Low frequency vibration isolation by Suspension Point Interferometer for extending the scientific reach of the future gravitational wave detectors

Yoichi Aso

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

July 14th 2007
7th Edoardo Amaldi Conference on Gravitational Waves
Sydney Convention and Exhibition Centre, Sydney, Australia

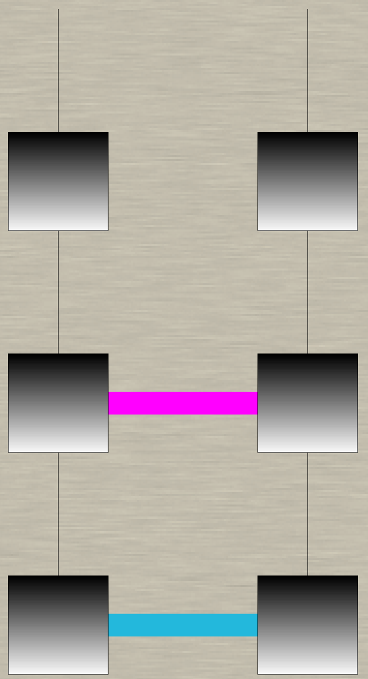
LIGO-G070446-00-Z

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

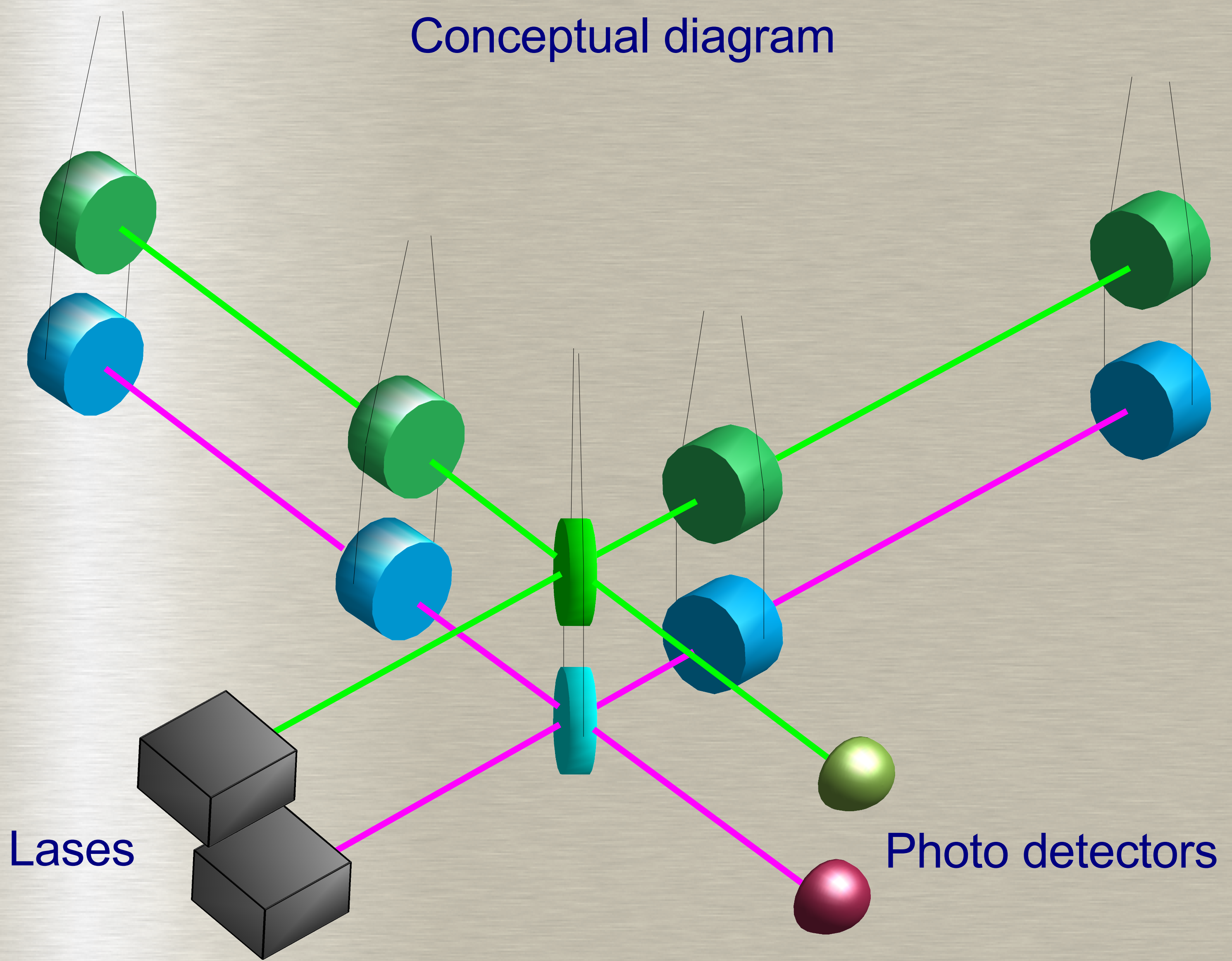
Contents

Suspension Point Interferometer

Originally proposed by Drever (1987)

Several possible configurations

Conceptual diagram

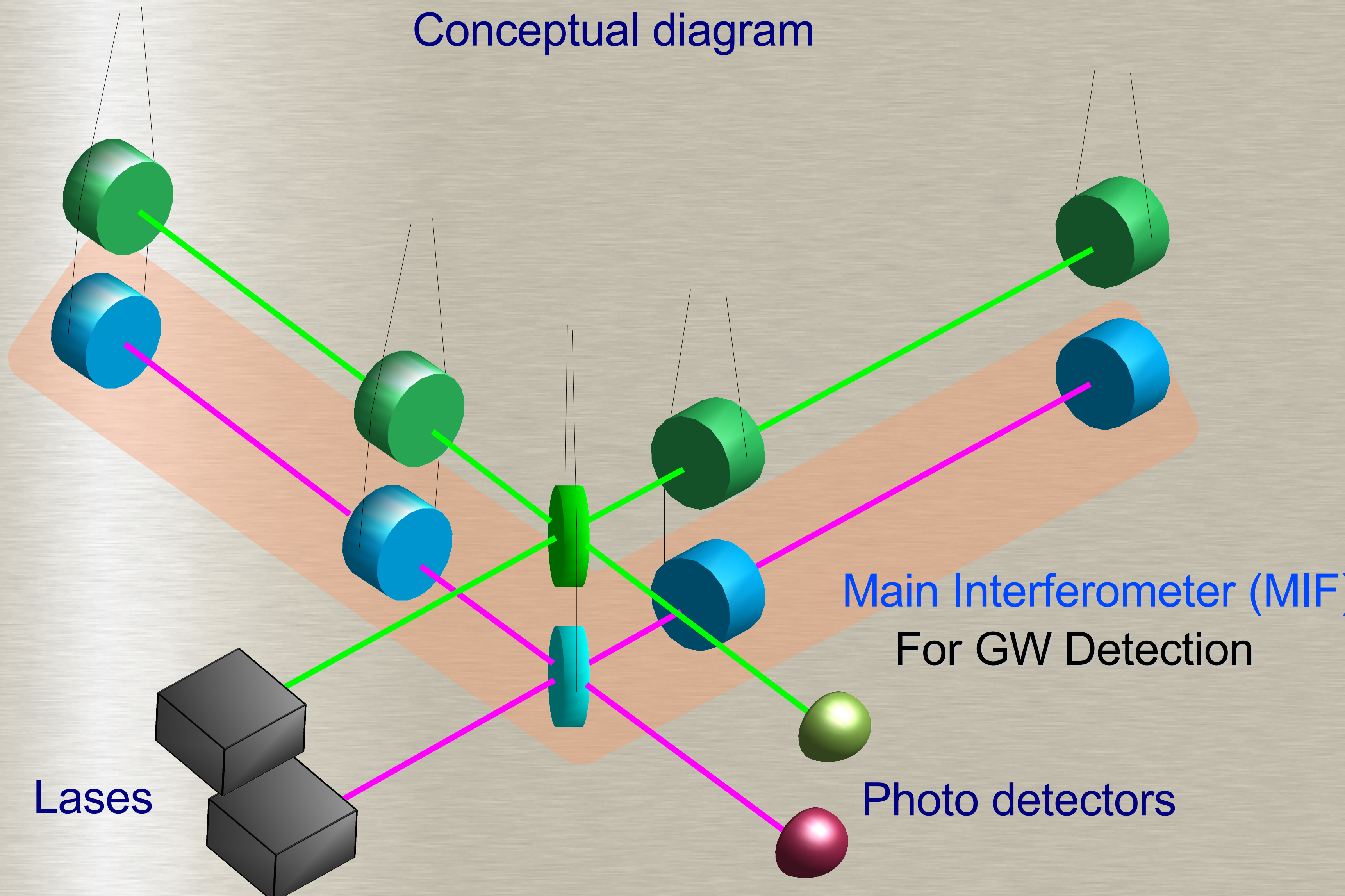


Suspension Point Interferometer

Originally proposed by Drever (1987)

Several possible configurations

Conceptual diagram

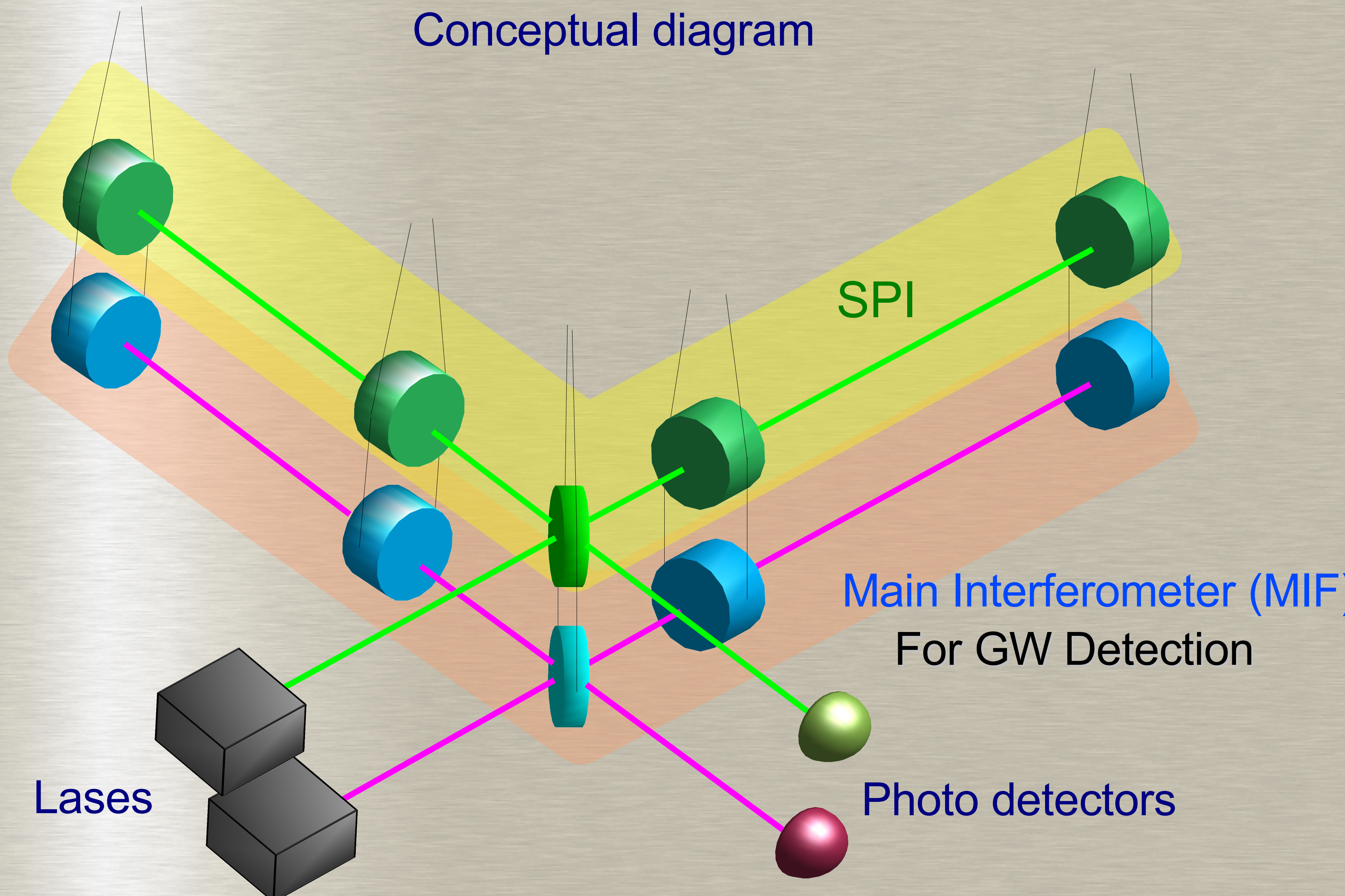


Suspension Point Interferometer

Originally proposed by Drever (1987)

Several possible configurations

Conceptual diagram

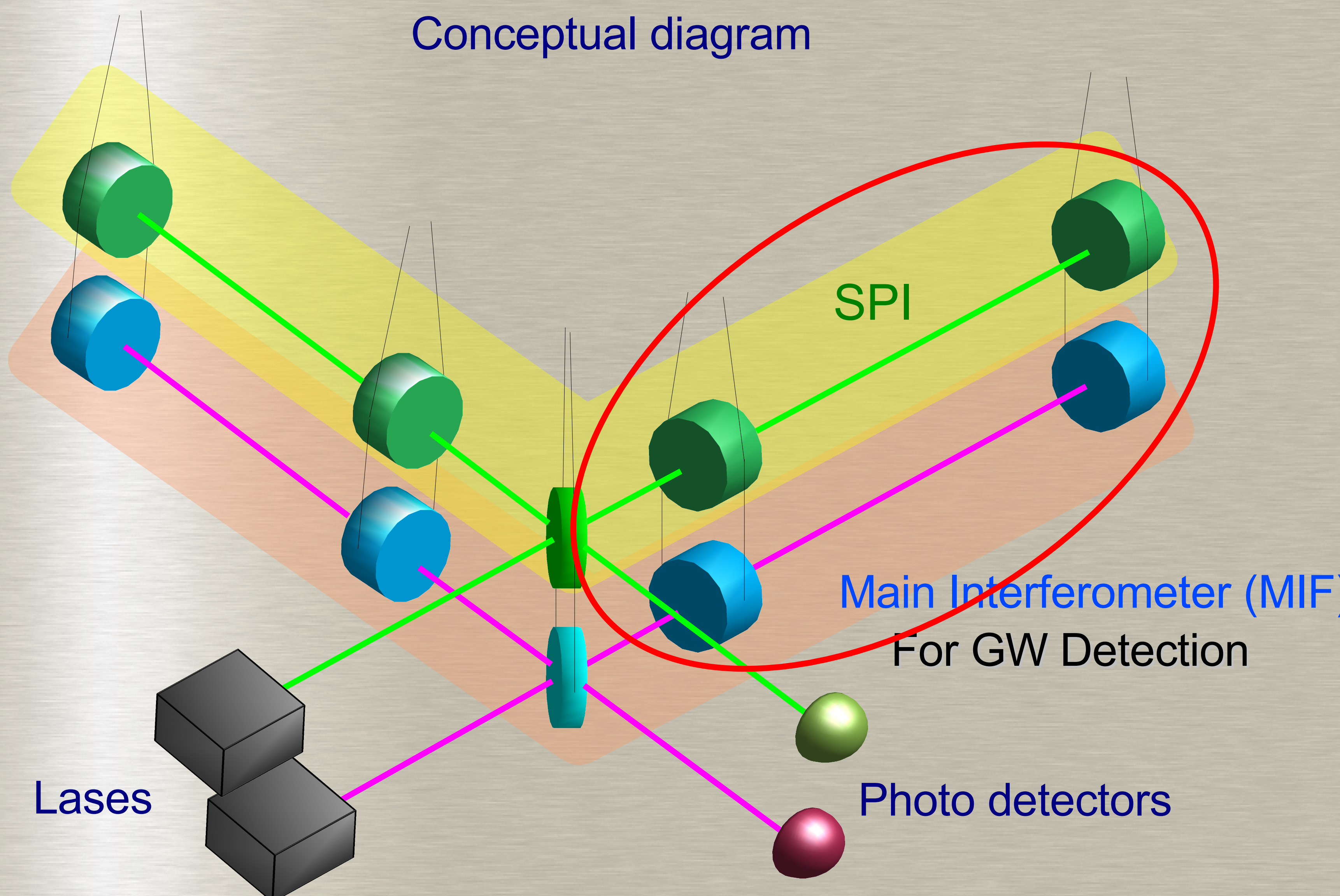


Suspension Point Interferometer

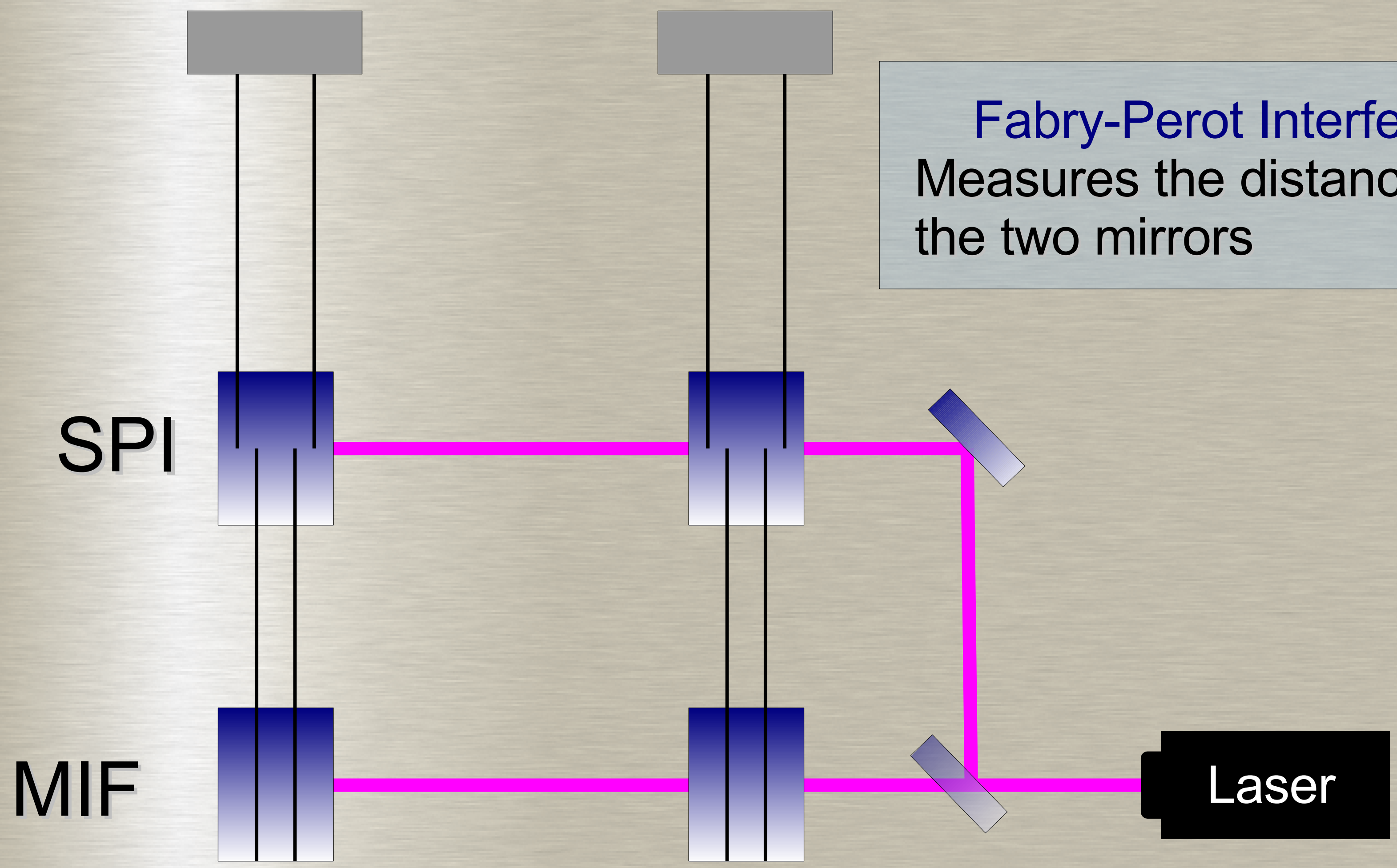
Originally proposed by Drever (1987)

Several possible configurations

Conceptual diagram



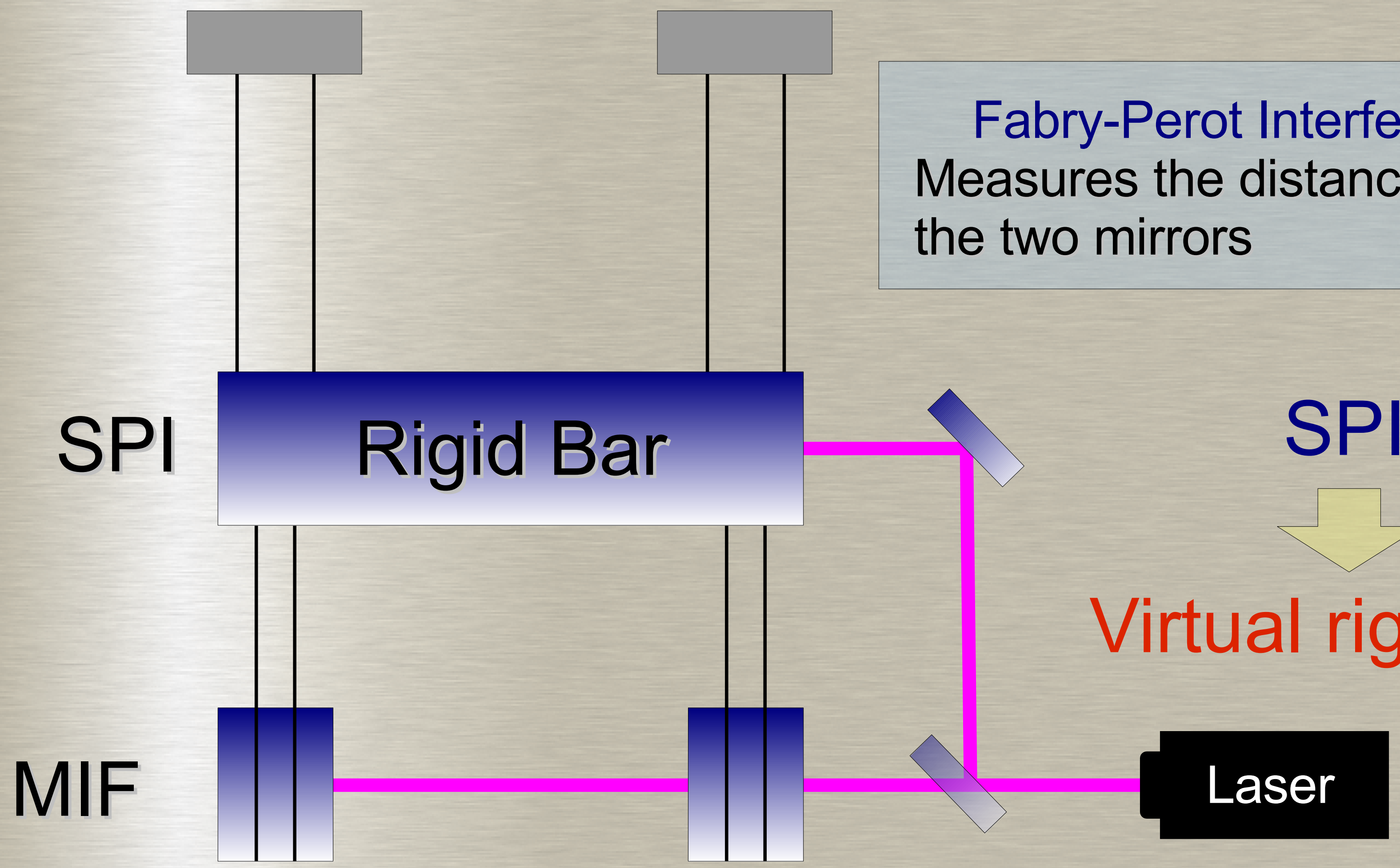
Working Principle of SPI: Fabry-Perot Arm



Fabry-Perot Interferometer
Measures the distance between the two mirrors

Working Principle of SPI: Fabry-Perot Arm

SPI is locked



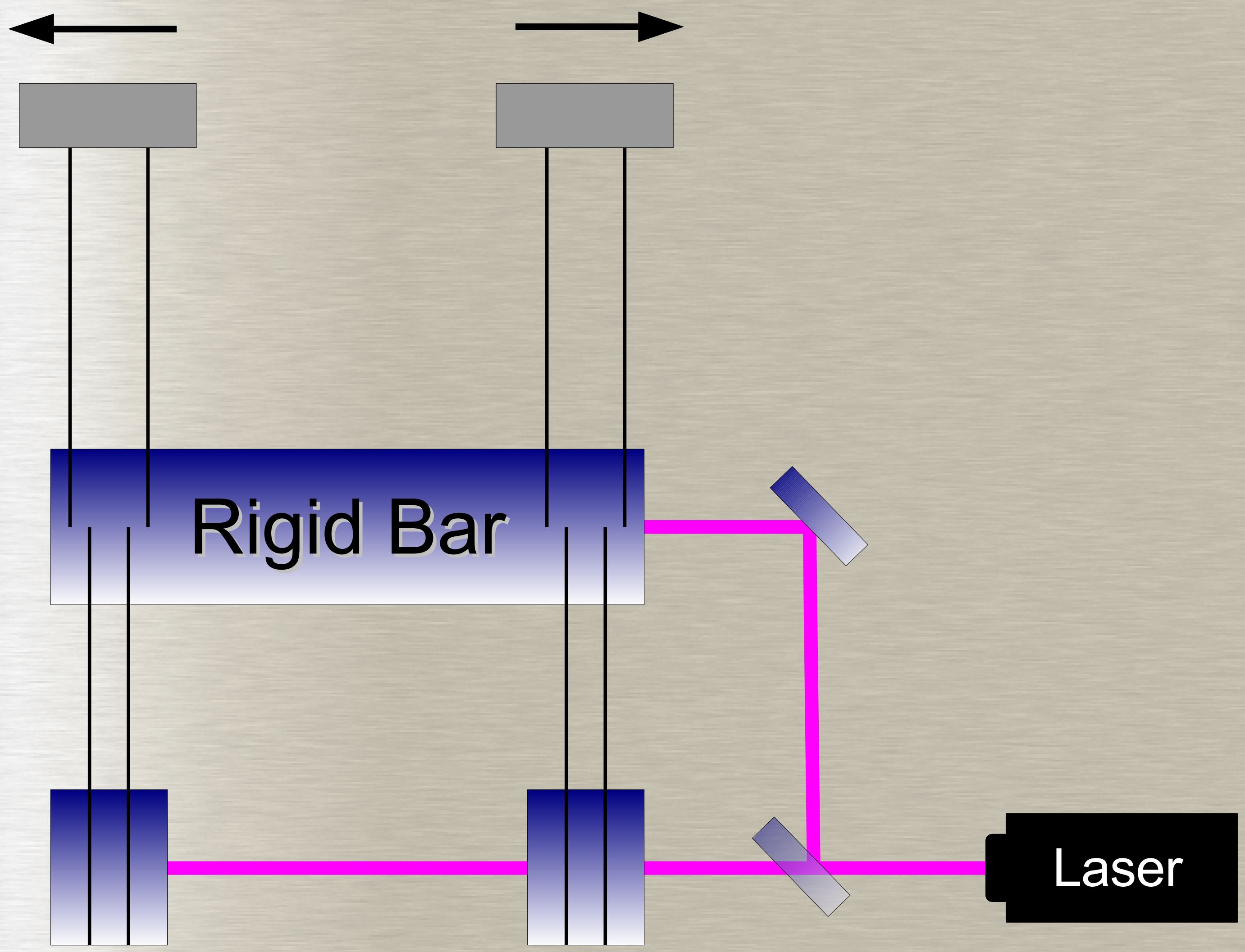
Fabry-Perot Interferometer
Measures the distance between the two mirrors

SPI

Virtual rigid bar

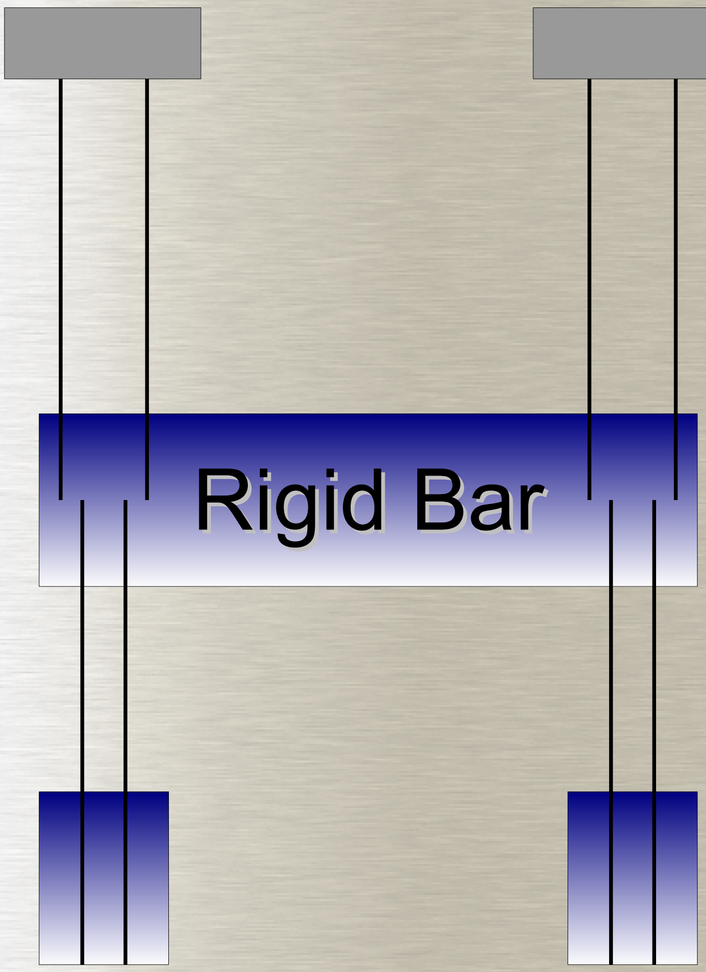
Working Principle of SPI: Fabry-Perot Arm

Differential Seismic Motion



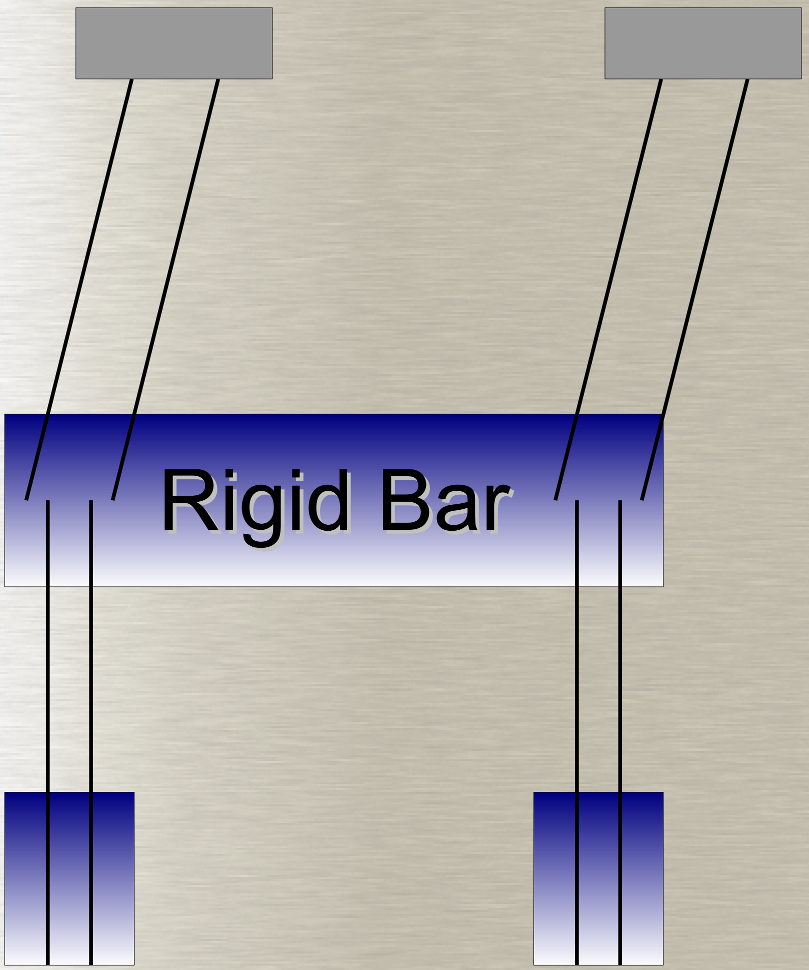
Working Principle of SPI: Fabry-Perot Arm

Common mode motion



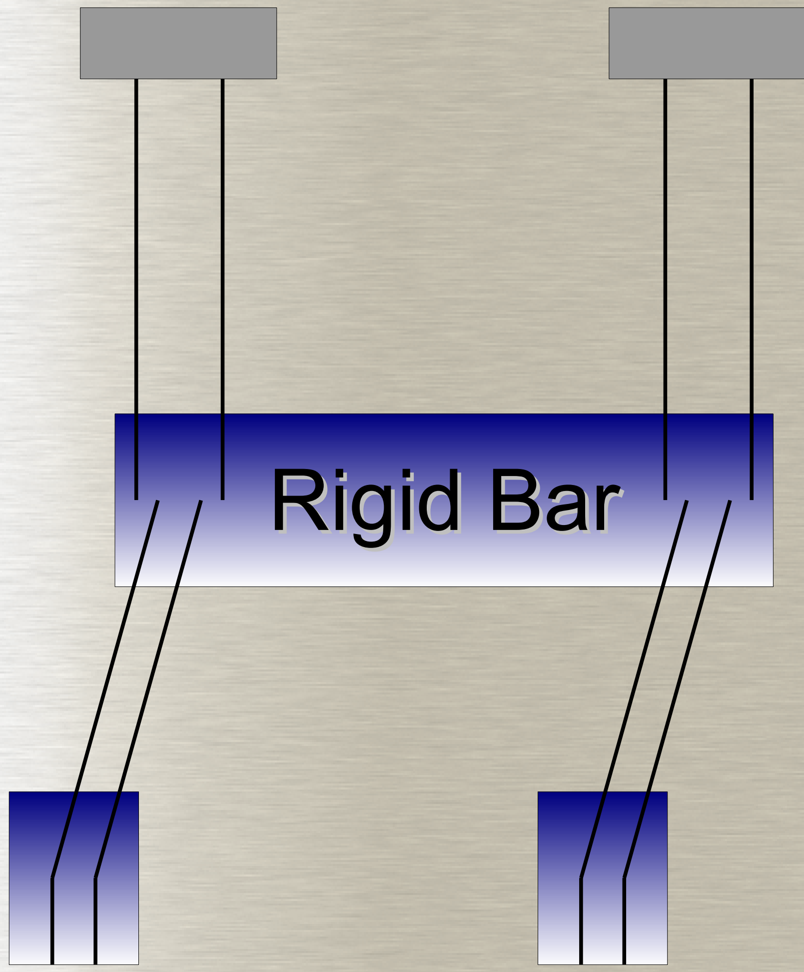
Working Principle of SPI: Fabry-Perot Arm

Common mode motion



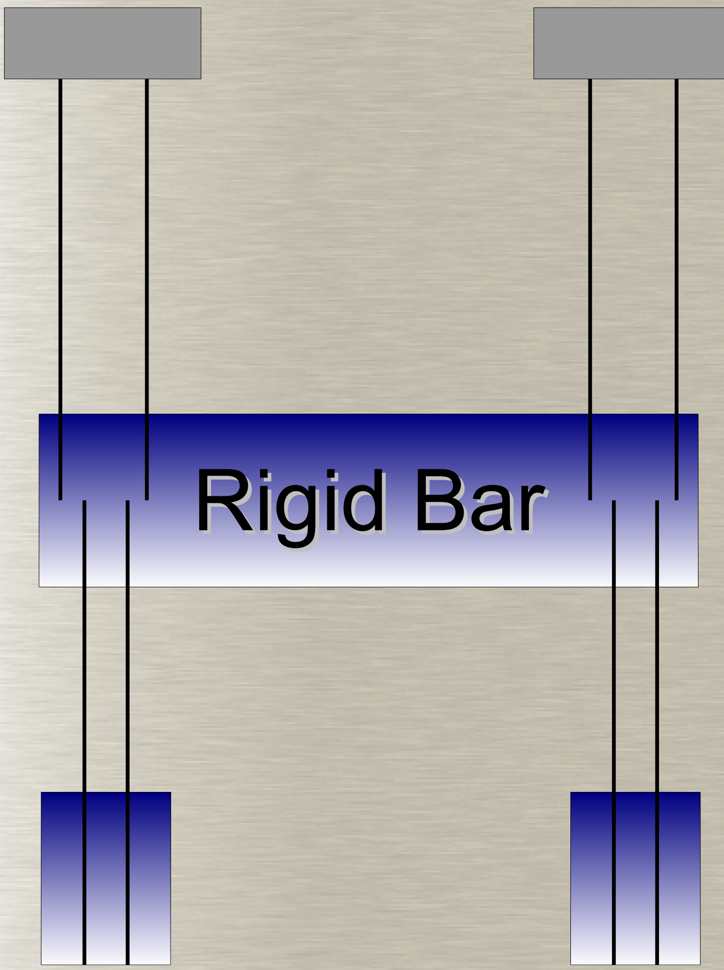
Working Principle of SPI: Fabry-Perot Arm

Common mode motion



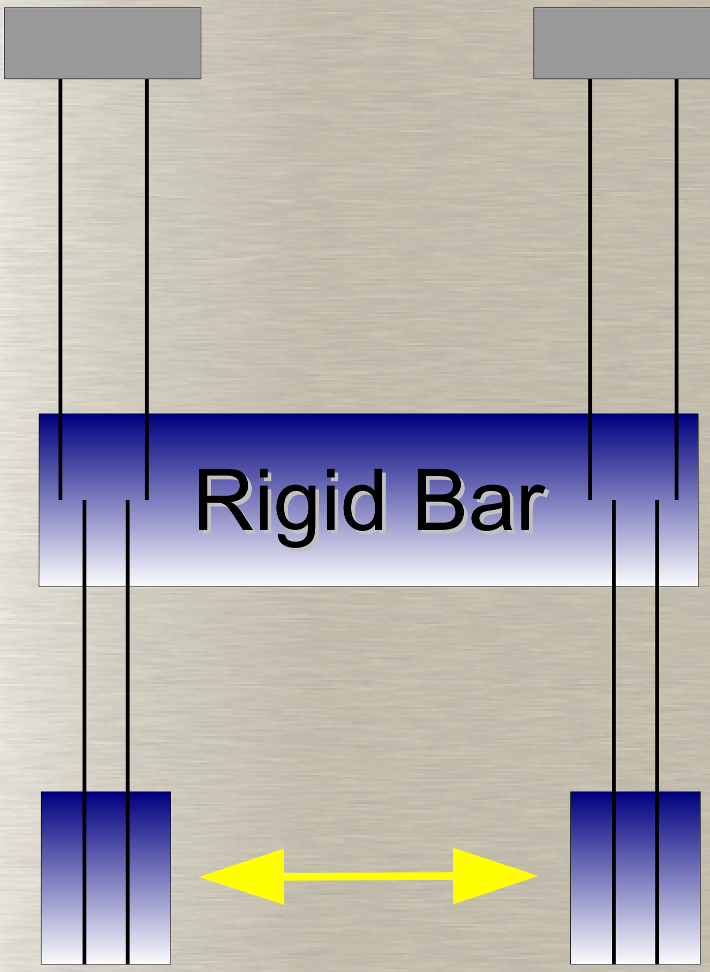
Working Principle of SPI: Fabry-Perot Arm

Common mode motion



Working Principle of SPI: Fabry-Perot Arm

Common mode motion

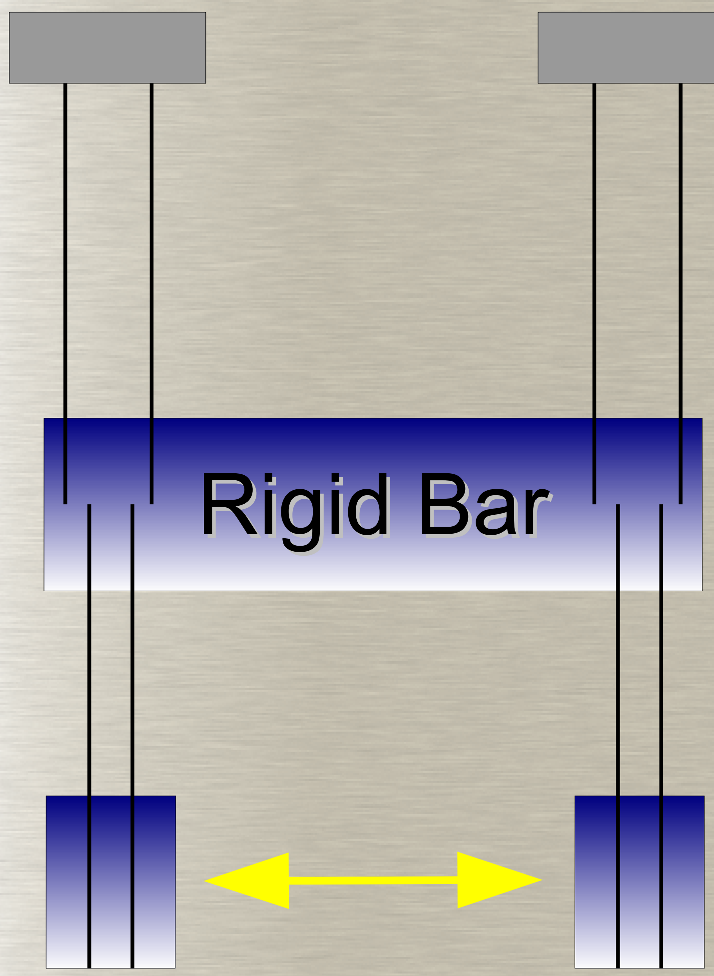


Identical Pendulums

No change in the distance

Working Principle of SPI: Fabry-Perot Arm

Common mode motion



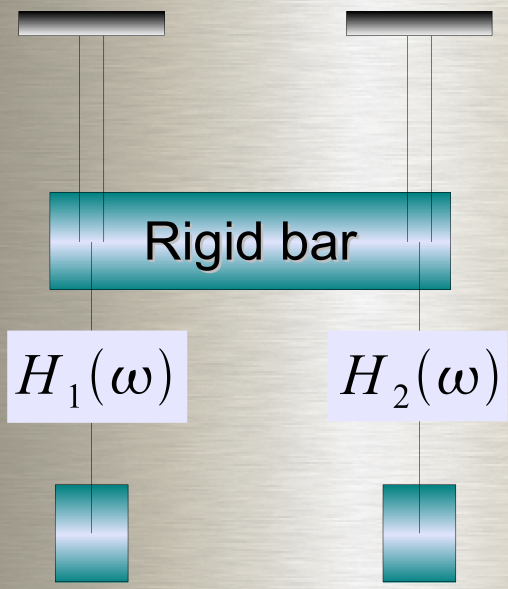
Identical Pendulums

Asymmetry ?

No change in the distance

Theoretical Performance

Common Mode Rejection Ratio (CMRR)



Transfer functions:

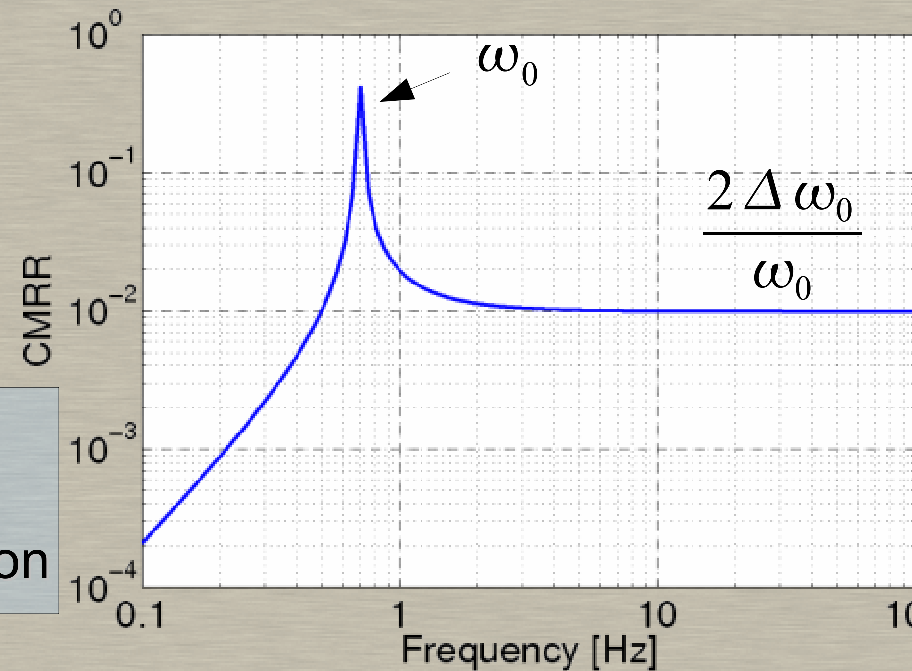
$$H_1(\omega), H_2(\omega)$$

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

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

Advantages of SPI

Characteristics

- Low Noise Sensor
- Displacement sensor (global sensor) → DC sensitivity
  → Ultra low-frequency vibration isolation

Benefits

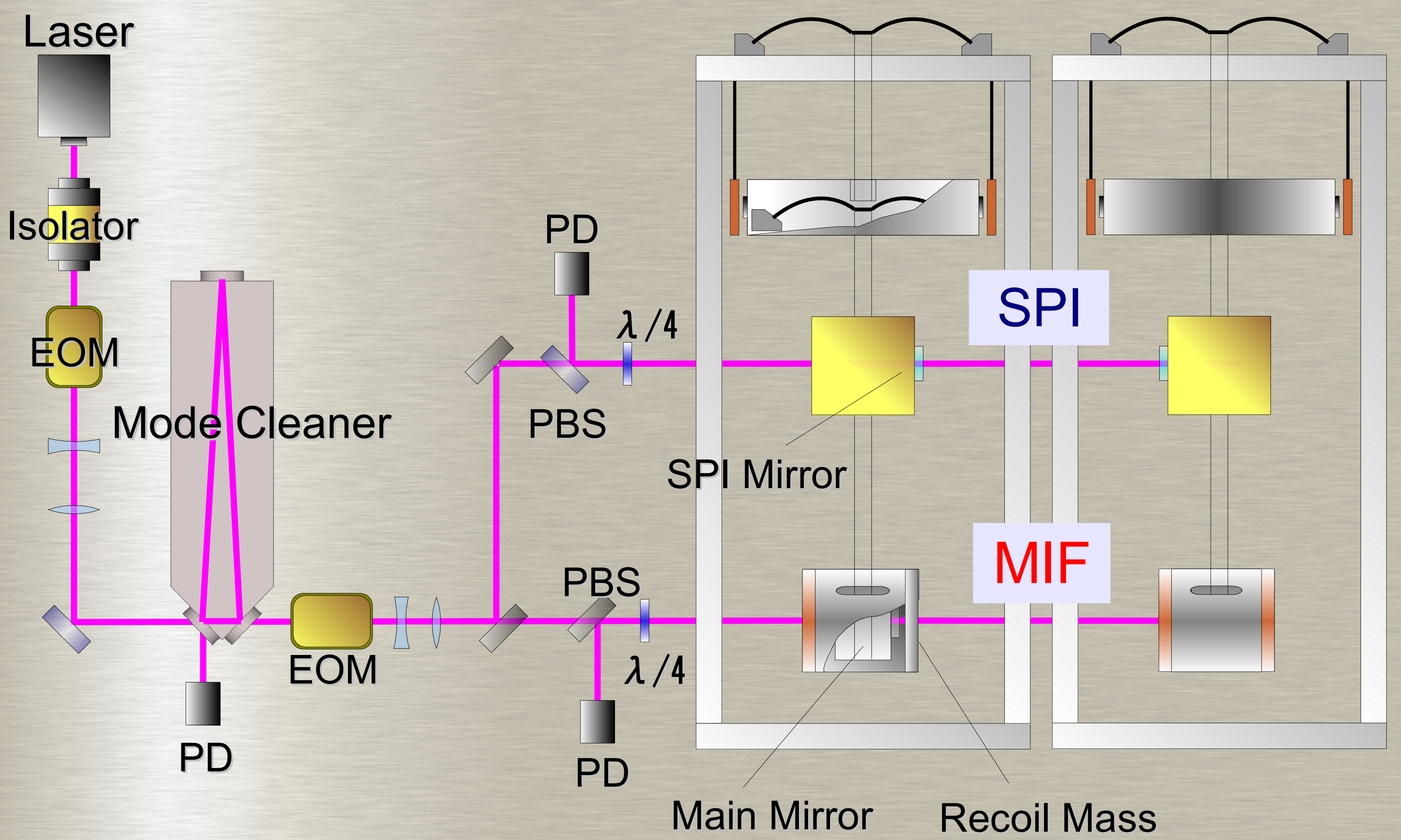
- Direct reduction of seismic noise in the observation band
- Reduction of the RMS motion of the mirrors
  - Stable Operation
  - Robust lock acquisition

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

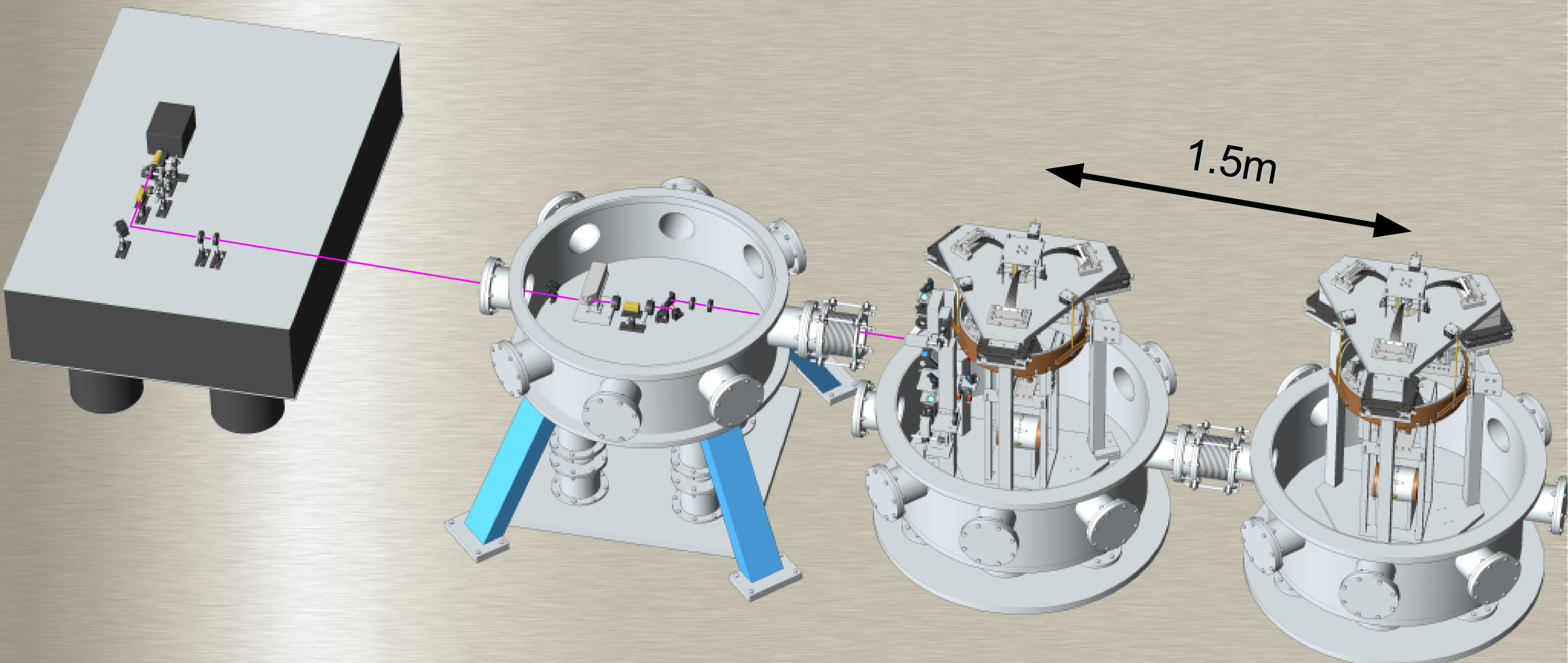
to name a few

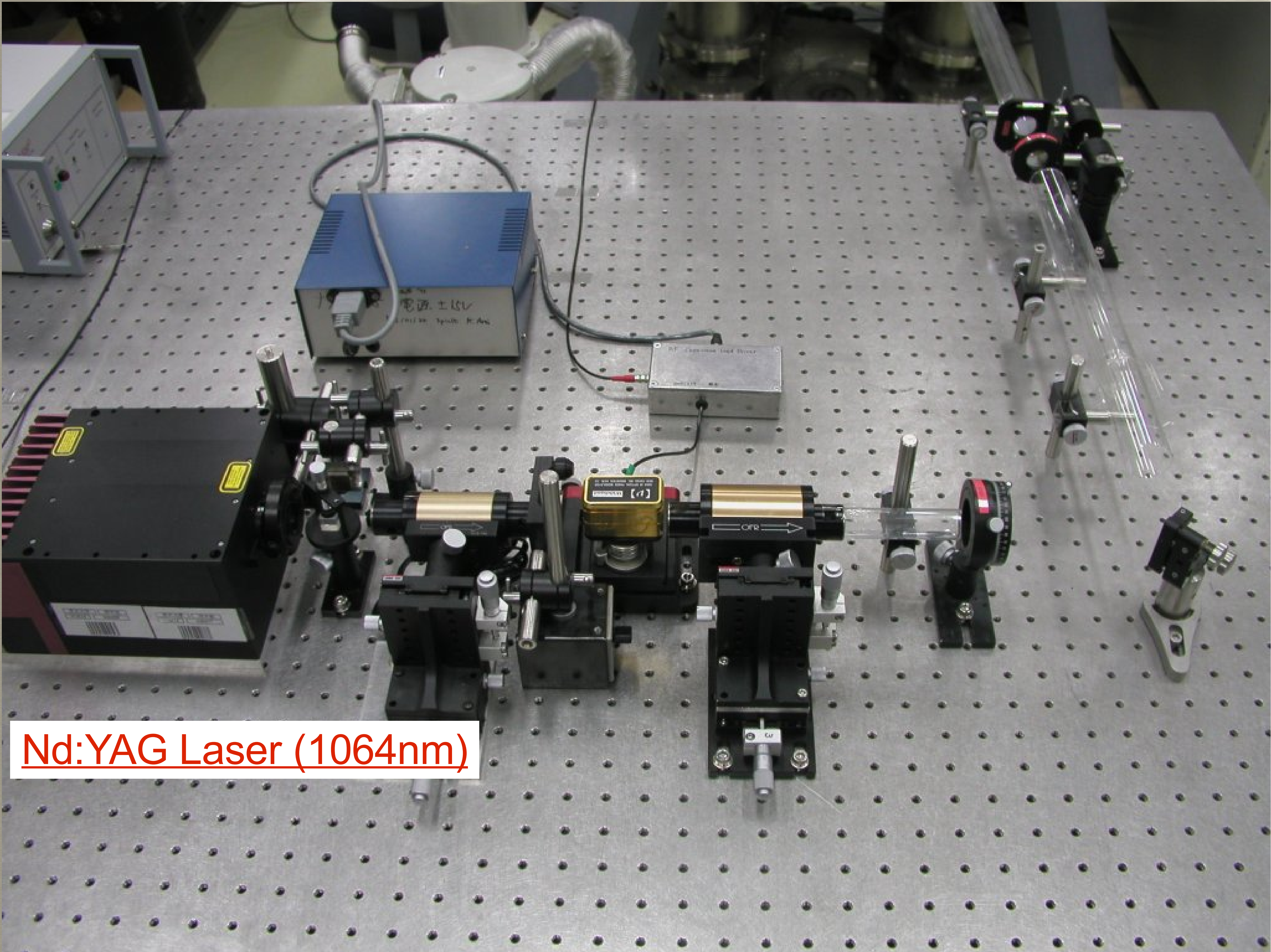
Prototype Experiment

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

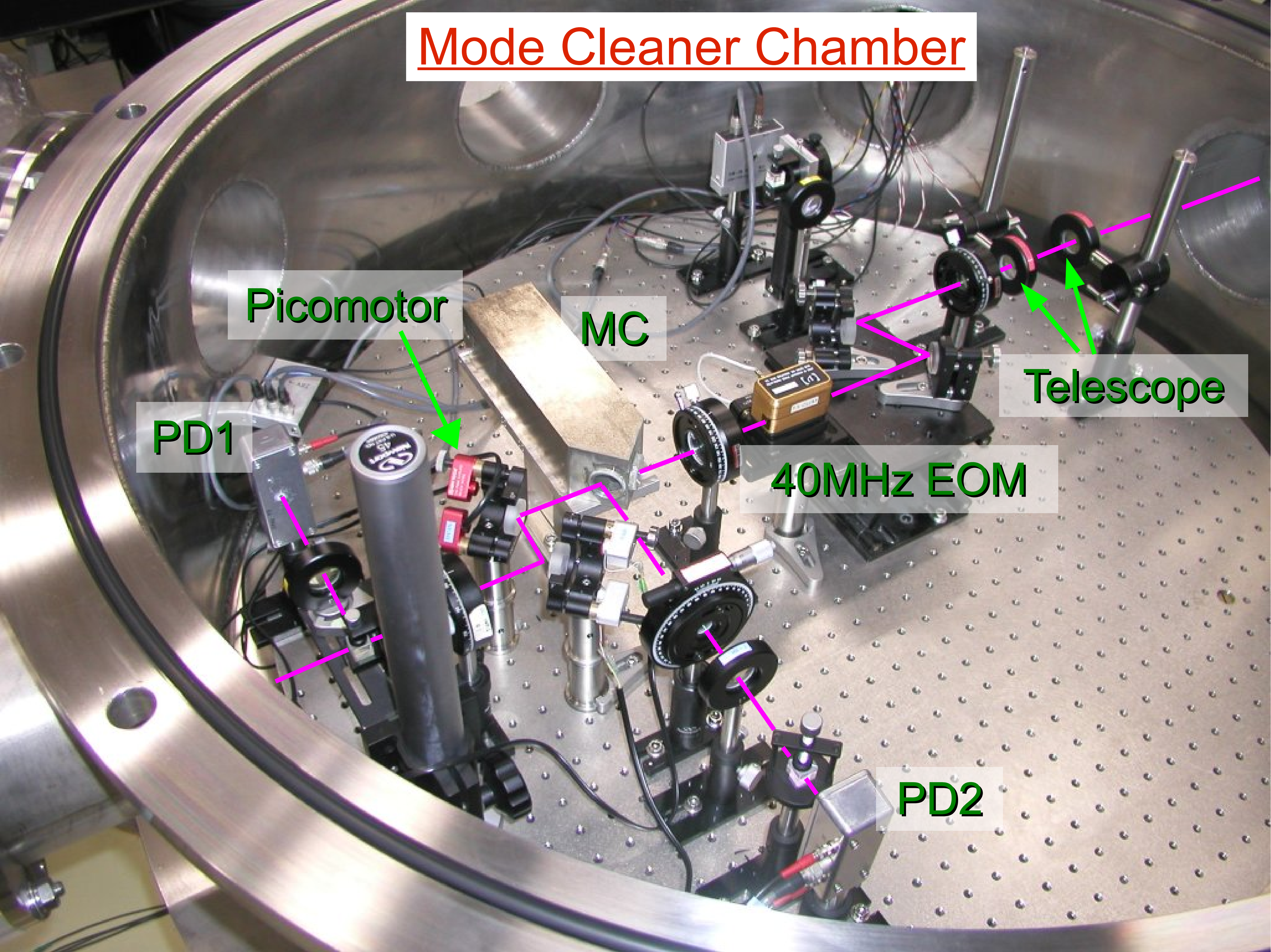


Overview of the experimental setup



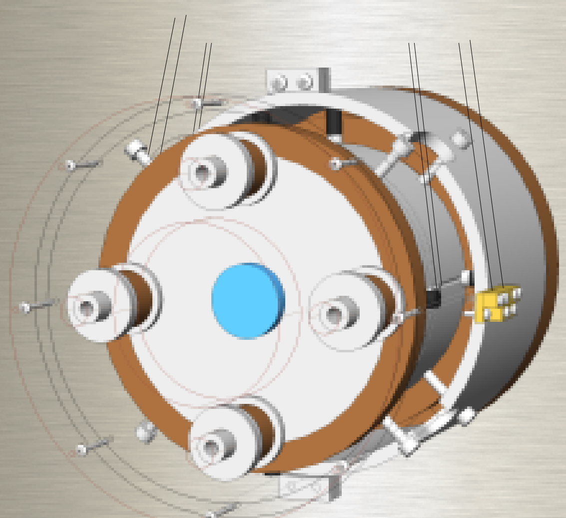

Nd:YAG Laser (1064nm)

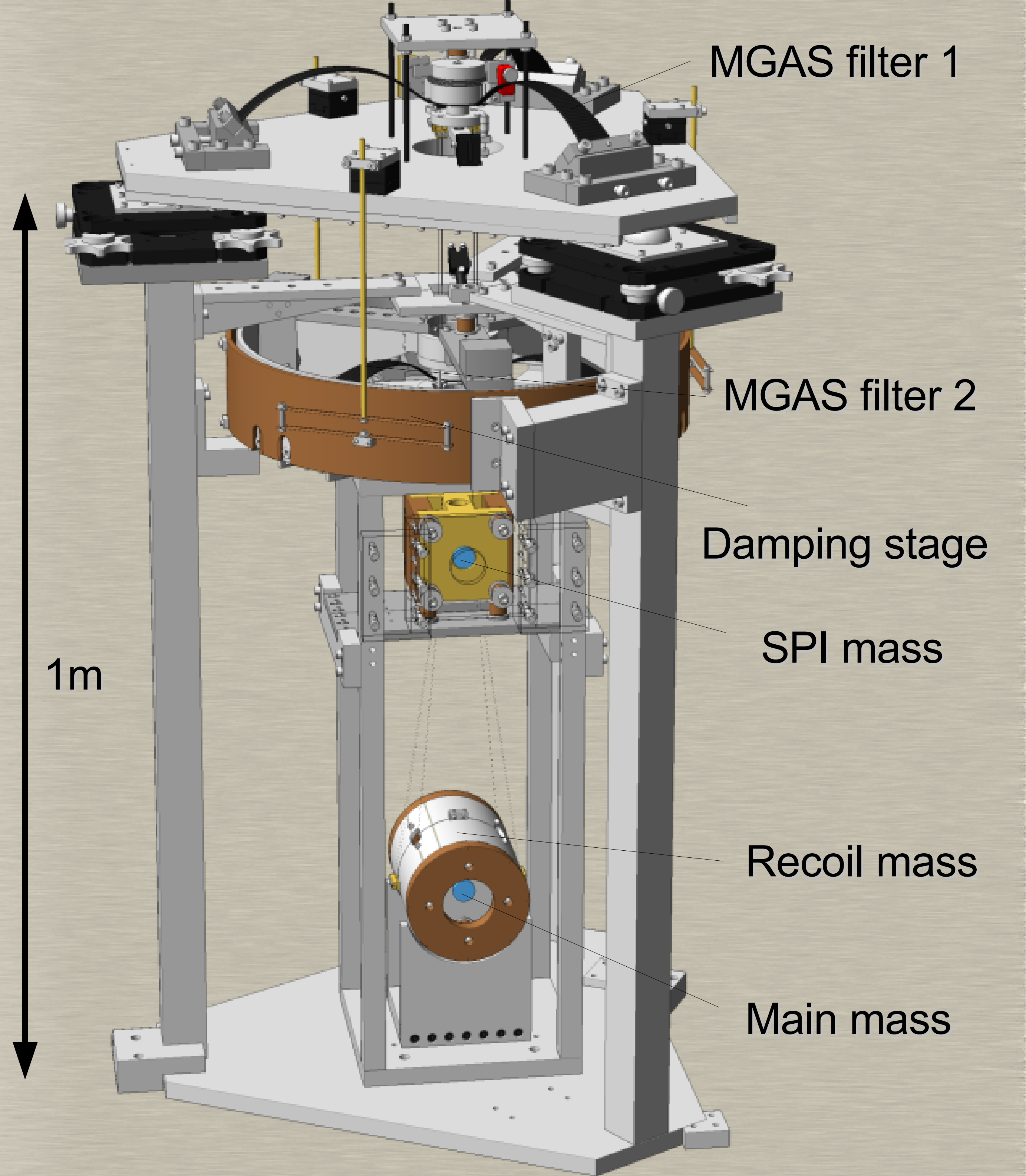
Mode Cleaner Chamber

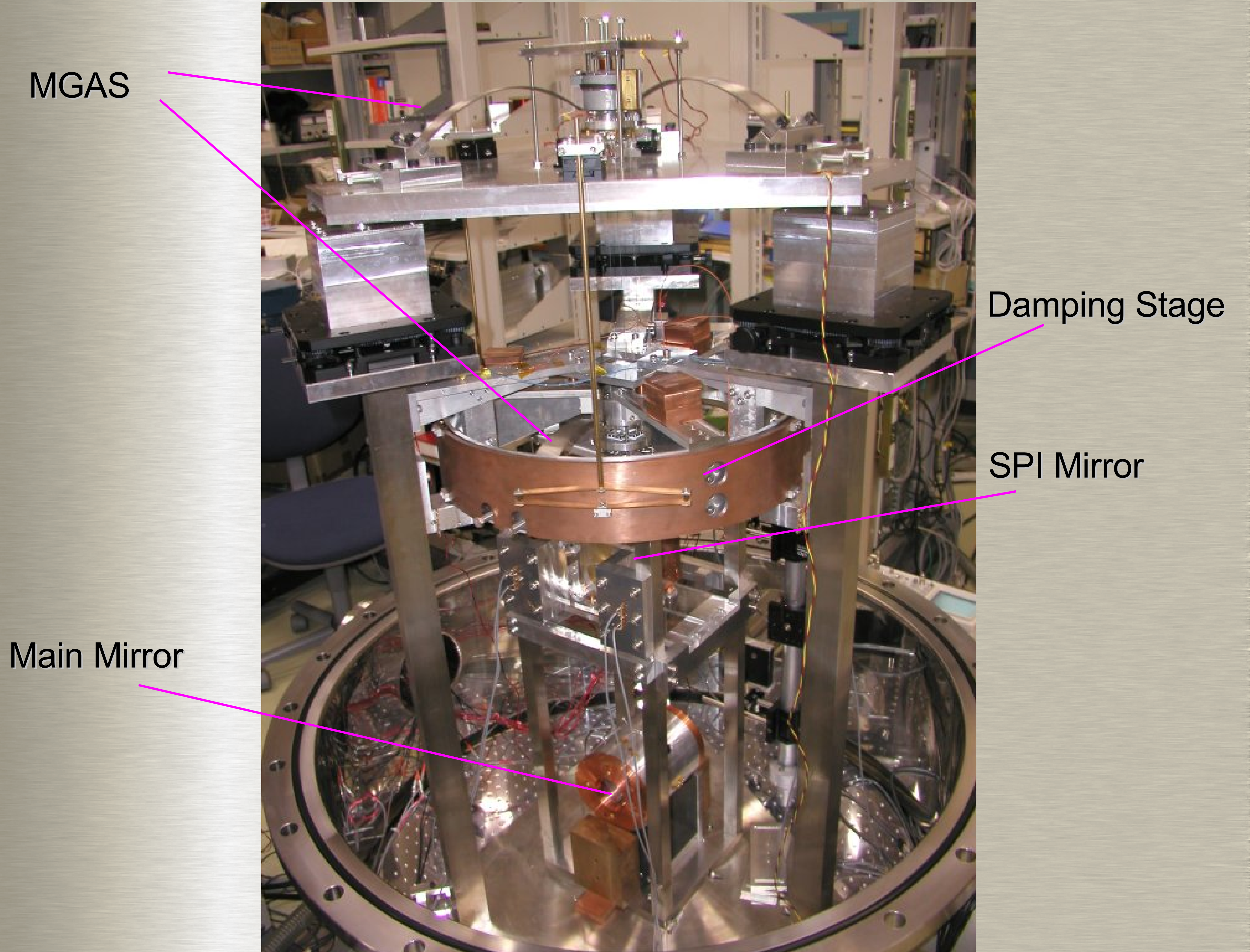


Suspension System

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



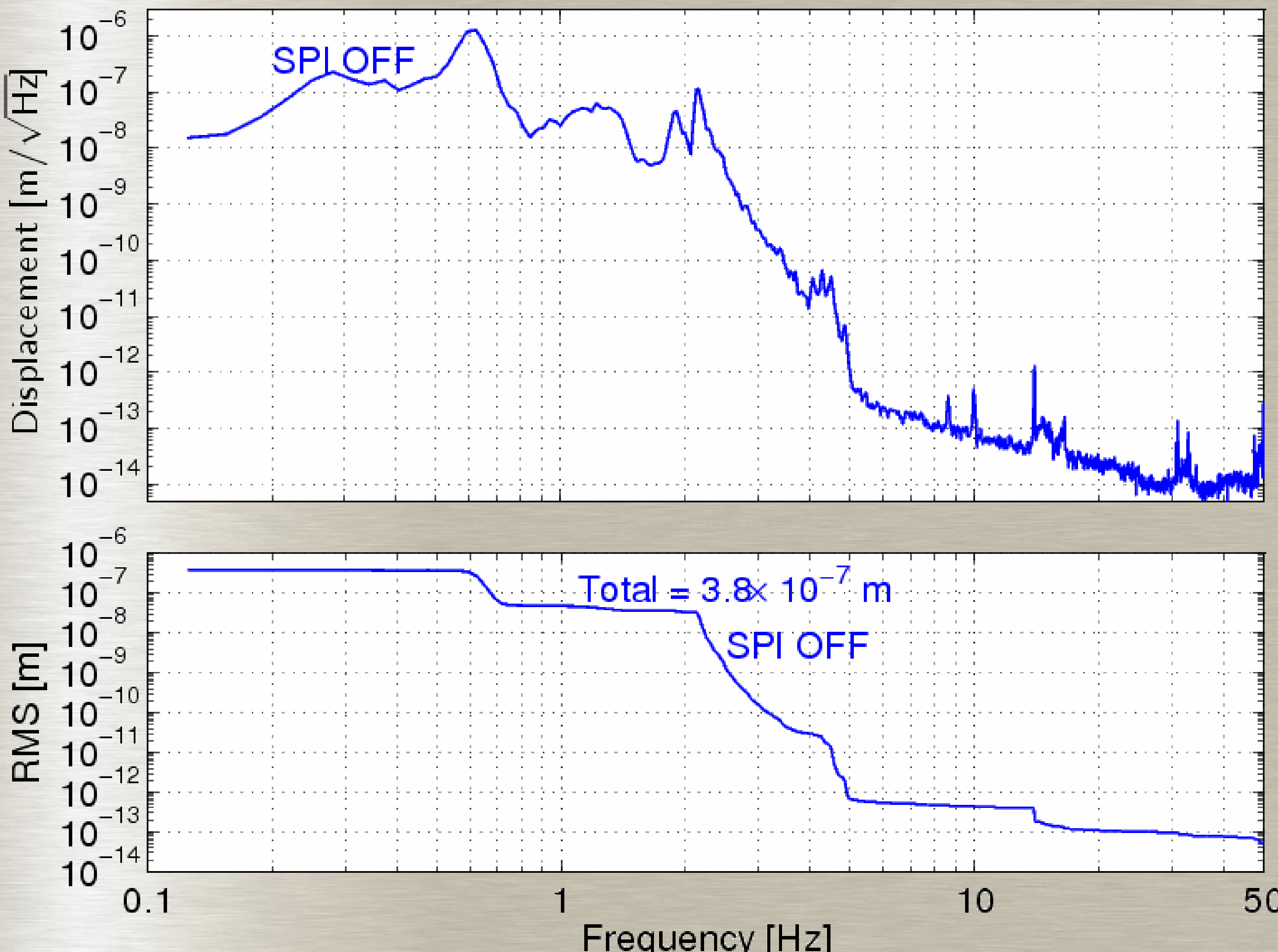



MGAS
Damping Stage
SPI Mirror
Main Mirror

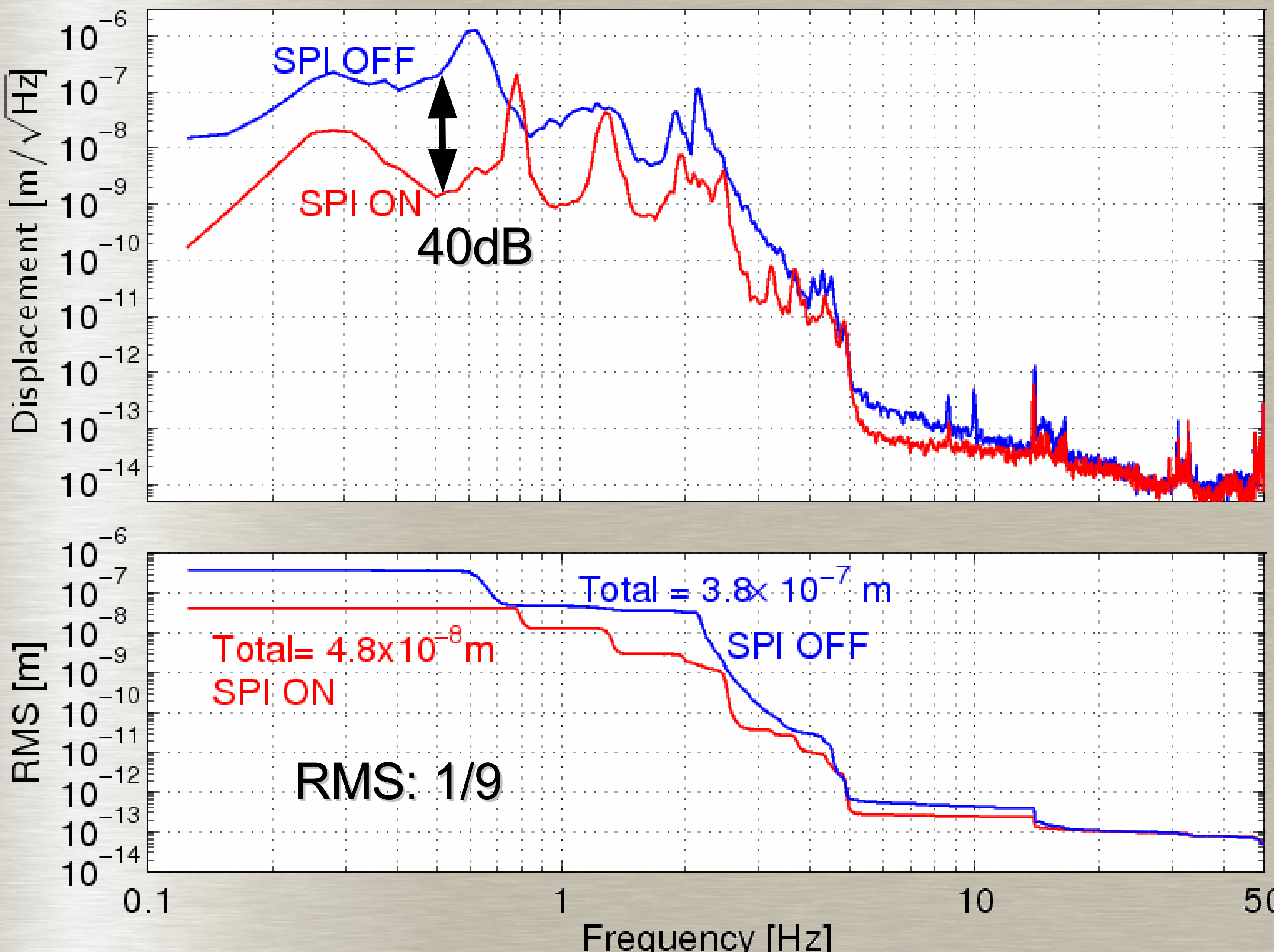
Results

- Spectral measurements
- Transfer function measurements

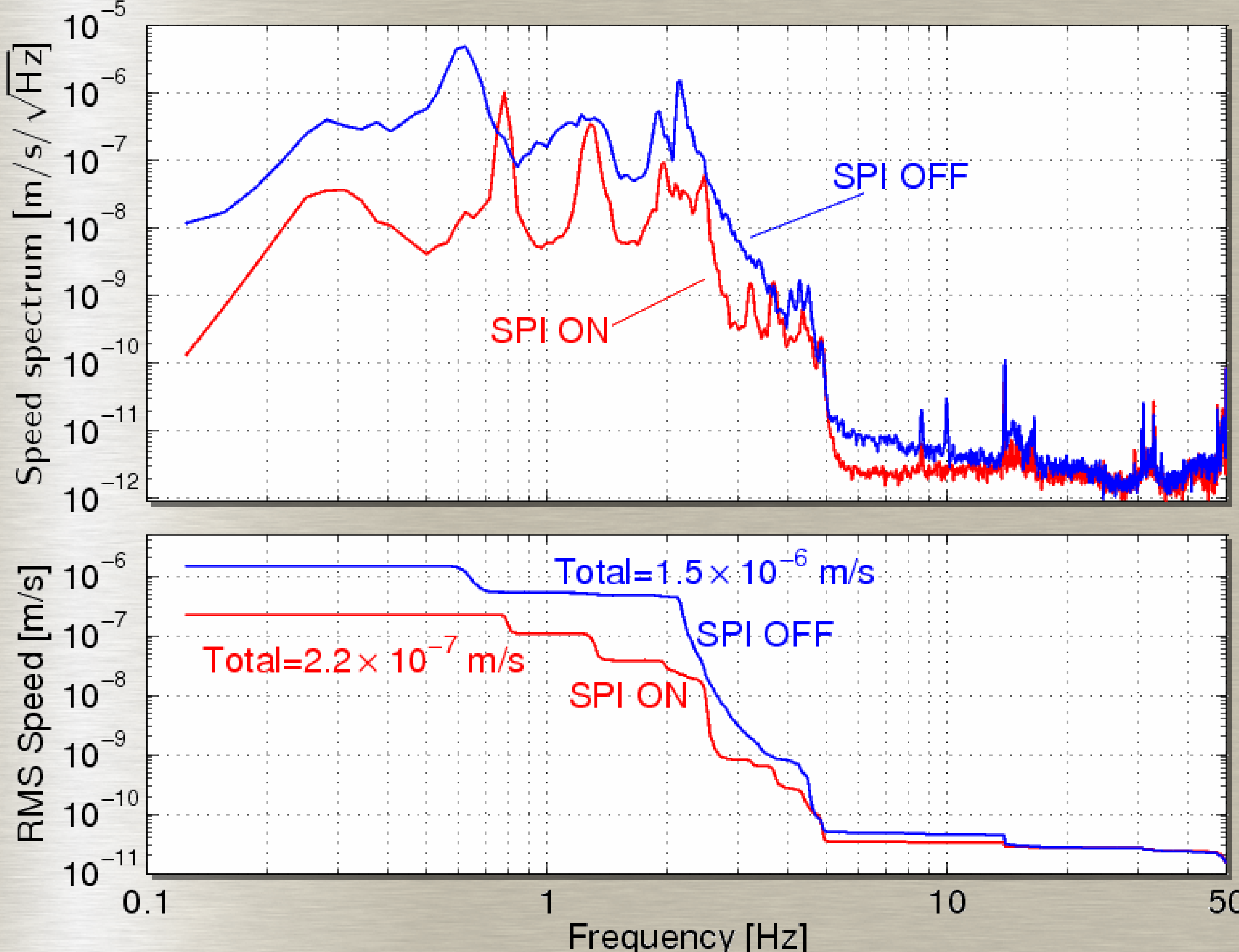
Displacement Equivalent Noise Spectrum (MIF)



Displacement Equivalent Noise Spectrum (MIF)



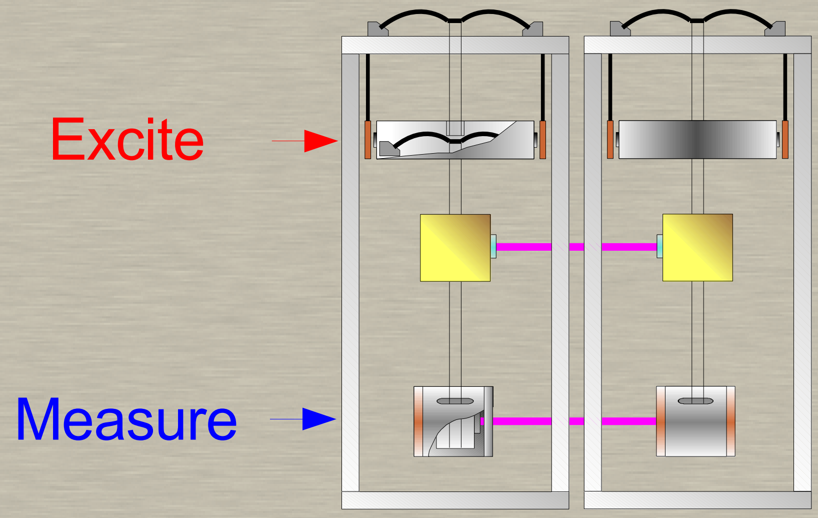
Mirror Speed Spectrum

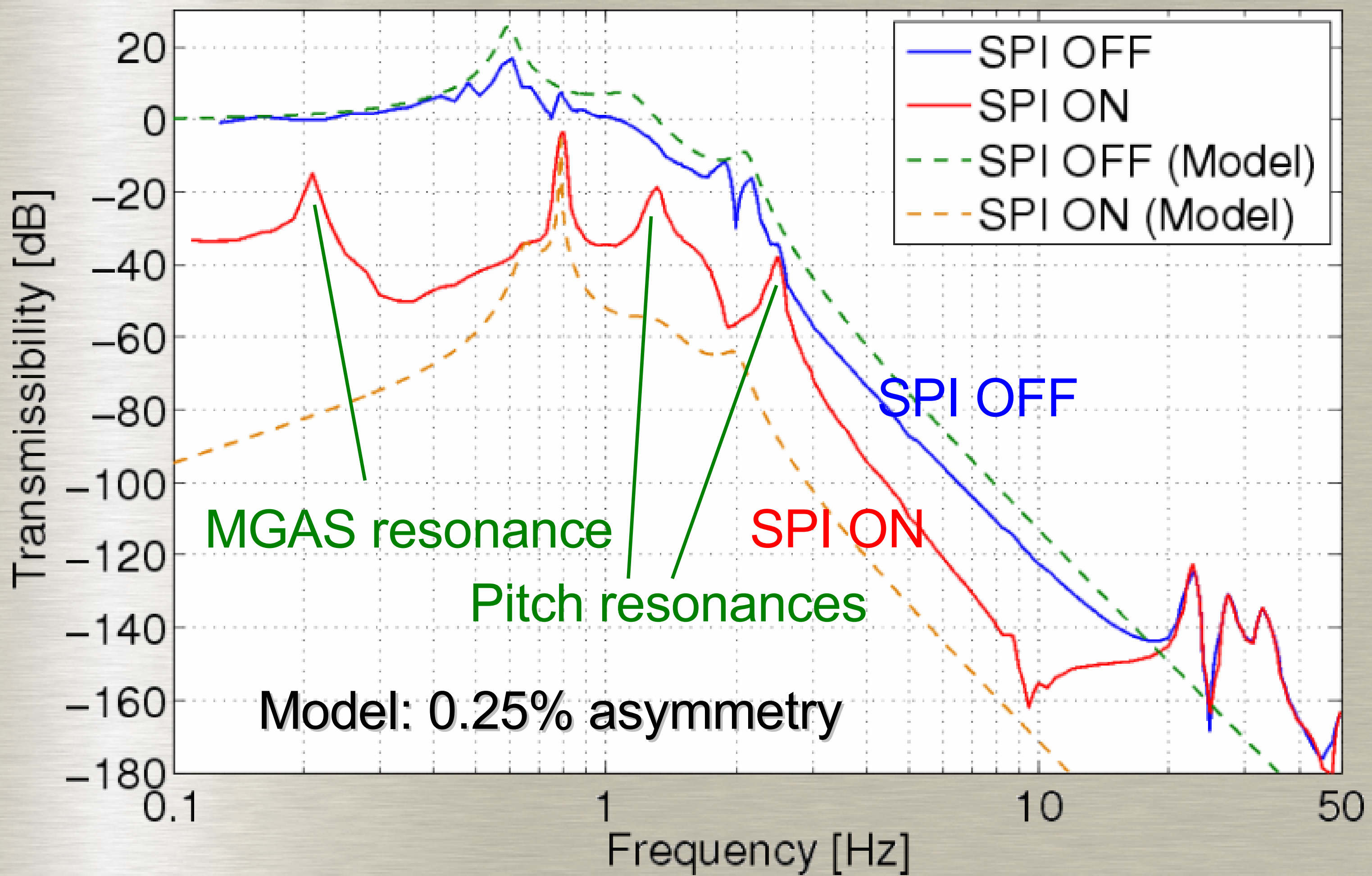


Speed RMS: 1/7 → Easier Lock Acquisition

Transfer Function

- Up to 20Hz
  ~ 40dB isolation



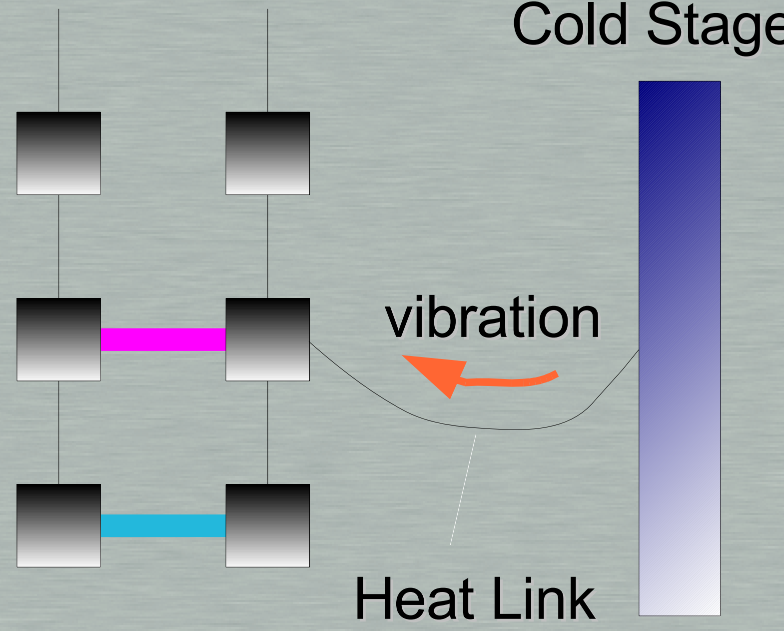


Future prospects

LCGT

- Cryogenic Mirror: heat link wires
- Vibration introduced from heat links
  → SPI can suppress it
- Located close to the MIF

Important: Low noise nature of SPI



Advanced LIGO

- High finesse cavity (RSE)
  → lock acquisition is difficult (when seismic activity is high)
- SPI to reduce the RMS mirror motion (considered as an option)
- Various configurations are considered
  - location
    suspension platform, penultimate mass, MIF itself with different color laser, etc...
  - Interferometer type
    Fabry-Perot, asymmetric Michelson, etc...
- Australian group is leading the effort

Conclusion

SPI: Low-noise low-frequency active vibration isolation scheme

Ultra low-frequency performance: RMS reduction

→ Stable operation, Robust lock acquisition, Technical noise mitigation

Low noise: heat link vibration suppression for LCGT

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

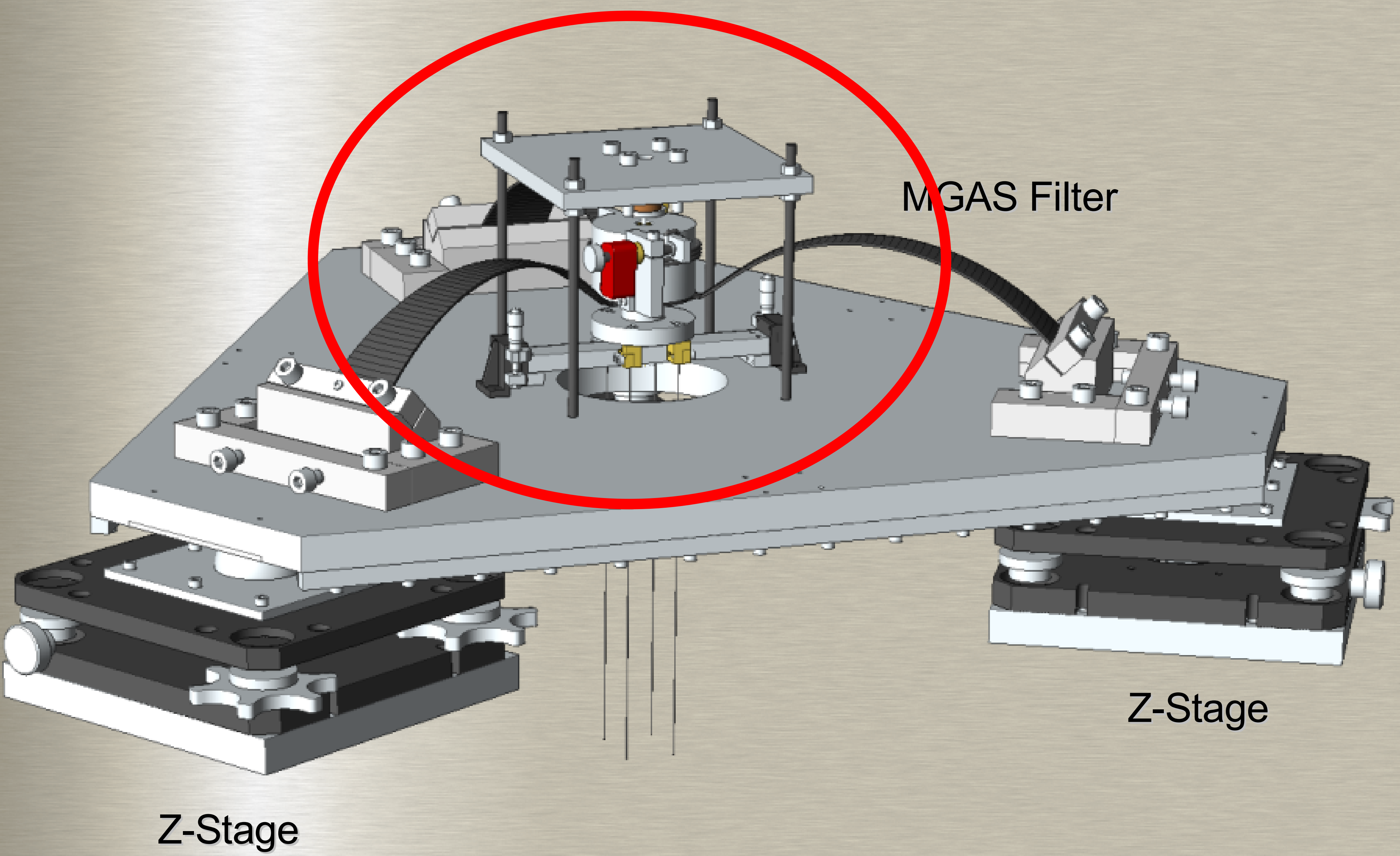
Future detectors are considering the employment of SPI

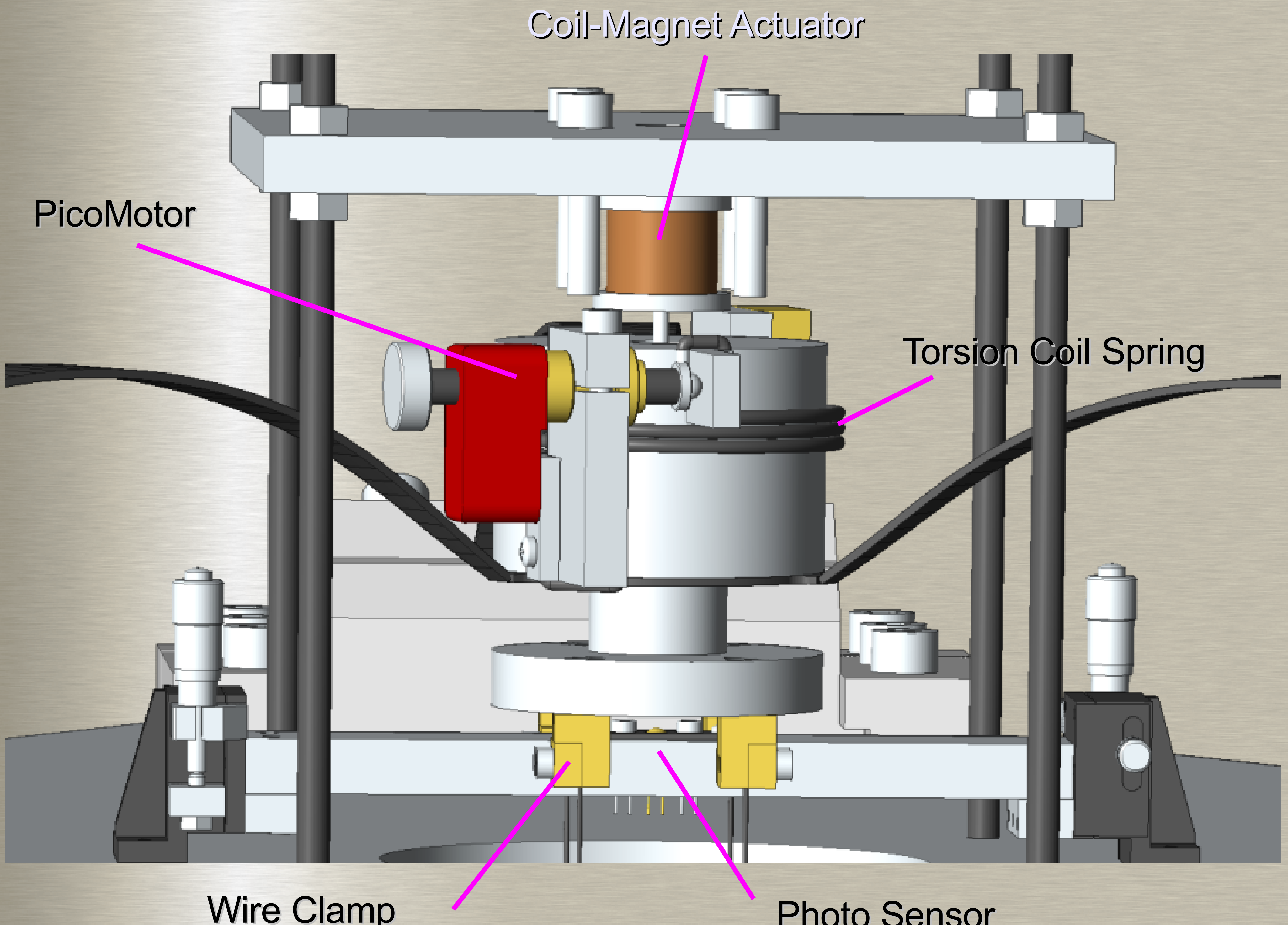
LCGT, Advanced LIGO

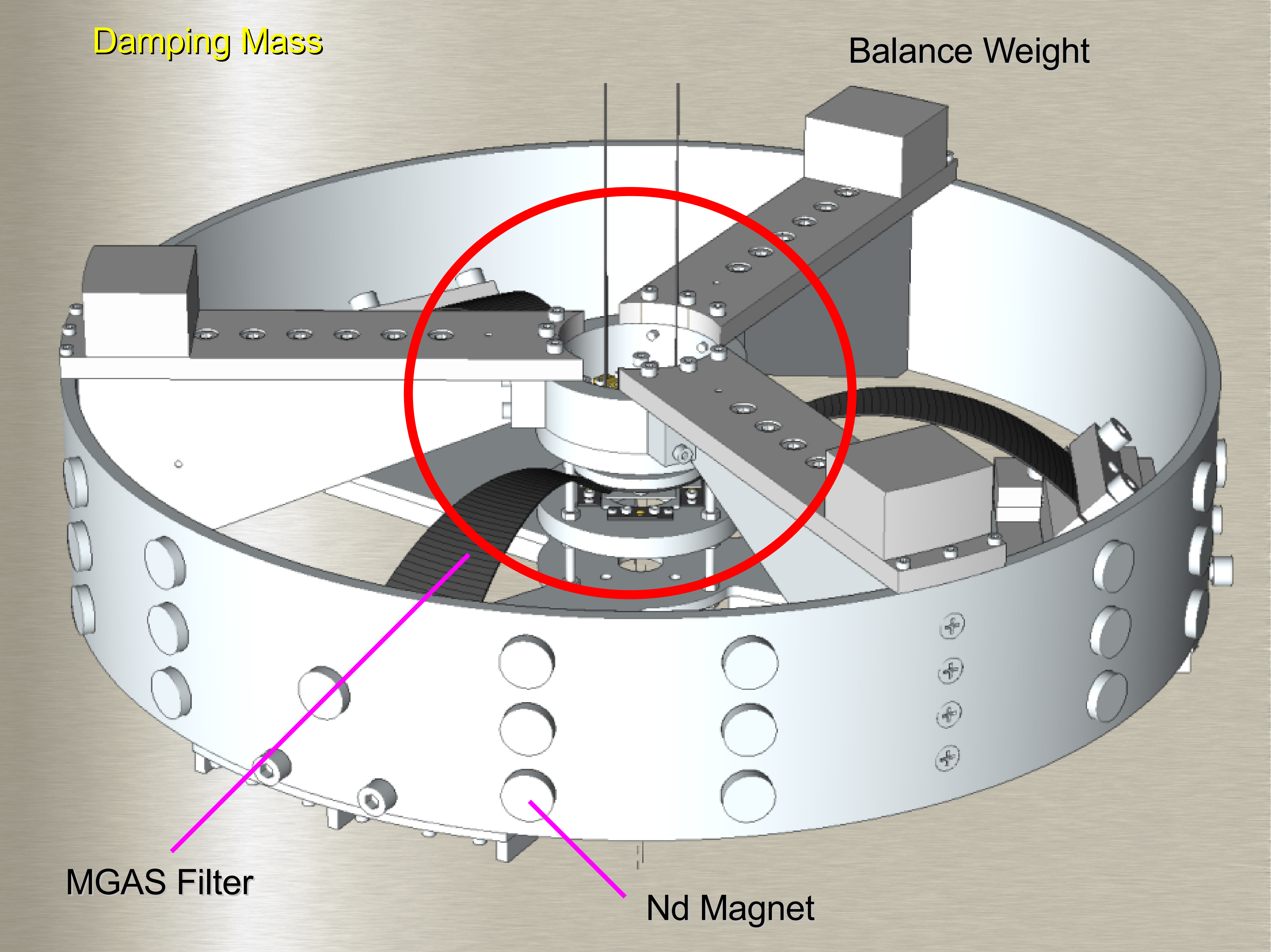
終

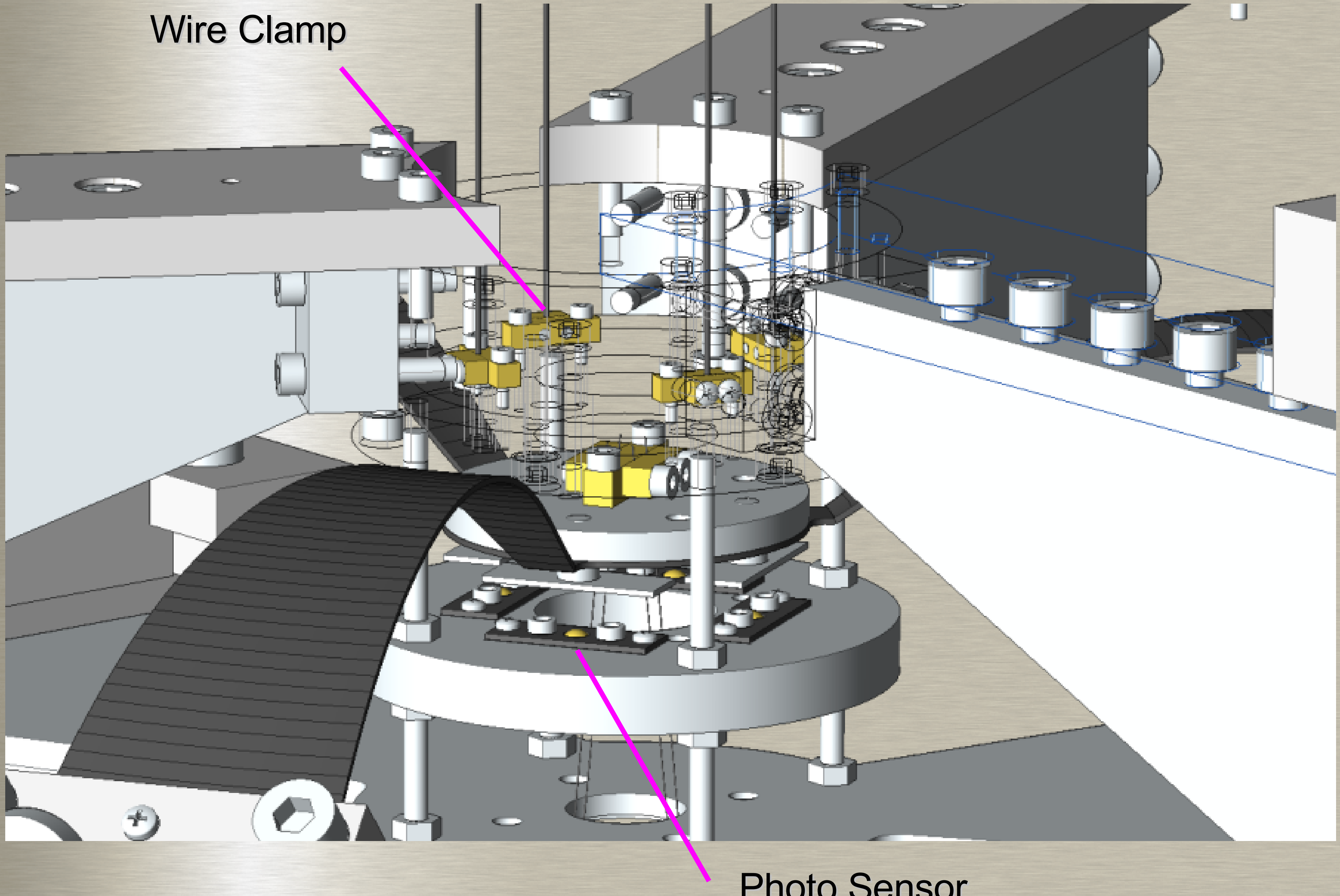
Extra Slides

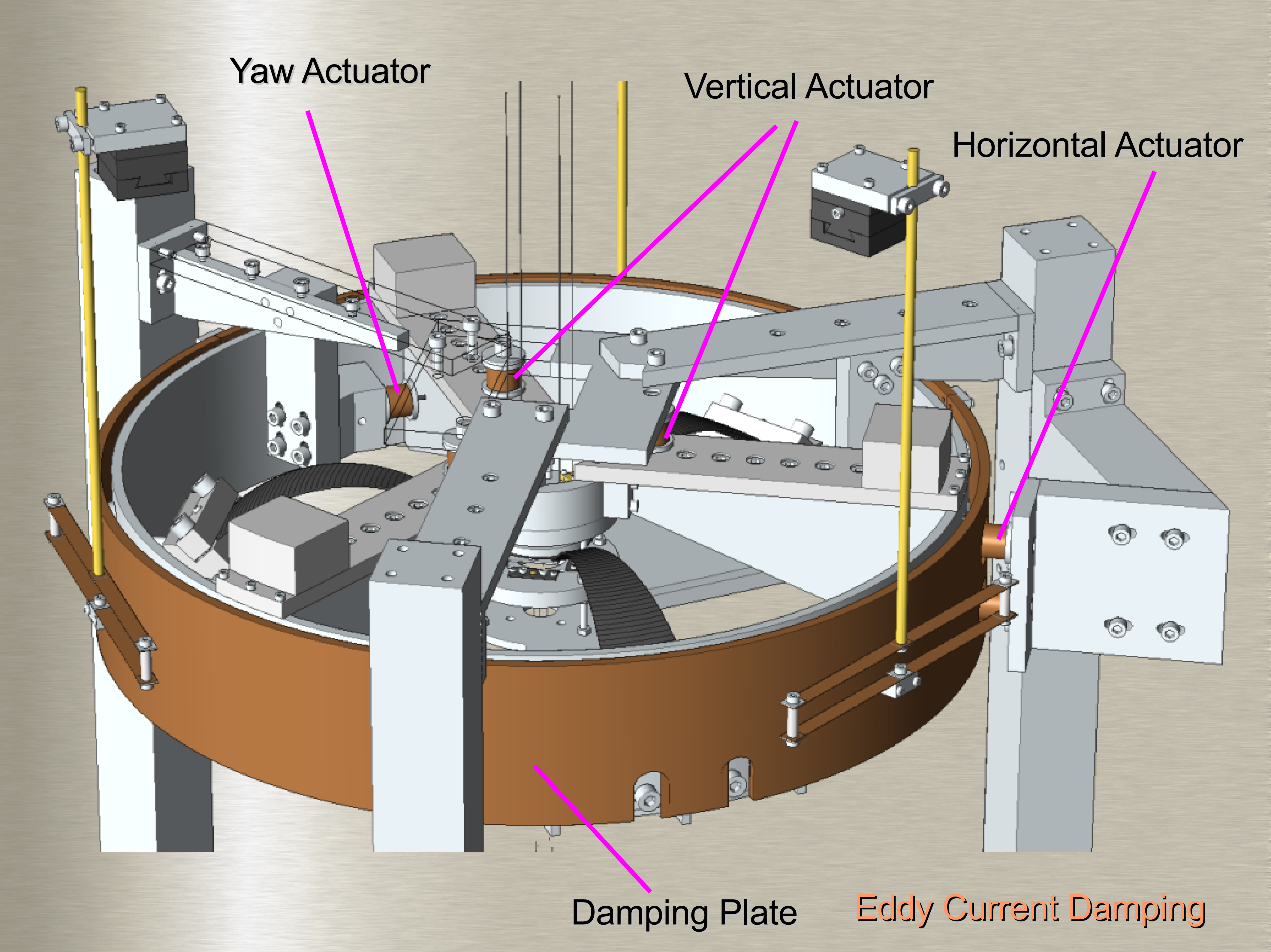
Top Stage




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

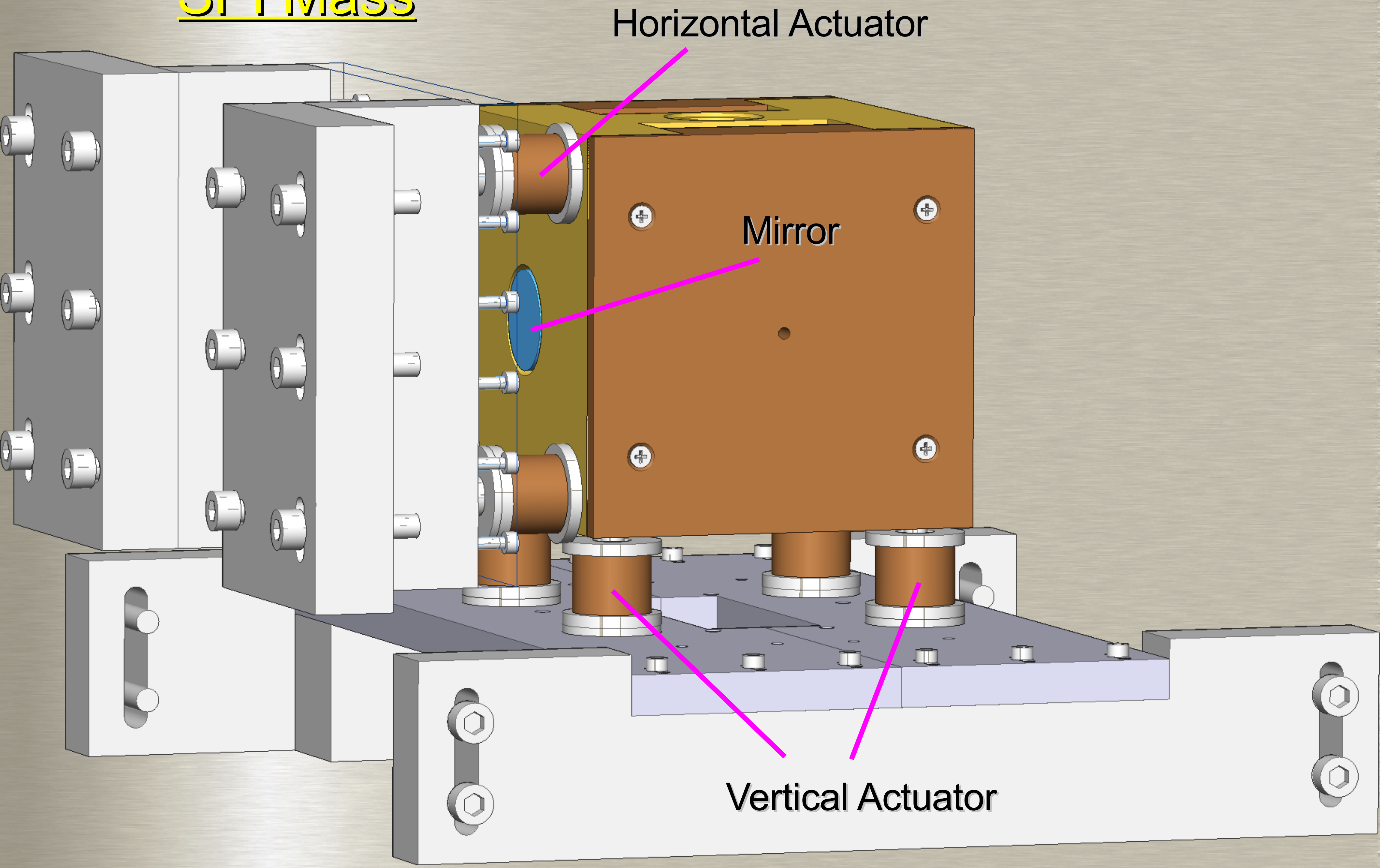

Damping Mass
Balance Weight
MGAS Filter
Nd Magnet


Wire Clamp
Photo Sensor

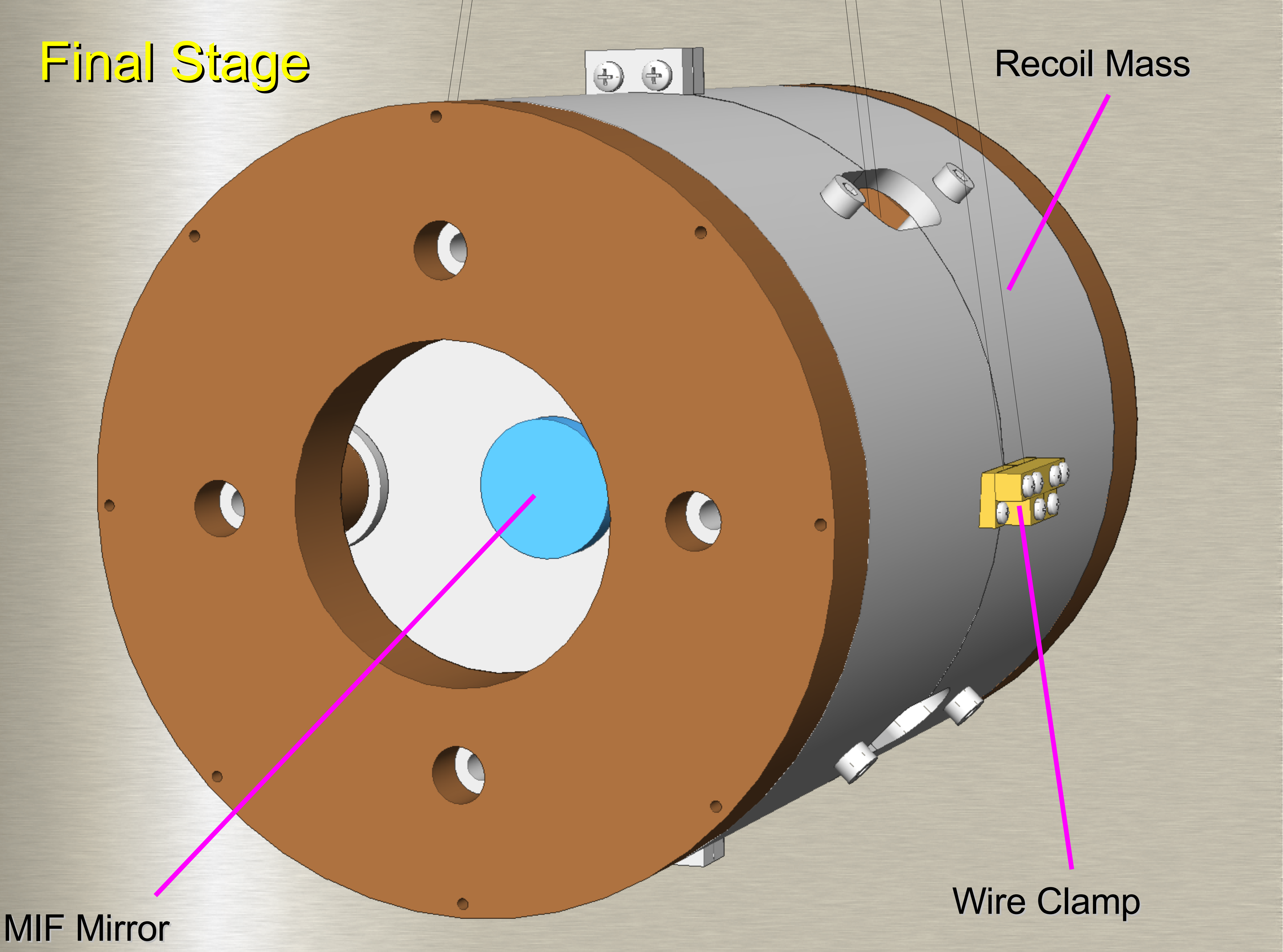


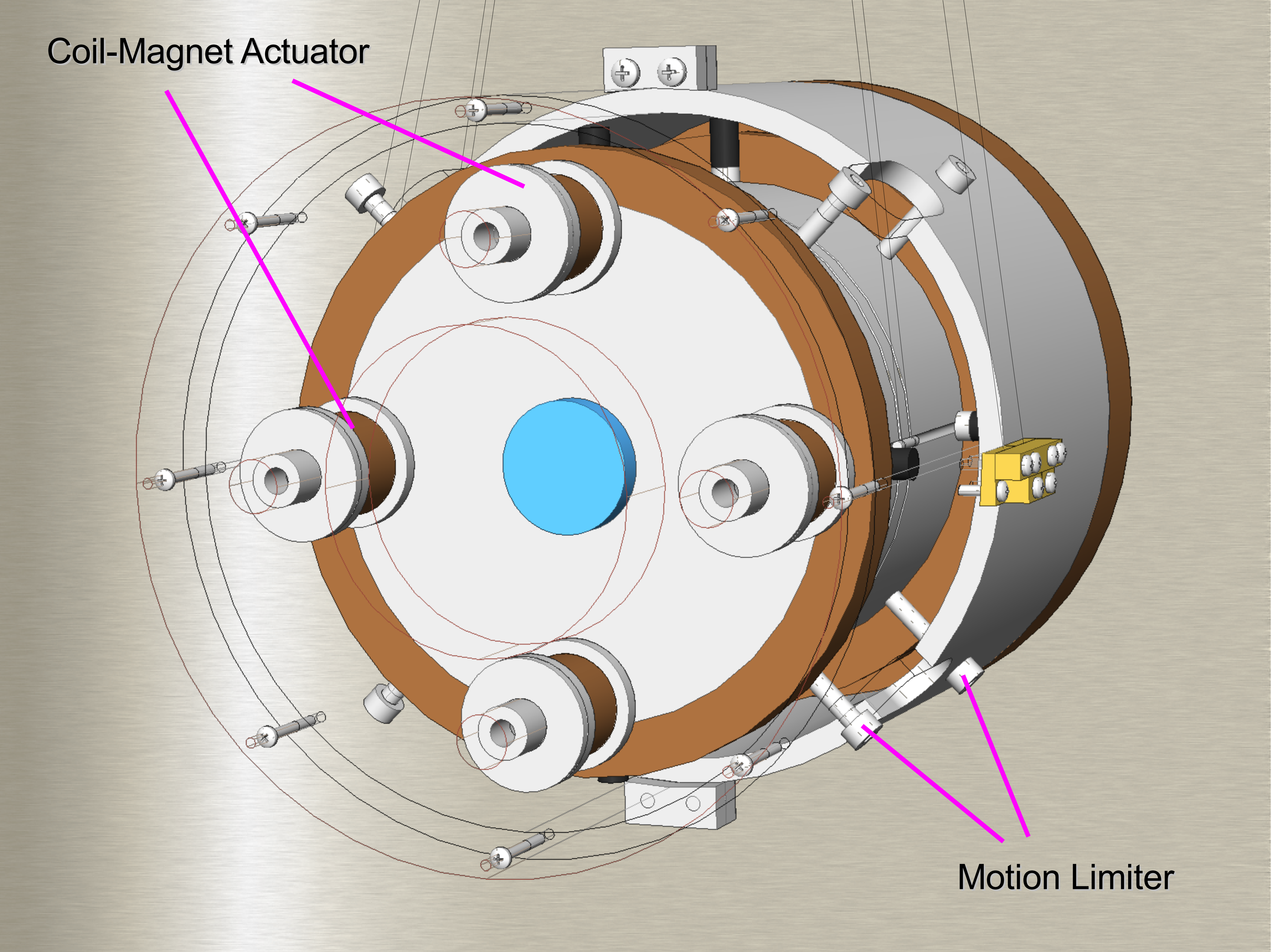
Eddy Current Damping

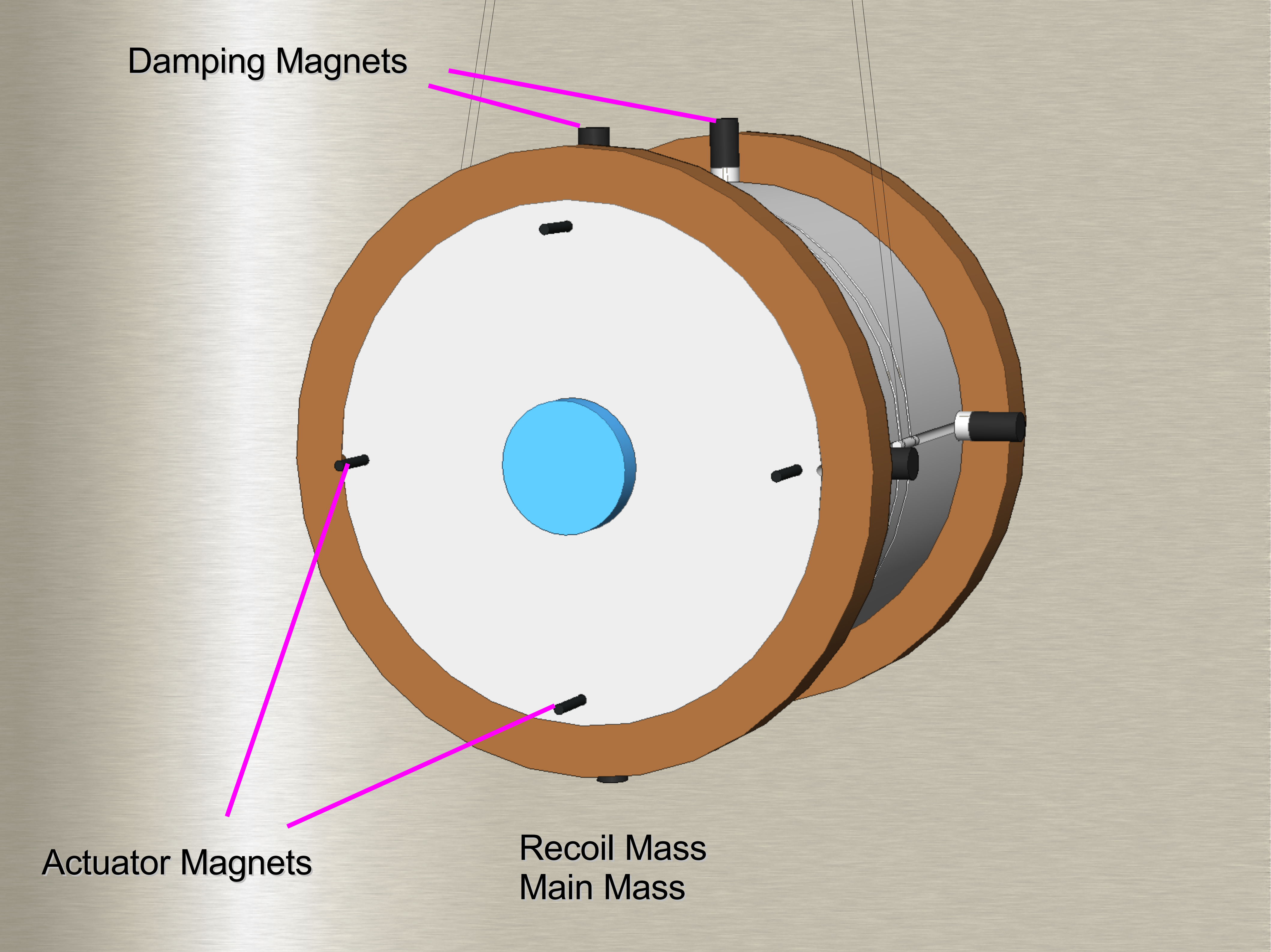
SPI Mass



Final Stage




Coil-Magnet Actuator
Motion Limiter

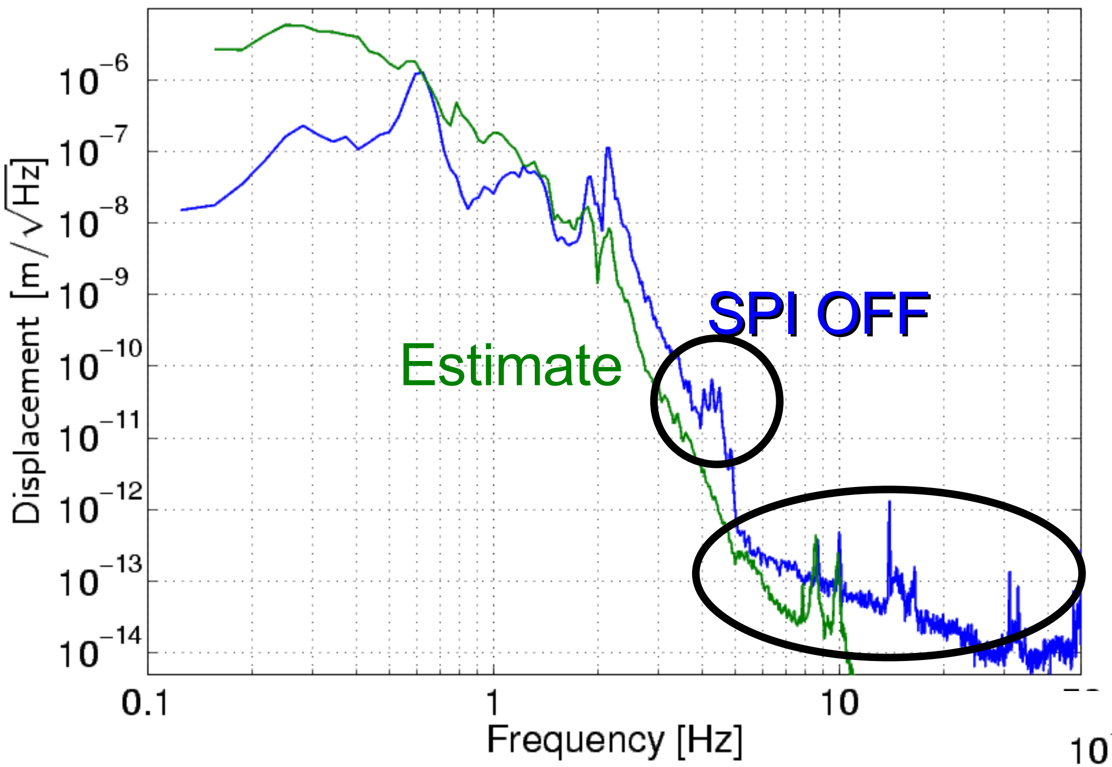

Damping Magnets
Actuator Magnets
Recoil Mass
Main Mass

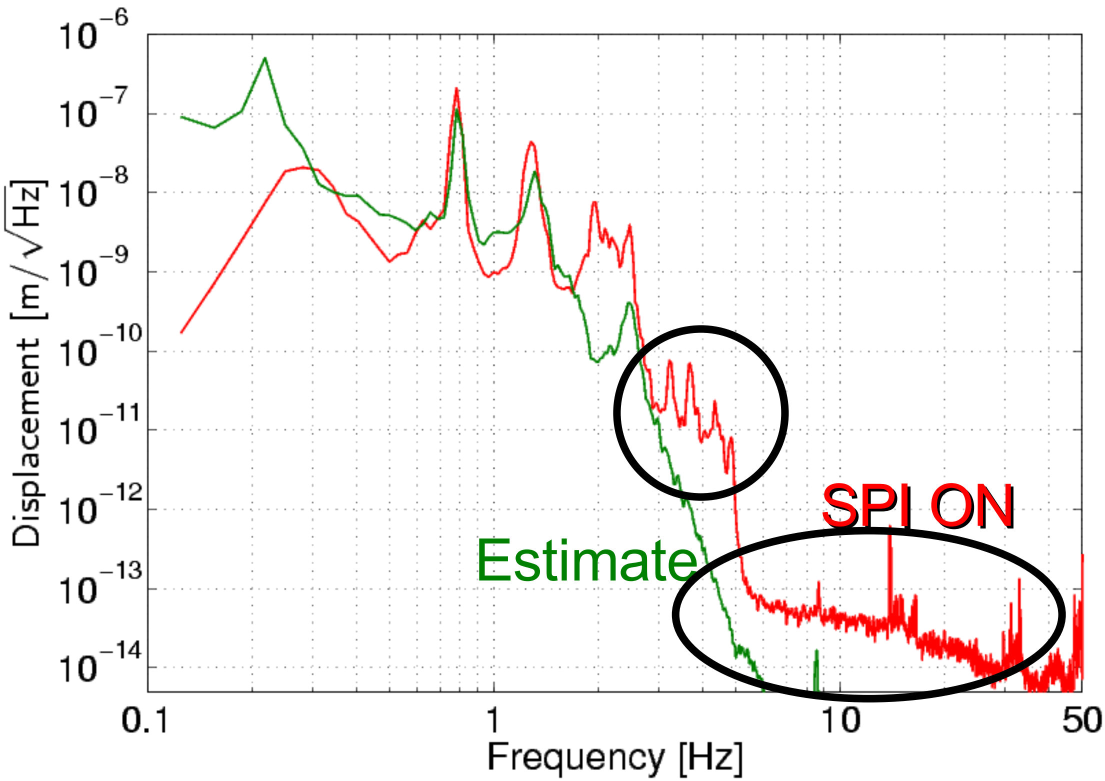
Seismic Noise Estimate

Suspension TF

× Seismic Motion

(Accelerometer)

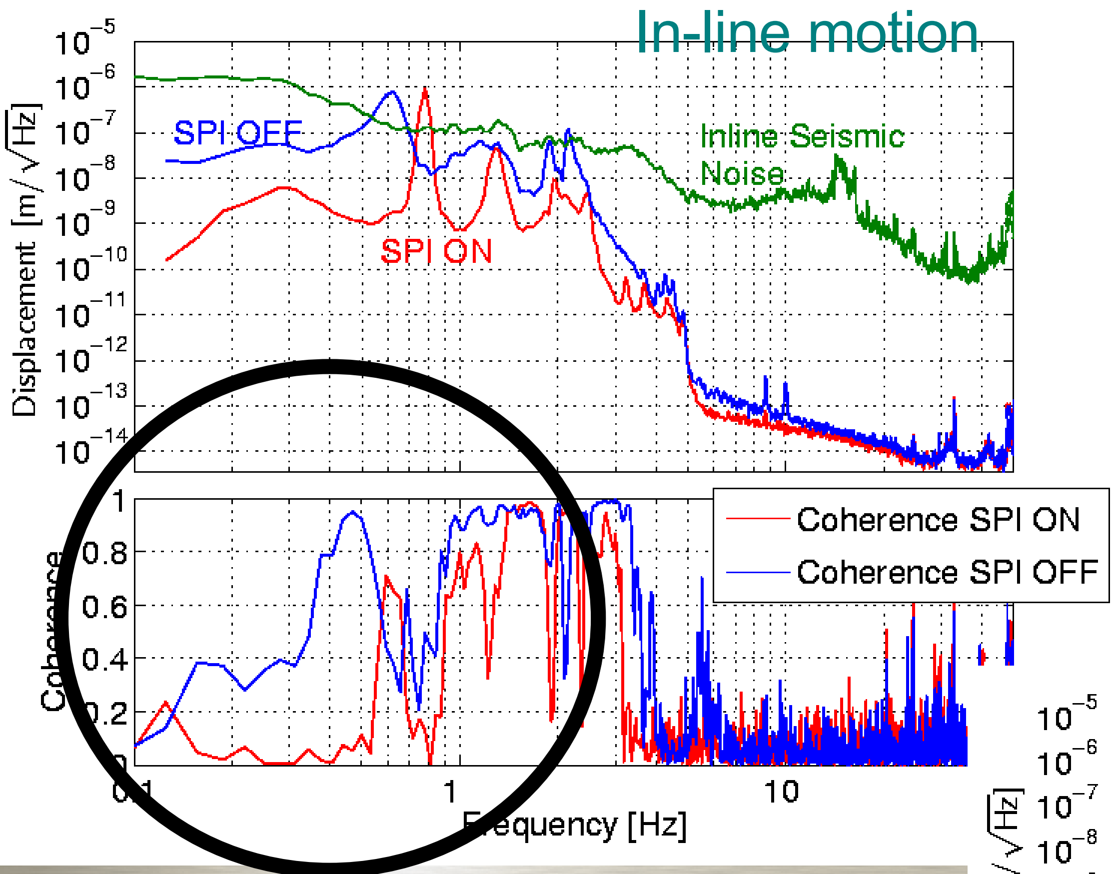




Seismic - IFO output Correlation

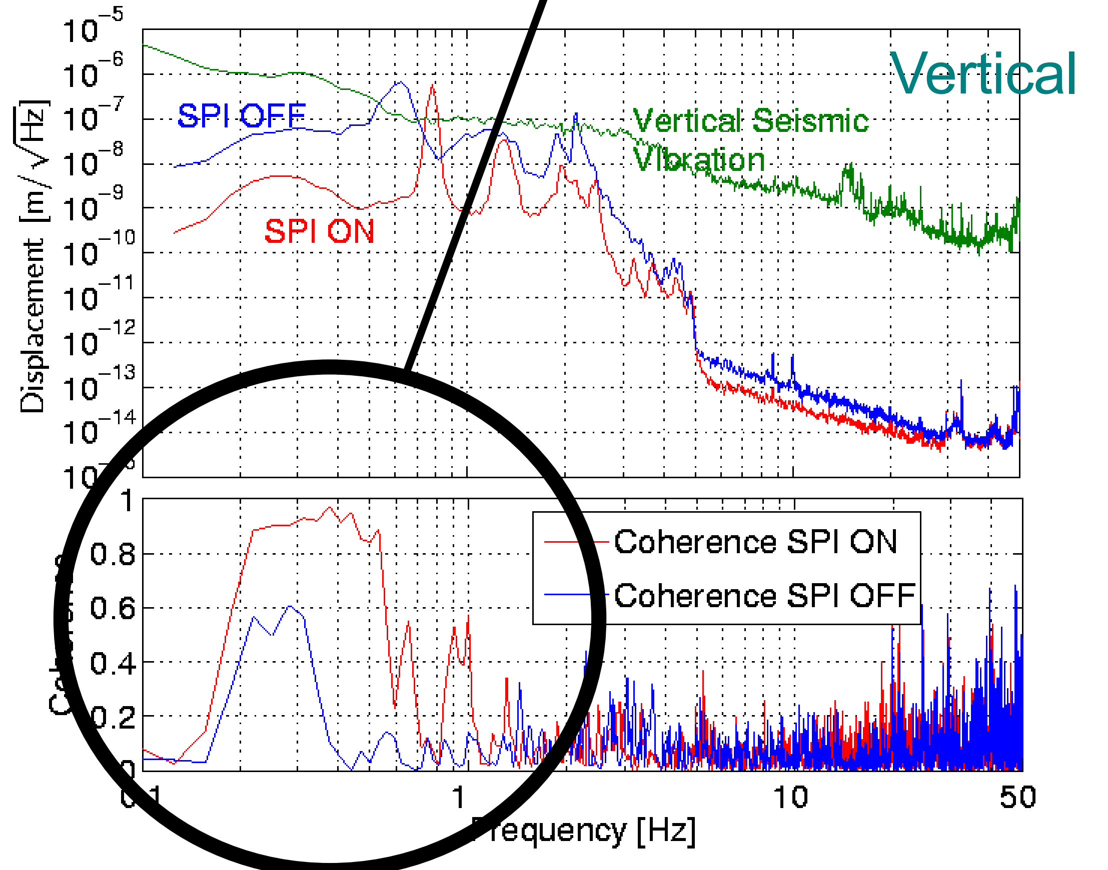
Seismic motion: measured by an accelerometer

Good correlation when SPI is ON

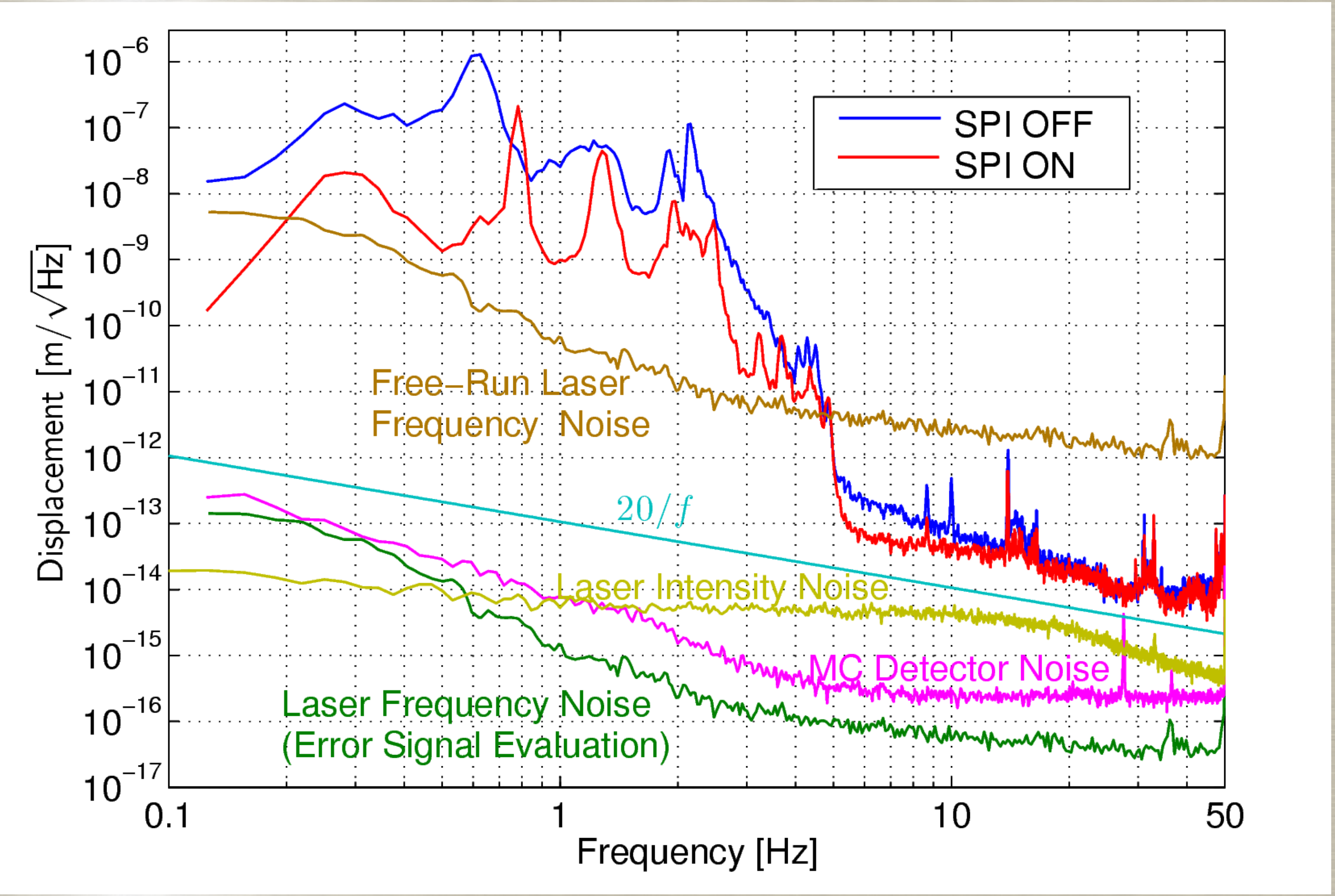


Good correlation when SPI is OFF

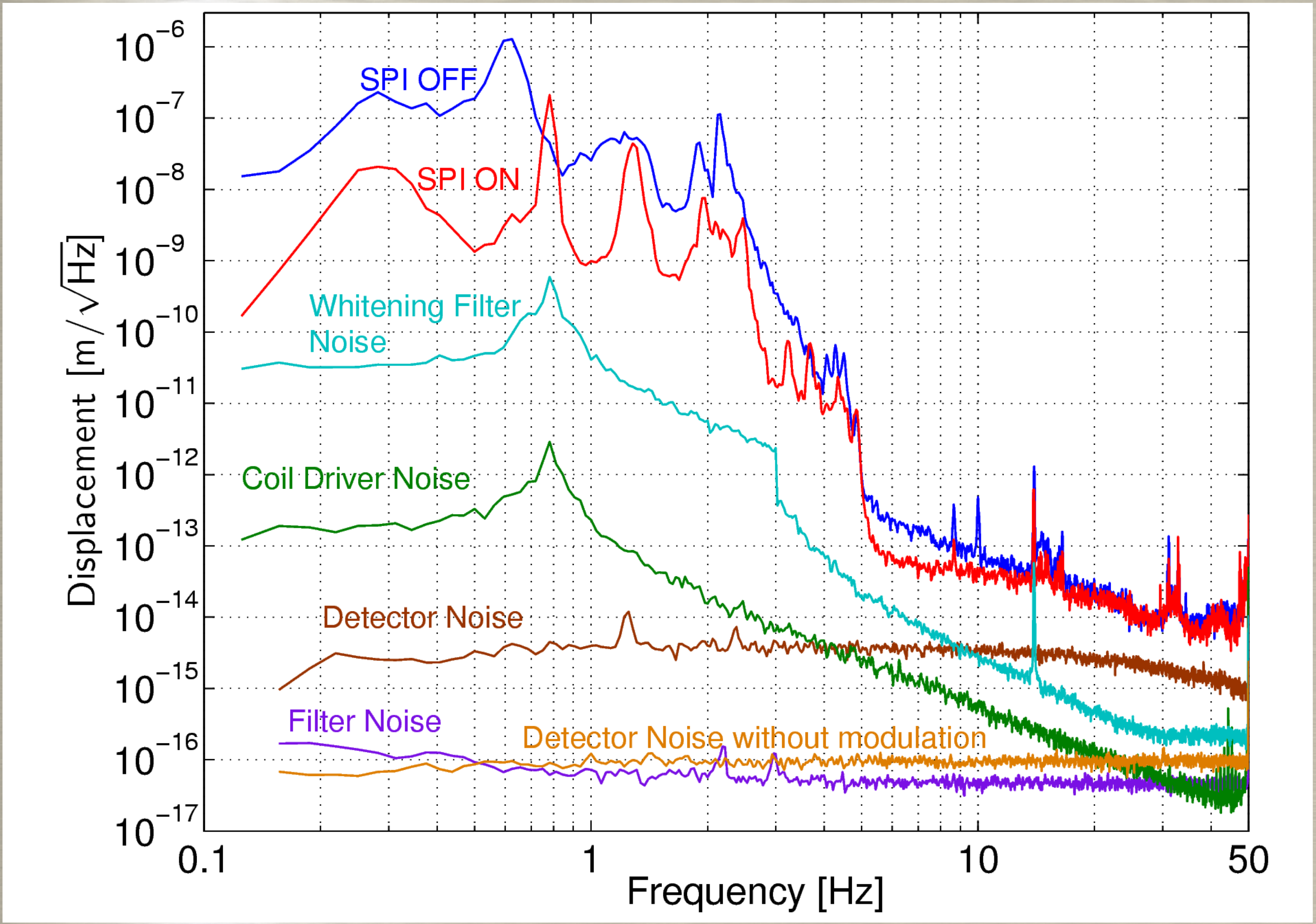
SPI ON
Vertical Motion is Dominant at low frequencies



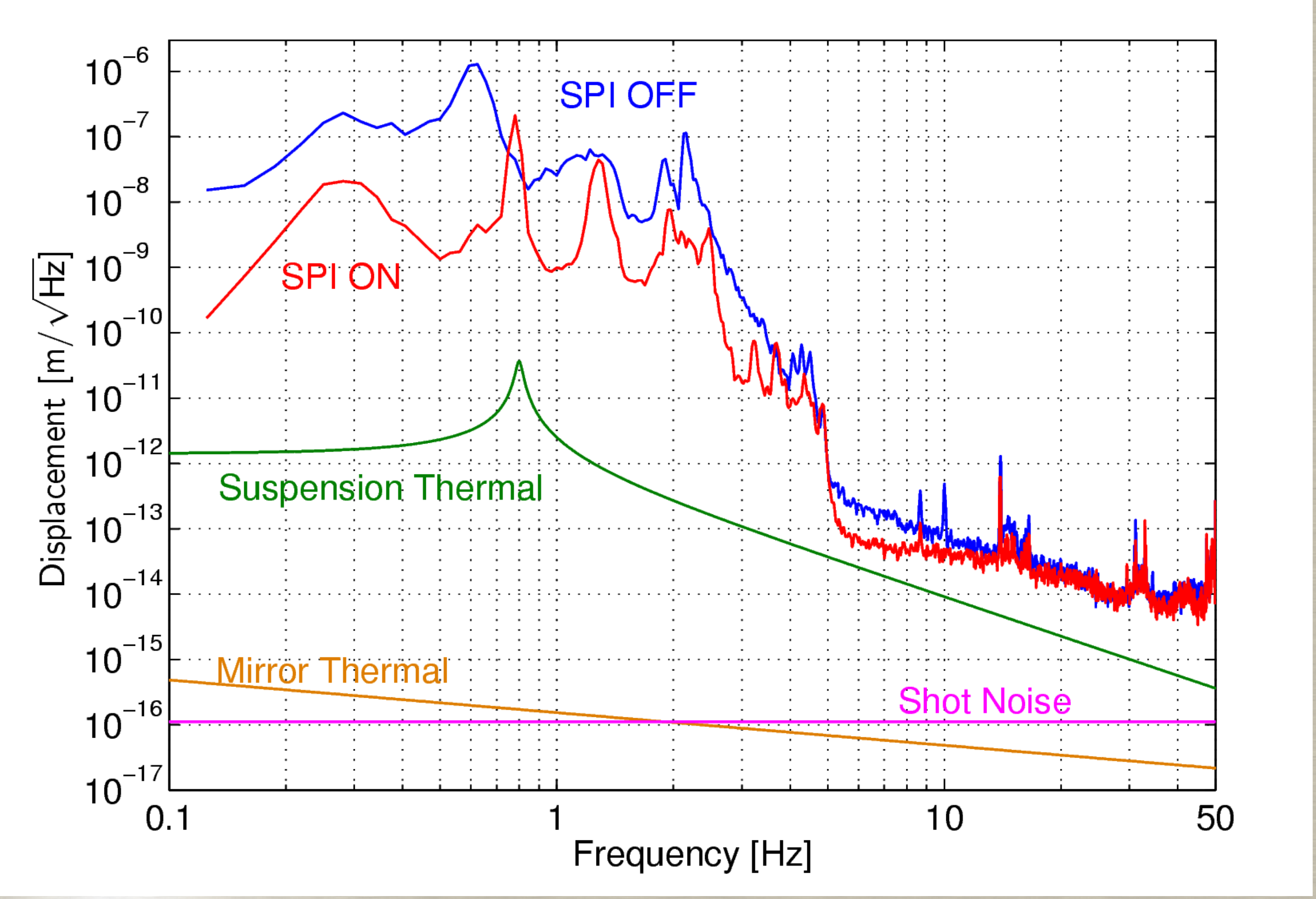
Laser Noises



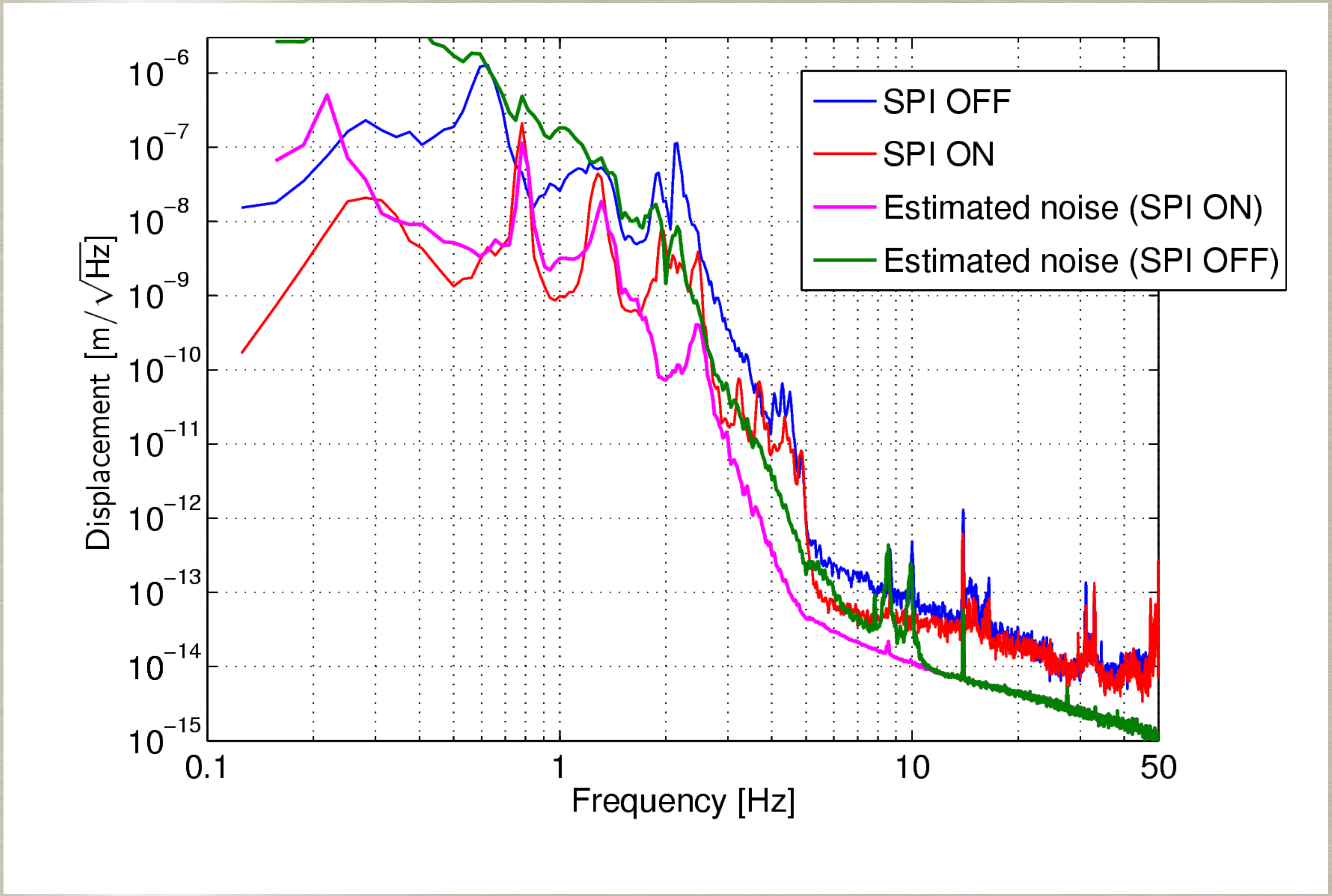
Electric Noises



Thermal noise, Shot noise



Total estimated noise



Noise shape: OK

Magnitude: Small discrepancy

Noise of the SPI