Precision Polarimetric techniques to measure Gas and Vacuum magnetic birefringence

G. Cantatore - Università e INFN Trieste

Summary

- Introduction & motivation
- Basic ellipsometric techniques
- Gas measurements
- Towards quantum Vacuum measurements with PVLAS Phase II
- Conclusions

Introduction

- Polarimetric measurements provide an extremely precise and versatile tool to investigate the properties of a medium
- The basic idea is to pass a light beam having an initially known polarization state through a medium and to measure how this state changes
- Normally the final polarization state contains information on the intrinsic properties of the medium
- If the medium is perturbed by some external agent (say a field) the parameters of the final polarization state contain information on the interactions between the field and the bulk of the medium, possibly revealing the medium intimate structure

Motivation

- We discuss here two interesting media having magneto-optical properties which can be investigated with IR-visible wavelengths
  - GASES -> Magnetic birefringence (Cotton-Mouton effect)
  - VACUUM (a zero pressure gas...) ->
    - magnetic birefringence (photon-photon scattering in QED)

Cotton-Mouton effect

- Gases subject to a (static) magnetic field become anisotropic optical media, with the field direction defining the optical axis
  - the effect of the field is to induce an anisotropy in the hypermagnetizability tensor η and in the electric (α) and magnetic (χ) moments of the gas molecules, resulting in different refractive indices for light polarized parallel or normal to the external field

$$\Delta n = n_{\parallel} - n_{\perp} = \frac{B^2 P}{4\varepsilon_0}\frac{\Delta\eta}{kT}$$

spherical molecules

$$\Delta n = n_{\parallel} - n_{\perp} = \frac{B^2 P}{4\varepsilon_0}\left(\frac{\Delta\eta}{kT} + \frac{2\Delta\alpha\Delta\chi}{15(KT)^2}\right)$$

axial molecules

(B is the magnetic field, P the gas pressure and T the temperature)

Cotton-Mouton effect for several gases

- The table (from C. Rizzo, A. Rizzo and D.M.Bishop. "The Cotton-Mouton effect in gases.", Int. Rev. in Phys. Chem. (1997) vol. 16 pp. 81-111) gives an idea of the order of magnitude of the effect for several gases in terms "unit birefringence"

- The unit birefringence is defined as
$$\Delta n_u = \Delta n \left(\frac{1\ \mathrm{T}}{B\ [\mathrm{T}]} \right)^2 \left(\frac{P_{atm}}{P} \right)$$

Table 2. Experimental values of Δn_u for inorganic species.

Species	Formula	Reference	λ (Å)	T (K)	Δn_u	T range (K)
Helium[a]	He	30[b]	5145	273·15	$(1{\cdot}80 \pm 0{\cdot}36) \times 10^{-16}$ [c]	
Neon[d]	Ne	29[e]	5145	298·15	$(2{\cdot}83 \pm 0.15) \times 10^{-16}$	
Argon[f]	Ar	18[g]	5145	273·15	$(6{\cdot}8 \pm 1{\cdot}0) \times 10^{-15}$ [h]	
Krypton[i]	Kr	18	5145	273·15	$(9{\cdot}9 \pm 1{\cdot}1) \times 10^{-15}$ [h]	
Xenon[k]	Xe	18	5145	273·15	$(2{\cdot}29 \pm 0{\cdot}10) \times 10^{-14}$ [h]	
Hydrogen	H_2	23[g]	5145	273·15	$(8{\cdot}28 \pm 0.57) \times 10^{-15}$ [j]	
		25	6328	286	$(8.82 \pm 0.25) \times 10^{-15}$	187–402
Deuterium	D_2	23[g]	5145	273·15	$(7.25 \pm 0{\cdot}72) \times 10^{-15}$ [j]	
		25	6328	285	$(10{\cdot}04 \pm 0{\cdot}75) \times 10^{-15}$	285–369
Carbon monoxide	CO	6	5461	293·15	$(-2{\cdot}24 \pm 0{\cdot}45) \times 10^{-13}$	
		17	6328	294·15	$(-1{\cdot}90 \pm 0{\cdot}12) \times 10^{-13}$	203–393
		11[l]	6328	293·15	$(-1{\cdot}80 \pm 0{\cdot}06) \times 10^{-13}$	
Nitrogen	N_2	6	5461	293·15	$(-2{\cdot}47 \pm 0{\cdot}17) \times 10^{-13}$	
		11[l]	6328	293·15	$(-2{\cdot}37 \pm 0{\cdot}12) \times 10^{-13}$	
		13	6328	293·15	$(-3{\cdot}06 \pm 0{\cdot}42) \times 10^{-13}$	
		14	5145	290·15	$(-2{\cdot}56 \pm 0{\cdot}13) \times 10^{-13}$	
		16	6328	293·15	$(-2{\cdot}62 \pm 0{\cdot}08) \times 10^{-13}$	203–393
		17	6328	294·15	$(-2{\cdot}43 \pm 0{\cdot}12) \times 10^{-13}$	203–393
		29	5145	298·15	$(-2{\cdot}26 \pm 0{\cdot}10) \times 10^{-13}$	

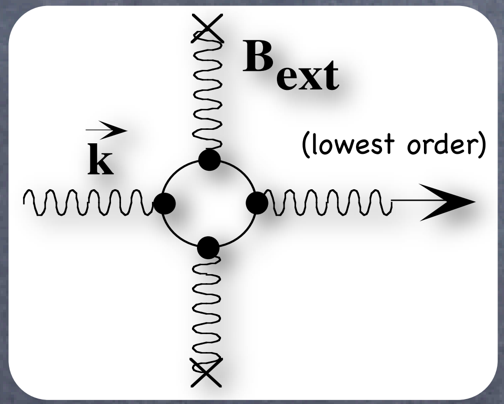
Photon-photon scattering in QED

- Non linearities in the Maxwell equations are predicted by the Heisenberg-Euler effective Lagrangian (1936).

$$L_{EH} = \frac{1}{2}\left(E^2 - B^2\right) + \frac{2\alpha^2}{45 m_e^4}\left[\left(E^2 - B^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right].$$

(in Heaviside-Lorentz natural units)

- Photon-photon scattering in QED (also Schwinger, 1951, Adler, 1971)



$$\Delta n = \frac{6\alpha^2}{45 m_e^4} B^2$$

- Polarization selective phase delay. "Detectable" as an induced birefringence on a linearly polarized laser beam propagating in vacuum in an external magnetic field

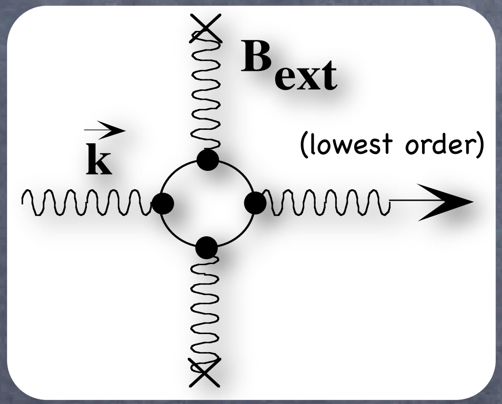
Photon-photon scattering in QED

- Non linearities in the Maxwell equations are predicted by the Heisenberg-Euler effective Lagrangian (1936).

$$L_{EH} = \frac{1}{2}\left(E^2 - B^2\right) + \frac{2\alpha^2}{45 m_e^4}\left[\left(E^2 - B^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right].$$

(in Heaviside-Lorentz natural units)

- Photon-photon scattering in QED (also Schwinger, 1951, Adler, 1971)



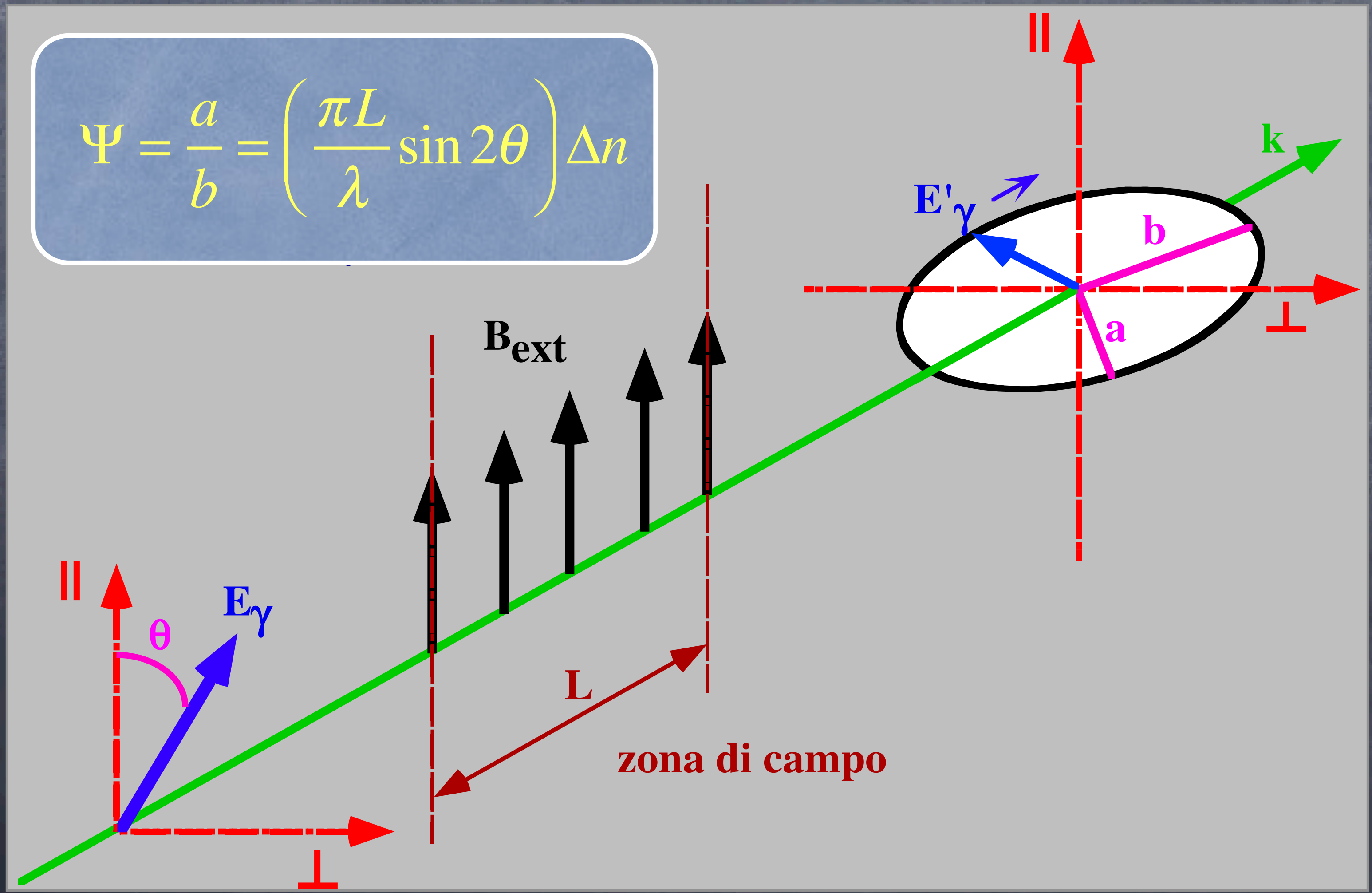
$$\Delta n = \frac{6\alpha^2}{45 m_e^4} B^2$$

- Polarization selective phase delay. "Detectable" as an induced birefringence on a linearly polarized laser beam propagating in vacuum in an external magnetic field

From birefringence to ellipticity

- The quantity that is actually measured in ellipsometry is not Δn (normally called the birefringence), but rather the ellipticity Ψ, that is the ratio of the semi-minor to the semi-major axes of the polarization ellipse

$$\Psi = \frac{a}{b} = \left(\frac{\pi L}{\lambda}\sin 2\theta\right)\Delta n$$



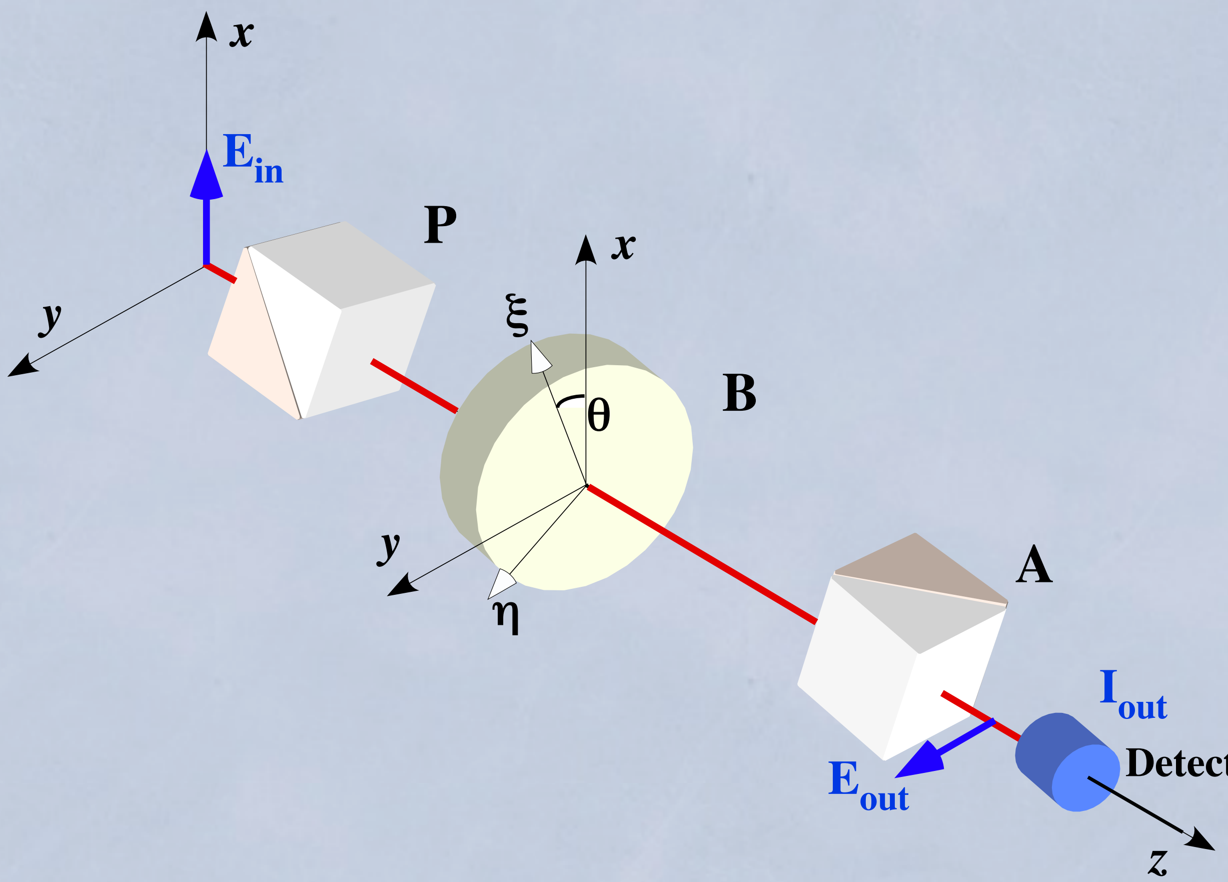
Some numbers

- Assume
  - $B = 2\ T = 390\ eV^2$ (in H.-L. units) -> a good permanent magnet
  - $L = 10^5\ m = 5 \cdot 10^{11}\ eV^{-1}$ -> a 0.5 m long magnetic zone amplified by a 200000 finesse Fabry-Perot resonator
  - $\omega = 1.17\ eV$ -> 1064 nm NdYAG laser

Gas	Δn	Ψ
Ne (1 atm)	$2.4 \cdot 10^{-15}$	$7.1 \cdot 10^{-4}$
He (1 atm)	$8.32 \cdot 10^{-16}$	$2.4 \cdot 10^{-4}$
Vacuum	$1.6 \cdot 10^{-23}$	$4.7 \cdot 10^{-12}$

Basic principle of ellipticity measurements

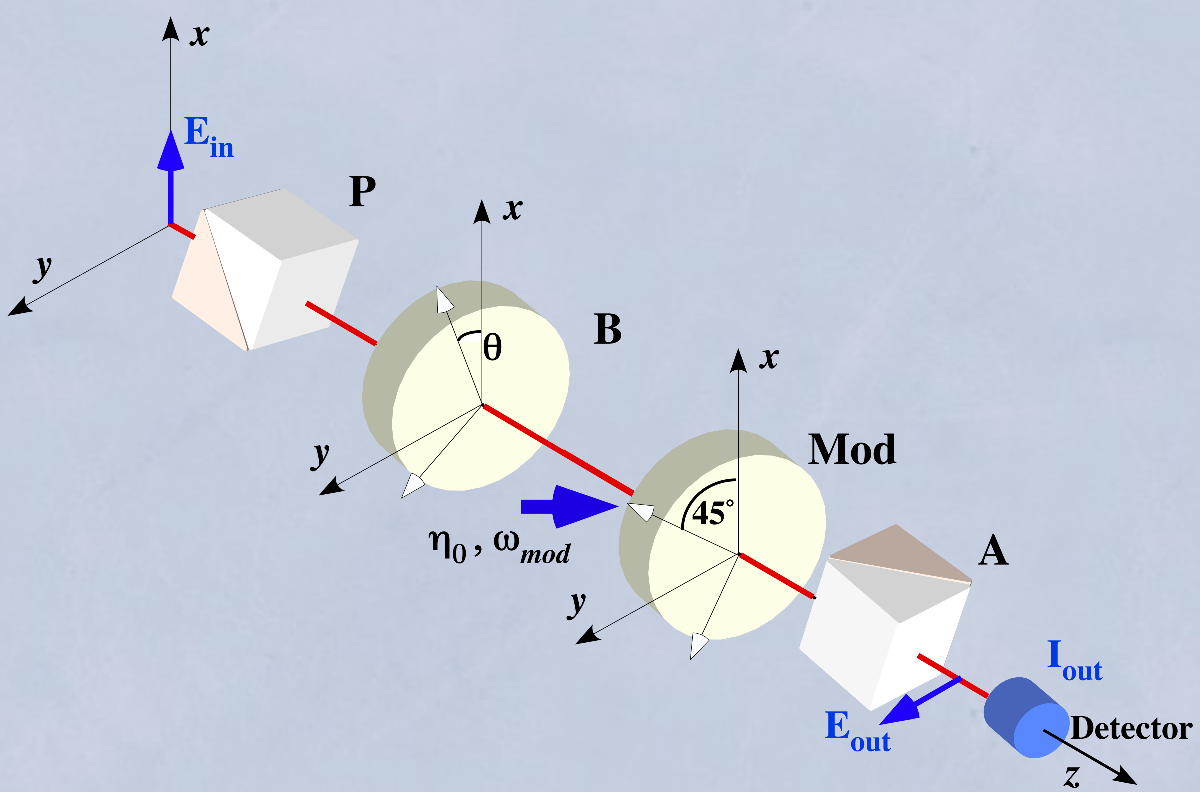
Basic principle of ellipticity measurements



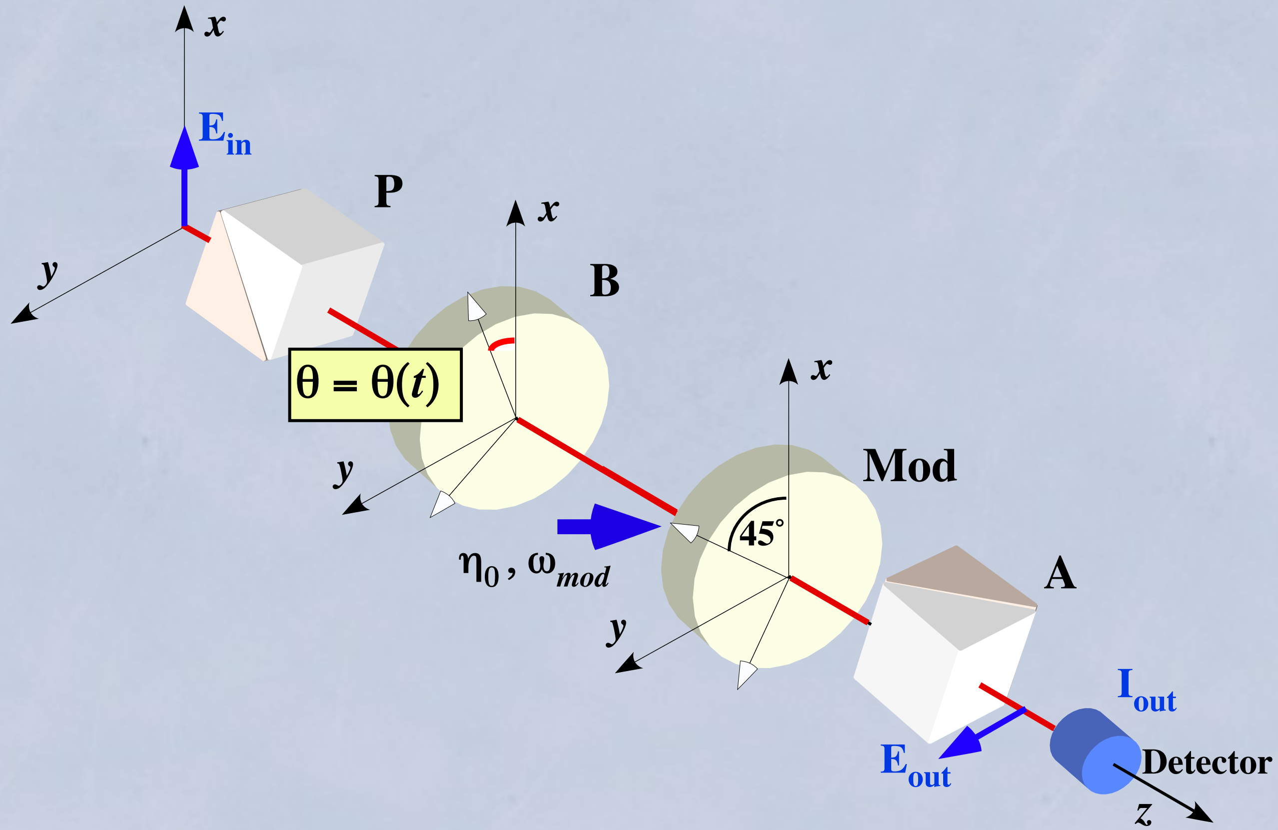
Static detection

Basic principle of ellipticity measurements

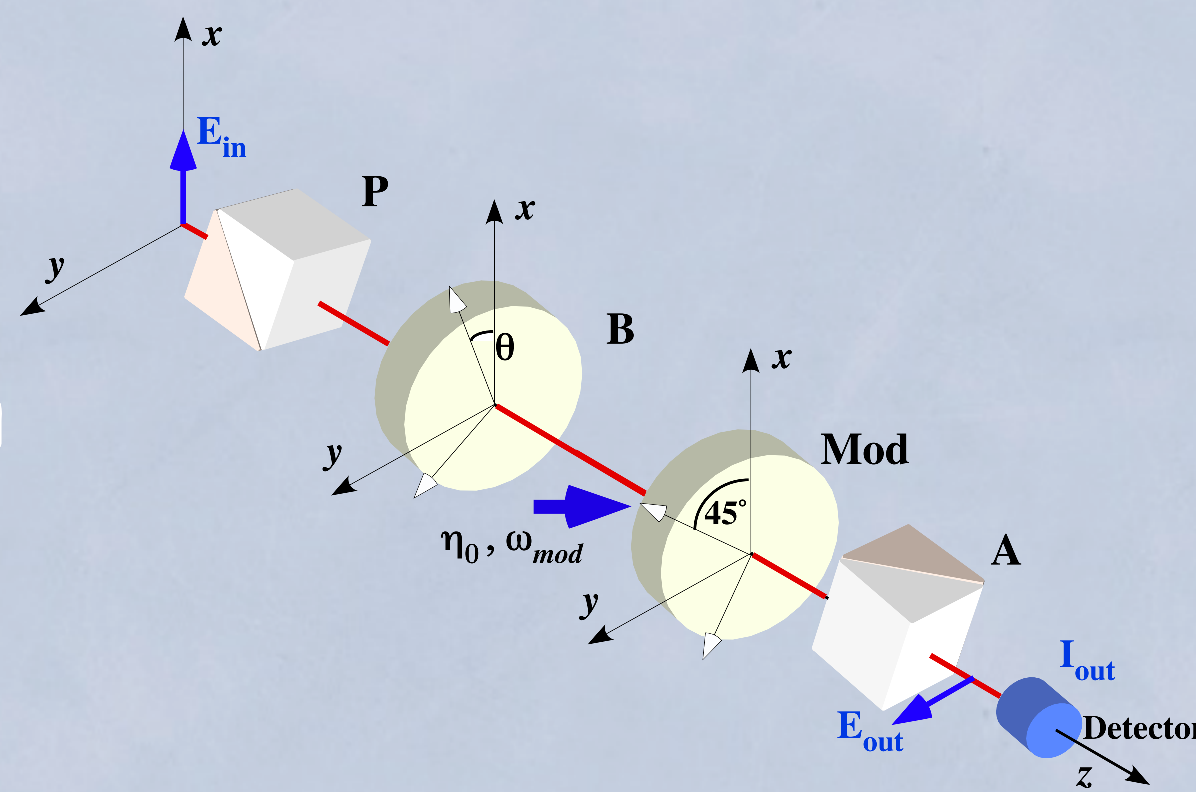
Homodyne detection



Basic principle of ellipticity measurements



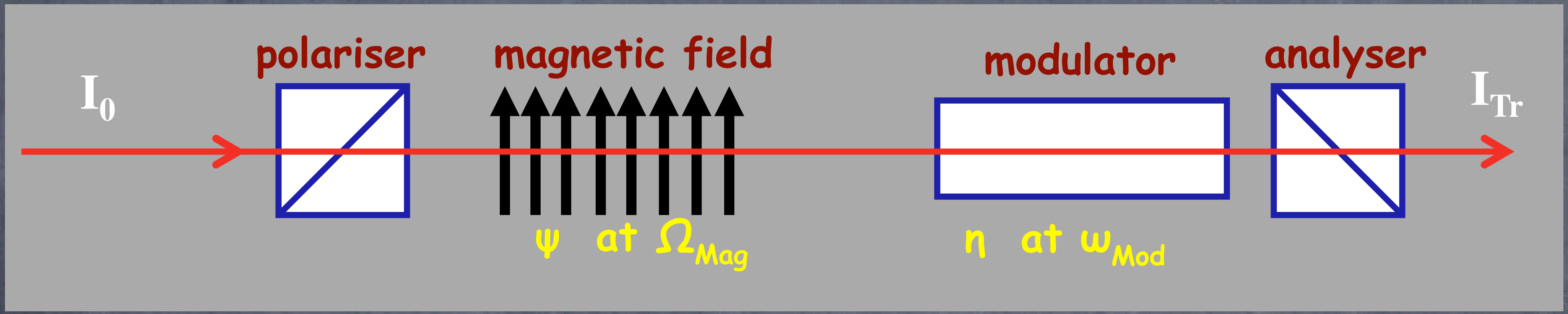
Heterodyne detection



Homodyne detection

Practical heterodyne ellipticity detection

- Static measurement is excluded: $I_{Tr} = I_0\left[\sigma^2 + \Psi(t)^2\right]$
- Solution: Modulate the effect and add a carrier $\eta(t)$ to signal at ω_{Mod}
- Keeping the initial polarization fixed and rotating the field at Ω_{Mag} produces an ellipticity at $2\Omega_{Mag}$



Ideally the transmitted intensity is given by,

$$I_{Tr} = I_0\left[\sigma^2 + \left(\Psi(t) + \eta(t)\right)^2\right] = I_0\left[\sigma^2 + \left(\Psi(t)^2 + \eta(t)^2 + 2\Psi(t)\eta(t)\right)\right]$$

The main frequency components appear at $\omega_{Mod} \pm 2\Omega_{Mag}$ and $2\omega_{Mod}$

In actual practice, nearly static spurious birefringences generate a 1/f noise at ω_{Mod}

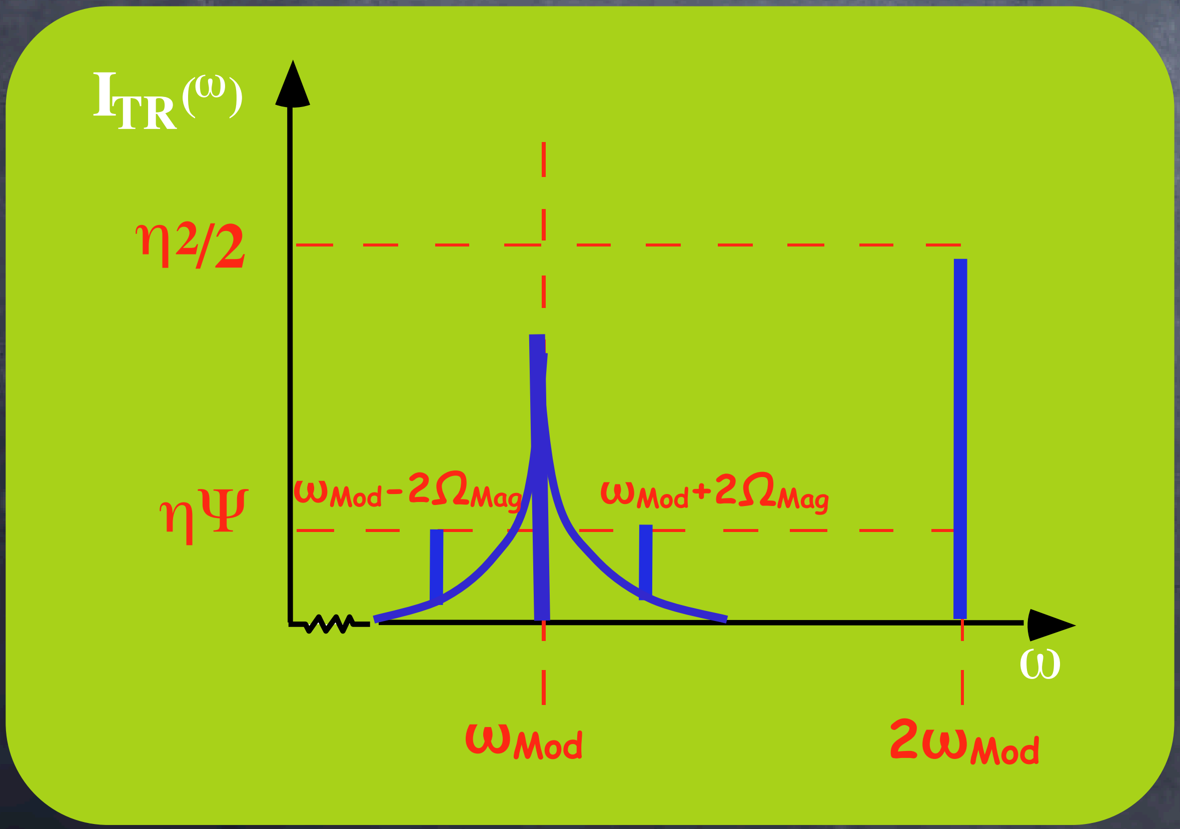
$$I_{Tr} = I_0\left[\sigma^2 + (\Psi(t)+\eta(t)+\alpha_s(t))^2\right]$$
$$= I_0\left[\sigma^2 + \left(\eta(t)^2 + 2\Psi(t)\eta(t) + \underline{2\alpha_s(t)\eta(t)} + \ldots\right)\right]$$

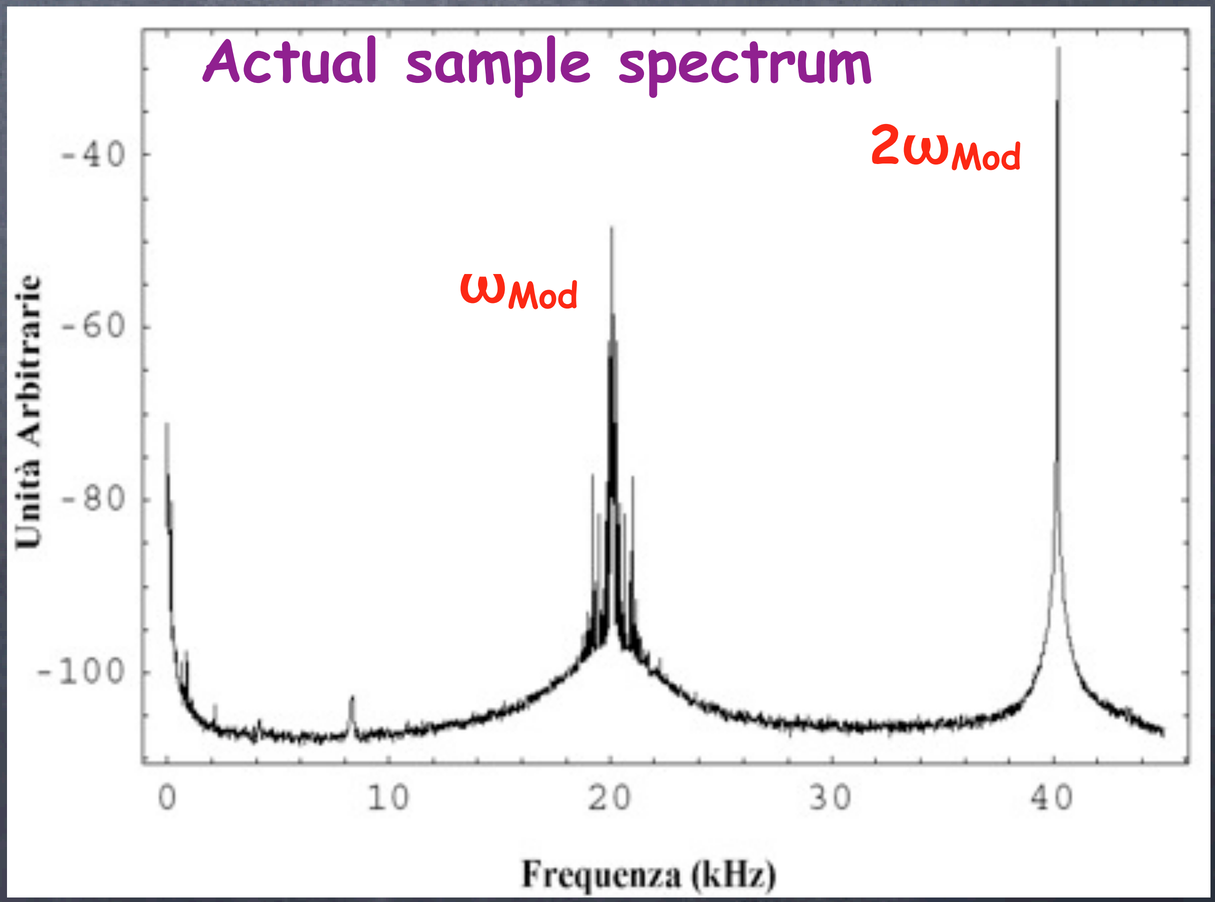
Normalization

Desired signal

Birefringence noise

- A small, time-varying signal can be extracted from a large noise background with the heterodyne tecnique





Basic features of sensitive ellipsometry

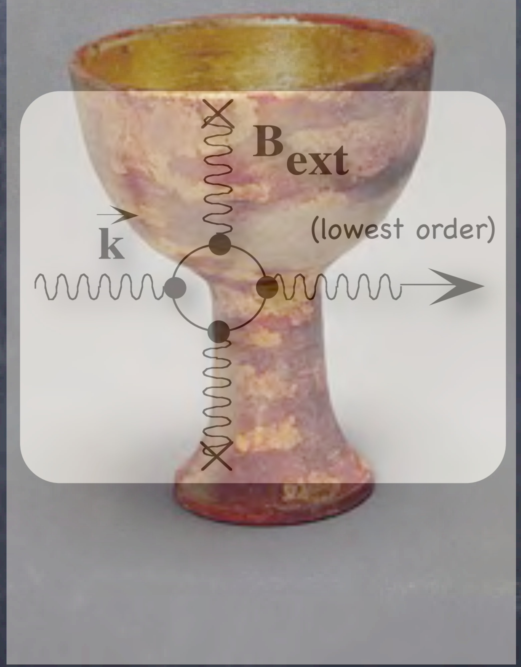
- Heterodyne detection (need modulator)
- Good extinction factor polarizers
- Control of spurious birefringences
- Amplification of optical path (need a resonant high-finesse Fabry-Perot)

Basic applications (so far...)

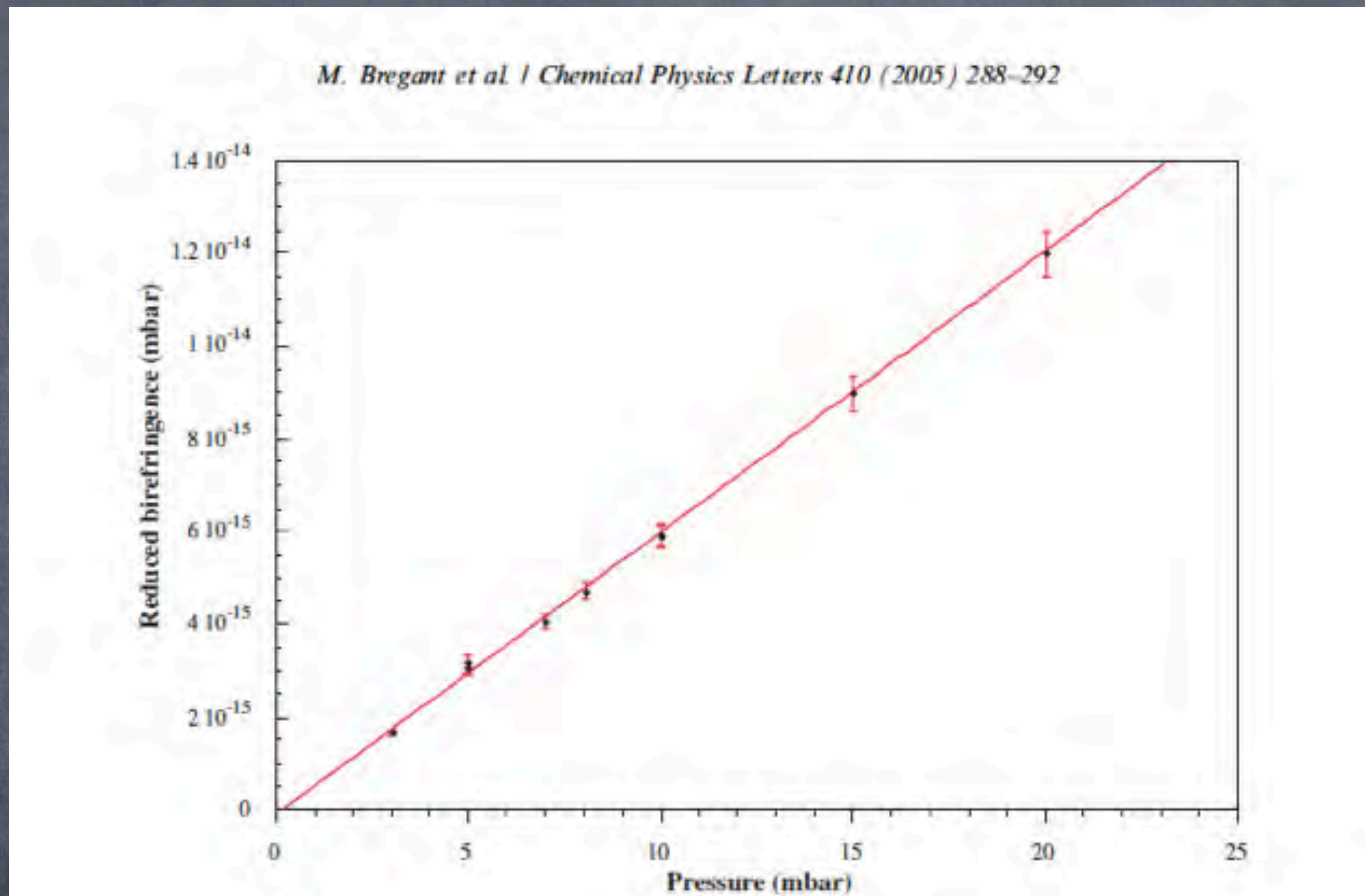
- Cotton-Mouton effect measurements
  - checks of theoretical models
  - instrument control and calibration
- QED processes in the quantum Vacuum
  - ... the Holy Grail ...

Basic applications (so far...)

- Cotton-Mouton effect measurements
  - checks of theoretical models
  - instrument control and calibration
- QED processes in the quantum Vacuum
  - ... the Holy Grail ...

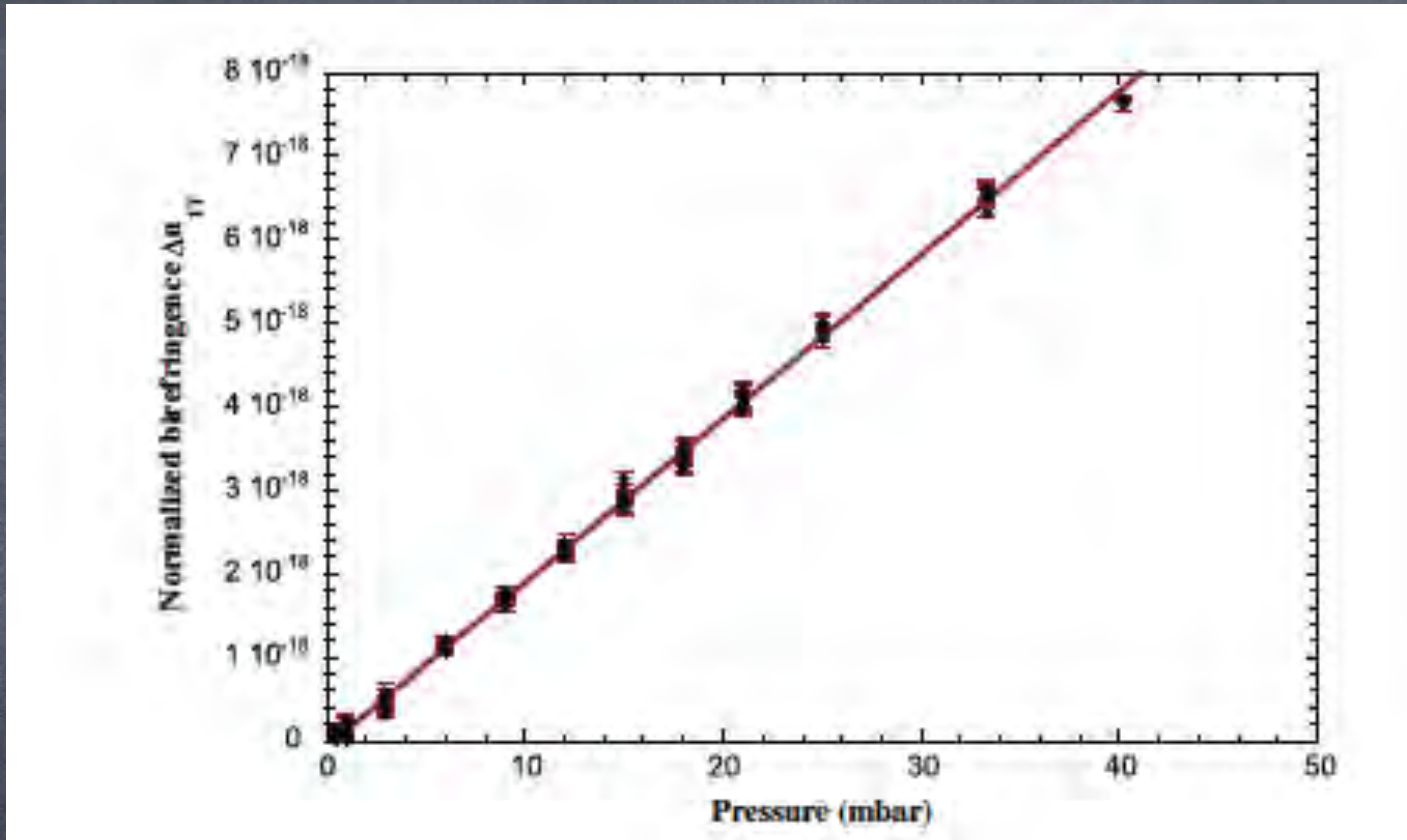


C-M of Neon vs. pressure



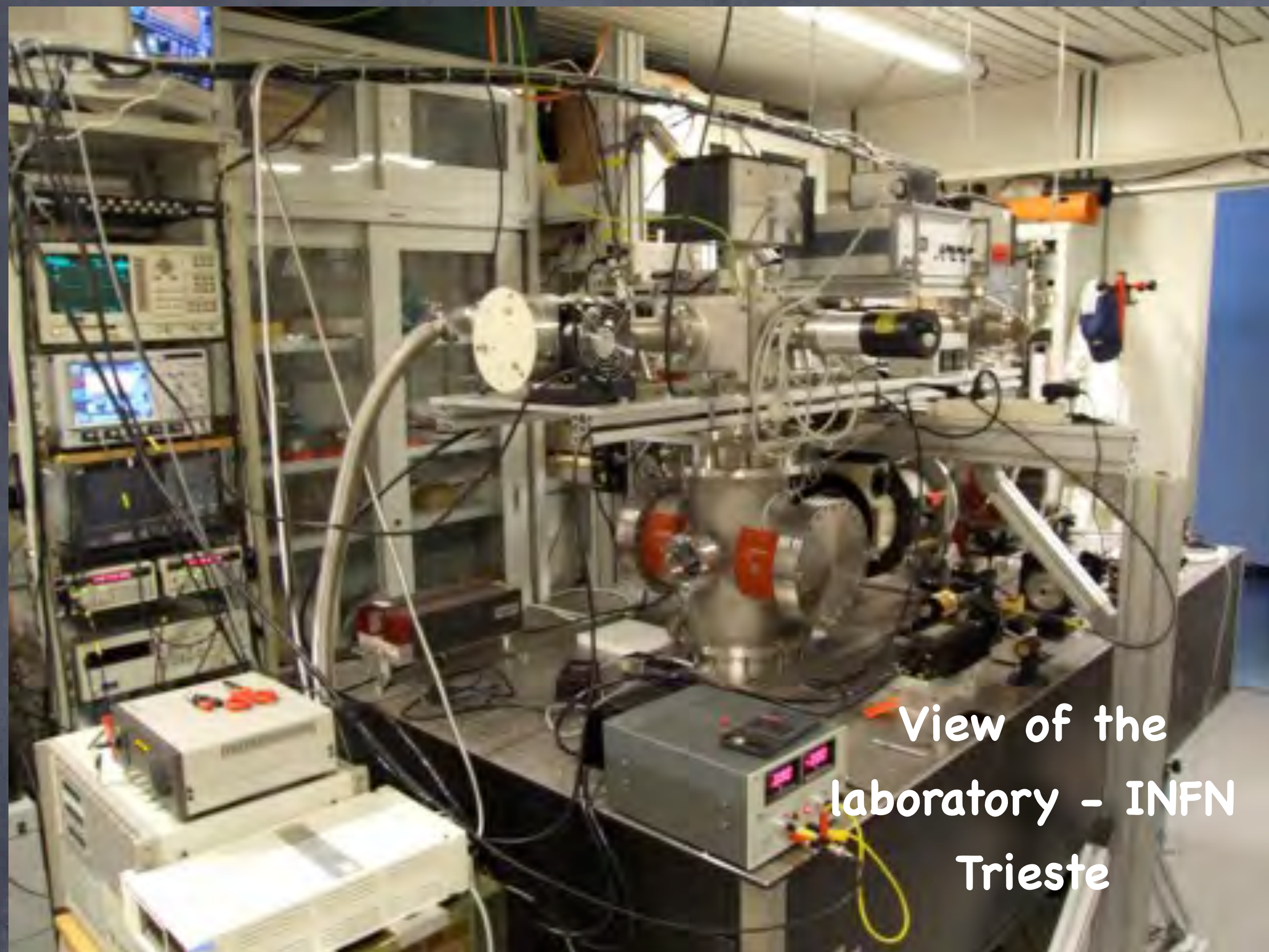
- From Bregant et al., "A precise measurement of the Cotton-Mouton effect in neon." Chemical Physics Letters (2005) vol. 410 (4-6) pp. 288-292

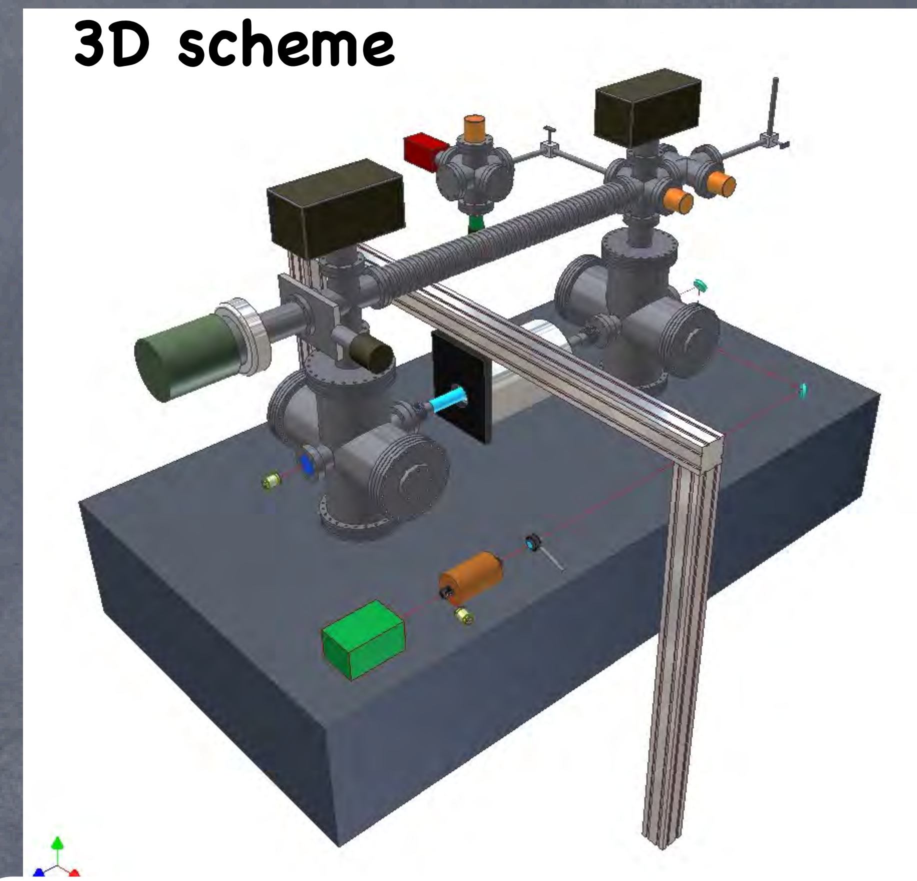
C-M of Helium vs. pressure

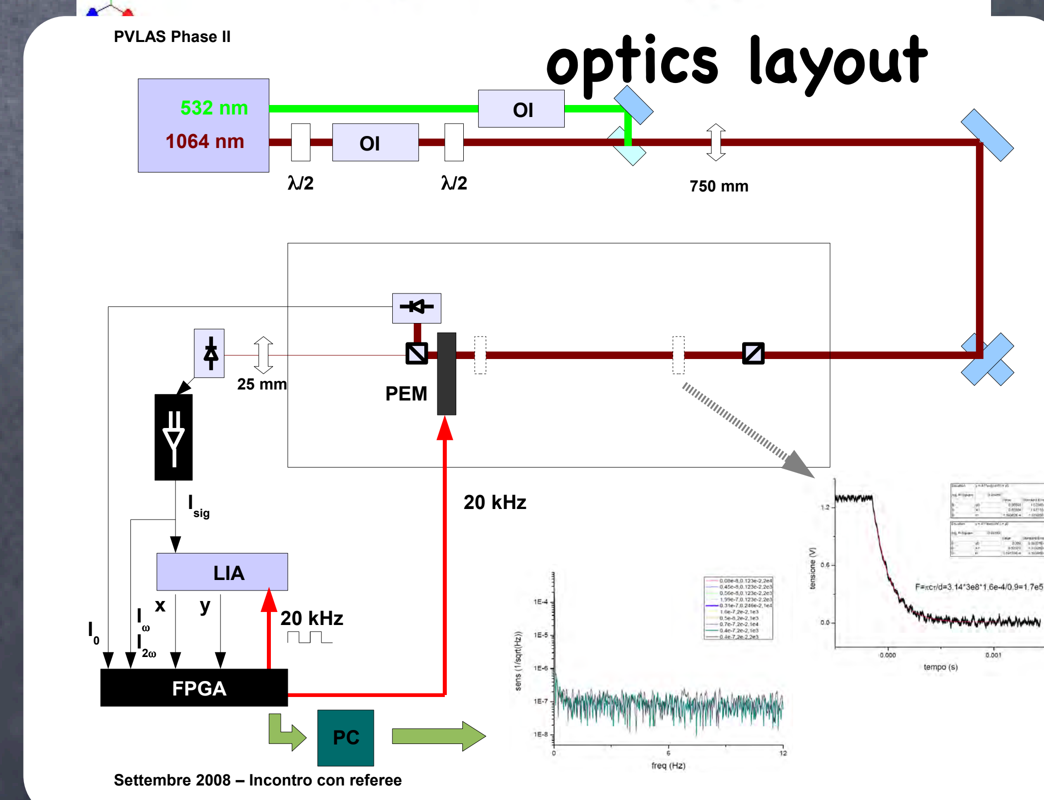


- From Bregant et al. "New precise measurement of the Cotton-Mouton effect in helium.", Chemical Physics Letters 471 (2009) 322-325

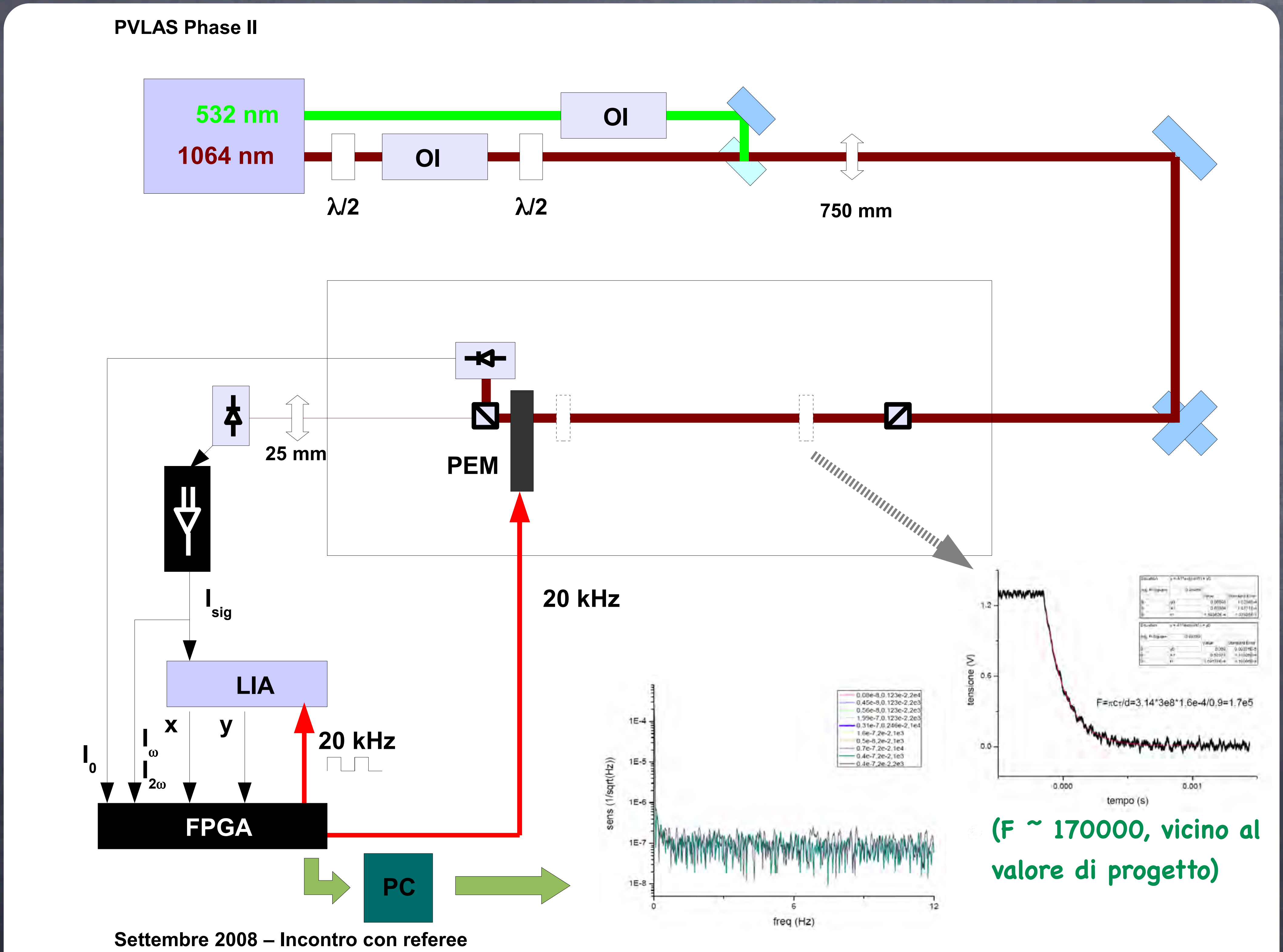
PVLAS Phase II - Table-top heterodyne ellipsometer



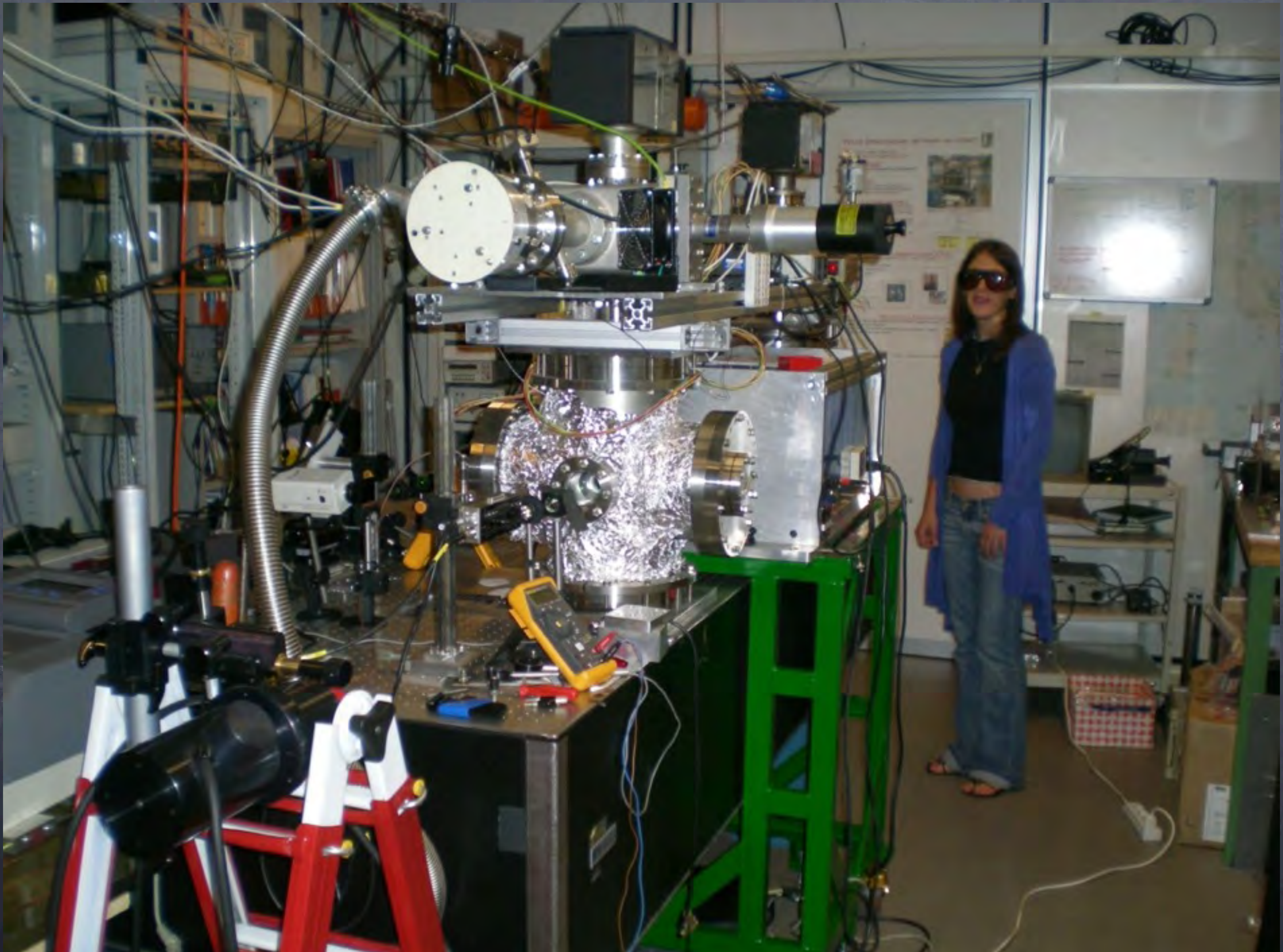




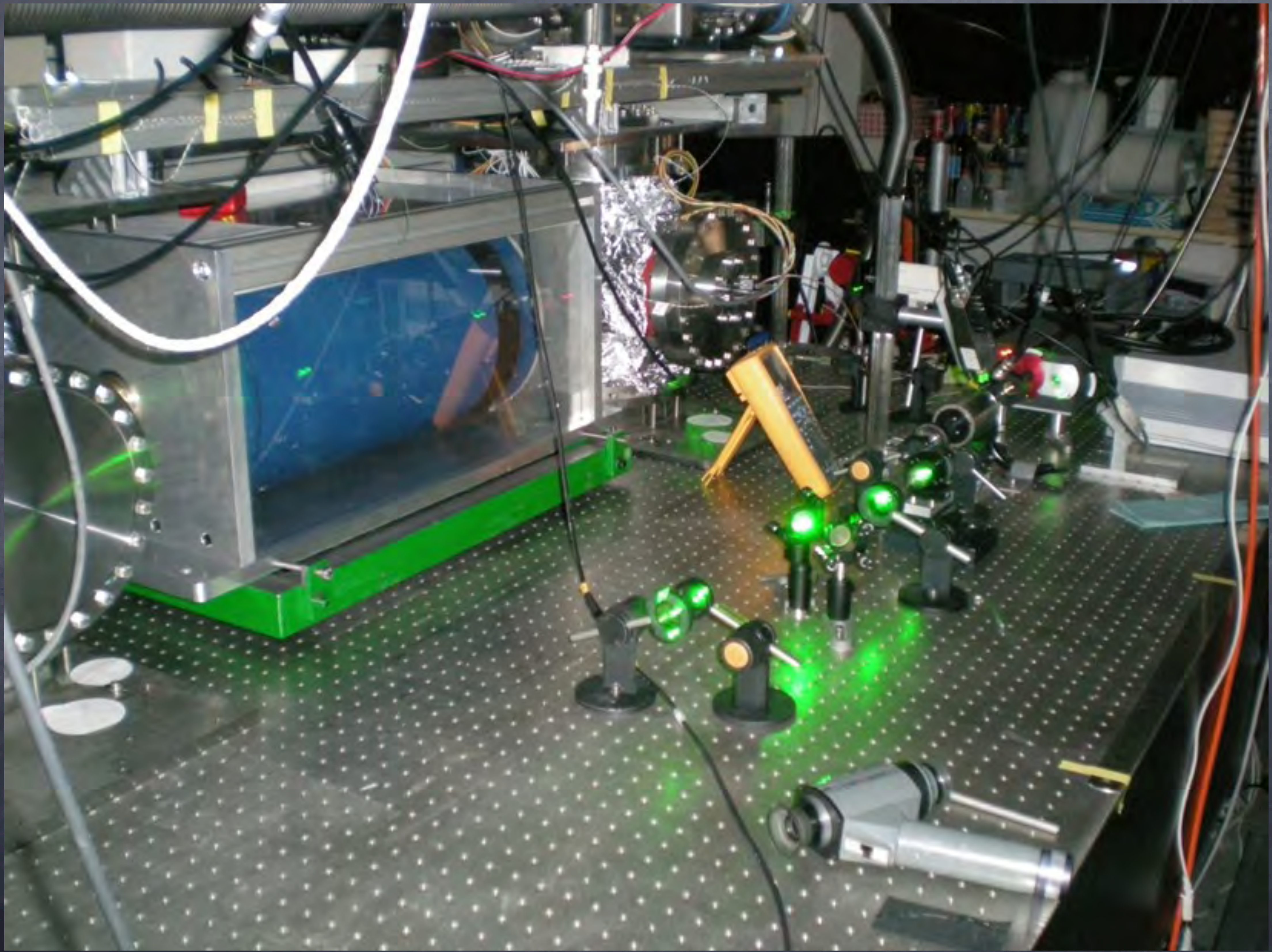
Present optics layout schematic



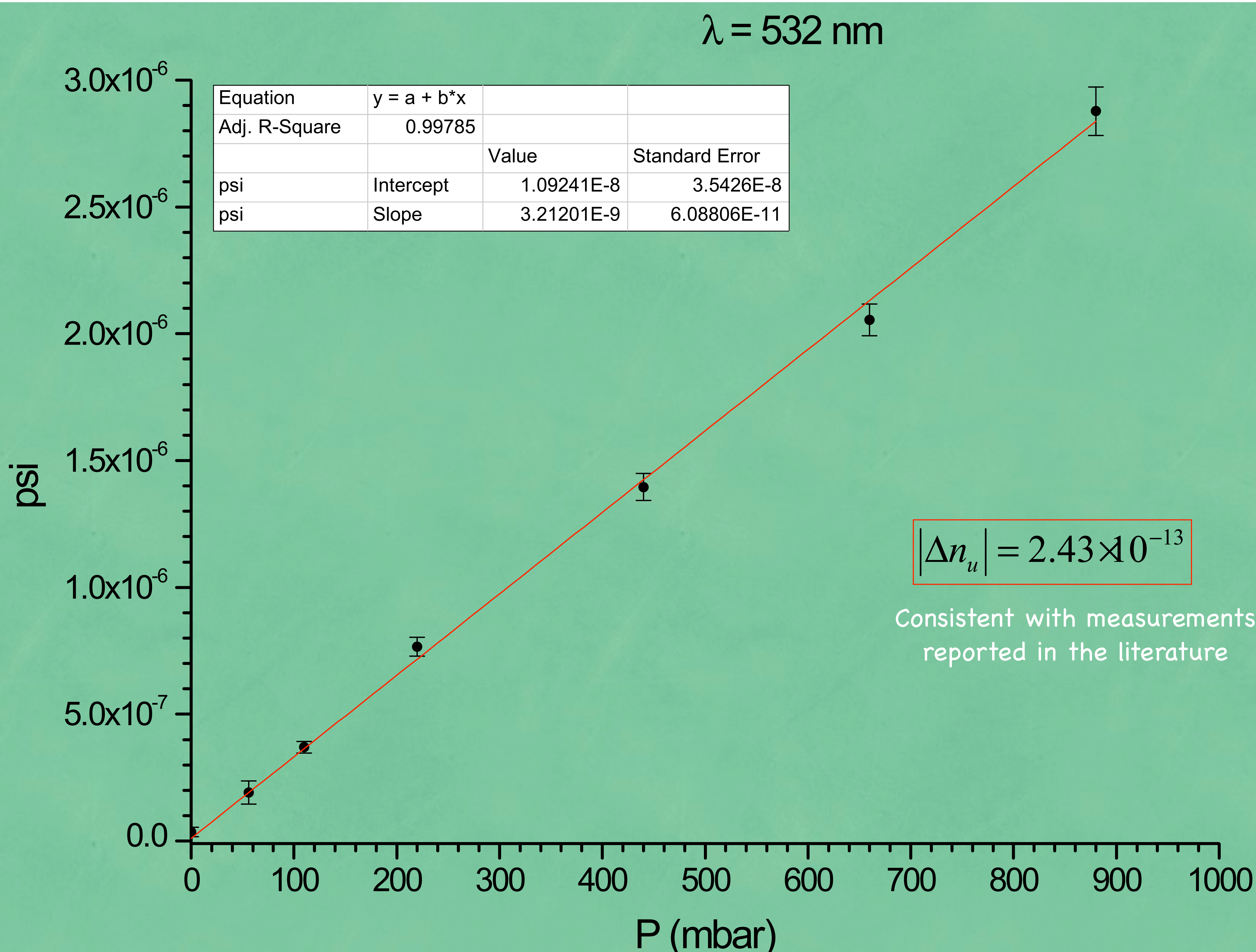
(F ~ 170000, vicino al valore di progetto)



Detail of the rotating permanent magnet



Test Cotton-Mouton measurements in Nitrogen



Equation	y = a + b*x		
Adj. R-Square	0.99785		
		Value	Standard Error
psi	Intercept	1.09241E-8	3.5426E-8
psi	Slope	3.21201E-9	6.08806E-11

$$\boxed{|\Delta n_u| = 2.43 \times 10^{-13}}$$

Consistent with measurements reported in the literature

PVLAS Phase II ellipsometer development stages

- **Prototype (already existing)**
  - 900 mW at 1064 nm, 20 mW at 532 nm
  - Mirror Integrated Modulator
  - 1 m long Fabry-Perot with F≈220000
  - 2.3 T, 50 cm long, permanent dipole magnet
  - analog frequency locking, environmental screens
- **Advanced**
  - intensity stabilization to reduce laser Residual Intensity Noise
  - birefringence modulation directly on cavity mirrors
  - low noise electronics
  - digital frequency locking, improved acoustic isolation
- **Advanced Power Upgrade**
  - 600 mW at 532 nm
  - light injection and extraction via optical fiber

Config.		IR		GREEN		
		Prototype	Advanced	Prototype	Advanced	Adv. power upg.
	Sens. $[1/\sqrt{\mathrm{Hz}}]$	10^{-8}	$6 \cdot 10^{-10}$	10^{-8}	$6 \cdot 10^{-9}$	10^{-9}
	Min. det. angle in 400 std. days	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-13}$	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-12}$	$3 \cdot 10^{-13}$
One magnet 2.3 T, L = 0.5 m	ψ^0_{QED}	$3.1 \cdot 10^{-17}$	$3.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$
	ψ_{QED} (F=220000)	$4.3 \cdot 10^{-12}$	$4.3 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$
	Min. meas. time (std. 8-hr. days)	188	0.675	47.1	16.9	0.471
Two magnets 2.3 T, L = 0.5 m	ψ^0_{QED}	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$
	ψ_{QED} (F=220000)	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$1.7 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$
	Min. meas. time (std. 8-hr. days)	47.1	0.169	11.7	4.2	0.12

Table IV: Minimum measurement times necessary to detect QED photon-photon scattering for several apparatus configurations.

Conclusions

- Precision optical polarimetry is a sophisticated technique requiring the integration of different areas of competence
- Once mastered it provides a powerful way to investigate optically active media and offers a sensitive diagnostic tool
- The study of the magnetic birefringence of gases is a traditional field of application
- The present (and future!) challenge is honing the technique to reach the necessary sensitivity to attack QED microscopic processes, bringing particle physics back to the table-top environment