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Novel prototype filter for the ET Superattenuator

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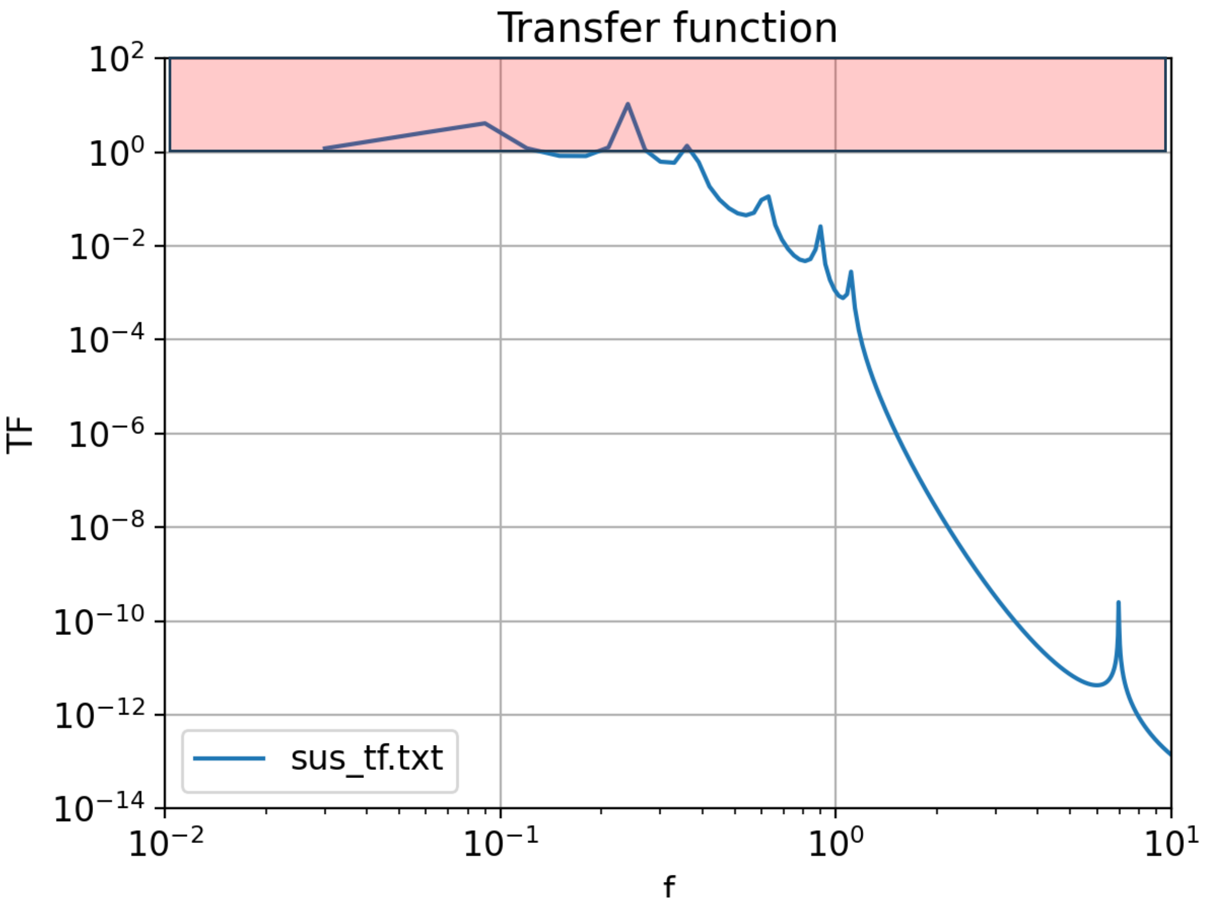
General principles adopted in Virgo

- **Ground motion 10^{-7} m $Hz^{-1/2}$ at 1 Hz vs 10^{-18} m $Hz^{-1/2}$ at 10 Hz**
- **Test mass asks for a very loose link**
  - Low pass filter with a steep frequency cut below the detection band
  - Cascade of harmonic oscillators (Second Order Sections)
  - Loose springs and high masses
- **Dissipation to be avoided, not compatible with loose link**
- **Loose link through local active control limited by sensor noise**
- **Passive isolation for a large fraction of the chain**
- **But amplification at normal modes**



ET-LF requirements

LF noise is given by

- Microseism motion
- Newtonian noise
- Upconversion of residual motion into the detection band
- Control noise

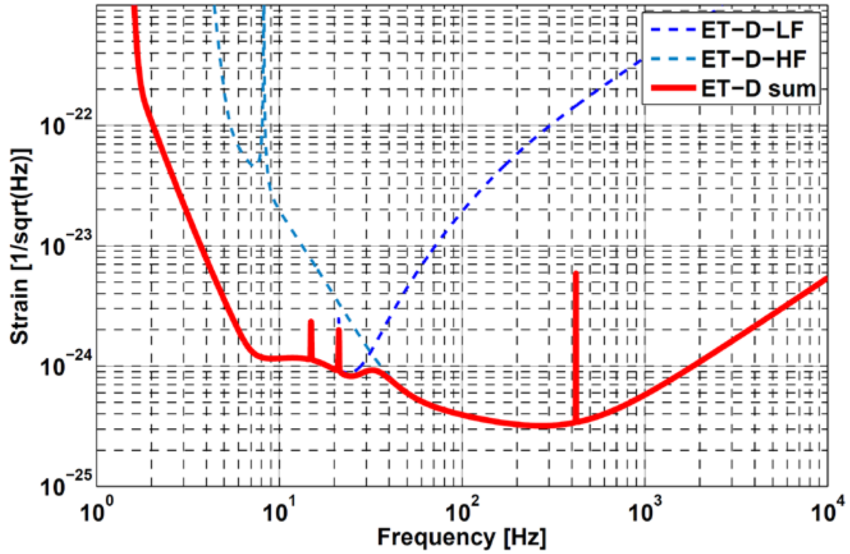
Design curve based on 17 m tall suspensions

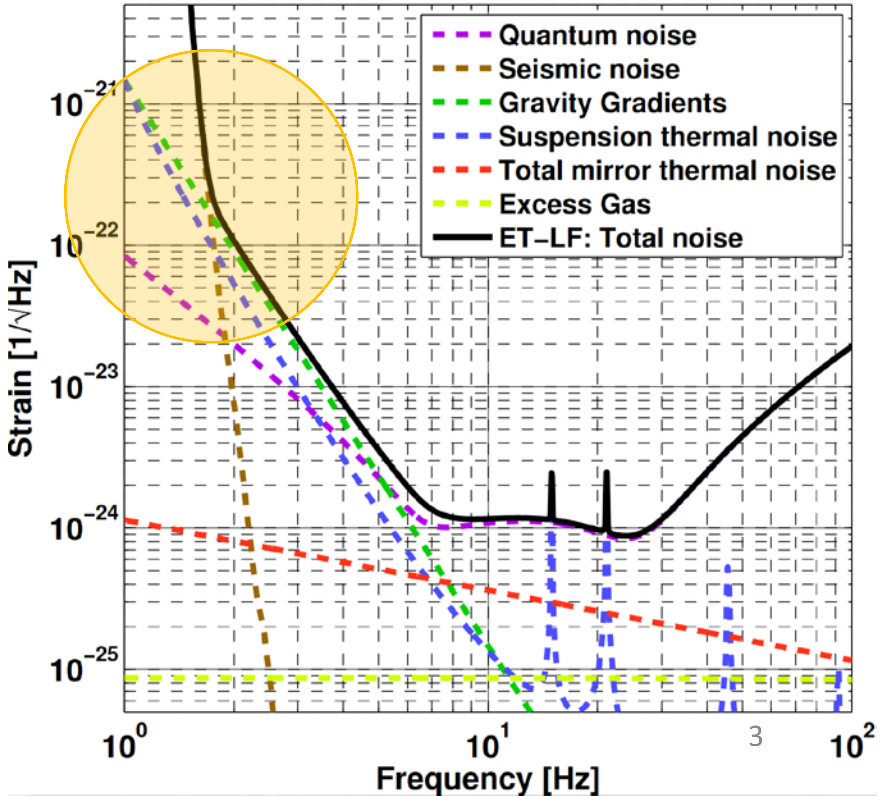
Reduction to less than 10 m:

- Significantly lower cavern excavation cost
- Suspension management similar to Virgo

Newtonian noise crossing:

$2\ 10^{-22}\ \mathrm{Hz}^{-1/2}$ at 1.8 Hz (AdV: 3.2 Hz)

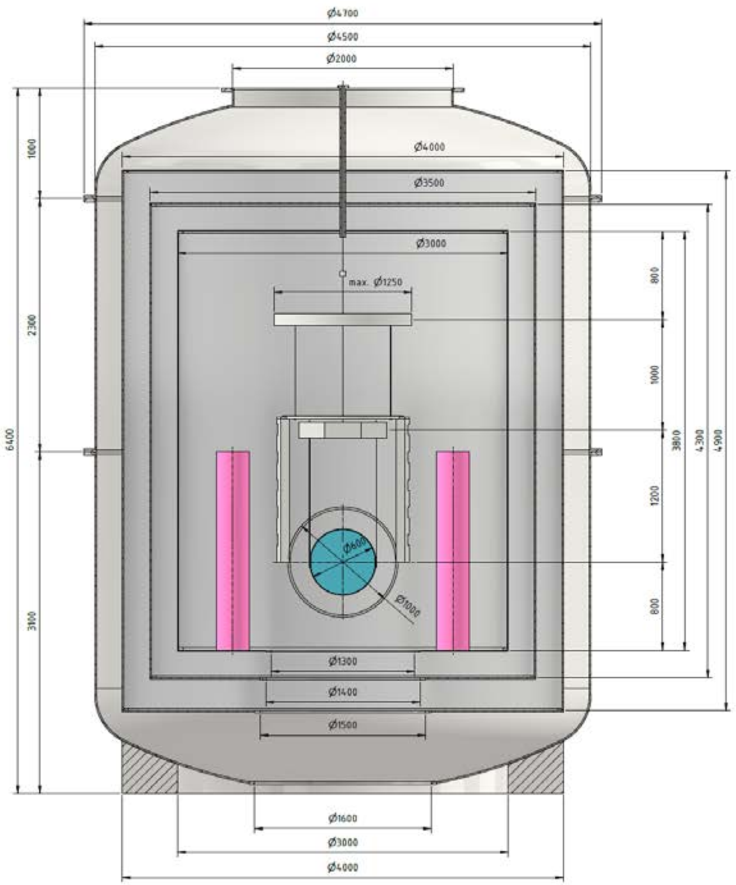


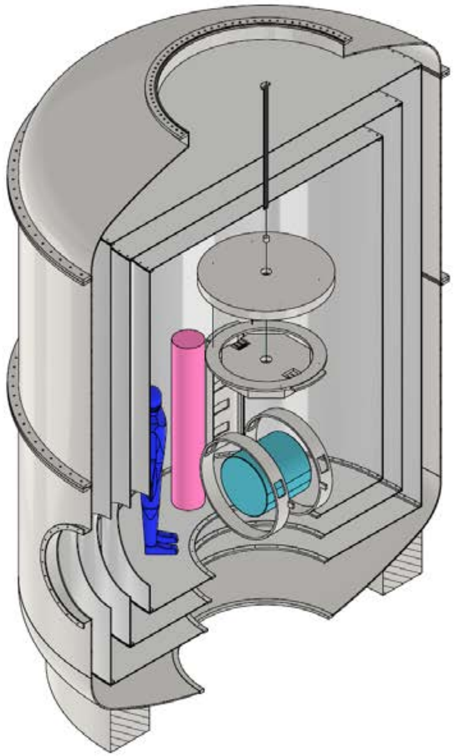


ET EINSTEIN TELESCOPE

Challenge: Fit suspension in 10 m

1. **Act on ground / suspension interface actively**
2. **Act on suspension point actively/passively**
3. **Superattenuator chain design**
4. **Payload design compatibility: large occupancy announced ϕ 4700 h 6400**

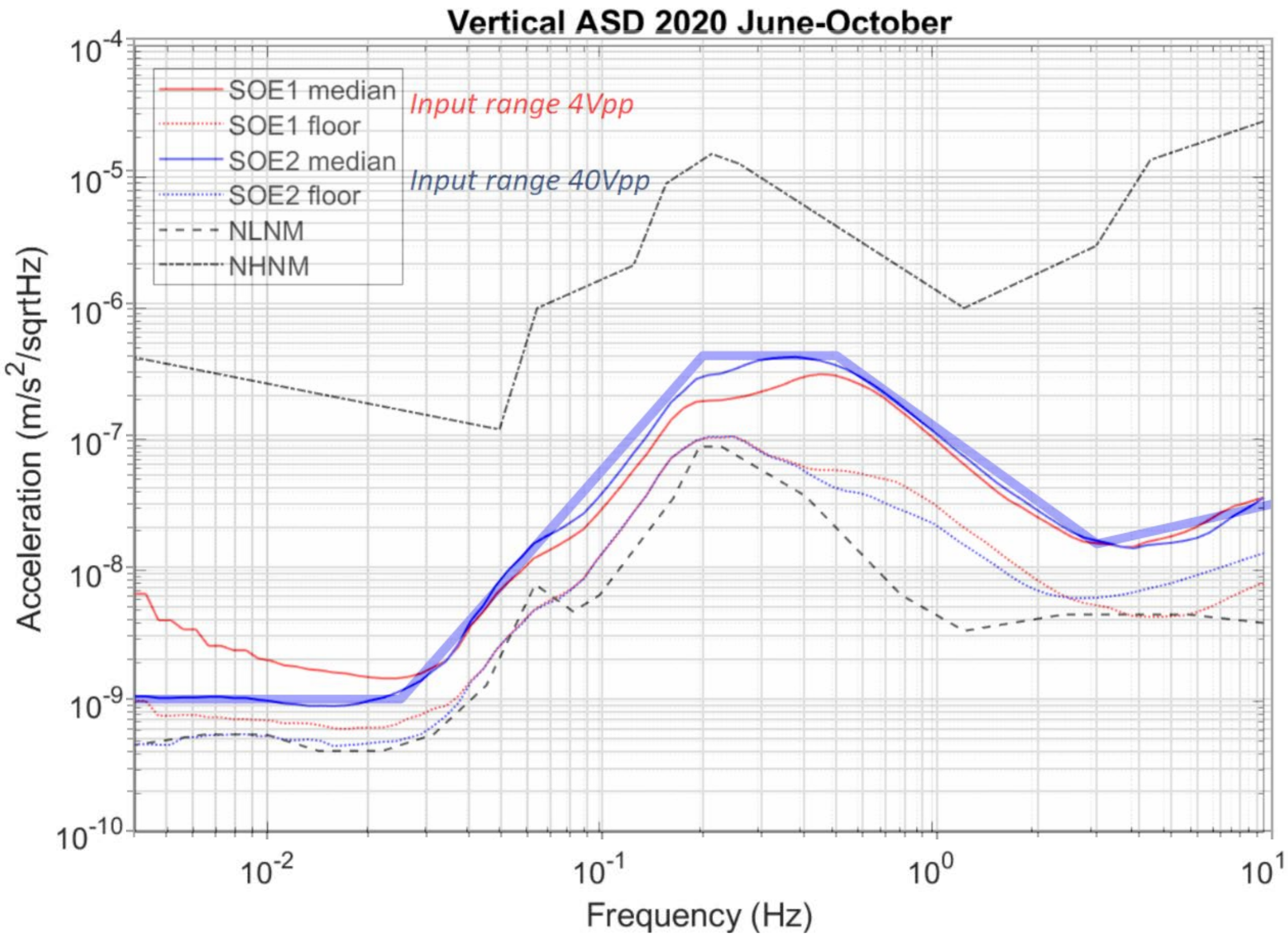




ET Seismic levels

Sardinia vertical

$3\ 10^{-8}\ ms^{-2}\ Hz^{-1/2}$ at 2 Hz



Seismic landscape

Vertical displacement spectrum

Virgo: 5 10^{-10} m $Hz^{-1/2}$ at 10 Hz
SOE: 3 10^{-10} m $Hz^{-1/2}$ at 2 Hz

RMS displacement over 100 s

Virgo: 10^{-6} m comparable to λ
SOE: 10^{-7} m well below λ

Strain

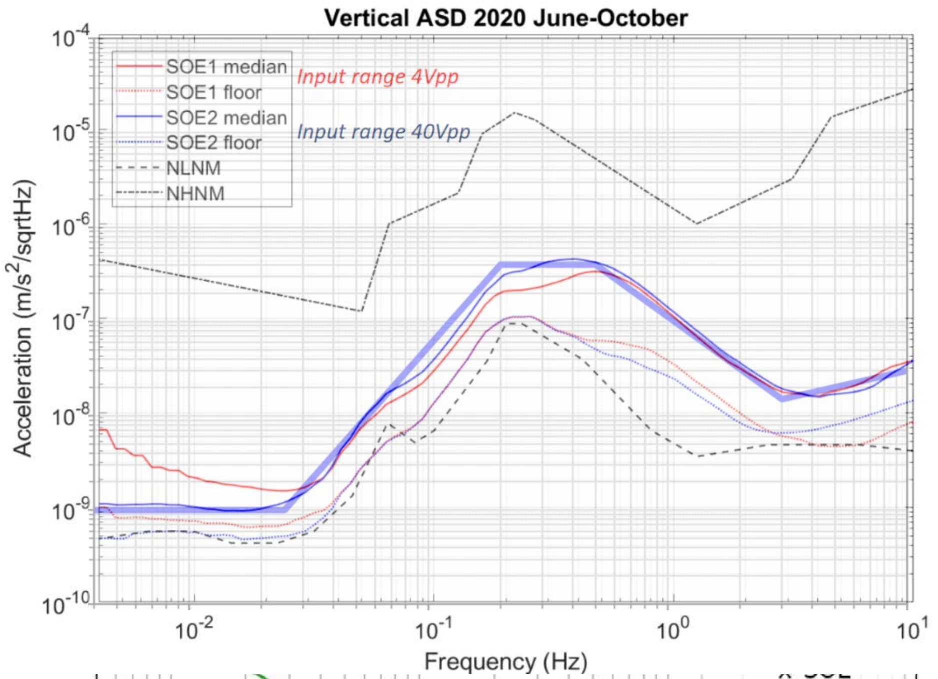
Virgo: 2 10^{-22} $Hz^{-1/2}$ at 10 Hz
ET: 2 10^{-22} $Hz^{-1/2}$ at 2 Hz

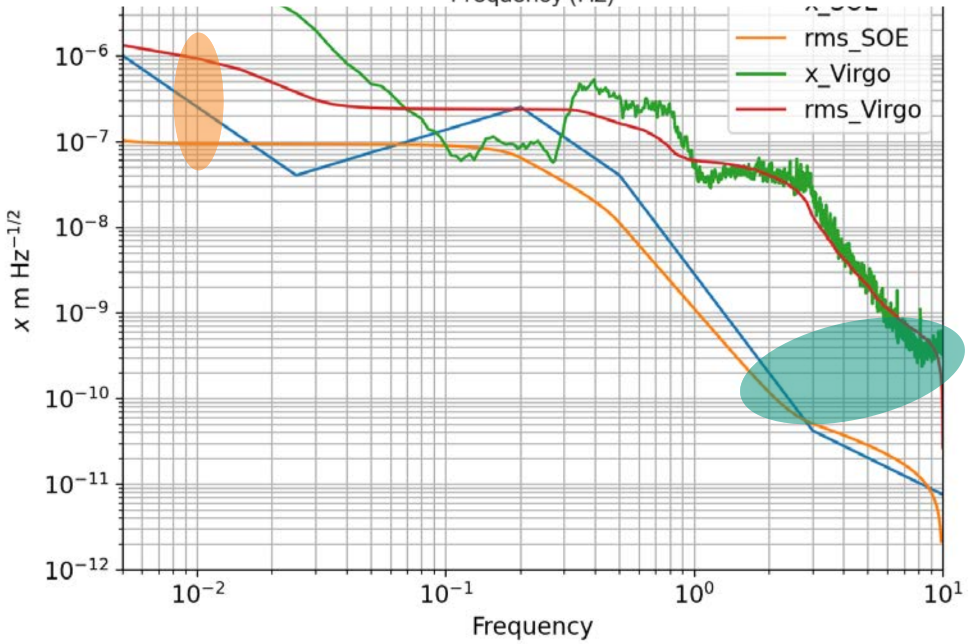
Four uncorrelated mirrors

Virgo: 1.5 10^{-18} m $Hz^{-1/2}$ at 10 Hz
ET: 10^{-18} m $Hz^{-1/2}$ at 2 Hz

With factor 10 safety factor

Virgo: 1.5 10^{-19} m $Hz^{-1/2}$ at 10 Hz
ET: 10^{-19} m $Hz^{-1/2}$ at 2 Hz





Attenuation required

Einstein Telescope

Vertical displacement spectrum

SOE: $3\ 10^{-10}$ m $Hz^{-1/2}$ at 2 Hz

30 mHz Inverted pendulum

Attenuation at 2 Hz: $2.3\ 10^{-4}$

Motion at 2 Hz: $7\ 10^{-14}$ m $Hz^{-1/2}$

Noise floor for local sensing

With factor 10 safety factor

ET: 10^{-19} m $Hz^{-1/2}$ at 2 Hz

Full seismic attenuation required

ET: $1.5\ 10^{-6}$ at 2 Hz

Virgo

Vertical displacement spectrum

Virgo: $5\ 10^{-10}$ m $Hz^{-1/2}$ at 10 Hz

30 mHz Inverted pendulum

Attenuation at 10 Hz: $9\ 10^{-6}$

Motion at 10 Hz: $5\ 10^{-15}$ m $Hz^{-1/2}$

Beyond noise floor for local sensing

With factor 10 safety factor

Virgo: $1.5\ 10^{-19}$ m $Hz^{-1/2}$ at 10 Hz

Full seismic attenuation required

Virgo: $A = 3\ 10^{-5}$ at 10 Hz

Attenuation required

Einstein Telescope

Full seismic attenuation required

ET: $1.5 \; 10^{-6}$ at 2 Hz

Mandatory filters

Mirror: pendulum at 0.46 Hz

Marionetta

Assume 2 filters mode at 0.75 Hz:

$A = 2.7 \; 10^{-2}$ at 2 Hz

Remaining attenuation required

$A_{ch} = 5.6 \; 10^{-5}$ at 2 Hz

Virgo

Full seismic attenuation required

Virgo: $A = 3 \; 10^{-5}$ at 10 Hz

Mandatory filters

Mirror: pendulum at 0.6 Hz

Marionetta

Assume 2 filters mode at 0.75 Hz:

$A = 5.6 \; 10^{-3}$ at 10 Hz

Remaining attenuation required

$A_{ch} = 5.4 \; 10^{-3}$ at 10 Hz

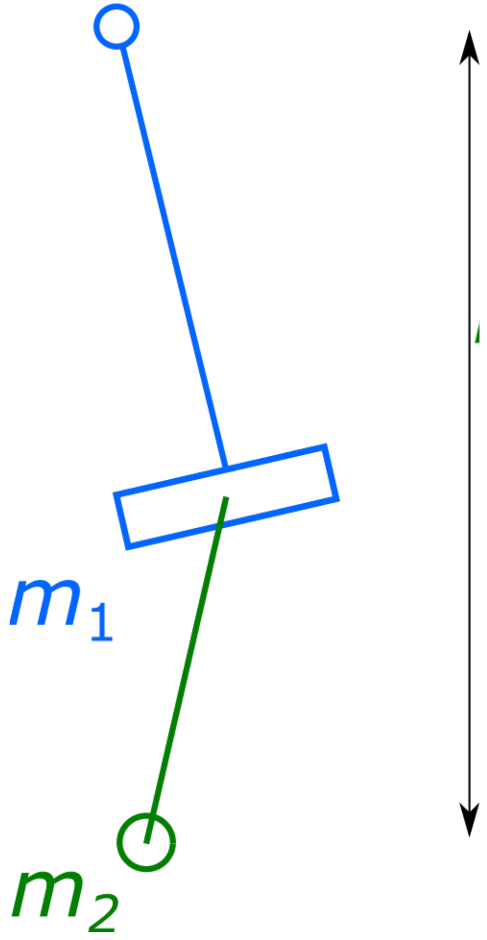
The Superattenuator

Cascade of pendulums

Using inertia and gravity

To using inertia, springs and gravity

Shortening the path to the test mass

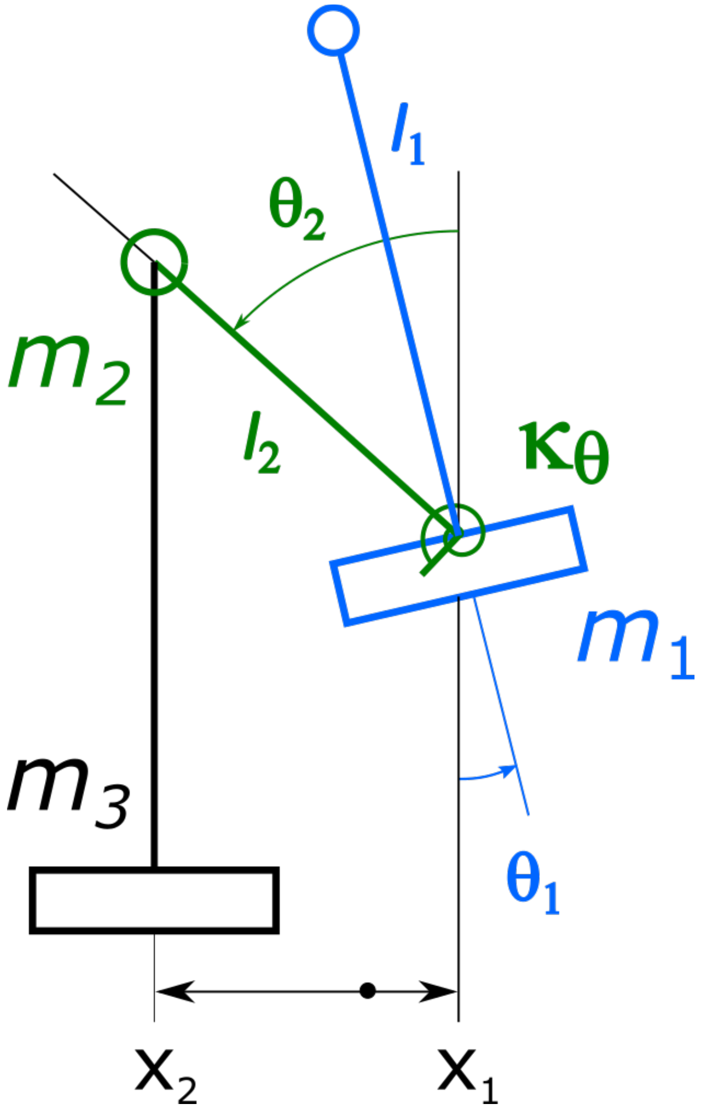


Pendulum – Inverted pendulum

How to soften a suspension stage

- Spare length
- For κ_θ sufficiently stiff, the system is stable

- `l1:  1.544, # Pendulum length\`
- `l2:  0.520, # IP length\`
- `T1: 2551.0, # Pendulum tension\`
- `T2: 1766.0, # IP compression\`
- `m1:   80.0, # Pendulum mass\`
- `m2:   80.0, # Filter mass\`
- `m3:  100.0, # Load\`
- `I1s:  20.0, # Pendulum moment of inertia \`
- `I2s:   0.8, # IP moment of inertia\`
- `k:  1700.0, # flex joint elastic constant\`



Normal mode frequencies
0.68 Hz 0.74 Hz

Attenuation of Pendulum-Inverted Pendulum

$$A = \left(\frac{f_0^2}{f^2 - f_0^2}\right)^2$$

Horizontal attenuation of a single PIP
No damping

For $f_0 = 0.75$ Hz

A_2 : attenuation at 2 Hz $2.7\ 10^{-2}$

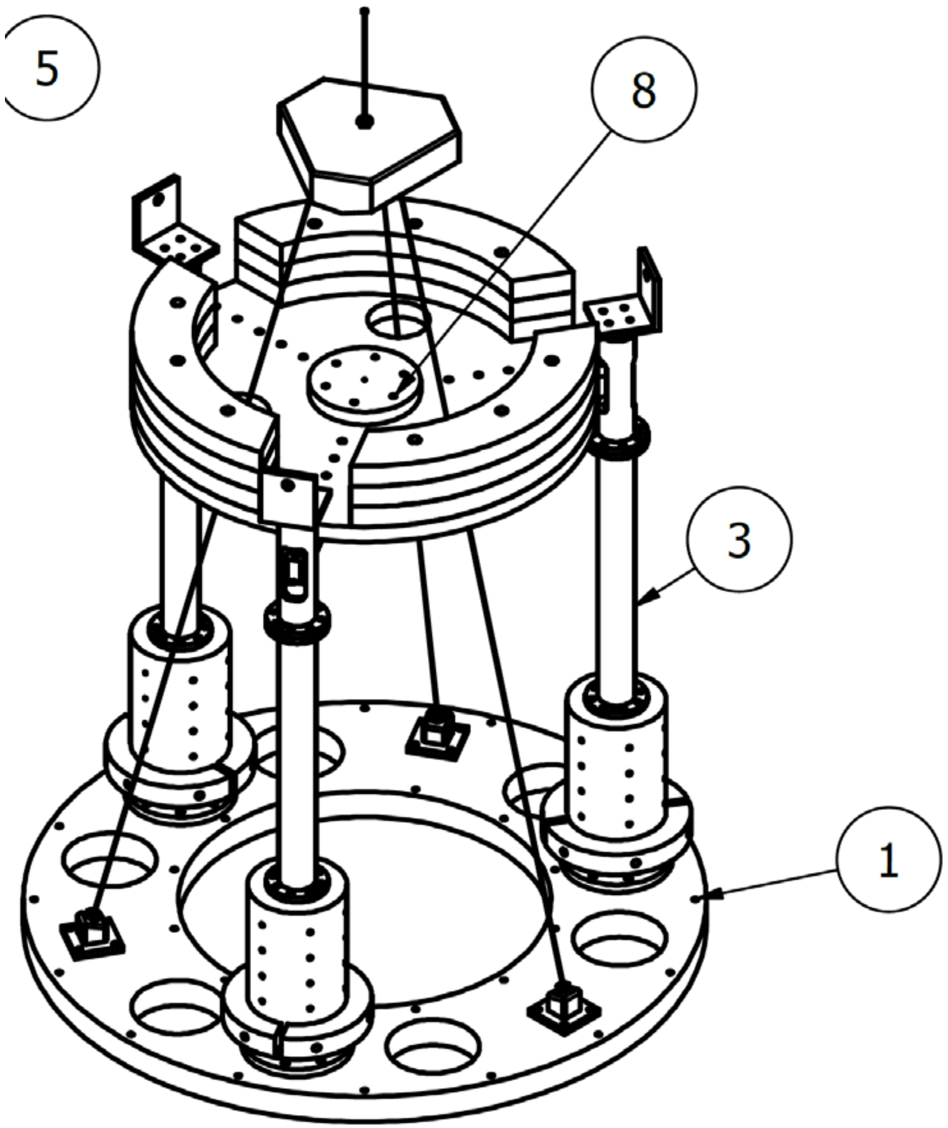
Two PIP

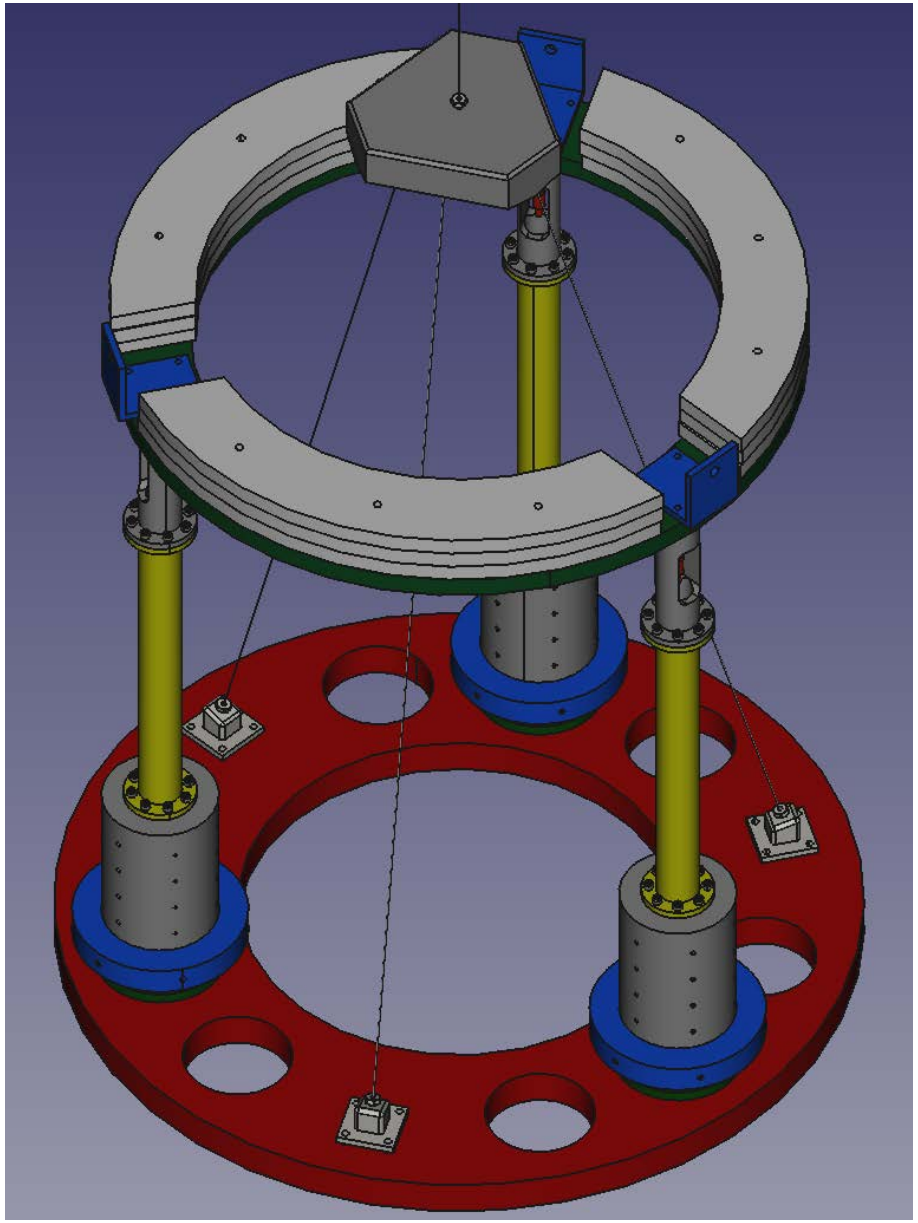
A_2 : attenuation at 2 Hz $7.2\ 10^{-4}$

Three PIP

A_2 : attenuation at 2 Hz $1.9\ 10^{-5}$

Basic structure

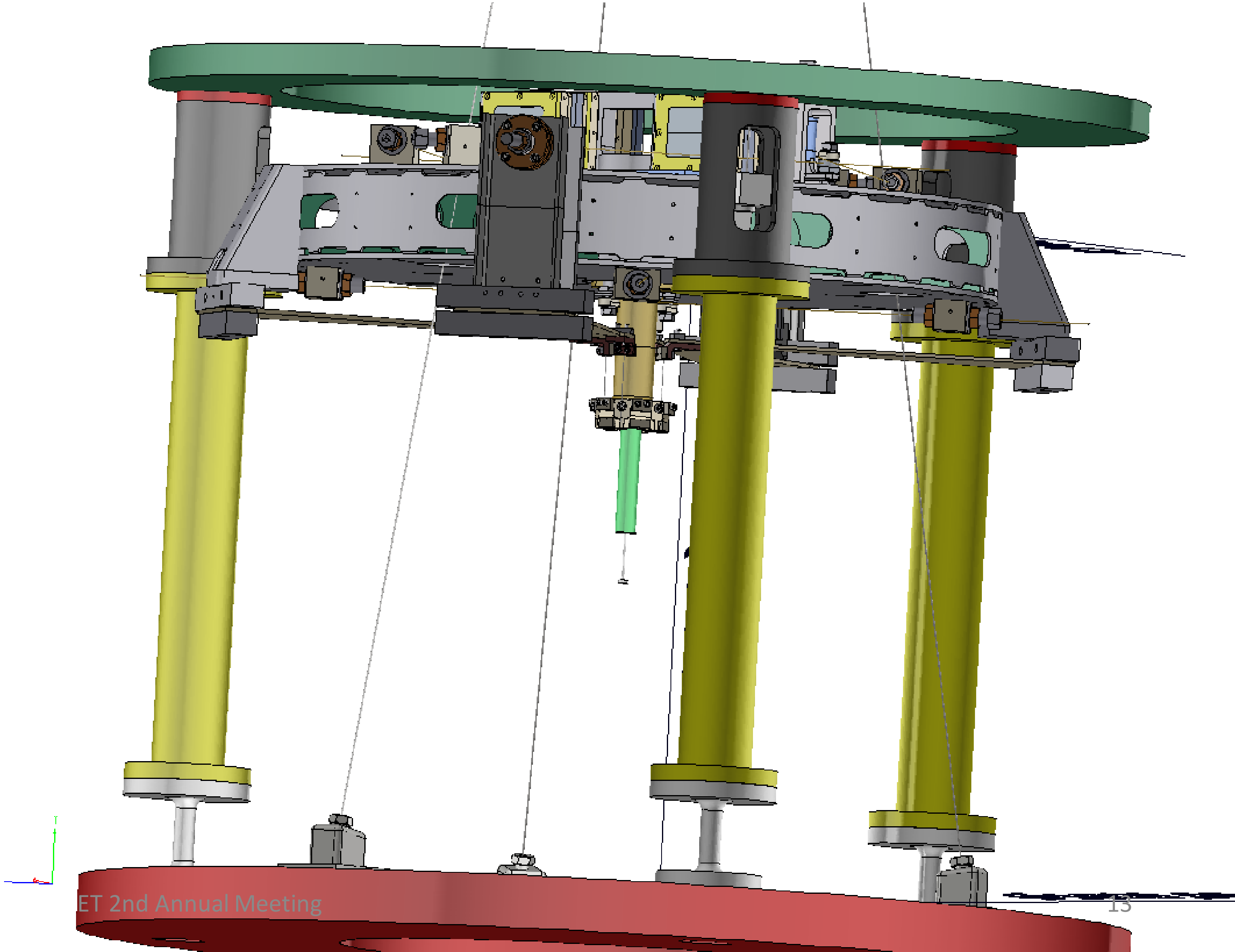




Use a standard F7 filter frame

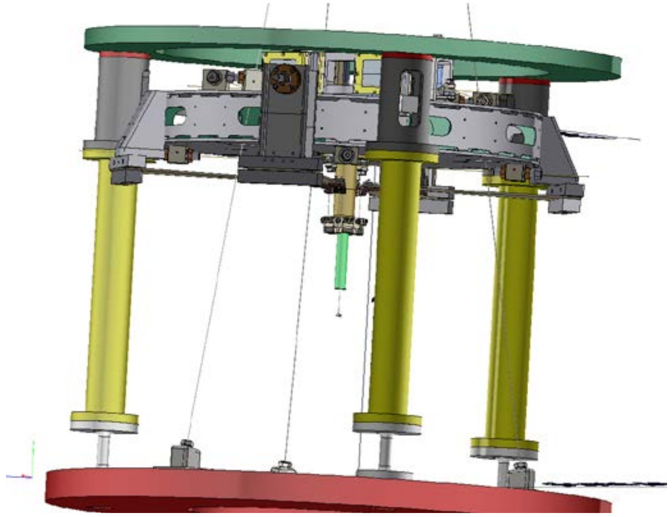
Standard filter addition for vertical attenuation

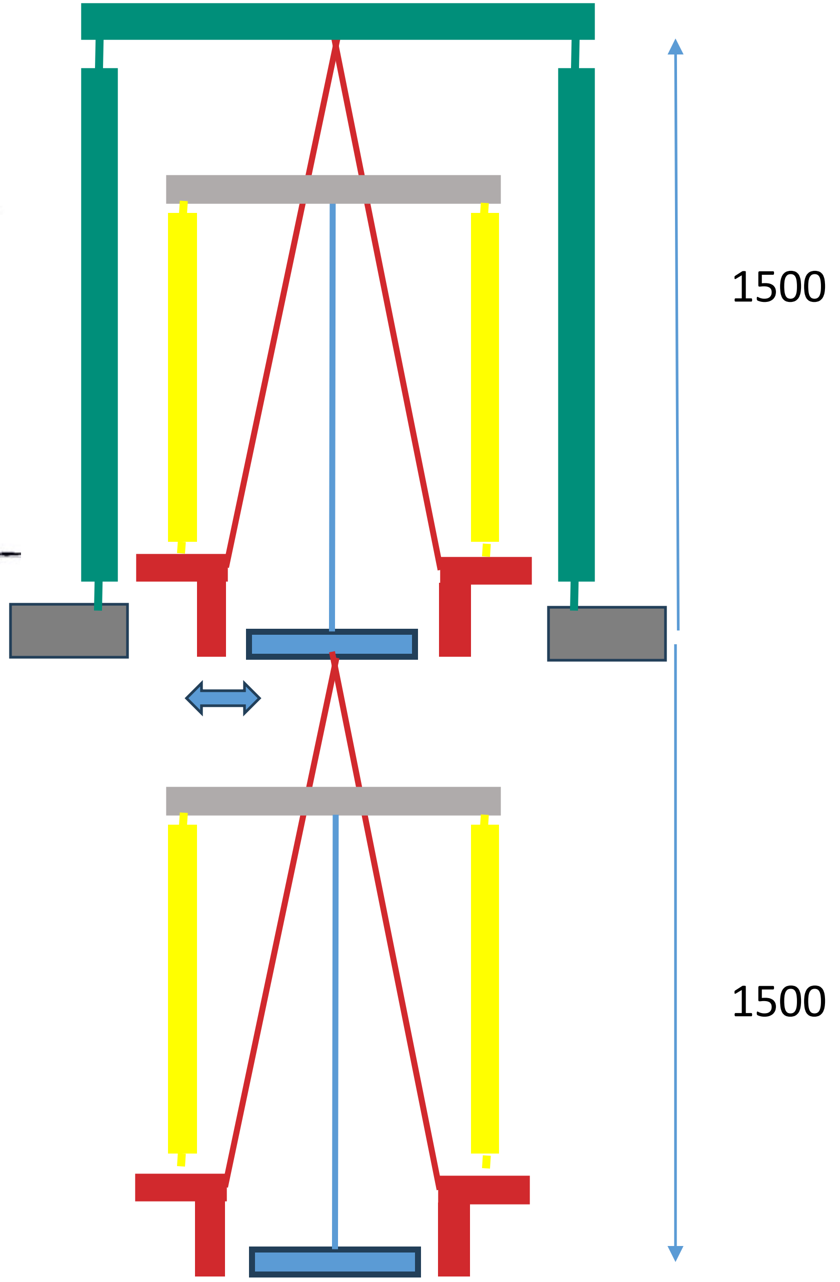
- Filter suspended to IP legs
- IP counterweights not represented
- Includes one stage of vertical attenuation
- Hook to next stage above first pendulum mass
- Additional vertical attenuation can be suspended below the filter



Additional considerations

- **The high part of a suspension chain can be built**
  - Starting from an IP
  - Hanging a pendulum
  - Adding an Inverted Pendulum (-> PIP)
  - Suspend a vertical isolation filter
  - That suspends another PIP
  - Possibility to apply inter-filter feedback

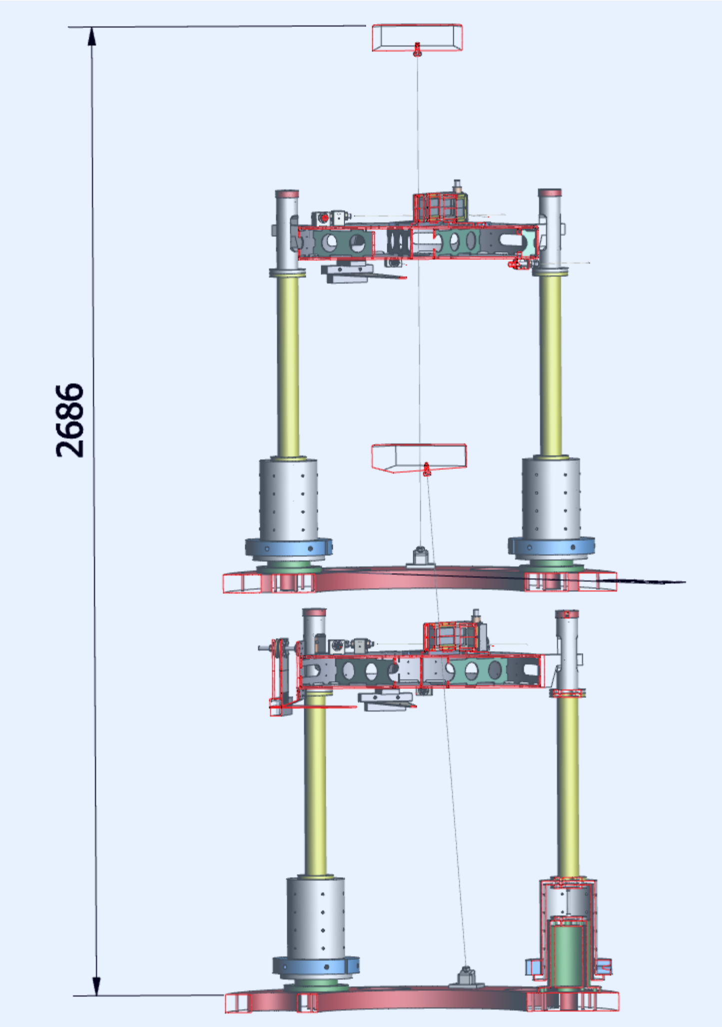


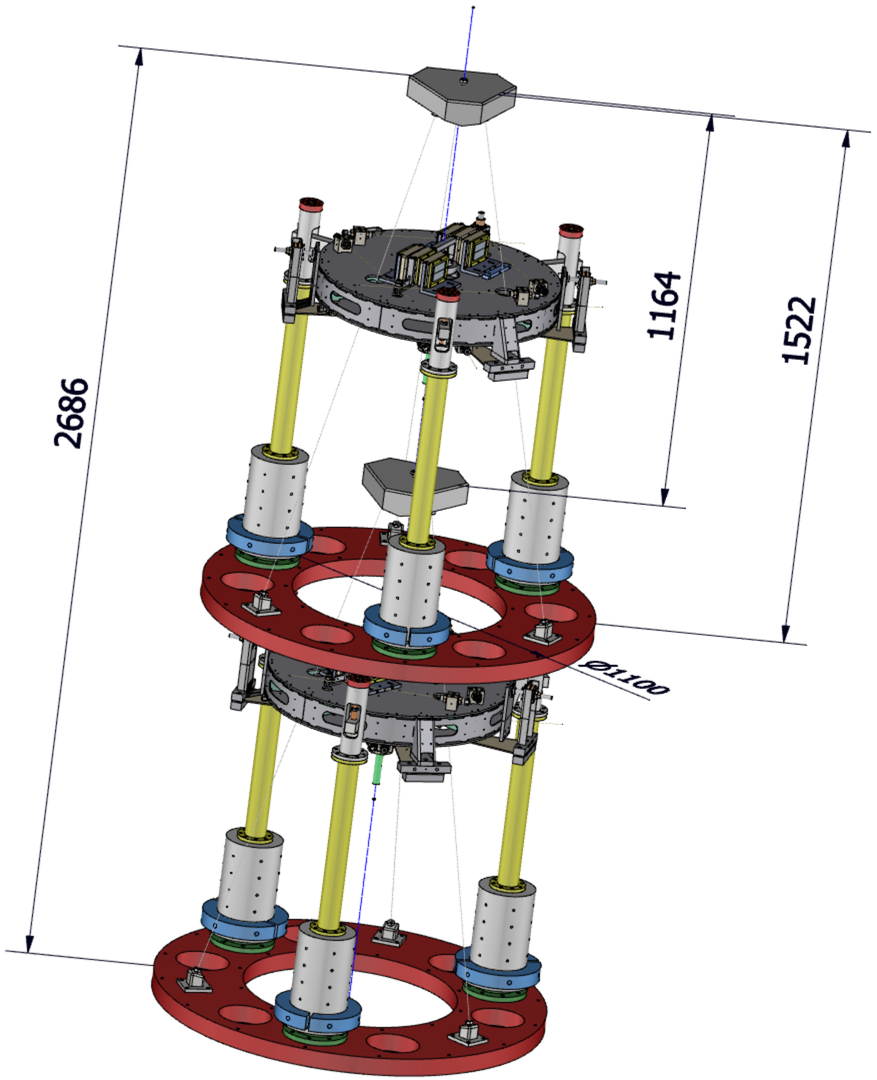


e-PIP

Work in progress on entangled PIP

Four filters in 2.70 m





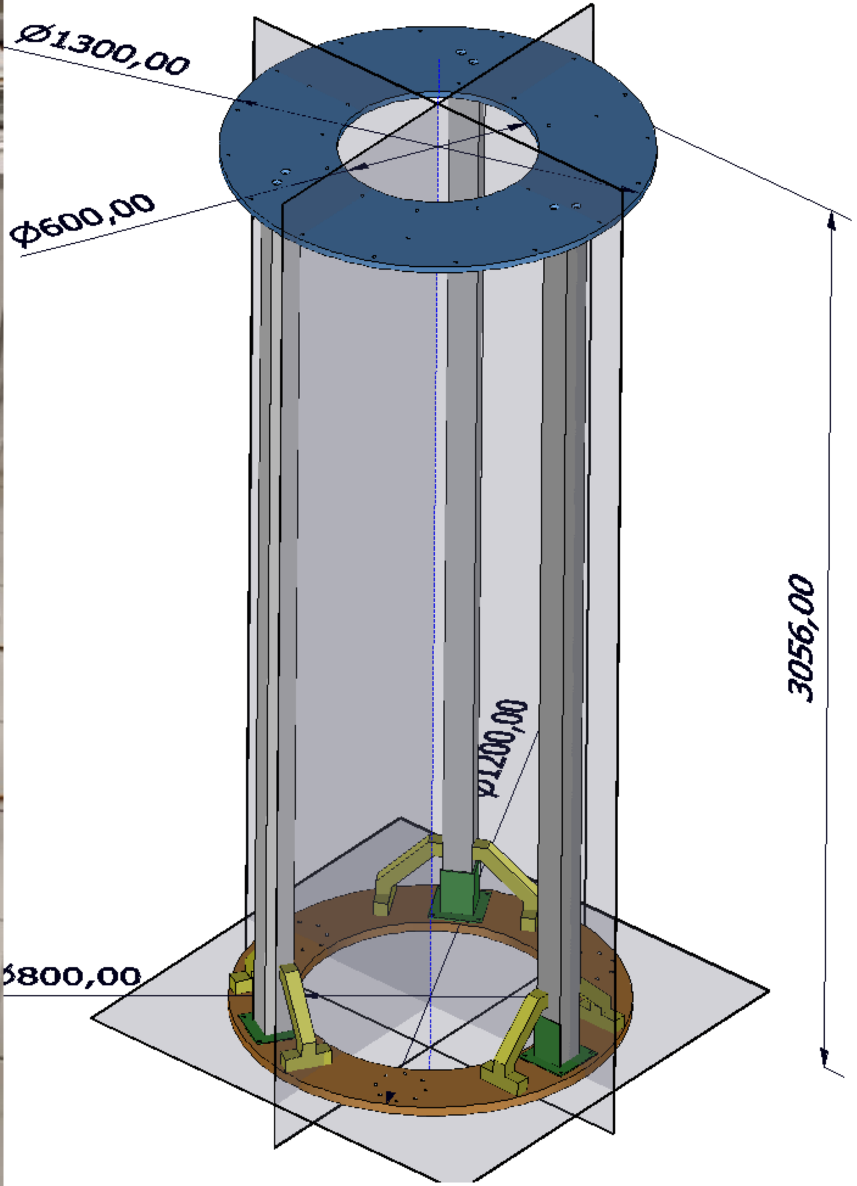
Prototype being assembled

A prototype has been built and is being assembled

- SarGrav funding
- Grad students back to the lab

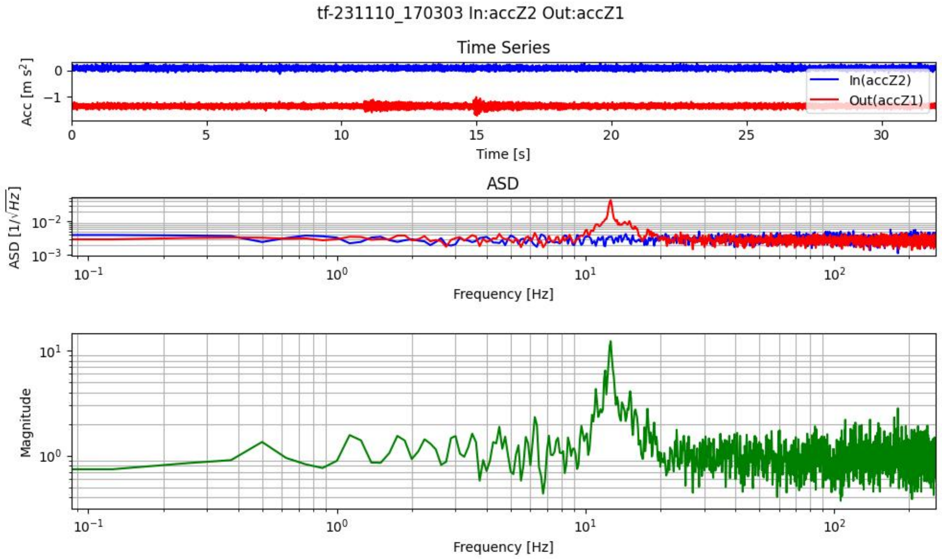
Goals

- Verify the dynamical behaviour: large roll-displacement coupling
- Expected resonances
- Cross coupling
- Vertical bouncing modes



Testing low cost components

- Accelerometers: Arduino shields with USB ascii readout
- First «sound» last week
- Preparing for large number of channels for ML applications
- To be complemented with LVDT readout
- In future optical readout (thnx O. Gerberding and Hamburg group)



Overall length

- **A PIP chain can be built**
  - Hook of the second PIP above the first filter
  - Current PIP length 1.55 m
  - Two PIP can live in 2.70 + 0.30 = 3.0 m accounting for a dedicated vertical attenuation stage
  - Three PIP can live in 4 m
- **The goal of a 10 m tall suspension seems in sight**

Thoughts from redesign

Reviewing what had been designed 20+ years ago

- **Current prototypes and variants are reproductions or evolutions of current suspensions**
- **Successful for passive attenuation (Braccini 2011), measurement possible only with full interferometer**
- **Somewhat successful in introducing some active control**
  - Horizontal direction relies on interferometer signals (hierarchical global control)
  - Mode damping attempted in the vertical direction
  - Adaptive control during mild earthquakes (global IP control)
- **On the other hand LF performance is orders of magnitue above design level or known projections of measured noise**
- **LF noise is (in many's opinion) a mix of sensing noise in longitudinal and angular dof, diffused light and large motion at low frequency, not in order of importance or of causality, see also**
  - Yu et al Phys. Rev. Lett. 120, 141102
  - Hall et al Phys. Rev. D 103, 122004

On the suspension side the design must achieve the required attenuation AND low (below λ) residual motion and rotation