Optical design of ’shining light through wall’ experiments

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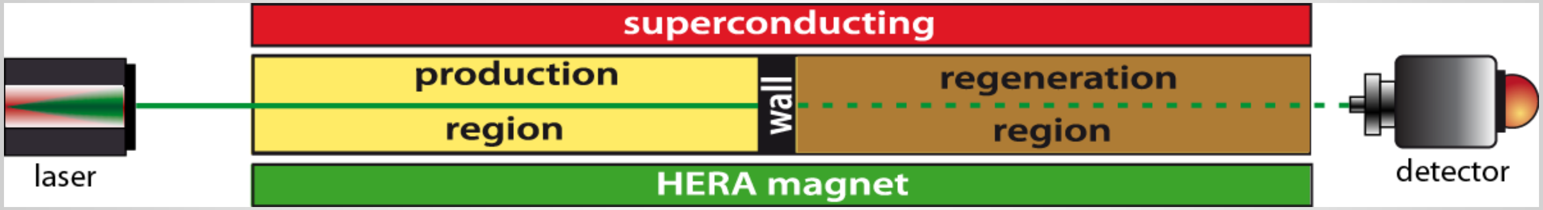
underlying concept



- light on right side of the *wall* oscillates into WISPs with probability P
- WISPs transvers through wall without attenuation
- WISPs oscillate on left side of *wall* back into light with probability P'
- photon to axion conversion probability

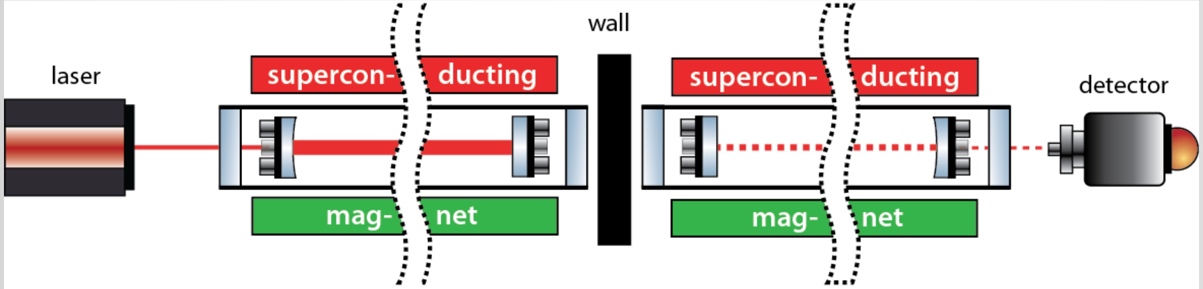
$$P = \frac{1}{4}\frac{1}{\beta_a\sqrt{\epsilon}}\left(g_{a\gamma\gamma}B_0L\right)^2\left(\frac{2}{qL}\sin\left(\frac{qL}{2}\right)\right)^2$$

β_a *axion speed*
$q = k_a - k_\gamma$ *(momentum transfer)*
$g_{a\gamma\gamma}$ *axion – photon coupling*
B_0 *magnetic field strength*
L *interaction length*
E_0 *field amplitude on left side*

- amplitude of WISPs field through wall $a = E_0\sqrt{P}$
- amplitude of regenerated E-field on right side of *wall* $E_r = \sqrt{P'}\,a$
- regenerated photon/s on detector: $n \propto |E_r|^2 = P'P\,|E_0|^2$

optical design goals

- make regenerated EM field as large as possible ($E_r = E_0 \sqrt{P\,P'}$)
    - high power of light source (laser)
    - Fabry Perot resonator (optical cavity) on left side to enhance light field
- detect regenerated EM field with high sensitivity
    - light detection scheme with low dark noise
        - photon counting with low dark rate (CCD, transition edge detector)
        - optical heterodyne readout scheme to overcome dark noise of photodetector
    - use optical recycling techniques to increase signal on detector

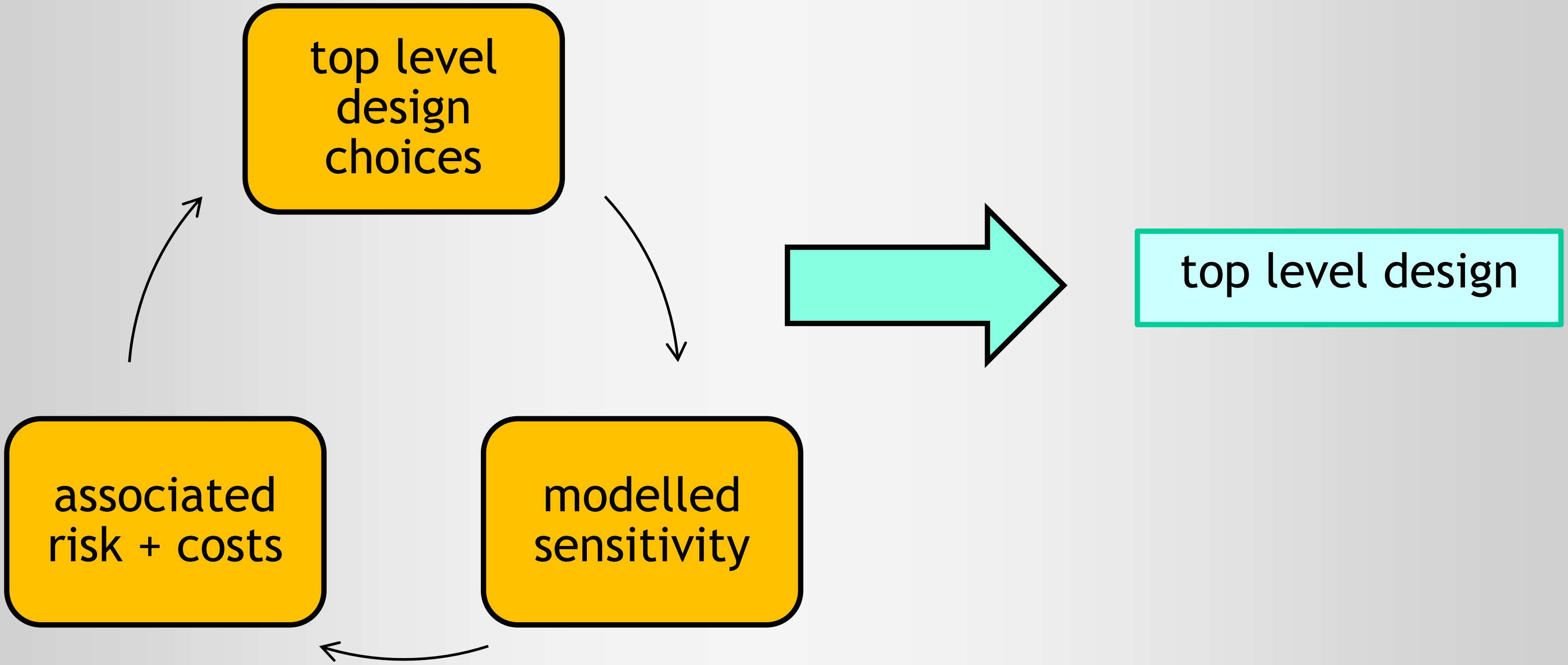


optical design - limitations

- “hard” physical limits
    - available aperture
    - available coatings (scatter loss)
    - limits set by environment (length and alignment fluctuations due to seismic, vibrations, …)
- how much risk is acceptable
    - durability of coatings (intrinsic, cleanliness)
    - radius of curvature fabrication tolerances
    - cavity stabilization (g-factor, rms residuals)
- available resources

optical design process

design goals and limitations ⇒ top level design choices



top level design choices

modelled sensitivity

associated risk + costs

top level design

go to next level of detail …

optical design choices

- make regenerated EM field as large as possible ($E_r = E_0 \sqrt{P\,P'}$)
  - high power of light source (laser)
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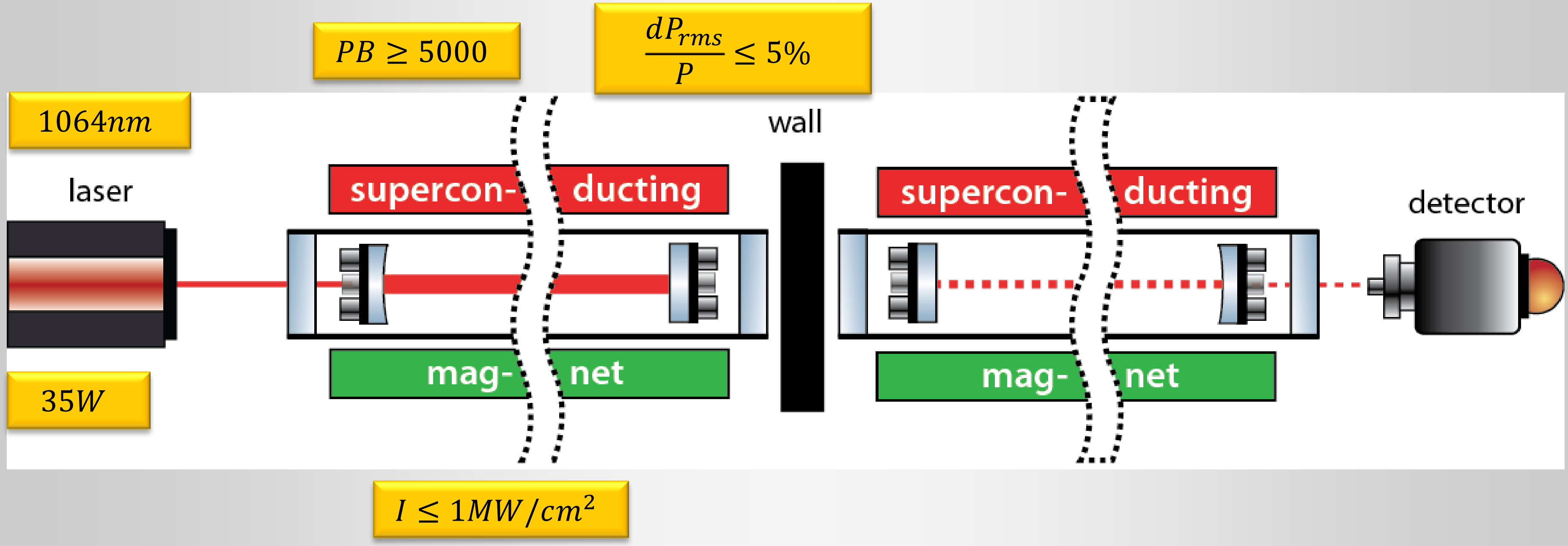
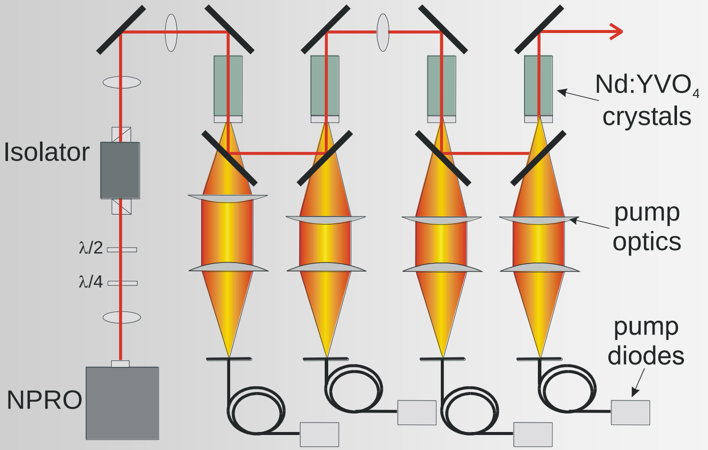
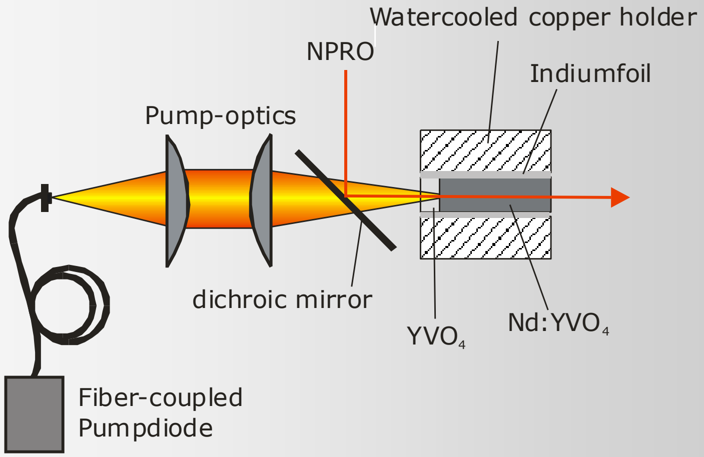
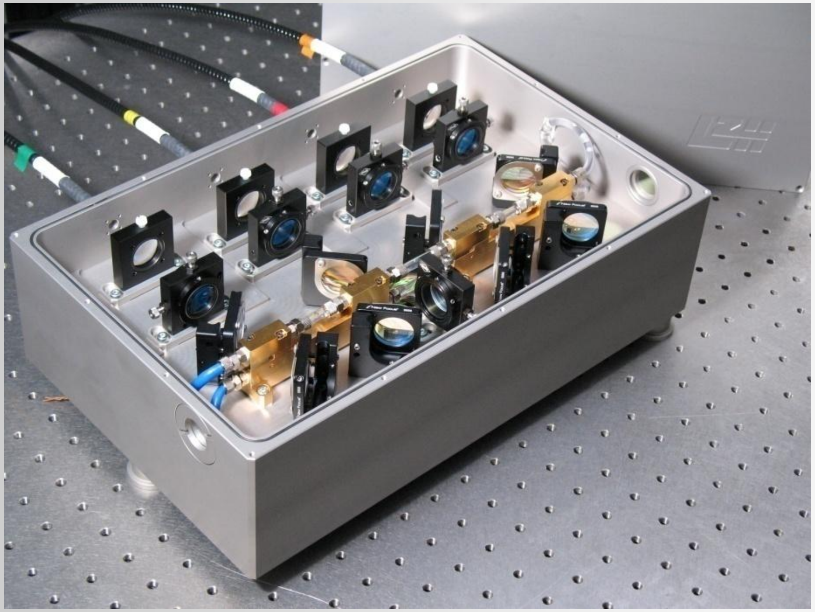


(exemplarily parameters of ALPS II design)

35W laser system



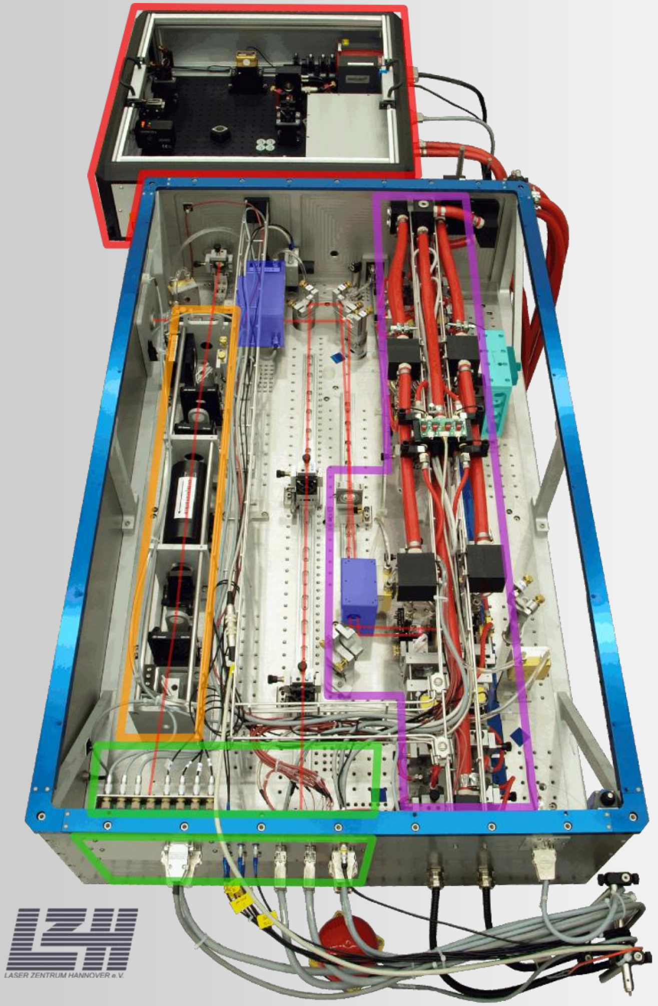


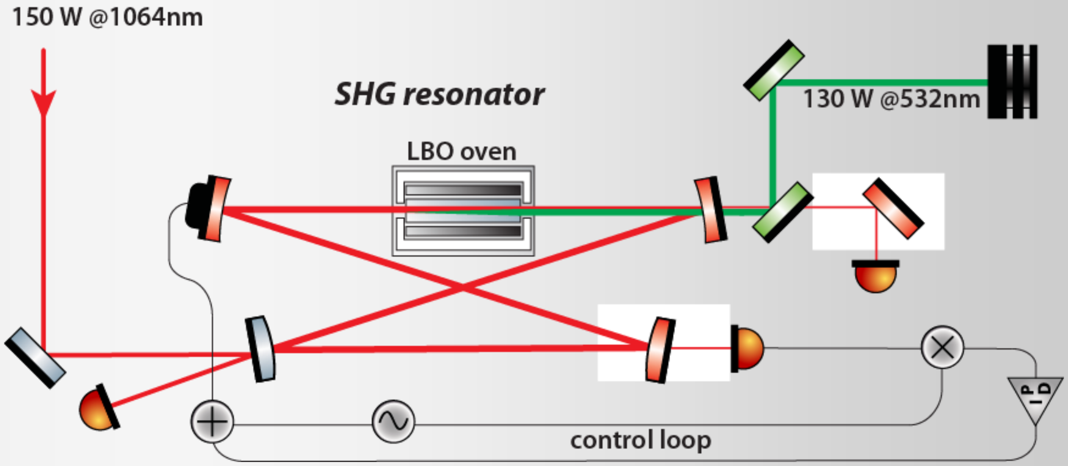


- Crystal:
  3 x 3 x 10 mm^3 Nd:YVO_4
  8 mm 0,3 % dot.
  2 mm undoped endcap
- Pump diode:
  808 nm, 45 W
  400 µm fiber diameter
  NA=0,22
- amplifier:
  38W for 2W seed and 150W pump

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

180W laser @ 1064nm / 130W laser @ 532nm





T. Meier et al., Opt. Lett. **35**,No.22,p 3742 (2010)

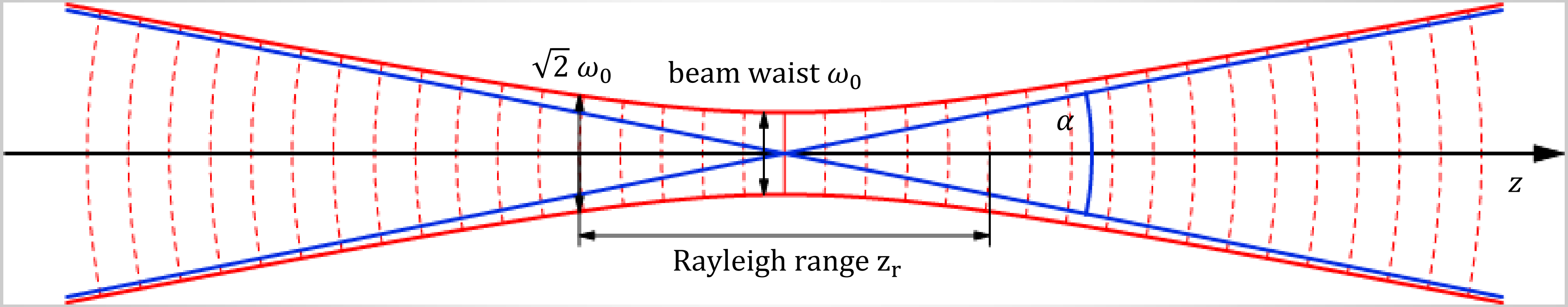
single-mode, single-frequency laser with high spatial purity are available

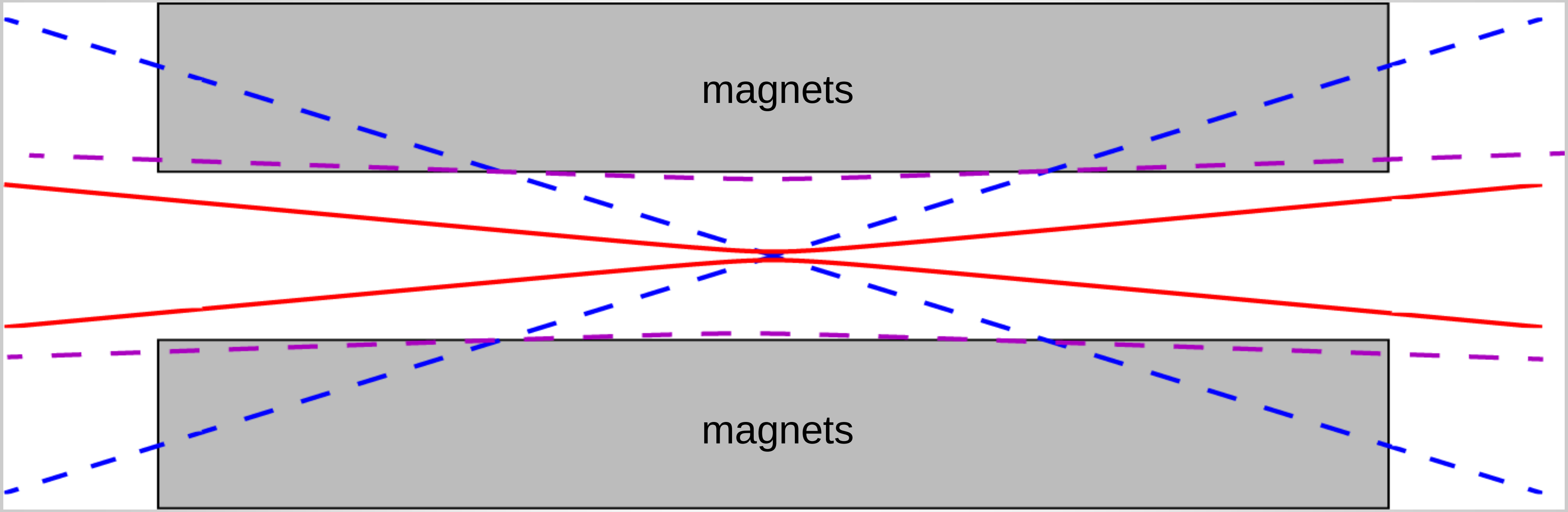
- 180W @ 1064nm
- 130W @ 532nm

Winkelmann et. al, Appl. Phys. B. **102**, No.3, 529 (2011)

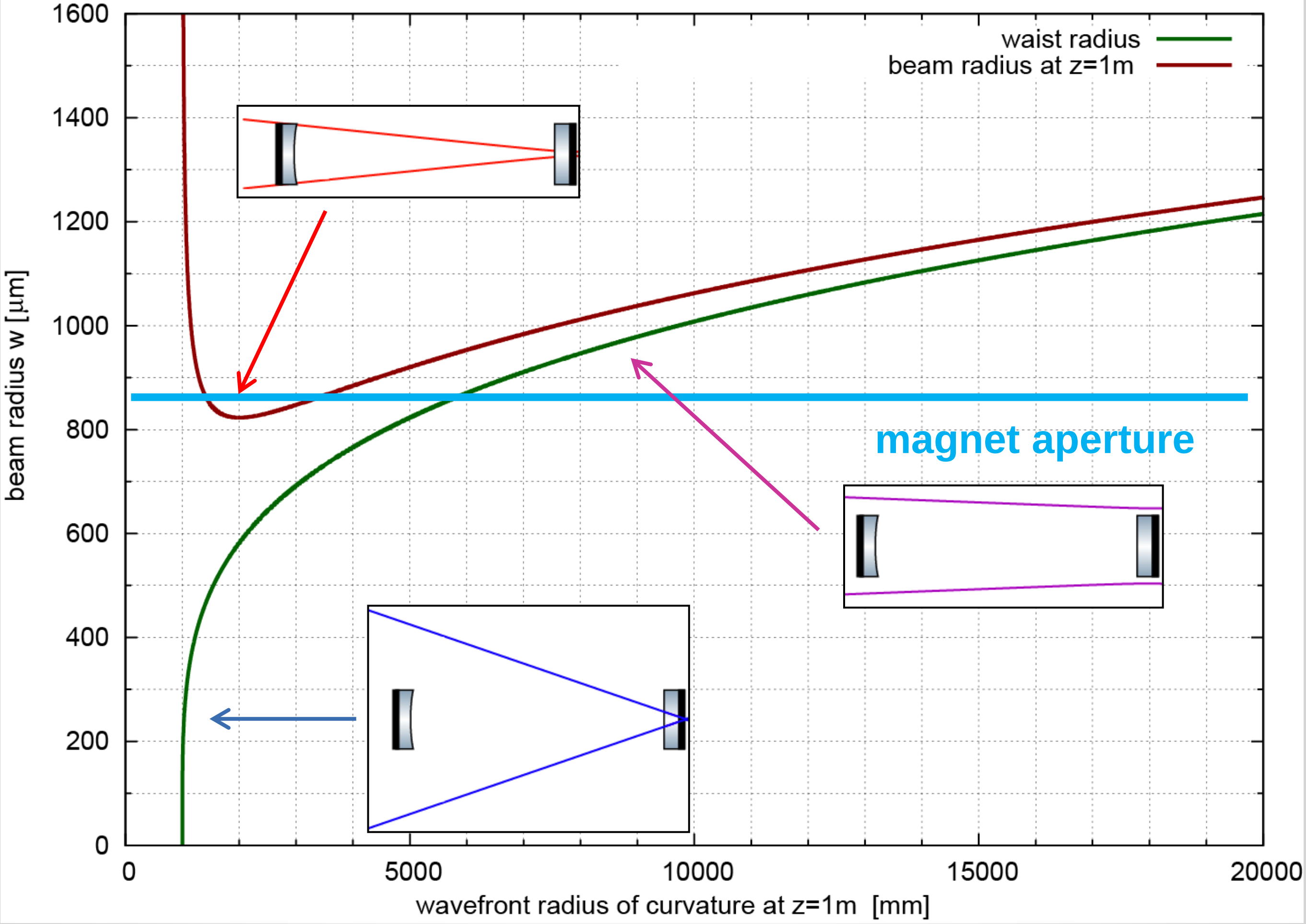
Kwee et al, Opt. Express, **20**, No. 10, 10617 (2012)

Gausssian beam must fit to magnet aperture





radius of curvature of mirrors

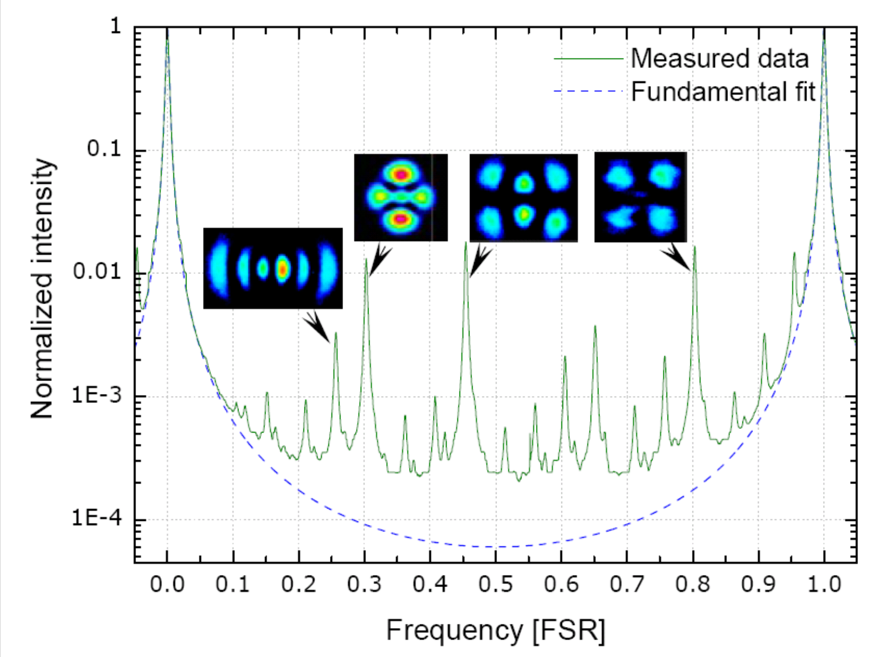


optimization: minimal clipping losses at aperture
$\Rightarrow\ z_R = L$ (minimal beam radius on curved mirror)

radius of curvature of mirrors

radius of curvature of mirror must match wavefront curvature of desired gaussian beam:

$$R(z) = z\left(1+\left(\frac{z_r}{z}\right)^2\right) \xRightarrow{z=z_r=L} R(z_r) = 2z_r = 2L$$



example of higher order modes

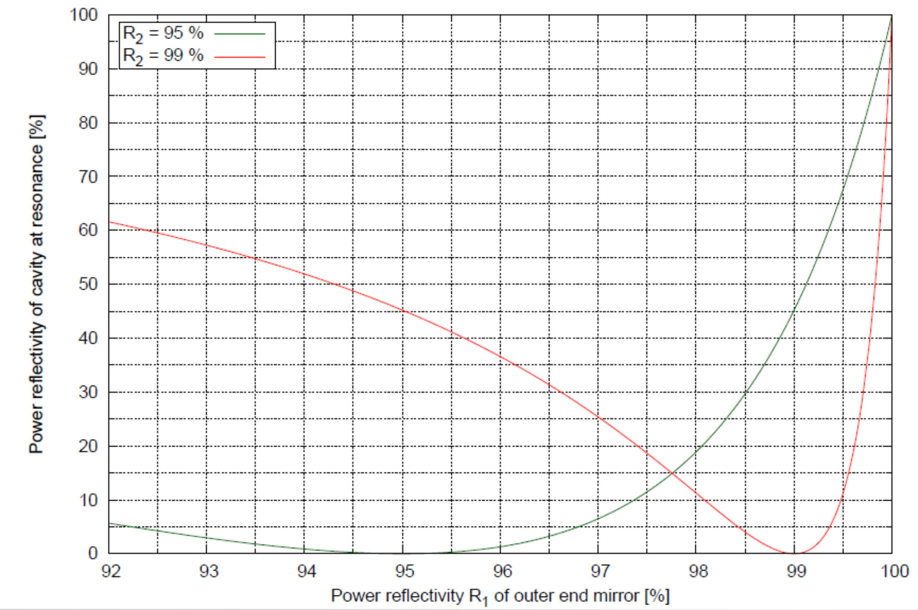
- higher order mode spacing
  $\Delta f = \frac{1}{4}(n+m) * FSR$

  $\Rightarrow$ order 4 modes resonate at same lenght as $\mathrm{TEM}_{0,0}$
- this might cause problems in length and alignment control
- optimize for small aperture losses <u>and</u> no *higher-order modes with low mode number* close to TEM_{00} resonance

mirror reflectivity

$$PB_m \approx \frac{4T_{in}}{(T_{in}+T_{out}+A)^2}$$

$$Finesse\ F = \frac{FSR}{FWHM} \approx \pi\, PB_m$$

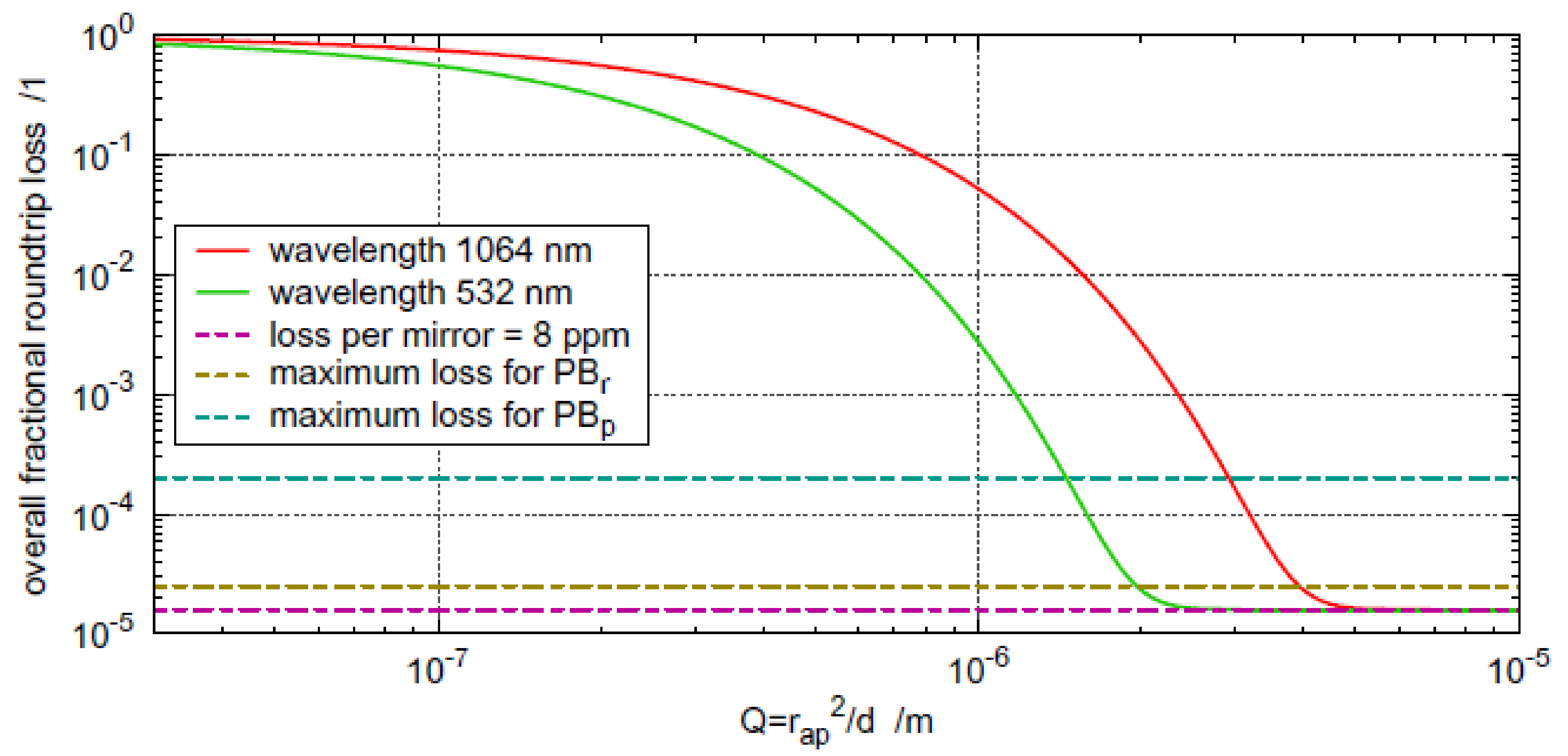


- mirror reflectivity needs to be optimized to get highest power buildup
- goal: impedance matched case

$$T_{in} = T_{out} + A$$

- estimate of losses in cavity is an important design parameter
  - scattering mirrors
  - difraction loss apertures
  - absorption loss mirrors
- durability of mirrors

ALPS II mirror reflectivity optimization



r_{ap} : *radius of magnet aperture*

d = *magnet length*

$PB_p = 5000$

$PB_r = 40000$

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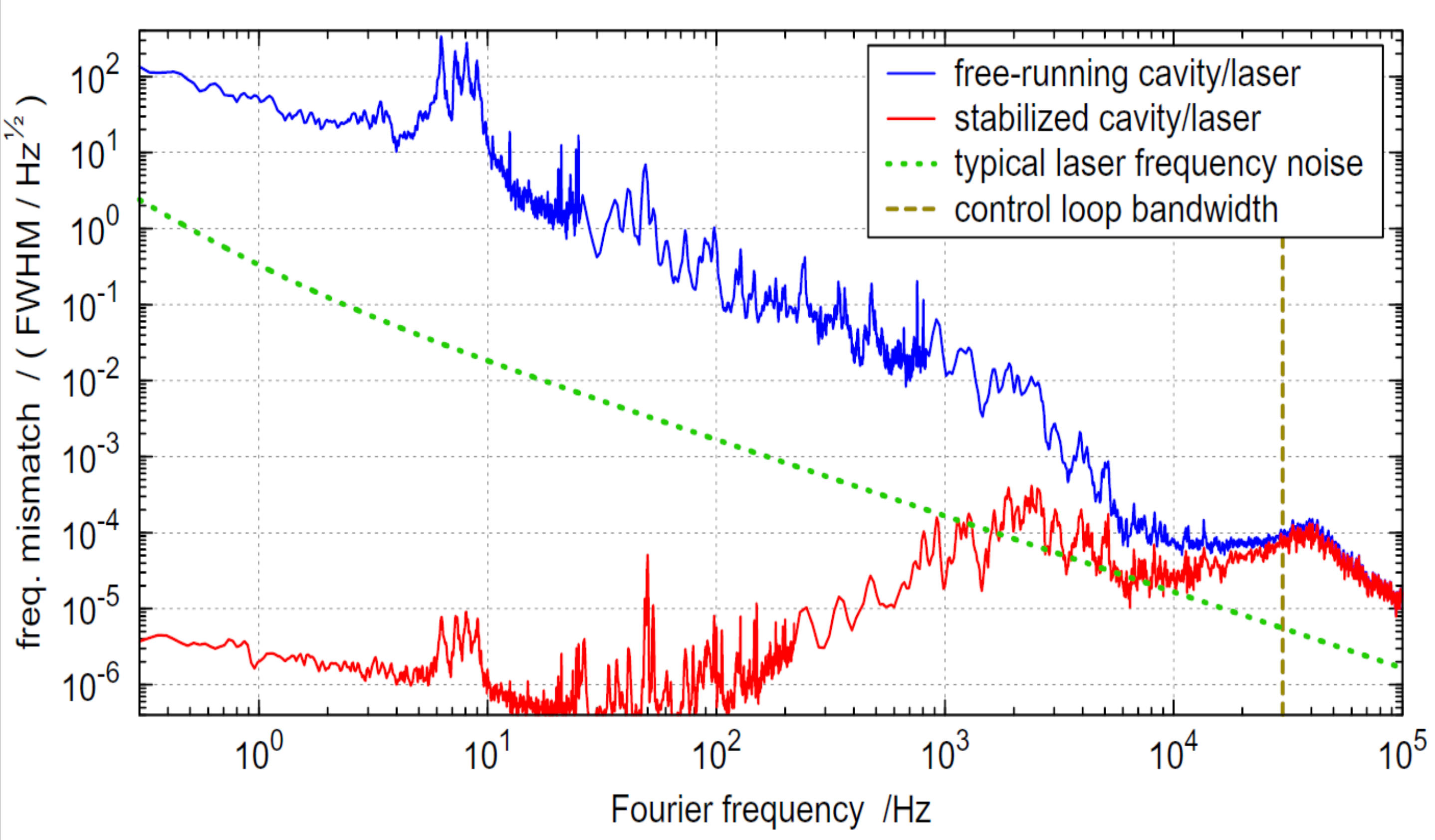
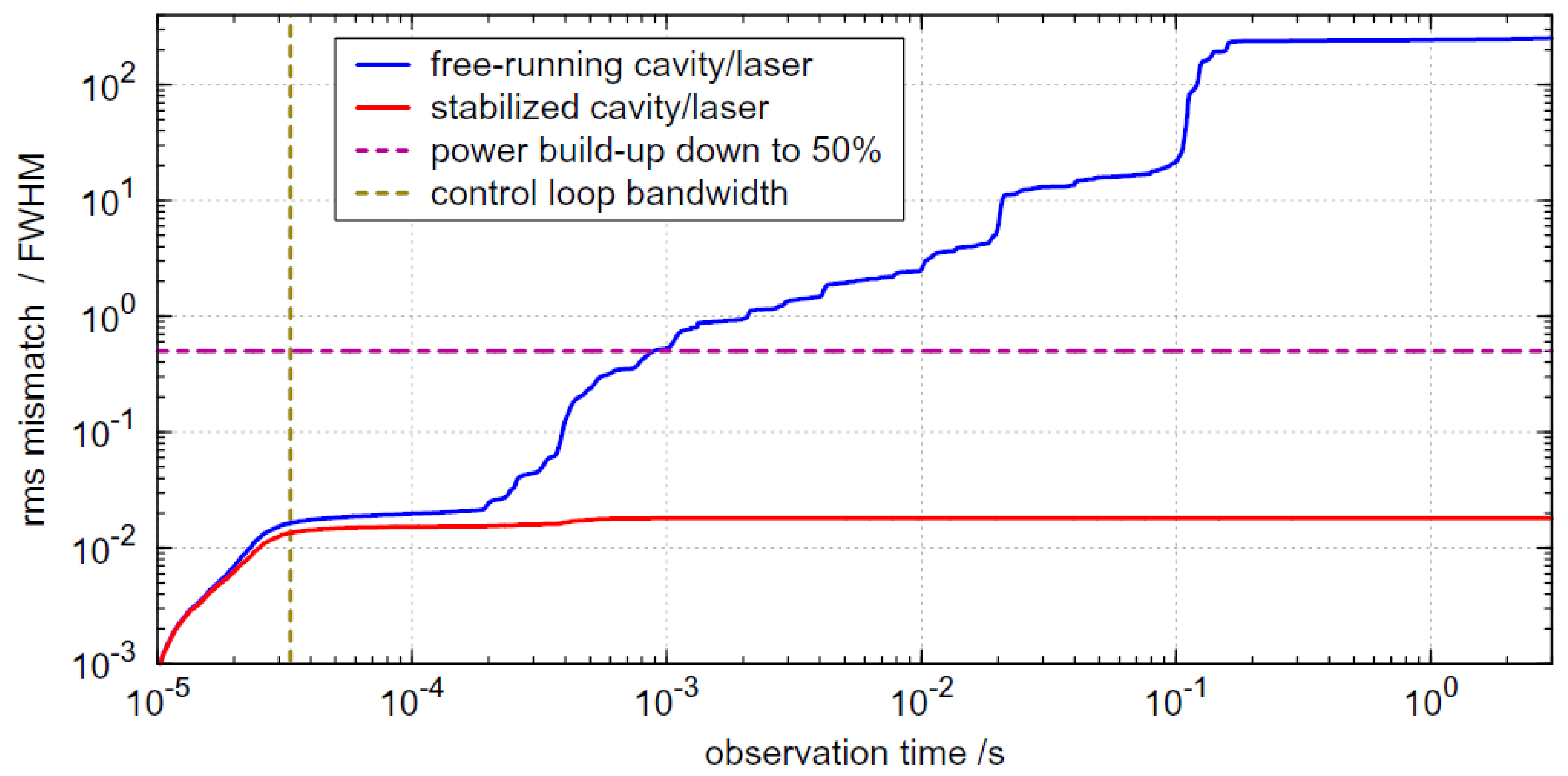
length and frequency fluctuations

frequency mismatch between one of the cavity resonance frequencies and laser frequency $\Delta\nu$ has to be small:



control frequency mismatch laser – cavity

- uncontrolled (free running) rms-mismatch $\Delta\nu_{free}^{rms}$ determines control loop range and lock-acquisition speed
- remaining mismatch $\Delta\nu^{rms}$ with servo control determines power-buildup fluctuations



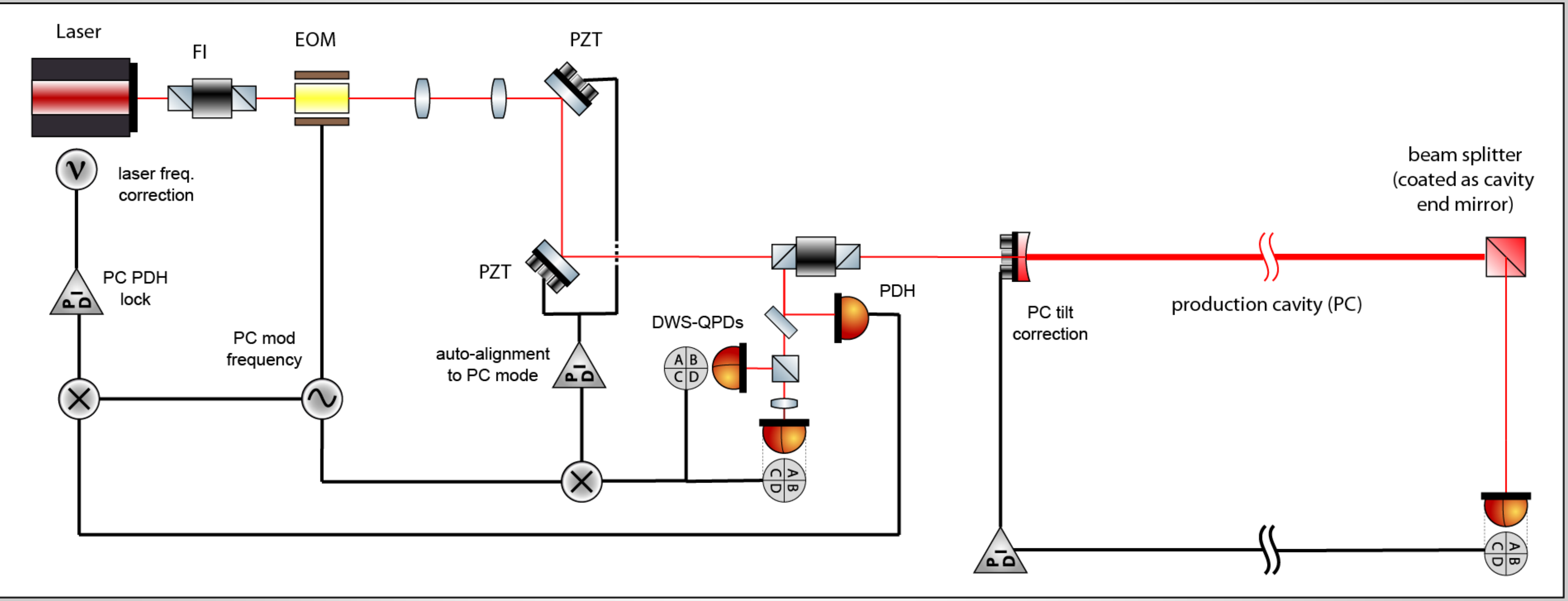
alignment control

- small alignment mismatch (lateral, diameter, ROC) as well as small alignment fluctuations

$$PB \approx \frac{4T_{in}}{(T_{in}+T_{out}+A)^2}\,\frac{1}{\left(1+\left(\frac{\Delta\nu}{FWHM/2}\right)^2\right)}\left(1-\frac{\Delta\nu_{00}}{\nu_{00}^{opt}}\right)$$

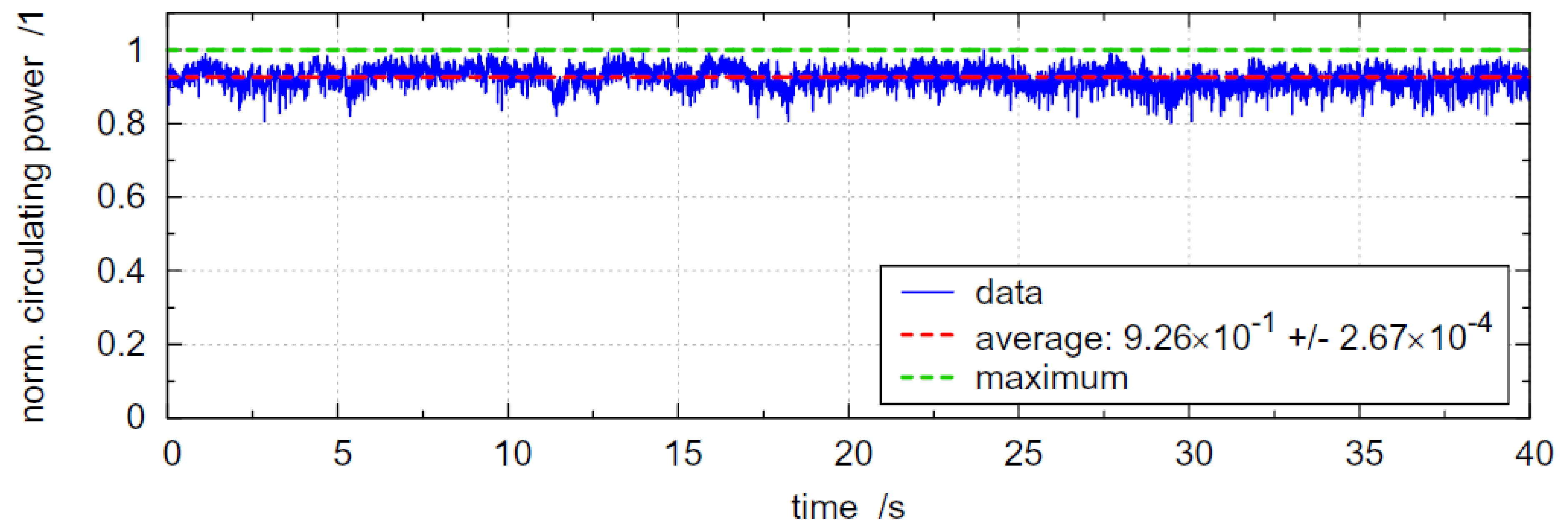
- active alignment control needs:
  - either high stability between position sensing photodiode or differential wavefront sensing
  - again range of actuator is an issue
  - no lock acquisition: error signal is valid once length control is in operation

matching of laser to generation cavity

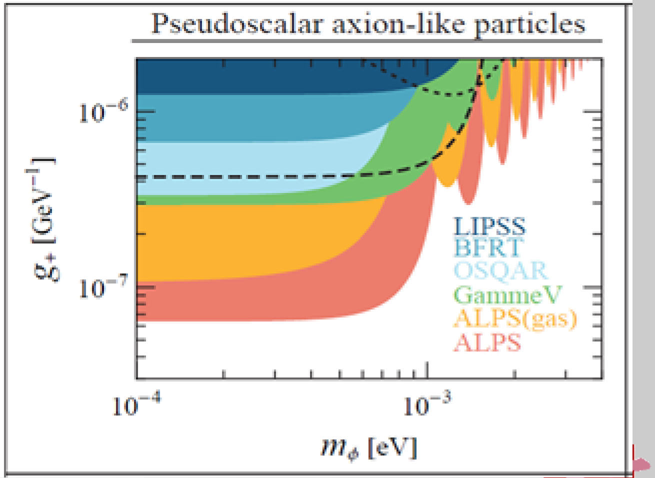


- length / frequency control via Pound-Drever-Hall technique with appropriate actuators
- alignment control via split quadrant diodes (DC or heterodyne)

It works: ALPS1 experiment



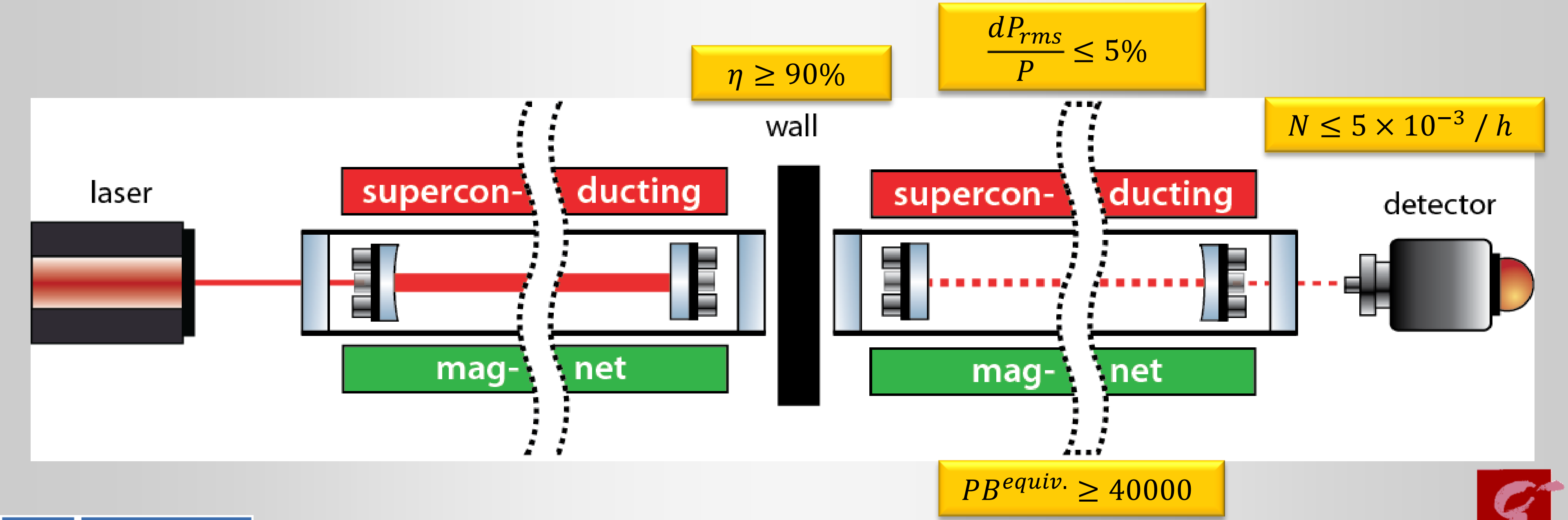
- Circulating power: up to 1.4 kW at 532 nm
- Average over 55 h: 1.04 kW
- Factor 100 higher than pulsed systems



K. Ehret et al., NIM A, ***612****:83–96*
K. Ehret et al., Phys. Lett. B, **689**:149–155

optical design goals

- detect regenerated EM field with high sensitivity
  - use optical recycling techniques to increase power of regenerated light
  - light detection scheme with low dark noise
    - photon counting with low dark rate (transition edge detector)
    - optical heterodyne readout scheme to overcome dark noise of photodetector



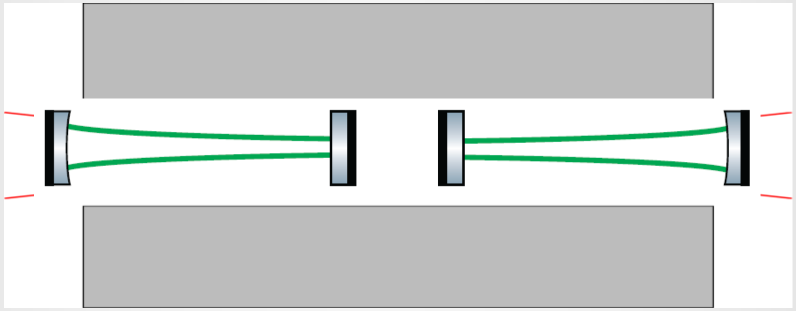
(exemplary parameters of ALPS II design)

requirements - regeneration side

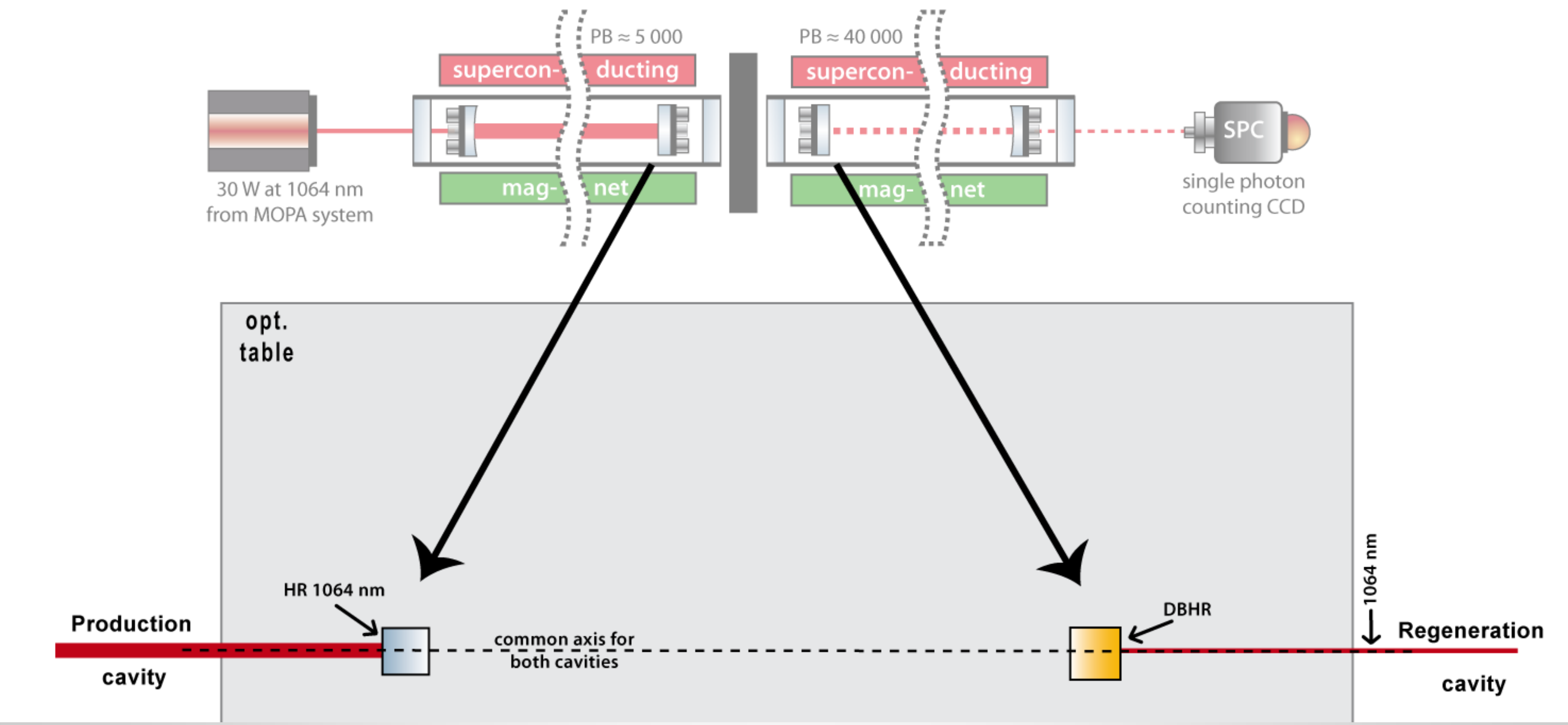
- high cavity Finesse (high power buildup)
  - ⇒ low diffraction loss by apertures (magnets)
  - ⇒ low scattering (and absorption) of mirrors
- small $\Delta\nu := \nu_{production} - \nu_{regeneration}$
  - ⇒ small length fluctuations of cavity
  - ⇒ active length stabilization control loop with high bandwidth and sufficient range
- small spatial mismatch of regenerated EM field and cavity Eigenmode
  - ⇒ small lateral and angular fluctuation of cavity Eigenmode (with respect to production cavity Eigenmode)
  - ⇒ active stabilization of differential angular and lateral fluctuations (with high enough range and bandwidth)

matching production and regeneration cavity

- regenerated mode is identical to mode in generation cavity (photons have identical properties)
- match resonance frequency
- spatial mode matching
  - axial (two planar mirrors at distance)
  - lateral/angular (active control)
- without control beam hitting the detector ($N \leq 10^{-3}/h$)
  - use control beam of different wavelength/polarization/spatial path
  - attenuate control beam by factor $\alpha = 10^{19}$

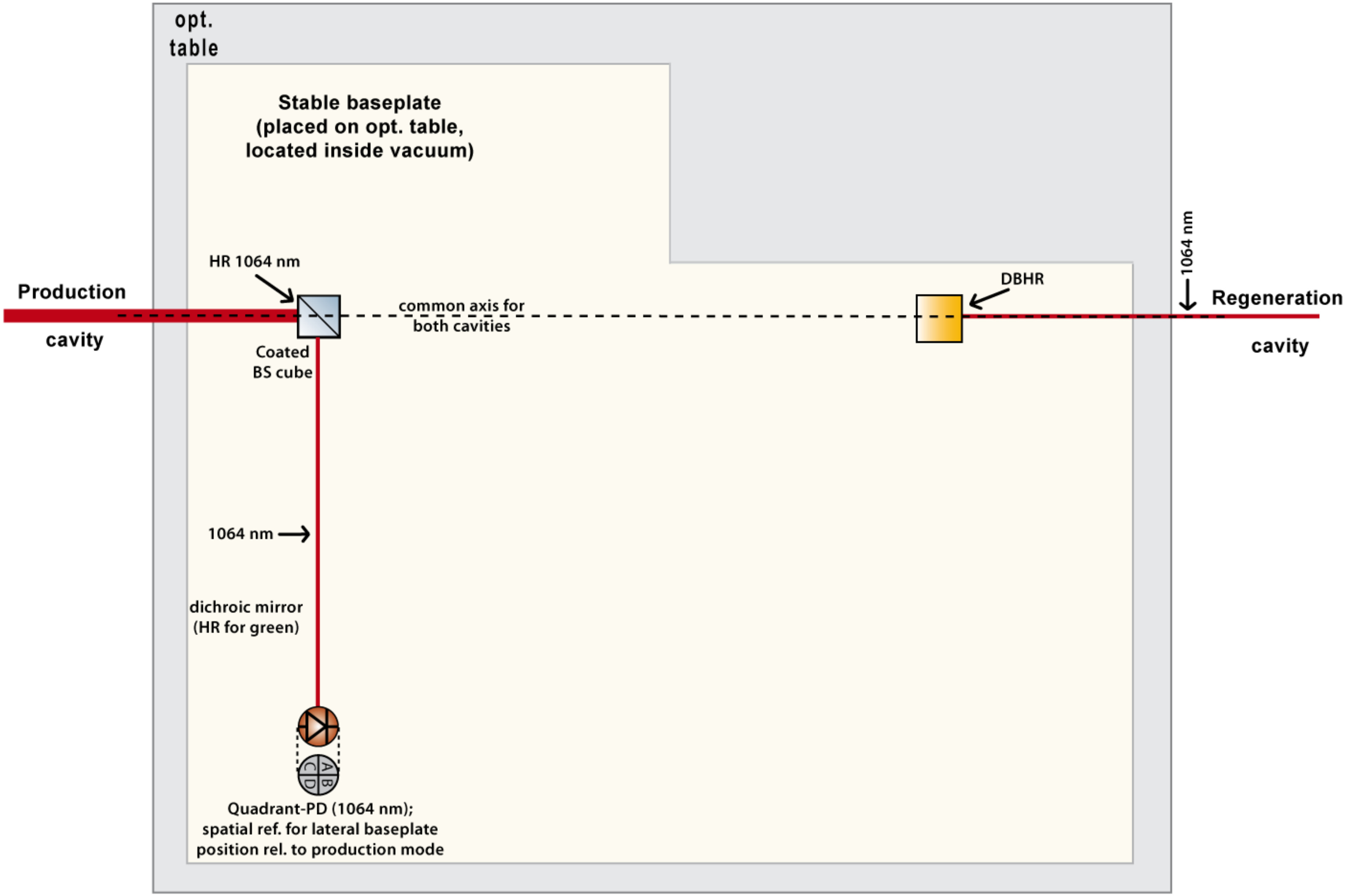


ALPSII solution: large Δλ and photon counting

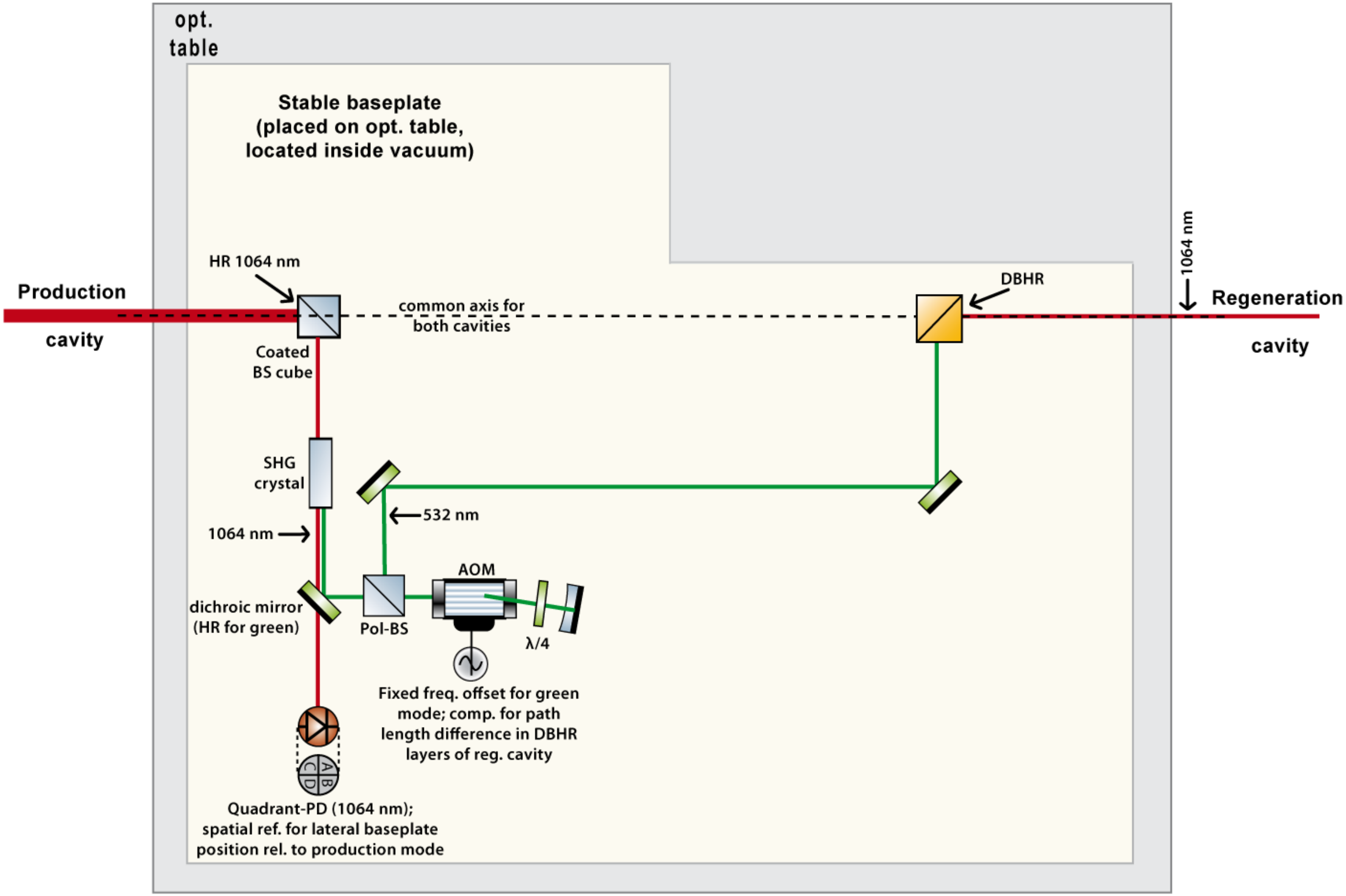


- mount central mirror of production cavity (PC) and regeneration cavity (RC) rigidly on base-plate
- use alignment markers rigidly mounted on base-plate to stabilize Eigenmodes of cavities to be co-linear

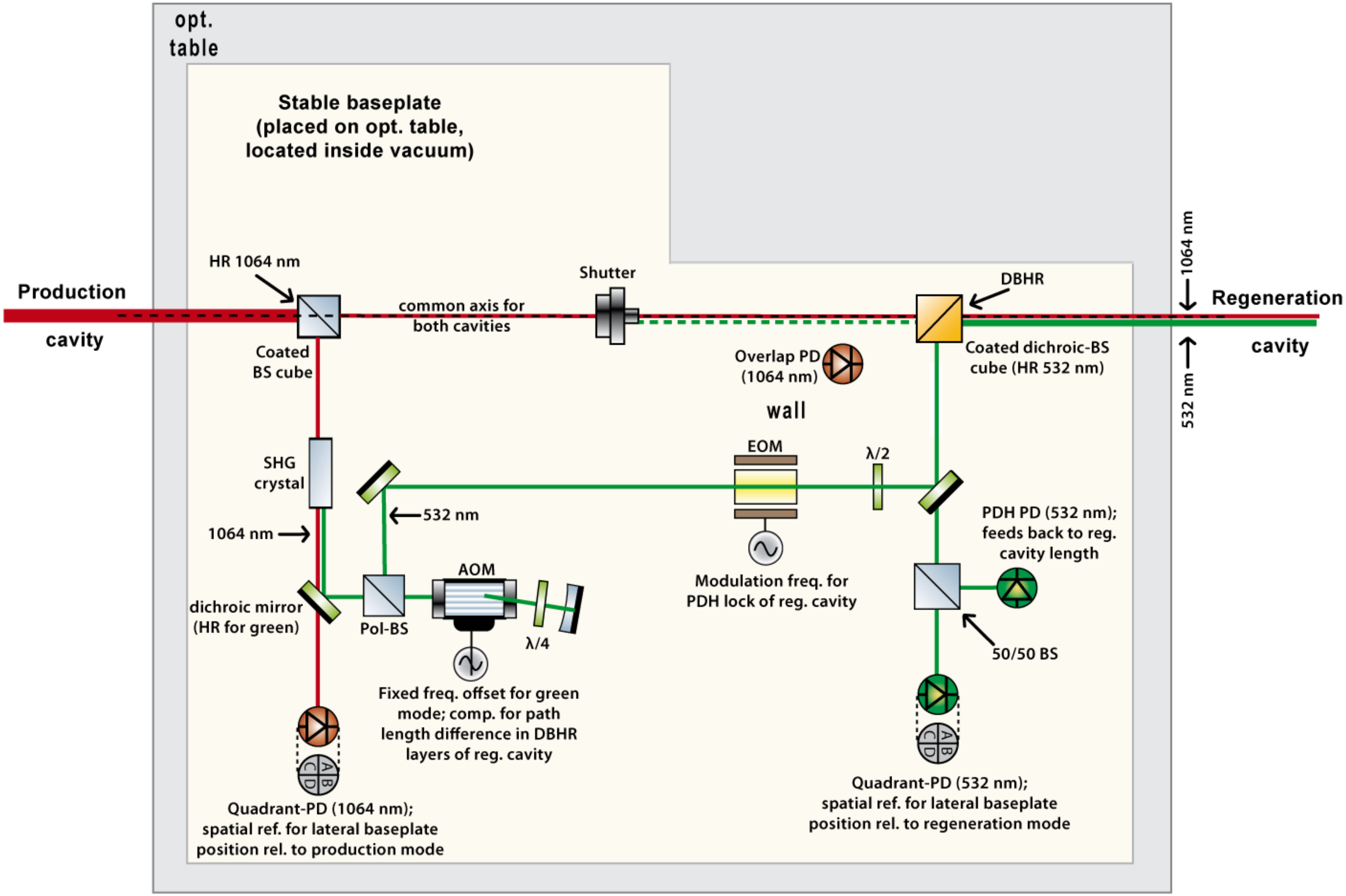
fix production cavity mode



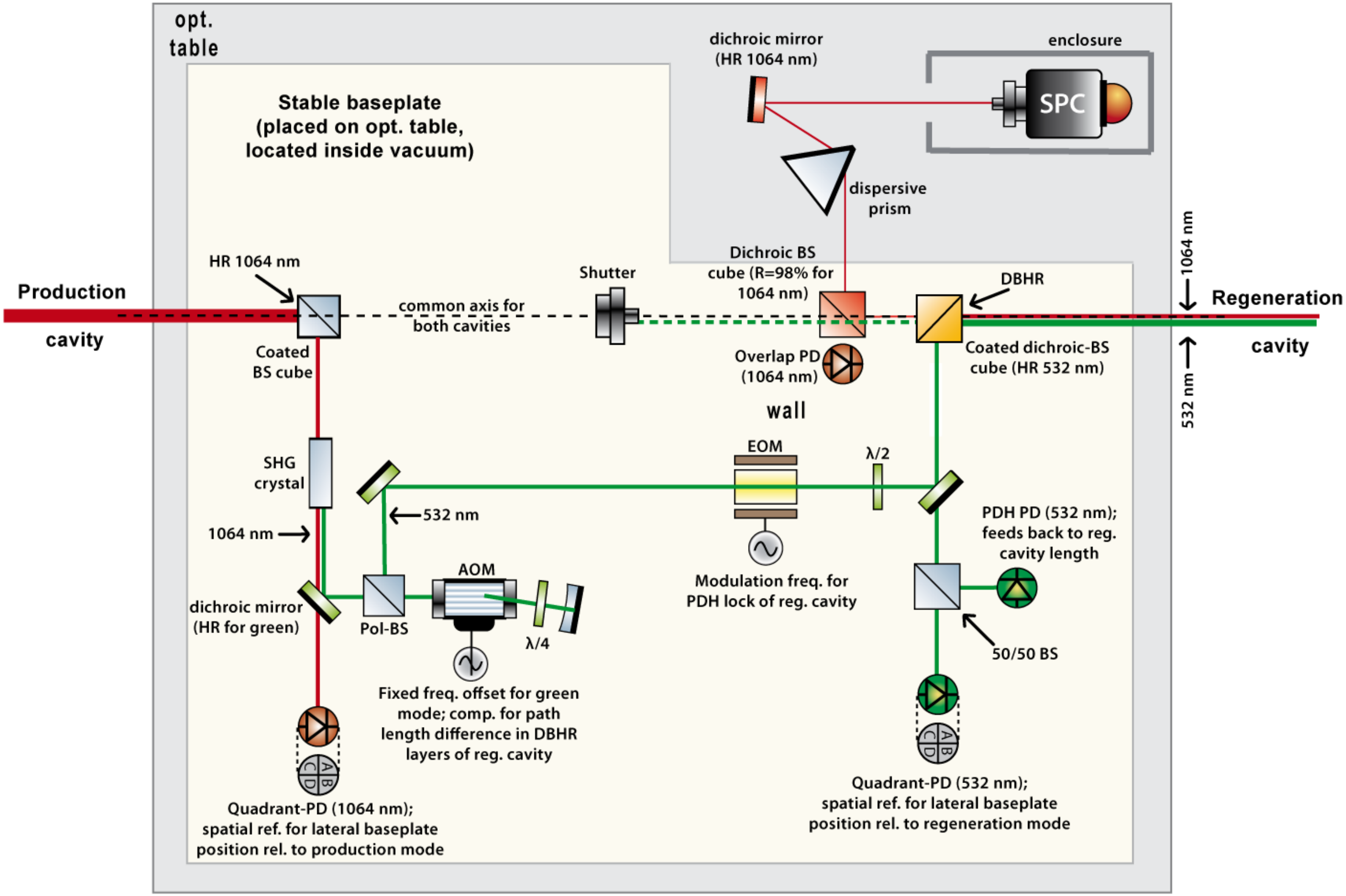
match SHG beam to regeneration cavity



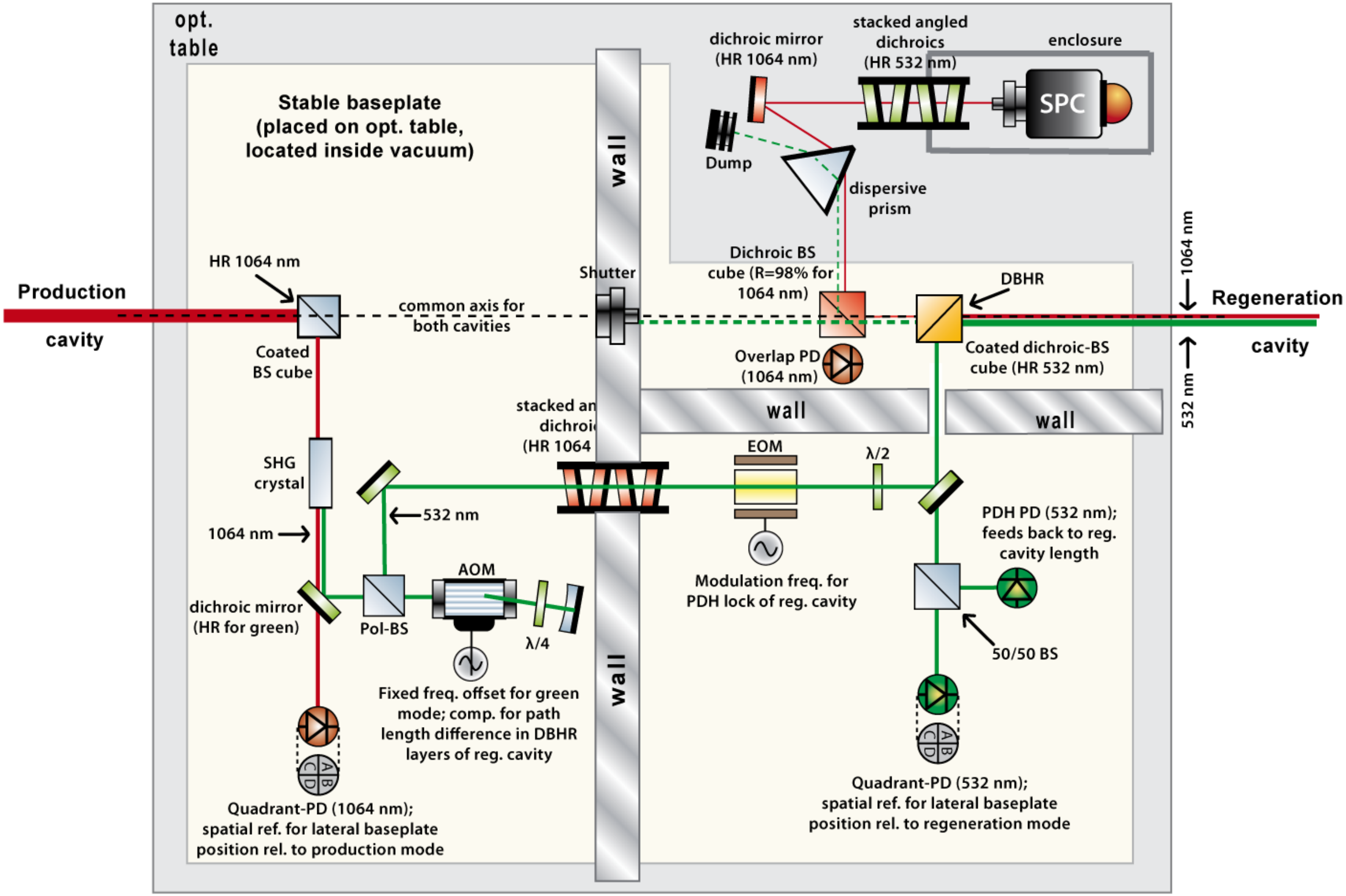
lock and fix alignment of regeneration cavity



single photon detector



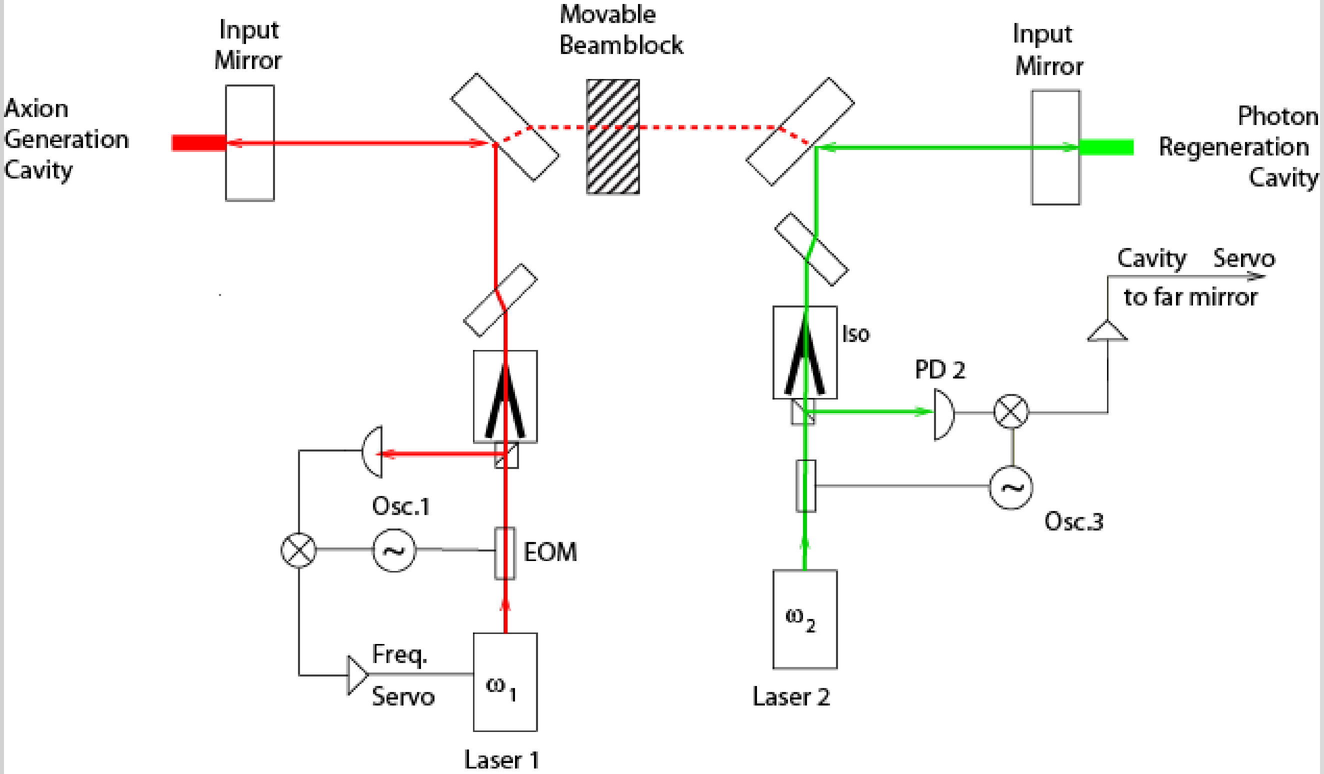
block all direct laser photons



ALPSII – special issues

- mirror show differential phase shifts for main and control beam
- low drift/fluctuations of components on central board
- central cavity mirrors need to be parallel $\alpha \leq 10\mu rad$
- control beam must be attenuated by $\alpha = 10^{19}$
- free running rms motion low enough to allow for lock acquisition
- spectral density of free running mirror motion compatible with control loop parameters (actuator range, spectral gain shape)

small Δλ and heterodyne detection



Müller et. al, Phys. Rev. D, **80** (2009)

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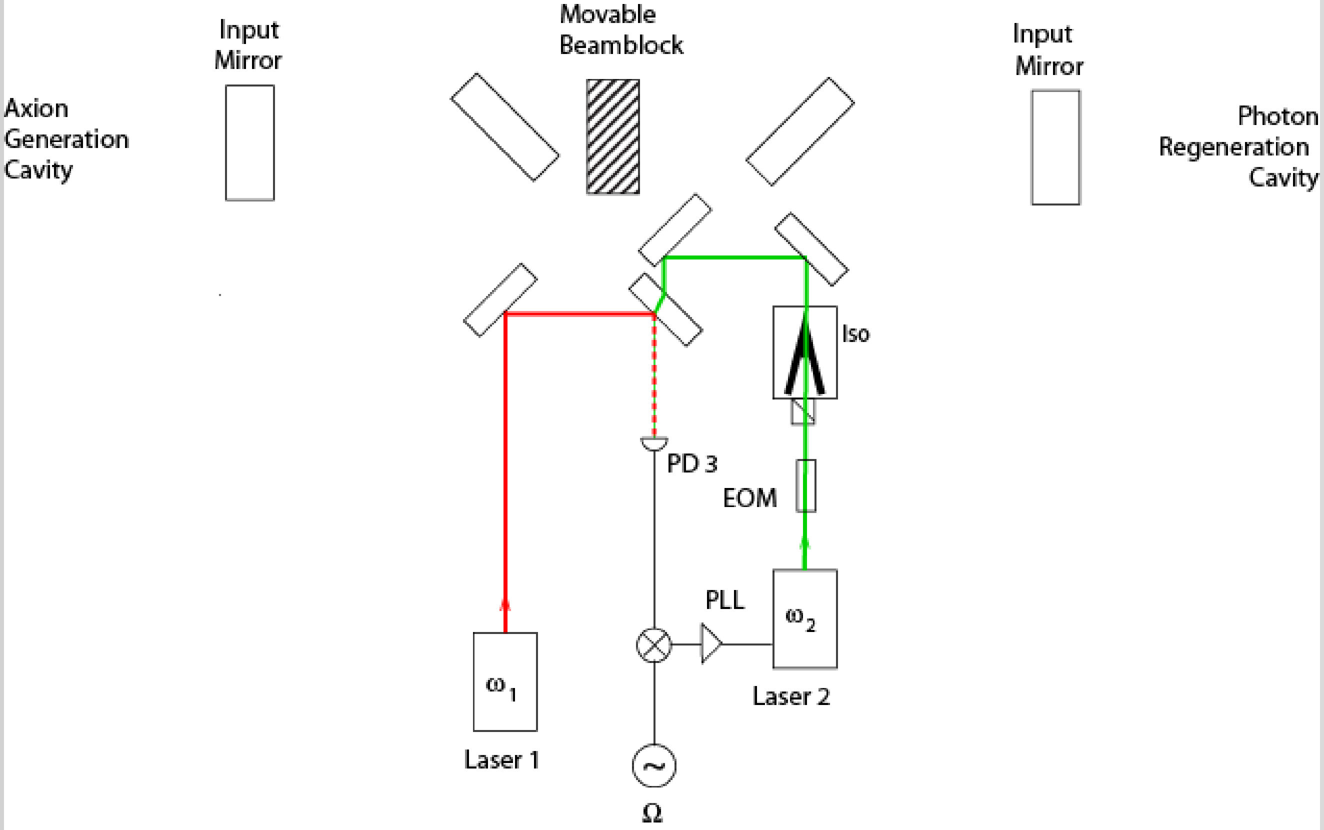

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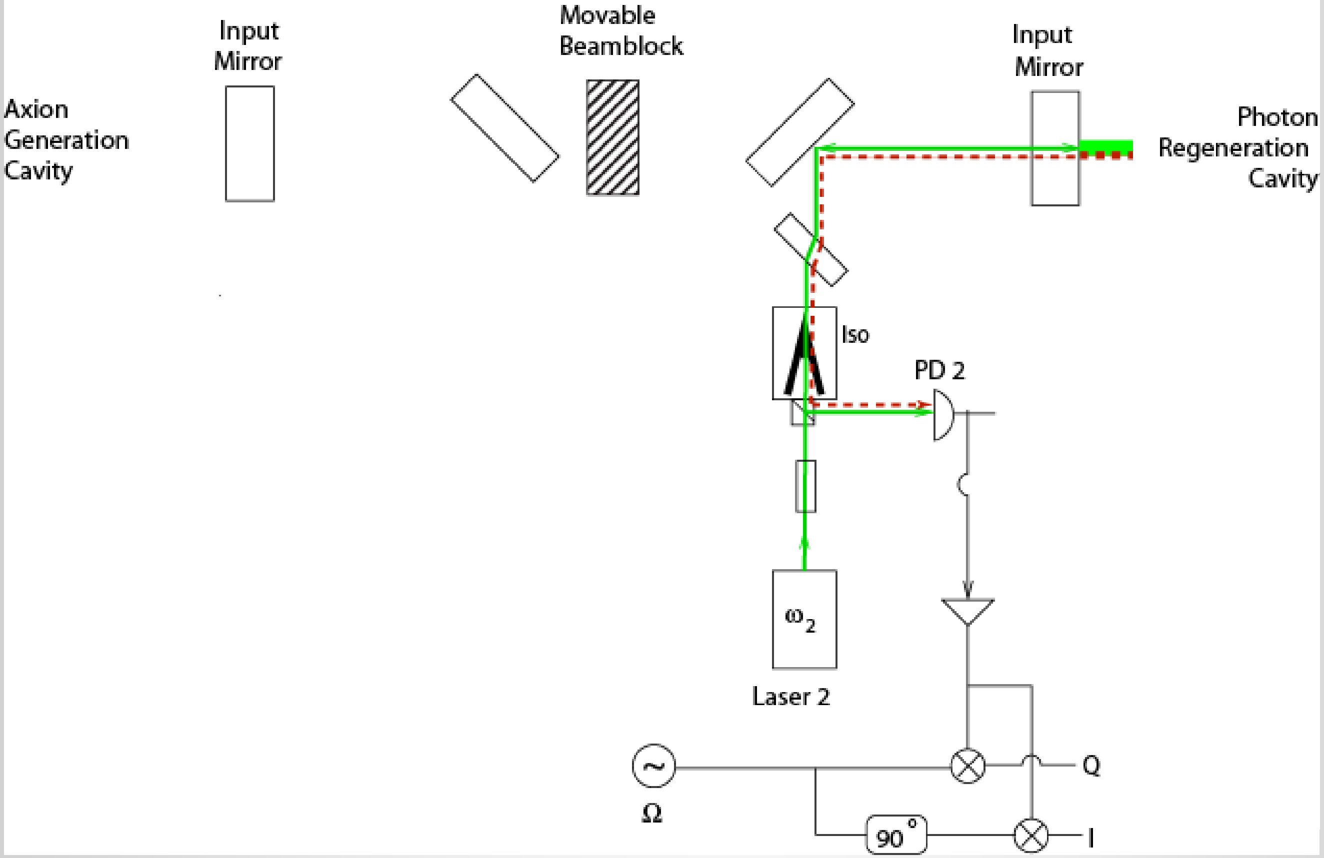

Müller et. al, Phys. Rev. D, **80** (2009)

summary

- treat laser as gaussian beam
- optimize gaussian beam wrt magnet aperture
- choose mirror curvature for stable cavity operation and reasonable higher-order-mode spacing
- optimize mirror reflectivity
  - acceptable intensity (generation side only)
  - lock acquisition / available loop gain
- design length and alignment control for production and regeneration cavity
- choose control beam compatible with detection scheme

thanks to all members of the ALPS collaboration in particular Tobias Meier and Robin Bähre