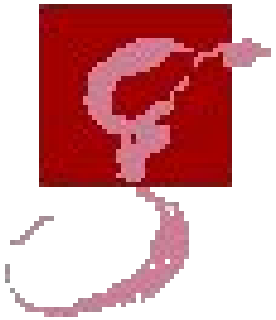
Stabilization of the advanced LIGO Pre-Stabilized Laser (PSL)

Oliver Puncken

Outline

- Requirements and overview
- Beam shaping
- Intensity stabilization
- Frequency stabilization



Outline

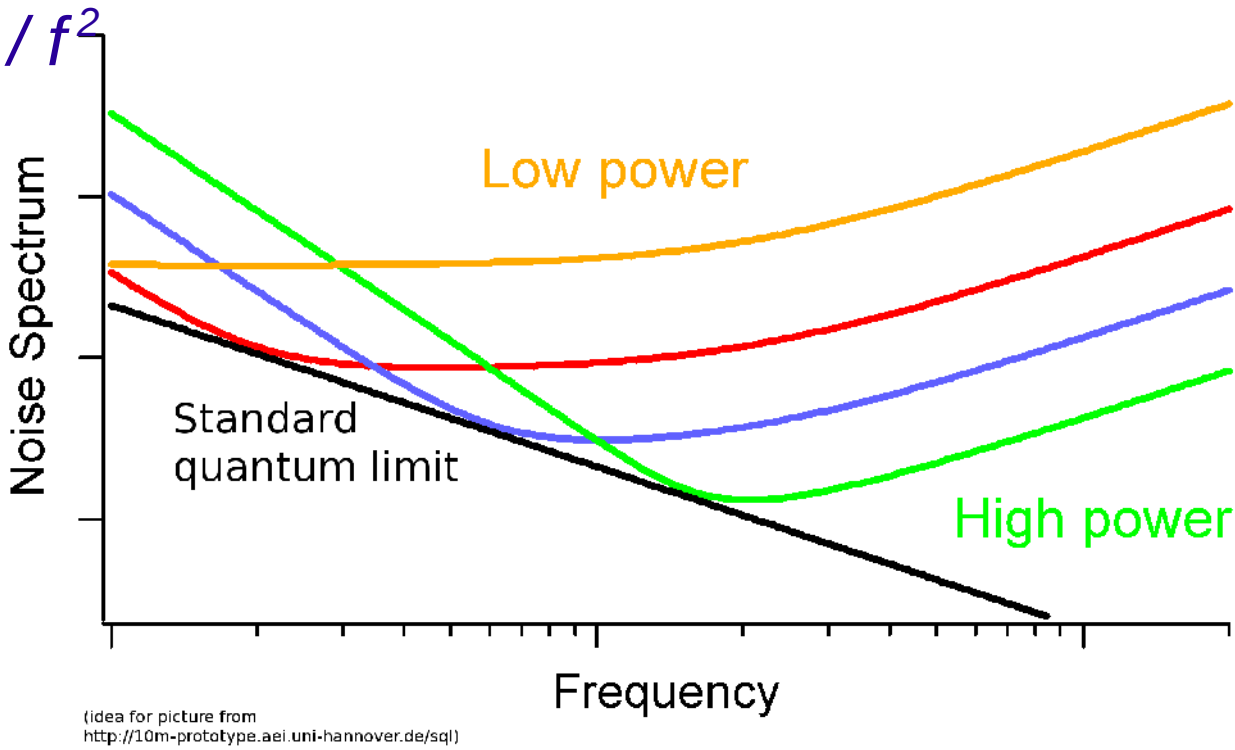
- **Requirements and overview**
- Beam shaping
- Intensity stabilization
- Frequency stabilization

Requirements for the PSL

- **Output power: 180 W**

  Quantum noise consists of

  - shot noise $\sim f / \sqrt{P}$
  - radiation pressure $\sim \sqrt{P} / f^2$
  - more power helps at high frequencies



Requirements for the PSL

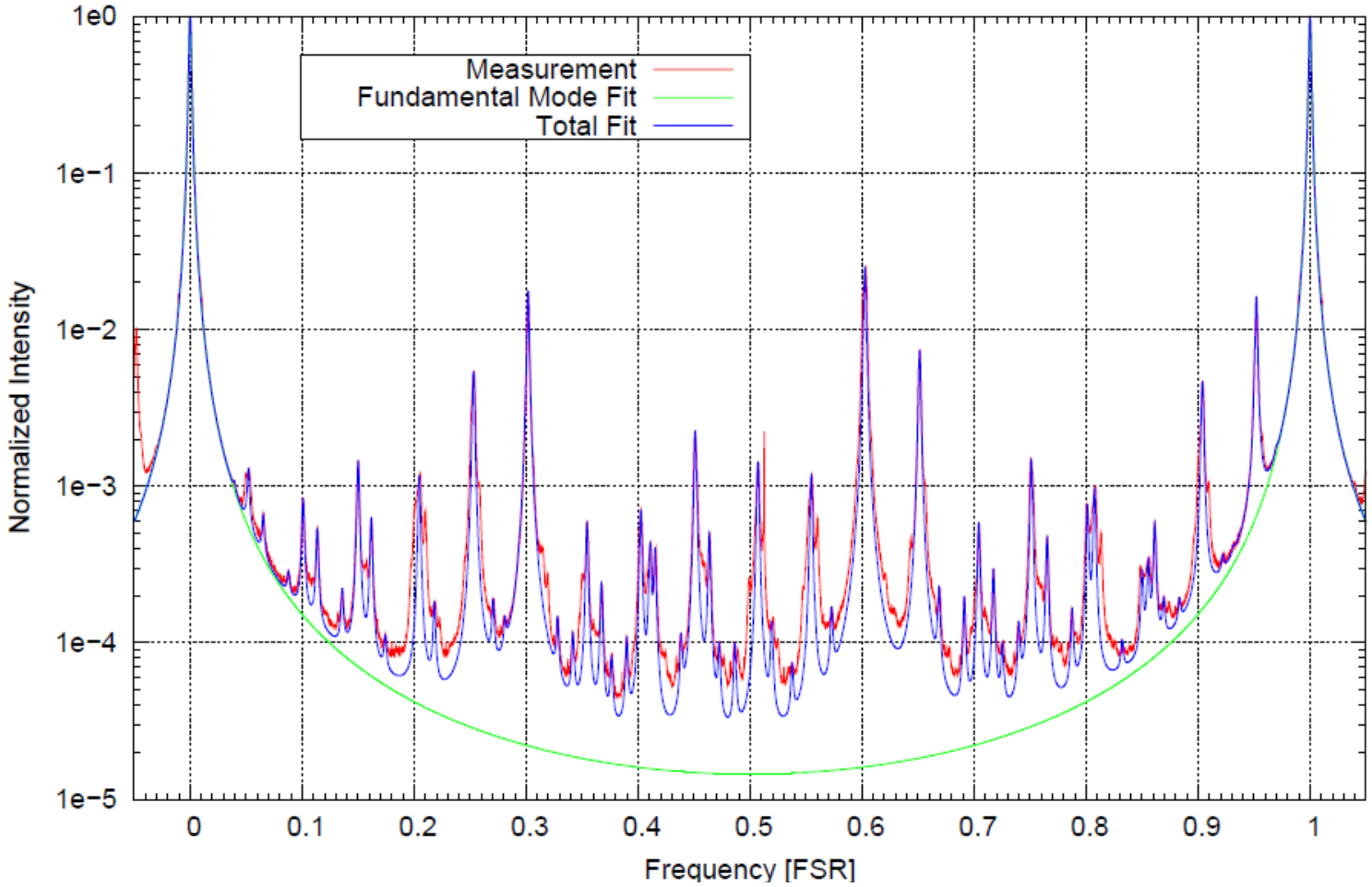
- Output power: 180 W ☺
- Linearly polarized output ☺
- High reliability ☺
- Easy maintenance ☺

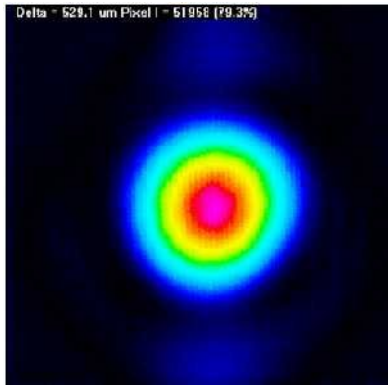
Requirements for the PSL

- Output power: 180 W ☺
- Linearly polarized output ☺
- High reliability ☺
- Easy maintenance ☺
- **Single transverse mode operation**

Higher order mode content of the unfiltered PSL

- 8.2 % in non-TEM_{00} modes

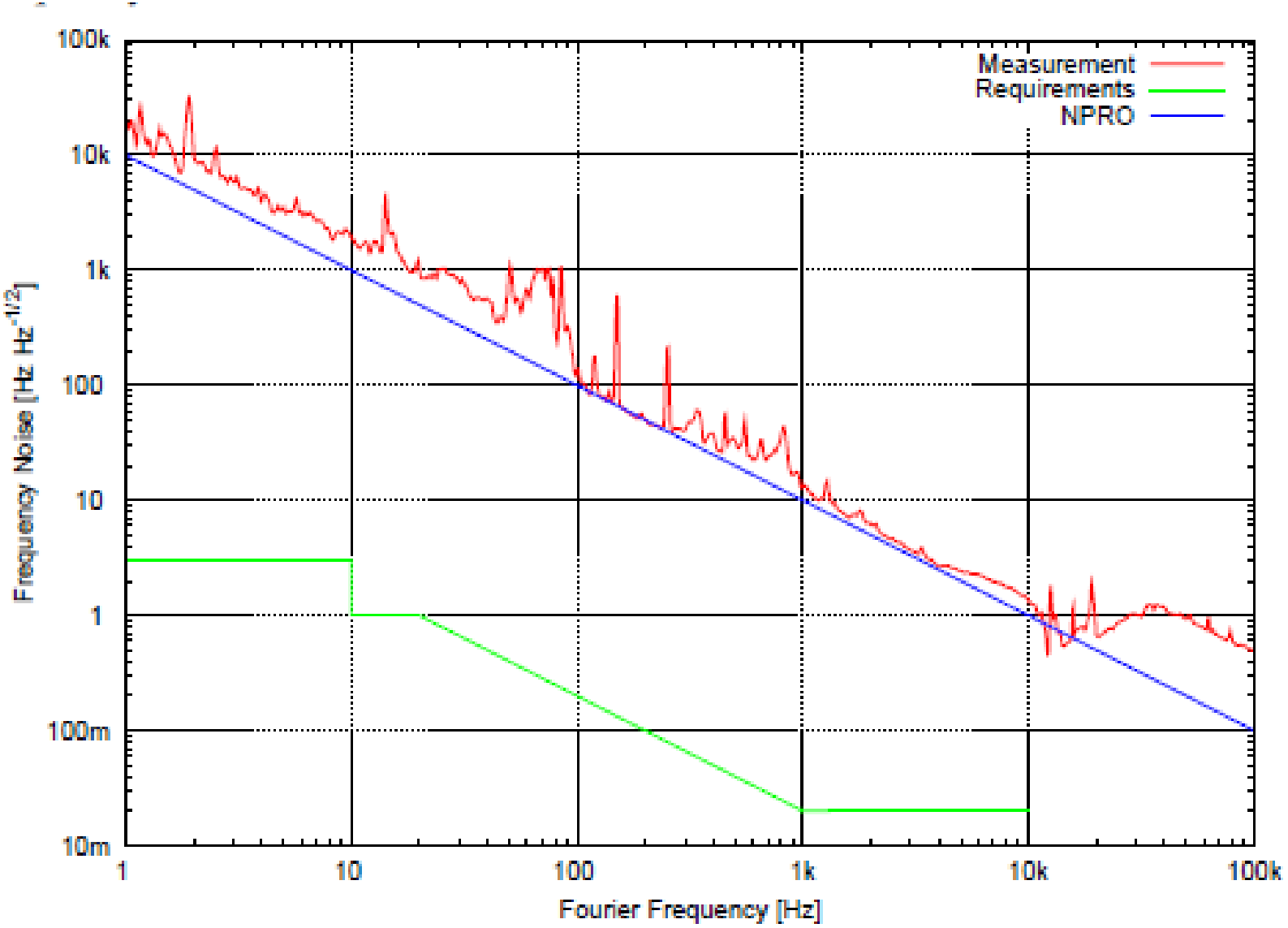




Requirements for the PSL

- Output power: 180 W ☺
- Linearly polarized output ☺
- High reliability ☺
- Easy maintenance ☺
- Single transverse mode operation ☹
- **Frequency stability: 10 Hz / $Hz^{1/2}$ @ 10 Hz**

Frequency noise of the unstabilized PSL



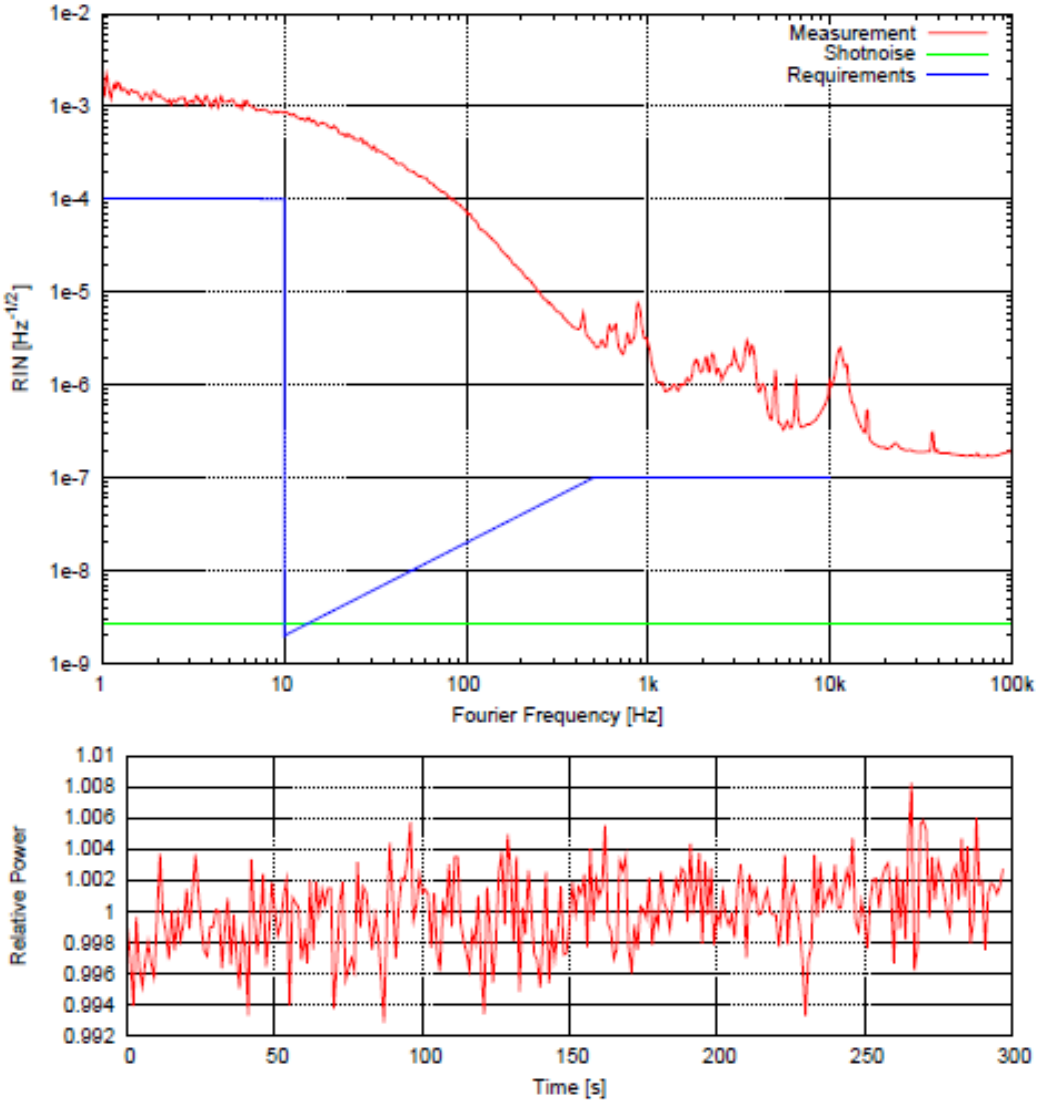
Requirements for the PSL

- Output power: 180 W ☺
- Linearly polarized output ☺
- High reliability ☺
- Easy maintenance ☺
- Single transverse mode operation ☹
- Frequency stability: 10 Hz / $Hz^{1/2}$ @ 10 Hz ☹
- **Amplitude stability: $2 \cdot 10^{-9}$ / $Hz^{1/2}$ @ 10 Hz**

Requirements

- Power noise downstream suspended modecleaner:
  10 Hz: $2 \cdot 10^{-9}$ /√Hz
  10-500 Hz: $2 \cdot 10^{-10} \cdot f$ /√Hz
  f > 500 Hz: 10^{-7} /√Hz
- Various coupling paths:
  - Direct sensing by output photodiode (since dark port not completely dark)
  - Radiation pressure fluctuations to suspended optics
  - Coupling into control loops

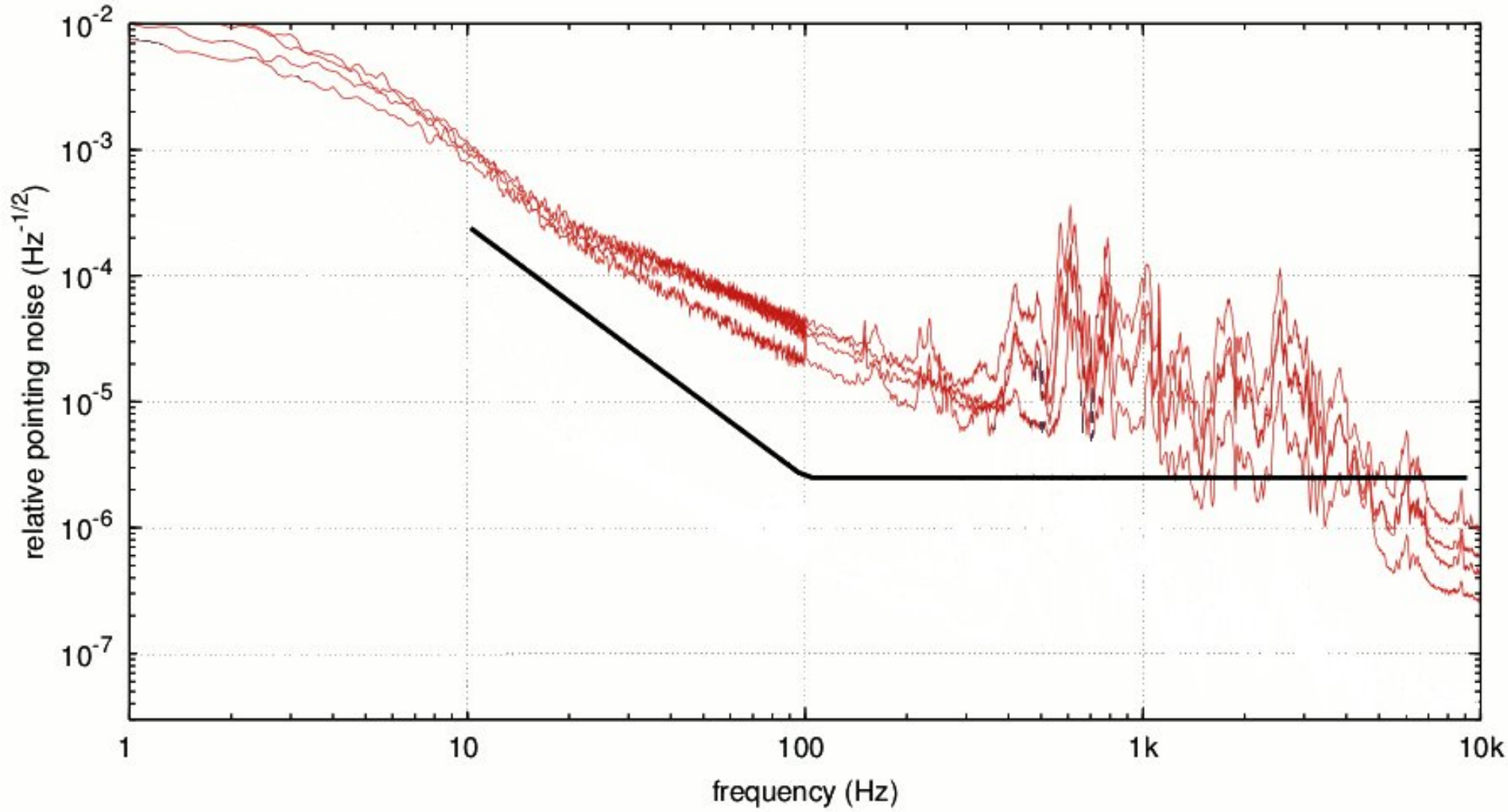
Power noise of the unstabilized PSL



Requirements for the PSL

- Output power: 180 W ☺
- Linearly polarized output ☺
- High reliability ☺
- Easy maintenance ☺
- Single transverse mode operation ☹
- Frequency stability: 10 Hz / $Hz^{1/2}$ @ 10 Hz ☹
- Amplitude stability: $2 \cdot 10^{-9}$ / $Hz^{1/2}$ @ 10 Hz ☹
- **Pointing**

Pointing noise of the PSL



Requirements for the PSL

- Output power: 180 W ☺
- Linearly polarized output ☺
- High reliability ☺
- Easy maintenance ☺
- Single transverse mode operation ☹
- Frequency stability: 10 Hz / $Hz^{1/2}$ @ 10 Hz ☹
- Amplitude stability: $2 \cdot 10^{-9}$ / $Hz^{1/2}$ @ 10 Hz ☹
- Pointing ☹

Outline

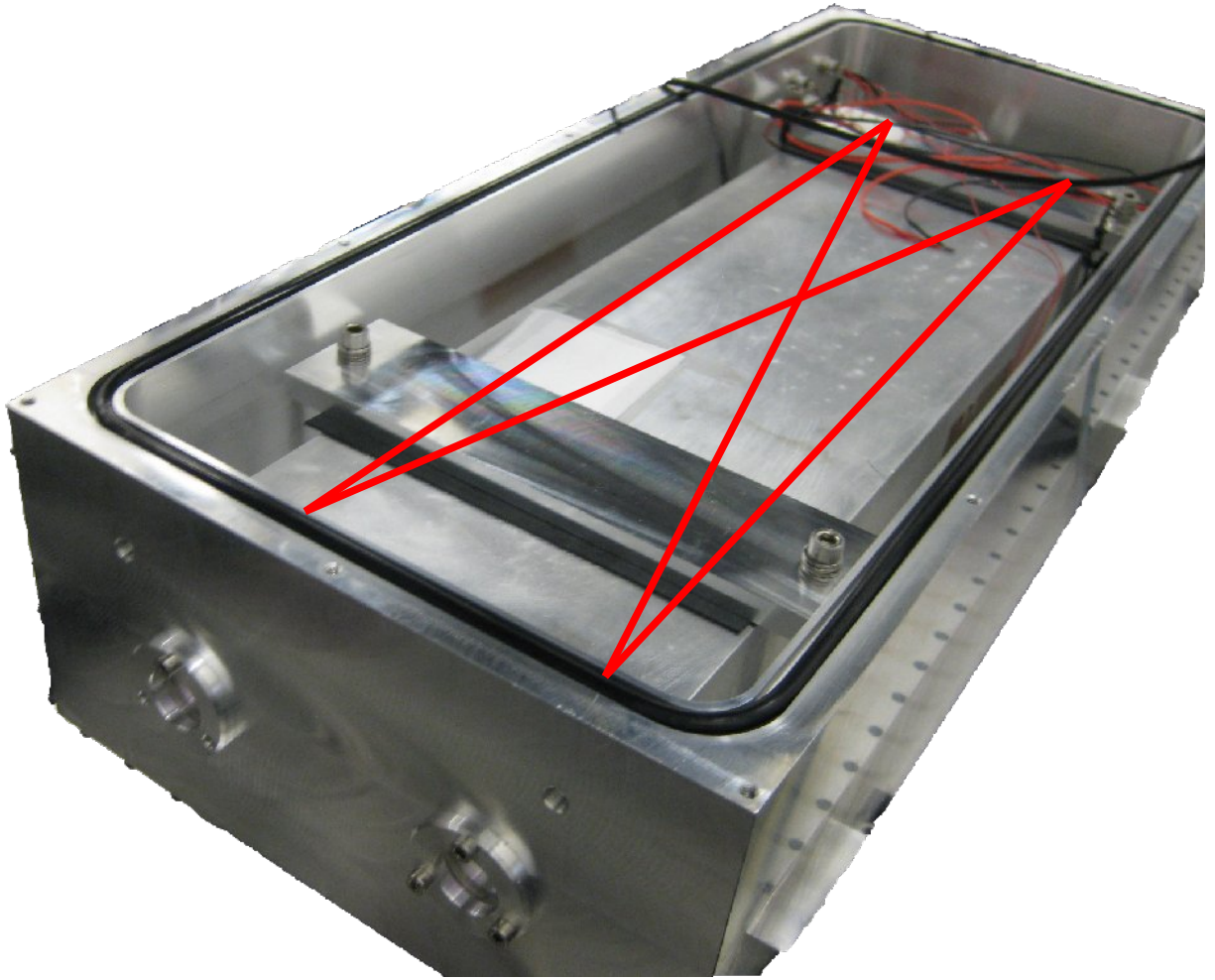
- Requirements and overview
- **Beam shaping**
- Intensity stabilization
- Frequency stabilization

Beam shaping

- High power pre-modecleaner (PMC)
  - Spacer with glued mirrors in bow-tie configuration
  - PZT-mirror changes round trip length by 2.5 µm (2.5 FSR) with a voltage range from 0 V to 400 V for locking and scanning
  - Long range actuation by heating the spacer (43 FSR/K)
  - Inside a tank as contamination protection

High power PMC

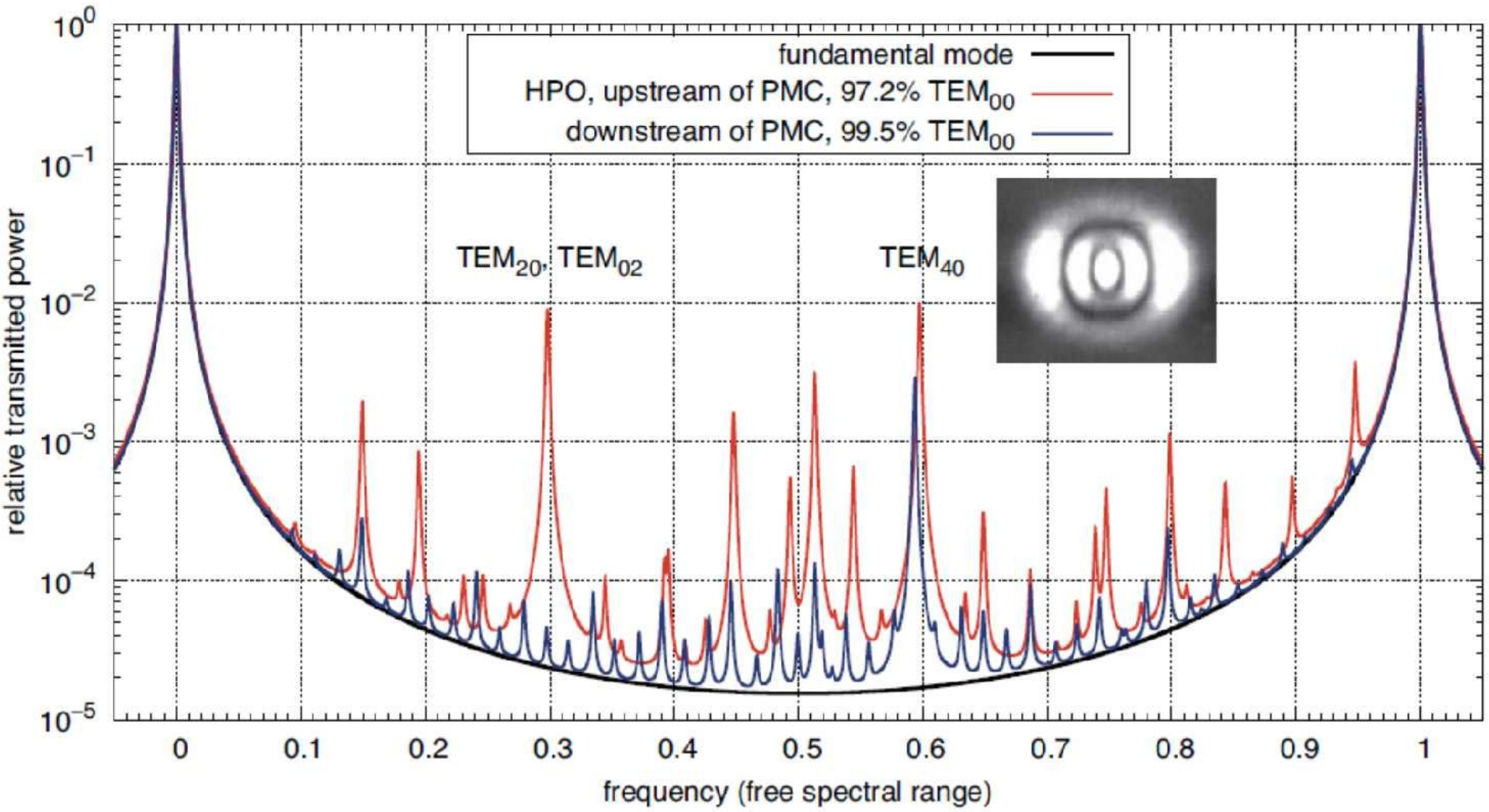
- Finesse: 124
- Round-trip length: 2m
- Intra-cavity power at 200 W: 8 kW
- FSR: 150 MHz
- HWHM: 560 kHz



High power PMC

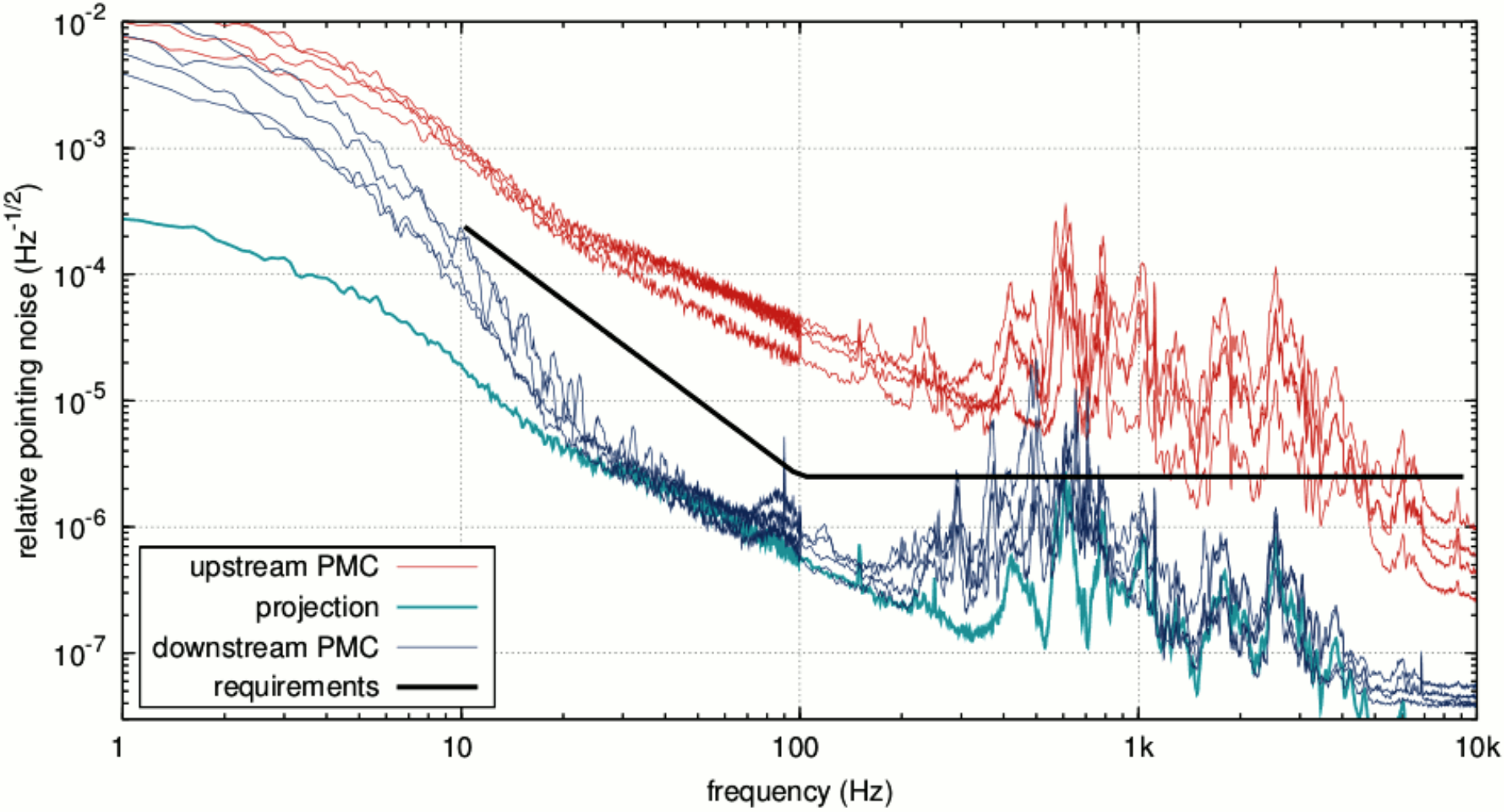
- Mode filtering
- Pointing noise supression
- Supression of RF power noise

Mode filtering



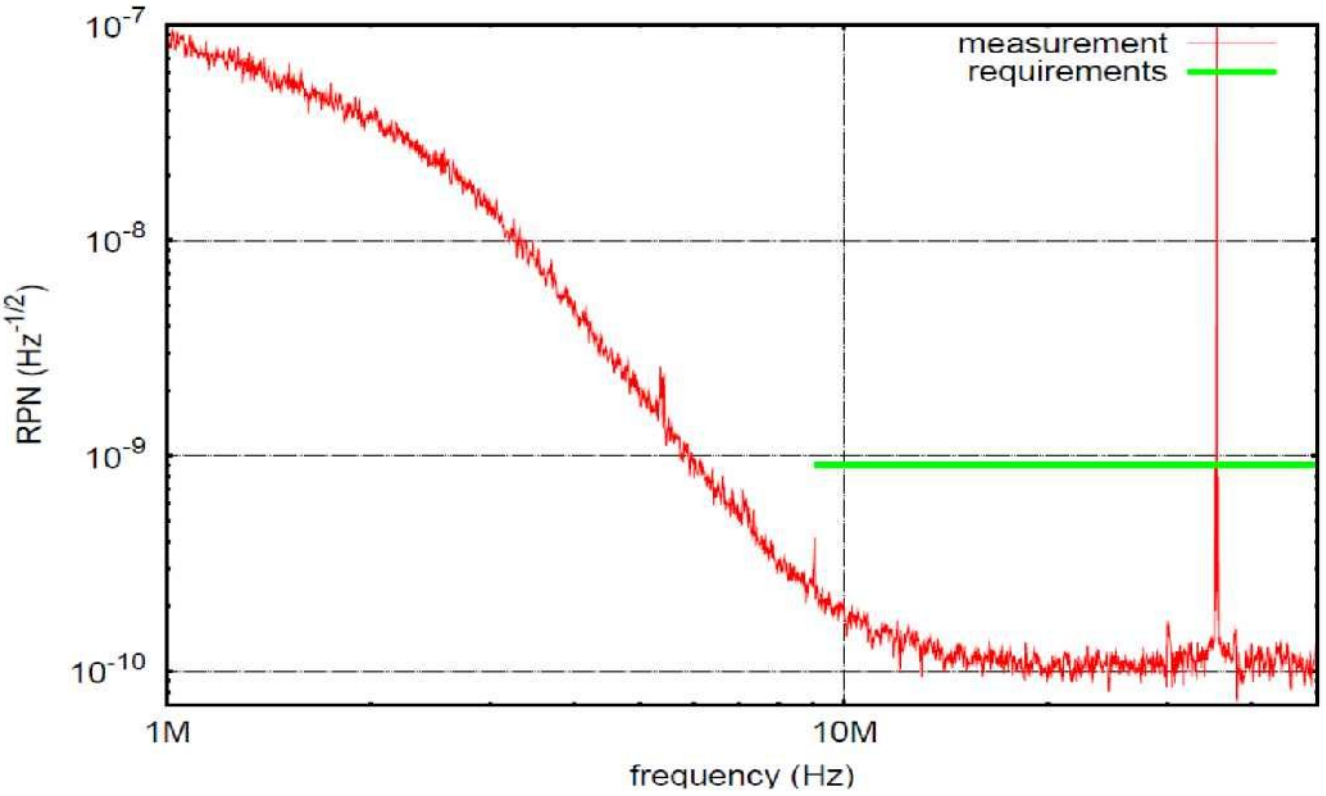
Pointing noise suppression

- PMC filters pointing noise with a factor of 63



Suppression of RF power noise

- Filtering of technical RPN in the MHz frequency range
- Transfer function
  ≡ low-pass
  → filtering by a factor of 11
  at 9 MHz



Outline

- Requirements and overview
- Beam shaping
- **Intensity stabilization**
- Frequency stabilization

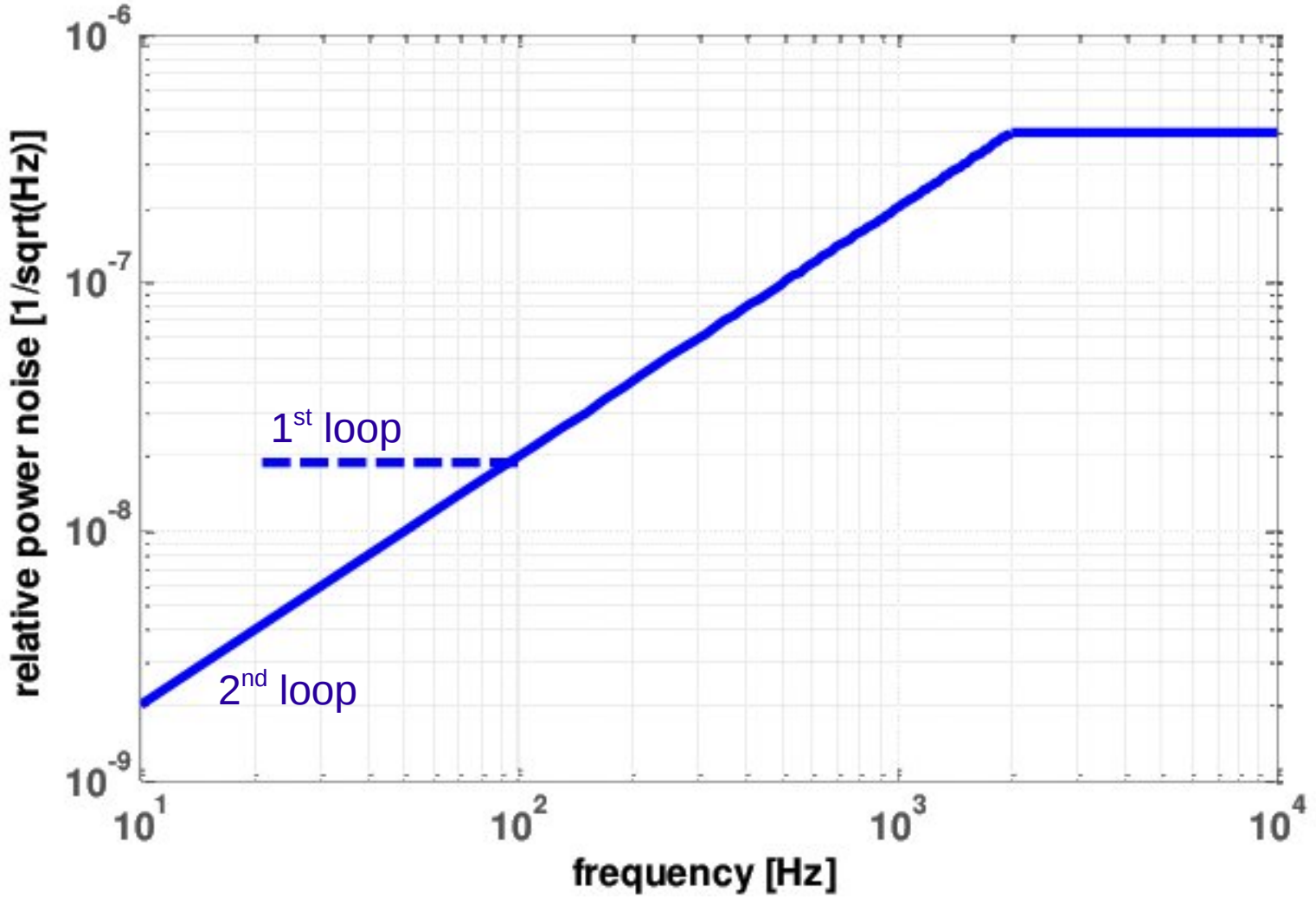
Noise in lasers

- Quantum noise
- Technical noise
- Relaxation oscillation

Noise in lasers

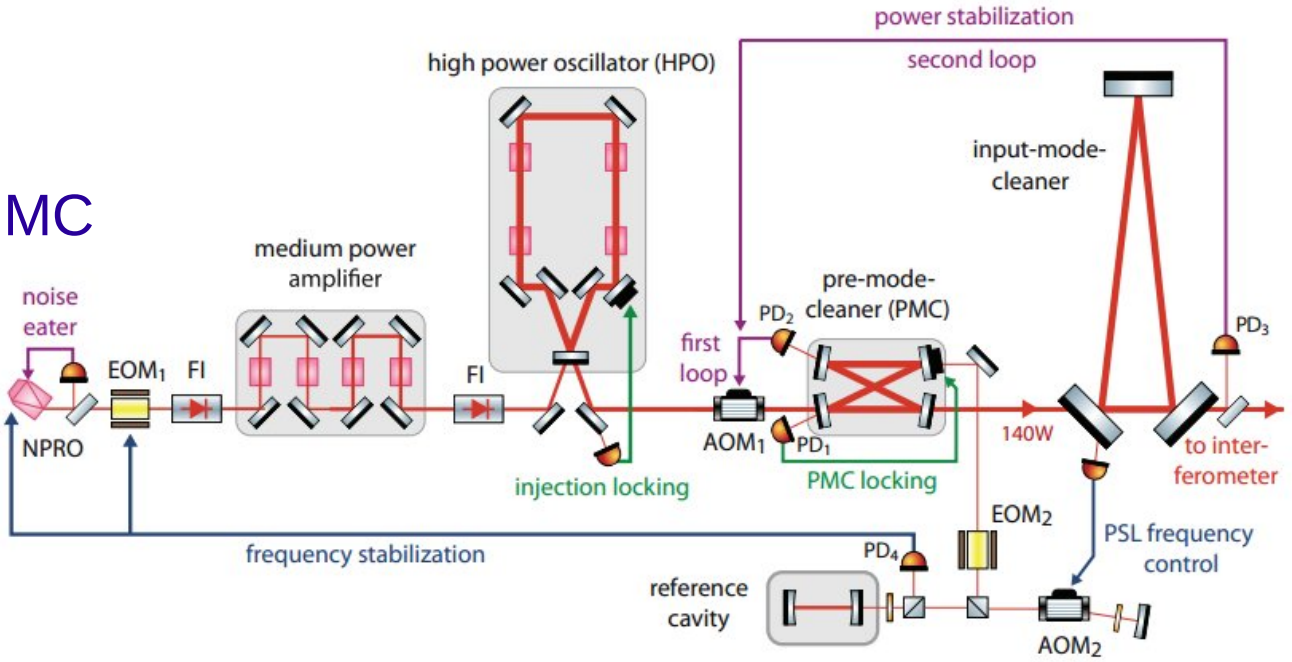
- Quantum noise
- Technical noise — Acoustic enclosure, low noise power supplies, smart cooling water distribution
- Relaxation oscillation — "Noise eater"

Requirements



Stabilization scheme

- Consists of inner loop and outer loop
- Inner loop ("1st loop")
  - Sensor: photodetector in transmission of the PMC
  - Control: high power AOM
- Outer loop ("2nd loop")
  - photodetector in vacuum between suspended MC and PRM
  - injected to the error point of the 1st loop

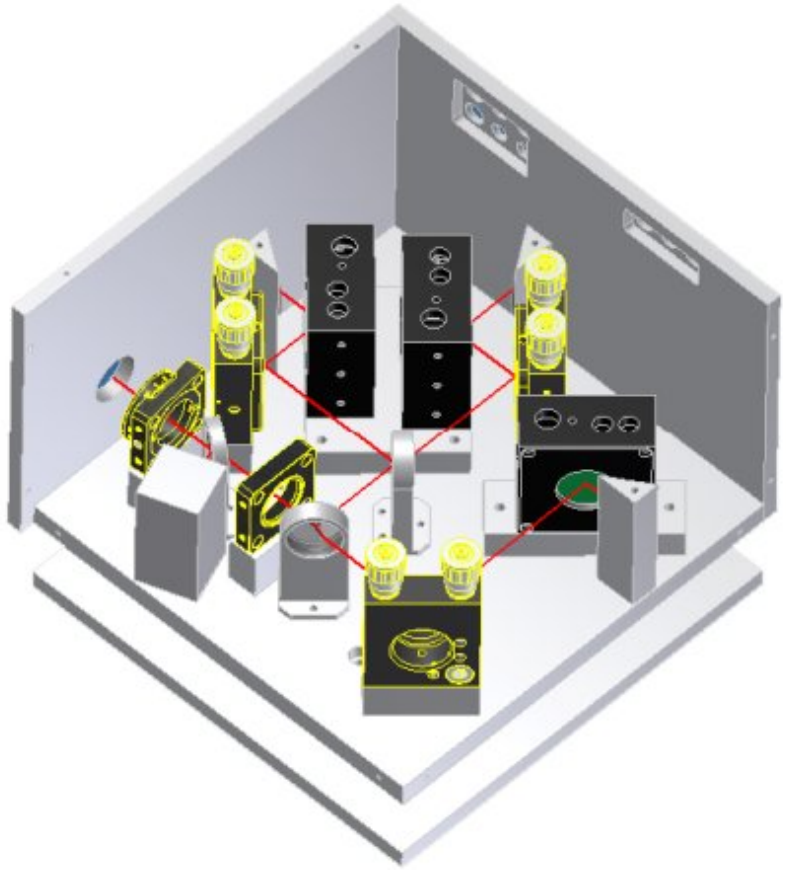


1st loop

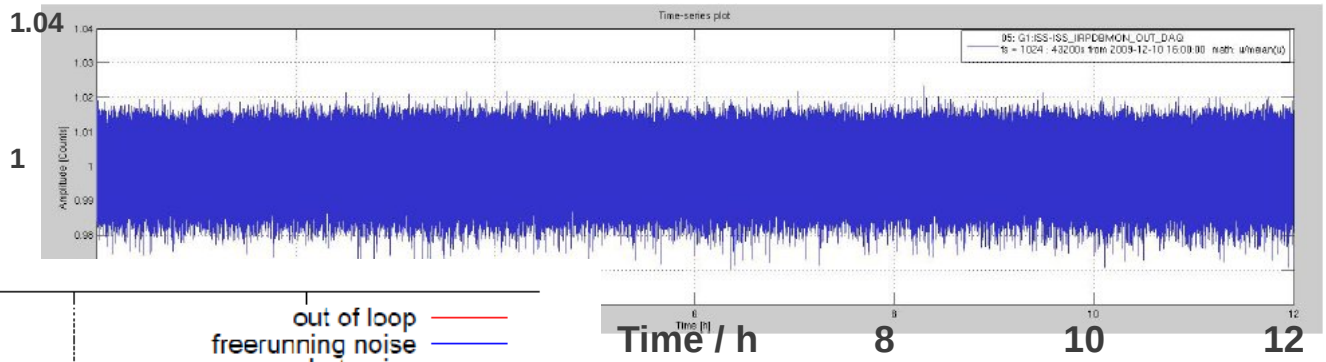
- Two photodiodes to allow out-of-loop diagnostics.
- Requirements:
  - less than 5% peak-to-peak power fluctuations over a period of 24 hours
  - the in-loop and the out-of-loop photodiode should be interchangeable by an electronic switch

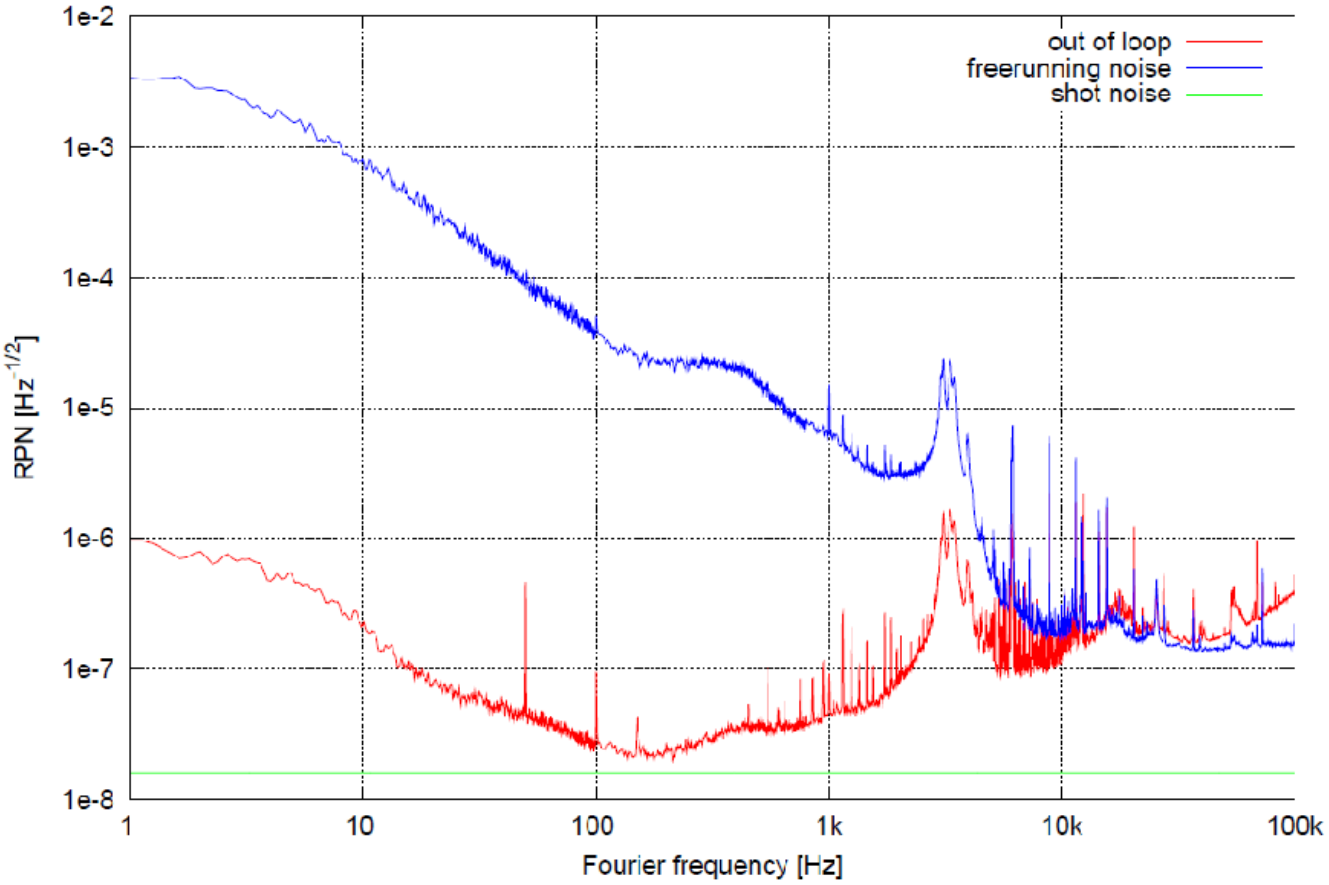
1st loop stabilization box

- shields against scattered light
- Sensing box with in-the-loop, out-of-loop and quadrant photodiode



Performance

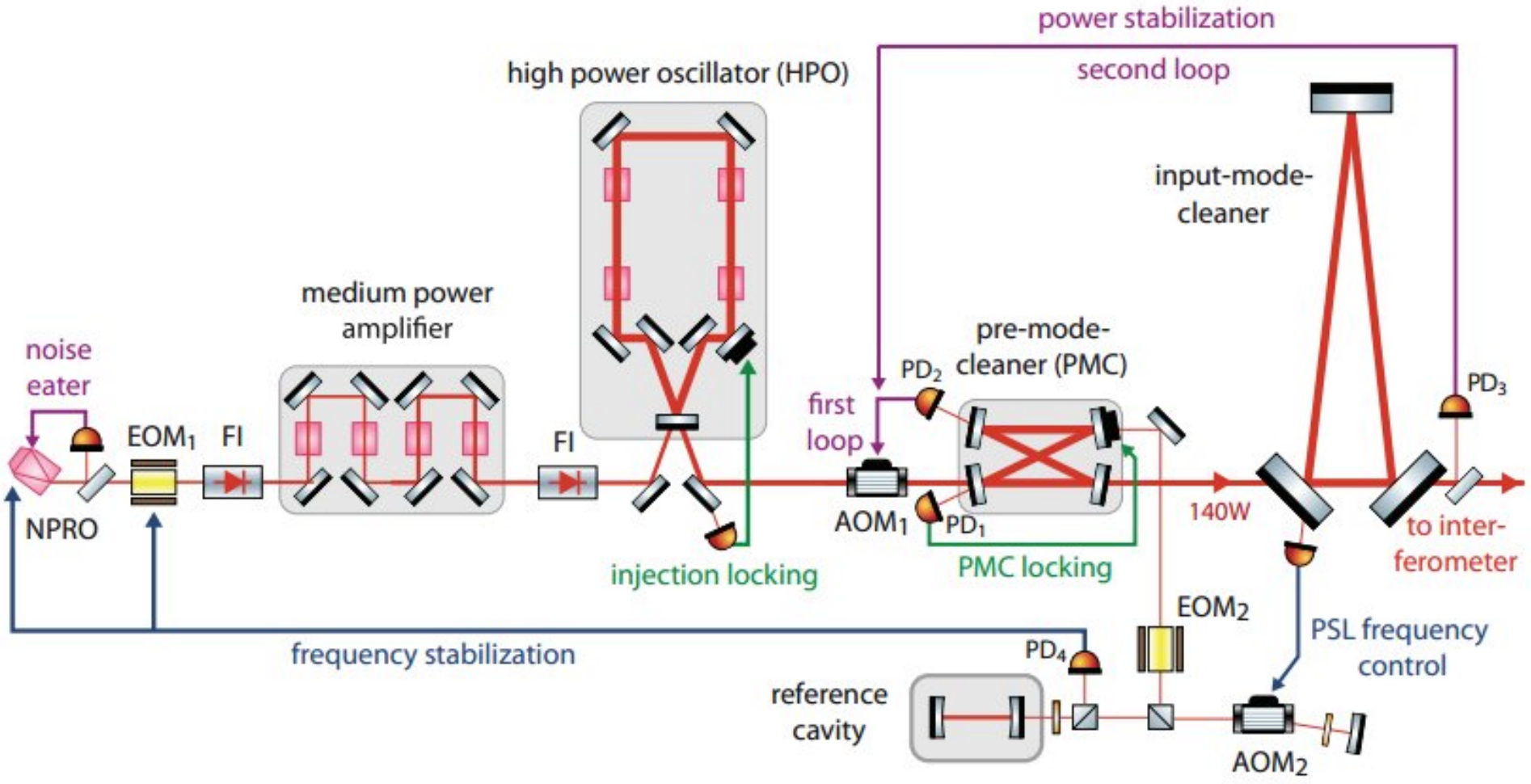




peak to peak power fluctuation of about 5% in between a 12 h period

Power noise of the high power laser. Out of loop performance of the 1st loop power stabilization.

Stabilization scheme
ISS, 2nd loop



2nd loop power stabilization

- Traditional power stabilization needs to detect a rather large photocurrent in order to lower the quantum noise
- Thermal effects
  $\Rightarrow$ cooling, low-noise readout

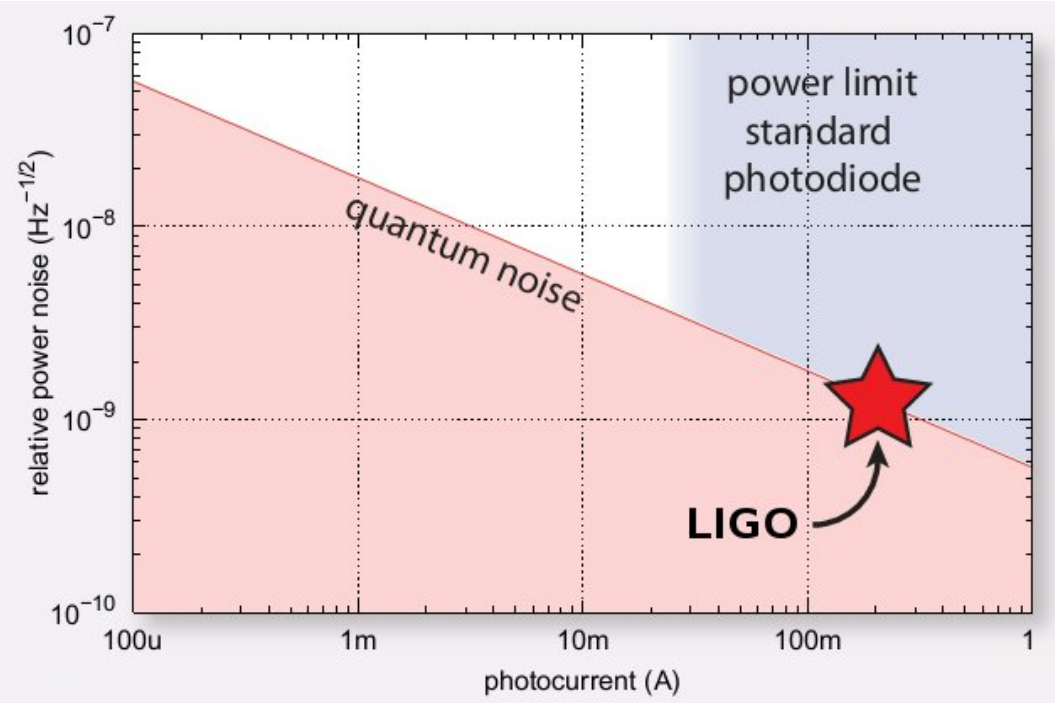
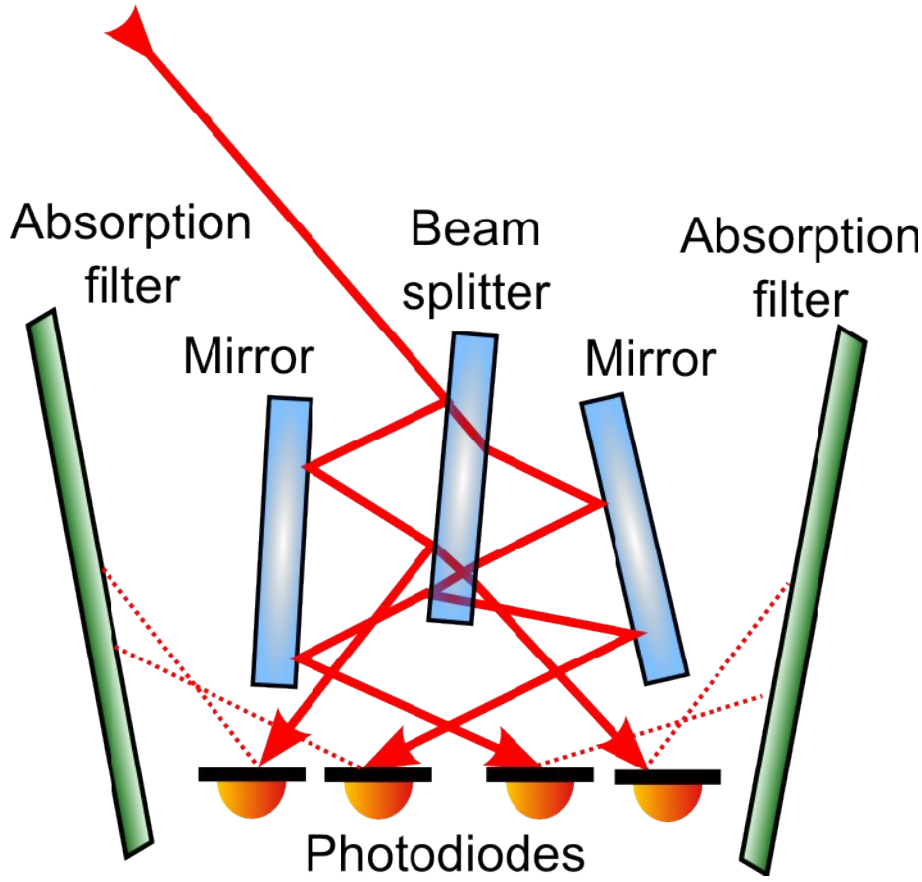
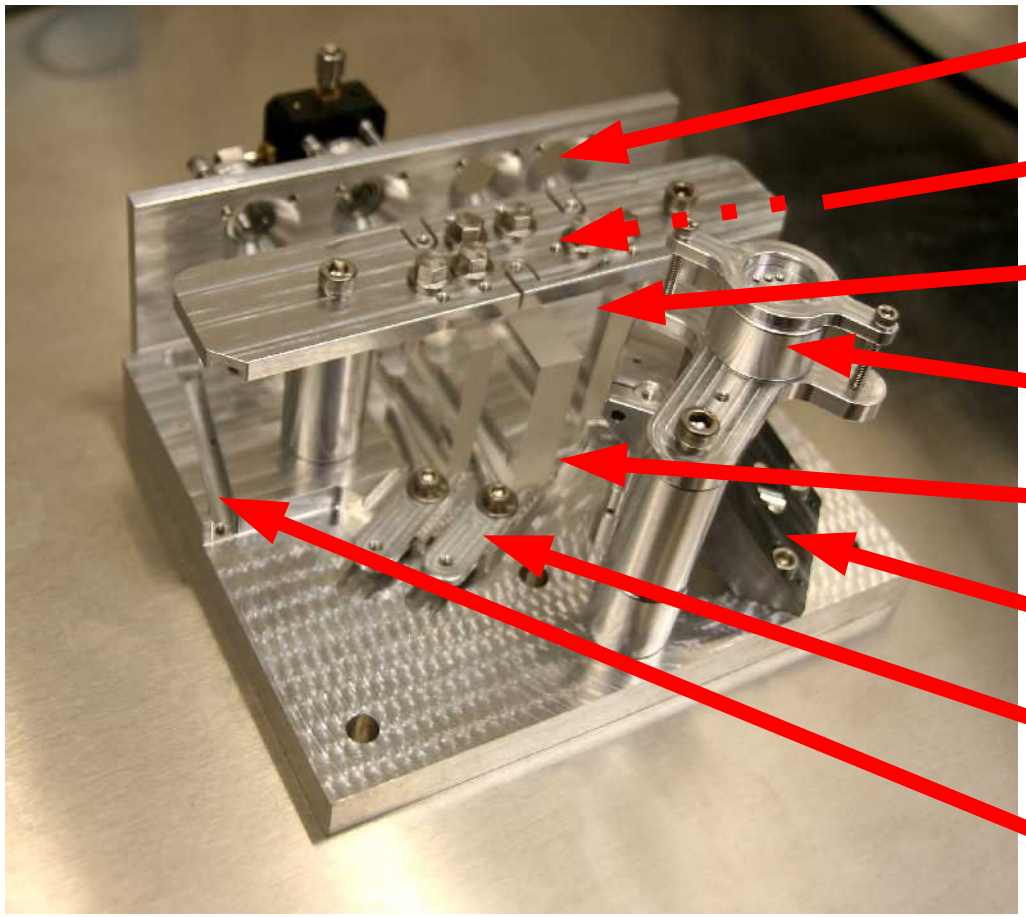


Photo detector array

- Traditional power stabilization needs to detect a rather large photocurrent in order to lower the quantum noise
- Thermal effects
  $\Rightarrow$ cooling, low-noise readout ☹
- Distribute the power to four photodiodes, each read out by its own electronics ☺



Photodiode array



Out-of-loop photodiodes

In-loop photodiodes

Mirror

Quad-photodiode

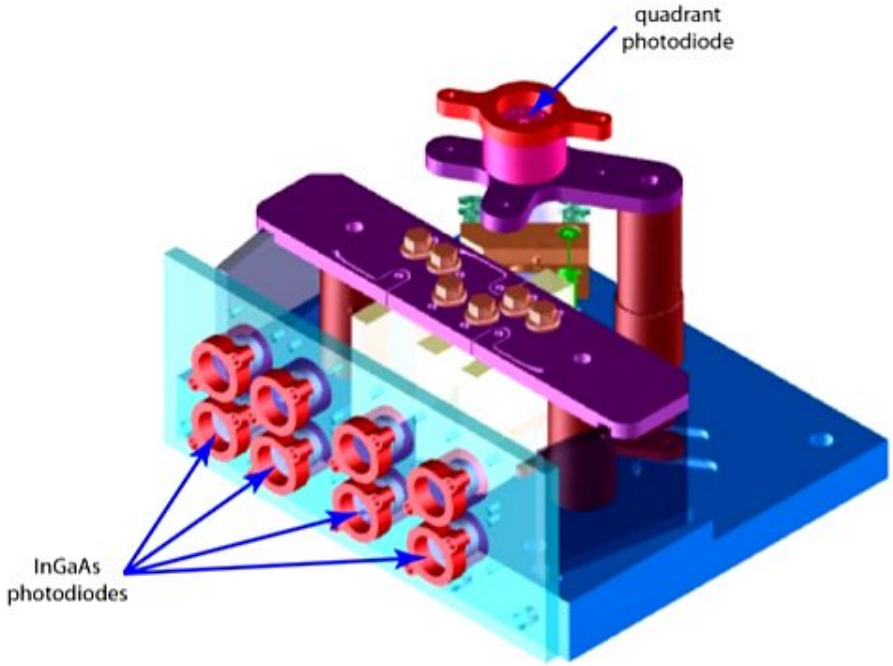
Beamsplitter

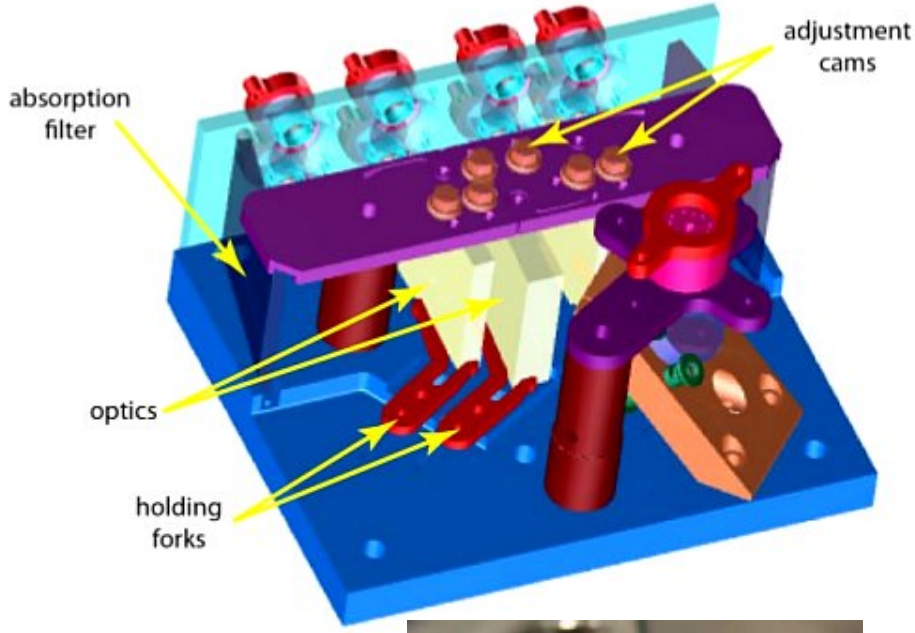
Periscope with BS

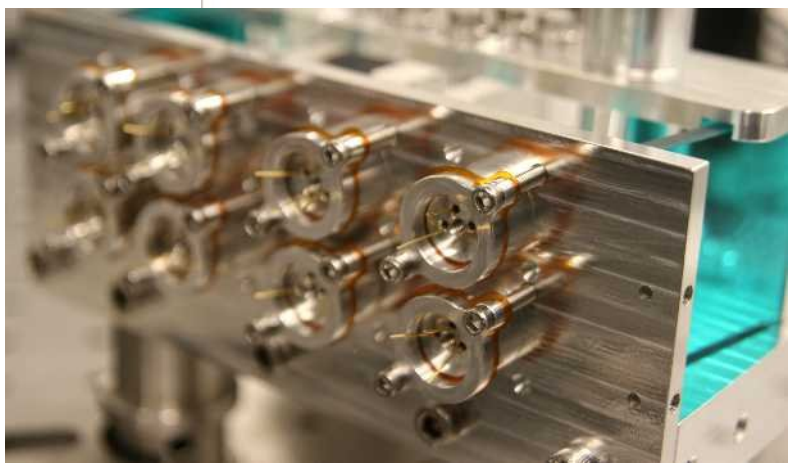
clamping forks

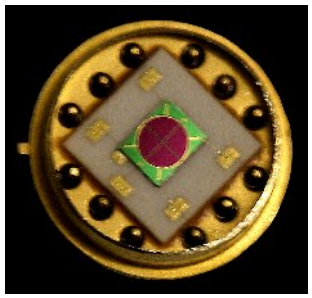
Groove for filters

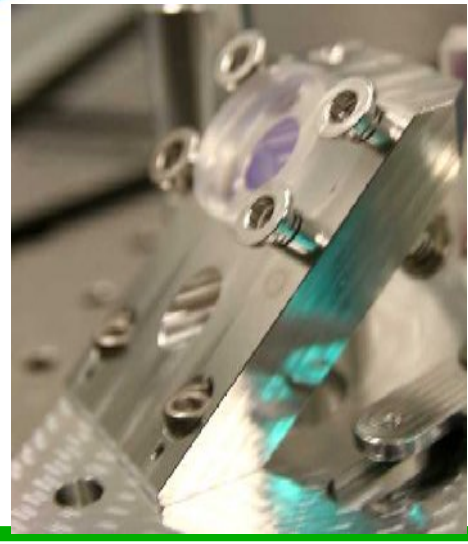
Photodiode array





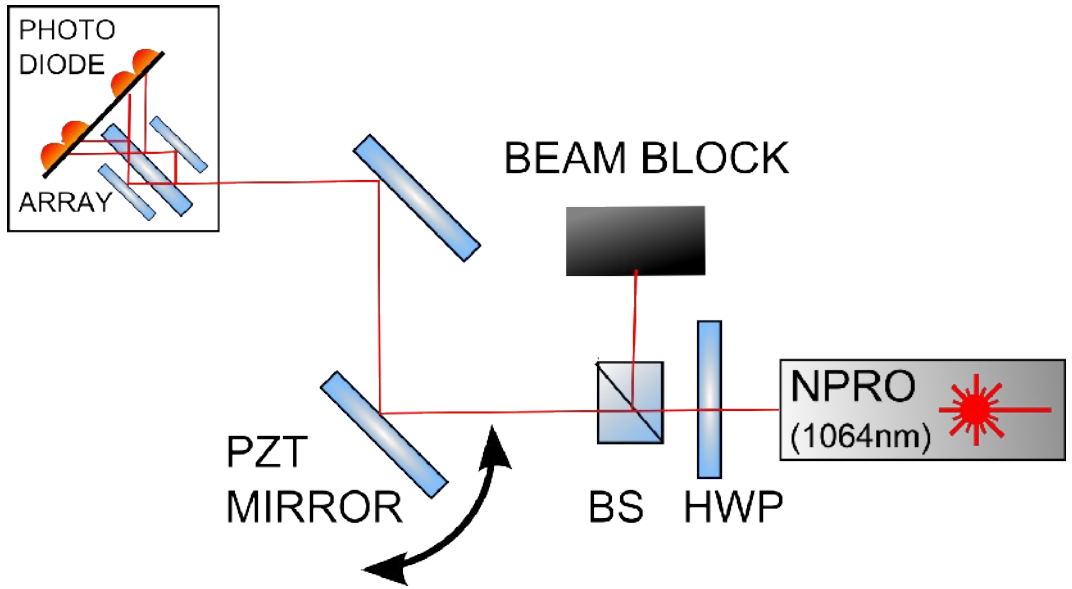


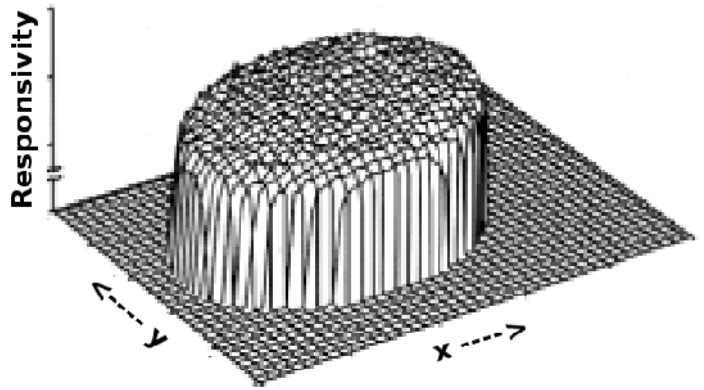




Photodiode array assembly

- Photodiodes can be moved transversely by 1 mm
- Alignment to the position of the smallest coupling to lateral beam jitter
- Determine by modulating the beam pointing





Photodiode array assembly

- Photodiodes can be moved transversely by 1 mm
- Alignment to the position of the smallest coupling to lateral beam jitter
- Determine by modulating the beam pointing

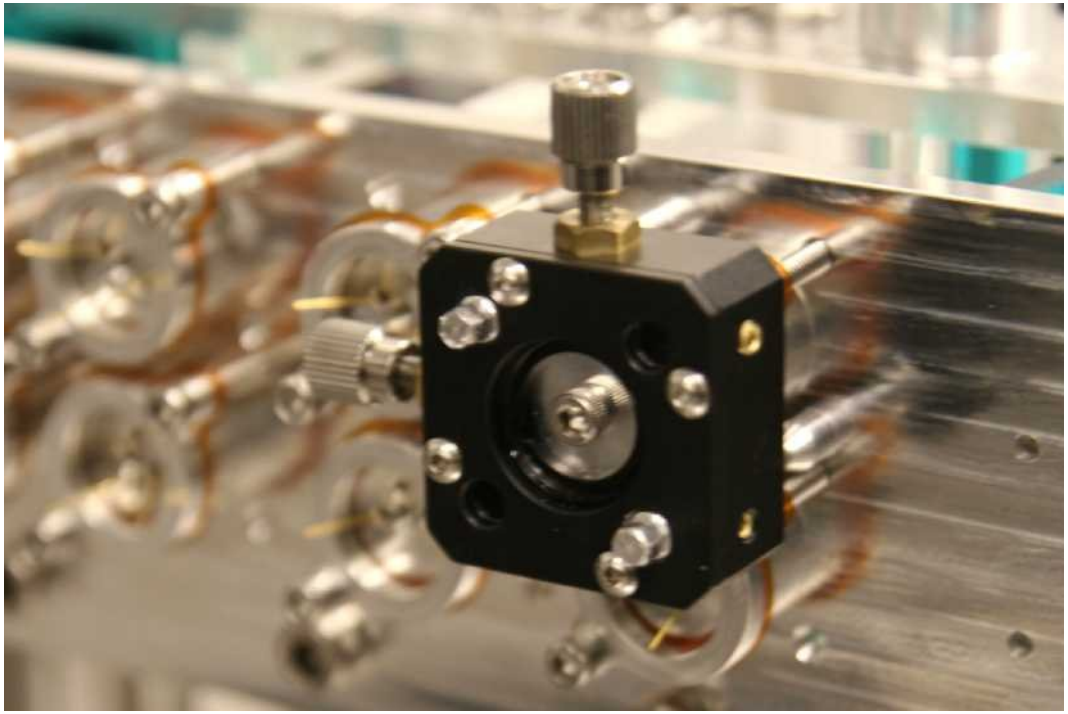


Photo diode array - installation

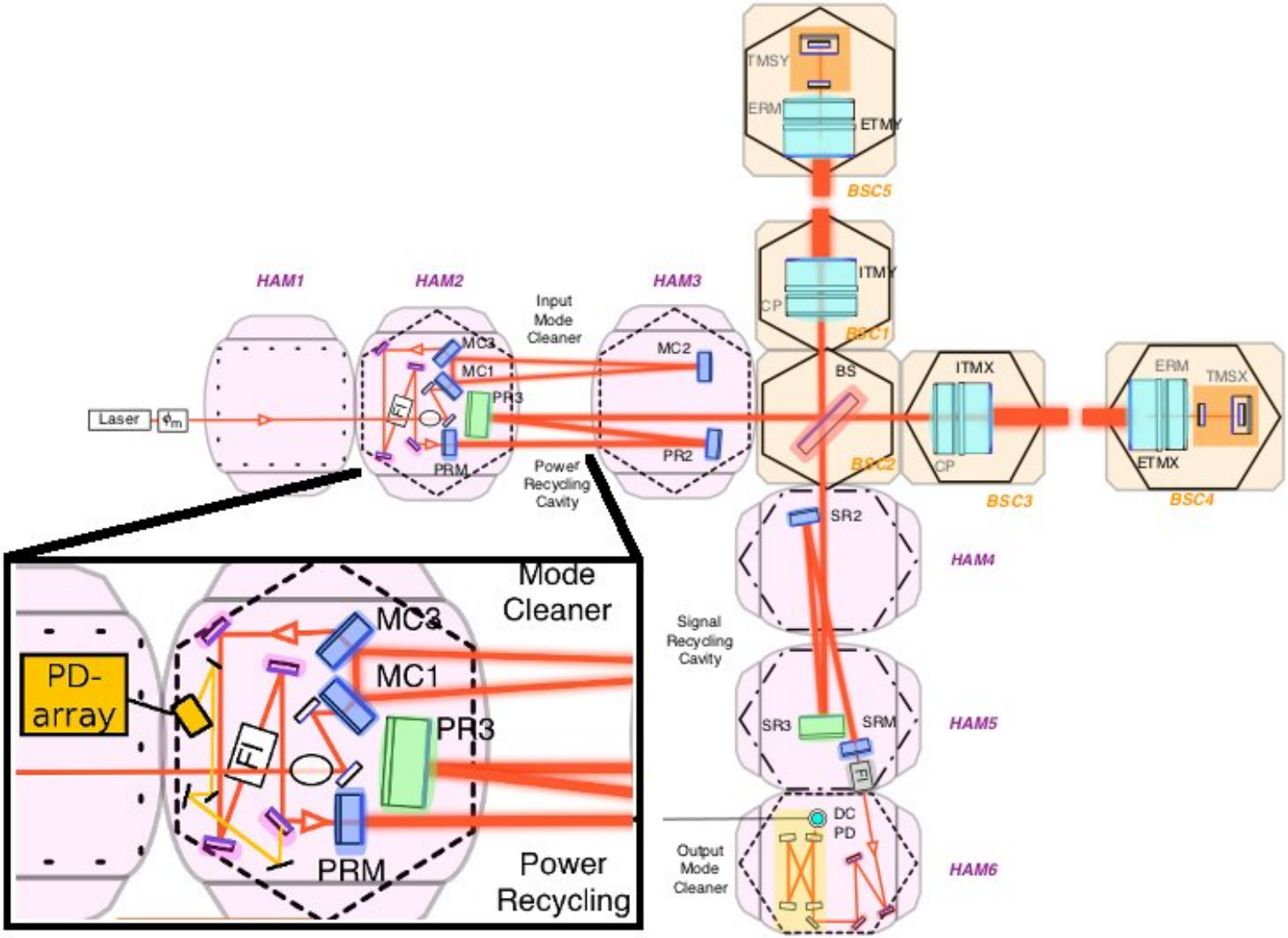
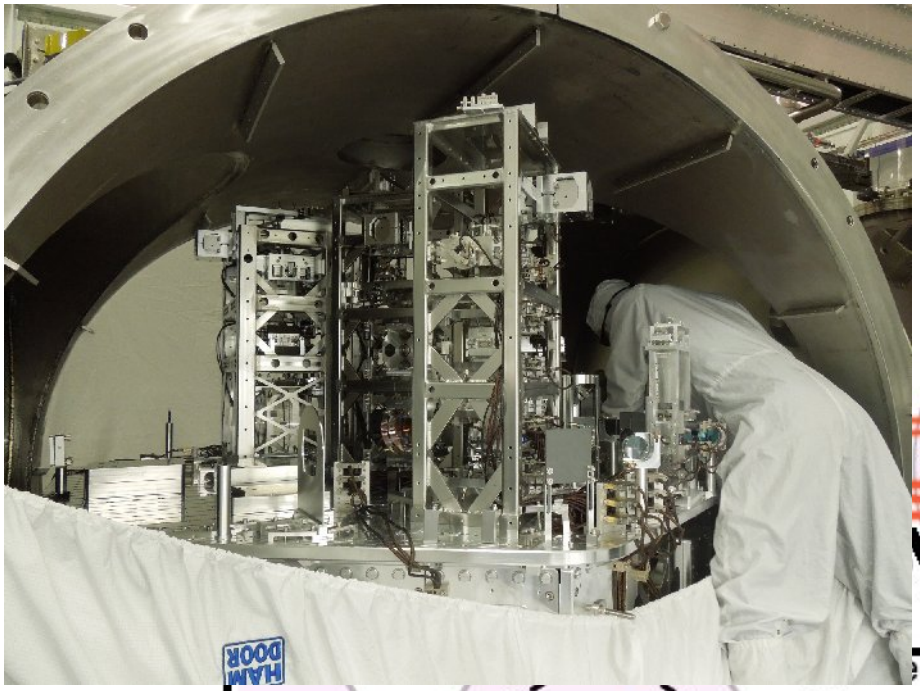
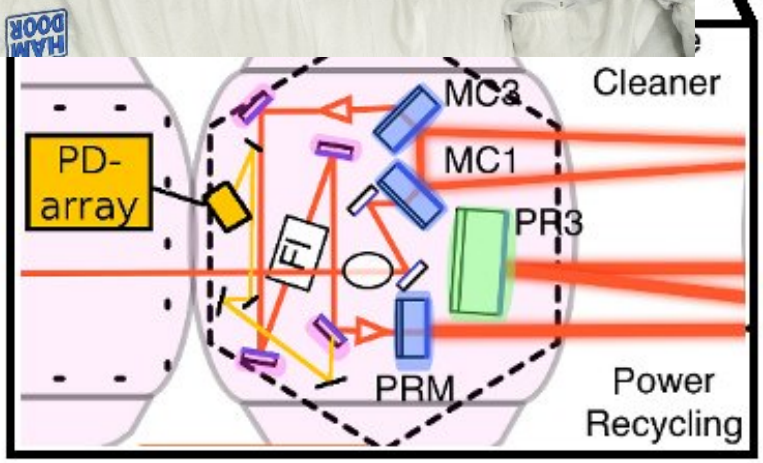
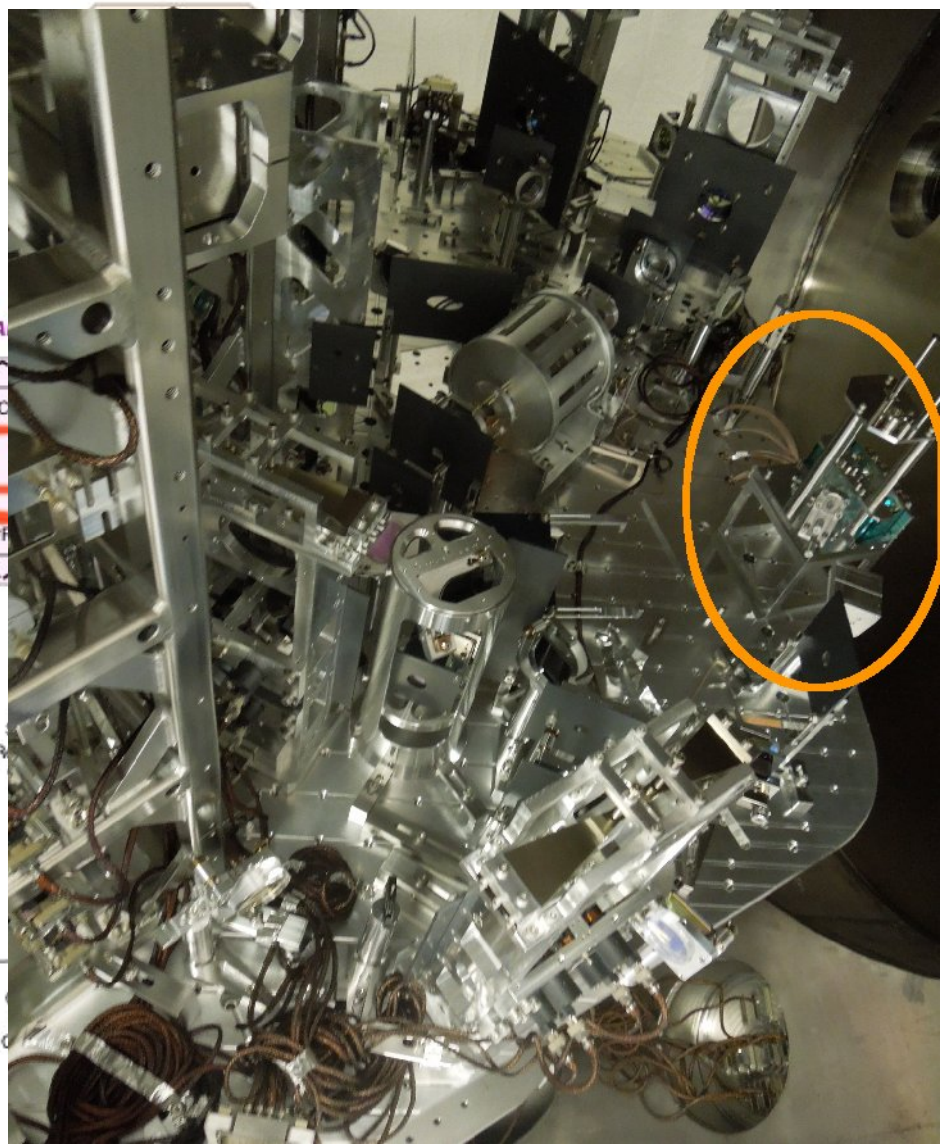


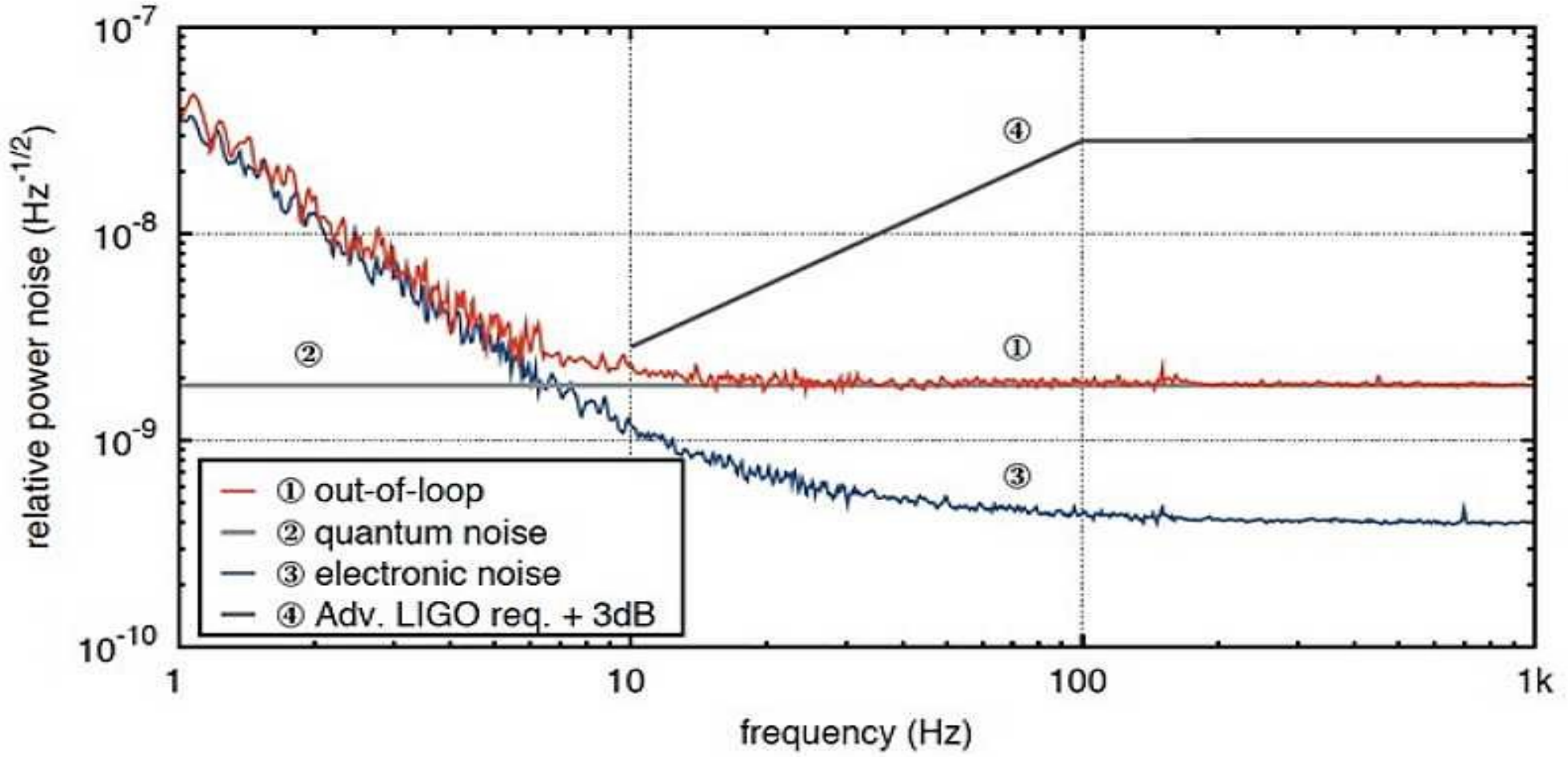
Photo diode array - installation







Performance (2W NPRO)

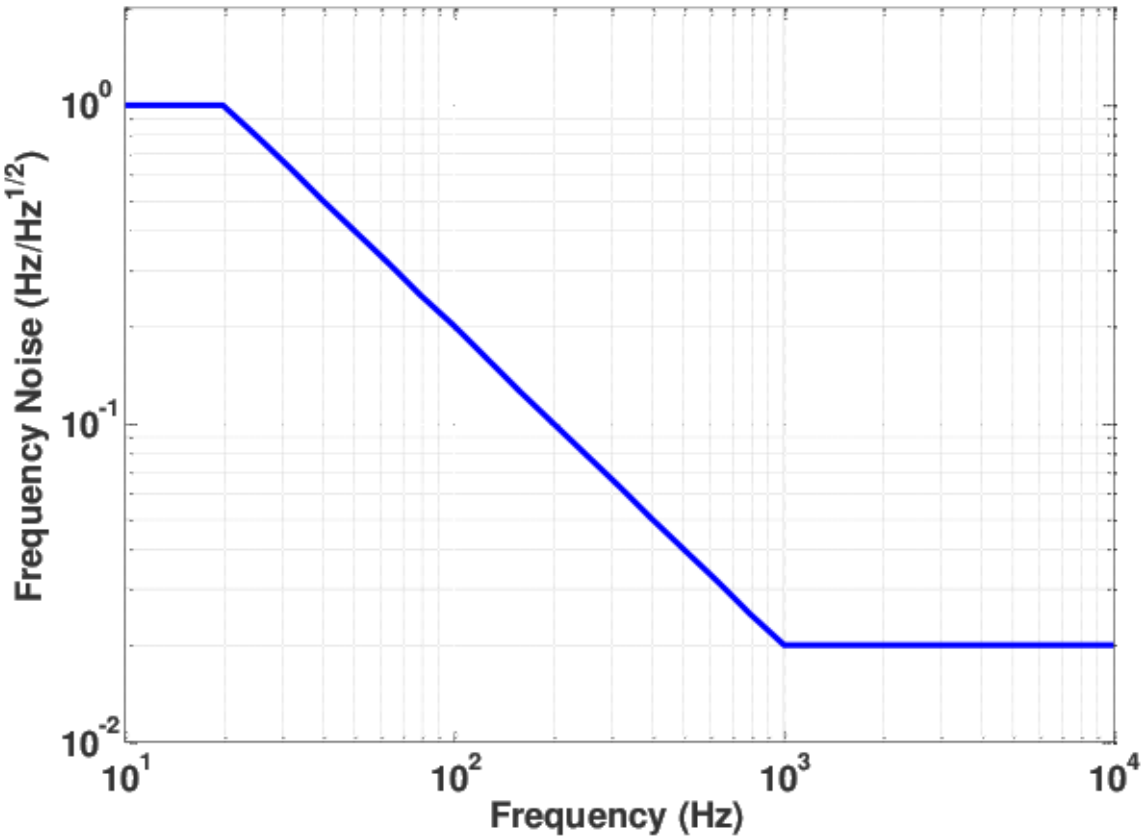


Outline

- Requirements and overview
- Beam shaping
- Intensity stabilization
- **Frequency stabilization**

Requirements

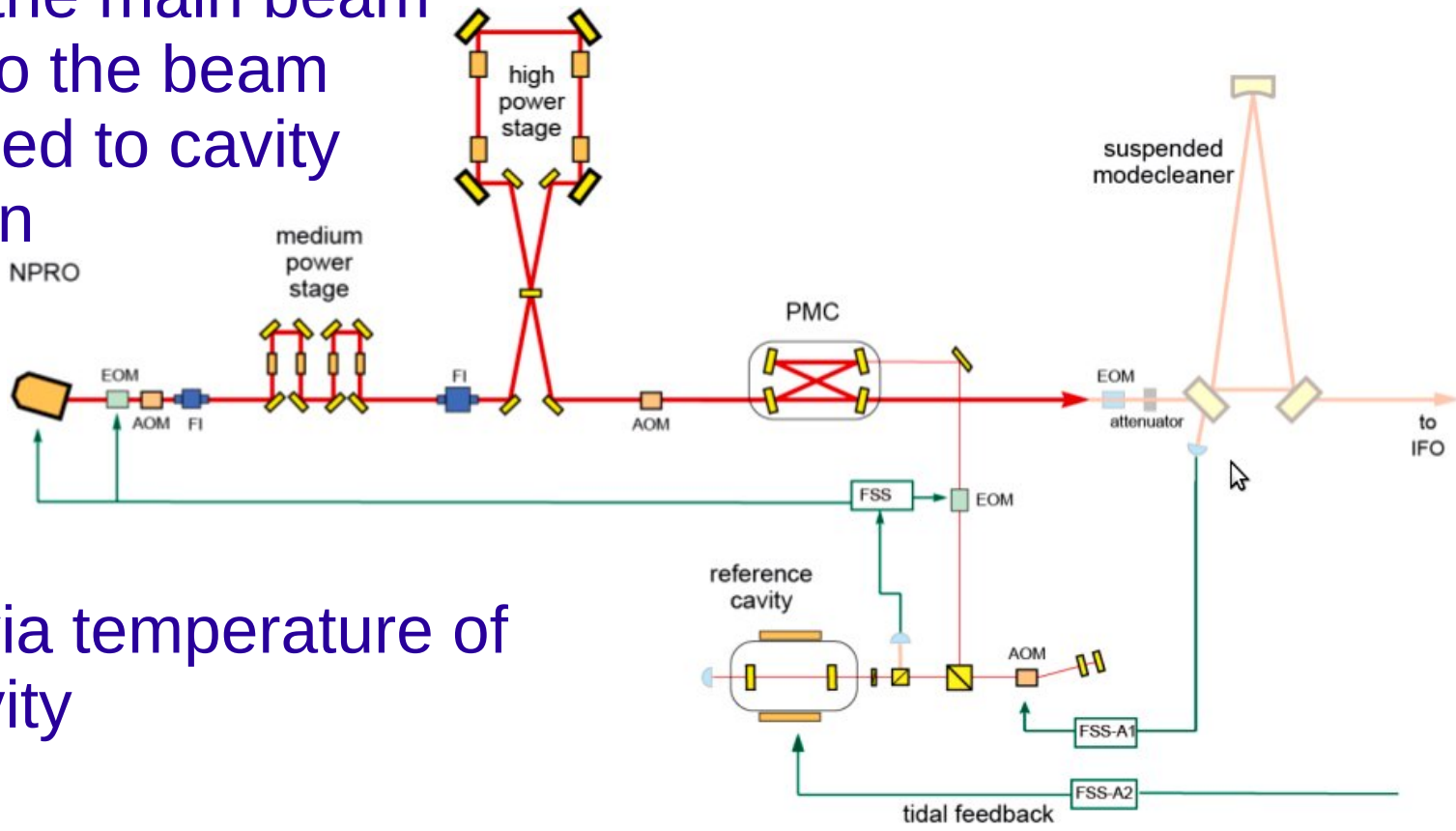
- Long term (>100 sec.):
  $(\Delta\nu/\nu)_{laser} << (\Delta L/L)_{tidal}$
  → *ν stable within 500 kHz*
- Control band (0.1-10Hz):
  $(\Delta\nu/\nu)_{laser} << (\Delta L/L)_{seismic}$
  → *1-10 Hz: <3 Hz-rms*
  0.4-1Hz: <100 Hz-rms
  0.1-0.4Hz: <1000 Hz-rms
- GW band (10 Hz-10 kHz):
  → see figure



Frequency stabilization scheme

- Nested loops utilizing the increasing frequency sensitivity of three Fabry-Perot cavities:
  - **PSL reference cavity**
  - IO mode-cleaner
  - Interferometer's long arm cavities
- Actuators for PSL frequency stabilization:
  - NPRO temperature (slow)
  - NPRO PZT (fast)
  - Phase control via EOM (high-speed)

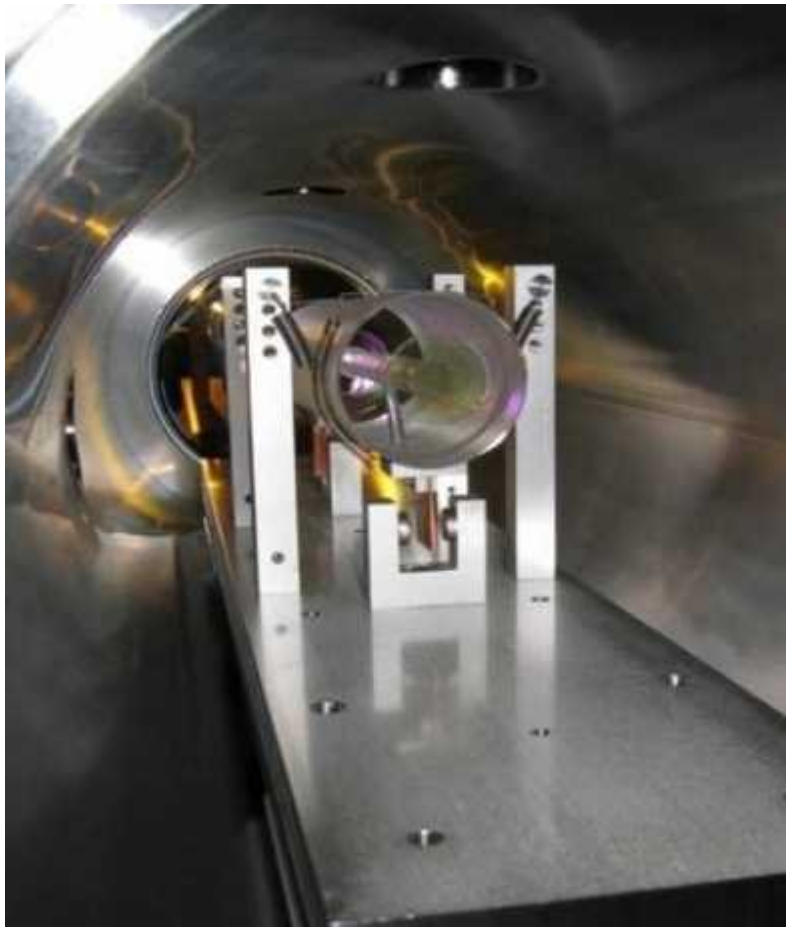
- Double-pass AOM changes frequency of the main beam with respect to the beam that is stabilized to cavity
  → stabilization to sus-pended MC



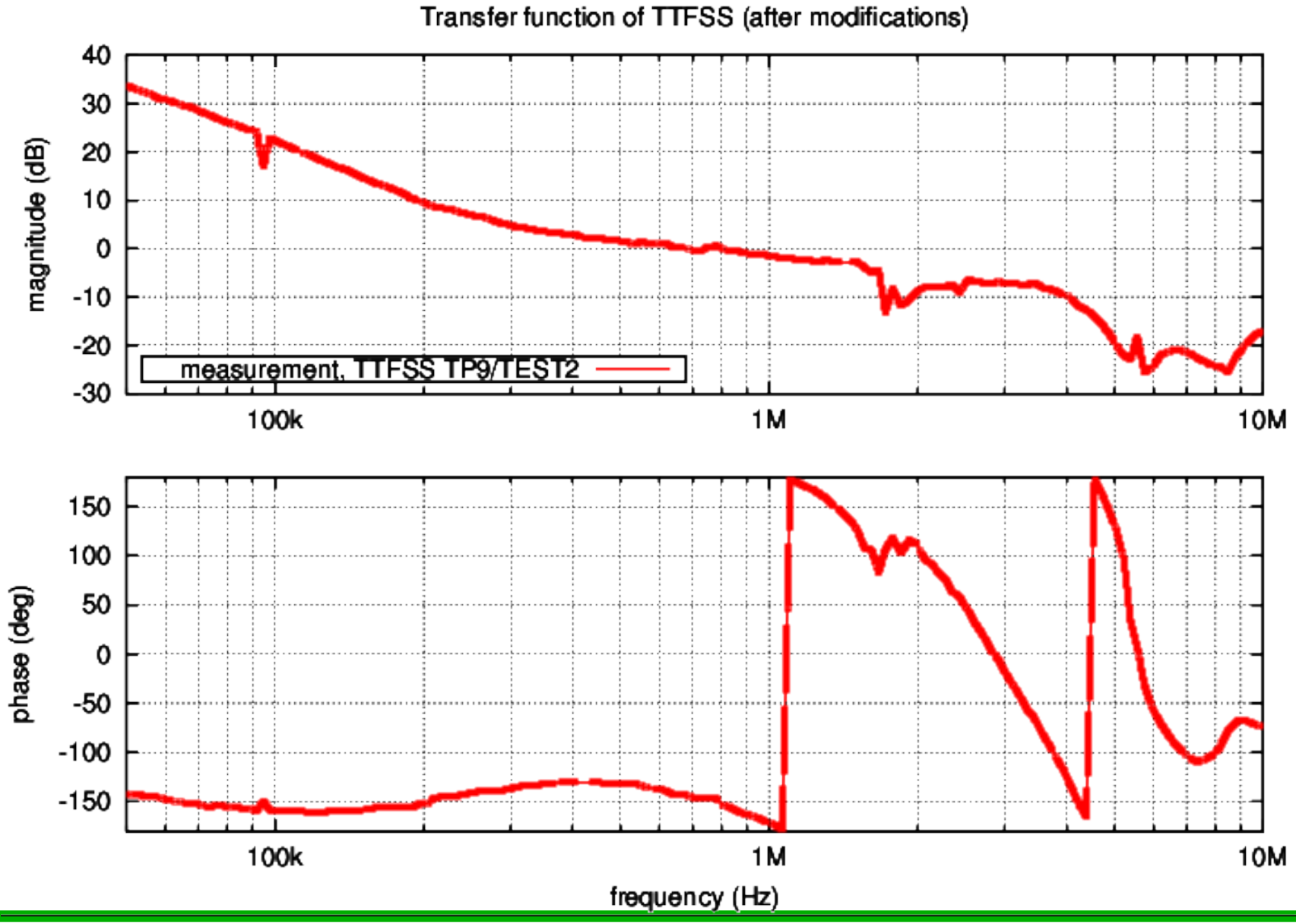
- Long term stabilization via temperature of reference cavity
- In general: Pound-Drever-Hall scheme

Reference cavity

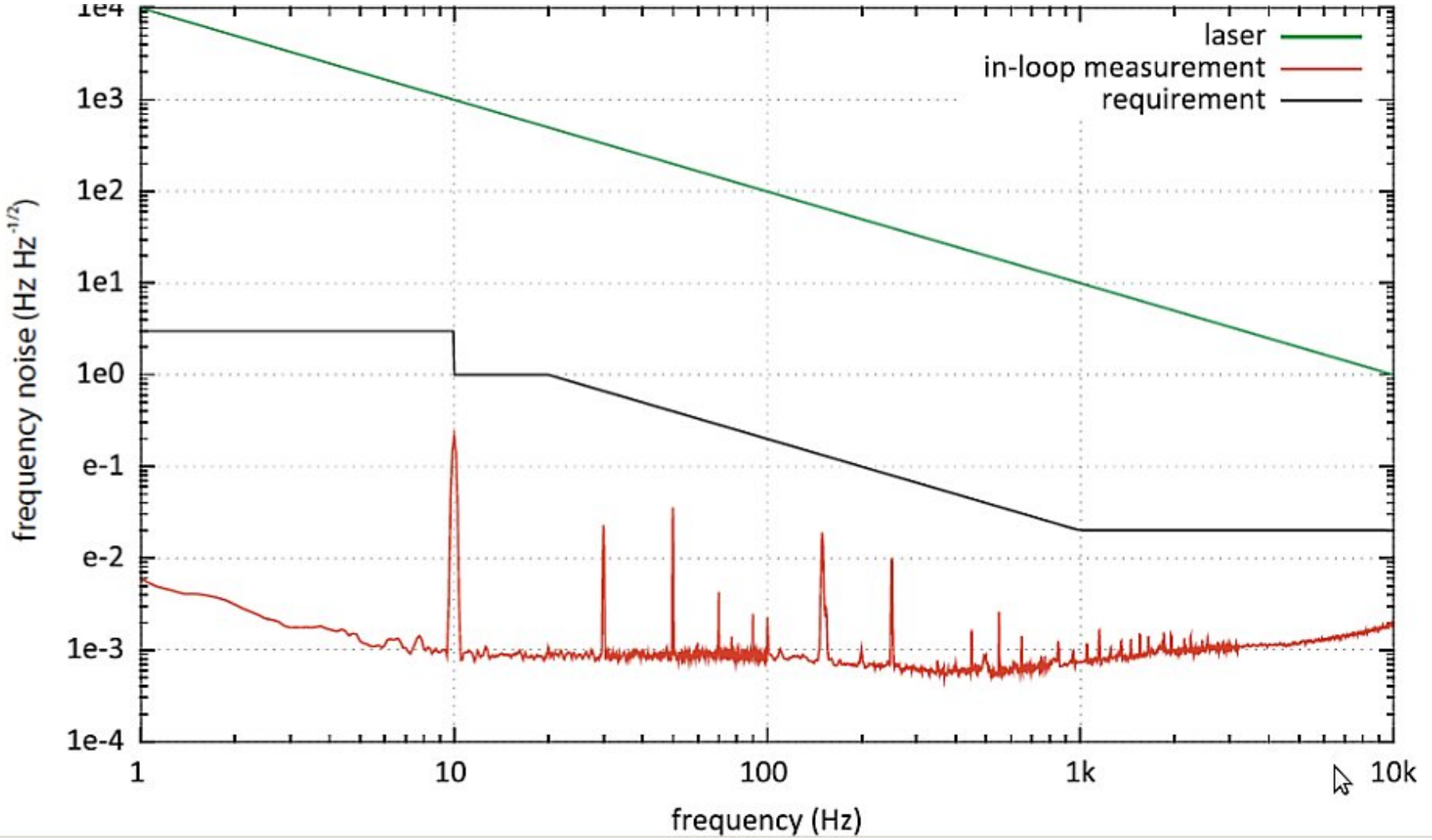
- Thermally, seismic isolated fused silica reference cavity
  - Length: 203 mm
  - Finesse: ≈ 10,000
  - FSR: 736 MHz
  - FWHM: 77.4 kHz
- Feedback to EOM phase corrector, NPRO PZT, NPRO temperature
- Need compensation of PMC pole @ 575 kHz



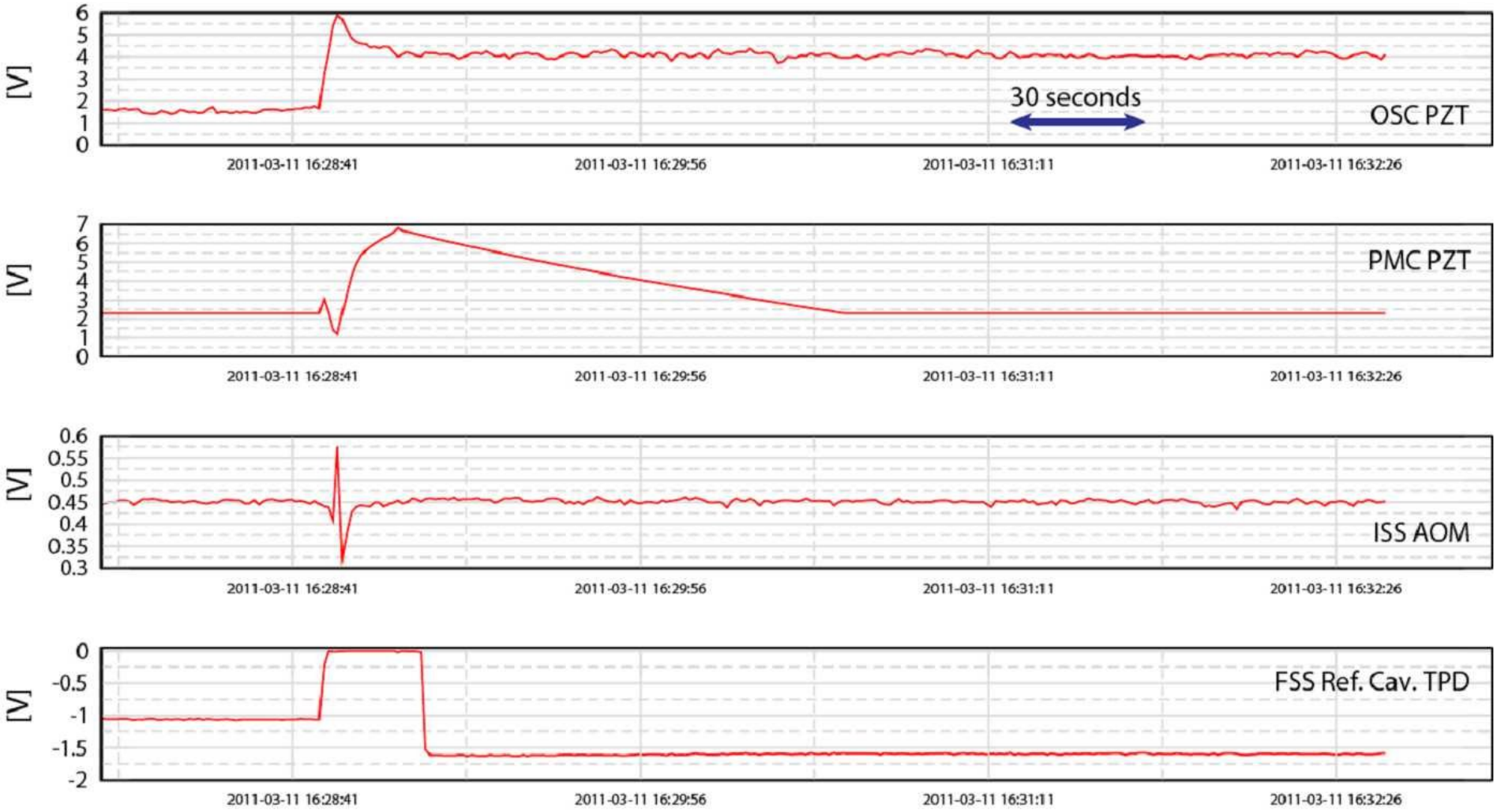
Frequency stabilization



In loop frequency noise



Overall PSL lock aquesition



Acknowledgment

Data and pictures taken from:

(former) LZH researchers: Oliver Puncken, Marcin Damjanic, Maik Frede, Raphael Kluzik, Dietmar Kracht, Bastian Schulz, Christian Veltkamp, Peter Weßels, Ralf Wilhelm, Lutz Winkelmann et al.

(former) AEI researchers: Christina Bogan, Patrick Kwee, Jan Pöld, Frank Seifert, Benno Willke et al.

LIGO Document Control Center (DCC)

Thanks!