# The CAOS Infrastructure: Full-Scale Testing of Superattenuators for Future GW Detectors

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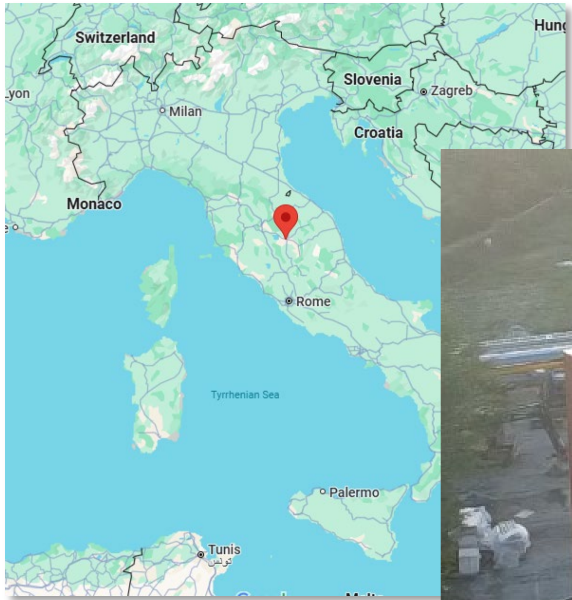
# Introduction

CAOS is one of the **ETIC infrastructure** facilities, located in **Perugia**.

This unique **international facility** specialises in developing new seismic filtering technology and low-noise controls using **full-size ET vacuum towers and superattenuators** (SAs).

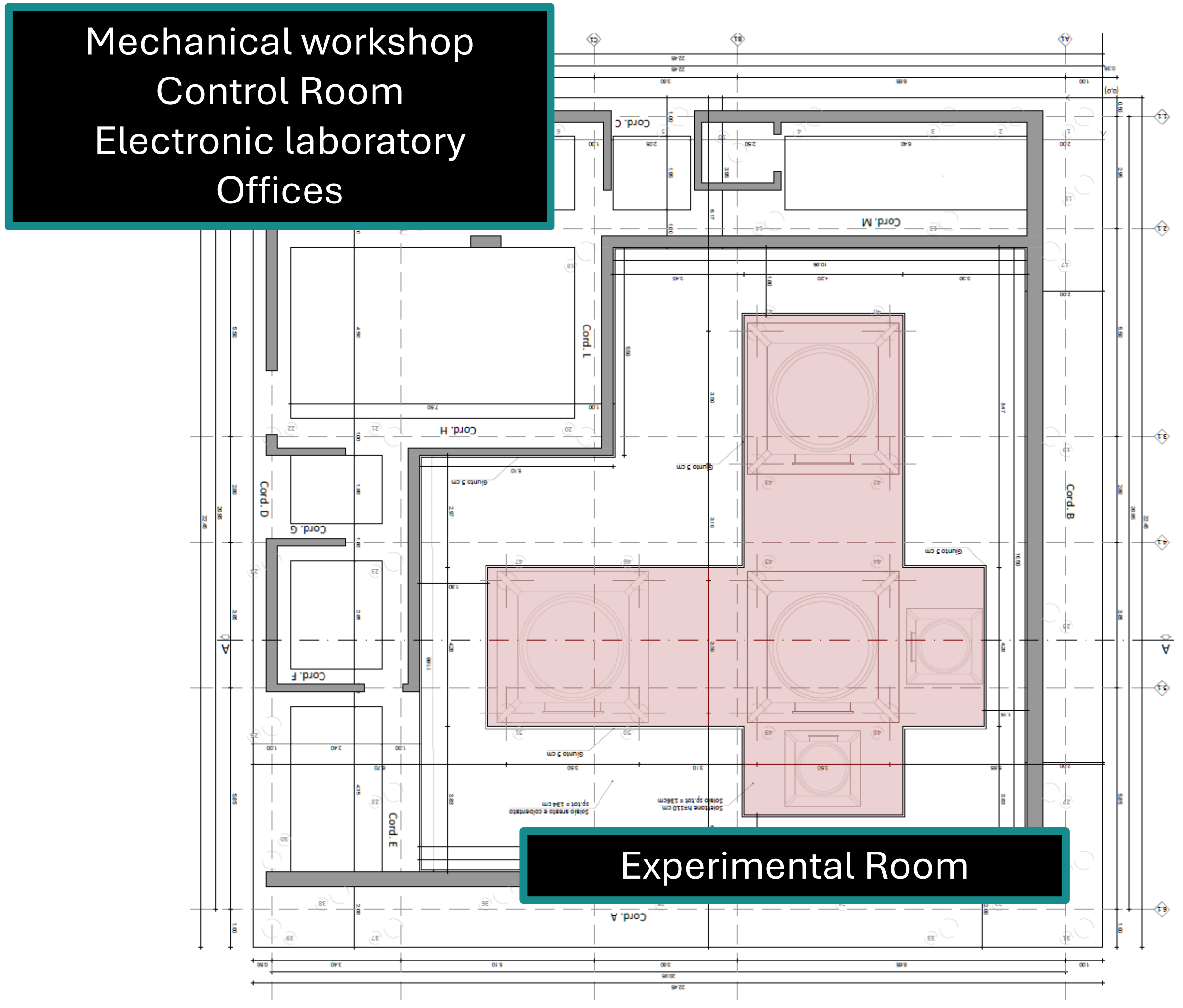
The expertise acquired at CAOS will contribute to the **development of technology** for third-generation gravitational wave detectors, as well as having applications in other fields, particularly seismology and early warning systems.




# Introduction

## The Building





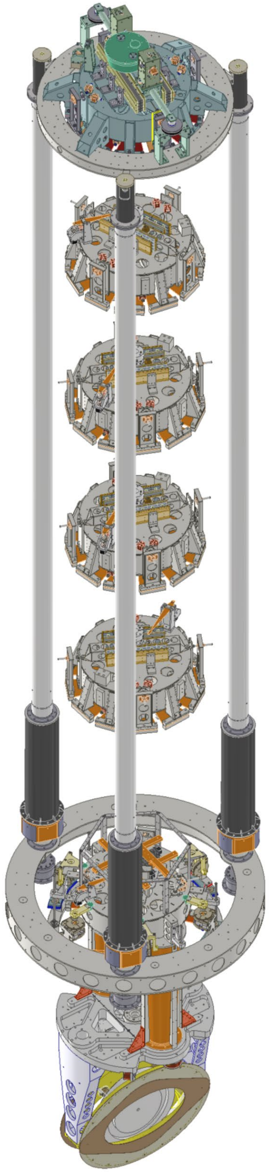

Total internal area: 441 $m^2$
Height (int.): 21 m

# Introduction

## Vacuum system and superattenuators

Vacuum towers **15 meter height**.

The CAOS base towers are based on the VIRGO base tower and are approximately **3.4 m tall.** They have a conical shape towards the ET solution.



The “traditional” research line, based on **AdV superattenuators** (inverted pendulum, filter chain, and payload), is adopted as the baseline solution in the **ET conceptual design.**

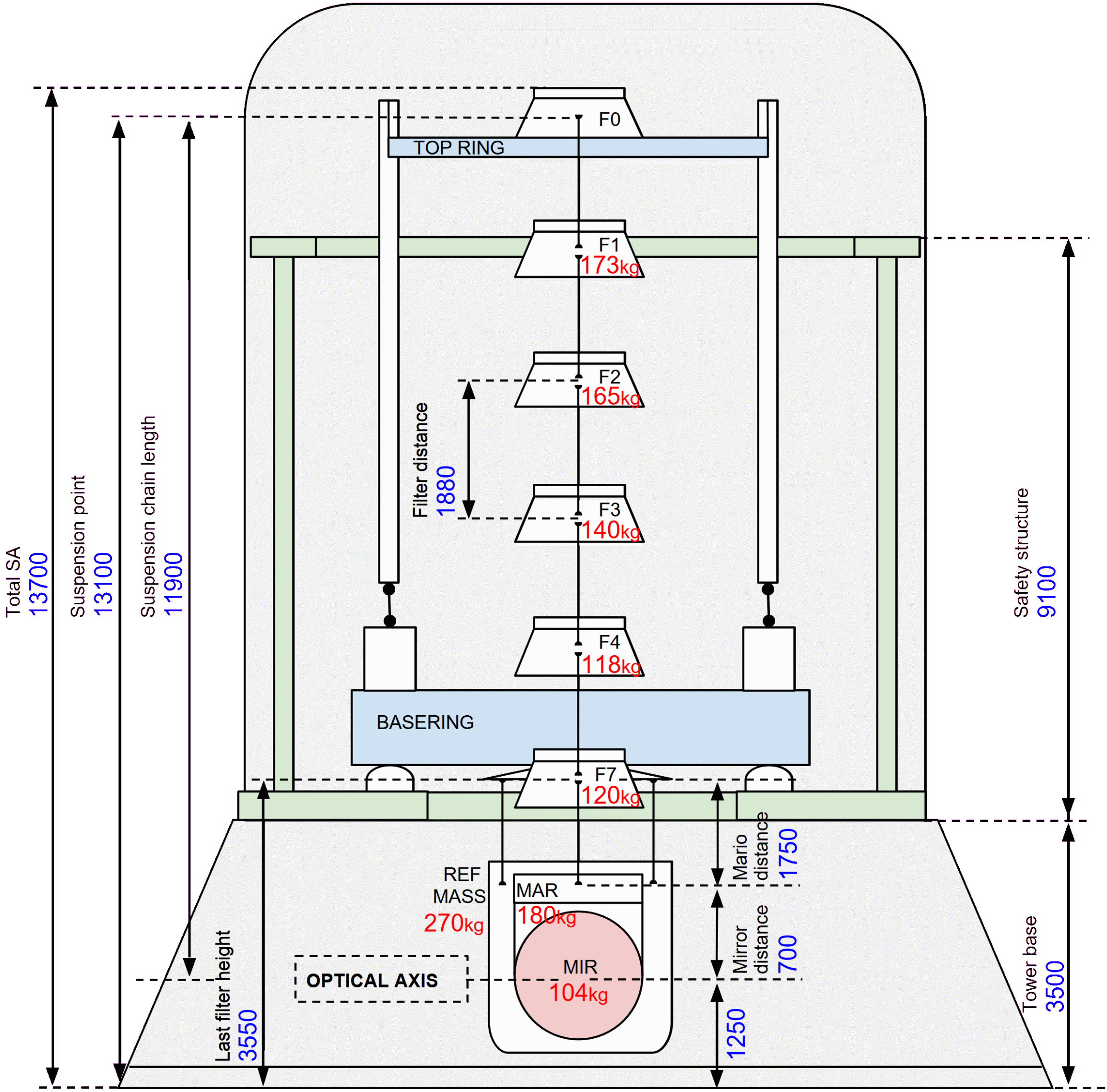
The CAOS facility will serve as a **key testbench for two AdV-based superattenuators**, rescaled to meet ET requirements (targeting a 3 Hz cutoff frequency), and will support a **Fabry–Pérot optical cavity approximately 6.5 m long**. In a later phase, the facility may be upgraded to operate as a full Michelson interferometer.

# CAOS Superattenuators

**The "Beam Splitter" (BS) Superattenuator** will be very similar to AdV Superattenuators (except for the height) to have a "technology benchmark";
**The "East End" (EE) Superattenuator** will help exploit new technologies to perform dedicated R&D on them (Disk 0, IP piezo, new crossbar,...)

Both superattenuators have undergone a redesign. This contribution presents several innovative features along with their analysis:

- A new concept for the **reaction mass suspension**
- Long Payload to study the impact of using the **same length for all SAs stages**
- A **new material** for the blade
- A novel design for the **magnetic antispring and crossbar** (the new crossbar concept is only in the EE superattenuator)



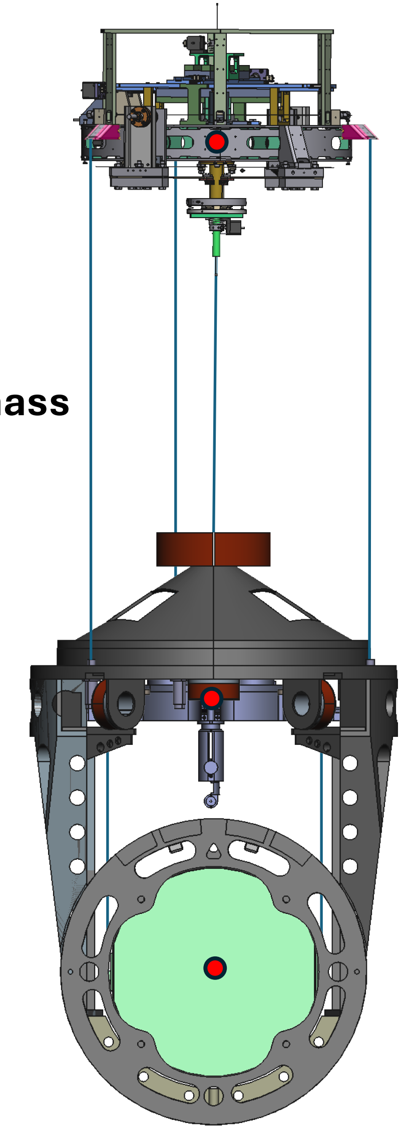
# New concept of reaction mass suspension

Payload derived from **AdV+ Phase 2 (Large Masses)**

Actuation Cage suspended below F7
→ Acts as a **free Reaction Mass**

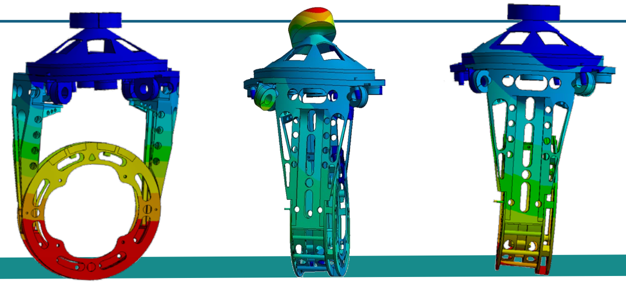
Center of Mass tuning
→ Adjusted with **counterweight hat**
→ Aligned with **Marionette CoM**

Reference Mass optimization
→ Based on **modal analysis simulations**
→ Target: **high resonance frequencies+ low mass**



| Counter-weight hat | Leg | Cradle | Mode 1 [Hz] | Mode 2 [Hz] | Mode 3 [Hz] |
|---|---|---|---|---|---|
| Al 60662<br>6 slots | Al 6061<br>Original | Ti Grade 5 | 59 | 72 | 85 |
| Same as above | Reinforced design | Same as above | 61 | 75 | 85 |
| Same as above | Same as above | Al 6061 | 63 | 77 | 85 |
| 4 slots | Same as above | Same as above | **63** | **78** | **88** |

**Mode shape**

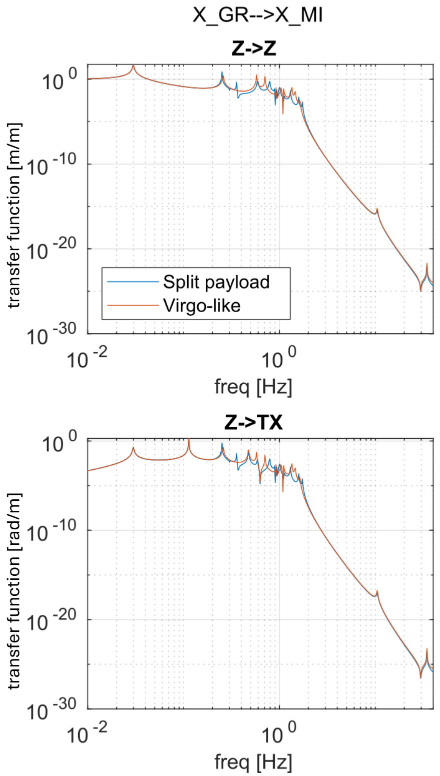


# New concept of reaction mass suspension

The coupling between different DOFs that normally occurs during the actuation is expected to decrease.

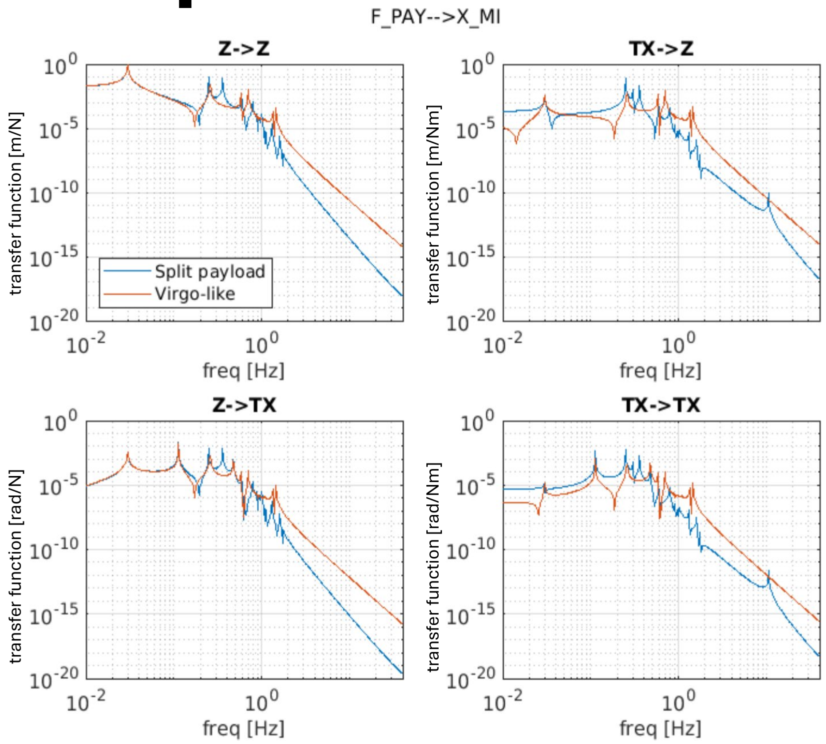
Preliminary OCTOPUS **simulations** have been performed of the **passive isolation performance** of the split-payload superattenuator.

The outcomes are compared with the ones of a CAOS-sized superattenuator with equally spaced 0-7 Filters, terminating in an AdV+ Phase 2 payload.



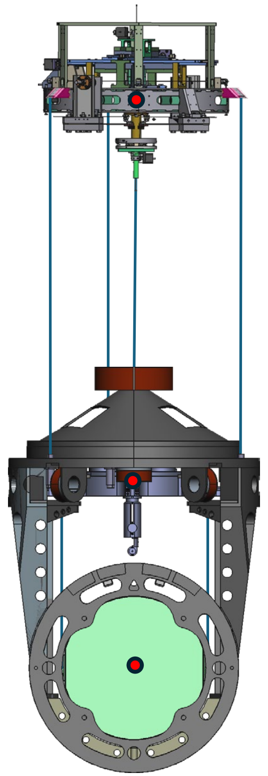

**Passive Isolation Performance**
Ground *z*-displacement → Mirror response:
**z displacement (top)**
**$\theta_x$ angle (bottom)**

Comparison with Virgo-like configuration:
→ **No observable performance degradation**




**Control-to-Mirror Coupling**
External **forces and torques** → mirror motion evaluated
Split payload:
→ Forces applied to **Reference Mass**
Virgo-like:
→ Forces applied to **Filter 7 + Actuation Cage**

**Reduced coupling of control forces to the mirror**
→ **Better isolation from actuation-induced motion**



# Long Payload – same length for all stages

Two main configurations was studied:

**Short payload:** last stage suspension fibers length kept at 0.7 m like in Virgo:

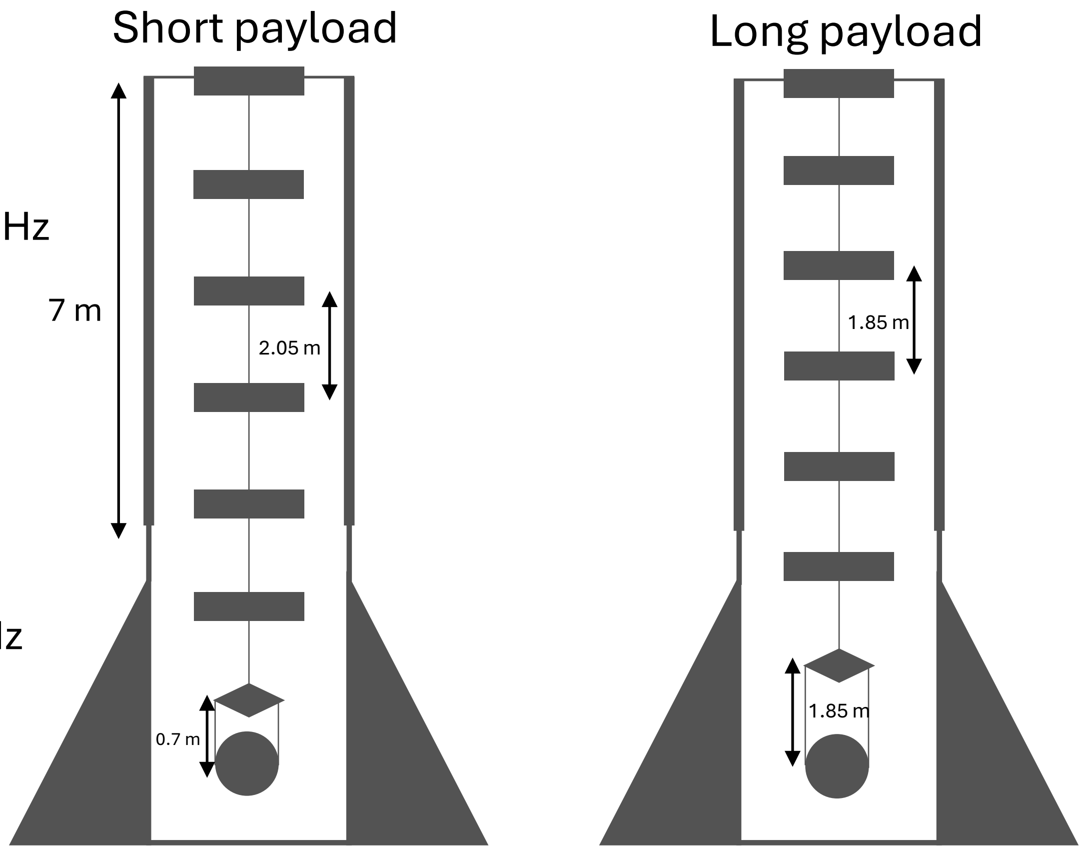
**Pros:** violin mode of the fibers at an higher frequency, i.e. $f_{FS} \approx \mathbf{390}$ Hz

**Cons:** pendulum mode of the payload at an higher frequency, i.e. $f_{FS} \approx \mathbf{0.6}$ Hz

**Long payload:** last stage suspension fibers length as long as the upper stages:

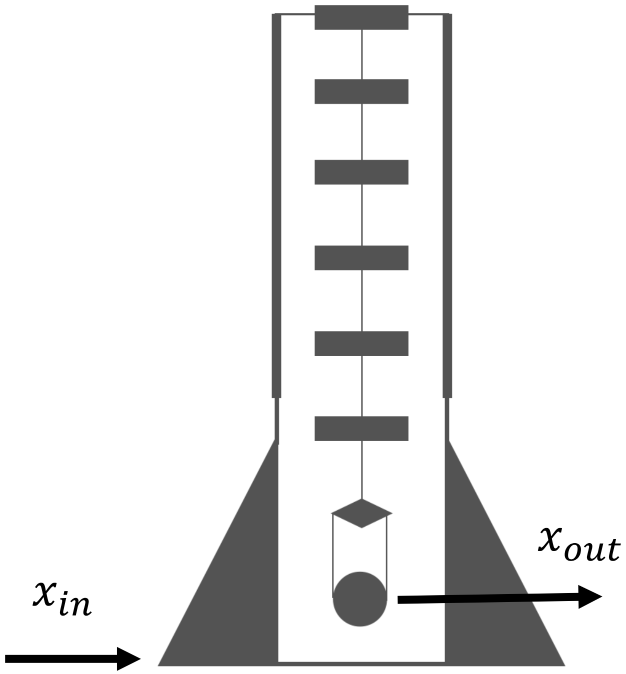
**Pros:** pendulum mode of the payload at a lower frequency, i.e $f_{FS} \approx \mathbf{0.4}$ Hz

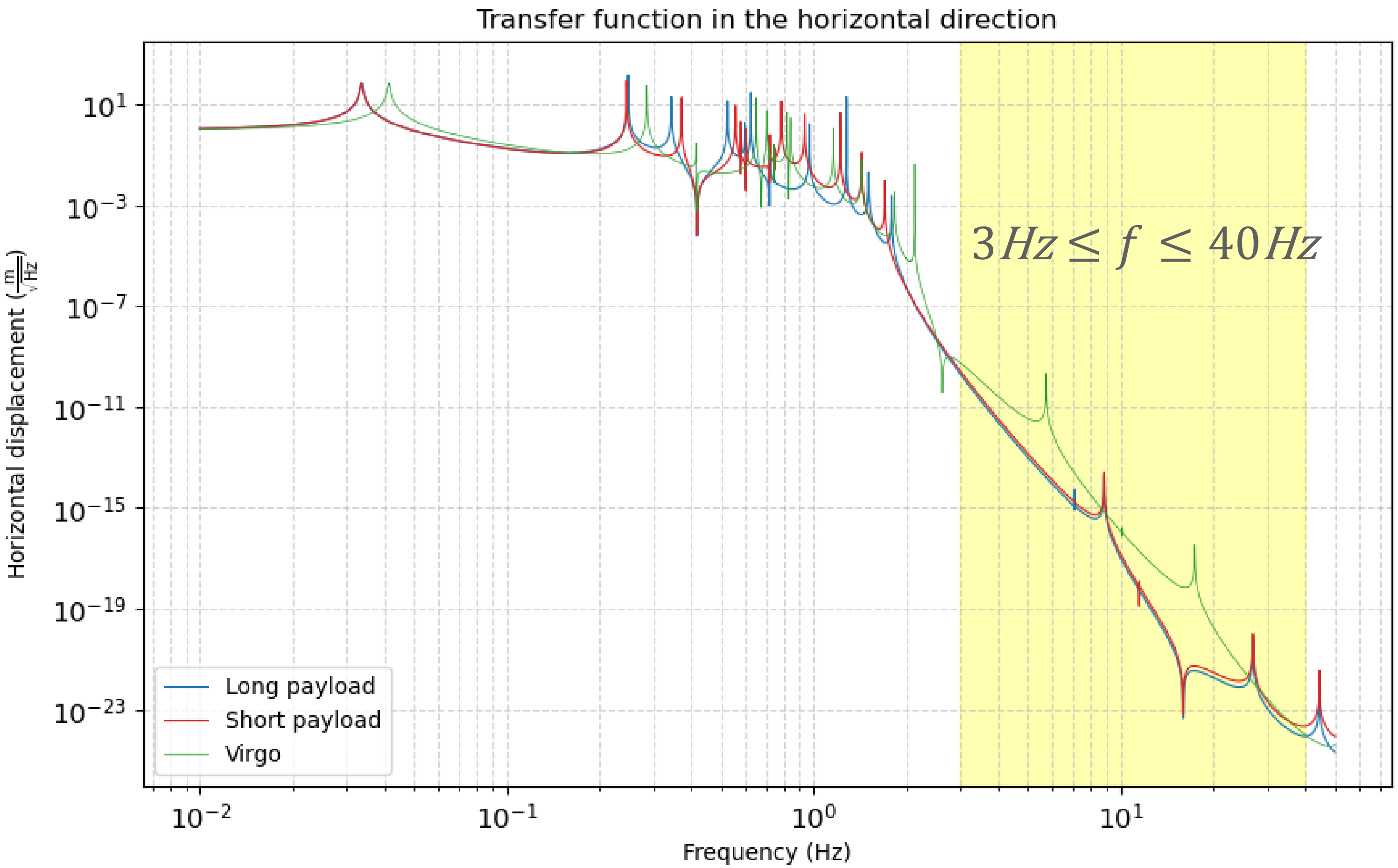
**Cons:** violin mode of the fibers at a lower frequency, i.e. $f_{FS} \approx \mathbf{147}$ Hz




For the following simulations Fused Silica fibers have been considered

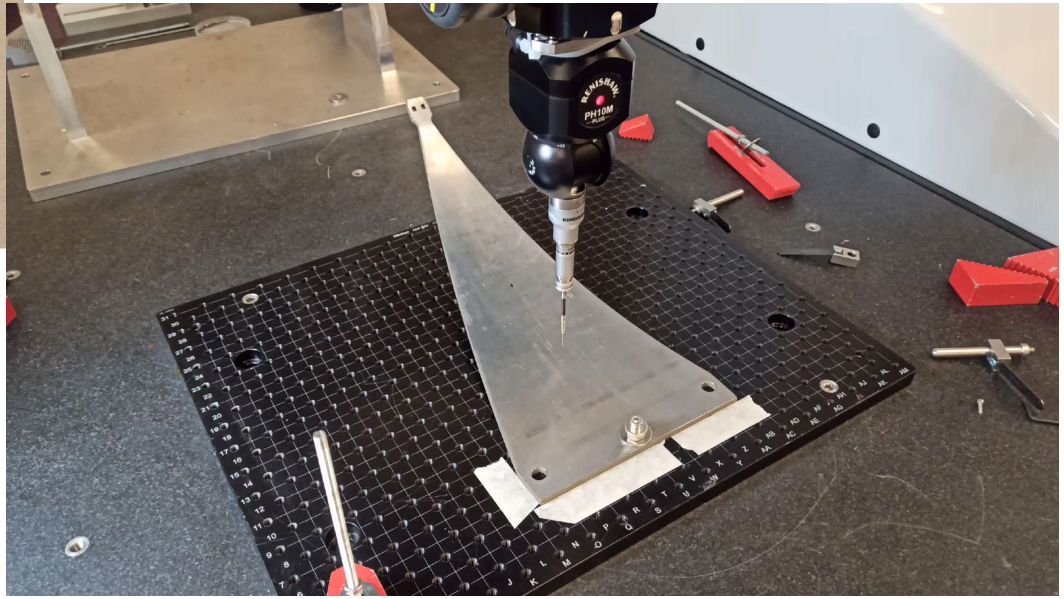
# Long Payload – same length for all stages



# New material for the blade

The material used in Virgo, maraging steel, is very expensive and currently difficult to procure due to ongoing global conditions.




Studies on titanium blades are in progress. Preliminary results from the rolling process show promising curvature radius measurements. Heat treatment and mechanical properties are still under investigation.

# A novel design for the magnetic antispring and crossbar

**Why New MAS Are Needed**

- Support **higher loads** required for ET
- Improve **vertical attenuation performance**
- Mitigate **spurious resonances in vertical** attenuation due to the crossbar

**How to improve them (NGSA Project):**

Replace the ferrite magnets (**0.35 T, 60x20x15 mm**) with rare earth, Ni-coated magnets (**SmCo** or NeFeB, **0.80 T, Ø10x5 mm**);

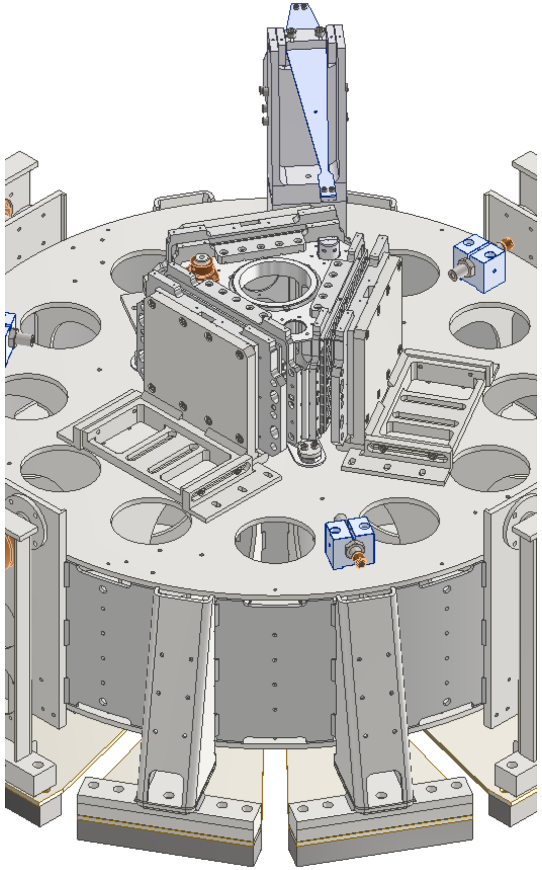
- This brings larger anti-stiffness (higher $F_0$) with a reduced volume, mass, and magnetic surface;

↓

- The reduced surface and mass permit **redesigning the crossbar** reducing its length and mass;

↓

- This brings several positive effects:
  - Stiffening of the crossbar and reducing its mass to **reduce the impact on the vertical transfer function**
  - More **symmetric distribution of the masses** of the filter, mitigating differences between the in-plane moments of inertia;

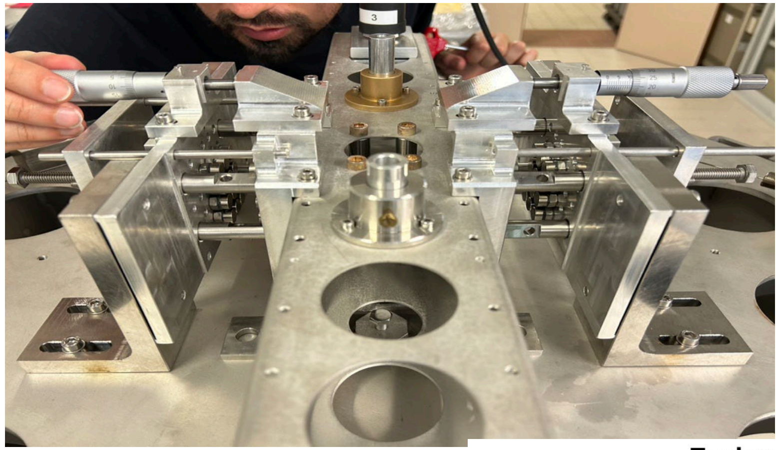


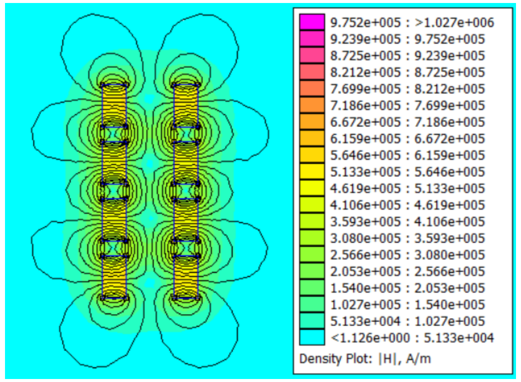
CAOS filter with innovative crossbar

# A novel design for the magnetic antispring and crossbar

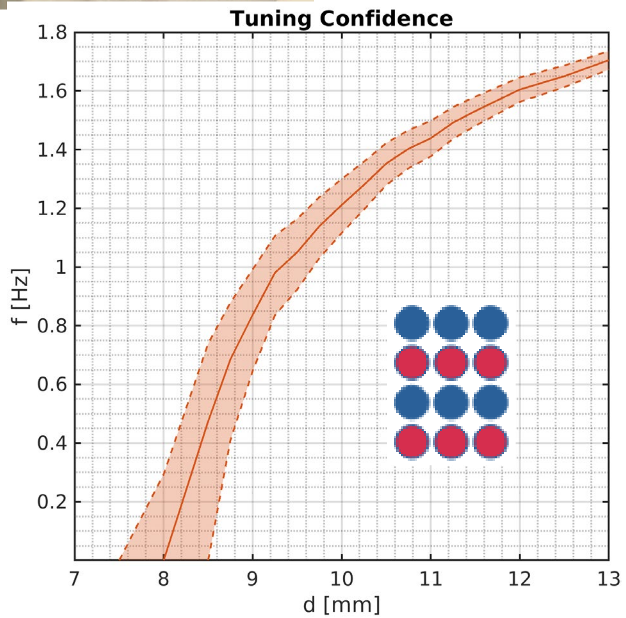
**Experimental setup**

- Within **NGSA and CAOS projects**, a mechanical filter (AdV stile) has been assembled @ **INFN Pisa Laboratory** and equipped with nMAS prototype;
- Actual eigenfrequency measured without nMAS **2,06 Hz** (vs usual 1,5Hz for AdV filters)
- Mass of the mobile parts + suspended mass of about 62,3 kg
- **From the simulations**, with this inputs a 4x3 nMAS configuration “+-+-” should permit to tune the filter with the orange curve.



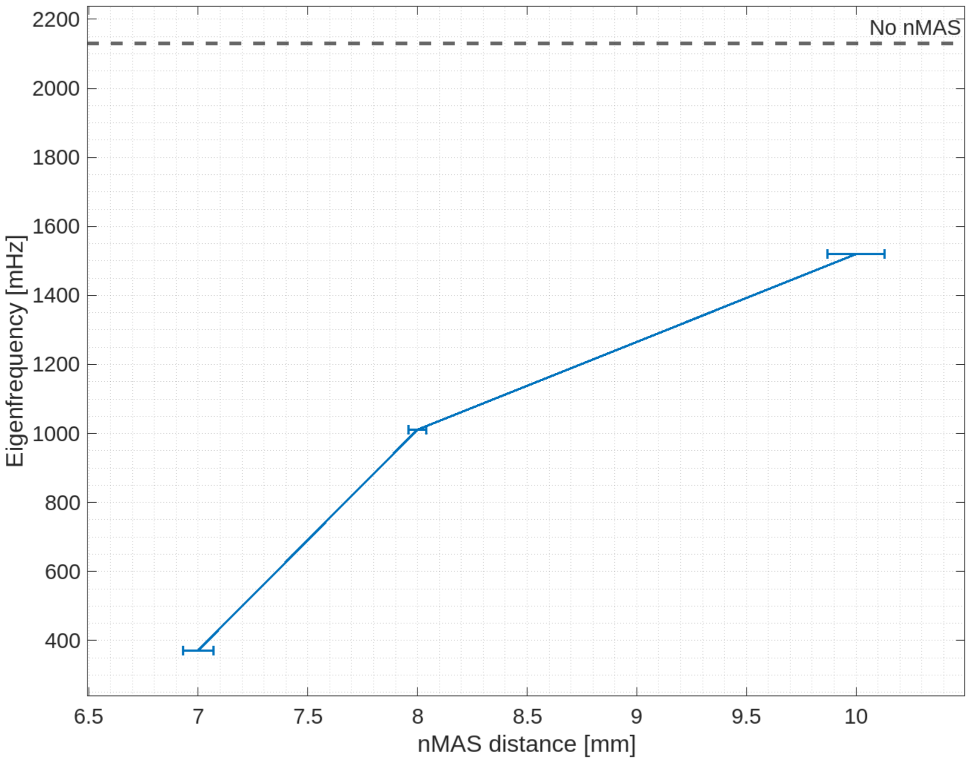


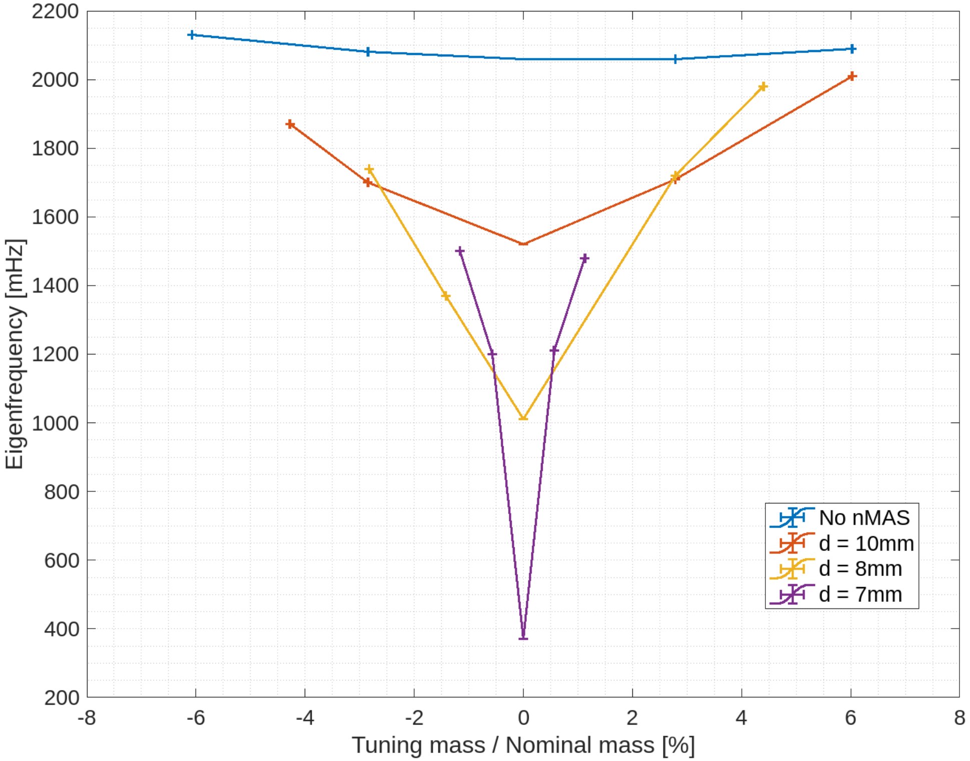

[https://www.femm.info/](https://www.femm.info/)



# A novel design for the magnetic antispring and crossbar

- Tested configurations at 10, 8, and 7 mm
- Tuning masses added/removed to vertically adjust the equilibrium position of the filter
- Despite simulations underestimating the anti-stiffness, values down to 370 mHz @ 7 mm were achieved
- Results show excellent repeatability



# Conclusions

- The International laboratory CAOS will collect the **expertise of the Italian and international gravitational wave community**. It will be a testing facility suited to worldwide collaborations, like a sort of **gym for GW technologies**.

- Within this framework the CAOS facility represents a unique **full-scale testbed for the development of next-generation superattenuators for ET**. Both the BS and EE systems have been redesigned, providing a flexible platform for benchmarking and technological R&D.

- Comprehensive design simulations and experimental tests have been carried out to assess the **main innovative features** of the CAOS superattenuators respect to AdV superattenuators design.

- In the near future, **more complex assemblies**—such as the filter equipped with crossbar and body—will be tested on a dedicated bench at the INFN Pisa laboratory, paving the way for the **integration of the full system inside the CAOS towers**.