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Conceptual Study of a 6-D Active Preisolator

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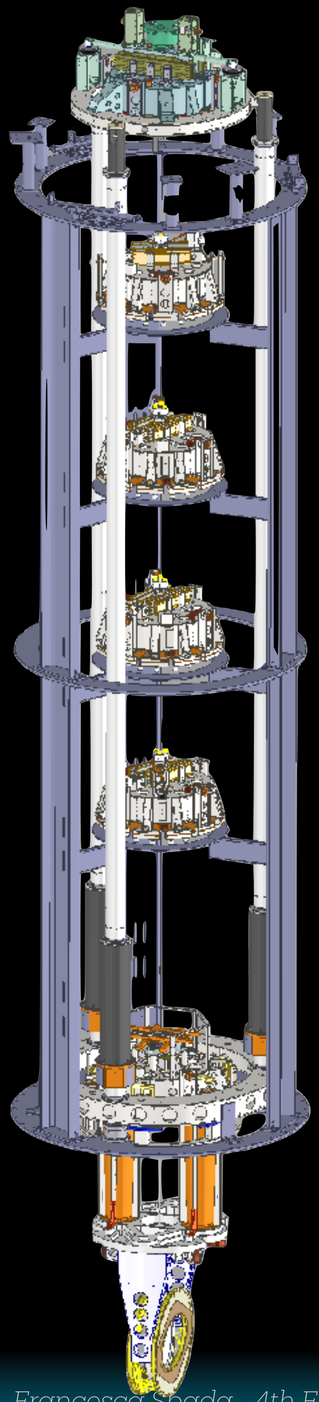


Background

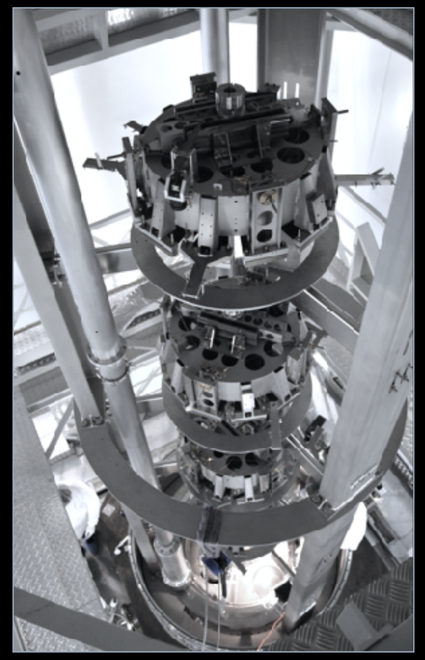
The ET 2011 CDR and 2020 Update consider a **17 m-tall** seismic isolator based on the **AdV+ Superattenuator** as the *baseline solution* for the ET-LF test masses.

- **attenuation of seismic noise** is achieved through a **chain of passive mechanical filters**

Signature technologies employed:

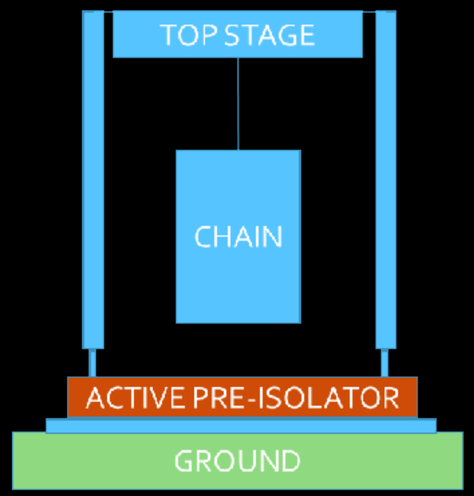
- **Inverted pendulum**
  - first isolation stage
  - very low-frequency attenuation of horizontal translation
  - precise positioning with minimal control forces
- **Filters** with **triangular cantilever spring blades**
  - effective seismic vertical attenuation
  - low tilt frequency
- **Magnetic anti-springs**
  - reduce vertical stiffness
  - easy integration and tuning
  - vacuum compatibility
  - contactless action on the filter

- **Active controls** used to **keep the SA at its working** point and to **damp normal modes**



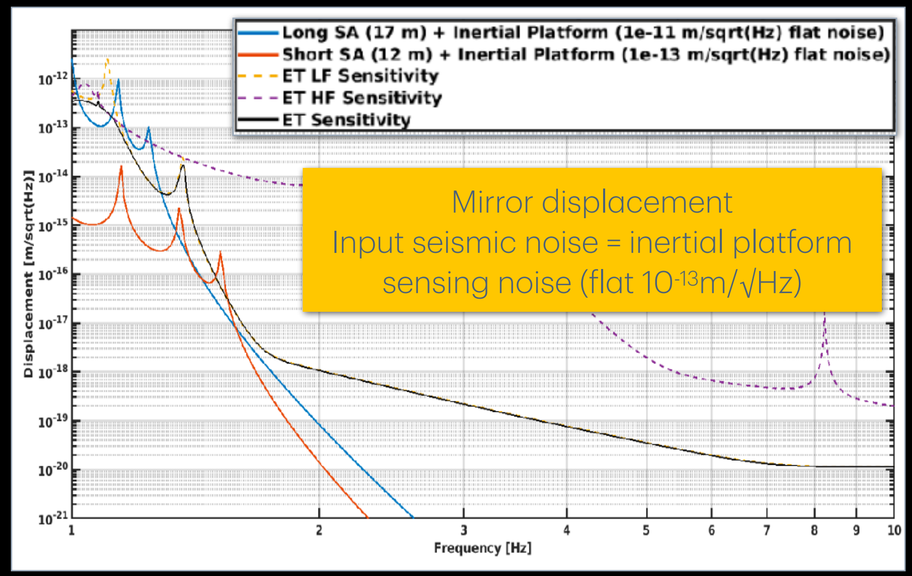
Exploring the advantages of active pre-isolation

For next-generation gravitational wave detectors, **extending the detection band down to 2 Hz**, improvements are necessary to meet more demanding requirements



Seismic platforms

- employed as the **first stage of isolation** help reducing seismic noise *before* entering the passive chain
- provide active control
- can improve the compactness



*[*Design Report Update 2020 for the Einstein Telescope, Sep. 2020]*

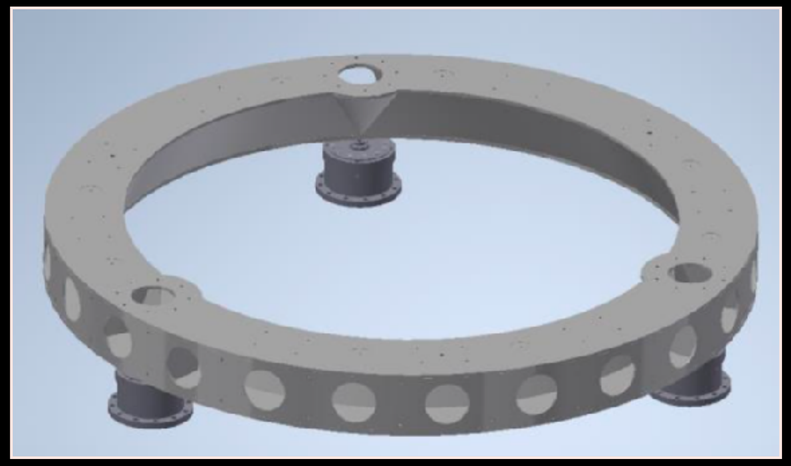
The SA IP can be used as a structural element between a platform and suspension point allowing support of heavy payloads and precise positioning with minimal control forces

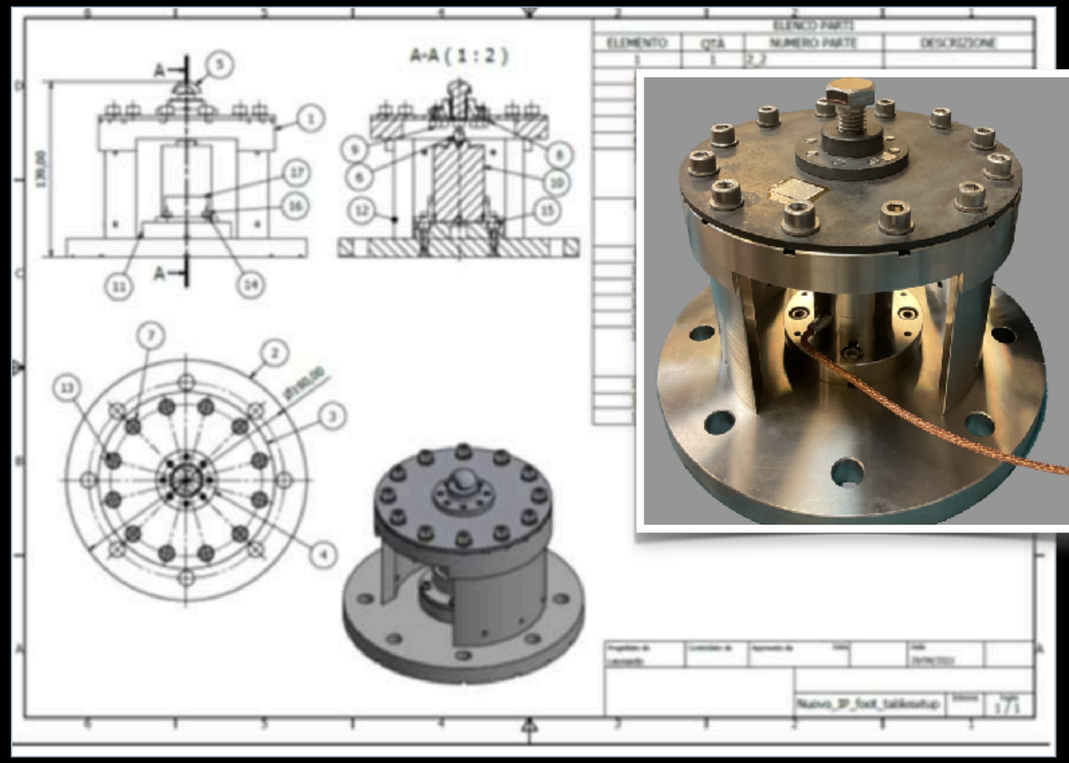
R&D focus is at upgrading the Superattenuator base-ring into an active isolation platform

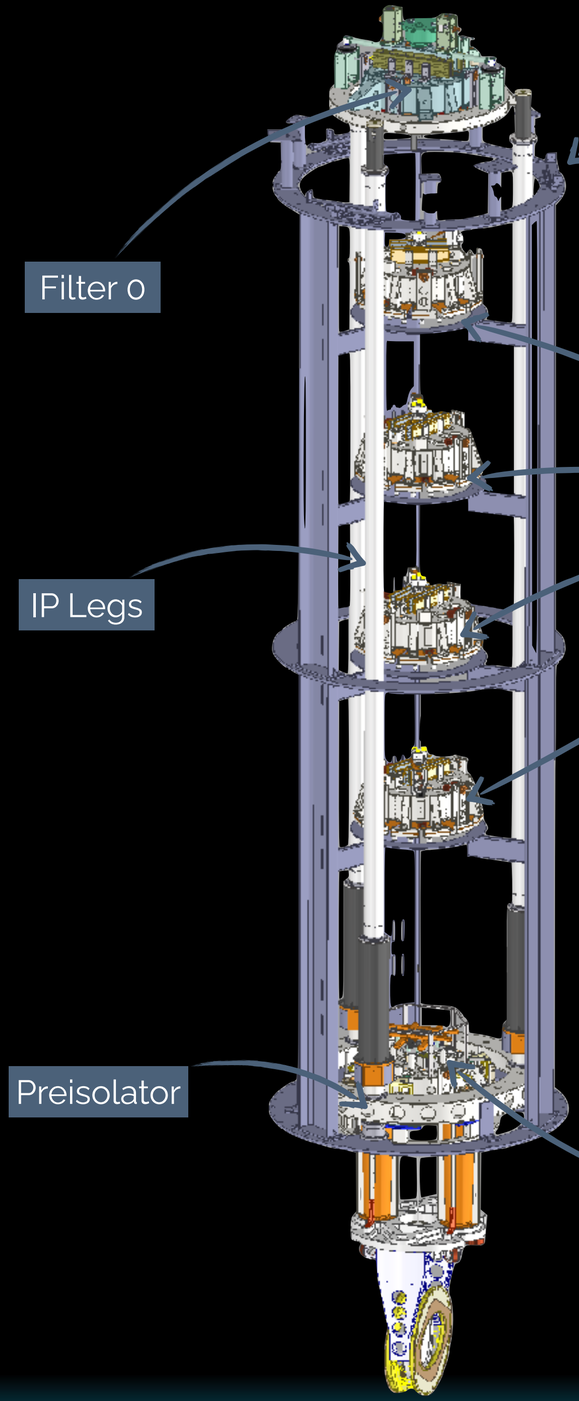
Exploring the advantages of active pre-isolation

A natural starting point:

The Superattenuator **base-ring** was originally equipped with **piezoelectric actuators** mounted in a **stainless steel foot** with a 3 mm **maraging steel membrane**







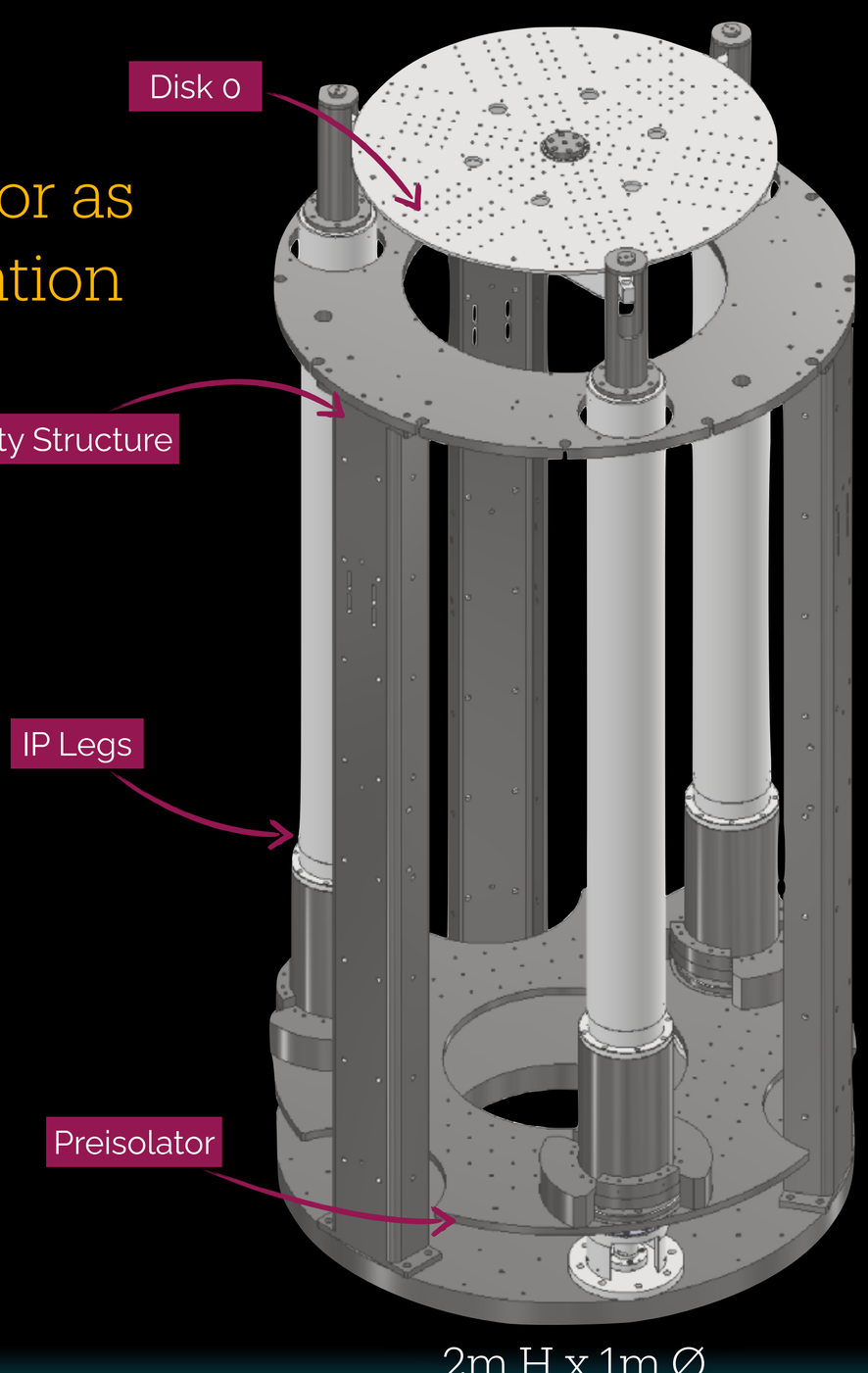
A home-sized Superattenuator as testbench for active pre-isolation

Short term:

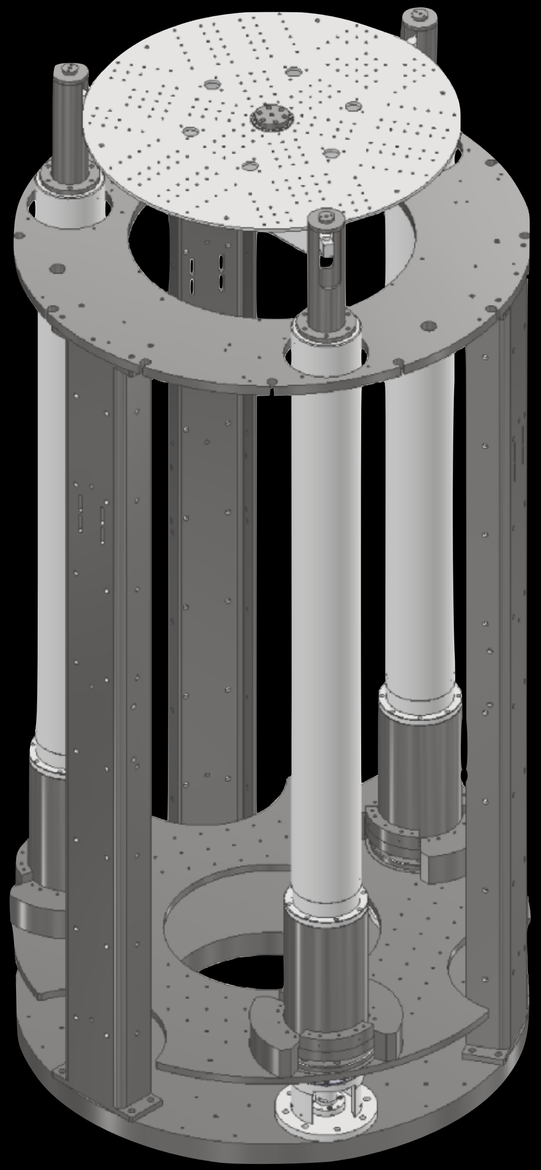
- Characterize active pre-isolator along **vertical degrees of freedom (ϑ_x, ϑ_y, z)**
- Measure **transfer functions**
- **Full testbench simulation**

Medium term:

- Upgrade to a **6DOF** pre-isolator
- Operate in vacuum



2m H x 1m Ø

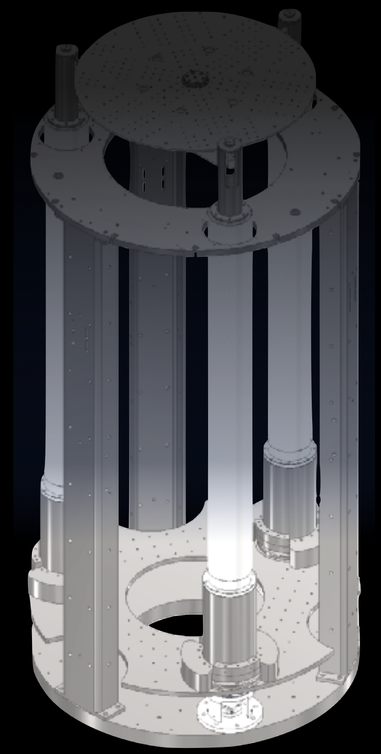


3DOF integration

The experimental setup integration was completed in April 2025 *(*)*

- **Base-ring** equipped with **three AdV+-like feet**
  - Piezoelectric custom **actuators**
  - **LVDT** sensors with sub-μm sensitivity
  - **Lobed flange** 1 m ⌀
- Three-legged **Inverted Pendulum**
  - Leg length 1.37 m
  - Leg diameter 0.13 m
- **Top stage** (Disk 0)
  - equipped with **triaxial accelerometer**

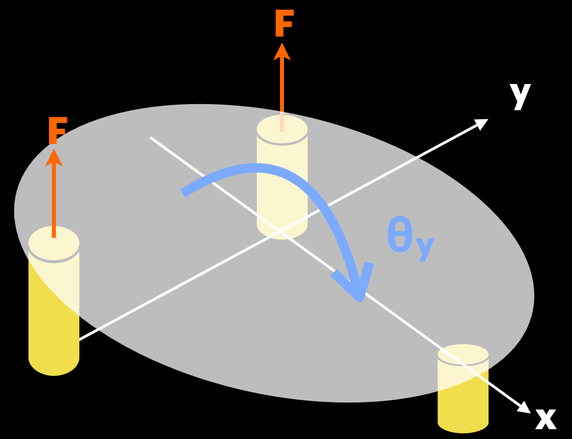
(*) F.Spada, G.Balestri, A.Buggiani,F.Frasconi, A.Gennai, L.Lucchesi, L.Orsini, F.Pilo, P.Prosperi, P.Ruggi https://apps.et-gw.eu/tds/?call_file=ET-0270A-25_UpgradingTheSuperattenuatorTow.pdf

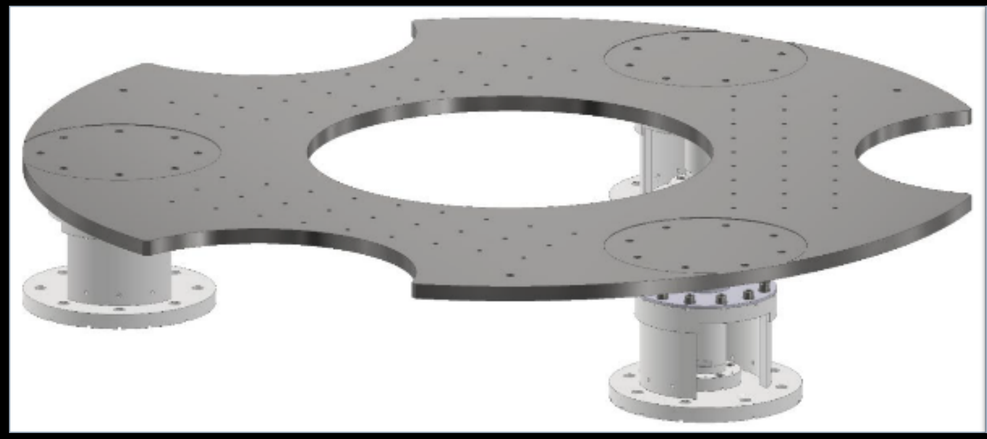


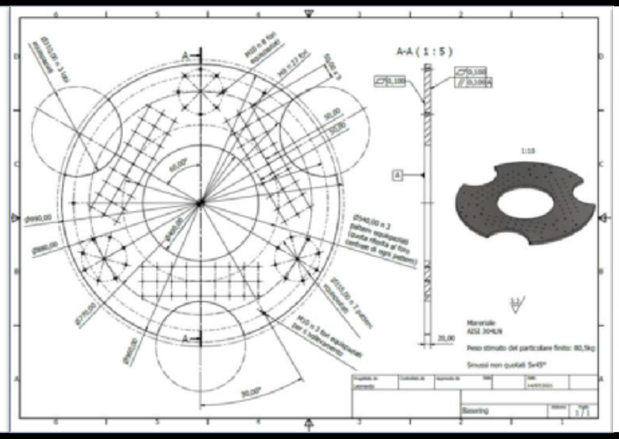
Base Ring

- AdV+ **piezoelectric actuator**
  - Customized P-216K033 PICA preloaded piezo actuator

  The 120° circular arrangement of the actuators allows control of vertical and angular excitations
- AdV+ **foot** geometry
  - AISI 304 stainless steel structure with 3 mm thick 250-grade maraging steel membrane
- **LVDT displacement sensors** with sub-μm sensitivity
- Extensive actuator/foot characterization carried out in 2024/2025 (*)

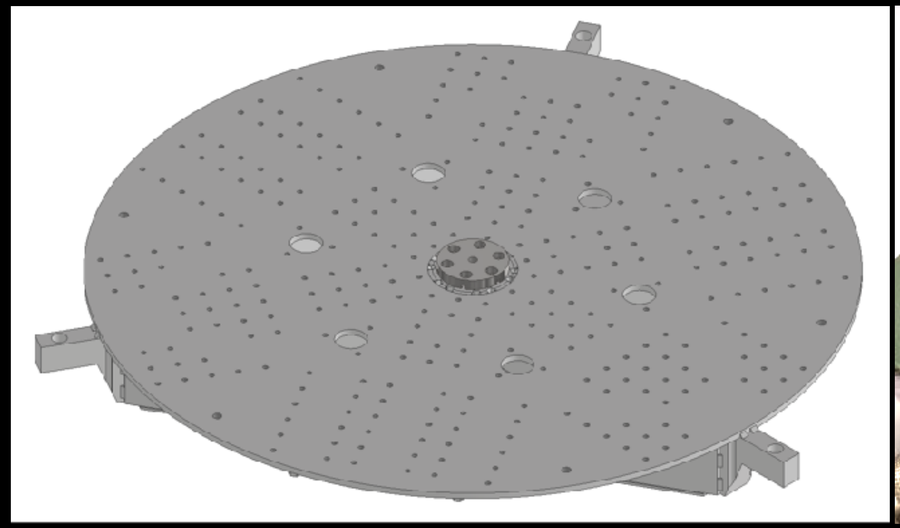


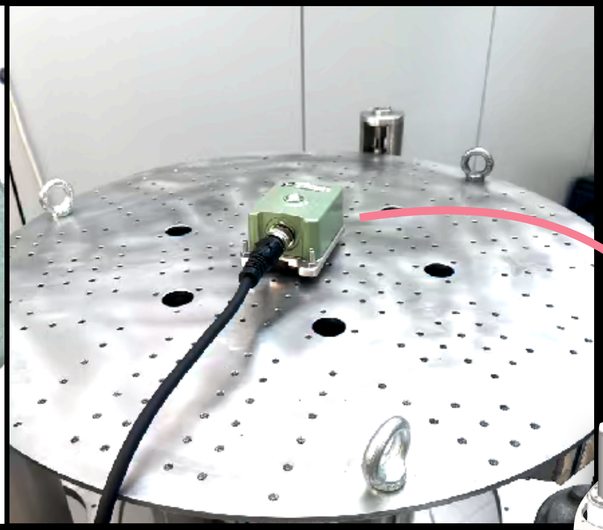


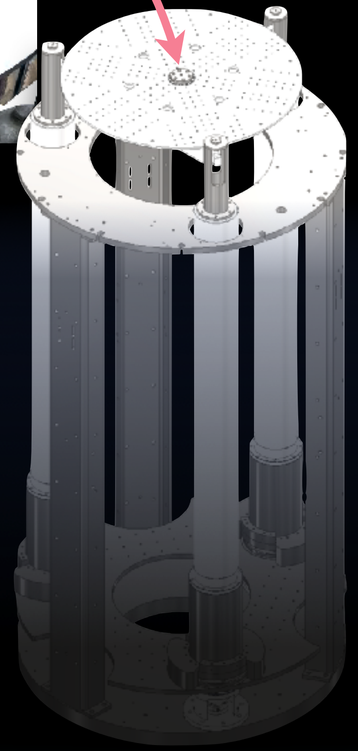


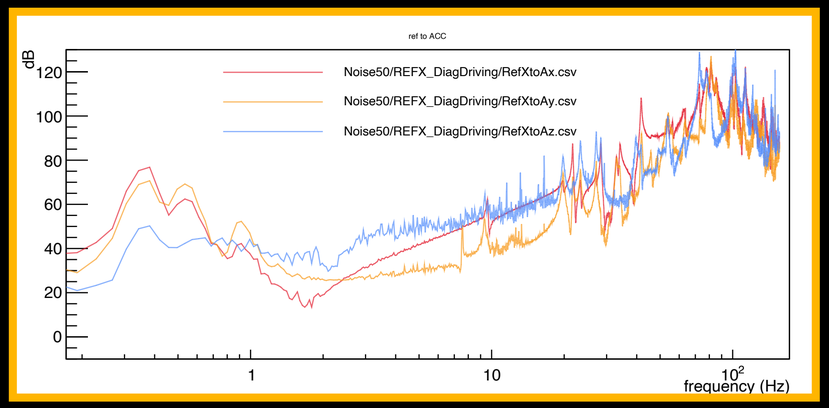
(*) F.Spada, G.Balestri,F.Frasconi, A.Gennai, L.Lucchesi, L.Orsini, F.Pilo, P.Prosperi, P.Ruggi https://apps.et-gw.eu/tds/?call_file=ET-0621A-24_EnhancingSeismicIsolationForNe.pdf

Top Stage





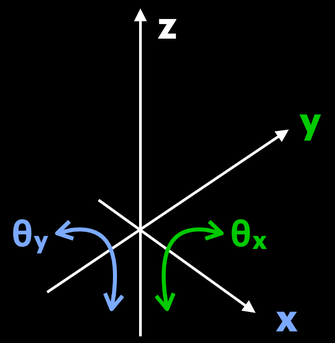


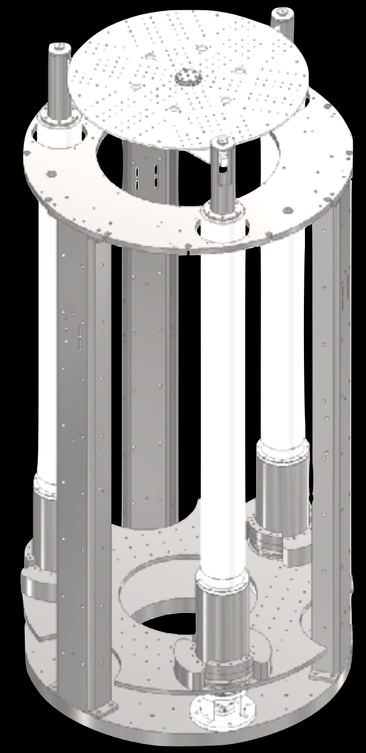


- **Total weight 49 kg**
- equipped with a Nanometrics Titian force balance **triaxial accelerometer**
  - **measure transfer functions** from Base Ring to Top Stage
- *No payload suspended*

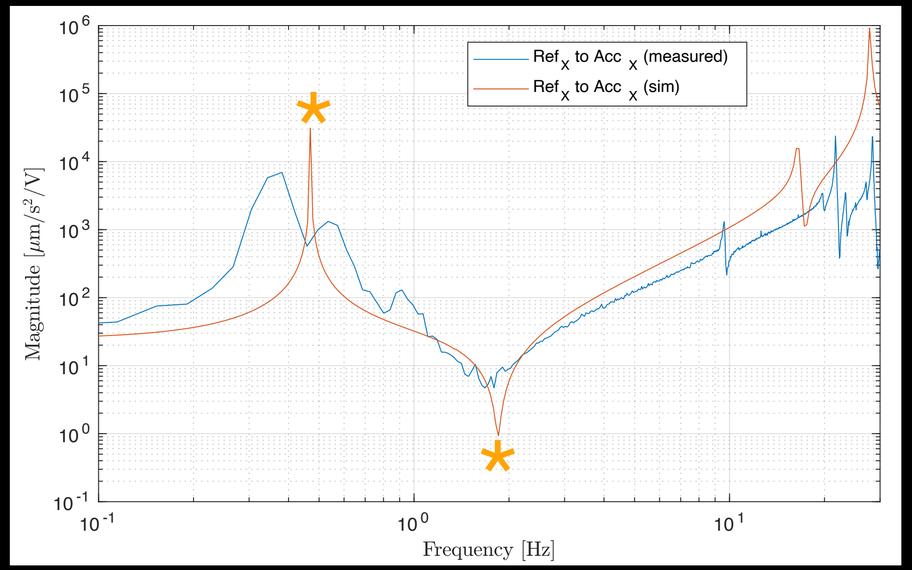
Simulation

- **Octopus-based(*) full test bench simulation**

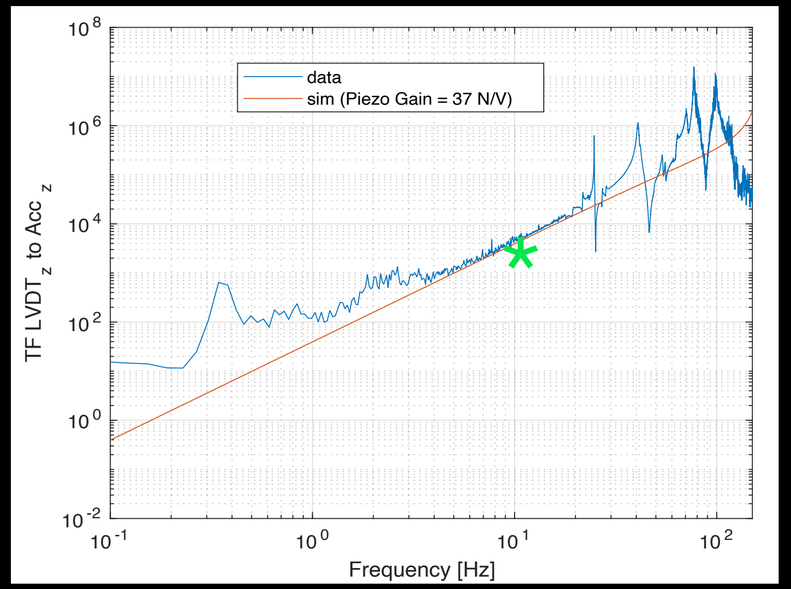




- **Input:** construction parameters (masses, barycenter positions, inertia, ...)



- **Tuning:** actuator gain, sensor calibration, stiffness of mechanical components, ...

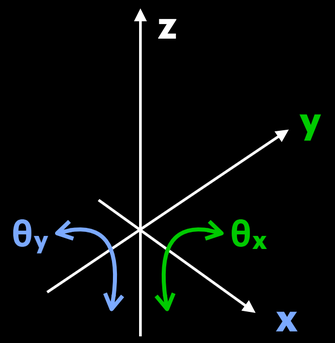


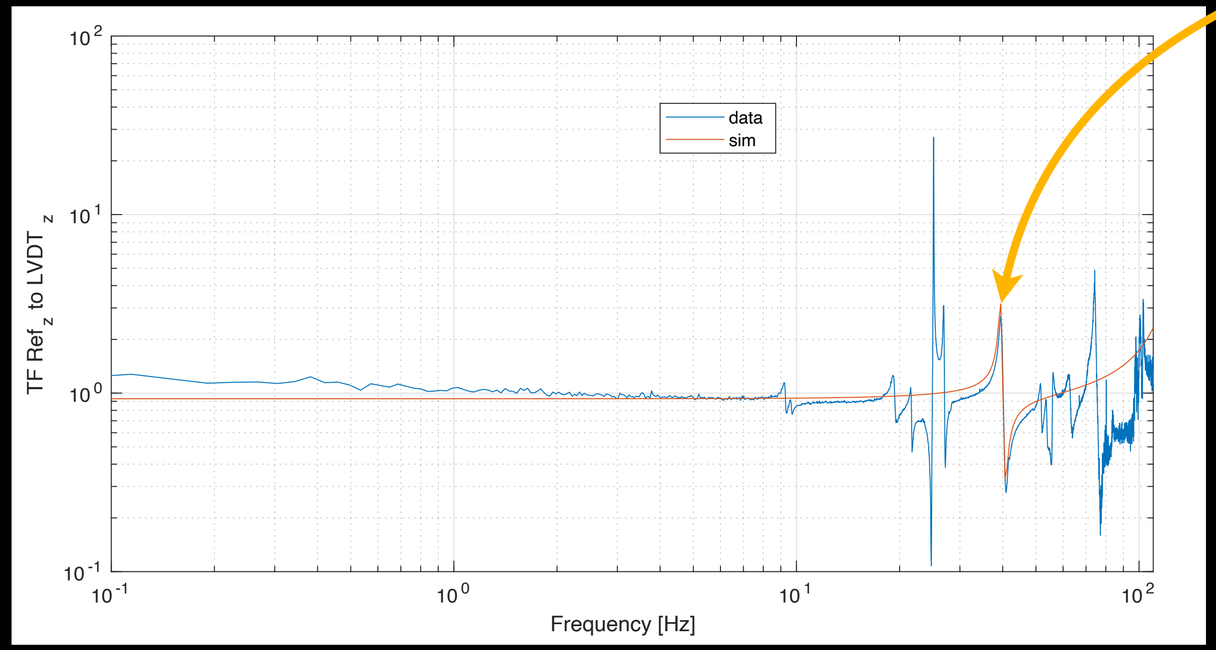
*P.Ruggi, M.Pinto, L.Trozzo, G.Cella, E.Majorana, G.Losurdo, P.Chessa, A.Longo, A.Viceré, https://doi.org/10.1103/PhysRevD.112.022002

Simulation

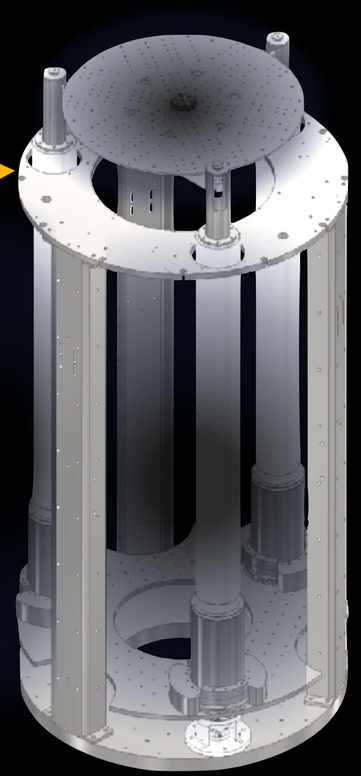
Features not reproduced in the simulation

- resonances, higher frequency pole–zero pairs
- originate from **non-modelled components**, **couplings** between degrees of freedom, system **anisotropies**

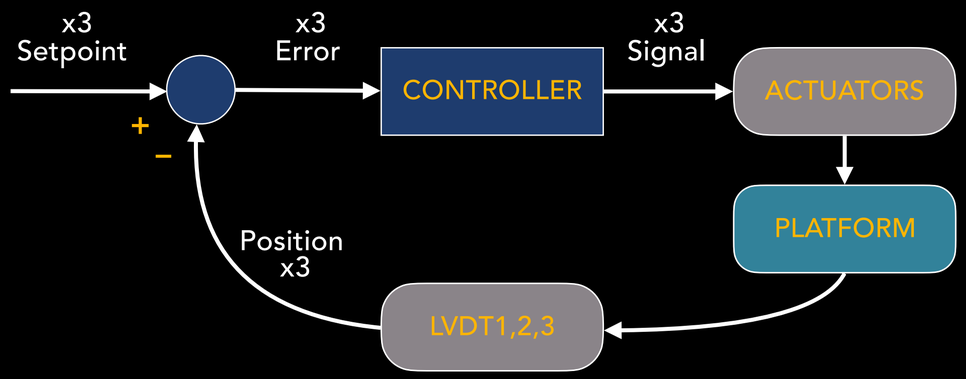


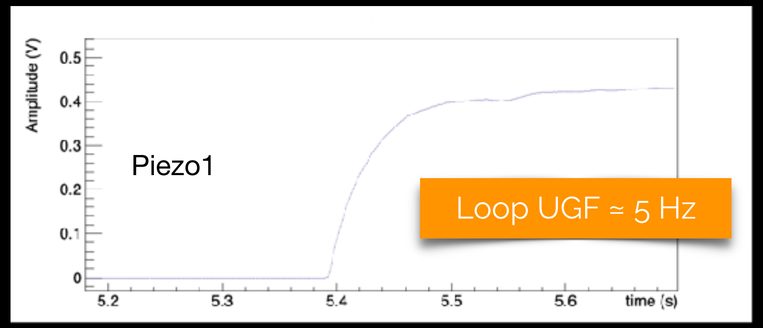


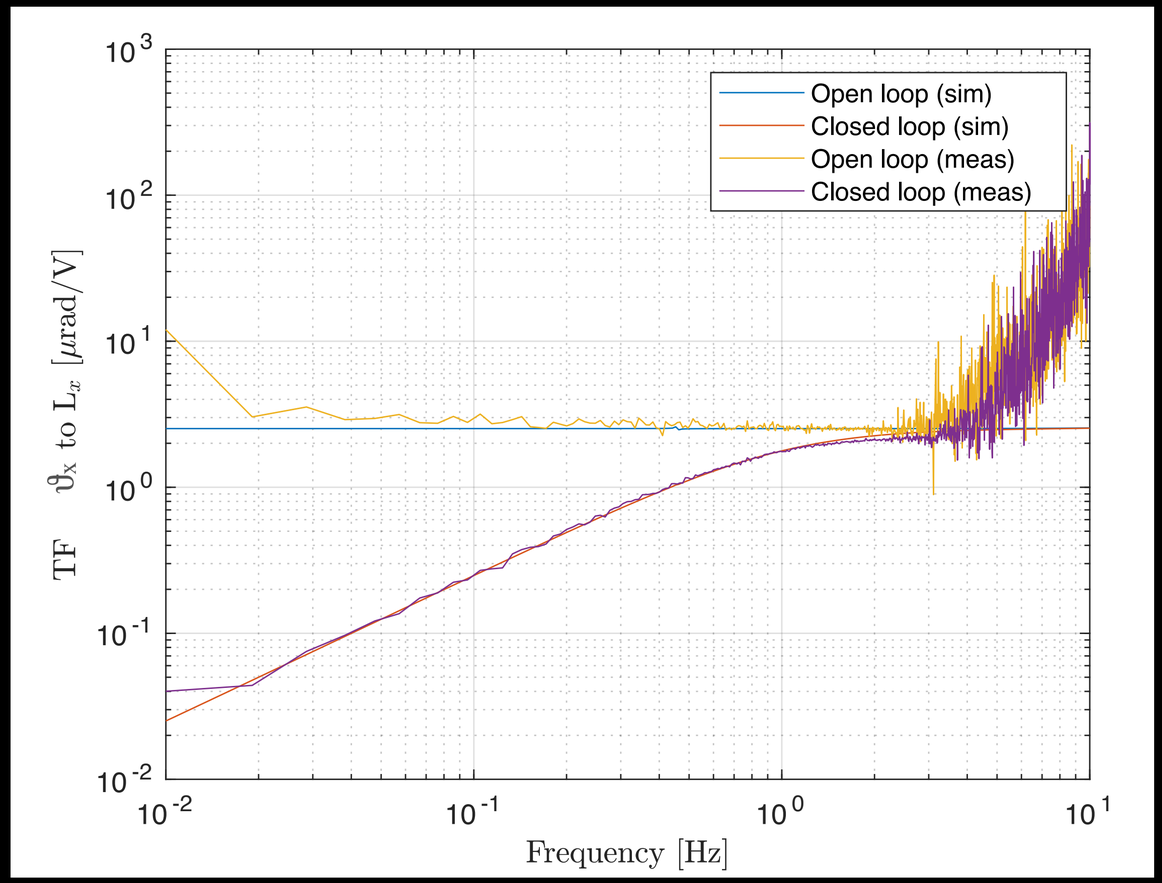
e.g. due to safety structure being elastically coupled to the ground



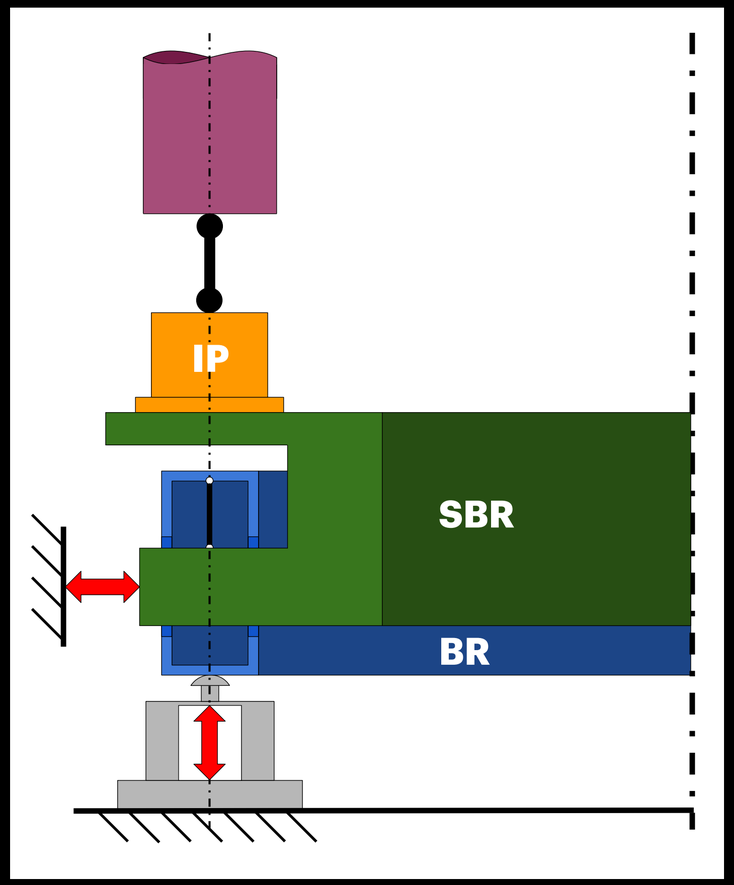
Controls included in simulation



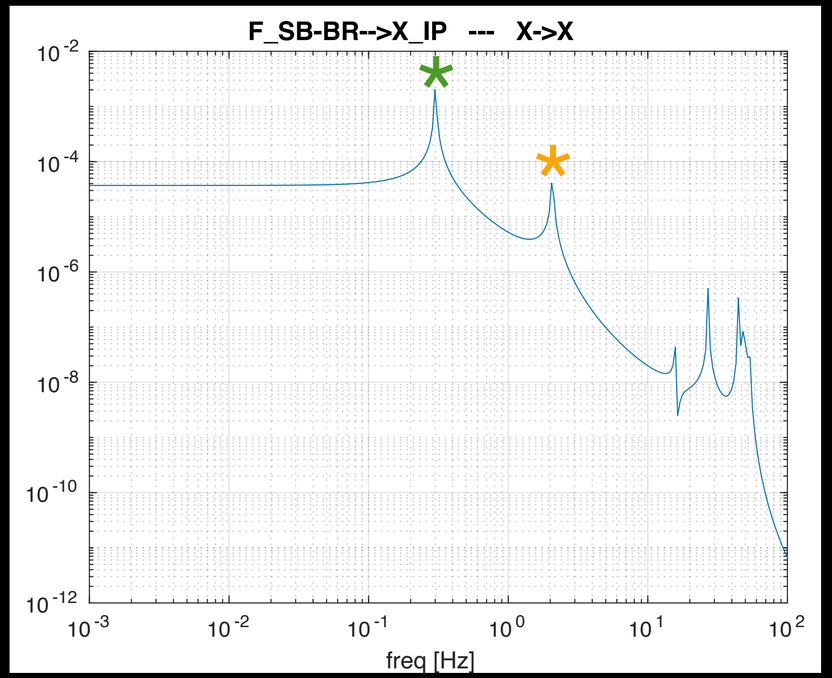




Conceptual design for 6DOF



- **Upgrade to 6DOF —> additional horizontal suspended actuation stage**
- **Base ring (BR)**: open circular frame designed to host an additional suspended stage inside
  - provides the interface for **vertical actuation** as in the current configuration
- **Horizontal actuation stage (SBR)**: suspended by wires within the inner opening of the BR
  - also supports the **Inverted Pendulum (IP) legs**.



Conclusions

- A **compact 3DoF active pre-isolator test bench** has been integrated and characterized
  → reproduces the **key dynamical features** of a full-scale suspension in a controlled, measurable setup
- Measurements and **Octopus-based simulations** show good agreement
  → remaining discrepancies linked to unmodelled couplings and structural anisotropies
- **Control loops implemented and simulated**
  → **an essential step toward realistic modelling of an active isolation platform**
- The test bench is a fundamental tool
  → **validation of mechanical models**, **sensor/actuator choices**, and **control strategies** before designing the full ET isolator
- **Next step: from conceptual to constructive 6DoF design**
  → geometry, actuation scheme, and control parameters to be defined through simulation-guided optimization
- **Control simulation is crucial**
  → for an active platform, loop dynamics and stability margins are as important as mechanical performance