Vacuum magnetic birefringence

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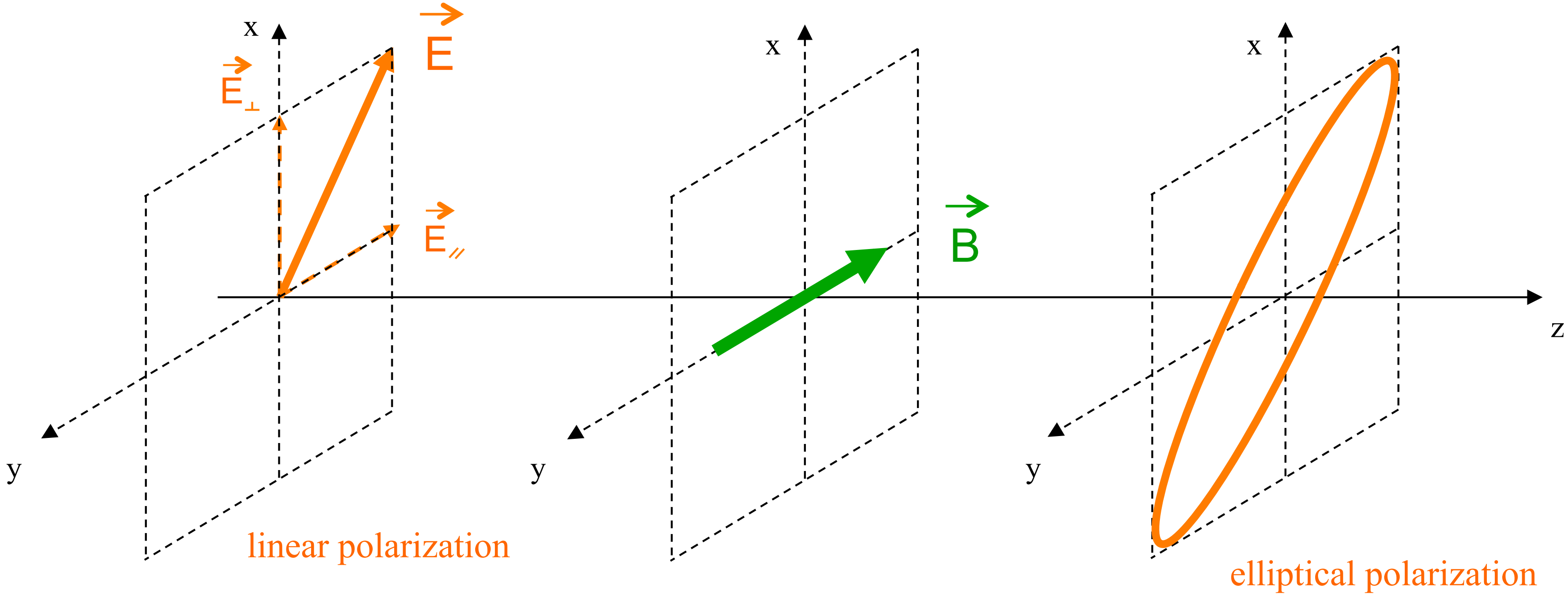

Magnetic linear birefringence

Cotton-Mouton effect

Voigt effect

$$\Delta n = (n_{//} - n_{\perp}) \alpha \ \mathbf{B^2}$$

- This effect exists in any medium

R. Battesti and C. Rizzo, Rep. Prog. Phys. ***76****, 016401 (2013)*

- QED theory predicts that this effect also exists in vacuum
    - Due to the creation of virtual positron-electron pairs
      → *nonlinear interaction between electromagnetic fields*
    - Calculated in the 70s :

$$\Delta n = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4 c^5}\left(1+\frac{25}{4\pi}\alpha\right)\frac{B^2}{\mu_0}$$

At the lowest orders in α

Fondamental constants : Codata 2010

$$\Delta n = \left[(4.031699 \pm 0.000005)\times 10^{-24}\right]\left(\frac{B}{1\,\mathrm{T}}\right)^2$$

O(α^3)

O(α^4) **?**

O(α^5) **?**

Δn measurement to a few ppm

⇕

Pure QED test

Z. Bialynicka-Birula and I. Bialynicki-Birula, Phys. Rev. D ***2****, 2.34 (1970)*
V. I. Ritus, Sov.Phys. JETP ***42****, 774 (1975)*

A bit of history of experiments on vacuum magnetic birefringence

1979 Iacopini & Zavattini proposal

1993 BRFT experiment final results

1991 … PVLAS experiment

1996 … Q&A experiment

2000 … BMV experiment

2006… OSQAR experiment

2006 PVLAS signal ?… Not an axion !

2008, 2012 … PVLAS results

2013 BMV results

R. Battesti and C. Rizzo, Rep. Prog. Phys. ***76****, 016401 (2013)*

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In summary :

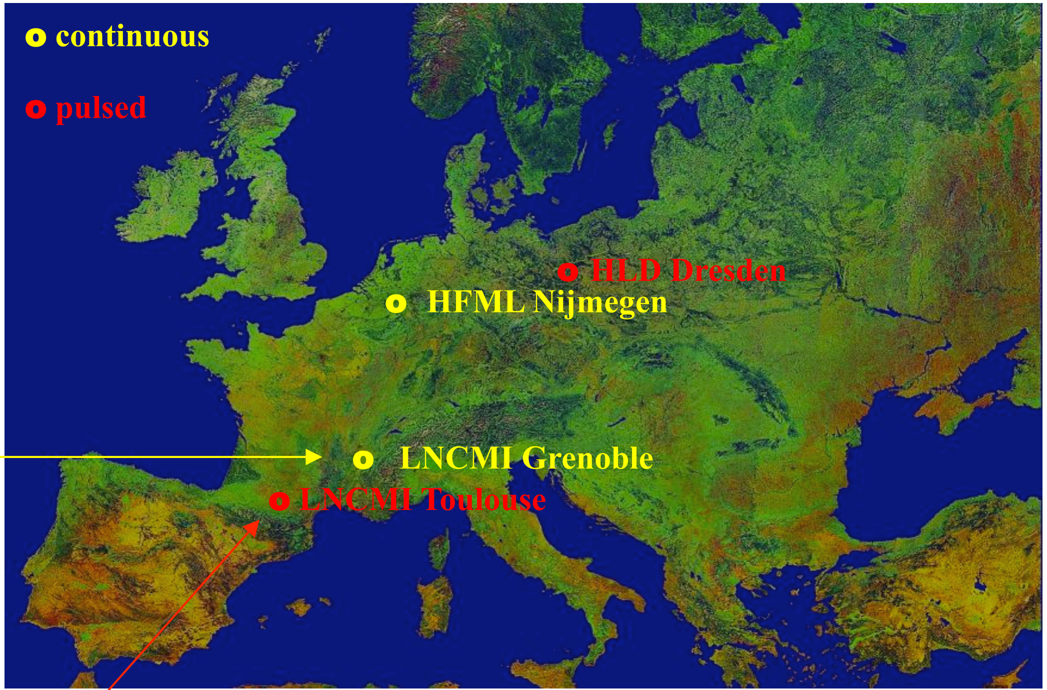
$$\Delta n = k_{\mathrm{CM}}\, B^2 \qquad \text{with} \qquad k_{\mathrm{CM}} \approx 4.10^{-24}\ \mathrm{T}^{-2}$$

Not yet experimentally observed

- BMV project at the LNCMI of Toulouse, France

A table top very sensitive ellipsometer coupled with pulsed magnetic fields

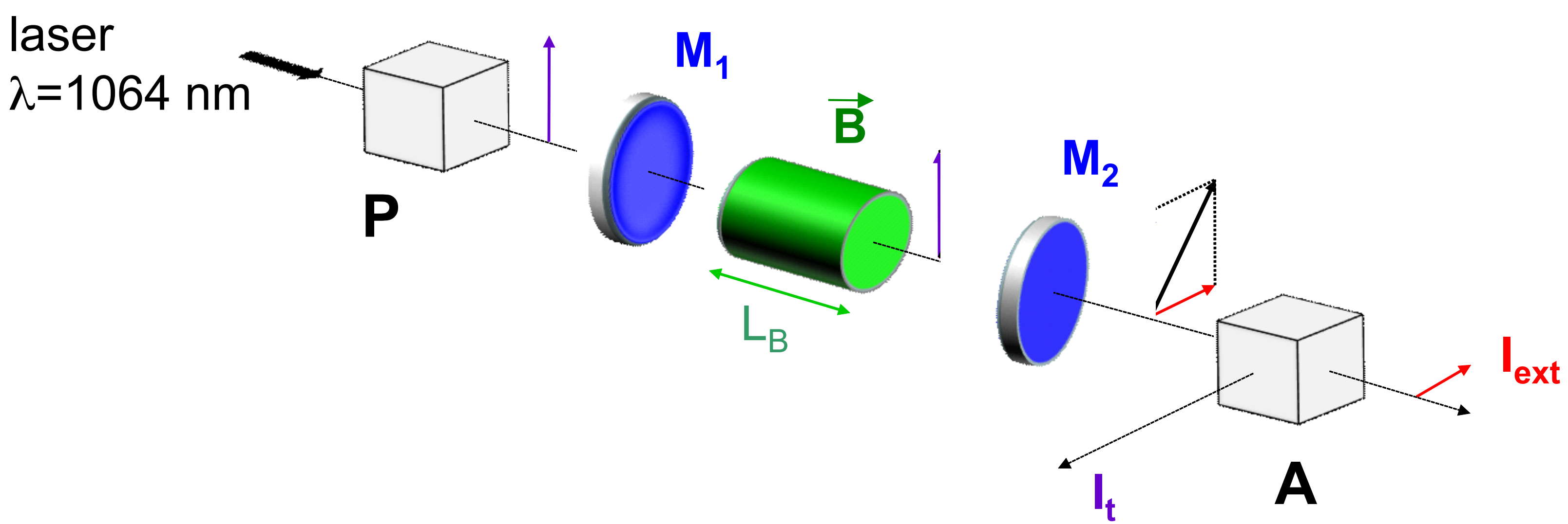
Laboratoire
National des
Champs
Magnétiques
Intenses



Member of the EMFL

European **M**agnetic **F**ield **L**aboratory
with the HFML of Nijmegen
and the HLD of Dresden.

The ellipsometer



- P and A : polarisers crossed at maximum extinction
- Ellipticity :

$$\Psi = \frac{\pi}{\lambda} k_{CM} \left(\frac{2F}{\pi}\right) B^2 L_B$$

- Key elements :

  ⇨ Magnetic field : special magnets developed at LNCMI to have a B^2L_B as high as possible

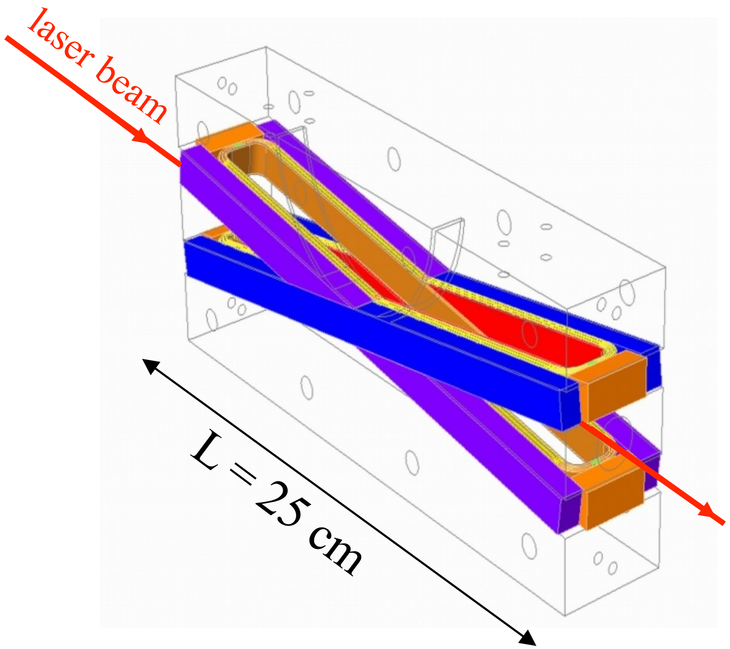
  ⇨ Fabry-Perot cavity : to increase the optical path in B

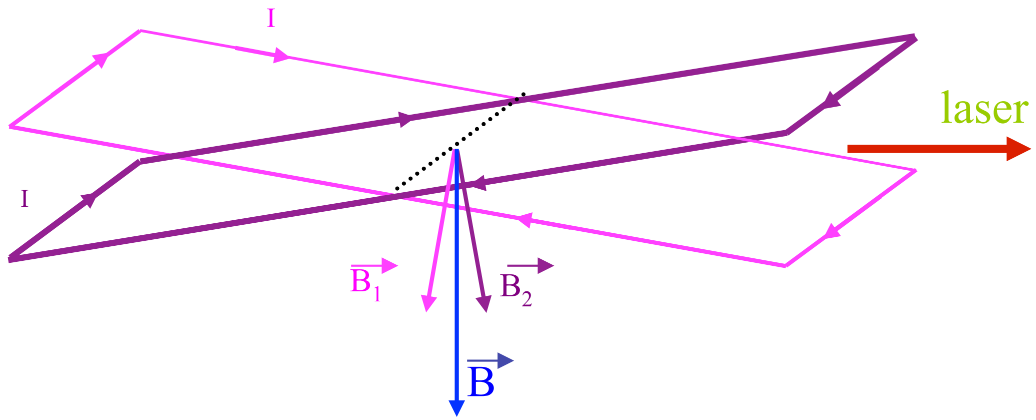
R. Battesti et al., EPJD ***46****, 323 (2008)*

Pulsed transverse magnetic field

X coil geometry ⇒ high transverse magnetic field

Unconventional pulsed magnets developed at LNCMI



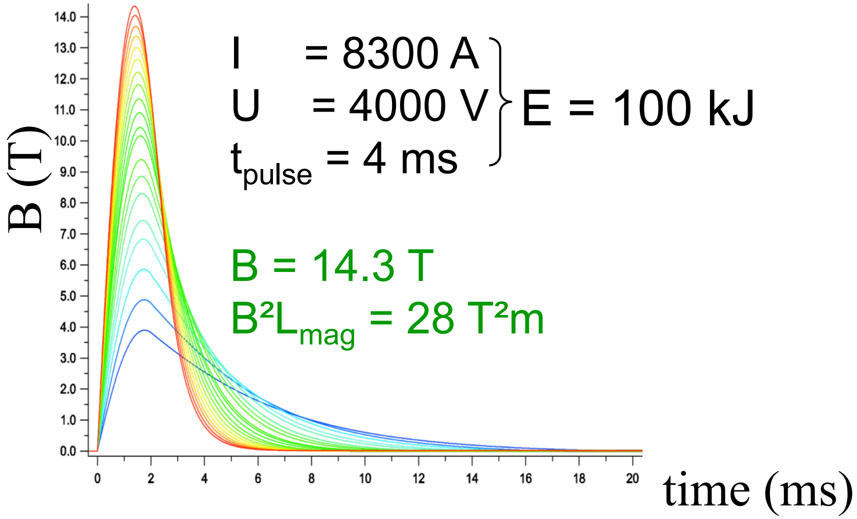


Voigt configuration

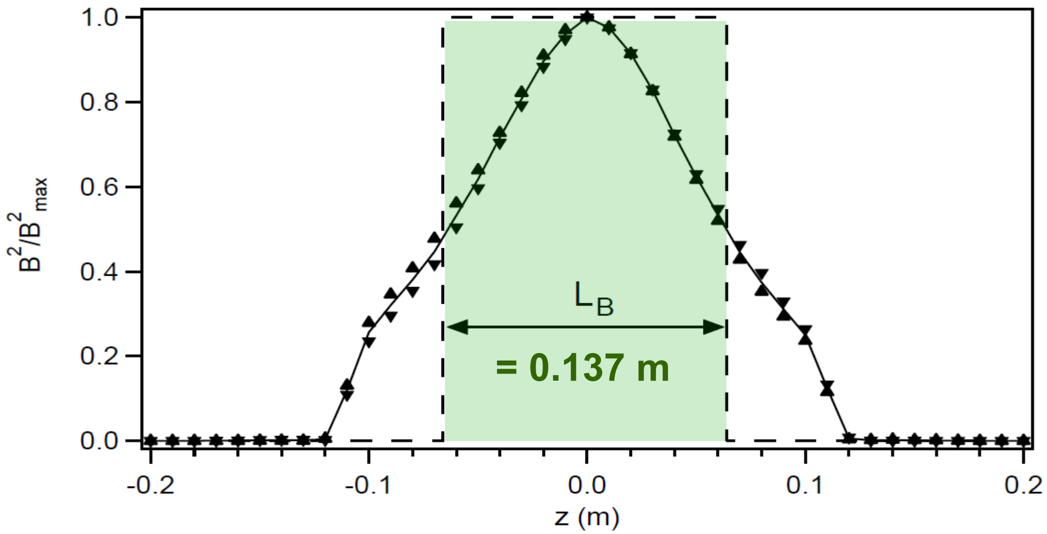
*R. Battesti et al., EPJD **46**, 323 (2008)*

Pulsed transverse magnetic field

- Time evolution:



- Longitudinal profile:

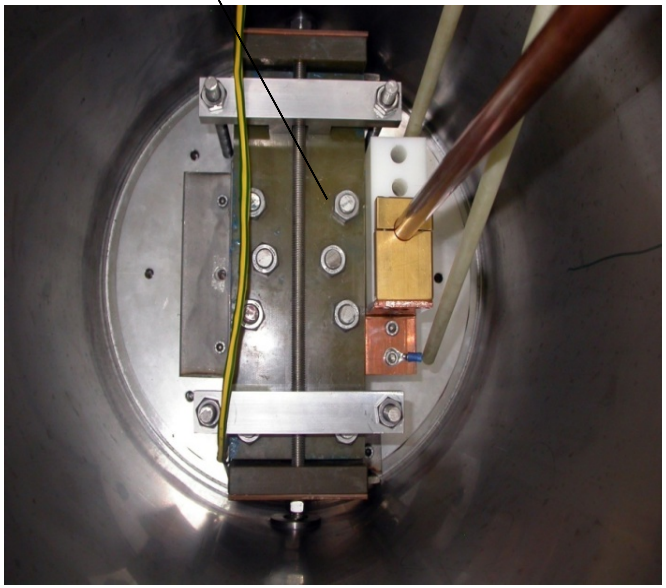


Currently:

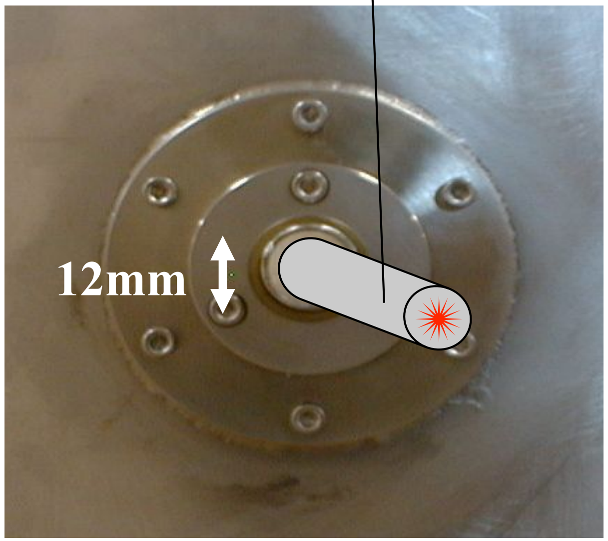
$B_{max} = 6.5$ T

$B^2_{max} L_B = 5.7$ T^{2}m

External reinforcement to contain the magnetic pressure



Hole to let the laser in

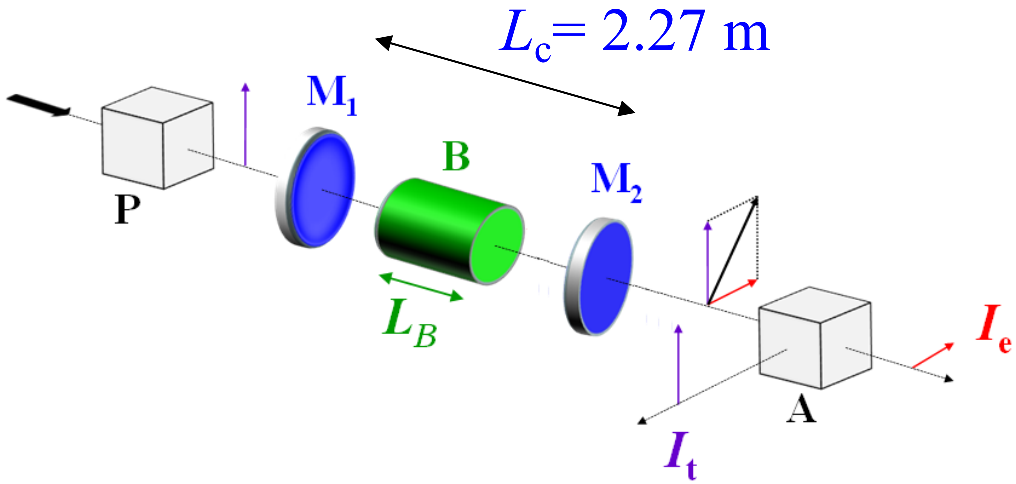


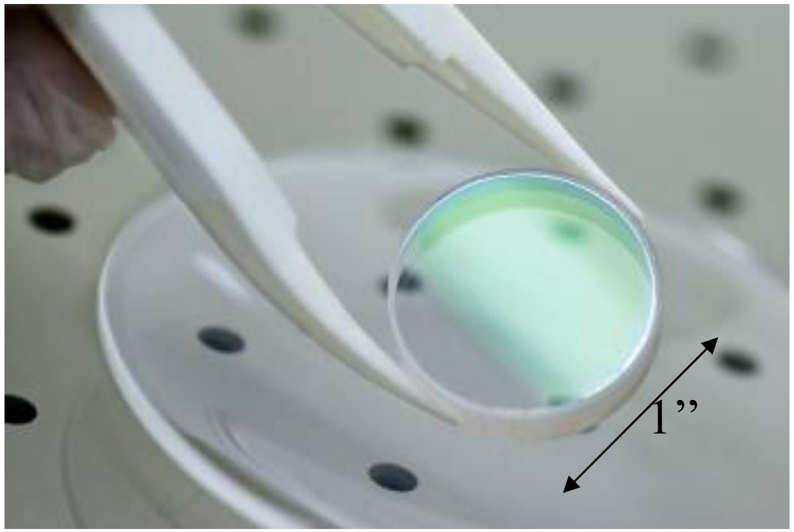
Immersion in liquid nitrogen to avoid consequences of heating

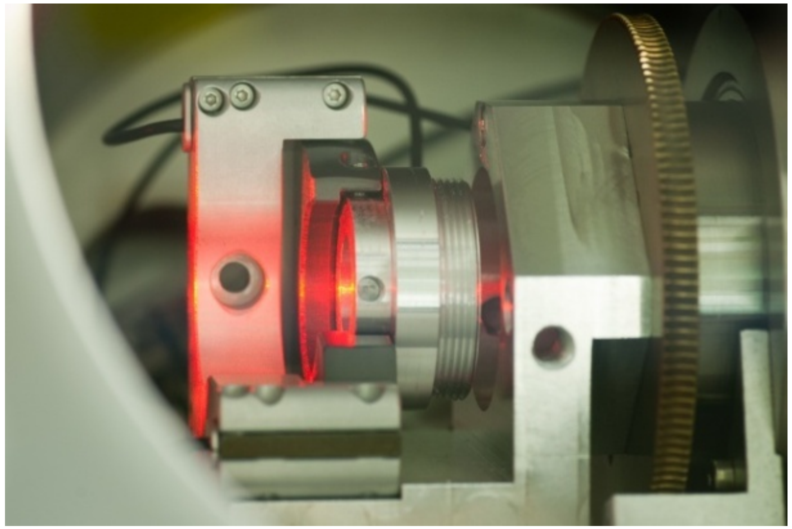
The Fabry-Perot cavity

- Ellipticity :

$$\Psi = \frac{\pi}{\lambda} k_{\mathrm{CM}} \left(\frac{2\,F}{\pi} \right) B^2 L_B$$



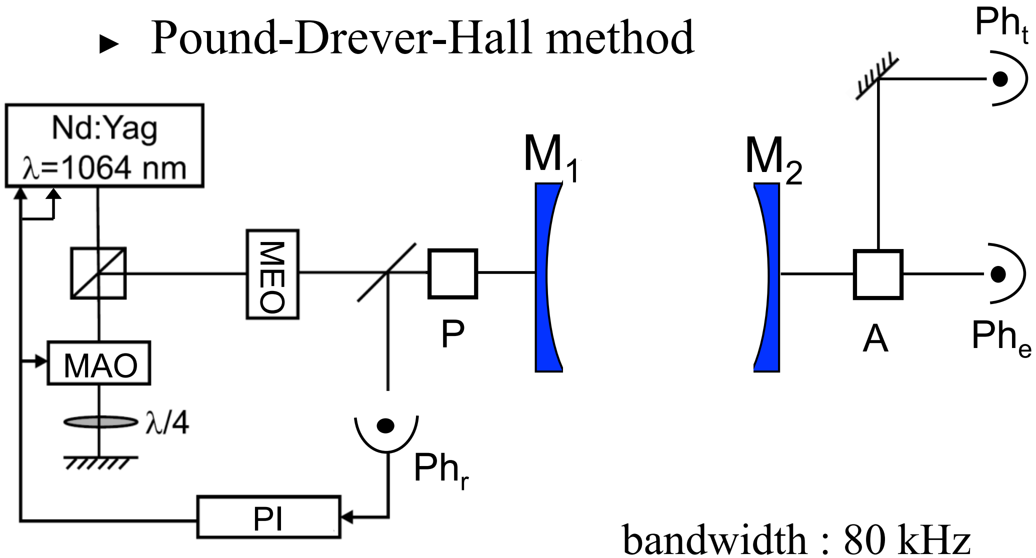


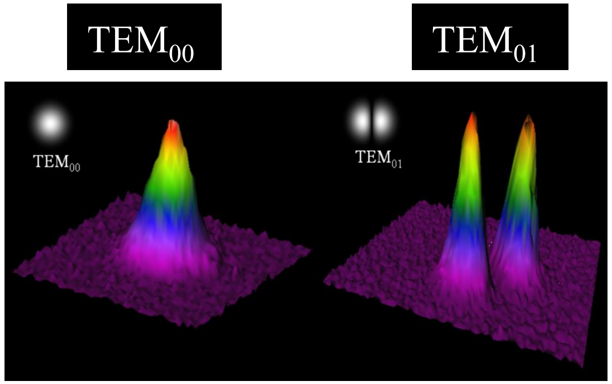


ATFilms Precision Optics, Technical Solutions

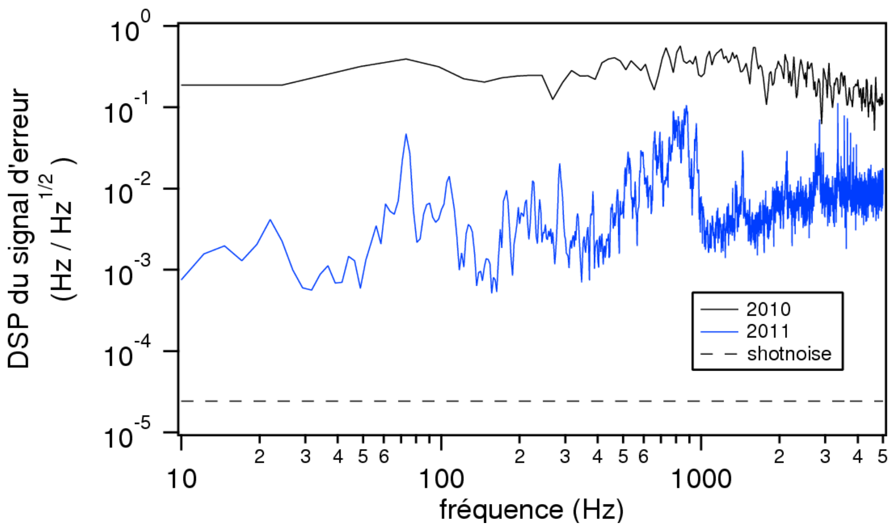
Locking of the laser on the cavity

- Pound-Drever-Hall method





bandwidth : 80 kHz

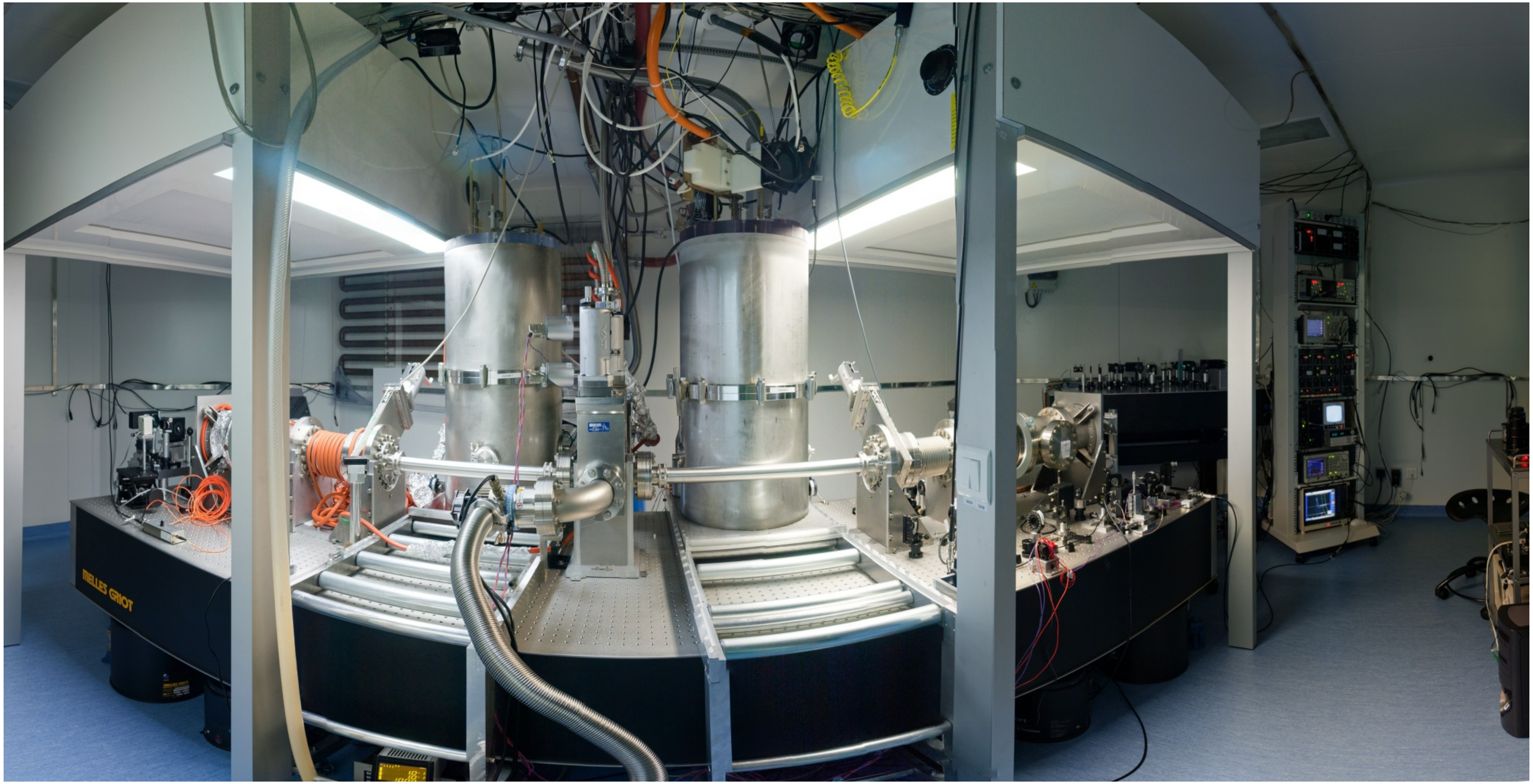


➡ in 1s, correction of laser frequency (2.8.10^{14} Hz) of **0.02 Hz**

⇔ $\Delta L_c < 1$ **fm**

	VIRGO	PVLAS	aLIGO	BMV Biréfringence Magnétique du Vide
L_c	3 km	6.4 m	4 km	2.27 m
τ	159 ms	442 ms	970 ms	1.08 ms
$F = \frac{\pi c \tau}{L_c}$	50	70 000	230	450 000
$\Delta\nu = \frac{c}{2 L_c F}$	1 kHz	360 Hz	164 Hz	147 Hz

➡ One of the **sharpest** cavities of the world high reflectivity mirrors → experiment mounted in a **clean room**

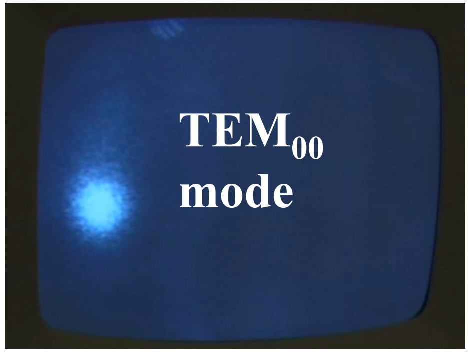


NB: Magnets removed from light path

Data acquisition

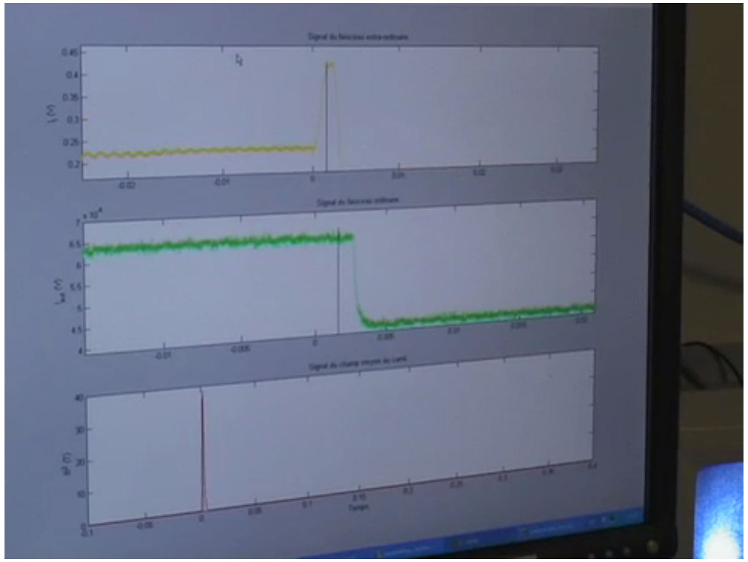
Alignment of the cavity mirrors

Laser locked on the cavity

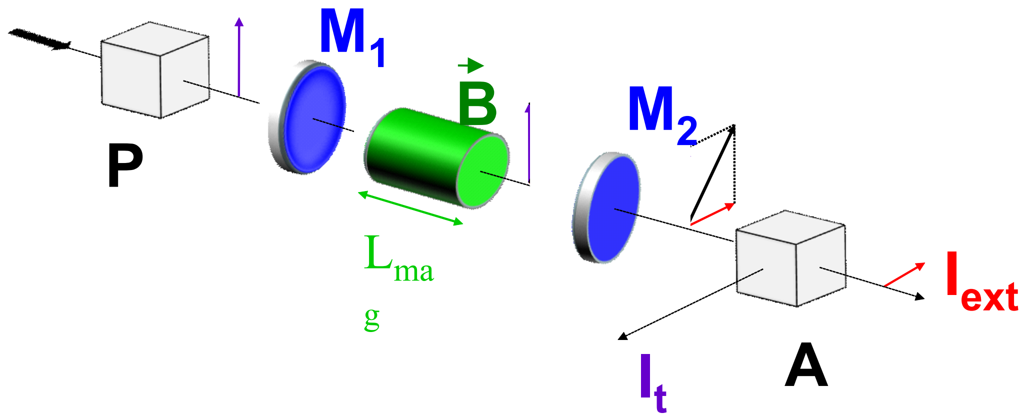


Shot

Data analysis



- Both signals I_t and I_{ext} are used:



$$\frac{I_{ext}}{I_t} = \sigma^2 + \left[\Psi(t) + \Gamma\right]^2$$

polarizers extinction
≈ 4.10^{-7}

Cavity static ellipticity
≈ 10^{-6}

$$\sigma^2 = \left(\frac{I_{ext}}{I_t}\right)_{\text{without cavity}}$$

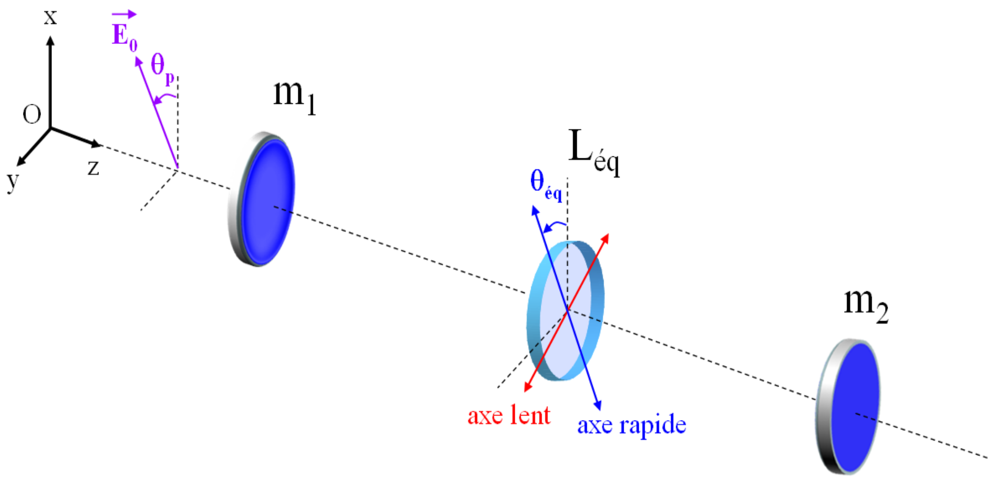
Ellipticity to be measured, proportional to B²(t)

$$\frac{I_{ext}}{I_t} \approx \sigma^2 + \Gamma^2 + 2\Gamma\Psi(t) \quad \text{for} \quad \Psi \ll \Gamma$$

F. Bielsa, *et al.*, Appl. Phys. B **97**, 457 (2009)

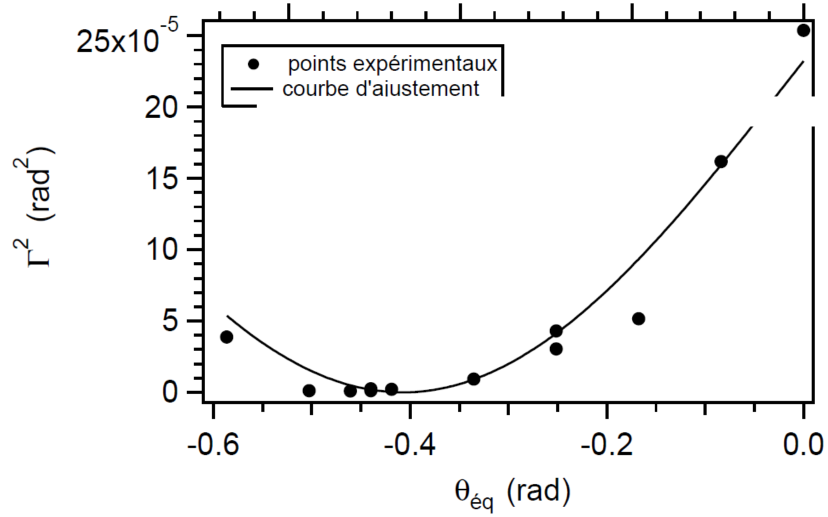
Γ = Static ellipticity of the cavity

$$|\Gamma| = \sqrt{\left\langle \frac{I_e}{I_t} \right\rangle_{\text{before pulse}} - \sigma^2}$$



$$\Gamma = \frac{F}{\pi}\delta_{éq}\sin 2\left(\theta_{éq} - \theta_p\right)$$

Γ can be tuned by turning both M_1 and M_2 :



$\delta_{éq} = (7.8 \pm 0.4)\times 10^{-8}$ rad $\qquad \theta_p = (66 \pm 2)°$

➡ typically, $\Gamma \sim 8\times10^{-3}$ rad

Data analysis : the simplest case i.e. « big signals »

$$\frac{I_{ext}}{I_t} \approx \sigma^2 + \Gamma^2 + 2\Gamma\Psi(t) \qquad \text{for} \qquad \Psi << \Gamma$$

$$\Rightarrow \quad Y(t) = \frac{\frac{I_e}{I_t} - \sigma^2 - \Gamma^2}{2|\Gamma|} = \gamma\,\Psi(t) \quad \text{with } \gamma = \text{sign of } \Gamma$$

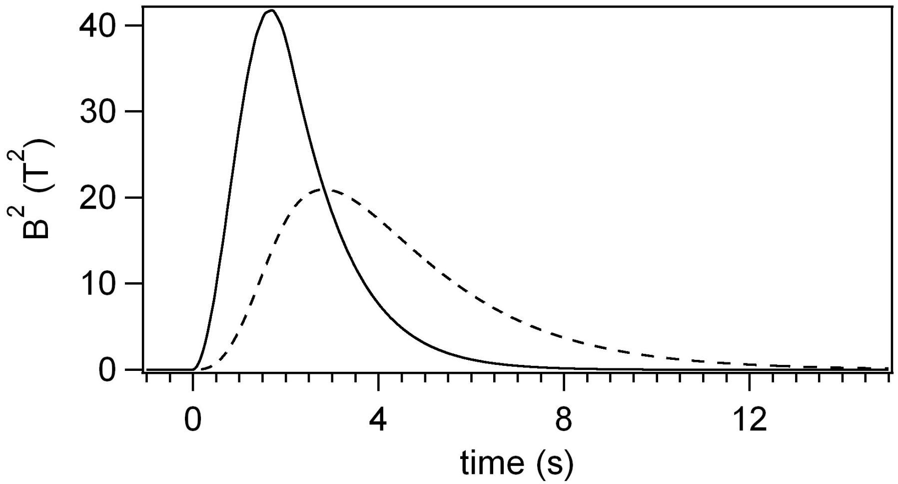
- Y(t) fitted by $\alpha_{CM} B^2_{\text{filtered}}(t)$

in T^{-2}

$$Y = \alpha_{CM} B^2_{\text{filtered}}(t) \quad \text{and} \quad k_{CM} = \frac{\lambda}{2FL_0}\alpha_{CM}$$

B^2_{filtered} takes into account the first order low pass filtering of the cavity

cutoff frequency: $\nu_c = 1/4\pi\tau$ = 75 Hz

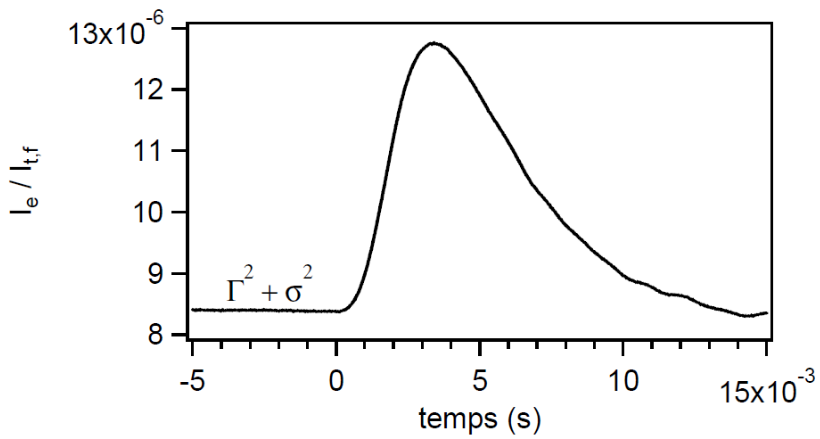


P. Berceau et al., Appl. Phys. B **100**, 803 (2010)

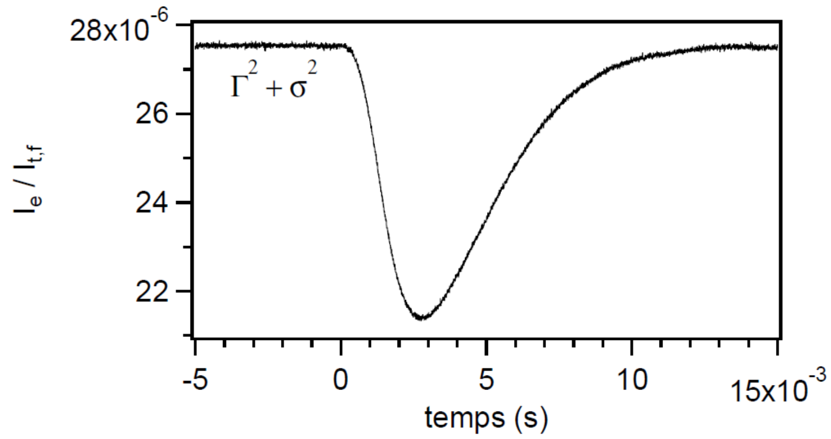
$$\frac{I_{ext}}{I_t} \approx \sigma^2 + \Gamma^2 + 2\Gamma\Psi(t)$$

The signal to be measured **depends on Γ** : gas measurements are used to deduce its sign.

- N_2 pulses ($\Delta n_{CM} < 0$) B = 3 T, P = 10^{-3} atm



$$\left.\begin{array}{l} 2\Gamma\Psi > 0 \\ \Psi < 0 \end{array}\right\} \Leftrightarrow \Gamma < 0$$



$$\left.\begin{array}{l} 2\Gamma\Psi < 0 \\ \Psi < 0 \end{array}\right\} \Leftrightarrow \Gamma > 0$$

➡ **Γ sign can be changed turning cavity mirrors**

Data acquisition and analysis : general case

- Using symmetry properties of $$Y(t) = \frac{\frac{I_e}{I_t} - \sigma^2 - \Gamma^2}{|\Gamma|} \neq \gamma\, \Psi(t)$$

4 data series $Y_{\Gamma B}$

$$\begin{cases} Y(t)_{>>} & \Leftrightarrow \Gamma>0,\ \text{B parallel to Ox} \\ Y(t)_{><} & \Leftrightarrow \Gamma>0,\ \text{B antiparallel to Ox} \\ Y(t)_{<<} & \Leftrightarrow \Gamma<0,\ \text{B antiparallel to Ox} \\ Y(t)_{<>} & \Leftrightarrow \Gamma<0,\ \text{B parallel to Ox} \end{cases}$$

- We then derive a more general expression for Y(t)

$$\begin{cases} Y_{>>} = a_{>>}S_{++} + b_{>>}S_{+-} + c_{>>}S_{--} + d_{>>}S_{-+} \\ Y_{><} = a_{><}S_{++} + b_{><}S_{+-} + c_{><}S_{--} + d_{><}S_{-+} \\ Y_{<<} = a_{<<}S_{++} + b_{<<}S_{+-} + c_{<<}S_{--} + d_{<<}S_{-+} \\ Y_{<>} = a_{<>}S_{++} + b_{<>}S_{+-} + c_{<>}S_{--} + d_{<>}S_{-+} \end{cases}$$

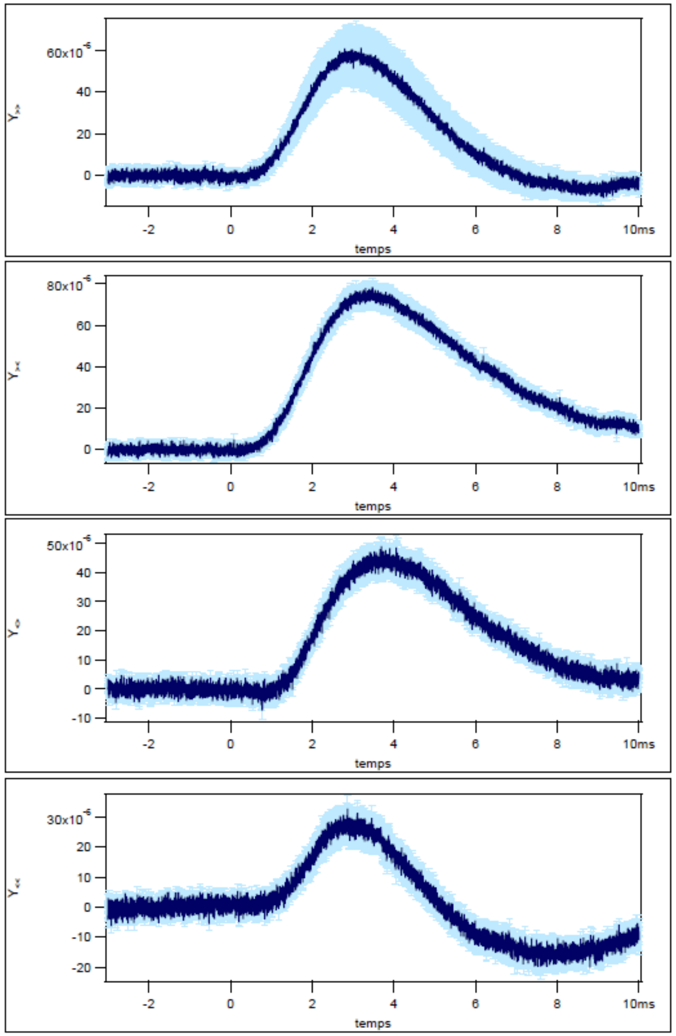
$S_{\Gamma B}$ = function with a given symmetry

+ even parity

- odd parity

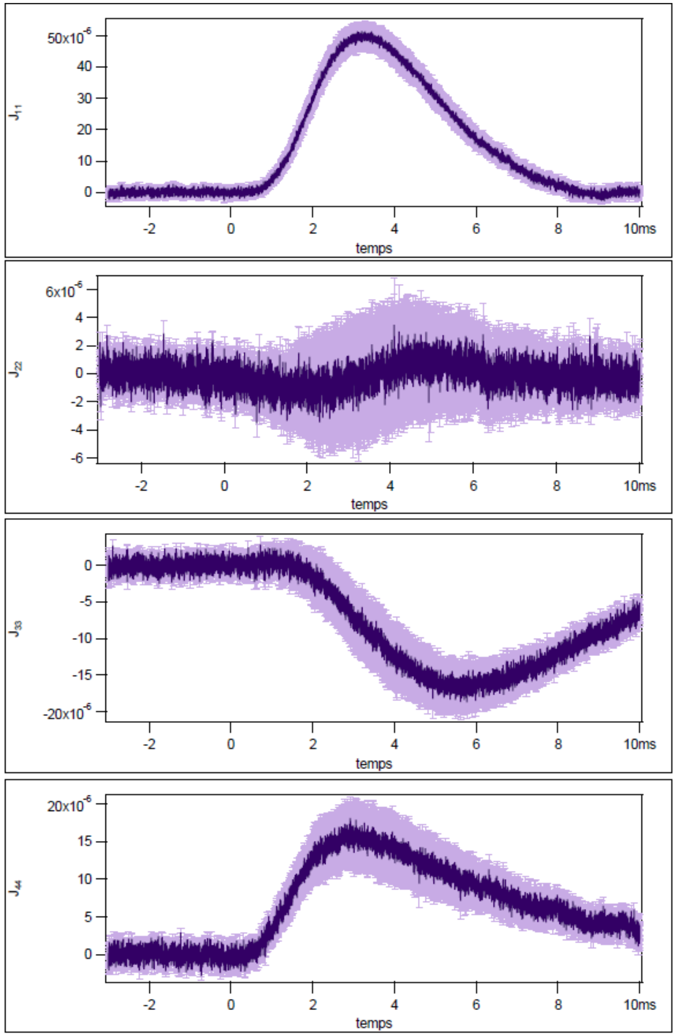
Magnetic linear birefringence $\Rightarrow S_{-+}$

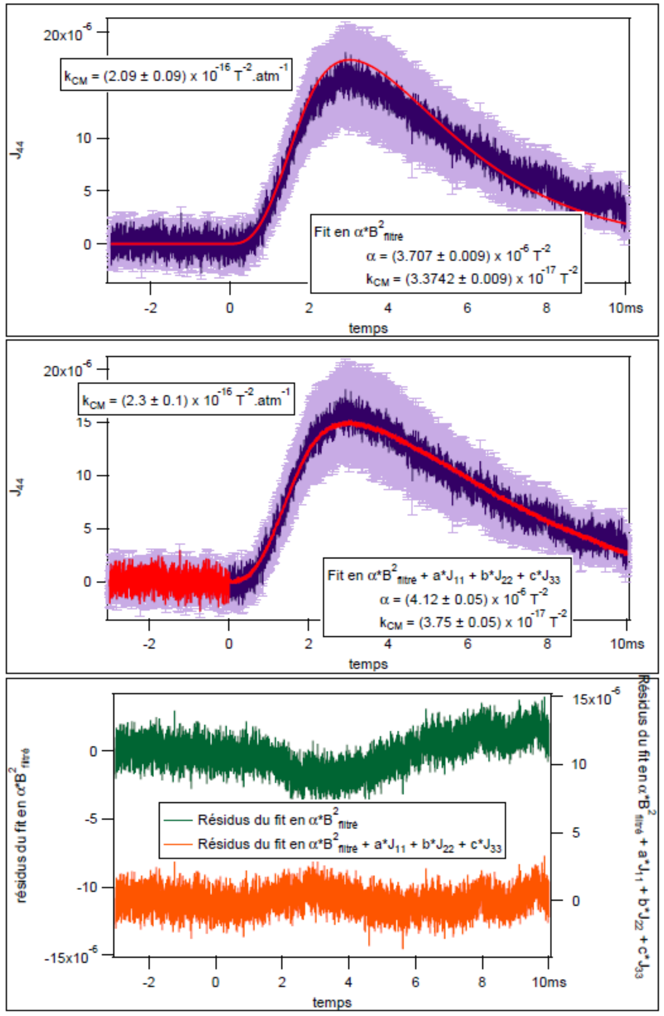
160 mbar of Helium gas



$$
\begin{aligned}
J_1 &= \frac{Y_{>>} + Y_{><} + Y_{<<} + Y_{<>}}{4} \simeq \bar{a} S_{++}, \\
J_2 &= \frac{Y_{>>} - Y_{><} - Y_{<<} + Y_{<>}}{4} \simeq \bar{b} S_{+-}, \\
J_3 &= \frac{Y_{>>} - Y_{><} + Y_{<<} - Y_{<>}}{4} \simeq \bar{c} S_{--}, \\
J_4 &= \frac{Y_{>>} + Y_{><} - Y_{<<} - Y_{<>}}{4} \\
&\simeq \Delta a S_{++} + \Delta b S_{+-} + \Delta c S_{--} + d\, S_{-+}
\end{aligned}
$$

Y





J

Our preliminary value : k_{CM} = (2.3 ± 0.1) 10^{-16} T^{-2} atm^{-1}

Theory (22.5 °C) = 2.22 10^{-16} T^{-2} atm^{-1}

≈ 100 pulses

In vacuum $S_{-+} \sim 0$

$$J_1 = \frac{Y_{>>} + Y_{><} + Y_{<<} + Y_{<>}}{4} \simeq \overline{a} S_{++},$$

$$J_2 = \frac{Y_{>>} - Y_{><} - Y_{<<} + Y_{<>}}{4} \simeq \overline{b} S_{+-},$$

$$J_3 = \frac{Y_{>>} - Y_{><} + Y_{<<} - Y_{<>}}{4} \simeq \overline{c} S_{--},$$

$$J_4 = \frac{Y_{>>} + Y_{><} - Y_{<<} - Y_{<>}}{4} \simeq \Delta a S_{++} + \Delta b S_{+-} + \Delta c S_{--}.$$

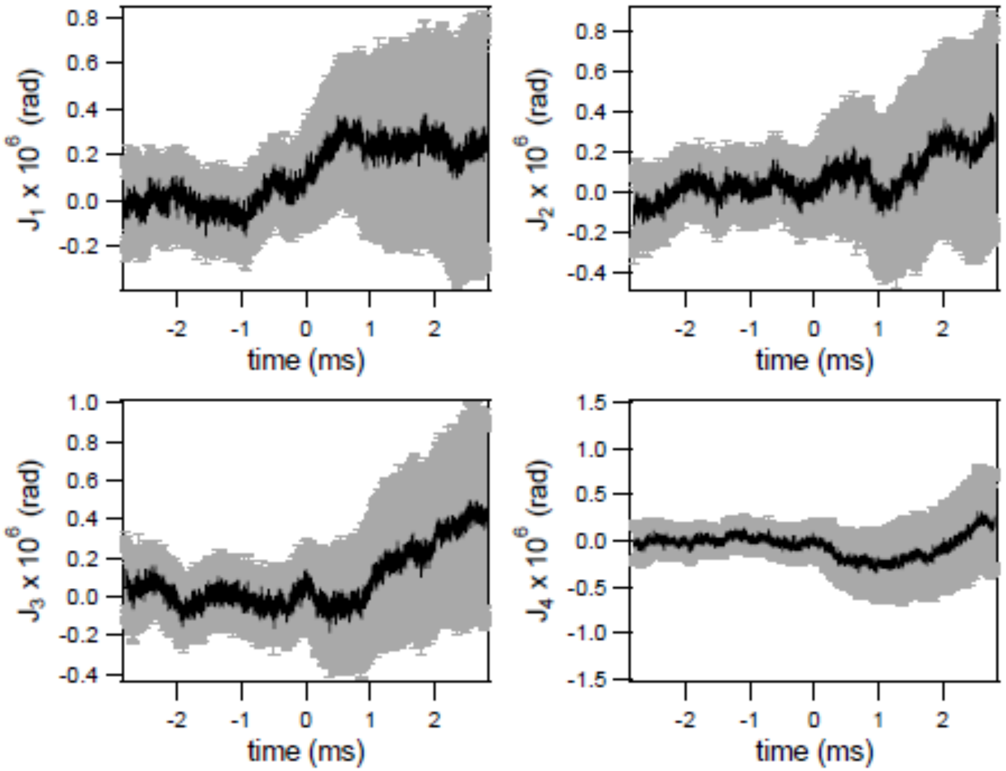


FIG. 3: Terms J calculated with more than a hundred pulses. Black: mean value; Gray: 3σ statistical uncertainties.

A. Cadène et al., arXiv:1302.5389 (2013), submitted to PRL

Systematic effects

❑ Possible magnetic linear birefringence effects:

• Residual gaz :

P<10^{-7} mbar

Gaz analyser: most important contributions come from N_2 and O_2

$$\Rightarrow \quad k_{\mathrm{CM}} = 1.5 \times 10^{-23}\ \mathrm{T}^{-2}$$

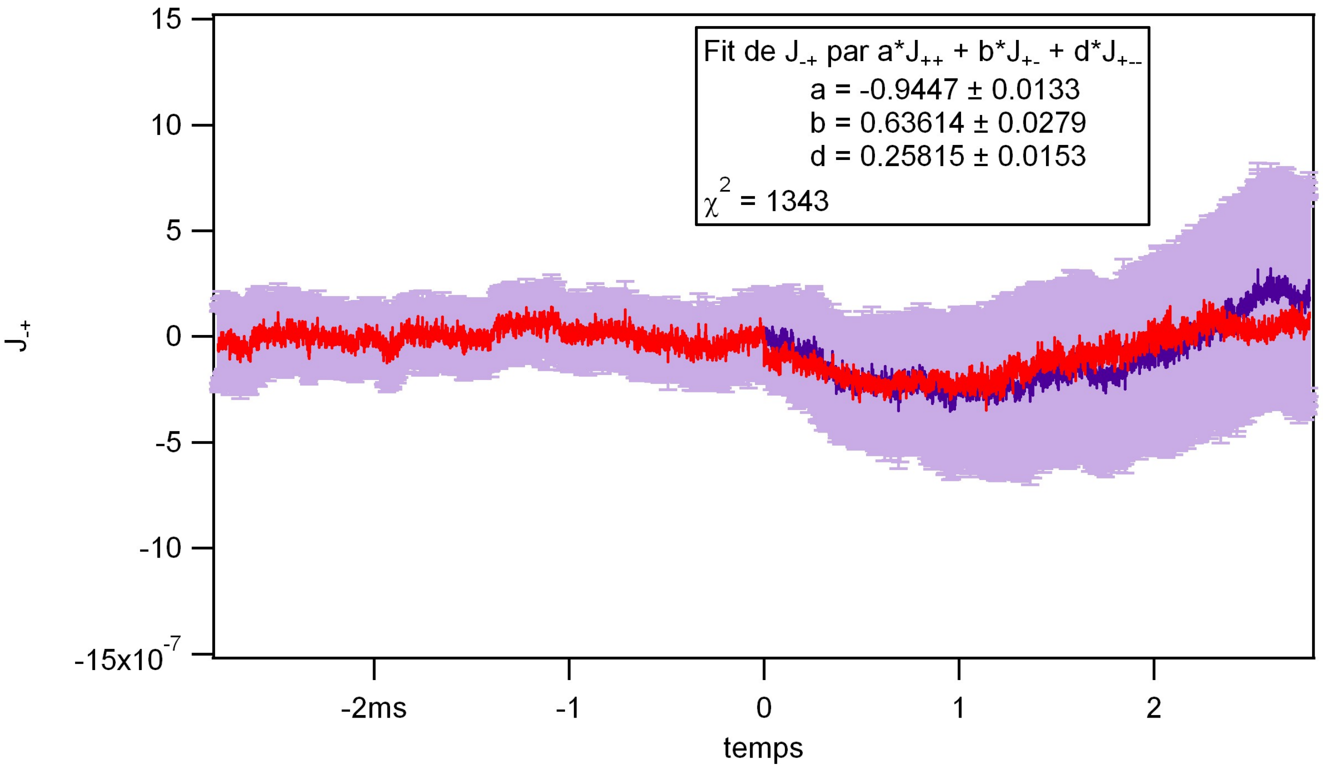
• Effect of cavity mirrors

B_{mirror} = 150 μT

$$\Rightarrow \quad k_{\mathrm{CM}} = 1 \times 10^{-24}\ \mathrm{T}^{-2}$$

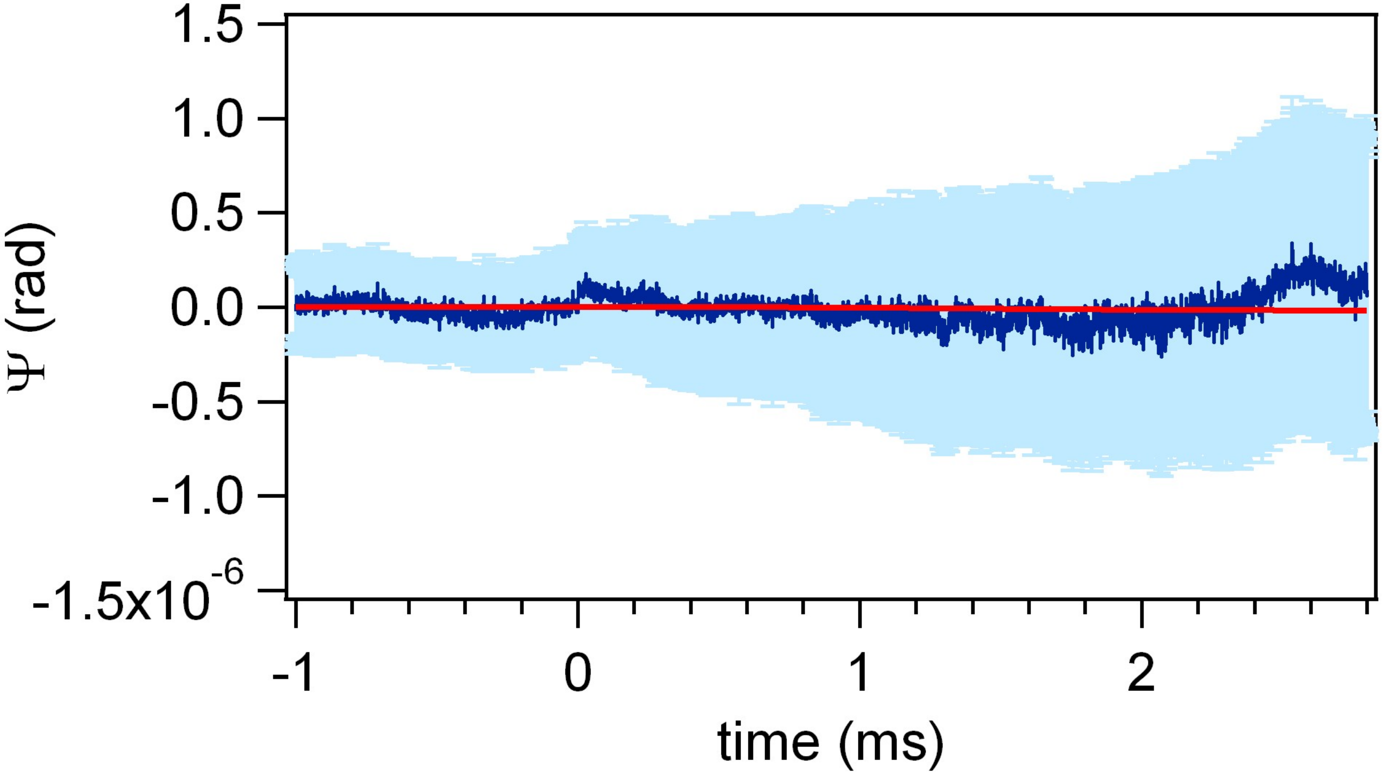
➡ No magnetic linear birefringence systematic effect at the level of the expected noise floor.

- Symmetry functions can be measured with a linear combination of functions Y
- This allows to measure and to overcome systematic effects that might mimic the CM effect



As expected, J_4 is a linear combination of S_{++}, S_{+-}, S_{--} !

J_4 residual : $S_{-+} \sim 0$

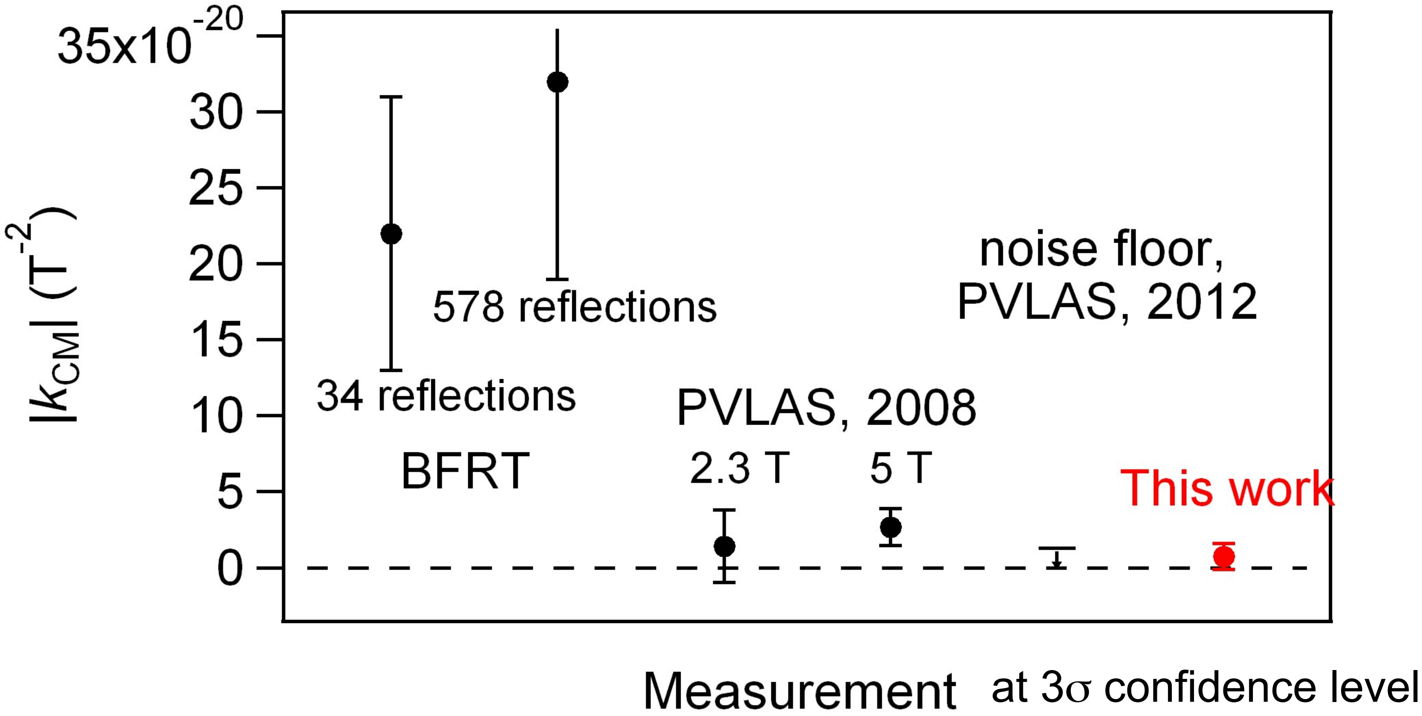


$$k_{CM} = (-7.4 \pm 8.7) \times 10^{-21}\ \mathrm{T}^{-2}$$ at 3σ confidence level

A. Cadène et al., arXiv:1302.5389 (2013), submitted to PRL

Comparison

A. Cadène et al., arXiv:1302.5389 (2013), submitted to PRL

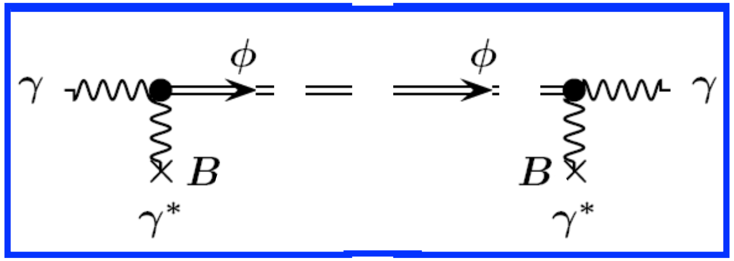


BFRT Collaboration: R. Cameron *et al*., *Phys. Rev. D* **47**, 3707 (1993)

PVLAS, 2008: E. Zavattini *et al*., *Phys. Rev. D* **77**, 032006 (2008)

PVLAS, 2012: G. Zavattini *et al*., *Int. J. of Mod. Phys. A* **27**, 1260017 (2012)

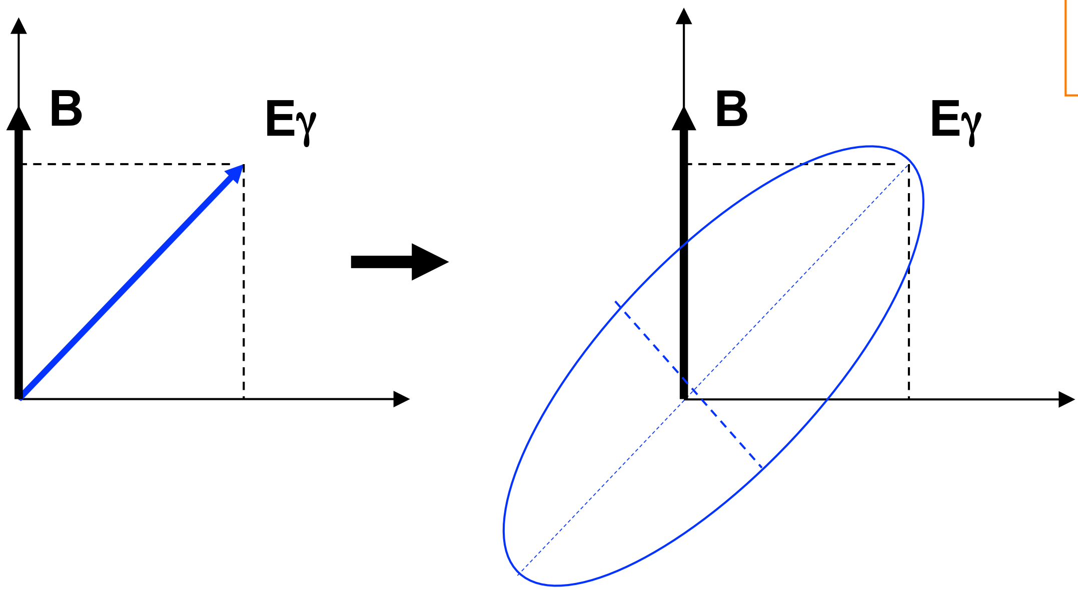
Axion physics as by-product !



$\Delta n > 0 \Rightarrow$ **Pseudoscalar**

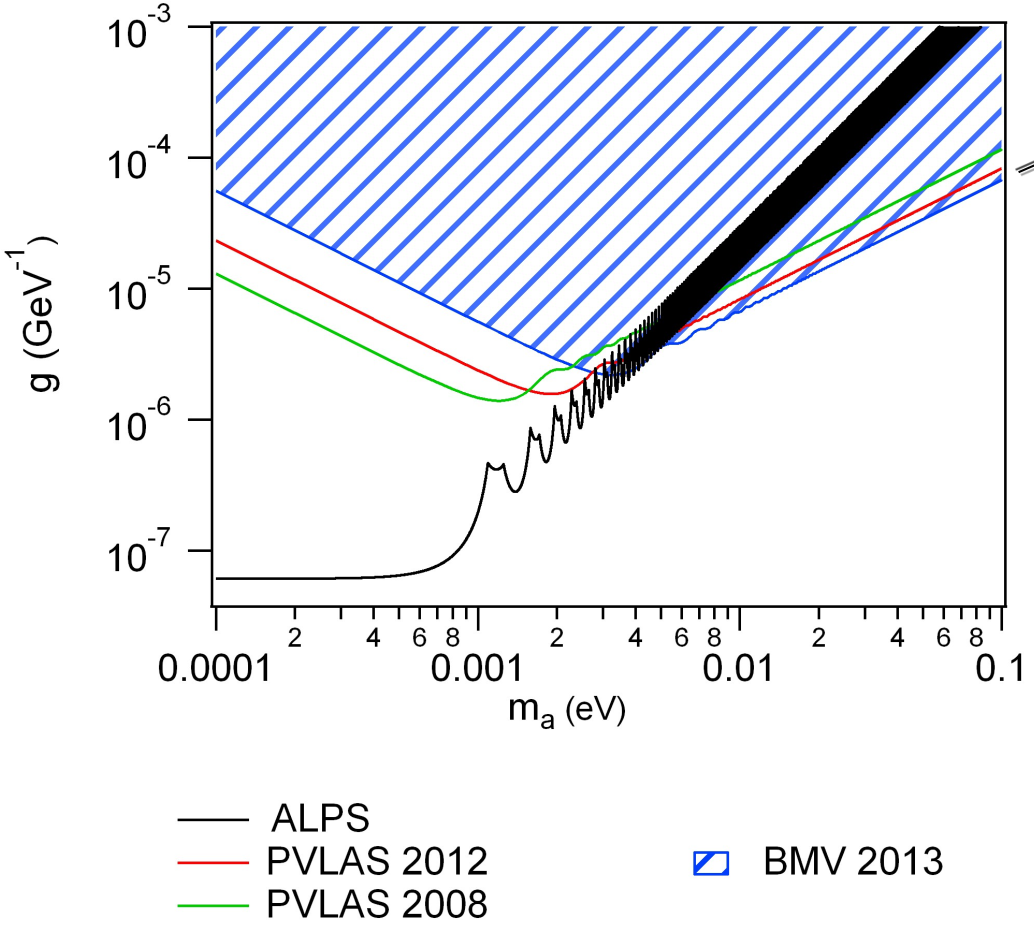
$\Delta n < 0 \Rightarrow$ **Scalar**

Ellipticity



L.Maiani, R.Petronzio et E.Zavattini, *Phys. Lett. B* **175** (1986) 359

Typical limits on the mass of the axion and its coupling constant coming from our recent results compared to other existing limits :



Limits also apply to large masses

Conclusion

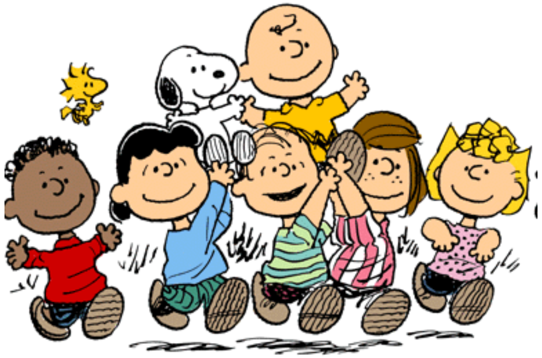
- Status
  - Coupled high magnetic field and one the best Fabry-Perot cavities
  - Measurements performed on gases and in vacuum

➡ Needed sensitivity improvement: **almost 3 orders of magnitude**

- Future
  - Increase the transverse magnetic field : new XXL-coil

$B^2L_{mag} > 300\ T^2m$

- Improvement of the ellipticity sensitivity (Decrease of Γ^2 and σ^2 (10^{-8}))



Thanks to the whole laboratory staff and to all the colleagues involved in the project.

Biréfringence Magnétique du Vide

- Rémy Battesti
- Paul Berceau
- Agathe Cadène
- Mathilde Fouché
- Carlo Rizzo

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Vacuum magnetic birefringence

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CNRS UPR 3228

Laboratoire National des Champs Magnétiques Intenses

CNRS UPR 3228 **; UPS** (Université Paul Sabatier,Toulouse) ; **INSA** (Institut National des Sciences Appliquées,Toulouse) ; **UJF** (Université Joseph Fourier, Grenoble)

2 sites : static field in Grenoble up to 35 T
pulsed field in Toulouse 80 T non destructive
170 T semi destructive

The 3 missions of the LNCMI :

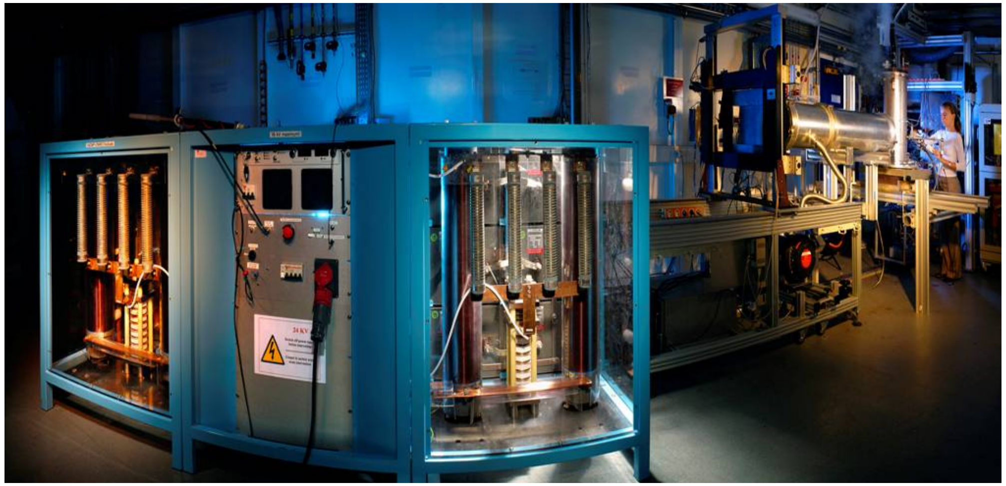
- technological and scientific development of experiments under high magnetic field

- open its potential to scientists through collaborative agreements and contracts

- create European partnerships with other installations to develop techniques

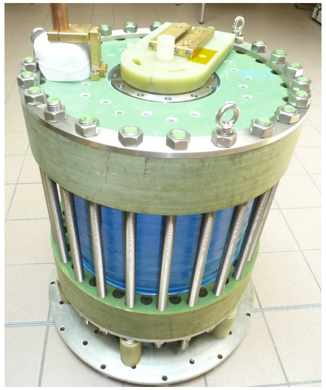
The pulsed field facility in Toulouse with its 6 capacitors banks from 10 kJ to 14 MJ

3 are mobile



To perform experiments in other facilities and combine magnetic field with intense lasers, X-rays, or neutrons (LULI, ESRF, ILL, CLIO…)

Combination of high magnetic field, low temperature and high pressure

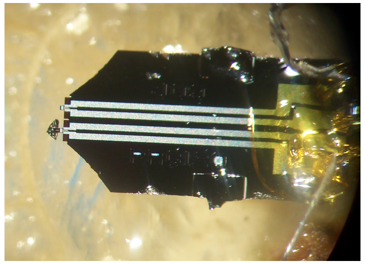


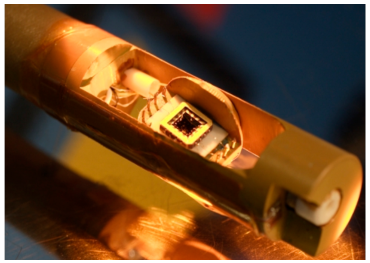
60 – 80T

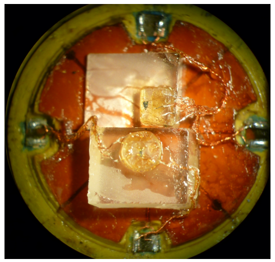
300 K – 50 mK

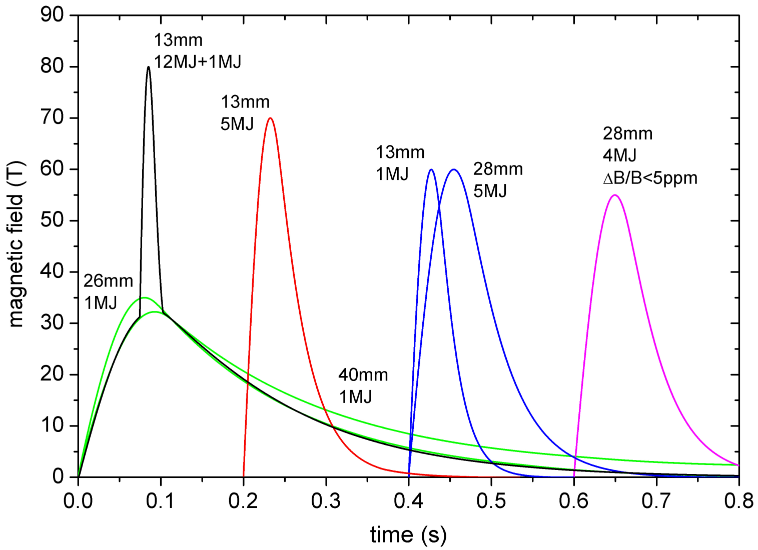
1 – 10 GPa

many different experimental techniques









mainly solid state physics !

Coil development for pulsed magnetic field

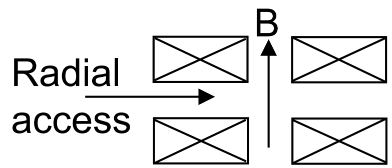
standard solenoids : high field, long pulse, suited to many types of experiments

specific magnets : magnetic field is not the only parameter

• access perpendicular to magnetic field

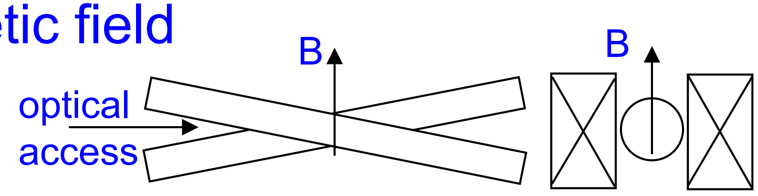
30 T split-pair coil for X-rays diffraction at ESRF

40 T for plasma physics at LULI



• long optical path with transverse magnetic field

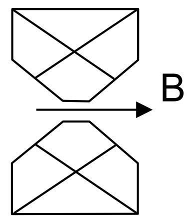
30 T XXL coil for vacuum magnetic birefringence



• conical access in the magnet bore

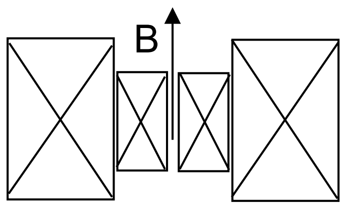
30 T coils with axial access and conical bore for X-ray diffraction

40 T wide angle conical access solenoid with a high duty-cycle for neutron scattering

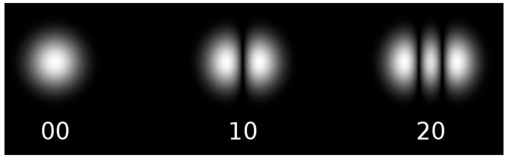


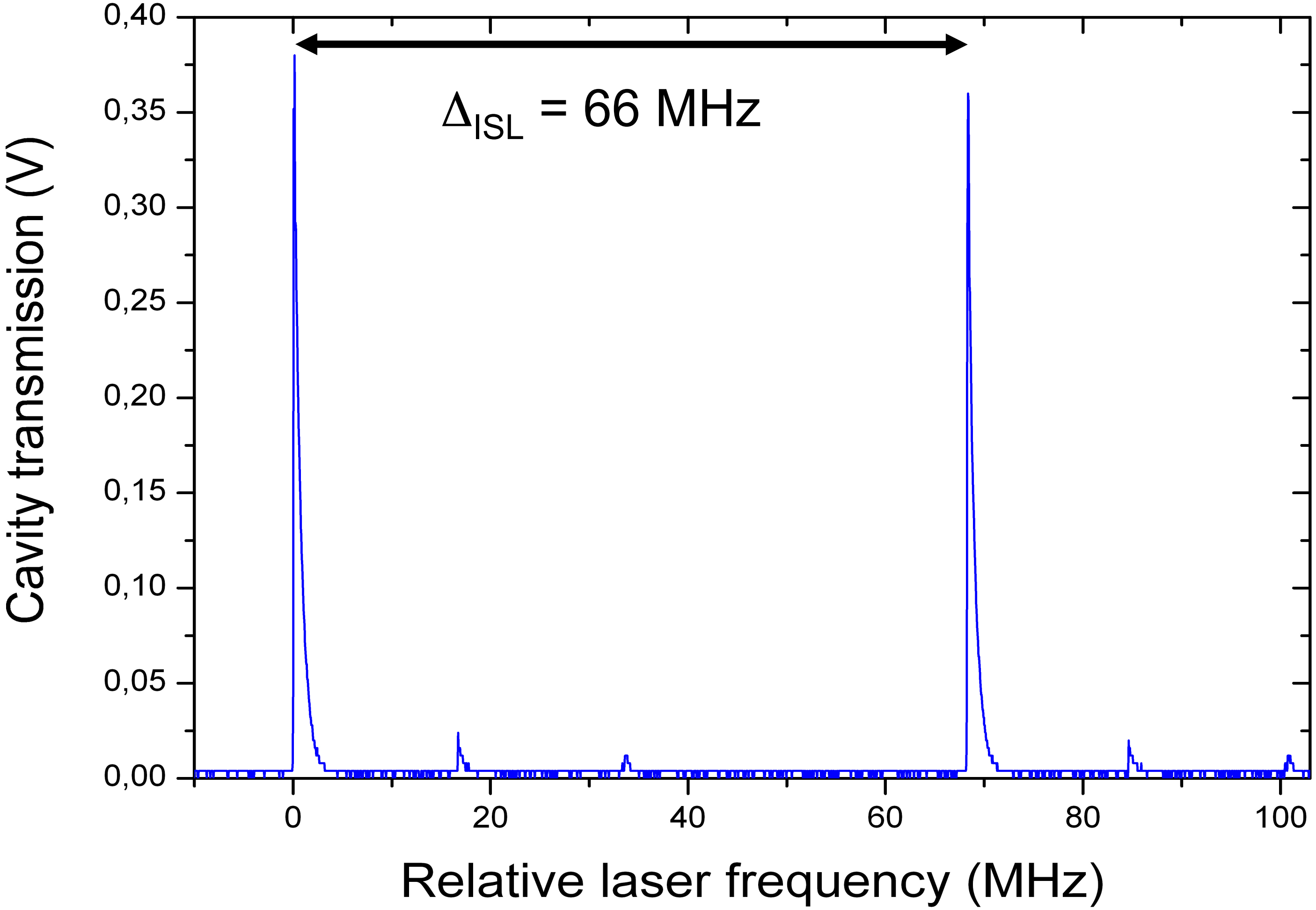
• high field nested-coils

85 T long pulse dual coil system

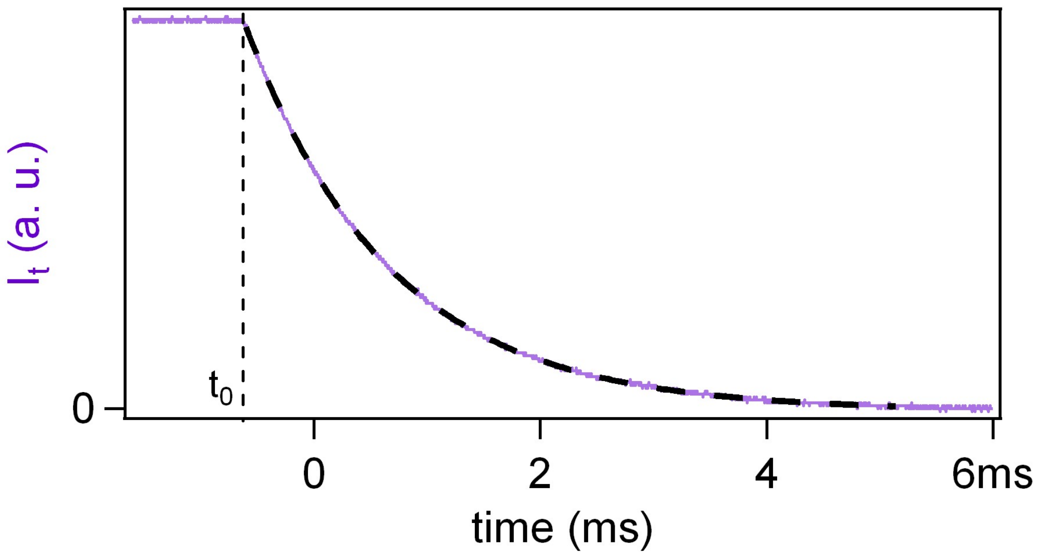


$\Delta_{ISL} = c/2L_c$





❑ Finesse :



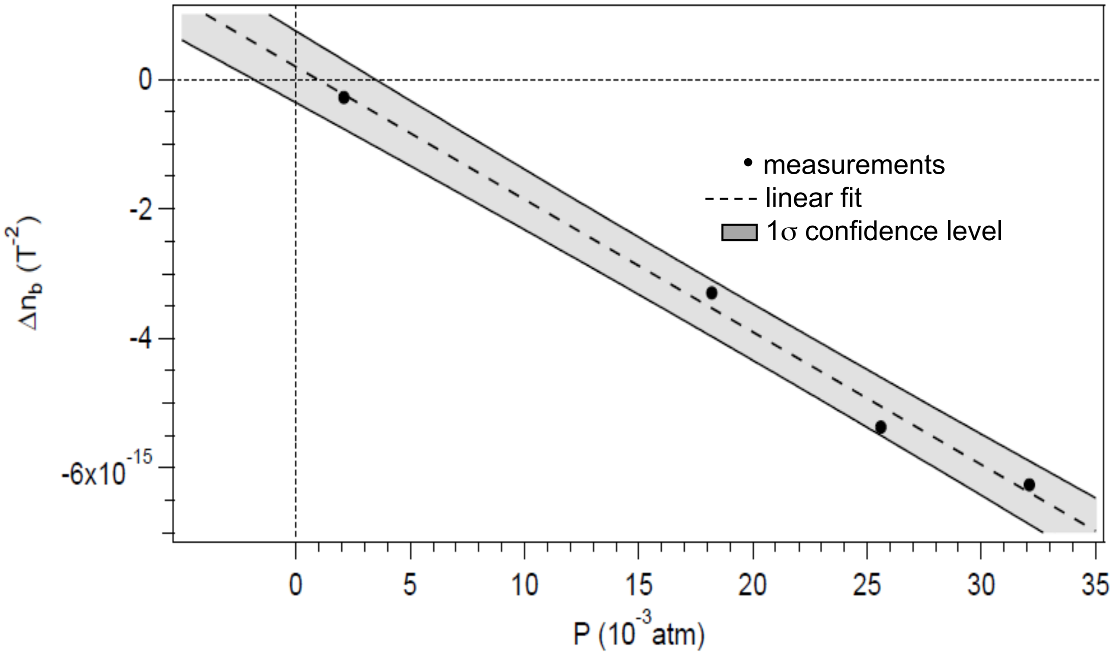
- photon lifetime in the cavity (L_c = 2.27 m long) :
  τ = 1.08 ms

- flight distance in the cavity = 325 km

$$F = \frac{\pi c \tau}{L_c} = 450\,000$$

- Magnetic birefringence of **nitrogen *vs* pressure**

$$\Delta n_b = \frac{\alpha_{\mathrm{CM}}}{4\pi\tau\Delta^{\mathrm{FSR}}}\frac{\lambda}{L_B}\frac{1}{\sin(2\theta)} = f(P)$$



P. Berceau et al., Phys. Rev. A ***85****, 013837 (2012)*

$$\Delta n_b \ (\mathrm{P{=}1\ atm,\ B{=}\ 1\ T}) \times 10^{-13}$$

$$(-2.00 \pm 0.08 \pm 0.06)$$

Standard Model Quantum vacuum

- H. Euler et B. Kochel (1935), W. Heinsenberg et H. Euler (1936)

$$\mathcal{L}_{\mathrm{HE}} = \sum_{i=0}^{\infty} \sum_{j=0,\mathrm{even}}^{\infty} c_{i,j} \mathcal{F}^i \mathcal{G}^j \underset{B<<B_{\mathrm{cr}}}{\overset{E<<E_{\mathrm{cr}}}{=}} \frac{1}{2}\mathcal{F} + \frac{2}{45}\frac{\alpha^2\hbar^3}{m_e^4 c^5}\left(\mathcal{F}^2 + 7\mathcal{G}^2\right)$$

Lorentz invariants:

$$\mathcal{F} = \left(\varepsilon_0 E^2 - \frac{B^2}{\mu_0}\right) \qquad \mathcal{G} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\vec{E}\cdot\vec{B}\right)$$

$$= \underbrace{\frac{1}{2}\left(\varepsilon_0 E^2 - \frac{B^2}{\mu_0}\right)}_{\text{Maxwell}} + \underbrace{\frac{2}{45}\frac{\alpha^2\hbar^3}{m_e^4 c^5}\varepsilon_0^2\left[\left(E^2 - cB^2\right)^2 + 7c^2\left(\vec{E}\cdot\vec{B}\right)^2\right]}_{\text{QED}}$$

R. Battesti and C. Rizzo, Rep. Prog. Phys. ***76****, 016401 (2013)*

$$\Delta n_{\mathrm{CM}} = \left(\frac{2\alpha^2\hbar^3}{15 m_{\mathrm{e}}^4 c^5}\right)\frac{B_0^2}{\mu_0}$$

QED has no free parameters :
k_{CM} has to be accurately and precisely measured to test L_{HE}. This is our main goal !

Beyond Standard Model

Exemple : axion physics

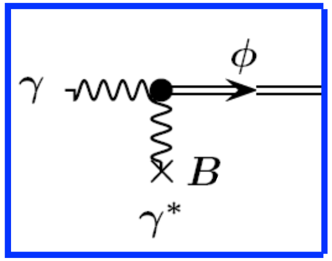
Axion : pseudoscalar, spinless, chargeless particle coupling with two photons

$$L_a = g \ \Phi_a \mathcal{G}$$

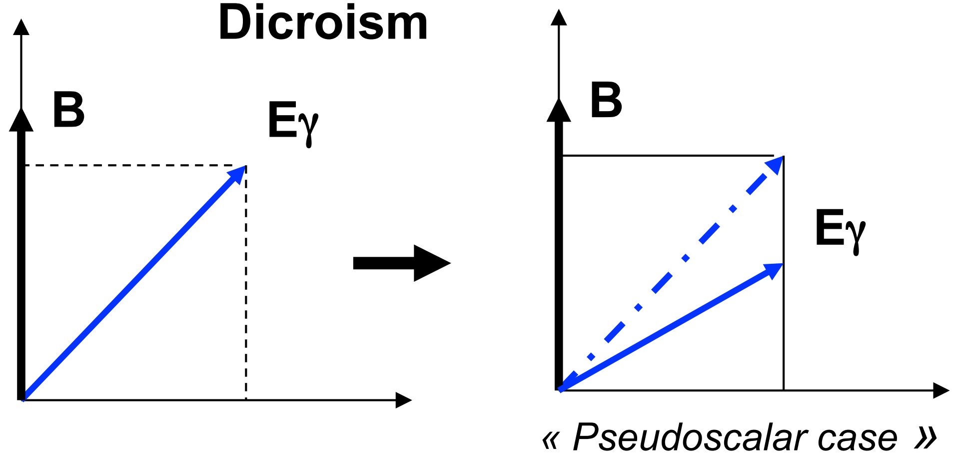
Two free parameter theory : *g* coupling constant and m_a mass of the axion

Axion can be detected in an experiment like the BMV one !

Real particle



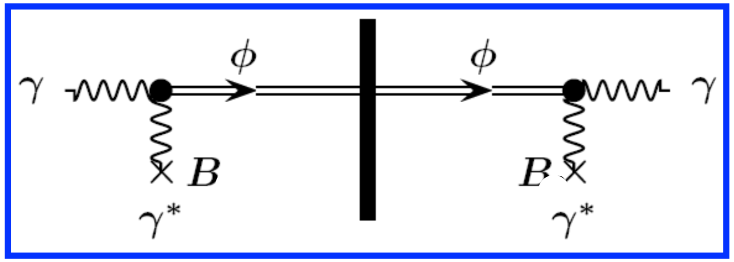
Dicroism



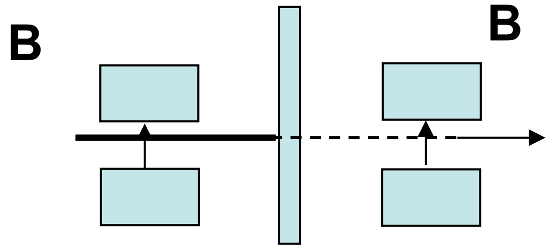
« BL » effects

L.Maiani, R.Petronzio et E.Zavattini, *Phys. Lett. B* **175** (1986) 359

Photon regeneration



wall



wall

K. Van Bibber *et al.*, *Phys. Rev. Lett.* **59** (1987) 759