Techniques for the stabilization of the ALPS-II optical cavities

Robin Bähre for the ALPS collaboration

9^{th} PATRAS workshop for Axions, WIMPs and WISPs
Schloss Waldthausen, Mainz
2013 Jun 26^{th}

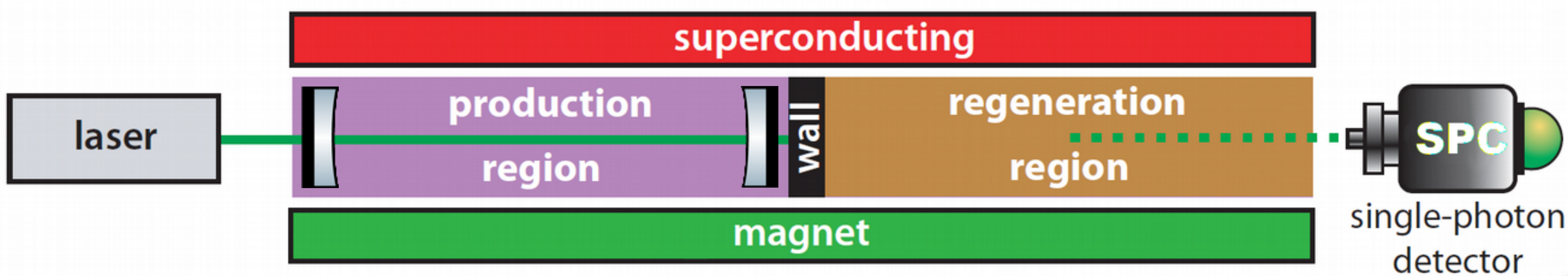
MAX-PLANCK-GESELLSCHAFT

Outline

- How LSW experiments can be improved by resonant optical techniques?
- Why are there challenging requirements on the optical design in ALPS-II?
- How we can meet these requirements?
- What has been achieved so far on behalf of the optical design of ALPS-II?

Light-Shining-Through-a-Wall (LSW)

- exploit coupling to EM fields for production and (indirect) detection of ALPs
- straight-forward approach, model independent
- ALP production in the lab is much weaker than from astronomical sources
- but: coherent light source offers many advantages



ALPS experiment conducted at DESY, 2009

ALPS-II

Production flux

- tap full potential of 35 W laser LIGO
- increase wavelength
- increase production build-up

Detector

- build detector with very low dark rate

weakest detectable coupling within certain mass region:

$$g = \frac{1}{B\,L}\sqrt{2}\,\sqrt[4]{\frac{h\,c\cdot SNR}{15\,P_{inc}\,PB_{p}\,\lambda}}\cdot\sqrt[8]{\frac{n_{dark}}{t_{m}}}$$

todays talks by:
J.-E. von Seggern
J. Dreyling-Eschweiler

Magnet and interaction regions

- increase interaction length
- (stronger magnets)

what else?

resonant enhancement of regenerated signal

Projected improvements in ALPS-II

Parameter	Scaling	ALPS-I	ALPS-IIc	Improvement
wavelength	$g \sim 1 / \lambda^{1/4}$	λ = 532 nm	λ = 1064 nm	1.2
production power	$g \sim 1 / P^{1/4}$	P = 1 kW	P = 150 kW	3.5
regen. signal gain	$g \sim 1 / PB^{1/4}$	$PB_r = 1$	$PB_r = 40000$	14
detector dark noise	$g \sim 1 / n_d^{1/8}$	n_d = 2 mHz	n_d = 1 μHz	2.6
detector efficiency	$g \sim 1 / \varepsilon^{1/4}$	$\varepsilon = 0.9$	$\varepsilon = 0.75$	0.96
measurement time	$g \sim 1 / t^{1/8}$	t = 10 h	t > 10 h	1
magnetic field	$g \sim 1 / (B\,L)$	BL = 22 Tm	BL = 468 Tm	21
total for ALPs				> 3000
total for HPs				~ 150

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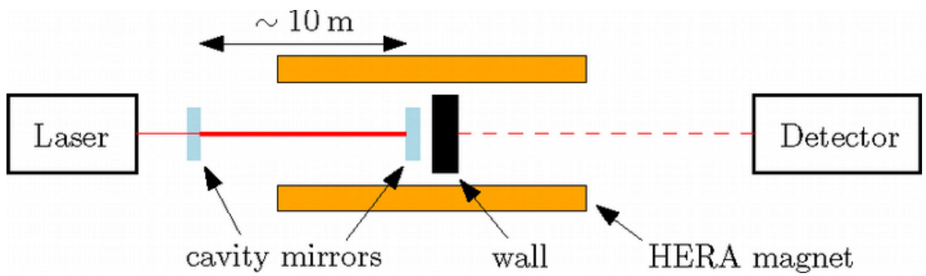
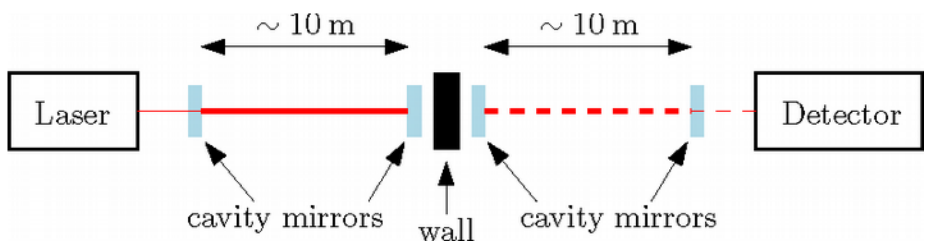
The ALPS project stages

ALPS-I



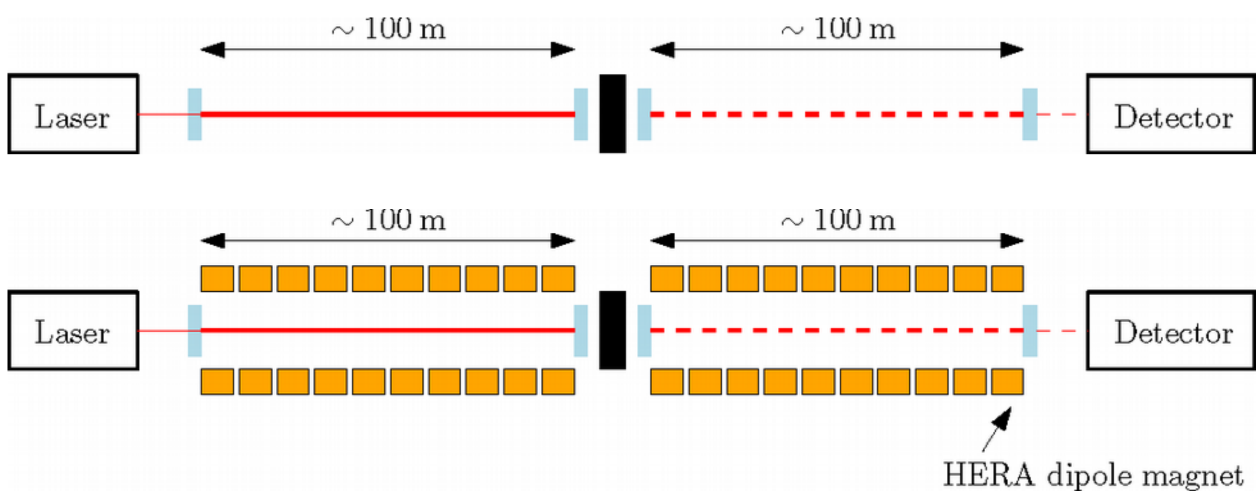
P(532nm) ~ 4 W   L ~ 4,5 m
PB_{PC} ~ 250

ALPS-IIa



P(1064nm) = 30 W   L = 10 m
PB_{PC} = 5000 PB_{RC} = 40000

ALPS-IIb/c

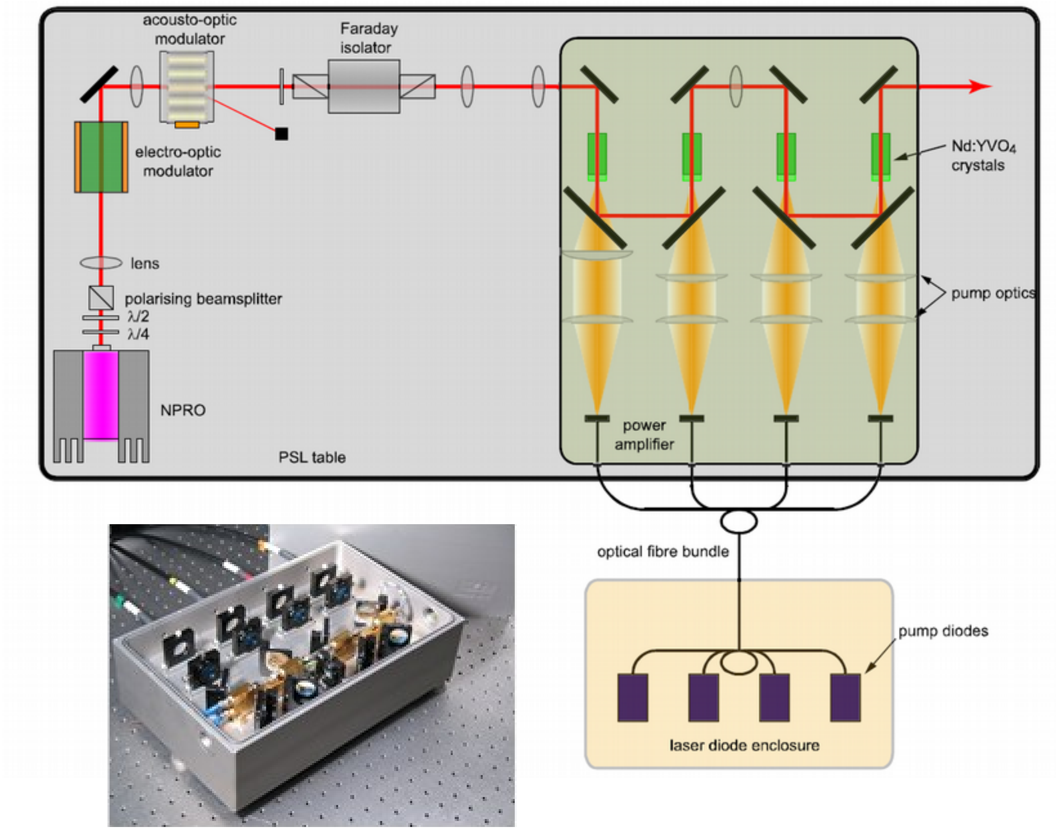


P(1064nm) = 30 W
L = 100 m
$Q_{PC} \sim 4 \cdot 10^{12}$
$Q_{RC} \sim 3 \cdot 10^{13}$

Improvements on the production side

Laser light source

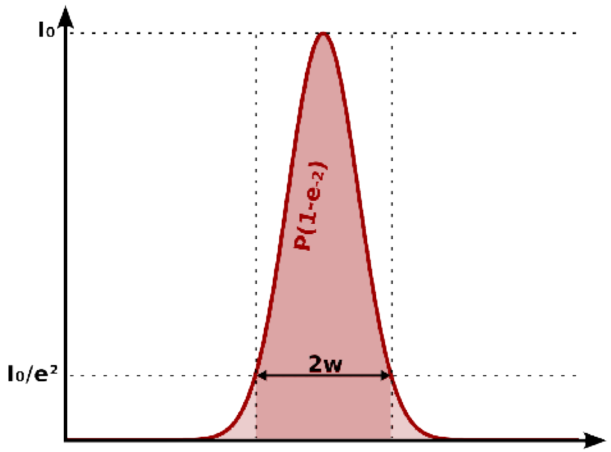
- 35 W @ 1064 nm laser power
- single mode
- single frequency
- high intrinsic frequency stability
- frequency modulation with PZT
- enhanced LIGO laser



Frede et al., Optics Express, Vol. 15, Issue 2, pp. 459-465 (2007)

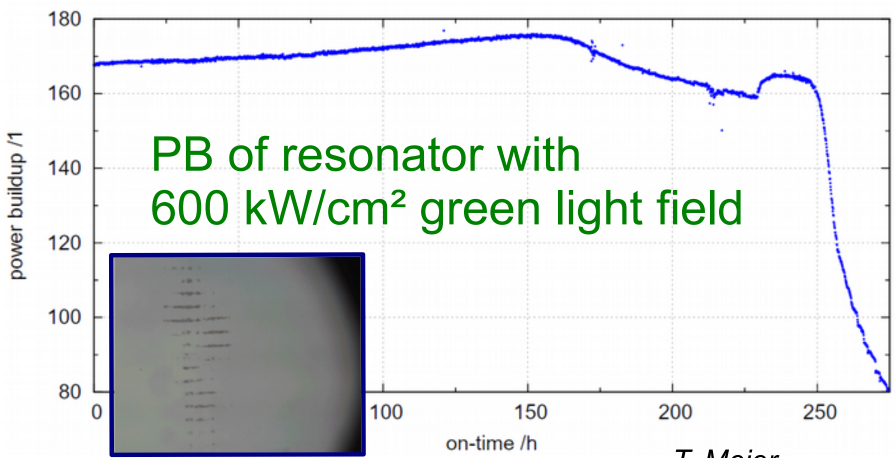
Circulating field in production cavity

Gaussian beam profile



- High intensities on the mirrors can
  - destroy the dielectric coatings
  - alter or distort Gaussian beam properties
- ~500 kW/cm² have been operated safely in Gravitational Wave Detection for years
- green light rather than infrared known to cause problems

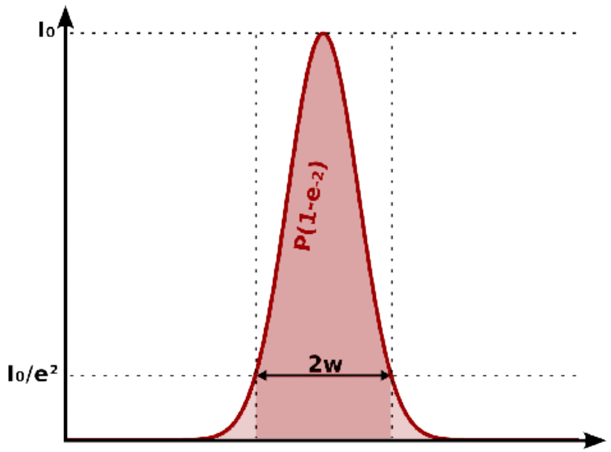
- change from green to infrared
- limit PB_{PC} to 5000
  → 580 kW/cm² (ALPS-IIa)
  → 300 kW/cm² (ALPS-IIb/c)



T. Meier

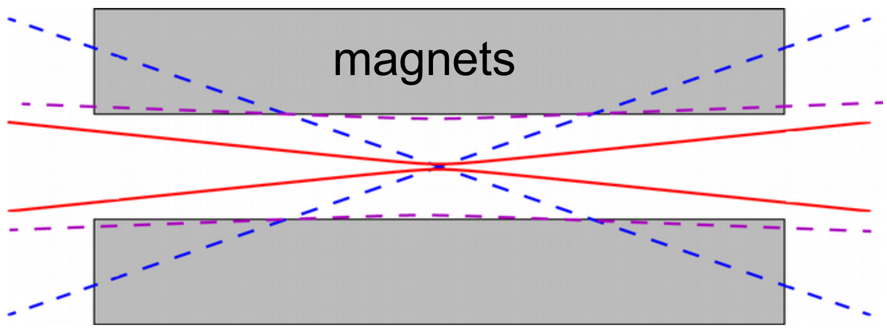
Aperture and optimum mode diameter

Gaussian beam profile



ALPS-IIc: Superconducting dipoles introduce aperture with diameter 2r = 40 mm for the cavity modes

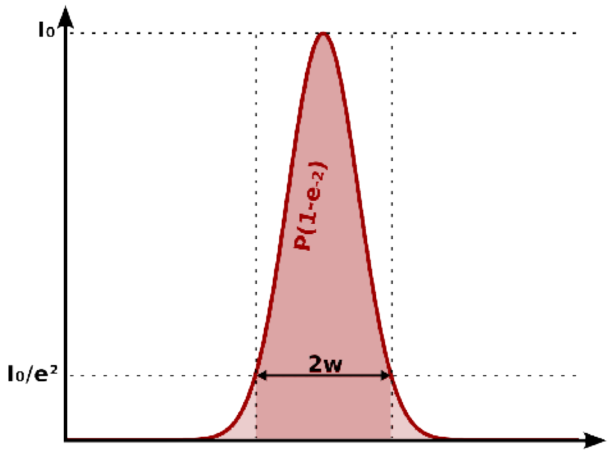
$$\frac{\Delta P}{P} = -e^{-2r^2/w^2}$$



optimum curvature radius
$L = z_r \Leftrightarrow w_0^2 = L*\lambda/\pi$

Aperture and optimum mode diameter

Gaussian beam profile



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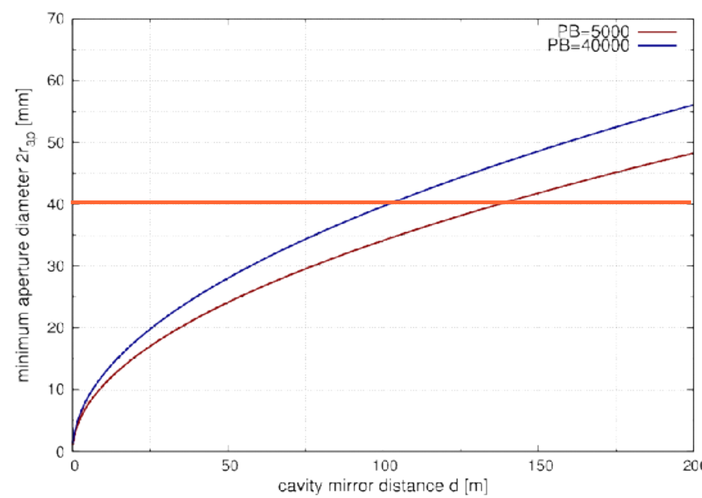
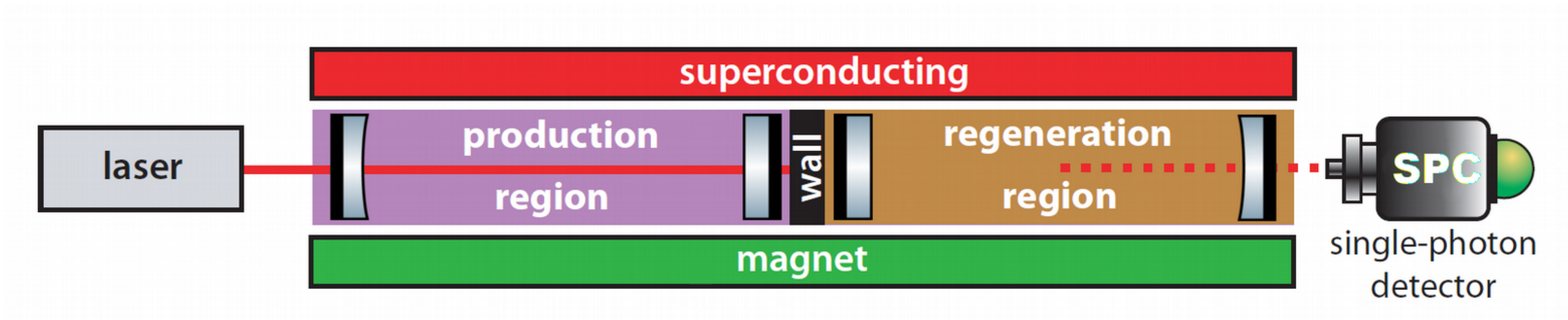


optimum curvature radius
$L = z_r \Leftrightarrow w_0^2 = L \cdot \lambda/\pi$

assuming 8 ppm additional losses / mirror

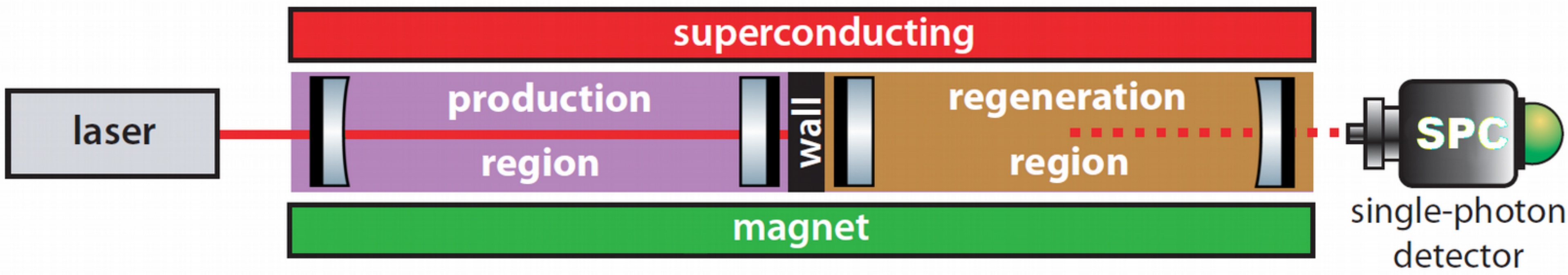
Improvements on the regeneration side

LSW with resonantly enhanced regeneration



- cavities on production & regeneration side improve signal
- signal enhancement ~ power build-up (PB) of both cavities

LSW with resonantly enhanced regeneration



both cavities must be resonant to laser frequency and share same optical axis

↓

length & alignment control

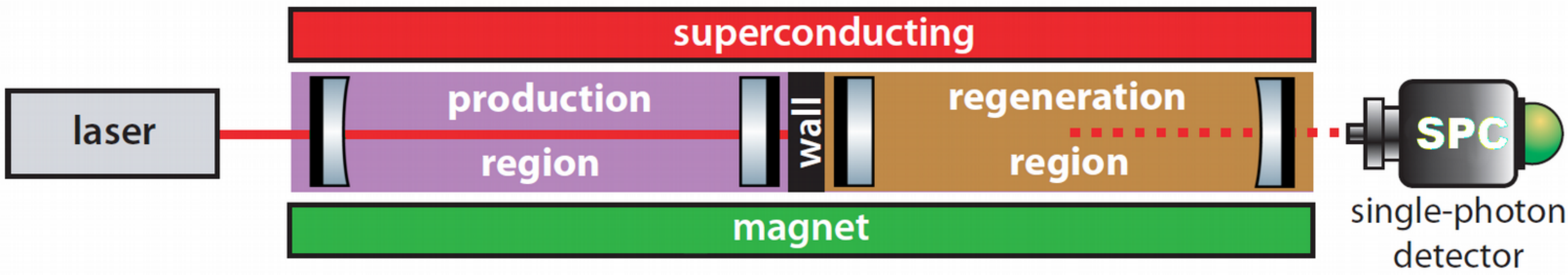
detector looking for signal photons leaving RC

↓

RC clear of spurious photons

discriminate between signal field and auxiliary field used for locking the RC

LSW with resonantly enhanced regeneration



both cavities must be resonant to laser frequency and share same optical axis

↓

length & alignment control

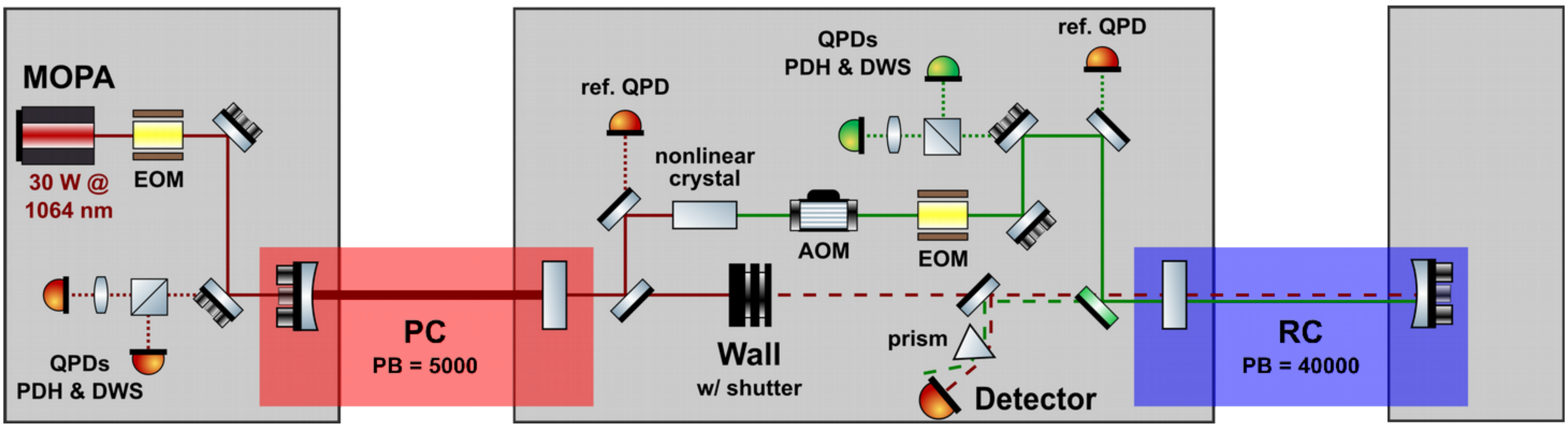
detector looking for signal photons leaving RC

↓

RC clear of spurious photons

use different wavelength for locking e.g. SH frequency

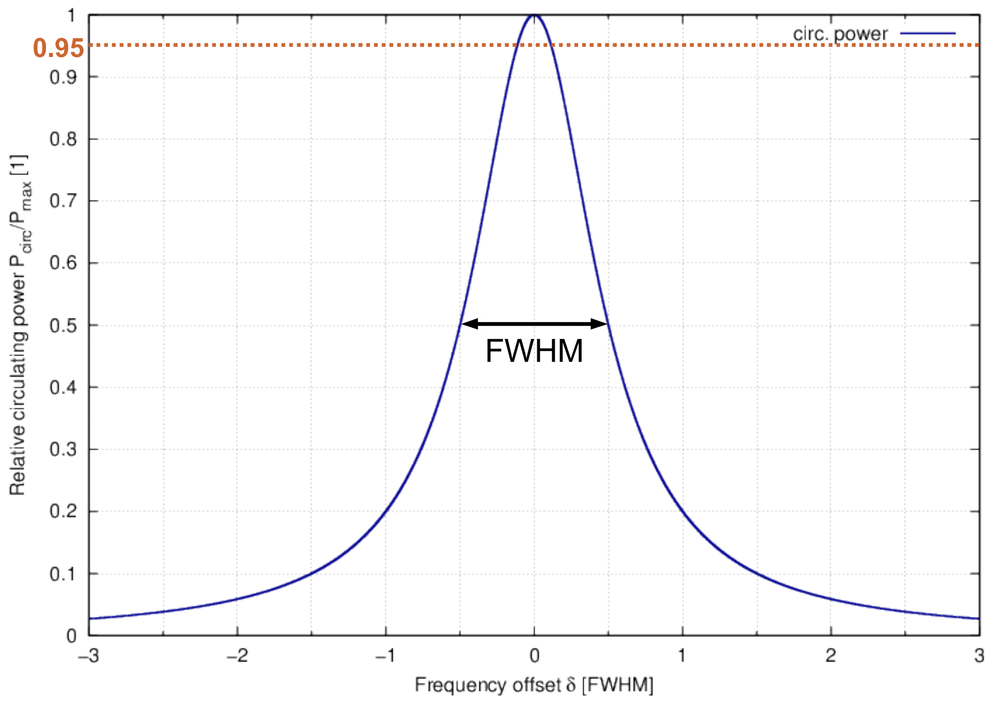
Optical layout



Length control

- in order to achieve 95% of the resonance PB, mistuning has to be <1/10 of the linewidth (FWHM)
- cavity length change per FWHM

$$\Delta L_{\mathrm{FWHM}} = \frac{\lambda}{2 \cdot F}$$



- PC (ALPS-IIb/c):

$$\Delta L_{\mathrm{FWHM,\,PC}} = 11 \;\mathrm{pm}$$

$$\Delta L_{.95,\,\mathrm{PC}} < 1.1 \;\mathrm{pm}$$

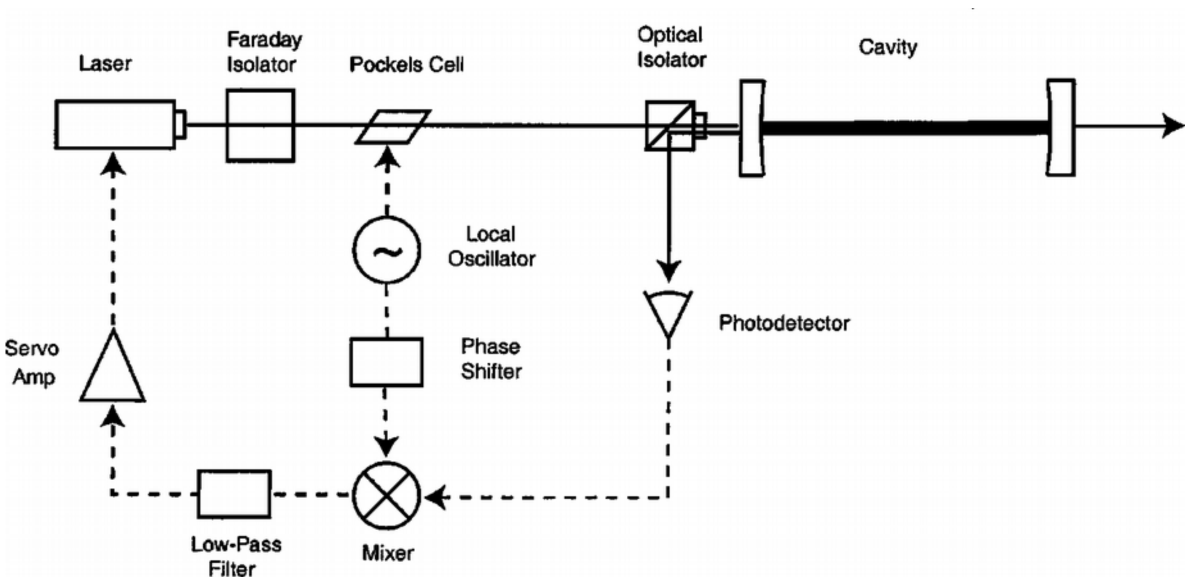
- RC (ALPS-IIb/c):

$$\Delta L_{\mathrm{FWHM,\,RC}} = 1.5 \;\mathrm{pm}$$

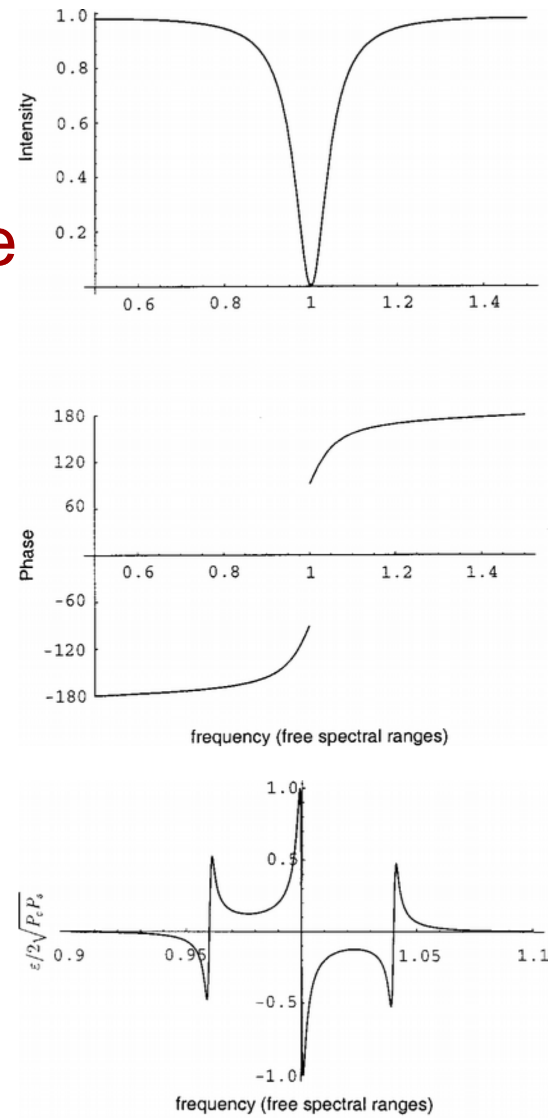
$$\Delta L_{.95,\,\mathrm{RC}} < 0.15 \;\mathrm{pm}$$

Pound-Drever-Hall

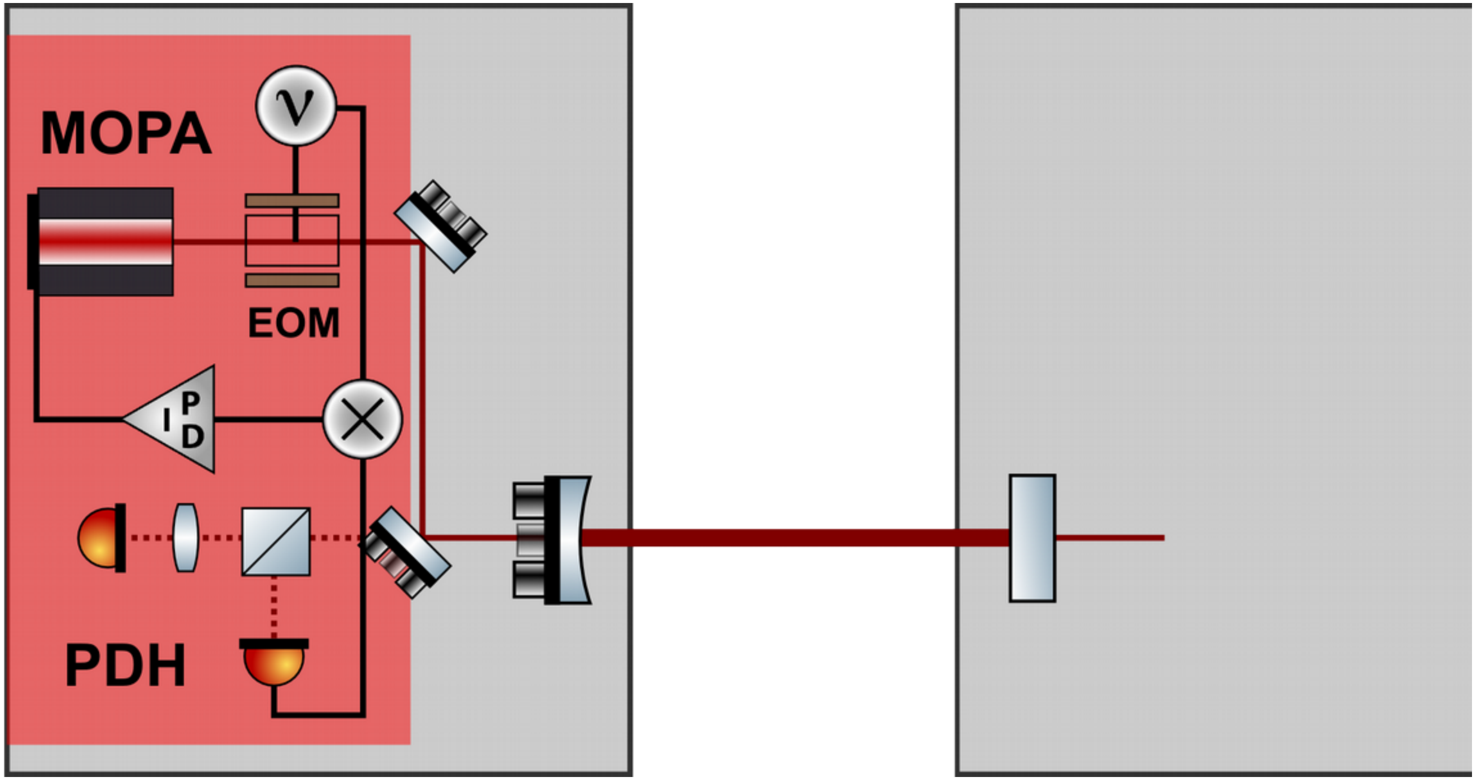
- Pound-Drever-Hall technique allows to sense small frequency offsets between the cavity resonance and the injected light
- useful sensor for cavity locking



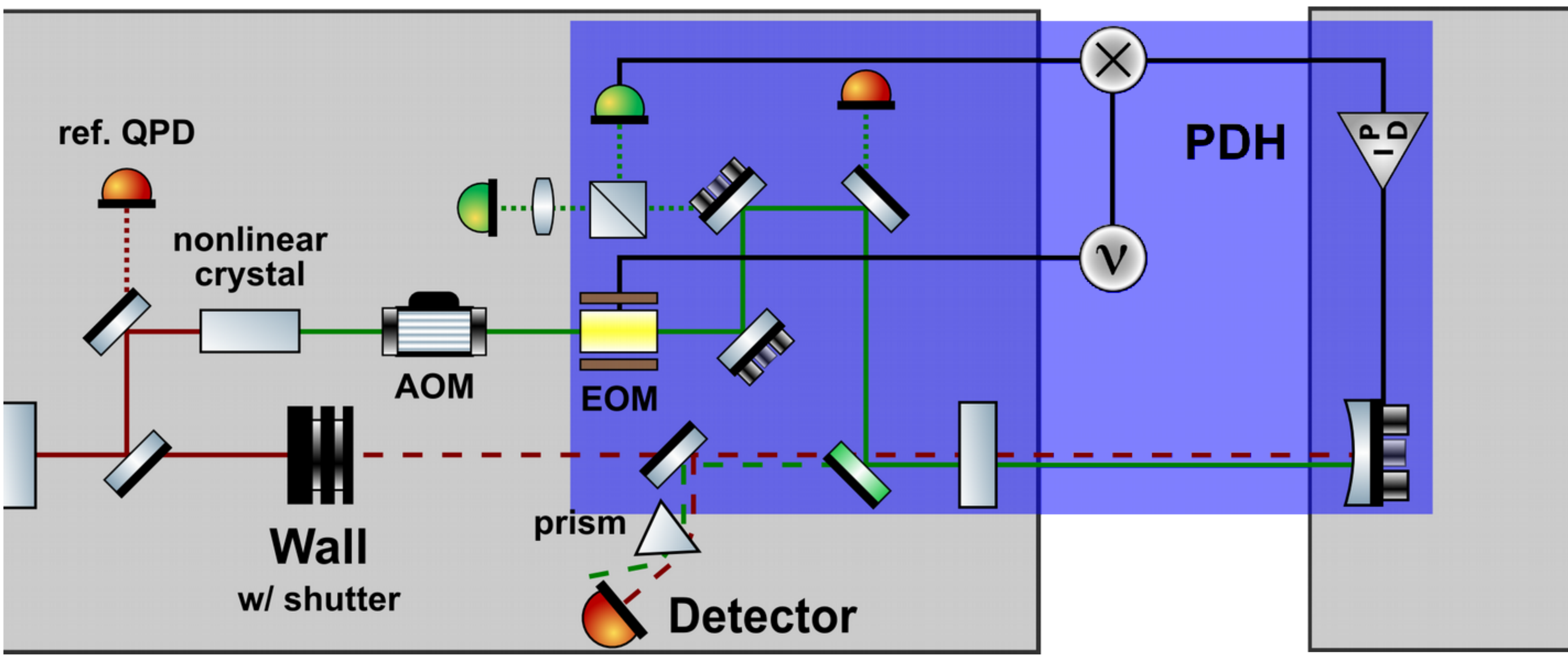
E. Black, An introduction to Pound–Drever–Hall laser frequency stabilization



Length control - PC



Length control - RC



Alignment control

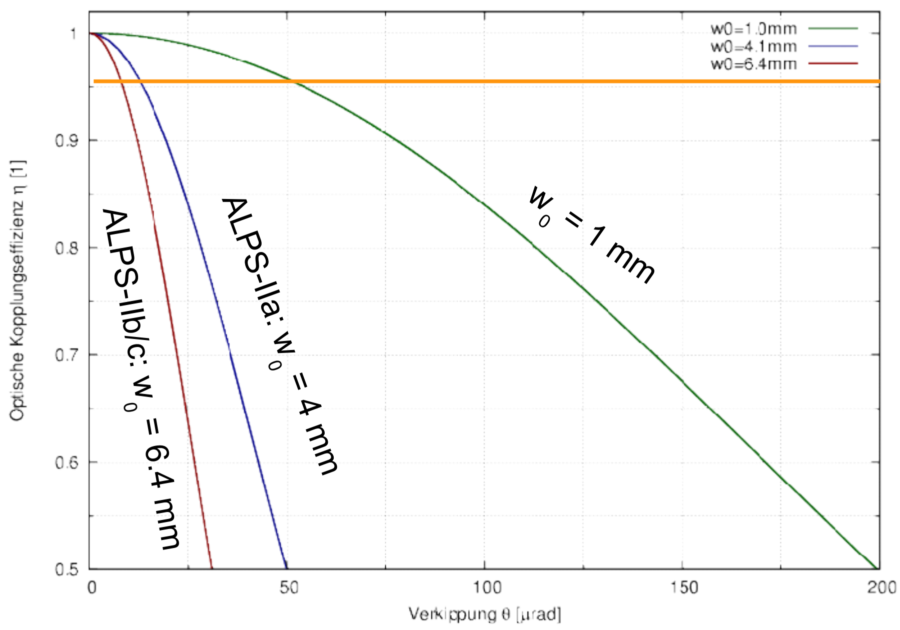
- displacement

- tilt

- ALPS-IIc requirement:

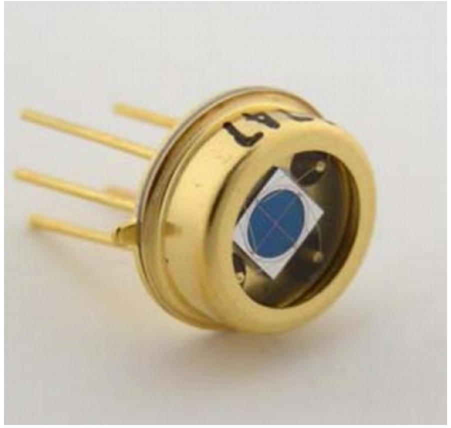
$$\Delta\theta_{.95} < 10 \text{ microrad}$$

large beam diameter make cavity modes more susceptible to tilt

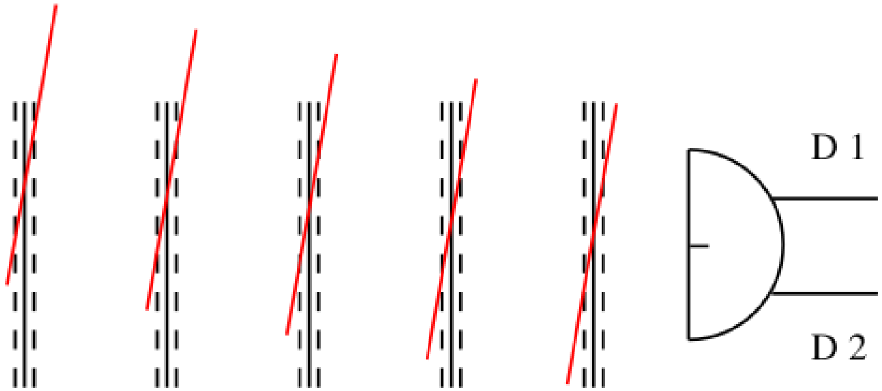


Differential Wavefront Sensing

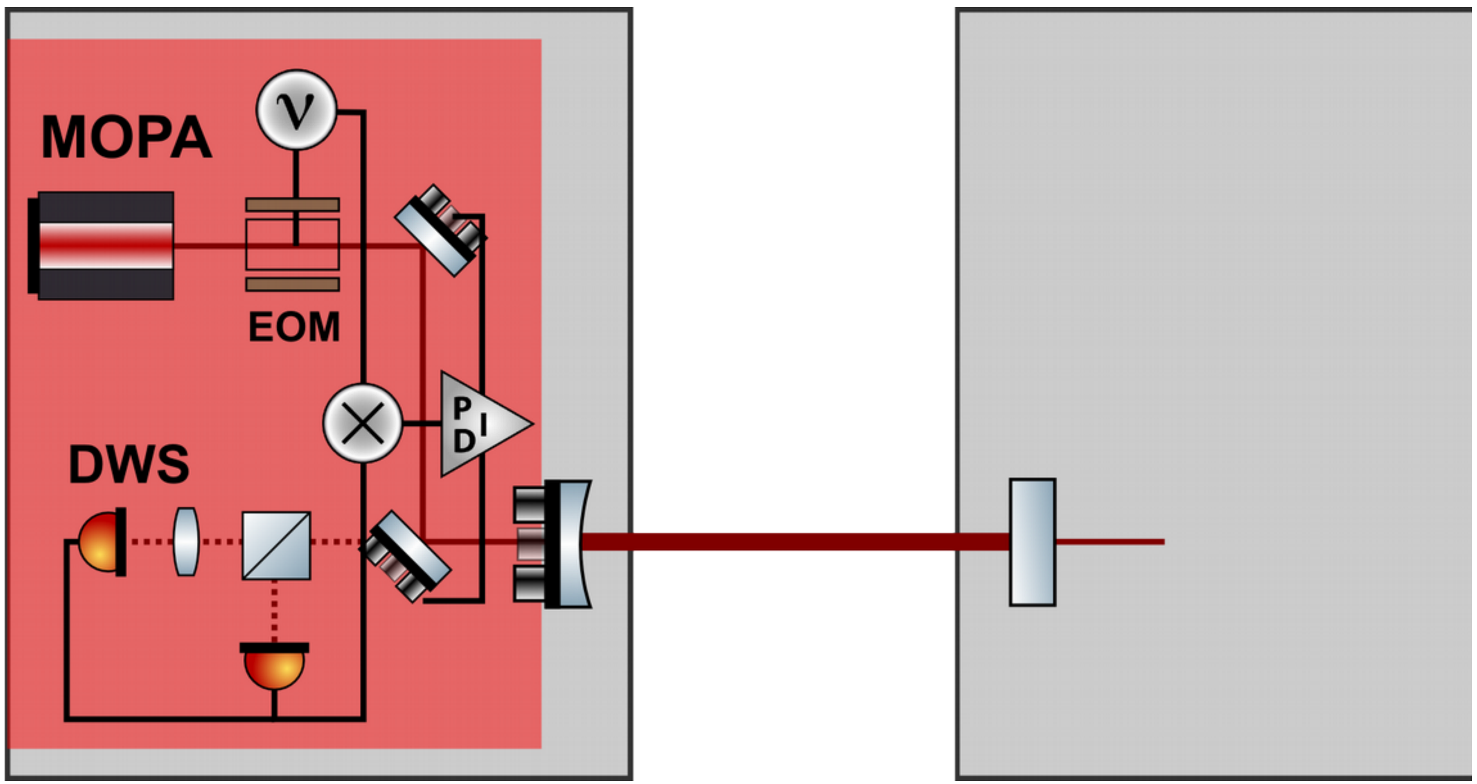
- Auto-alignment technique for optical modecleaners
- DWS uses sideband modulation
- differential phase is detected at independent Guoy positions along the reflected beam
- Piezo-electric mirrors can correct for misalignments



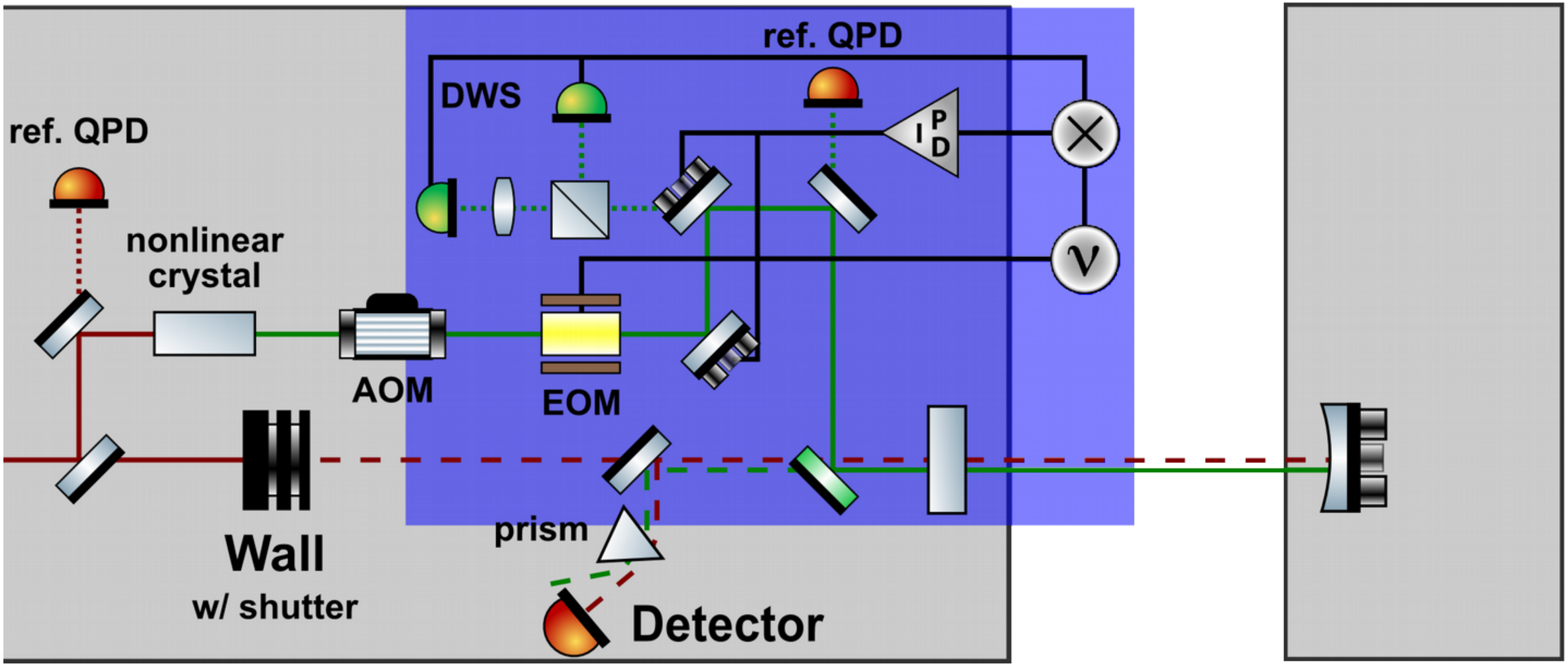
First Sensor QPD



Auto-alignment - PC

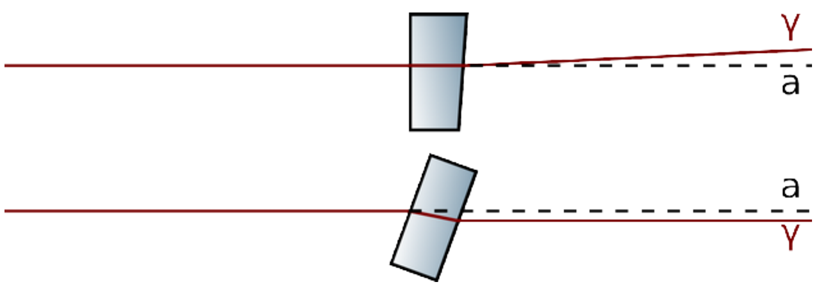


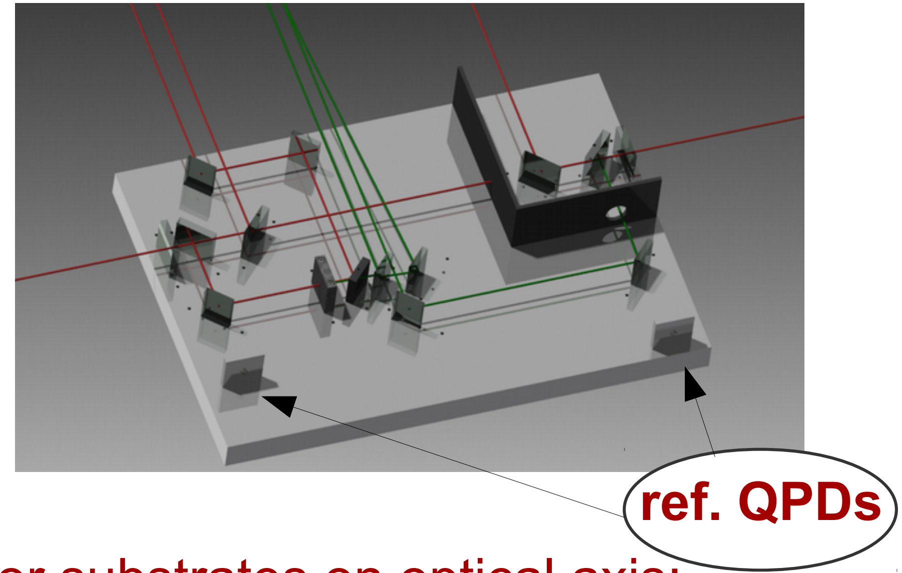
Auto-alignment - RC

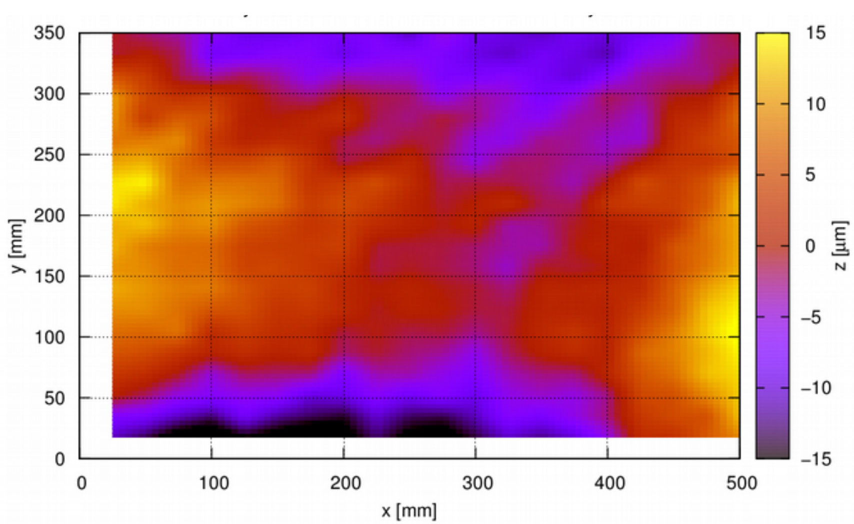


Central Board

axions don't refract







CMM measurement of ALPLAN surface

<u>for substrates on optical axis:</u>

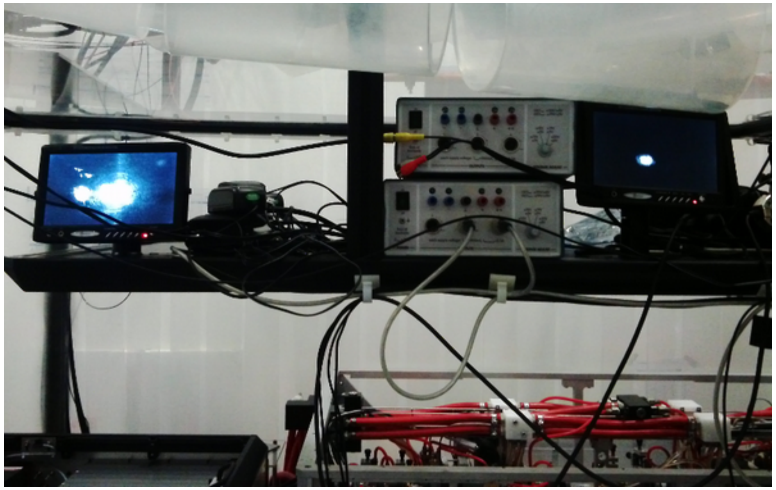
- ultra-low wedge
- tilt compensation

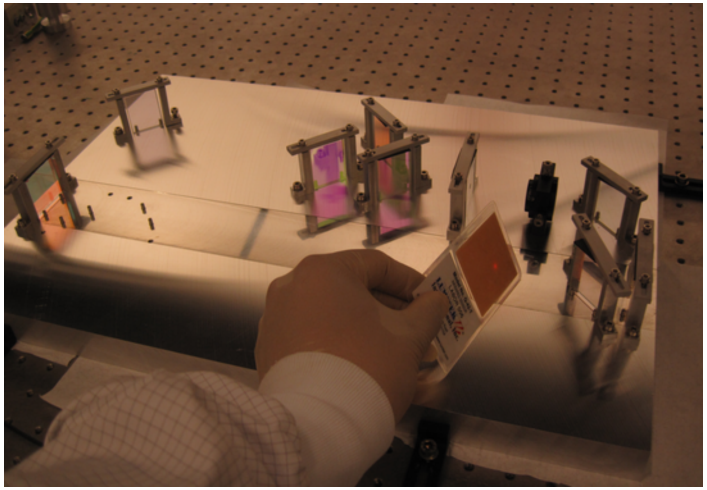
<u>for central board:</u>

- high surface planarity
- low thermal effects on planarity

Table-top experiment and results

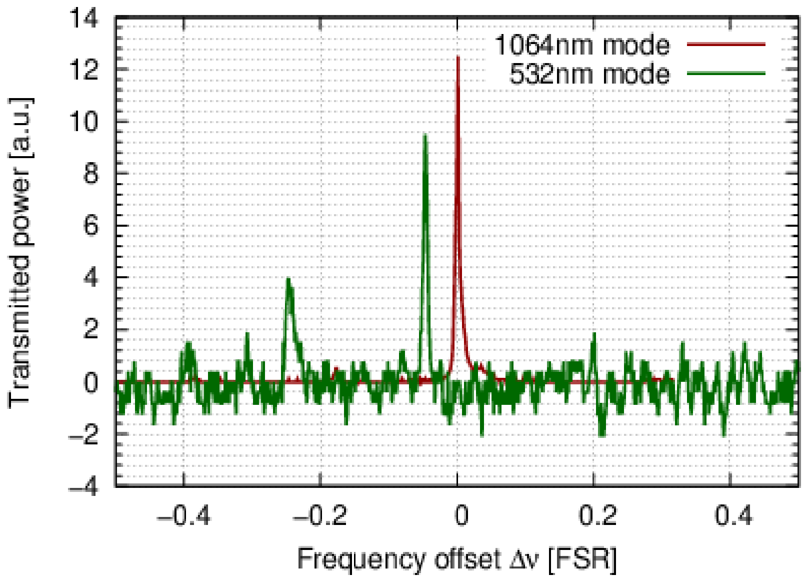
- demonstrate stabilization techniques
- table-top setup at AEI Hannover
- central breadboard and two 1m-cavities with PB 100



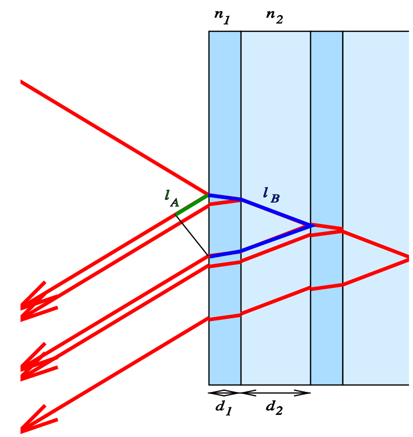


- dichroic stabilization of RC was achieved
- locked for >10 min, small dichroic phase diff.

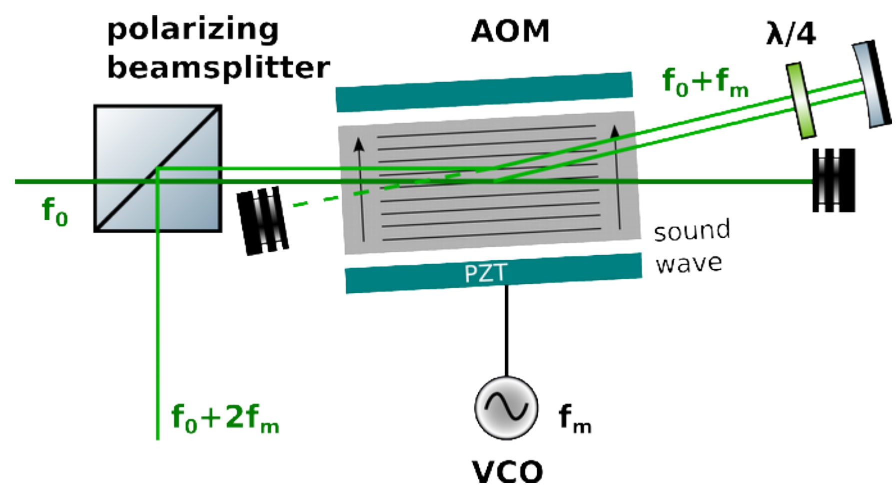
Dichroic Phase Shift



eff. penetration depth



- different penetration depth for IR and green mode
- measure and correct with frequency-shifting AOM



Summary

- the improved optical design of ALPS-II will enhance the sensitivity in ALPs and HP searches
- the ALPS cavities have to be controlled with respect to frequency and spatial alignment
- a table-top experiment is performed, which has already partly demonstrated the cavity stabilization concept to work