# The advanced LIGO pre-stabilized laser (PSL)

Oliver Puncken

# Outline

- Requirements for the advanced LIGO PSL
- Laser concept
- Mode selection in high power lasers
  - Transverse mode selection
    - Pump concepts
    - Apertures
    - Geometric aspects
  - Longitudinal mode selection
    - Concepts
    - Pound Drever Hall locking

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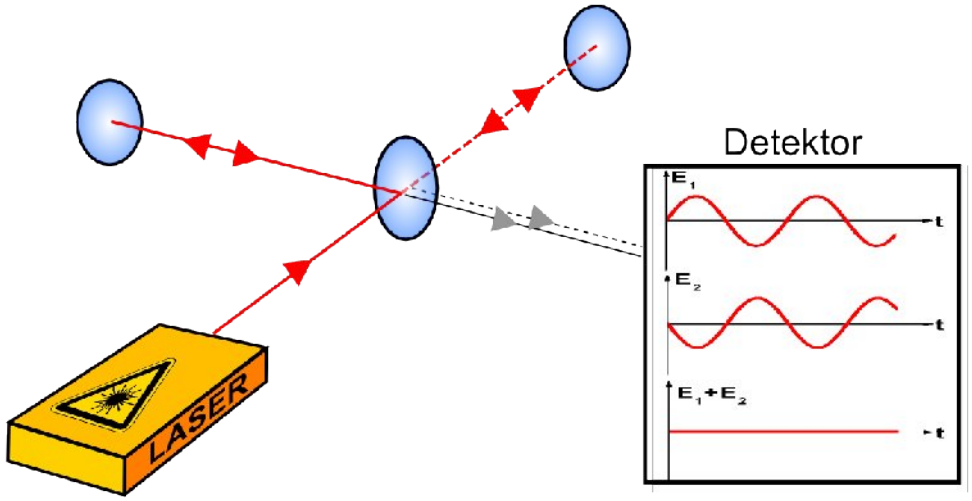
# Motivation: Detection of GWs

- General Relativity:
  A binary system of stars looses energy to gravitational radiation
- The amplitude of gravitational waves is rather weak ($\approx 10^{-21}$)
  → interferometric detection
- Task:
  - Effective coupling of light into high finesse interferometer
  - Reduction of noise



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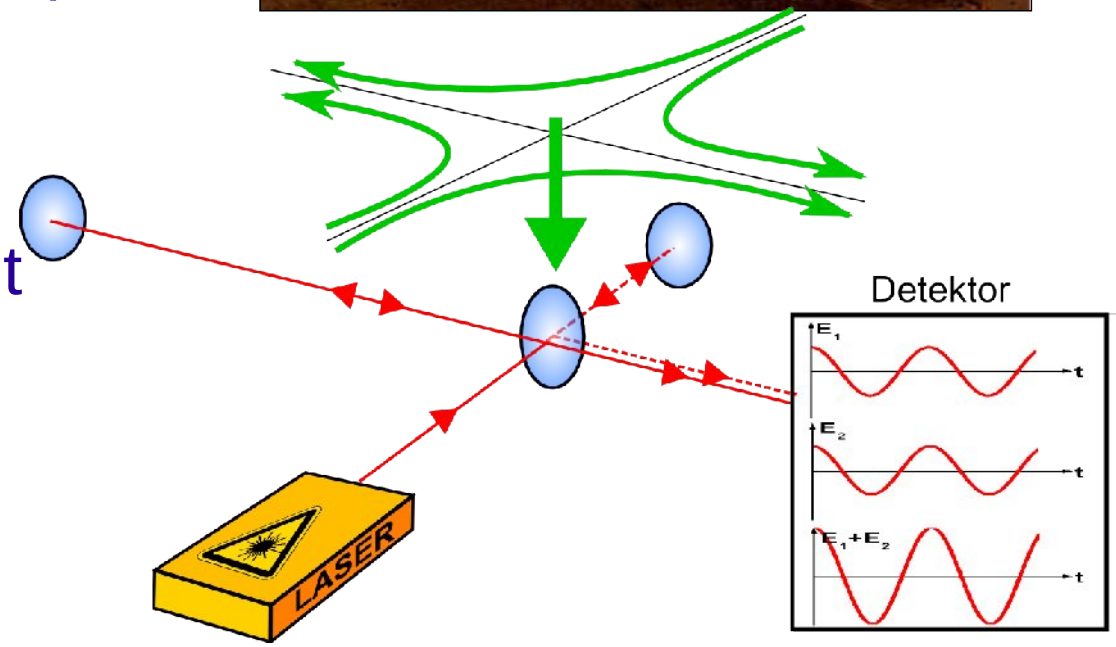

# Requirements for the PSL

- Output power: 180 W
- Single mode operation
- Linearly polarized output
- Frequency stability: 10 Hz / $Hz^{-1/2}$ @ 10 Hz at PSL and $10^{-7}$ Hz / $Hz^{-1/2}$ @ 10 Hz at the interferometer
- Amplitude stability: $2 \cdot 10^{-9}$ / $Hz^{-1/2}$ @ 10 Hz
- High reliability
- Easy maintenance

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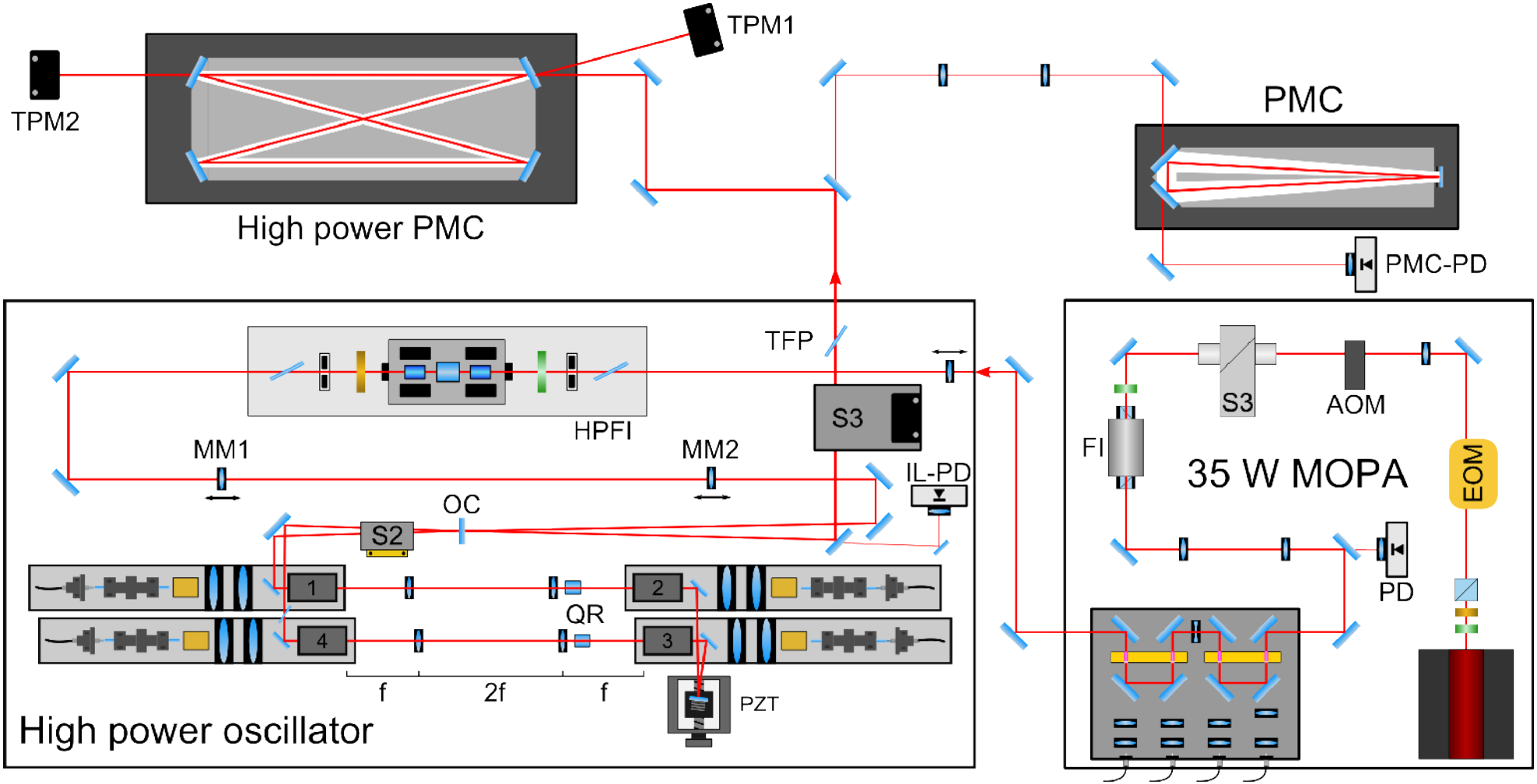
# Laser overview



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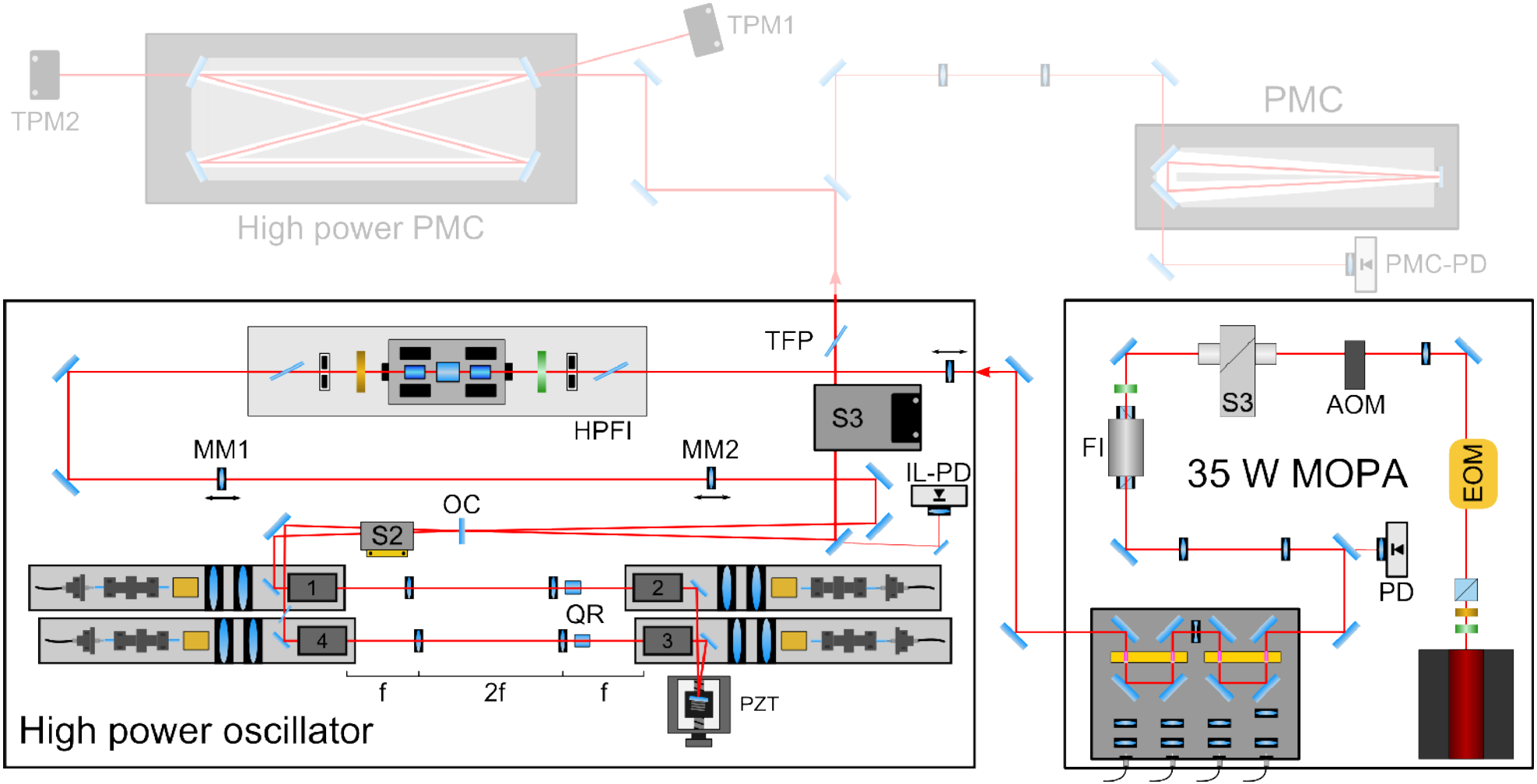

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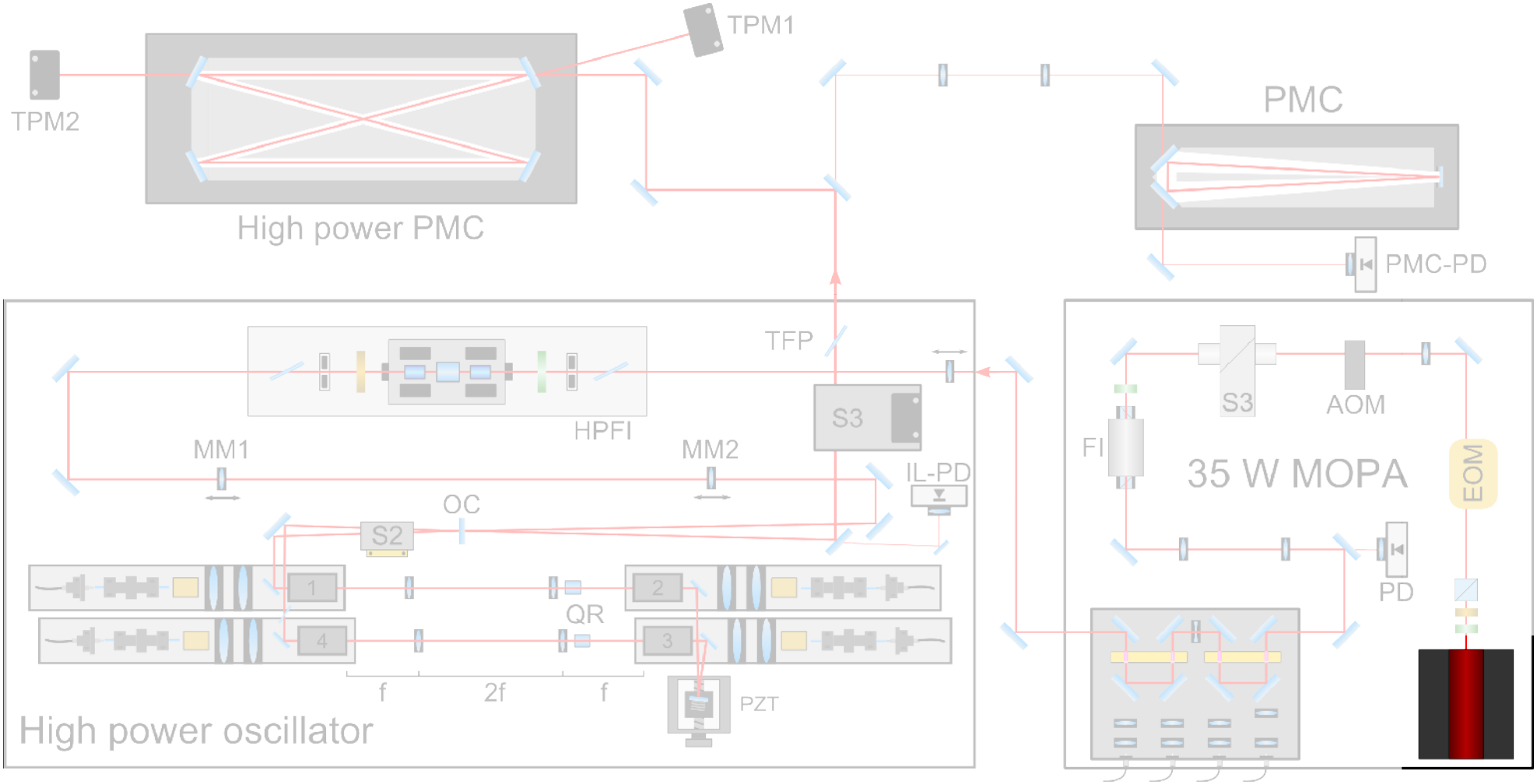
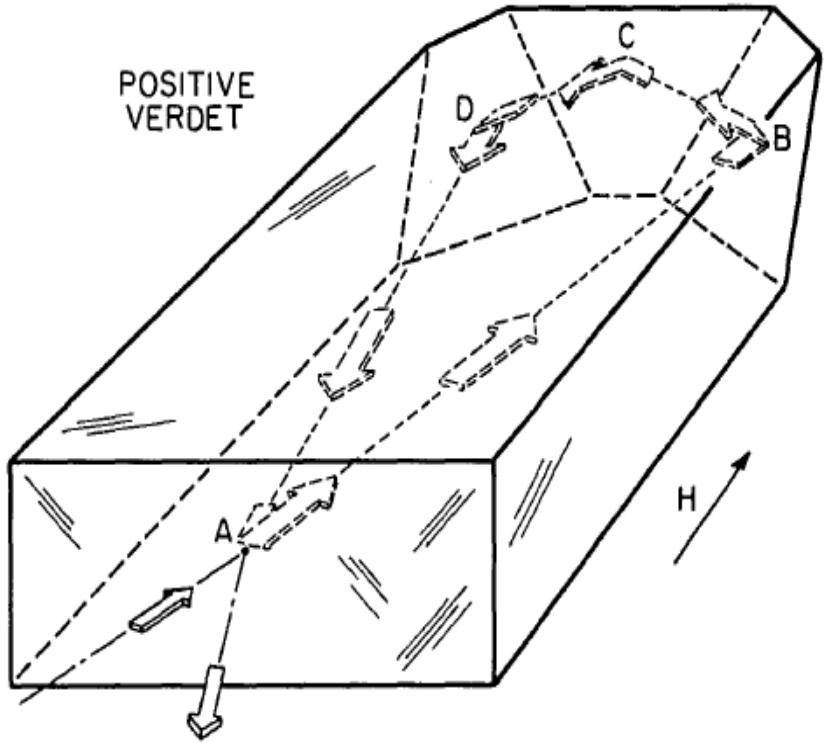
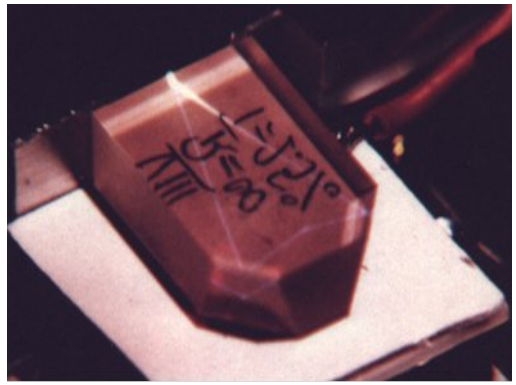


# Non planar ring oscillator (NPRO)

- Monolitic ring laser with short resonator
- Unidirectional by polarization rotation in combination with magnetic field
- Characteristics:
  - Nd:YAG laser (1064 nm)
  - Single transverse mode
  - Single frequency (1 kHz linewidth)
  - Low power noise
  - Linearly polarized
  - Output power: 2 W

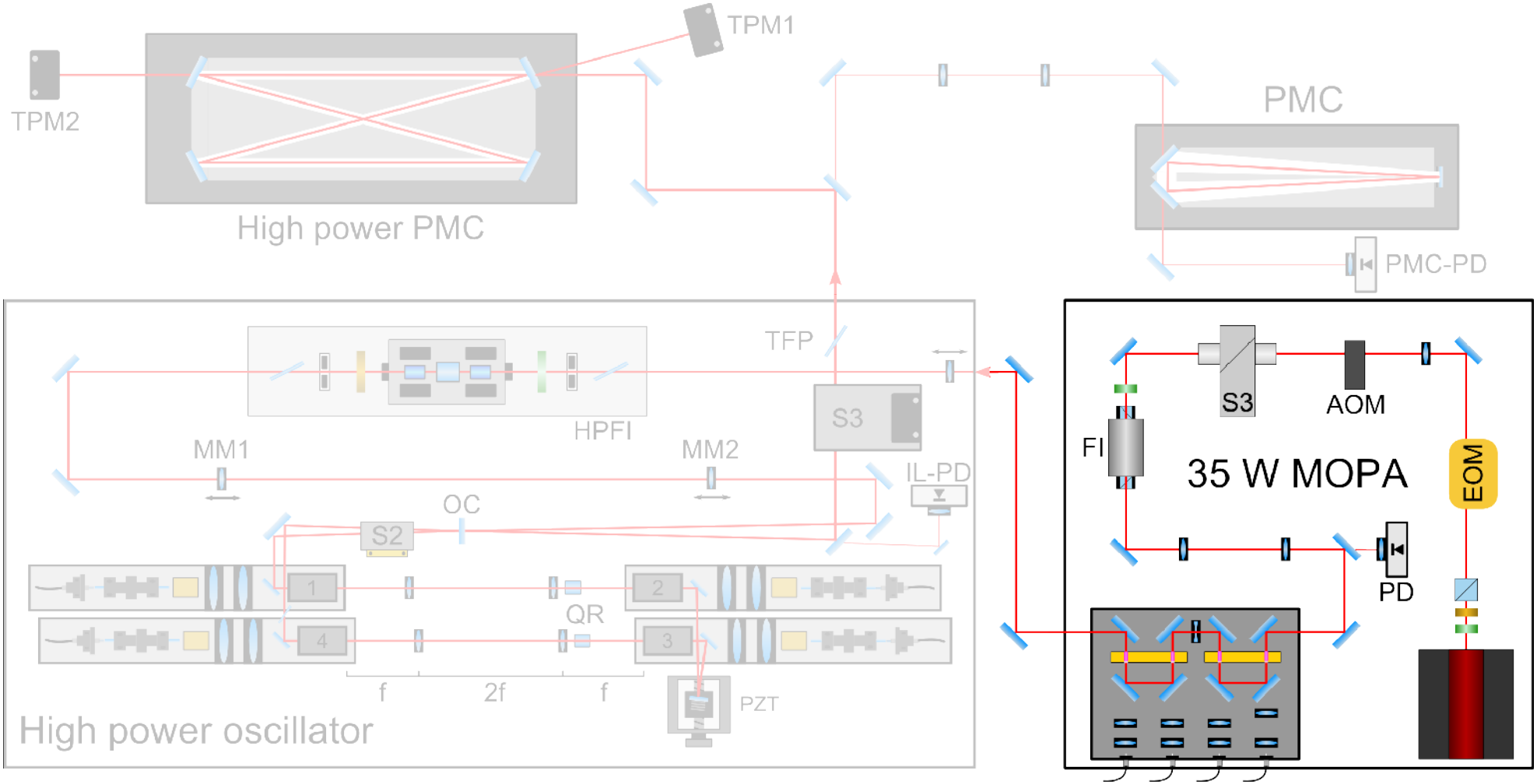




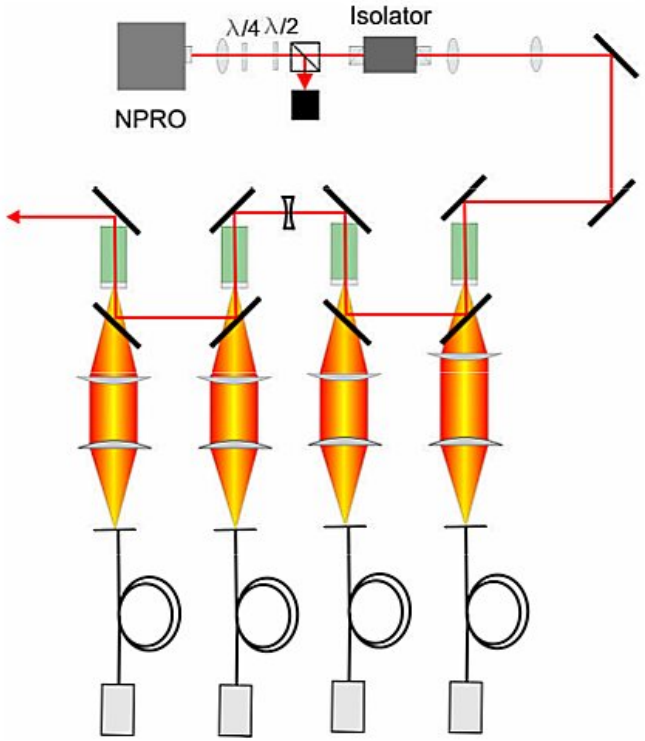
Picture: T. J. Kane, R. L. Beyer: Optics Letters 10, S. 65, 1985

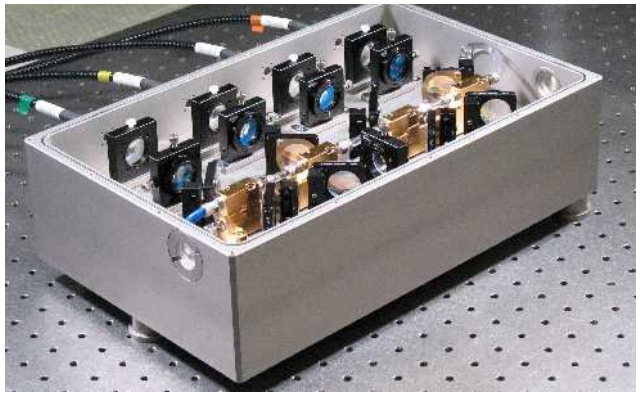
# Laser overview



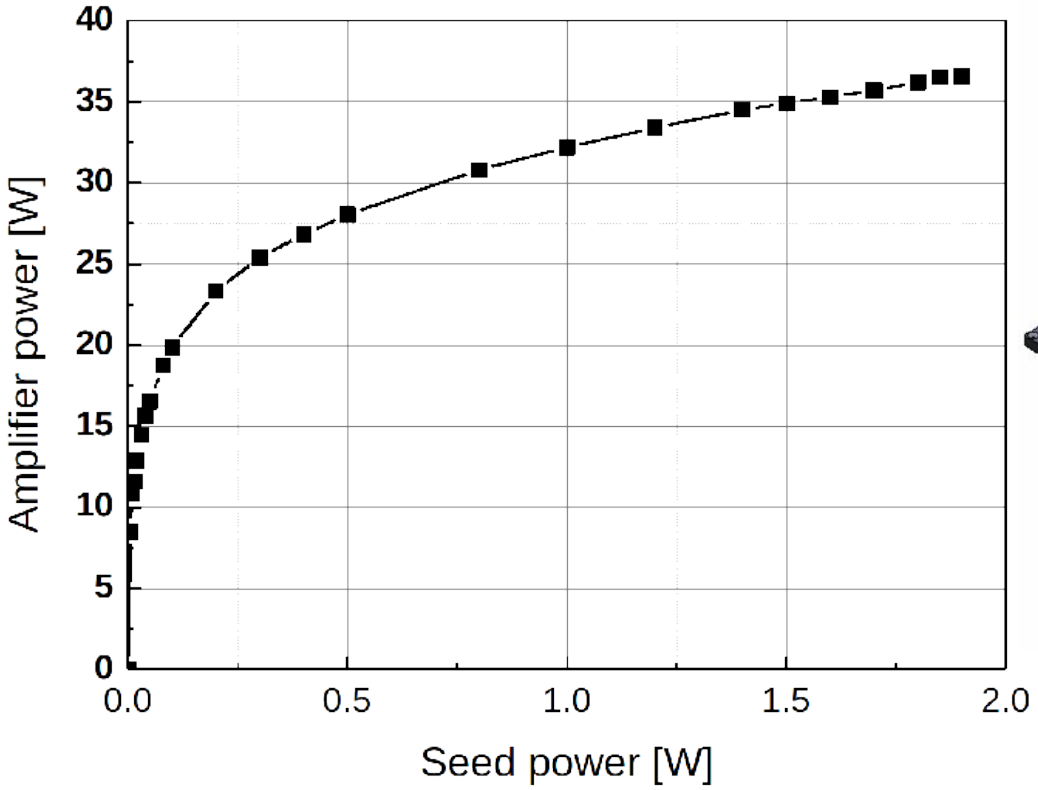
# Amplifier

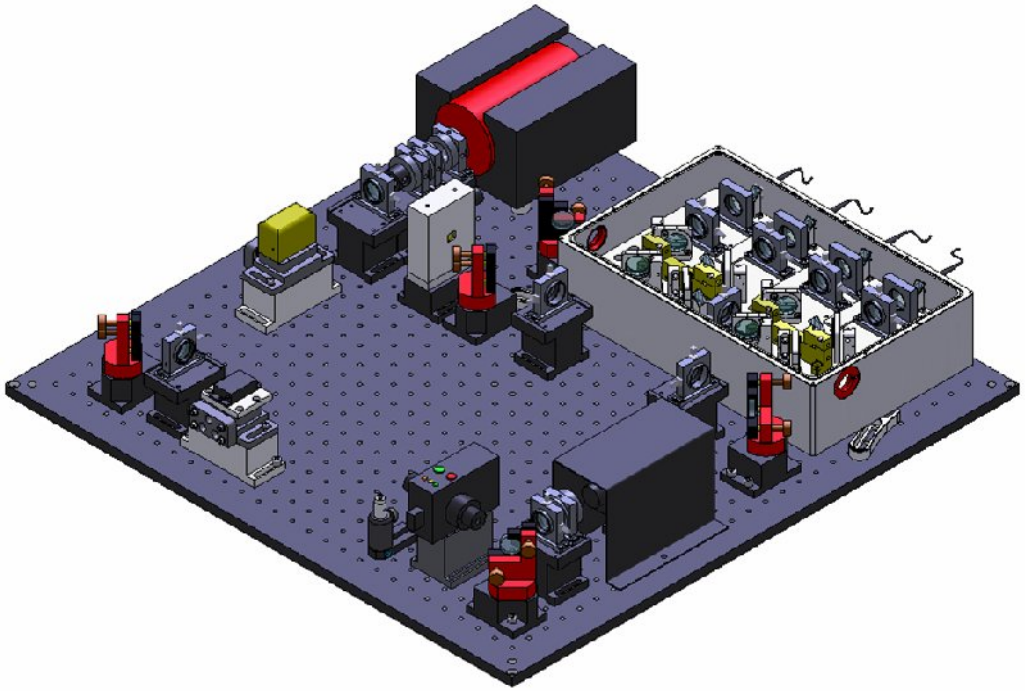
- 4-stage Neodymium Vanadate Amplifier
  - 40 W pump power per stage
  - 35 W output power
  - Gain medium:
    - 3x3x10mm Nd:$YVO_4$
    - 8 mm 0.3 at.% doped, 2 mm undoped endcap
    - Naturally birefringent → linearly polarized output



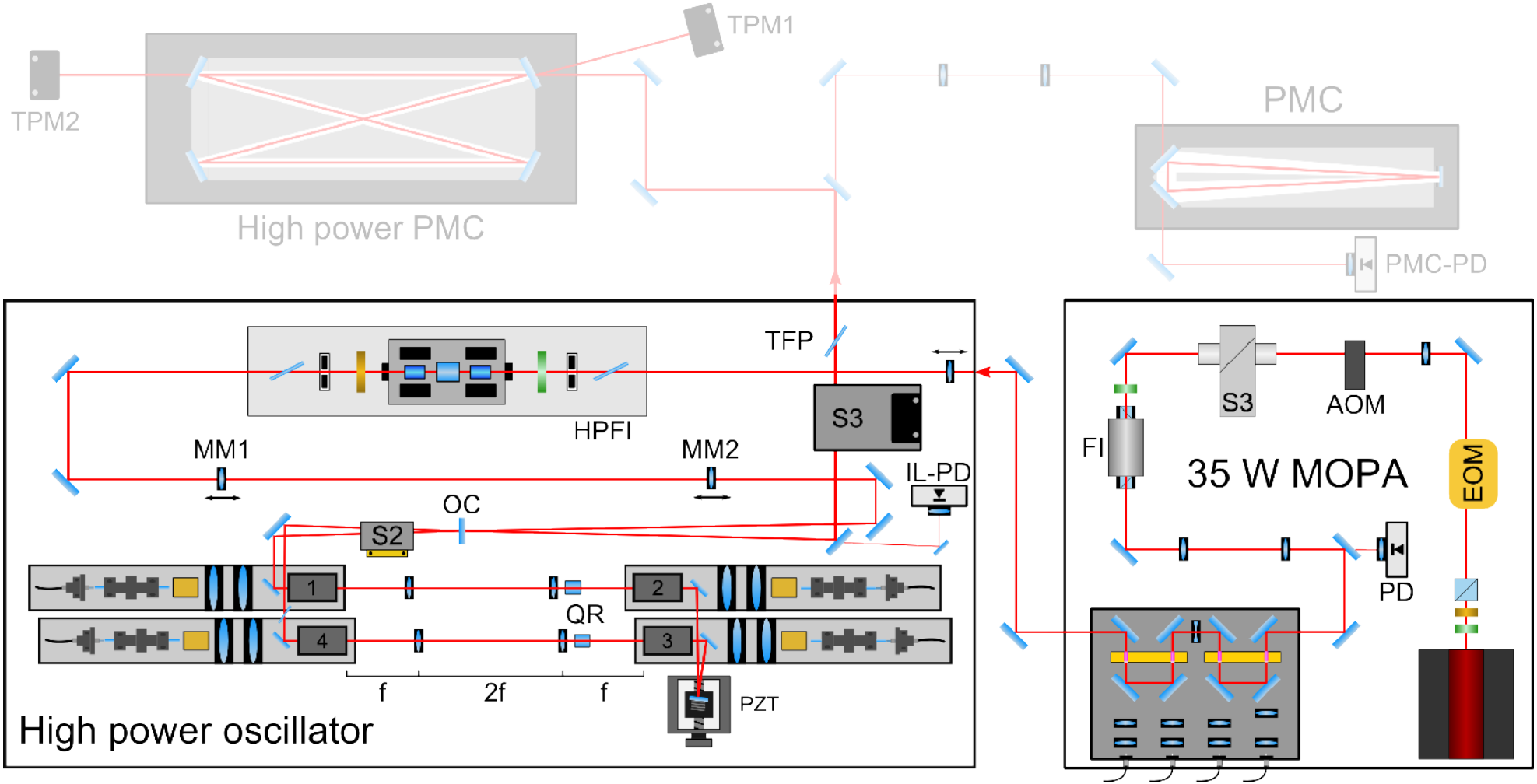
# Frontend (35 W eLIGO laser)



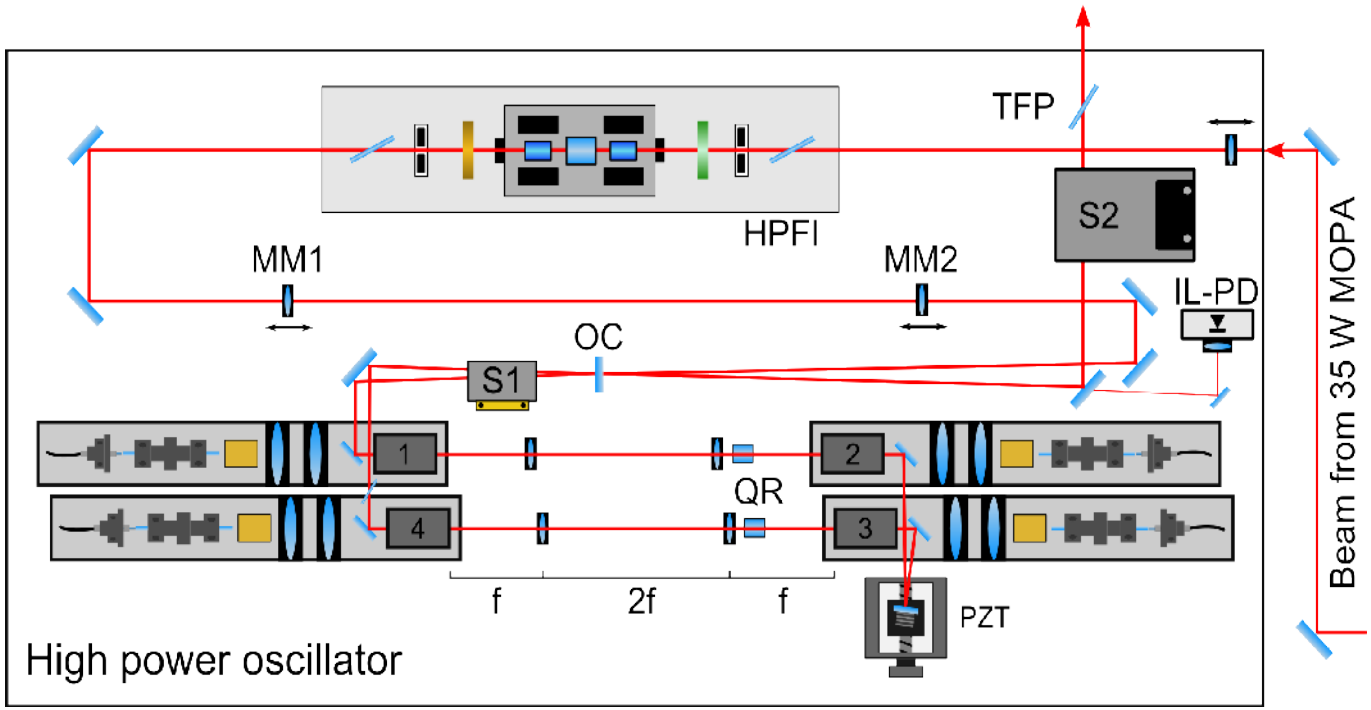



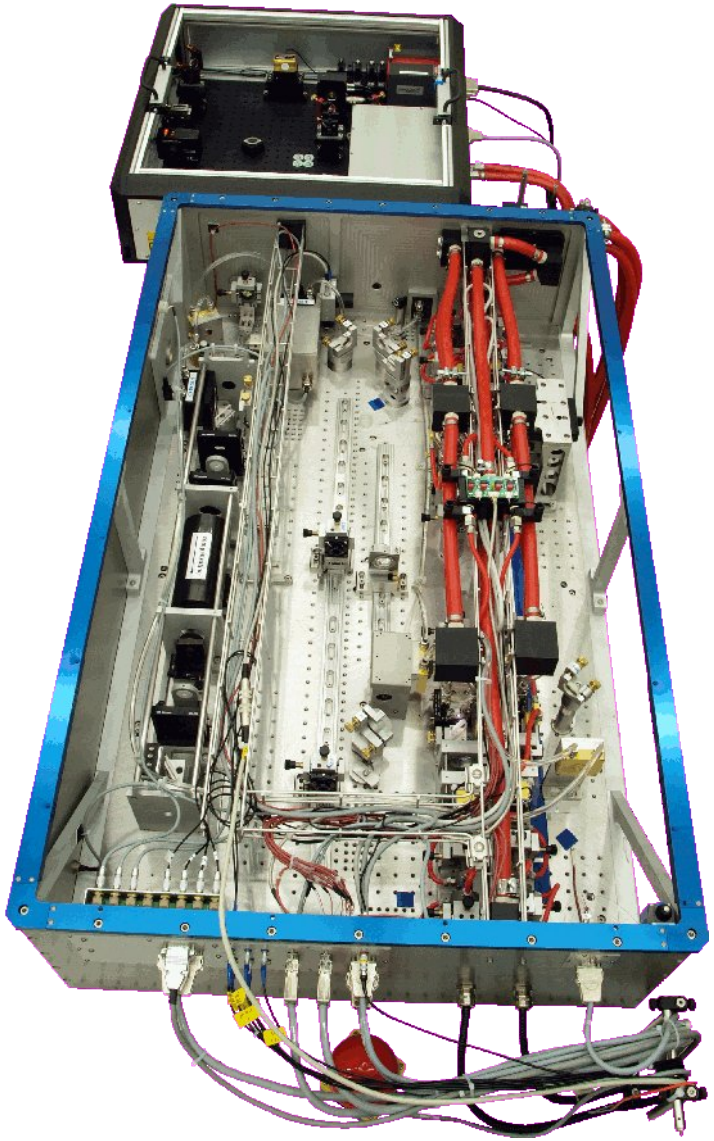
neoLASE

# Laser overview



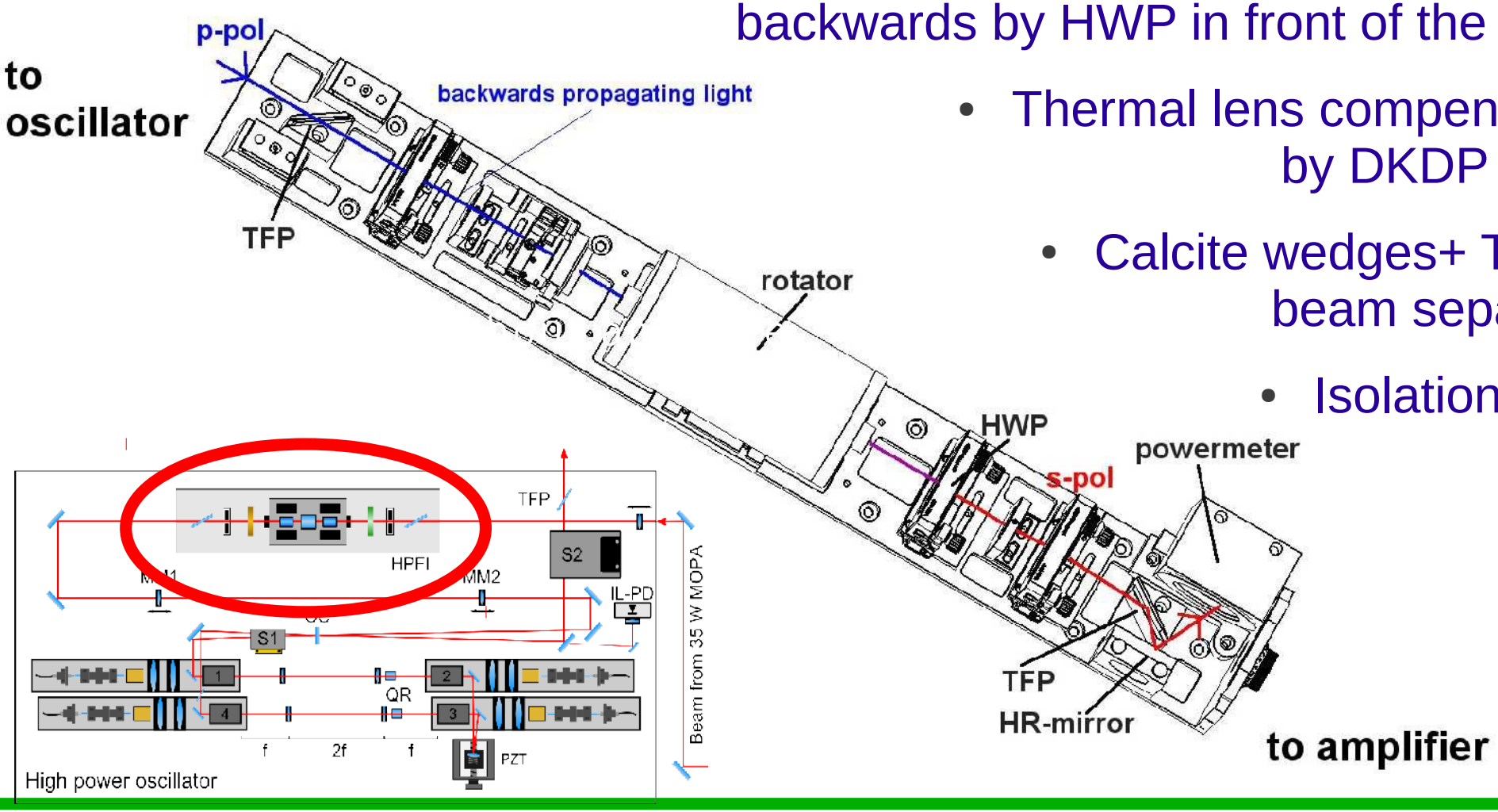
# High power oscillator



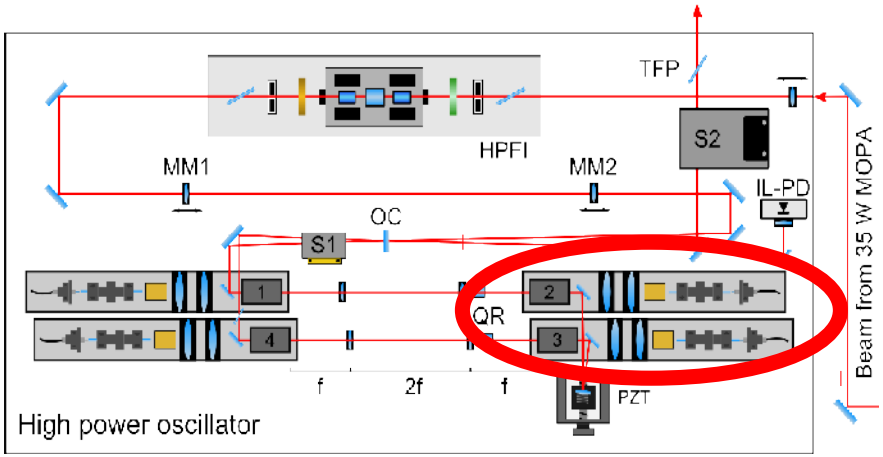



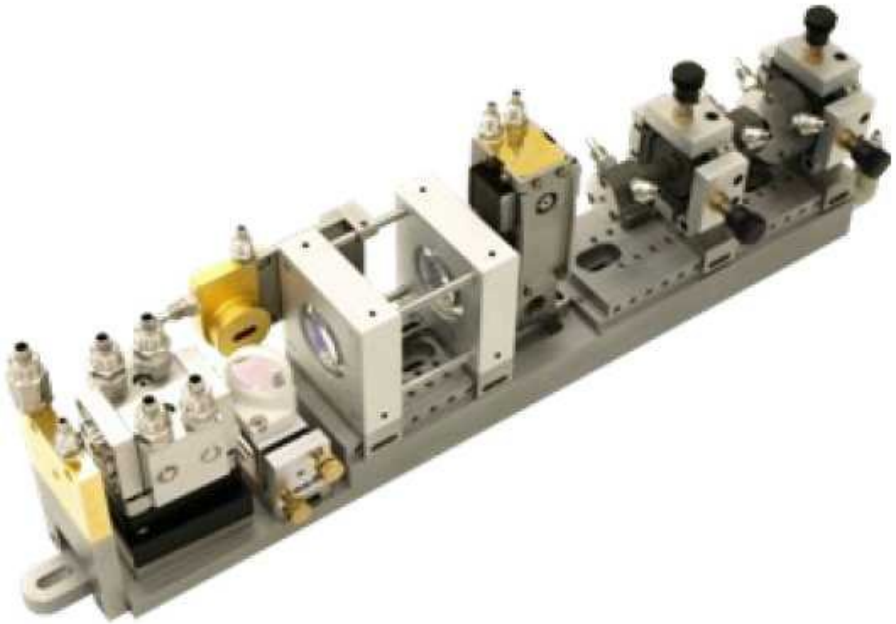
# High power Faraday isolator

- 67° quartz rotator between two 22.5° TGG crystals
- Polarization rotation of 180° forward and 90° backwards by HWP in front of the rotator
- Thermal lens compensation by DKDP crystal
- Calcite wedges+ TFP for beam separation
- Isolation: 35dB



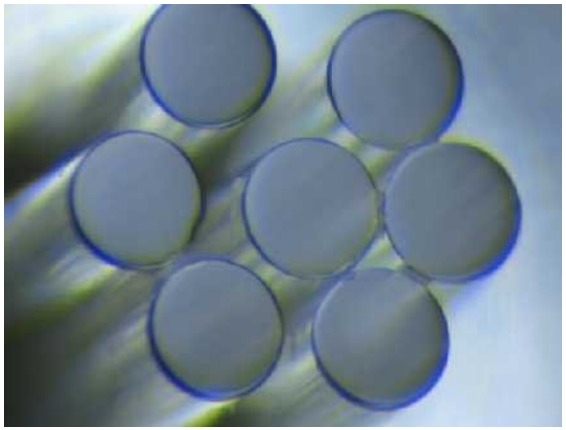
# Pump heads



- Components of the pump heads:
  - Fiber bundle tip and mount
  - Homogenizer
  - Pump light diagnostics
  - Pump optics
  - Dichroic mirror
  - Laser crystal in pump chamber

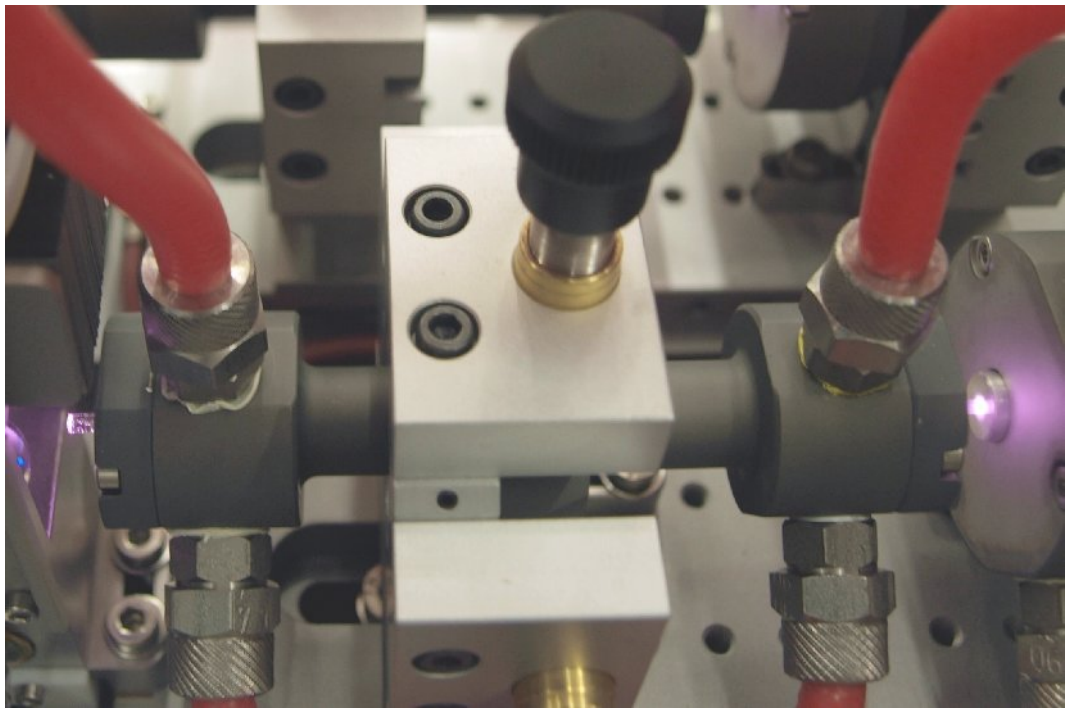
# Pump light source



- Requirements:
  - 250 W pump power (optical-optical efficiency of 20 %, 50 W output power per crystal)
- Diode box and fiber bundle
  - 4x7x Jenoptik diode laser
  - 808 nm  @ 25 °C
  - FWHM < 3 nm
  - Fiber: 7 x 400 µm in densest packing of cylinders
  - Homogenizer

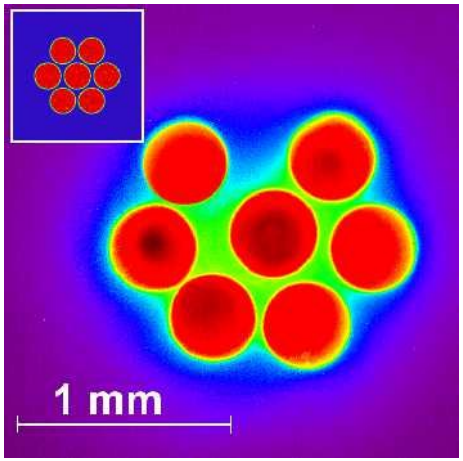
# Pump light source

- Homogenizer:
  - Glass rod, guiding pump light by reflections at the barrel



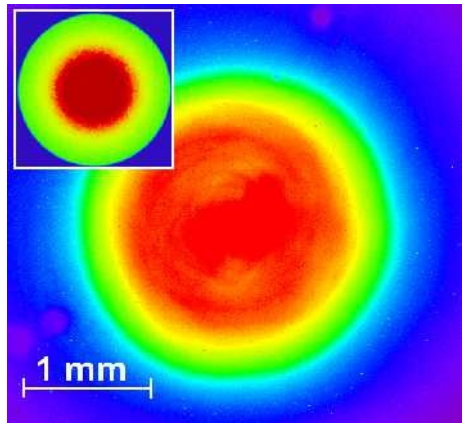
# Pump light source

- Homogenizer:
  - Glass rod, guiding pump light by reflections at the barrel
  - Prevent *hot spots* inside the crystal
  - → homogenized pump light spot



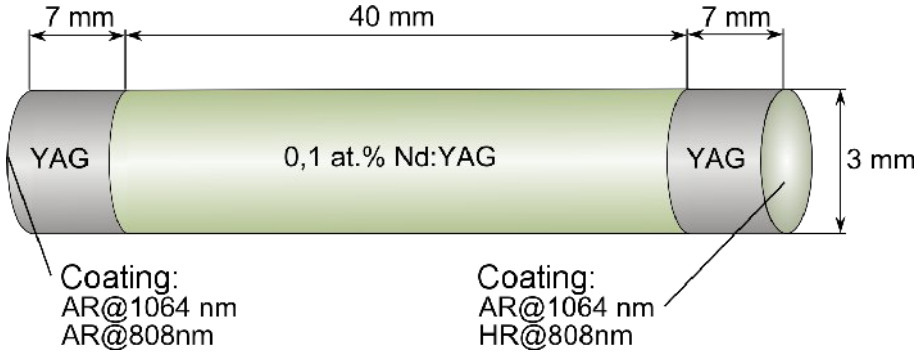

Radial intensity distribution at homogenizer entrance

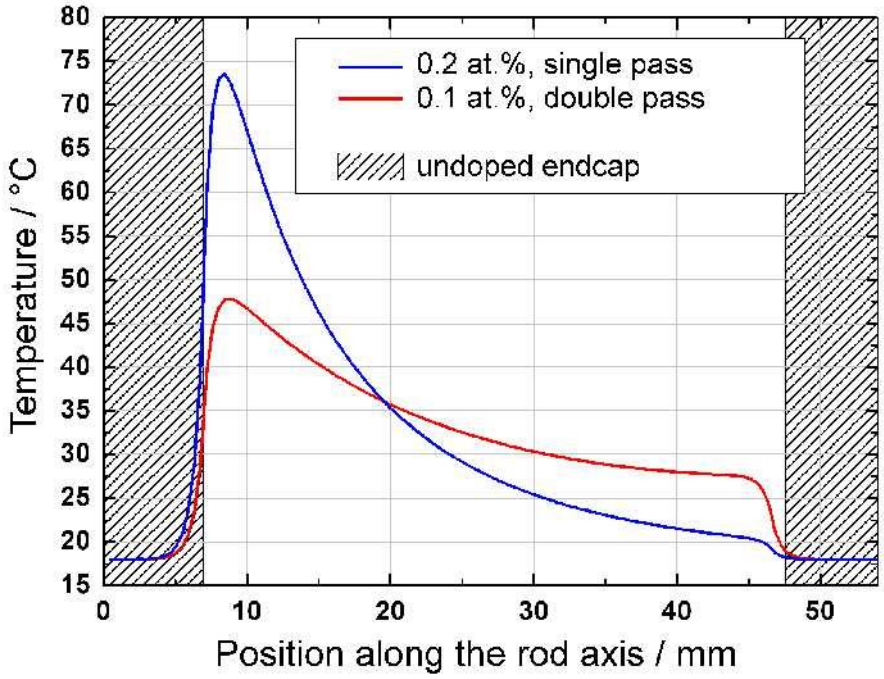
Radial intensity distribution at homogenizer exit



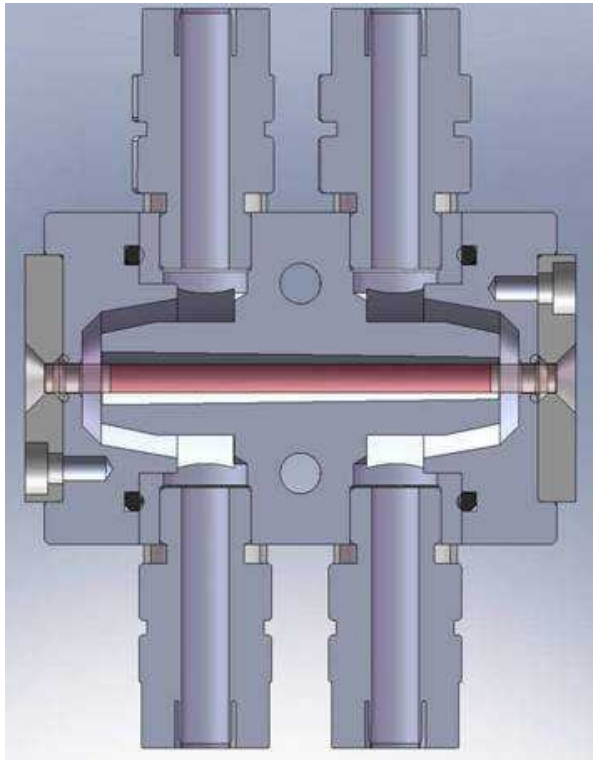
# Nd:YAG laser crystals

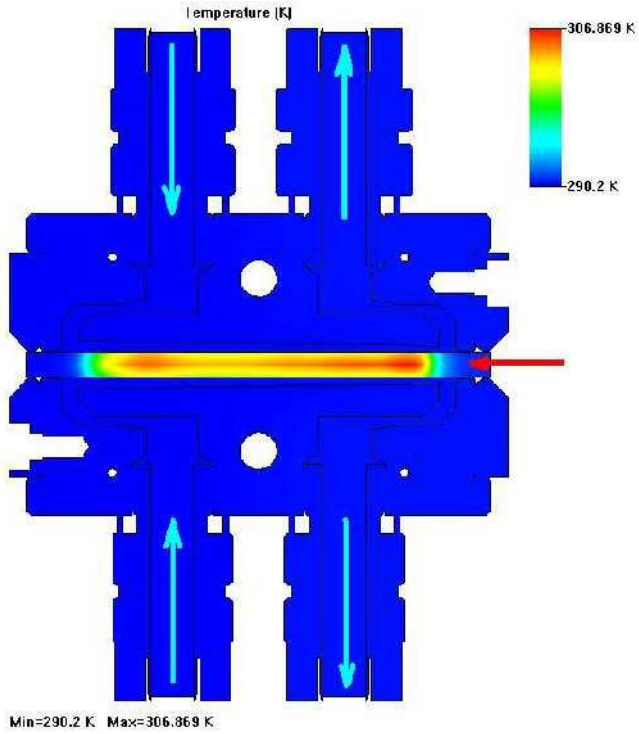
- 250 W pump power
- Heat fraction: 26 %
- Damage threshold: about 130 Mpa
- longitudinal temperature gradient as small as possible by pump light double-pass

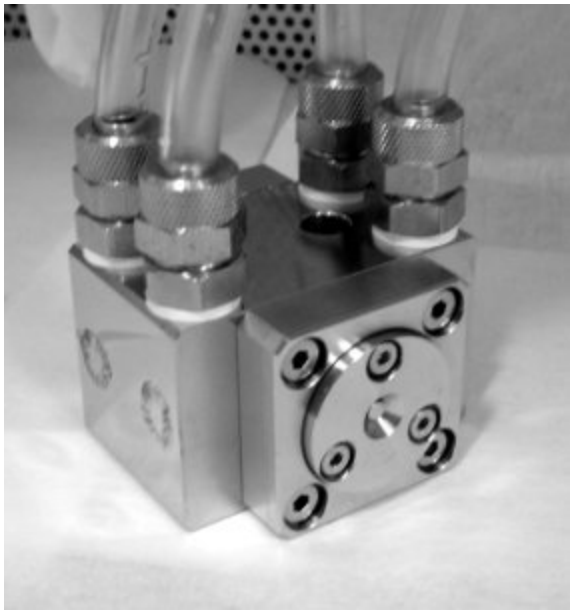


# Water cooled pump chambers

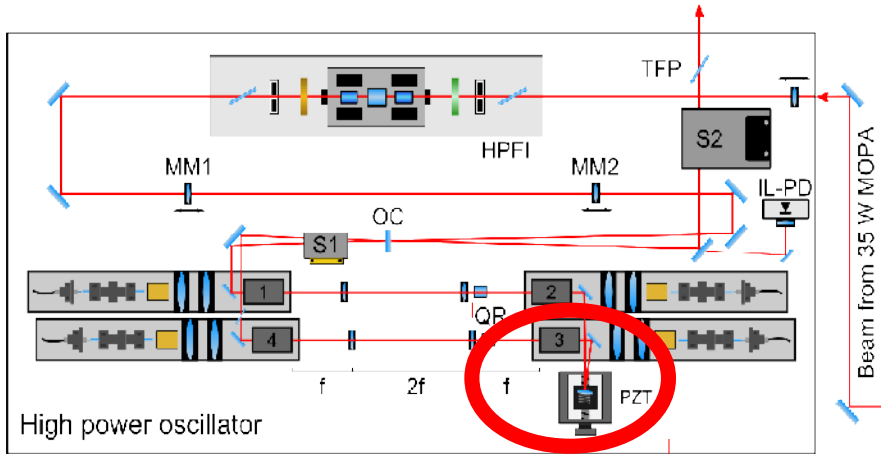




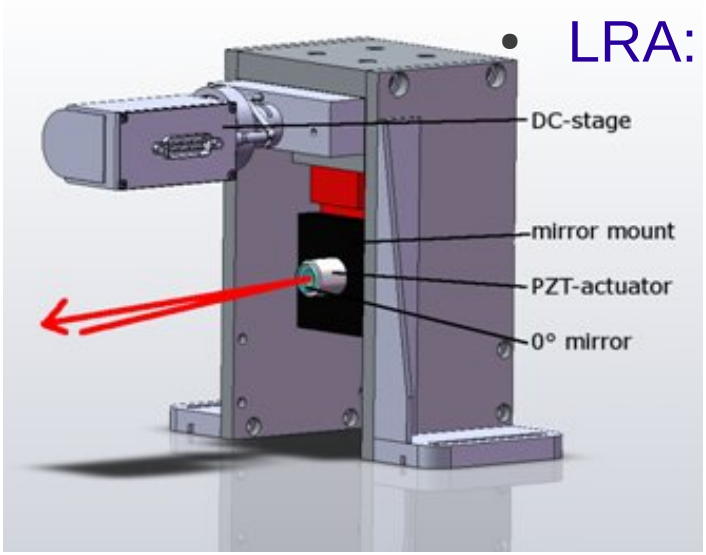



- Water flow from inlet does not directly hit the crystal
  → less acoustic noise
- Water flow as high as possible
- Turbulent water flow for optimal cooling

# Long range actuator

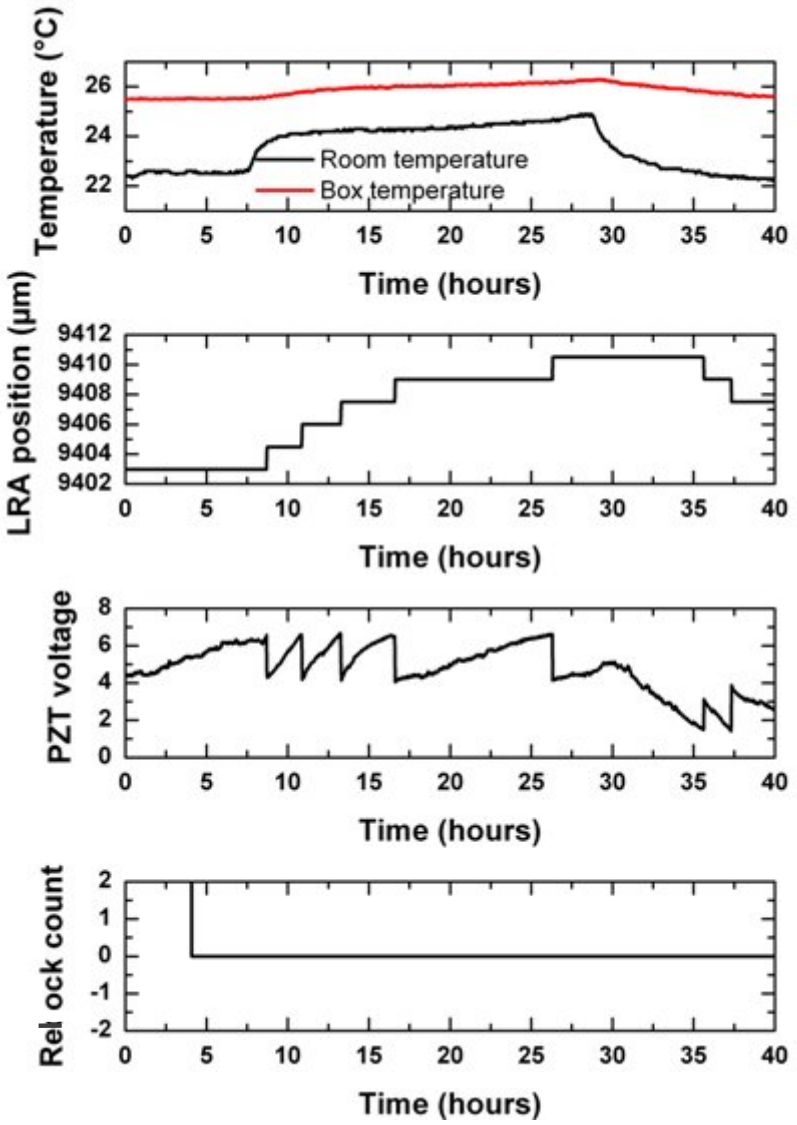



- Compensates for length drifts due to temperature fluctuations:
  - resonator length about 1.8 m
  - $\Delta T=3$ K $\rightarrow$ $\Delta L=54$ µm
  - Range of PZT alone: 5.5 µm
  - LRA: 25 mm in 100 nm steps



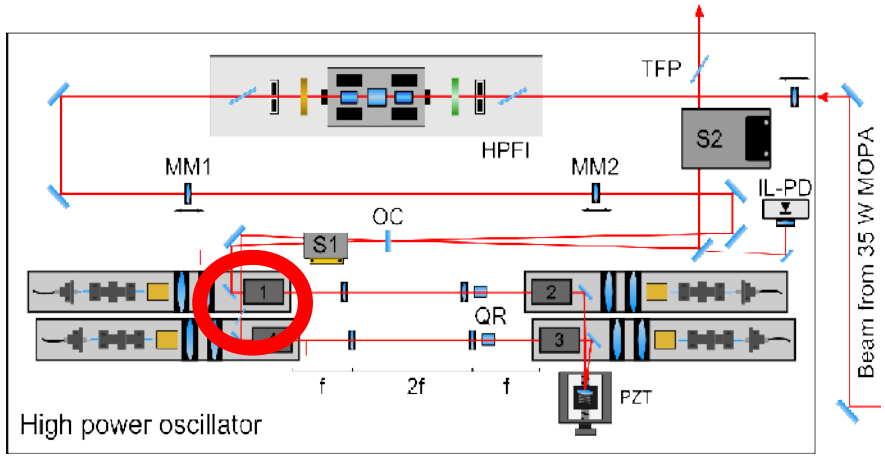

- Adjustment of resonator length during installation

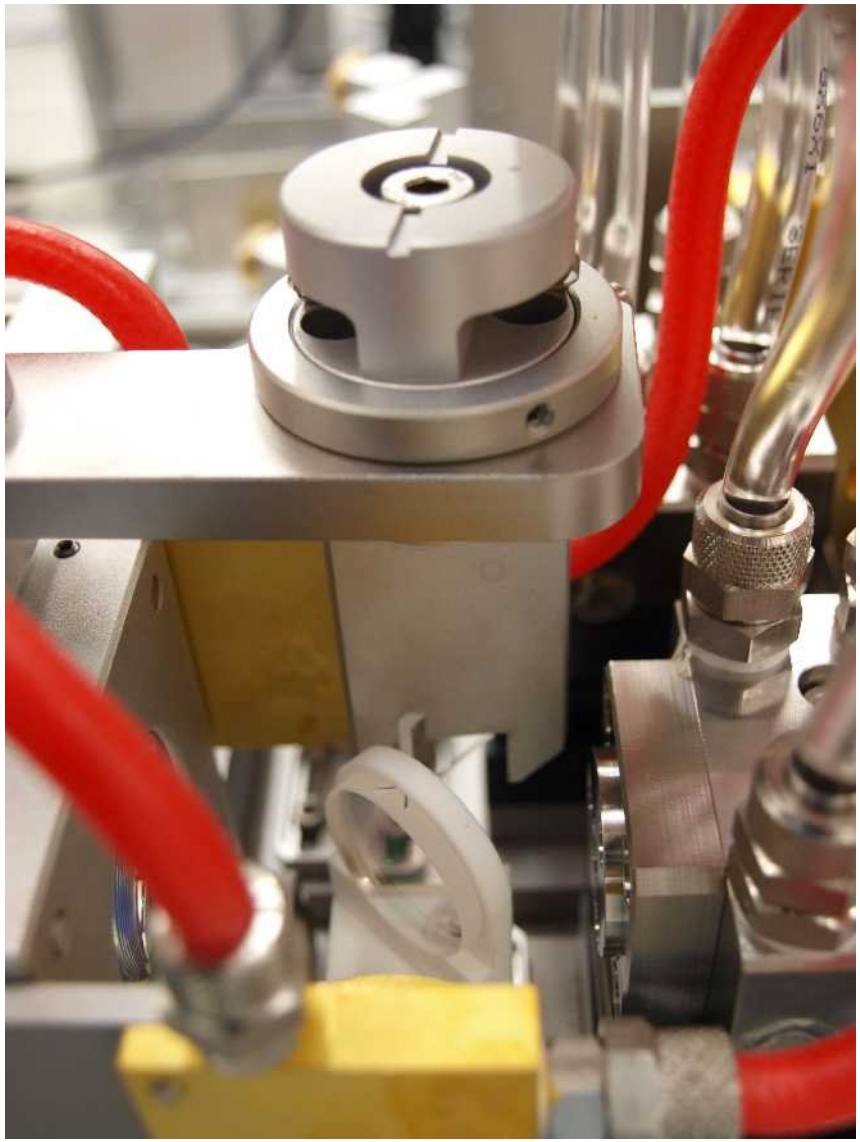
# Long range actuator




- LRA movement does not cause frequency disturbances
- Output power and beam quality can be held at constant levels

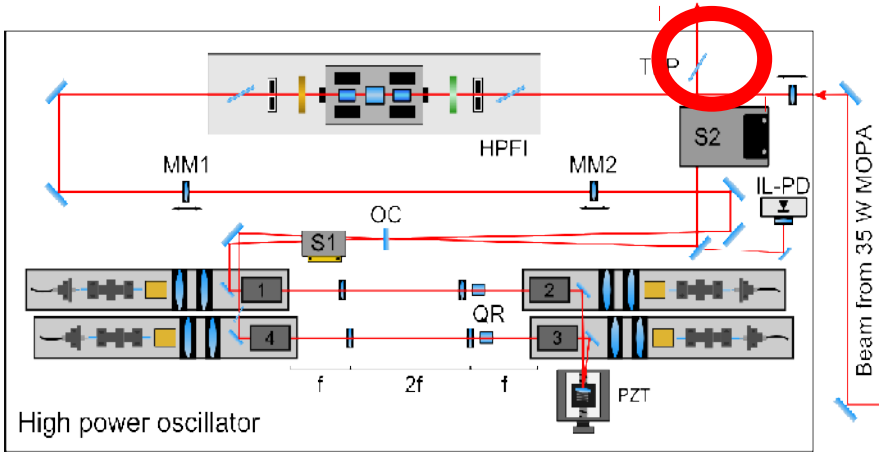
# Brewster plate

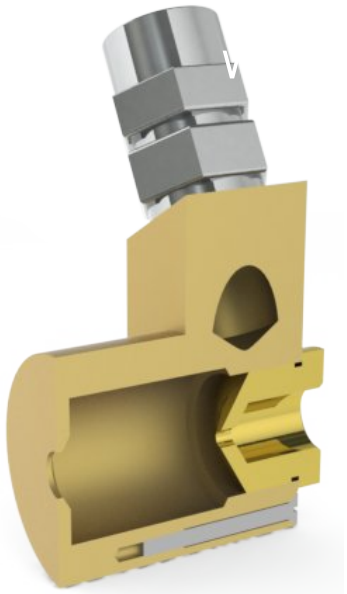


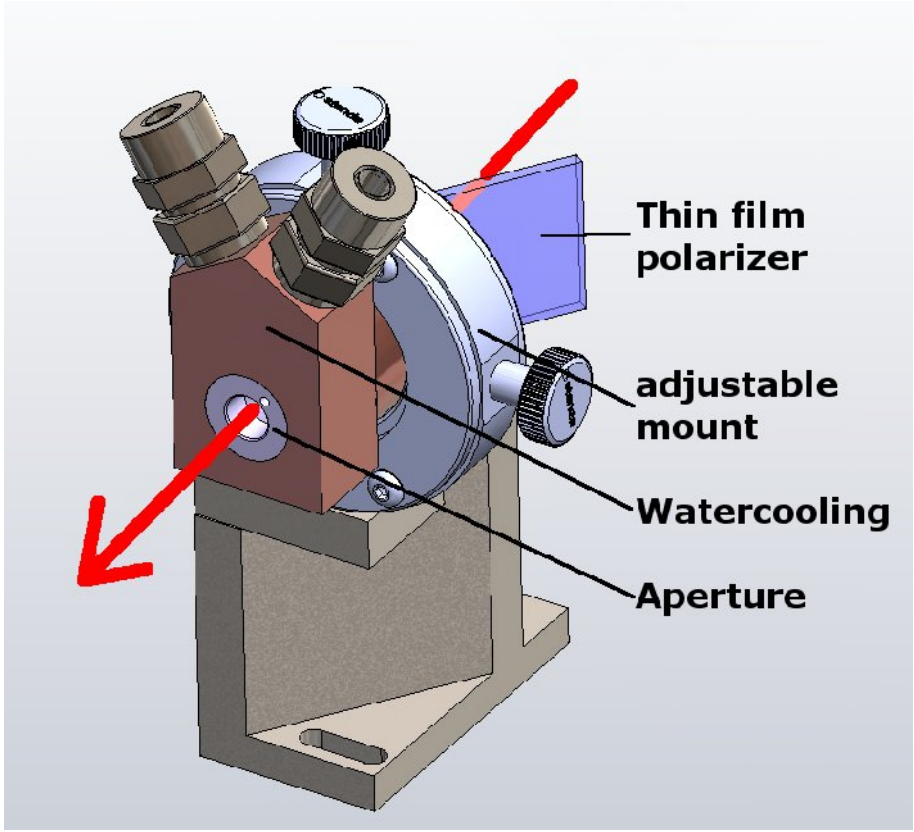



- Brewster plate ensures linearly polarized output
- Depolarized light is dumped and monitored

# Corona aperture





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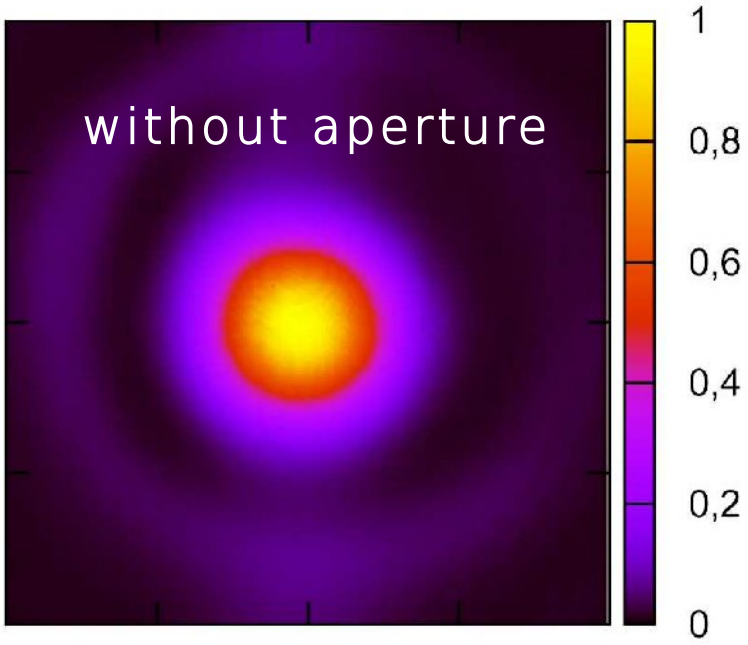


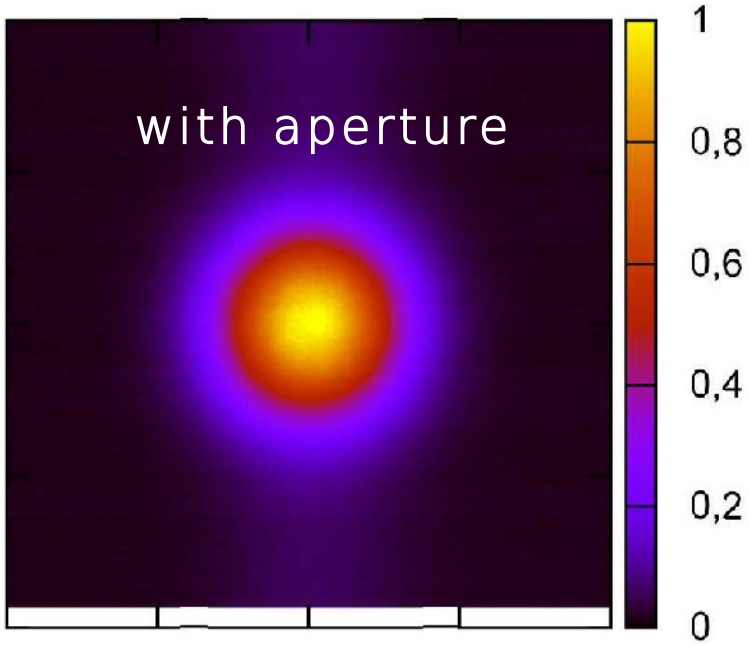


| | |
|---|---|
| laser output power | 220W ± 3% |
| power sum at PMC without aperture | 208W ± 3% |
| power sum at PMC with aperture | 180W ± 3% |
| transmitted power through PMC w/o power stabilization | 168W ± 3% |
| reflected power at PMC without power stabilization | 12W ± 3% |

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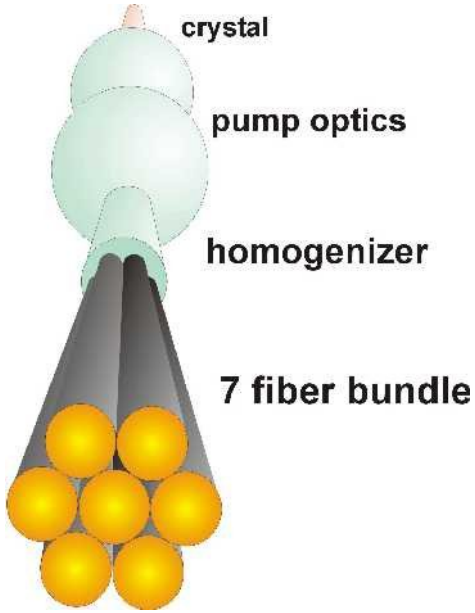
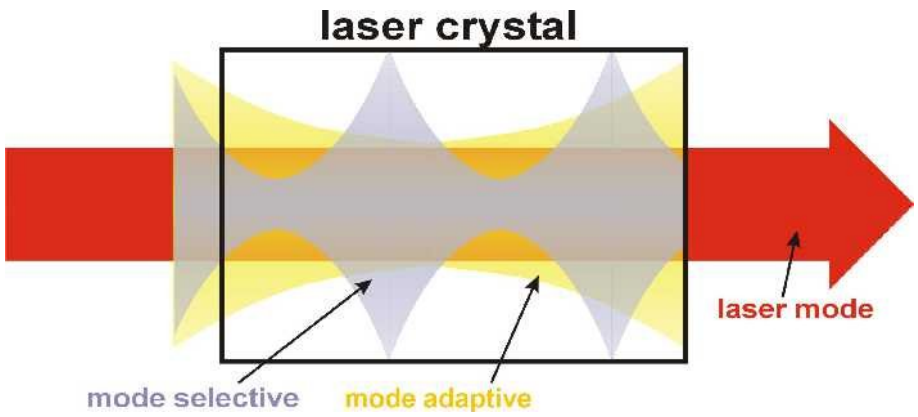
- Laser concept
- **Mode selection in high power lasers**
  - **Transverse mode selection**
    - Apertures
    - Geometric aspects
  - Longitudinal mode selection
    - Concepts
    - Pound Drever Hall locking

# Transverse mode selection

- In general: create high resonator losses for higher-order modes
- Higher-order modes are characterized by larger diameters
- Ansatz:
  - **High efficiency by matching the volume of the fundamental mode to the pump volume**
  - Aperture inside the resonator
  - Match the resonator geometry

# Longitudinal pumping




- Fiber coupled pump (→ high reliability, easy maintanance)
- Good mode / pump overlap (→ high efficiency)
- Mode selective pumping (→ mode control)

# Transverse mode selection

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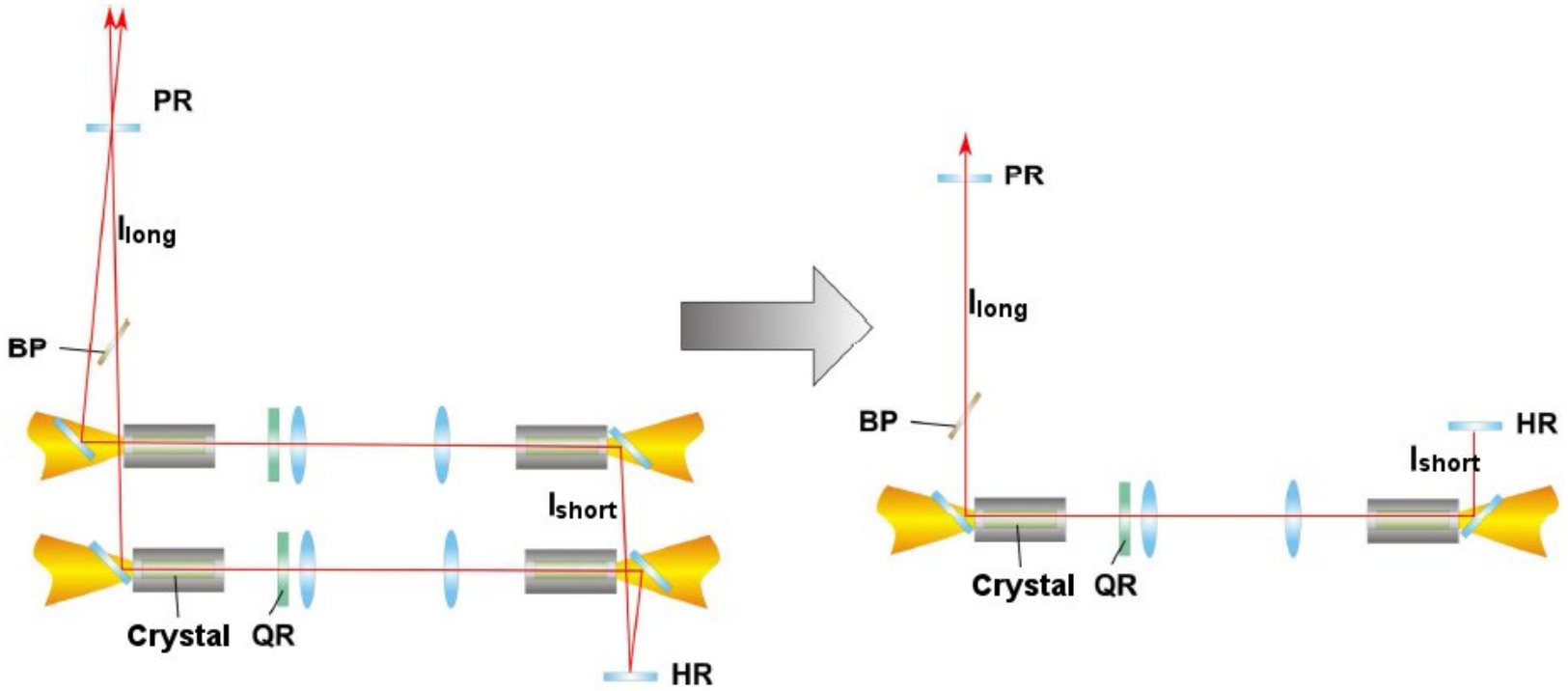
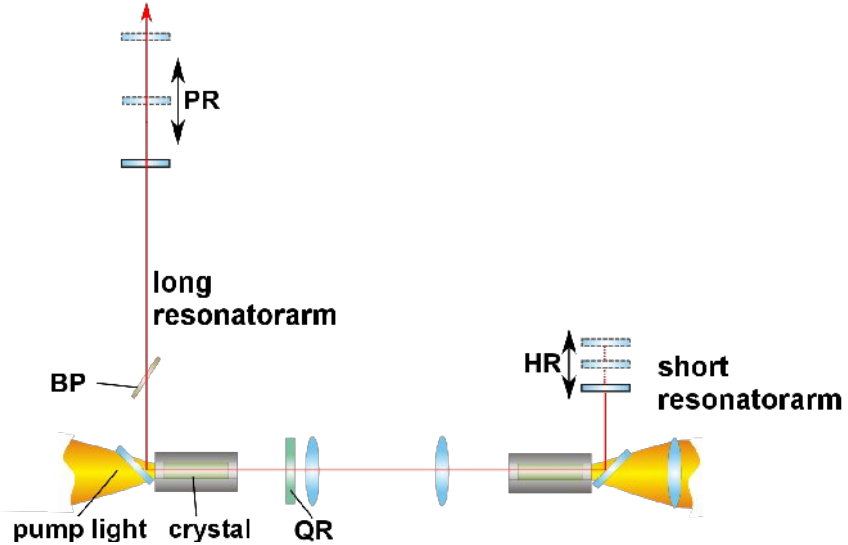
# Step 1: Simplification

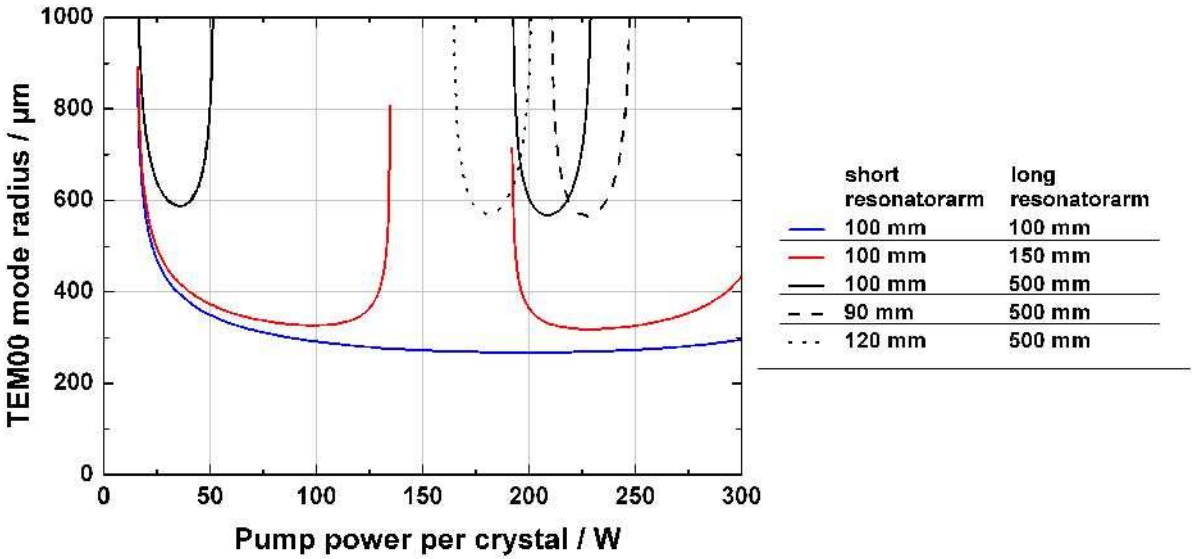



- Requirements:
  - $TEM_{00}$ operation
  - 160 W output
  - Linearly polarized

- $TEM_{00}$ operation
- 80 W output
- Linearly polarized

# Step 2: Phenomenology
## (details in lecture "Thermo-optical effects")



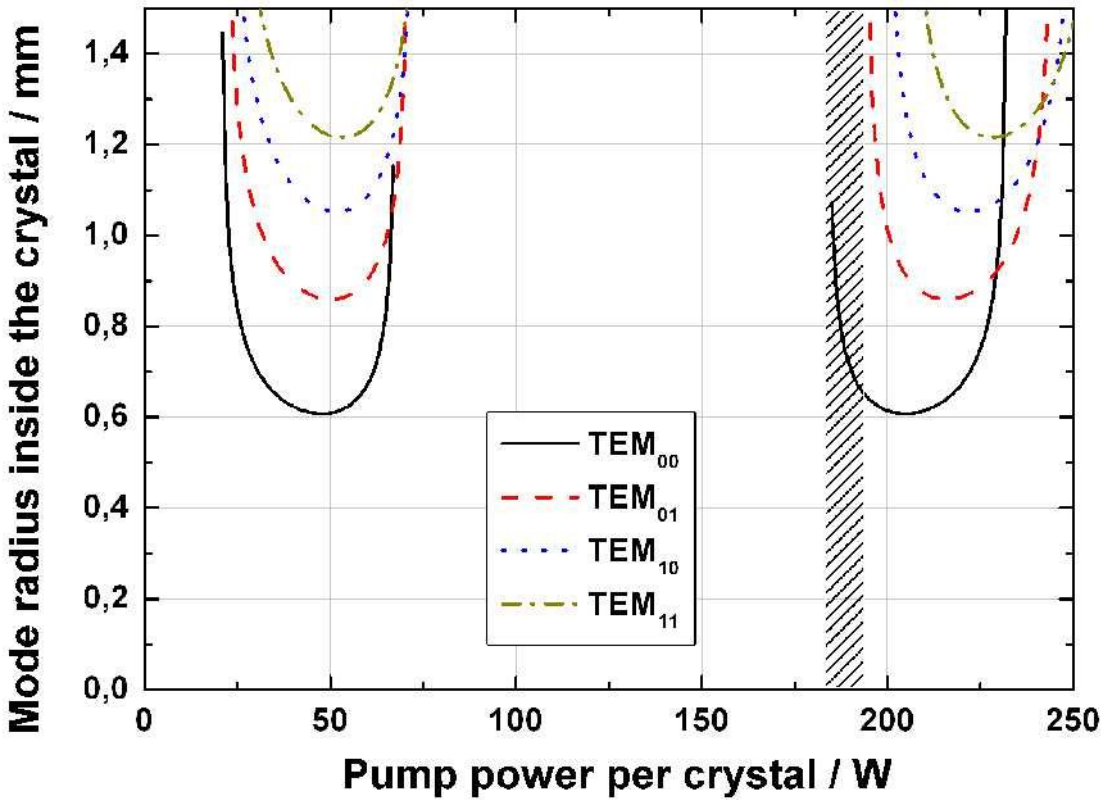




- The long resonator arm changes the mode radius and the width of the "stability range"
- The short resonator arm changes the position of the second stability range with respect to the pump power

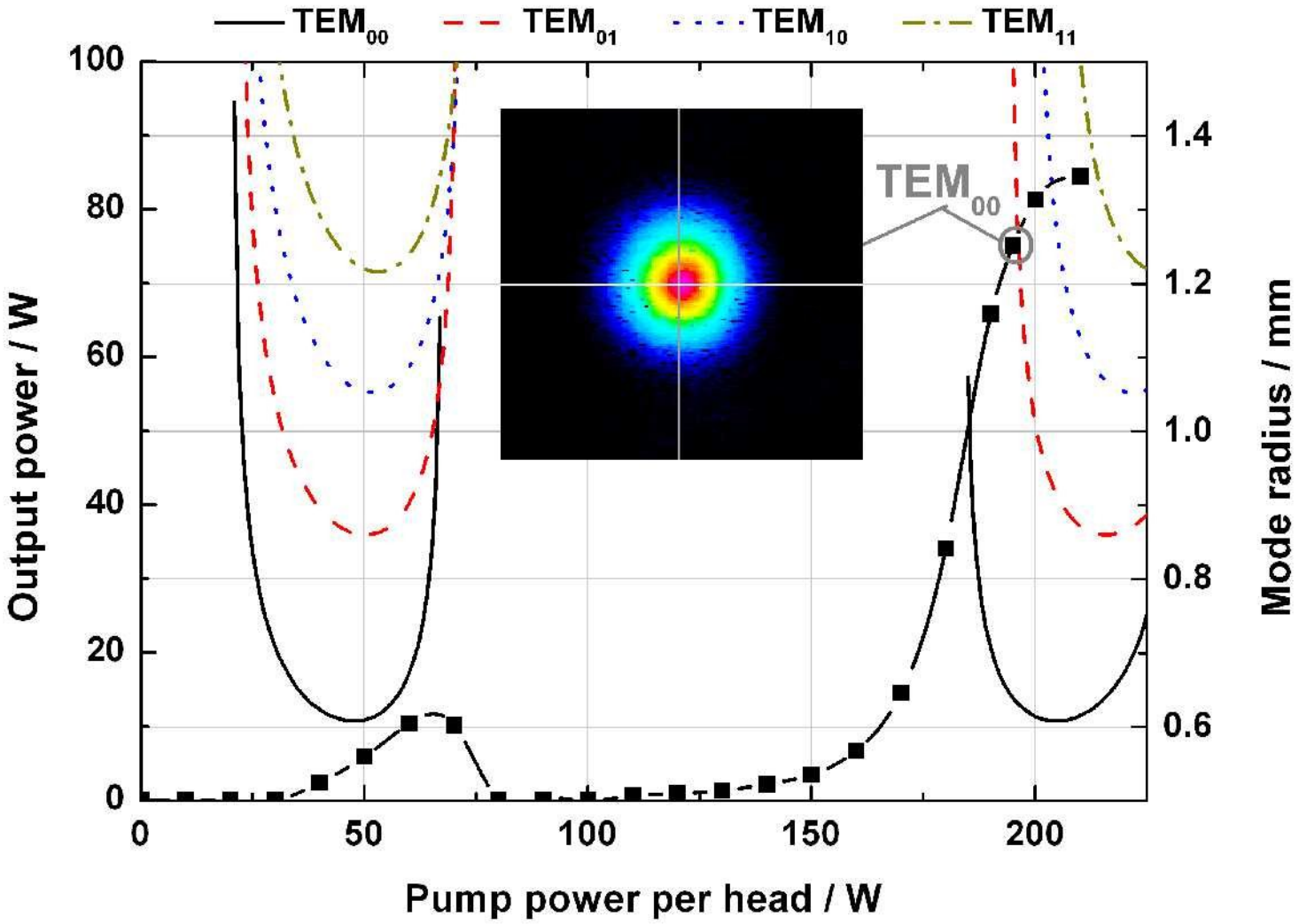
# Step 3: $TEM_{00}$ working point

- The mode radius can be taken as a stability criterion
- Due to thermal aberrations, the higher-order modes are shifted towards higher pump powers

  → $TEM_{00}$-only region



# Step 4: Reality check



# Outline

- Requirements for the advanced LIGO PSL
- Laser concept
- **Mode selection in high power lasers**
  - Transverse mode selection
    - Apertures
    - Geometric aspects
  - **Longitudinal mode selection**
    - Concepts
    - Pound Drever Hall locking

# Longitudinal mode selection

- Several options:
  - Reduction of resonator length to let just one longitudinal mode fit within the gain profile (e.g. NPRO)
  - Introduction of frequency dependent losses by etalons, etc.
  - Support of a certain mode by optical feedback (DFB diodes)
  - **Injection locking**

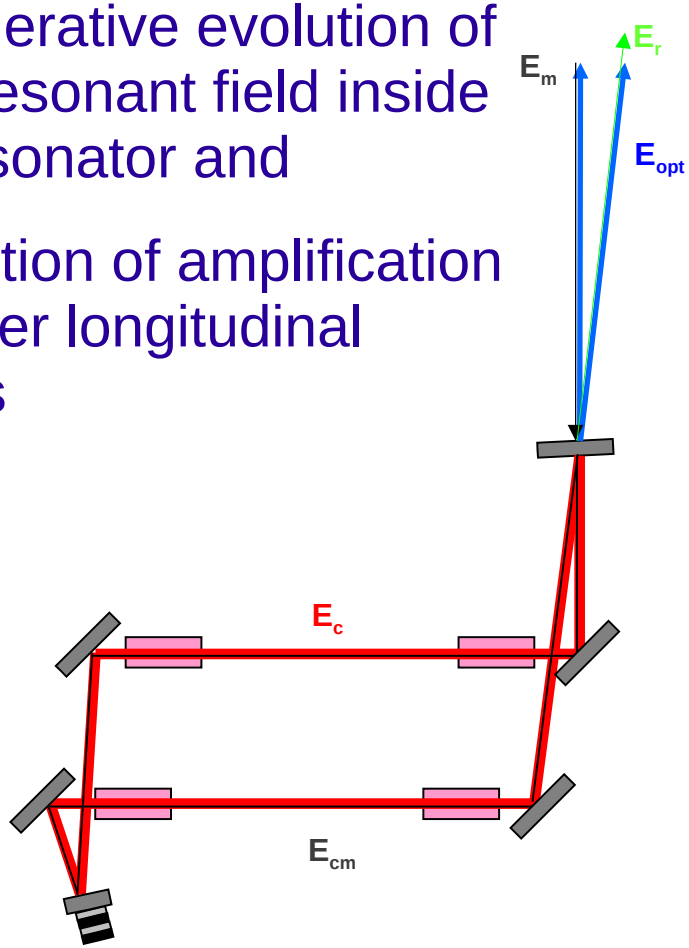
# Injection locking

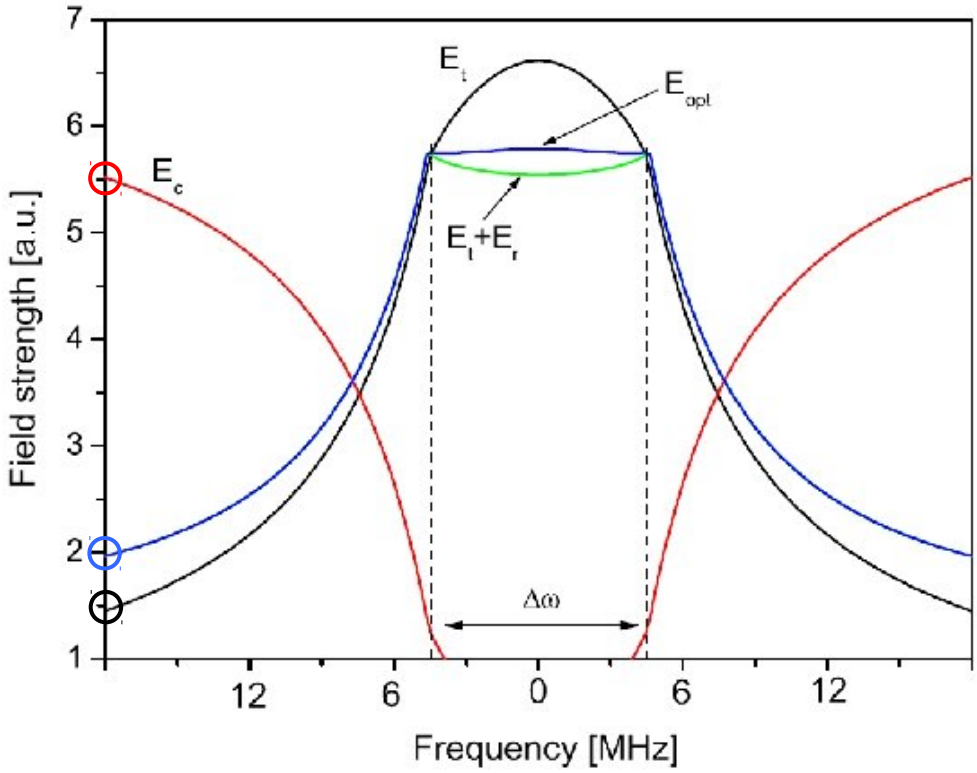
- EM-field of a single-frequency **master laser** is coupled to **slave oscillator**
- Beam size is mode-matched to intracavity beam waist
  → for $TEM_{00}$ operation the slave oscillator has to have a Gaussian profile!
- Resonance frequency of slave can be altered by piezo driven mirror
- Locking stability depends on quality of the slave resonator, $Q$, the frequency, $\nu$, and the seed and oscillator powers, $P_m$ and $P_s$
- Locking bandwidth is given by

$$\Delta\nu = 2\,\nu_0 / Q \cdot ( P_m / P_s )^{1/2}$$

# EM field behavior

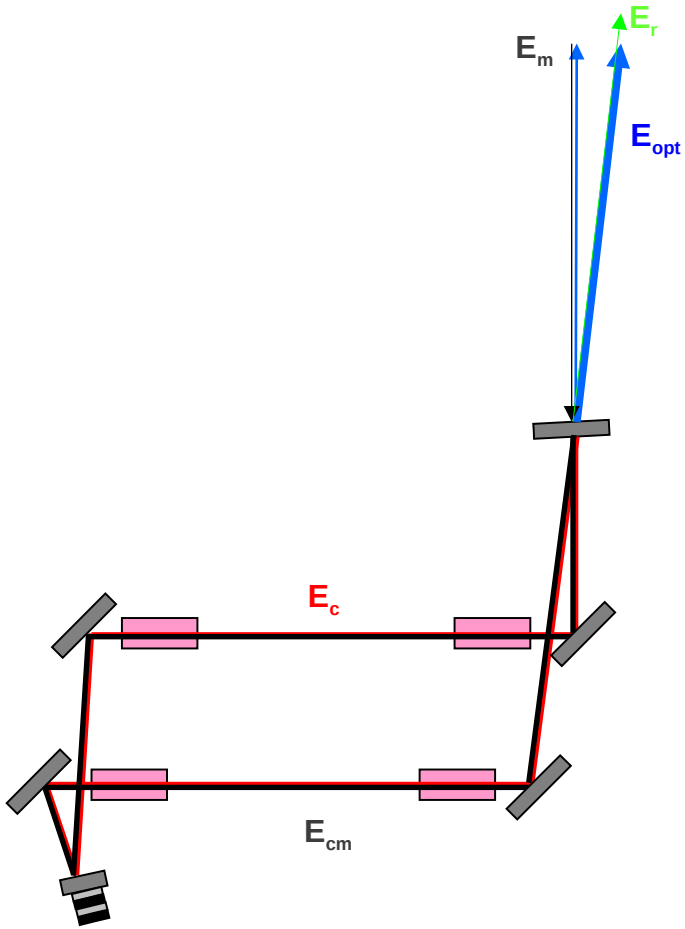
- Coupling to injected field via saturable amplification
- Regenerative evolution of near-resonant field inside the resonator and
- Reduction of amplification for other longitudinal modes

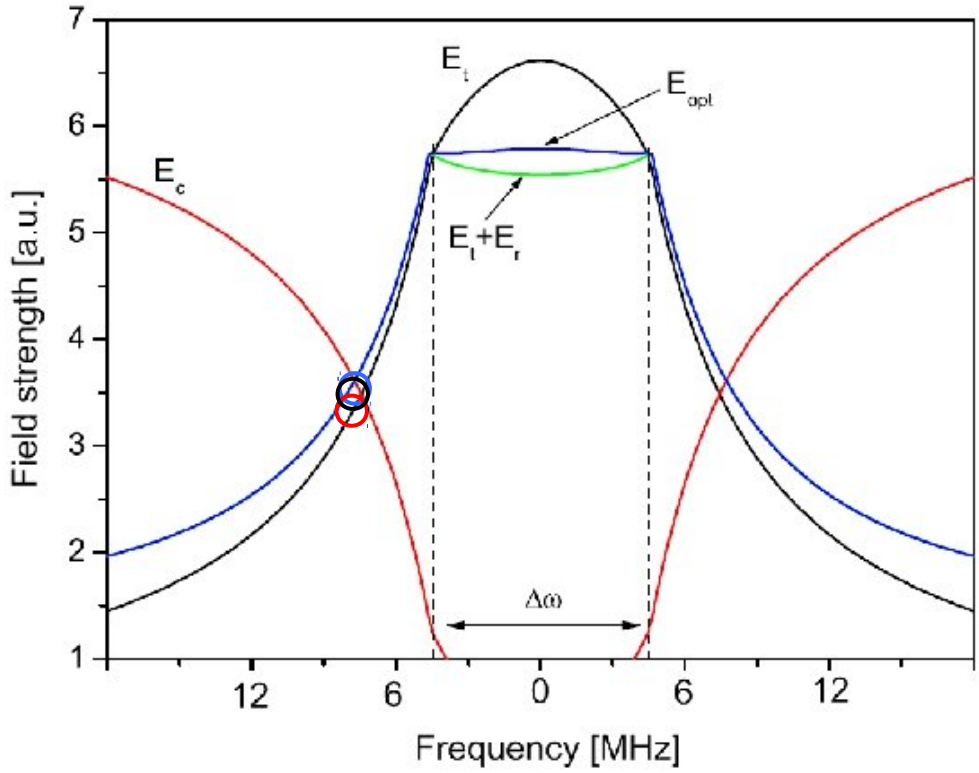



$E_m$ → EM-field of the coupled Master Laser
$E_r$ → reflected field component of $E_m$ at the PR mirror
$E_c$ → cavity internal Laser field
$E_{cm}$ → cavity internal Master field
$E_{opt}$ → resulting field during Injection Locking

# EM field behaviour

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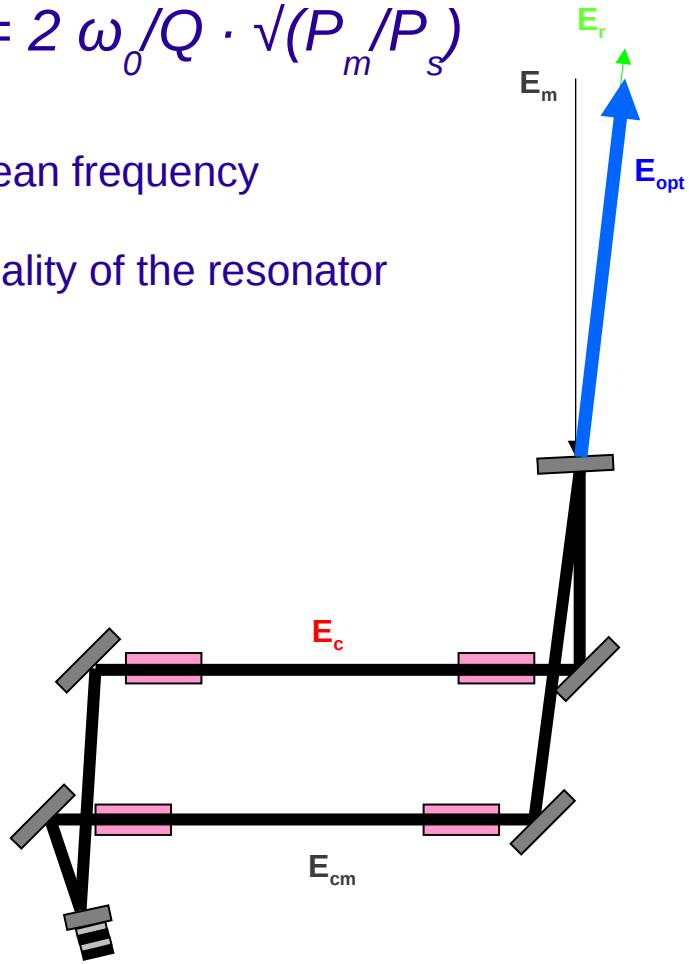
# EM field behaviour

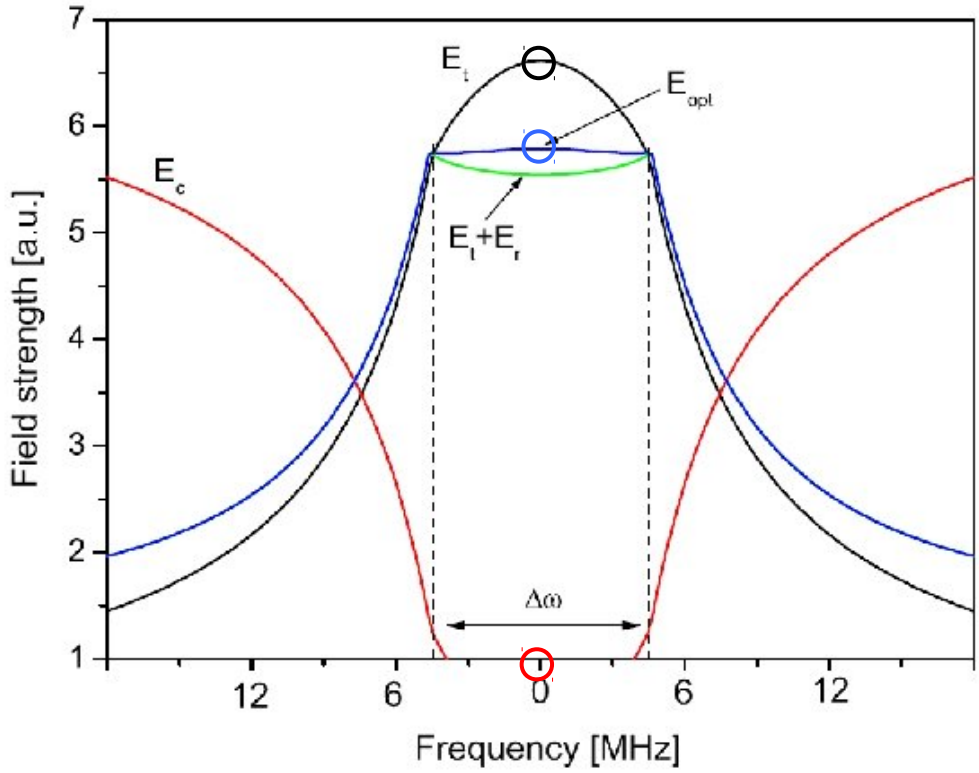
## Locking bandwidth:

$$\Delta\omega = 2\,\omega_0/Q \cdot \sqrt{(P_m/P_s)}$$

$\omega_0$ : mean frequency

$Q$ : Quality of the resonator

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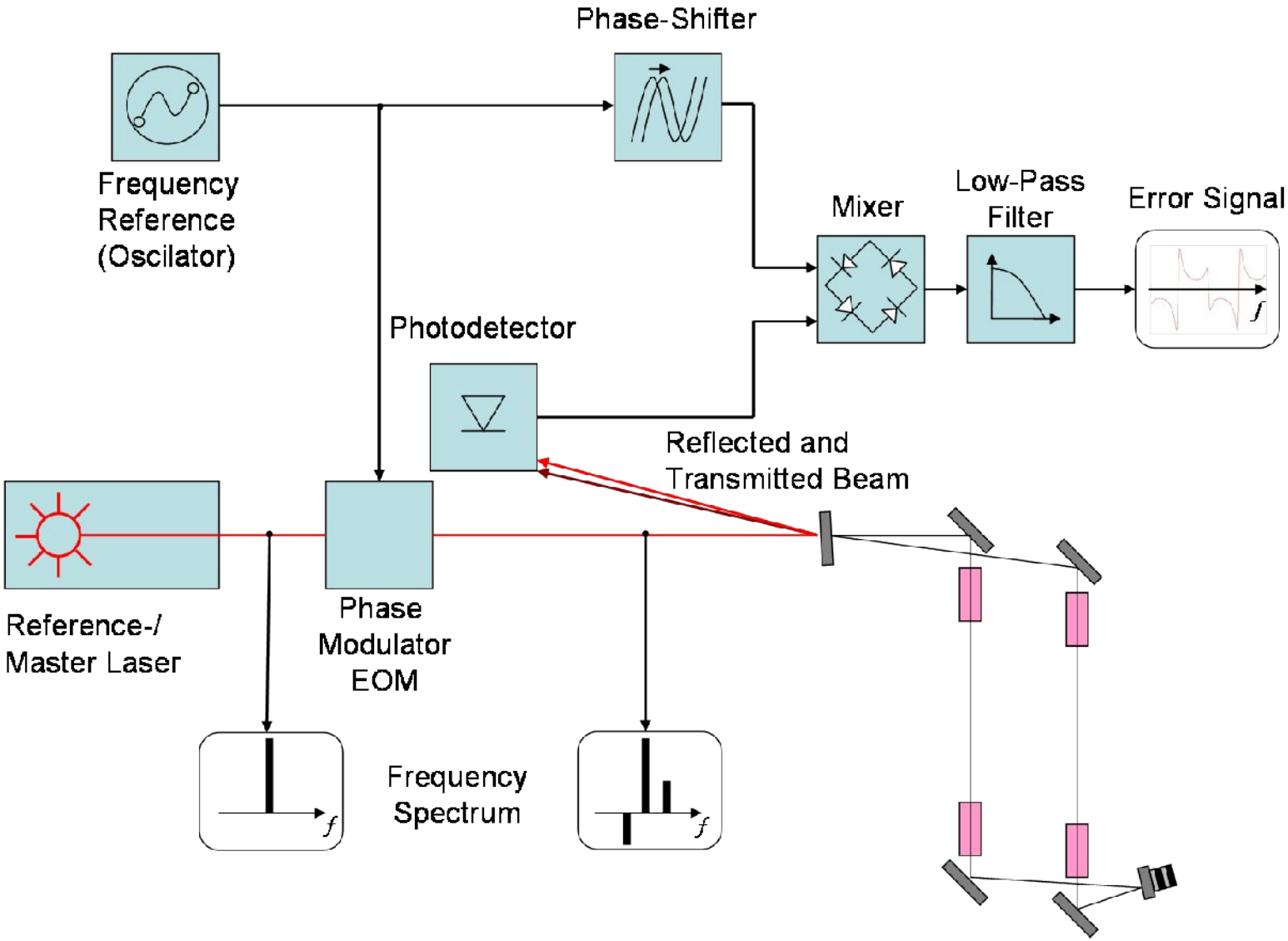
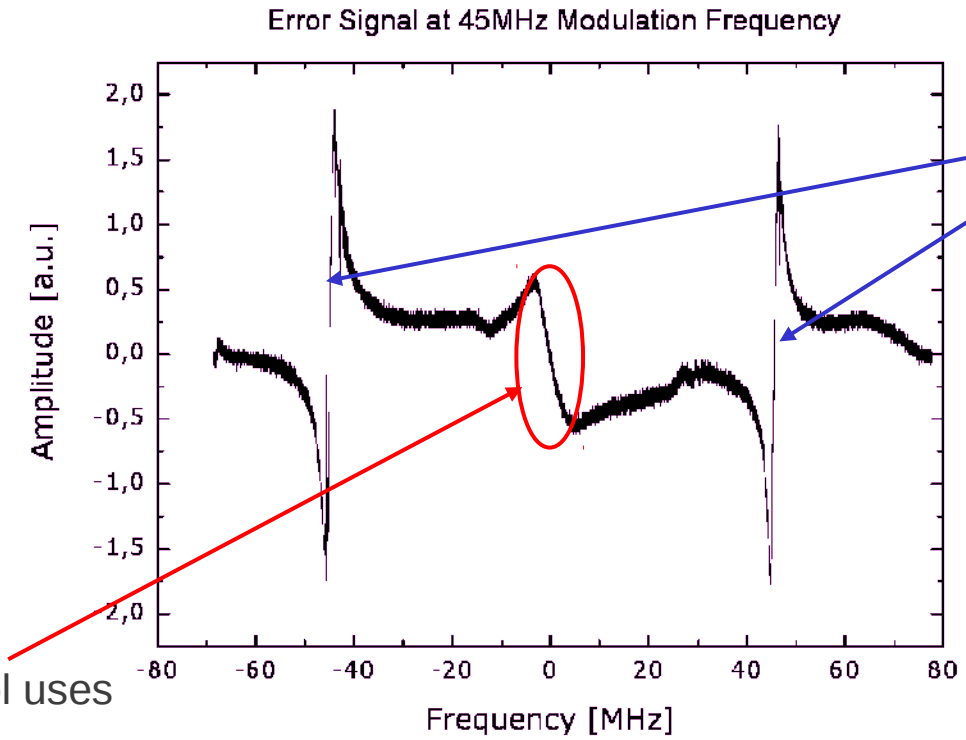
# Automated scheme: Pound Drever Hall locking



# Pound Drever Hall locking – system behavior




Zero-crossings with opposing sign

- PI- oder PID-control uses zero-crossing
- Locking range: about 8 MHz

# 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.

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LIGO Document Control Center (DCC)

Thanks!