Improving the bandwidth and stability of interferometric gravitational wave detectors with suspension point interferometers

Yoichi Aso

Columbia University, New York, NY, USA
University of Tokyo, Tokyo, Japan

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LIGO Caltech

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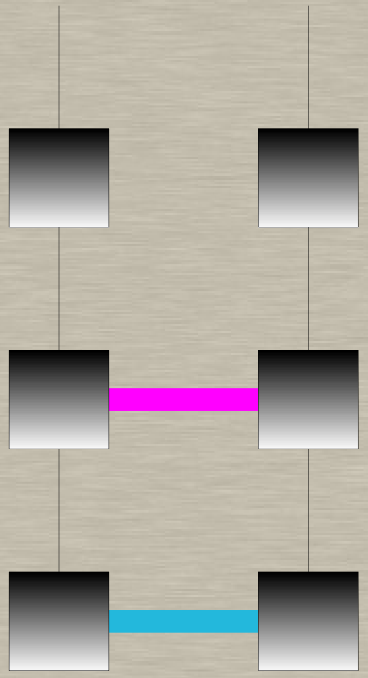
NASA Goddard Space Flight Center

Introduction

Suspension Point Interferometer (SPI)

Active vibration isolation scheme

Sensor: Auxiliary laser interferometers



Advantages

- Ultra low-frequency vibration isolation
- Reduced RMS mirror motion
  - Stabilization of the interferometer
  - Robust lock acquisition
  - Reduction of various technical noises

Prototype Experiment : 1.5m Fabry-Perot interferometers

Maximum 40dB noise suppression below 10Hz (in spectrum)

Mirror RMS motion → 1/9

Mirror RMS speed → 1/7

Future detectors: Advanced LIGO, LCGT, LISA

Seismic Noise

The dominant noise source of ground based GW detectors at low frequencies

Various impacts on the IFO

Duty cycle

- Stability of the interferometer
- Readiness of lock acquisition

Sensitivity

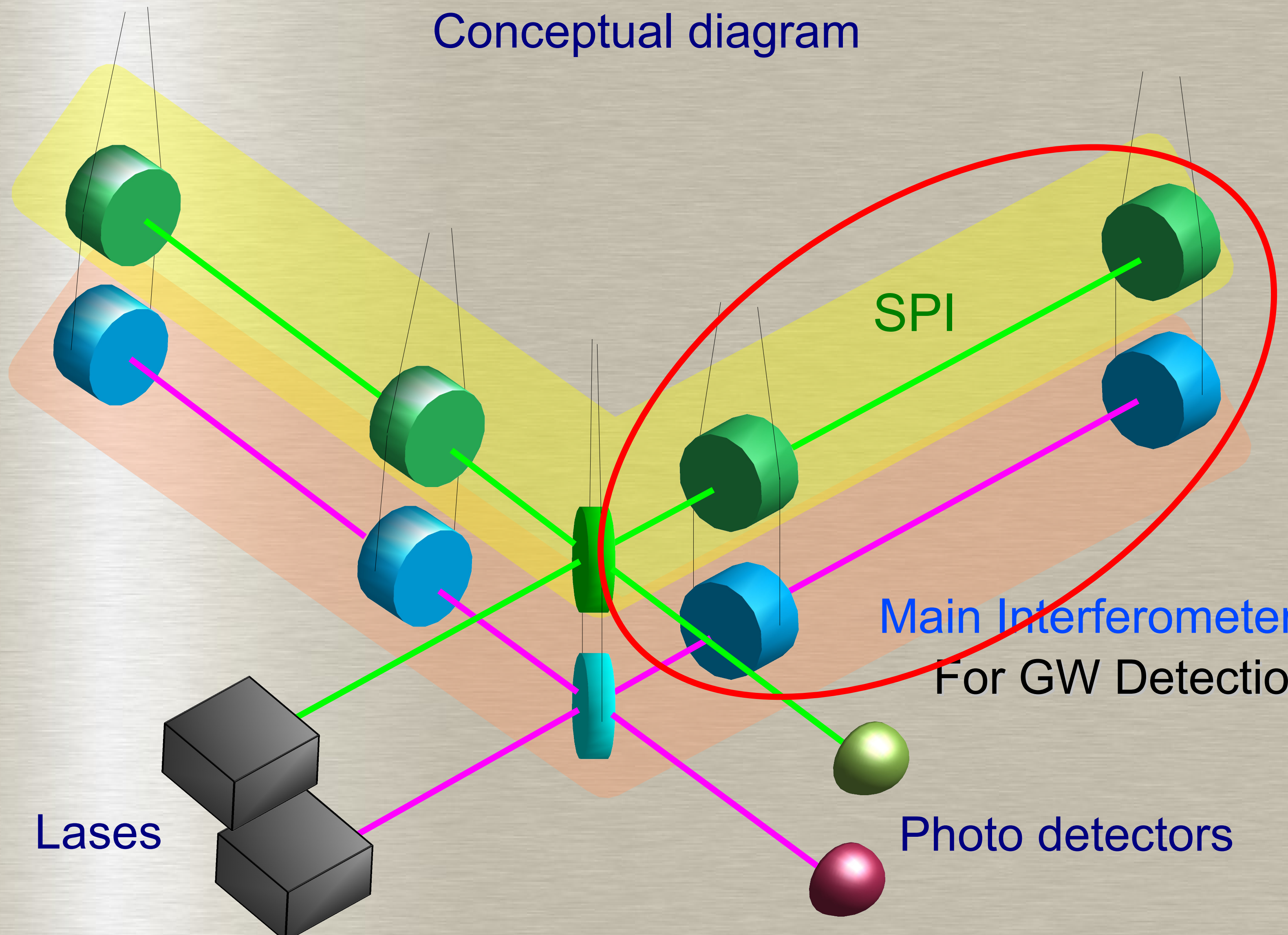
- Low frequency limit of the observation band
- Noises coupled with low frequency mirror motions
  - Up-conversion by non-linearity of the detection system
  - Horizontal-Pitch coupling by feedback forces
  - Contrast defect (Laser noises)
  - Actuator noise

Suspension Point Interferometer

Originally proposed by Drever (1987)

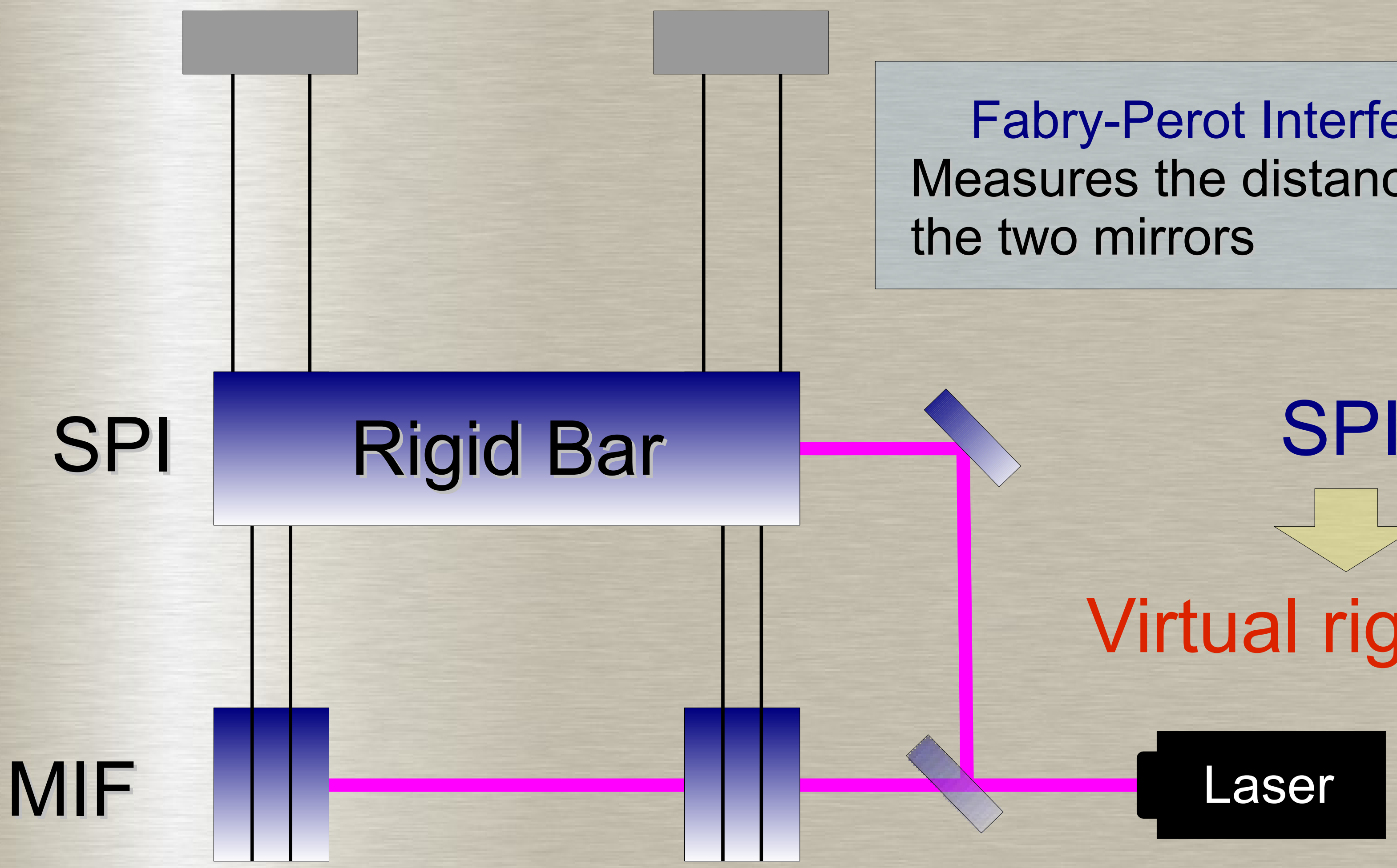
Several possible configurations

Conceptual diagram



Working Principle of SPI: Fabry-Perot Arm

SPI is locked

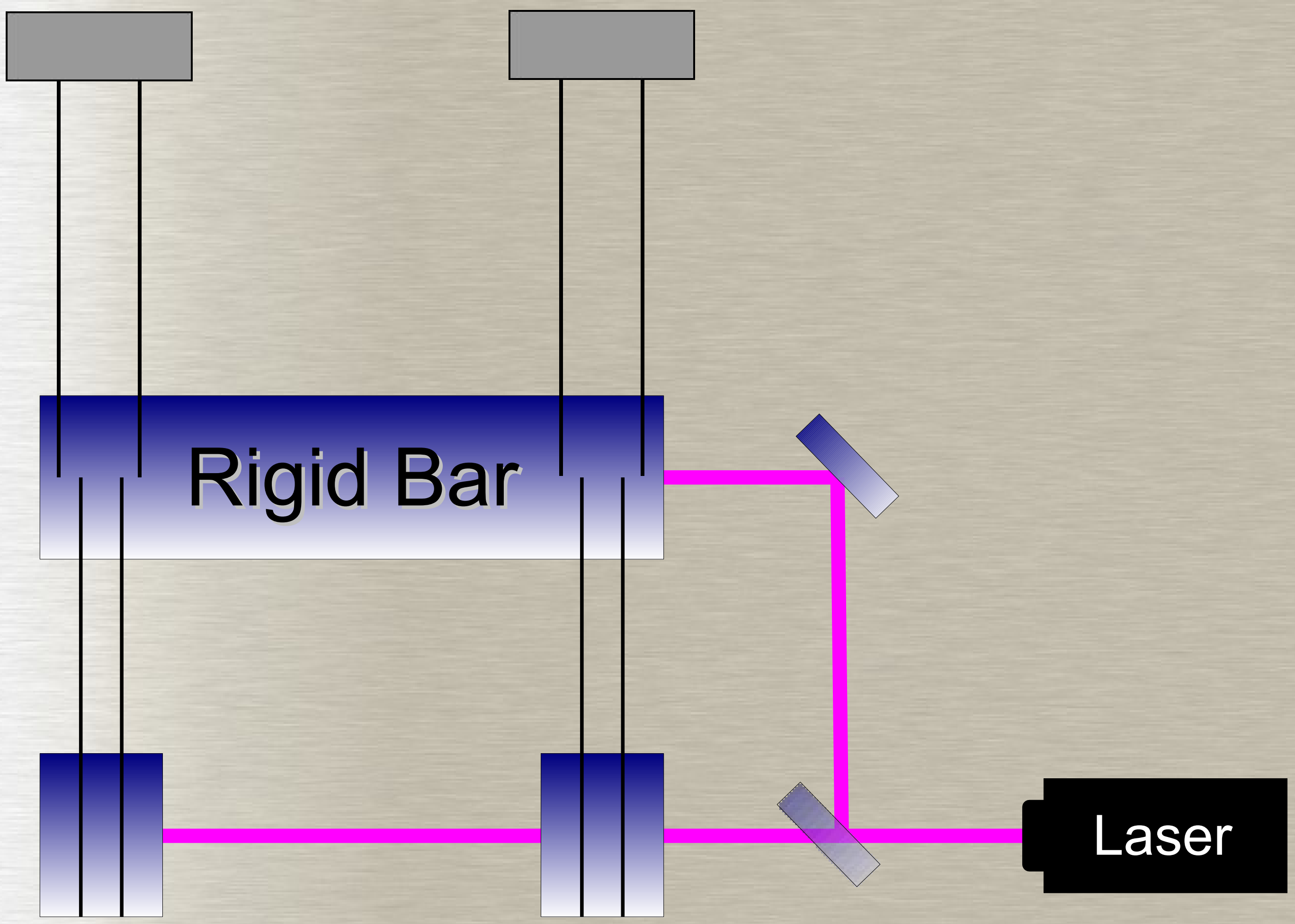


Fabry-Perot Interferometer
Measures the distance between the two mirrors

SPI
Virtual rigid bar

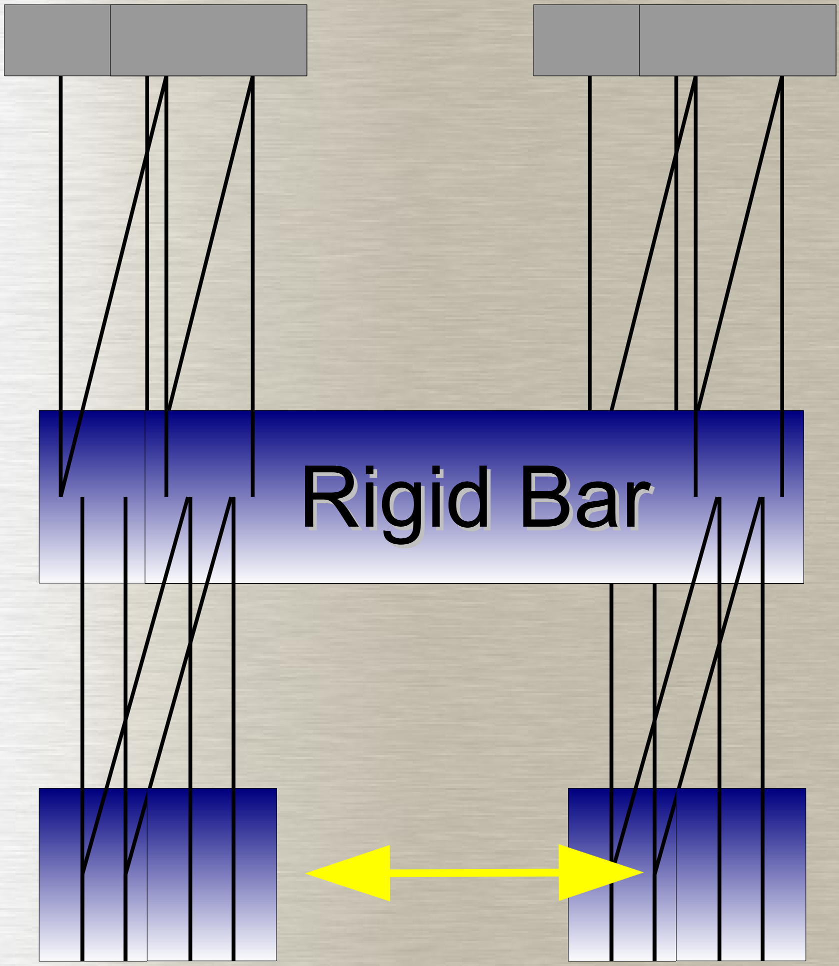
Working Principle of SPI: Fabry-Perot Arm

Differential Seismic Motion



Working Principle of SPI: Fabry-Perot Arm

Common mode motion



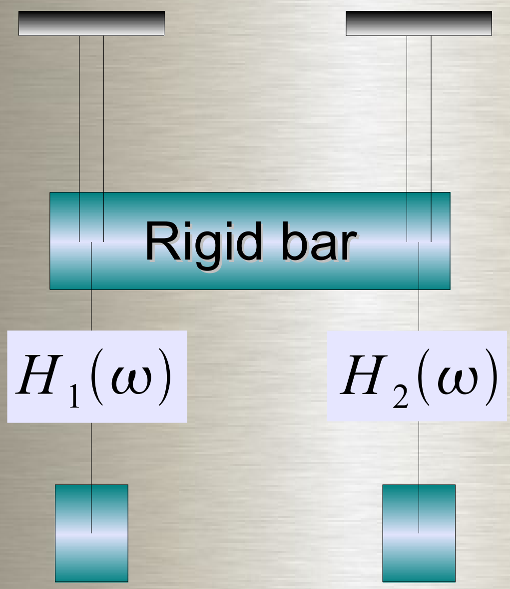
Identical Pendulums

Asymmetry ?

No change in the distance

Theoretical Performance

Common Mode Rejection Ratio (CMRR)



Transfer functions:

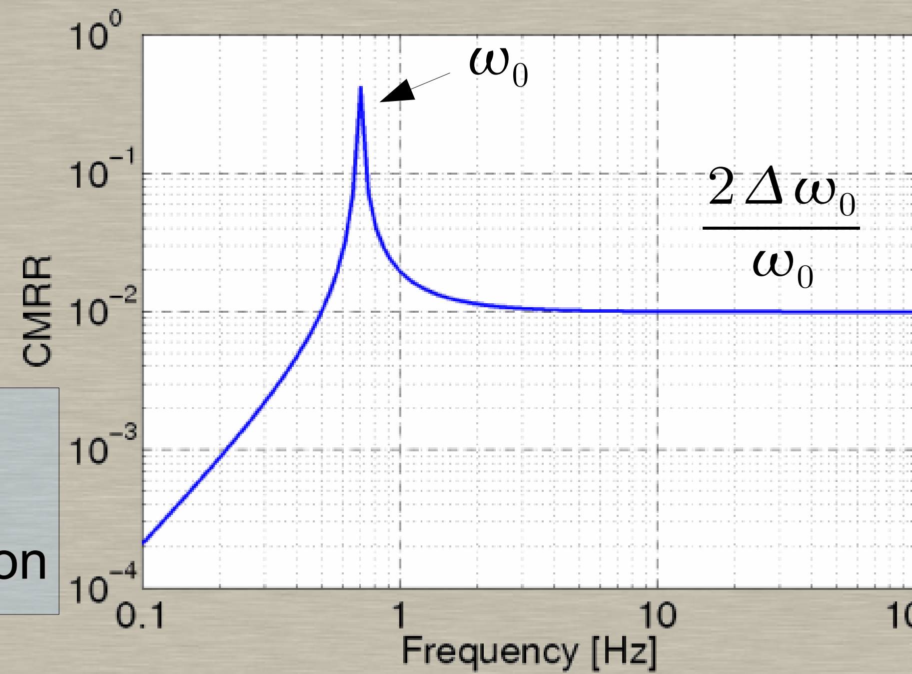
$$H_1(\omega), H_2(\omega)$$

$$CMRR = 2\left|\frac{H_1 - H_2}{H_1 + H_2}\right|$$

Conversion coefficient

Common motion → Differential motion

Example: CMRR of Simple Pendulums



Simple Pendulums

Average resonant frequency: ω_0

Resonant frequency difference: $\Delta\omega_0$

$$\mathrm{CMRR} = \frac{2\Delta\omega_0}{\omega_0}$$

Symmetry is Important

Other Factors

- Cross coupling from other degrees of freedom
  Vertical, Pitch, Yaw etc ...
- Control gain of SPI
- Noise of SPI

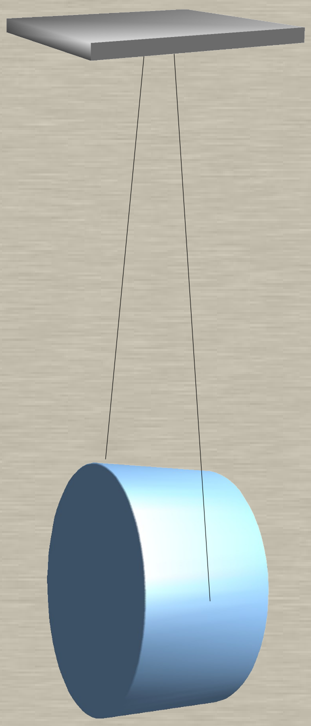
Comparison with conventional vibration isolation techniques

Passive vibration isolation

Harmonic Oscillators (Pendulum etc.)

Isolation: above the resonant frequency

Low frequency: no isolation
At the resonance: vibration amplification



Active vibration isolation

Measure the ground motion by sensors

Cancel the vibration by feedback

Widely used sensor: Accelerometers
No DC sensitivity

Reference frame
= Local inertial frame

SPI

Measuring the same DOF as the main interferometer

Global Displacement Sensor DC sensitivity

DC vibration isolation performance

Low noise (Potentially as good as the main interferometer)

Advantages of SPI

Characteristics

- Low Noise Sensor
- Displacement sensor (global sensor) ⟶ DC sensitivity

⟶ Ultra low-frequency vibration isolation

Benefits

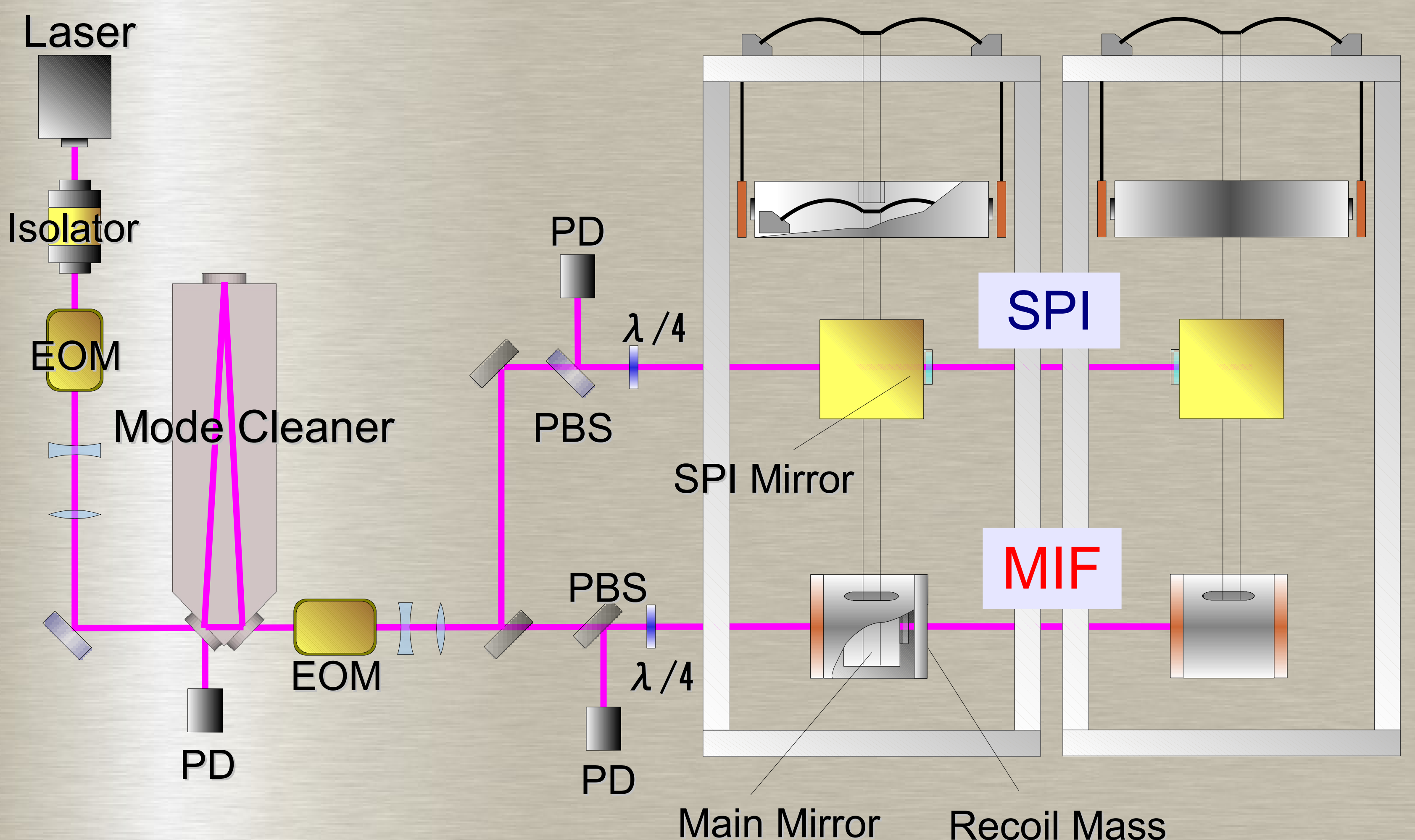
- Direct reduction of seismic noise in the observation band
- Reduction of the RMS motion of the mirrors
  - Stable Operation
  - Robust lock acquisition

  } Duty Cycle Improvement
  - Technical noises
    - Laser noises
    - Actuator noises
    - Up-conversion noise by non-linearity

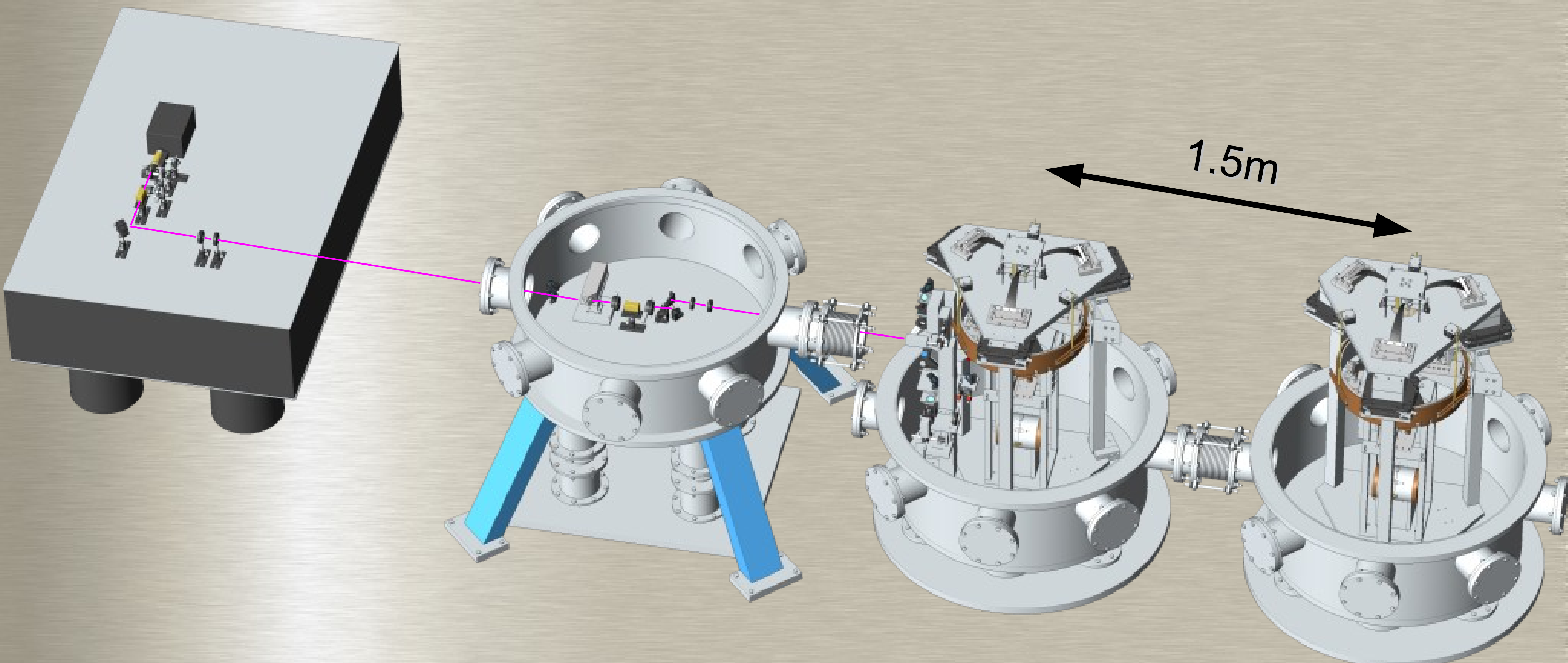
to name a few

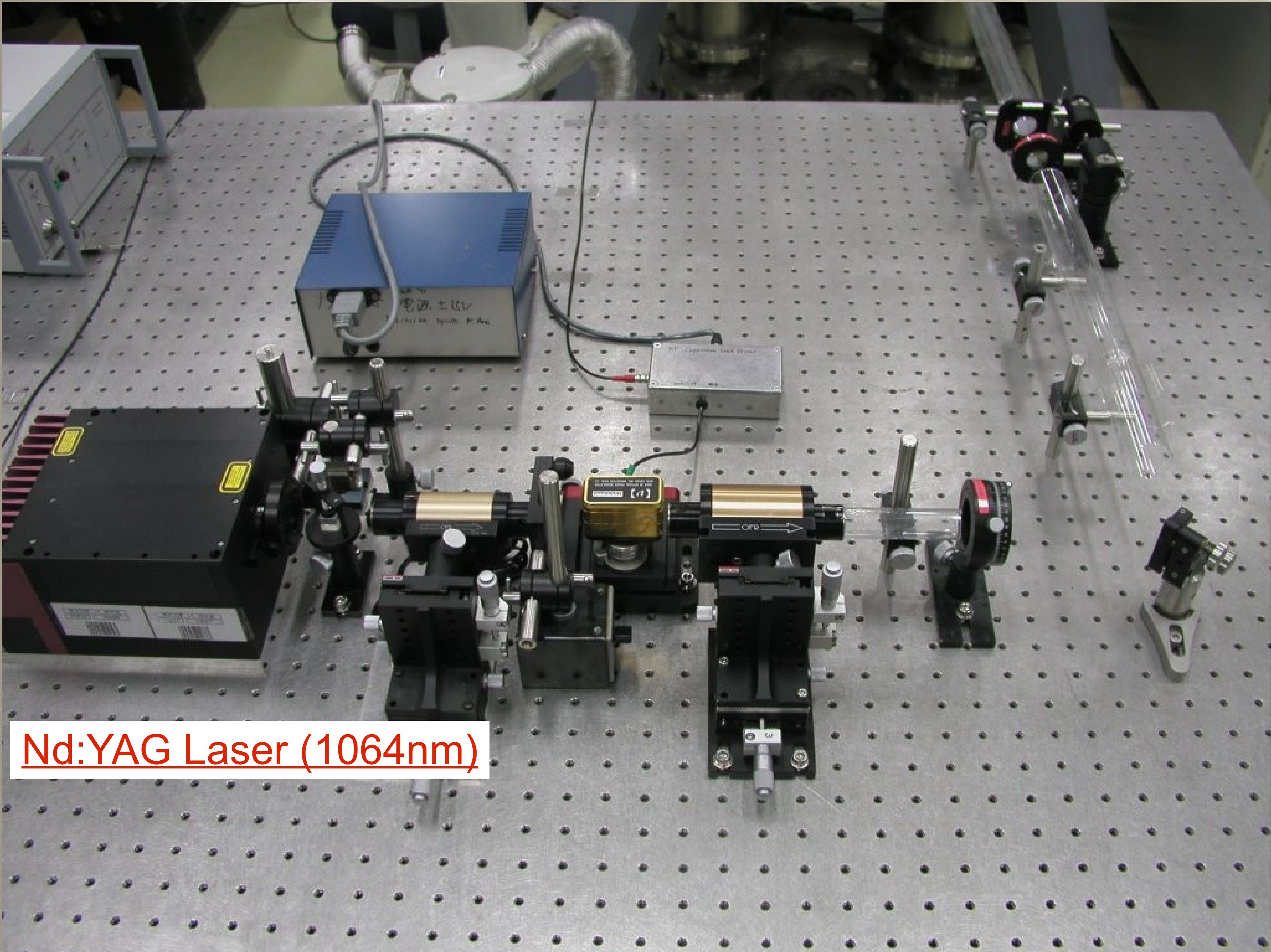
Prototype Experiment

- 1.5m long Fabry-Perot interferometers
- Triple pendulum suspensions
- Triangular rigid cavity mode-cleaner: Frequency Stabilization

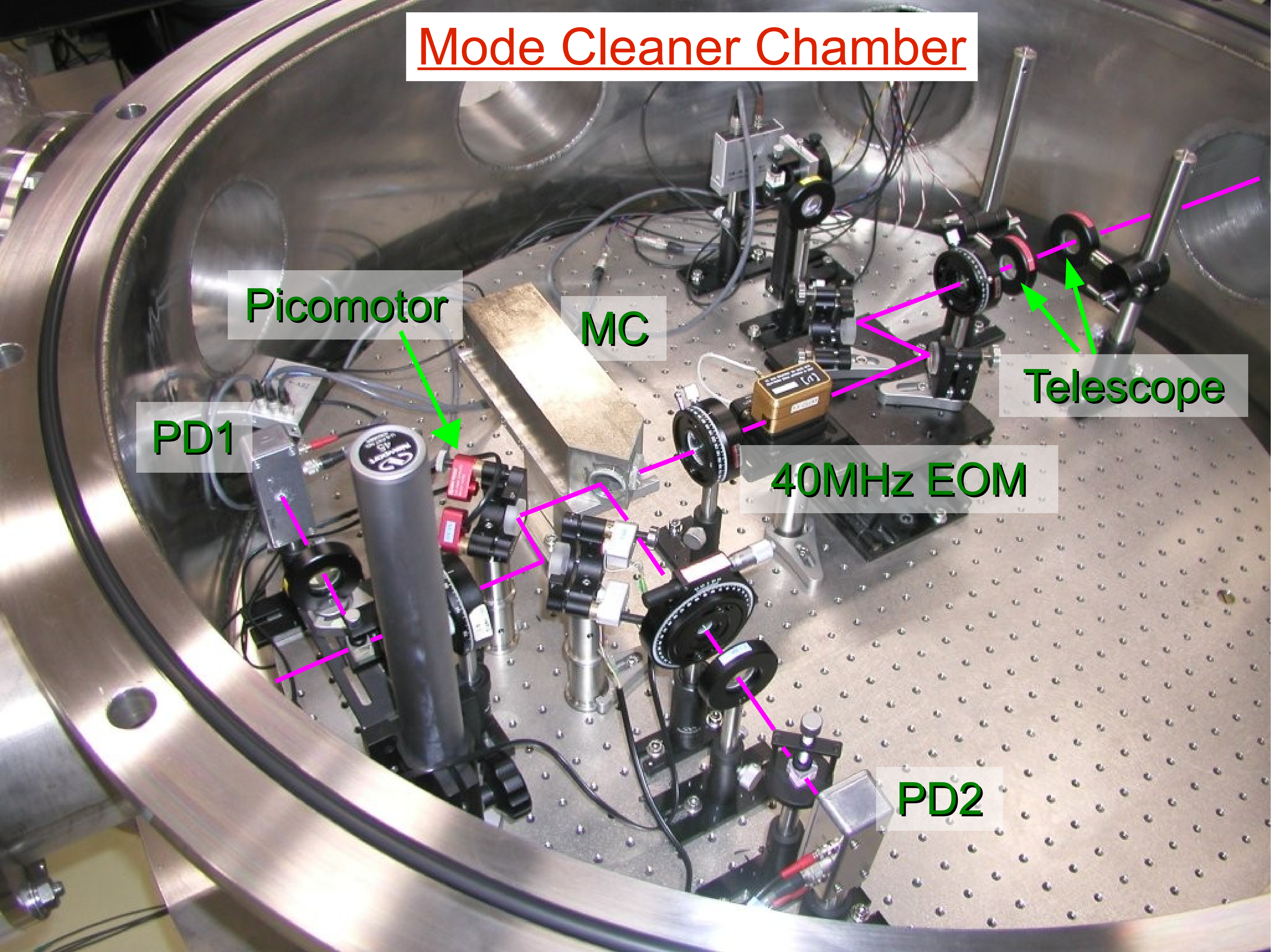


Overview of the experimental setup



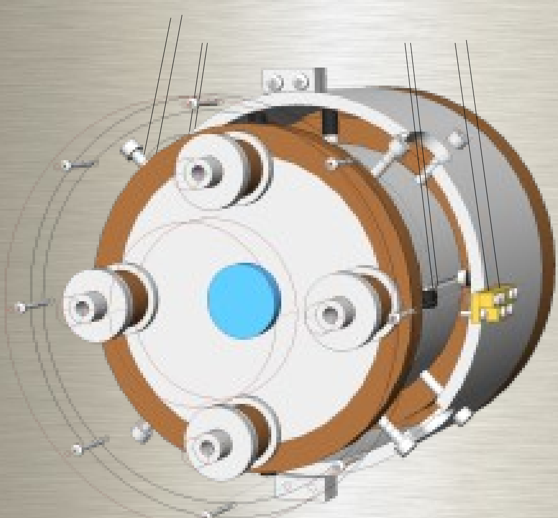


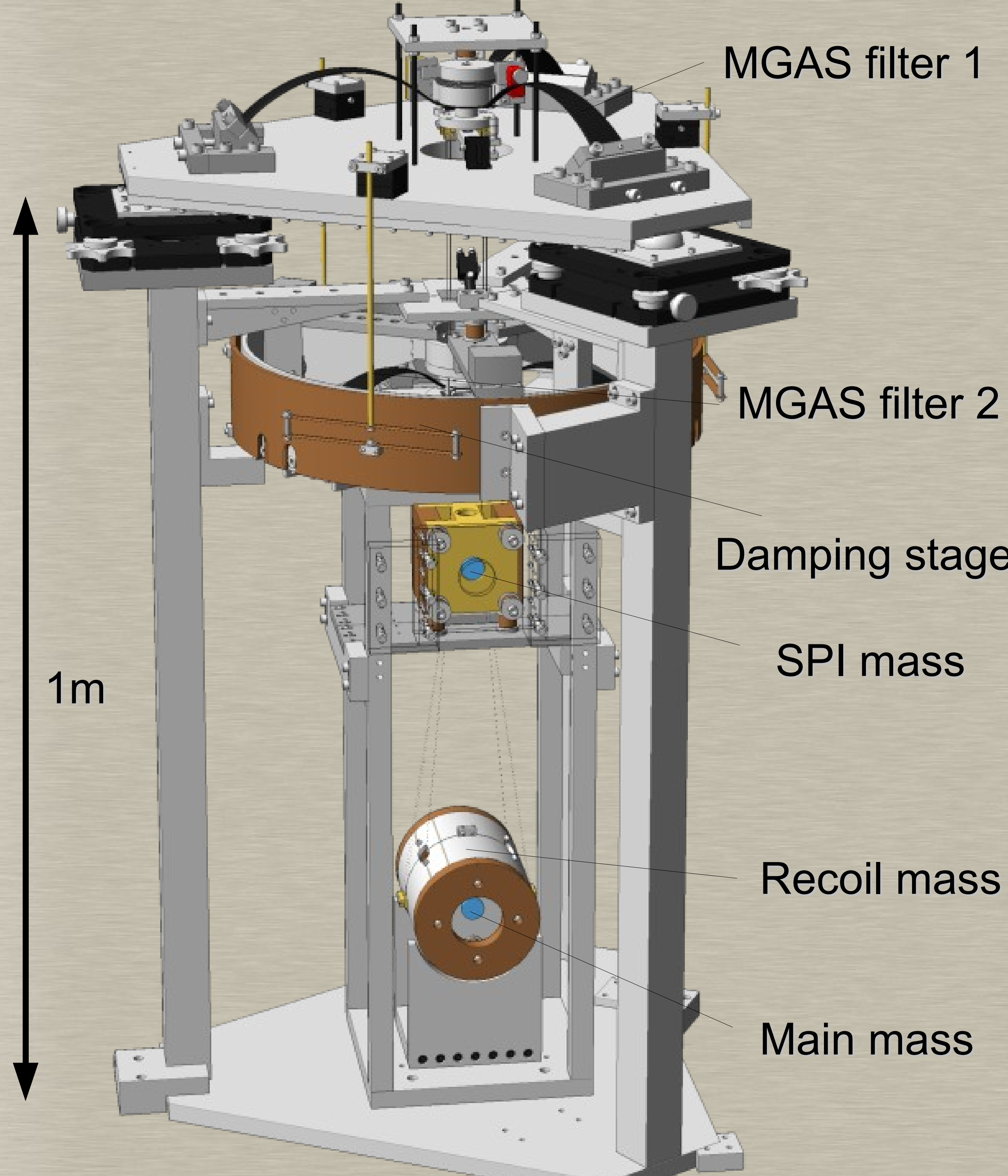
Nd:YAG Laser (1064nm)

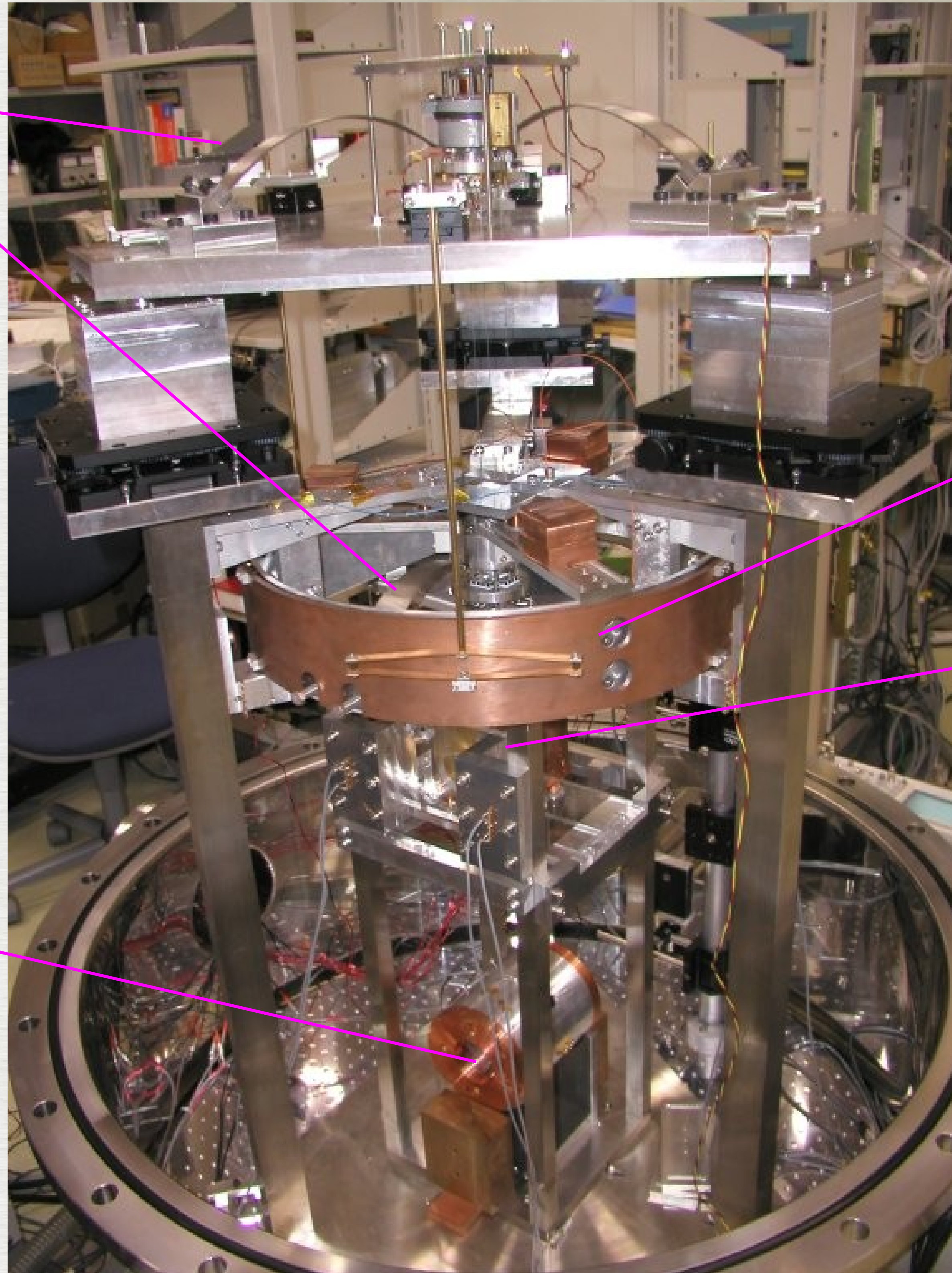

Mode Cleaner Chamber
Picomotor
MC
Telescope
PD1
40MHz EOM
PD2

Suspension System

- Triple Pendulum
- Two MGAS filters (vertical isolation) Resonance ~ 200mHz
- Temperature drift compensation servo for MGAS filters
- Recoil mass to actuate the main mirror






MGAS
Damping Stage
SPI Mirror
Main Mirror

MGAS Filter

MGAS=Monolithic Geometric Anti Spring

Low Frequency Vertical Spring

Avoid vertical vibration to overwhelm the horizontal motion

Elastic force, gravity
Positive Spring (restoring force)

+

Buckling
Negative Spring

↓

Extremely small spring constant

MGAS Filter
used in this experiment

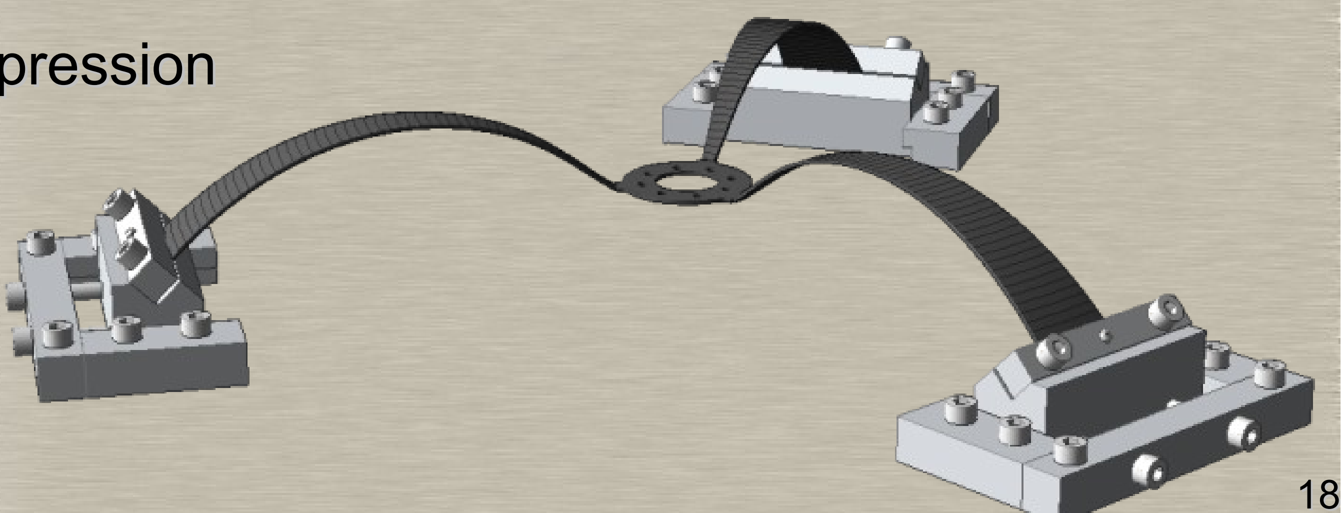
Dia. 40cm, Maraging Steel

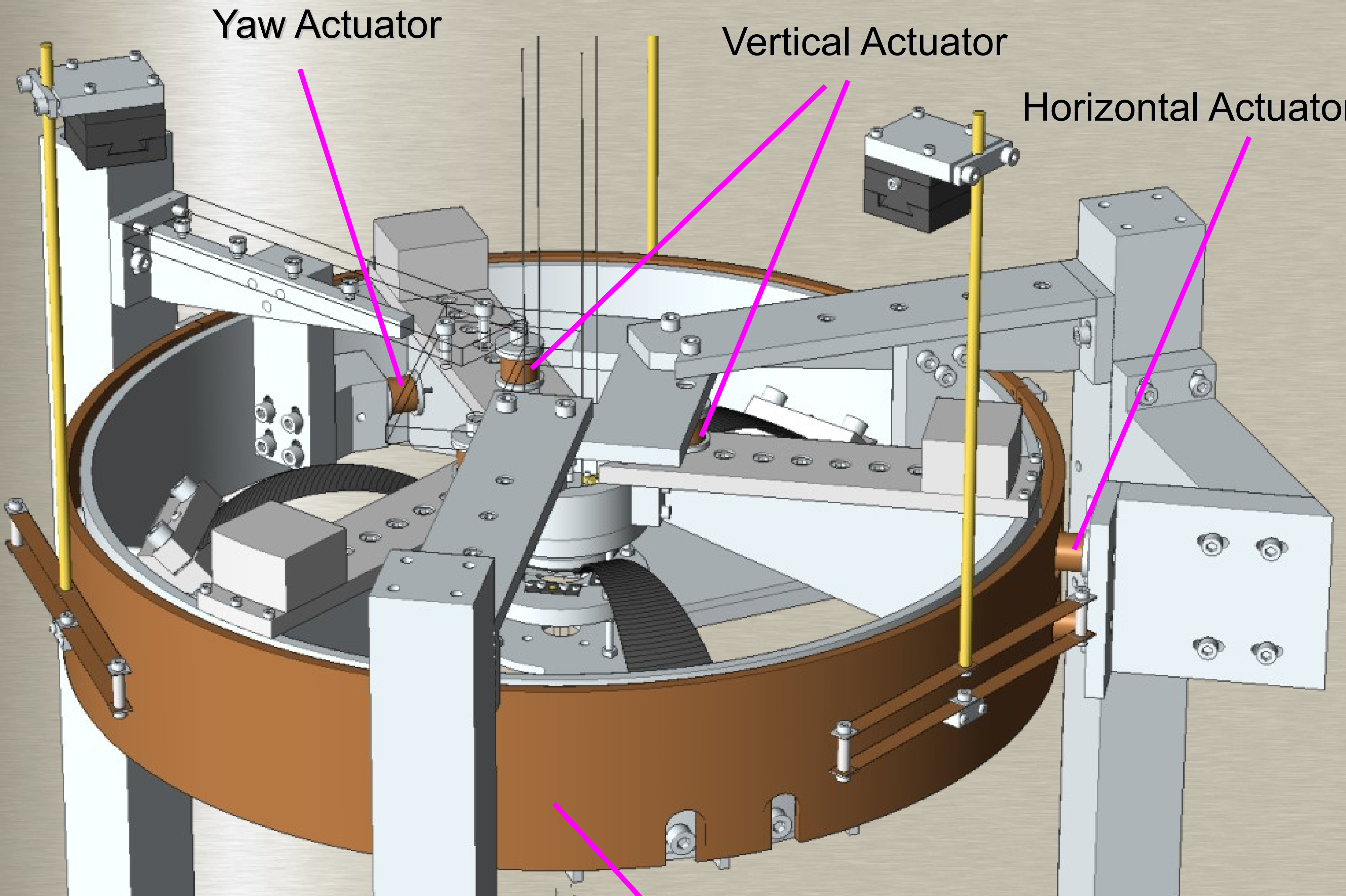
Resonant frequency < 0.2Hz

Tuning: load, horizontal compression

Large temperature drift

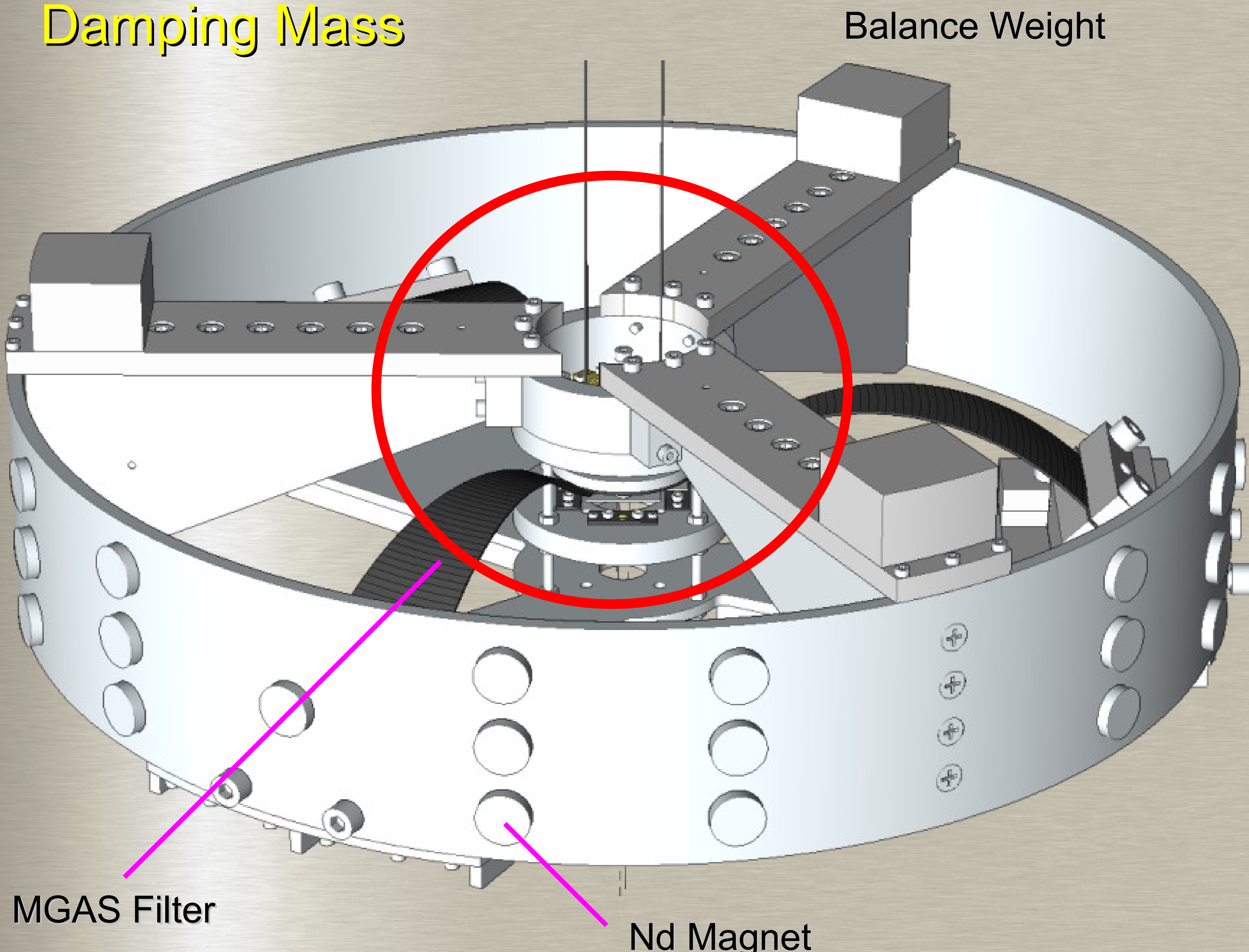
Compensation servo

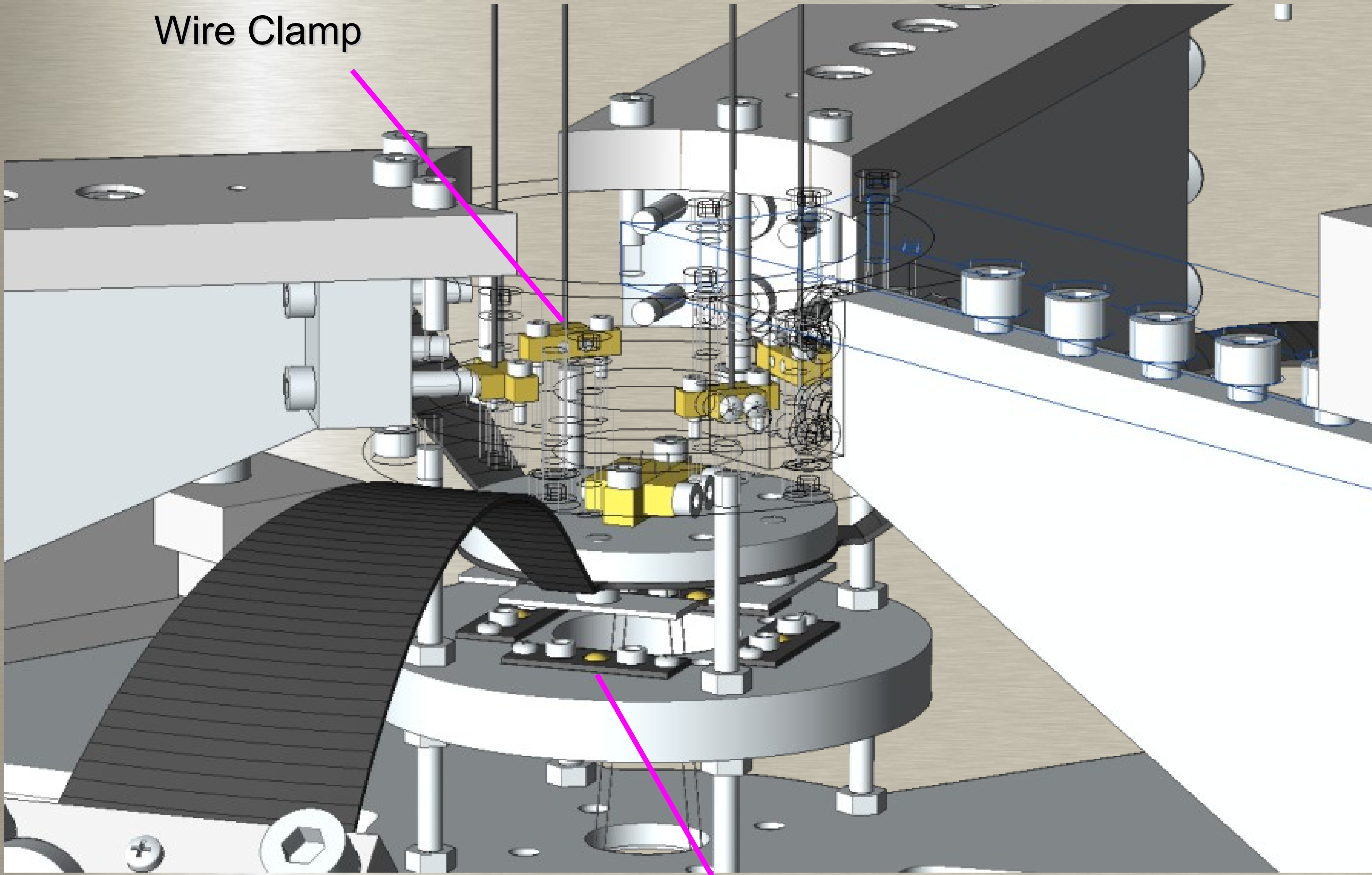




Eddy Current Damping

Damping Mass




Wire Clamp
Photo Sensor

Sensor: Fabry-Perot Cavity
Actuator: Coil-Magnet
UGF: 1kHz
Gain: 80dB@10Hz

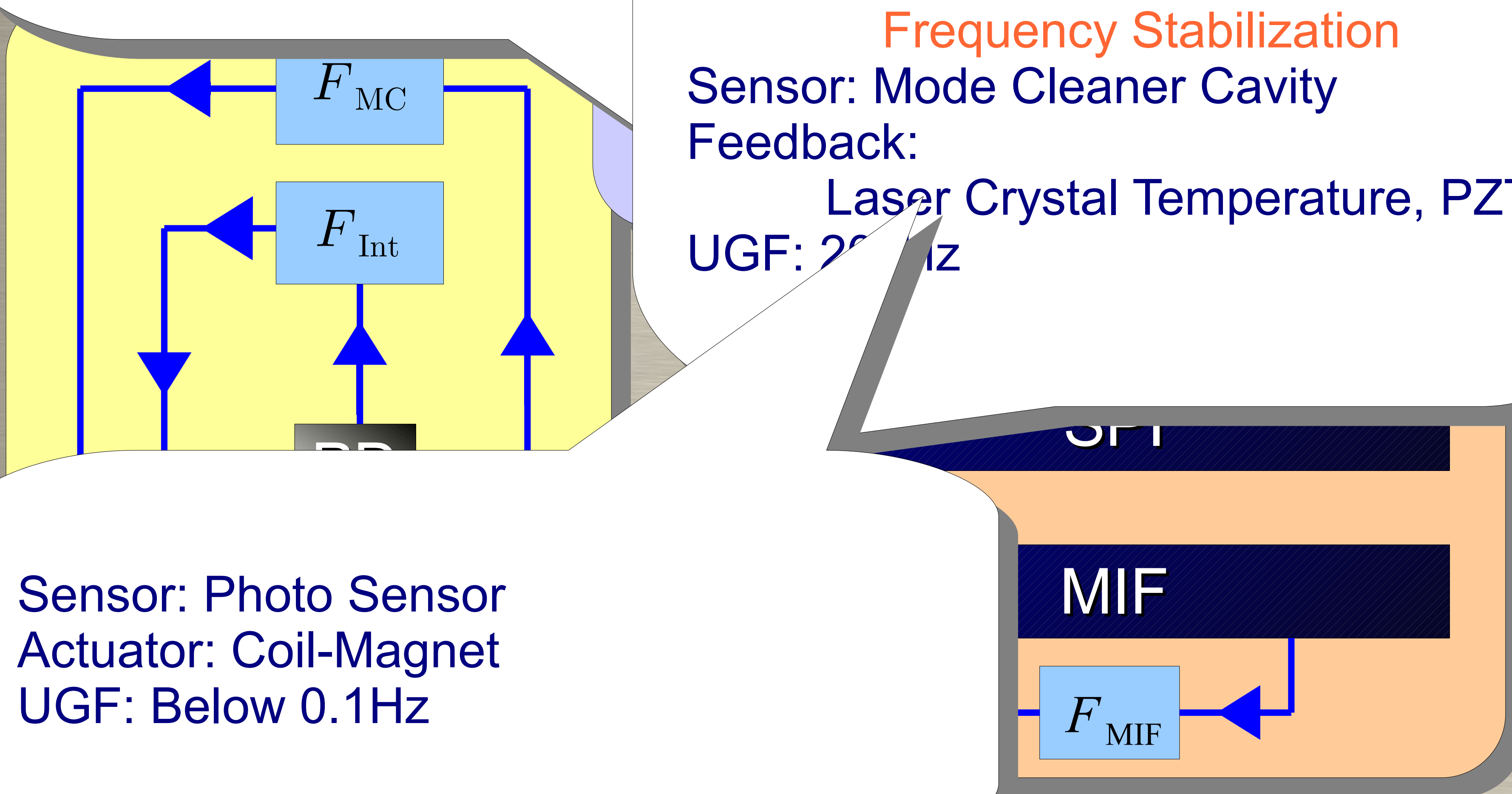
Intensity Stabilization

Sensor: Photo Detector
Feedback: LD Current
UGF: 1kHz

Frequency Stabilization

Sensor: Mode Cleaner Cavity
Feedback:
Laser Crystal Temperature, PZT

Sensor: Photo Sensor
Actuator: Coil-Magnet
UGF: Below 0.1Hz

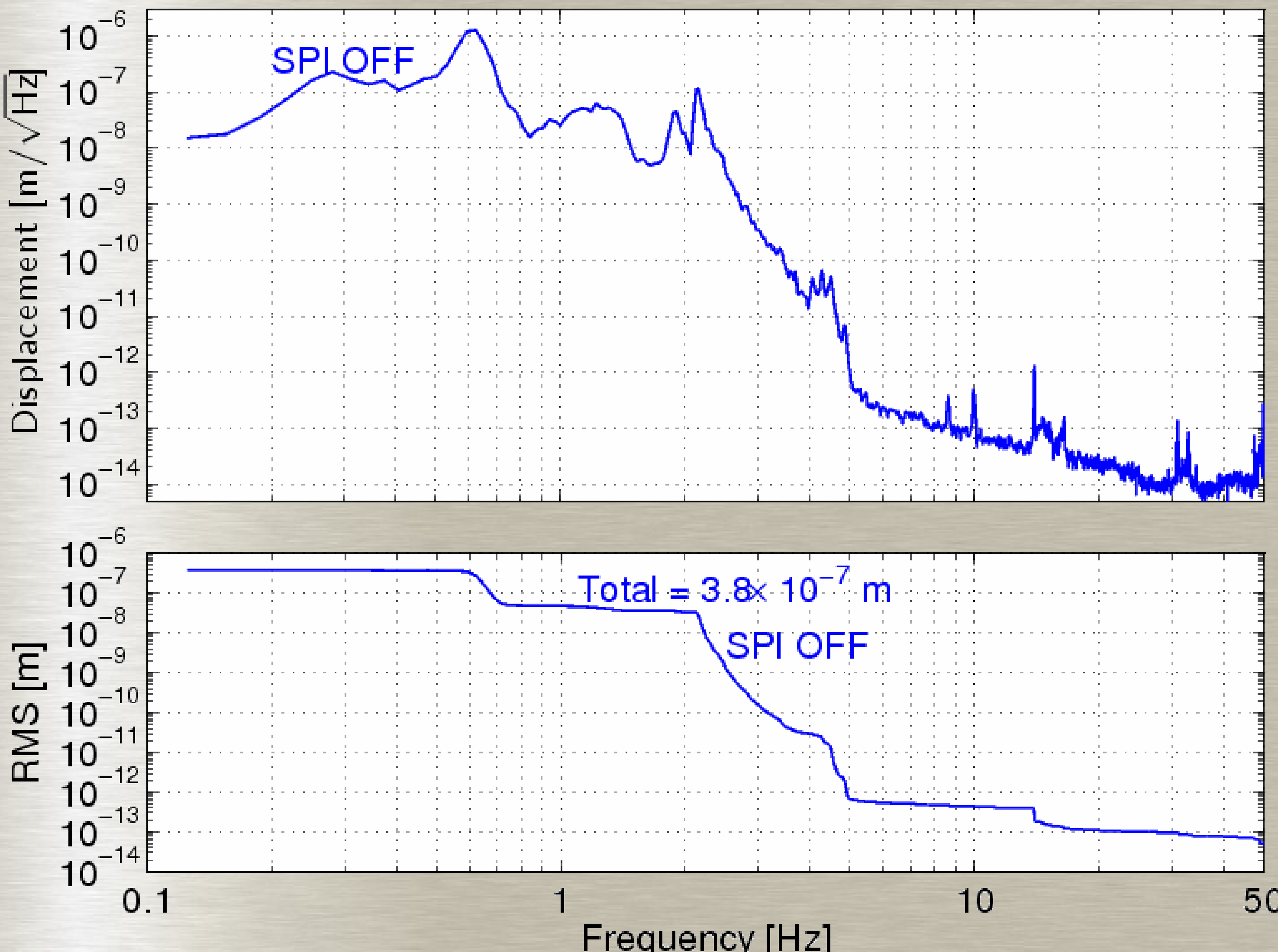


Length Control

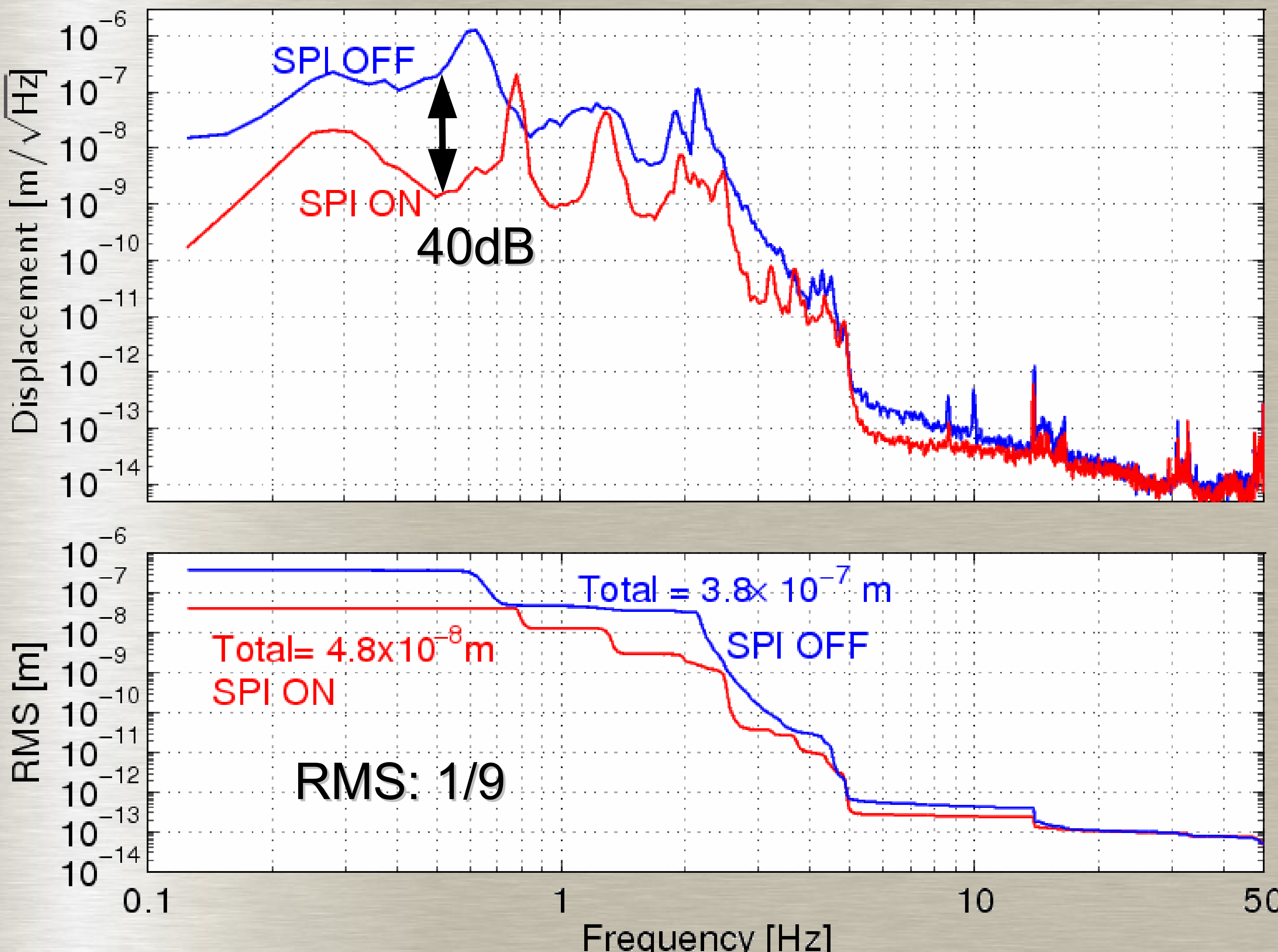
Results

- Spectral measurements
- Transfer function measurements

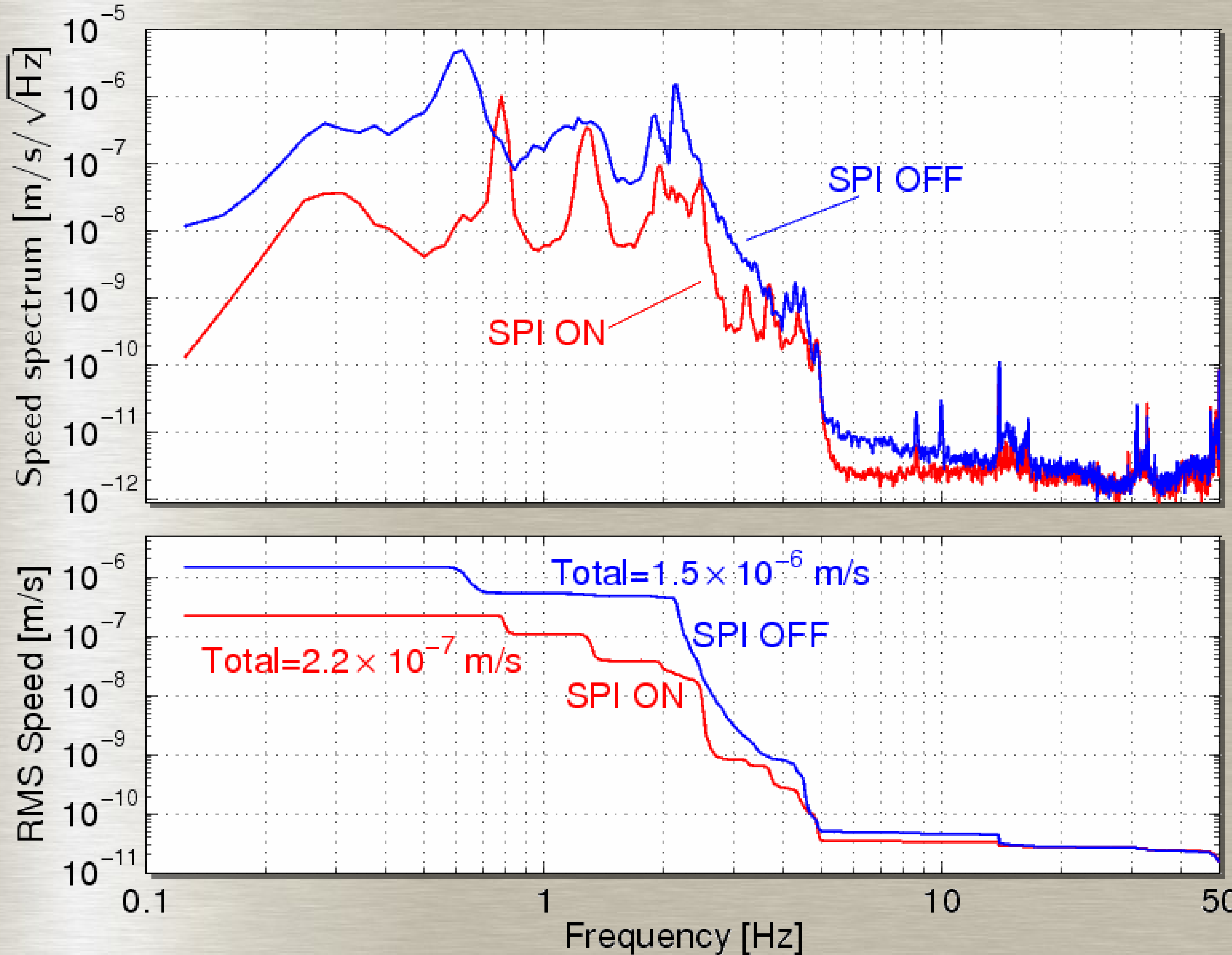
Displacement Equivalent Noise Spectrum (MIF)



Displacement Equivalent Noise Spectrum (MIF)



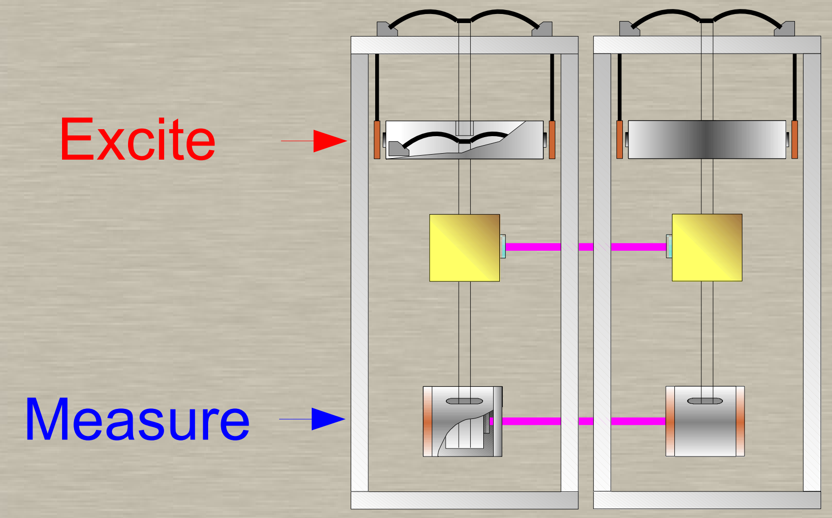
Mirror Speed Spectrum

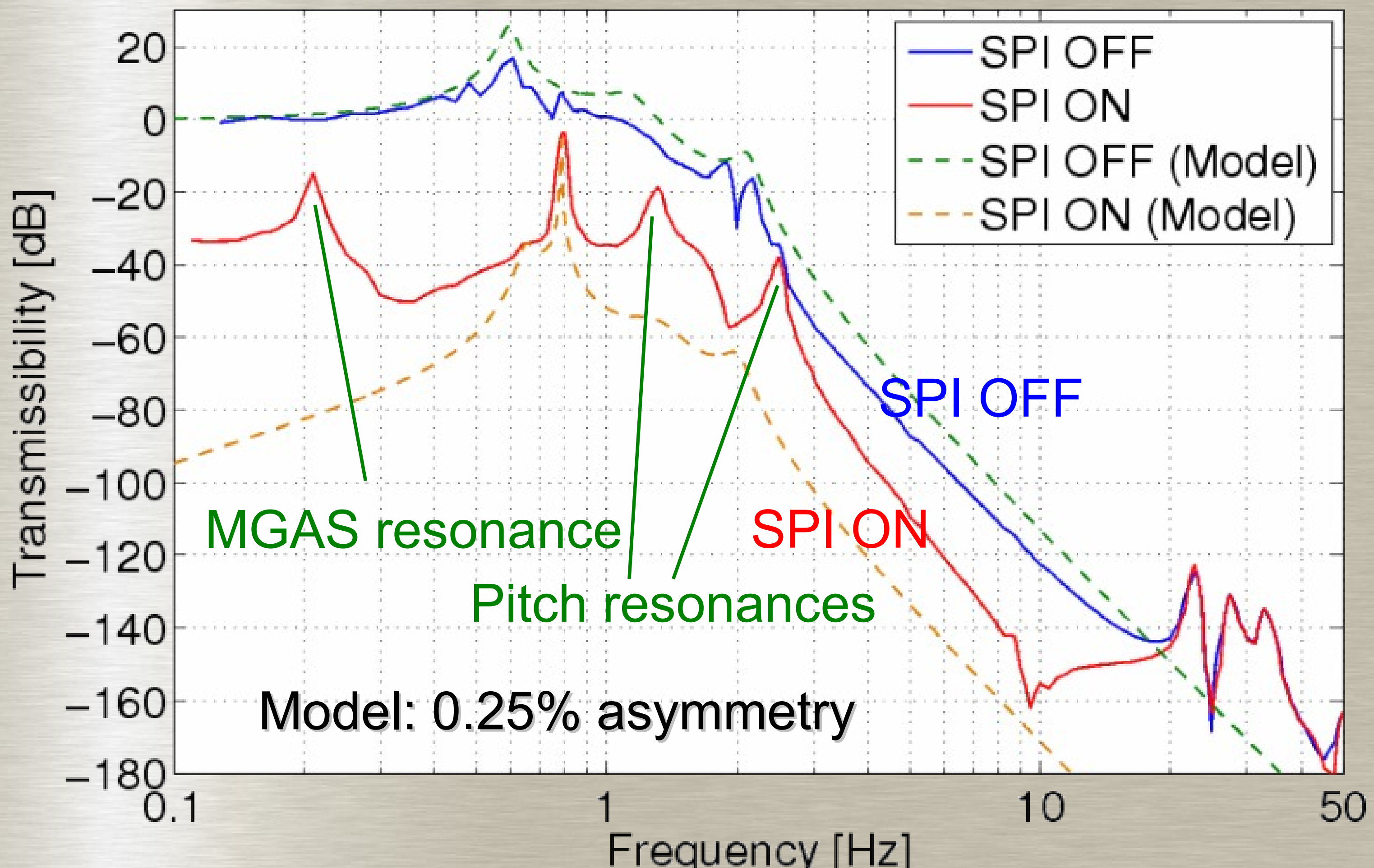


Speed RMS: 1/7 → Easier Lock Acquisition

Transfer Function

- Up to 20Hz
  ~ 40dB isolation





Advanced LIGO SPI

Primary Motivation

Robust Lock Acquisition

First fringe lock of FP arms is necessary

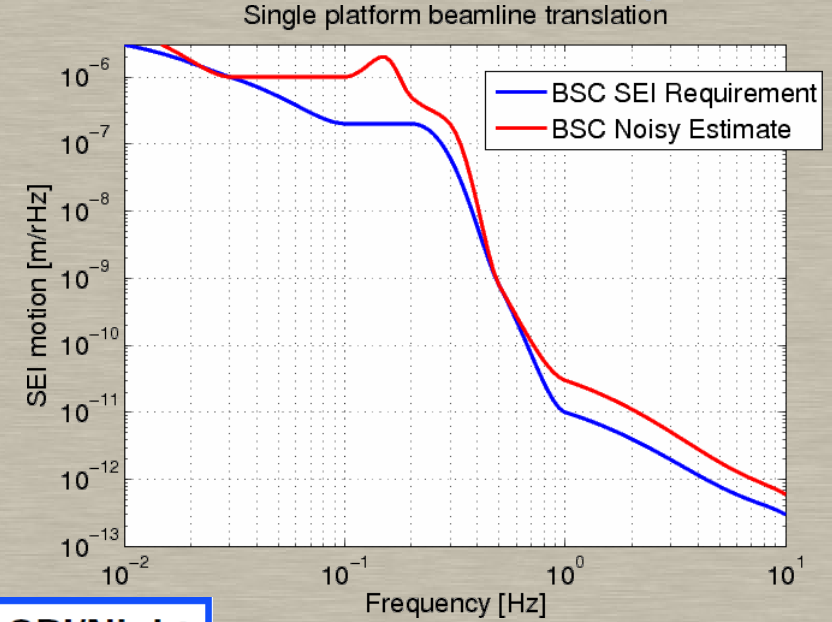
RMS mirror speed ~$10^{-6}\ \mathrm{m/sec}$ in noisy time

→ First fringe lock is difficult

Reduce the mirror speed by SPI

less than 25 nm/sec is required

Estimates of BSC vibration by Rana



	Lockable mirror speed	Day	Night	SPI/Day	SPI/Night
Raw error	25nm/sec	9.5%	32%	56%	98%
Normalized	25nm/sec	9.5%	32%	56%	98%
Guide lock	500nm/sec	90%	100%	100%	100%

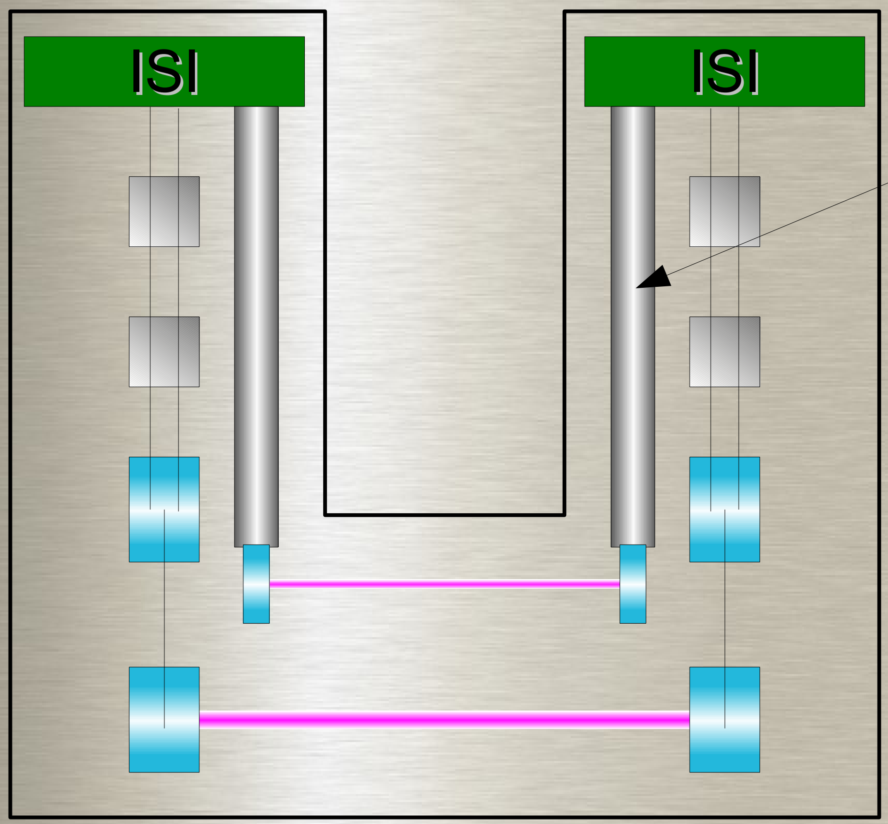
by O. Miyakawa

During Operation

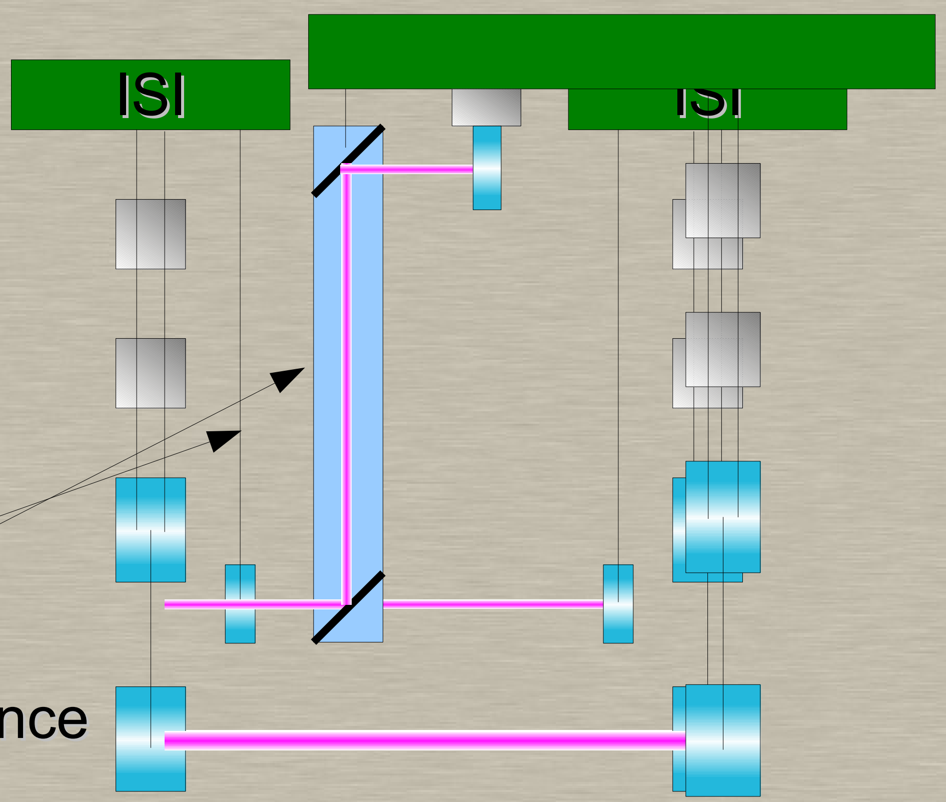
- Improved stability / duty cycle
- Reduced up-conversion noise
- Reduced pitch motion (horizontal-to-pitch coupling)
- Better contrast
- Other noises related to large low-frequency motion of the mirrors

AdvLIGO SPI Configuration

- Penultimate masses are not exposed to the beam tube
- Hang SPI mirrors from the seismic platform
- Actuation: seismic platform (ISI)



But rigid mount is not usable because of tilt coupling

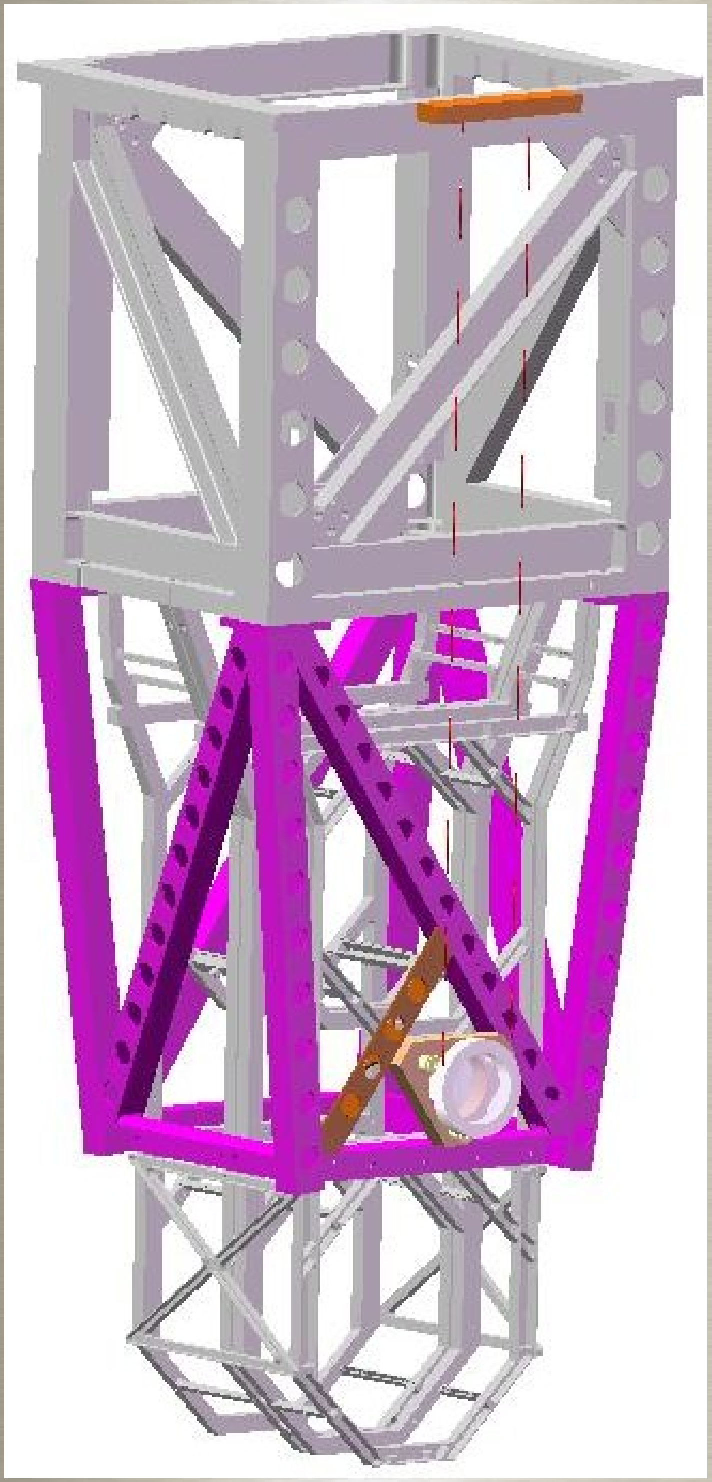


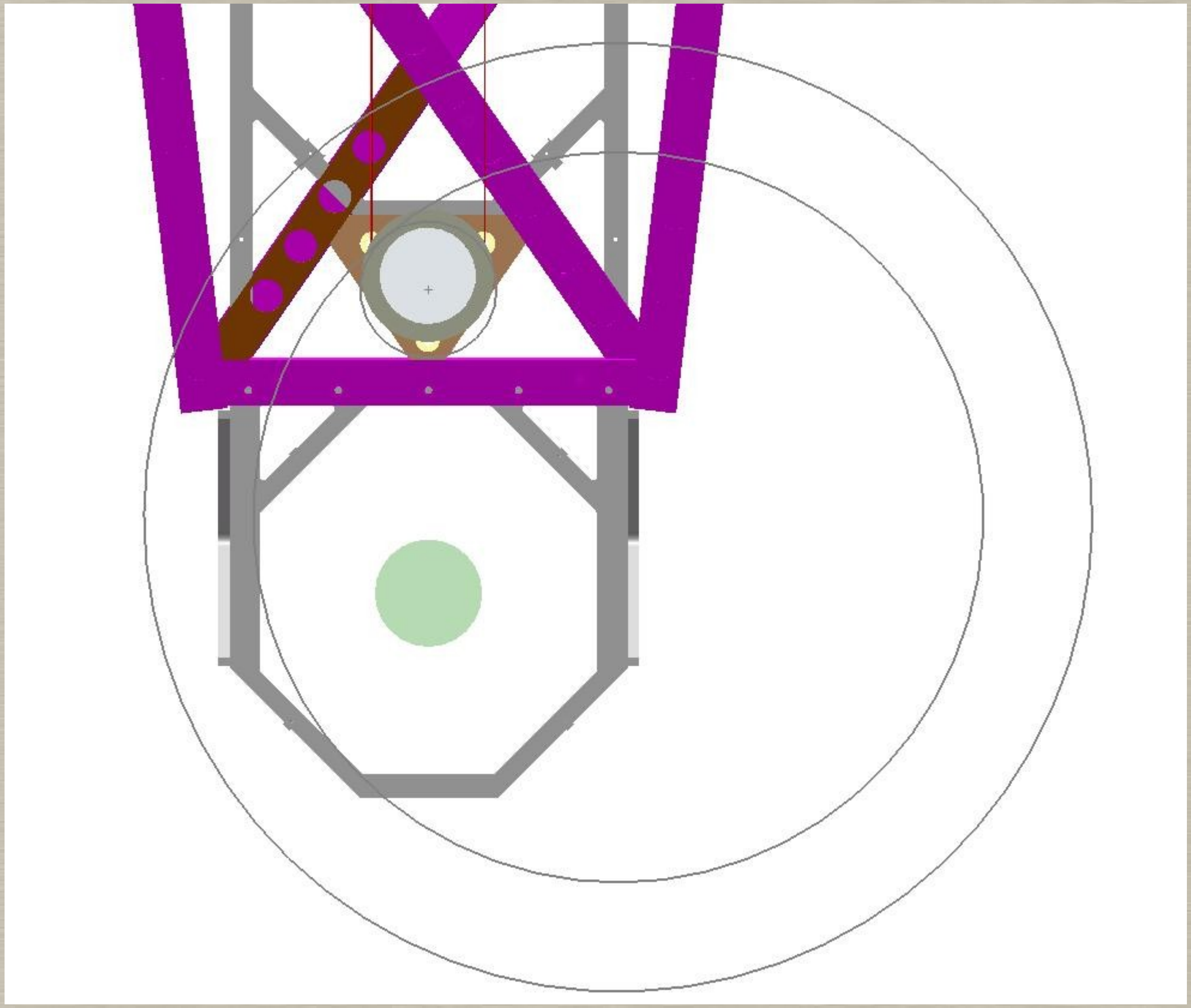
Decouple the tilt by a pendulum
(Matt Evans)
A bit degrading high frequency performance

Alternative configuration
Suspended Periscope

Single Pendulum SPI

(Drawings by Dennis Coyne)





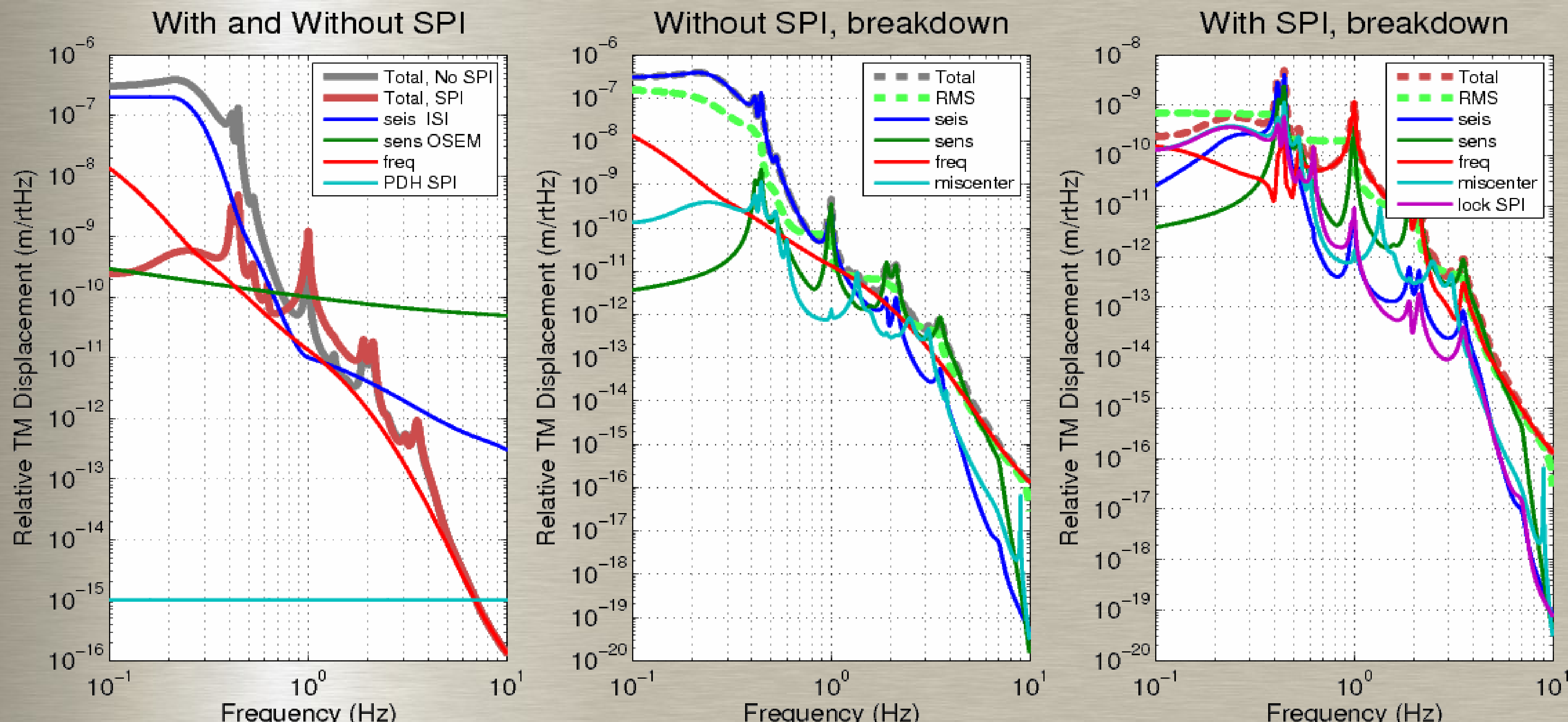
AdvLIGO SPI Performance Estimates

(simulation code by Matt Evans)

SPI: Single pendulum suspended from ISI

Fabry-Perot-Michelson, Arm finesse = 10, Input power = 1mW

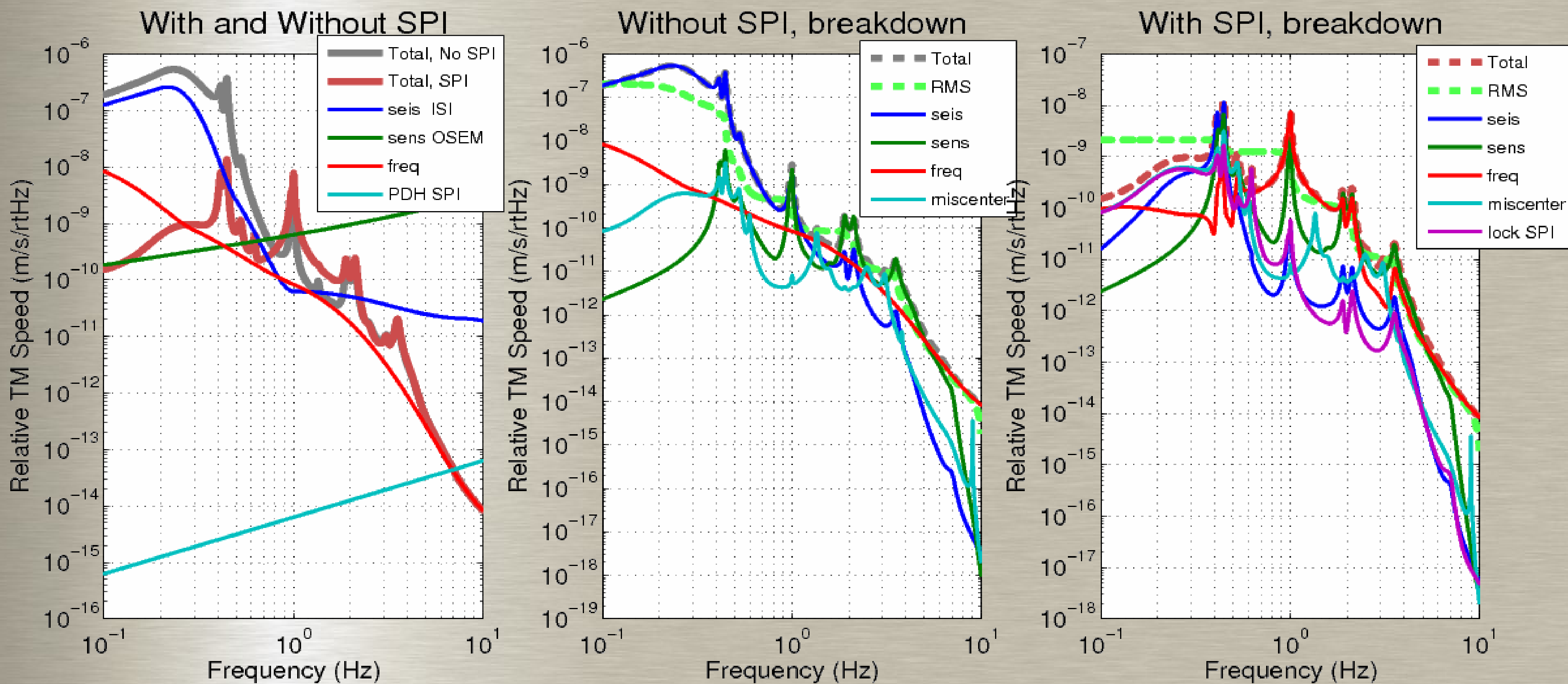
SPI feedback to ISI, UGF = 8Hz



Total RMS: $0.15\,\mu\,\mathrm{m}$ (Without SPI), $0.7\,\mathrm{nm}$ (With SPI)

More than a factor of 200 reduction

Speed Spectra



Total RMS: $0.2\,\mu$ m/sec (Without SPI), $2.1\,\mathrm{nm/sec}$ (With SPI)

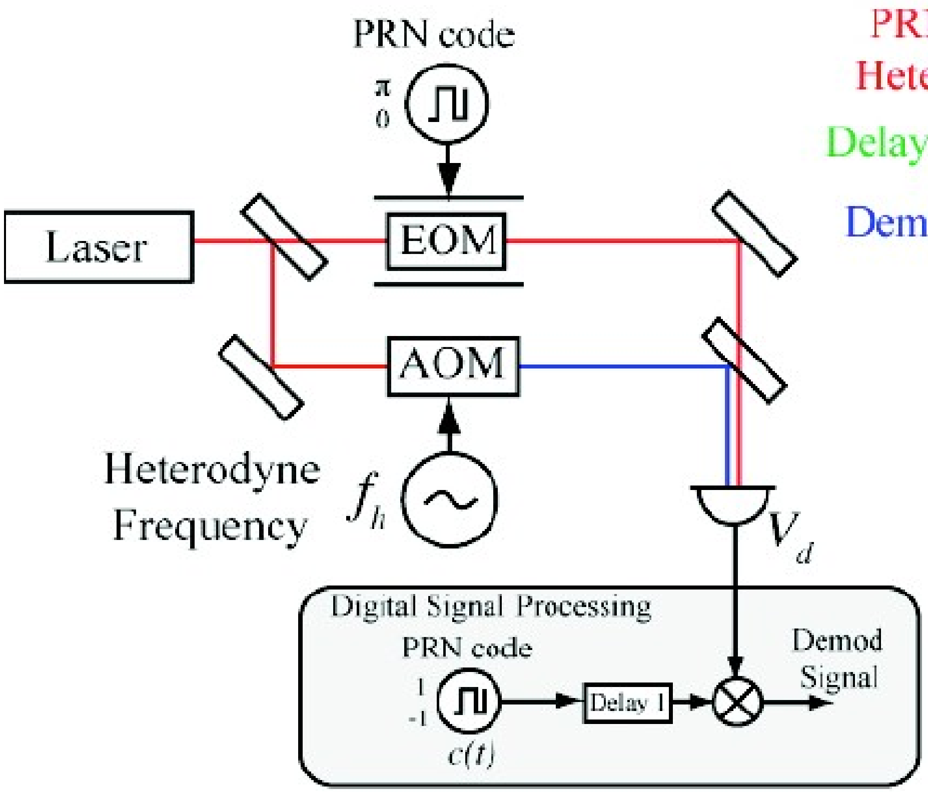
About a factor of 100 improvement.
Less than 25nm/sec

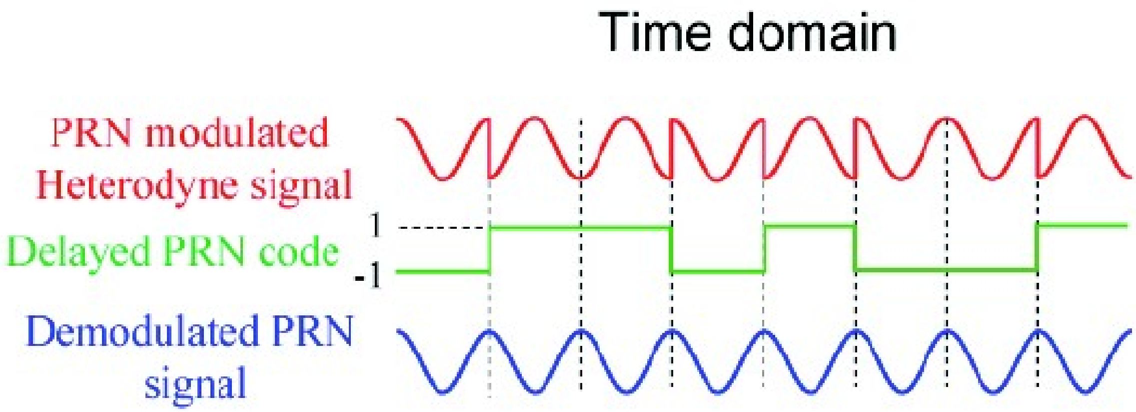
More discussions can be found below

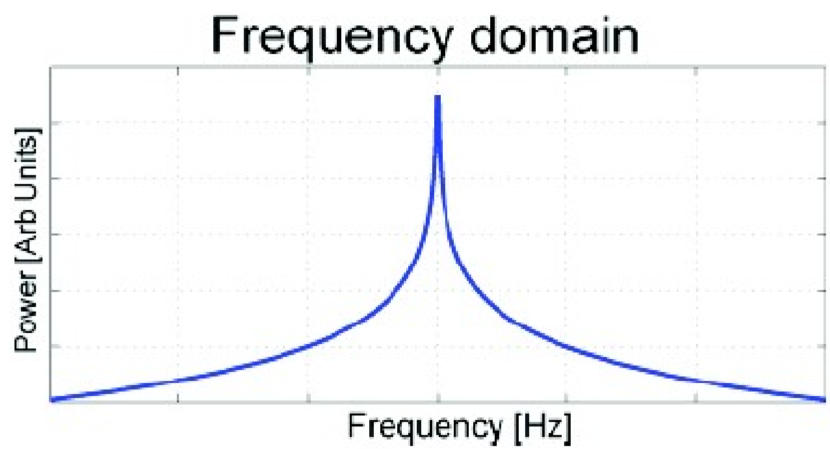
http://ilog.ligo-wa.caltech.edu:7285/advligo/SPI_SPI
http://www.ligo.caltech.edu/docs/T/T070209-00.pdf

Pseudo Random Noise Heterodyne Interferometry & Lock Acquisition Interferometer

- A new idea for Advanced LIGO lock acquisition by ANU group
- Heterodyne interferometry with PRN digital modulation
- Distinguish the motions of multiple objects in the light path by time delayed PRN demodulation
- Large dynamic range with a reasonable sensitivity (~ 1nm)
- Pre-lock the mirrors with this technique (Lock acquisition interferometer)

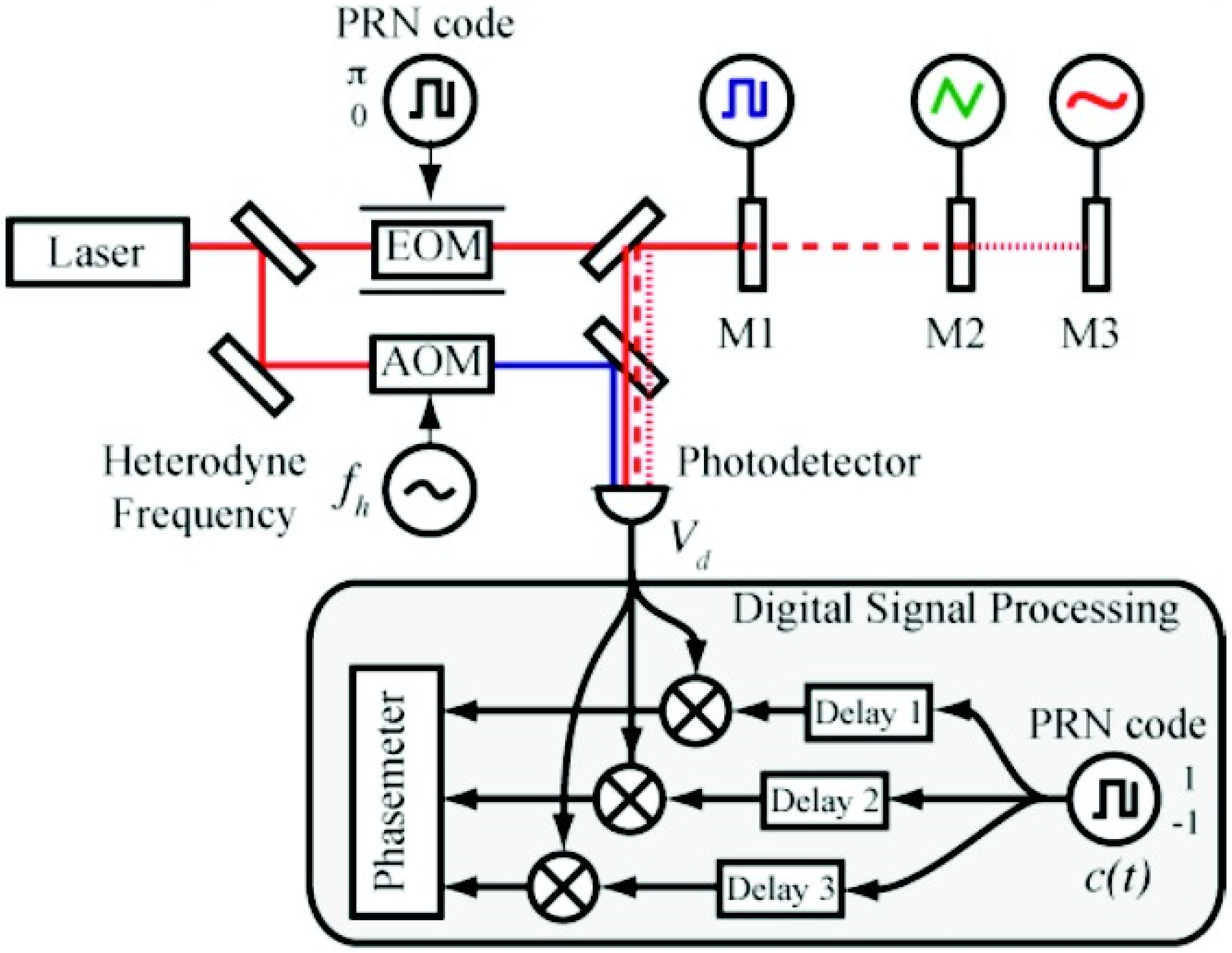






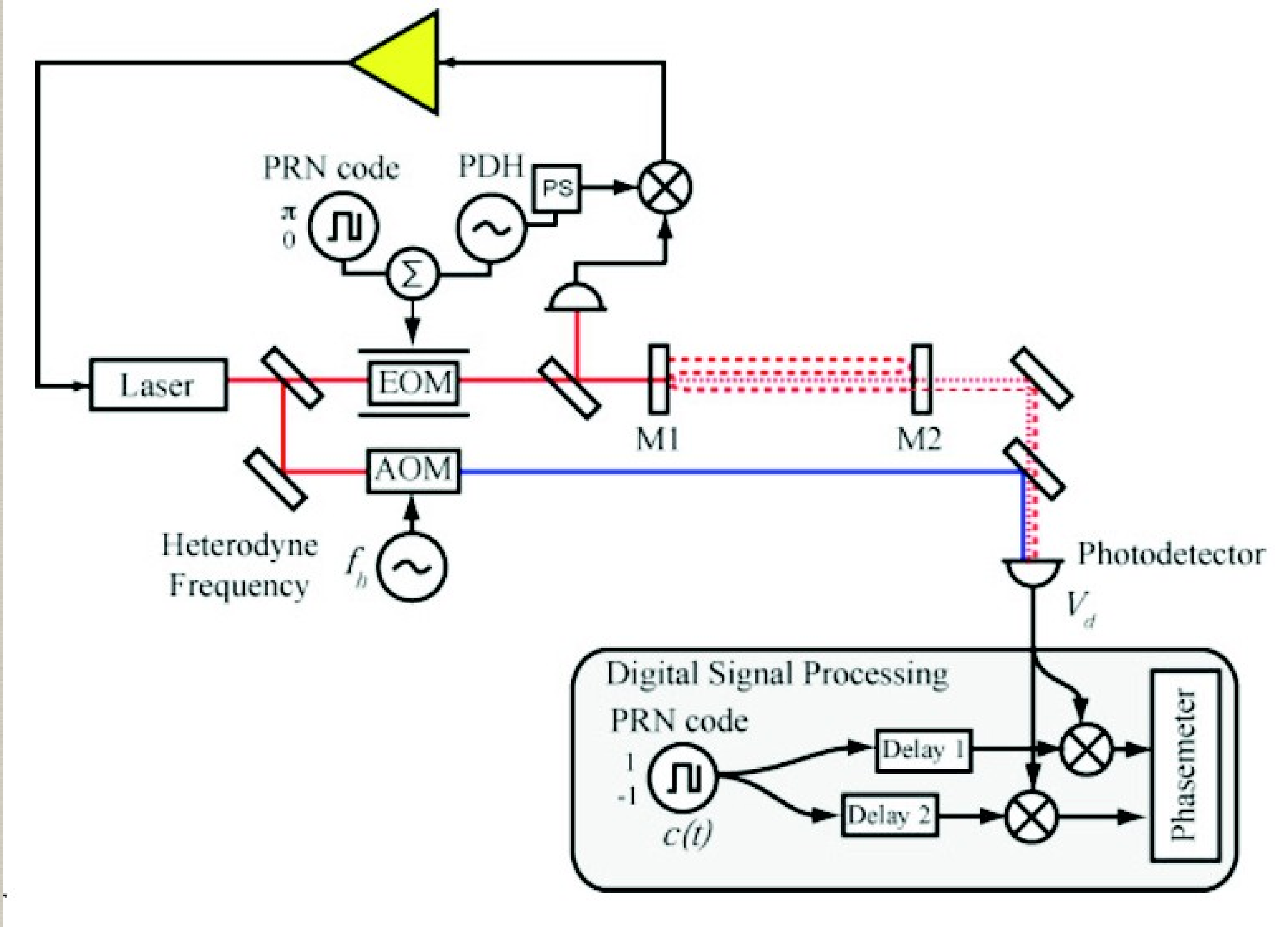
- Monitor the positions of individual mirrors by the PRN technique before the main interferometer is locked
- Apply feedback forces to bring the mirrors to the appropriate positions for the operation of the interferometer

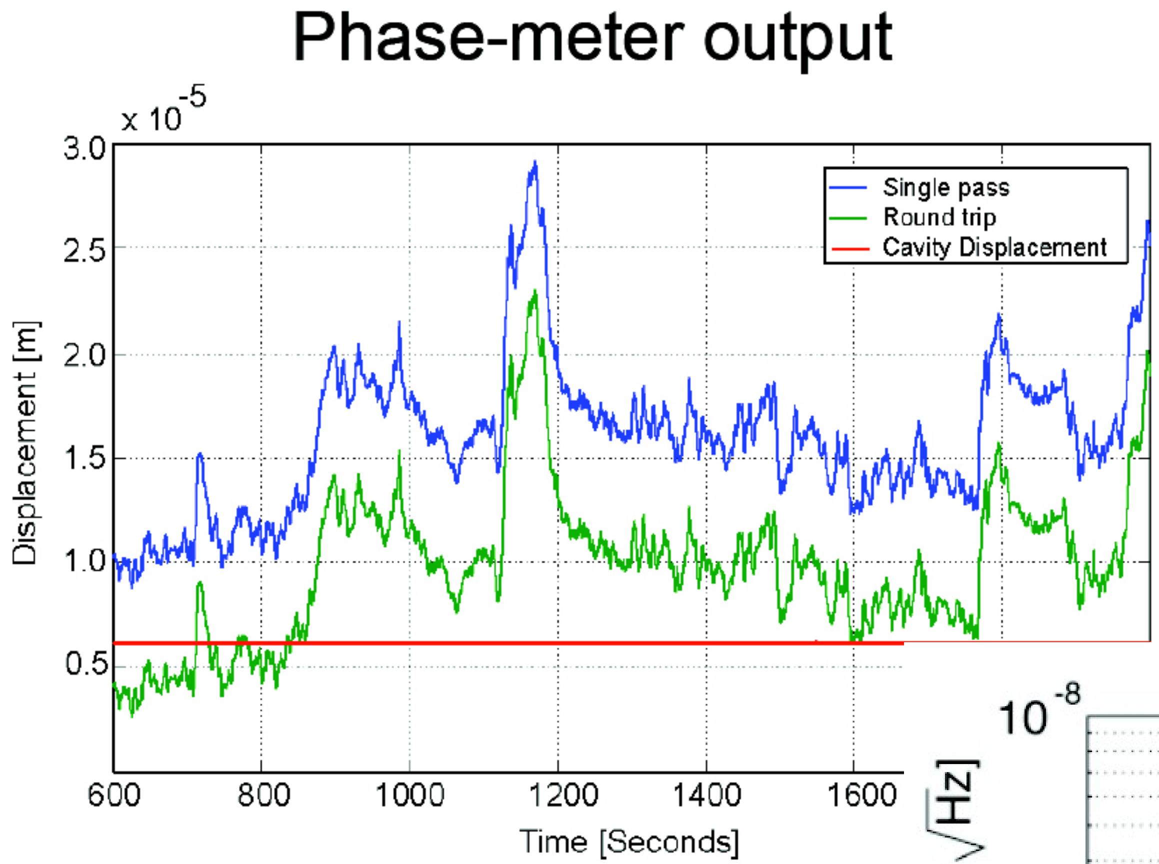
Use for multi element interferometers

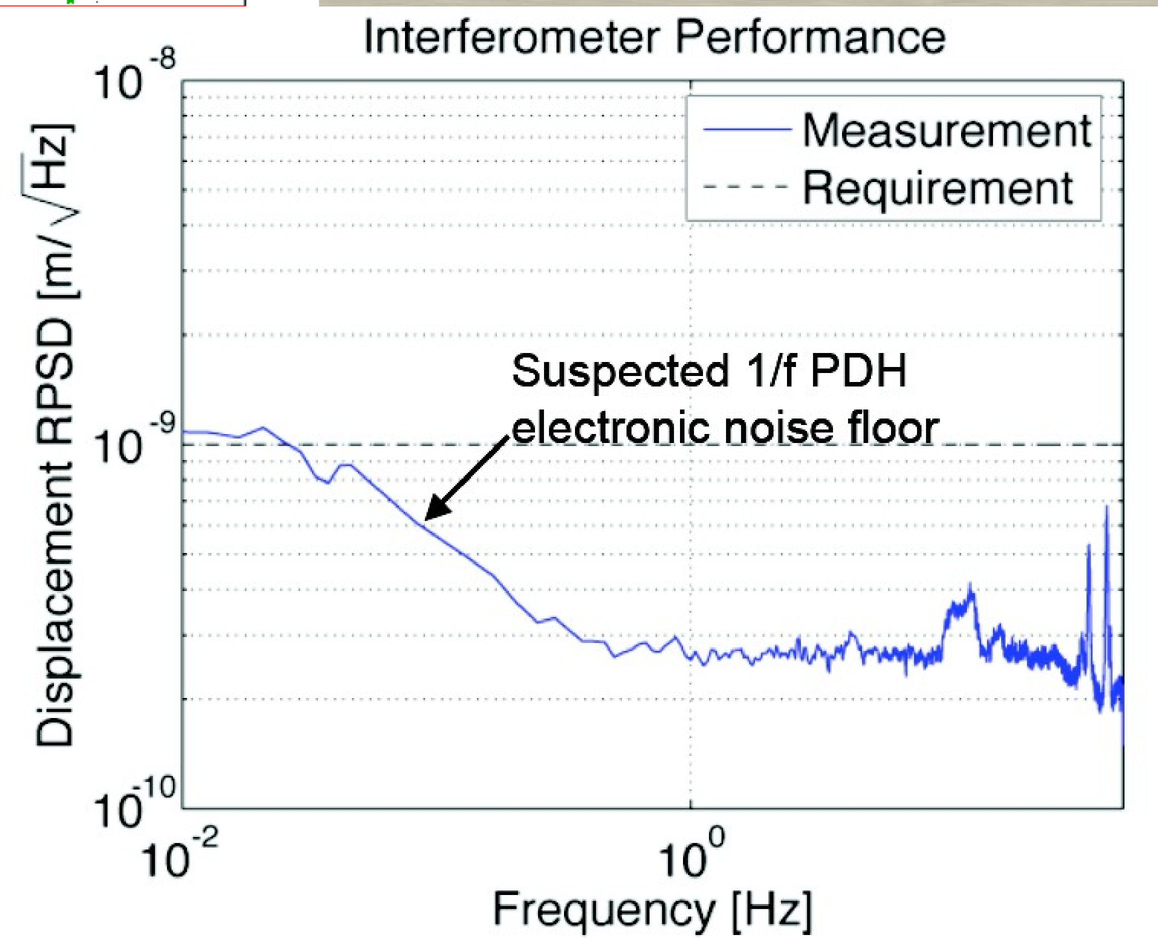


Experimental Demonstration at ANU

Displacement sensitivity characterized by comparison with PDH locking of FP cavity



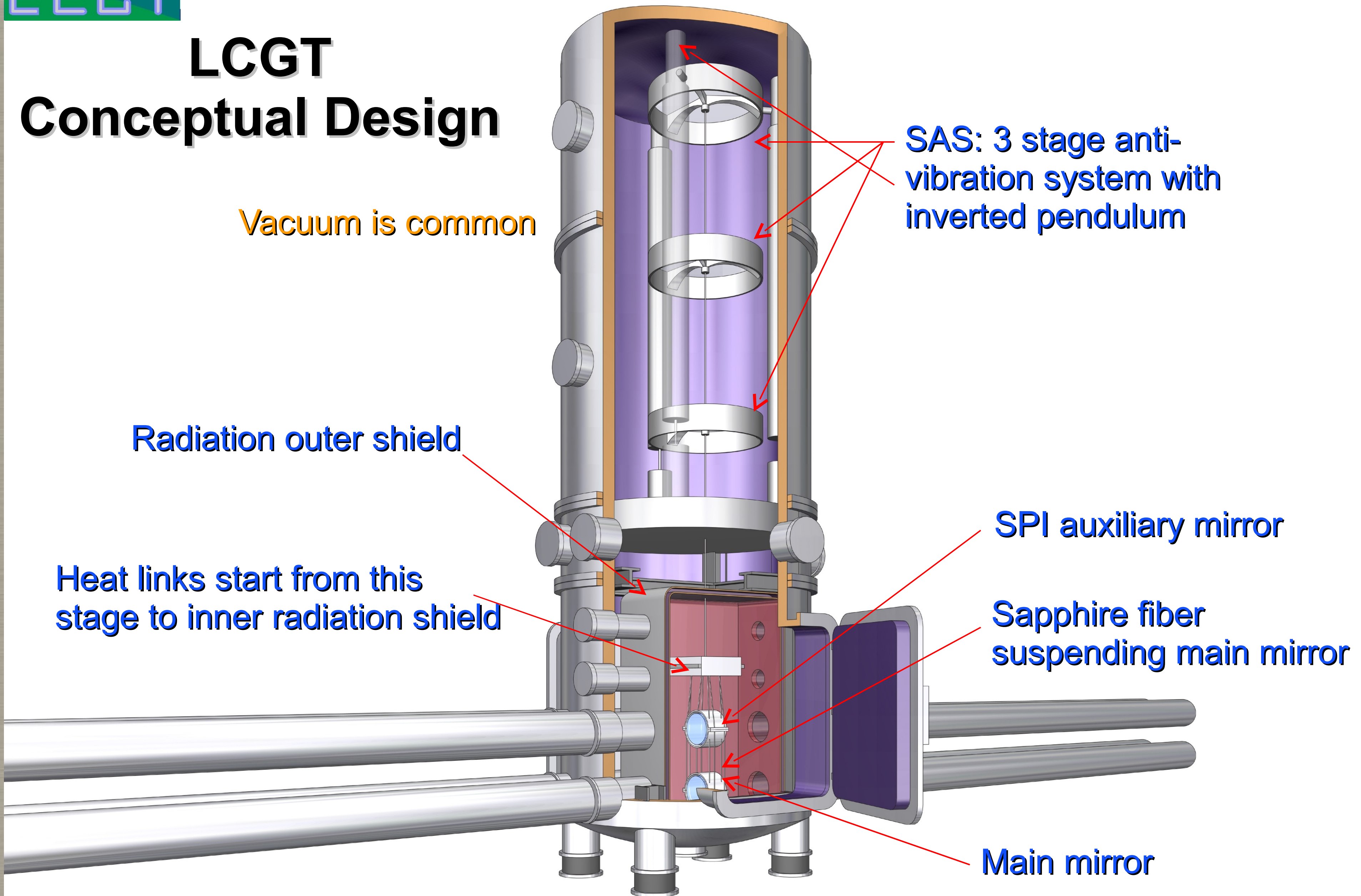

Phase-meter output
x 10^-5
3.0
2.5
2.0
1.5
1.0
0.5
Displacement [m]
Single pass
Round trip
Cavity Displacement
600
800
1000
1200
1400
1600
Time [Seconds]

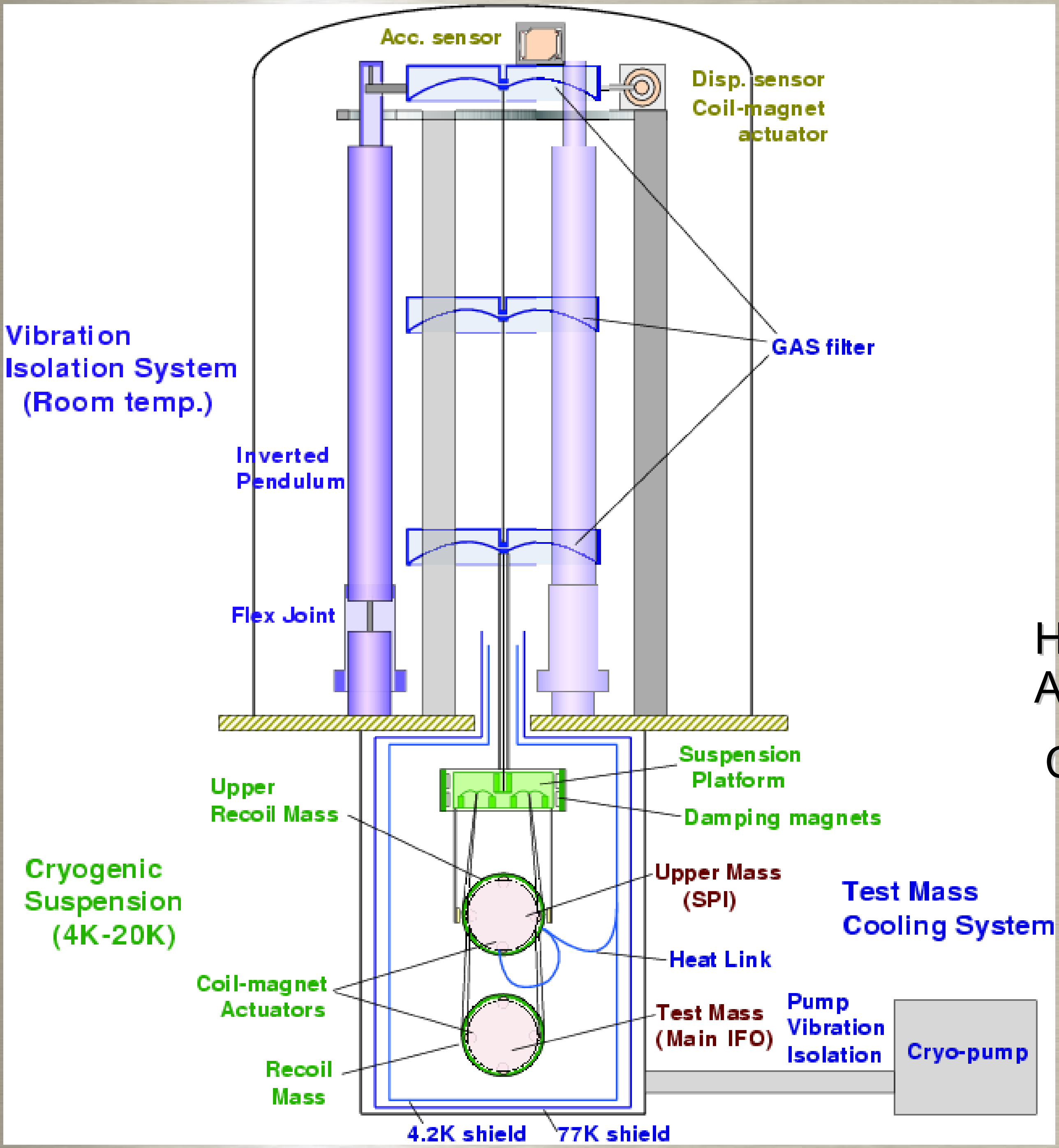

Interferometer Performance
10^-8
10^-9
10^-10
Displacement RPSD [m/√Hz]
Measurement
Requirement
Suspected 1/f PDH
electronic noise floor
10^-2
10^0
Frequency [Hz]

LCGT and SPI

LCGT

Conceptual Design





Cool down mirrors:
Heat link wires

Extra vibration
is introduced

Suppress it by an SPI

Heat links:
Attached to the penultimate mass

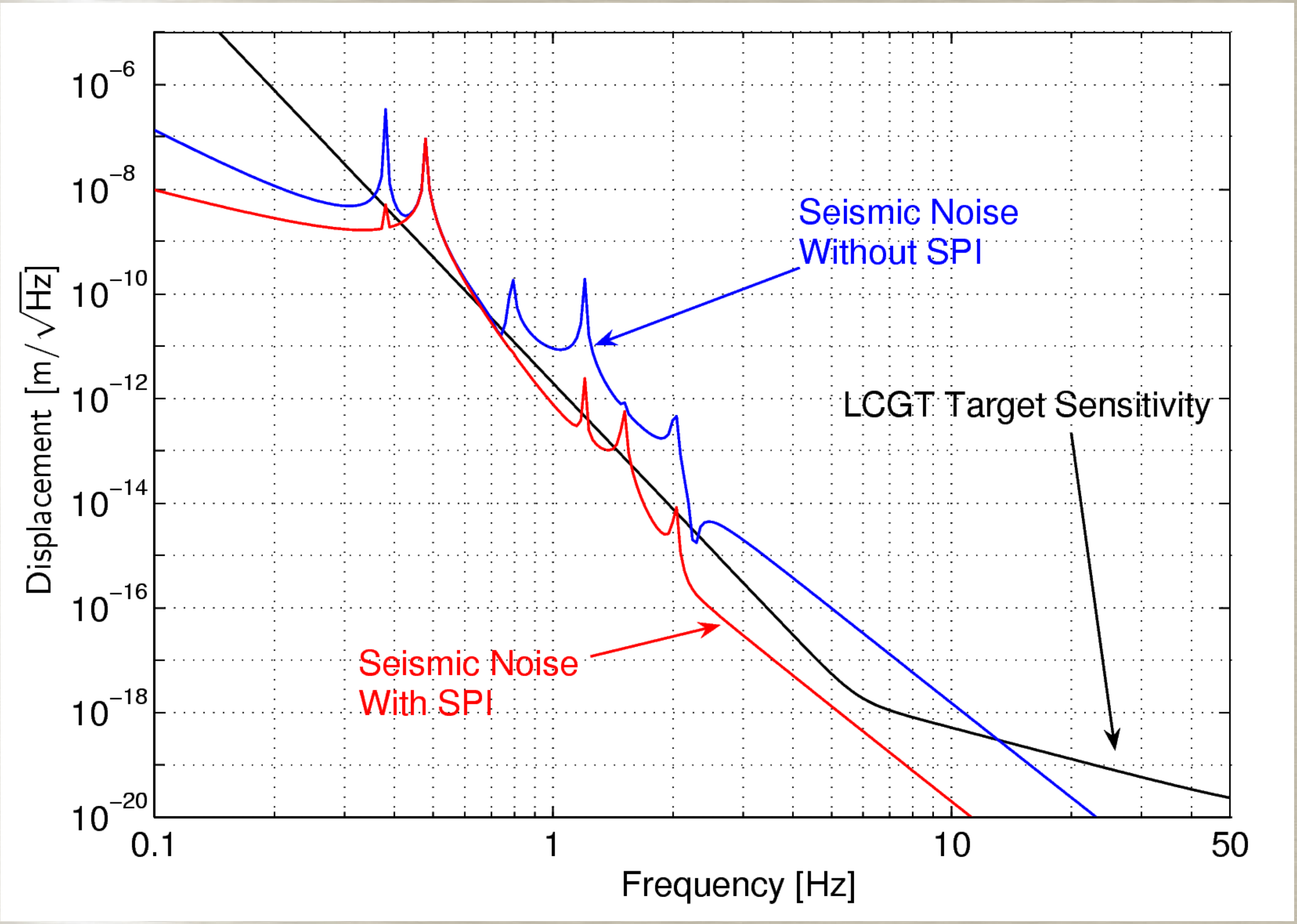
Close to the main interferometer

Low noise sensor is critical

Vibration introduced from heat links

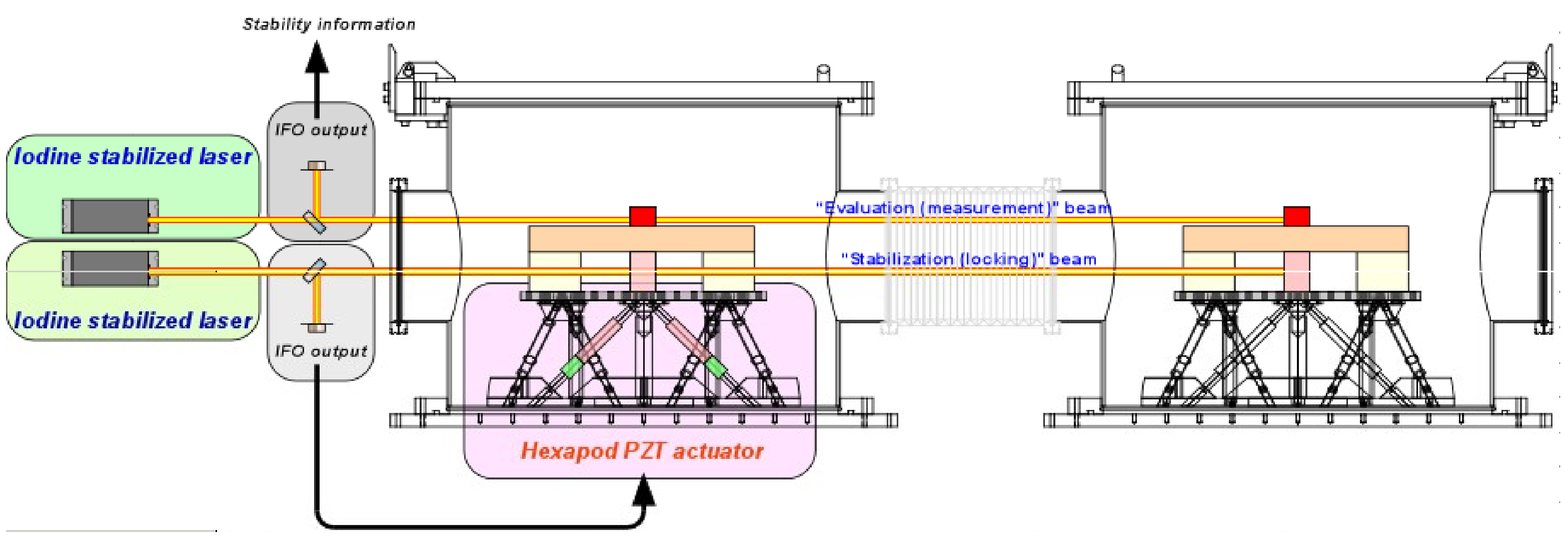
(simulation by T. Uchiyama)

Point mass model of LCGT SAS
-40dB isolation enhancement by SPI
Vertical to horizontal coupling = 1%



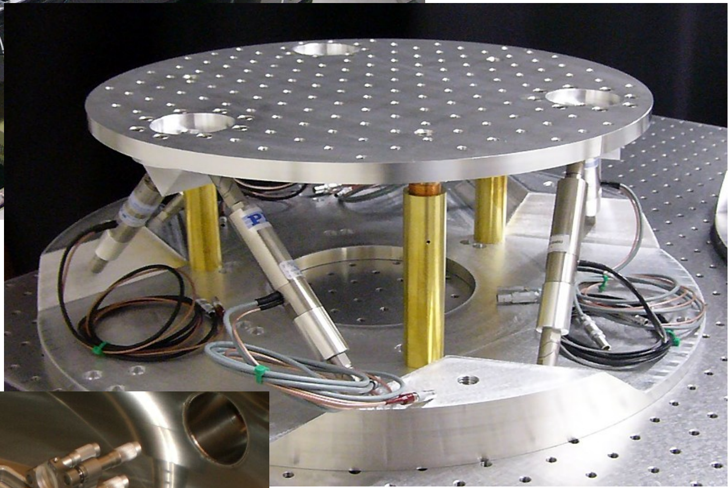
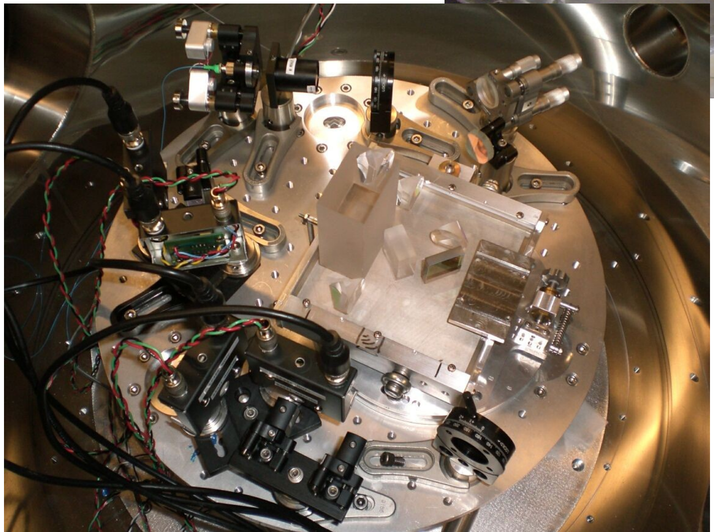
Verifying LISA interferometer

- Stable environment for high sensitivity
  - Testing of each optical bench needs moderate thermally stable environment (like LTP).
  - Testing of two (or more) optical benches/spacecrafts
    - Needs extremely stable environment between two benches (~10pm/rtHz)
    - Drifts of mechanical/optical components: ~1um (=1,000,000pm)
  - Every LISA testbed is designed to become insensitive to the relative bench motion.
    - The motion is the GW signal that LISA is supposed to detect.
- Detection and active suppression of environmental motions
  - Using multiple stabilization interferometers and multi-DOF actuators



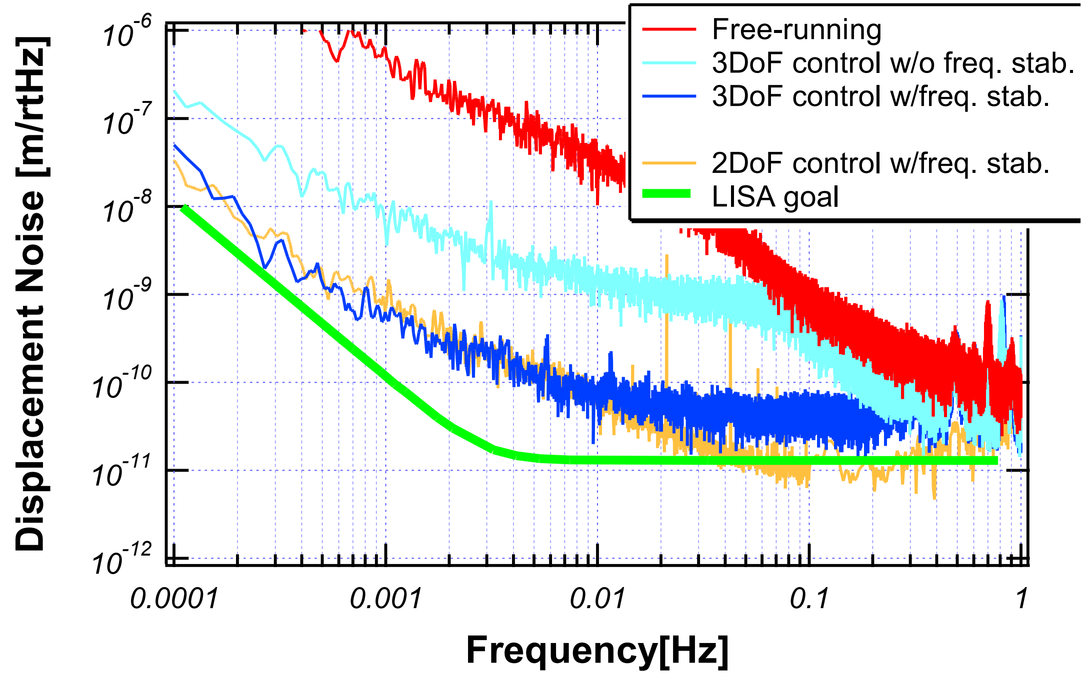
Photographs

- Installed components
  - Vacuum system
  - Hexapod
  - Control system
    - Digital control (3 DOFs)
  - Iodine stabilized lasers
  - Interferometers
    - Silicate bonded optics on ULE plates
    - 3 stabilization interferometers
      - Length, yaw & pitch motion
    - 1 measurement interferometer

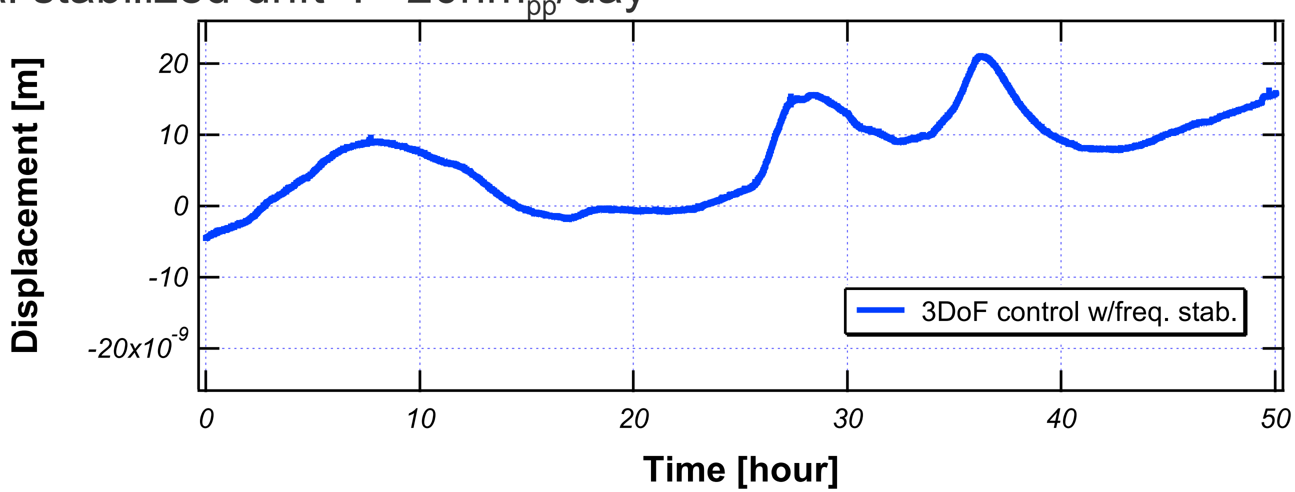




Stabilization results

- Current control performance
  - In spectrum
    - Gain ~1000 achieved
    - 3rd beam (pitch) didn't help stability
      - Still above LISA requirement



  - In time-domain
    - Typical free-running drift : ~4um_{pp}/day (over 1m separation)
    - Typical stabilized drift : ~20nm_{pp}/day



Conclusion

SPI: Low-noise low-frequency active vibration isolation scheme
Ultra low-frequency performance: RMS reduction

→ Stable operation, Robust lock acquisition, Technical noise mitigation

Prototype Experiment

1.5m Fabry-Perot interferometer, Triple pendulum suspension

Spectral measurements

- Noise spectrum: maximum 40dB reduction
- Displacement RMS: 1/9
- Velocity RMS: 1/7

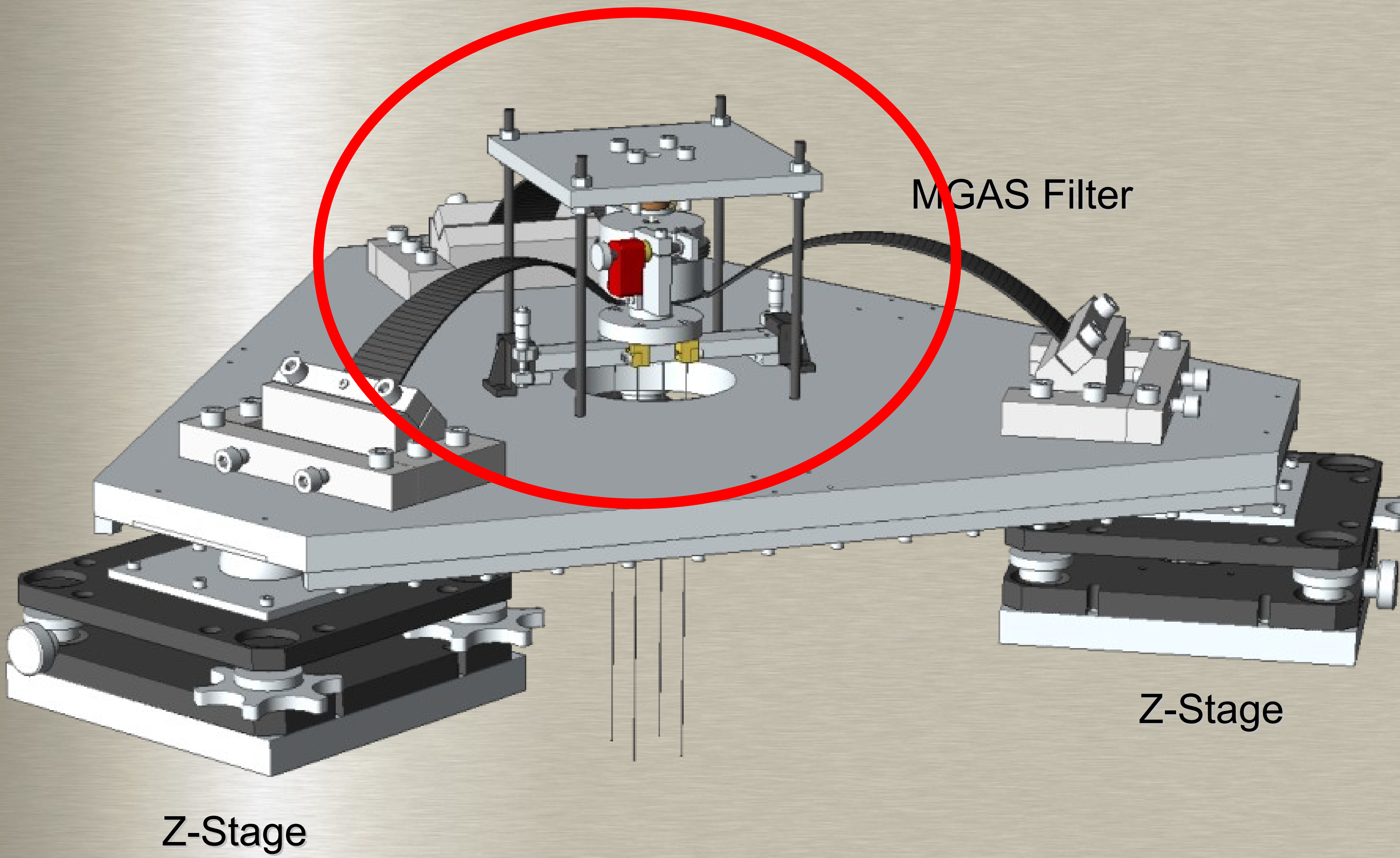
Transfer function measurements

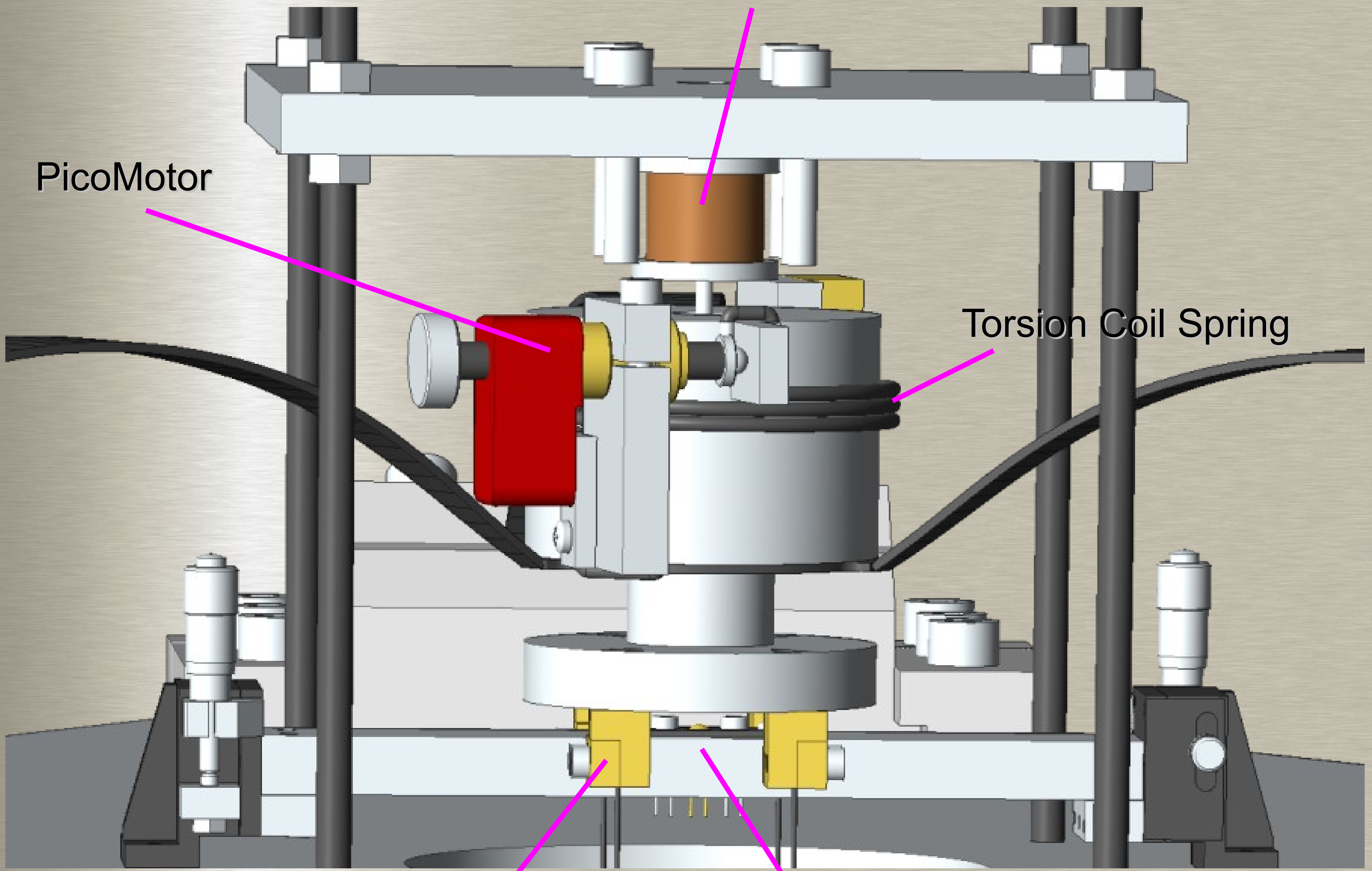
- Vibration isolation performance improvement: more than 40dB up to 20Hz

Future detectors are considering the use of SPI
LCGT, Advanced LIGO
LISA Test

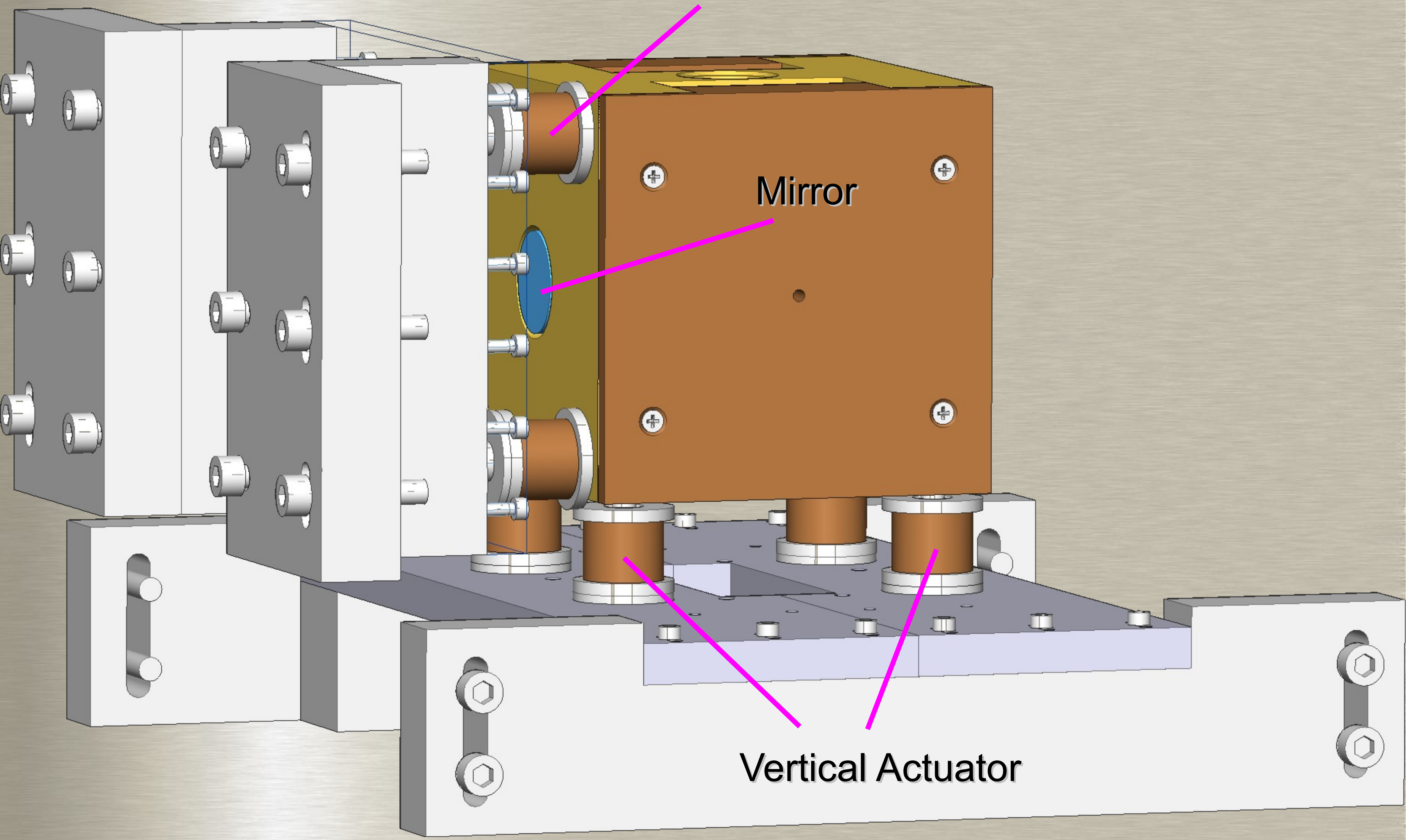
Extra Slides

Top Stage

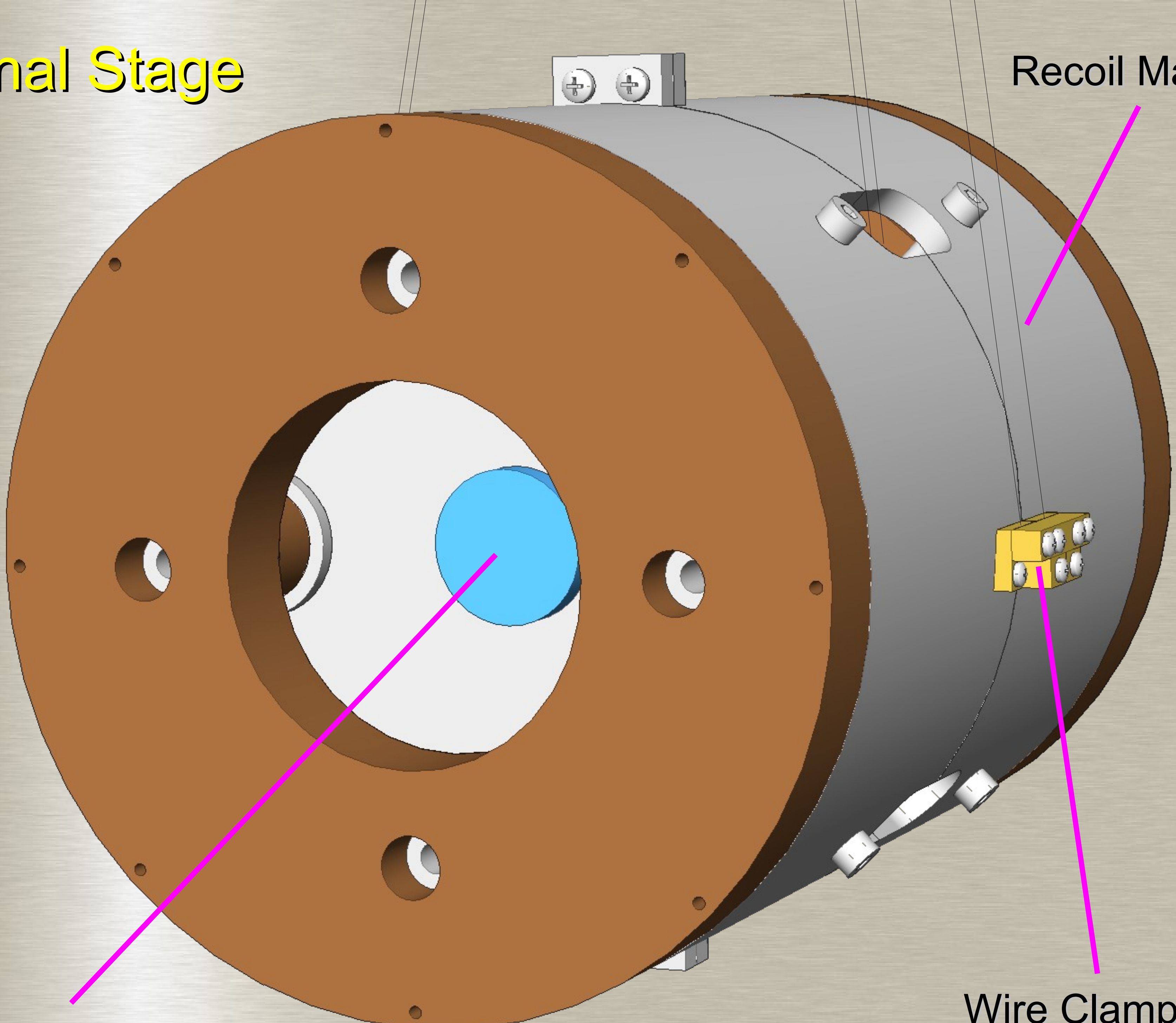


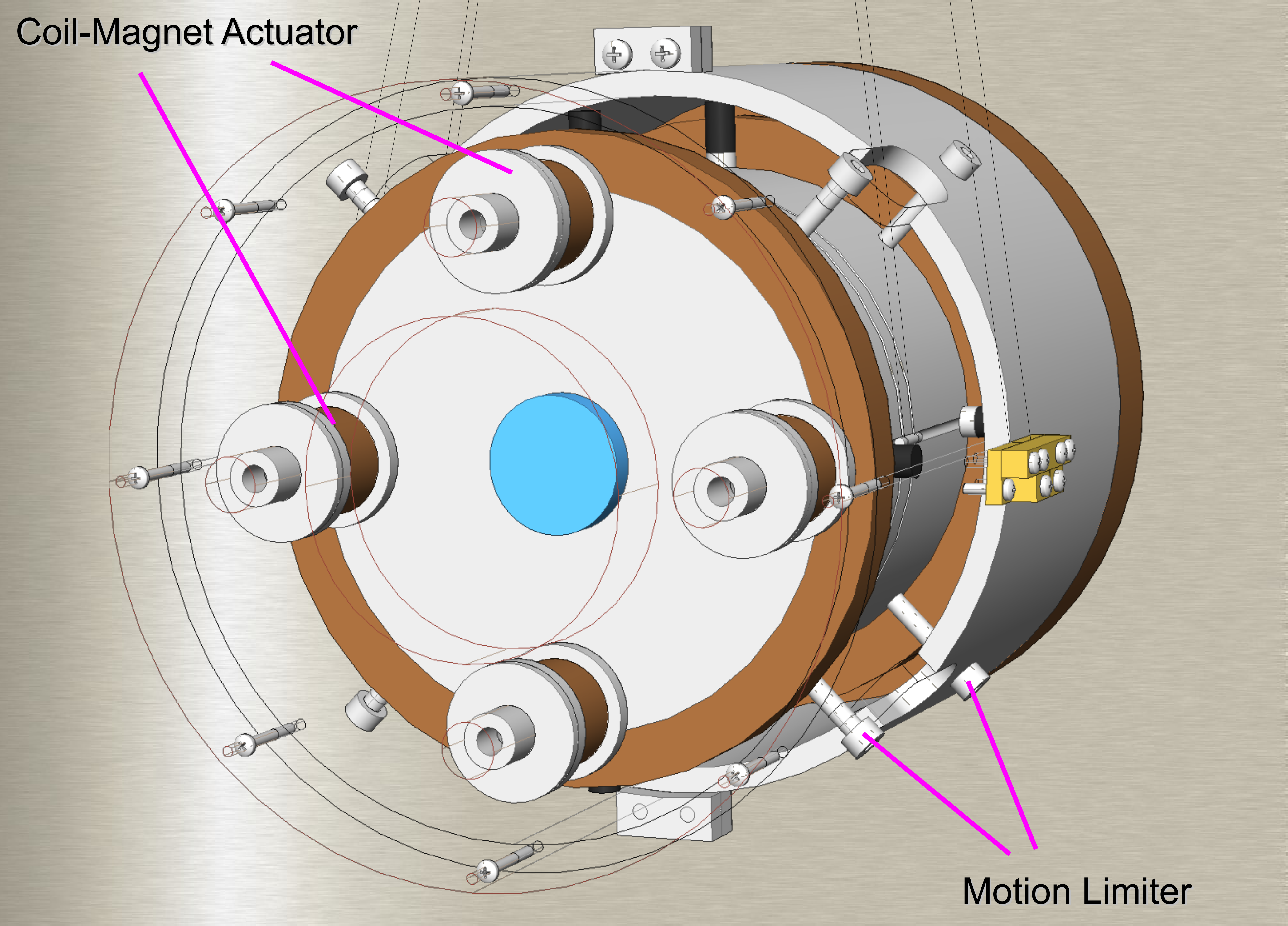

Coil-Magnet Actuator
PicoMotor
Torsion Coil Spring
Wire Clamp
Photo Sensor

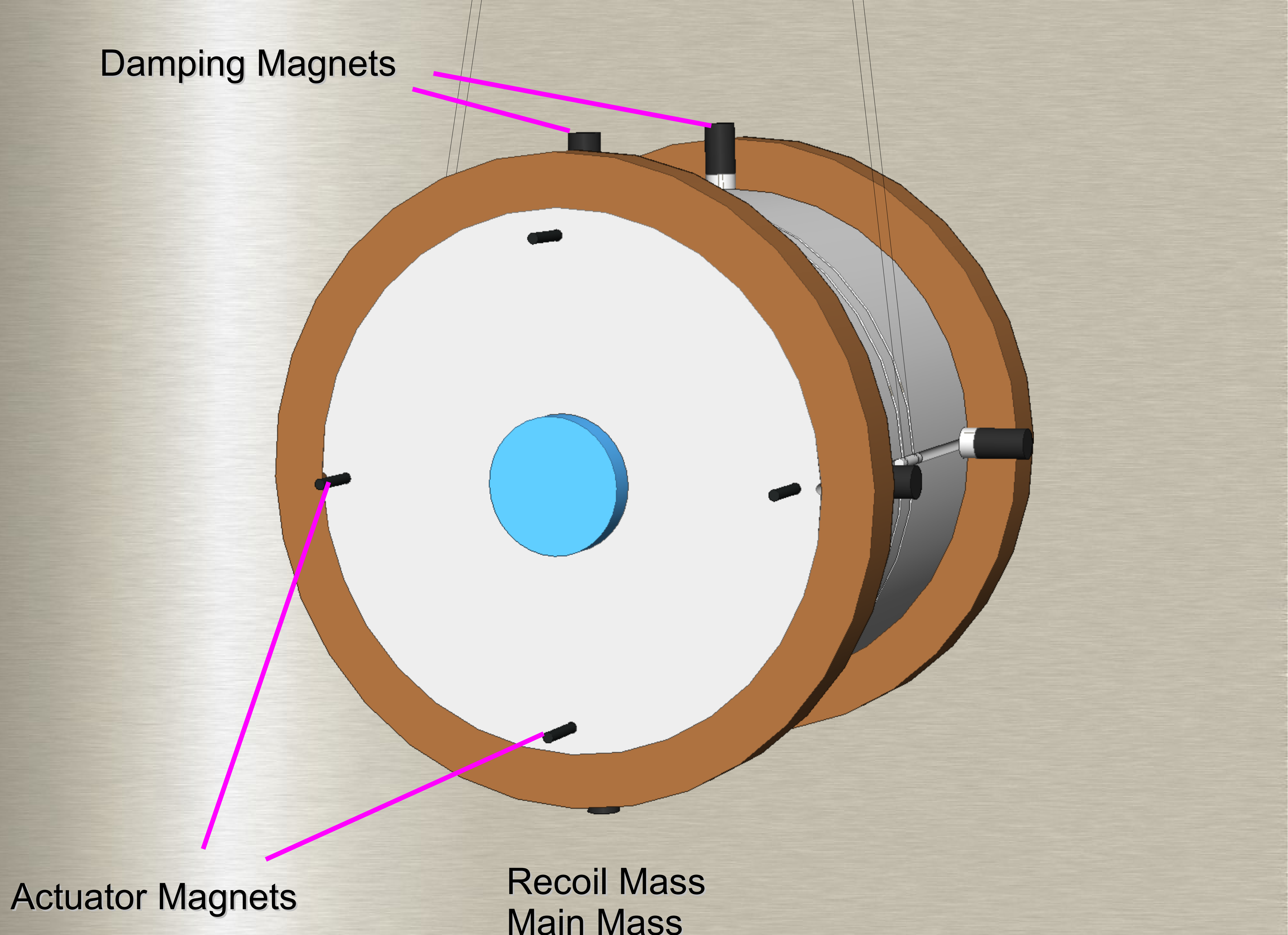
SPI Mass

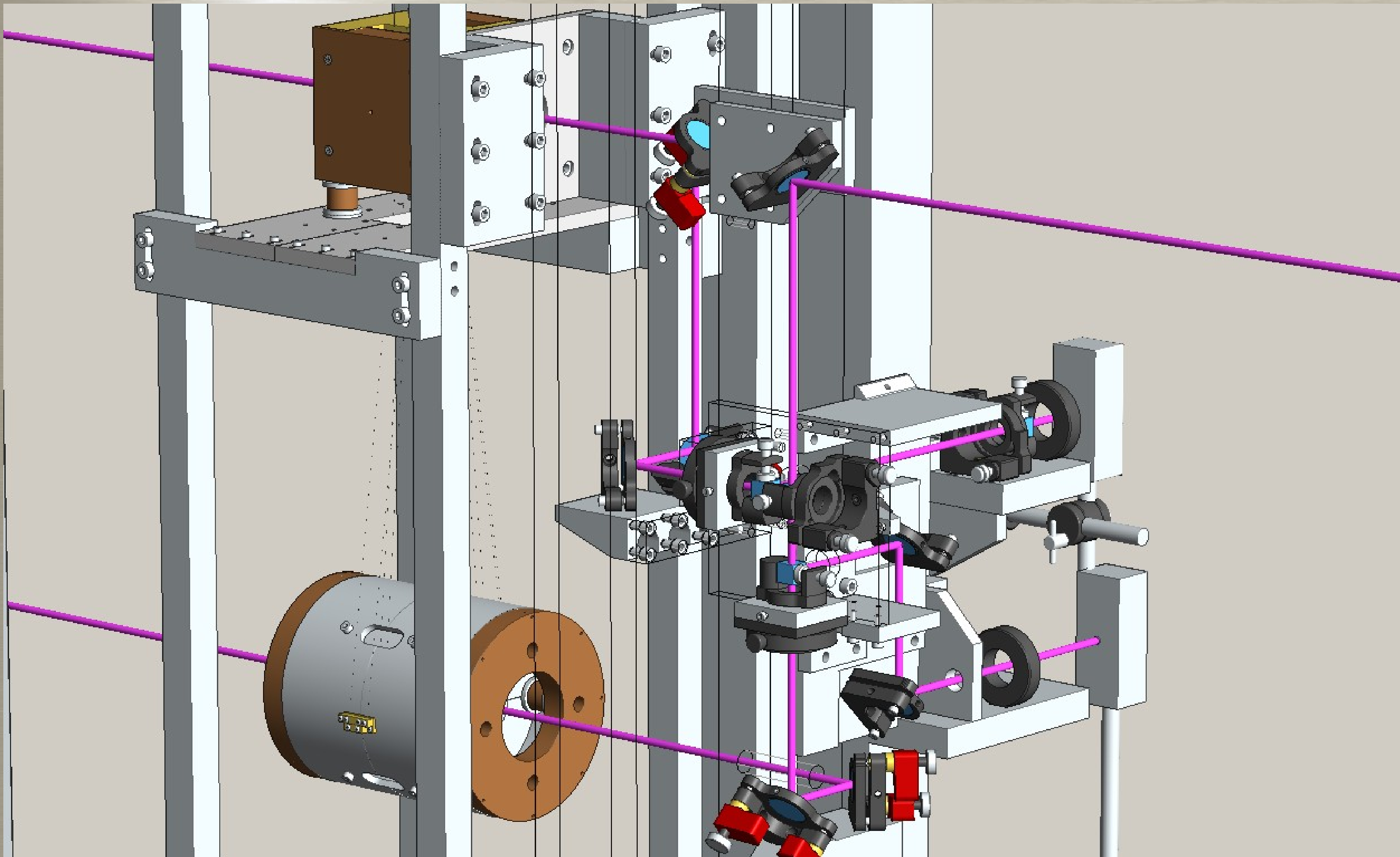


Final Stage




Coil-Magnet Actuator
Motion Limiter


Damping Magnets
Actuator Magnets
Recoil Mass
Main Mass

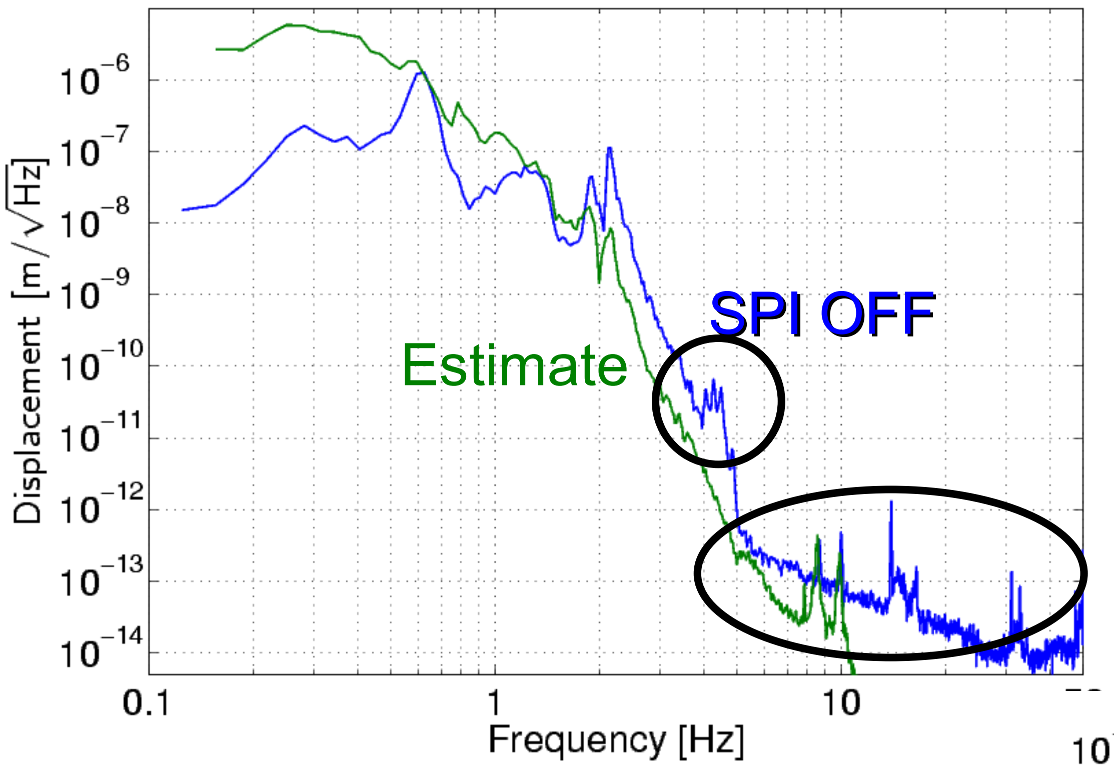


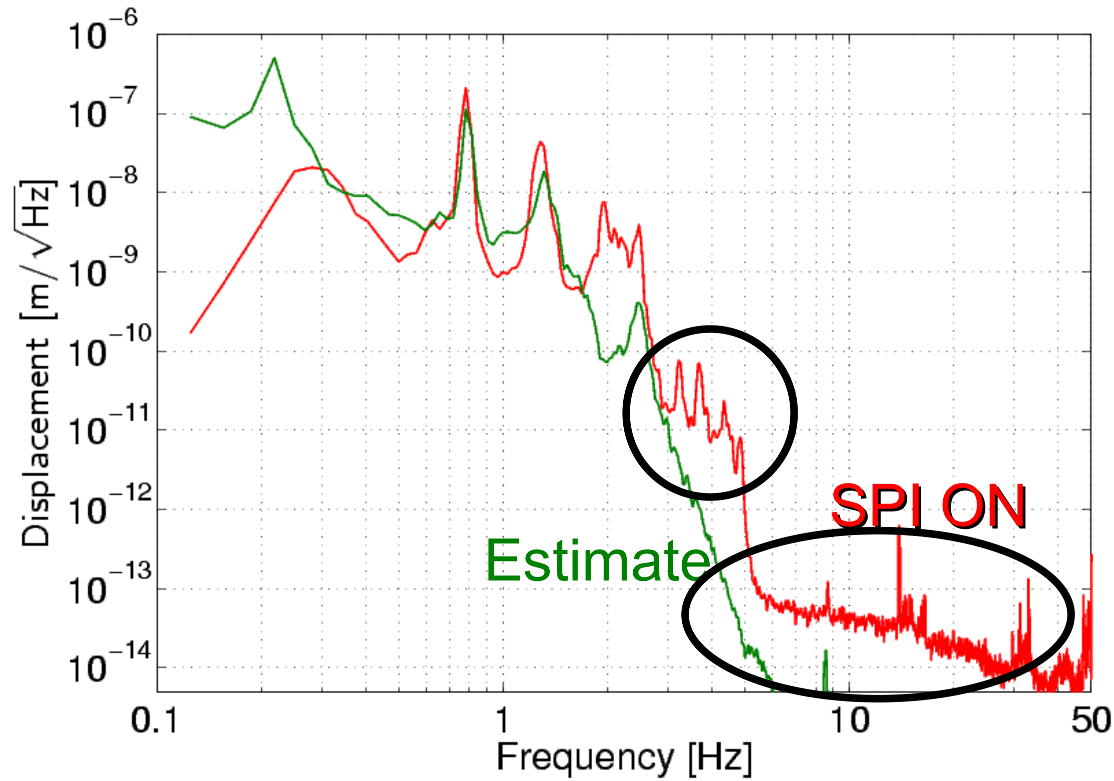
Seismic Noise Estimate

Suspension TF

× Seismic Motion

(Accelerometer)

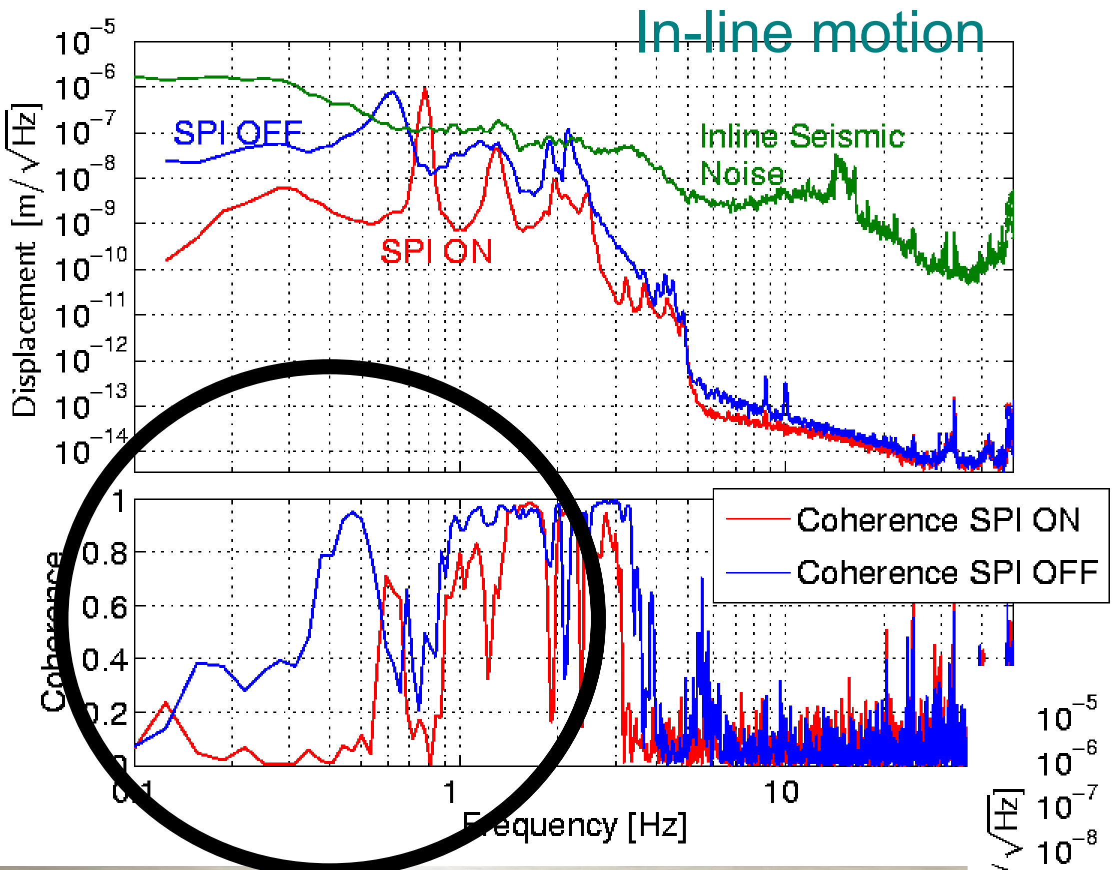




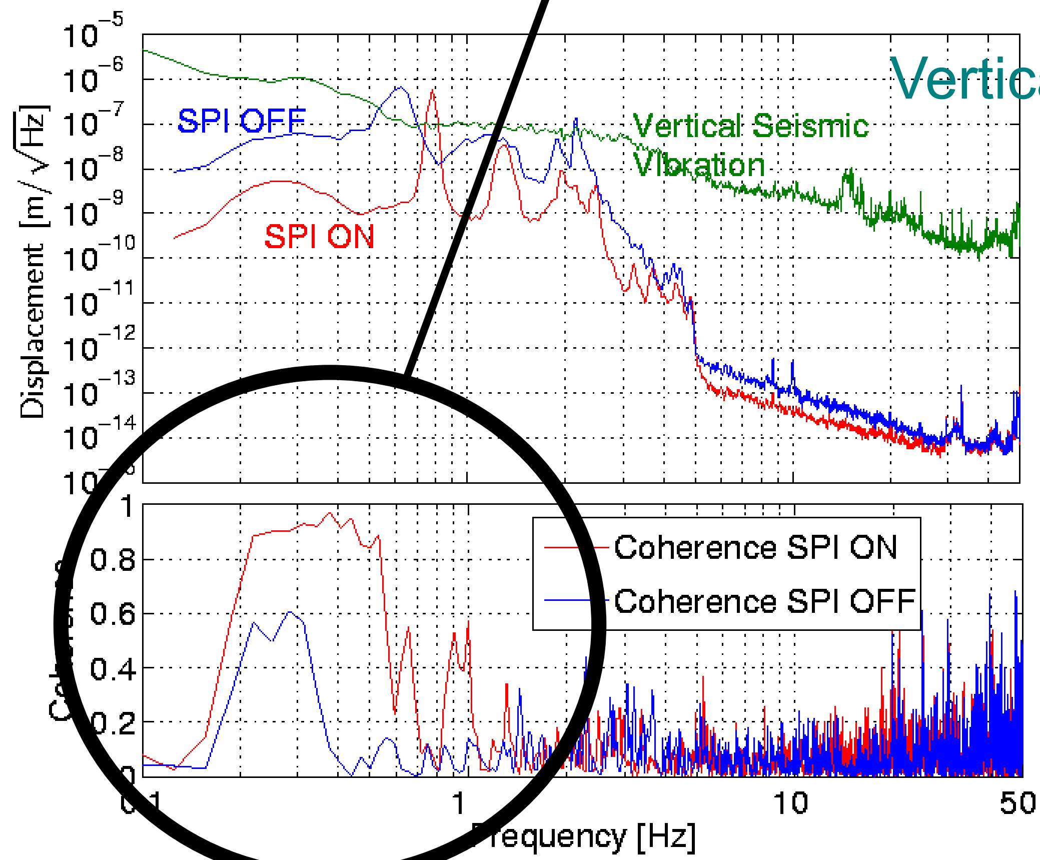
Seismic - IFO output Correlation

Seismic motion: measured by an accelerometer

Good correlation when SPI is ON



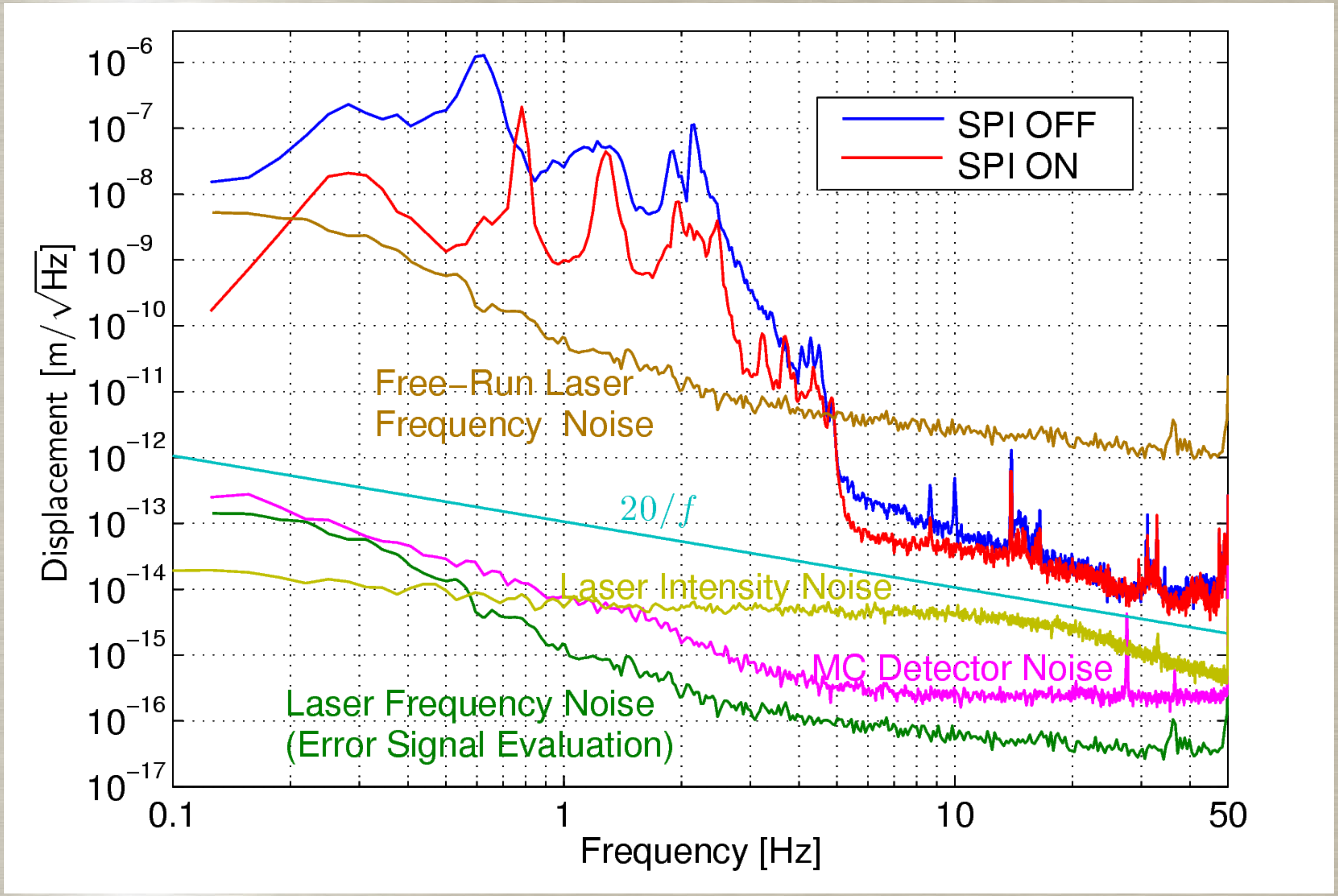
Good correlation when SPI is OFF



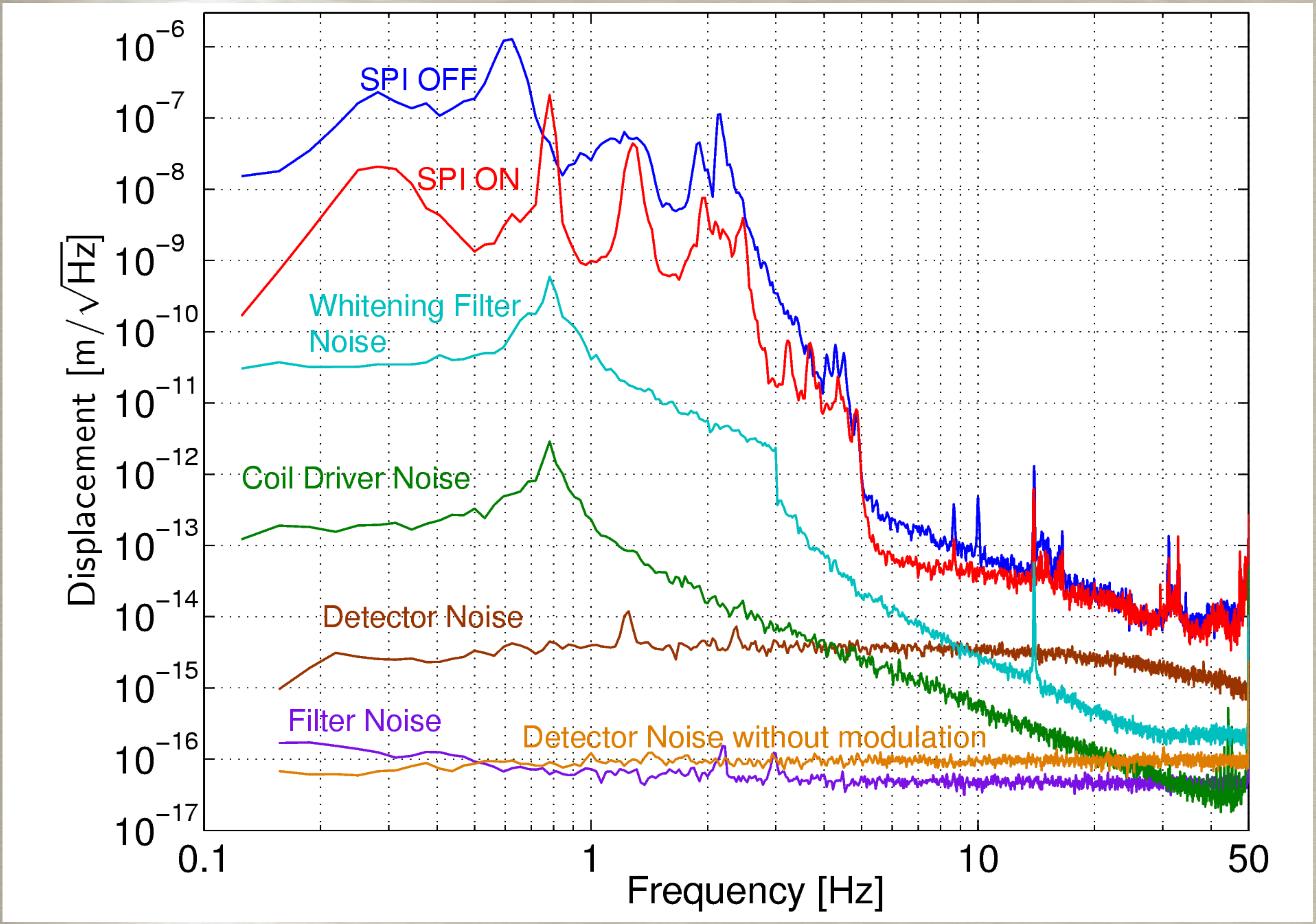
SPI ON

Vertical Motion is Dominant at low frequencies

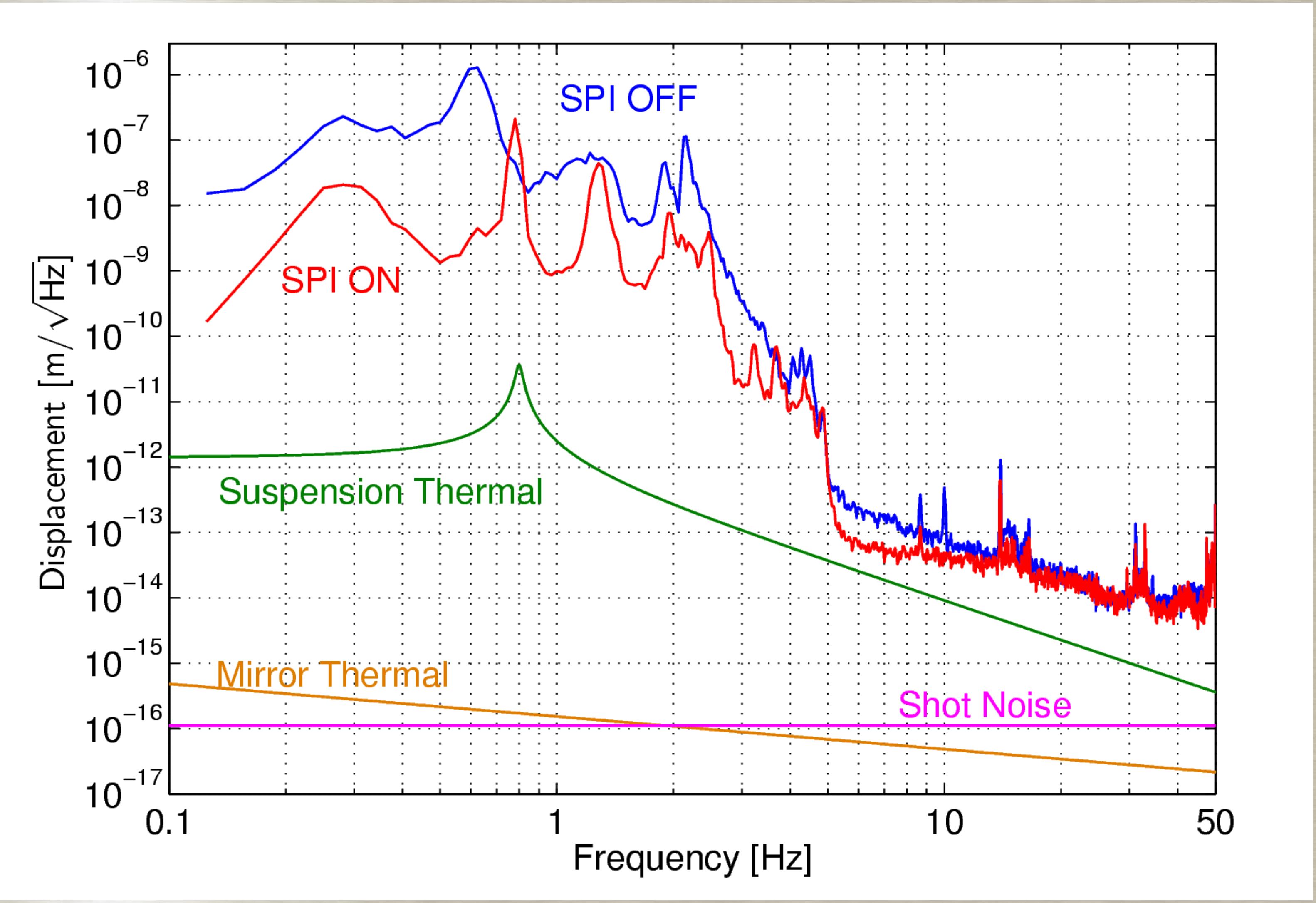
Laser Noises



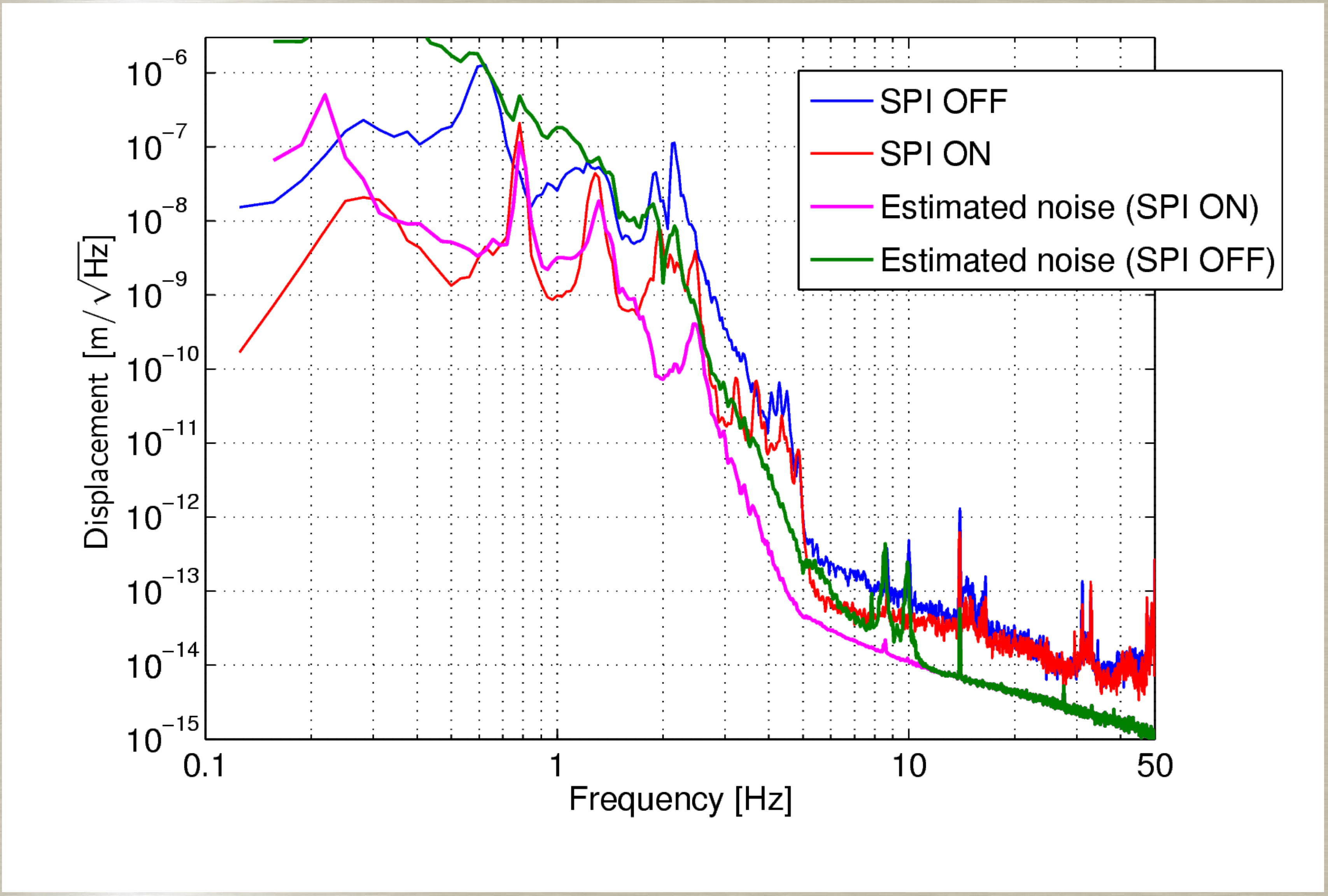
Electric Noises



Thermal noise, Shot noise



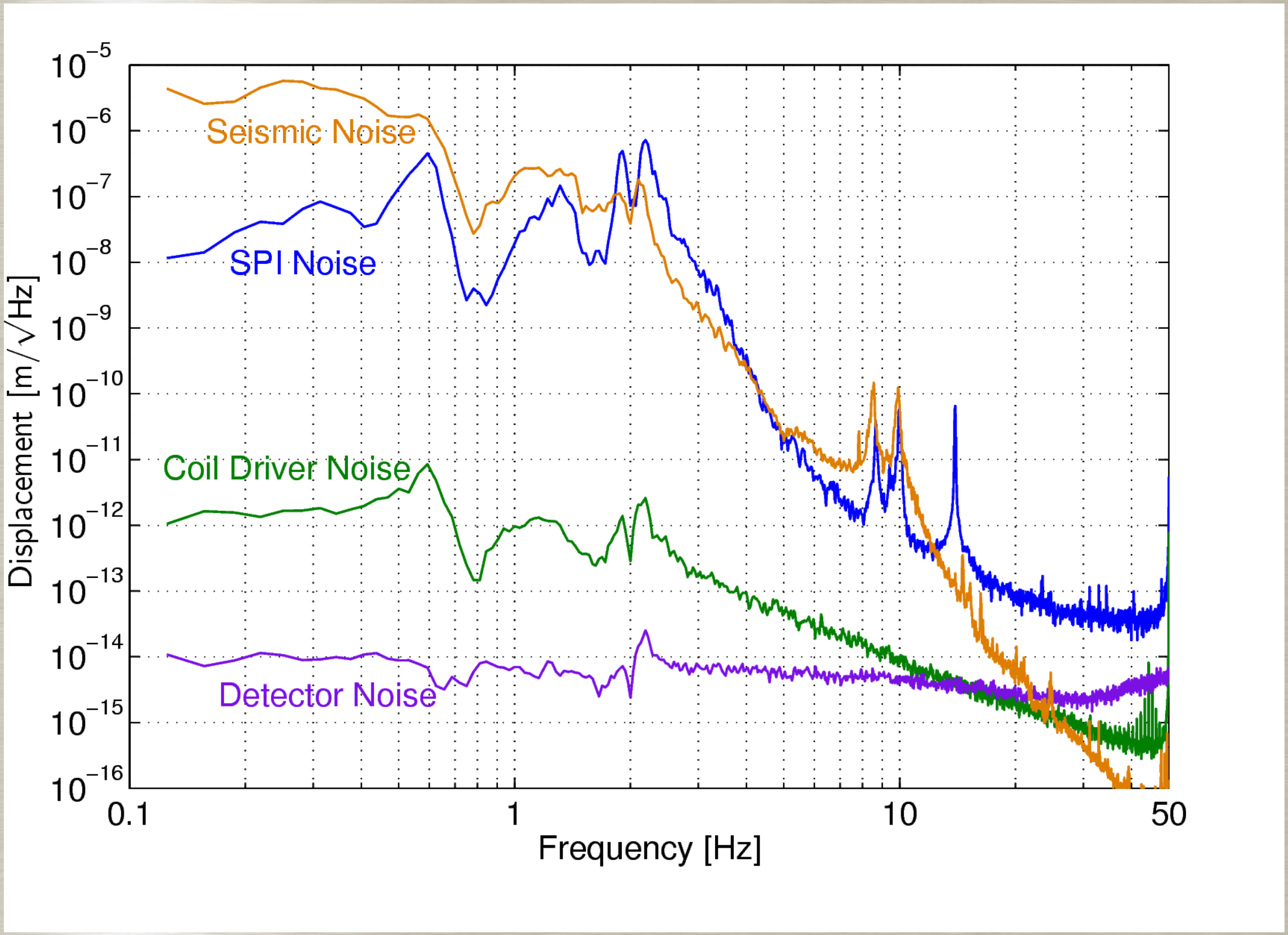
Total estimated noise

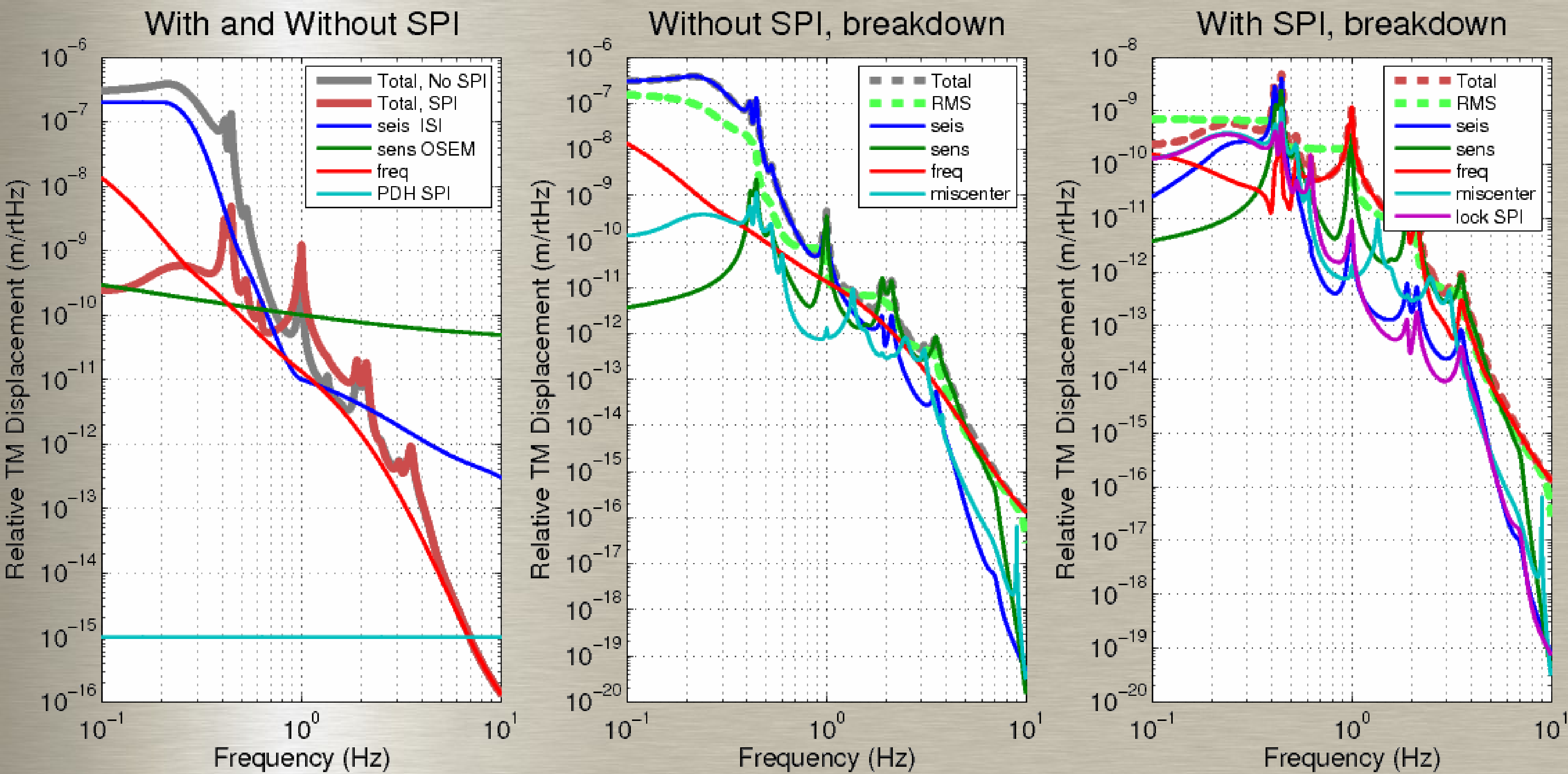


Noise shape: OK

Magnitude: Small discrepancy

Noise of the SPI




With and Without SPI
Total, No SPI
Total, SPI
seis ISI
sens OSEM
freq
PDH SPI
Relative TM Displacement (m/rtHz)
Frequency (Hz)
Without SPI, breakdown
Total
RMS
seis
sens
freq
miscenter
Relative TM Displacement (m/rtHz)
Frequency (Hz)
With SPI, breakdown
Total
RMS
seis
sens
freq
miscenter
lock SPI
Relative TM Displacement (m/rtHz)
Frequency (Hz)