The VMB@CERN experiment

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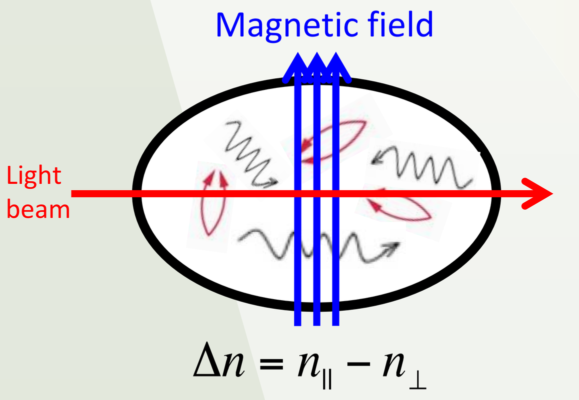
VACUUM MAGNETIC BIREFRINGENCE

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 on the direction of the applied field:

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

BIREFRINGENCE — DICHROISM

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

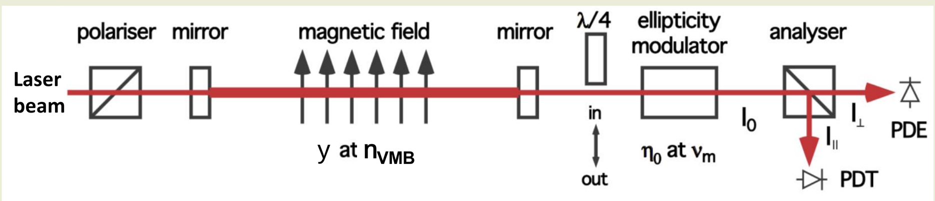
$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \lambda_e^3}{m_e c^2}\right) = 1.32\cdot 10^{-24}\ \mathrm{T}^{-2}$$

[W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)]
[H Euler, *Ann. Phys.* **26**, 398 (1936)]
[J. Schwinger, Phys. Rev., 82, 664 (1951)]

$\Delta n_{QED} = 3A_e B^2 = 4\times 10^{-24}$ @ 1 T magnetic field
VACUUM MAGNETIC BIREFRINGENCE

$\Delta\kappa_{QED} \simeq 0$
NO VACUUM MAGNETIC DICHROISM

EXPERIMENTAL METHOD

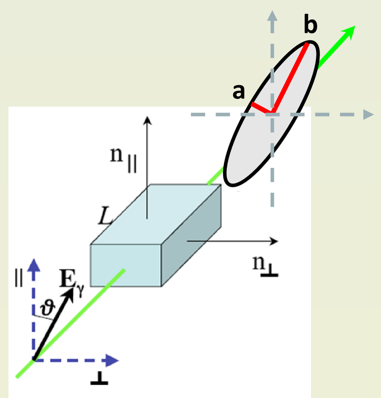


Experimental method:
- Perturb the quantum vacuum with an external B field
- Probe with a (polarised) light beam
- Detect changes in the polarisation state

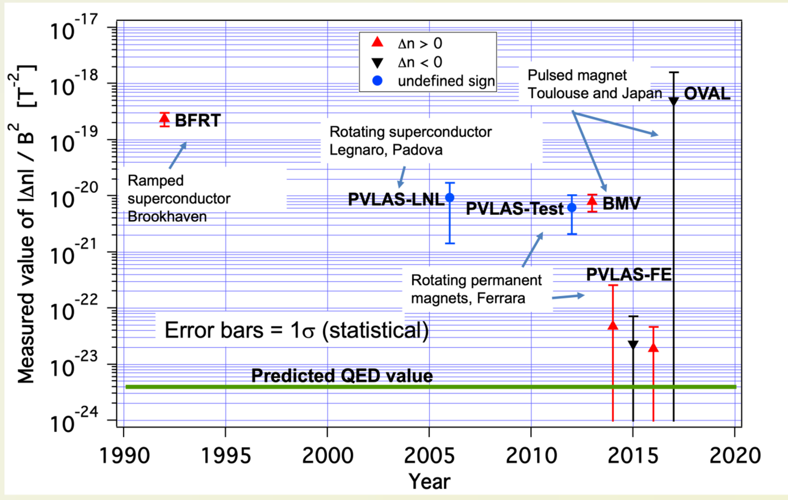
- High magnetic field — **Effect α B^2**
- Long optical path — **Optical cavity $N = 2F/\pi$**
- High sensitivity polarimeter — **Modulation of the signal**

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

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

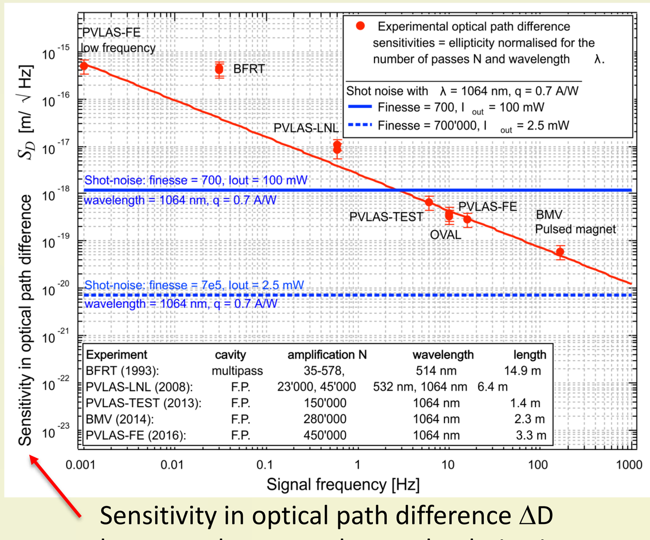


CURRENT LIMITS



[A. Ejlli et al. Phys. Reports 871:1 (2020)]

INTRINSIC NOISE



Sensitivity in optical path difference ΔD between the two orthogonal polarisations

Experiments never reach shot-noise limited sensitivity once the optical cavity is inserted.

Intrinsic noise coming from the cavity mirrors 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 a high finesse but rather increase the signal (B^2L)!

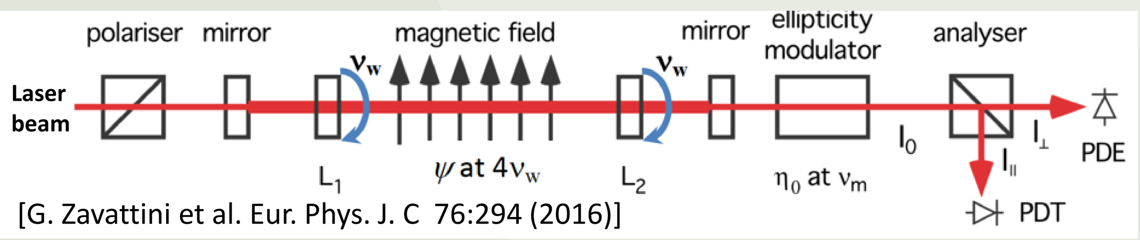
VMB@CERN: A NOVEL MODULATION SCHEME

LHC dipoles at CERN provide the best opportunity to maximize B^2L:

LHC dipole magnet $B^2L \approx 1200\ \mathrm{T}^2\,\mathrm{m}$
PVLAS permanent magnets $B^2L \approx 10\ \mathrm{T}^2\,\mathrm{m}$

but field in superconducting magnets cannot be modulated fast enough!!

Solution: Rotate the polarisation instead of magnetic field!



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

LoI submitted to CERN: CERN-SPSC-2018-036/SPSC-I-249

Modulate the VMB signal using two co-rotating half waveplates (HWP) inside the cavity:
- Polarisation rotates inside the magnetic field but is fixed on the mirrors (no mirror birefringence signal)
- Maximum finesse ≈ 800 - 3000 (depending on the losses of the waveplates)

The expected ellipticity signal is:

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

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

signal — systematics

Signal is at 4th harmonic of the rotation

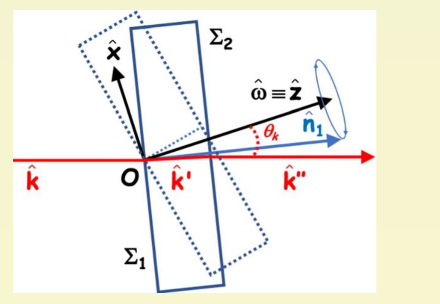
Waveplate defects have different frequency components

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

$\alpha_{1,2}^{(0)} \approx \mathbf{10^{-3}}$ (thickness error) @ 2nd harmonic — $\alpha_{1,2}^{(1)} \approx \mathbf{10^{-6}}$ (wedge error) @ 1st and 3rd harmonic

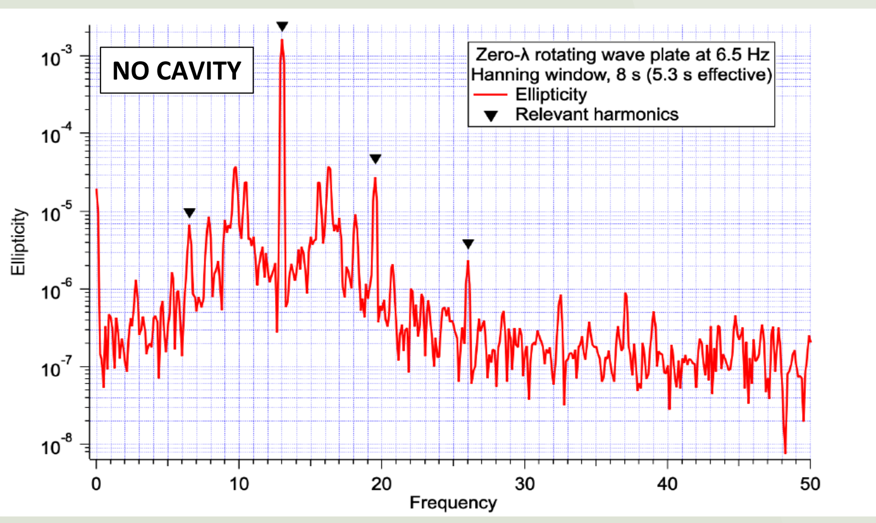
$\alpha_{1,2}^{(2)}$ appears @ 4th harmonic just like a magnetic birefringence signal => $\alpha^{(2)} < \psi_0 \approx \mathbf{10^{-14}}$ /pass

$\alpha_{1,2}$ also depend on the position and alignment of the HWPs with respect to the laser beam:



- **ω** = HWP rotation axis;
- $\mathbf{n_1}$, $\mathbf{n_2}$ = normal to the optical surfaces Σ_1 and Σ_2 of the HWP;
- **k** = incoming light beam, forming a small constant angle θ_k with **ω**;

TEST SETUP IN FERRARA



[G. Zavattini et al. Eur. Phys. J. C 82:159 (2022)]

A proof of principle feasibility study for the experiment started in 2020 at the INFN unit of Ferrara to validate the new modulation scheme.

Ellipticity spectrum with a zero-λ waveplate (no polarization rotation) to study systematics.

- 'Large bump' centered around 2nd harmonic
- Broadband noise
- Peaks at various harmonics (triangles) due to the imperfections of the rotating waveplate

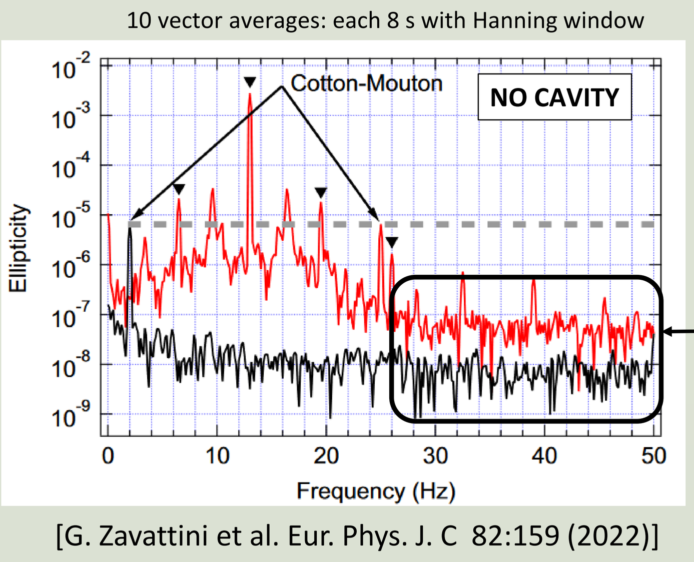
The presence of a greater-than-expected peak at the 4th harmonic → potential showstopper!

WORKAROUND: SLOW AMPLITUDE MODULATION OF THE MAGNETIC FIELD

- Rotating the polarisation with the waveplates shifts the signal to 'high frequency'.
- Magnet modulation separates the VMB signal from the peaks due to the systematic effects.

Method was validated measuring the Cotton-Mouton effect (magnetic birefringence in gasses) in air at atmospheric pressure.

10 vector averages: each 8 s with Hanning window



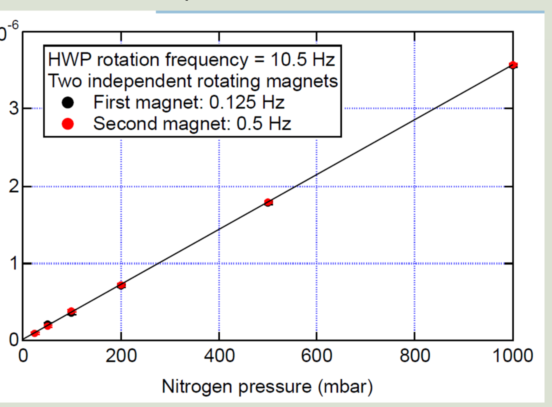
[G. Zavattini et al. Eur. Phys. J. C 82:159 (2022)]

- **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 peaks at the 1st, 2nd, 3th and 4th harmonic are due to the rotating HWPs.

The difference in noise is due to the relative phase (rotation) noise of the HWPs motors → Need to improve HWP mechanics!



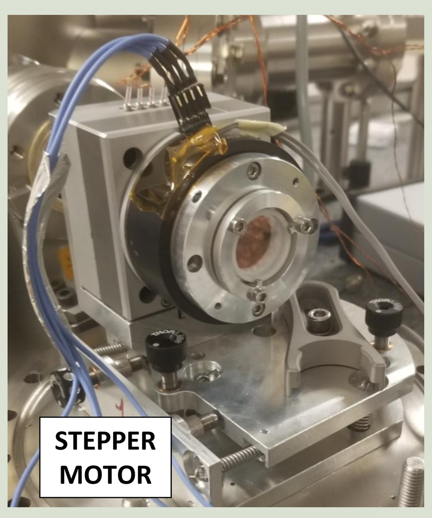
[G. Zavattini et al. Eur. Phys. J. C 82:159 (2022)]

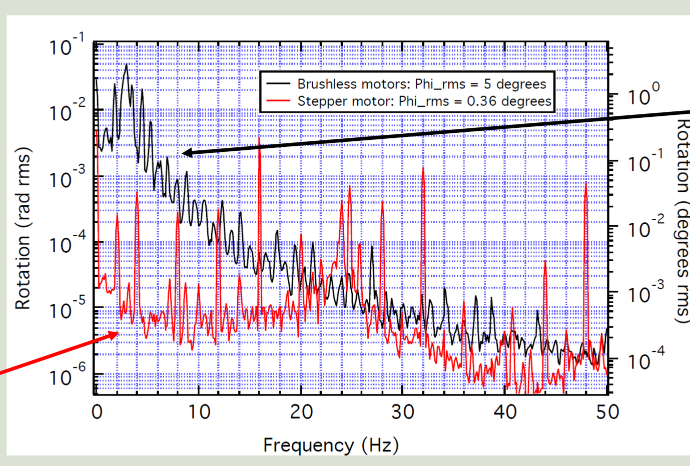
The same method was used to obtain the most precise measurement of the Cotton-Mouton effect in N_2 gas @ 1064 nm

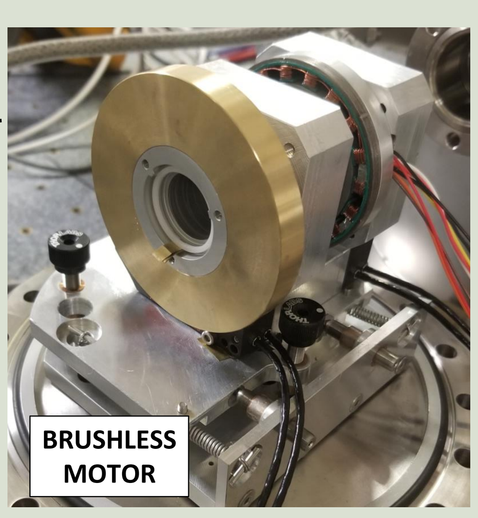
$$\Delta n_u^{(1064\ \mathrm{nm})} = (2.380 \pm 0.007^{(\mathrm{stat})} \pm 0.024^{(\mathrm{sys})})\times 10^{-13}\ \mathrm{T}^{-2}\mathrm{atm}^{-1}$$

REDUCING BROADBAND NOISE: NEW 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!







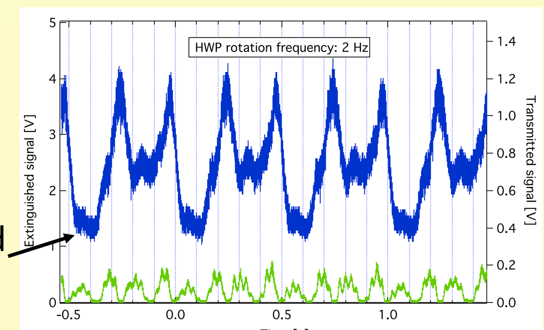
FABRY-PEROT OPTICAL CAVITY

Cavity mirrors have a nominal finesse F ≈ 3000. AR coating on HWPs ≈ 0.1% / surface → 0.4% total extra losses.
Finesse reduces to F ≈ 1200 → N ≈ 800.
In order to lock the laser to the cavity a well-defined linear polarisation between the cavity mirrors is needed:

$$N\,\alpha_{1,2} \ll 1 \rightarrow \alpha_{1,2} \lesssim 10^{-4}$$

Commercial waveplates do not guarantee this precision and phase retardation $\alpha_{1,2}$ from π is dominated by $\alpha_{1,2}^{(0)} \approx \mathbf{10^{-3}}$ (thickness error).

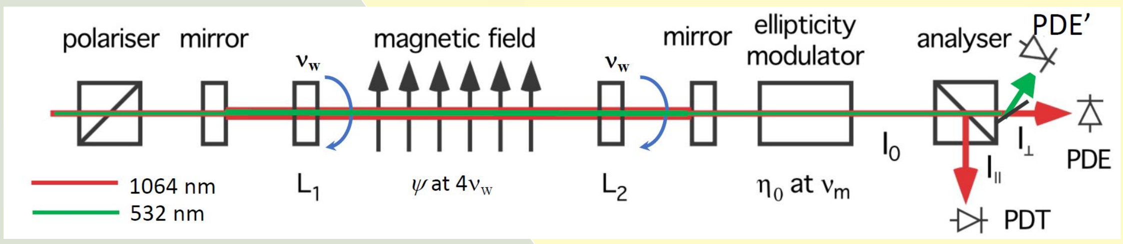
$\alpha_{1,2}^{(0)}$ is temperature dependent: by changing the temperature of the HWPs with ring heaters (by a few °C) we can reduce the value of $\alpha_{1,2}^{(0)}$ by more than a factor 100 and achieve a stable locking (hours).



There is still a large intensity noise due to the residual N $\alpha_{1,2}$ now dominated by the 1st, 3rd and 4th harmonic which are due to the HWP alignment.

FURTHER REDUCTION OF PEAKS: ALIGNMENT WITH GREEN LASER

Injecting in the polarimeter an auxiliary green laser beam @ 532 nm (HWP@1064 nm → FWP@532 nm, polarization is not rotated in green) allows real-time control of the alignment of the individual waveplates.



- The 532 nm green laser beam (that is not resonant in the cavity) is aligned to pass through the waveplates in the same point as the 1064 nm beam;
- Each waveplate is rotated one at a time and aligned independently;
- When both waveplate has been adjusted using the 532 nm beam, the 1st, 3rd and 4th harmonics are strongly reduced also at 1064 nm as expected.
- An active feedback system can be set up to further reduce the residual peaks with the cavity engaged.

FUTURE WORK AND MILESTONES

Second half of 2022:
- Demonstrate shot-noise capability without cavity and an output power of about 50 mW in Ferrara.
- Design of vacuum and LHC magnet interfaces to optics.

First half of 2023:
- Vibration noise study in SM18 @ CERN.

Second half of 2023:
- Installation at CERN of a complete polarimeter (no cavity) with an LHC dipole to implement the HWPs control system.

2025:
- Perform accurate Cotton-Mouton measurements (no cavity).
- Frequency modulation study of the LHC magnet.
- Installation of the 20m long optical cavity.

2026:
- Calibration of full setup and data taking.

ACKNOWLEDGEMENTS

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