VMB@CERN

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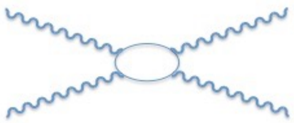
On behalf of the VMB@CERN collaboration

LoI at http://cds.cern.ch/record/2649744?ln=en

VMB@CERN is an initiative which aims at putting together all the present experience from different experiments which attempted to measure Vacuum Magnetic Birefringence

VMB@CERN - France, Italy, Poland, Switzerland, Taiwan, UK,


a) Leptonic e^+e^- LbL scattering


b) Leptonic e^+e^- vacum birefringence

Diffusion of light-by-light and vacuum magnetic birefringence.

$$\Delta n = 3A_e B_{\text{ext}}^2 = 4 \times 10^{-24} B_{\text{ext}}^2$$ with B in Tesla


c) Leptonic e^+e^- vacuum birefringence with second order radiative corrections.

Radiative corrections to first order birefringence: 1.45%


e) Birefringence due to virtual spin zero bosons (e.g. axions)

Contribution of hypothetical neutral particles which couple to two photons (axion-like particles)

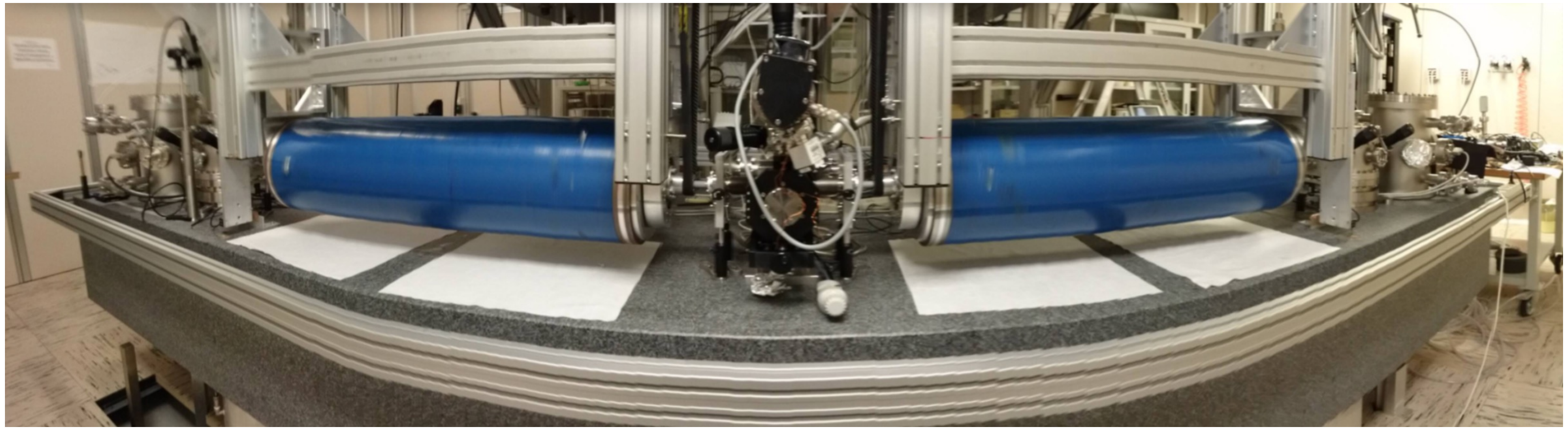
PVLAS-FE experiment has set the best limit on VMB.

PVLAS-FE polarimeter was based on:

- Very high finesse Fabry-Perot cavity
- Rotating magnetic field for signal modulation
- Heterodyne detection

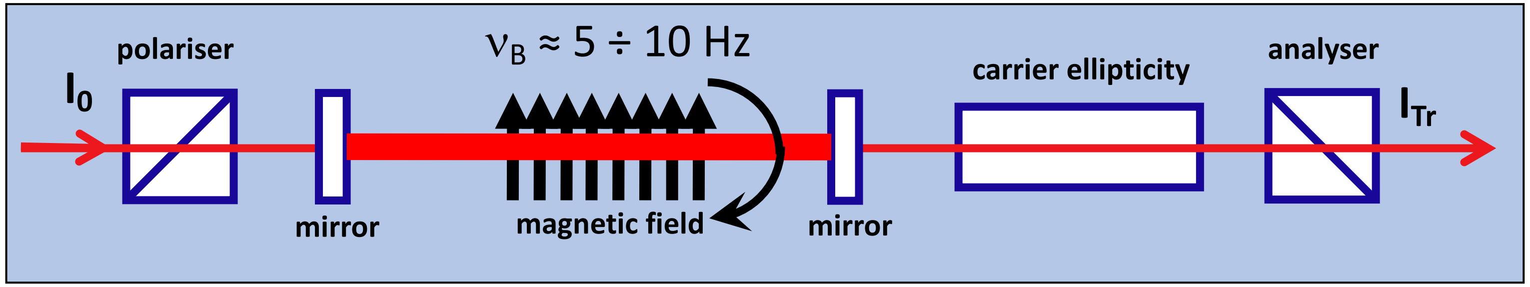
$$\Psi(t) = N\pi \frac{\int \Delta n \, dL}{\lambda} \sin 2\vartheta(t)$$

Optical path difference

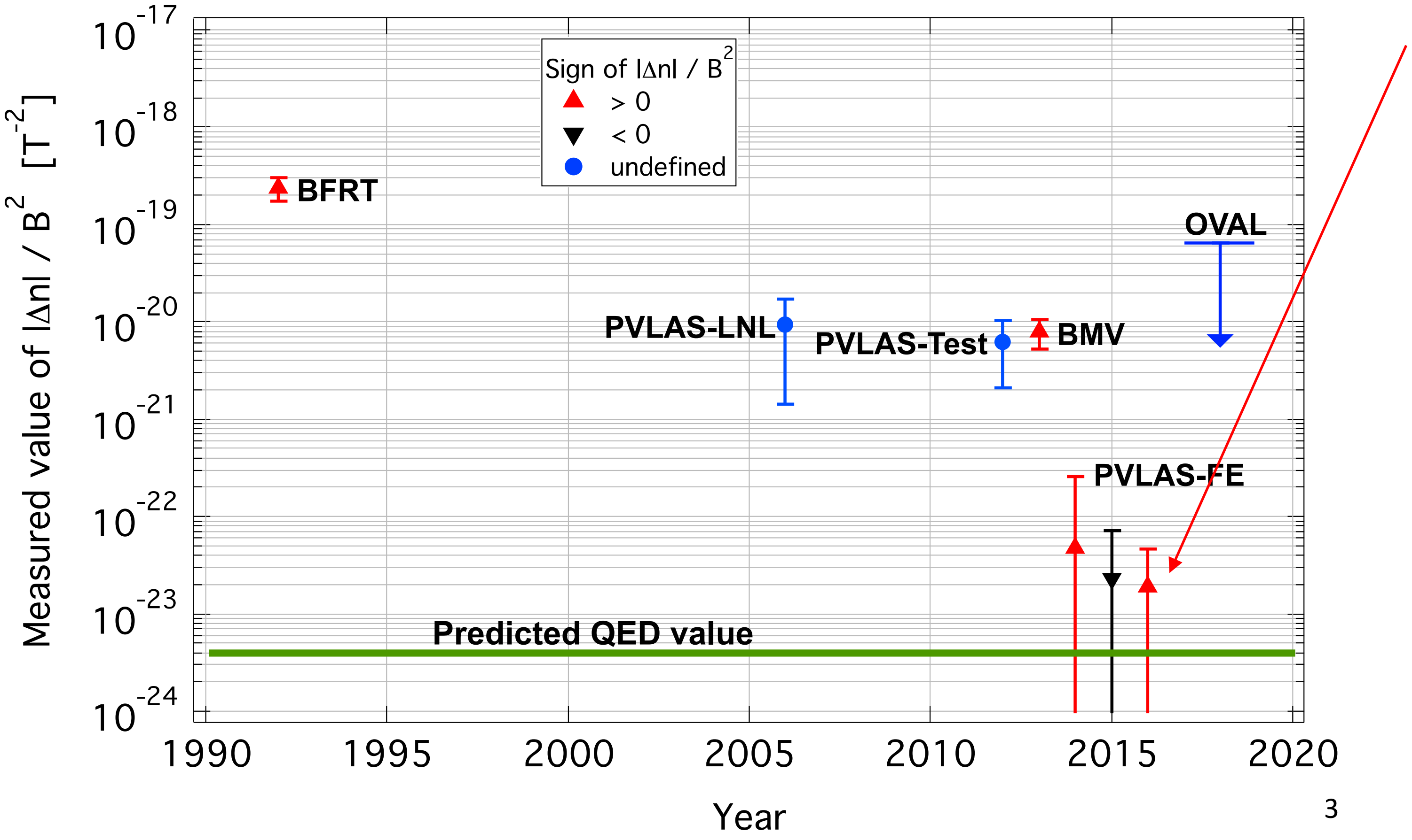


PVLAS-FE result

Equivalent passes N ≈ 4.5x10^5
Signal frequency ≈ 10 ÷ 20 Hz
B_{ext} = 2.5 T
$L_{eff} = L_B$ N ≈ 800 Km



Expected optical path difference signal $\Delta\mathcal{D} = \int 3A_e B^2\, dL = 4.2 \times 10^{-23}$ m

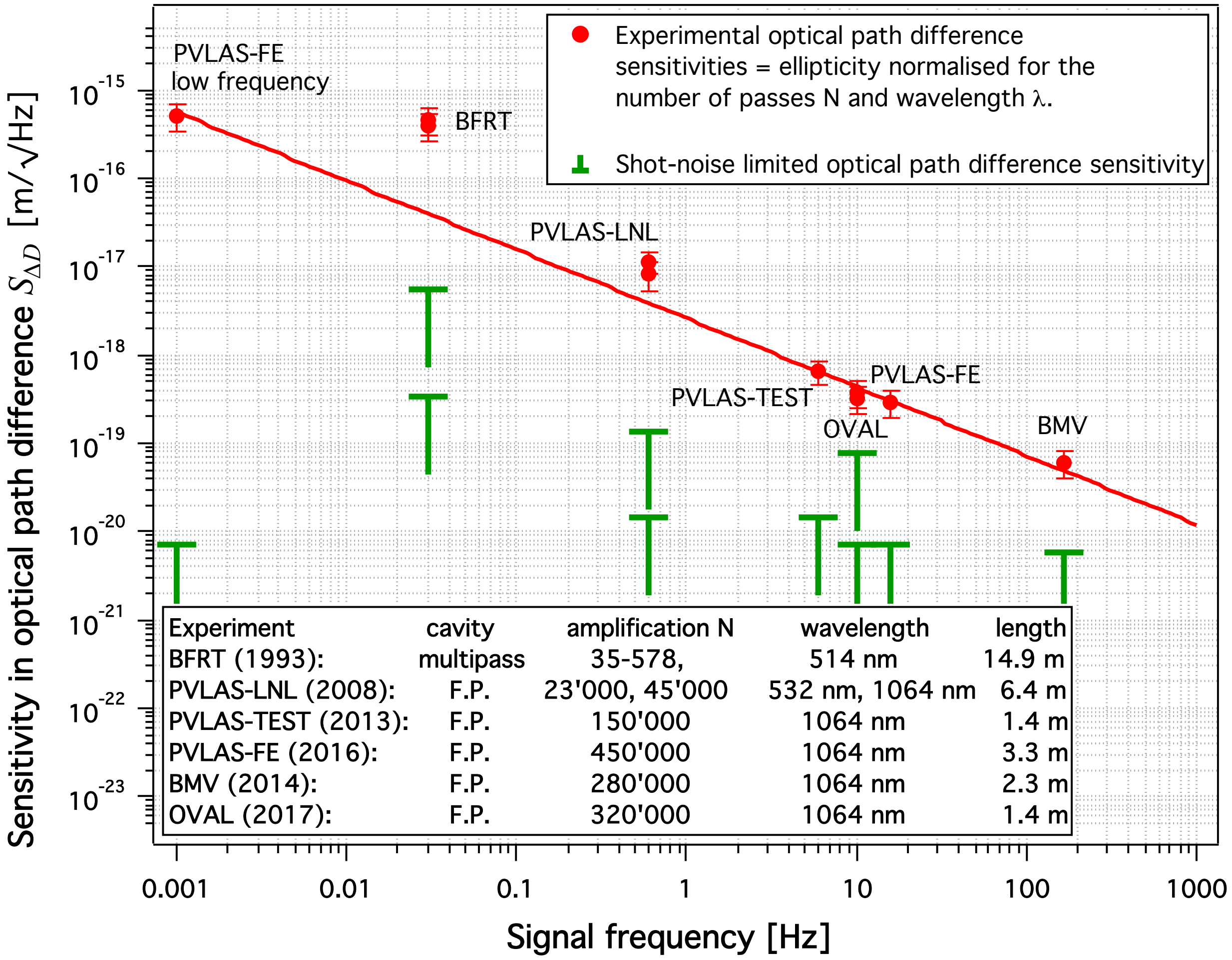


- The 2016 PVLAS data point corresponds to an integration of $T \approx 5\cdot10^6$ s.
- The use of permanent magnets allowed detailed debugging.
- PVLAS could not close the gap by further integration.
- Limiting noise source was the birefringence thermal noise of the mirrors (we believe).
- With N ≈ 4.5x10^5 the thermal noise was 20 times greater than shot-noise.
- $S_{\Delta\mathcal{D}} = 4 \times 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ @ ≈ 15 Hz

A. Ejlli et al (PVLAS Collaboration), Phys. Rep. 871 (2020) 1

Cavity intrinsic noise

- We showed that the optical path difference sensitivity $S_{\Delta\mathcal{D}}$ **does not** depend on *N* (for large *N*)
- The mirror coating noise is multiplied by *N* just like a VMB signal. For *N* ≥ 10^4 the S/N ratio does not improve (for our output power ≈ 10 mW and ν_B ≈ 15 Hz)
- All other VMB experiments have suffered from the same **common noise source**



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

BFRT: R. Cameron et al. PRD, **47** (1993) 3707
PVLAS-LNL: M. Bregant et al. PRD, **78** (2008) 032006
PVLAS-TEST: F. Della Valle et al. NJP, **15** (2013) 053026
PVLAS-FE: F. Della Valle et al. EPJC, **76:24** (2016) 1
BMV: A. Cadène et al. EPJD, **68:16** (2014) 1

<u>Must increase the optical path difference signal</u>

$$\Delta\mathcal{D} = 3A_e \int B_{\rm ext}^2 \, dL$$

Spare superconducting LHC dipole

G. Zavattini et al. (PVLAS Collaboration), Eur. Phys. J. C 78 (2018) 585

VMB@CERN with one spare LHC dipole magnet

VMB signal $B_{\mathrm{LHC}}^2\, L = 1200\ \mathrm{T}^2\mathrm{m}$ ➡ $\Delta\mathcal{D} = 3A_e B^2 L = 4.8 \times 10^{-21}\ \mathrm{m}$

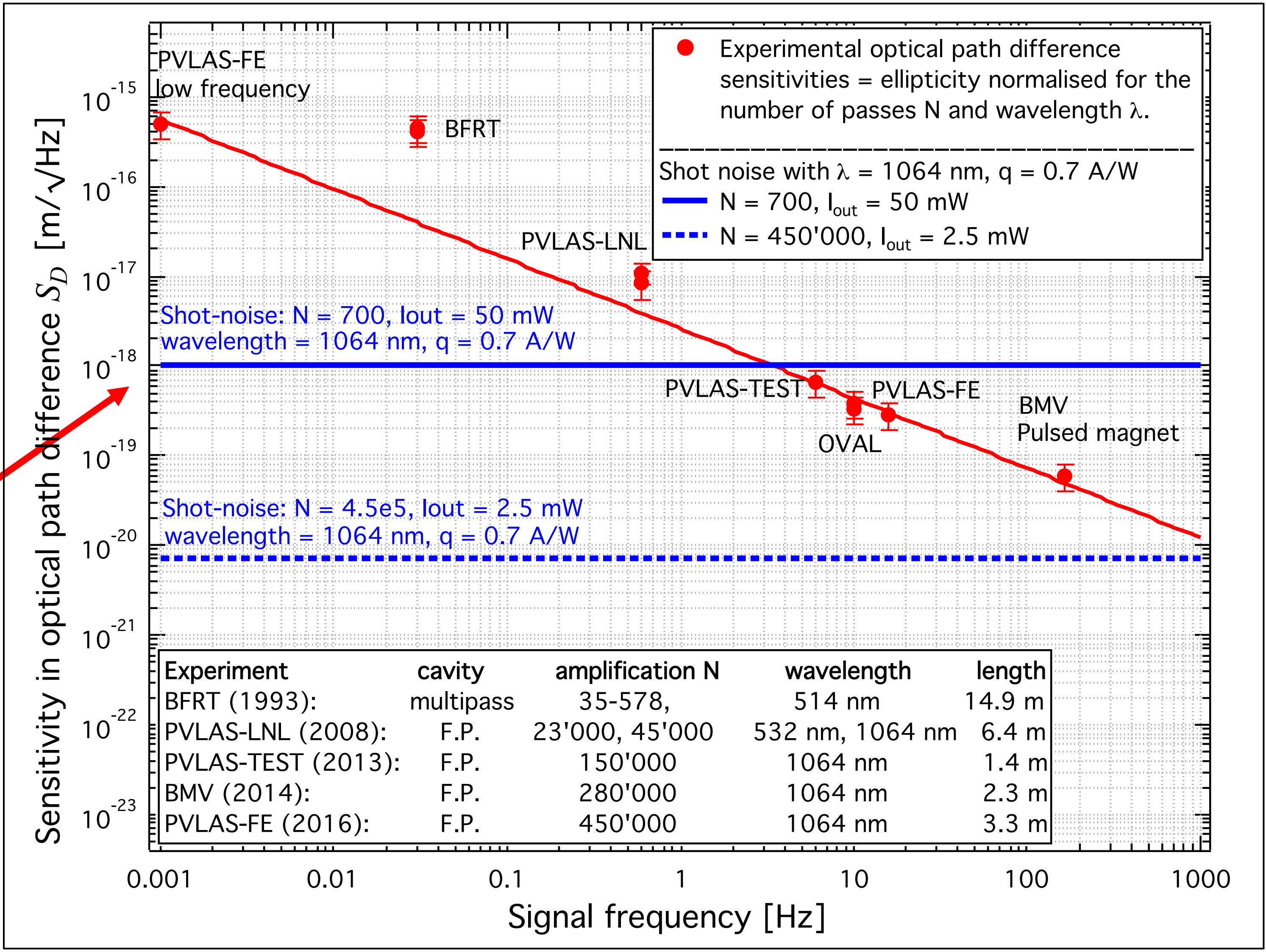
Desired integration time for SNR = 1

$$\Rightarrow T = 12\ \mathrm{h}$$

⬇

$$S_{\Delta\mathcal{D}} = \Delta\mathcal{D}\sqrt{T} \approx 10^{-18}\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

Such a sensitivity can be reached with
- 50 mW output power
- $N \approx 700$



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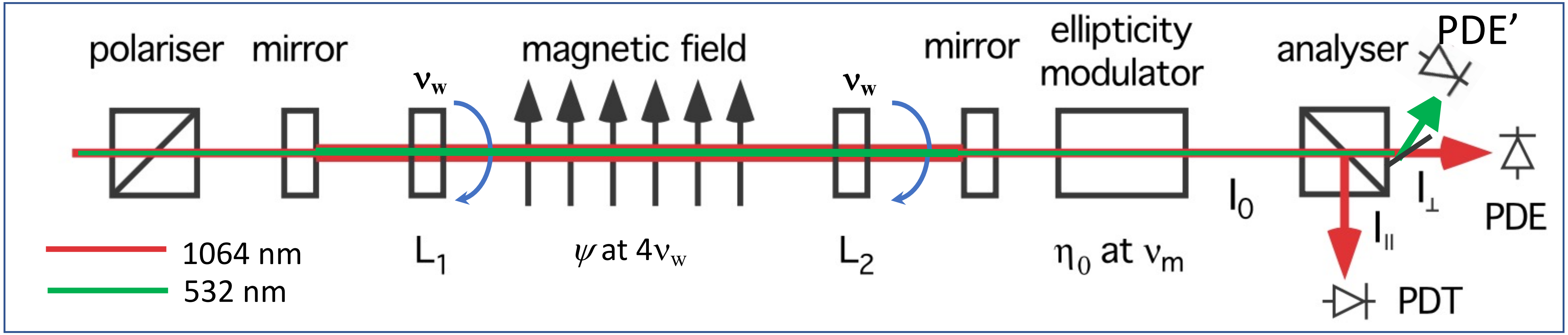
Scheme for VMB@CERN: two co-rotating half-wave plates *inside* the F.P.

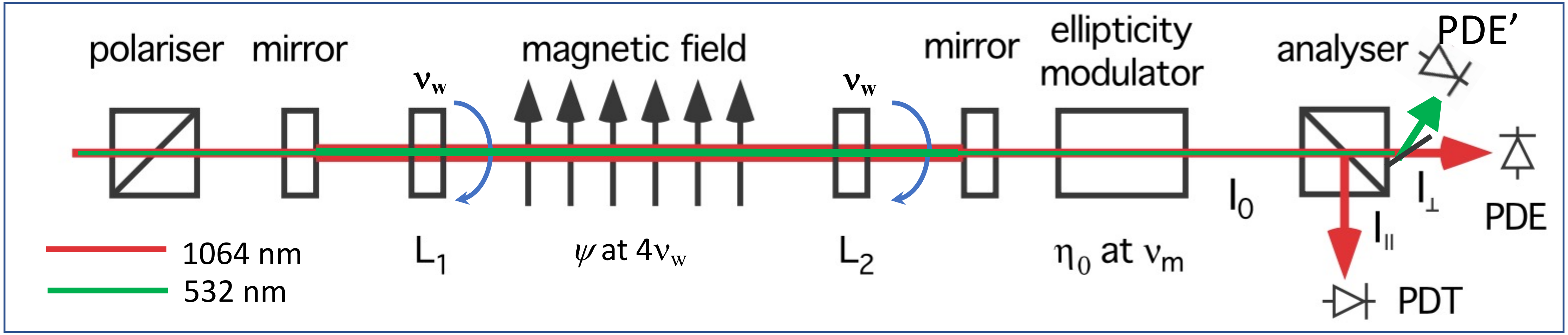


$$\Psi(t) = \Psi_0 \sin 4\phi(t) + N\frac{\alpha_1}{2}\sin 2\phi(t) + N\frac{\alpha_2}{2}\sin(2\phi(t) + 2\Delta\phi)$$

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

- Allows the use of (quasi) static superconducting fields ≈ 9 T
- Already demonstrated N ≈ 1000 with two NON rotating commercial HWPs inside the Fabry-Perot
- Demonstrated locking (unstable) of the laser to the F.P. with the rotating HWPs @ 0.5 Hz. Problem is $N\alpha_{1,2} > 1$
- Resonant 1064 nm beam carries the VMB signal
- Non resonant 532 nm beam (HWP -> FWP) will allow online systematic studies due to the rotating wave plates
- The LHC dipoles at CERN are the best present opportunity to maximize B^2L

Scheme for VMB@CERN: two co-rotating half-wave plates *inside* the F.P.



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

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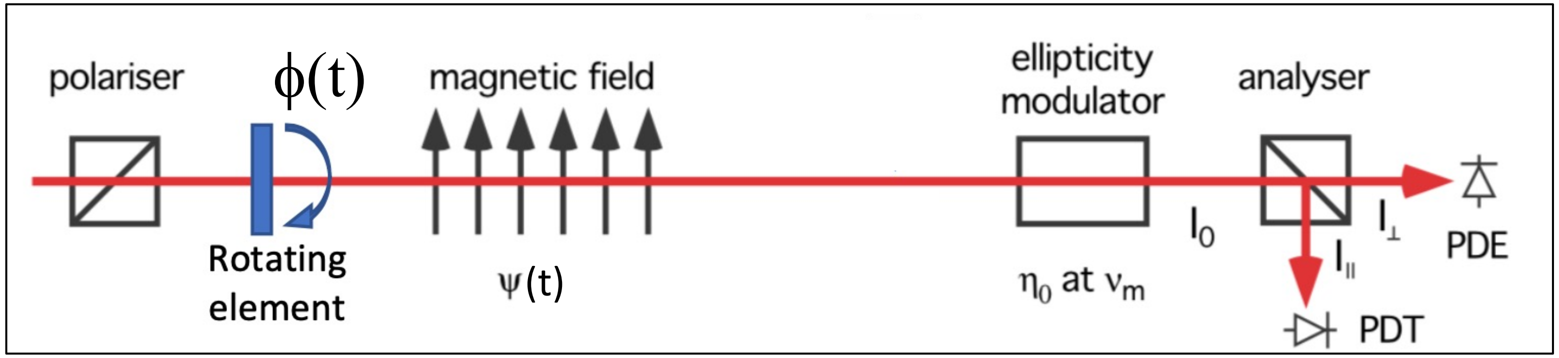
Systematics due to a rotating neutral wave plate (no F.P.)



$$\psi(t) = \psi_0 \sin 4\phi(t) + \frac{\alpha(t)}{2} \sin 2(\phi(t) + \phi_0)$$

Contribution from the rotating element

- α(t) represents the residual intrinsic retardation including mechanical defects
- α(t) can be expanded in harmonics of ϕ(t). If the beam is not perfectly centered:

$$\alpha(t) = \alpha^{(0)} + \alpha^{(1)} \cos\left(\phi(t) + \phi^{(1)}\right) + \alpha^{(2)} \cos\left(2\phi(t) + \phi^{(2)}\right) + \ldots$$

- $\alpha^{(1)}$ is due to $\vec{\nabla}(\Delta n L)$ (e.g. wedge if $\Delta n =$ const) of the wave plate.

Systematics due to a rotating neutral wave plate (no F.P.)

If the rotation axis has a transverse oscillation (non ideal bearings) then $\alpha^{(1)} = \alpha^{(1)}(t)$ generating further harmonics. DANGER

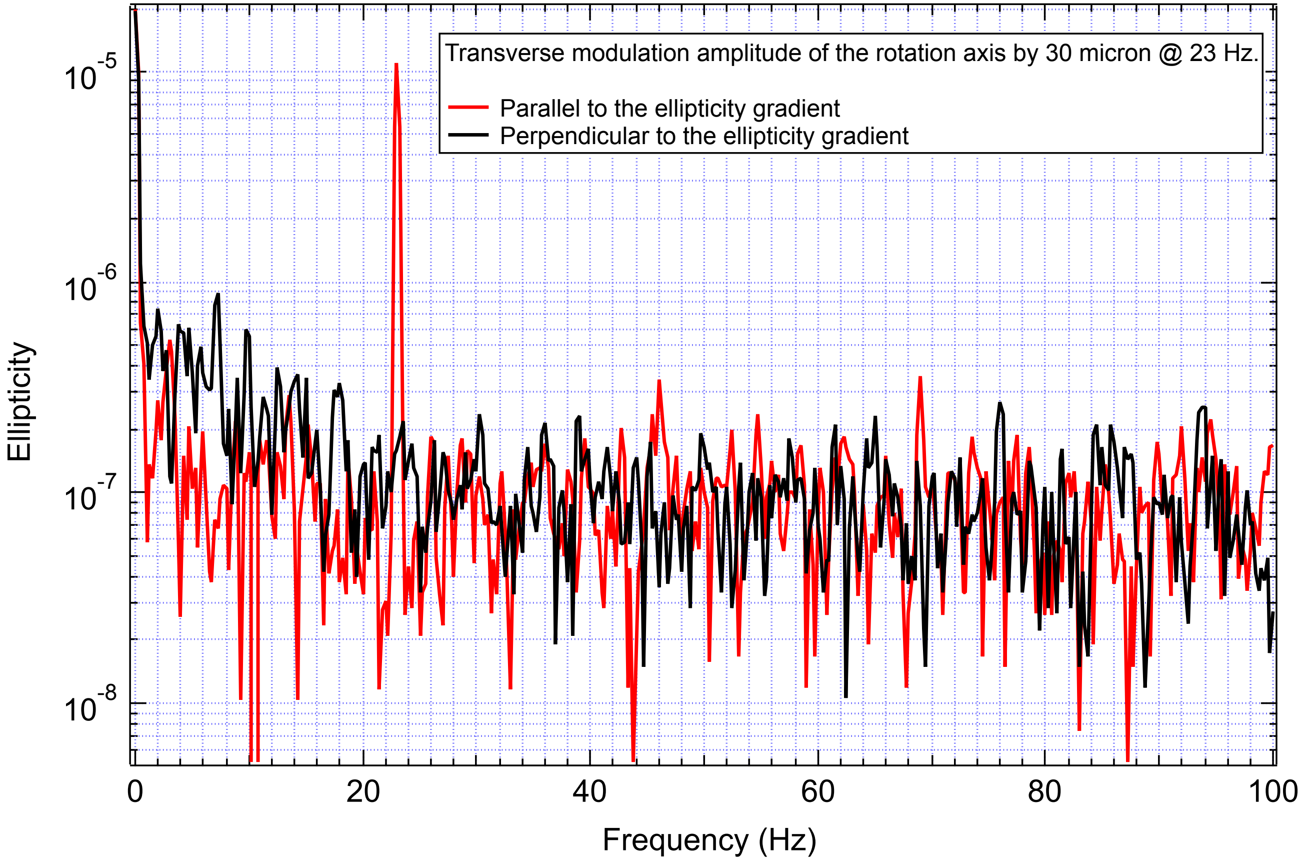
$$\alpha(t) = \alpha^{(0)} + \alpha^{(1)} \left[1 + \Delta\vec{r} \cdot \vec{\nabla}(\Delta n L) \underbrace{\cos\left(\phi(t) + \phi'\right)\right] \cos\left(\phi(t) + \phi^{(1)}\right)}_{} + \ldots$$

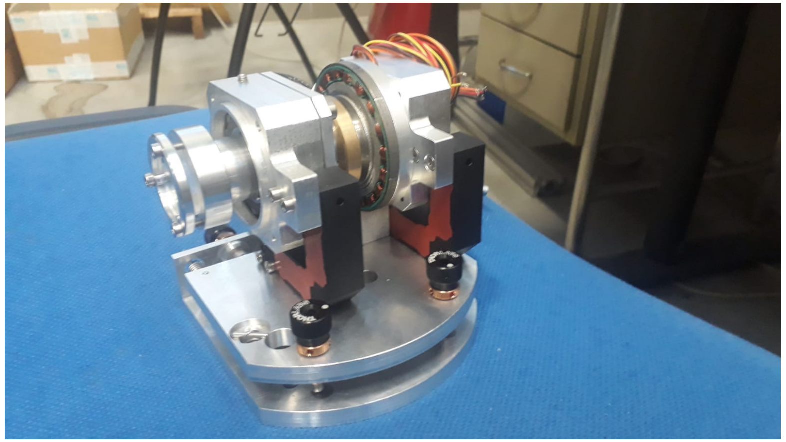
$$\psi(t) = \psi_0 \sin 4\phi(t) + \frac{\alpha(t)}{2} \sin 2(\phi(t) + \phi_0)$$

This axis oscillation coupled to the $\vec{\nabla}(\Delta n L)$ will generate a fourth harmonic!!

Transverse oscillating glass element – non rotating case

- Measured value of $\vec{\nabla}(\Delta n L)$ using a dual XY piezo mount sustaining the rotating shaft. The optical element was made to oscillate transversely.
- With the oscillation parallel to $\vec{\nabla}(\Delta n L)$ an ellipticity signal is generated. With the oscillation perpendicular to $\vec{\nabla}(\Delta n L)$ no ellipticity is generated.





$$\frac{d\psi}{dx} = \frac{10^{-5}}{30 \times 10^{-6}} \approx 0.3\ \mathrm{m}^{-1}$$

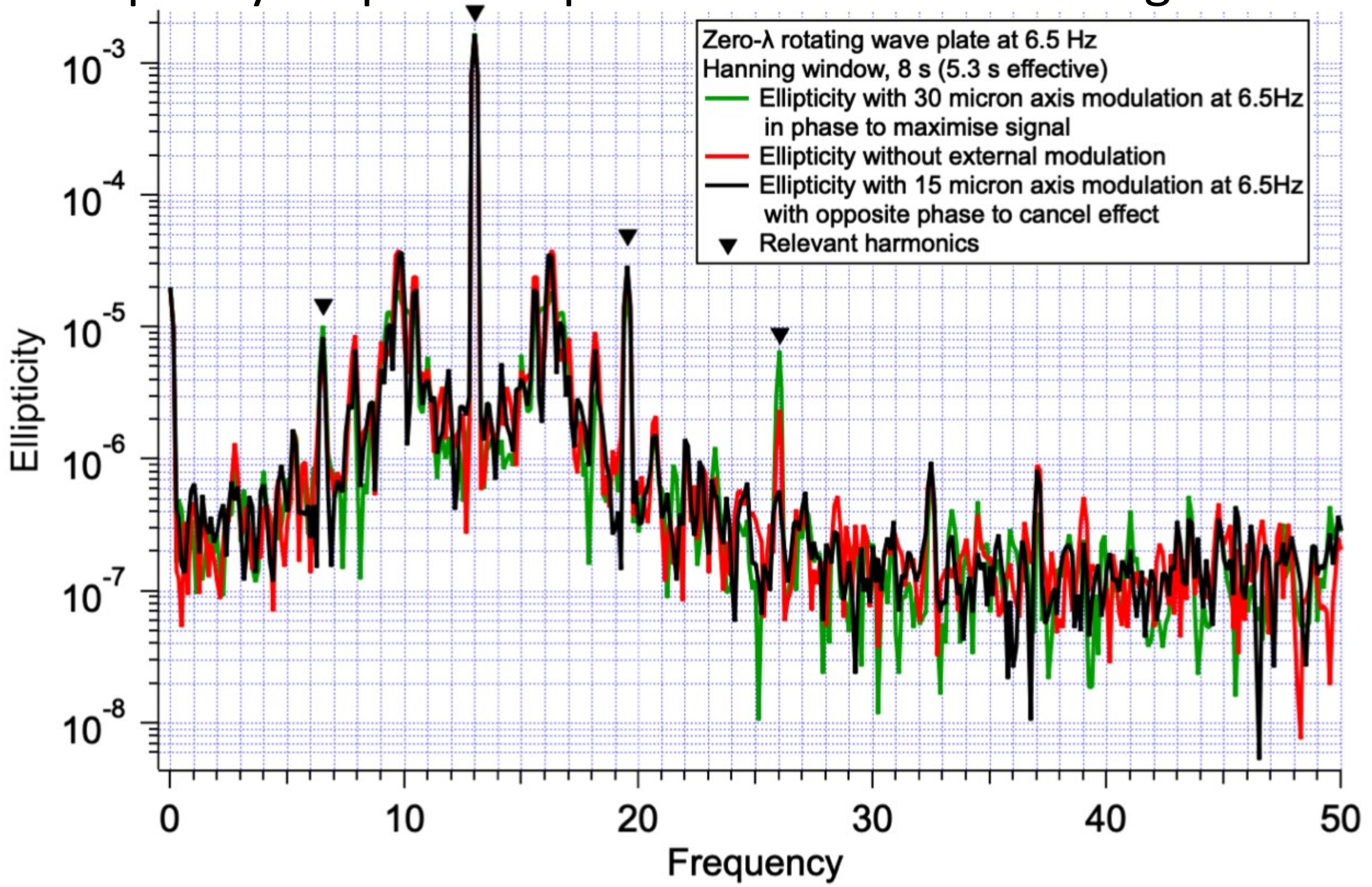
$$\Downarrow$$

$$\nabla(\Delta n L) \approx 10^{-7}$$

Transverse oscillating zero-wave plate – rotating case

- Same study was performed with the rotating glass element. Both the rotating and the oscillation frequency were the same: ν = 6.5 Hz.
- Used brushless motors driven by sinusoidal current: non standard. Generates some phase noise around the driving frequency but allows long term vector integration.

Ellipticity amplitude spectrum with the rotating element



Signal at 4ν = 26 Hz

Red:
Signal due to the intrinsic axis oscillation during rotation.

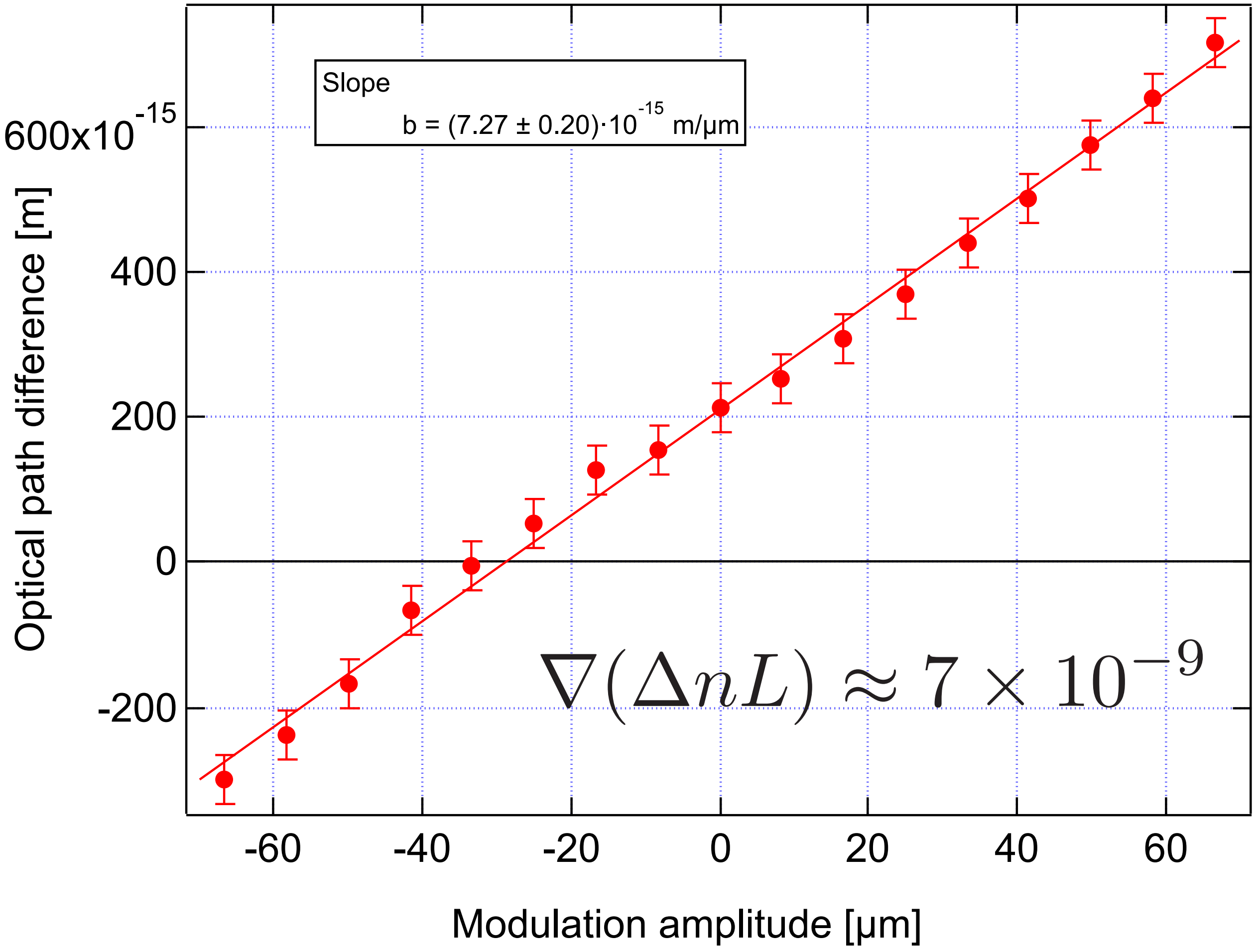
Green:
Intrinsic oscillation + external oscillation using the piezo: constructive phase and amplitude 30 µm.

Black:
Intrinsic oscillation + external oscillation using the piezo: destructive phase and amplitude 15 µm.

Serious issue

Transverse oscillating zero-wave plate – rotating case

- Measured the optical path difference as a function of the external axis modulation in phase with the intrinsic oscillation.
- Determined the stability requirement for measuring VMB



$$\nabla(\Delta n L) \approx 7 \times 10^{-9}$$

With an LHC dipole the optical path difference to be measured is:

$$\Delta\mathcal{D} = 3A_e B^2 L = 4.8 \times 10^{-21}\ \mathrm{m}$$

The axis transverse stability is therefore

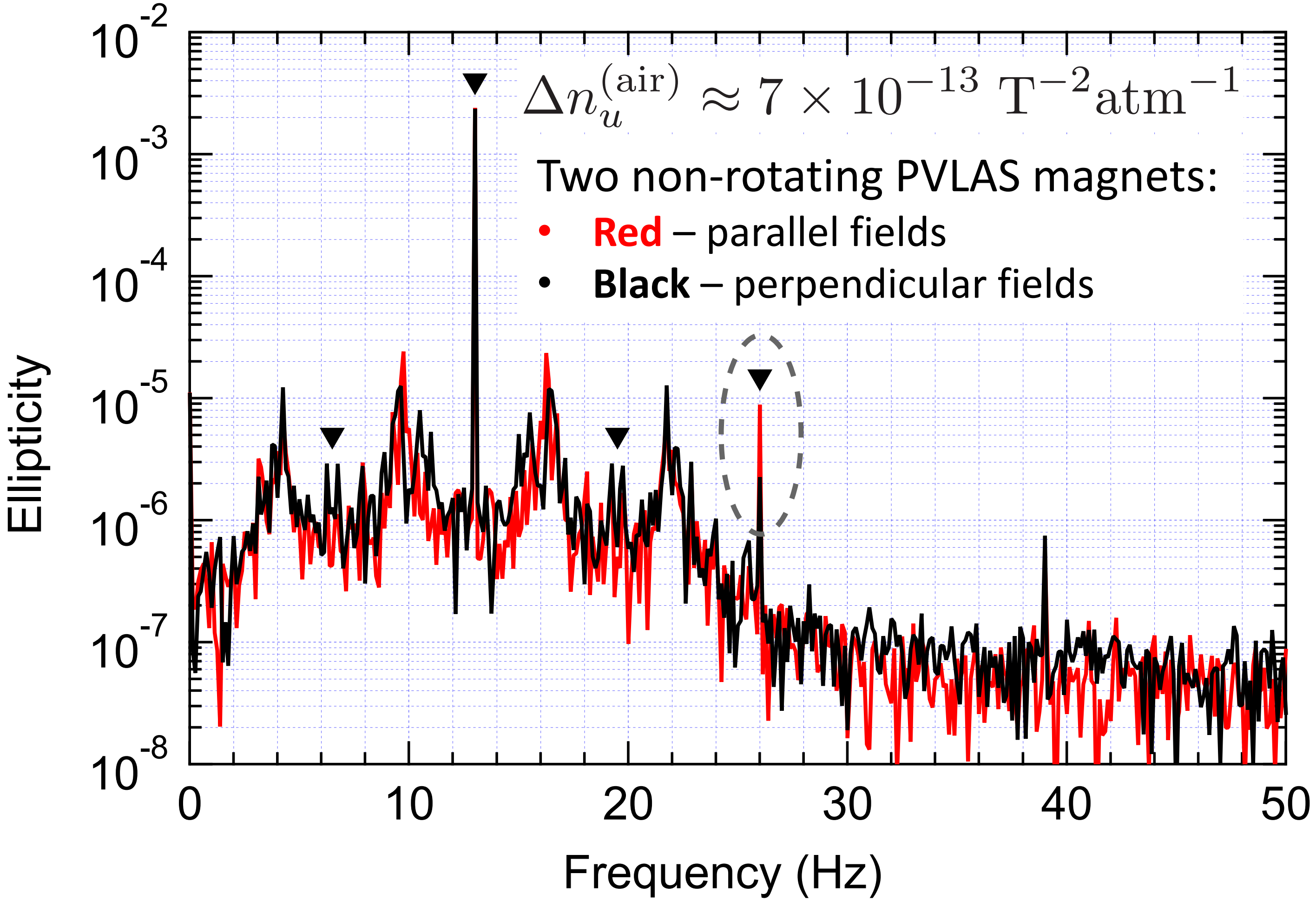
$$\Delta r_{\mathrm{axis}} \lesssim \frac{\Delta\mathcal{D}}{\nabla(\Delta n L)} = 7 \times 10^{-13}\ \mathrm{m}$$

Impossible: Show stopper?

Two co-rotating HWPs (no F.P.): Cotton-Mouton effect of air

Cotton-Mouton effect: $\Delta n_{\mathrm{CM}} = \Delta n_u B_{\mathrm{ext}}^2 P$

Δn_u = unitary birefringence expressed in tesla^{-2} atmosphere^{-1}



4ν peak is at 26 Hz

- **Black:** Fourth harmonic is due to the intrinsic axis modulation causing $\alpha^{(1)}(t)$
- **Red:** intrinsic modulation + Cotton-Mouton effect in air
- Vector sum of the two effects

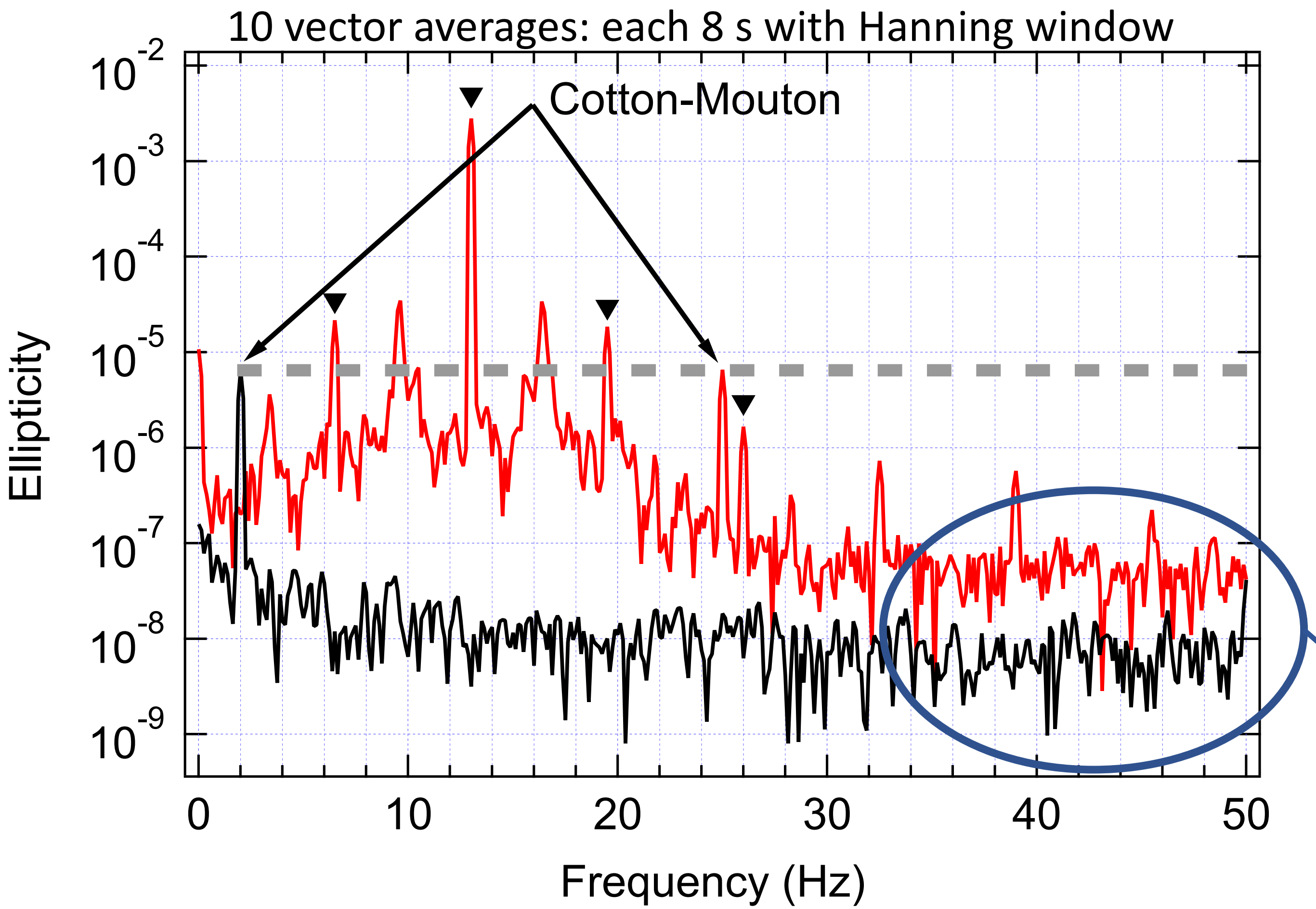
One must separate the two effects:

Modulate the magnetic field

Two co-rotating HWPs (no F.P.): Cotton-Mouton effect of air

Comparison of ellipticity spectra in air in two cases:

- **Red** – one PVLAS magnet rotating at 0.5 Hz and HWPs at 6.5 Hz
- **Nero** – one PVLAS magnet rotating at 1 Hz and non-rotating HWPs



The signal 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.

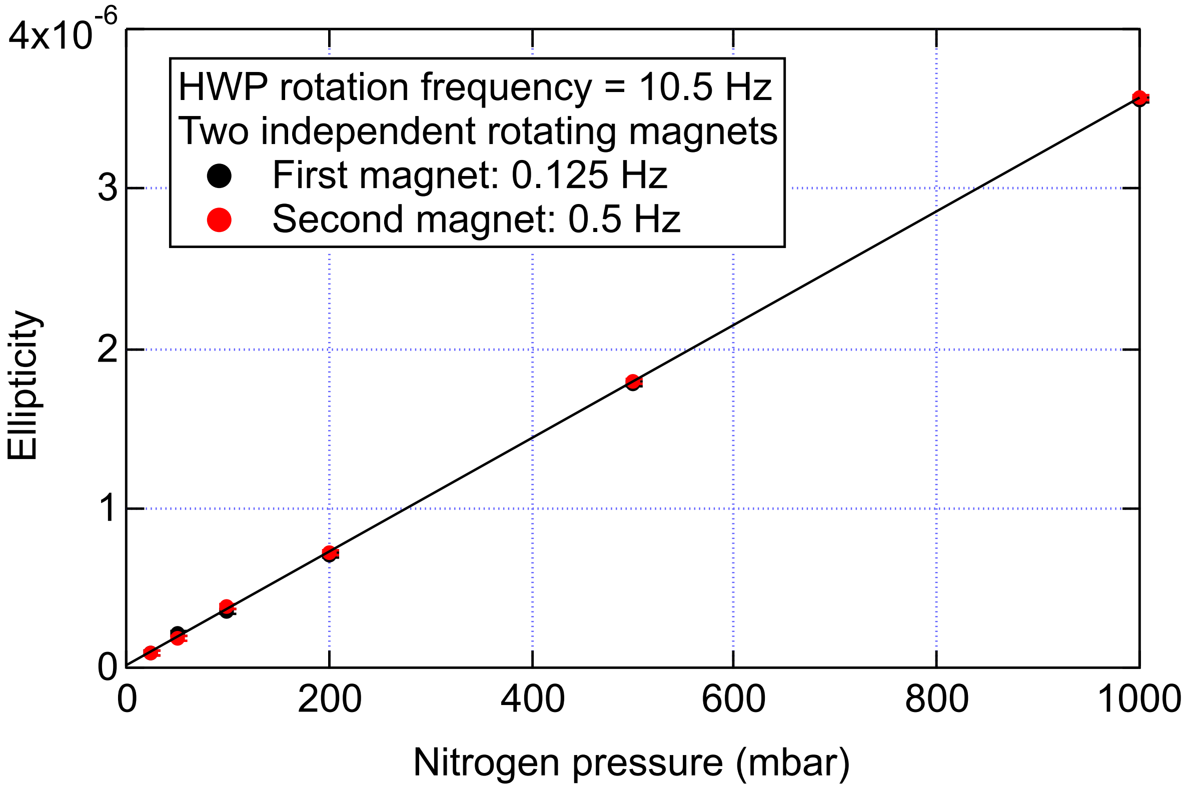
Magnetic field must be modulated:

- How narrow is the systematic signal at 26 Hz?
- How fast can the LHC dipole be ramped?

The difference in noise is due to the degraded extinction caused by the rotating HWPs.

Cotton-Mouton effect in Nitrogen gas @ 1064 nm

Polarimeter was put in vacuum and pure N_2 gas was injected



- Most precise measurement of the Cotton-Mouton effect in N_2 gas.
- The scheme with two co-rotating HWPs + slowly modulated field works

Cotton-Mouton unitary birefringence

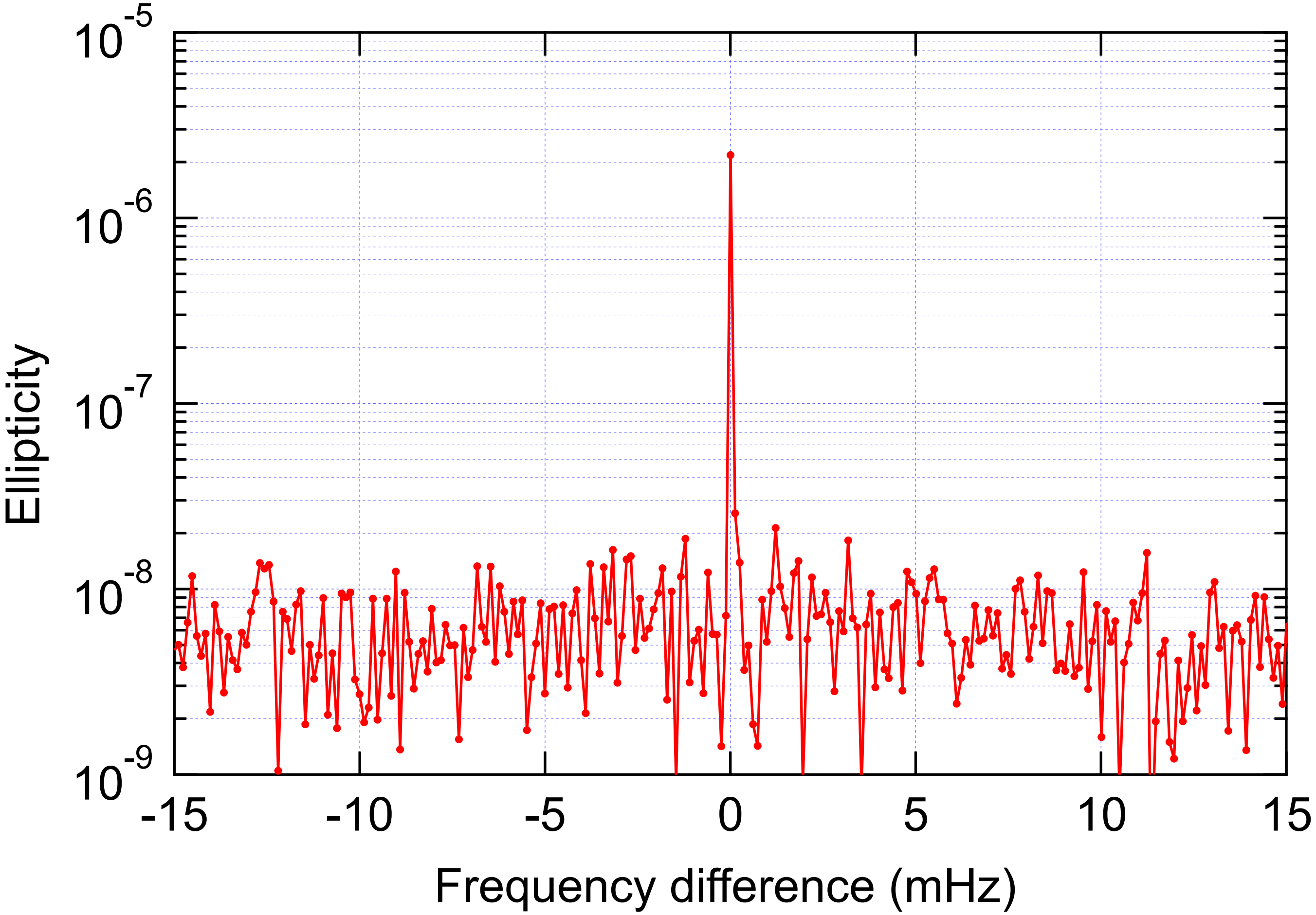
$$\Delta n_{\mathrm{u}}^{(1064\ \mathrm{nm})} = (2.380 \pm 0.007^{(\mathrm{stat})} \pm 0.024^{(\mathrm{sys})}) \times 10^{-13}\ \mathrm{T}^{-2}\mathrm{atm}^{-1}$$

arXiv:2110.03943

Frequency width of the 26 Hz signal

Modulate the LHC dipole field?

- Ellipticity spectrum around 26 Hz.
- Bin width = 0.122 mHz.
  Integration = 8196 s.
- To be repeated with the cavity.
- My understanding is that an LHC dipole can be modulated at full depth in current at a few mHz .



Next step: implement the Fabry-Perot cavity

- Installed the cavity mirrors with a nominal value of $N \approx 2000$.
- Laser was successfully locked with the non-rotating HWPs inside the Fabry-Perot. The resulting equivalent passes was $N \approx 1000$. HWPs introduce losses ≈ 10^{-3}, as expected.
- Laser was successfully locked also with the rotating HWPs at ≈ 0.5 Hz. Very unstable.
- Issue: the residual phase retardation $\alpha_{1,2}$ from π is $\alpha_{1,2} \approx 10^{-3}$ dominated by $\alpha^{(0)}_{1,2}$

$$N\alpha_{1,2}^{(0)} \gtrsim 1$$

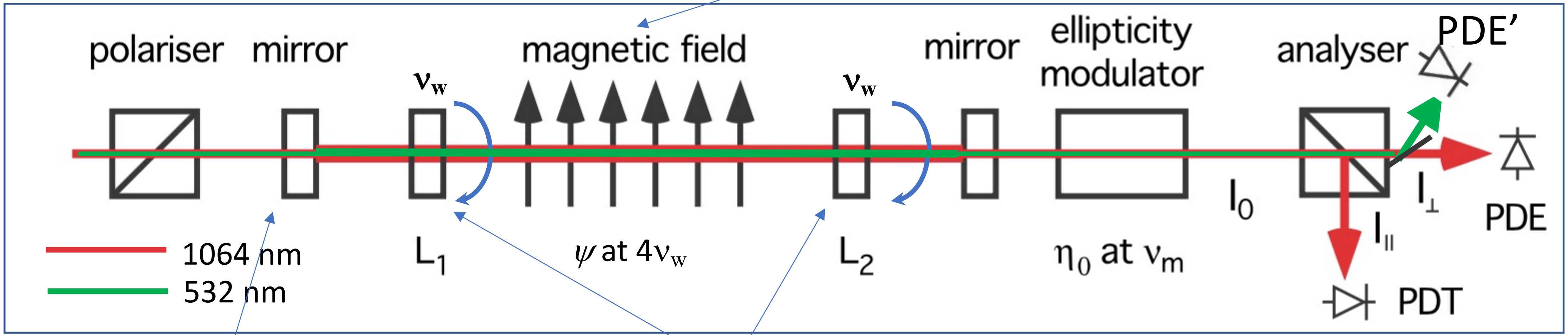
Polarisation is no longer well defined inside the Fabry-Perot.

Fabry-Perot is unstable

- Preliminary tests have shown that $\alpha^{(0)}_{1,2}$ can be controlled and reduced by more than a factor 100 by adjusting the temperature of the HWPs. Few degrees is sufficient
- Installation of ring heaters is underway which should allow a stable locking with the rotating HWPs

Expected VMB@CERN optical configuration

- Slowly modulate the magnetic field
- Few mHz with an LHC dipole

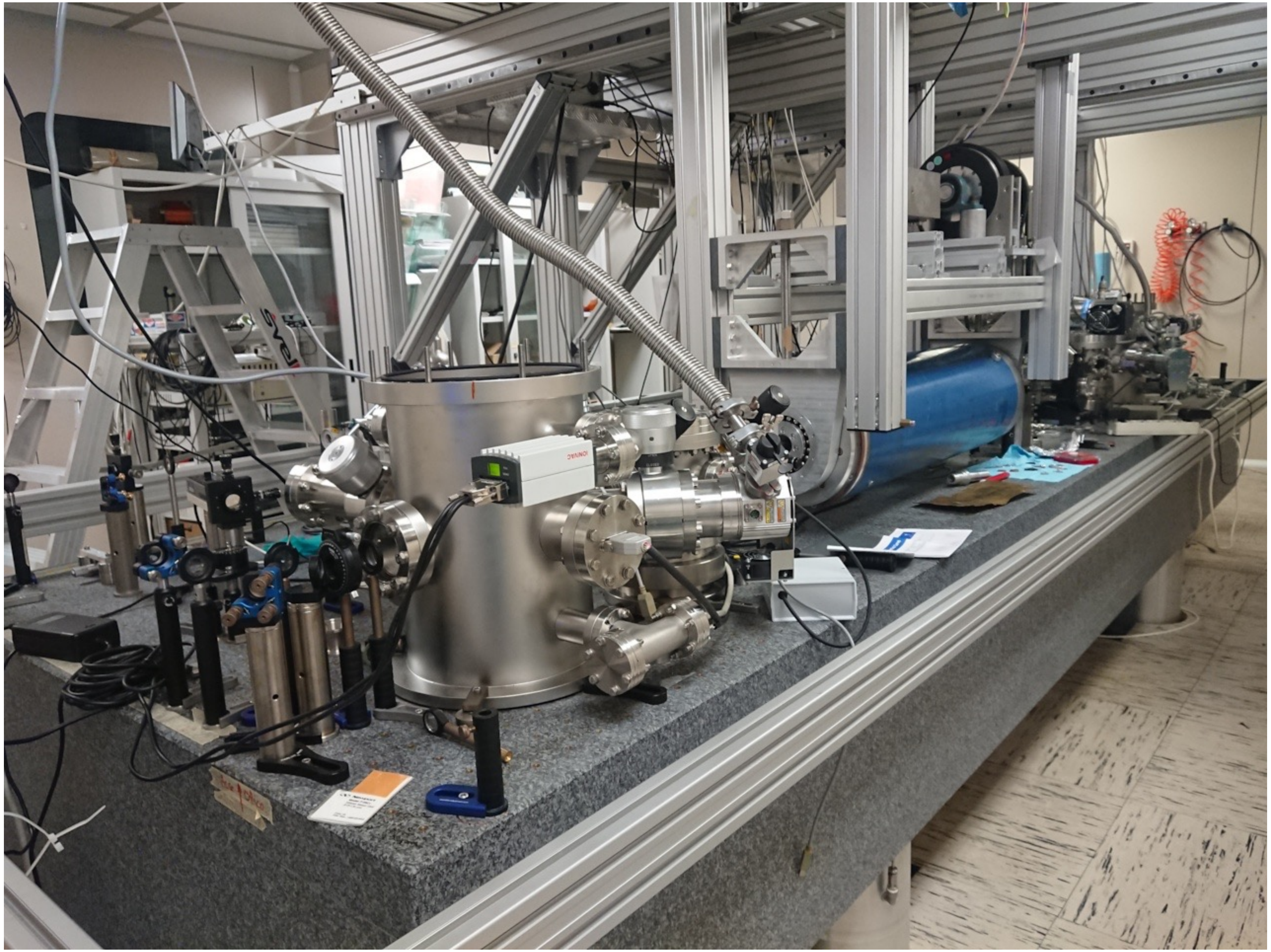


- Temperature control to reduce $\alpha^{(0)}_{1,2}$ for stable locking during rotation
- Reduce rotation phase noise to improve extinction

Mirrors for 1064 nm are transparent to 532 nm light

Ferrara laboratory

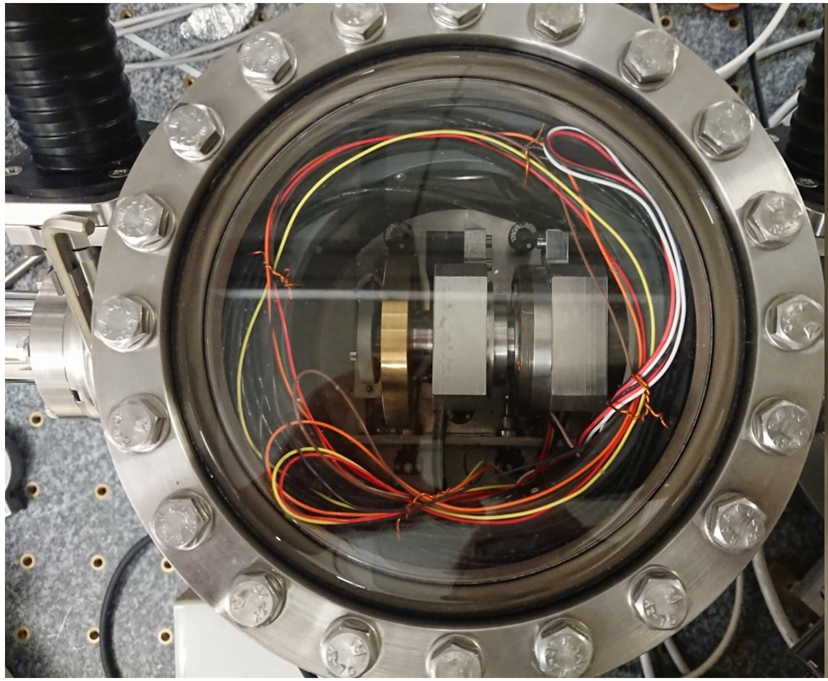
Input end



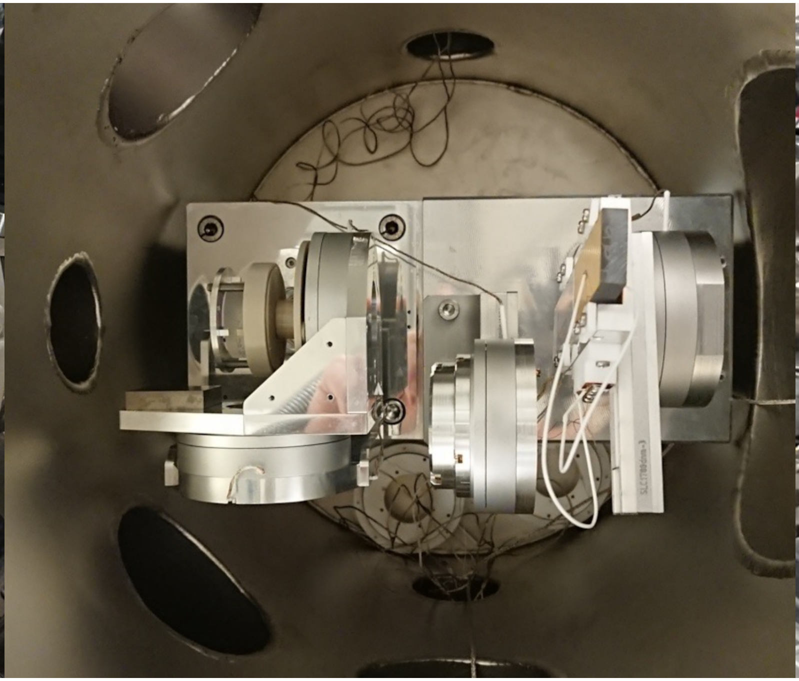
Ferrara laboratory

Output end

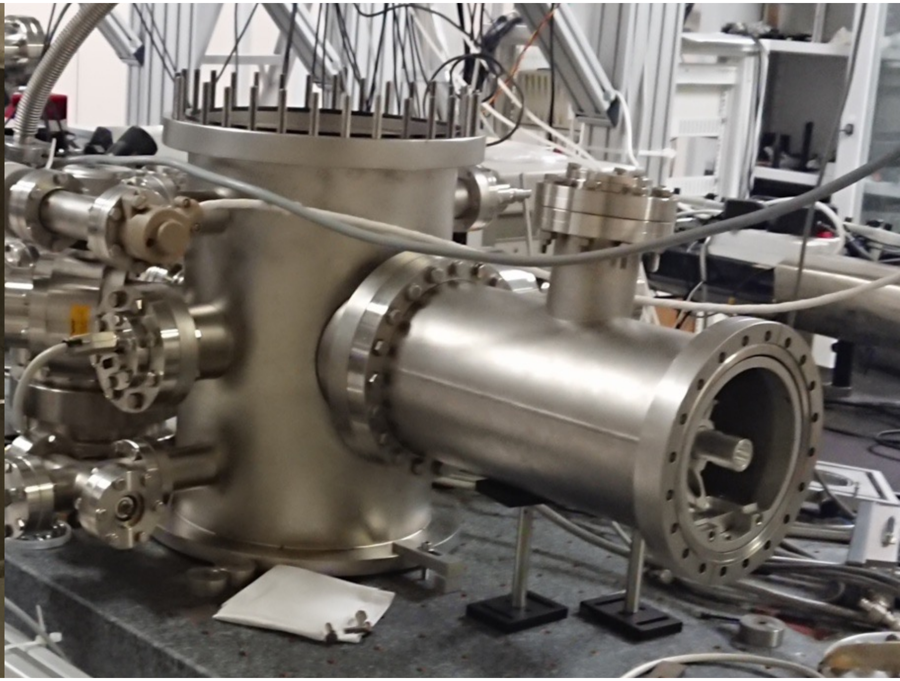
Rotating wave plate



Mirror, QWP, PEM (modulator)



Faraday rotator chamber, analyzer



Thank you for your attention!