APNS: Alignment and Pointing Noise Suppression

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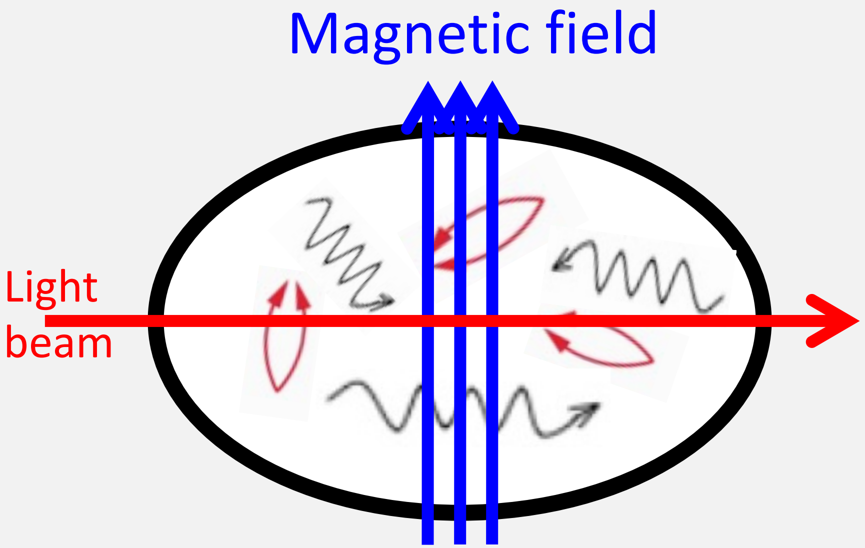
G.A. 754496

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

Light propagation in an external field



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:

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

BIREFRINGENCE DICHROISM

Experimental method:

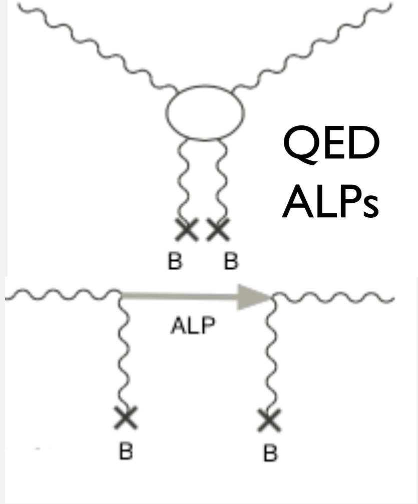
- Perturb the quantum vacuum with an external B field
- Probe with a (polarised) light beam
- Detect changes in the polarisation state

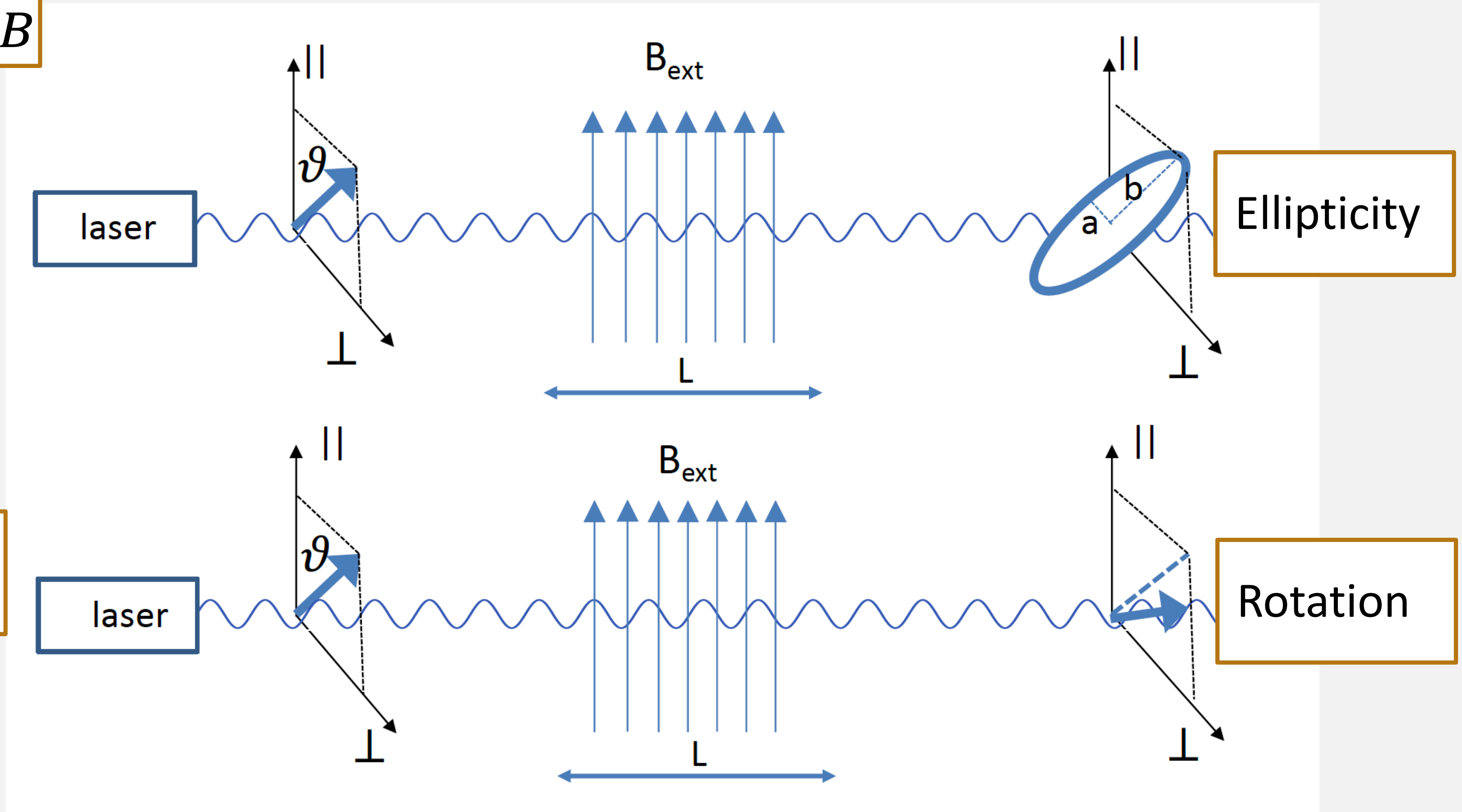
INFN Istituto Nazionale di Fisica Nucleare

Fellini Fellowship for Innovation at INFN

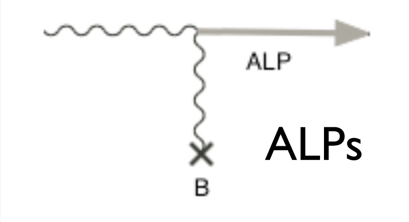
MEASURABLE QUANTITIES

Birefringence Δn_B





Dichroism $\Delta \kappa_B$



VACUUM MAGNETIC BIREFRINGENCE

Lagrangian of the electromagnetic field by **Heisenberg, Euler and Weisskopf (1936)**
Maxwell's equations are still valid but they are no longer linear.

At lowest order, for fields much smaller than the critical field ($B \ll 4.4 \cdot 10^{9}$ T; $E \ll 1.3 \cdot 10^{18}$ V/m):

$$L = L_{em} + L_{EH} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c} \cdot \vec{B}\right)^2\right]$$

$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \lambda_e^3}{m_e c^2}\right) = 1.32 \cdot 10^{-24}\ \mathrm{T}^{-2}$$

[W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)]
[H Euler, *Ann. Phys.* **26**, 398 (1936)]

This Lagrangian was later validated in **the framework of QED** [J. Schwinger, Phys. Rev., 82, 664 (1951)]

$$\Delta n_B = 3A_e \mathrm{B}^2$$

VACUUM MAGNETIC BIREFRINGENCE

$$\Delta\kappa_B \simeq 0$$

NO DICHROISM

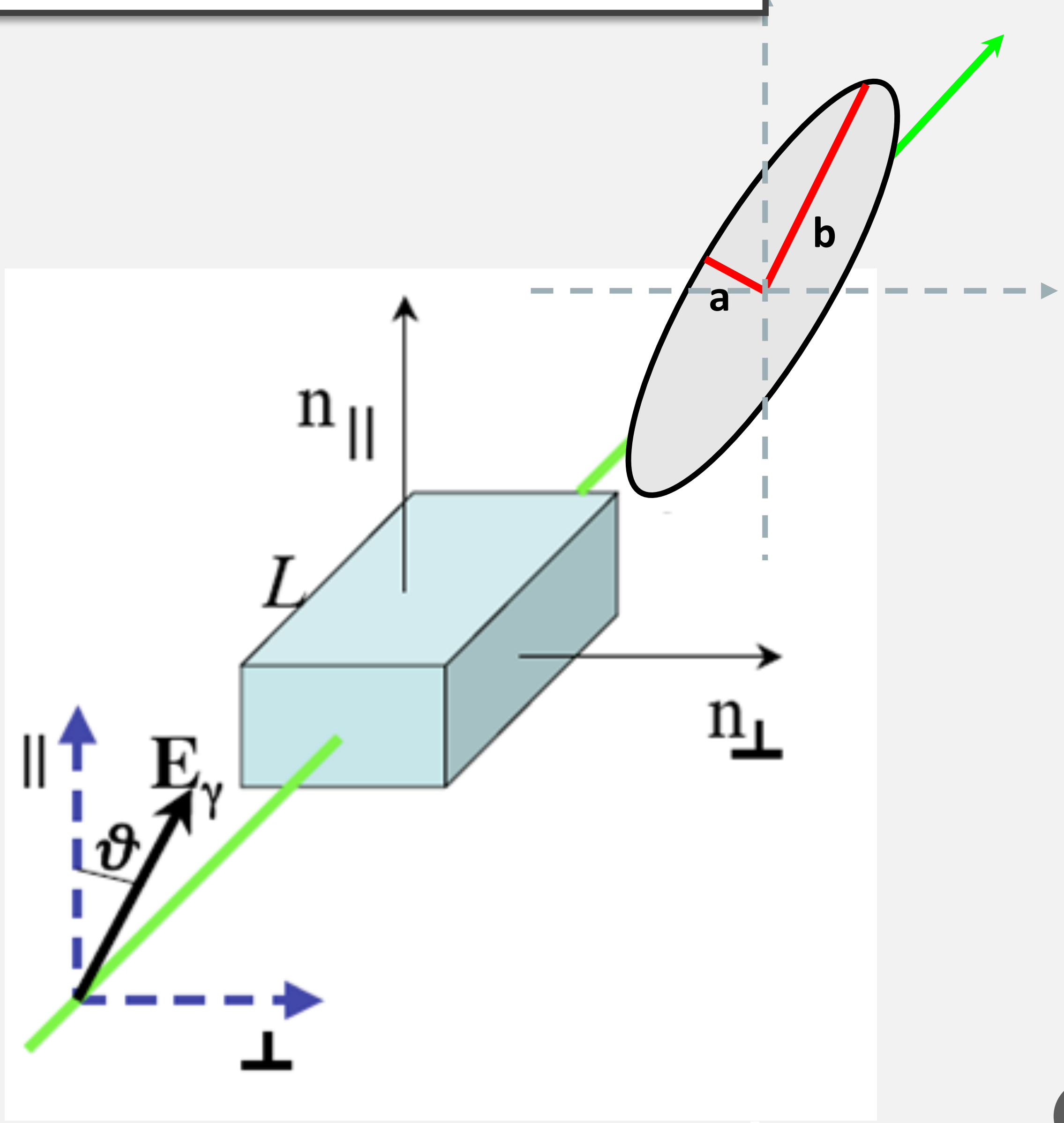
BIREFRINGENCE AND ELLIPTICITY

Index of refraction is different for the two orthogonal polarisations:

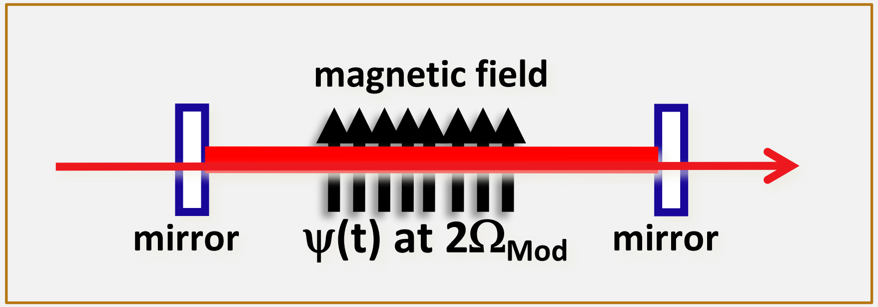
$$\Delta n = n_{||} - n_{\perp} \neq 0$$

A linearly polarised light beam propagating through a birefringent medium will acquire an **ellipticity** ψ:

$$\psi = \frac{a}{b} = \frac{\pi}{\lambda} \cdot \Delta n \cdot L \cdot \sin(2\theta)$$



KEY INGREDIENTS



PHYSICS 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:

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

➡

Key ingredients:

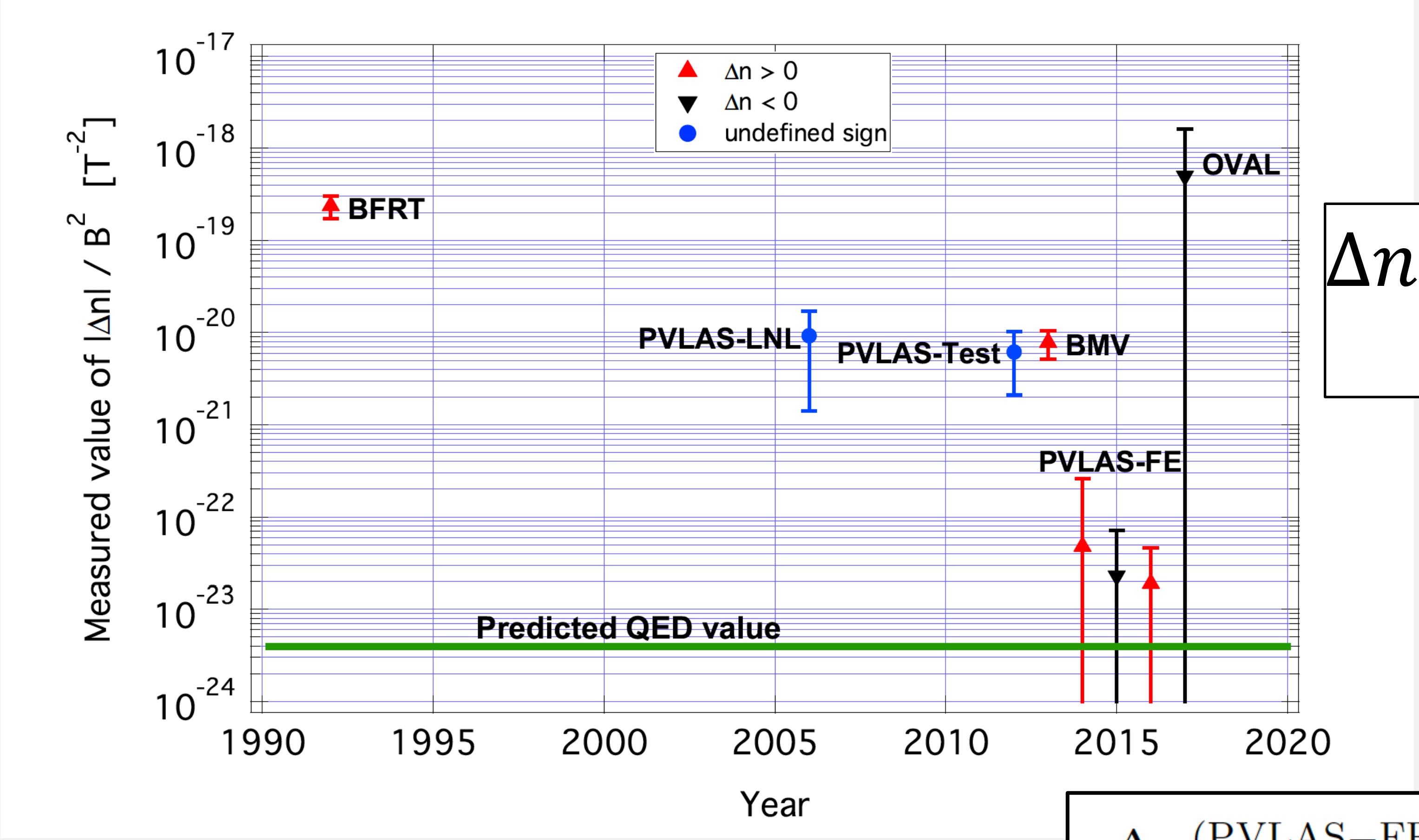
- High magnetic field
- Long optical path
- High sensitivity polarimeter

Superconducting magnets?

Fabry-Perot cavity
($N=2F/\pi$)

Modulation of the signal
decoupling from static effects

EXPERIMENTAL RESULTS



$$\Delta n_{QED} = 3A_e B^2 = 4\times 10^{-24}$$

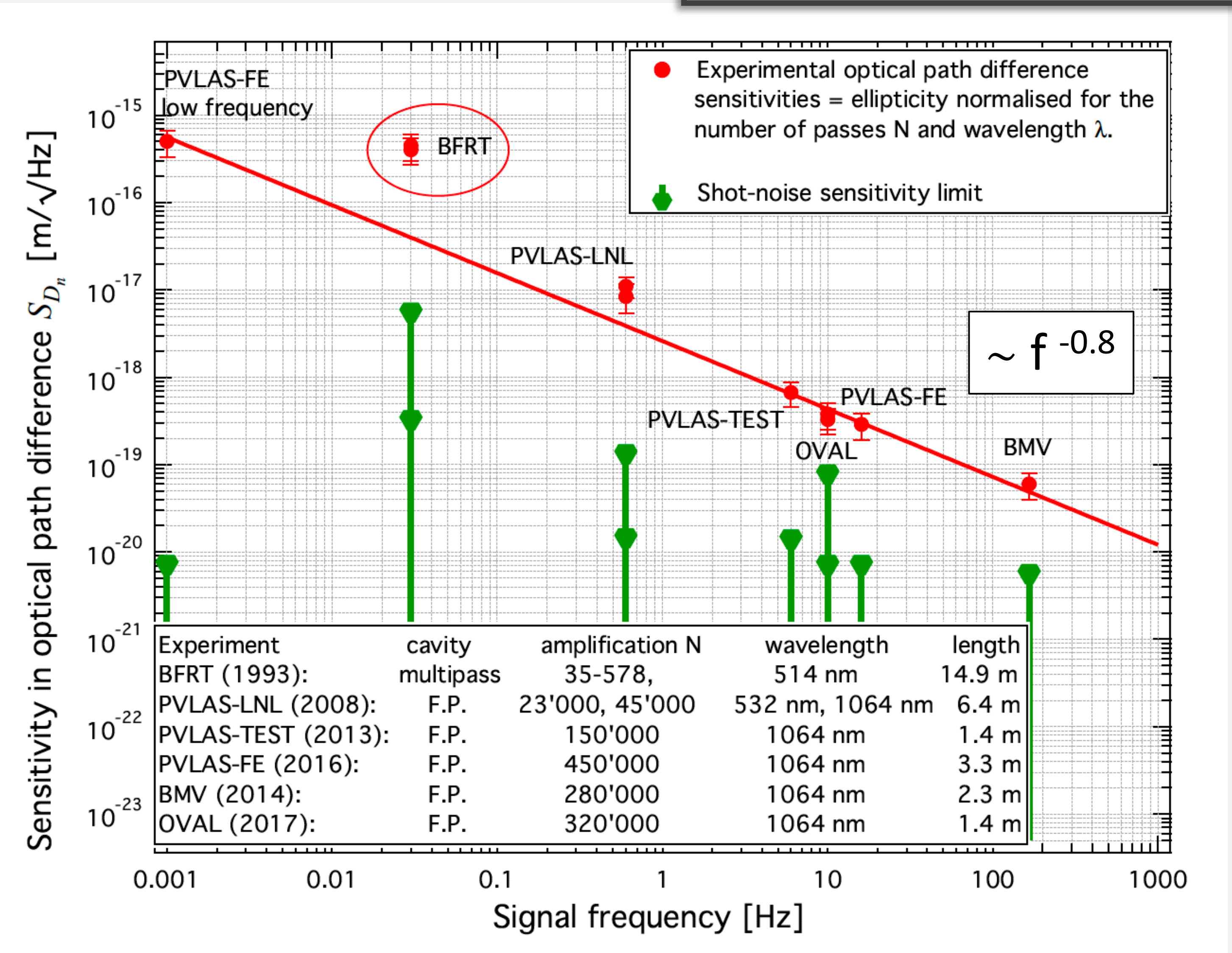
(for a 1 T magnetic field)

[A. Ejlli et al. Phys. Reports, 871 1-74 (2020)]

[F. Della Valle et al. (PVLAS collaboration), EPJ C 76, 24 (2016)]

$$\frac{\Delta n^{(\mathrm{PVLAS-FE})}}{B^2_{\mathrm{ext}}} = (+19 \pm 27) \times 10^{-24}\ \mathrm{T}^{-2}$$

SENSITIVITY



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

[A. Ejlli et al. Phys. Reports, 871 1-74 (2020)]

Intrinsic noise coming from the Fabry-Perot mirrors limits the sensitivity in optical path difference:

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

One would expect a constant S_ψ (given by the polarimeter), so:

larger finesse (larger N)

⇓

larger the induced ψ with a given Δn

⇓

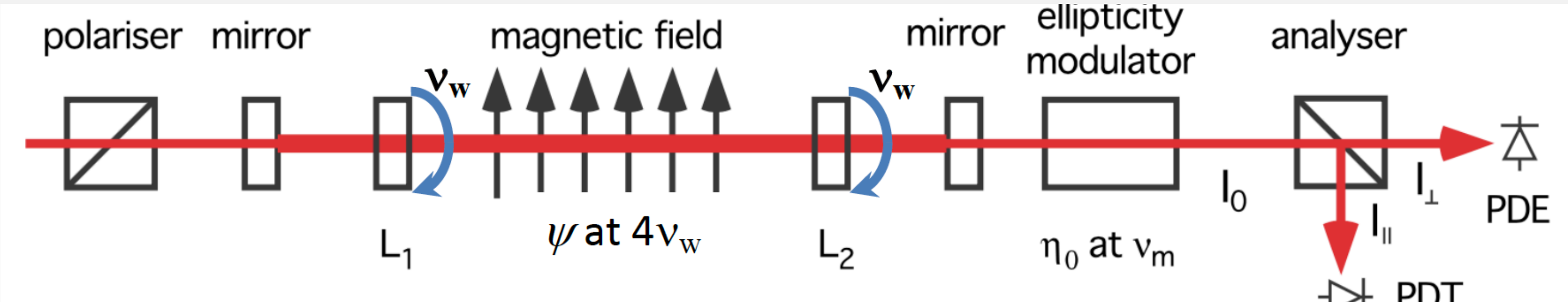
better OPL sensitivity

VMB@CERN

Clear indication for future experimental efforts:

increase the signal with higher B field → superconducting magnets

(LHC dipole magnet $B^2 \approx 81\ T^2$)



G. Zavattini et al. Eur. Phys. J. C (2016) 76:294

Proposed method to modulate the VMB signal using two co-rotating half waveplates inside the Fabry-Perot:

- Polarization rotation inside the magnetic field but fixed on mirrors
- Maximum finesse ≈ 1000 - 5000 (depending on the losses of the waveplates)

APNS PROJECT

("Alignment and Pointing Noise Suppression")

<u>Objective</u>

Develop an automatic alignment system for the injection and cavity optics

- Use of techniques that have been developed and used with success in GW interferometers

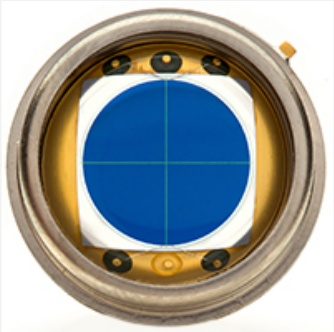
- Modify them in order to satisfy the needs of VMB experiments:
    - Stabilizing the cavity axis is not sufficient but it is required, in addition, that the resonant beam in the cavity always hits the same spot of the mirrors.
    - Movements of the beam on optical components are responsible for ellipticity noise that, if generated inside the cavity, are amplified in the same way as the signal of interest.

- Activity is in synergy with the VMBCERN experiment where most of these technology developments could be implemented.

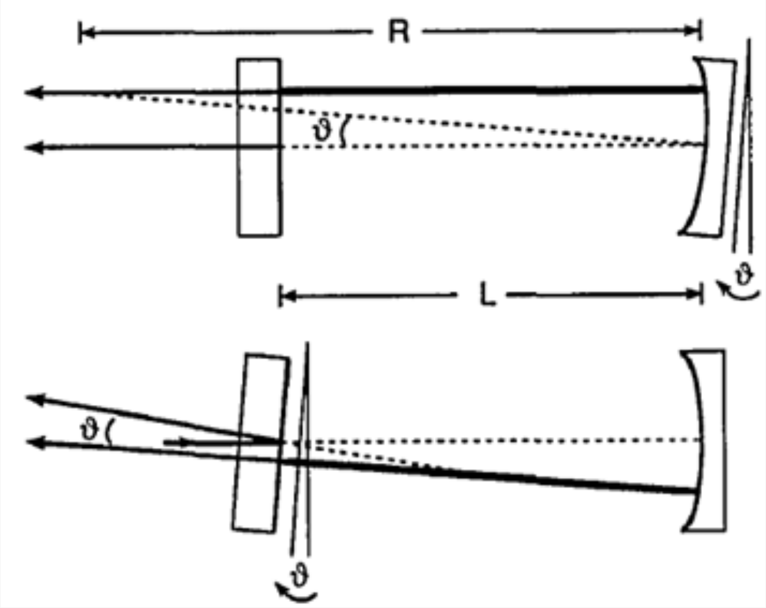
ALIGNMENT CONTROL

Spot position sensing — Center beam spot positions on mirrors

Differential wavefront sensing — Superimpose cavity axis with incoming beam



[www.first-sensor.com]



[D. Z. Anderson, Applied Optics, vol. 23, 17 (1984)]
[E. Morrison et al., Applied Optics (1994)]

Consider a beam misaligned into an optical cavity:

- Describe the input beam in the cavity basis (HG: Hermite-Gauss)
- From the cavity's point of view, input beam has a high-order mode content

Finesse 2

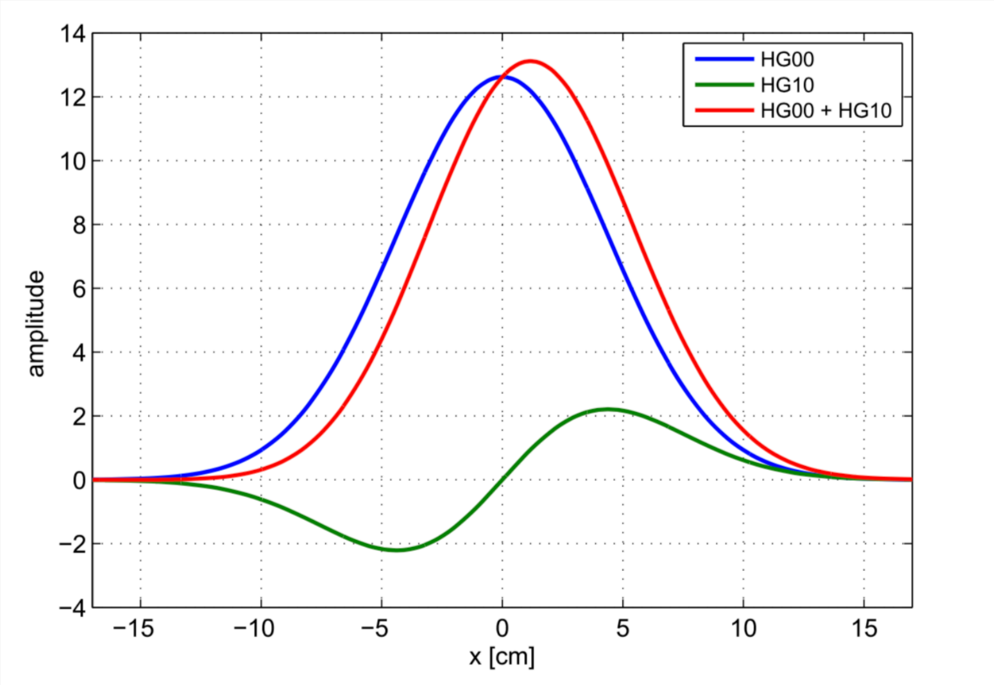
http://www.gwoptics.org/finesse/

DIFFERENTIAL WAVEFRONT SENSING

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

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

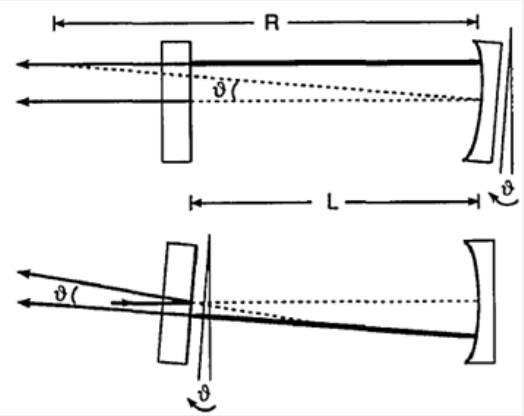
$$w(z) = w_0 \sqrt{1 + \left(\frac{z-z_0}{z_R}\right)^2}$$

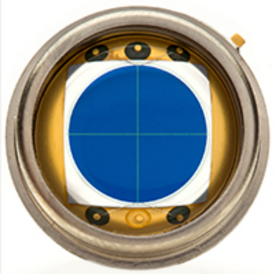


In the same way an angular misalignment α is a HG_{10} mode added in proportion α/Θ, 90^o out of phase, with the HG_{00} mode:

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

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





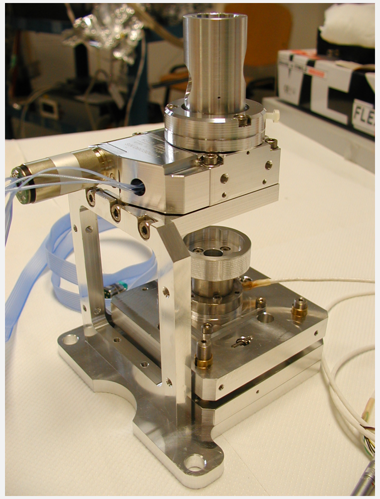
[www.first-sensor.com]

FERRARA TEST SET-UP

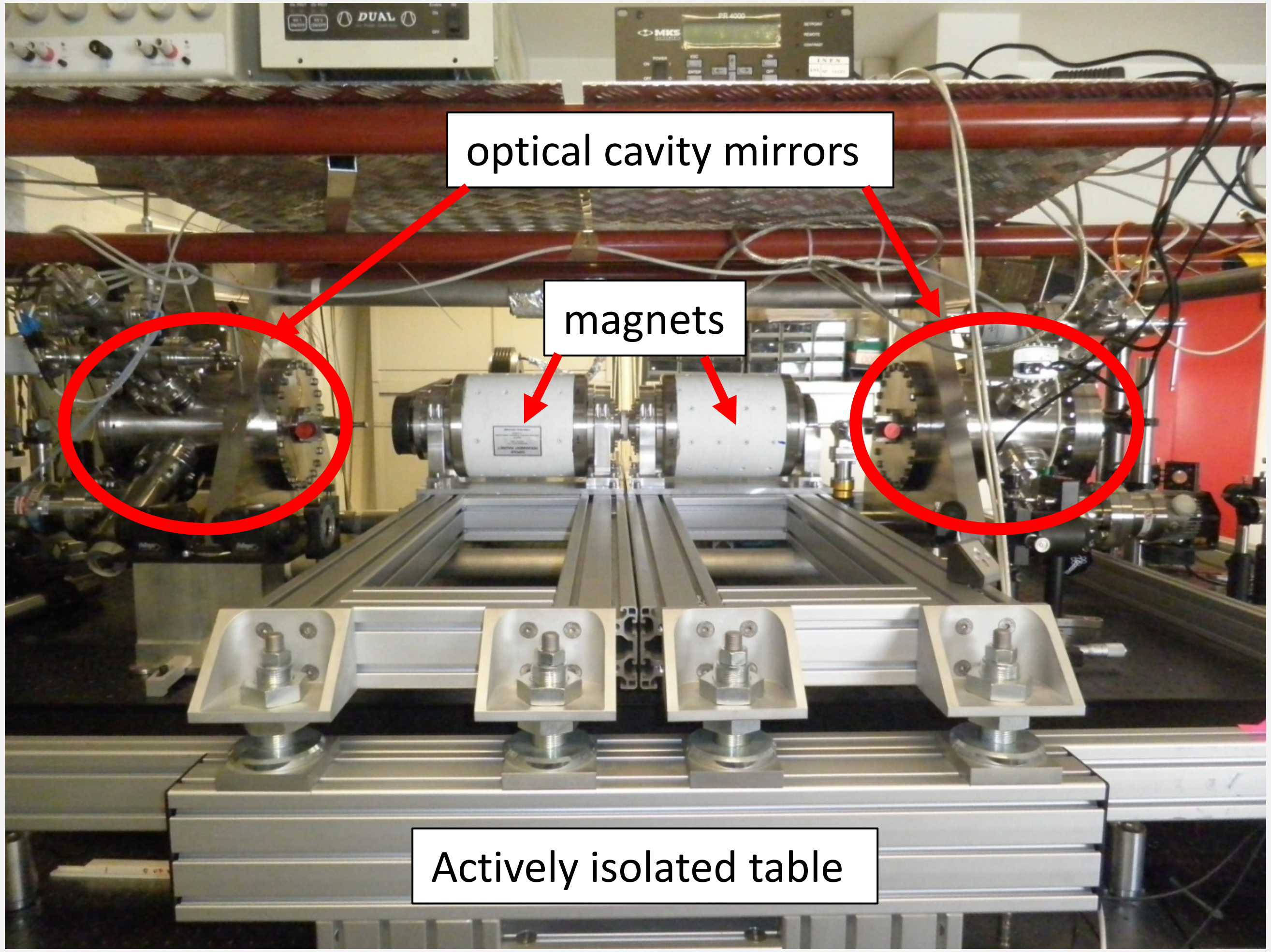
Test ellipsometer

- 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

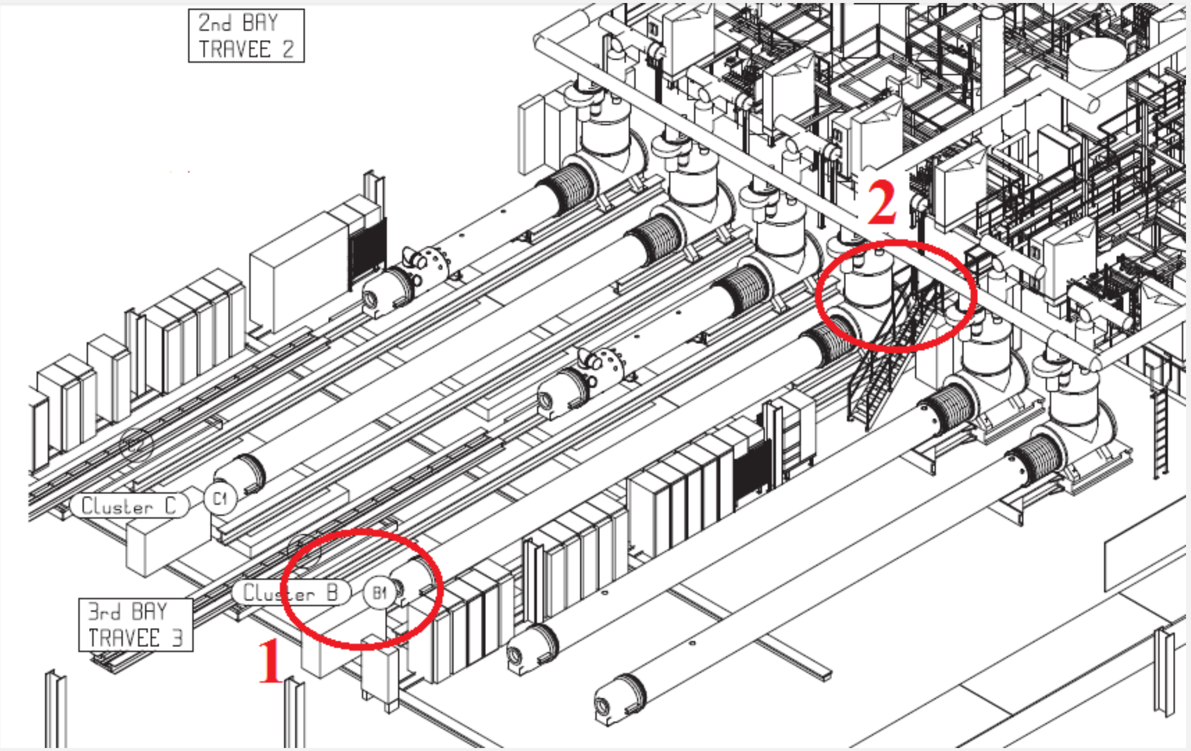


Vacuum-compatible actuators for moving the cavity optics



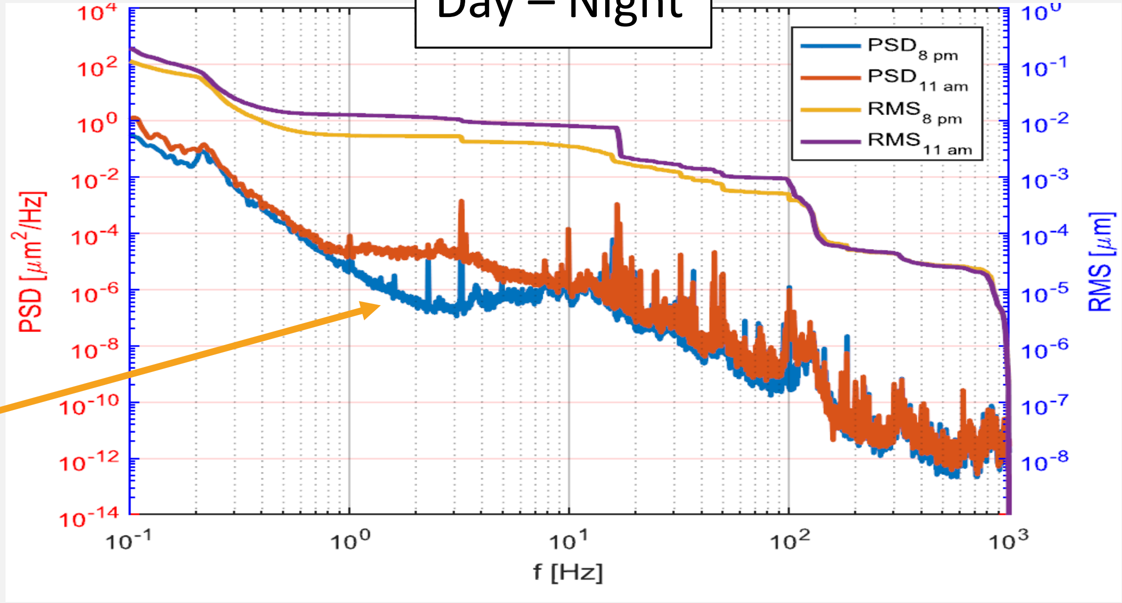
DISCUSSION AND EXTRA SLIDES

SEISMIC NOISE MEASUREMENTS SM18 (5-8 JULY 2016)



- 3-axis optical accelerometers
- 2 measurement points(sites)
- 65 hrs tot integration time

Day – Night

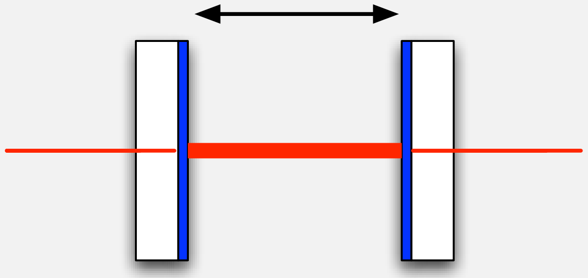


- Several peaks related to machinery and structural resonances
- Broadband noise (1-20 Hz) due to human activity in the hall.

FABRY PEROT CAVITY

The Fabry-Perot cavity increases the effective optical path inside the magnetic field region.

$$d = n\frac{\lambda}{2}$$

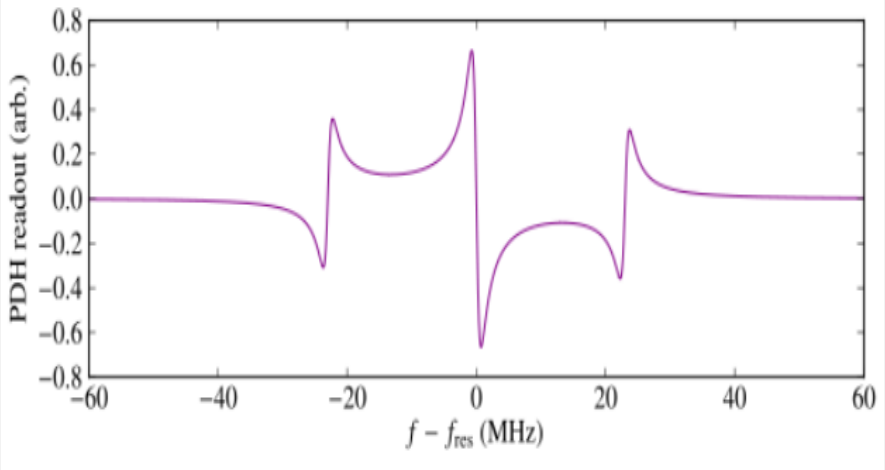


Amplification Pathlength

$$N = \frac{2F}{\pi}$$

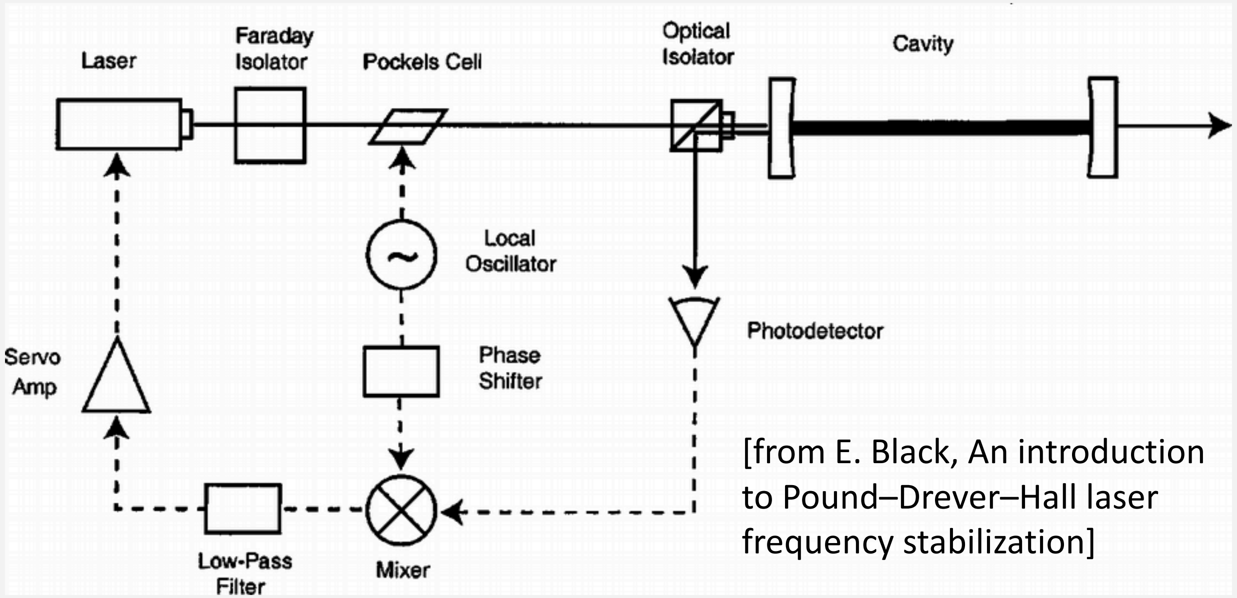
Finesse

$$F = \frac{\pi c \tau}{d}$$



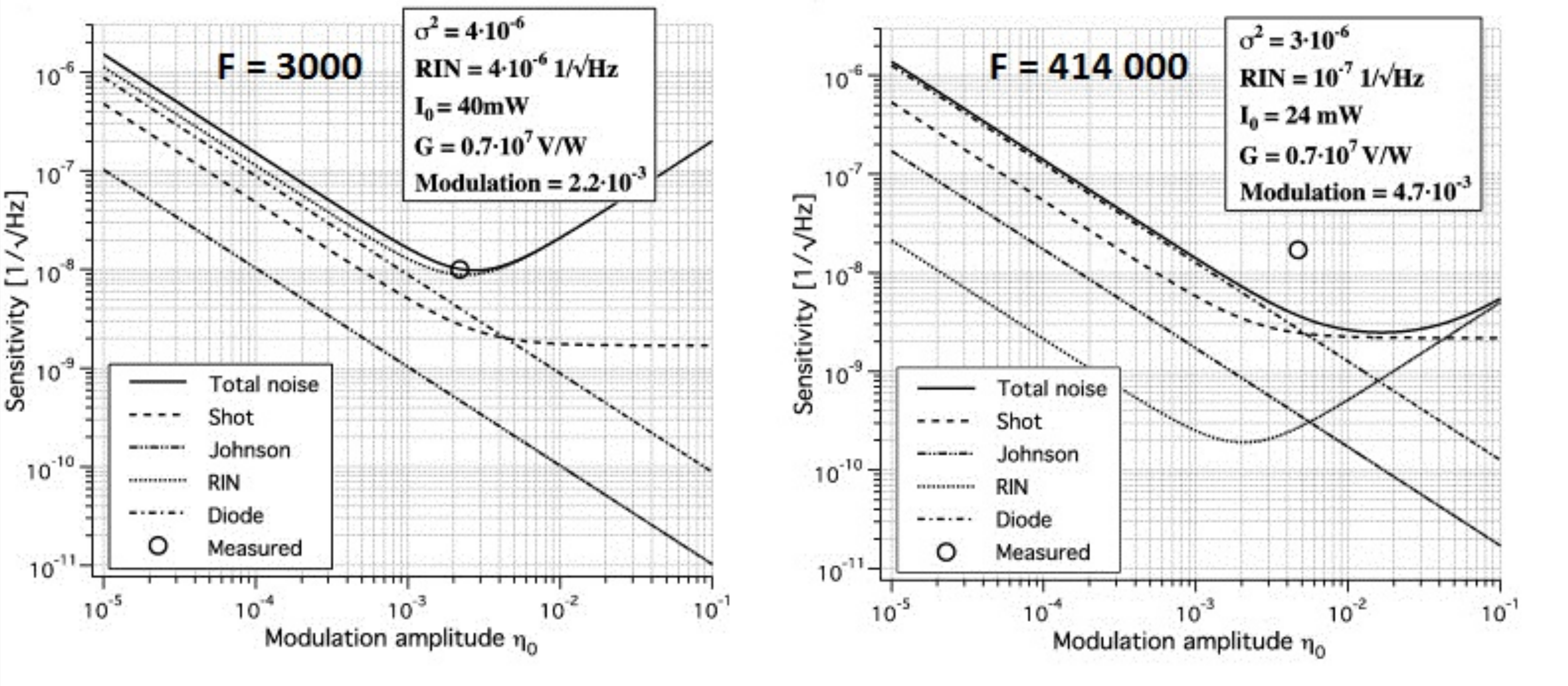
Injected laser light is frequency locked to the cavity length using a feedback circuit and the Pound-Drever-Hall technique:

- The laser is phase-modulated at a frequency greater than the feedback bandwidth -> PM sidebands
- The reflected light from the cavity beats with the PM sidebands and a locking error signal is generated.
- Light is detected in reflection with a photodiode and demodulated at the PM modulation frequency.
  The central part is linear.



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

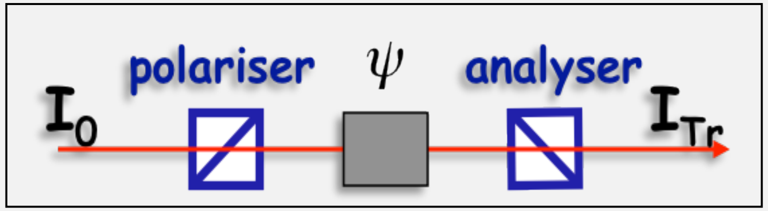
ELLIPTICITY SENSITIVITY



Noise budget OK. L = 50 cm Sensitivity worsened!!

[F. Della Valle et al., Optics Communications **283**, 4194 (2010)]

HETERODYNE DETECTION

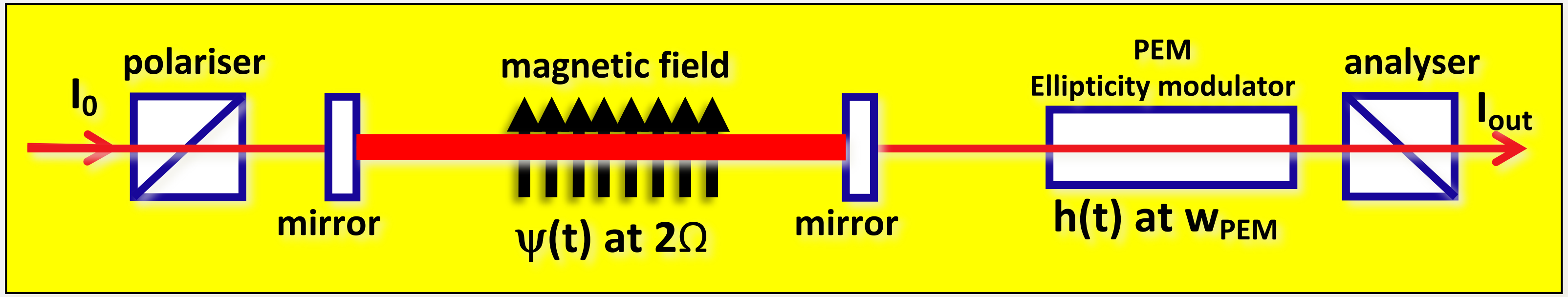


$$I_{\mathrm{Tr}} = I_0\left[\sigma^2 + \psi^2\right]$$

extinction $\sigma^2 \sim 10^{-7}$–10^{-8}

Static detection excluded!!

Signal is modulated in time and beats with a calibrated effect



$$I_{Tr} = I_0\left[\sigma^2 + \left(\psi(t) + \eta(t)\right)^2\right] = I_0\left[\sigma^2 + \left(\psi(t)^2 + \eta(t)^2 + 2\psi(t)\eta(t)\right)\right]$$

- **Signal linear in the birefringence**
- **Smaller 1/f noise**

COMPARISON WITH GW SEARCHES

VMB searches are sensitive to optical path length differences between two perpendicular polarisations.

GW interferometers look at an differential change along two separate optical paths.

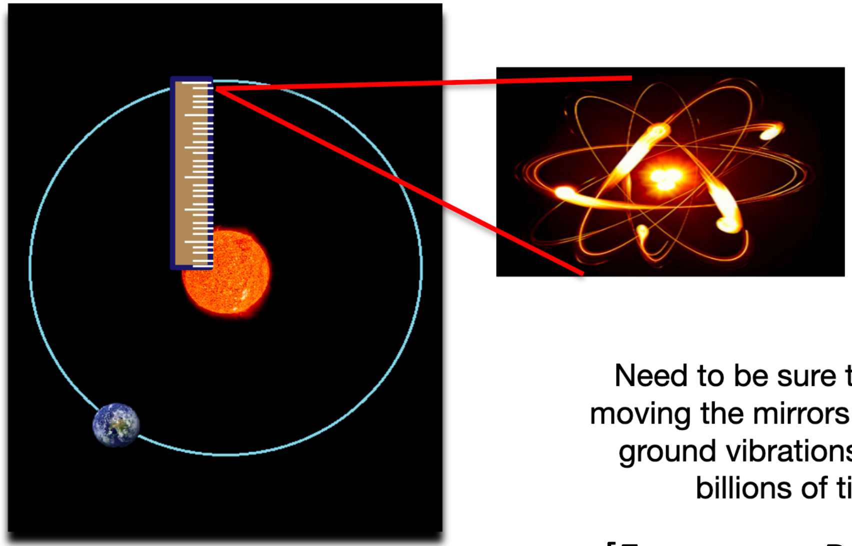
$$\frac{\Delta n^{(\mathrm{PVLAS-FE})}}{B_{\mathrm{ext}}^2} = (+19 \pm 27) \times 10^{-24}\ \mathrm{T}^{-2}$$

$B^2 L_{mag} \approx 10\ T^2 m \Longrightarrow \Delta n\ L_{mag} = 2 \cdot 10^{-22}$ m

A small displacement… really small

$$\frac{\textbf{Length variation}}{\textbf{Length}} \approx 10^{-21}$$

Equivalent to measure a displacement of the size of one atom compared to the Earth – Sun distance!



Need to be sure that nothing else is moving the mirrors by this tiny amount: ground vibrations, for example, are billions of times too big!

[Francesco Puosi, yesterday]