Lasers for Interferometric Gravitational Wave Detectors

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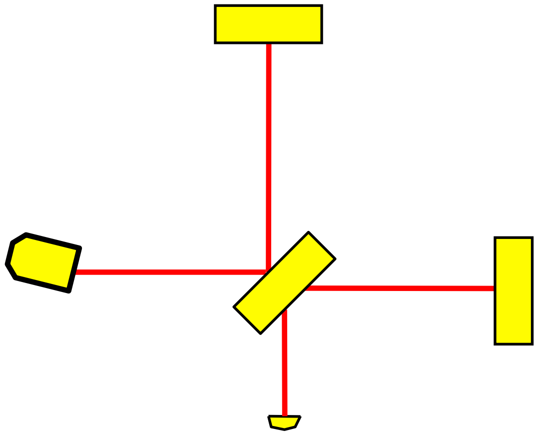
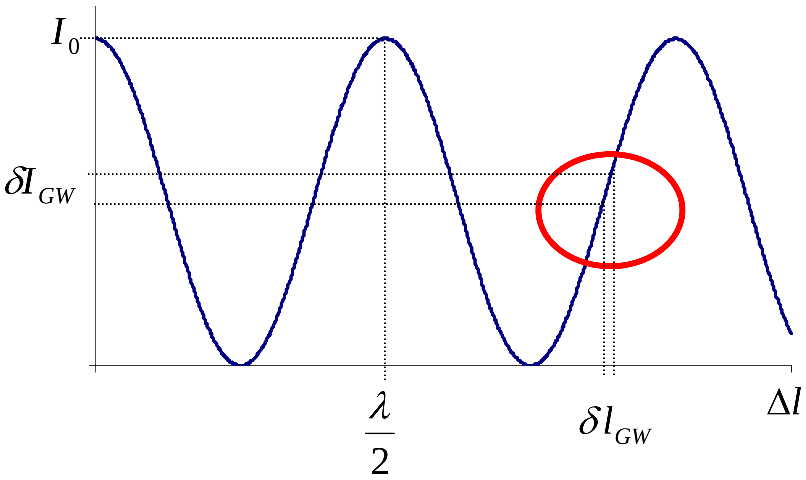
DFG-NSF Astrophysics Research Conference, Washington 2007

LIGO-G070395-00-Z

LASER ZENTRUM HANNOVER e.V.

Interferometer Response Function

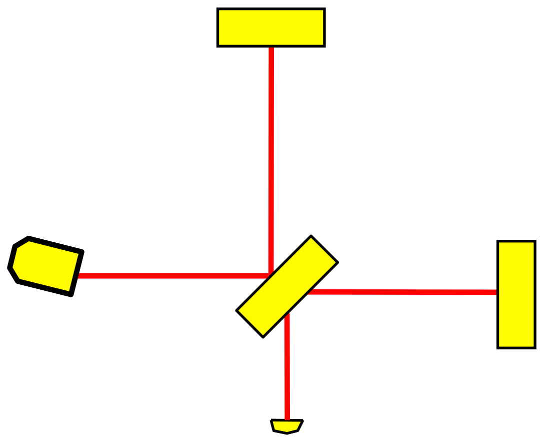




Signal:

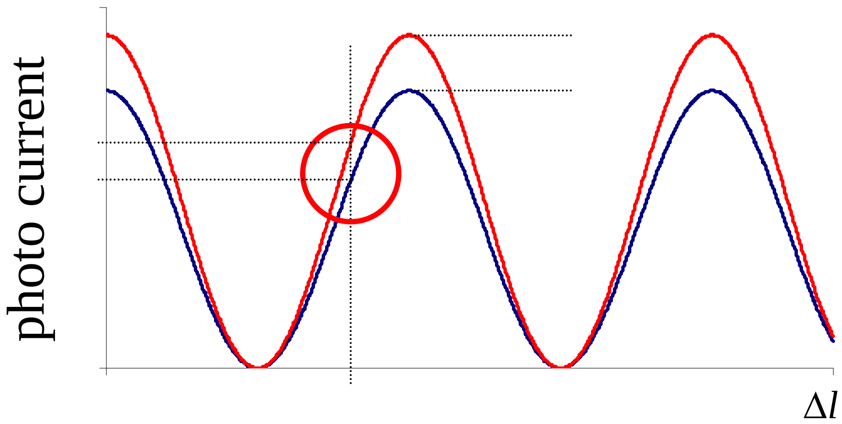
$$\delta I_{GW} = I_0 \cos^2\left(\frac{\omega}{c}\delta l_{GW}\right)$$

Noise Source – Power Fluctuations



Noise:

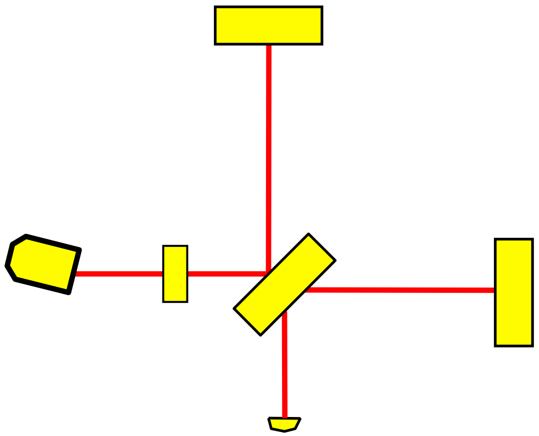
$$\delta I_{noise} = \delta I \cos^2\left(\frac{\omega}{c}\Delta l\right)$$



Power Noise in the Interferometer

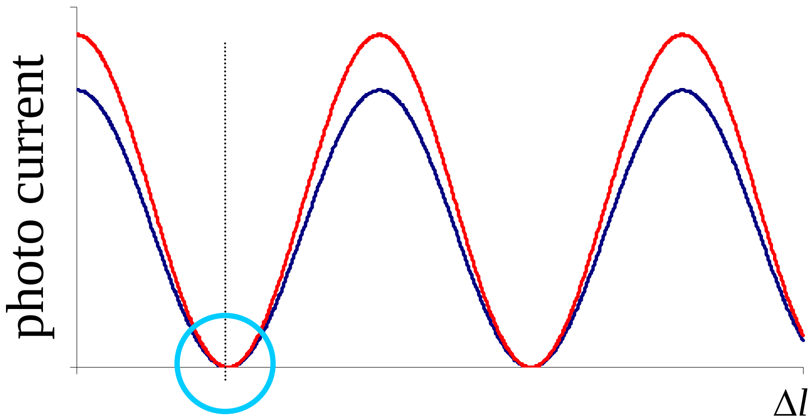
- fluctuations of the laser power
- relative stability of 10^{12} would be required – (not possible with todays technology)

Noise Sources – Shot Noise



S/N ratio

$$\left.\begin{array}{l}\delta I_s \propto I_0 \delta l_{GW} \\ \delta I_{SN} \propto \sqrt{I_0}\end{array}\right\} \Rightarrow \frac{\delta I_s}{\delta I_{SN}} \propto \sqrt{I_0}\,\delta l$$



„dark fringe“ operation point

- reduction of power noise contribution
- allows for power recycling and better $S/N_{\text{shot noise}}$ ratio
- increases sensitivity to „alignment“ fluctuations

Lasers for First Generation GWD

- high power laser system
  - solid-state laser at 1064nm (Nd:YAG / Nd:YVO)
  - laser diode pumped
  - 10-20W output power
  - injection-locked (GEO600, Virgo, TAMA) or master-oscillator power-amplifier systems (LIGO)
- pre-stabilization
  - two layers of frequency stabilization
  - spatial filtering (DC /AC) provided by suspended Fabry-Perot cavities (modecleaner)
  - power stabilization via feed-back control (DC-10kHz) and passive filtering (>1MHz)
  - final stabilization to and filtering by power recycling cavity
- lasers produced by commercial vendors (Lightwave Electronic, Sony) and research labs (Laserzentrum Hannover, Adelaide University)

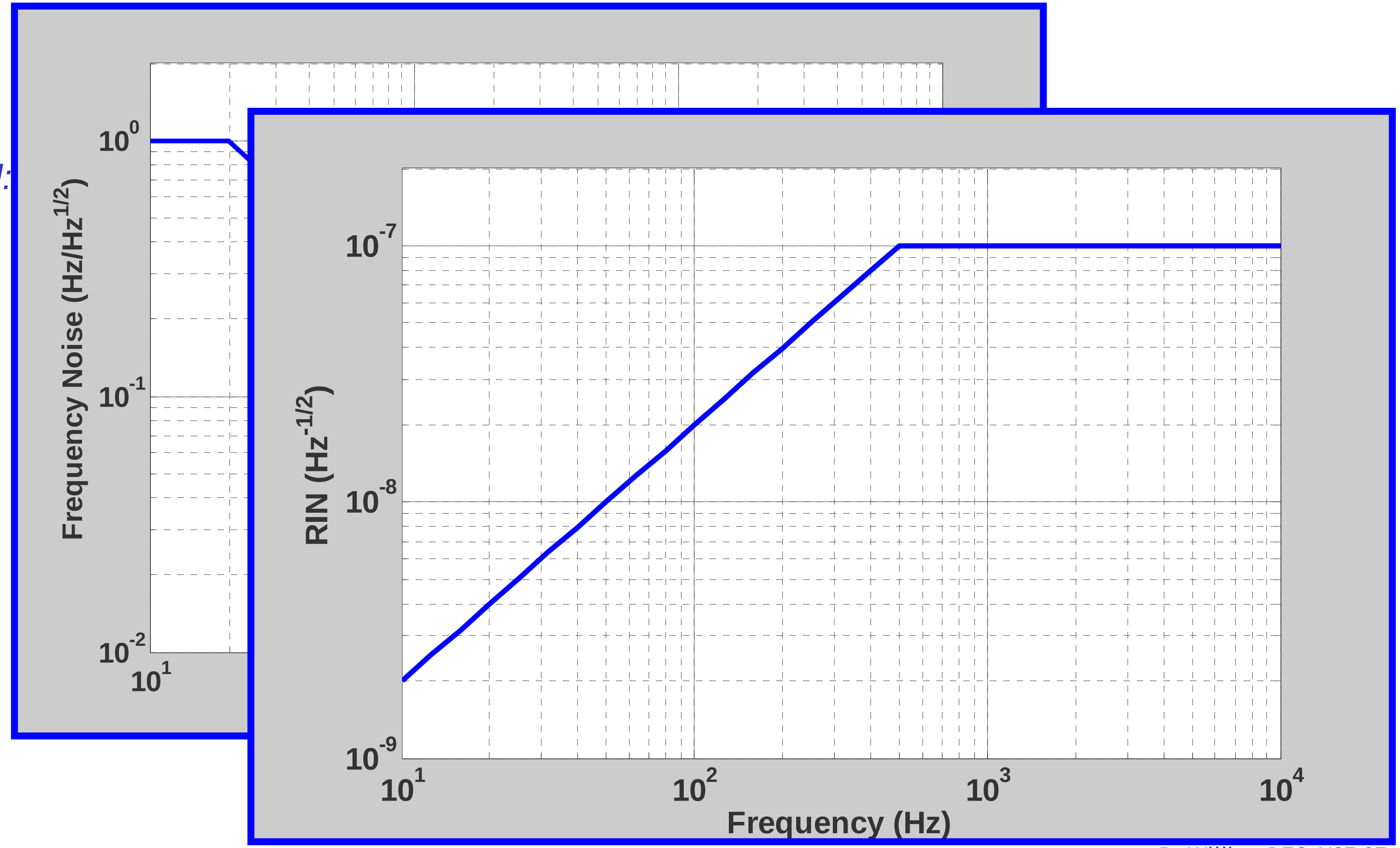
Advanced LIGO PSL – Requirements

Power / Beamprofile:

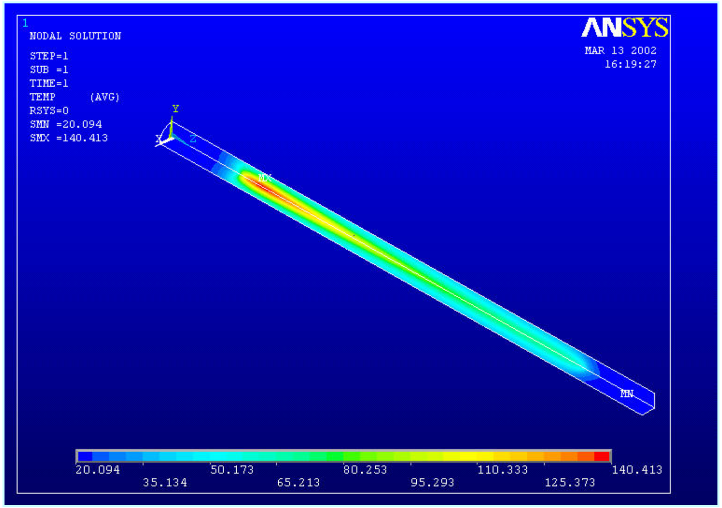
- 165W in gaussian TEM_{00} mode
- less than 5W in non- TEM_{00} modes

Drift:

Control:



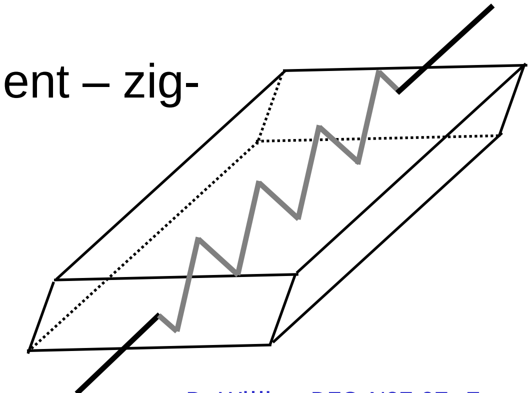
High Power Stage



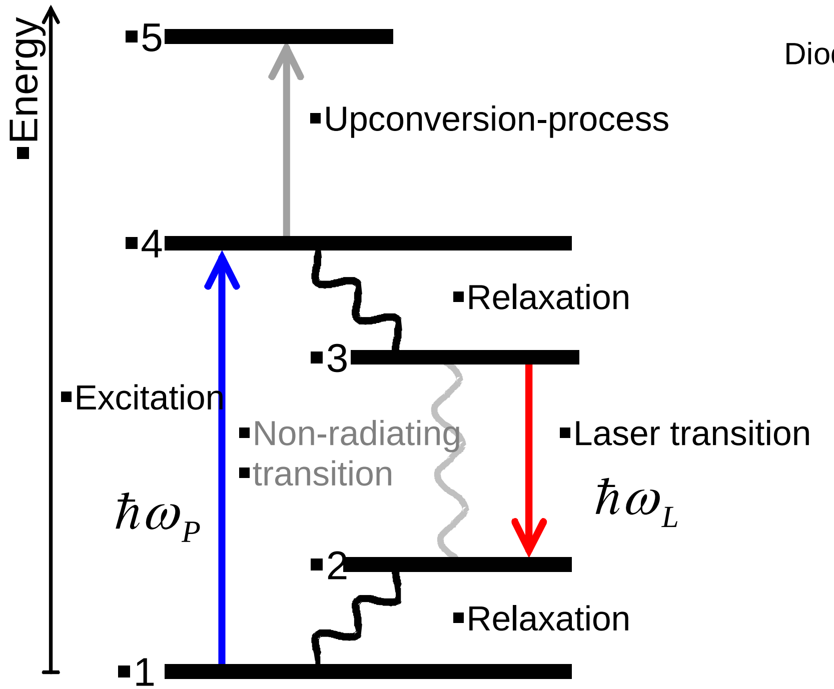
- goal: generate linear-polarized high-power beam with good spatial profile

- main problem: thermal design
  - stress fracture
  - thermal lensing – spatial profile
  - birefringence with tangential and radial principle axis

- solutions
  - reduce deposited heat – Yb:YAG, high efficiency
  - propagate beam perpendicular to temperature gradient – zig-zag, thin disc lasers
  - increase interaction length – fiber lasers
  - compensate birefringence

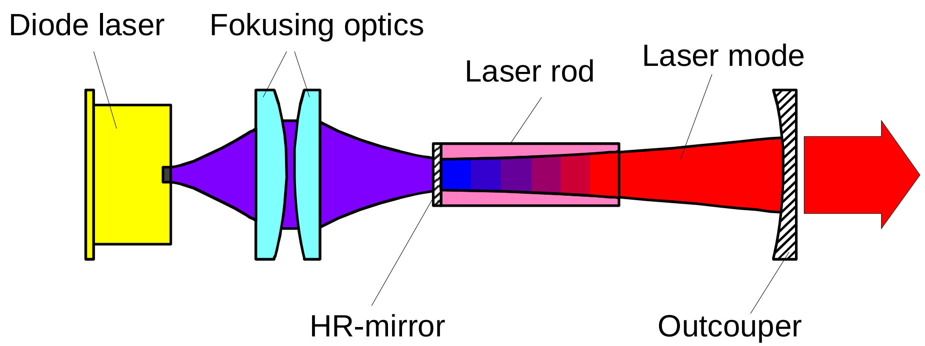


High Power Laser - Concepts

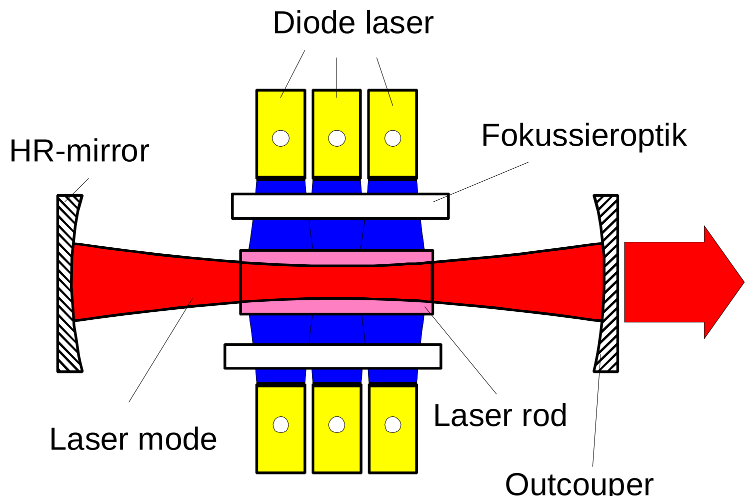


Energy difference $\hbar\omega_P - \hbar\omega_L$ is deposited as heat inside the active material

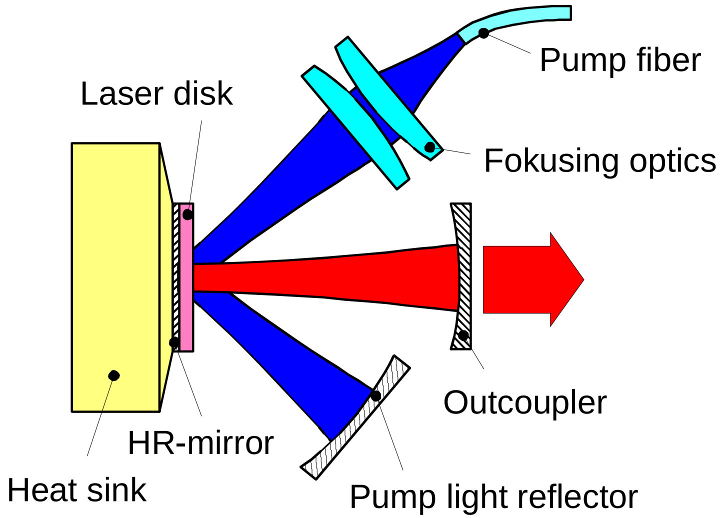
Longitudinal pumped laser

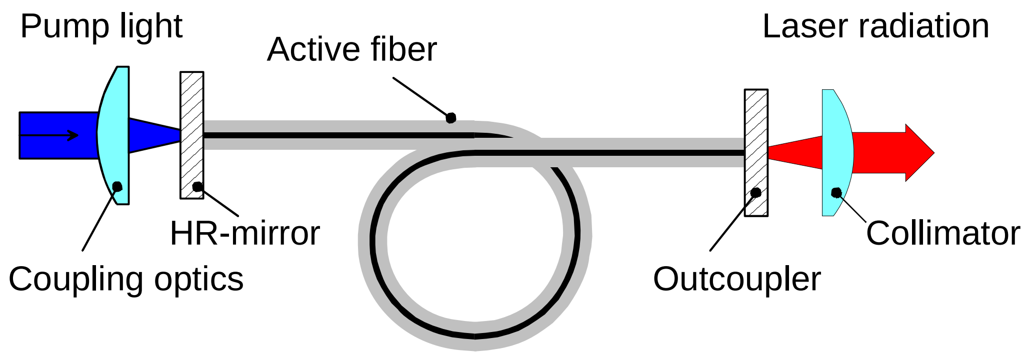


Transversal pumped laser



Novel Concepts





Thin disk laser

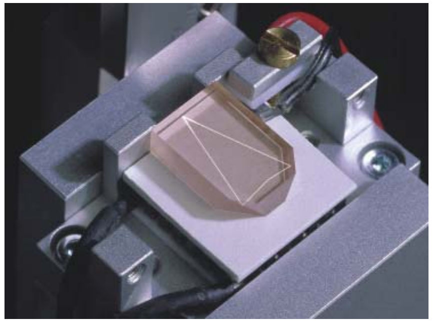
→ Lasermode parallel to temperature gradient

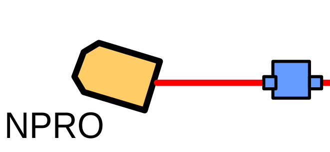
Fiber laser

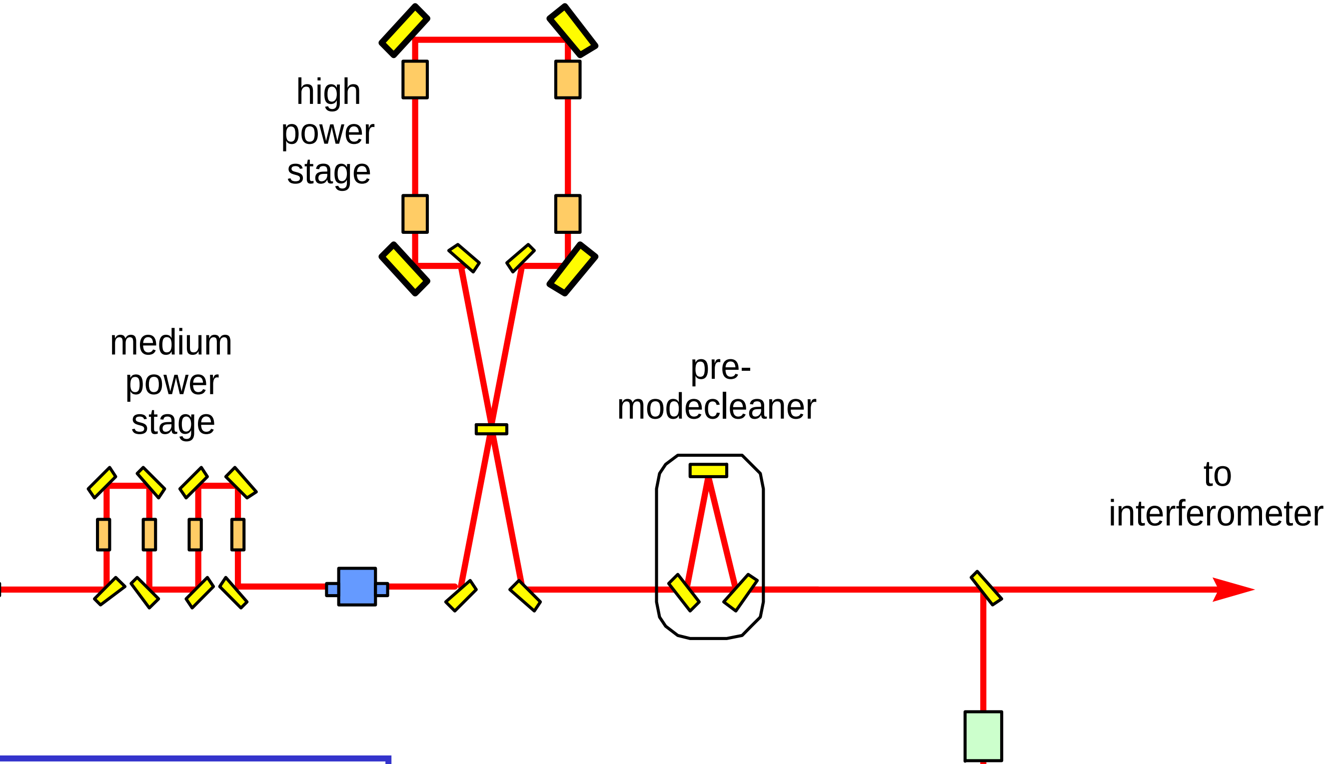
→ Lasermode defined by waveguide structure

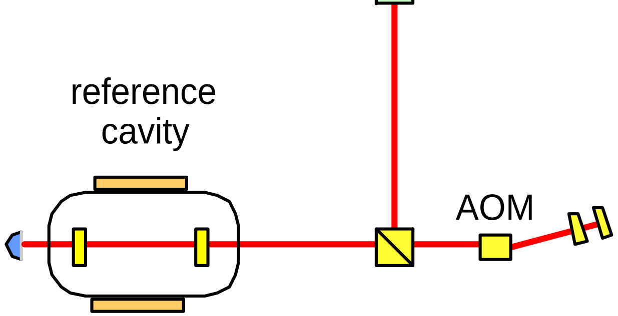
A. Tünnermann, H. Zellmer, W. Schöne, A. Giesen, K. Contag
New Concepts for Diode Pumped Solid State Lasers
R. Diehl (Ed.) High-Power Diode Lasers Topics in Applied Physics Vol. 78, P. 369-408 Springer Verlag, Heidelberg 2000

Advanced LIGO prestabilized Laser



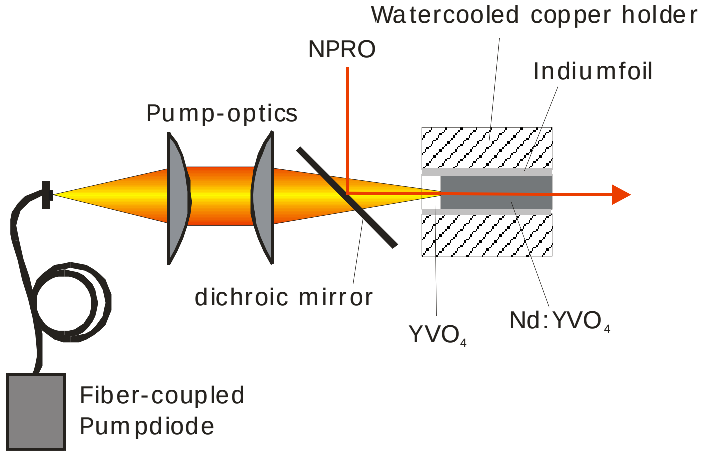


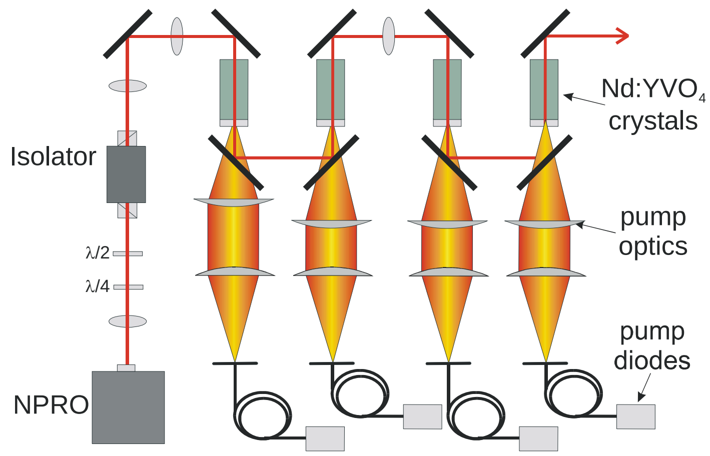


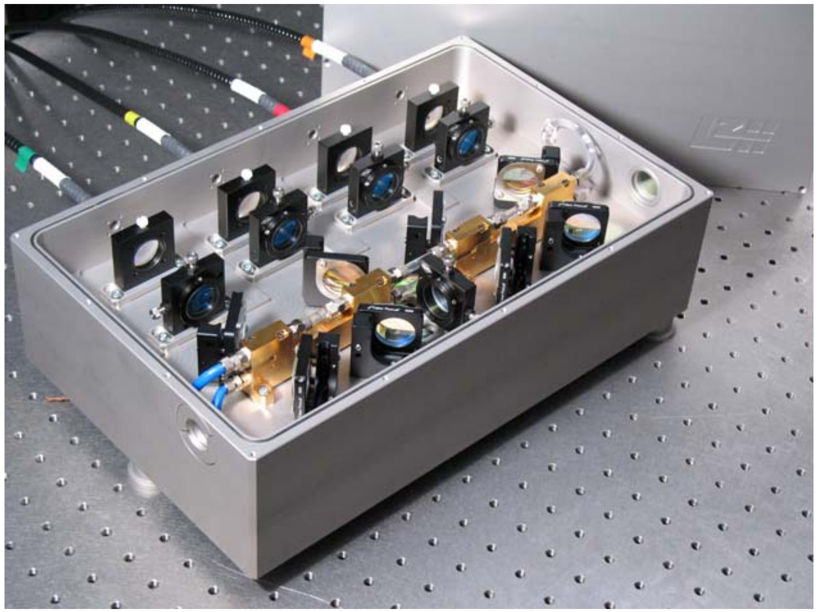


- MPI for Gravitational Physics (Albert-Einstein-Institut) will provide lasers as capital contribution to AdvLIGO
- laser build in cooperation with Laser Zentrum Hannover (LZH)

35W Amplifier Design





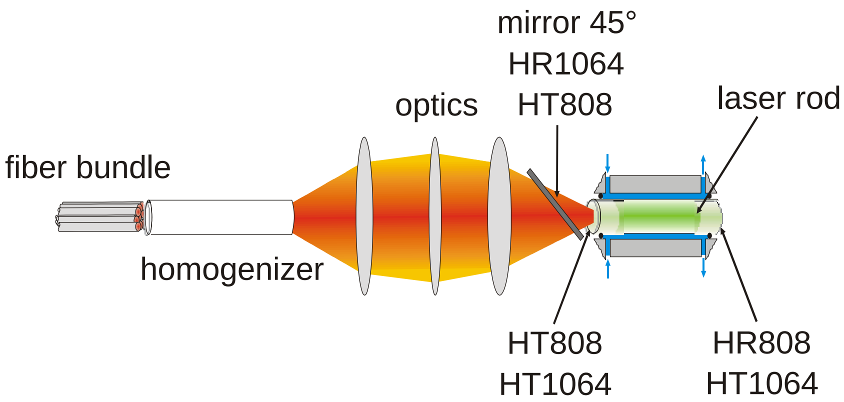


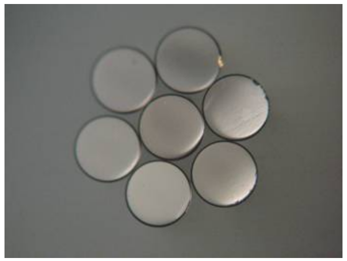
- Crystal:
  3 x 3 x 10 mm^3 Nd:YVO_4
  8 mm 0,3 % dot.
  2 mm undoped endcap
- Pump diode:
  808 nm, 45 W
  400 µm fiber diameter
  NA=0,22
- amplifier:
  38W for 2W seed and 150W pump

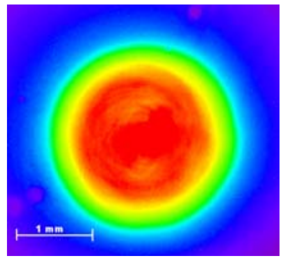
Frede et al, *Opt. Express* **22** p459 (2007)

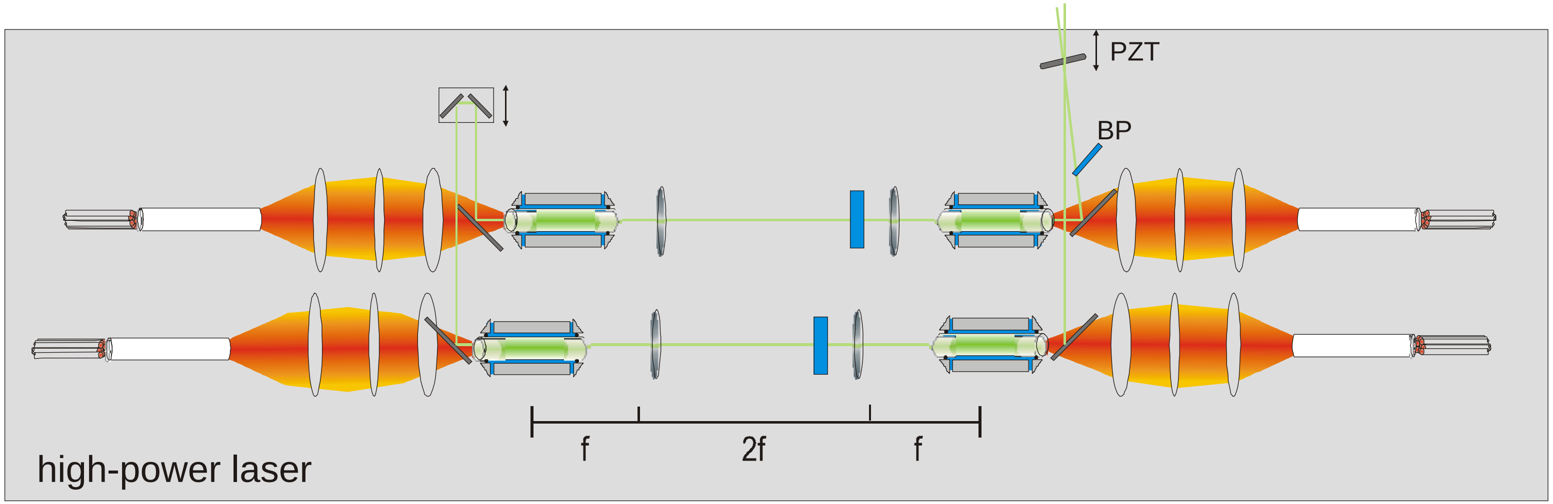
high power stage

- 7 pump fibers per head (7 x 45 W)
- pump light homogenizer
- two quarz rotators for birefringence compensation
- 195 W polarized single mode, single frequency demonstrated

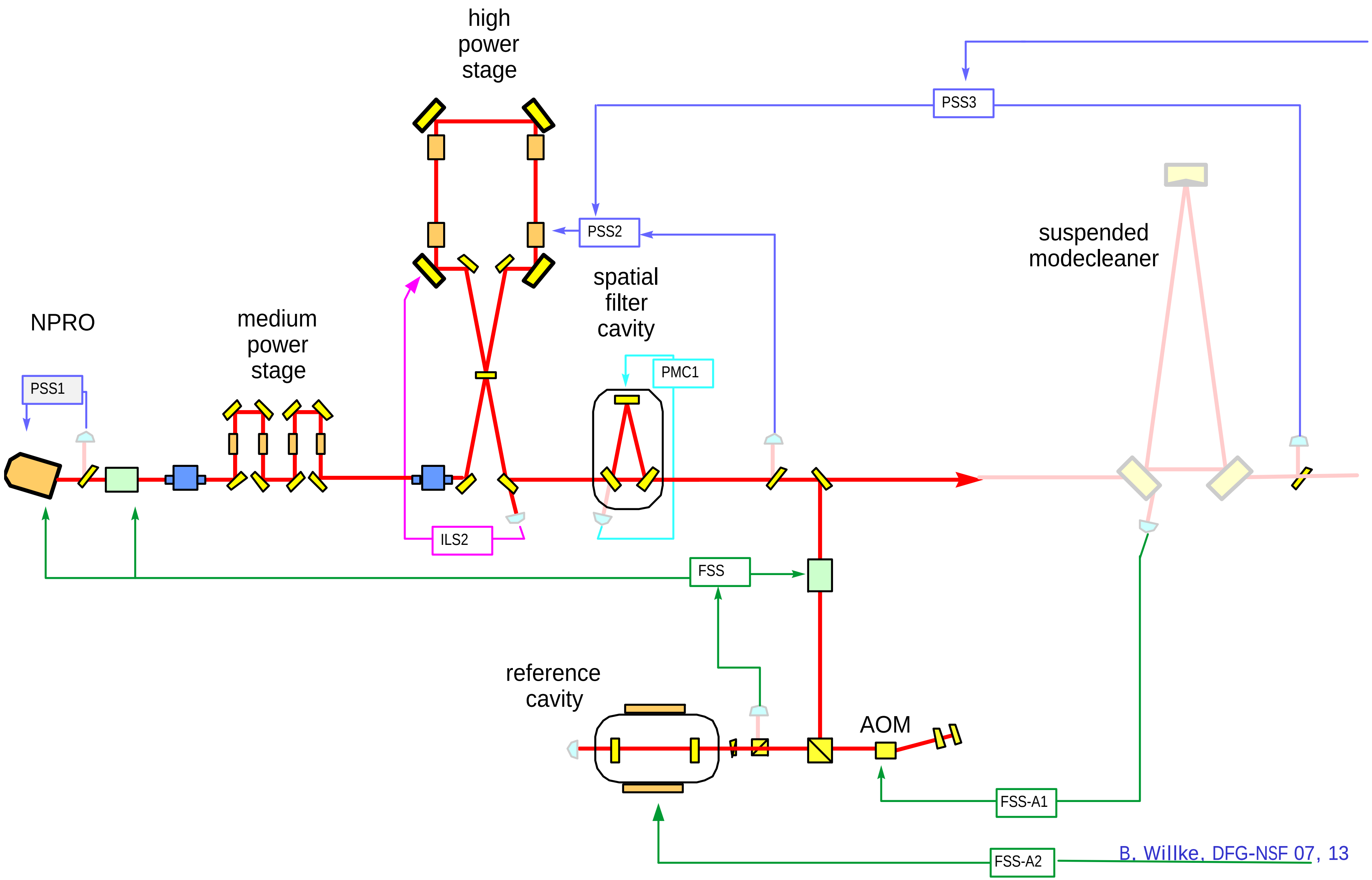




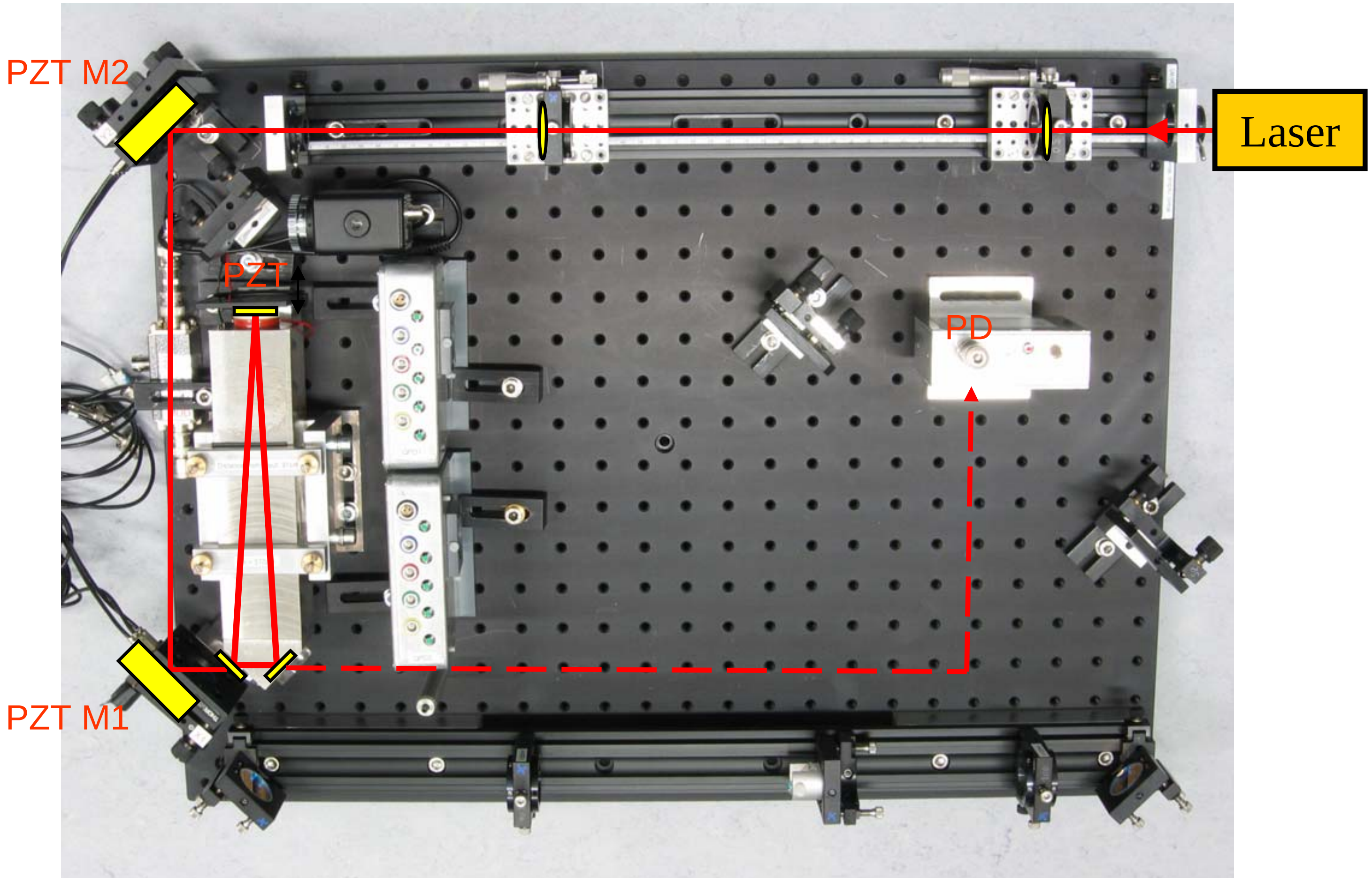




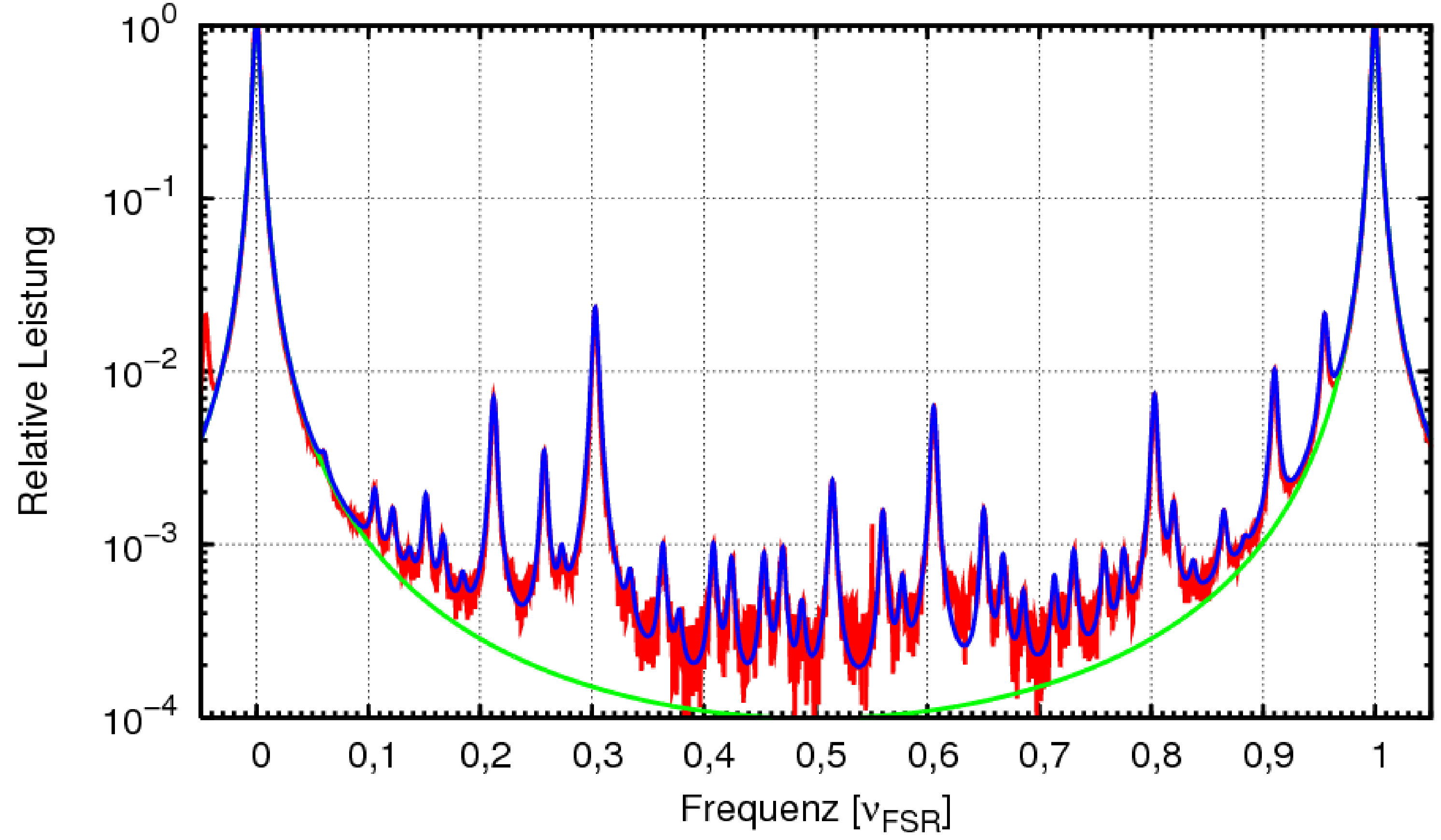
Stabilization Scheme



Beam Diagnostic Setup

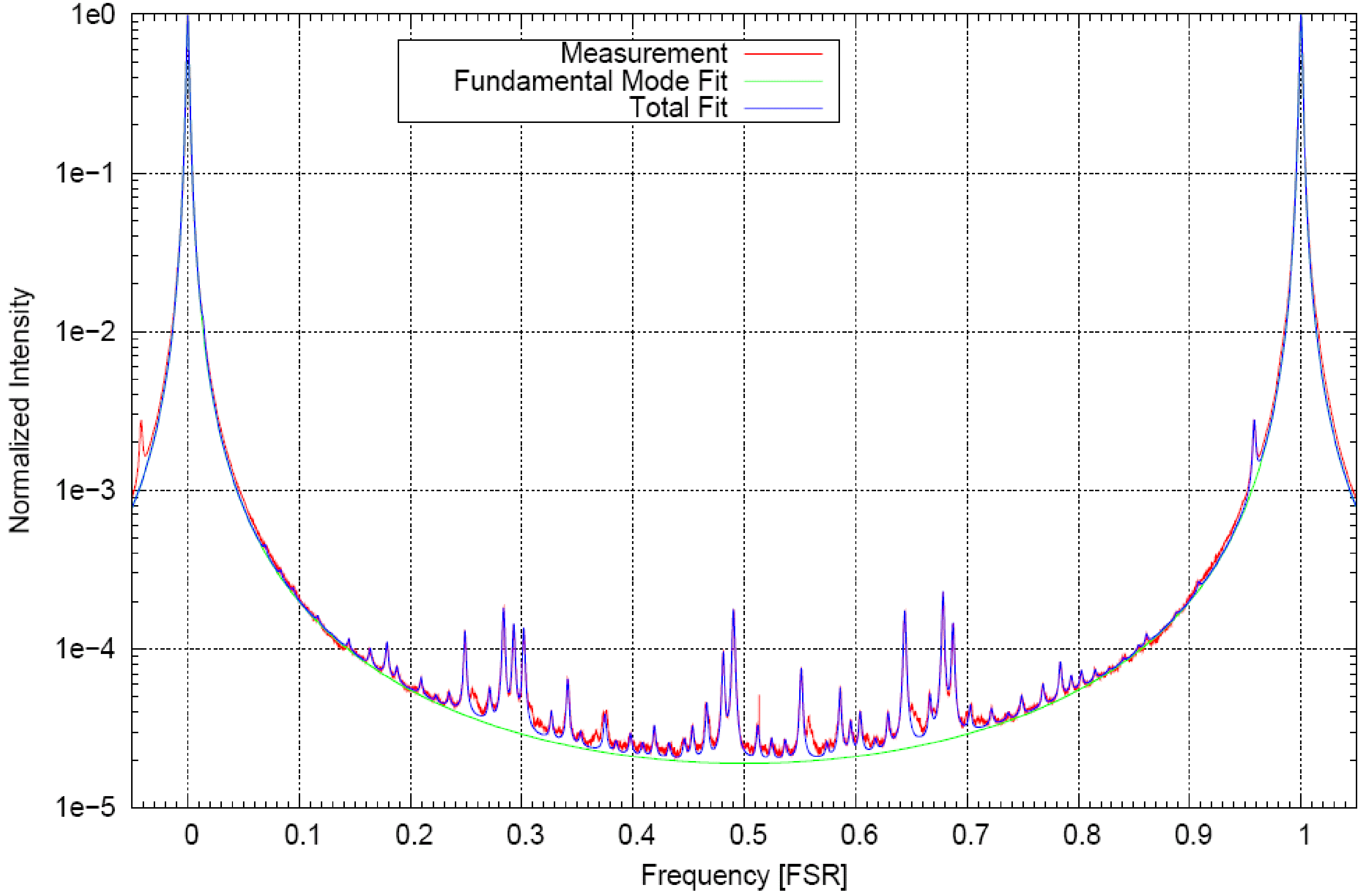


Spatial Mode Scan



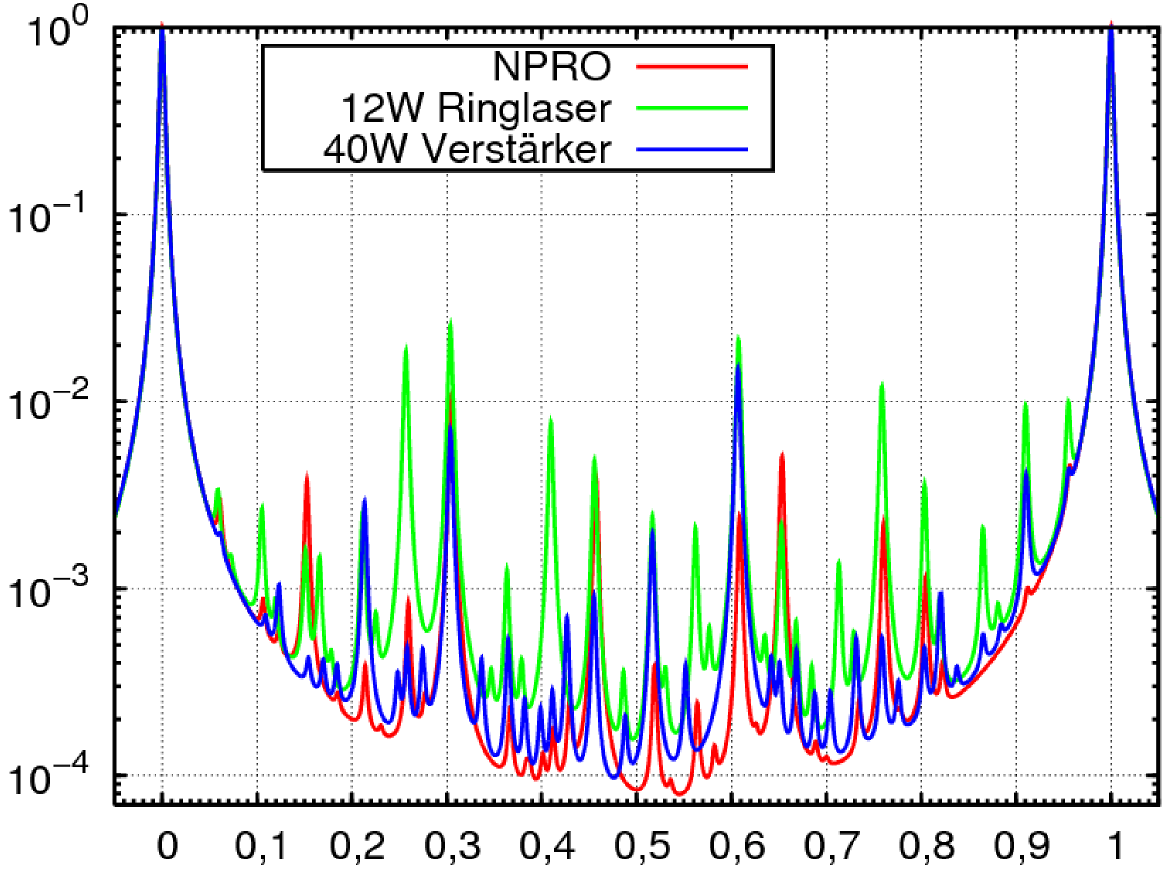
fundamental mode: 91,5%

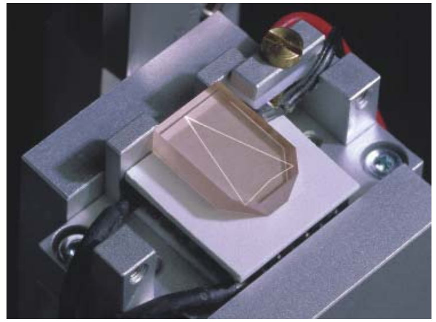
NPRO (filtered by a fiber and PMC)

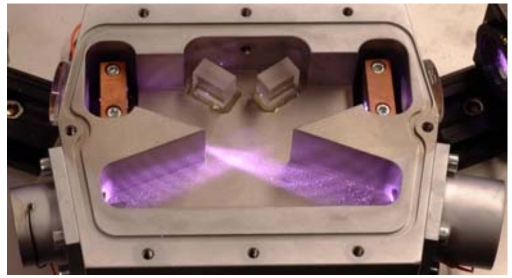


Finesse: 366 ±5
higher order mode power: 0.56% ±0.3%

Mode Scan - Examples





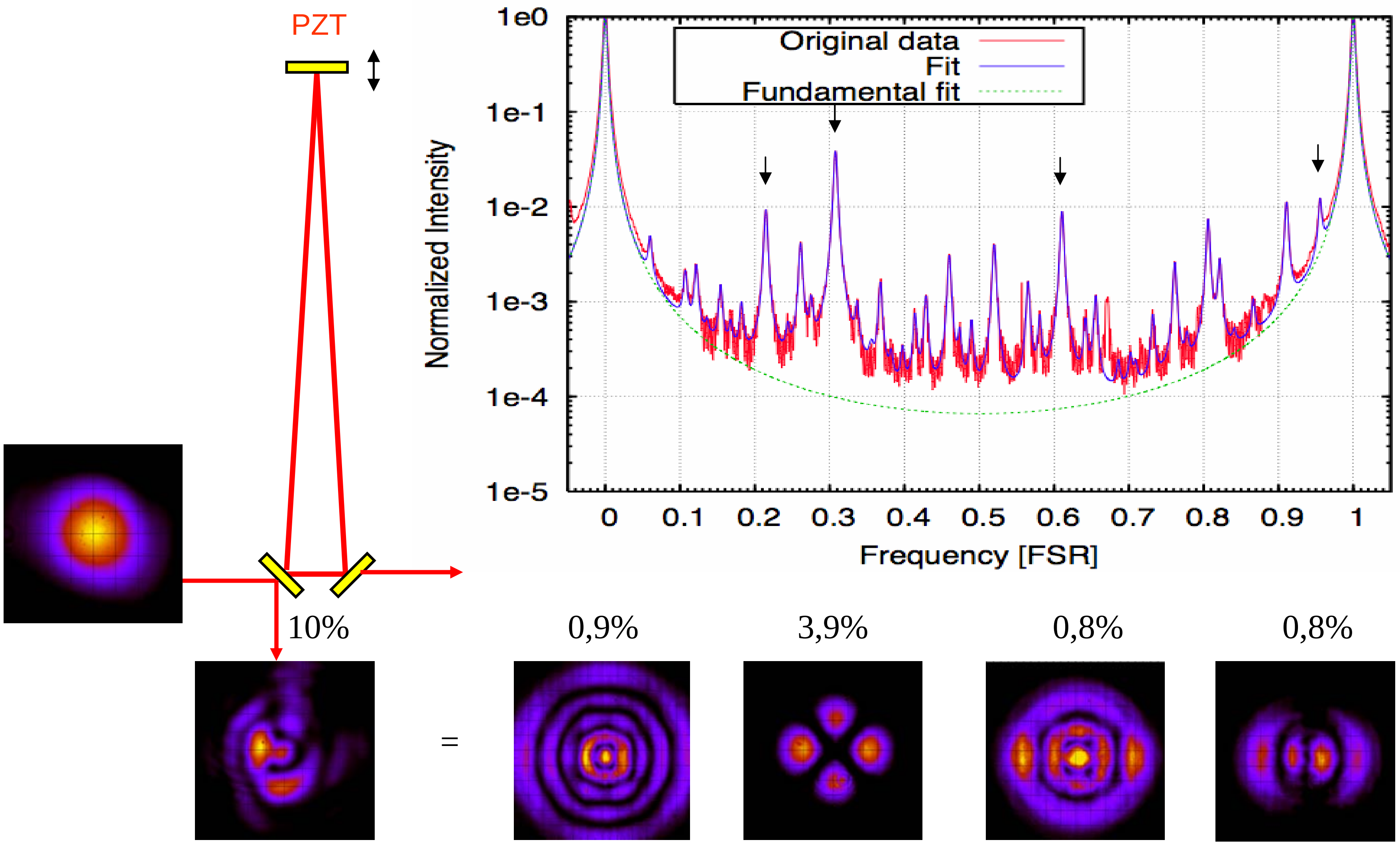


Nd:YAG NPRO : 96,7%

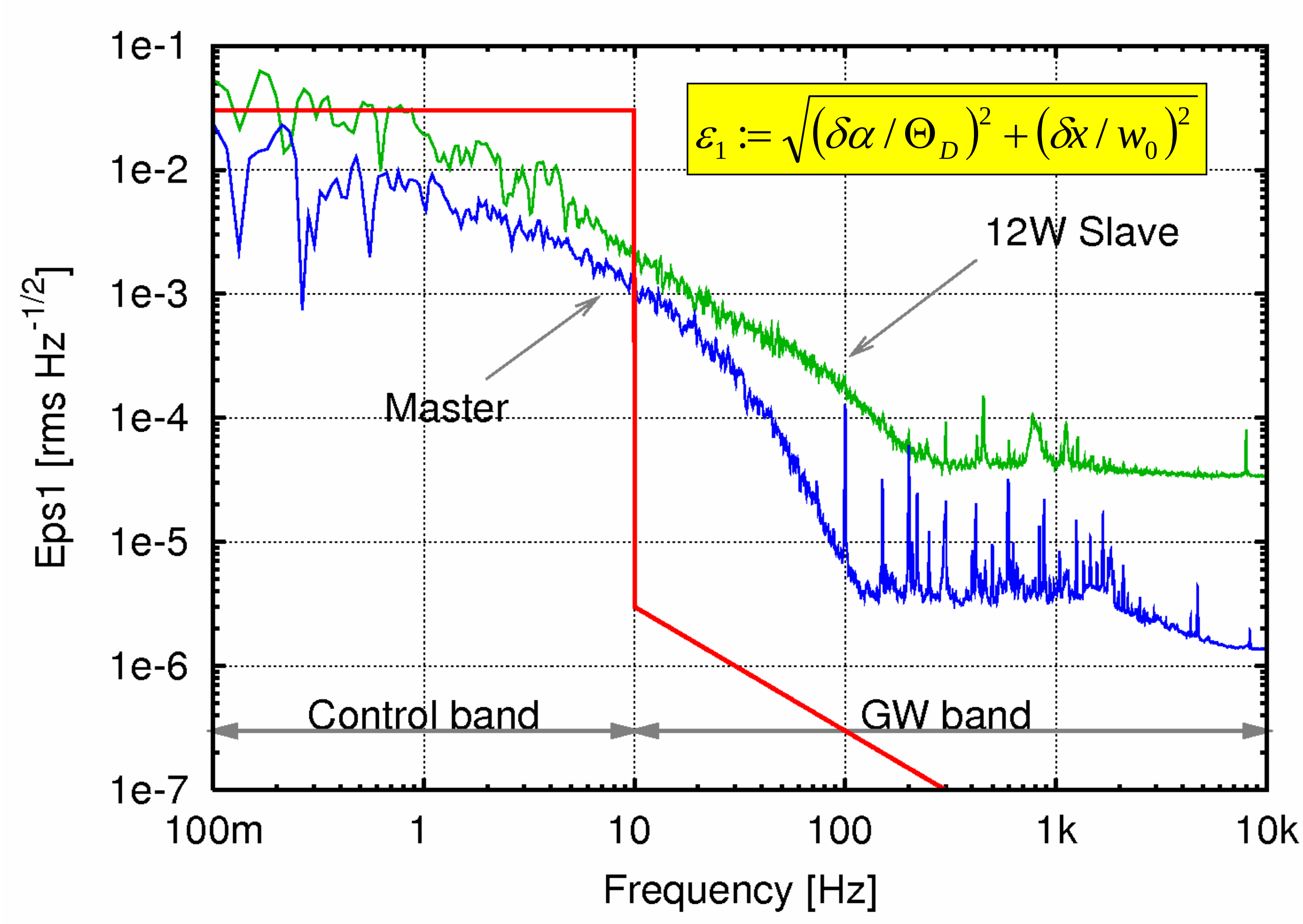
12W Nd:YAG oscillator: 88,4%

40W Nd:YVO amplifier: 96,1%

Gaussion Mode Expansion

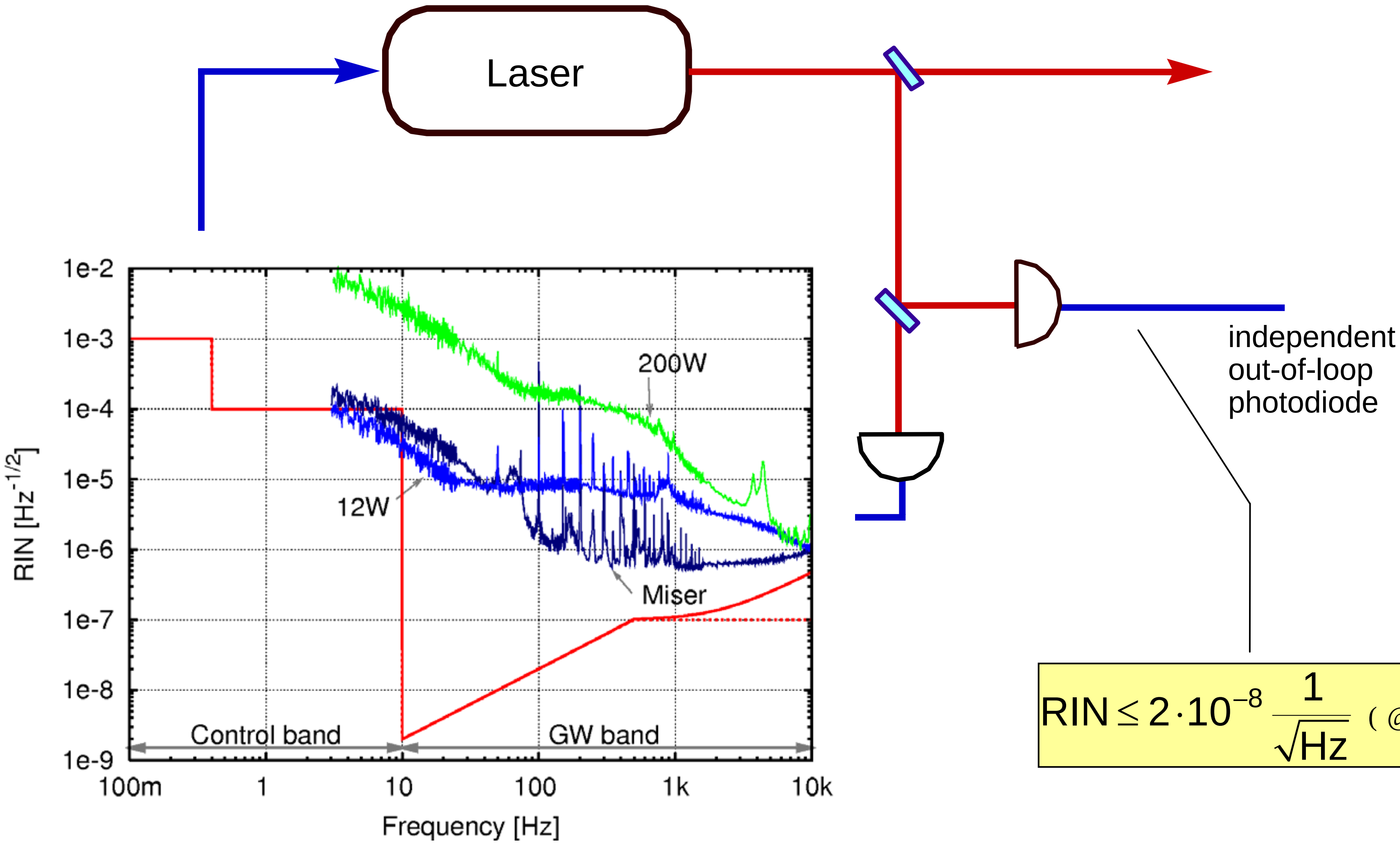


Beam Pointing Spectral Density



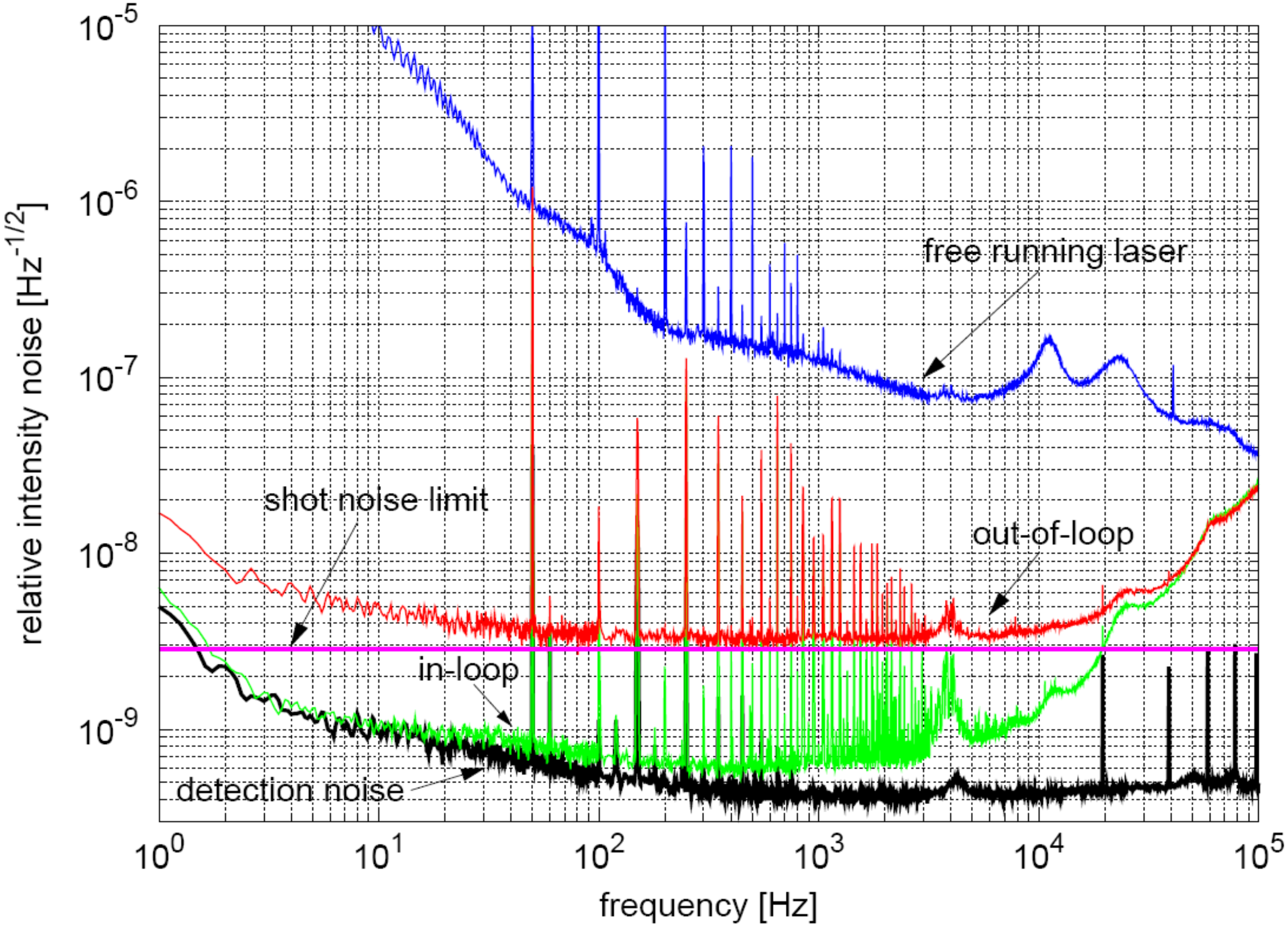
P. Kwee et al., submitted to Rev. Sci. Instrum. (2007)

Power Noise Reduction



$$\mathrm{RIN} \leq 2 \cdot 10^{-8} \frac{1}{\sqrt{\mathrm{Hz}}} \quad (@\,200\mathrm{Hz})$$

Power Noise Reduction



Seifert et al., Opt. Lett. 31 (2006) 2000

Summary

- GW community has developed
  - high-power lasers with high stability
  - high precision detectors and diagnostic tools
  - squeezed light sources
- what is required for the future
  - device to sense power noise down to shot noise of 1W at 10Hz
  - adaptive optics techniques to improve spatial beam profile or generate beam with non-gausian intensity destribution
  - high power laser at different wavelength
  - simplified systems like all fiber layouts
  - lasers with higher powers