Vibration attenuation

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Webinar on technical challenges of the Einstein Telescope

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Nikhef

Einstein Telescope

ET pathfinder

Why vibration attenuation ?

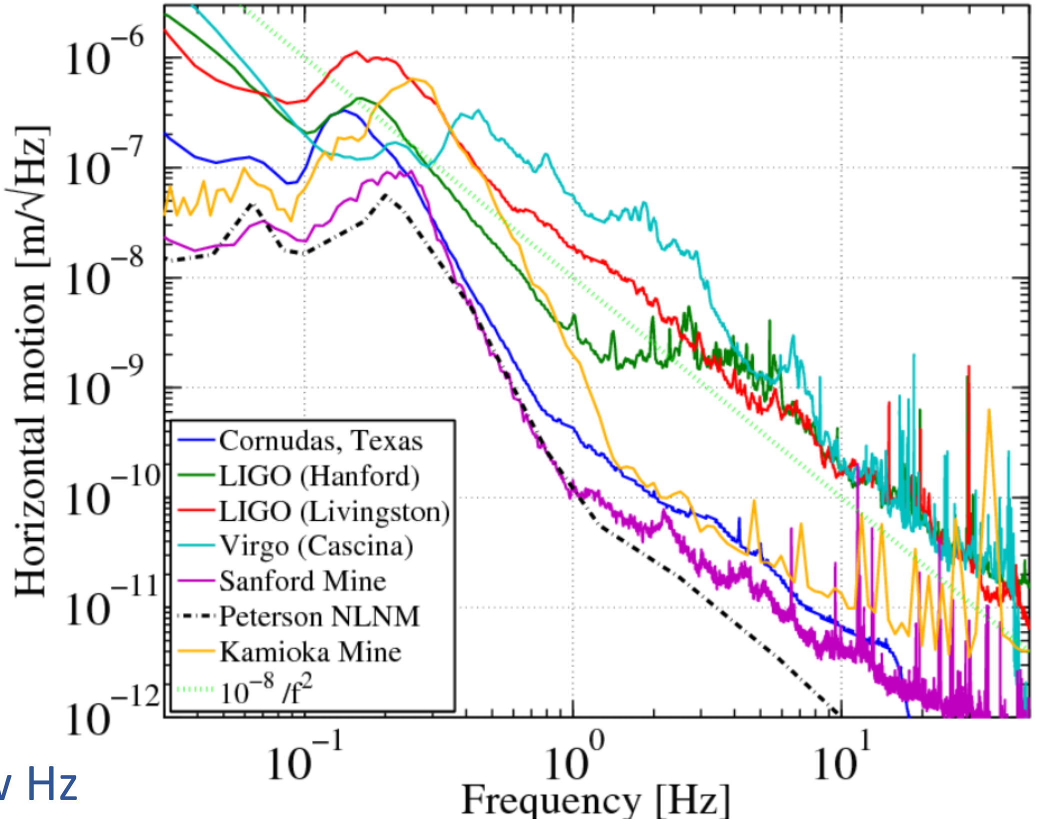
- **Gravitational waves** cause tiny vibrations of the distance between test masses: typically 10^{-20} - 10^{-18} m

  We don't want to measure any other vibration than that (above a few Hz)

- On earth, there is not such a quiet place.

- Therefore, almost all **optics** require vibration attenuation:
  - test masses
  - beam splitter
  - mirrors of recycling and squeezing cavities
  - Numerous optical benches

- Moreover, **alignment and locking** of the interferometer requires that the optics should not move too much below a few Hz



Vibration sources

1. **Direct on the mirrors:**
   - thermal noise of mirror suspension & coating
   - actuator noise
   - radiation pressure noise
   - Newtonian noise
2. **From close by:**
   - pumps
   - air conditioning
   - sound sources
   - cooling devices
3. **From far away:**
   - micro-seismic waves
   - wind
   - human activity: traffic, factories,…
   - (earth quakes, only damage control)

Reducing vibrations

1. **Direct on the mirrors:**
   - thermal noise of mirror suspension & coating
   - radiation pressure noise
   - Newtonian noise
   - actuator noise

Choose large mirror mass to reduce it

Can partially be subtracted with seismic sensor array

2. **From close by:**
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   - air conditioning
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Isolate mirror from vibration source

Isolation of mirrors from vibration sources

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- micro-seismic waves
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- **Passive isolation (> 1 Hz):**
  - $\boxed{\text{mechanical attenuation chain}}$ *This talk*
  - viscoelastic or Eddy current (resonant) dampers
  - Vacuum towers (no sound transmitted)
- **Actively (< 10 Hz) by sensing & actuation**
  - hierarchical control
  - SISO, MIMO
  - PID, Kalman, ….

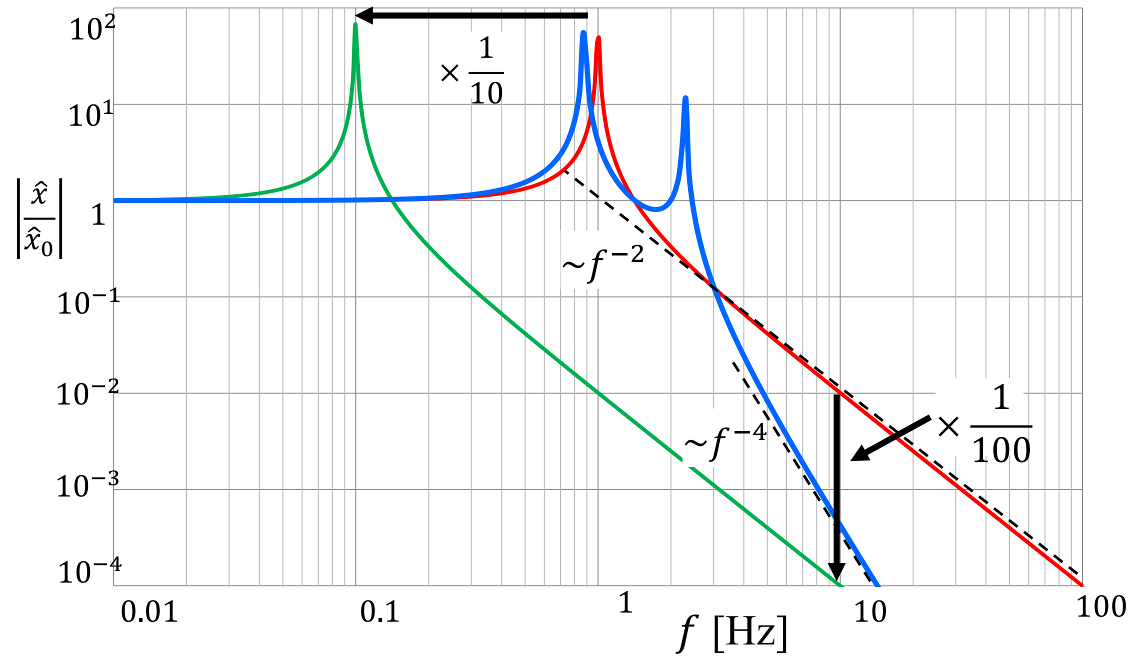
Passive vibration attenuation:

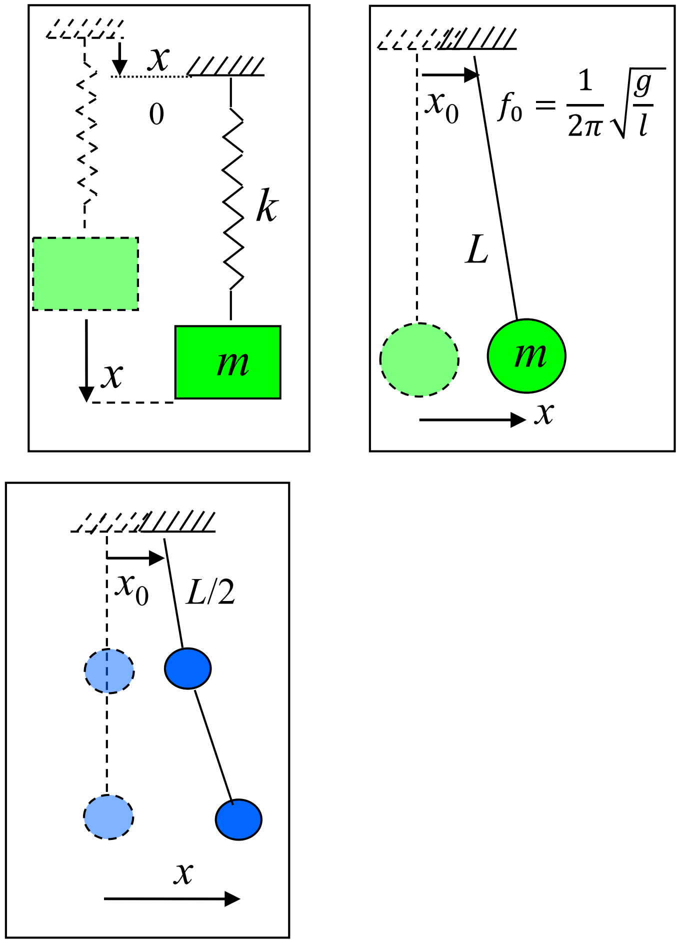
Mechanical oscillator
= vibration isolator above resonance

Equation of motion $m\ddot{x} = -k(x - x_0)$

Natural frequency $f_0 = \frac{1}{2\pi}\sqrt{k/m}$

Transfer function $T = \frac{\hat{x}}{\hat{x}_0} = \frac{1}{1 - f^2/f_0^2}$



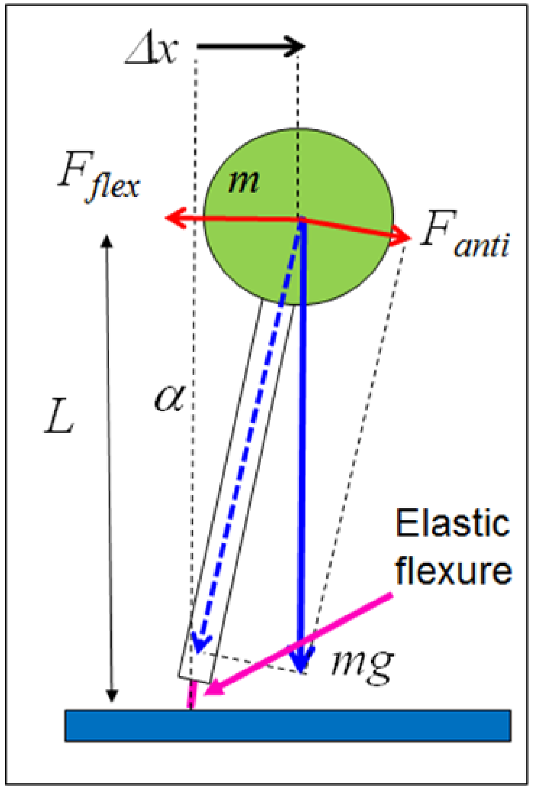


10 times lower f_0 → 100 times more isolation

N masses in cascade → isolation ~ f^{-2N}

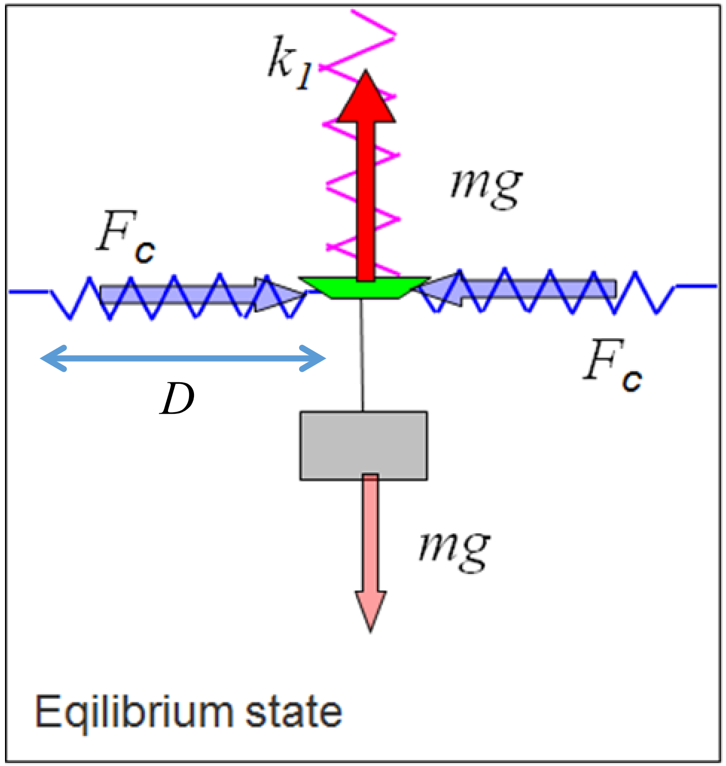
Introducing negative stiffness → lower f_0

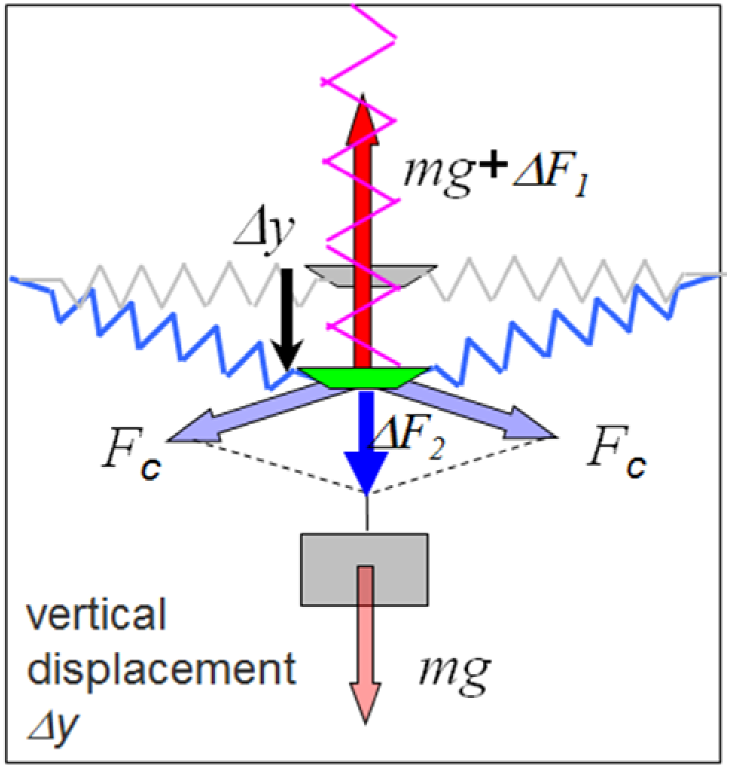
Horizontal: inverted pendulum



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_{elastic}}{m} - \frac{g}{L}}$$

Vertical: geometric anti-spring



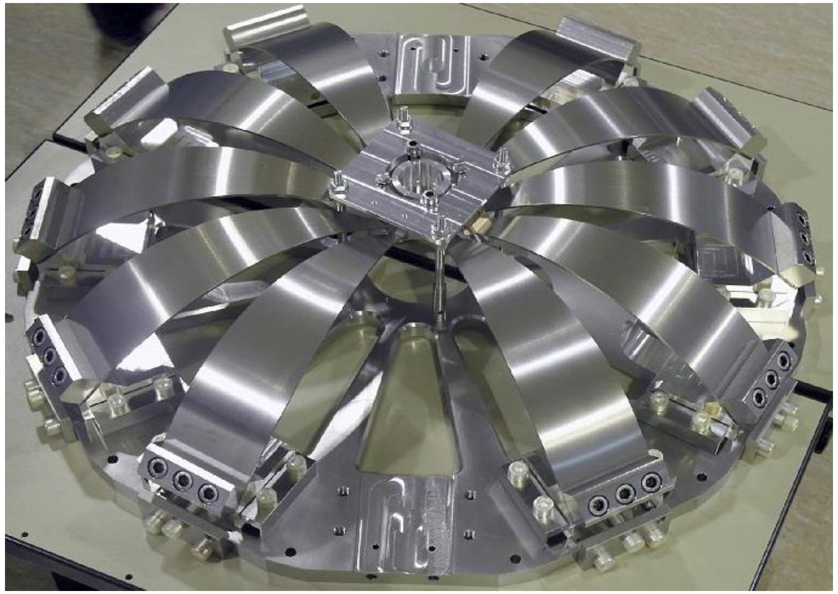


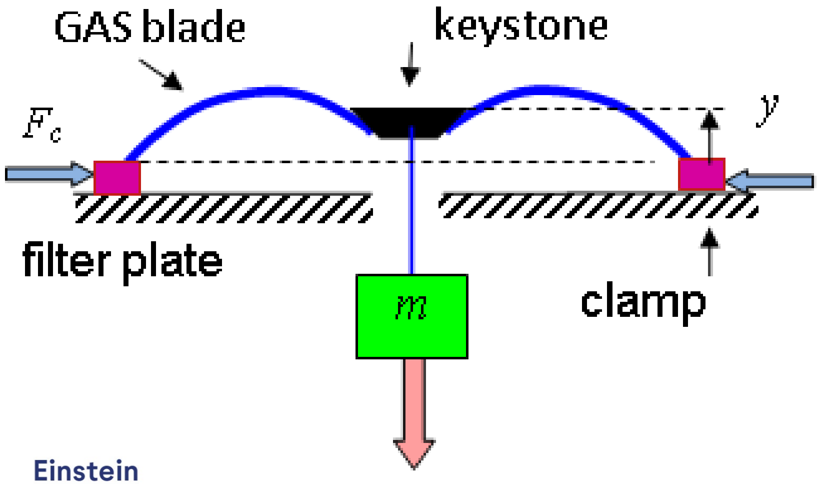
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_1}{m} - \frac{F_c}{mD}}$$

negative stiffness

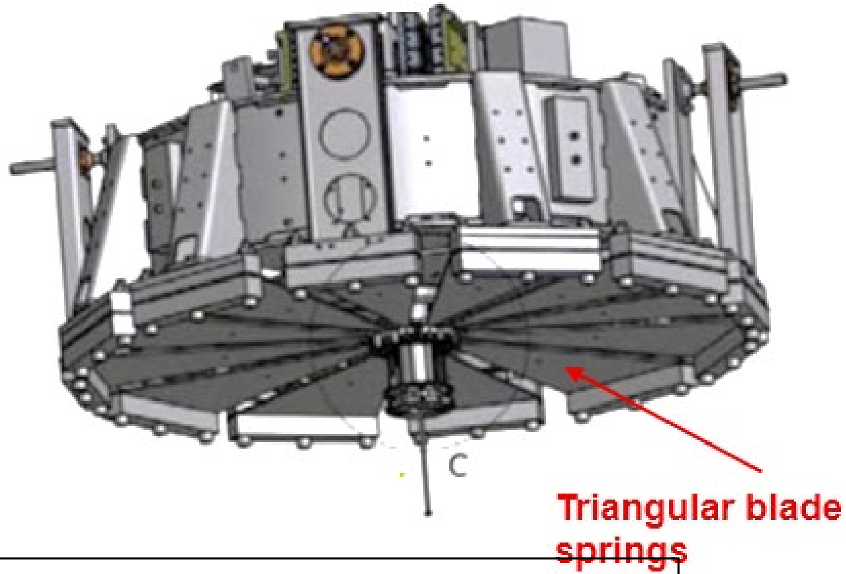
Geometric anti-spring filters @ Virgo

Elastic anti-spring in MultiSAS

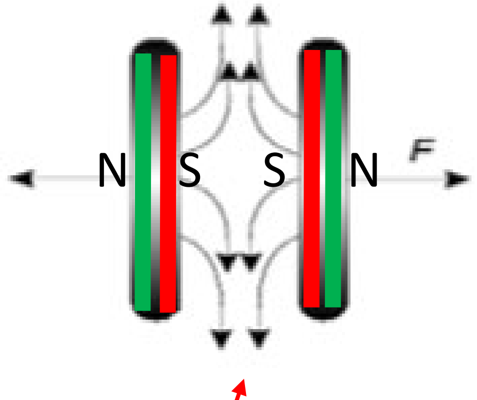




Magnetic anti-spring in Super Attenuator

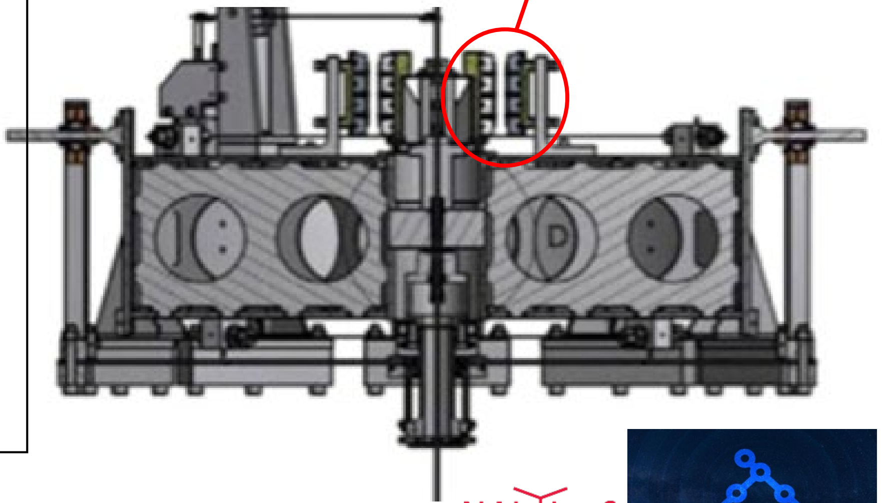


Oppositely placed permanent magnets

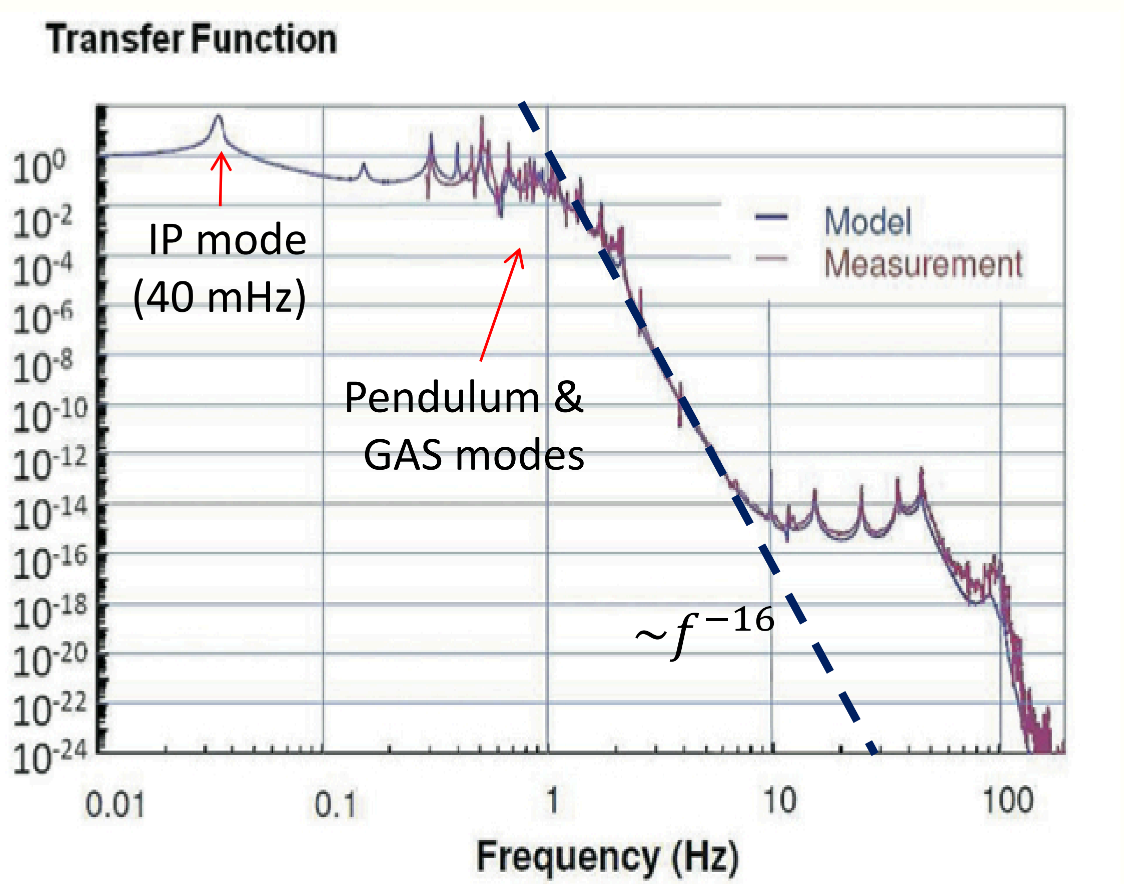


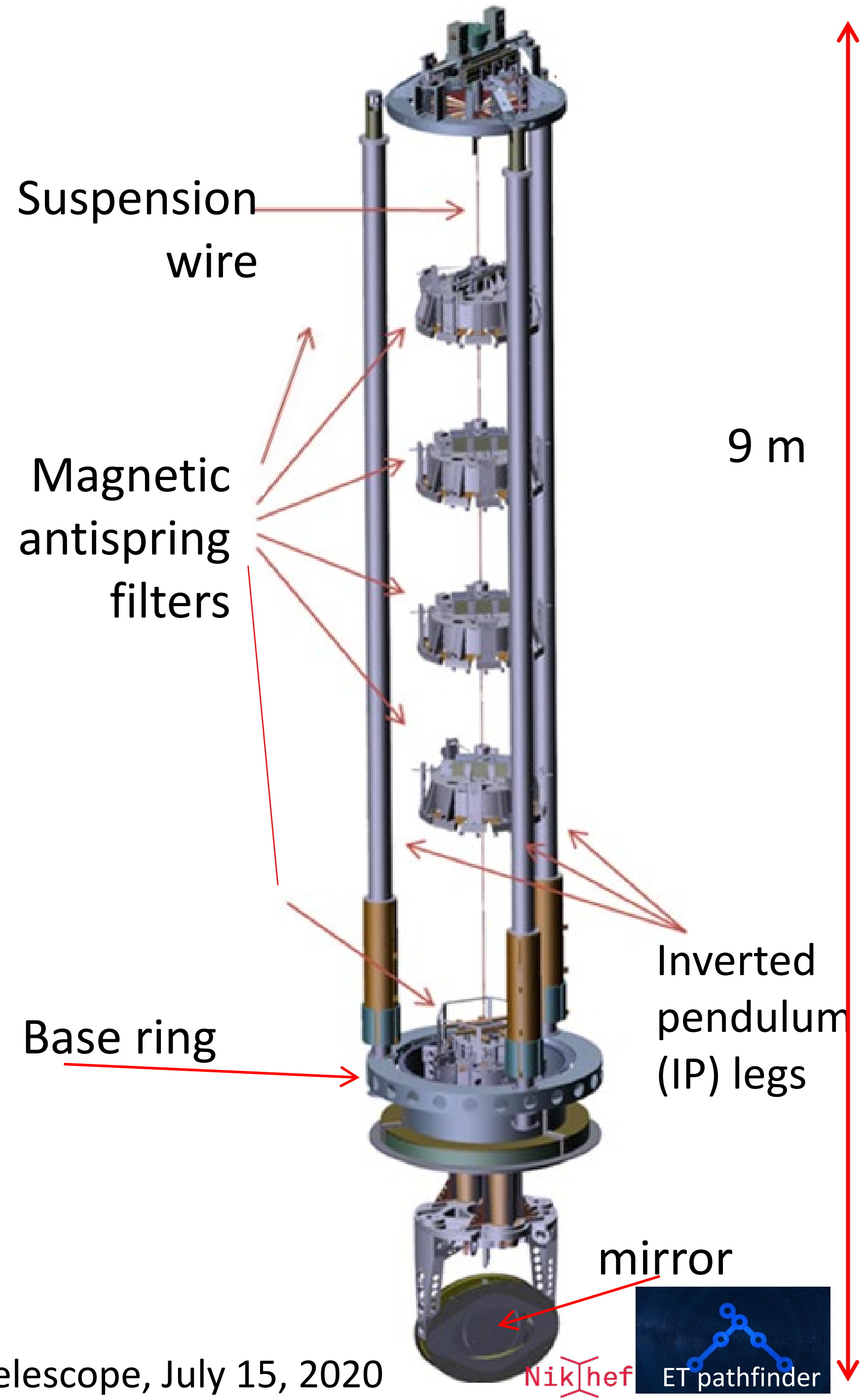
Filters
- Load up to 750 kg
- tunable down to ~ 200 mHz

Blades:
- maraging steel, statically loaded up to 1.6 GPa
- suffer from stress corrosion



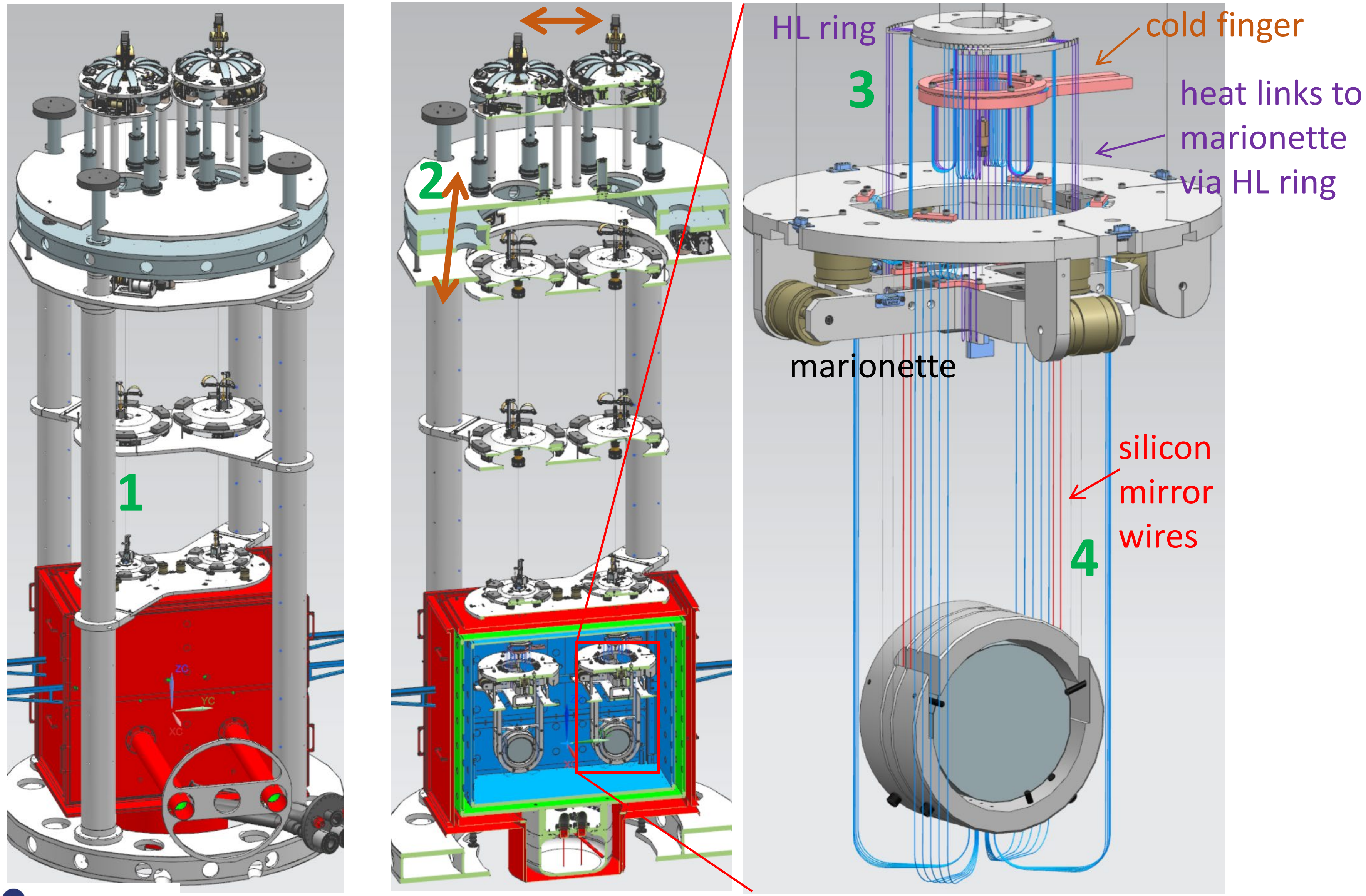
Virgo Super-attenuator: 6-DOF cascade suspension





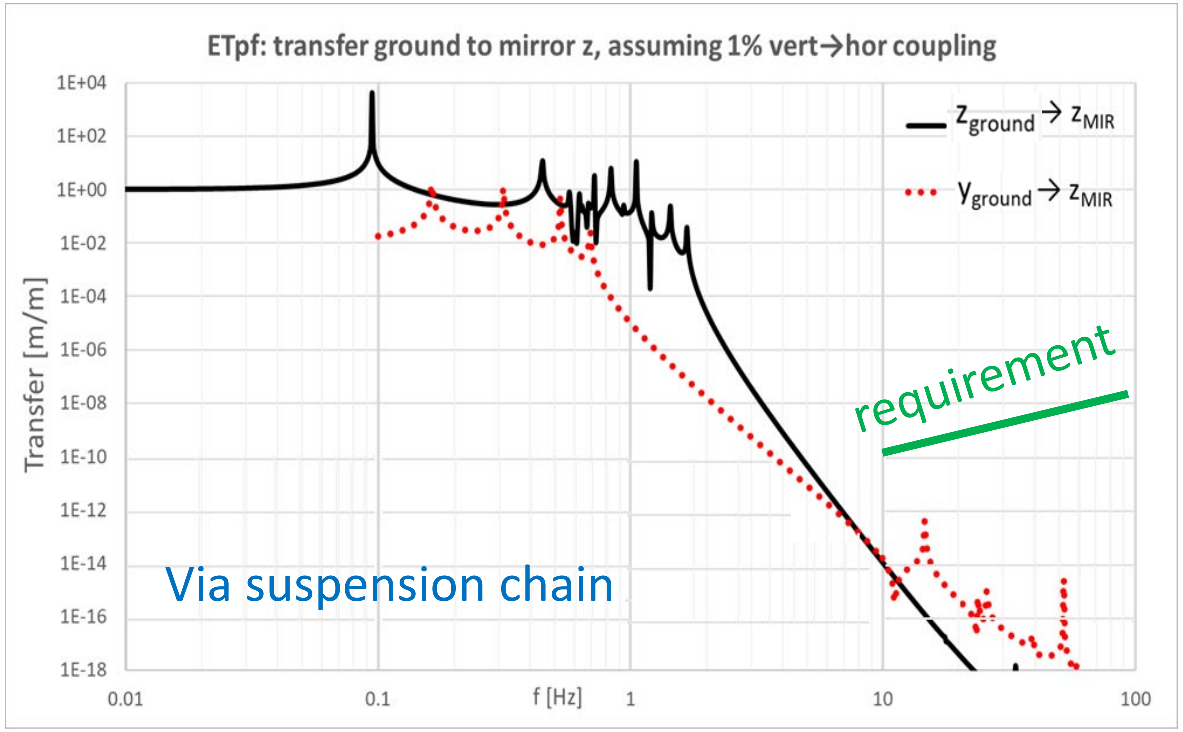
- above 5 (10) Hz : 240 (280) dB attenuation
- Below 5 Hz and DC: active damping & positioning
- Inertial sensing: geophones & accelerometers
- Relative displacement: LVDT sensor + cavity locking signals
- :uation : voice coil + magnet pairs

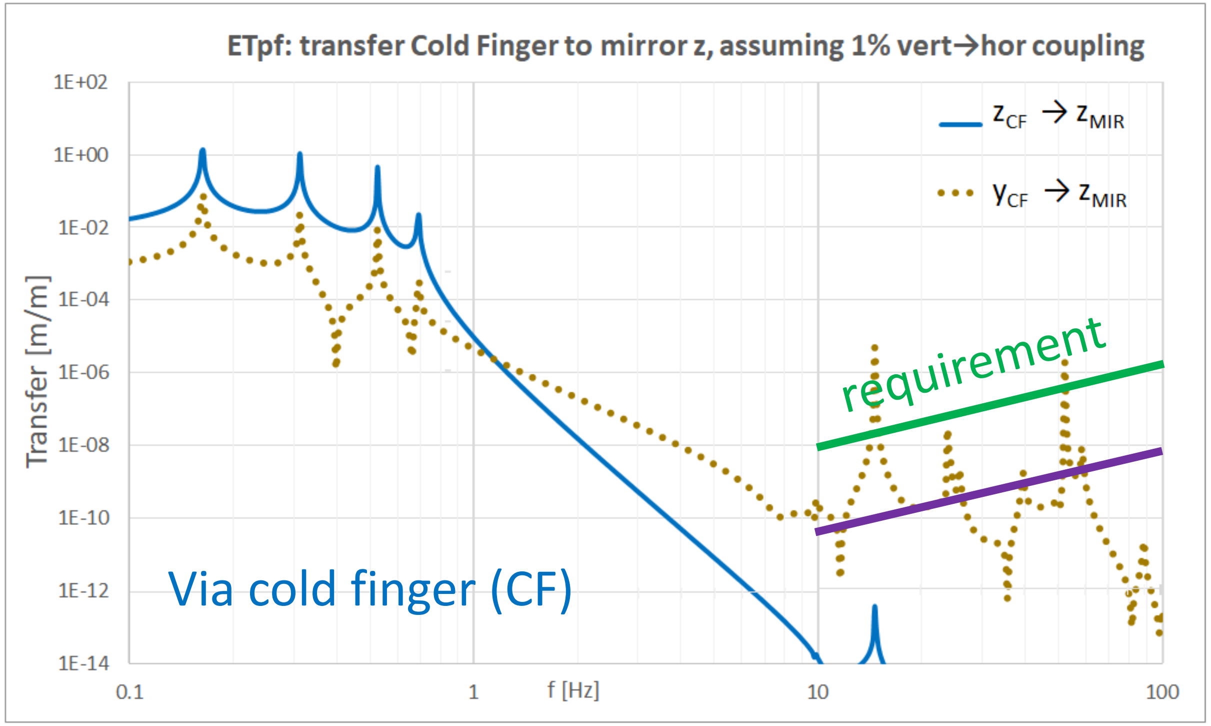
ET pathfinder cryogenic suspension challenges



1. four inverted pendulum (IP) legs instead of three: overconstrained system!
2. Inverted pendula both in series and parallel
3. heat link wires will transfer cold finger vibrations to the marionette via HL ring, by-passing the suspension chain
4. conflicting demands on mirror wires; they should be:
   - short and thick to reach lower temperature
   - long and thin to reach better vibration isolation

ET pathfinder modeled transfer from ground to mirror

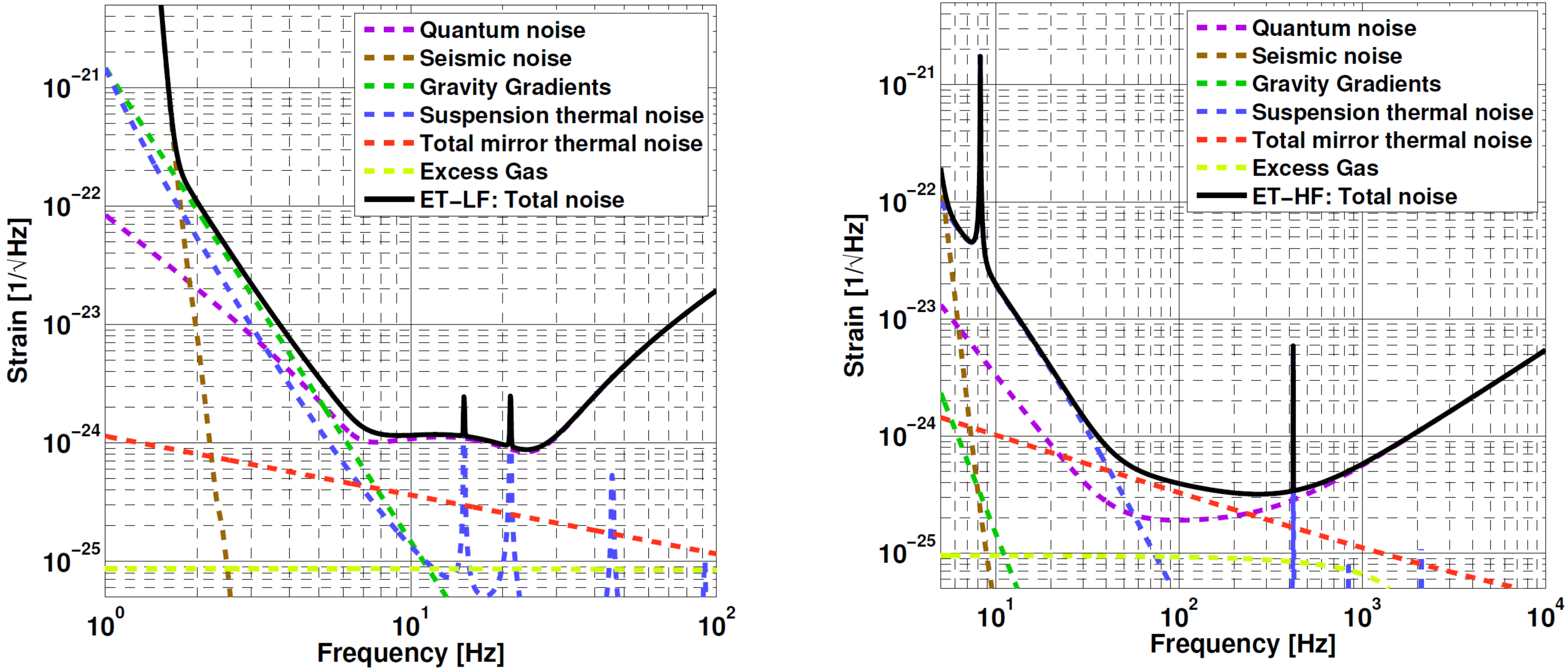




If CF moves with ground → on the edge

If CF moves more than ground (which is expected) → CF needs vertical isolation

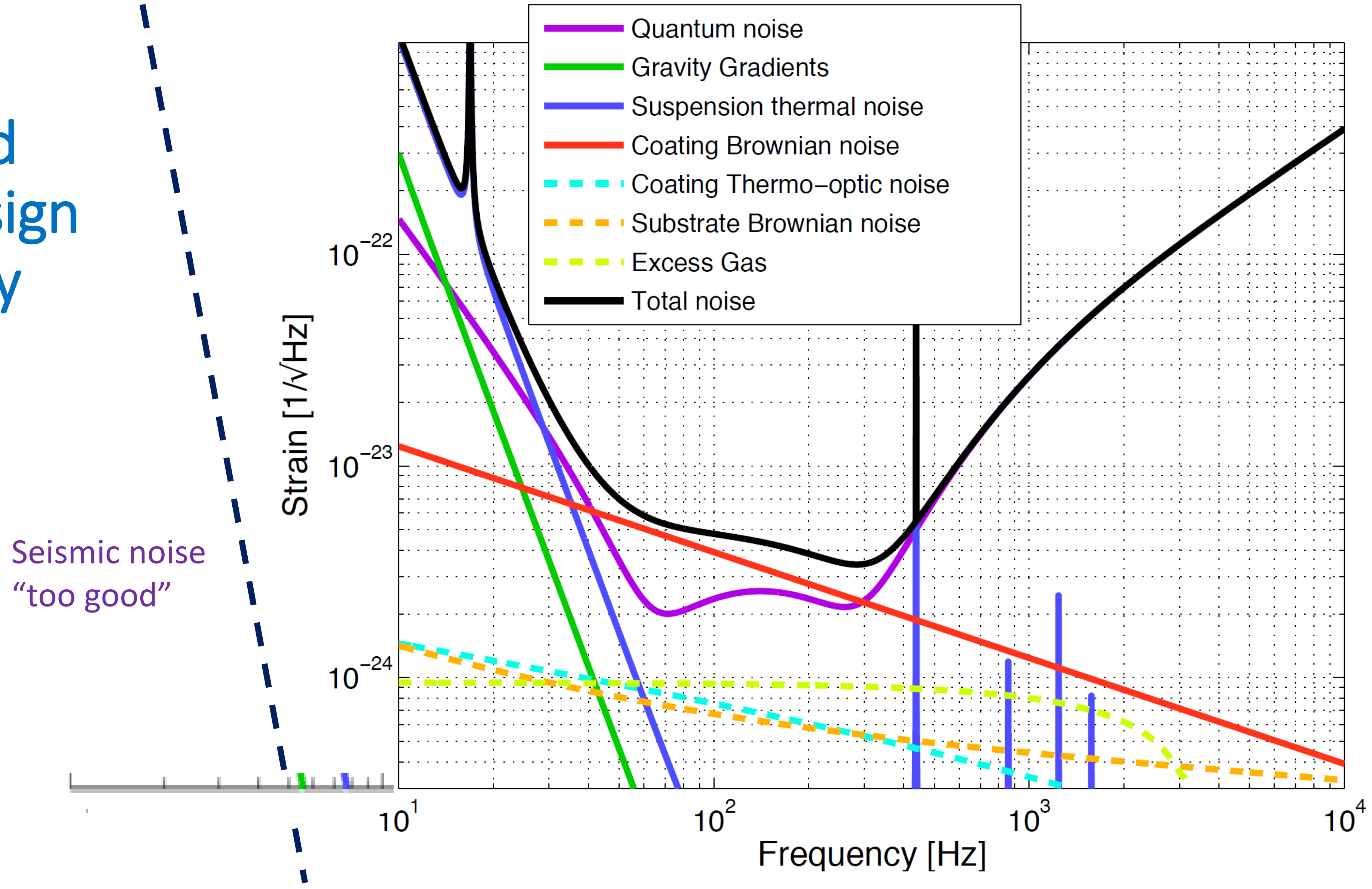
No challenge for ET vibration attenuation ?



Noise budget for the low- and high-frequency interferometer for the parameters used for the ET-D sensitivity curve as stated in table 10.

ET challenge for vibration attenuation ?

Advanced Virgo design sensitivity



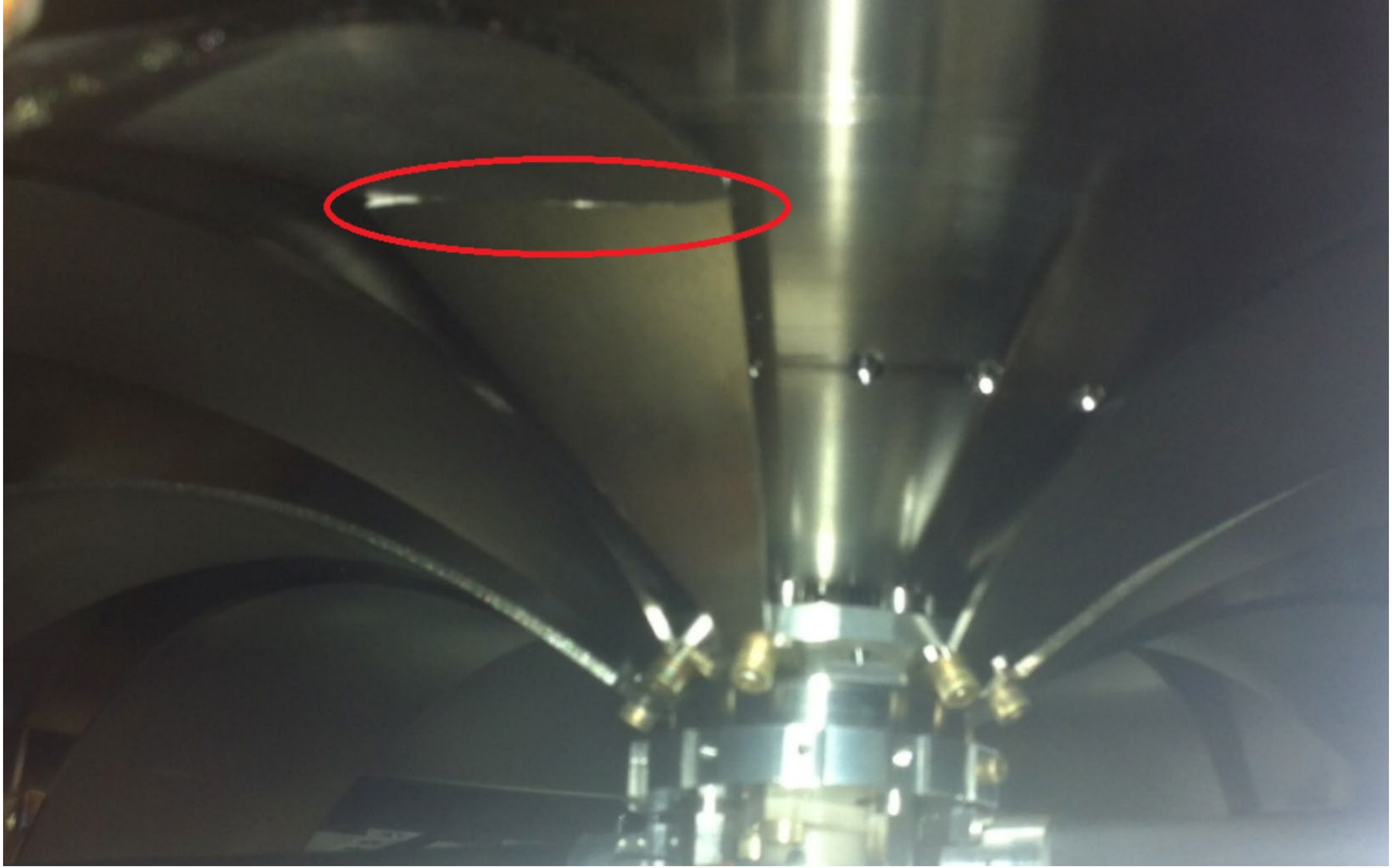
ET challenge for vibration attenuation ?

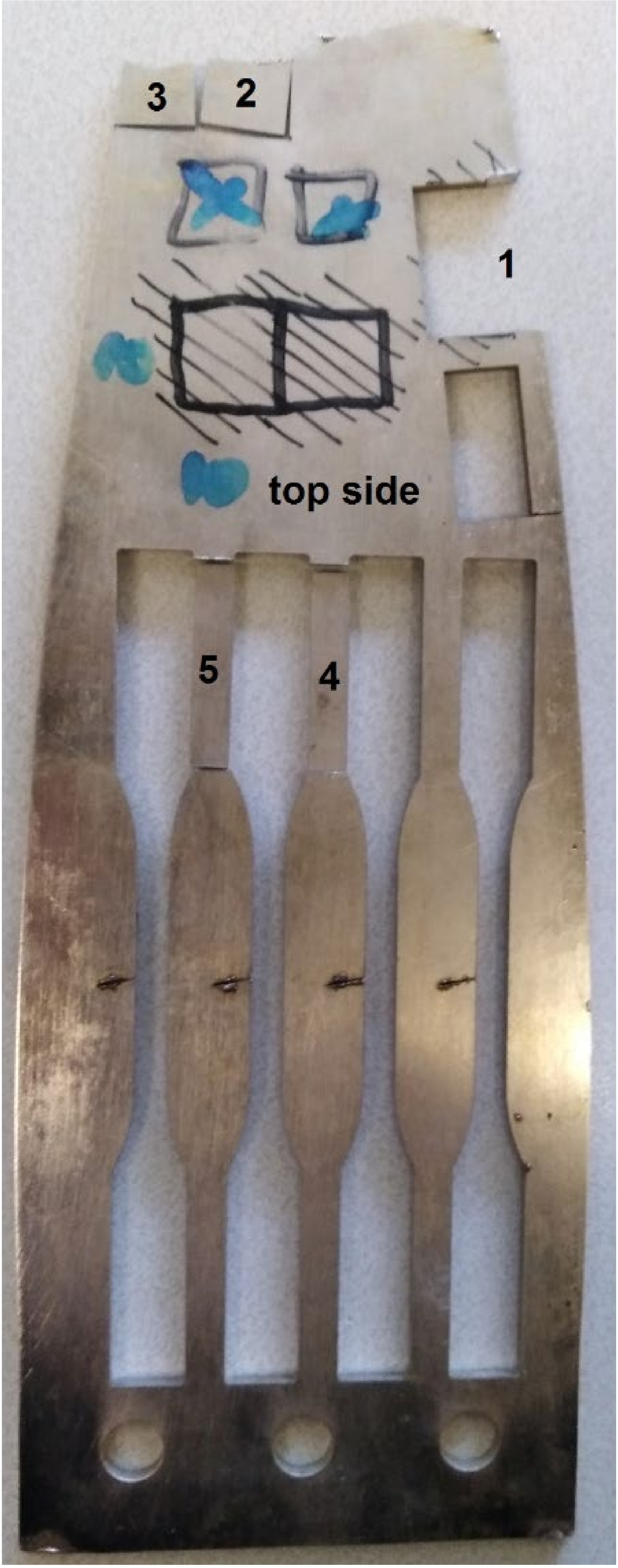
Yes, reduce vibration transfer from cold finger !!
reduce vibrations of cold finger itself

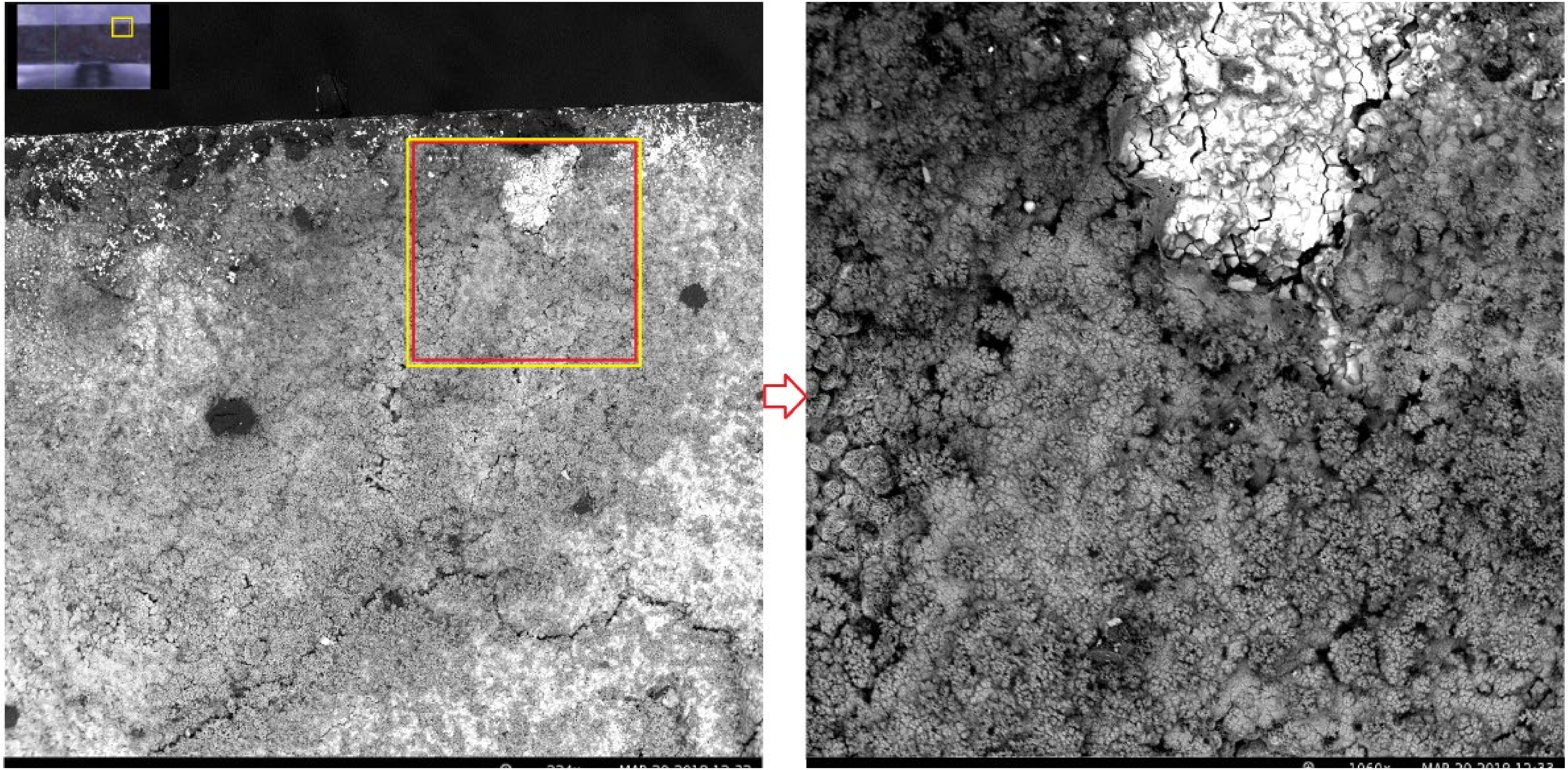
Yes, search for alternative for maraging steel
to prevent spontaneous failures (due to stress corrosion…?)

Yes, we need much more sensitive inertial sensors
to improve low-frequency vibration control

Yes, invent High-purity monocrystalline silicon suspension wire that can be connected




3
2
1
top side
5
4



Folded pendulum acelerometer

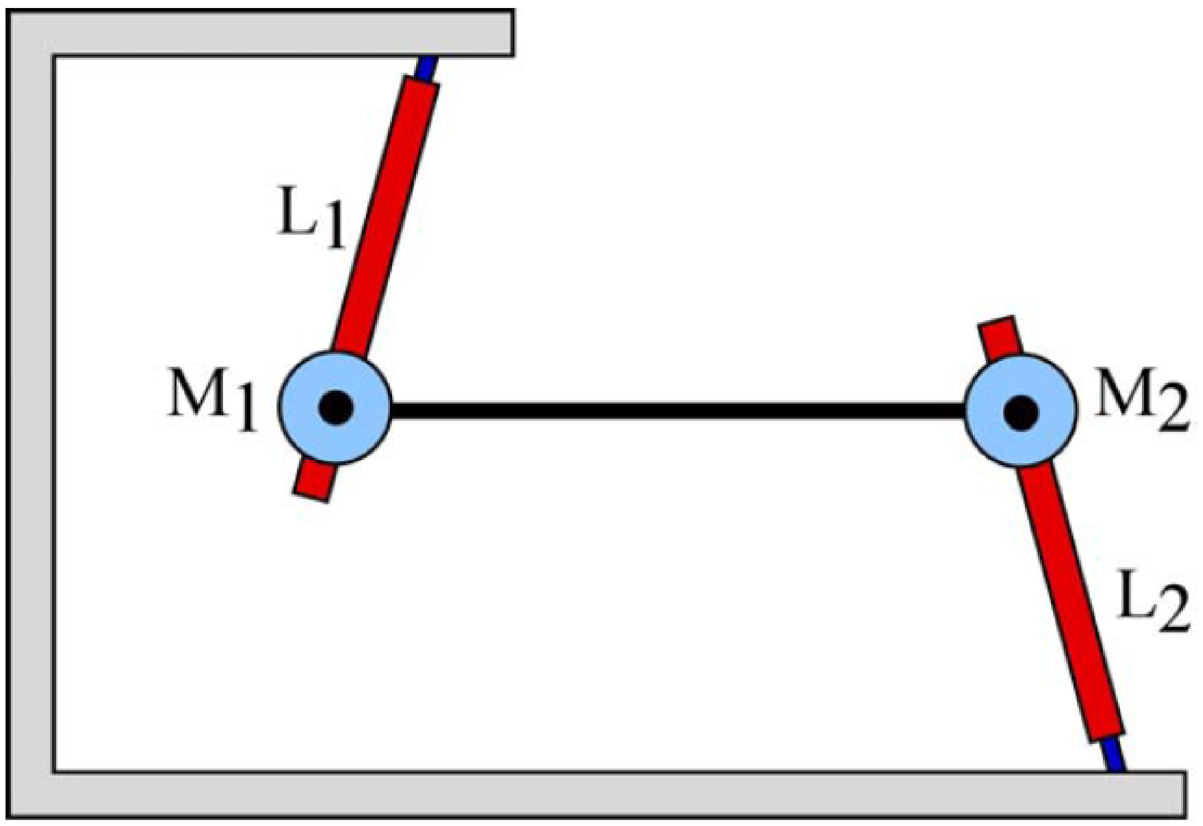
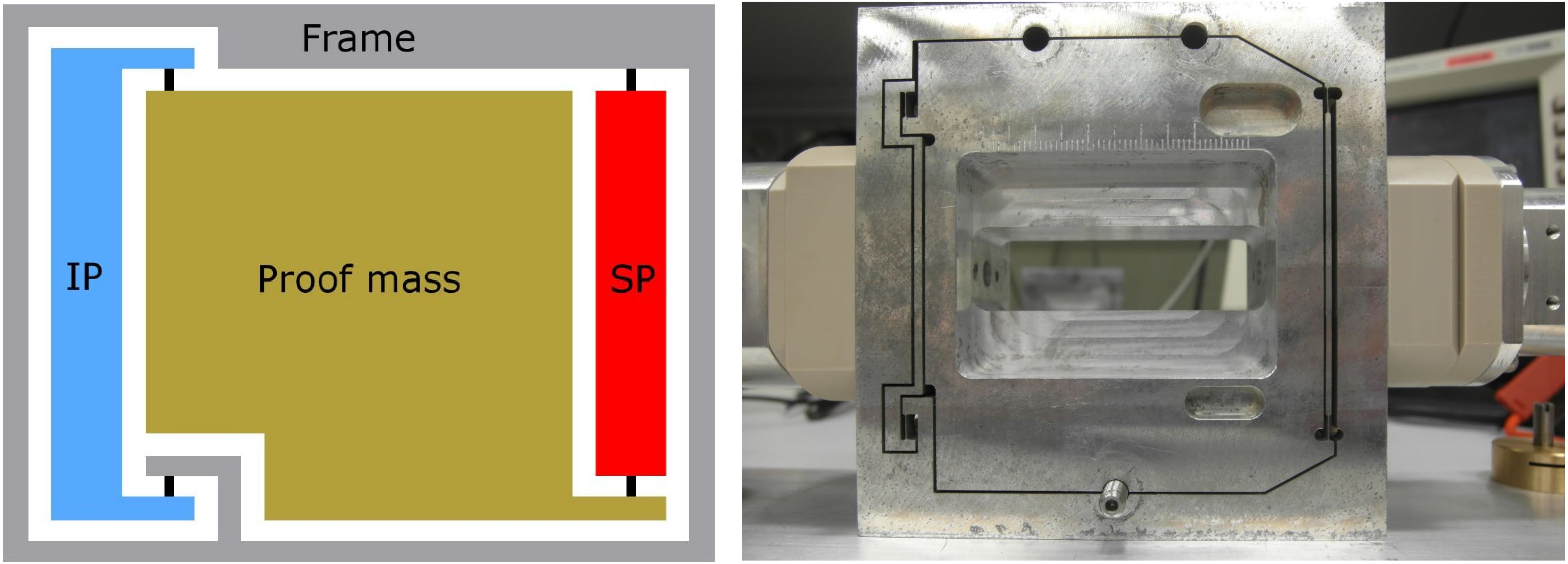
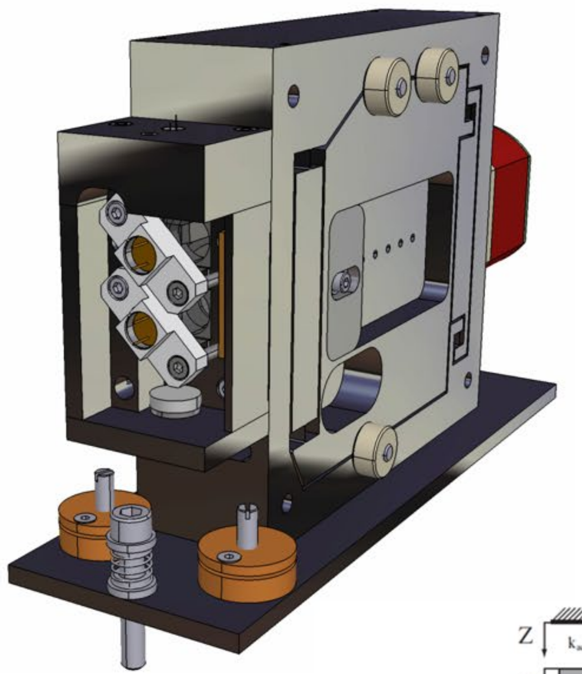


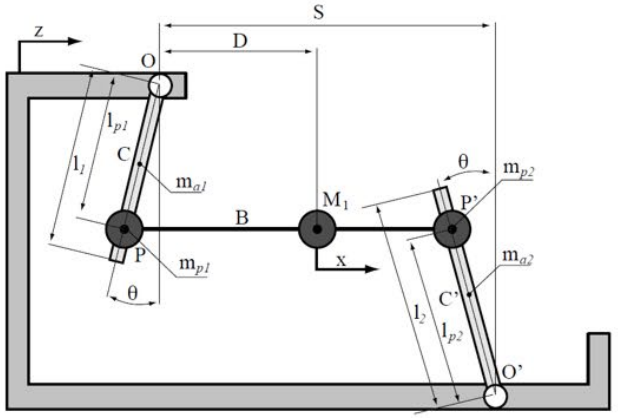
Fig.1. Basic model of folded pendulum. A simple pendulum and an inverted pendulum are rigidly connected by a massless beam. The pendula arms are also massless, rigid and provided with suitable flexures.


Frame
IP
Proof mass
SP

Monolithic double pendulum accelerometer with interferometric sensing

NIKHEF





pendulum

Inverted pendulum