EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COSMIC WISPERS
CA21106

VMB@CERN 2023

ŠTĚPÁN KUNC

ON BEHALF OF VMB@CERN COLLABORATION

1ST GENERAL MEETING OF COST ACTION COSMIC WISPERS (CA21106)

VMB@CERN collaboration

Collaboration to measure Vacuum Magnetic Birefringence
Started in 2019

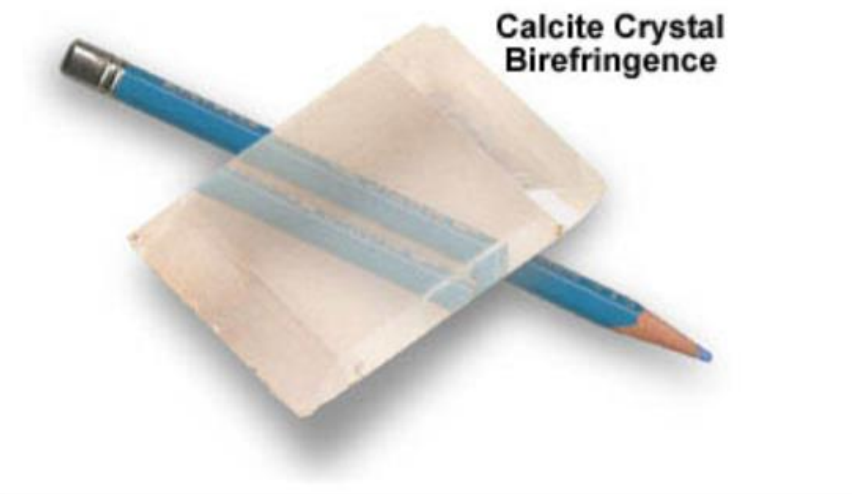
PVLAS + Q&A + OSQAR-VMB + LIGO group (Cardiff)

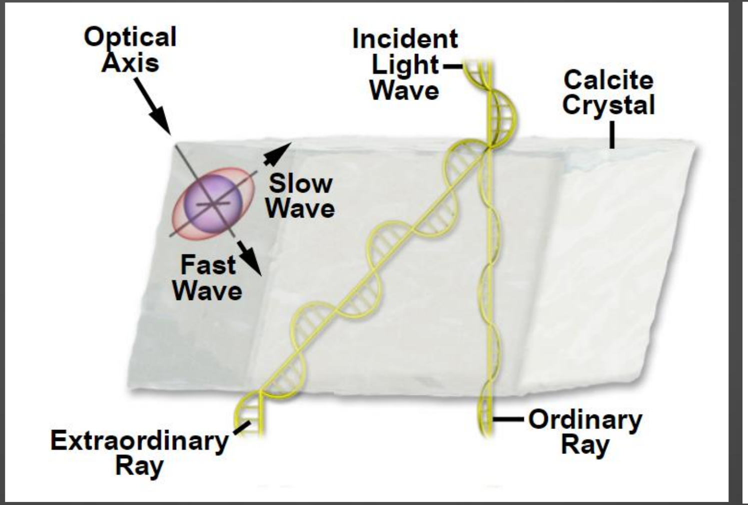
VMB@CERN

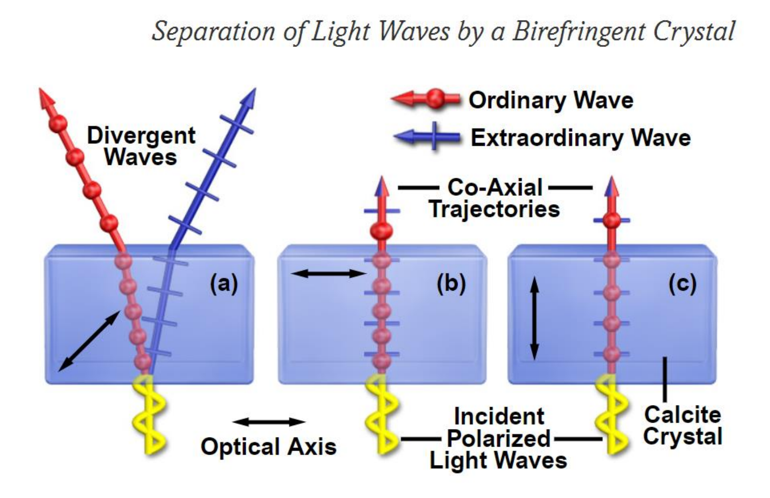
about 15 members from 10
Institutes from Czech Republic, France, Italy, Poland, Republic of China and Wales

Birefringence (double refraction)

- Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of the light
- First observed in islandic limestone (calcite) in 1669 by Rasmus Bartholin







http://olympus.magnet.fsu.edu

- Natural birefringence – Crystals, plastic, liquids, ……….
- Used for - polarizers, wave plates, ……

Induced Birefringence

Materials become birefringent when subjected to external forces, fields or during manufacturing processes

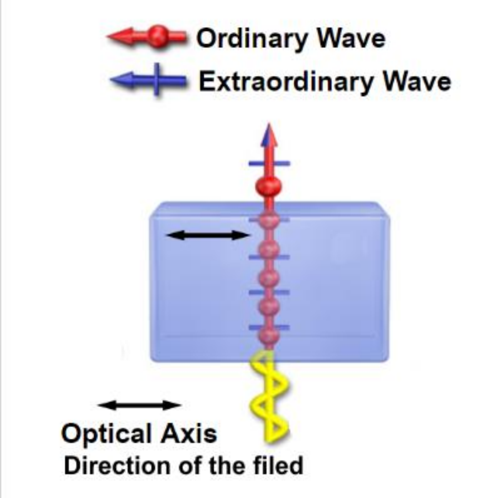
Mechanical force – stress-induced birefringence

Electric field – Kerr effect

Magnetic field – Cotton-Mouton effect

Field direction determines the optical axis of the material

What we measure is the optical path difference/ellipticity between the ordinary and extraordinary beam



http://olympus.magnet.fsu.edu

Light polarization shown on clear polystyrene cutlery between crossed polarizers

https://en.wikipedia.org/wiki/Birefringence

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

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

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2\lambda_e^3}{m_e c^2} = \mathbf{1.32\times10^{-24}\ T^{-2}} \longrightarrow \Delta n_B = 3A_eB^2$$

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

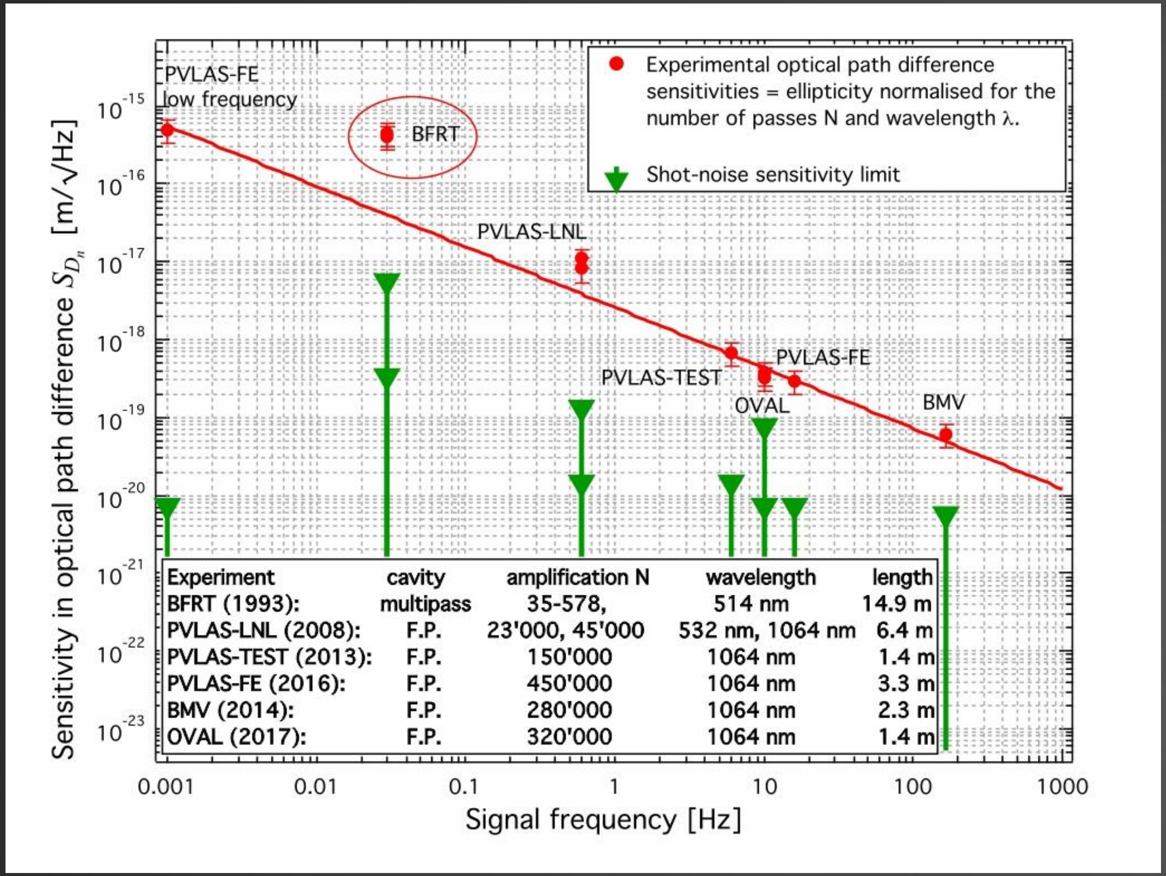
superconducting magnets – OSQAR – B = 9 T, L =14.3 m

- **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 mirror birefringence 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

Physics Reports 871 (2020) 1–74

No experimental effort has reached shot-noise sensitivity (green) with a high finesse F.P.

There seems to be a common problem afflicting all experiments

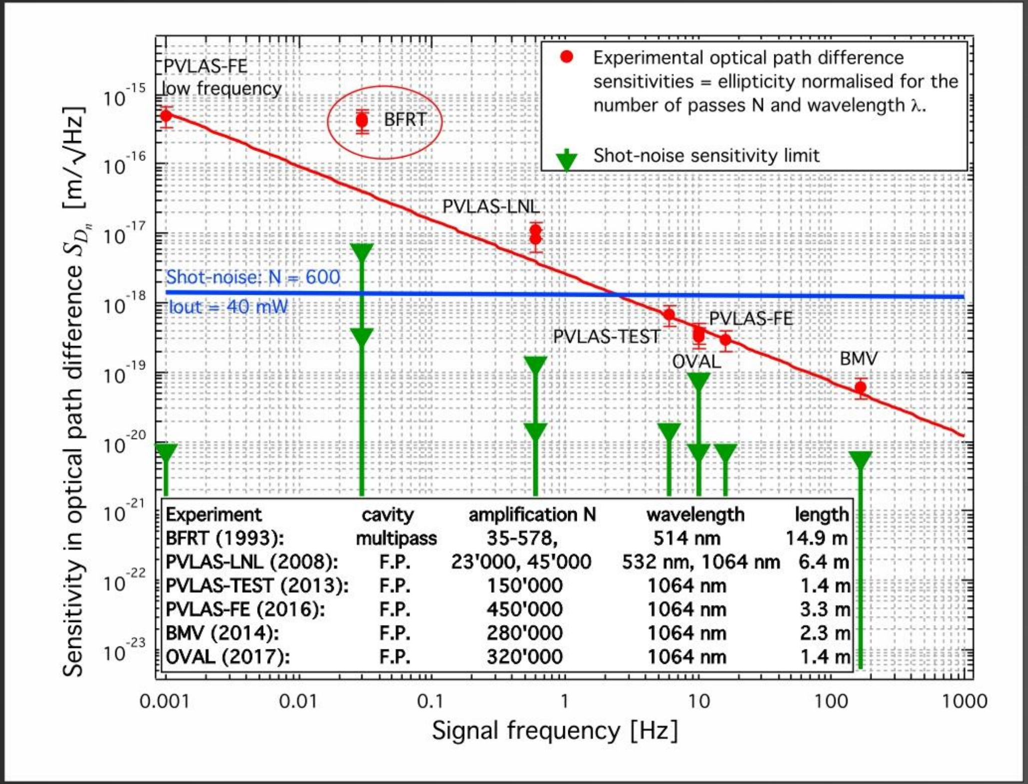
This noise seems to be an intrinsic property of the cavity mirrors (thermal noise in the tantala layers)

$$S_{ODP} \approx 2.6 \times 10^{-18} \nu^{-0.77}\ m/\sqrt{Hz}$$

Intrinsic noise

Sensitivity in optical path difference D_n does not depend on finesse

Intrinsic mirror birefringence noise



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An LHC dipole would satisfy the requirement for v > 2 Hz and *T* ≈ 1 day for SNR = 1
***T* = integration time and D_t = duty-cycle**
N = 600

$$\boxed{S_\psi = 2\times10^{-9}\,1/\sqrt{Hz}}$$

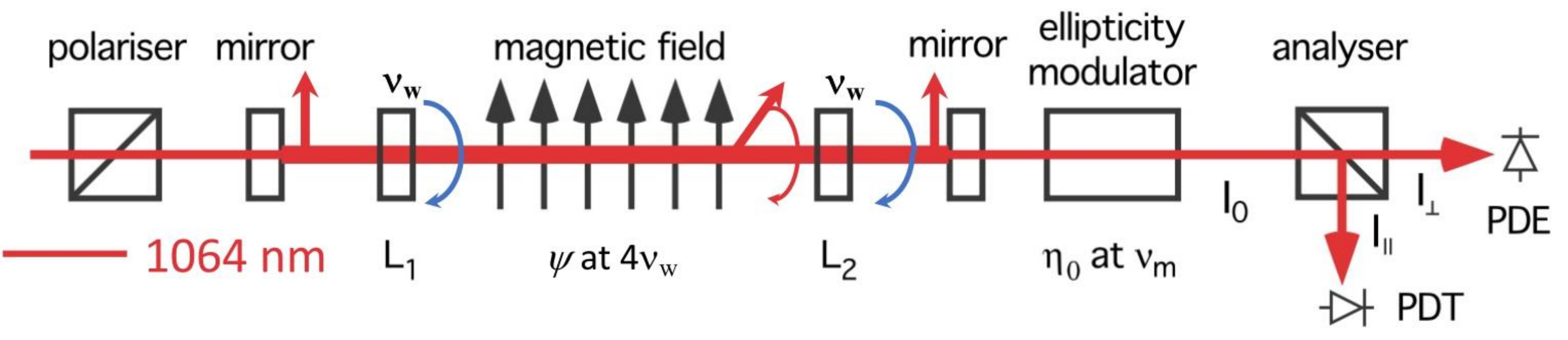
$$B_{ext}^2 \mathrm{L} > max \left\{ \begin{array}{l} \dfrac{1}{3A_e\sqrt{TD_t}}\dfrac{\lambda}{\pi N}\sqrt{\dfrac{e}{I_0 q}} \\ \dfrac{1}{3A_e\sqrt{TD_t}}2.6\times10^{-18}\nu^{-0.77} \end{array} \right.$$

Shot - noise

Intrinsic noise

Ellipsometer for LHC magnet

Idea: Rotating polarization in static magnetic field of LHC magnet



Scheme: two co-rotating half-wave plates *inside* the F.P.
Fix polarization on mirrors to avoid mirror birefringence signal

$$\psi(t) = N\psi_0 \sin 4\phi(t) + N\frac{\alpha_1(t)}{2}\sin 2\phi(t) + N\frac{\alpha_2(t)}{2} sin[2\phi(t) + 2\Delta\phi(t)]$$

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

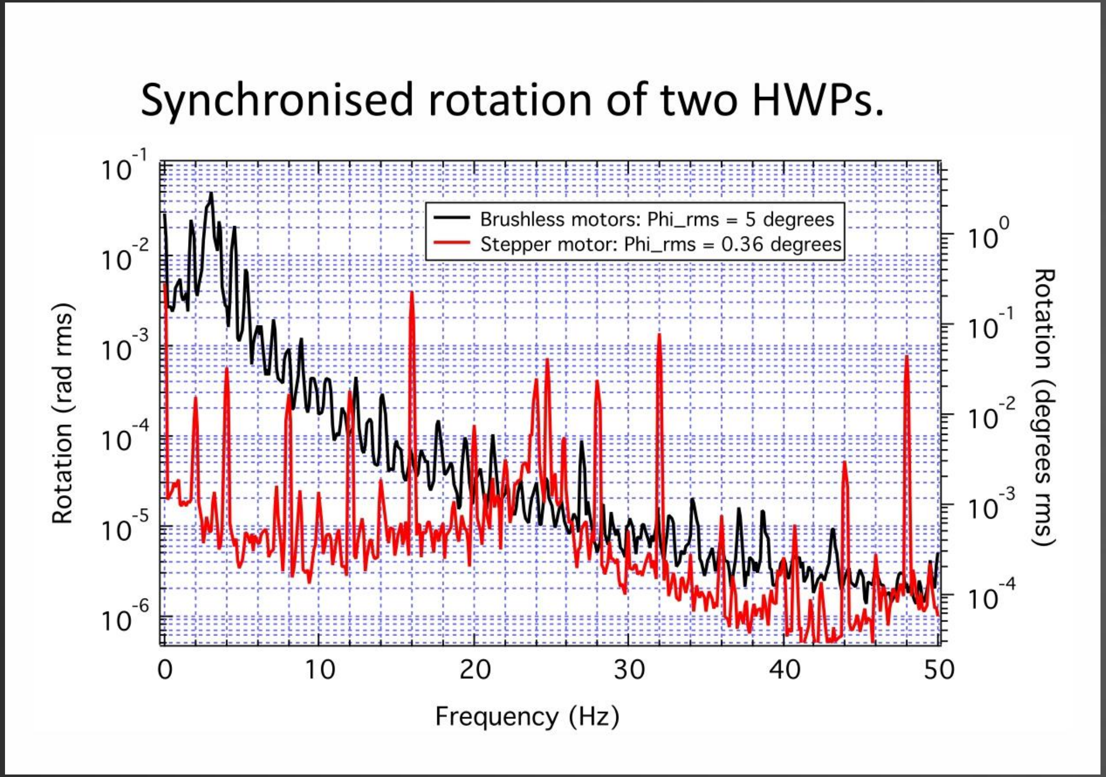
Main points to be demonstrated

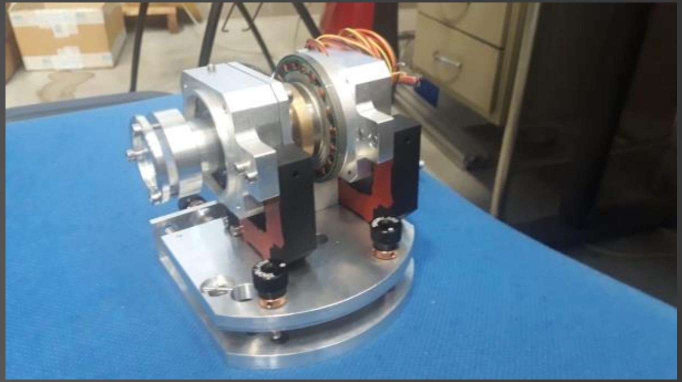
$$\psi(t) = N\psi_0 \sin 4\phi(t) + N\frac{\alpha_1(t)}{2}\sin 2\phi(t) + N\frac{\alpha_2(t)}{2} sin[2\phi(t) + 2\Delta\phi(t)]$$

1. Synchronous rotation of the wave-plates for good extinction - $[2\phi(t) + 2\Delta\phi(t)]$
2. Understand systematic effects at $4v_w$ and all other harmonics - $\alpha_{1,2}(t)$
3. Lock laser to the F.P. with the rotating HWPs inside - *N*
4. Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

Synchronous rotation of the wave-plates for good extinction - $[2\phi(t) + 2\Delta\phi(t)]$

Relative phase error: brushless vs. stepper motors (no cavity)





Brushless motor

Stepper motor

Extinction ratio with stepper motors (no cavity): **$\sigma^2 \approx 10^{-6}$ - Good**
Residual rotation could be corrected with a Faraday rotator

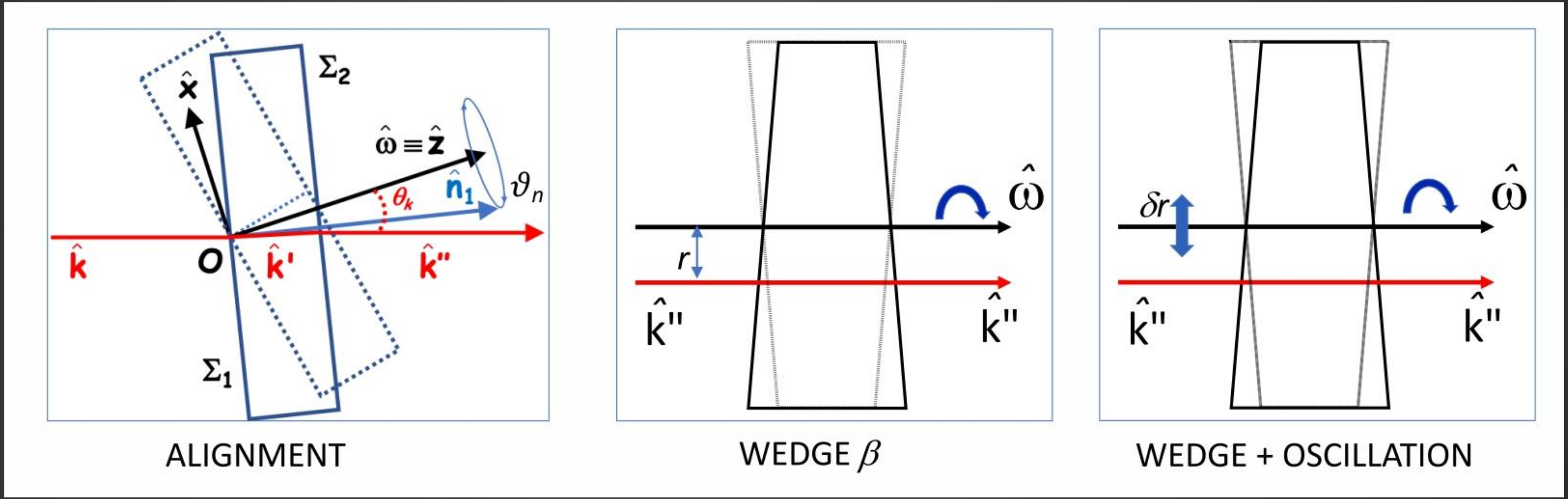
EPJC 82 (2022) 159

Understand systematic effects at $4v_w$ and all other harmonics - $\alpha_{1,2}(t)$

$$\psi(t) = N\psi_0 \sin 4\phi(t) + N\frac{\alpha_1(t)}{2}\sin 2\phi(t) + N\frac{\alpha_2(t)}{2} sin[2\phi(t) + 2\Delta\phi(t)]$$

$\alpha_{1,2}(t)$ – not only HWP defects but also sensitive to temperature T and axis stability r(t)

$$\alpha_{1,2}(\phi, T, r) = \alpha_{1,2}^{(0)}(T) + \alpha_{1,2}^{(1)}(\mathrm{r}(\mathrm{t}))\cos(\,\phi(t)) + \alpha_{1,2}^{(2)}\cos(2\,\phi(t)) + \cdots$$



ALIGNMENT WEDGE β WEDGE + OSCILLATION

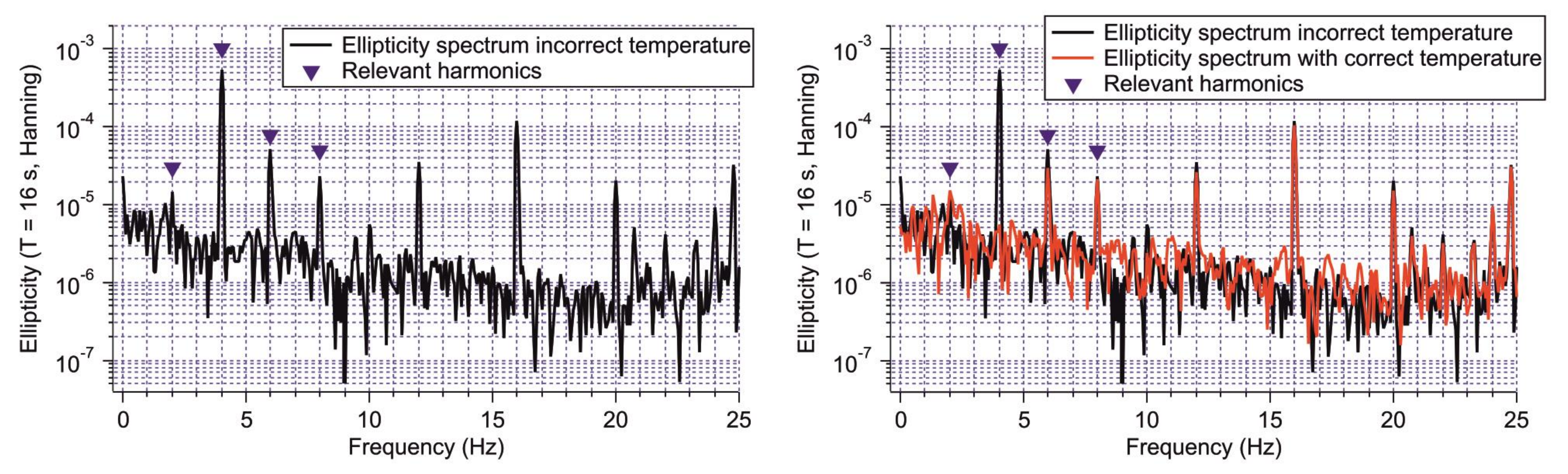
$\alpha_{1,2}^{(1)}(\mathrm{t})$ and $\alpha_{1,2}^{(2)}(t)$ – Generate 4th harmonic signal just like magnetic birefringence

Understand systematic effects at $4\upsilon_w$ and all other harmonics - $\alpha_{1,2}(t)$

2^{nd} harmonic dominates. For F.P. we need N $\alpha_{1,2}$ << 1

HWP can be aligned separately using a frequency doubled laser @ 532 nm – reduce 1^{st} ,3^{rd} , 4^{th} har

Temperature control can reduce 2^{nd} harmonic to have N $\alpha_{1,2}$ << 1 with N = 1000



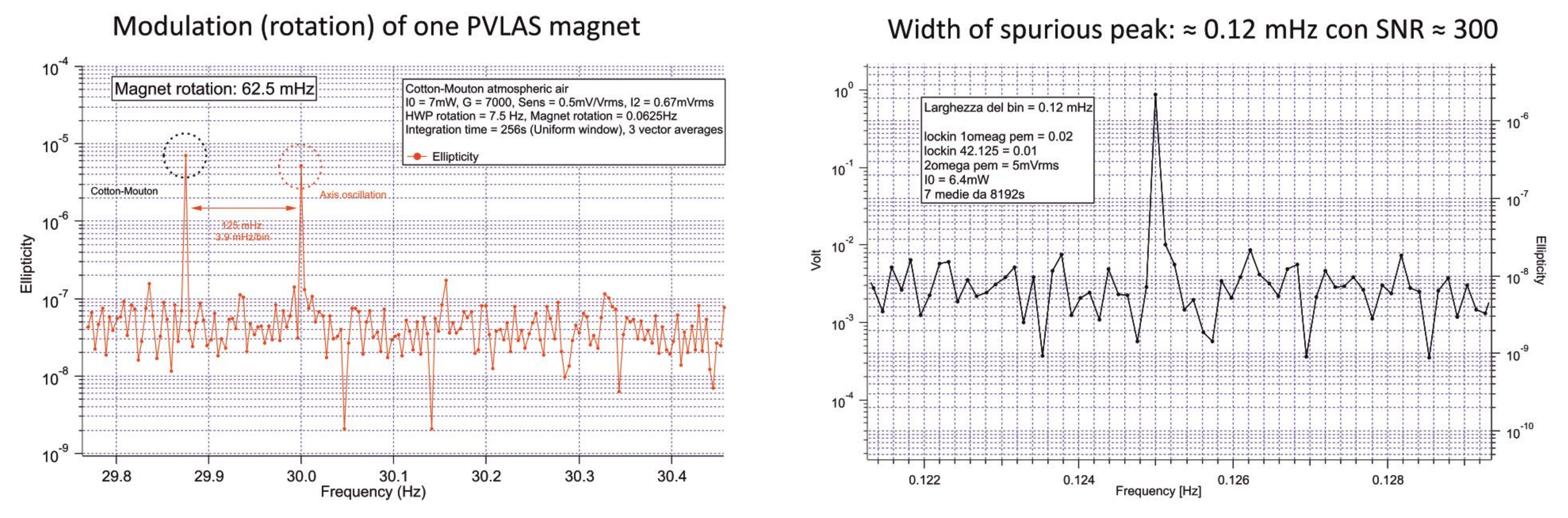
$\alpha_{1,2}^{(1)}(\mathrm{t})$ and $\alpha_{1,2}^{(2)}(t)$ – Generate 4th harmonic signal just like magnetic birefringence

Understand systematic effects at $4\upsilon_w$ and all other harmonics - $\alpha_{1,2}(t)$

$\alpha_{1,2}^{(1)}(\mathrm{t})$ and $\alpha_{1,2}^{(2)}(t)$ – Generate 4th harmonic signal just like magnetic birefringence

Modulate slowly the magnetic field to separate VMB signal from HWP defects

How fast we can modulate LHC magnet? How narrow is the systematic signal at 4th har.



Modulation (rotation) of one PVLAS magnet

Width of spurious peak: ≈ 0.12 mHz con SNR ≈ 300

Magnet rotation: 62.5 mHz

Cotton-Mouton atmospheric air
I0 = 7mW, G = 7000, Sens = 0.5mV/Vrms, I2 = 0.67mVrms
HWP rotation = 7.5 Hz, Magnet rotation = 0.0625Hz
Integration time = 256s (Uniform window), 3 vector averages

Larghezza del bin = 0.12 mHz

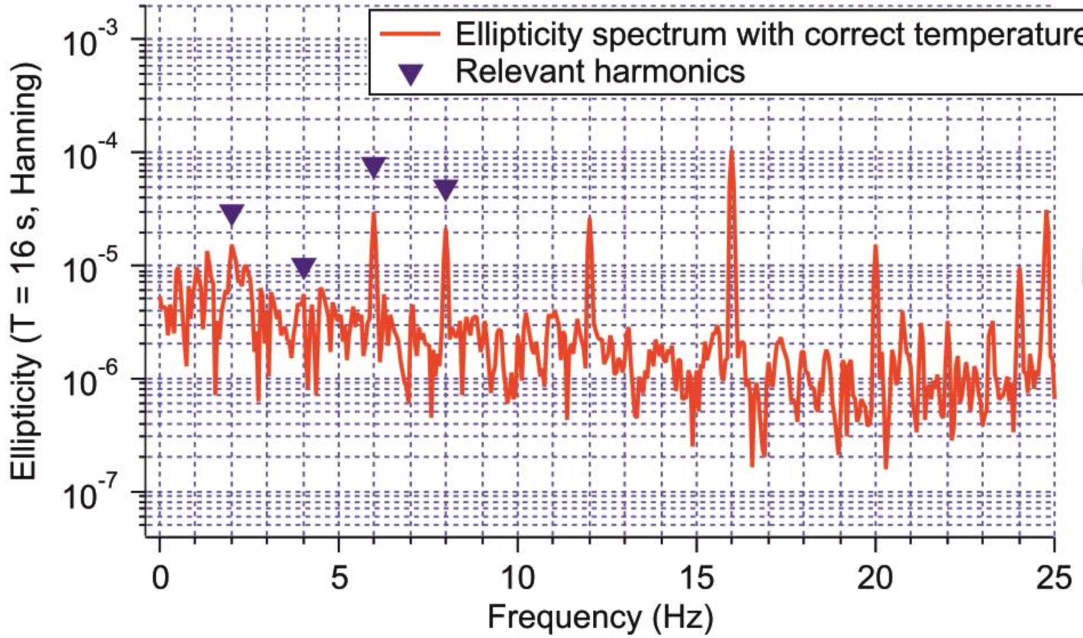
lockin 1omeag pem = 0.02
lockin 42.125 = 0.01
2omega pem = 5mVrms
I0 = 6.4mW
7 medie da 8192s

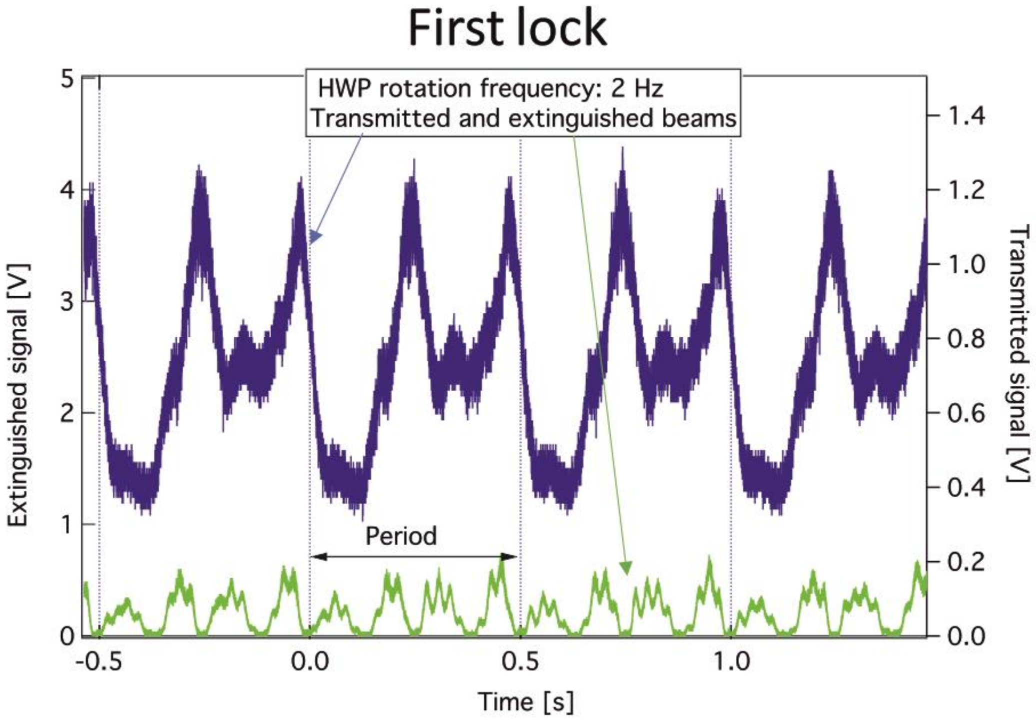
Modulating an LHC dipole magnet at a few mHz could be a solution

Lock laser to the F.P. with the rotating HWPs inside - *N*

Preliminary adjustments and temperature control can reduce N $\alpha_{1,2}$ << 1 with N ≈ 1000

Successfully locked cavity for the first time with rotating HWP



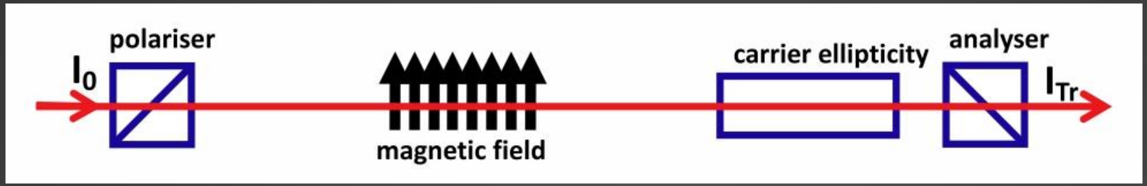

First lock

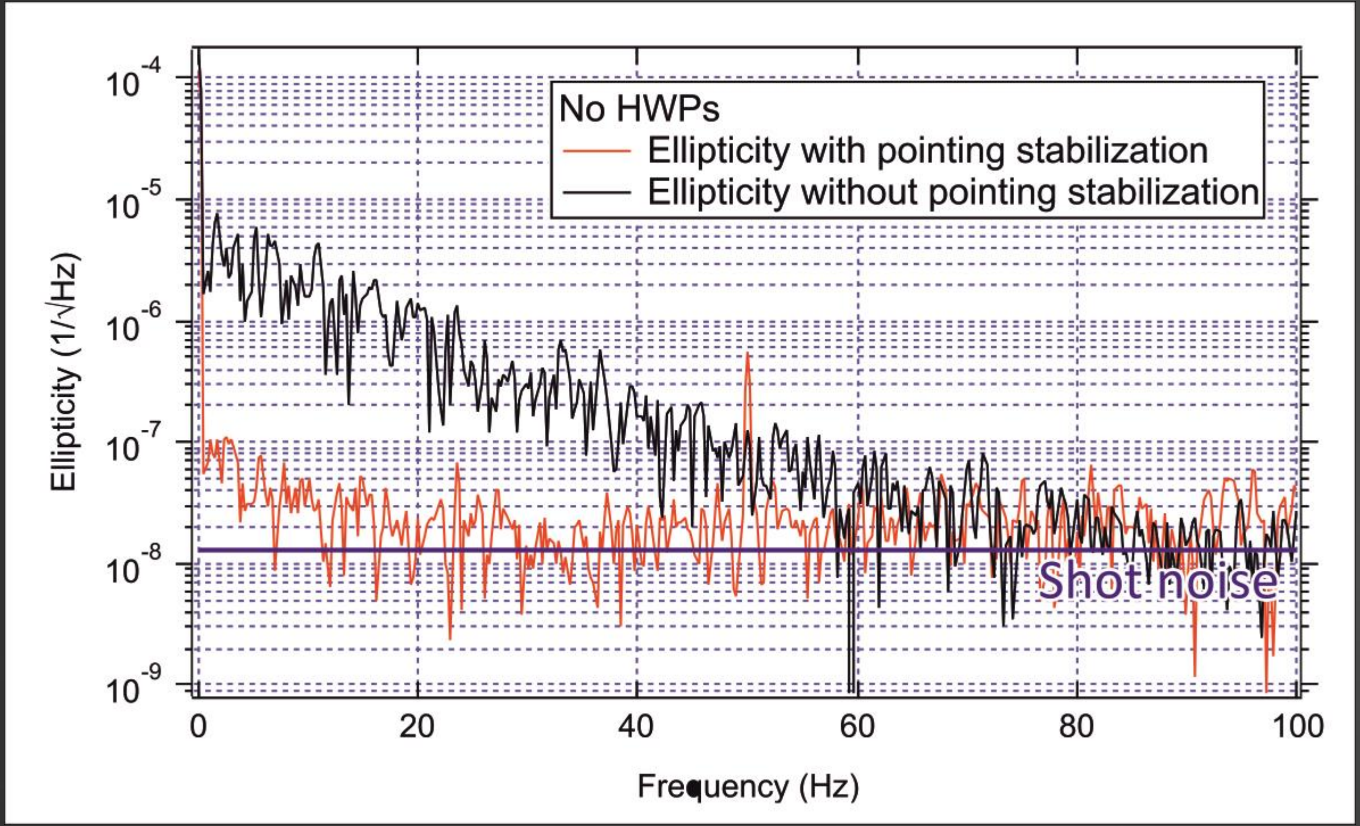
Unstable output intensity due to dust, first tests in open air system

Very stable locking - days

Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

A: No HWP no F.P.





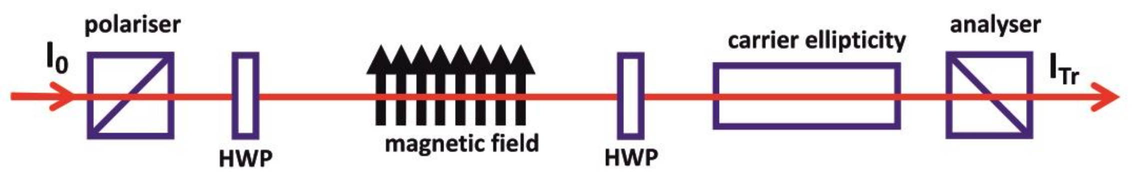
For VMB@CERN,
5 times better is necessary.

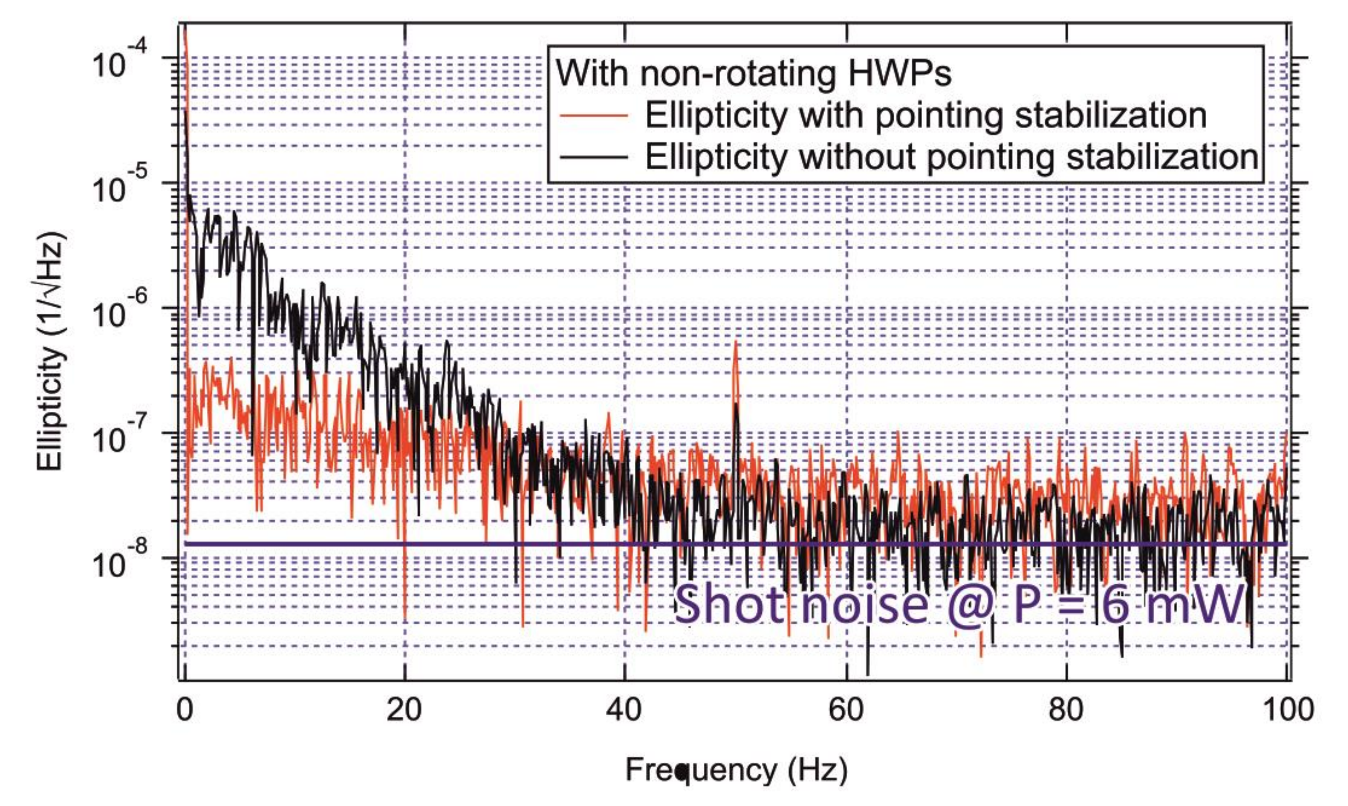
Beam pointing stabilization is necessary. Same results in vacuum.

This task should be automatically performed by the F.P. with stable mirrors

Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

B: HWP not rotating, no F.P.





Beam pointing stabilization is necessary.

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Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

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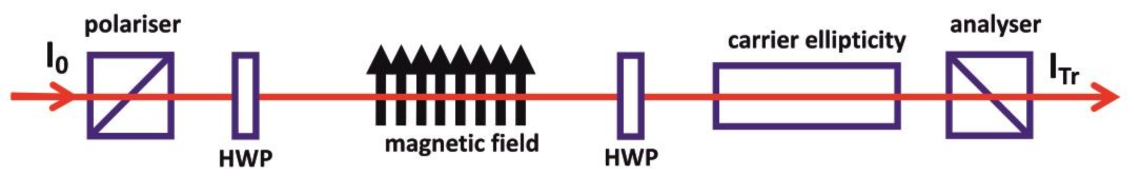
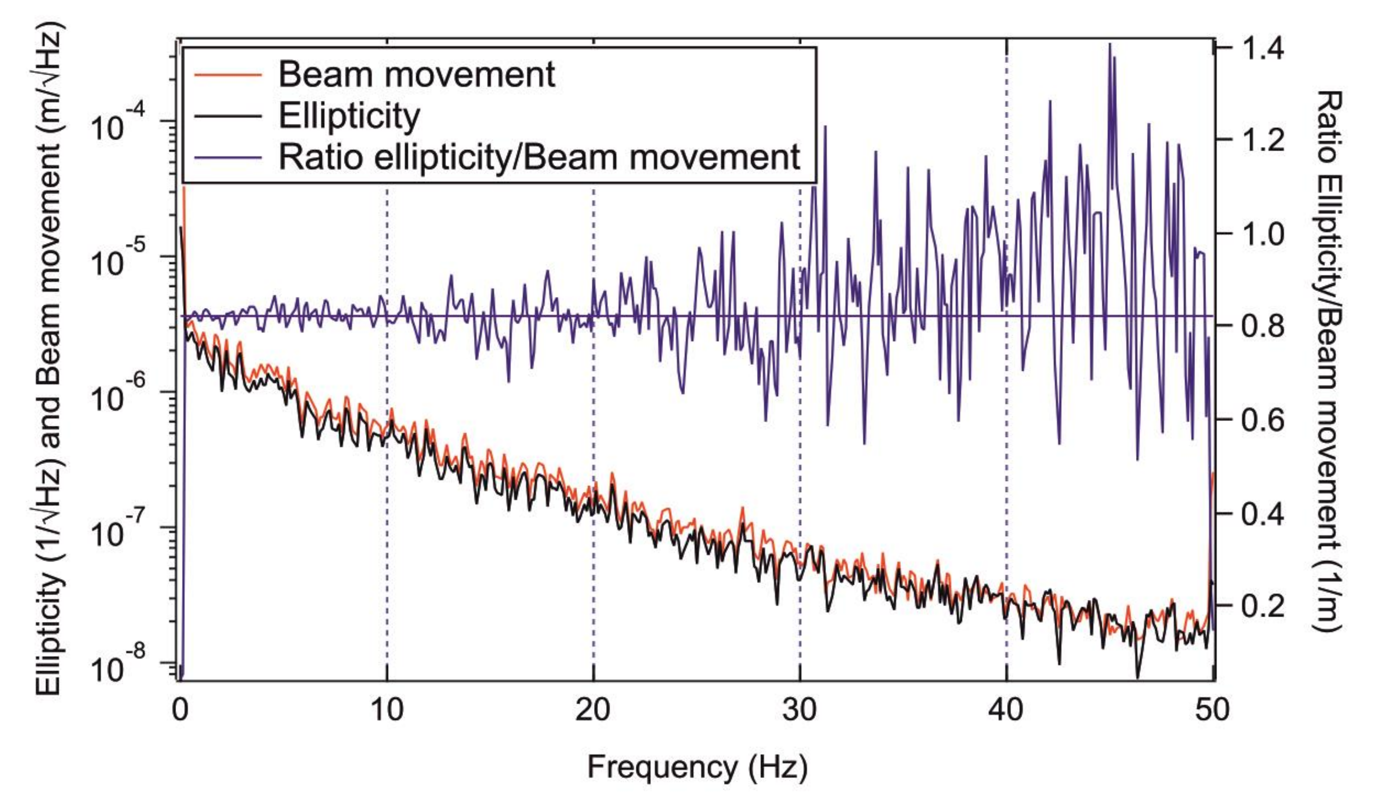


Beam movement at the output of the polarimeter compared to the ellipticity noise

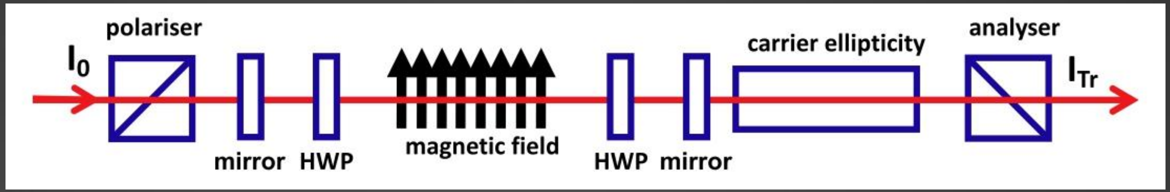


Ratio $10^{-6}/\mu m$

Consequence:
To reach the desired ellipticity sensitivity of $S_\psi \approx 2 \times 10^{-9}$ 1/√Hz one should control the beam stability down to $S_{\Delta x} \approx 10^{-9}$ m/√Hz

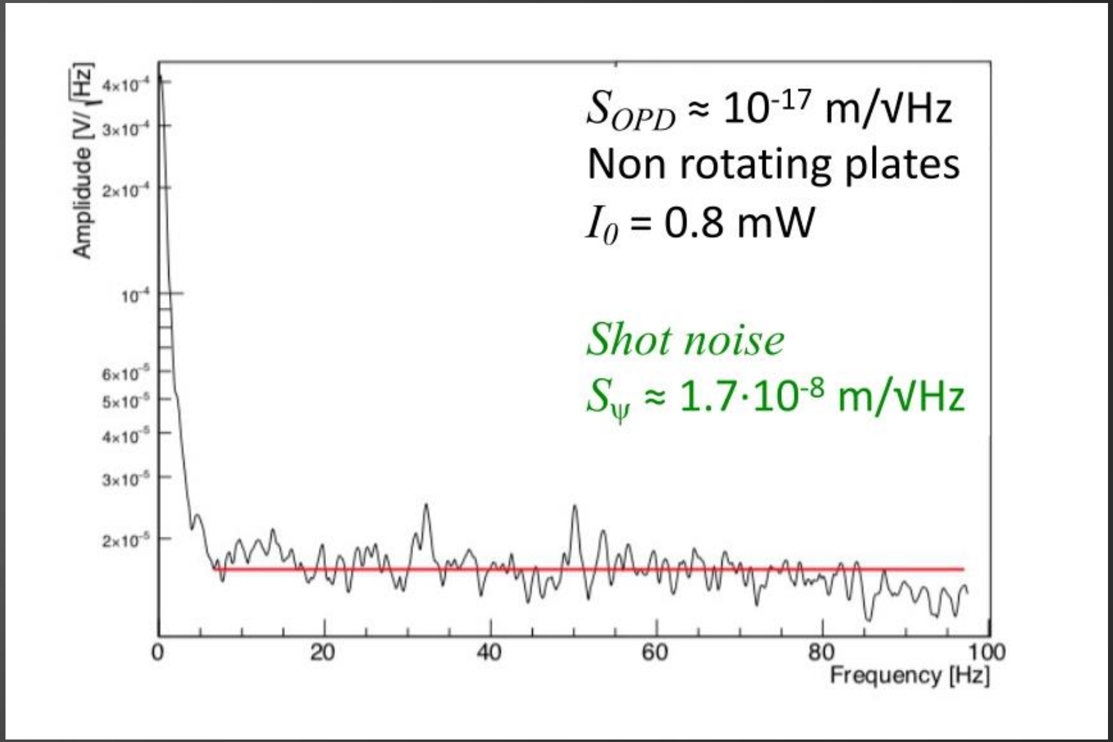
Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

C: HWP not rotating, F.P.



Could a static birefringence from the HPWs degrade the sensitivity?

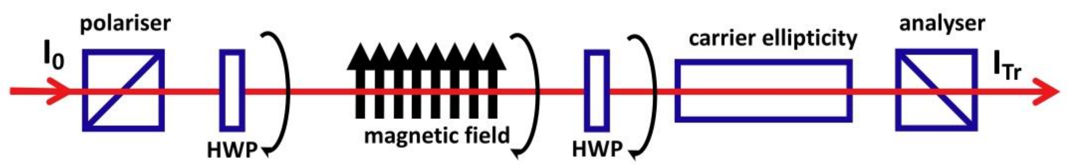
F = 850



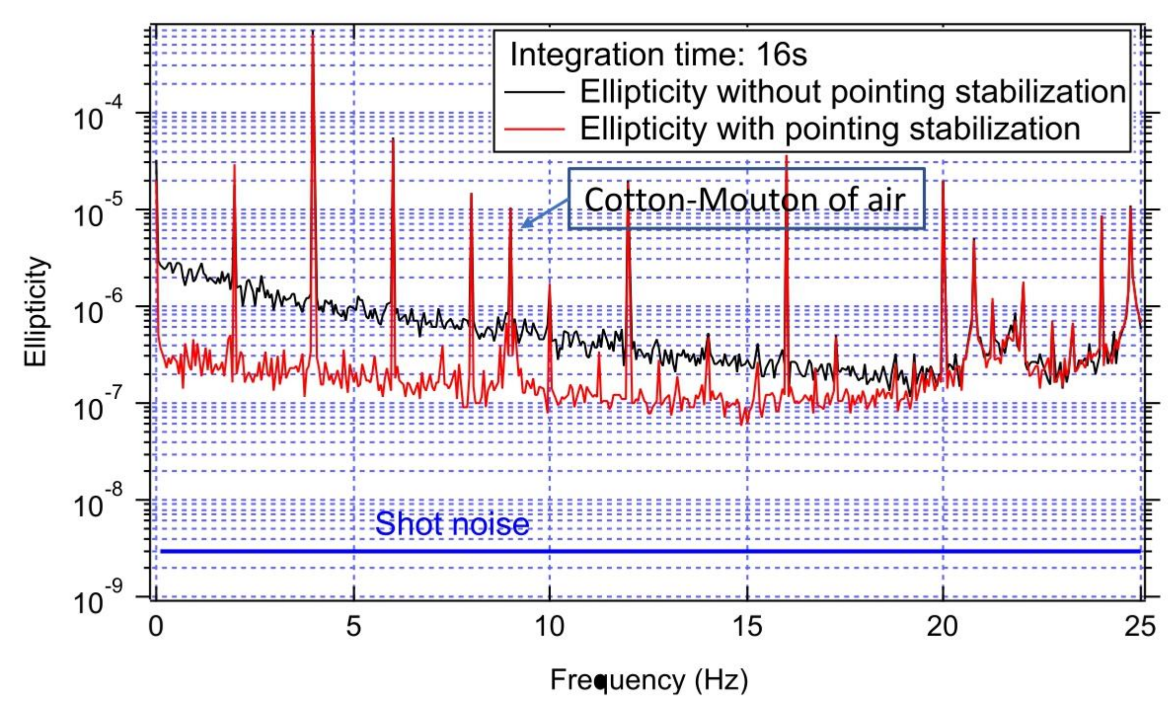
Sensitivity did not degrade with the presence of the HWPs and was compatible with shot-noise

Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

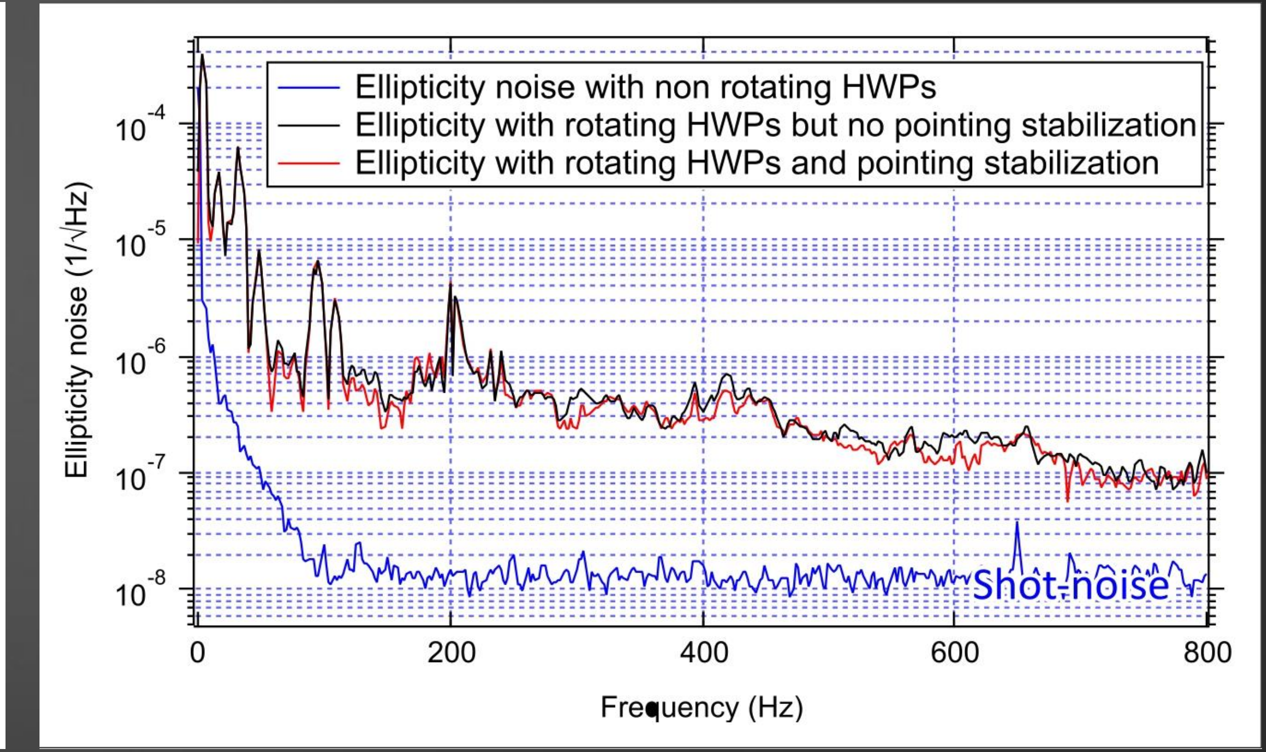
C: HWP rotating, no F.P., one magnet rotating



Ellipticity measurement with rotating HWPs and 1 magnet



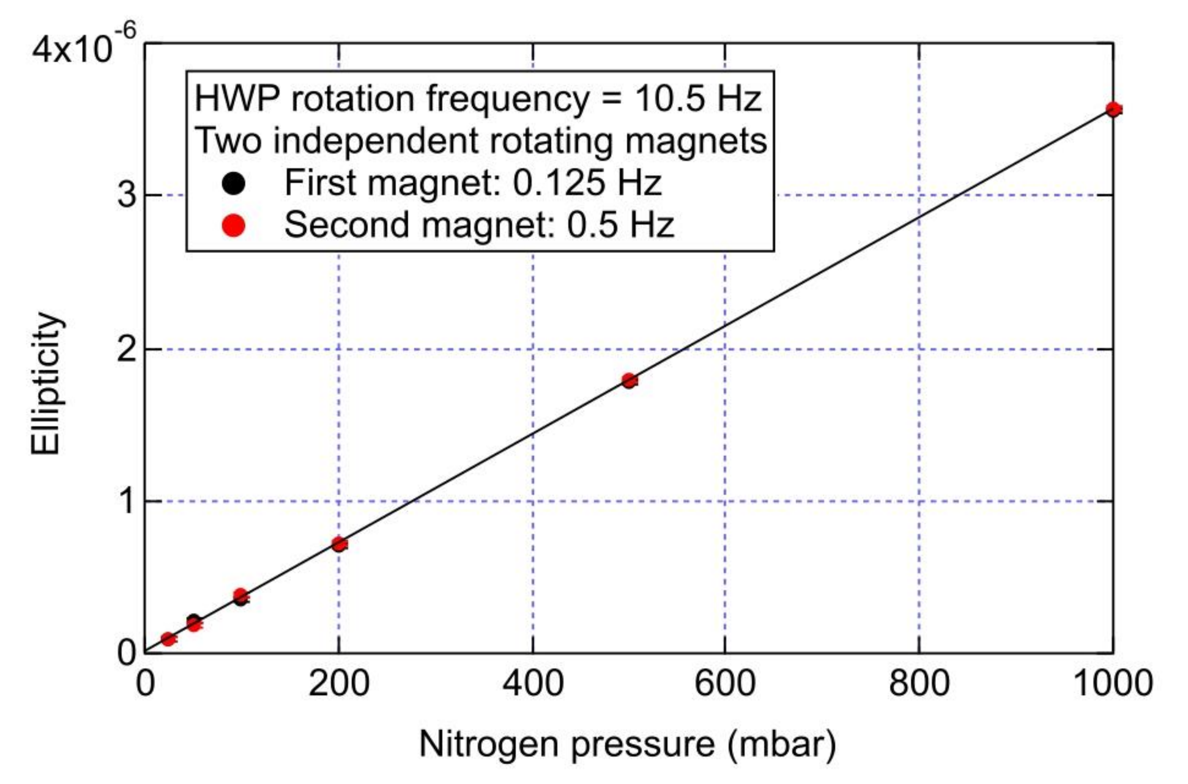
Co-rotating HWPs at 2 Hz with stepper motors Vs. non rotating HWPs



Even with the stabilized beam, the integrated shot-noise of 3 x 10^{-9} is not reached.
There is a wideband ellipticity noise generated by the rotation of the HWPs.

Test of the scheme with nitrogen

Polarimeter was put in vacuum and pure N_2 gas was injected
Used the two PVLAS permanent magnets



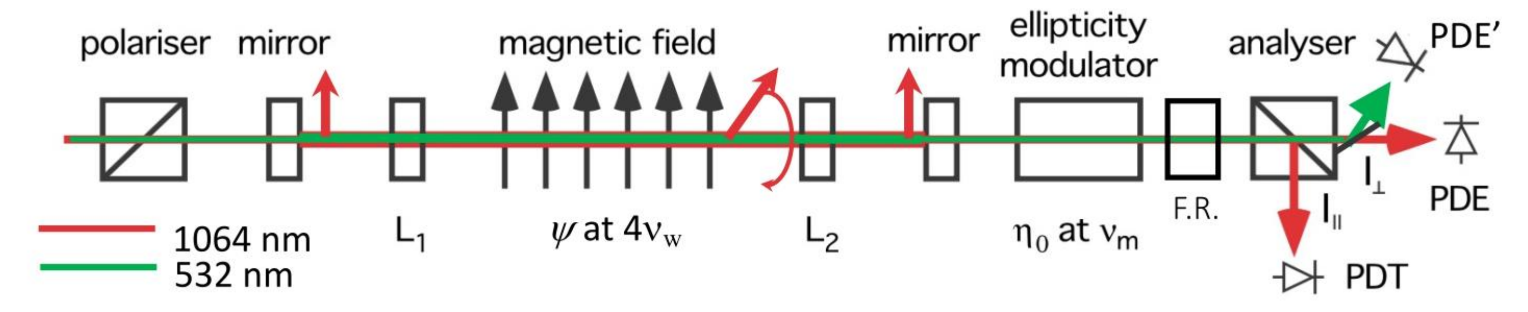
EPJC 82 (2022) 159

- 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

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

Conclusion



Present:

Synchronous rotation of the wave-plates for good extinction - $[2\phi(t) + 2\Delta\phi(t)]$

Understand systematic effects at $4v_w$ and all other harmonics - $\alpha_{1,2}(t)$

Lock laser to the F.P. with the rotating HWPs inside - *N*

Reach required sensitivity for LHC test in small lab - *noise without and with F.P.*

Future:

Full test with rotating HWP, F.P., feedback control - 2023/2024

Possible new mirror coatings

New optical scheme – rotate polarization without mechanical parts.