VMB@CERN

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ON BEHALF OF VMB@CERN COLLABORATION

PATRAS WORKSHOP 2019

VMB@CERN collaboration

New approach to measure Vacuum Magnetic Birefringence
Started in 2019

PVLAS + Q&A + OSQAR-VMB + LIGO group (Cardiff)

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about 15 members from 10
Institutes from Czech Republic, France, Italy, Poland, Republic of China and Wales

VMB - Light propagating in vacuum in an external magnetic field

- Linear Birefringence – polarization dependent index of refraction
- Linear Dichroism - polarization dependent index of absorption
- In external perpendicular magnetic field $\vec{B}$

$$\Delta n_{vac} = \Delta n_B + i\Delta k_B$$

$\Delta n_B \propto B^2$

Birefringence
Predicted by QED, ALP processes, Millicharged particles (MCP)

Dichroism
Predicted by ALP processes, Millicharged particles (MCP)

$\Delta k_B \propto B^2$

QED Vacuum Magnetic Birefringence

- H. Euler, B. Kockel - 1935
- They wrote an effective Lagrangian describing electromagnetic interactions in the presence of the virtual electron-positron sea

$$\mathcal{L}_{EK} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] + \cdots$$

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2\lambda_e^3}{m_e c^2} = 1.32 \times 10^{-24}\ \mathrm{T}^{-2} \longrightarrow \Delta n_B = 3A_e B^2$$

No linear Dichroism is expected in the framework of QED

Ellipticity

- We can not measure directly Δn_B
- What we measure is induced ellipticity ψ
- We determine optical path difference $D_n = \Delta n_B L$

Single pass $$\psi_0 = \frac{\pi 3 A_e B^2 L}{\lambda} \sin 2\delta$$

To obtain maximum signal ψ

we need high magnetic field B

in as long as possible region L

Pol. and B fields at 45° degree δ

Ellipsometer parameters

- **Long optical path – Fabry-Perot cavity**

High amplification factor N, PVLAS F = 770 000

Fabry Perot cavity $$\psi = \frac{\pi 3 A_e B^2 L}{\lambda} \boxed{\frac{2F}{\pi}} \sin 2\delta$$

N – amplification factor

- **High magnetic field $\boldsymbol{B}^2$**

Permanent magnets – PVLAS – B = 2.5 T

superconducting magnets – OSQAR – B = 9 T, L =14.3 m

- **Time dependent effect - to achieve high sensitivity**

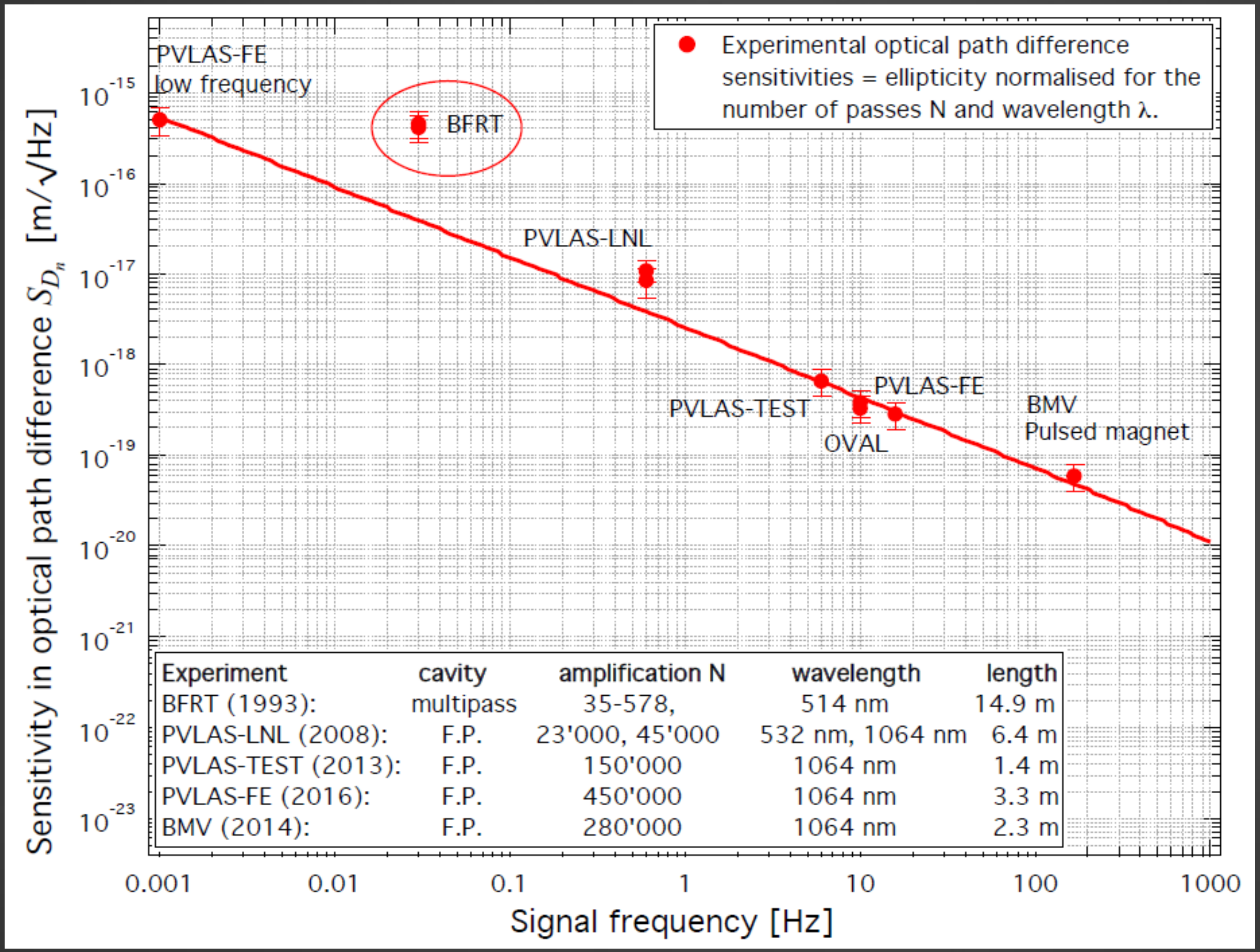
Time dependent magnetic filed - modulation - BRFT, pulsed – BMV,OVAL

Time dependent angle δ – PVLAS I-II – rotating the permanent magnets

Intrinsic noise

Sensitivity in optical path difference D_n between two orthogonal polarizations

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



PVLAS -

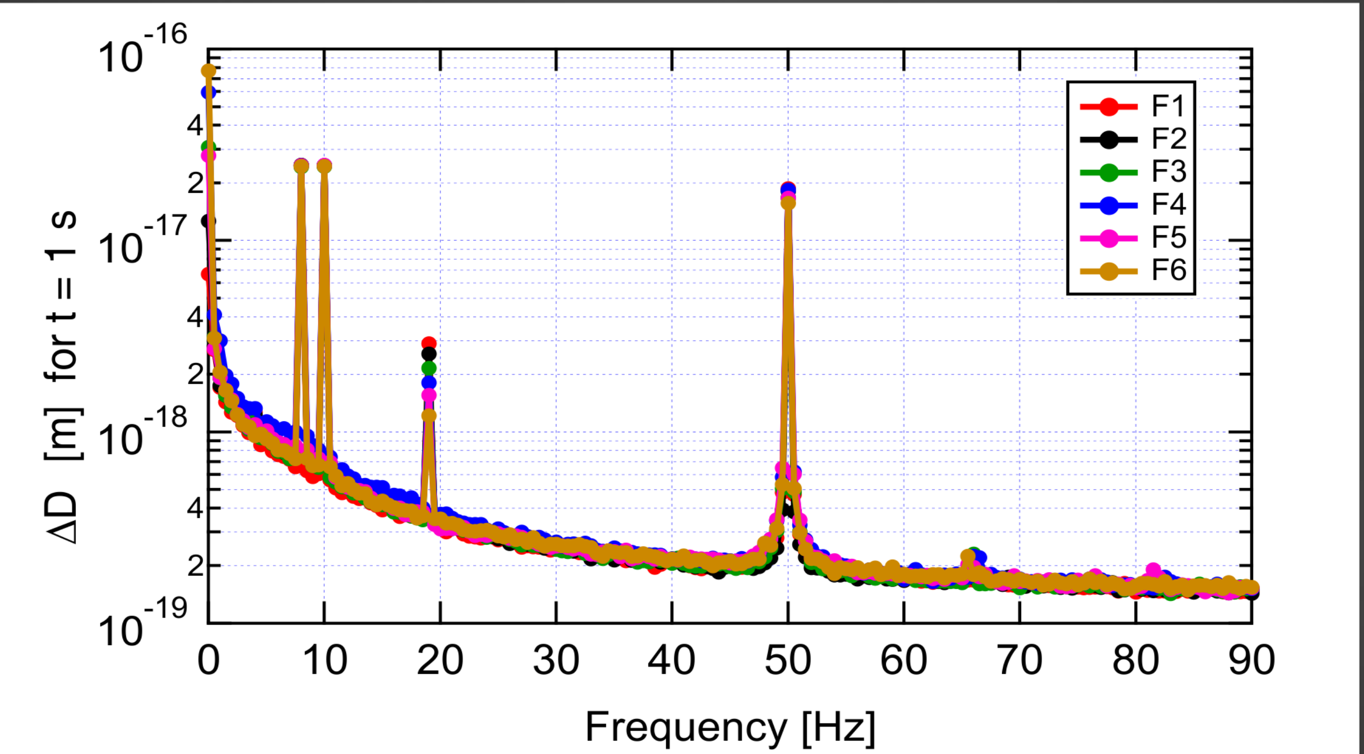
The ultimate level of shot noise was reached without the Fabry – Perot cavity.

But with the cavity there is an extra noise dominated by ellipticity due to the cavity mirrors even in the heterodyne modulation

Sensitivity in optical path difference D_n does not depend on finesse

Intrinsic noise

- Measured ellipticity noise and Cotton-Mouton signal as a function of the finesse
- Finesse range: 250’000 – 690’000



G. Zavattini et al. Eur. Phys. C 78:585 (2018)

- **Noise and Cotton-Mouton *ΔD* signals are independent of finesse**
- **Above finesse of ≈ 20 000 the intrinsic noise is dominant at ≈10 Hz**

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Use LHC dipole magnet and separate magnet from modulation

1. Increase signal

Use LHC magnet - $B^2L \approx 1200\ \mathrm{T}^2\mathrm{m}$ - almost impossible to modulate or rotate

2. Time dependent angle δ

Rotate the polarization instead of magnetic field

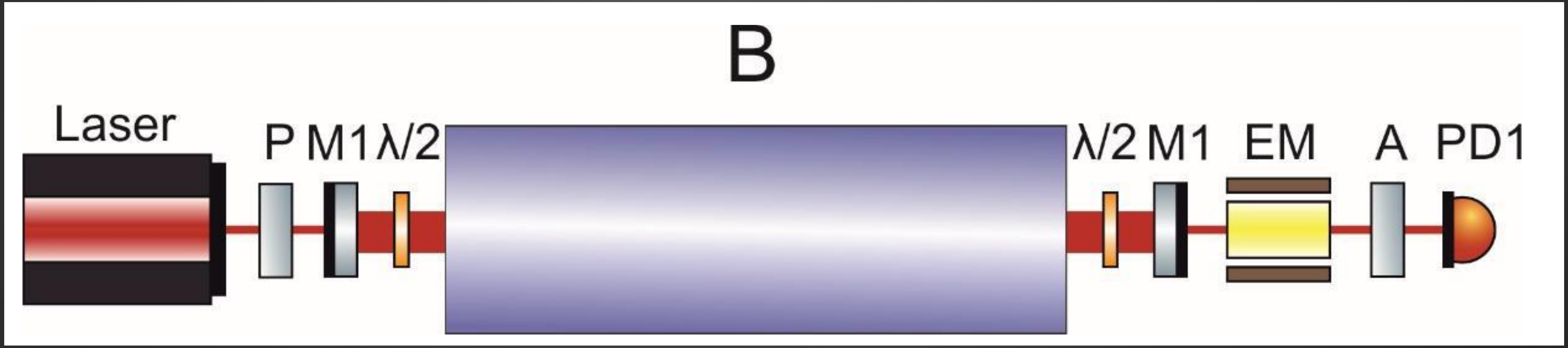
Use rotating half wave plates to produce modulation in VMB ellipticity

Profit from heterodyne measurement principle

Rotation of half wave-plates

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

Rotate polarization inside the magnetic field
Fix polarization on mirrors to avoid mirror birefringence signal
Insert two co-rotating half wave plates at frequency f with a fixed relative angle
Total losses ≈ 0.4% (commercial) finesse becomes F ≈ 800
Maybe 10 times lower loss is possible F ≈ 10 000



Signal

Output intensity solution

$$I(t) = I_0\{\eta(t)^2 + 2\eta(t)N[\psi_0 \sin 4\theta(t) + \alpha_1 \sin 2\theta(t) + \alpha_2 \sin(2\theta(t) + 2\Delta\theta)]\}$$

VMB signal appears at 4th harmonics of HWP rotation

Wave-plate defects $\alpha_{1,2}$

$$\alpha_{1,2}(t) = \alpha_{1,2}^{(0)} + \alpha_{1,2}^{(1)} \cos\theta(t) + \alpha_{1,2}^{(2)} \cos 2\theta(t) + \cdots$$

$\alpha_{1,2}^{(0)} \approx 10^{-3}$ (thickness error) – 2nd harmonic

$\alpha_{1,2}^{(1)} \approx 10^{-6}$ (wedge error) – 1nd and 3rd harmonic

$\alpha_{1,2}^{(2)} \approx ???$ (saddle error) – 4th harmonic

LHC magnet

Signal $D_n = 4 \times 10^{-24} B^2 \mathrm{L}$

Intrinsic noise $S_{D_n}^{(intristic)} = 2.6 \times 10^{-18} \nu^{-0.77}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

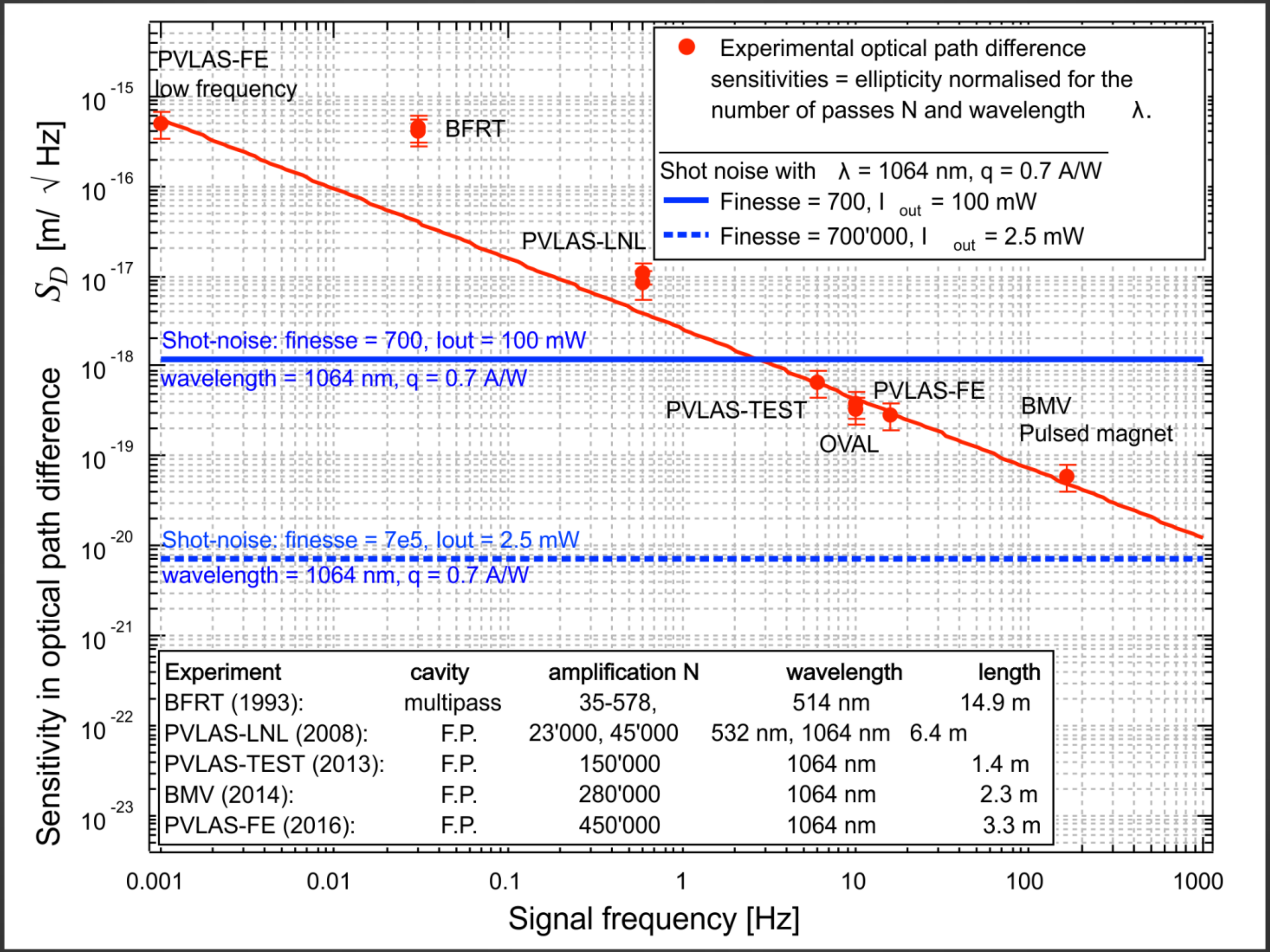
Shot noise $S_{D_n}^{(shot)} = \sqrt{\frac{e}{I_0 q} \frac{\lambda}{\pi N}}$

Measurement time $T = \left(\frac{S_{D_n}}{D_n}\right)^2$

LHC magnet $B^2 L = 1200\ \mathrm{T}^2\mathrm{m}$; $S_{D_n} = 10^{-18}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 3Hz

$T = 12$ h for S/N = 1

$S_{D_n} \approx 10^{-18}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ as goal sensitivity



Updated graph from G. Zavattini etal. Eur. Phys.J.C(2016)76:294

Conclusion

Rotating half wave-plates inside a Fabry-Perot cavity could be a viable solution to use high magnetic field of LHC magnet

Maximum finesse F ≈ 10’000

Defects may also be a limit but only at second order: $\boldsymbol{\alpha_{1,2}^{(2)}}$

With a sensitivity of $D_n \approx 10^{-18}$ m/√Hz and 1 LHC magnet, vacuum magnetic birefringence could be measured with S/N = 1 in about 1day.

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

Joint effort between past Vacuum Magnetic Birefringence experiments + LIGO: 16 authors, 7 countries.