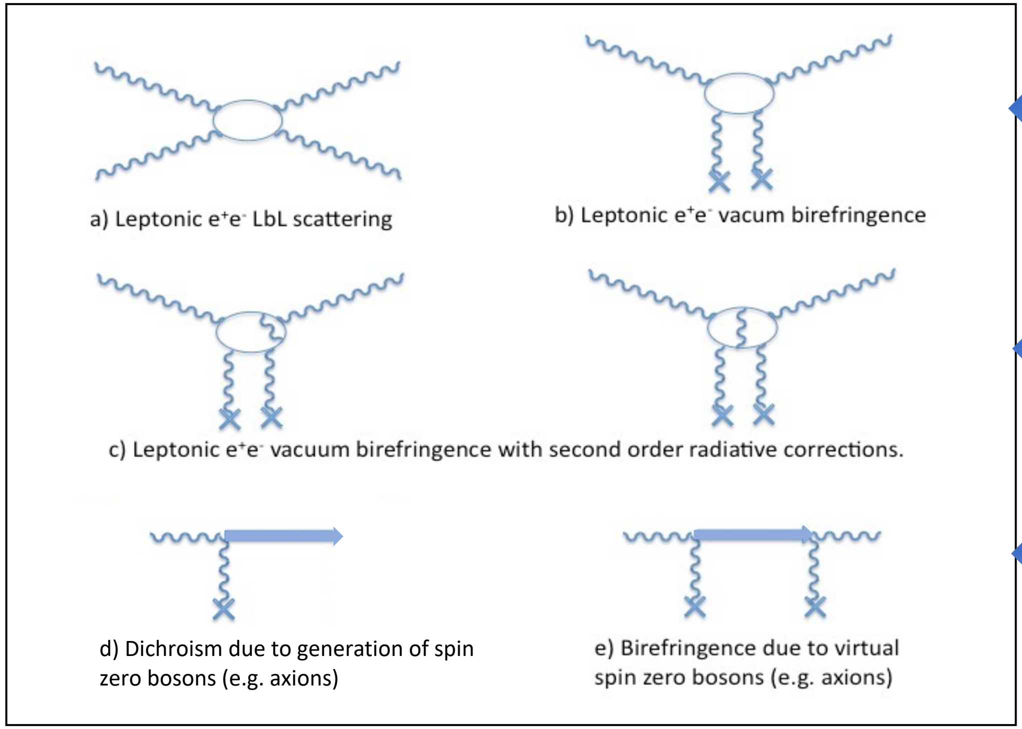
VMB@CERN - Status and plans

Experimental study of the speed of light in an external magnetic field in vacuum



Light-by-light interaction and vacuum magnetic birefringence.

Must be there: $\Delta n = 4 \times 10^{-24}\ B^2$ with B in Tesla.

Includes MCPs

Radiative correction 1.45%

Contributions from hypothetical neutral light particles coupling to two photons: ALPs

Euler-Kockel-Heisenberg Lagrangian predictes VMB

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

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2 \lambda\!\!\!^{-}{}_e^3}{m_e c^2} = 1.32 \times 10^{-24}\ \mathrm{T}^{-2}$$

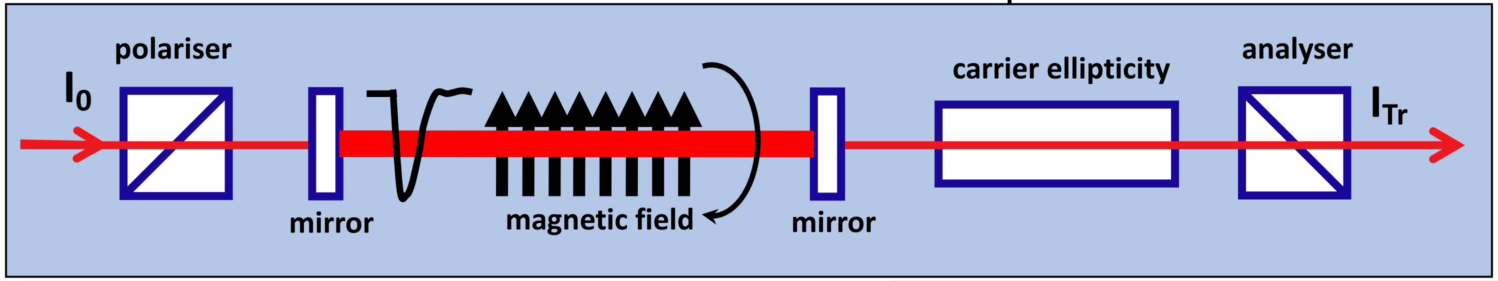
$$\Delta n = 3 A_e B_{\mathrm{ext}}^2$$

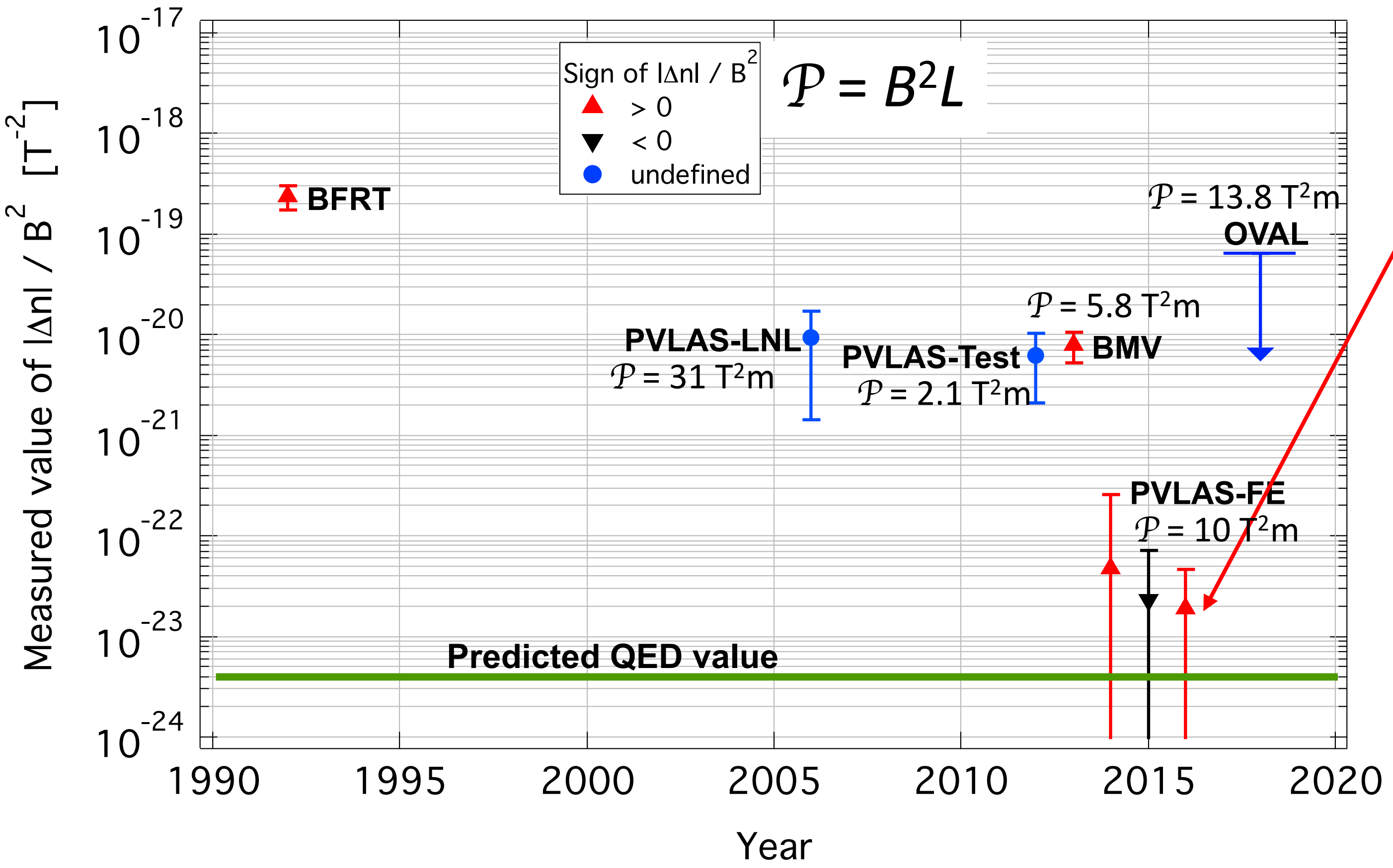
@ B_{ext} = 2.5 T

$\Delta n = 2.5 \cdot 10^{-23}$

State of the art

General scheme: modulated or pulsed field





- The PVLAS - FE result remains the most sensitive measurement yet performed: $\Delta n/B^2 = (1.9\pm 2.7)\cdot 10^{-23}$ T^{-2} with 2.5 T
- Permanent magnets allowed careful debugging of systematics: $B^2L = 10$ T^2m
- Optical path difference sensitivity: $S_{OPD} = 4\cdot 10^{-19}$ m/√Hz @ ≈ 15 Hz
- Cavity amplification was $N \approx 4.5\cdot 10^5$
- <u>Intrinsic thermal noise from the mirrors limited the sensitivity and the SNR</u>
- Measured noise was x10 shot-noise

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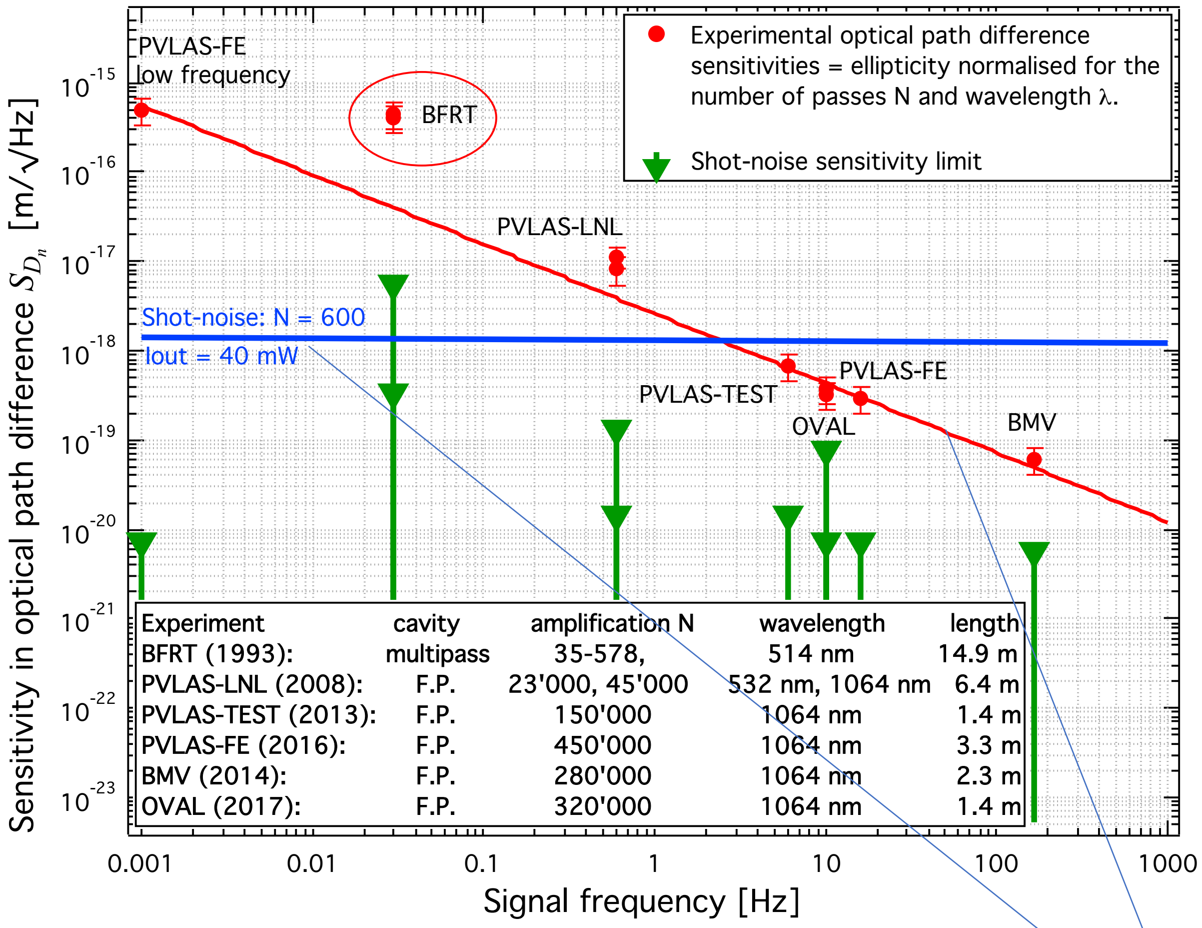
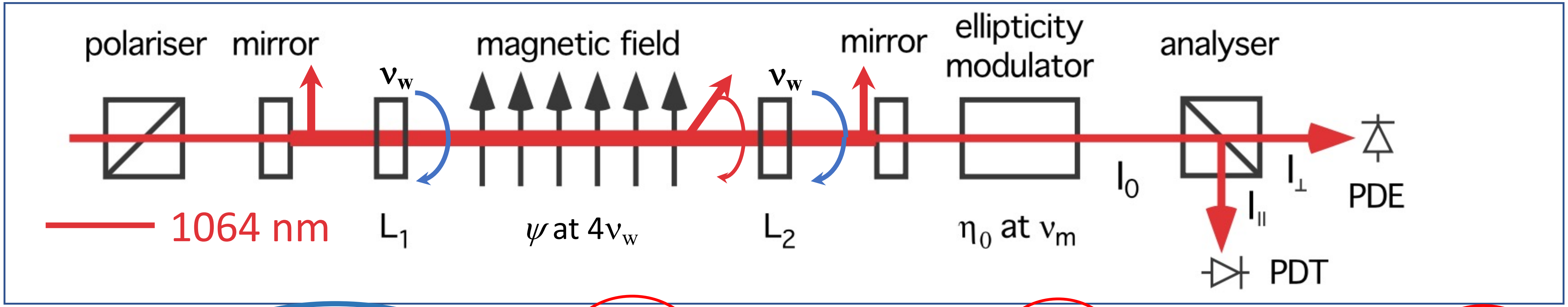
Intrinsic mirror birefringence noise



- 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 tantala layer)
- T = integration time and D_t = duty-cycle
- An LHC dipole would satisfy the requirement for $\nu > 2$ Hz and $T \approx 1$ day for SNR = 1

$$B_{\text{ext}}^2 L > \max \begin{cases} \dfrac{1}{3A_e\sqrt{TD_t}} \dfrac{\lambda}{\pi N}\sqrt{\dfrac{e}{I_0 q}} & \text{shot} - \text{noise} \\ \dfrac{1}{3A_e\sqrt{TD_t}} 2.6 \times 10^{-18} \nu^{-0.77} & \text{intrinsic noise} \end{cases}$$

Scheme: two co-rotating half-wave plates *inside* the F.P.



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

Signal @ $4\nu_w$

Spurious signals
Contain harmonics of ν_w

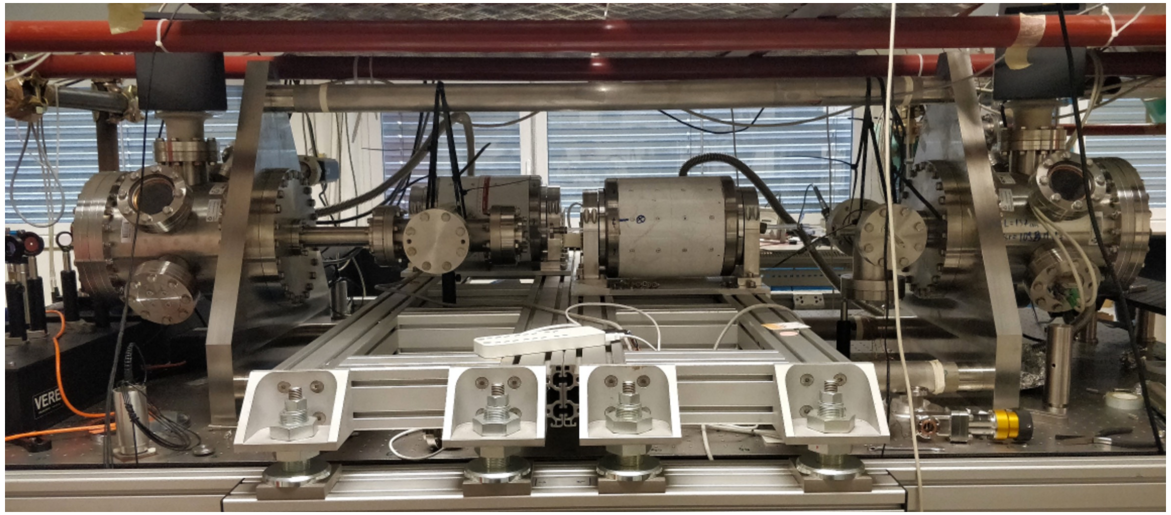
Relative rotation phase error
Degrades extinction

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

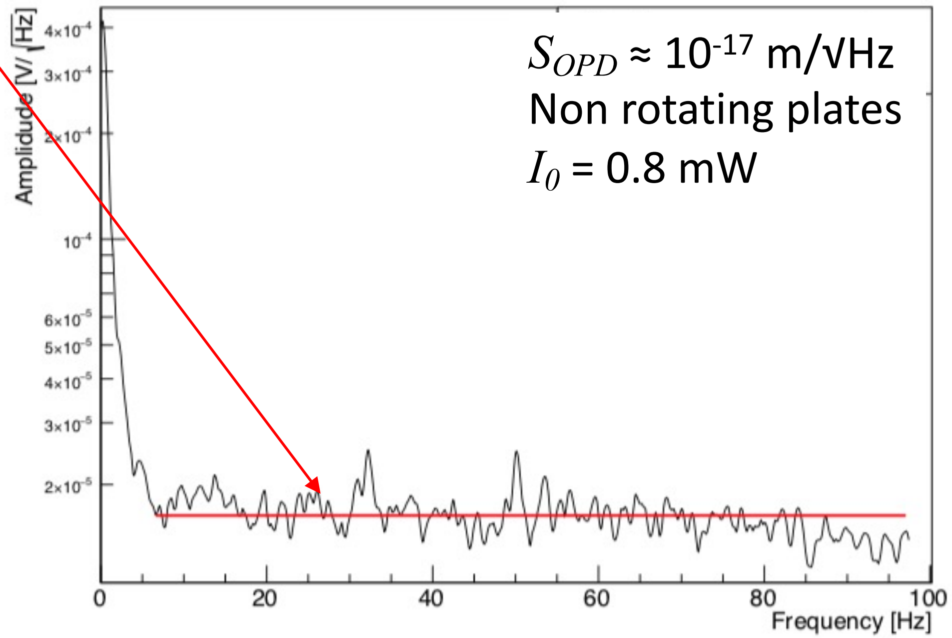
- Allows the use of (quasi) static superconducting fields with $B_{ext}^2L \approx 1000$ T^{2}m (LHC dipole)
- Critical points to be demonstrated:
  - ✓ Synchronous rotation of the wave-plates for good extinction ratio
  - ✓ Understand and mitigate systematic effects at $4\nu_w$
  - ✓ Total wave-plate ellipticity $\alpha_{1,2} << 1/N$ for correct functioning of the F.P.
  - ? Reach required optical path difference noise $S_{OPD} \approx 10^{-18}$ m/√Hz @ $4\nu_w$ with the F.P.

Noise with non-rotating HWPs inside the F.P.

- Important issue: Could a static birefringence from the HPWs degrade the sensitivity?
- Laser locking worked normally
- Measured a finesse of $F = 850$
- Sensitivity did not degrade with the presence of the HWPs and was compatible with shot-noise



Mirror ellipticity ≈ 10^{-6} /reflection

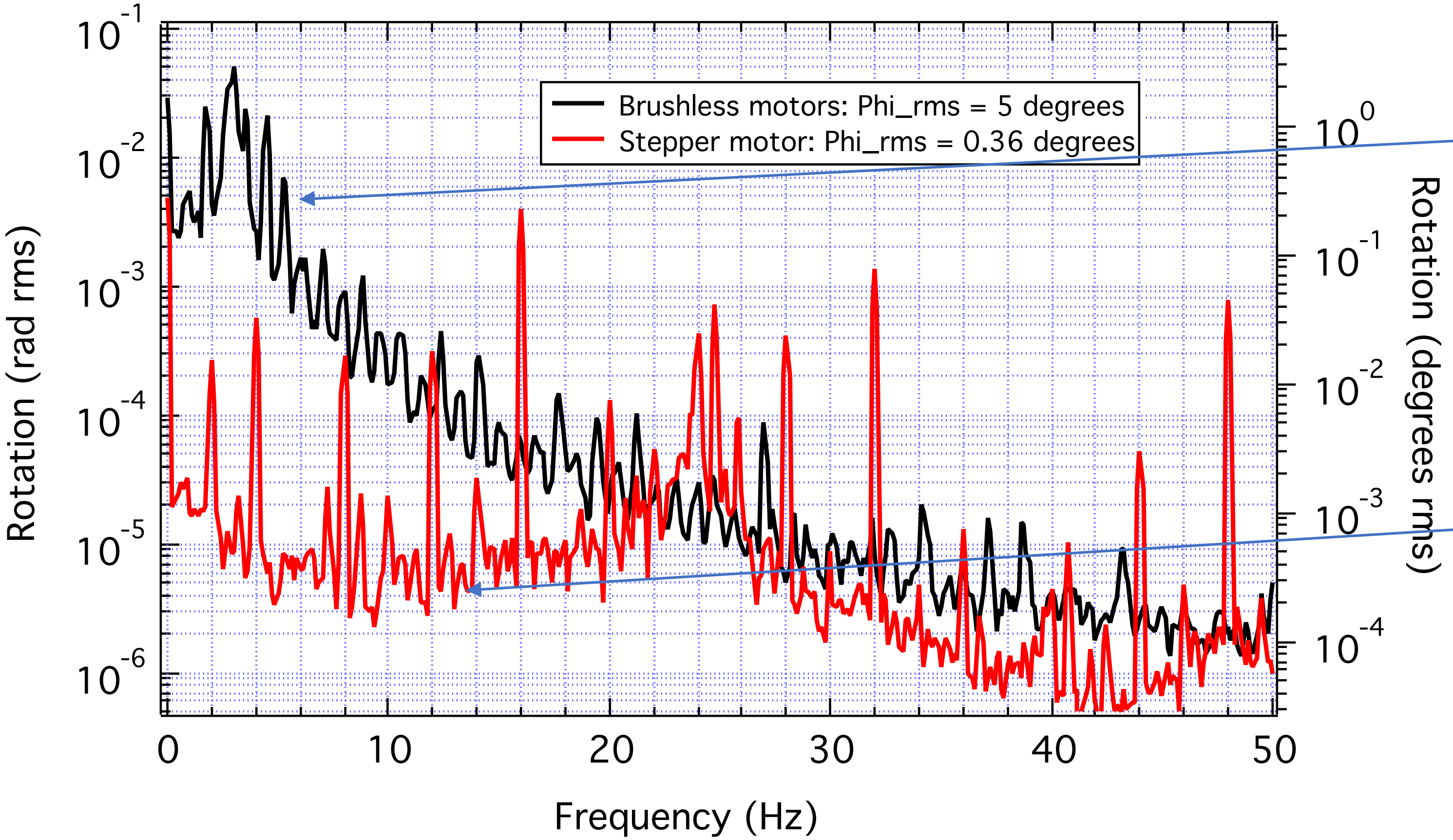


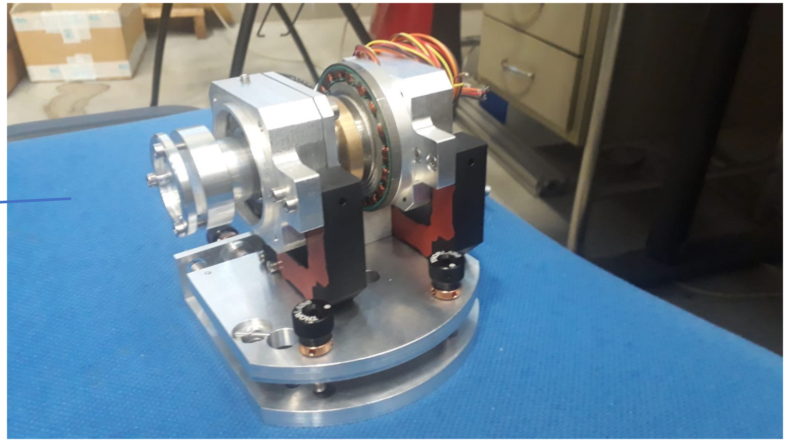
$OPD_{mirrors} \approx 10^{-13}$ m per reflection
$OPD_{intrinsic}$ in experiments > 10^{-19} m/√Hz ➡ $OPD_{intrinsic}/OPD_{mirrors} > 10^{-6}$ 1/√Hz

<u>If the OPD noise was proportional to the absolute OPD ➡ sensitivity would have been ≈ 10^{-12} m/√Hz</u>

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

Synchronised rotation of two HWPs.





- Extinction ratio with stepper motors (no cavity): $\sigma^2 \approx 5 \cdot 10^{-6}$. Good.
- Residual rotation will be corrected with a Faraday rotator already installed

HWP defect issues: temperature and alignment

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

Generating 4th harmonic from $\alpha_{1,2}(t)$: Expansion of the intrinsic HWP defects $\alpha_{1,2}(t)$:

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

- $\alpha^{(0)}_{1,2}$ (from manufacturer) depends on <u>TEMPERATURE</u> and appears @ 2nd harmonic
- $\alpha^{(1)}_{1,2}$ depends on wedge of wave-plates and their <u>ALIGNMENT</u>: appears @ 1st and 3rd harmonic
- $\alpha^{(2)}_{1,2}$ depends on <u>ALIGNMENT</u> generating 4th harmonic just like a magnetic birefringence signal
- <u>Time modulation of $\alpha^{(1)}_{1,2}$</u> due to transverse axis oscillation will also generate a 4th harmonic

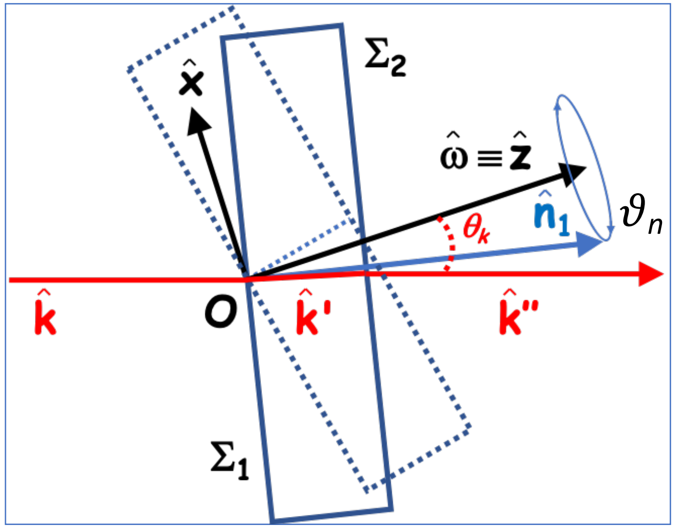
$$r(t) = r_0 + \delta r \cos(\phi(t) + \phi_{\delta r})$$

<u>The resulting ellipticity is the combination of the two HWPs.</u>

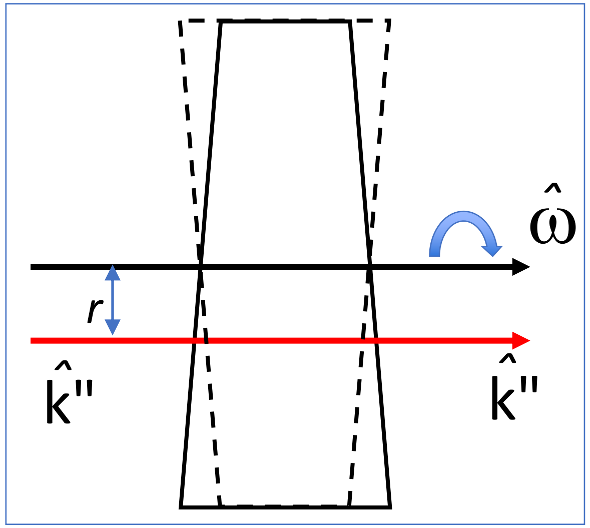
They can be aligned separately using a frequency doubled laser @ 532 nm (already installed)

Wave-plate alignment issues

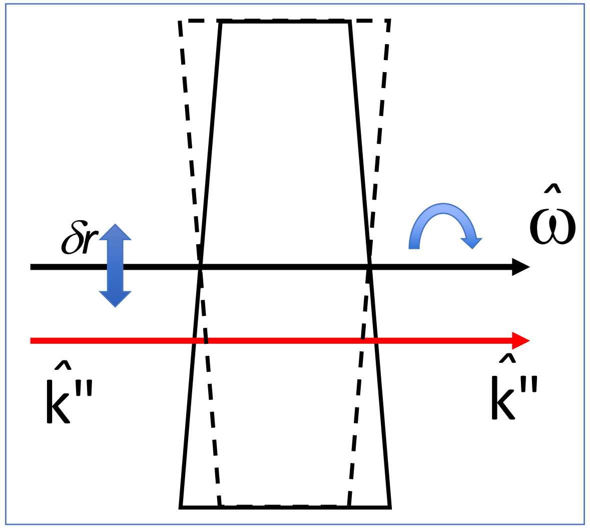
Temperature dependence of $\alpha^{(0)}_{1,2} = \frac{2\pi}{\lambda}(\Delta n D)(\mathrm{T})$



ALIGNMENT



WEDGE β



WEDGE + OSCILLATION @ ν_w

$$\alpha^{(1)}_{1,2} \approx \frac{2\pi}{\lambda}\Delta n \frac{D}{n^2}\vartheta_n \vartheta_k \qquad \alpha^{(1)}_{1,2} \approx \frac{2\pi}{\lambda}\Delta n\, \Delta r_0\, \beta \qquad \alpha^{(2)}_{1,2} \approx \frac{2\pi}{\lambda}\Delta n\, \delta r\, \beta$$

$$\alpha^{(2)}_{1,2} \approx \frac{2\pi}{\lambda}\Delta n \frac{D}{4n^2}\vartheta_n^2 \vartheta_k^2$$

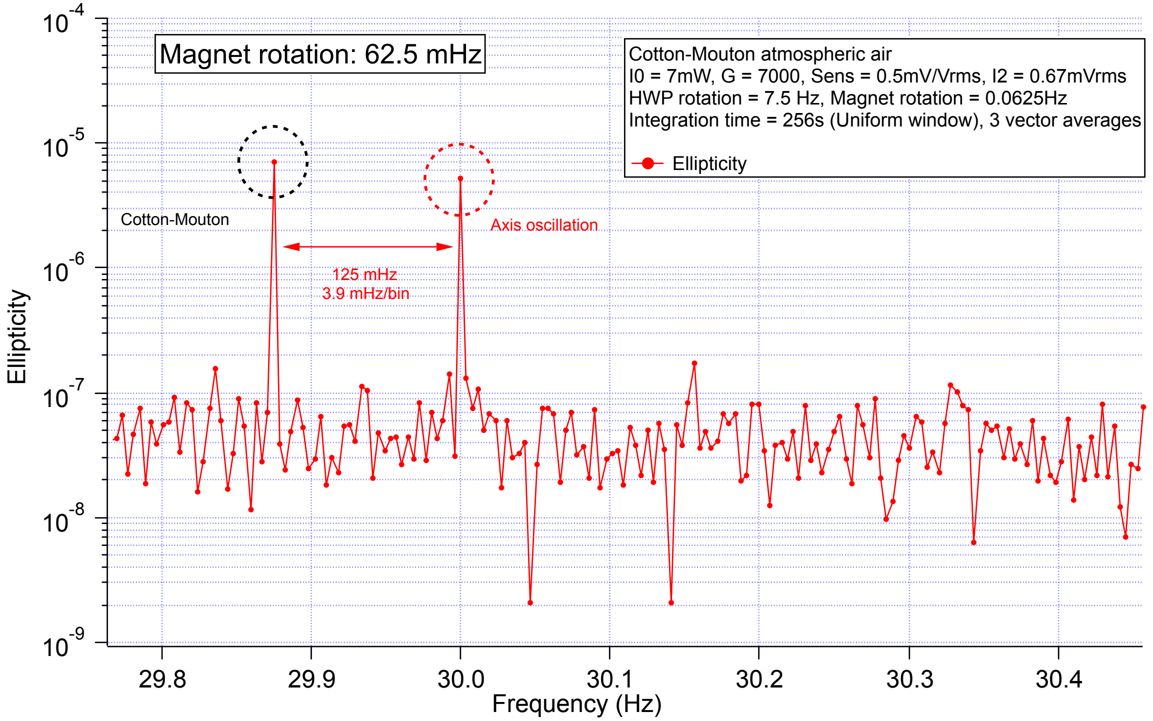
Generate 4th harmonic and cannot be controlled to VMB level

Systematic contribution must be separated from the VMB signal

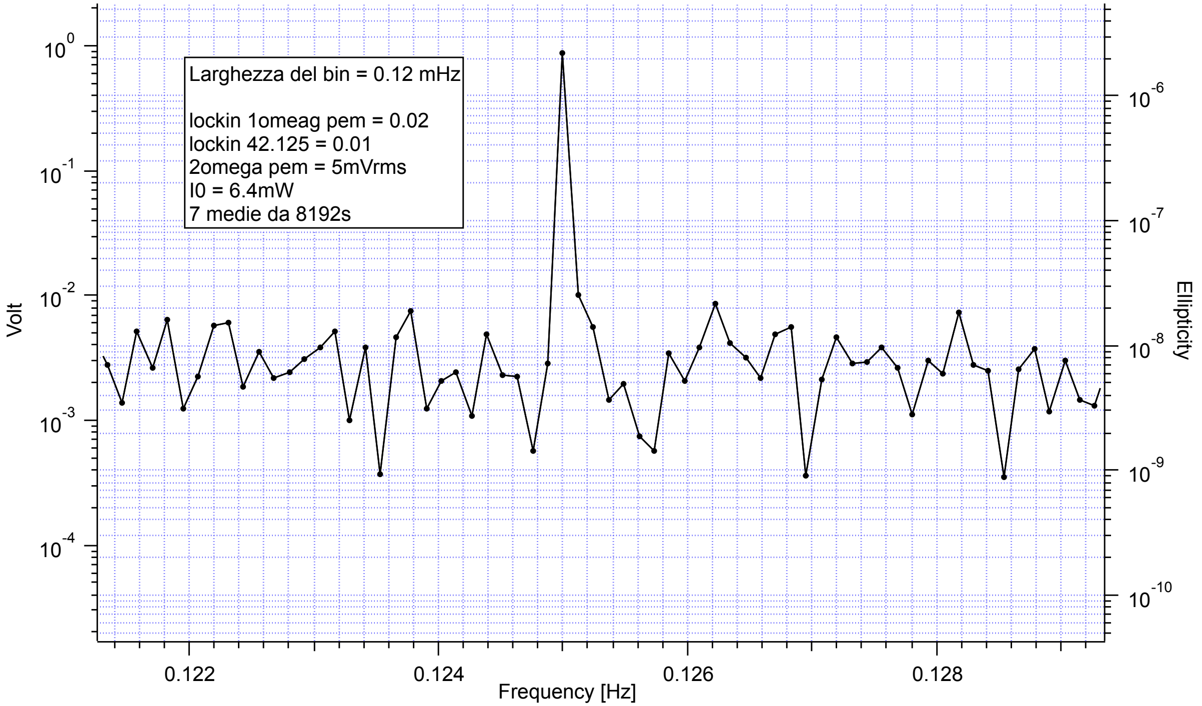
Separate 4th harmonic spurious from VMB signal

- Modulate the magnetic field (slowly) to separate the unavoidable 4th harmonic generated by the rotating HWPs. VMB signal remains far from the low frequency intrinsic noise.
- How fast can the LHC dipole be ramped? How narrow is the systematic signal at $4\nu_w$?

Modulation (rotation) of one PVLAS magnet



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



By modulating an LHC magnet at a few mHz could be a solution

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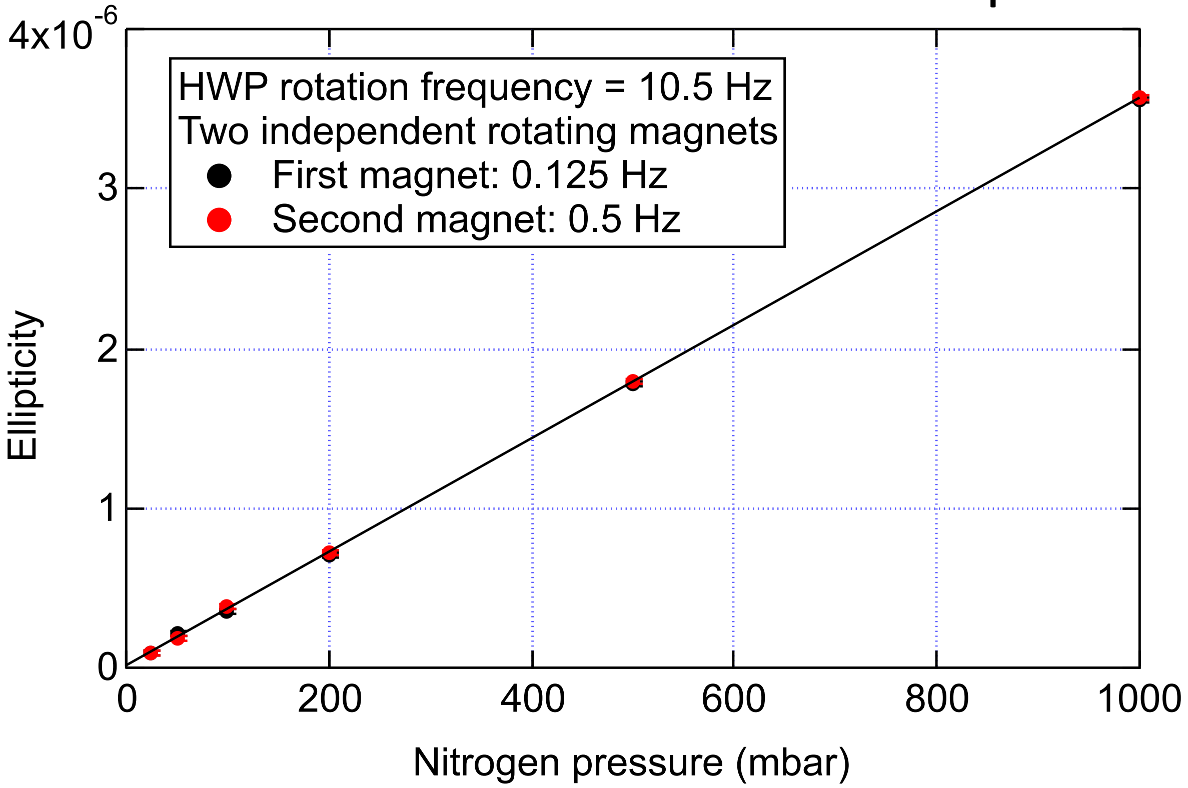
Cotton-Mouton effect in Nitrogen gas @ 1064 nm (no F.P.)

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



- 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

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

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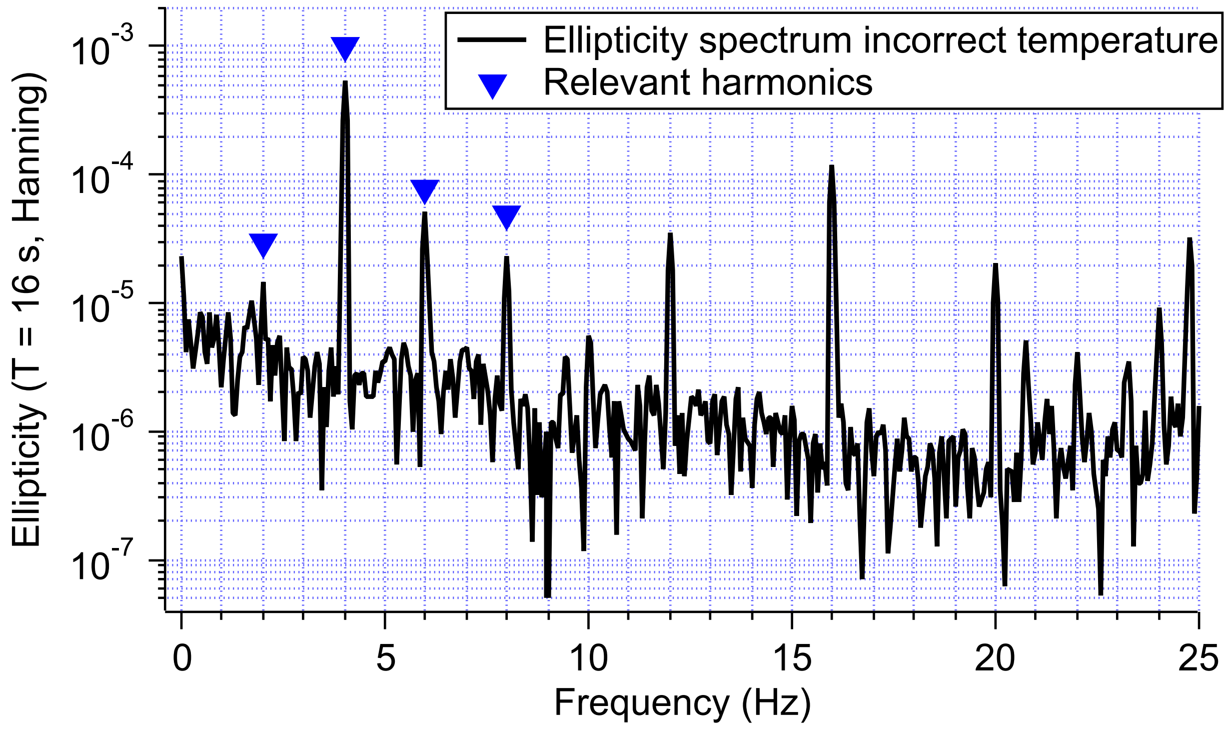
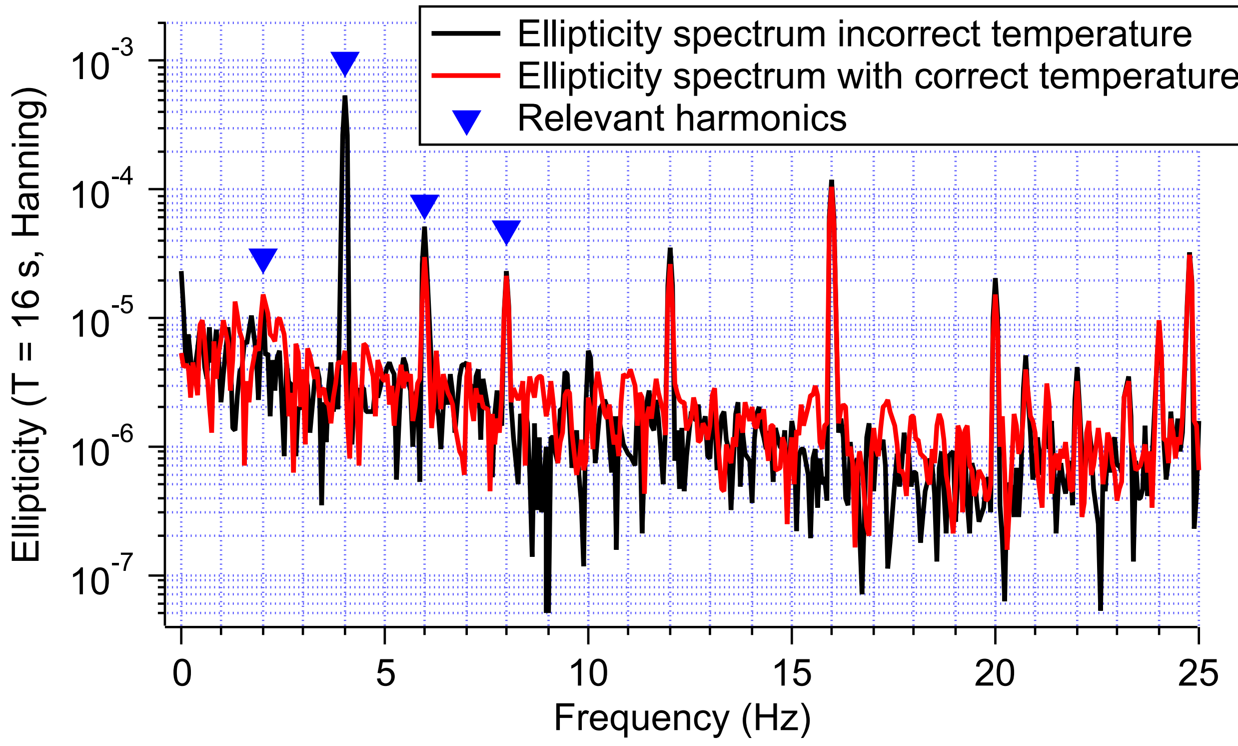
Temperature control of the second harmonic

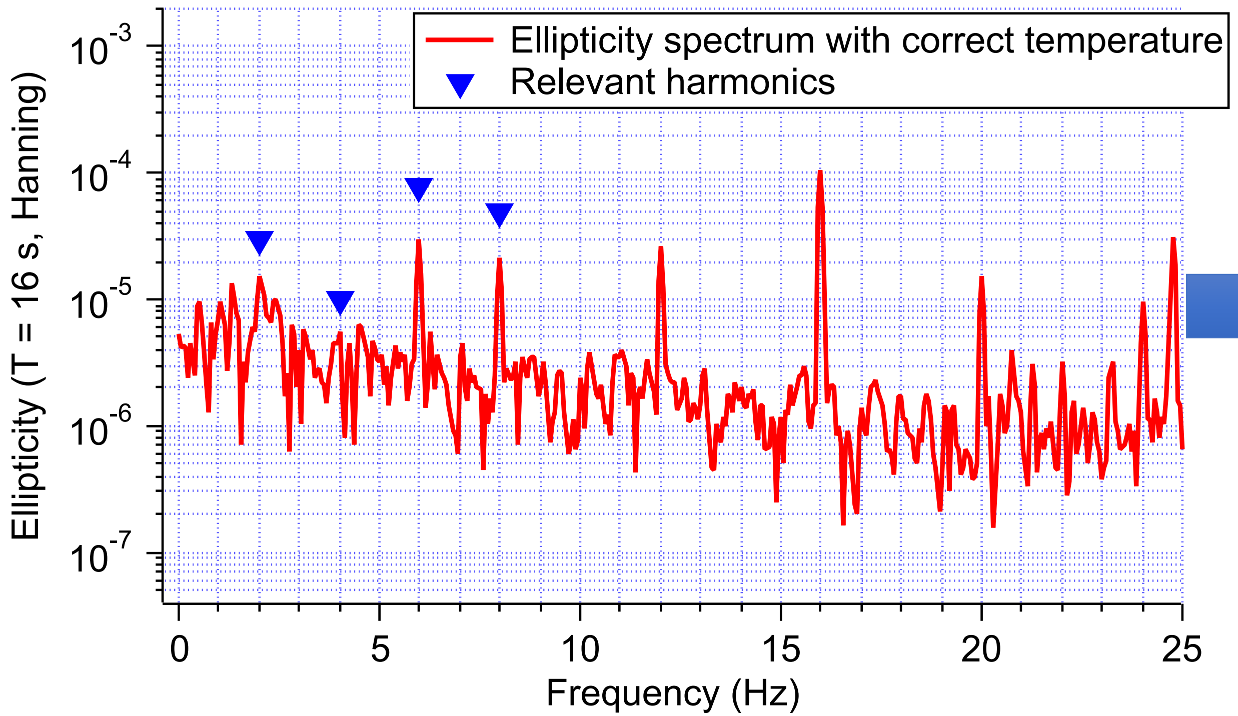
- 2nd dominates. For the F.P. to function we need $N\alpha_{1,2} \ll 1$
- Preliminary adjustments of each wave plate with the 532 nm laser => reduced 1st, 3rd and 4th harmonics also at 1064 nm
- Temperature control of one of the rotating HWPs has reduced 2nd harmonic systematic peak such that $N\alpha_{1,2} \ll 1$ with $N \approx 1000$



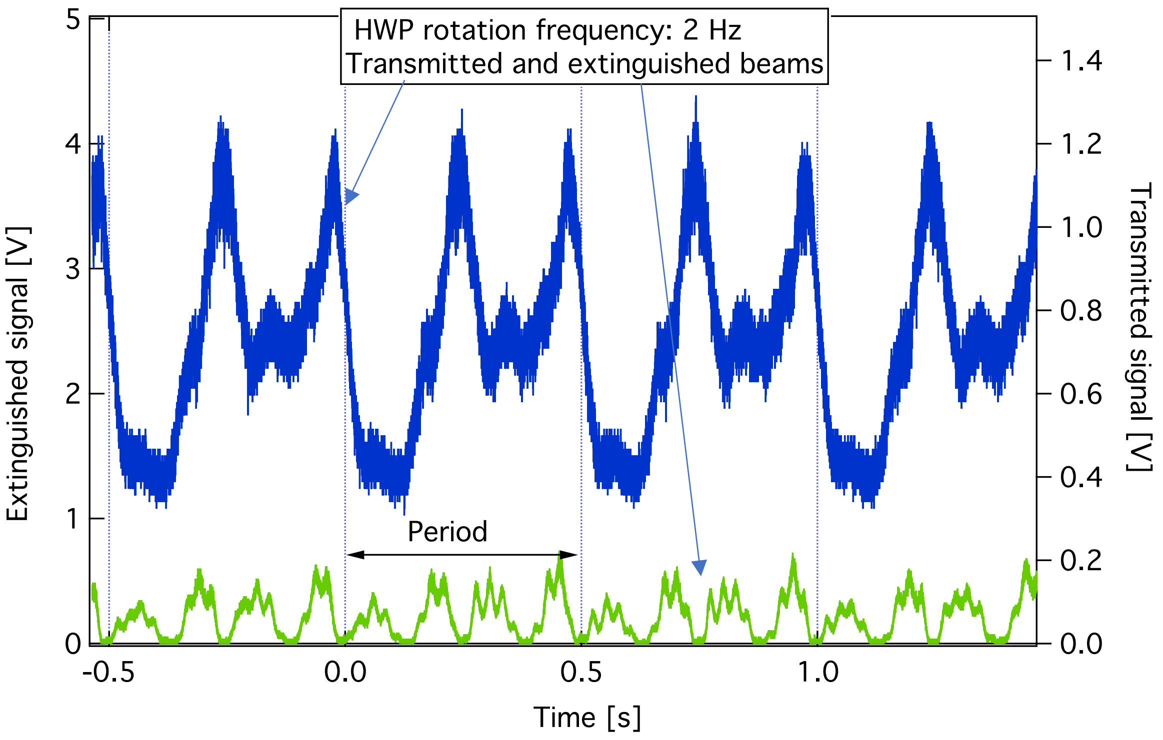


Fabry-Perot: first stable locking with rotating HWPs

- Preliminary adjustments and temperature control of the rotating HWPs have reduced systematic peaks such that $N\alpha_{1,2} \ll 1$ with $N \approx 1000$
- Successfully locked the cavity

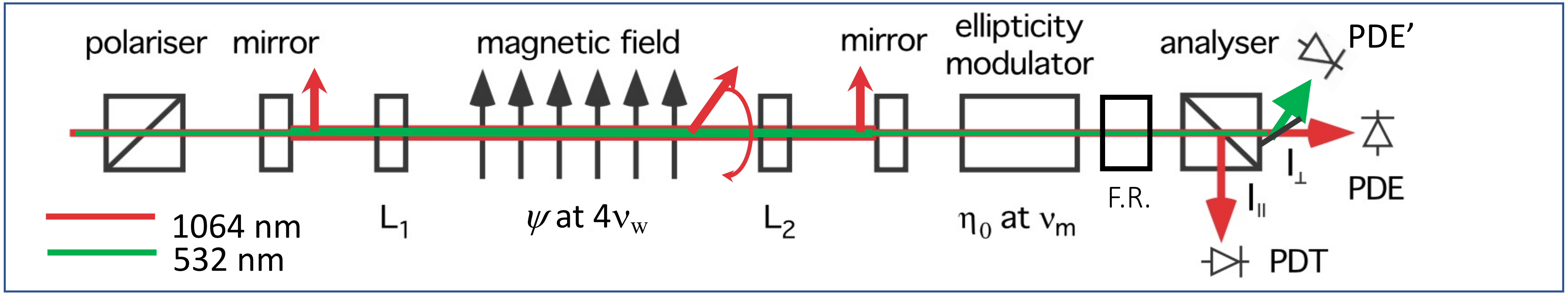


First lock



- Intensity modulation dominated by specks of dust on the HWPs.
- Apparatus was in air. No particular attention to cleanliness yet.
- But very stable locking (days)

Baseline scheme for VMB@CERN



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Signal @ $4\nu_w$

Spurious signals
Contain harmonics of ν_w

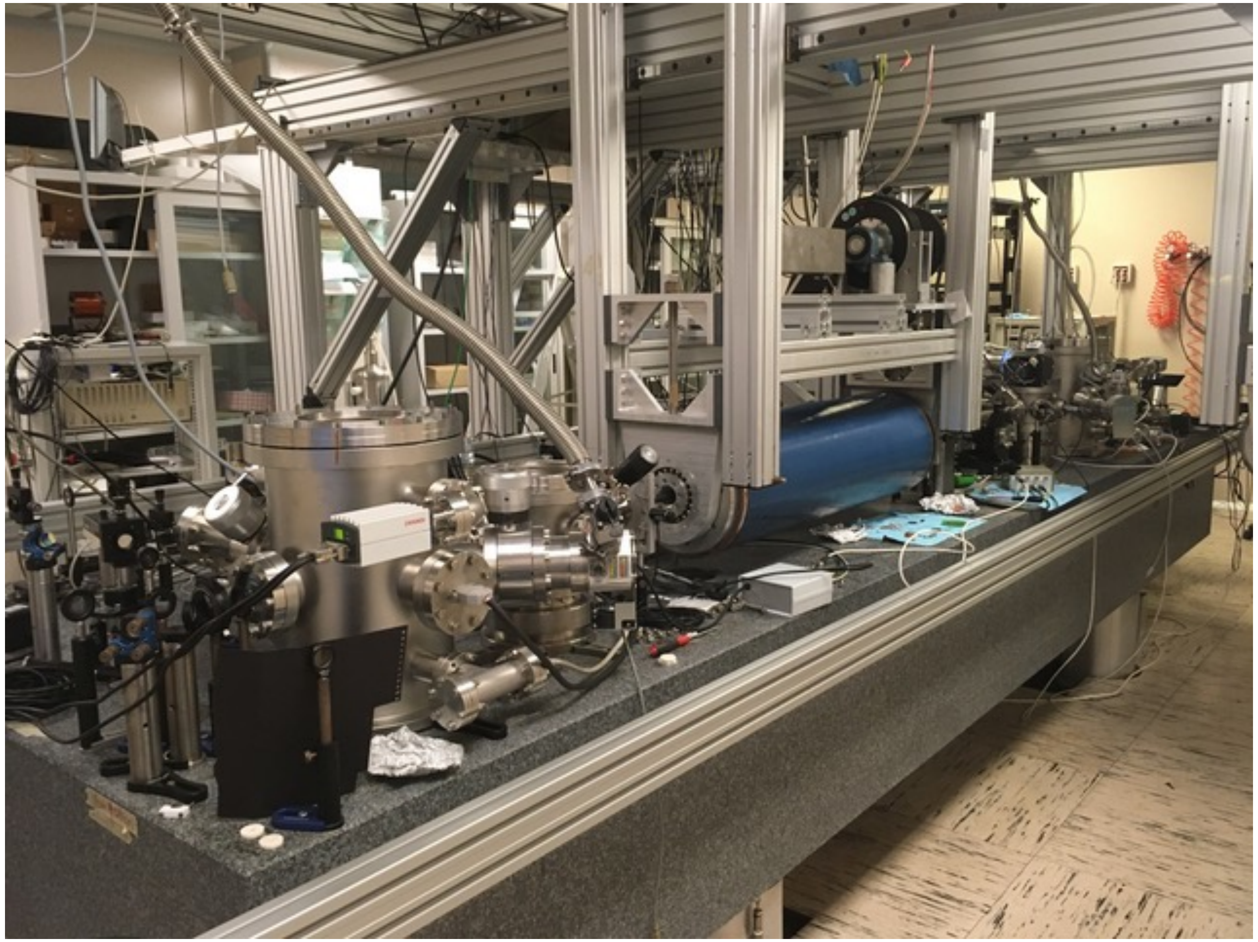
Relative rotation phase error
Degrades extinction

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

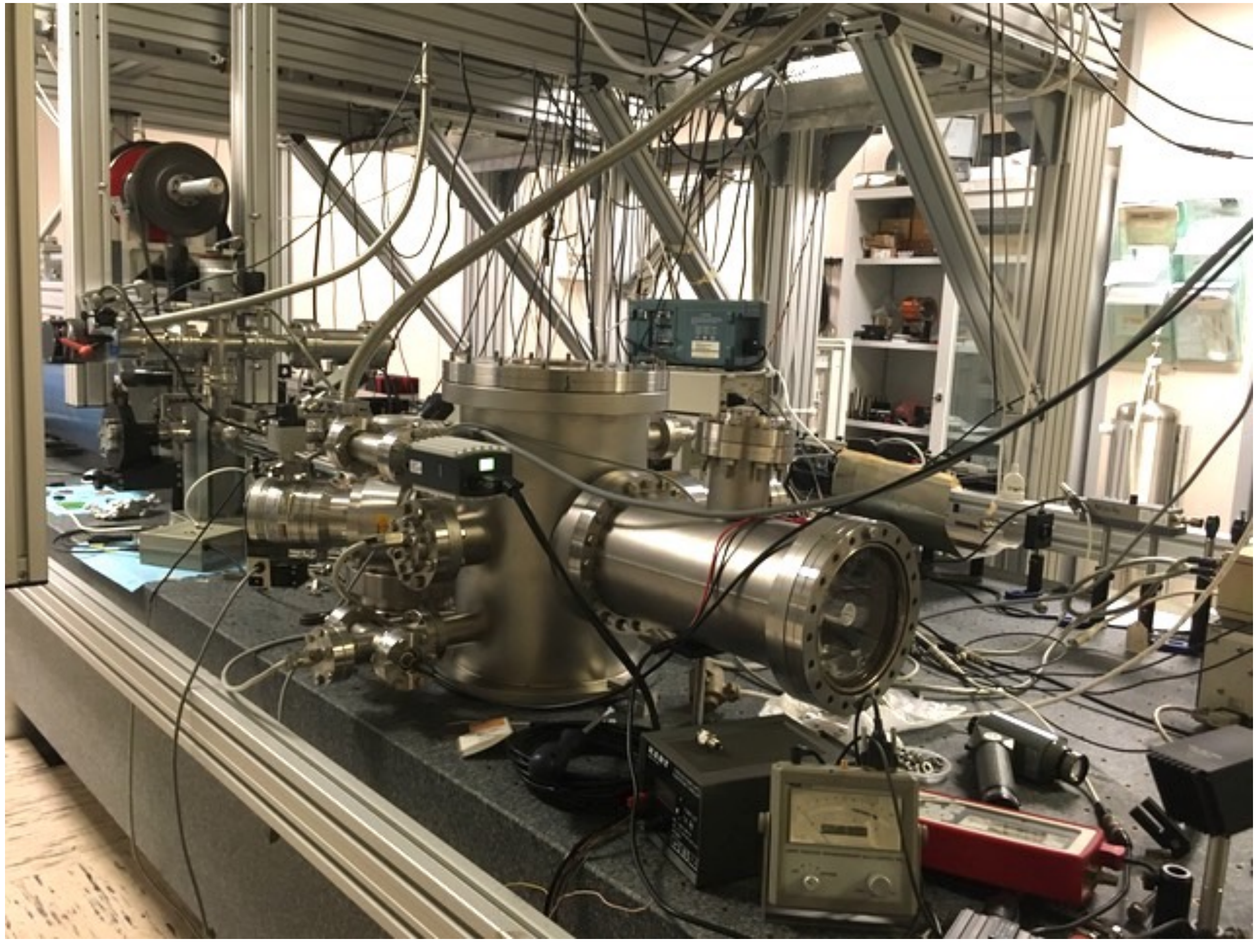
- Non resonant 532 nm beam (HWP -> FWP) allows independent positioning/orientation of the rotating wave plates to reduce 1st, 3rd and 4th harmonics
- Control the temperature of the wave-plates to reduce the dominating 2nd harmonic
- Use a Faraday rotator to reduce residual relative angular phase for optimizing extinction
- Low frequency ellipticity noise without the F.P. is due to input beam movement (≈ μrad). => Input beam stabilization. With the cavity this effect is expected to disappear.
- Demonstrated shot-noise sensitivity N ≈ 600 with two **NON-rotating** commercial HWPs inside the Fabry-Perot
- Demonstrated stable locking of the laser to the F.P. with the rotating HWPs @ 2.0 Hz with no active HWP control.

Pictures

General view from input side

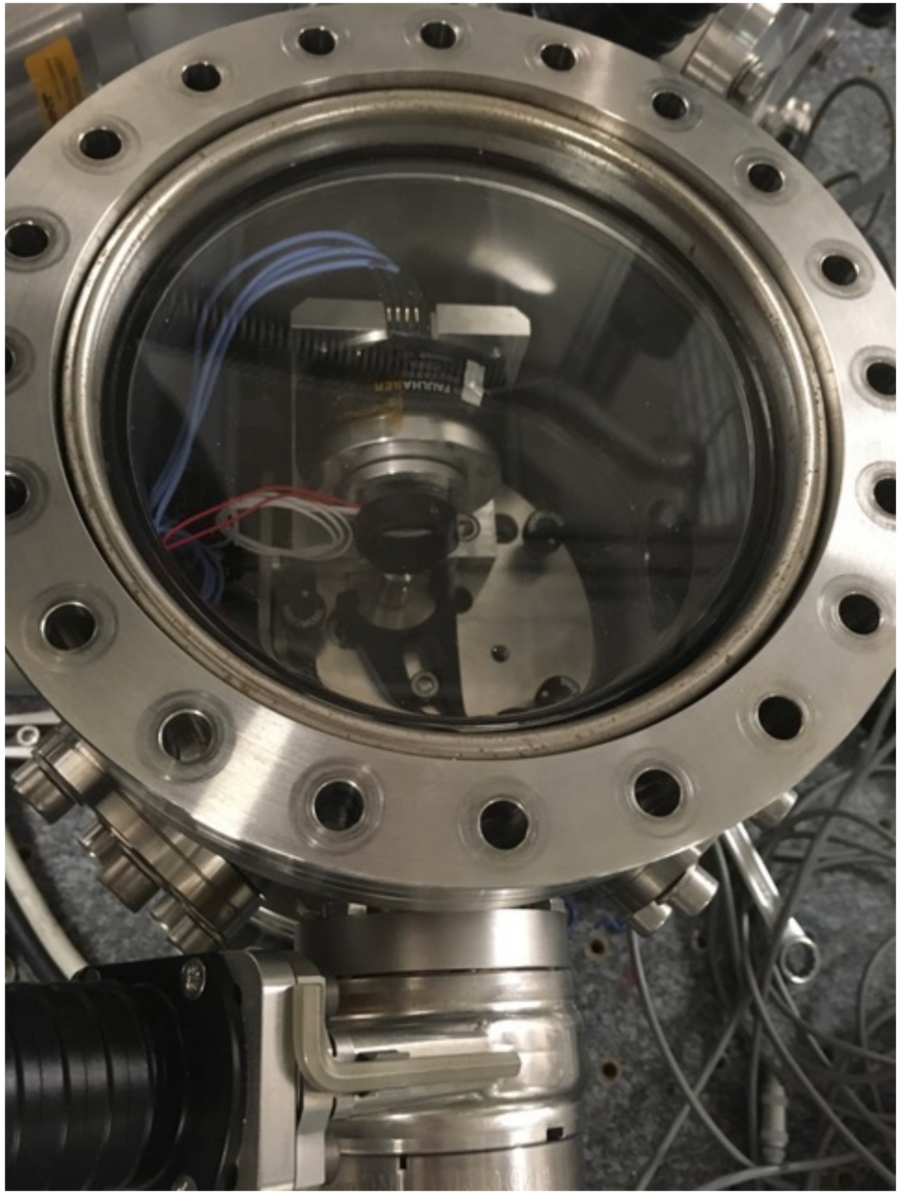


General view from output side



Pictures

Rotating HWP with ring heater



F.P. mirror holder, compensator, PEM modulator

Remaining work for 2022-23

- 2023 is the last R&D year financed by INFN. References to our LoI and to the PBC initiative paper: (https://cds.cern.ch/record/2649744/files/SPSC-I-249.pdf), (https://doi.org/10.1038/s41567-020-0838-4)
- Our results led us to write a Conceptual Design Report for the INFN - CSN 2.
- By the beginning of 2023 we should have a sensitivity value with the F.P.
- In early 2023 we aim at submitting a proposal to CERN.
- During end 2022 and 2023
  - Implement feedbacks on rotating wave plates
  - Possibility to rotate at ≈ 10 Hz
  - If we reach a good sensitivity with the F.P.:
    1. vibration measurements in SM18. Is there an alternative site?
    2. discuss infrastructure and space around and at the ends of the magnet
    3. start discussing the vacuum interface with CERN's engineers
    4. try to ramp a magnet to see how fast it can be done
    5. study ground movement with ramping magnet

Schedule 2022 - 2023

- Divided the project into 3 Work Packages: `Optics related issues', `LHC related issues' e `Infrastructure issues'.
- Time schedule (from INFN-CDR):

			Year 1		Year 2		Year 3		Year 4	
WP		Item	1st sem	2nd sem	1st sem	2nd sem	1st sem	2nd sem	1st sem	2nd sem
WP1	Optics FE	HWP positioning								
		HWP rotation								
		Laser pointing stability								
		FP cavity								
	Optics CERN	Seismic study								
		Laser pointing stability								
		FP cavity								
WP2	Magnet	Current modulation								
		Vacuum								
WP3	Infrastructure	Clean environments								
WP4	Measurements									

Conclusions

- Testing a new optical scheme for VMB measurements allowing the use of a (quasi) static superconducting LHC spare dipole
- Identified systematics and found ways to mitigate their effects
- Successfully locked the F.P. with the rotating HWPs inside
- Must implement various feedbacks and determine the final sensitivity
- Our results led us to submit a Conceptual Design Report for the INFN - CSN 2 and we aim at presenting our proposal to CERN-SPSC in early 2023