- Optical setup (Enzo)

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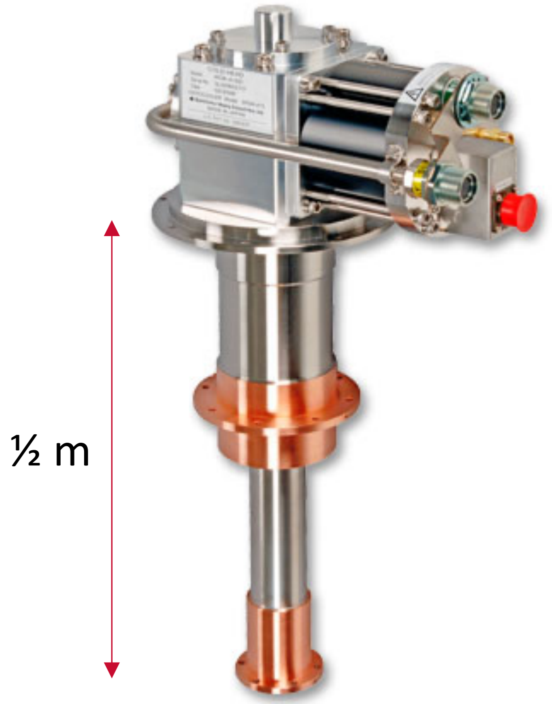
Cryogenic system requirements

	ET, ETPF	Mirror Coating Test Facility
Operation of system	Continuous	Discontinuous
Vibration-free condition	At all times	Only during measurements (~ ½ hour)
System cooldown	Weeks	A few days
Operating temperature	10 K, 123 K	10 K (123 K*)

Core concept

- Cold storage (battery)
- Mechanical cryocooler (charging battery)

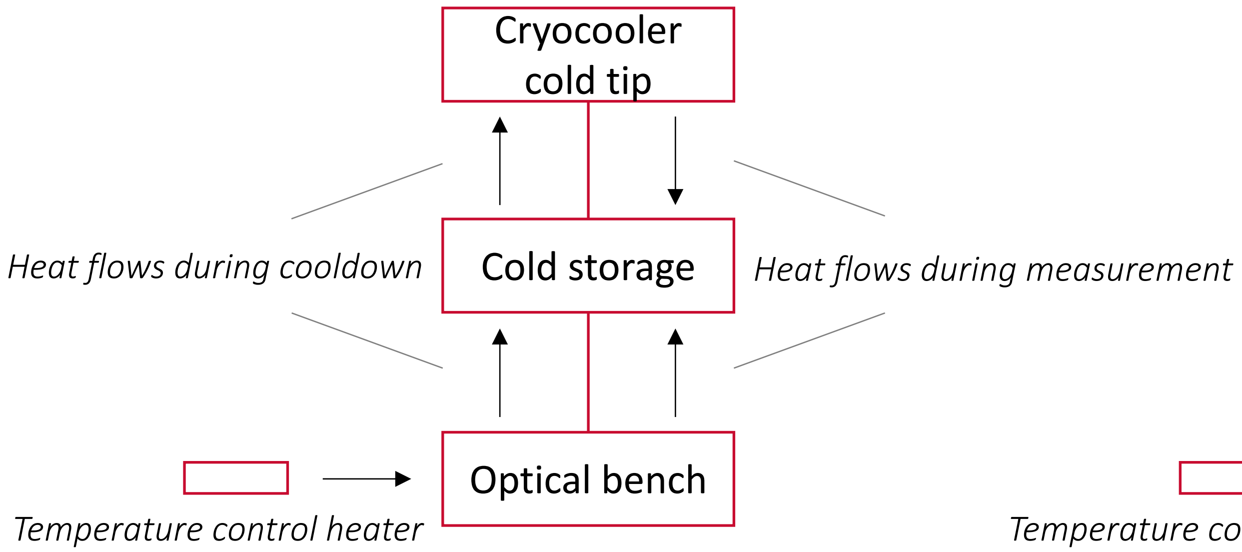
1. Cooler on, cool down cold storage
2. Cooler off, measure using stored cold



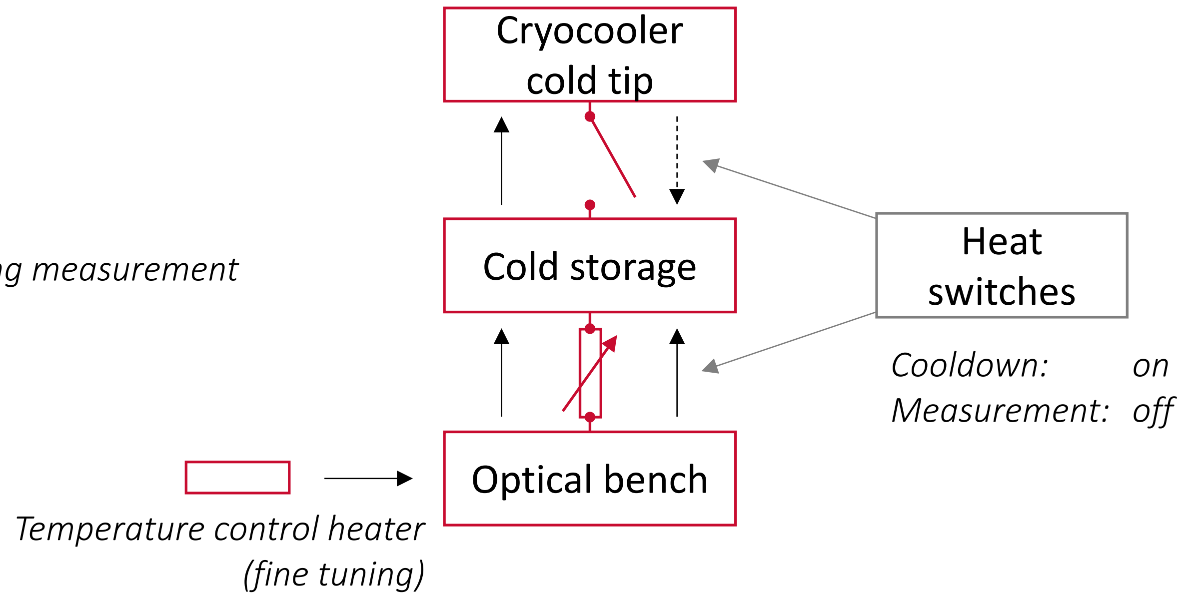
Sumitomo RDK 415D
1.5 W at 4 K

Operation

Other heat loads (radiative, supports/suspension) not drawn



Conducting links



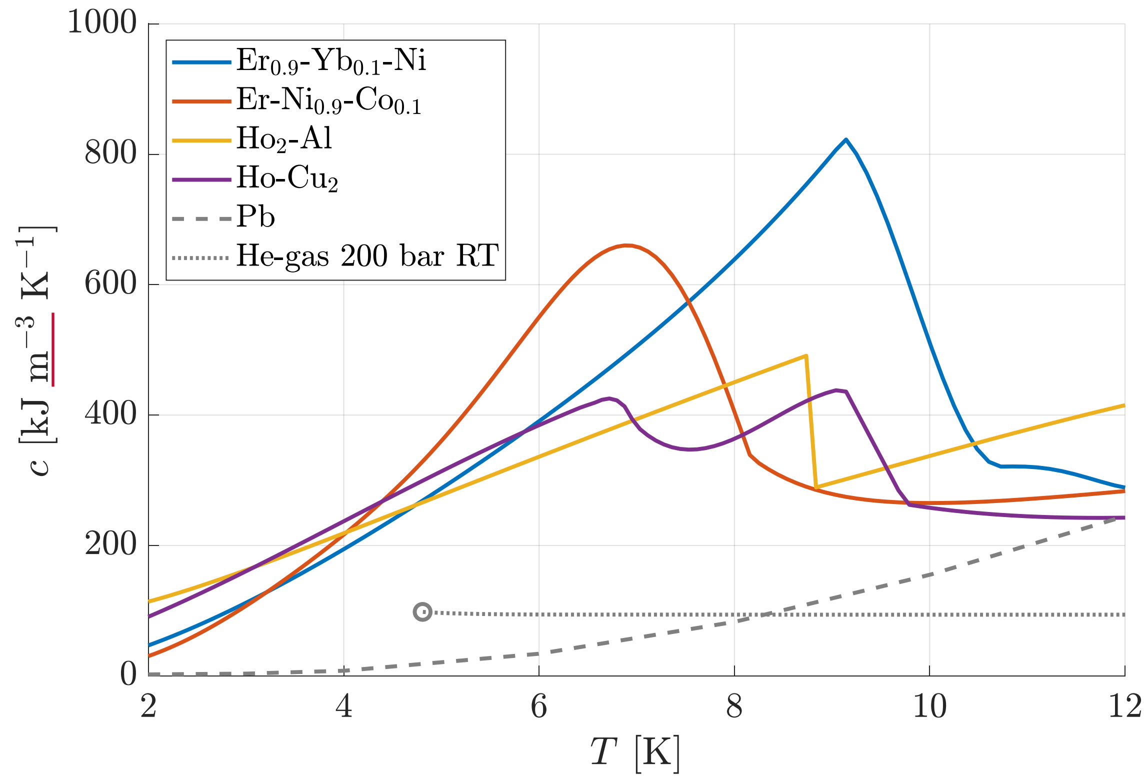
Heat switches

Cold storage

High heat capacity at $T < 10$ K

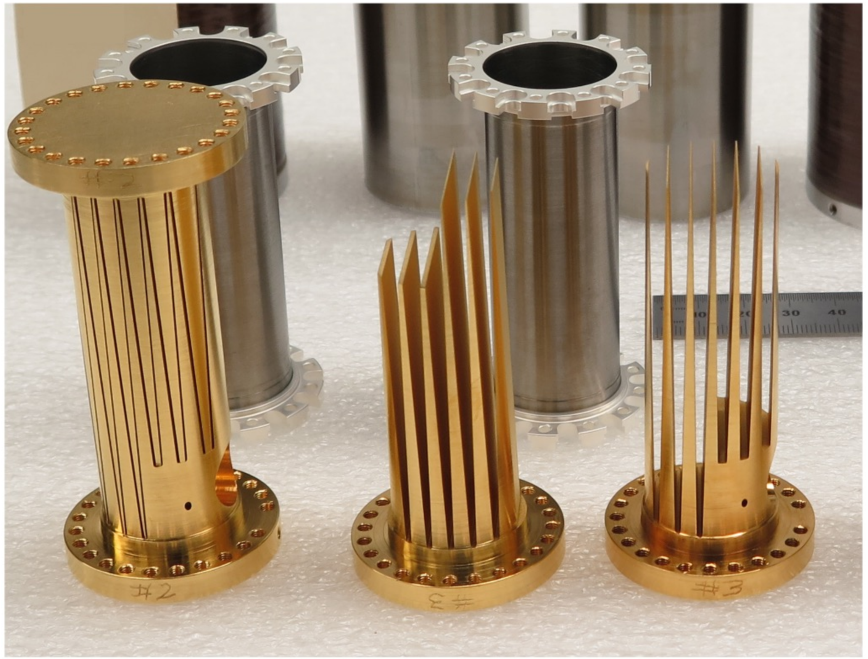
- Phase change material: latent heat
  - Helium (4.2 K, 1 bar)
  - Lanthanides (magnetic)

- Ordinary heat capacity
  - Lead
  - Helium gas

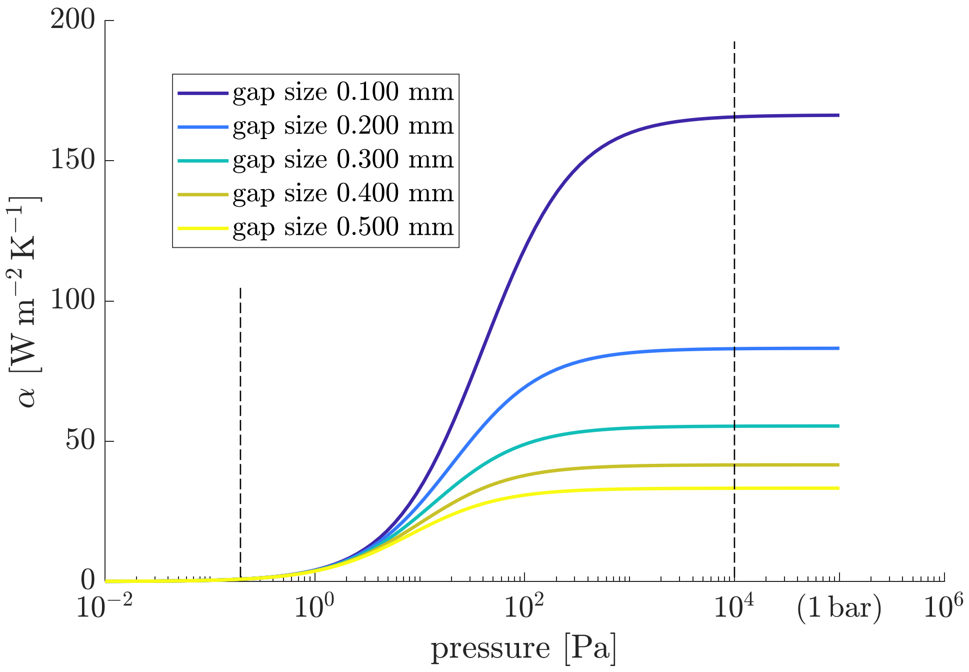


Heat switches

- Mechanical
- Gas-gap



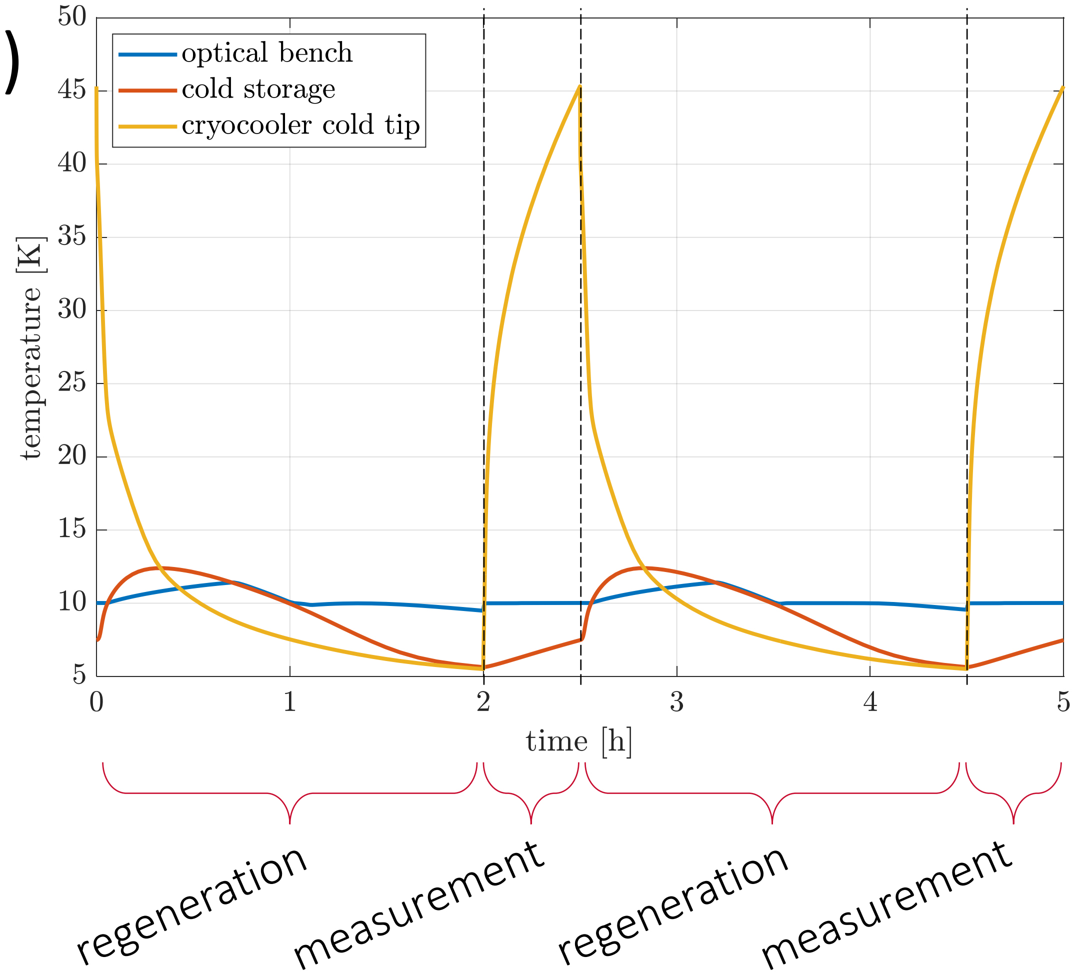
M.O. Kimball et al., NASA



off state transition regime on state

Simulation: cyclic operation

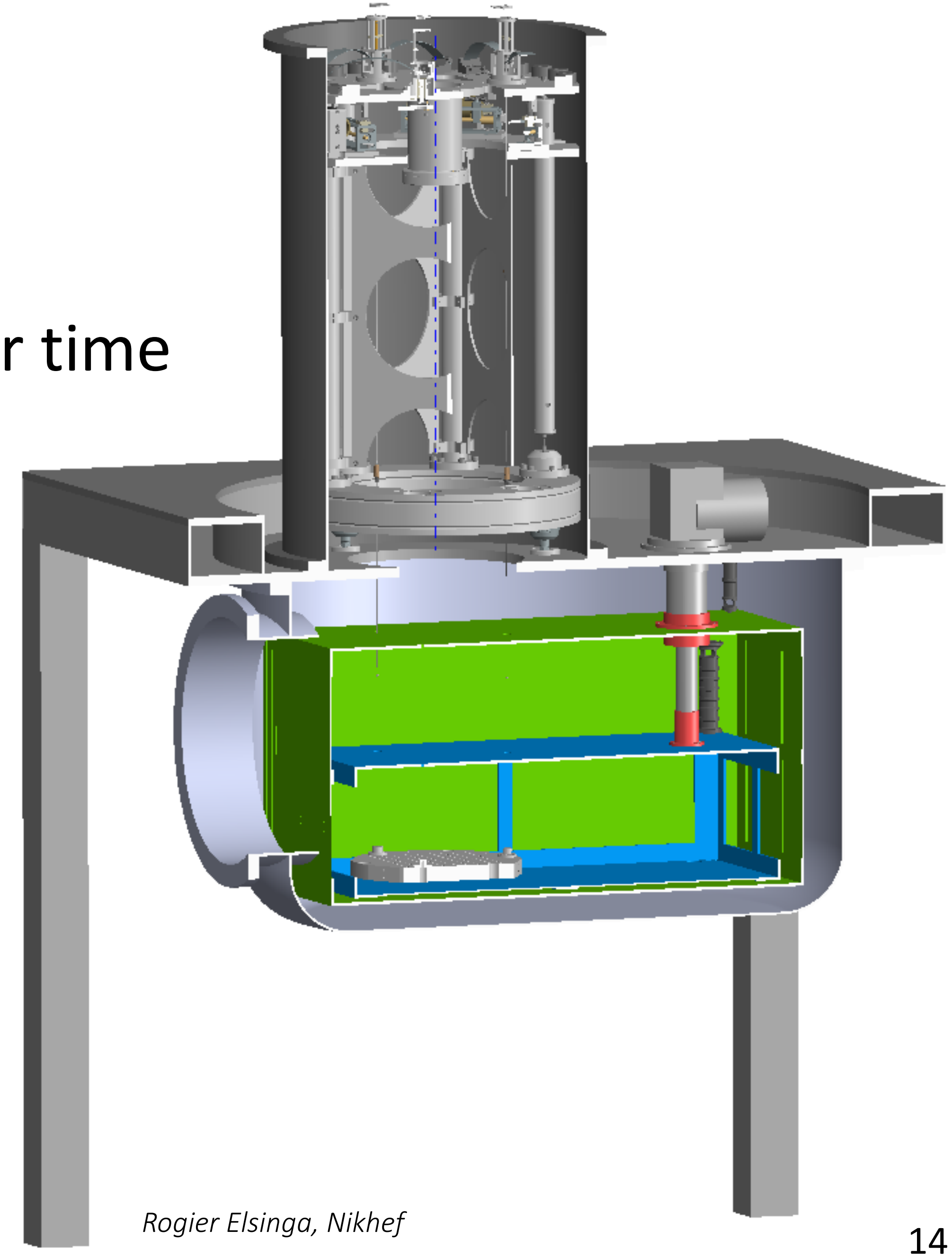
- 2 hours of regeneration (cooldown)
- ½ hour of measurement time



Phased approach

Modular system, replace components over time

1. Lead cold storage, conducting links (no heat switches)
   - System testing
   - Will not meet ½ hour measurement criterium
   - Target cryogenic assembly: end of 2024
2. Replace links by heat switches
3. Replace cold storage by helium gas or magnetic phase change material



Rogier Elsinga, Nikhef

Three main work packages

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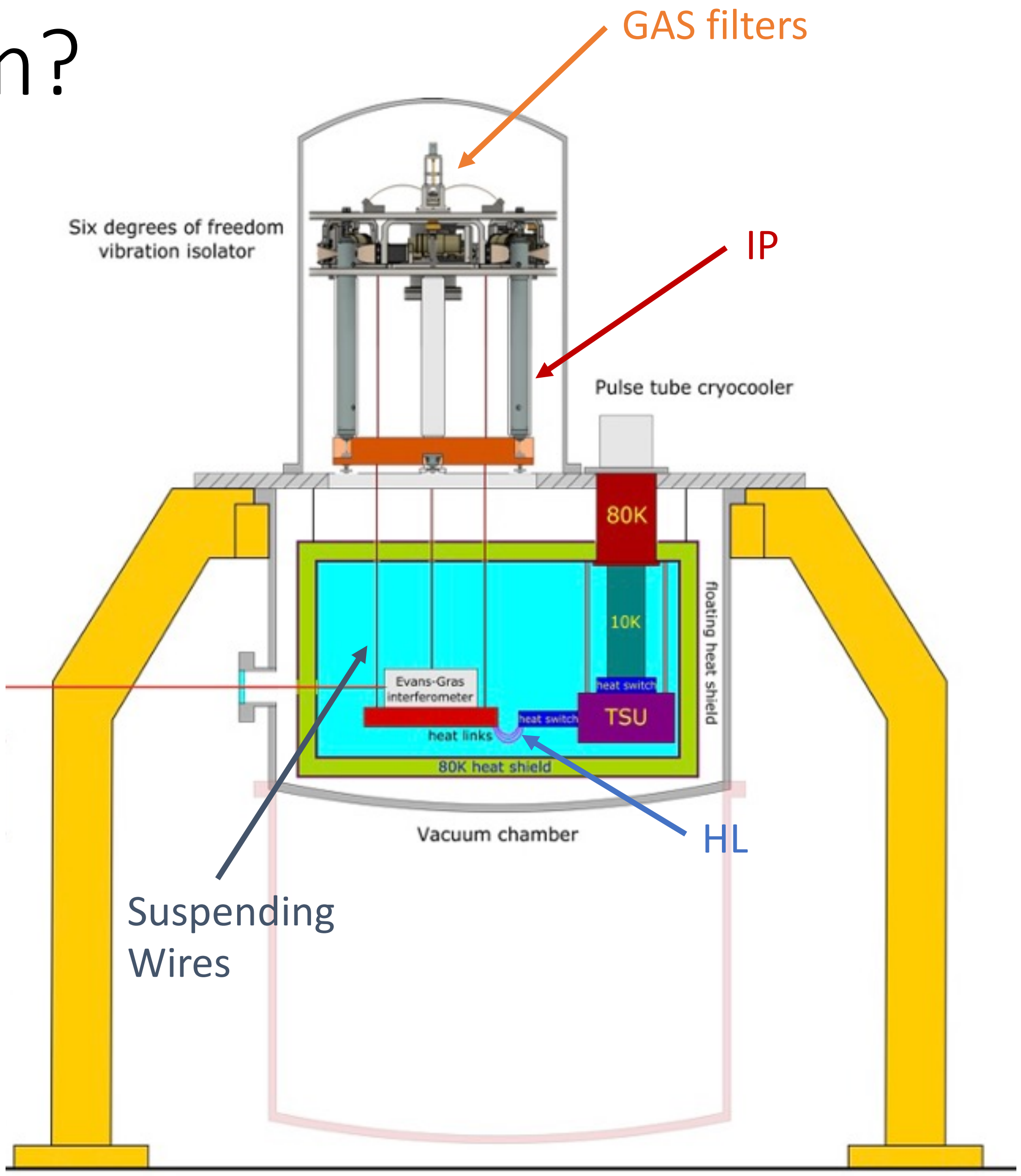
Why a vibration-isolation system?

1. Measuring the vibration injection due to heat-links by avoiding direct contribution from the ground.

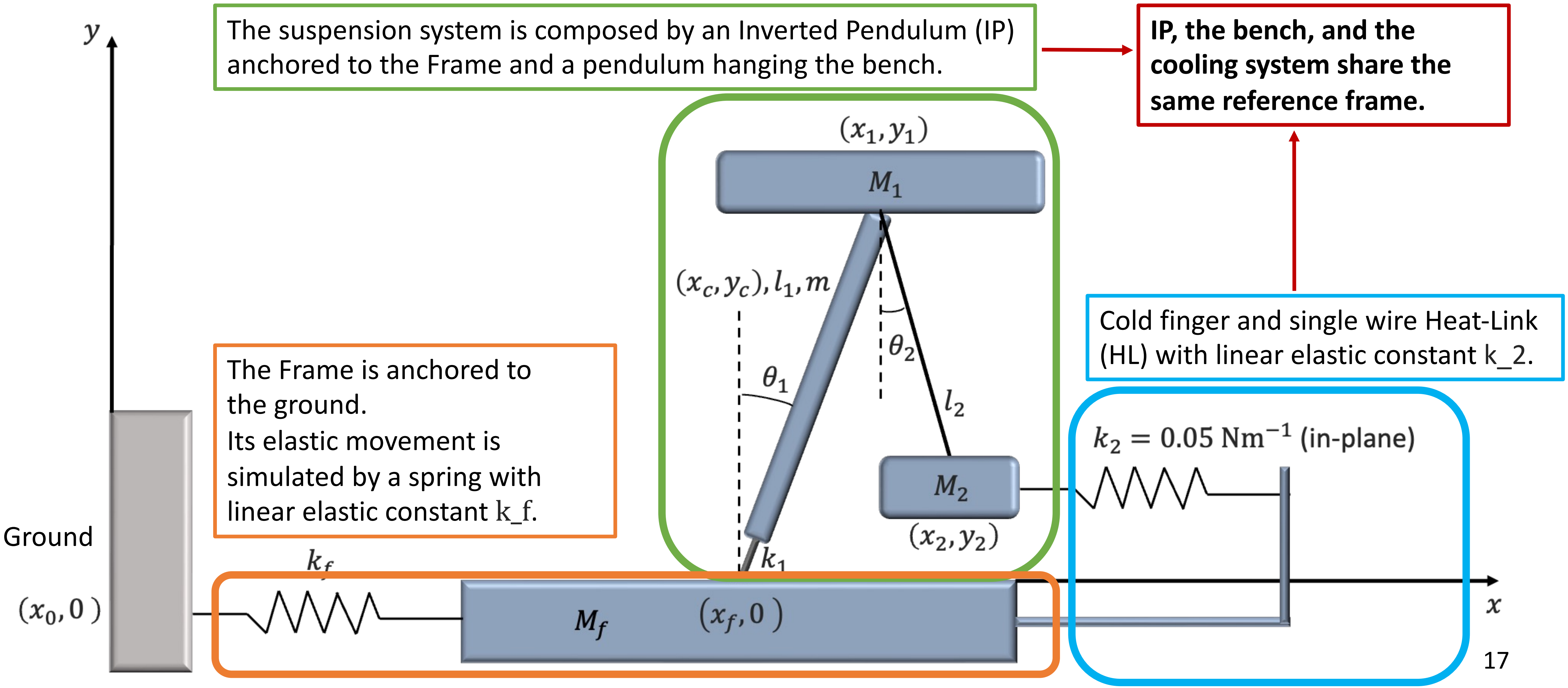
2. Testing sensors/actuators at cryogenic temperature (≥10 K).

The whole system is supported by a Frame and is composed by:

- 3 legs Inverted Pendulum (IP) - Longitudinal vibration.
- 1 stage with 3 pairs of Geometrical Anti Springs (GAS) - Vertical vibration.
- 3 Titanium alloy suspending wires hanging the optical bench.
- Heat-Links (HL) for thermal conduction from the Cryocooler to the bench.



Lagrangian model of the mechanics in a longitudinal DoF

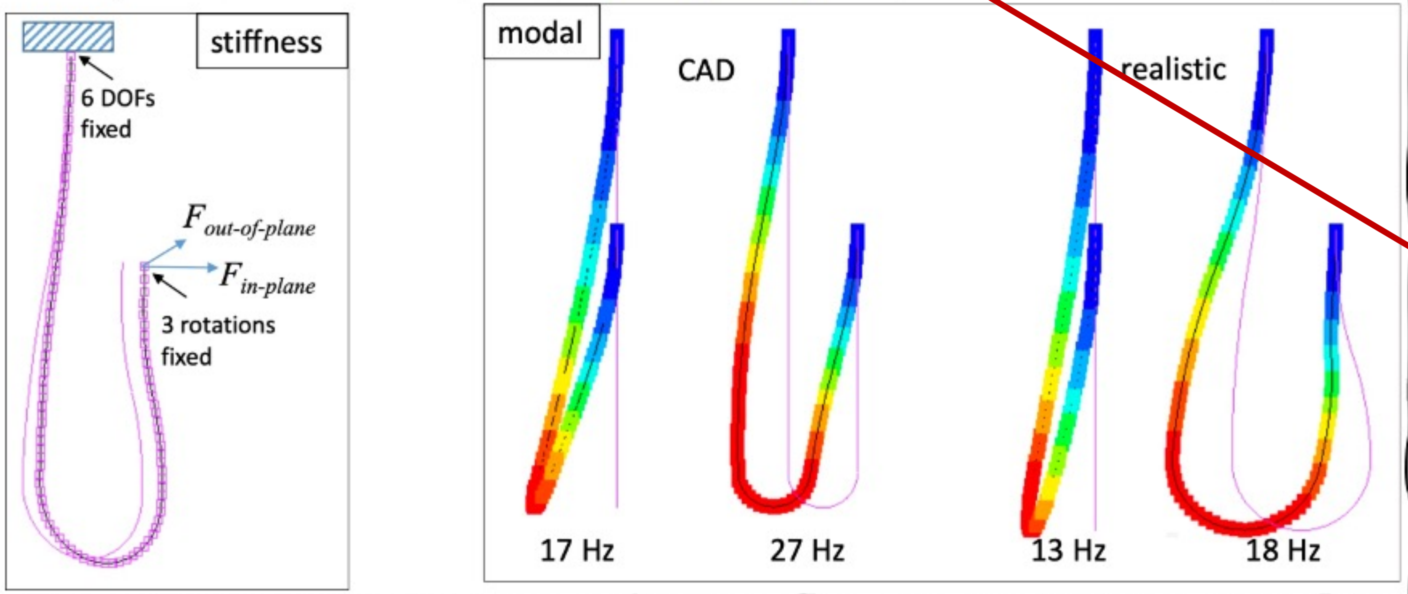


Stiffness of a single wire HL

For a fixed geometrical model

HL wire stiffness and modal shapes (FEM)

description		symbol	value (model: CAD)	realistic	unit	comment/formula
HL wires (FEM)	single wire stiffnesses	$k_{wire,in\text{-}plane}$	0.049	0.047	N/m	*from static FEM*
		$k_{wire,out\text{-}of\text{-}plane}$	0.037	0.035		
	total jellyfish stiffness	k_{Nwires}	0.345	0.326		$N_{HLwire}(k_{wire,in\text{-}plane}+k_{wire,out\text{-}of\text{-}plane})/2$
	1st in-plane mode	$f_{wire,in\text{-}plane}$	27	17	Hz	*from modal FEM*
	1st out-of-plane mode	$f_{wire,out\text{-}of\text{-}plane}$	18	13		



(Eric Hennes and Andrei Utina)

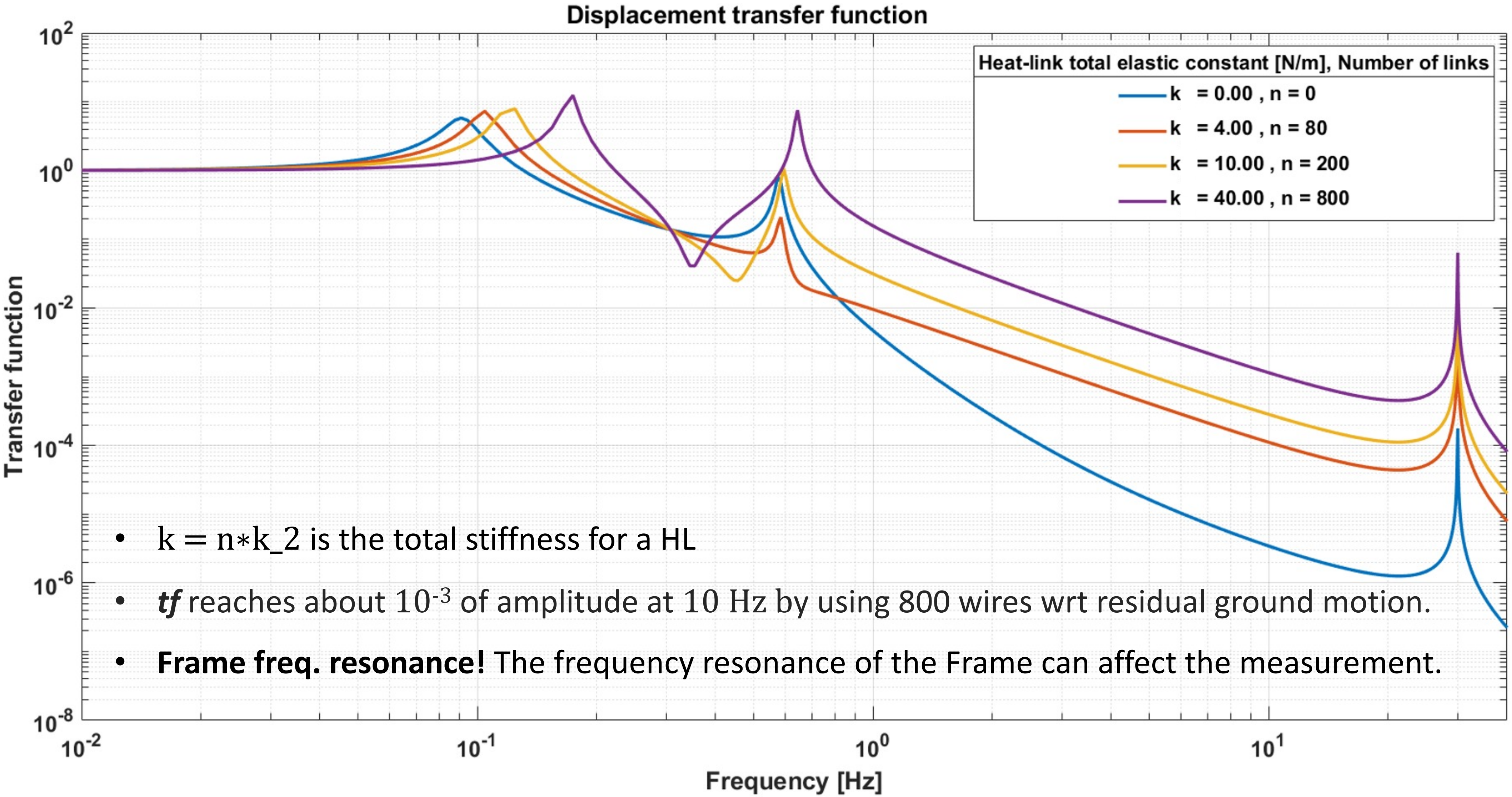
Single wire parameters	
Length l	0.2 m
Diameter d	2.5×10^{-4} m
Cross section s	$4.9\times10^{-8}\ \mathrm{m^2}$
Thermal conductivity $\chi(10\ \mathrm{K})$	$20000\ \frac{\mathrm{W}}{\mathrm{m*K}}$
Number of wires	n
Linear elastic constant k_2	0.05 N/m

k = n∗k_2 Total stiffness for a HL

T_R = l/χsn Thermal resistance

How many wires do we need in order to have a good cooling down without affecting the seismic isolation?

Displacement transfer function (tf) of the mechanics at the bench level

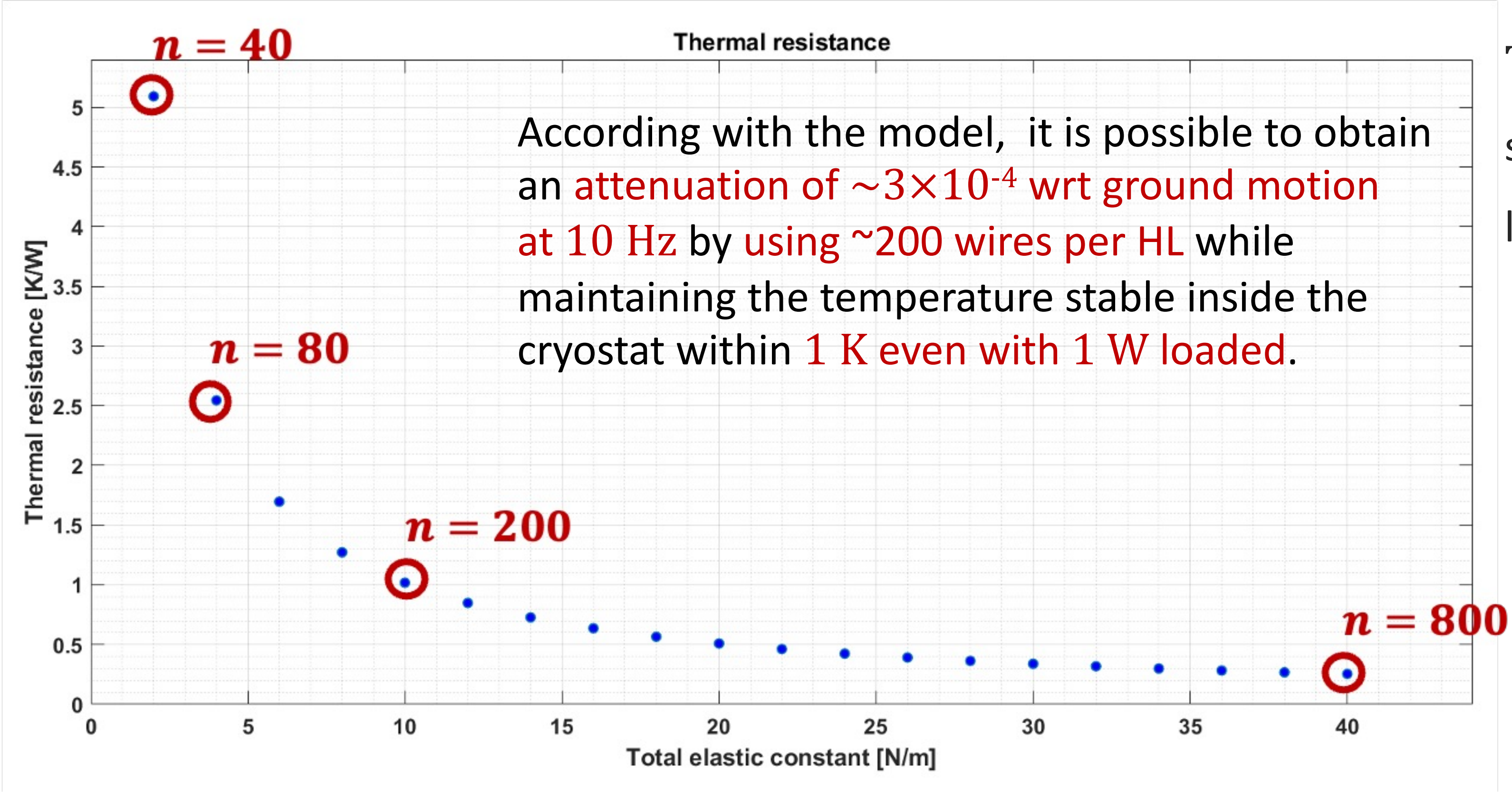


- $k = n * k\_2$ is the total stiffness for a HL
- ***tf*** reaches about 10^{-3} of amplitude at 10 Hz by using 800 wires wrt residual ground motion.
- **Frame freq. resonance!** The frequency resonance of the Frame can affect the measurement.

HL Thermal Resistance

T_R = l/χsn

Taking advantage from KAGRA experience

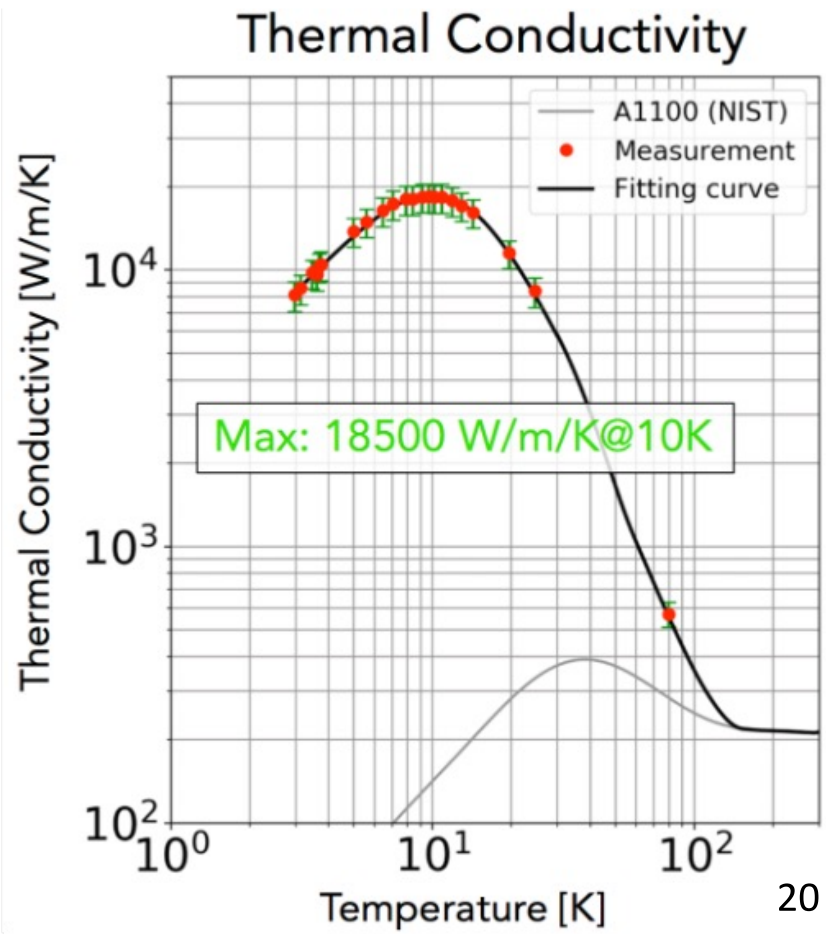


According with the model, it is possible to obtain an attenuation of $\sim 3\times10^{-4}$ wrt ground motion at 10 Hz by using ~200 wires per HL while maintaining the temperature stable inside the cryostat within 1 K even with 1 W loaded.

Thermal conductivity $\chi = 2\times10$^4 W/(m∗K)

s = 4.9×10^(-8) m^2

l = 0.2 m



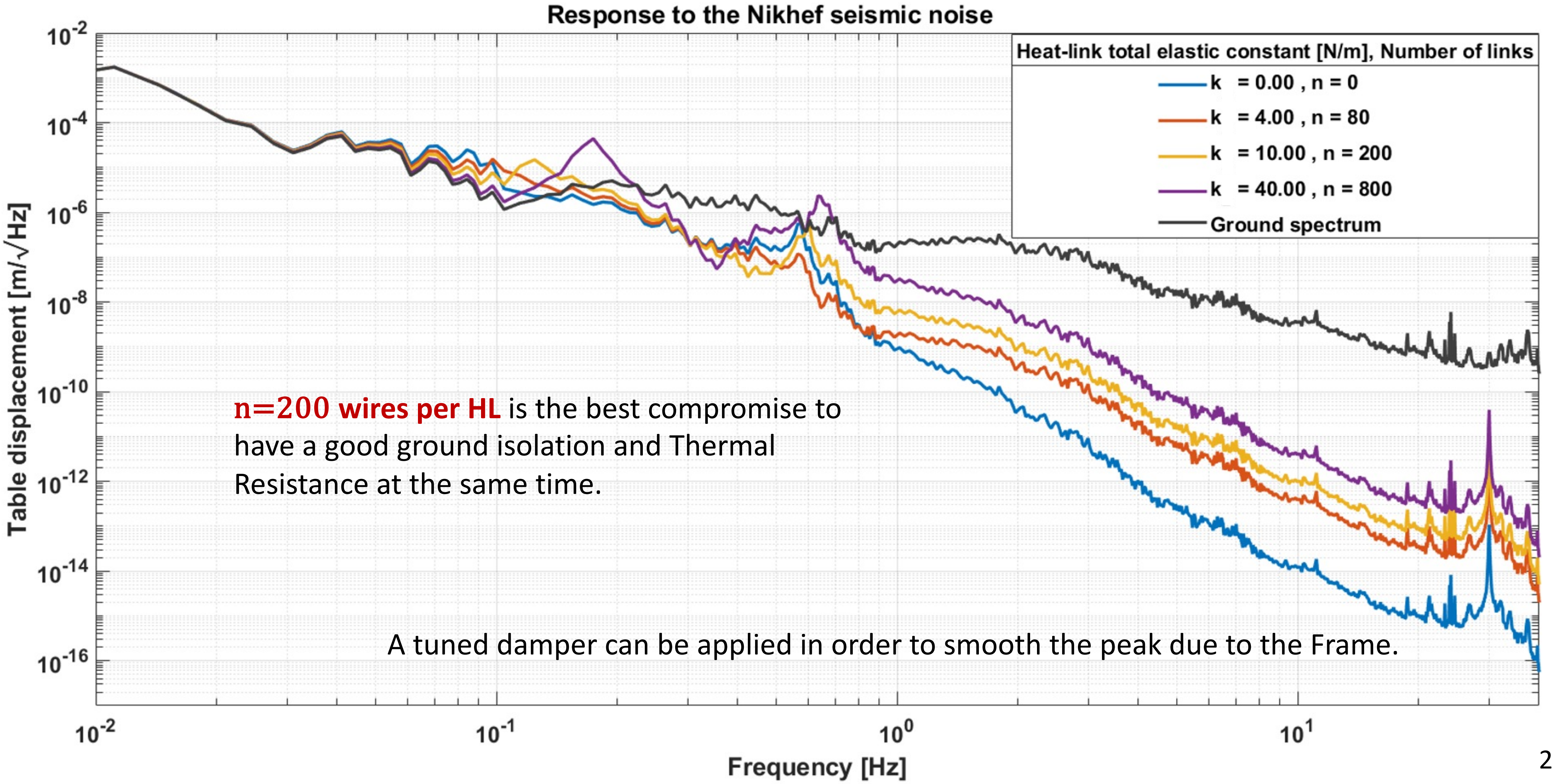
T_R = l/χsn =

1. n=800 → 0.25 K/W
2. n=200 → 1.02 K/W
3. n=80 → 2.55 K/W

Attenuation at 10 Hz:

1. ~10^(-3)
2. ~3×10^(-4)
3. ~10^(-4)

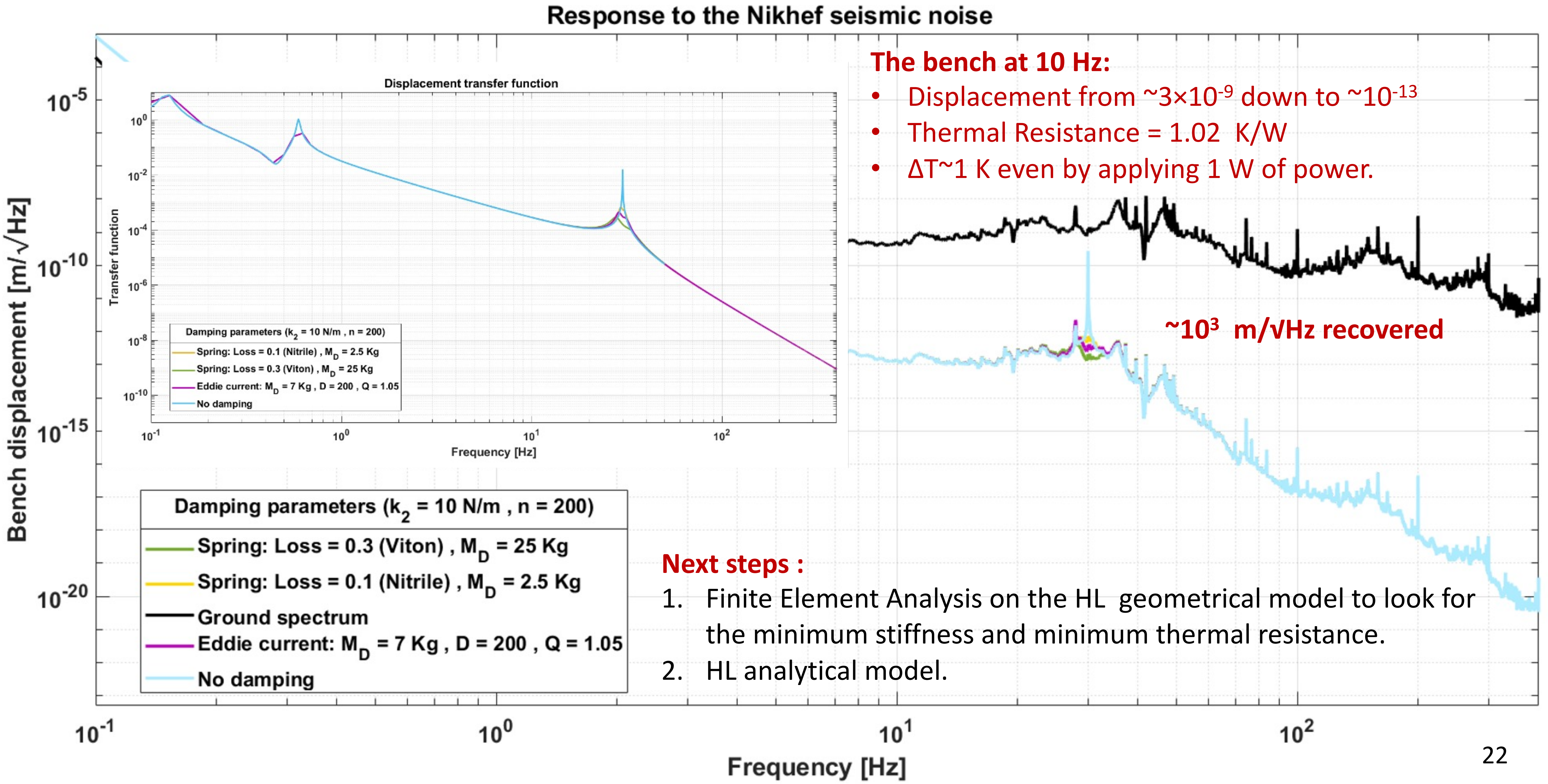
Expected noise level of the bench



n=200 wires per HL is the best compromise to have a good ground isolation and Thermal Resistance at the same time.

A tuned damper can be applied in order to smooth the peak due to the Frame.

Bench displacement after applying a tuned damper



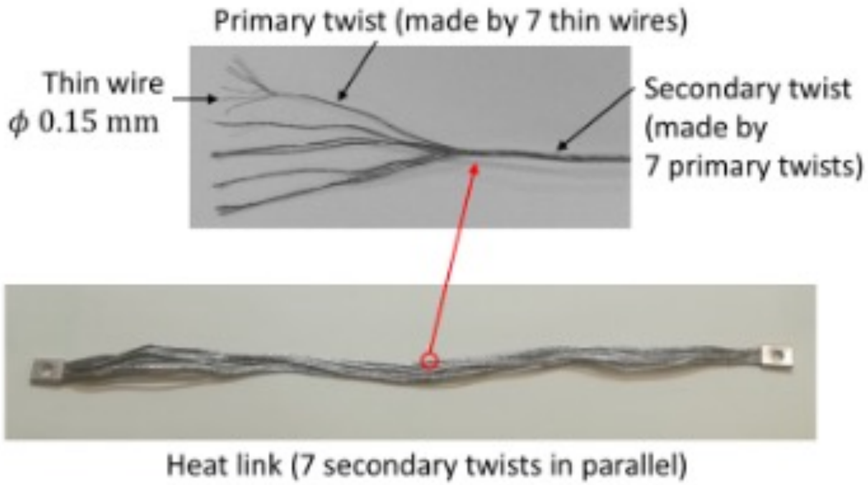
The bench at 10 Hz:

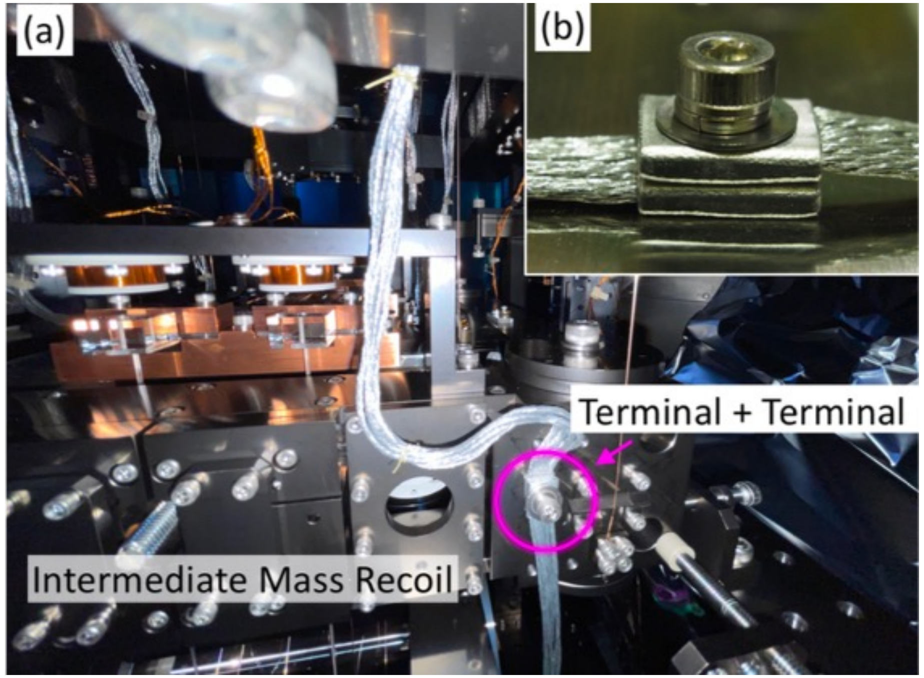
- Displacement from ~3×10^{-9} down to ~10^{-13}
- Thermal Resistance = 1.02 K/W
- ΔT~1 K even by applying 1 W of power.

Next steps :

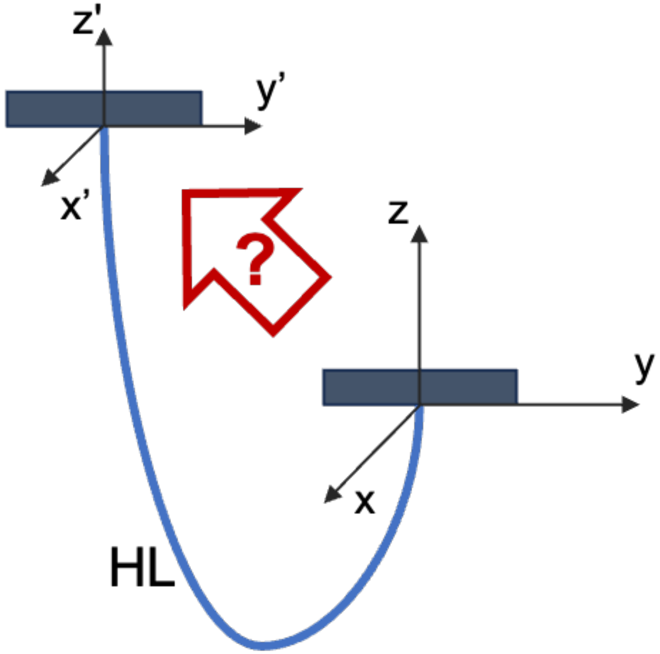
1. Finite Element Analysis on the HL geometrical model to look for the minimum stiffness and minimum thermal resistance.
2. HL analytical model.

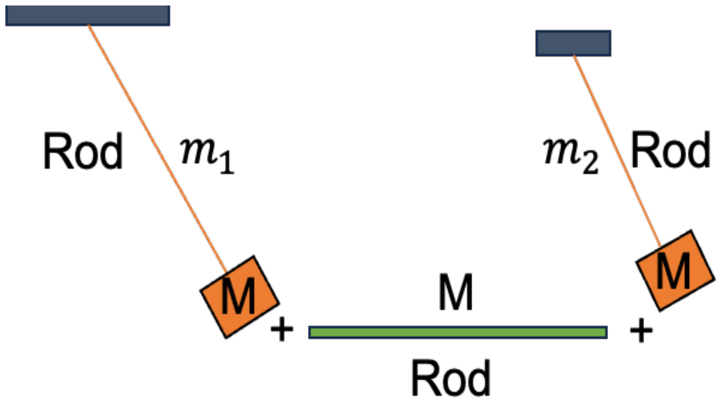
Heat Link analytical study





In both pictures: Heat-Links used at KAGRA





$$-EIy(z,t)'''' + Ty(z,t)'' = \rho\ddot{y}(z,t)$$

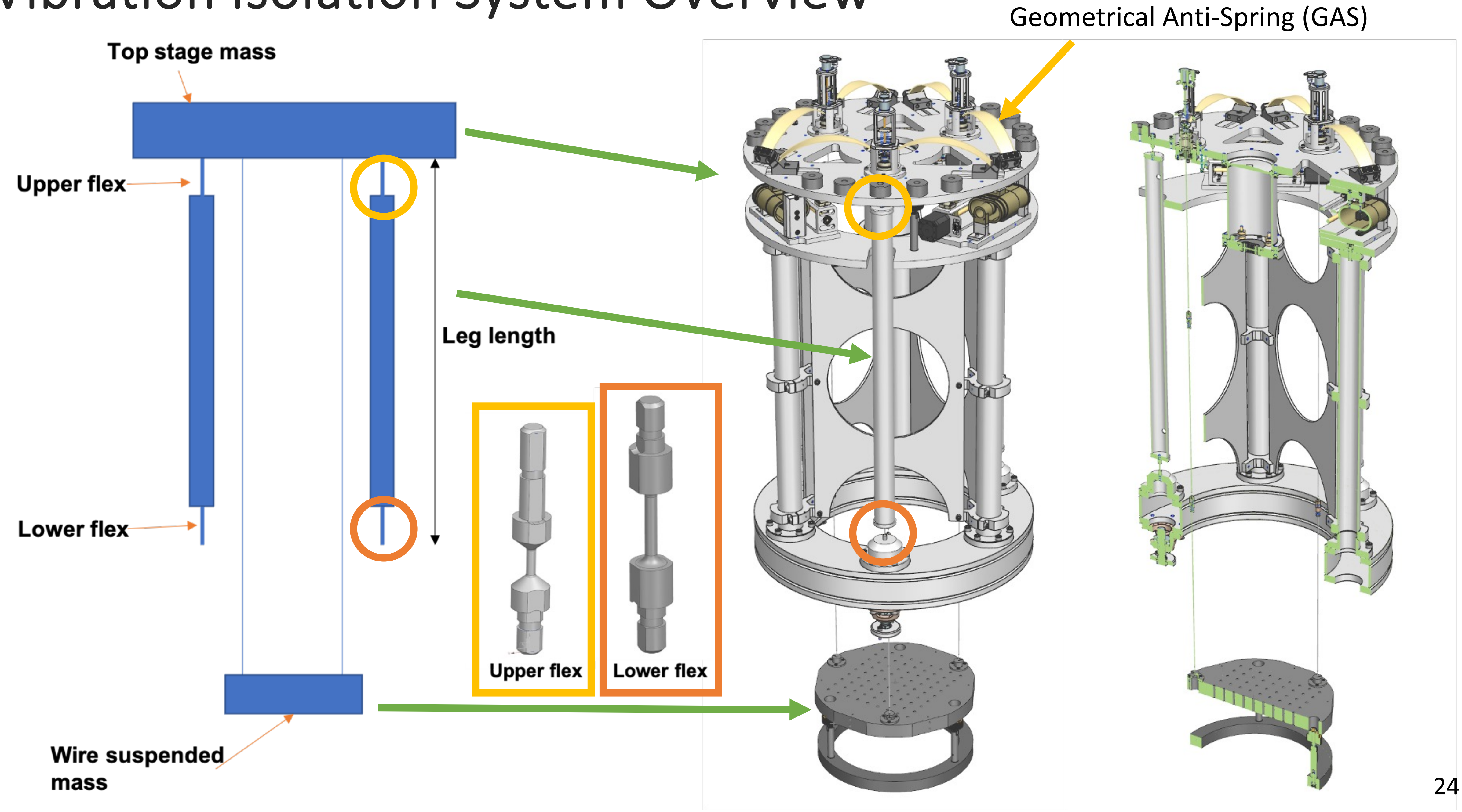
Where:

- E → Young Modulus
- I → Second moment of area
- T → Tension
- ρ → Mass per unit length

To solve in frequency domain for:

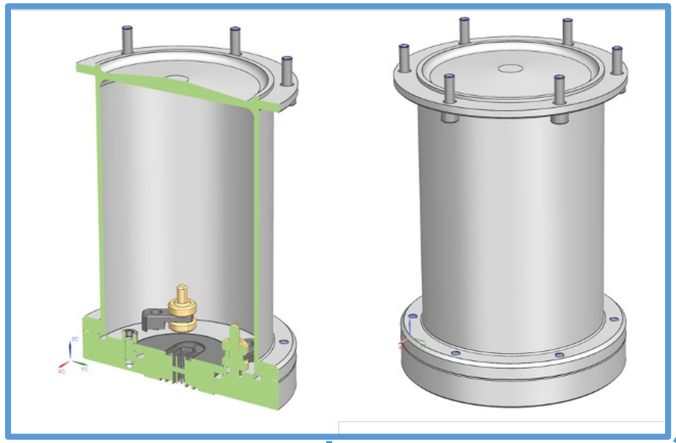
- Rod+mass pendulum
- Simply supported rod

Vibration Isolation System Overview



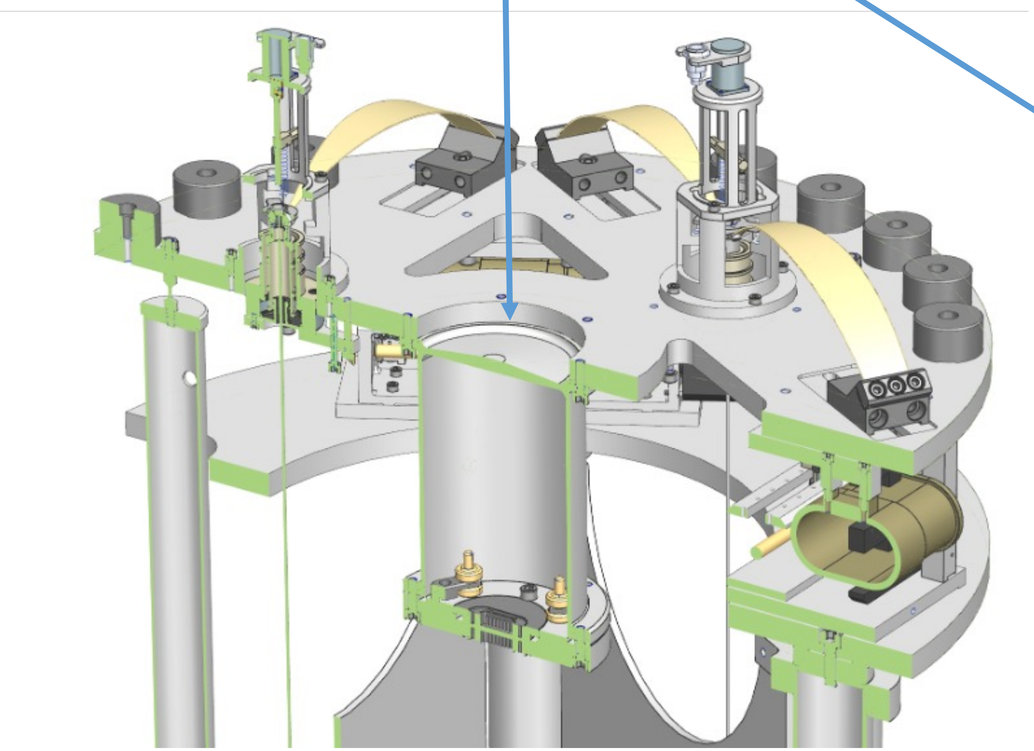
Top Stage: GAS blades+Seismometer

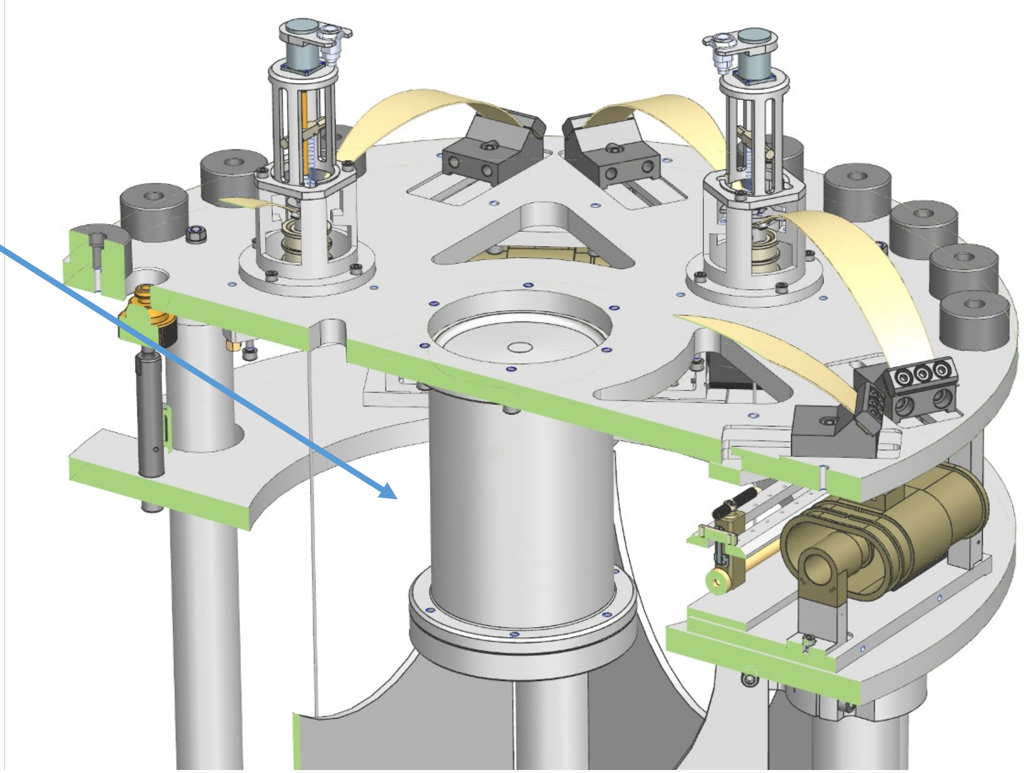
Nanometrics Trillium 120



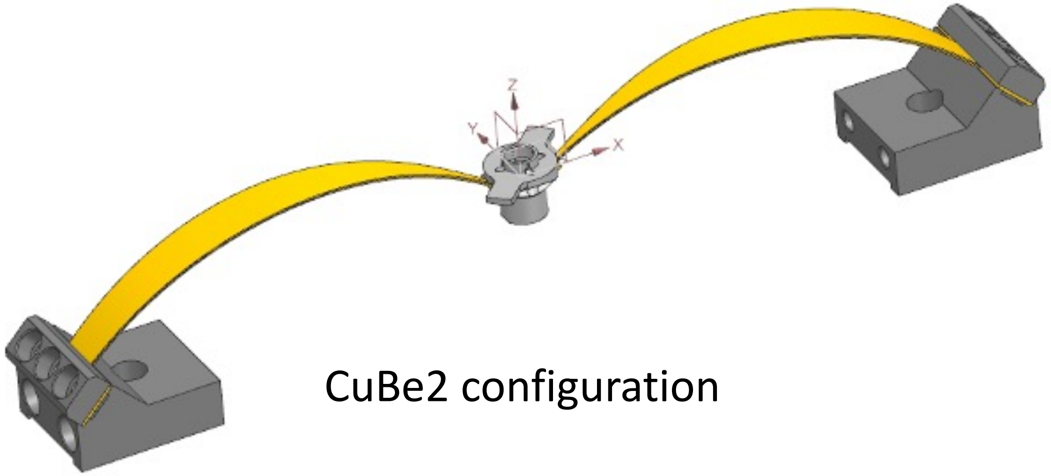
3 pairs of GASs for vertical seismic attenuation + vertical LVDTs.
A triaxial seismometer is hanged at the Top Stage from the bottom:

- It is used to sense the xy-inertial motion of the IP.
- The z-channel is used to subtract the ground from the vertical LVDTs.

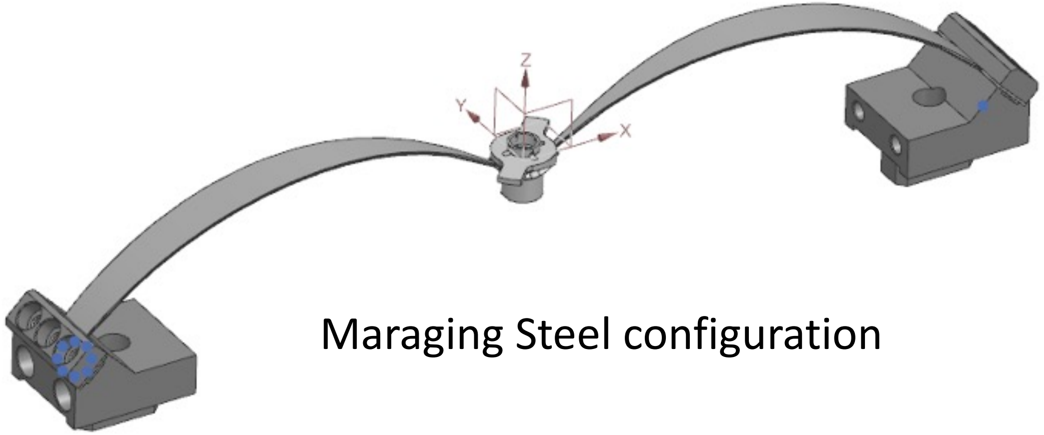




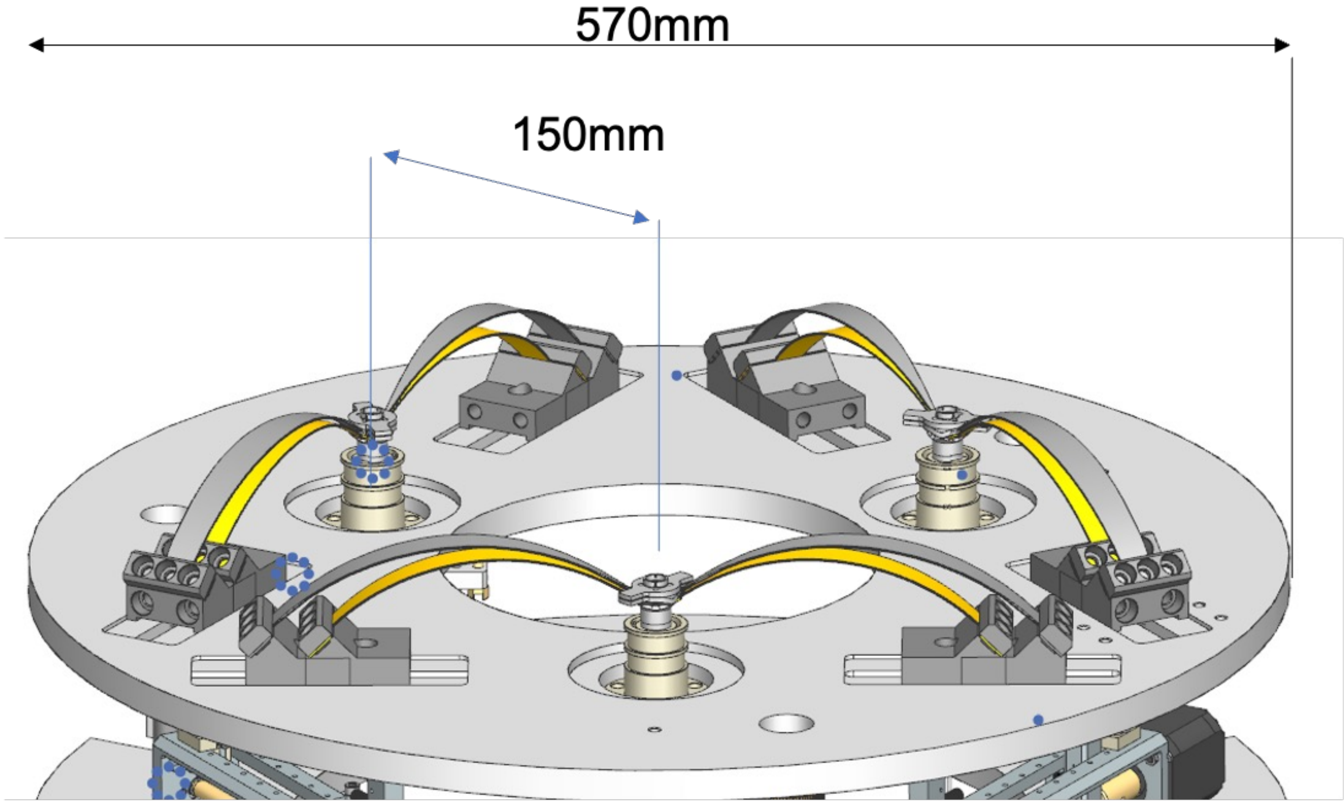
GAS filters



CuBe2 configuration



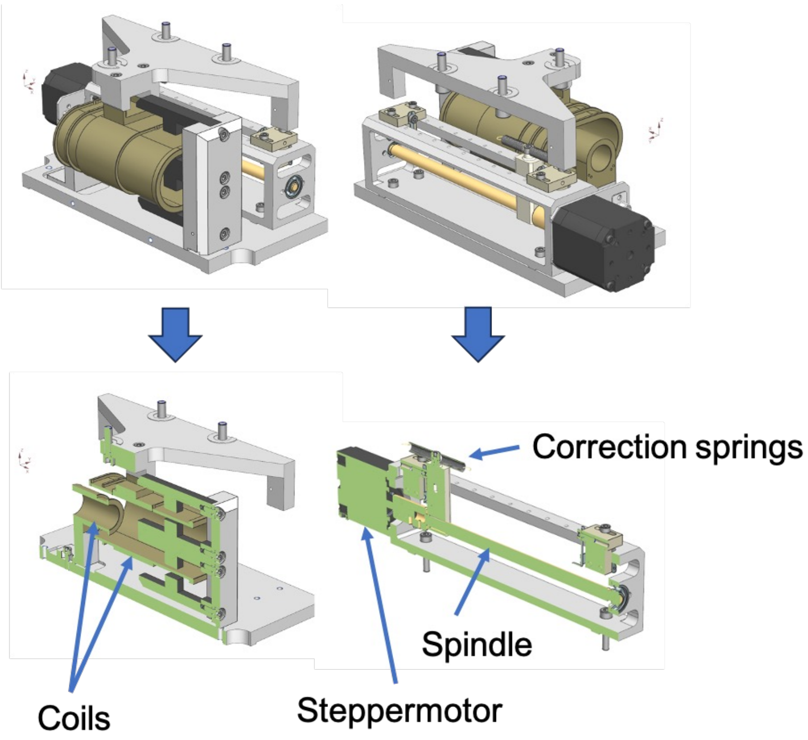
Maraging Steel configuration

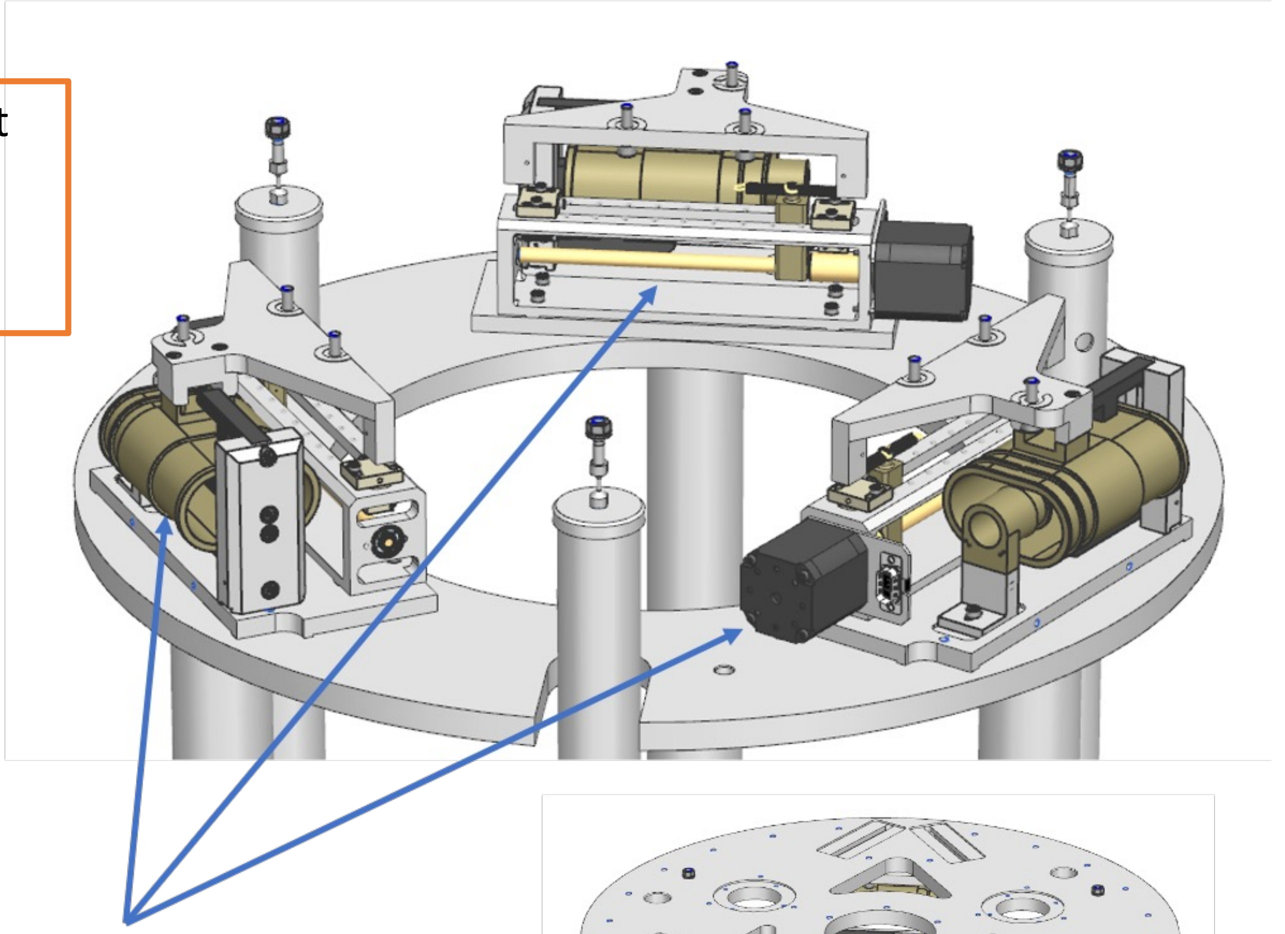


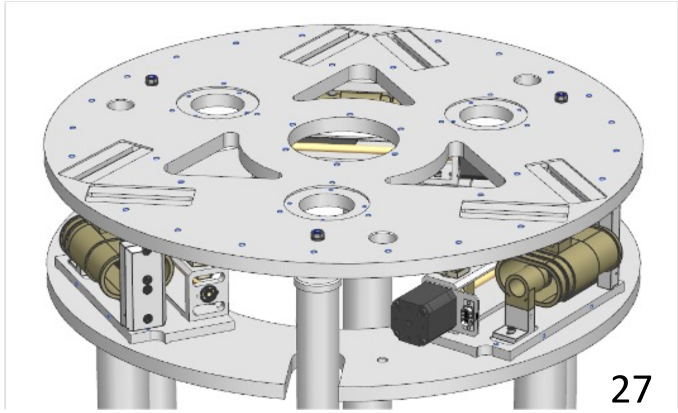
Both configurations are equally valid.
They will fit on a 570mm round plate with Pendulum wires on a radial position of 15cm.
-> CuBe2 blades have been chosen for practical reasons.

Top Ring: IP Correction Spring Assembly

- LVDTs are used to sense the position of the IP with respect to the Frame/Ground.
- Voice-coils are used for correction.
- StepMotors are used for static positioning.







Next Steps

Short term:

- Finalization of the analytical model of the heat-links
- Procurement of the mechanical components of the vibration-isolation system in progress;

Mid term:

- Implementation and checks of the vibration-isolation system in stand-alone;

Long term:

- Integration of the vibration-isolation system with the optical bread-board and the cryogenic system in the vacuum tank;

Three main parts

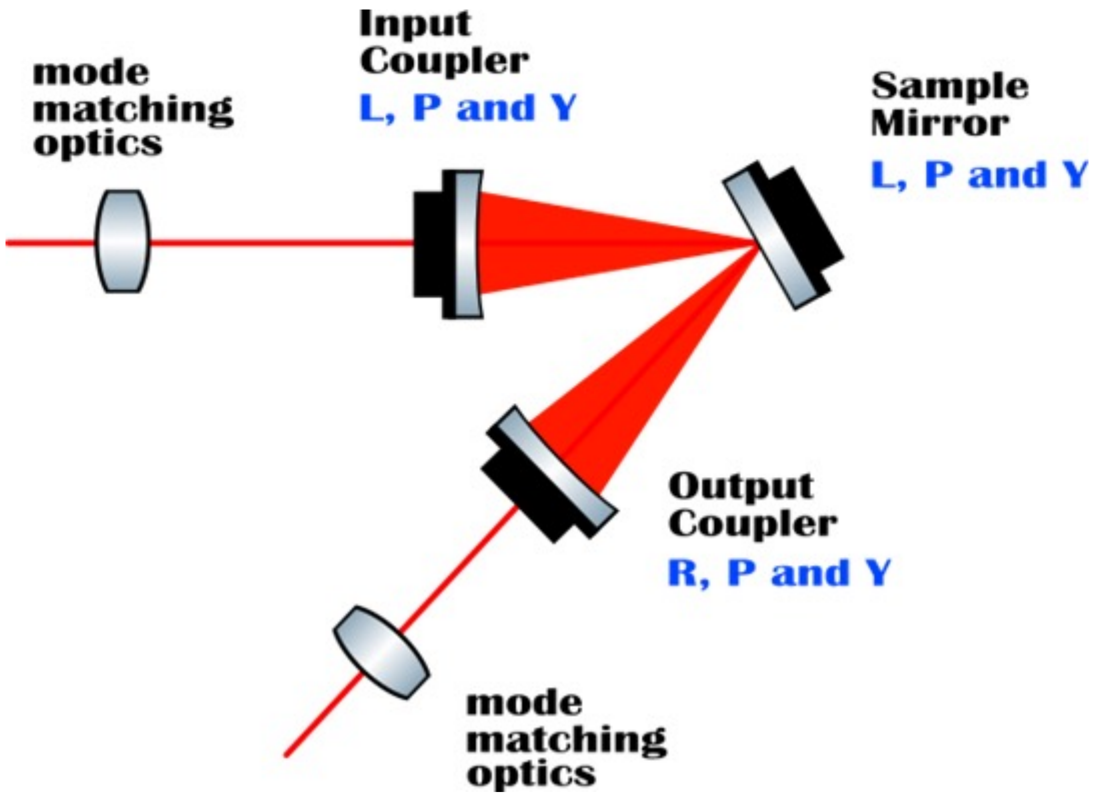
- Cryogenic Technology (Koen)
- Seismic Attenuation System (Enrico)
- Optical setup (Enzo)

Working Principle

Fluctuations of the longitudinal motion of the optical axis can be caused by the internal thermal noise of a mirror in an optical cavity. Fluctuations are produced by the internal damping inside the test mass.

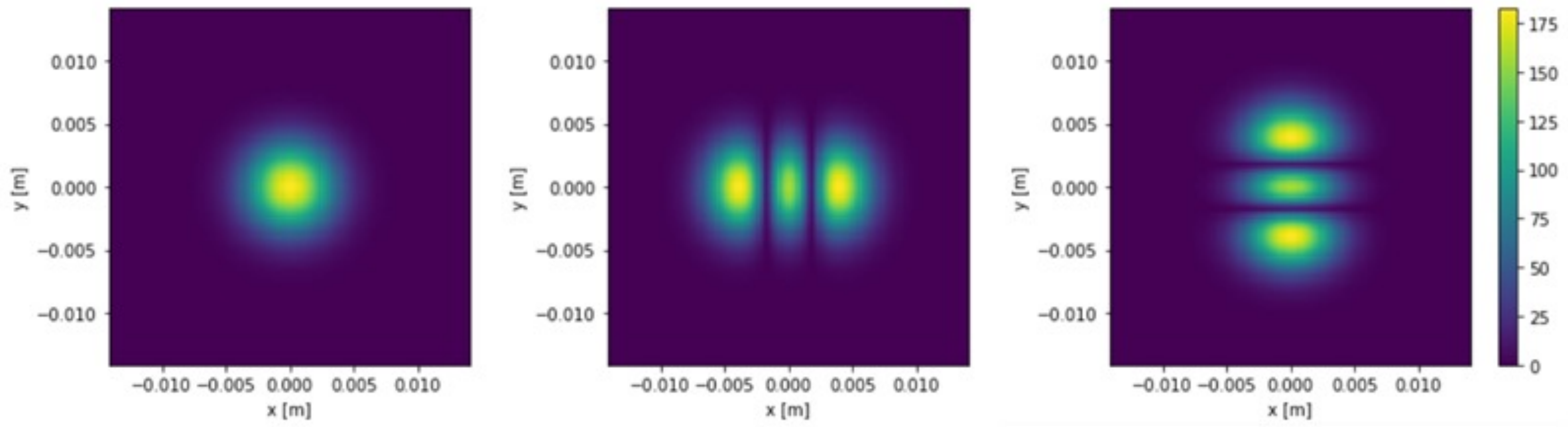
Measurement of the longitudinal displacement of the sample mirror by direct application of the fluctuation-dissipation theorem to the readout of the setup.

First implementation at MIT:
S. Gras and M. Evans
Phys. Rev. D **98**, 122001



Working Principle

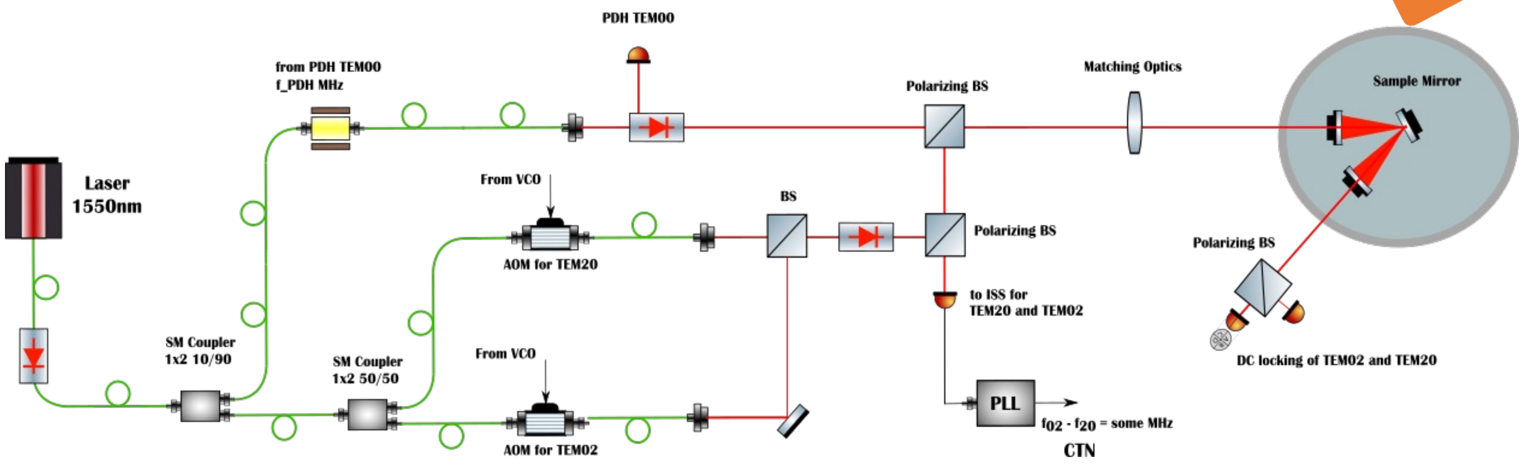
Folded cavity must allow co-resonance for the fundamental mode and two higher order modes (HoMs).
Thermal noise that is sensed by the TEM02 mode is different from the thermal noise sensed by the TEM20 mode, since they do not explore the same area of the sample mirror.

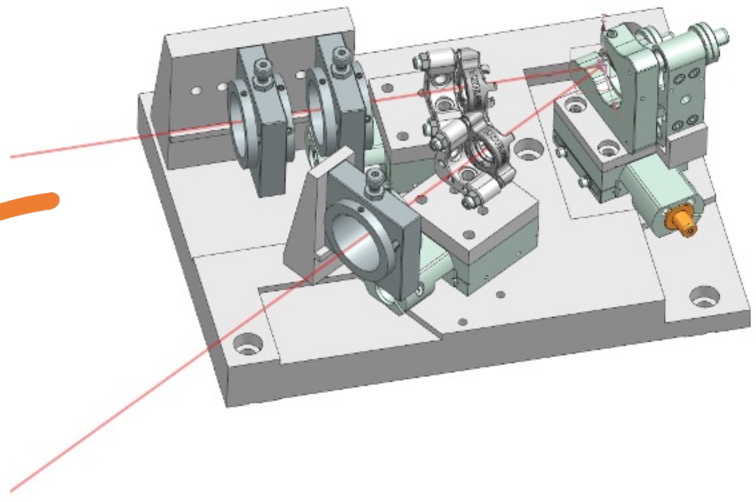


In the readout, for the HOMs, common noises such as length noise, frequency noise and thermal noise of the mirror can be decoupled from the Coating Thermal Noise (CTN). CTN is obtained from the beat note of the resonant frequencies of TEM02 and TEM20.

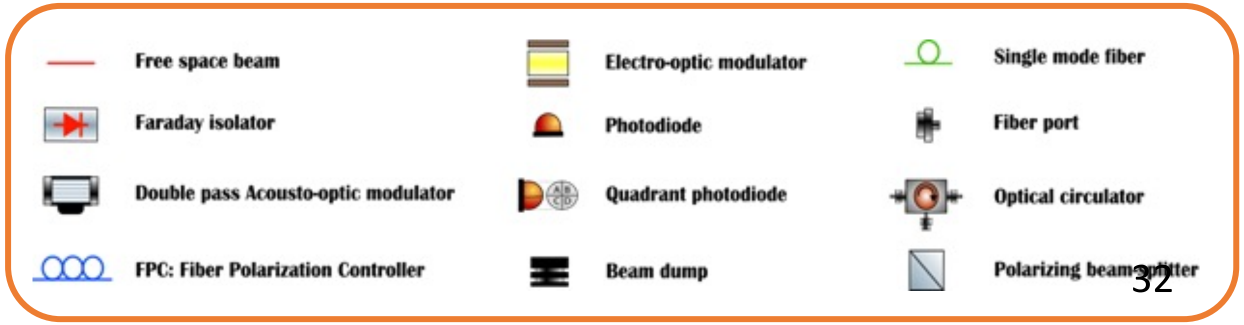
Optical Setup: Overview

1550 nm laser beam split into three beams: one is used to lock the cavity with the TEM00 mode, the two of others are shifted in frequency with Acousto-optic Modulators (AOMs) to have TEM02 and TEM20 resonant in the cavity.
In-vacuum high Finesse multi resonant folded cavity.





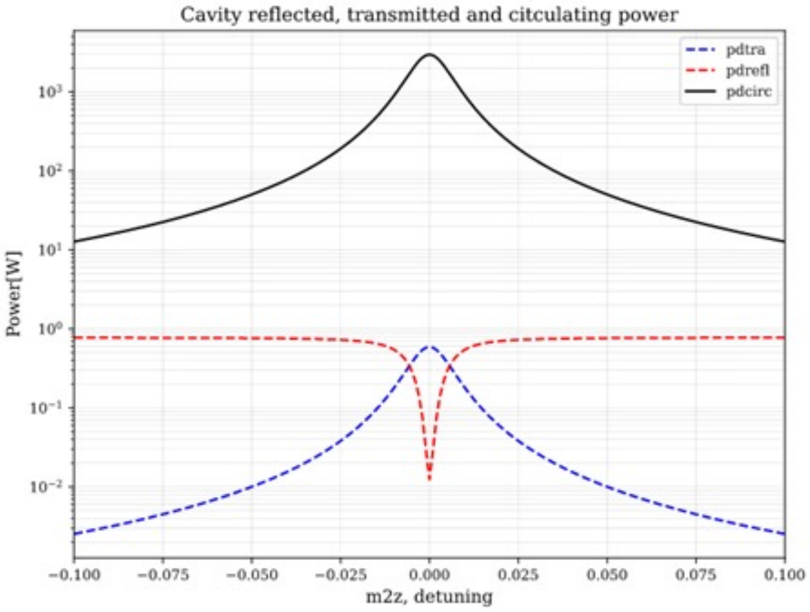
*Cavity design based on a similar AEI cavity design

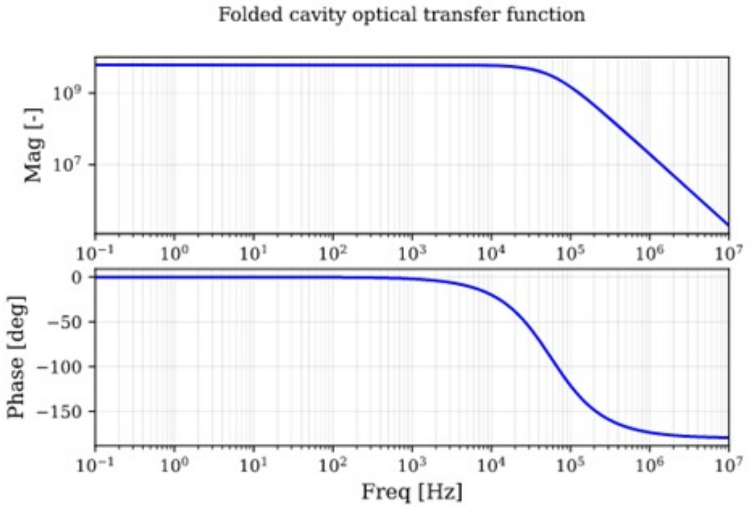


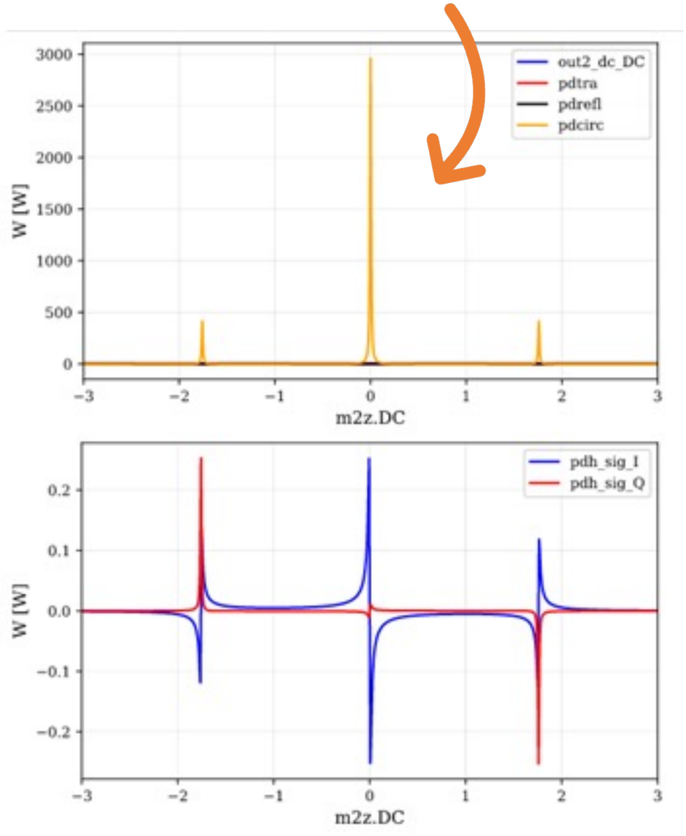
Optical Setup: Simulations

Sample mirror inside a folded high-Finesse optical cavity.
RoC Input mirror: 50 mm
RoC Output mirror: 50 mm

Fundamental (TEM00) is locked using a Pound-Drever-Hall (PDH) loop in reflection.



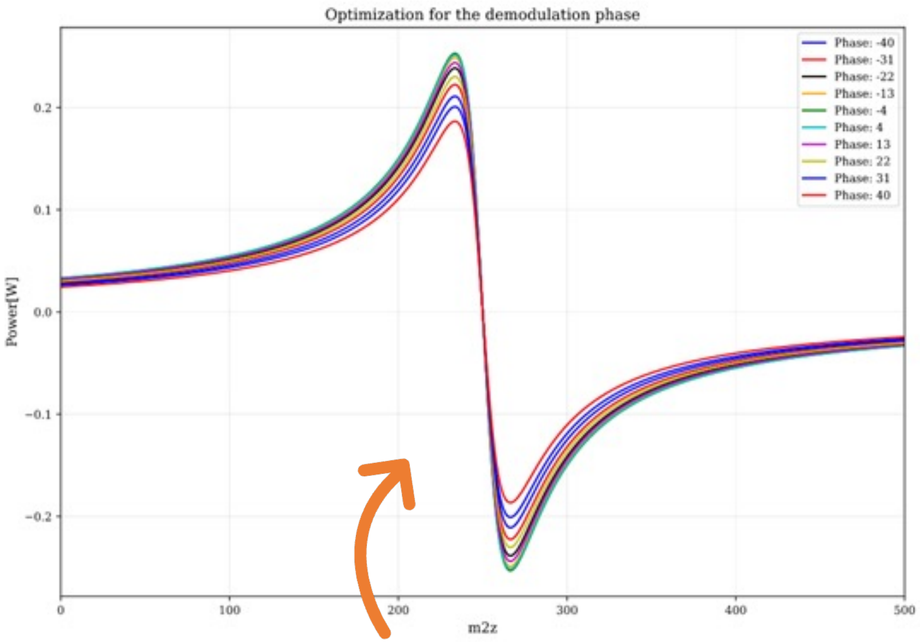


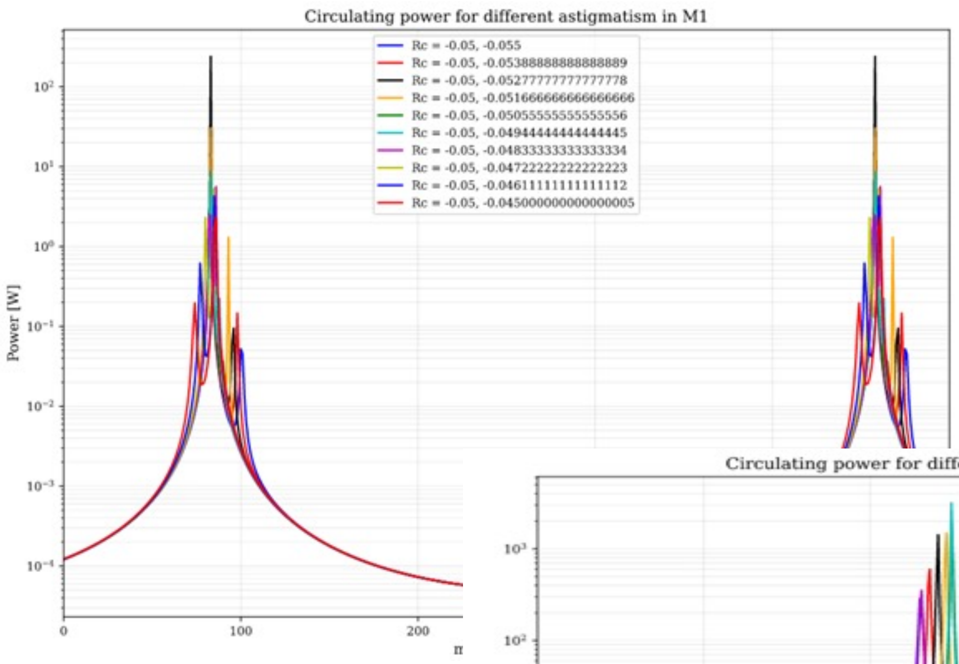


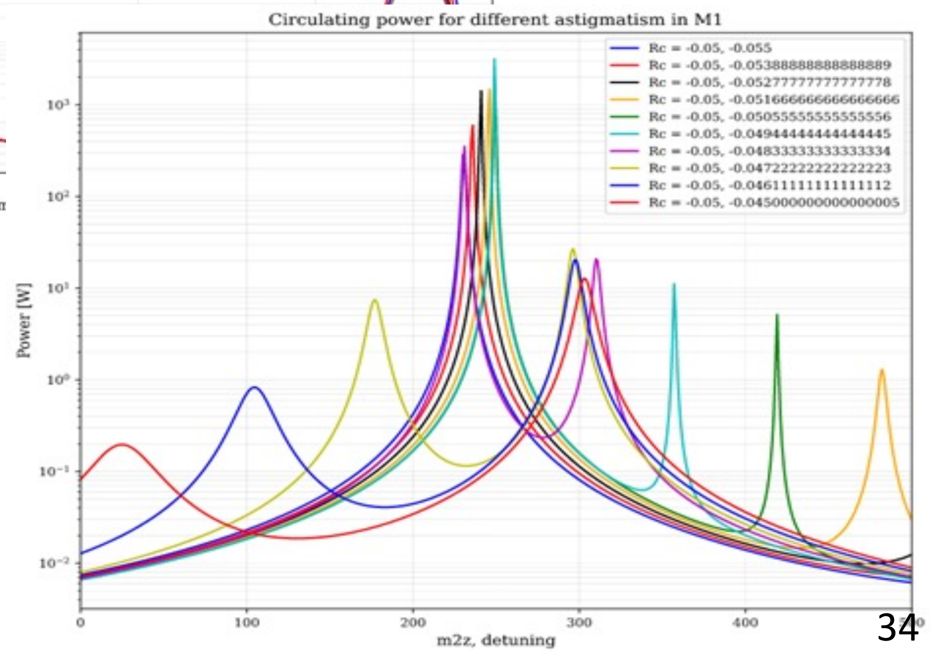
Pole of the cavity @ 56kHz
Cavity Finesse: ~13000

Optical Setup: Simulations

TEM00, TEM02 and TEM20 can co-resonate inside the folded cavity by tuning the orientation of the input mirror.



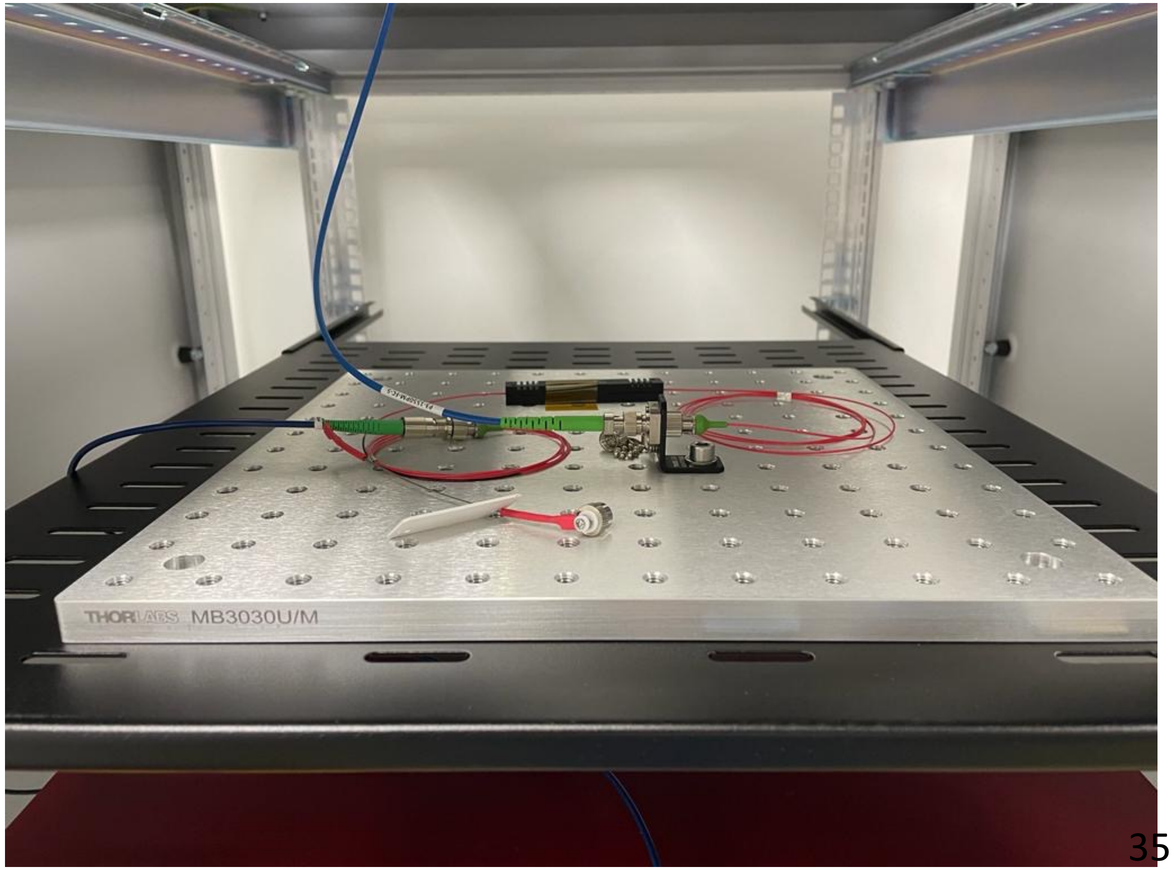




The error signal to lock the fundamental mode can/must be optimized.

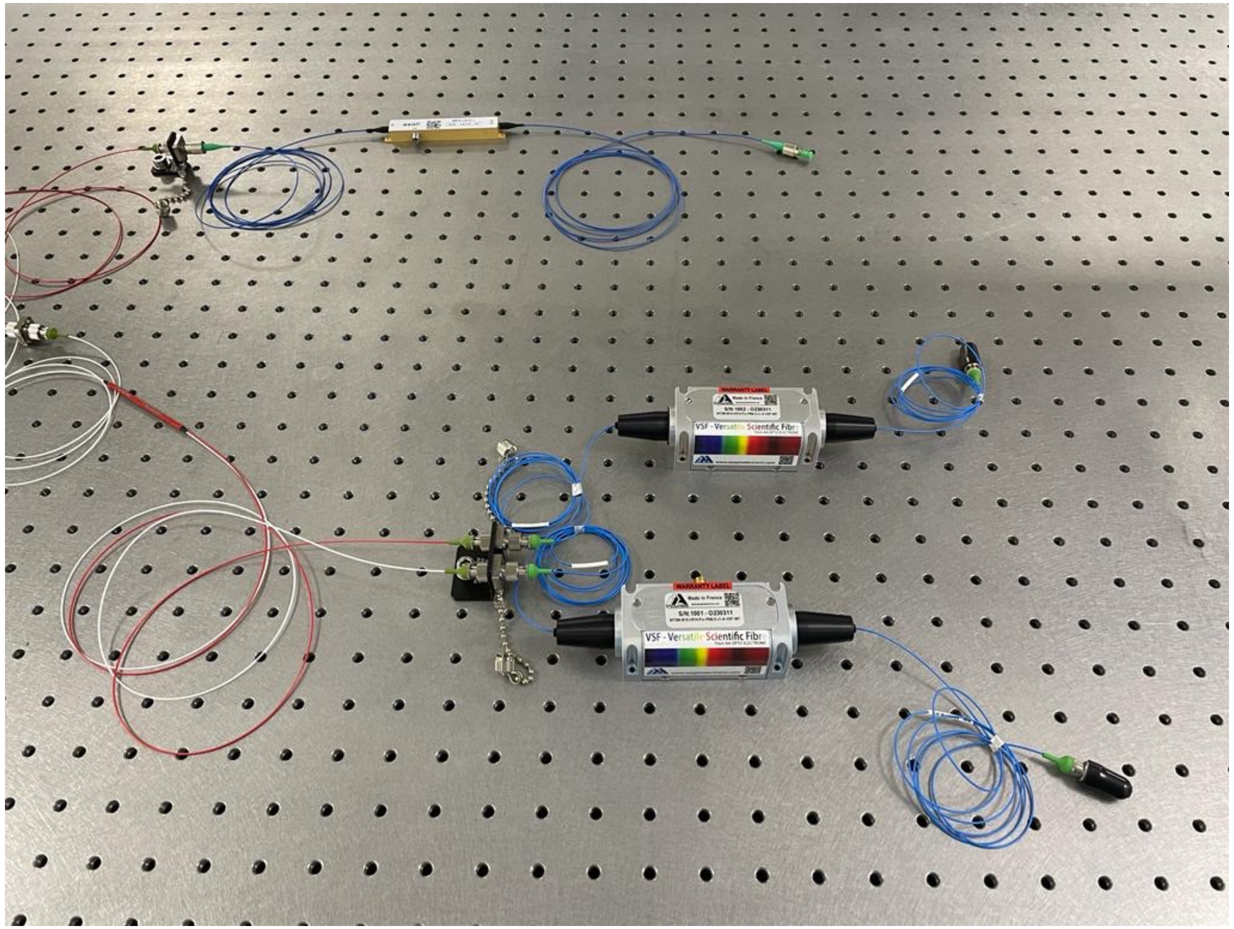
Optical Setup at Nikhef Lab

Main Laser and Faraday Isolator:
1550nm Main laser with 0.1-2W Output Power.



Optical Setup at Nikhef Lab

Electro-optic Modulator (EOM) and Acousto-optic Modulators (AOMs) installed in lab:



EOM modulation frequency ~ 15 MHz
AOM modulation frequency ~280MHz

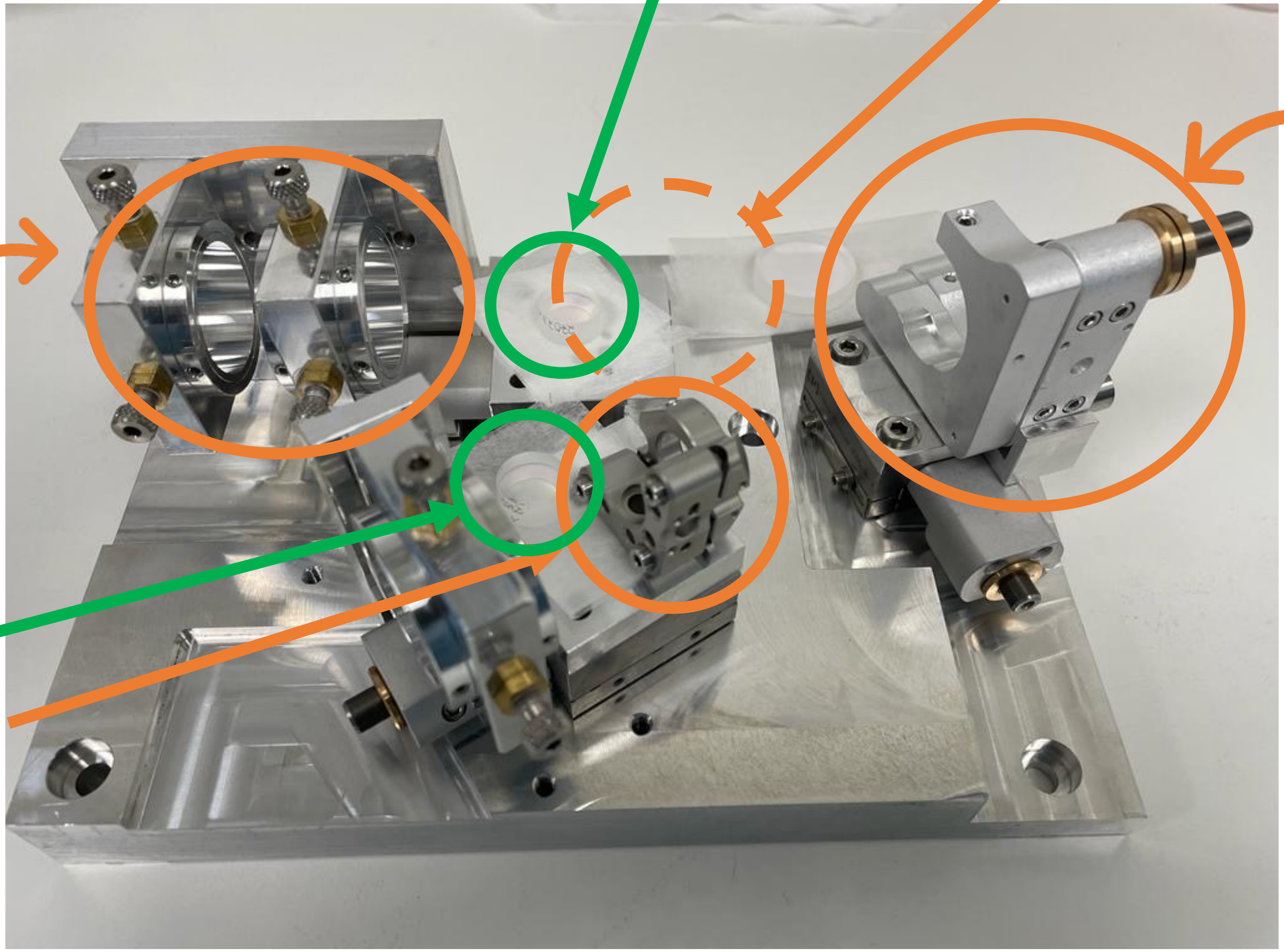
From here towards and in the folded cavity the laser is in-air.
Collimator and matching optics to be installed.

Optical Setup at Nikhef Lab

Mount of input coupler under test at cryogenic temperatures in Perugia.

Input coupler mirror.

Folded cavity:



Matching optics (TBC)

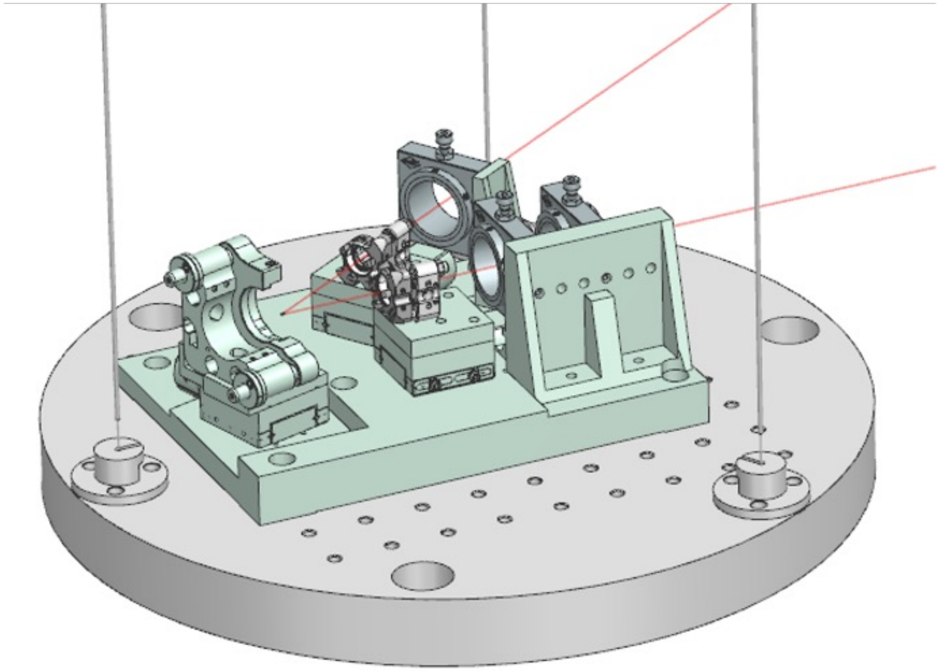
Mount for coating sample under test
Sample size: 1 inch.

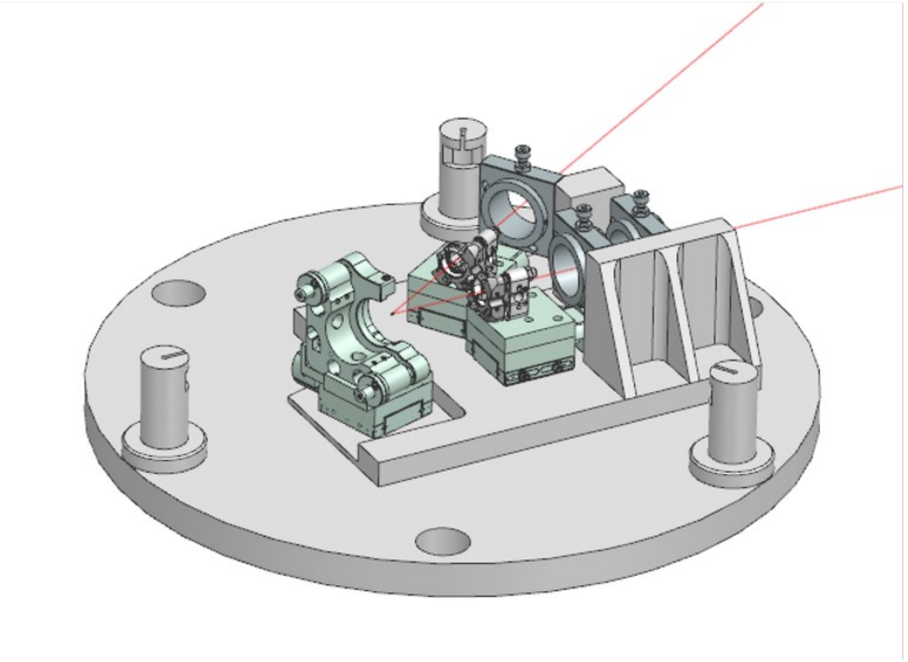
Output coupler mirror.

Mount of output coupler.

Integration of the optical breadboard

Two possible solutions:
- Removable breadboard to allow the cavity pre-alignment outside the vacuum tank.
- Monolithic cavity to reduce the residual motions.





Next Steps

Short term:

- Characterization of the optical beams in the lab;
- Design and procurement of the mode-matching telescope;
- Procurement of some electronics in progress;

Mid term:

- Have the 3 beams co-resonant in the cavity in lab;
- Lock the cavity in-air;

Long term:

- Integration of the optics in the full experiment;
- Measurements and characterization of the full system at room temperature;
- Measurements and characterization of the full system at cryogenic temperature

Backup: simulation