Seismic attenuation technology for the advanced Virgo gravitational waves detector

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Henk Jan Bulten, Eric Hennes, Frans Mul.

9 June 2011
TIPP 2011, Chicago

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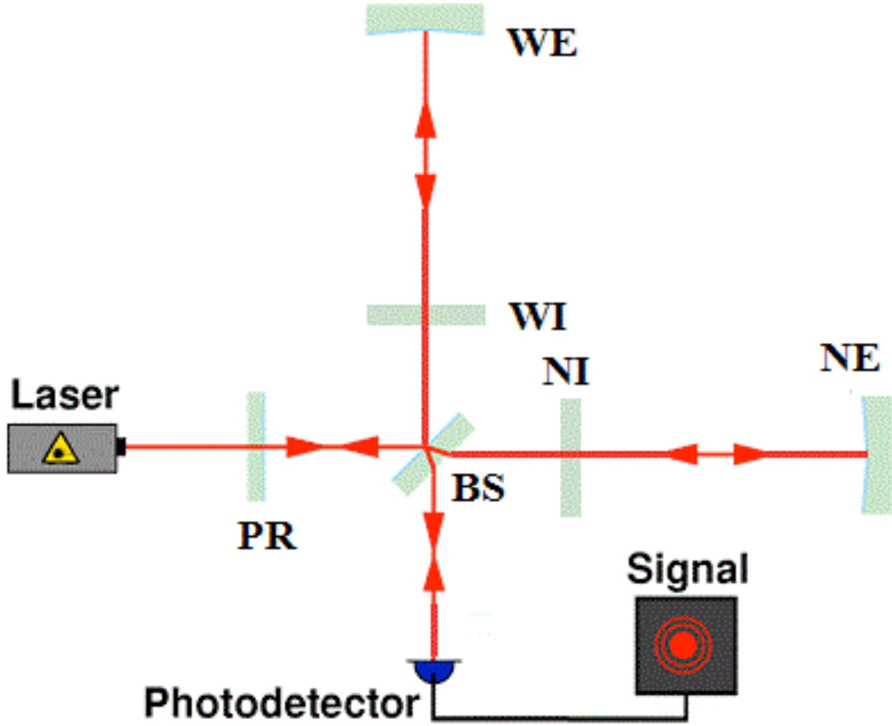
VIRGO

Virgo is a 3 km arm-length interferometer designed to measure gravitational waves



cross polarization

plus polarization

Global detector network:

LIGO - USA:
- 4 km Hanford
- 4 km Livingston

GEO 600 m - Germany

(LCGT 3 km - Japan)

(AIGO 4 km - Australia)

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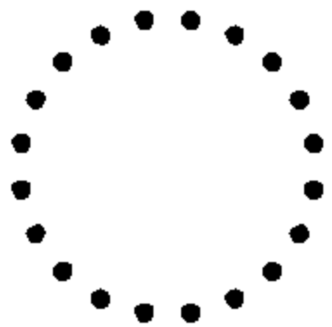

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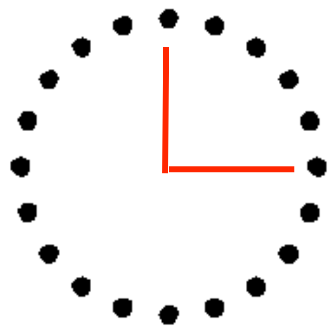

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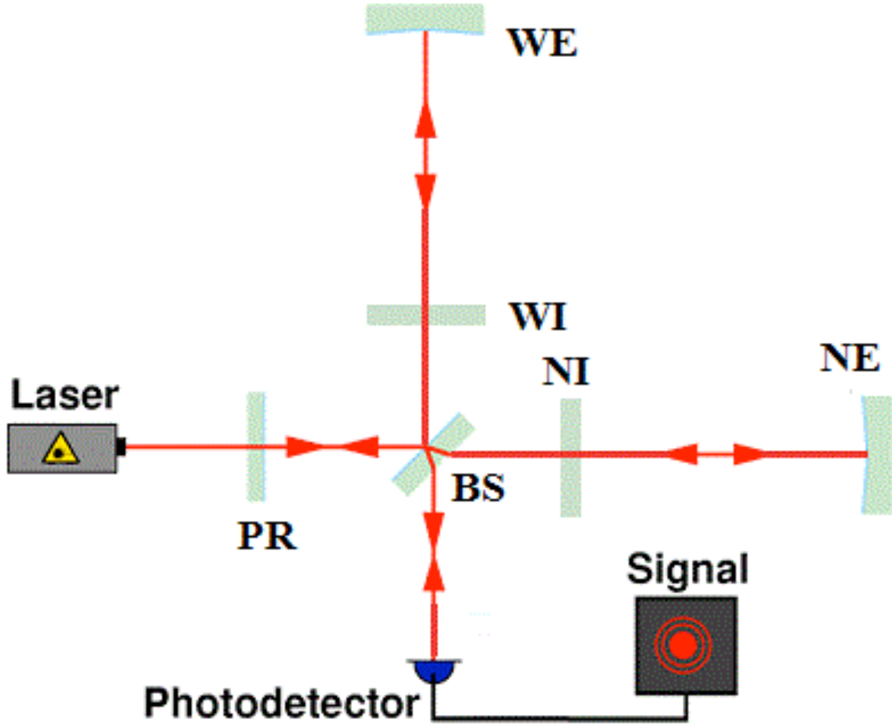

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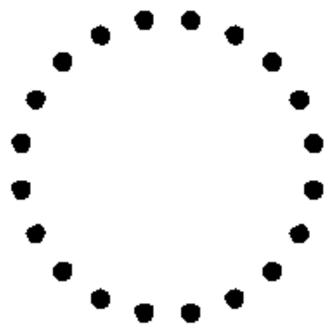

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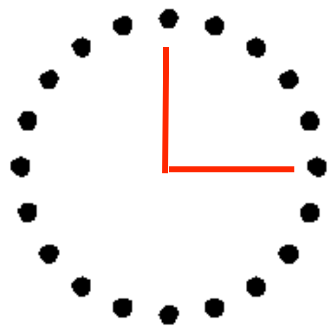
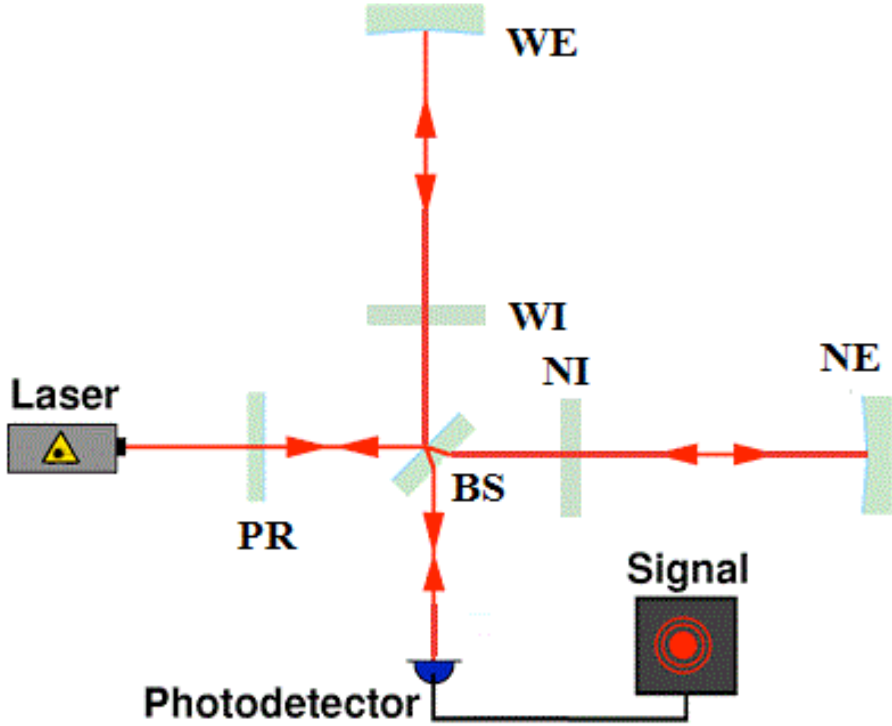


plus polarization

Strain, $h = \Delta L/L \approx 10^{-22}$



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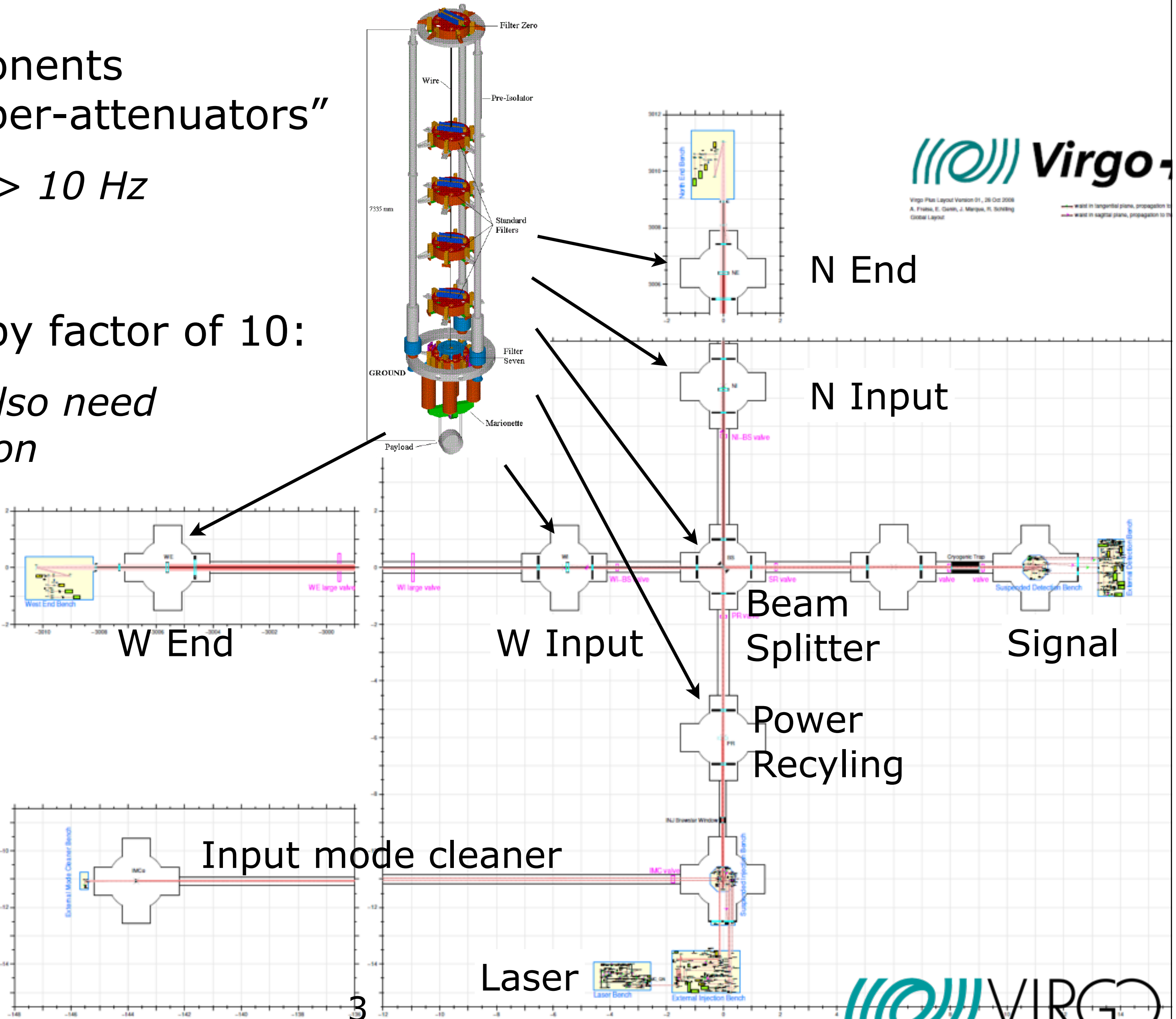
VIRGO

Seismic noise limits low frequency sensitivity of Virgo through vibration of optical components

- Main optical components suspended by “Super-attenuators”
  - *10^{14} suppression > 10 Hz*
- To improve strain by factor of 10:
  - *Optical benches also need seismic suppression*
  - *4 external*
  - *2 internal*
  - *Requirement: 40 dB > 10 Hz*



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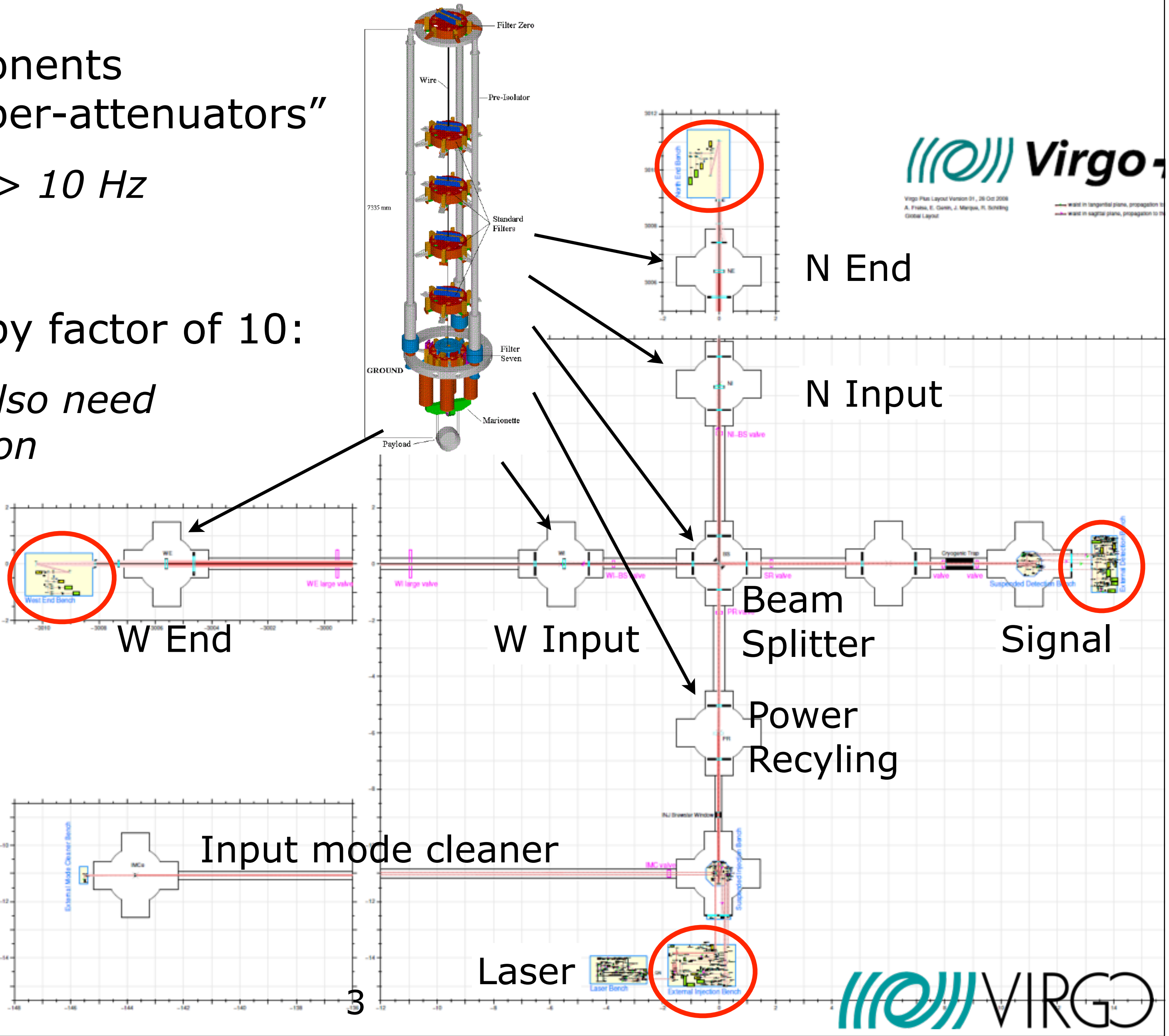

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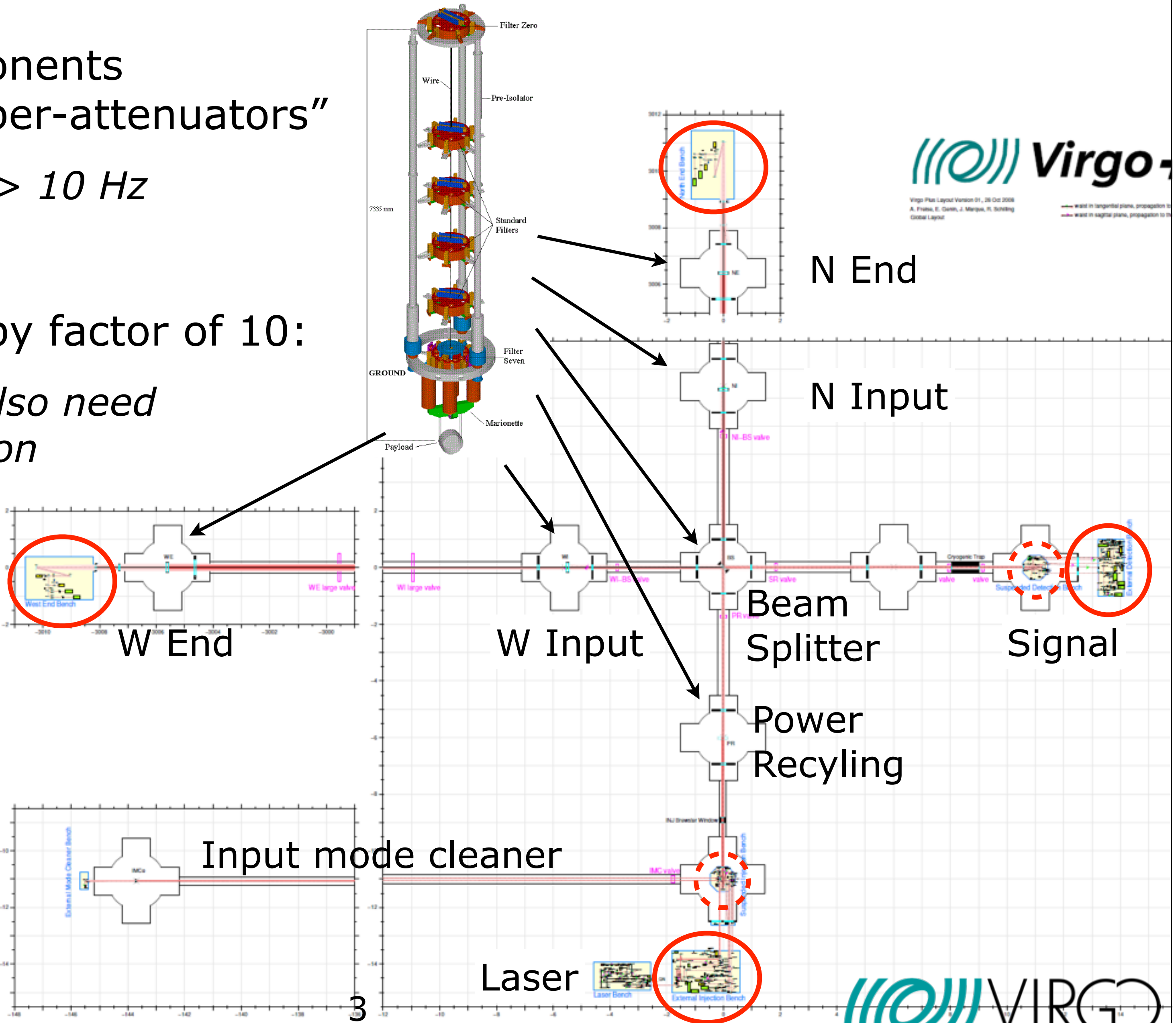

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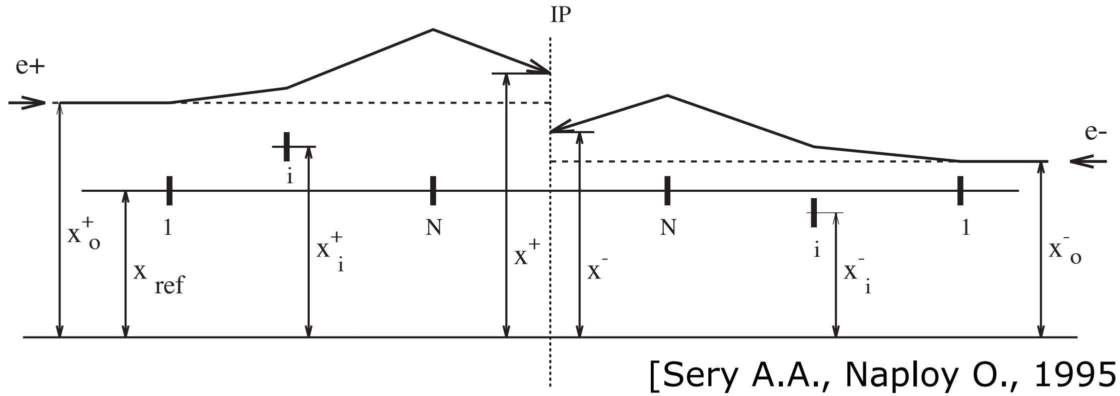
VIRGO

Seismic isolation systems also needed for future high-energy experiments

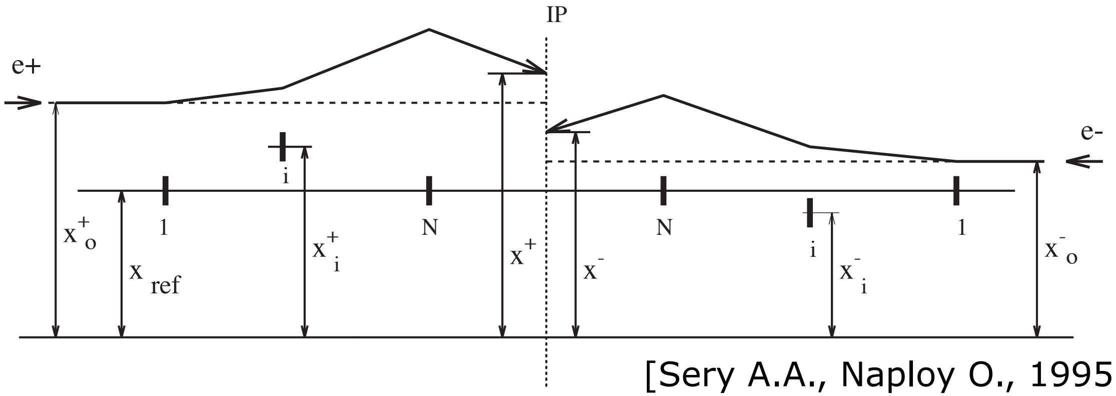


[Sery A.A., Naploy O., 1995]

Figure 7: Layout of the e^+ and e^- parts of a linear collider near interaction region.

Seismic isolation systems also needed for future high-energy experiments

- Linear Colliders CLIC / ILC
  - *Sub nano-meter interaction points*
  - *Quadrupole movement (ATL law)*



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Seismic isolation systems also needed for future high-energy experiments

- Linear Colliders CLIC / ILC
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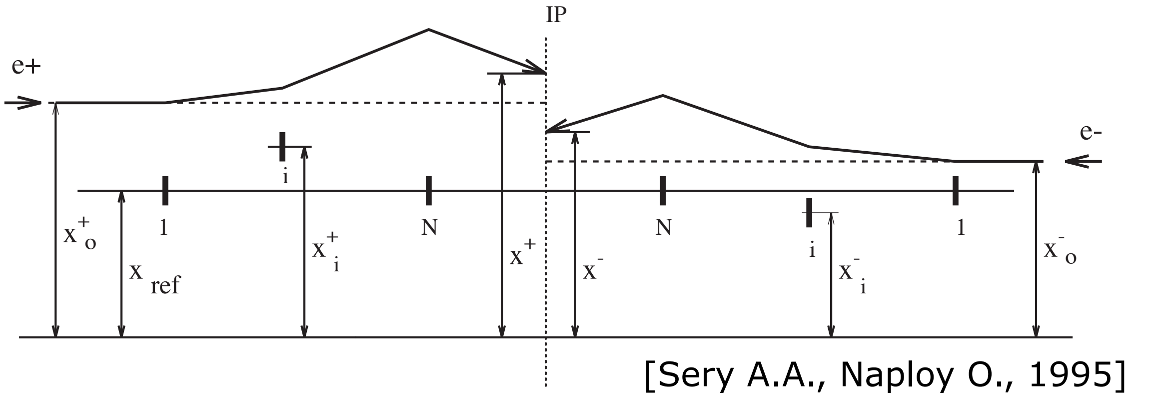
- Synchrotrons
  - *ESRF e-beam and X-ray vibration stability*



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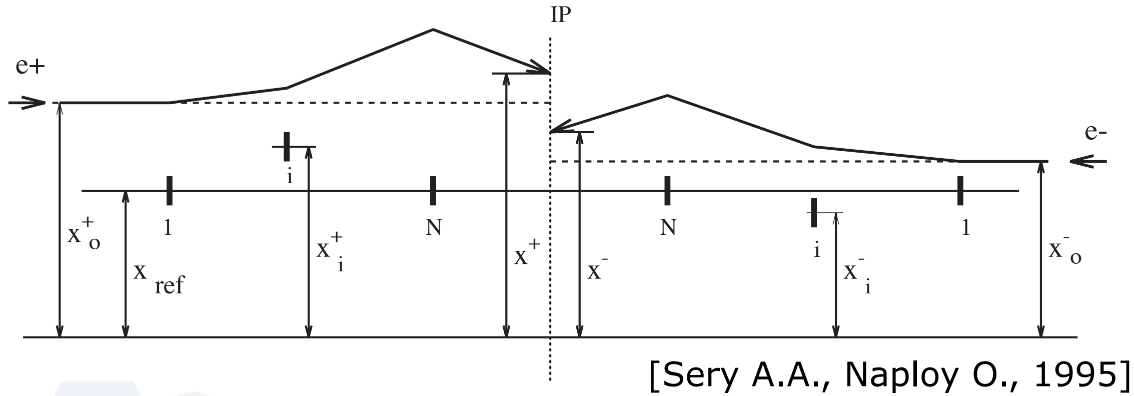

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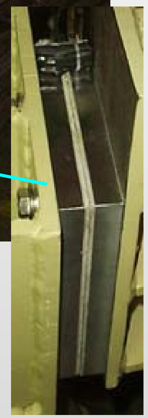
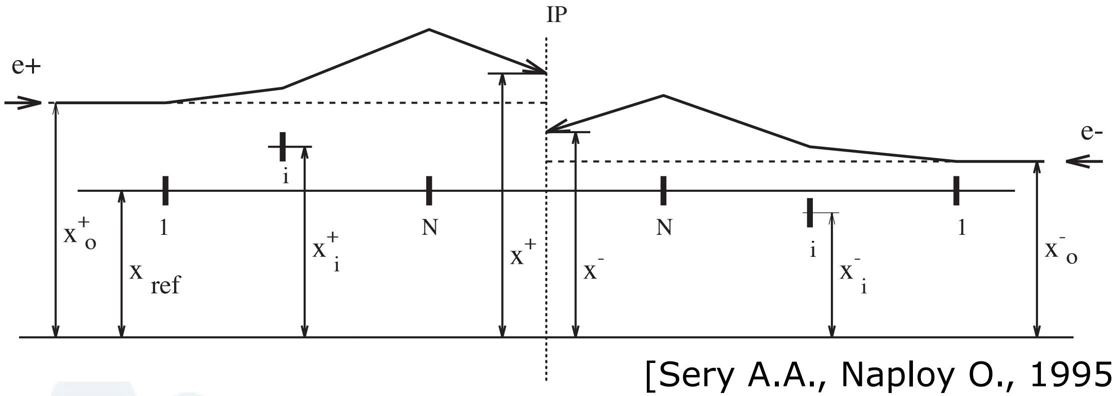


[Zang L., Lesourd M., 2010]

Seismic isolation systems also needed for future high-energy experiments

- Linear Colliders CLIC / ILC
  - *Sub nano-meter interaction points*
  - *Quadrupole movement (ATL law)*
- Synchrotrons
  - *ESRF e-beam and X-ray vibration stability*
- Free electron lasers
  - *DESY*
  - *FLASH Groningen*



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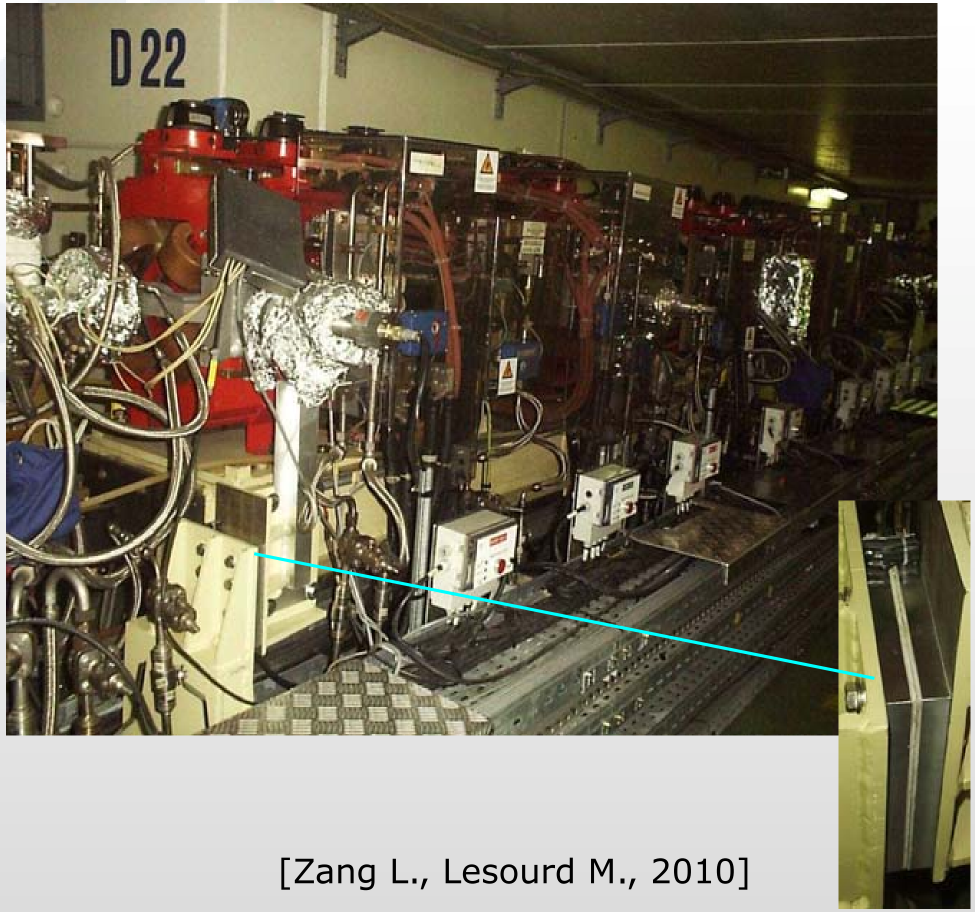

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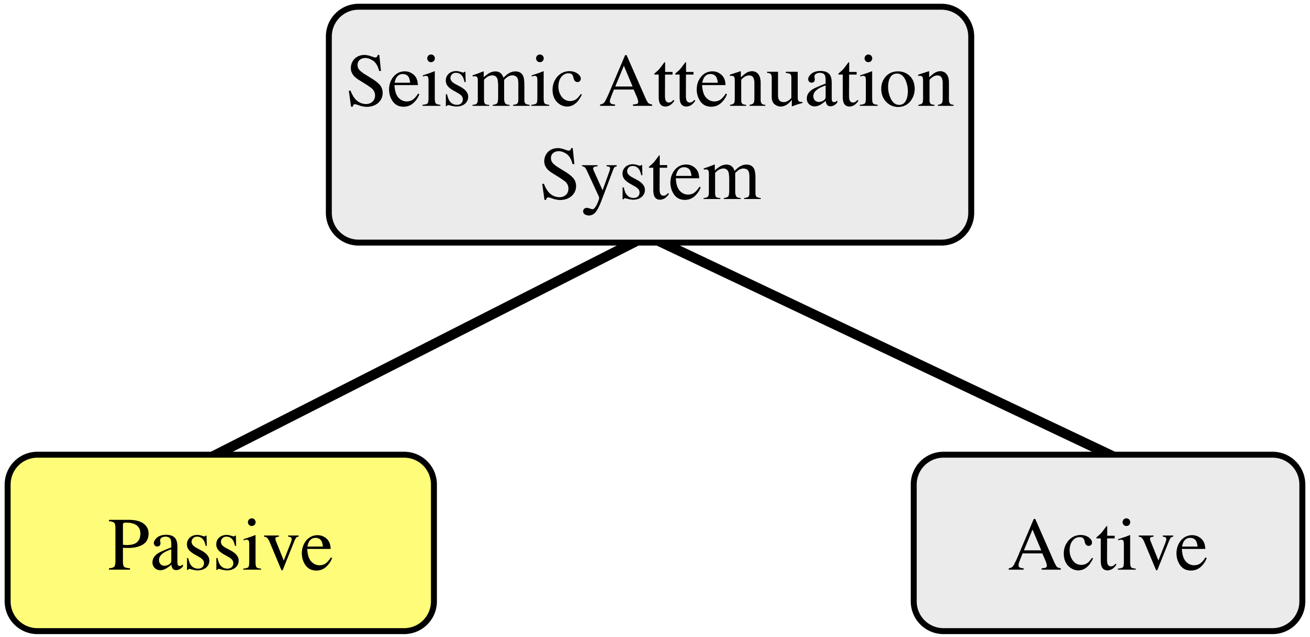
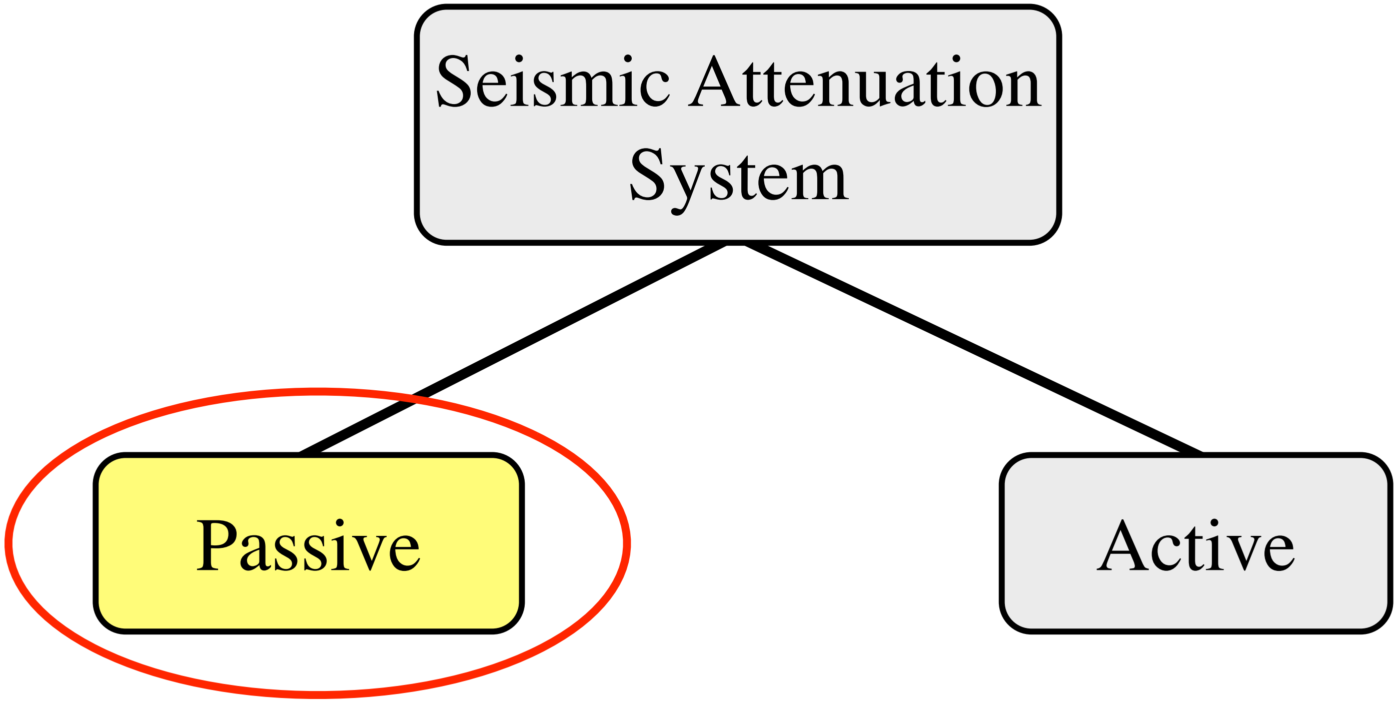

Seismic Attenuation System
Passive
Active


Seismic Attenuation System
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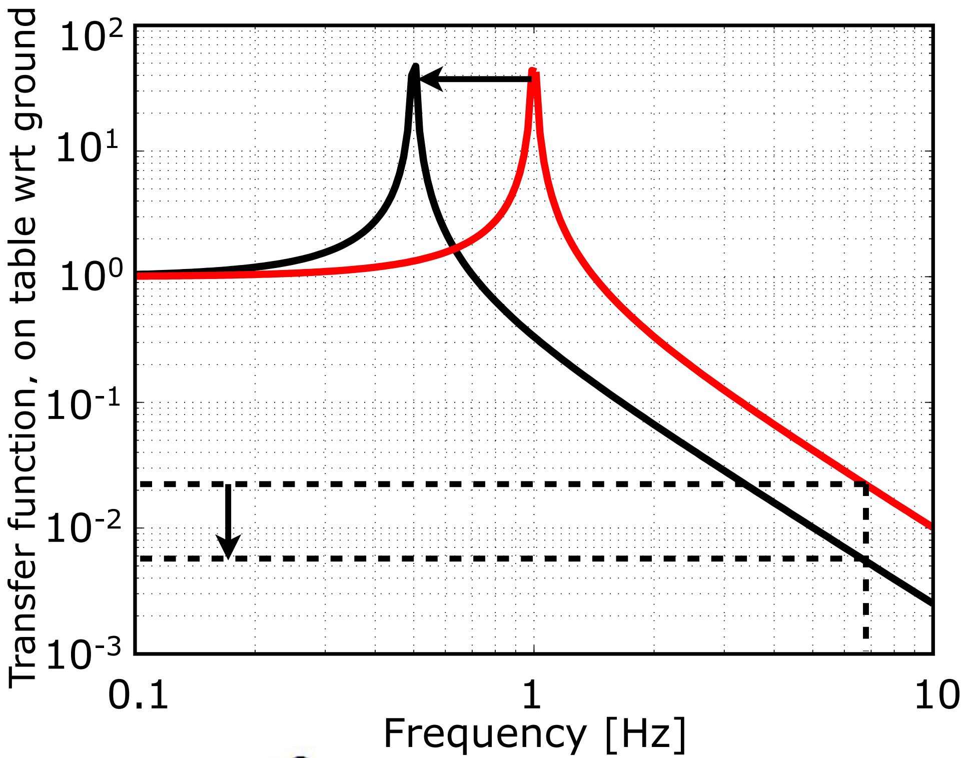
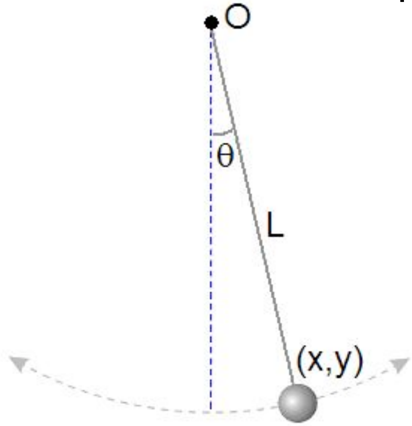
A passive isolation system utilizes the transfer function of harmonic oscillators

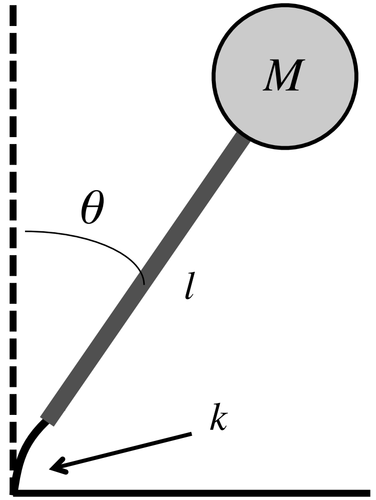
- Harmonic oscillator is a 2nd order low pass filter
- Transfer function:
  - *=1 @ low frequencies*
  - *> 1 @* $\omega_0 = \sqrt{\frac{g}{l}}$ / $\omega_0 = \sqrt{\frac{k}{M}}$
  - *~1/f^2 above resonance frequency*
- Virgo/LIGO measure from 10 Hz
  - *Want 40 dB suppression > a few Hz*
  - *Need $f_0 \approx 0.3$ Hz ⇒ $l \approx 3$ m*
  - *Long pendulum / low stiffness and high mass*
  - ***Or**, use short inverted pendulum and geometric anti-springs*



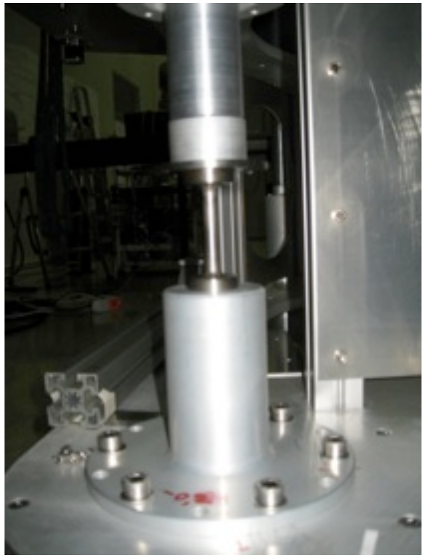


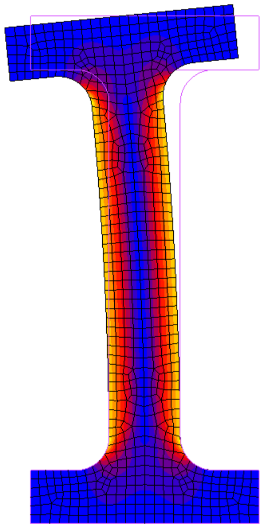
Inverted pendulum are used for the horizontal attenuation stage

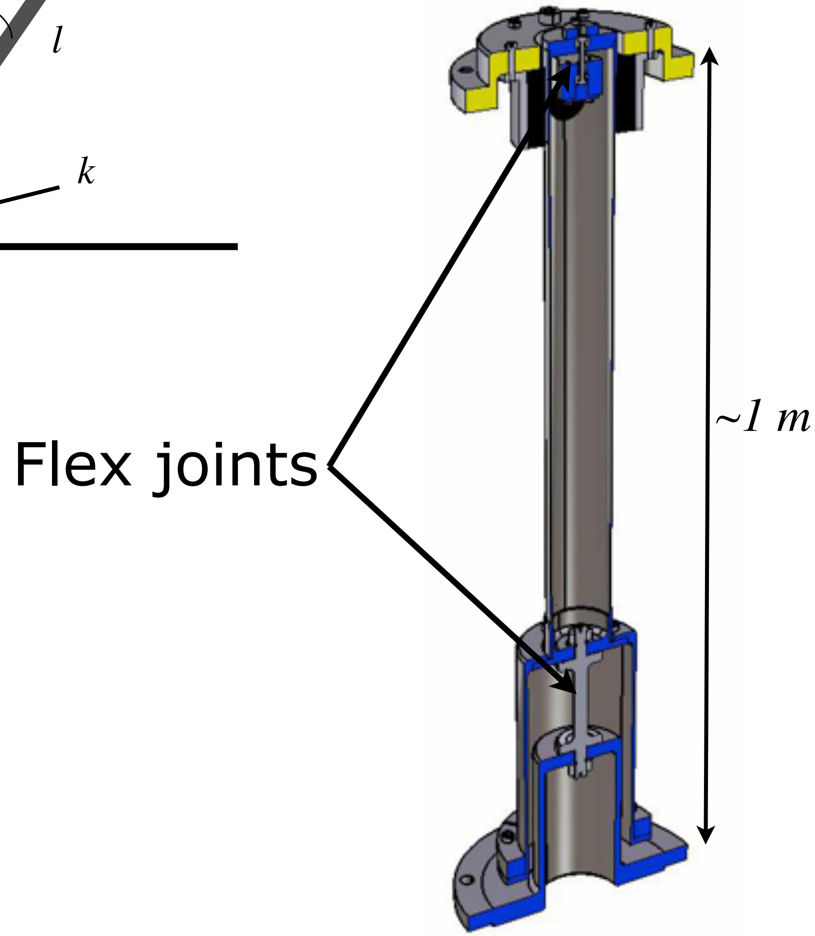
- Gravity acts as an anti-spring
- Maraging steel flex joints provide stiffness, k
- Tunable in eigenfrequency by adjusting the supported mass
- Counter weights can be tuned to adjust center of percussion



$$\omega_0 = \sqrt{\frac{k}{M} - \frac{g}{l}}$$

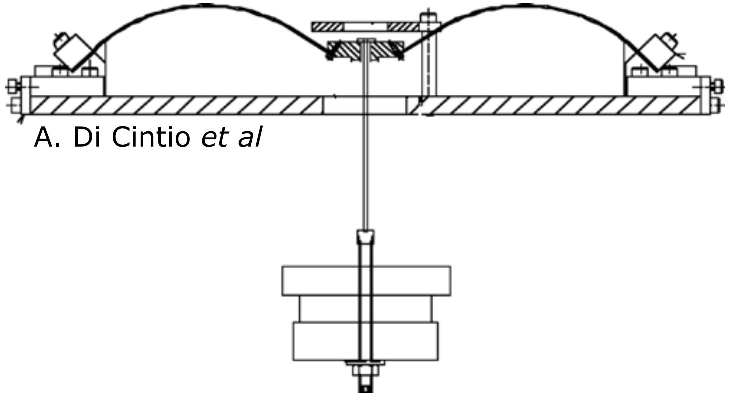




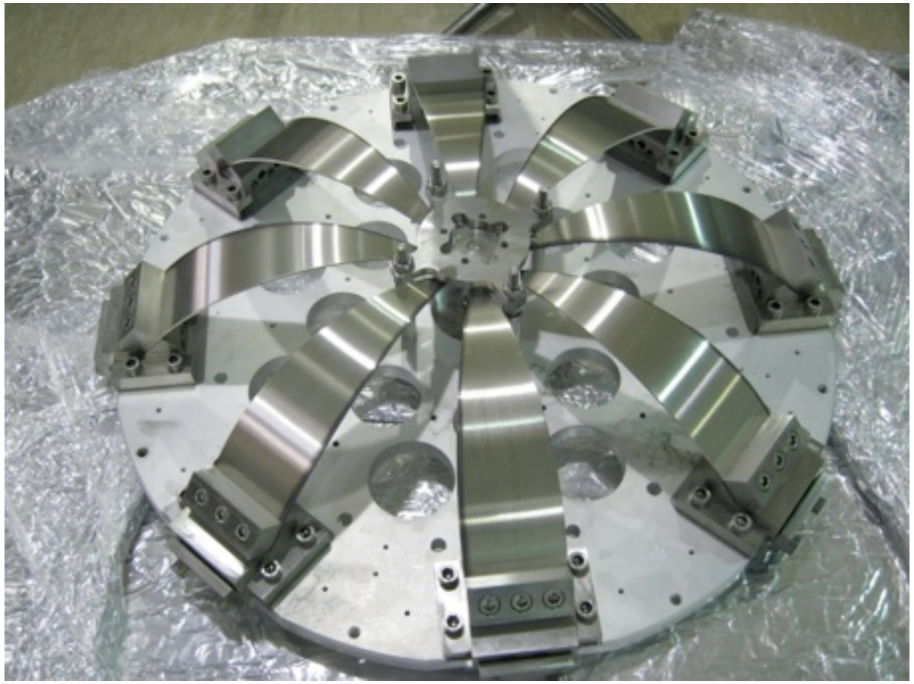


Geometrical anti-springs are used to provide vertical attenuation

- 8 maraging steel blades in pairs
- Opposite blades push against each other
  - *High pressure in radial direction*
  - *Low **vertical stiffness** in equilibrium position*
  - *Low eigenfrequency (~300 mHz)*
  - *Still capable of supporting high masses (~320 kg)*
  - *Strong filtering (>40 dB @ 10 Hz)*



A. Di Cintio *et al*



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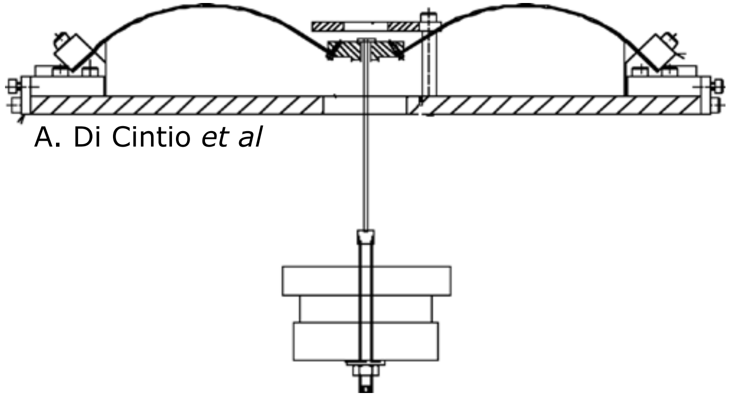

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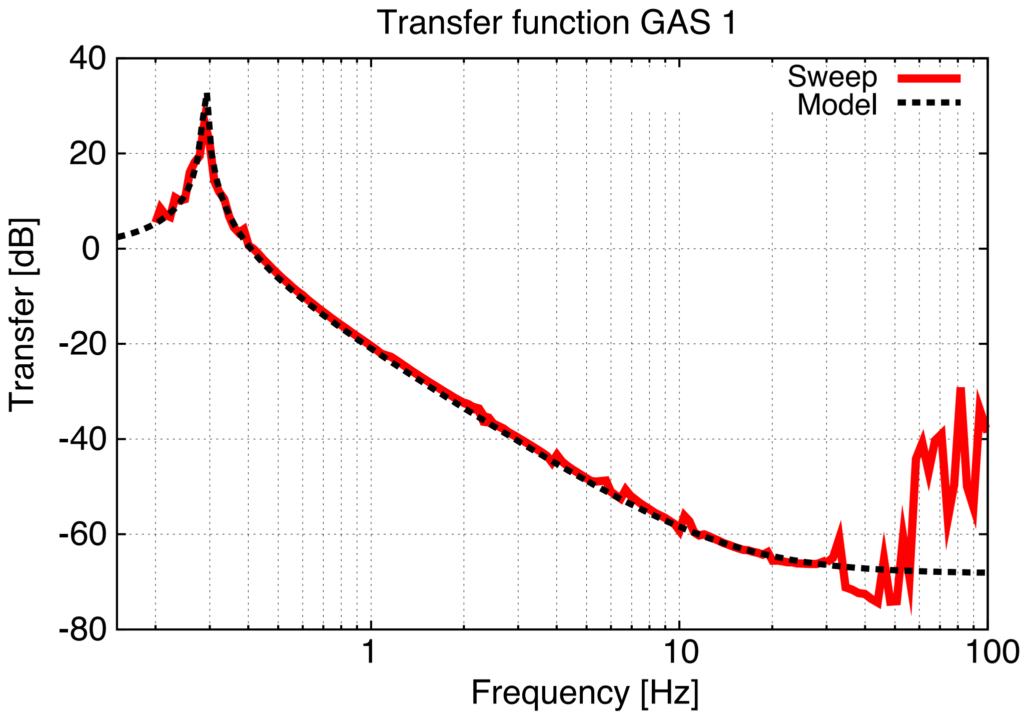
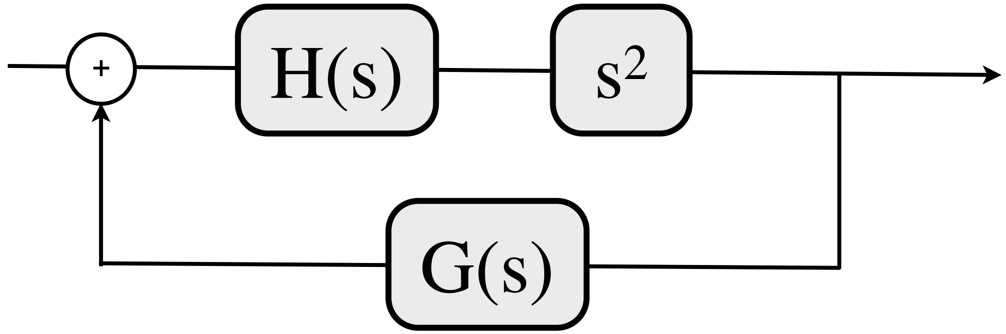
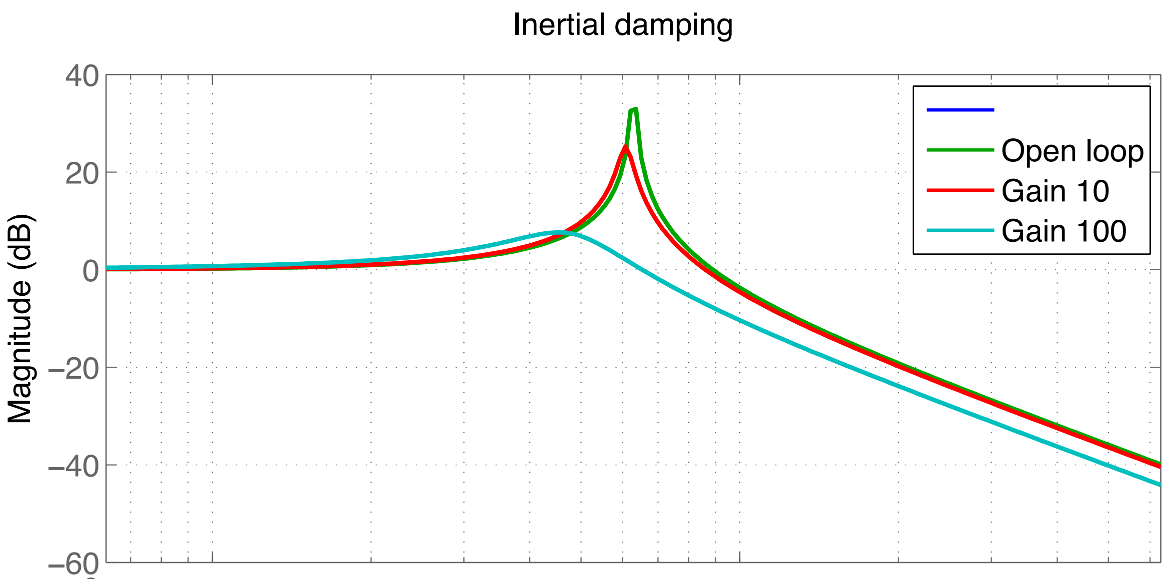


Movie GAS resonance

Feed-back control system used to actively damp resonant frequencies

- Order of magnitude damping of resonant frequencies required
- Calculations performed on Linux PC
- Feed-back done with electromagnetic actuators
- Sensing relies on displacement sensors and accelerometers





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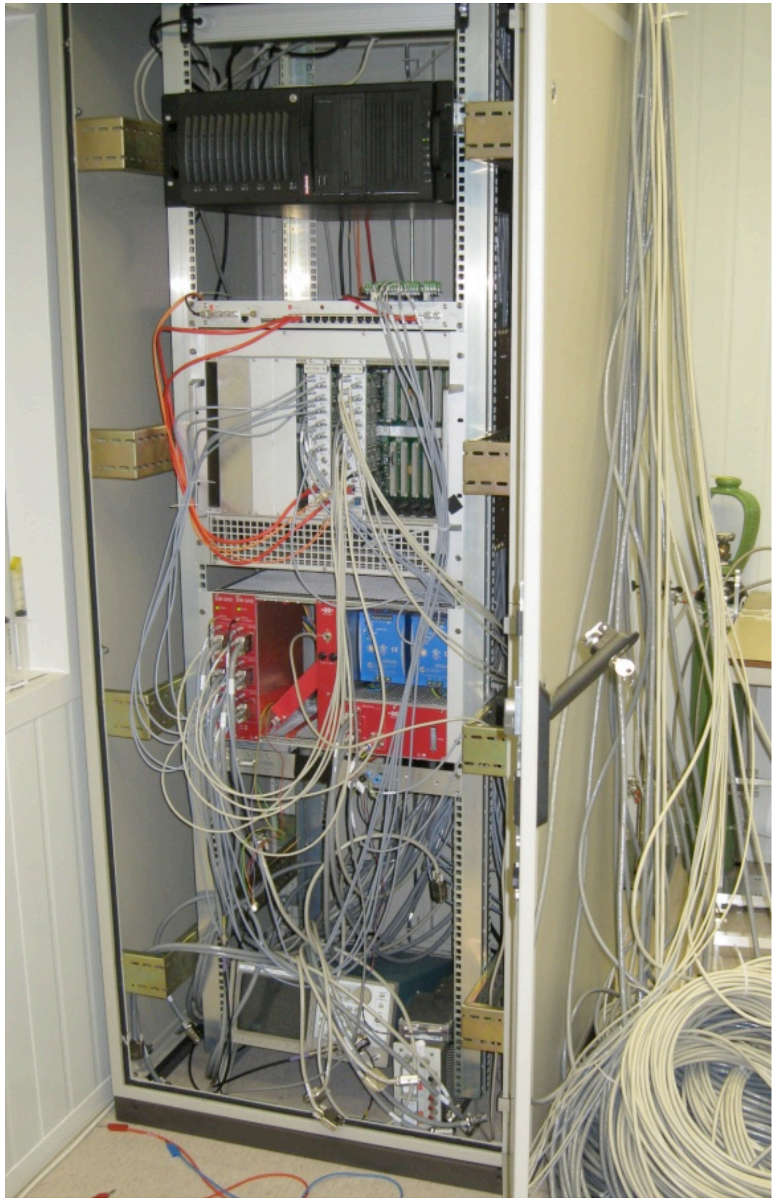
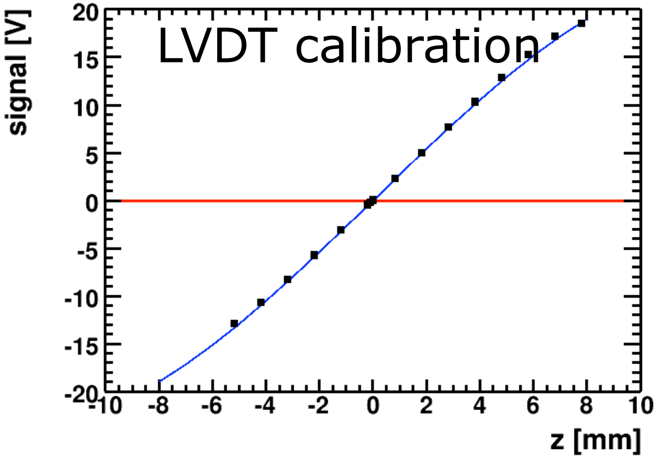
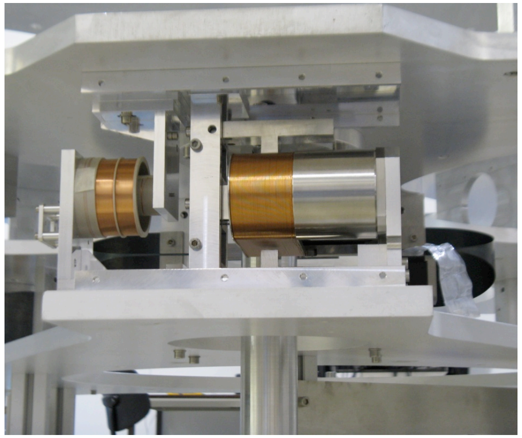


Sensing of bench motion for resonance damping

- Linear Voltage Displacement Transducers (LVDT)
  - *DC -> a few Hz*
  - *~ 1 nm sensitivity*





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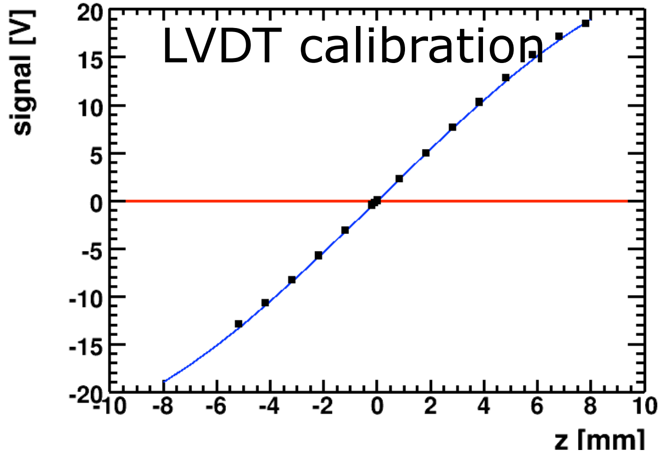
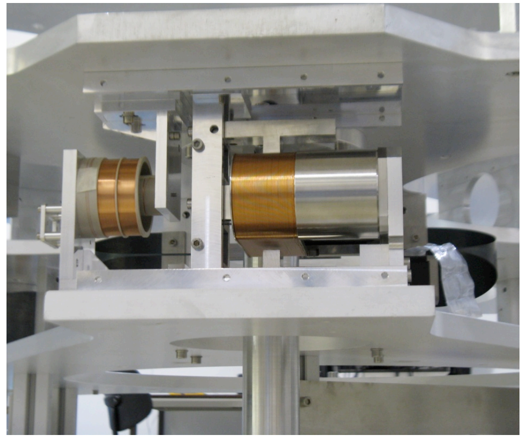
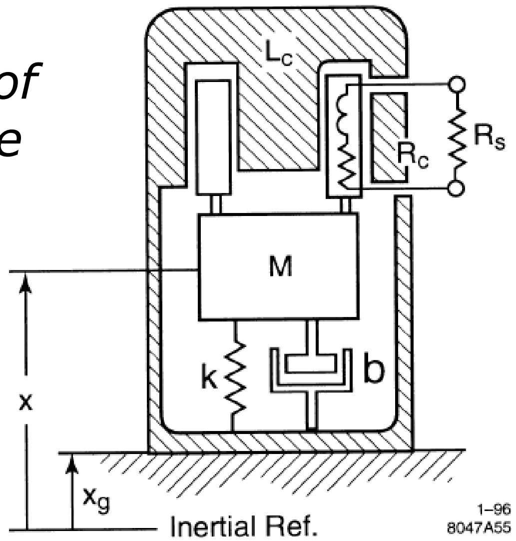
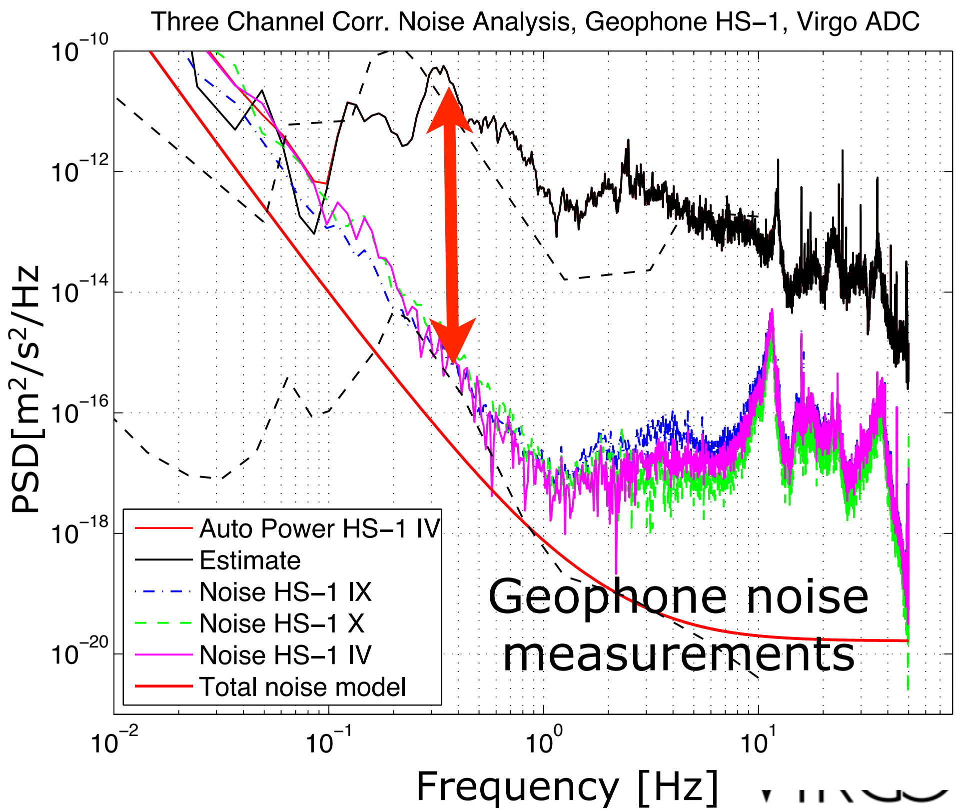




- Accelerometers (Geophones)
  - *Eigenfrequency ~ 1 Hz*
  - *0.1 -> 100 Hz*
  - *Motion 4 orders of mag. above noise level*





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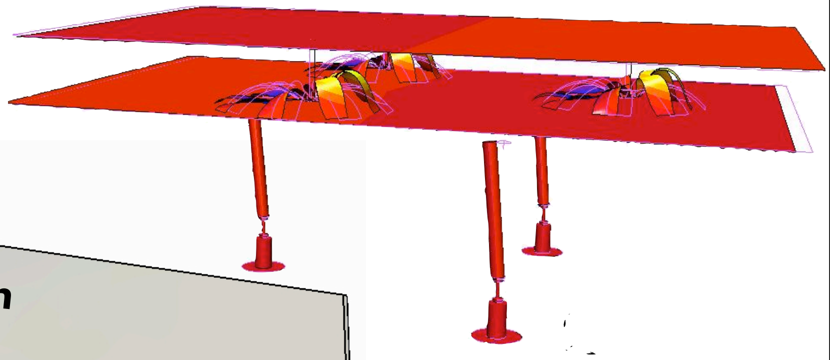
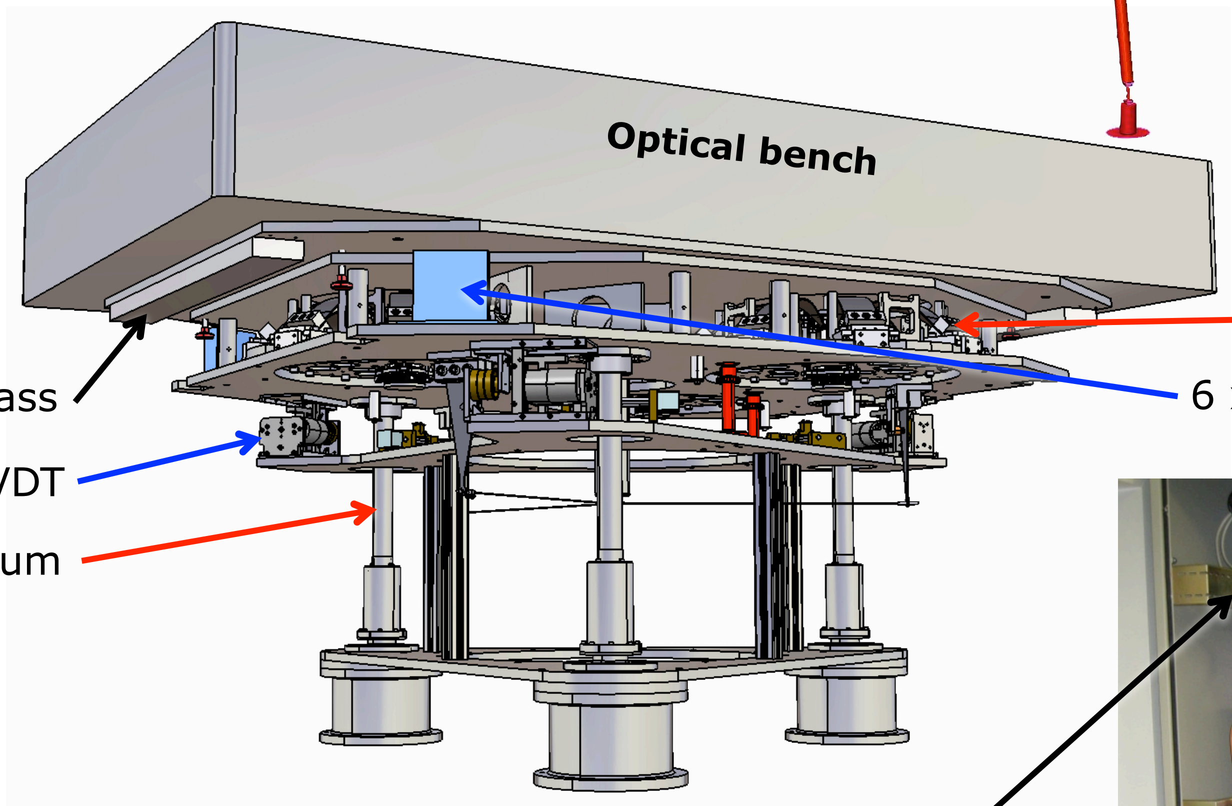
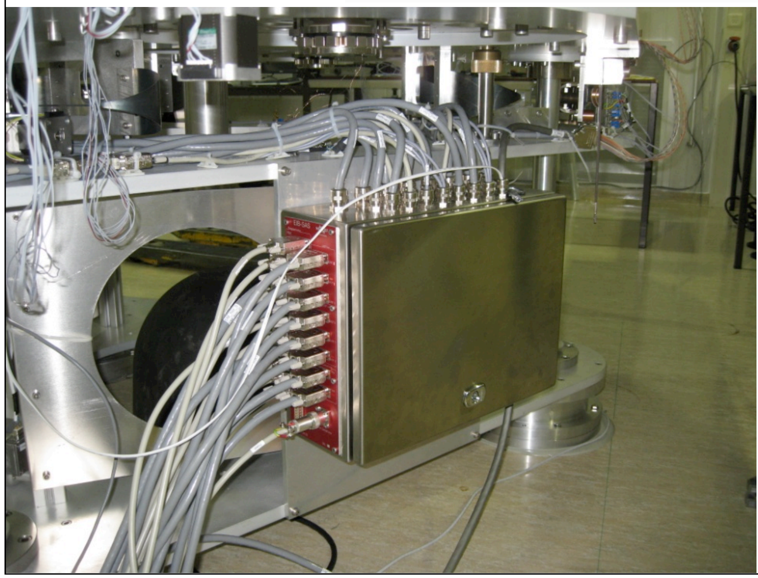
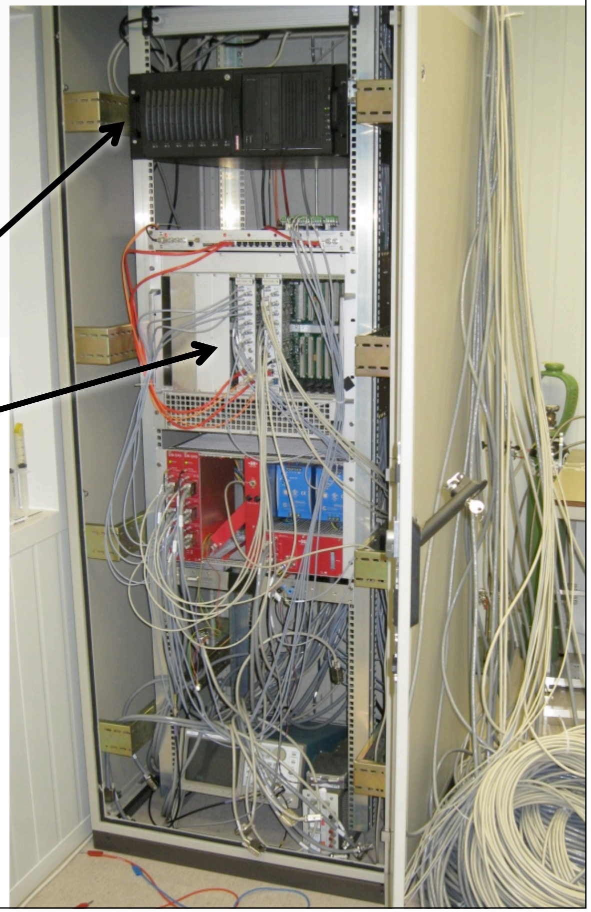
Putting it all together...



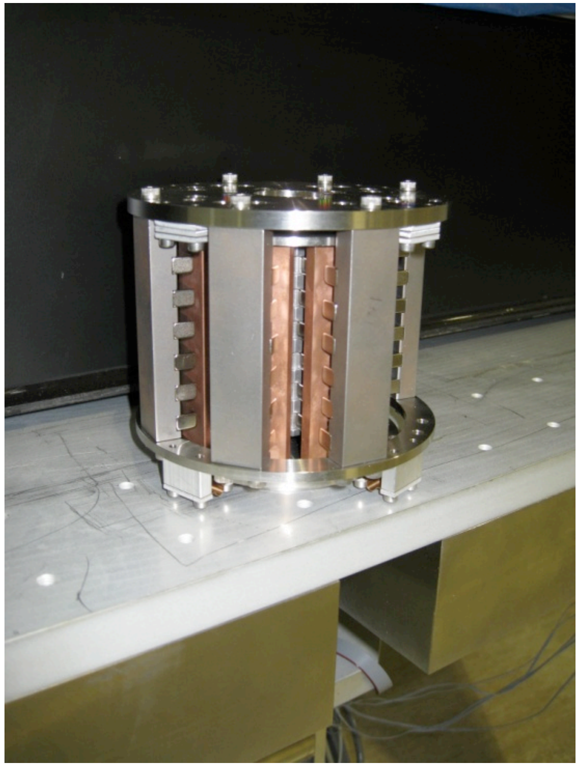


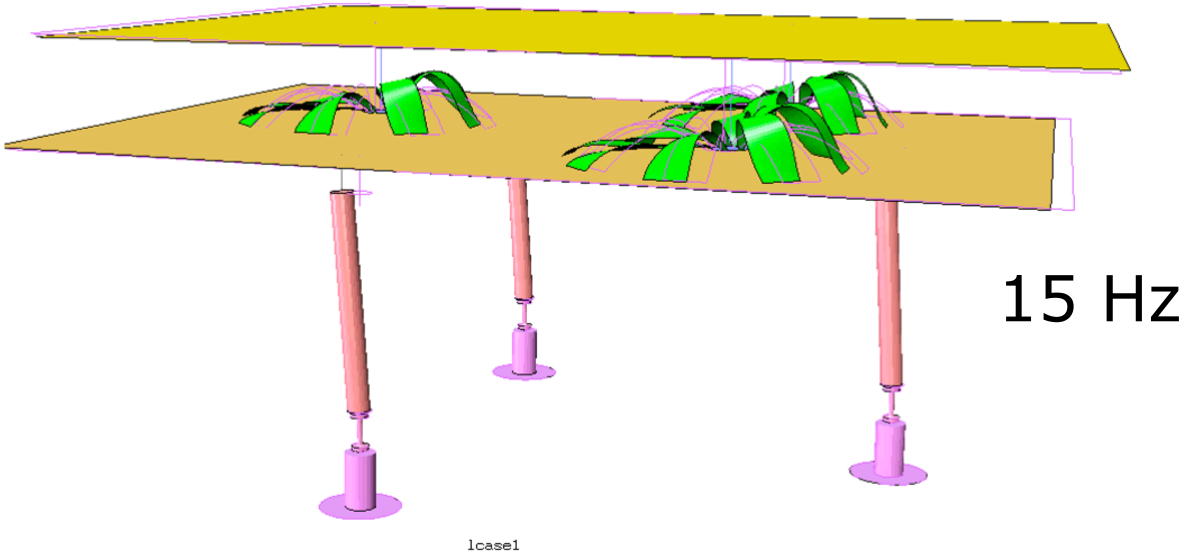




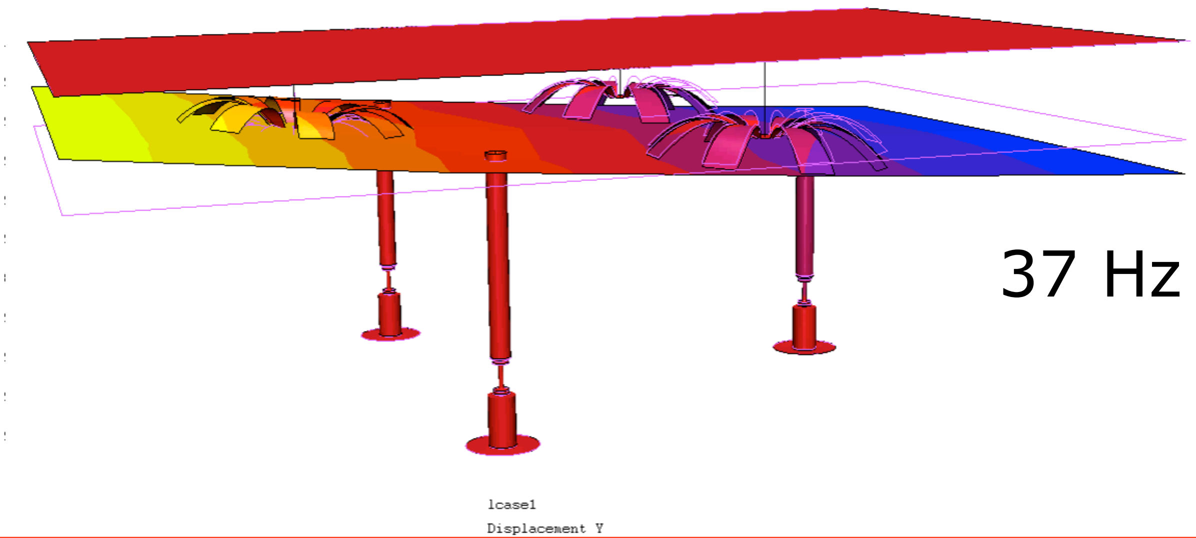
Peaks at higher frequencies are understood internal modes that can be damped

- Eddy-current dampers
- Horizontal and vertical dampers tunable to mode frequencies



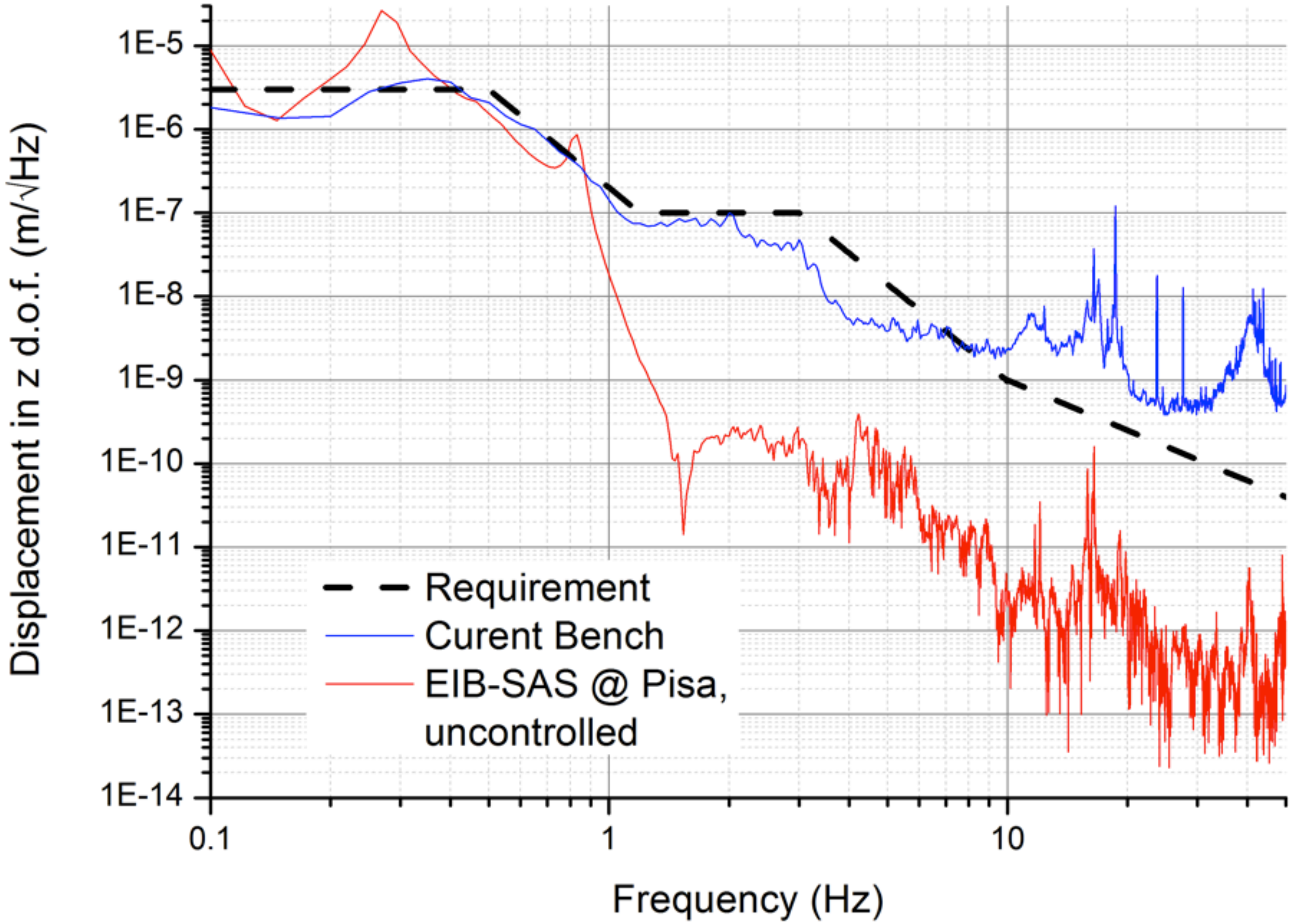


15 Hz

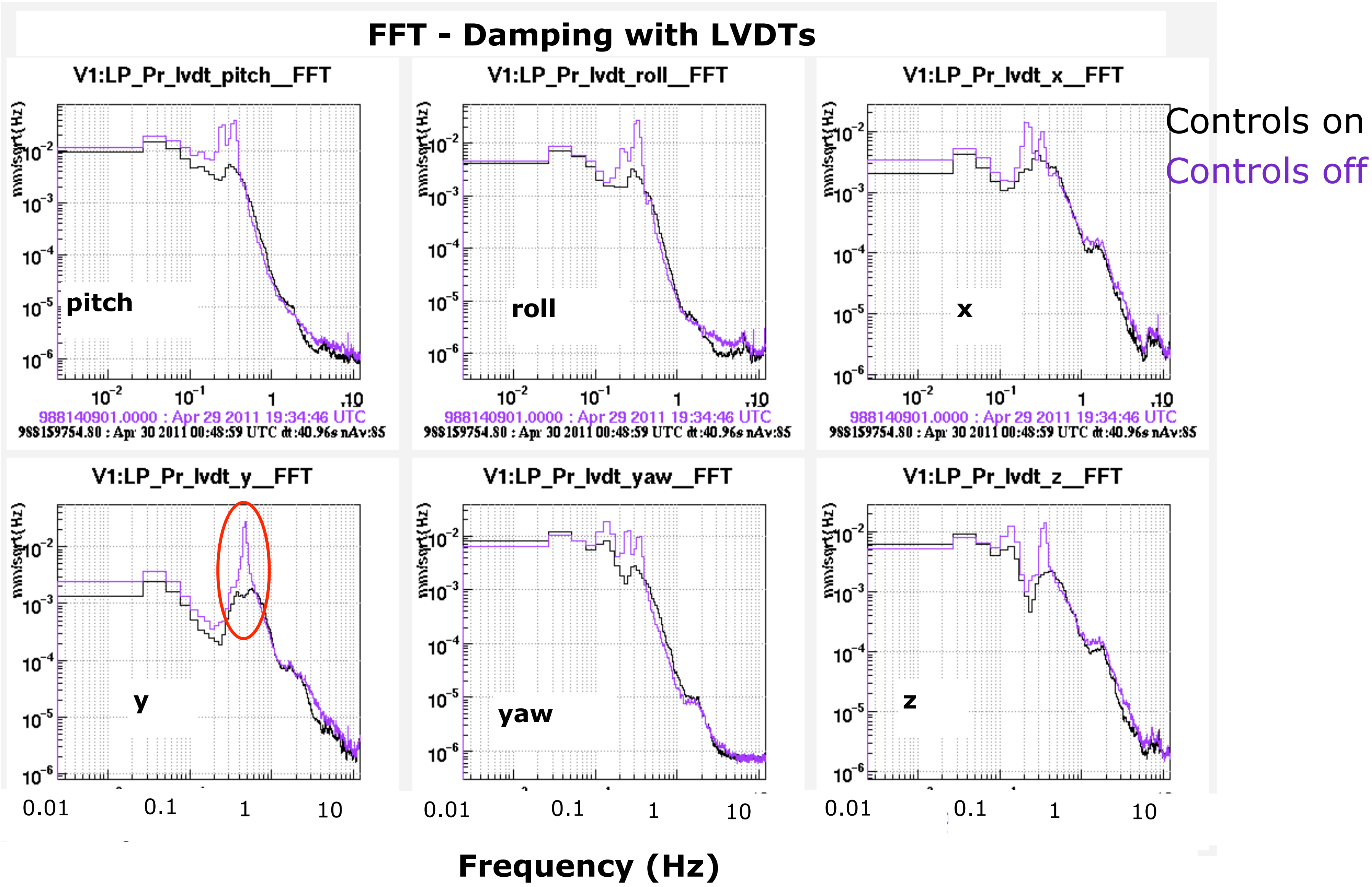


37 Hz

Eddy-current dampers reduce internal mode vibrations below requirements



Active control system can damp resonant frequencies by an order of magnitude



Summary

- Seismic motion
  - *Induces noise in gravitational waves detectors*
  - *Seismic noise also an issue in (future) high-energy experiments*
- Optical bench - Seismic attenuation system
  - *Passive*
  - *Based on harmonic oscillator transfer functions*
  - *Inverted pendulum and anti-springs used at low f_0*
  - *Attenuation of 40 dB available above 10 Hz*
  - *Resonant frequencies damped by active feedback system*
  - *Internal modes removed by tunable eddy-current dampers*

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