APNS: Alignment and Pointing Noise Suppression

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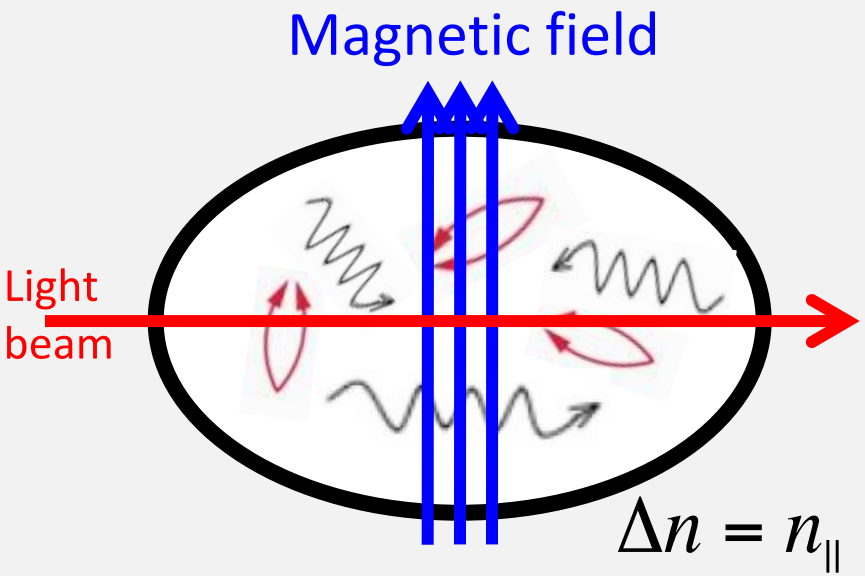
EXPERIMENTAL STUDY OF QUANTUM VACUUM

The vacuum is structured and has properties that can be studied.

Light propagation in an external field



$$\Delta n = n_{\parallel} - n_{\perp}$$

The complex index of refraction of vacuum is modified by an external magnetic field:

$$\tilde{n} = 1 + (n_B + i\,\kappa_B)$$

The induced changes depend also on the direction of the applied field:

$$\Delta\tilde{n} = \underbrace{\Delta n_B}_{\text{BIREFRINGENCE}} + \underbrace{i\,\Delta\kappa_B}_{\text{DICHROISM}}$$

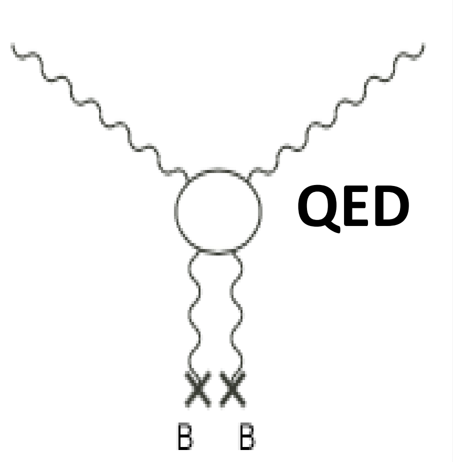
Experimental method:

- Perturb the quantum vacuum with an external B field
- Probe with a (polarised) light beam
- Detect changes in the polarisation state

OPTICAL PROPERTIES OF QUANTUM VACUUM

$$\Delta\tilde{n} = \Delta n_B + i\,\Delta\kappa_B$$

BIREFRINGENCE DICHROISM



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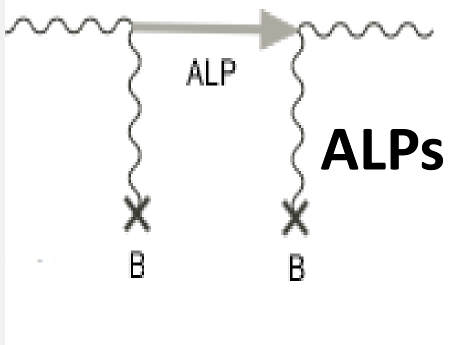
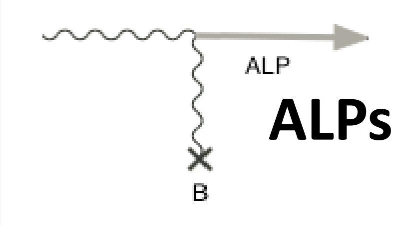
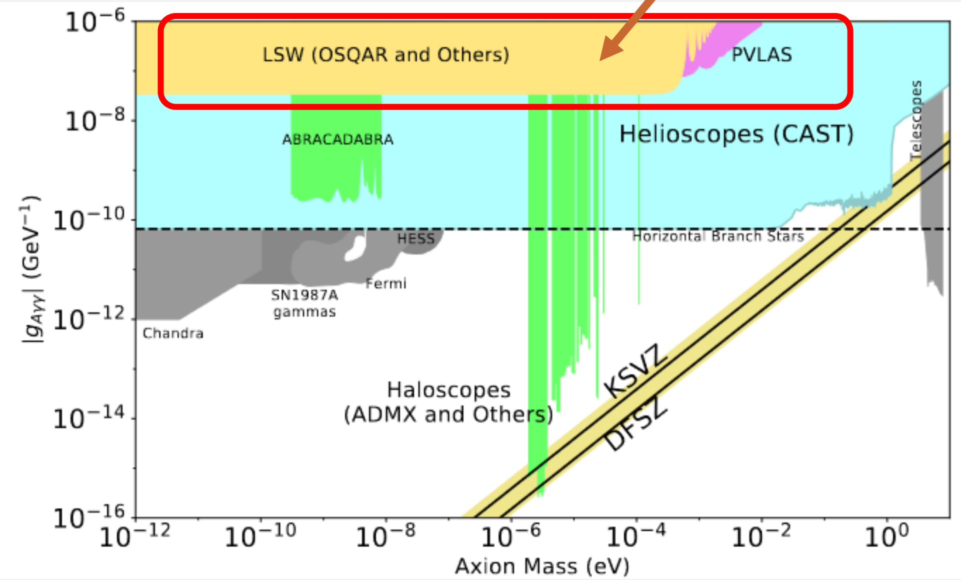


$\Delta n_{QED} = 3A_e B^2 = 4\times10^{-24}$ @ 1 T magnetic field

VACUUM MAGNETIC BIREFRINGENCE

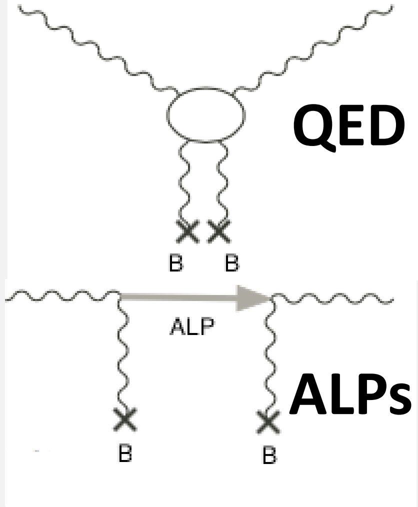


Model independent search for 'light' DM

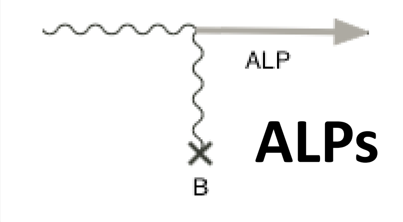


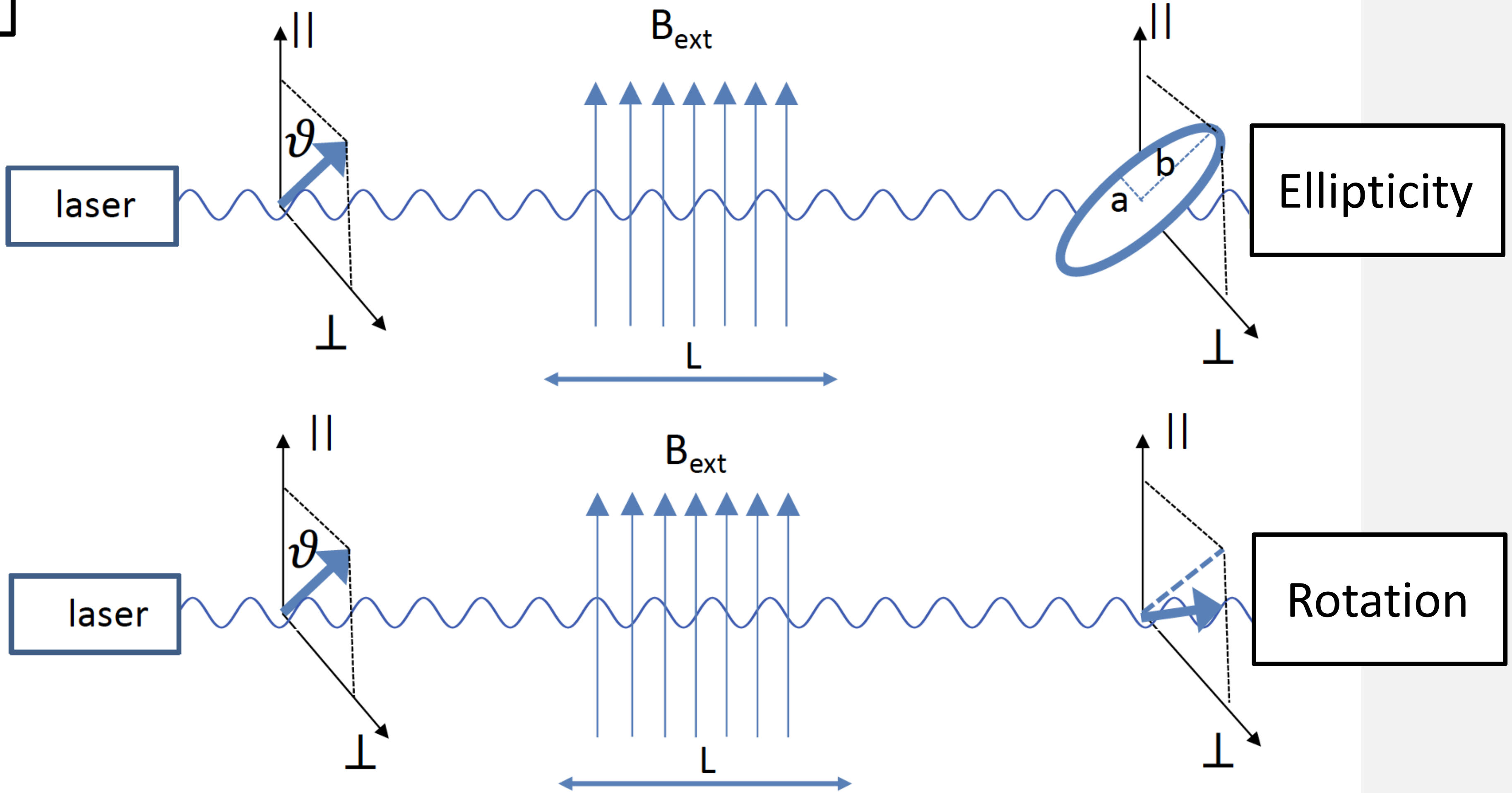
MEASURABLE QUANTITIES

Birefringence Δn_B

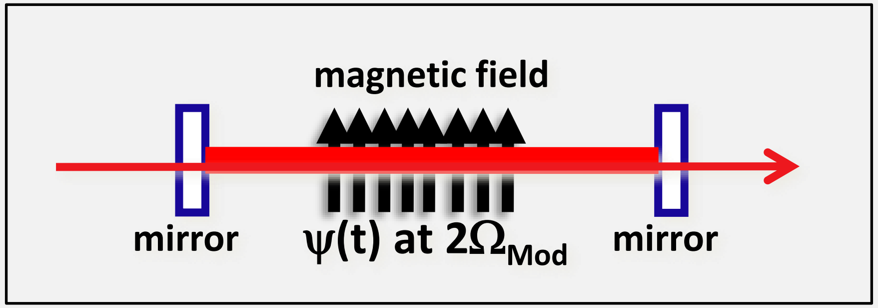


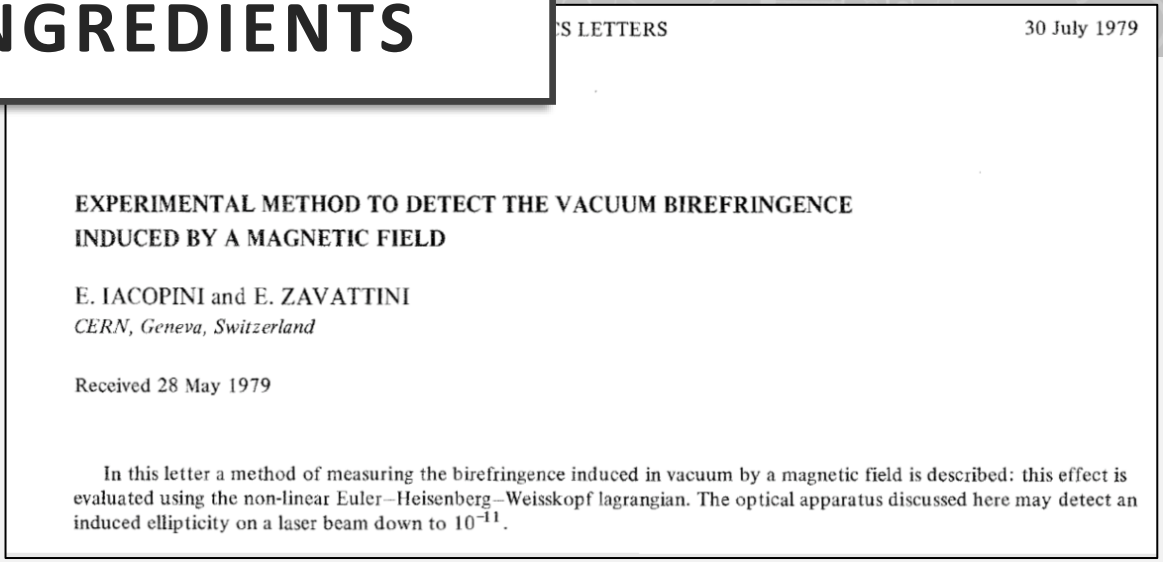
Dichroism $\Delta\kappa_B$





POLARIMETRY: INGREDIENTS




S LETTERS 30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

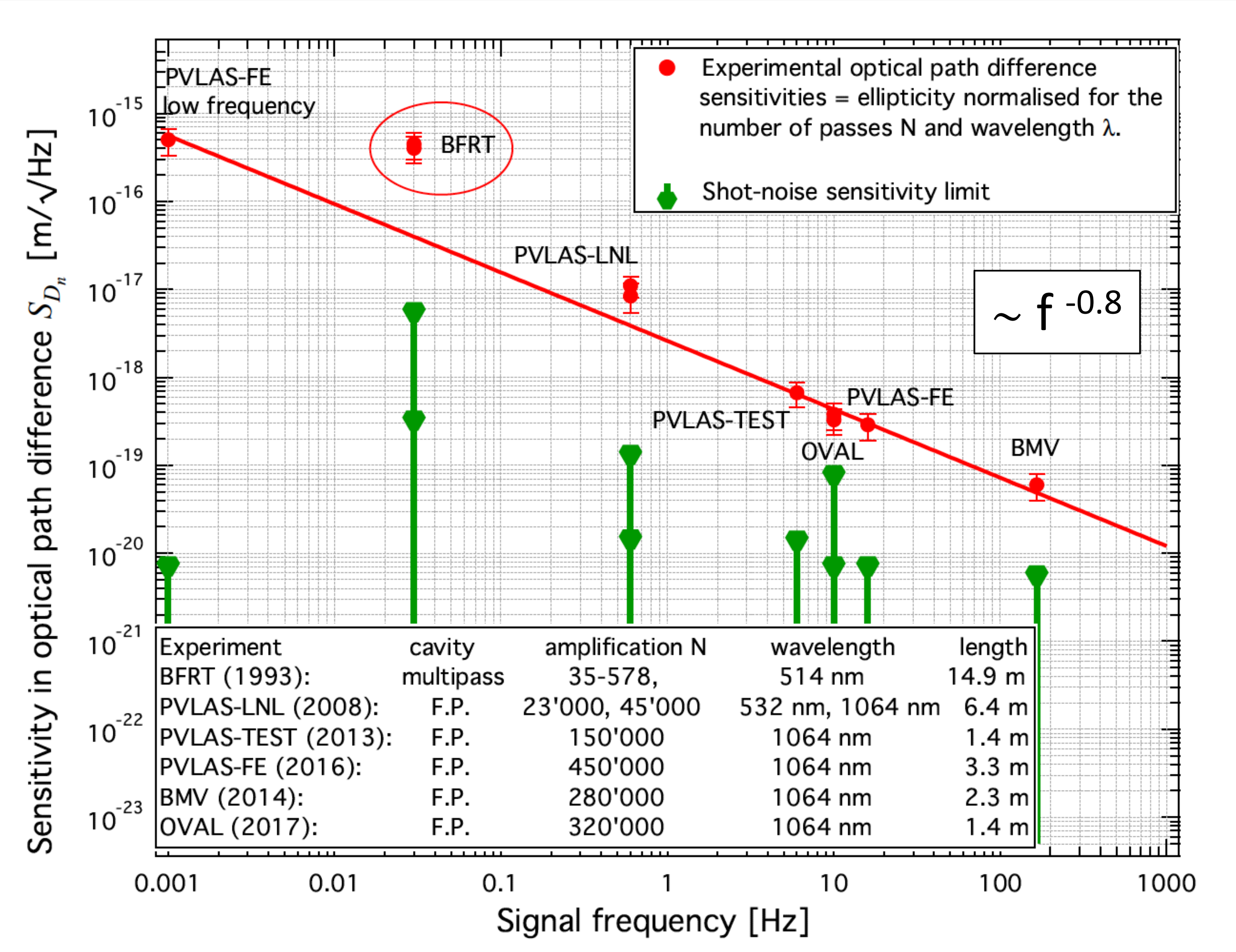
Experimental method:

- Apply an external magnetic field
- Probe with a laser beam
- Detect changes in the polarisation state

Key ingredients:

- High magnetic field **Effect α B^2**
- Long optical path **Optical cavity**
- High sensitivity polarimeter **Modulation of the signal**

INTRINSIC NOISE



Experiment	cavity	amplification N	wavelength	length
BFRT (1993):	multipass	35-578,	514 nm	14.9 m
PVLAS-LNL (2008):	F.P.	23'000, 45'000	532 nm, 1064 nm	6.4 m
PVLAS-TEST (2013):	F.P.	150'000	1064 nm	1.4 m
PVLAS-FE (2016):	F.P.	450'000	1064 nm	3.3 m
BMV (2014):	F.P.	280'000	1064 nm	2.3 m
OVAL (2017):	F.P.	320'000	1064 nm	1.4 m

- Experiments never reach shot-noise limited sensitivity once the cavity is inserted
- Intrinsic noise coming from the cavity limits the sensitivity in optical path difference:

$$S_{\Delta\mathcal{D}} = \frac{\lambda}{N\pi} S_{\Psi}$$

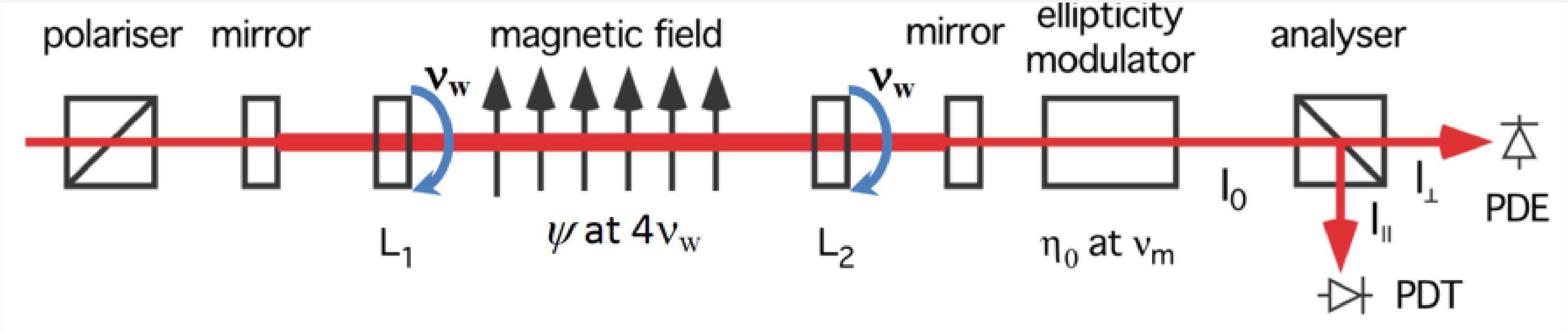
(ΔD does not depend on finesse)

No need for high finesse but rather increase the B field!

VMB@CERN

Increase the signal with higher B field → superconducting magnets (LHC dipole magnet $B^2 \approx 81\ T^2$)

CANNOT MODULATE FAST ENOUGH!!



Modulate the VMB signal using two co-rotating half waveplates (HWP) inside the cavity

$\alpha_{1,2}$ are the phase errors from π of the two HWPs and $\phi(t)$ is their rotation angle

$$\Psi(t) = \Psi_0 \sin \boxed{4\phi(t)} + N\frac{\boxed{\alpha_1}}{2}\sin 2\phi(t) + N\frac{\boxed{\alpha_2}}{2}\sin(2\phi(t) + 2\Delta\phi)$$

Signal is at 4th harmonic of the rotation

Waveplate defects have different frequency components

$$\alpha = \alpha^{(0)} + \alpha^{(1)}\cos\phi + \alpha^{(2)}\cos 2\phi$$

APNS PROJECT

(“Alignment and Pointing Noise Suppression")

CRITICAL TASKS:

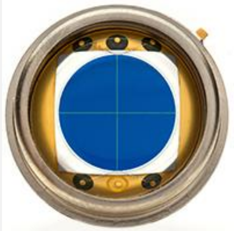
1. Build a cavity around a LHC magnet and keep it aligned (noisy environment).

Develop an automatic alignment system for the injection and cavity optics.

2. Control the alignment of the optics inside the cavity to reduce noise and systematics.

Differential wavefront sensing

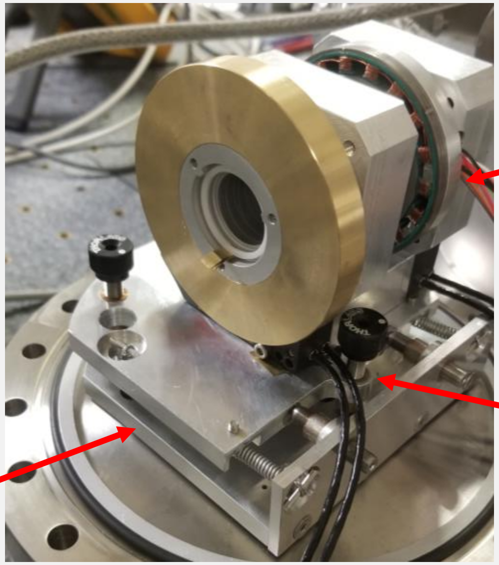
(technique developed in GW interferometry)



Optical Simulations with:

Finesse 2

http://www.gwoptics.org/finesse/

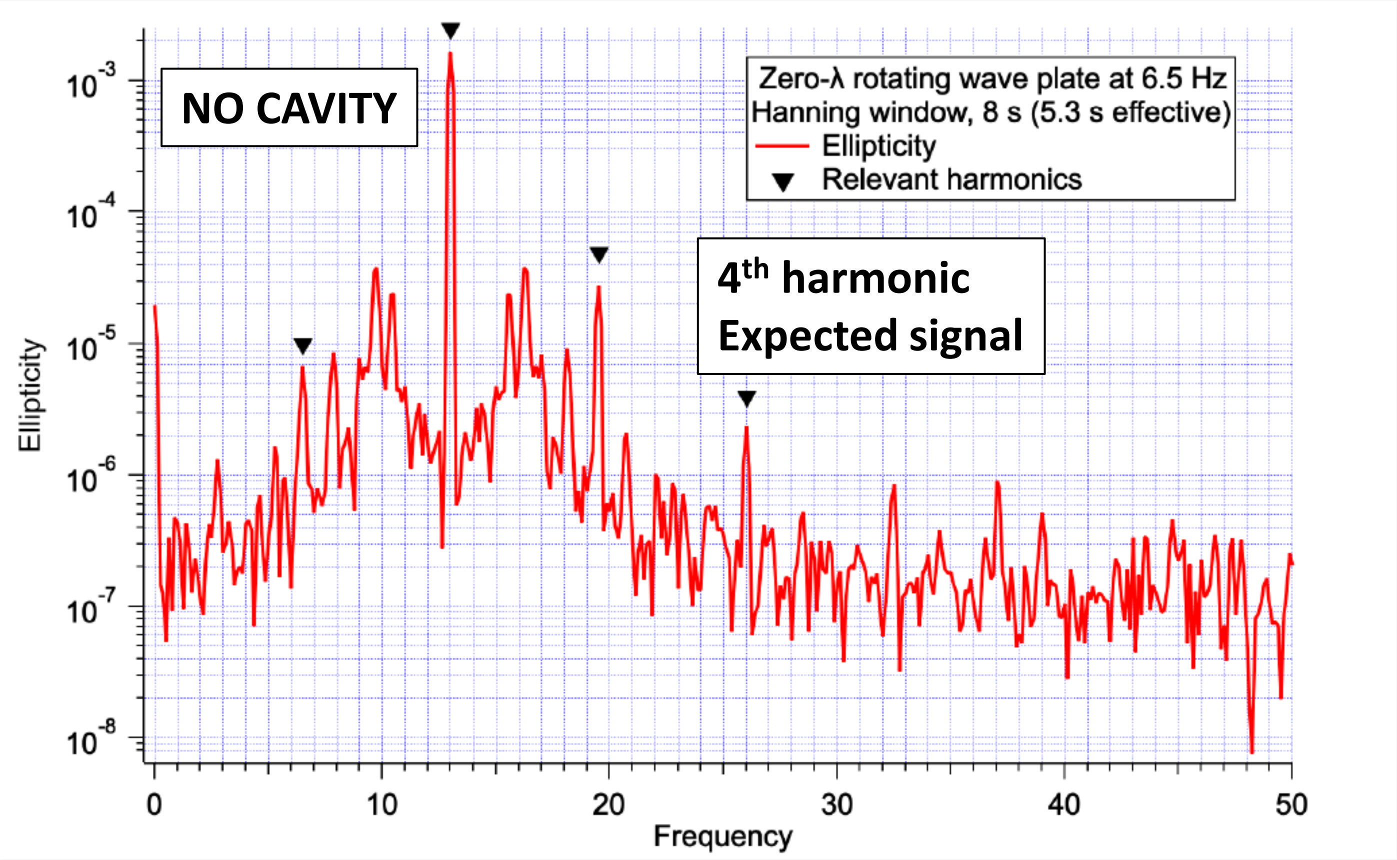


Motor

(Fine) Piezo alignment system

(Coarse) alignment plate

ELLIPTICITY SPECTRUM



FREQUENCY DOMAIN

FEATURES:

- ‘Large bump’ centered around 2nd harmonic
- Broadband noise
- Peaks at various harmonics (triangles) are due to the rotating waveplate
- Presence of peak at 4th harmonic

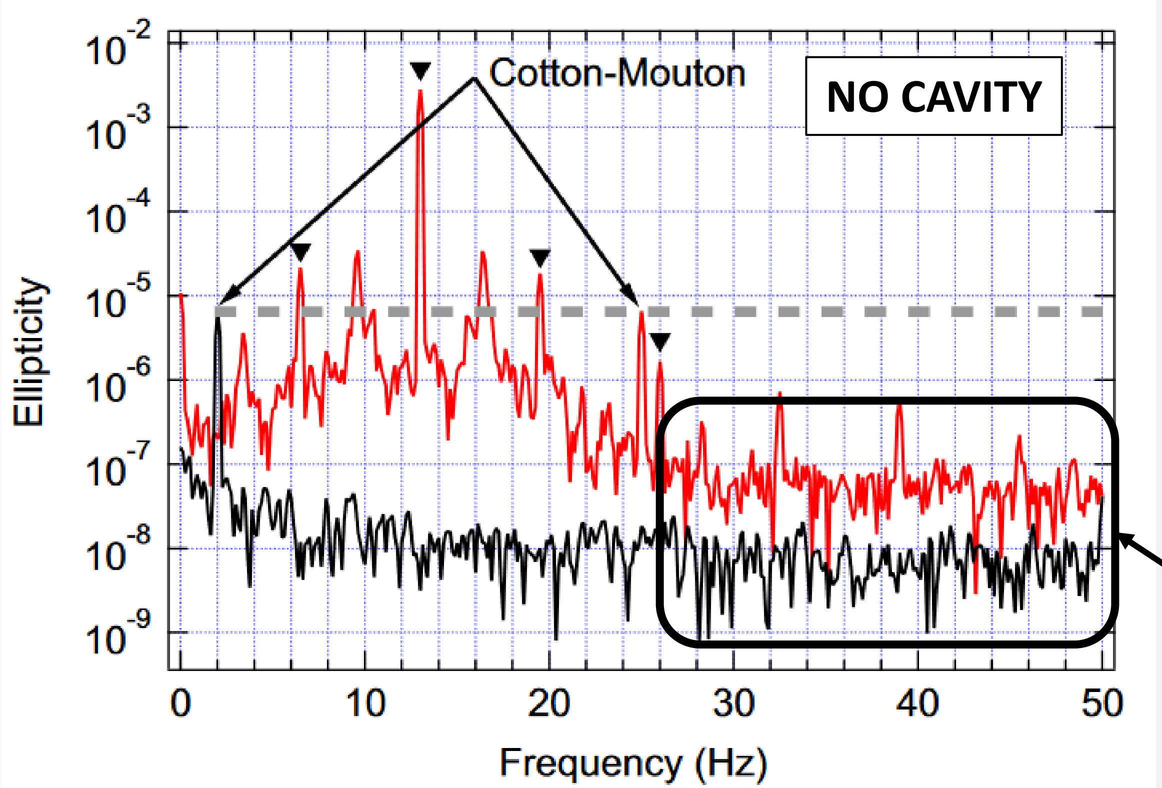
<u>POSSIBLE SHOWSTOPPER!</u>

COTTON-MOUTON OF AIR

Cotton-Mouton effect: Magnetic birefringence in gasses

Found a workaround: MODULATE THE MAGNETIC FIELD!

10 vector averages: each 8 s with Hanning window



- **Red** – magnet rotating at 0.5 Hz and HWPs at 6.5 Hz
- **Black** – magnet rotating at 1 Hz and non-rotating HWPs

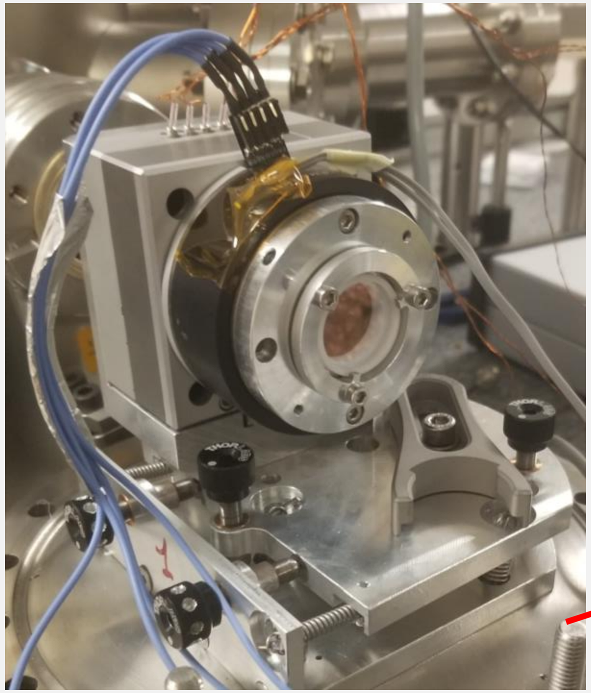
The peak in **red** at 25 Hz is due to the Cotton-Mouton of air and has the same amplitude as the signal in **black** at 2 Hz.

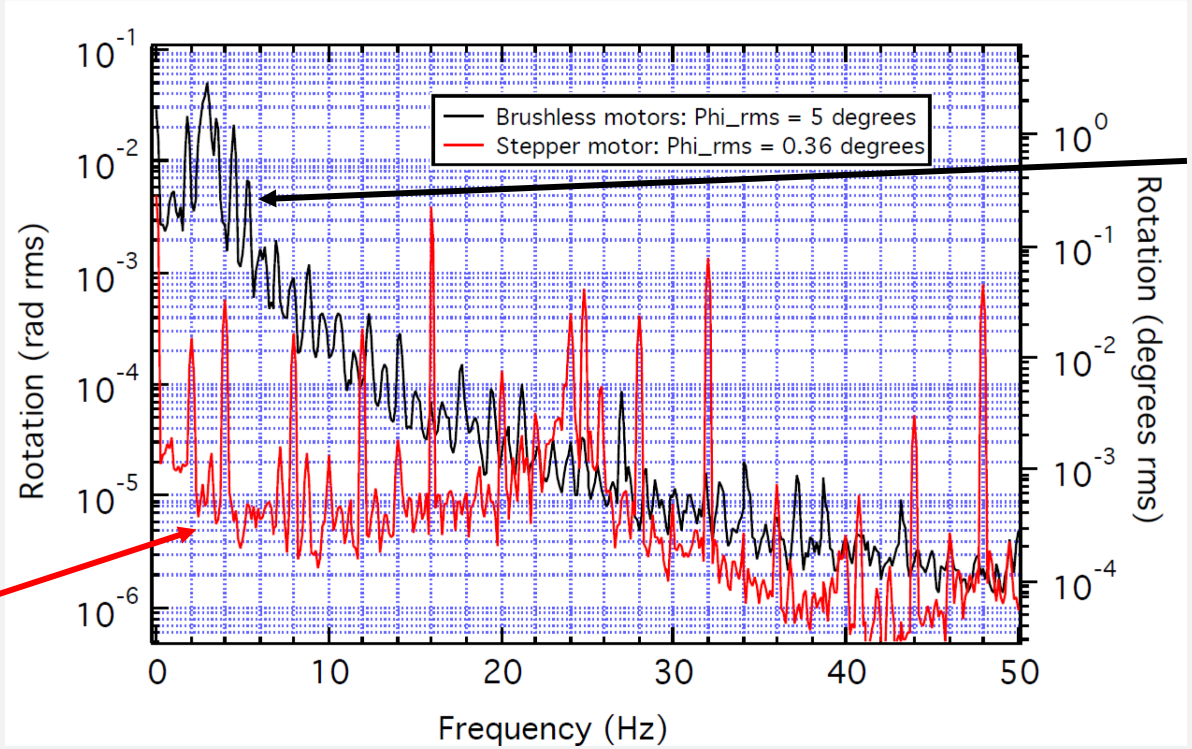
The difference in noise is due to the relative phase (rotation) noise of the HWPs motors.

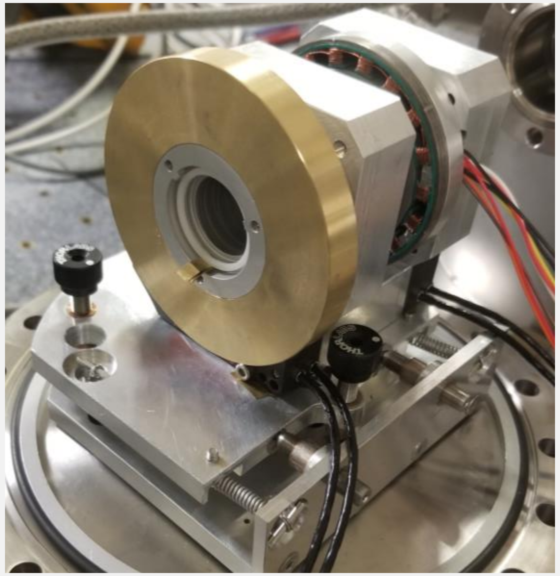
WAVEPLATE MECHANICS

New stepper motors with a more accurate rotation (absolute phase) control

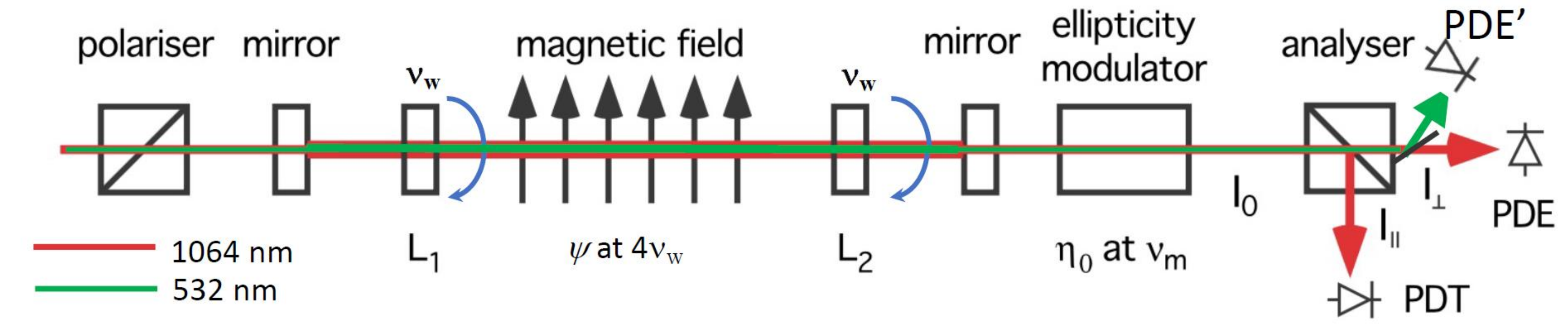
- relative rotation rms noise between the two HWPs was improved by a factor ≥ 10







GREEN LASER



Injecting in the polarimeter a green laser beam @ 532 nm (HWP -> FWP) allows real-time control of the systematics due to the rotating HWPs

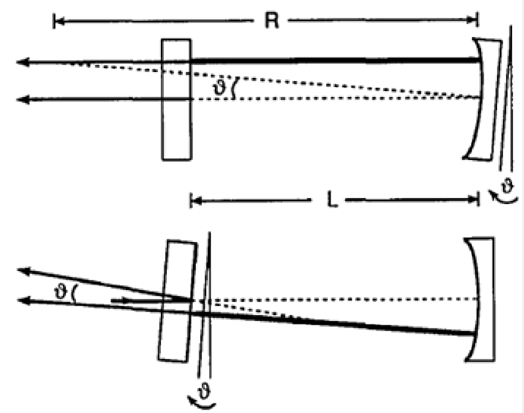
- Further reduction of harmonics

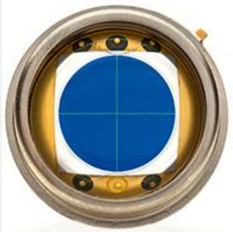
➡

Demonstrated locking (noisy) of the cavity with the rotating HWPs

DIFFERENTIAL WAVEFRONT SENSING

Superimpose cavity axis with incoming beam





Consider a beam misaligned into an optical cavity:

- Describe the input beam in the cavity basis:

Displacing a HG_{00} beam by a, can be approximated by adding a HG_{10} mode in proportion a/ω_0:

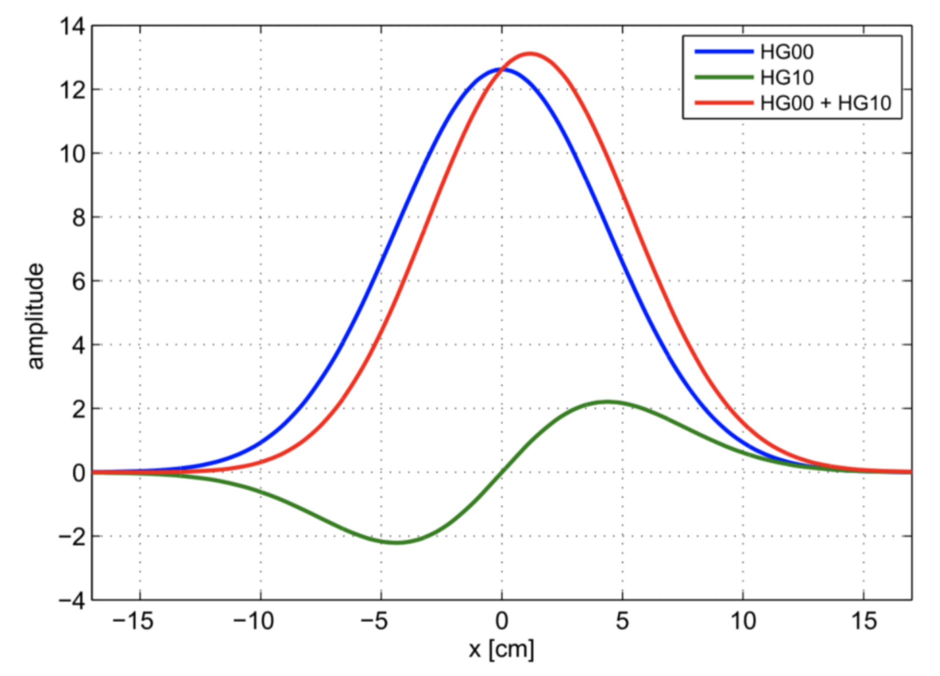
$$u_{00}(x-a,y,z_0) \approx u_{00}(x,y,z_0) + \frac{a}{w_0} u_{10}(x,y,z_0)$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z - z_0}{z_R} \right)^2}$$

In the same way an angular misalignment α is a HG_{10} mode added in proportion α/Θ, 90^{o} out of phase, with the HG_{00} mode:

$$u_{00}^{\alpha\mathrm{tilt}}(x,y,z_0) \approx u_{00}(x,y,z_0) + \mathrm{i}\frac{\alpha}{\Theta} u_{10}(x,y,z_0)$$

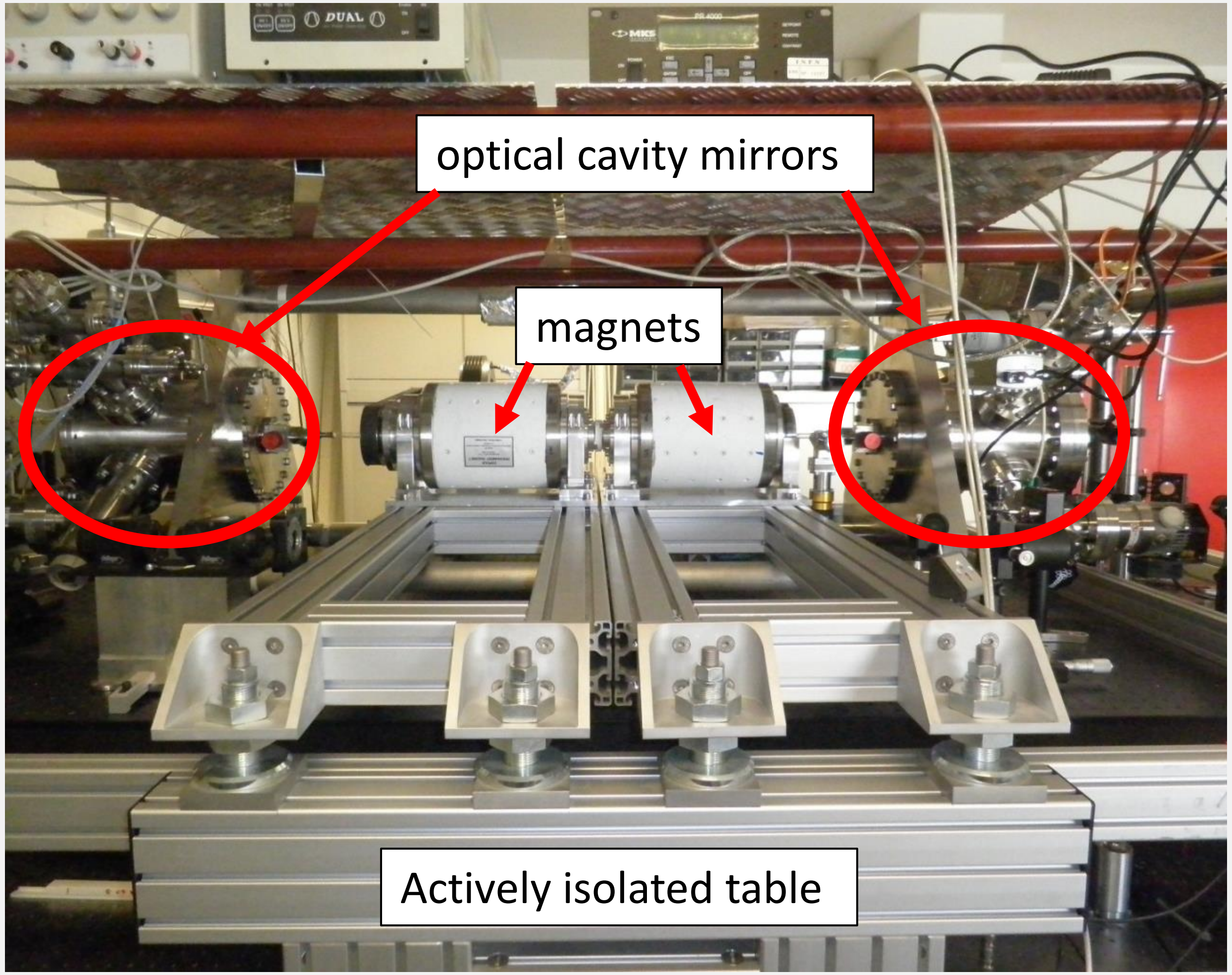
$$\Theta = \arctan\left(\frac{w_0}{z_R} \right) \approx \frac{w_0}{z_R} = \frac{\lambda}{\pi w_0}$$

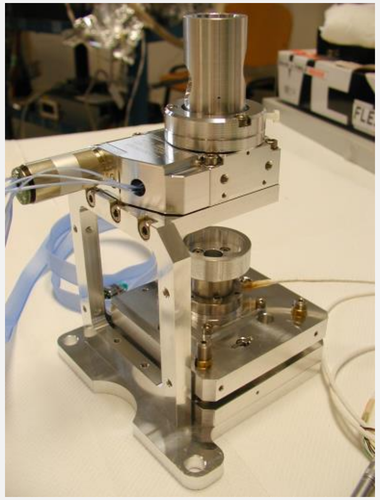


TEST SETUP

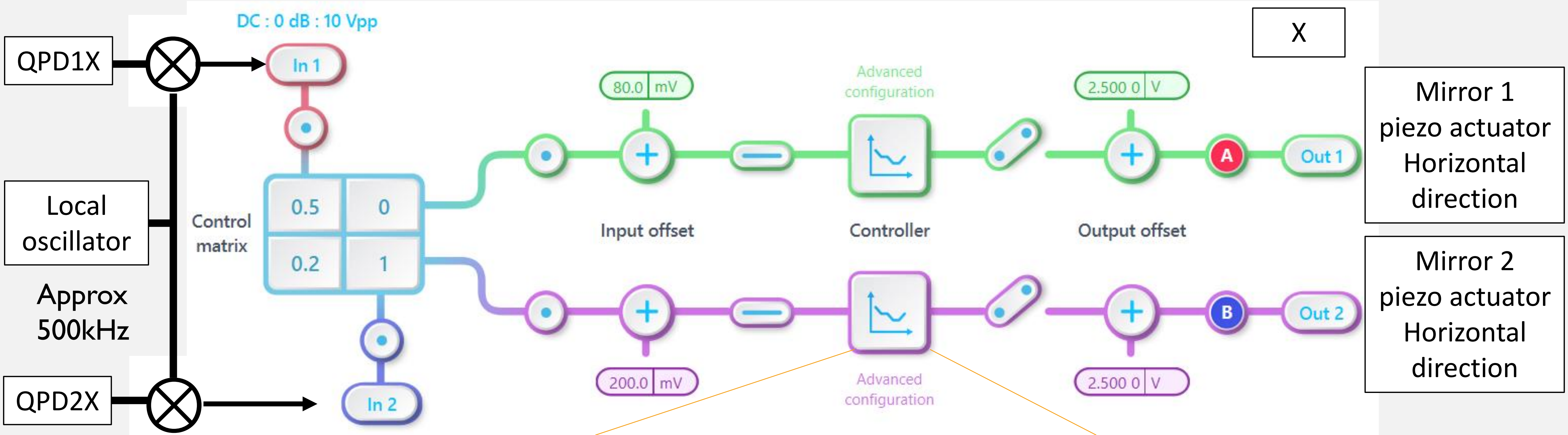
Polarimeter

- 1.4 m Fabry-Perot optical cavity F = 3000
- Optical table with active isolation system
- Two 2.3 T, 20 cm long permanent magnets (currently out of beam line)
- quadrant photodiodes to generate error signals for the alignment
- Vacuum-compatible actuators to move the cavity and beam injection optics





ALIGNMENT FEEDBACK



QPD1X

Local oscillator

Approx 500kHz

QPD2X

X

Mirror 1 piezo actuator Horizontal direction

Mirror 2 piezo actuator Horizontal direction

Section A

Section B

Overall gain: +1.0 dB

Proportional gain: +0.0 dB

Integrator gain: +16.1 dB

Differentiator gain: -54.0 dB

Integrator corner: 518.8 mHz

Differentiator corner: 312.5 kHz

☑ Advanced mode

4 d.o.f. horizontal tilt and displacement
vertical tilt and displacement

2 separate feedback loops

FPGA-based system with GUI (no VHDL!!)

CONCLUSIONS

TAKE-AWAY MESSAGE:

Movements of the optical components and of the beam on them are responsible for ellipticity noise that, if generated inside the cavity, is amplified just like the signal of interest.

⇨ need to control alignment of optical components inside the cavity!

ACTIVITY HIGHLIGHTS:

1. Built a test polarimeter equipped with Differential Wavefront Sensing
2. Improved rotating waveplate mechanics
3. New approach (workaround): modulation of magnetic field
4. Realtime sensing of waveplate systematics
5. Demonstrated locking (noisy) of the cavity with the rotating HWPs