Quantum vacuum and magnetic fields

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l'Europe s'engage en France

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OUTLINE

1. Quantum vacuum seen by an experimentalist in optics

   Magnetic and electric properties of a quantum vacuum, R. Battesti and C. Rizzo, *Rep. Prog. Phys.* **76**, 016401 (2013)

2. Inverse Cotton Mouton Effect of vacuum

3. Vacuum Magnetic Birefringence

What is «vacuum» mean ?

- **Aristotle :**
  - ***«The investigation of similar questions about the void, also, must be held to belong to the physicist - namely whether it exists or not, and how it exists or what it is »***
  - **«A place deprived of body»**

- **in *Webster's New World Dictionary* :**
  - **1- a space with nothing at all in it; completely empty space.**
  - **2- an enclose space, as that inside a vacuum tube, out of which most of the air or gas has been taken, as by pumping.**

What is «vacuum» mean ?

Phenomenological definition :

Region of space in which a monochromatic electromagnetic plane wave propagates at a velocity that is equal to c.

In classical electrodynamics, vacuum electromagnetic properties are simply represented by two fundamental constants : the vacuum permittivity ϵ_0 and the vacuum permeability μ_0

$$\mathbf{D} = \epsilon_0 \mathbf{E}$$

$$\mathbf{B} = \mu_0 \mathbf{H}$$

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

Any variation of the velocity of light with respect to c is ascribed to the fact that light is propagating in a medium

$$\mathbf{D} = [\epsilon]\ \mathbf{E}$$

$$\mathbf{B} = [\mu]\ \mathbf{H}$$

$$n(\mathbf{E},\mathbf{B}) = \frac{\sqrt{\epsilon\mu}}{\sqrt{\epsilon_0 \mu_0}}$$

$$n \equiv 1$$

$$\frac{\epsilon}{\epsilon_0} = 1 \qquad \frac{\mu}{\mu_0} = 1$$

Vacuum : Lorentz invariant

- Only 2 Lorentz invariants in electromagnetism :

$$F = \left(\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right)$$

$$G = \sqrt{\frac{\epsilon_0}{\mu_0}}(\mathbf{E} \cdot \mathbf{B})$$

- Lagrangian has to be relativistic invariant and therefore can only be a function of F and G

$$L = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} c_{i,j} F^i G^j .$$

Constitutive equations

$$\boxed{\mathbf{D} = \frac{\partial L}{\partial \mathbf{E}}} \quad \text{et} \quad \boxed{\mathbf{H} = -\frac{\partial L}{\partial \mathbf{B}}}$$

$$\mathbf{D} = 2\epsilon_0 c_{1,0}\mathbf{E} + \sqrt{\frac{\epsilon_0}{\mu_0}}c_{0,1}\mathbf{B} + 2\epsilon_0 c_{1,1}G\mathbf{E} + \sqrt{\frac{\epsilon_0}{\mu_0}}c_{1,1}F\mathbf{B} + 4\epsilon_0 c_{2,0}F\mathbf{E} + 2\sqrt{\frac{\epsilon_0}{\mu_0}}c_{0,2}G\mathbf{B}$$

$$\mathbf{H} = 2c_{1,0}\frac{\mathbf{B}}{\mu_0} - \sqrt{\frac{\epsilon_0}{\mu_0}}c_{0,1}\mathbf{E} + 2c_{1,1}G\frac{\mathbf{B}}{\mu_0} - \sqrt{\frac{\epsilon_0}{\mu_0}}c_{1,1}F\mathbf{E} + 4c_{2,0}F\frac{\mathbf{B}}{\mu_0} - 2\sqrt{\frac{\epsilon_0}{\mu_0}}c_{0,2}G\mathbf{E}$$

with

$$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P}$$
$$\mathbf{H} = \frac{1}{\mu_0}\mathbf{B} - \mathbf{M}$$

P

existence of a polarization of a vacuum as in any optical non linear medium

Quantum electrodynamics provides the most complete theoritical treatment for the c_{ij} coefficient prediction

Quantum Electrodynamics is assumed to be C, P, T invariant

	C	P	T
$\vec{E}$	-	-	+
$\vec{B}$	-	+	-
$\vec{E} \cdot \vec{B}$	+	-	-
$E^2 - B^2$	+	+	+

so F is C, P, T invariant but G violates P and T

the only contributions in the lagrangian are the even power of G

$$L = c_{00} F^0 G^0 + c_{10} F^1 G^0 + c_{20} F^2 G^0 + c_{02} F^0 G^2 + c_{12} F^1 G^2 + ...$$

Energy density of vacuum

$$U = \mathbf{E}\frac{\partial L}{\partial \mathbf{E}} - L$$

$$c_{1,0} = \frac{1}{2}$$

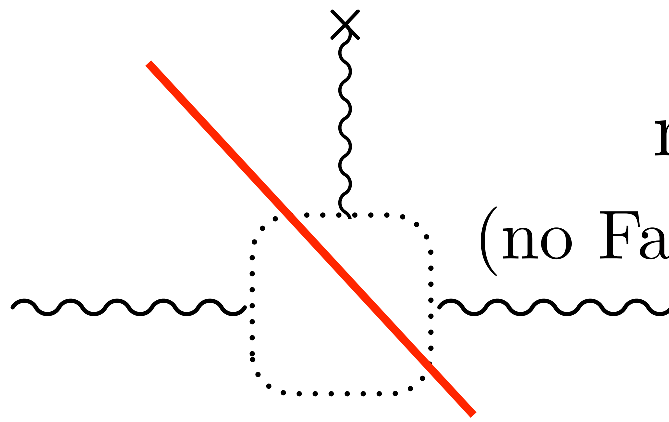
$$\begin{aligned}
U &= \frac{1}{2}\left(\epsilon_0 E^2 + \frac{B^2}{\mu_0}\right) + c_{2,0}\left(\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right)\left(3\epsilon_0 E^2 + \frac{B^2}{\mu_0}\right) \\
&+ c_{0,2}\frac{\epsilon_0}{\mu_0}(\mathbf{E}\cdot\mathbf{B})^2 + c_{3,0}\left(\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right)^2\left(5\epsilon_0 E^2 + \frac{B^2}{\mu_0}\right) \\
&+ c_{1,2}\frac{\epsilon_0}{\mu_0}(\mathbf{E}\cdot\mathbf{B})^2\left(3\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right)
\end{aligned}$$

Non linear interactions in a vacuum

3 waves interaction

terms in :

$$\cancel{\begin{array}{l} E^3, \\ E^2 B, \\ E B^2, \\ B^3 \end{array}}$$



not allowed in a vacuum

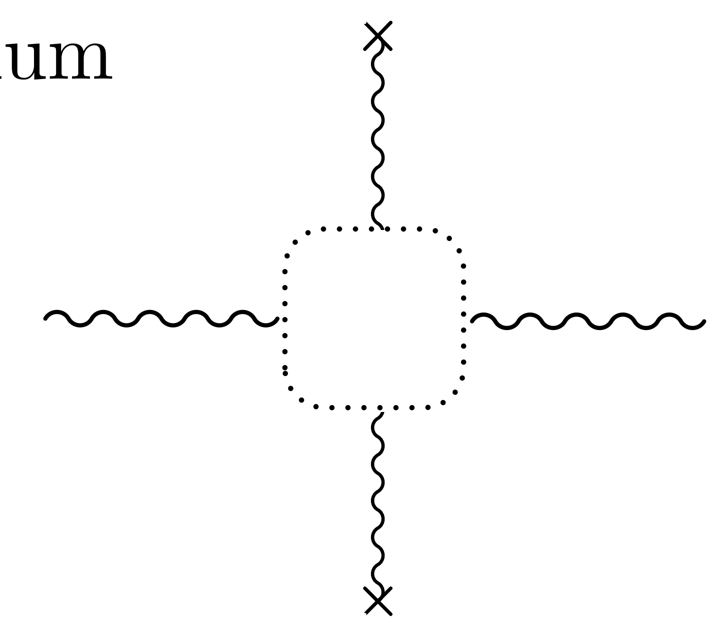
(no Faraday effect in vacuum for example)

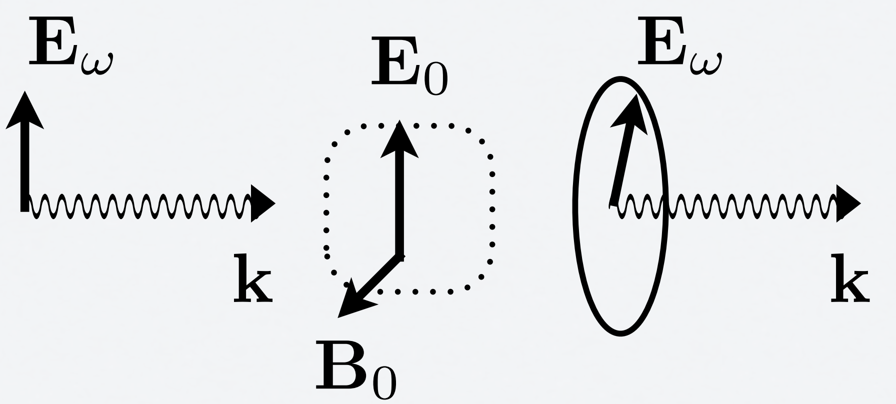
4 waves interaction

terms in :

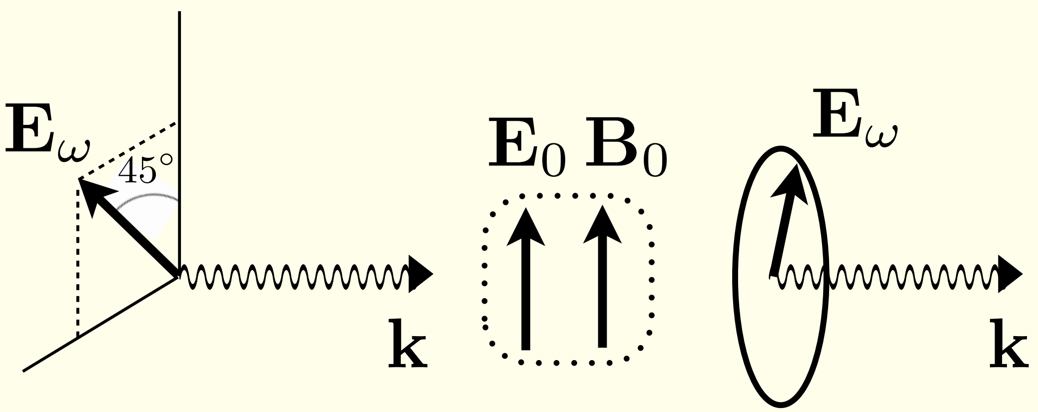
$$\begin{array}{l} E^4, \\ E^2 B^2, \\ B^4 \end{array}$$

allowed in a vacuum

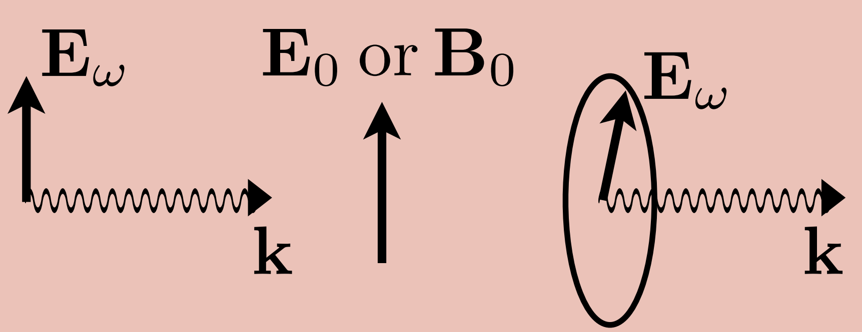




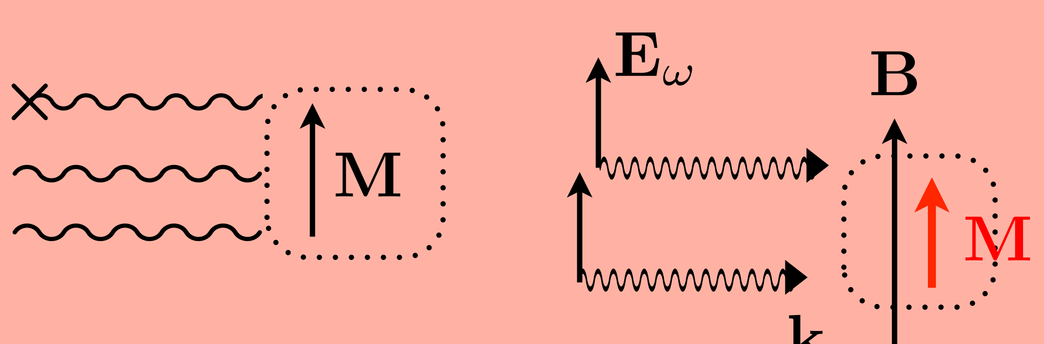
Linear magneto-electric birefringence



Jones linear biréfringence



Kerr effect or Cotton-Mouton effect



Inverse Cotton-Mouton effect

Polarization and magnetization

$$\mathbf{D} = 2\epsilon_0 c_{1,0}\mathbf{E} + \cancel{\sqrt{\frac{\epsilon_0}{\mu_0}} c_{0,1}}\mathbf{B} + \cancel{2\epsilon_0 c_{1,1} G}\mathbf{E} + \sqrt{\frac{\epsilon_0}{\mu_0}}\cancel{c_{1,1} F}\mathbf{B} + 4\epsilon_0 c_{2,0} F\mathbf{E} + 2\sqrt{\frac{\epsilon_0}{\mu_0}} c_{0,2} G\mathbf{B}$$

$$\mathbf{P} = 4c_{2,0}\epsilon_0\mathbf{E}F + 2c_{0,2}\sqrt{\frac{\epsilon_0}{\mu_0}}\mathbf{B}G \qquad \mathbf{M} = -4c_{2,0}\frac{\mathbf{B}}{\mu_0}F + 2c_{0,2}\sqrt{\frac{\epsilon_0}{\mu_0}}\mathbf{E}G$$

$$\begin{aligned} \mathbf{E} &= \mathbf{E}_0 + \mathbf{E}_\omega \\ \mathbf{B} &= \mathbf{B}_0 + \mathbf{B}_\omega \end{aligned}$$

$$\begin{aligned} \mathbf{P} = {} & 4c_{2,0}\epsilon_0(\mathbf{E}_\omega + \mathbf{E}_0)\left(\epsilon_0 E_0^2 - \frac{B_0^2}{\mu_0} + 2\epsilon_0\mathbf{E}_\omega\cdot\mathbf{E}_0 - \frac{2\mathbf{B}_\omega\cdot\mathbf{B}_0}{\mu_0}\right) + \\ & 2c_{0,2}\frac{\epsilon_0}{\mu_0}(\mathbf{B}_\omega + \mathbf{B}_0)(\mathbf{E}_\omega\cdot\mathbf{B}_0 + \mathbf{E}_0\cdot\mathbf{B}_\omega + \mathbf{E}_0\cdot\mathbf{B}_0) \end{aligned}$$

$$\begin{aligned} \mathbf{M} = {} & -4c_{2,0}\frac{(\mathbf{B}_\omega + \mathbf{B}_0)}{\mu_0}\left(\epsilon_0 E_0^2 - \frac{B_0^2}{\mu_0} + 2\epsilon_0\mathbf{E}_\omega\cdot\mathbf{E}_0 - \frac{2\mathbf{B}_\omega\cdot\mathbf{B}_0}{\mu_0}\right) + \\ & 2c_{0,2}\frac{\epsilon_0}{\mu_0}(\mathbf{E}_\omega + \mathbf{E}_0)(\mathbf{E}_\omega\cdot\mathbf{B}_0 + \mathbf{E}_0\cdot\mathbf{B}_\omega + \mathbf{E}_0\cdot\mathbf{B}_0), \end{aligned}$$

Heisenberg-Euler Lagrangian

W. Heisenberg and H. Euler, Z. Phys. 98 (1936), 714

Fields can create matter if they are strong enough

If they are not strong enough to create matter, electromagnetic fields polarize the vacuum : virtual possibility of creating matter (electron-positron pairs)

$$L_{HE} = \frac{1}{2}\left(\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right) + \alpha \int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3} \times \left\{ i\eta^2 \sqrt{\frac{\epsilon_0}{\mu_0}}(\mathbf{E}\cdot\mathbf{B}) \frac{cos\left(\frac{\eta}{\sqrt{\epsilon_0}E_{cr}}\sqrt{C}\right) + conj.}{cos\left(\frac{\eta}{\sqrt{\epsilon_0}E_{cr}}\sqrt{C}\right) - conj.} + \epsilon_0 E_{cr}^2 + \frac{\eta^2}{3}(\epsilon_0 E^2 - \frac{B^2}{\mu_0}) \right\}$$

$$\text{with } C = \left(\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right) + 2i\frac{\epsilon_0}{\mu_0}(\mathbf{E}\cdot\mathbf{B})$$

NOT EXPERIMENTALLY TESTED

α : fine structure constant

$E_{cr} = \frac{m_e^2 c^3}{e\hbar}$: critical electric field ($\simeq 10^{18}$ V/m)

Heisenberg-Euler Lagrangian

At the lowest orders in the fields ($E \ll E_{cr}$ and $B \ll B_{cr}$) :

$$L_{HE} = L_0 + L_{EK}$$

with $$L_{EK} = c_{2,0}F^2 + c_{0,2}G^2$$

$$c_{2,0} = \frac{2\alpha^2\hbar^3}{45m_e^4c^5} = \frac{\alpha}{90\pi}\frac{1}{\epsilon_0 E_{cr}^2} = \frac{\alpha}{90\pi}\frac{\mu_0}{B_{cr}^2} \simeq 1.67 \times 10^{-30} \left[\frac{m^3}{J}\right],$$

$$c_{0,2} = 7c_{2,0}$$

and therefore

$$\boxed{L_{EK} = \frac{2\alpha^2\hbar^3}{45m_e^4c^5}\epsilon_0^2[(E^2 - c^2B^2)^2 + 7c^2(\mathbf{E}\cdot\mathbf{B})^2]}$$

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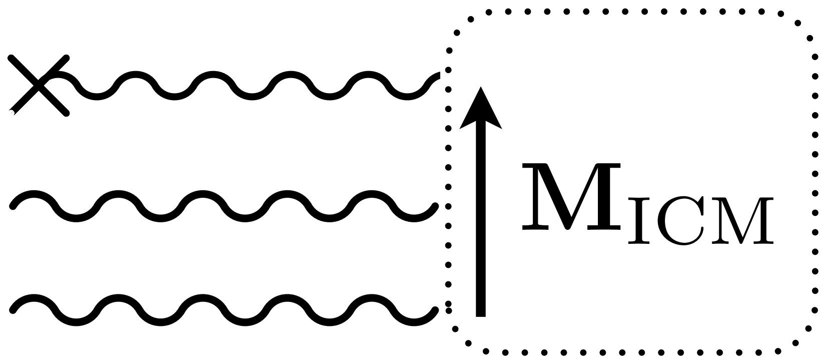
ICME



The interaction between two photons of the electromagnetic wave and a photon of the static magnetic field gives rise to a magnetization M.

$$\mathbf{M}_{ICM} = 14 c_{2,0} \frac{\epsilon_0}{\mu_0} \mathbf{E}_\omega (\mathbf{E}_\omega \cdot \mathbf{B}_0) + 8 c_{2,0} \mathbf{B}_\omega \frac{\mathbf{B}_\omega \cdot \mathbf{B}_0}{\mu_0^2}$$

$\mathbf{E}_\omega \| \mathbf{B}_0,\ \mathbf{B}_\omega \perp \mathbf{B}_0$

$$\mathbf{M}_{\mathrm{ICM}\|} = 14 c_{2,0} \frac{I_\omega}{c} \frac{\mathbf{B}_0}{\mu_0} \Longrightarrow$$

$$c_{2,0} = 1,7 \times 10^{-30}\ \mathrm{m}^3/\mathrm{J}$$

$$\mathrm{B}_0 = 10\ \mathrm{T}$$

$$I_\omega = 10^{19} \mathrm{W}/\mathrm{m}^2$$

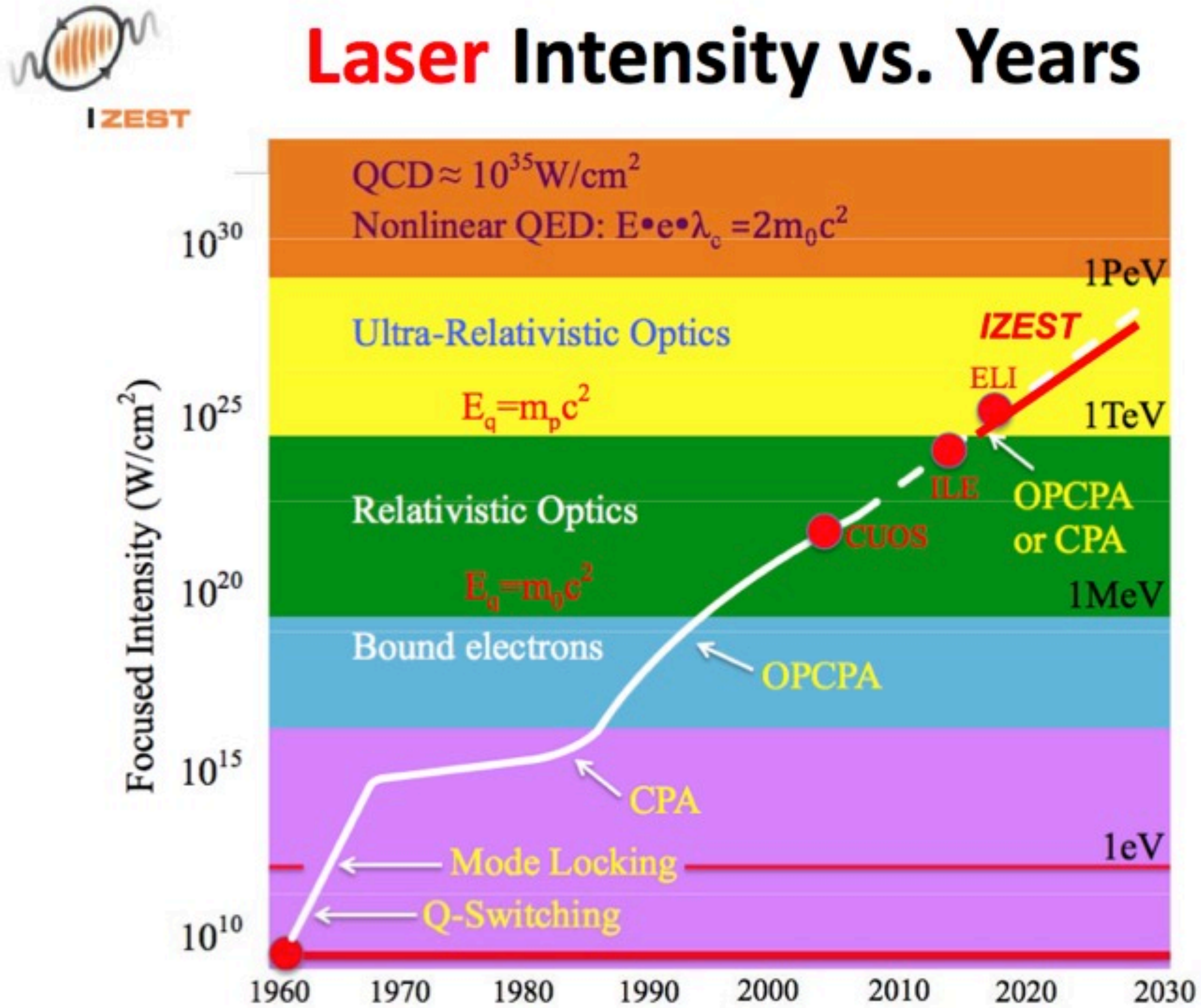
$$\Downarrow$$

$$\mu_0 \mathbf{M}_{\mathrm{ICM}\|} = 8 \times 10^{-18}\ \mathrm{T}$$

$\mathbf{E}_\omega \perp \mathbf{B}_0,\ \mathbf{B}_\omega \| \mathbf{B}_0$

$$\mathbf{M}_{\mathrm{ICM}\perp} = 8 c_{2,0} \frac{I_\omega}{c} \frac{\mathbf{B}_0}{\mu_0}$$

Rizzo *et al*, *EPL*, **90**, 64003 (2010) http://www.izest.polytechnique.edu

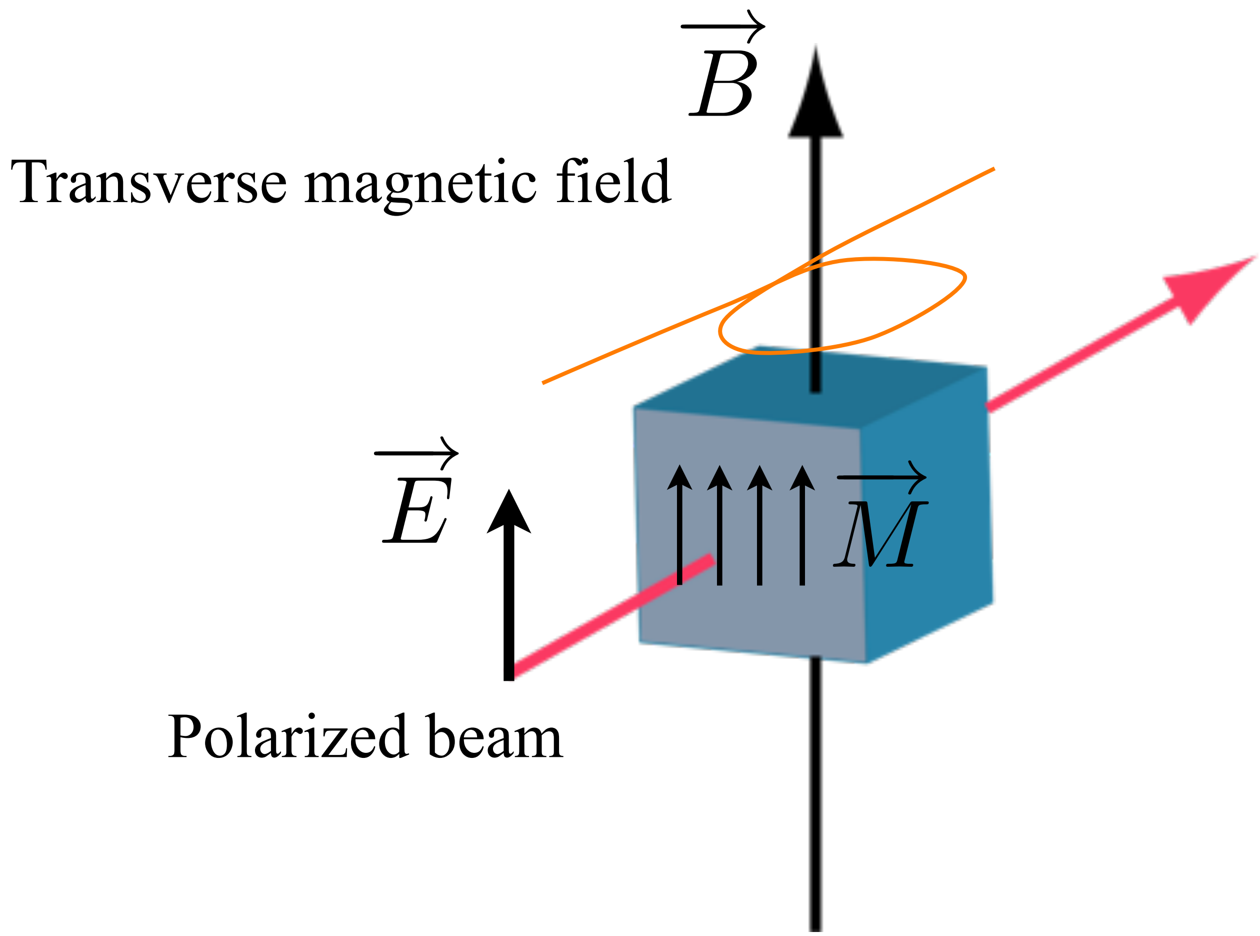


why not...

$I_\omega = 10^{26} \mathrm{W/m^2}$ $\quad \mathrm{B_0} = 30\ \mathrm{T}$ $\quad \Longrightarrow \quad \mu_0 \mathbf{M}_{\mathrm{ICM}\parallel} = 2 \times 10^{-10}\ \mathrm{T}$

ICME in a TGG crystal

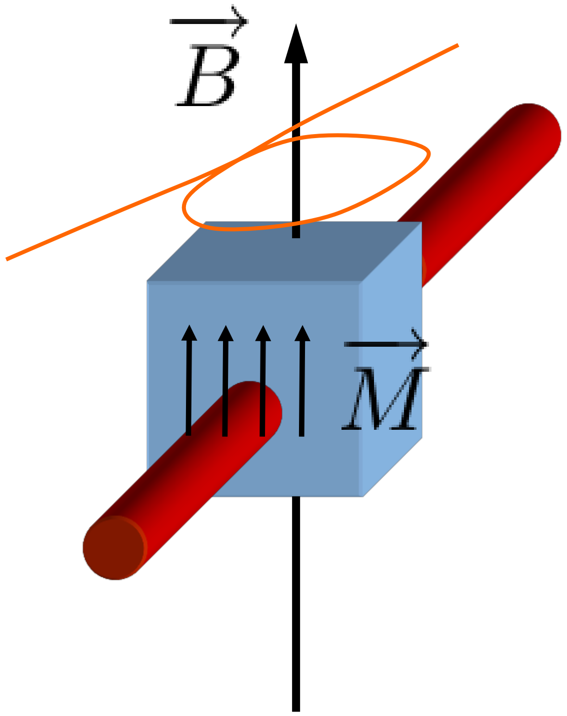
A linearly polarized beam induces a magnetization in a medium subjected to a transverse magnetic field



$$\overrightarrow{M} \propto \overrightarrow{E}^2 \overrightarrow{B} \propto P_{laser} \overrightarrow{B}$$

Principle of ICME measurement

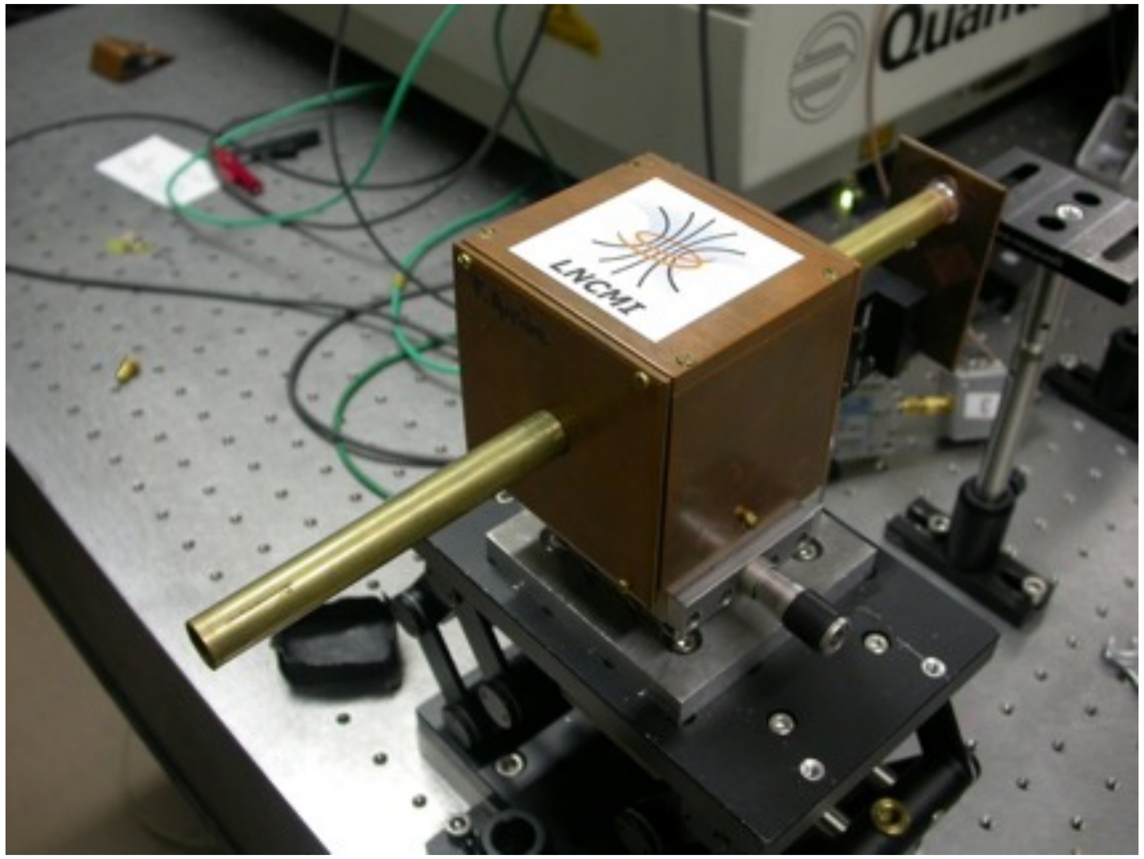
$$\overrightarrow{M} \propto P_{laser} \overrightarrow{B}_{ext}$$



$$\overrightarrow{B}_{ind}$$

$$V(t) = -\frac{dB_{ind}}{dt}$$

$$V(t) = cte \times B_{ext} \times \frac{dP_{laser}}{dt}$$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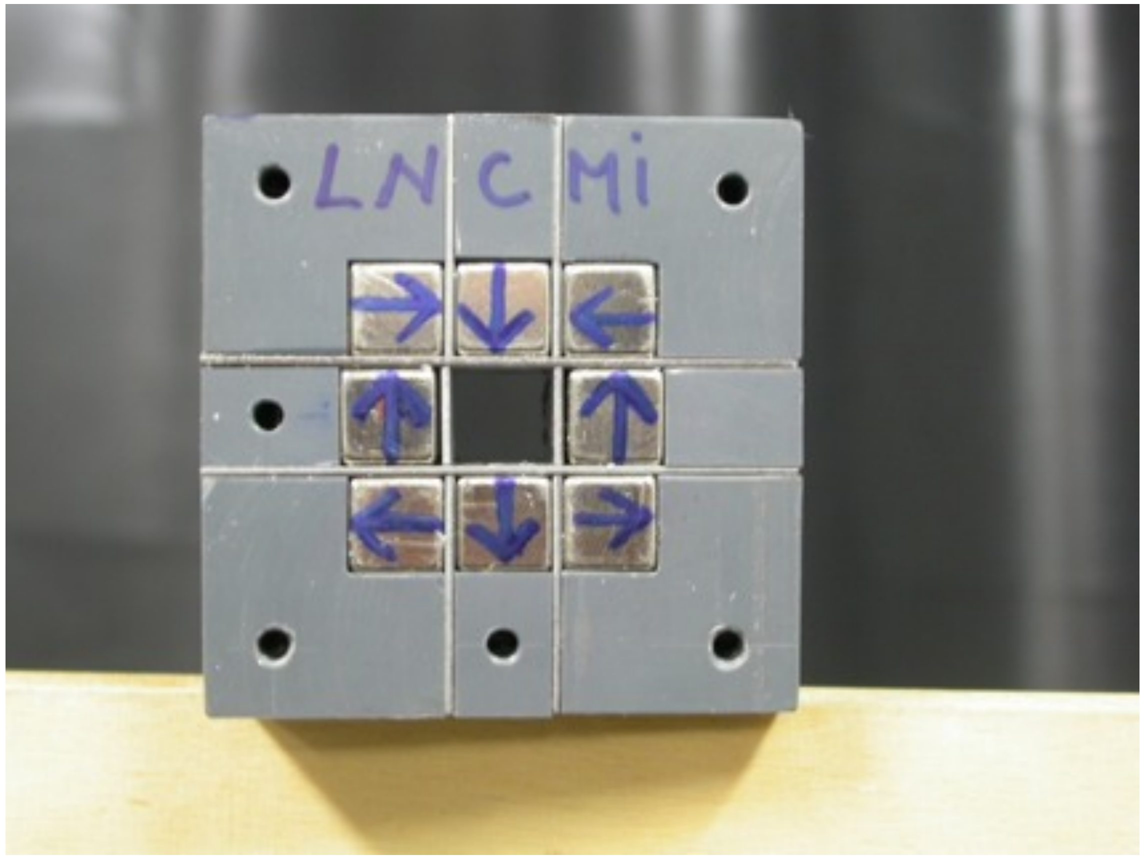
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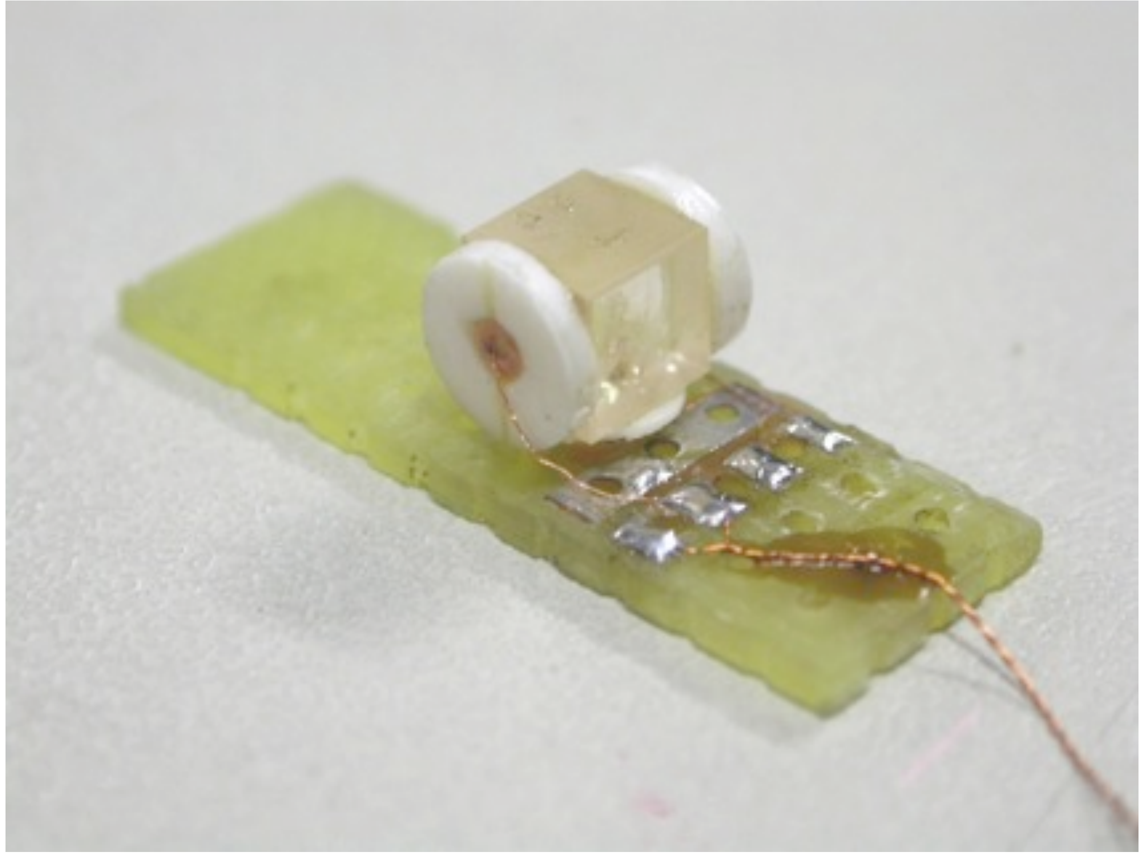
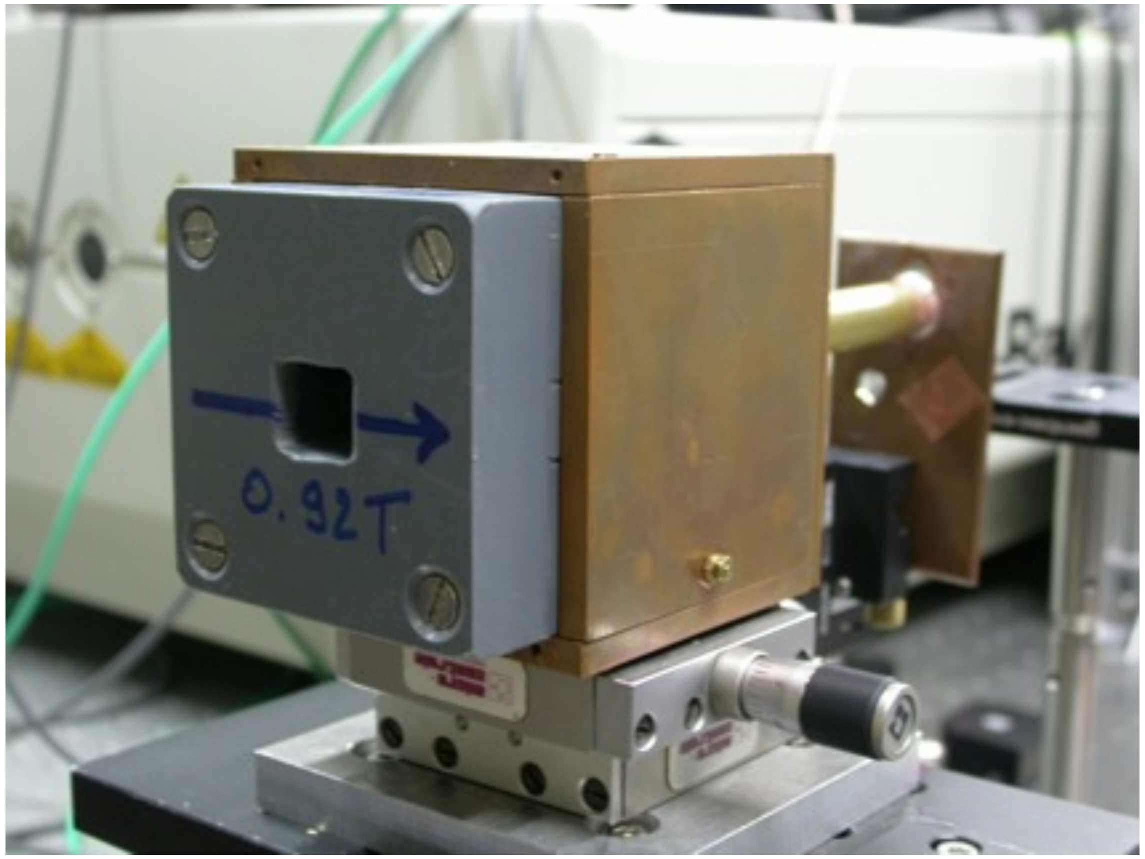
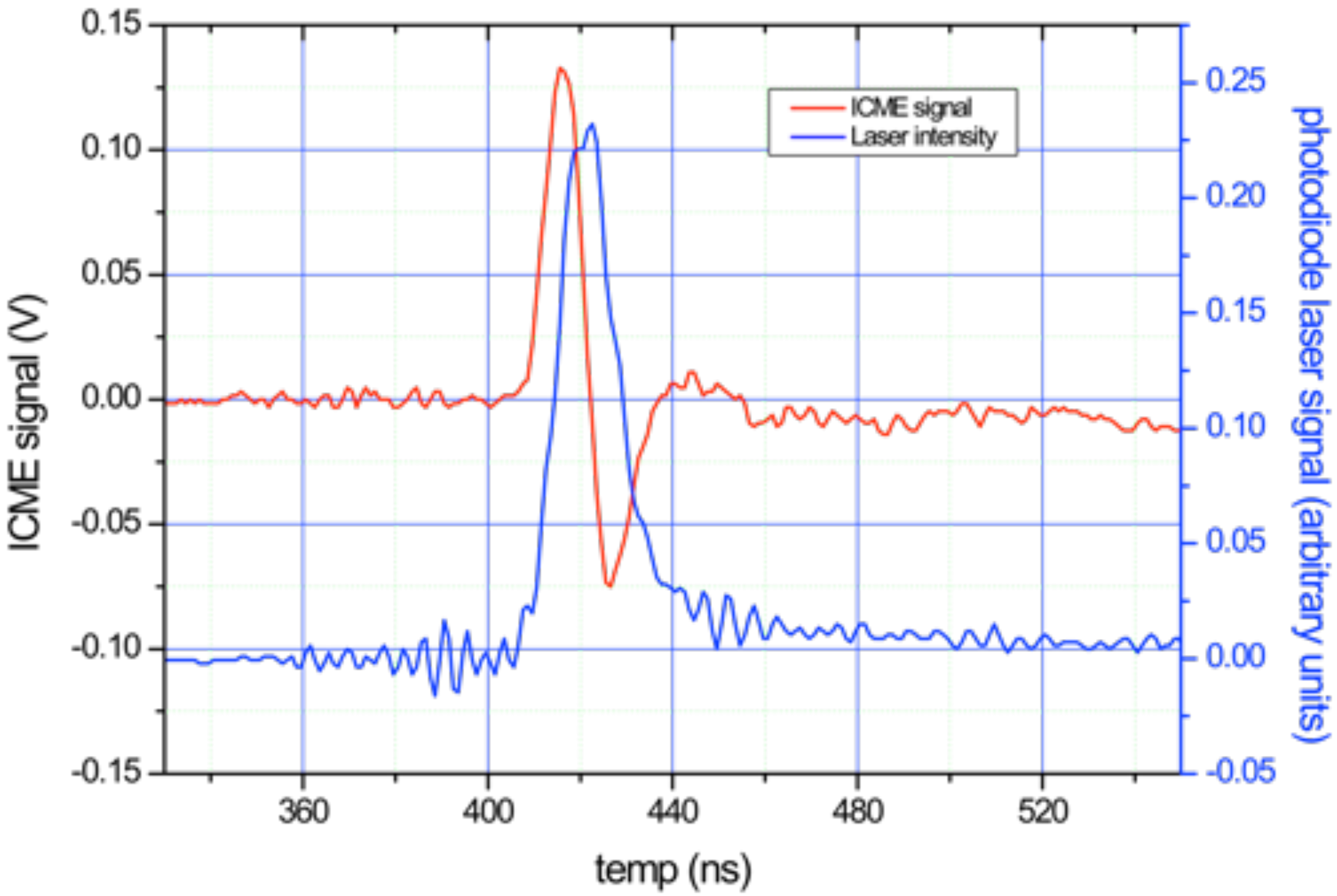
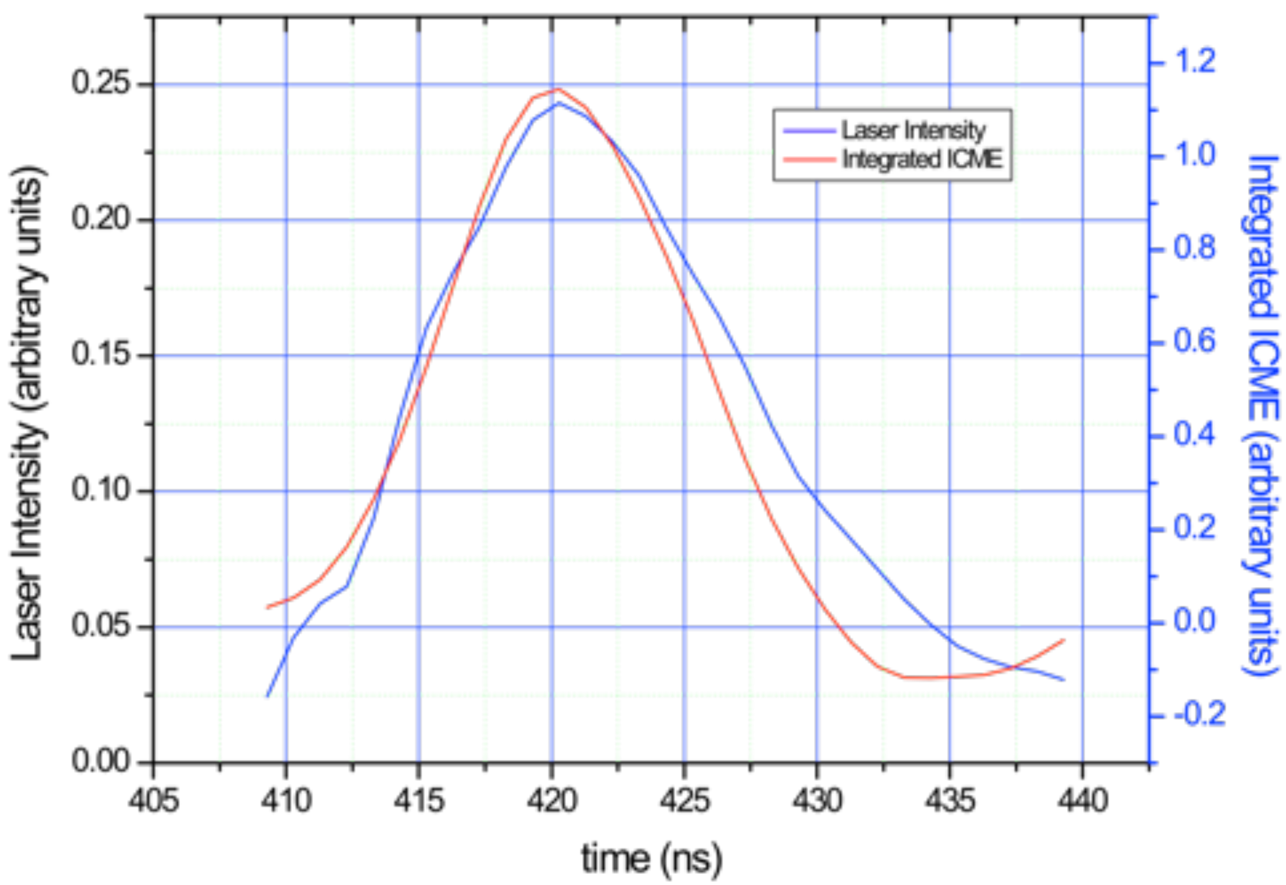


0.92T

Results in a TGG crystal

$$V(t) = -gA_e bB_{ext}\frac{dP_{laser}(t)}{dt}$$





The signal is proportionnal to the time derivative of the power density of the laser.

A. Baranga *et al*, *EPL* **94**, 44005 (2011)

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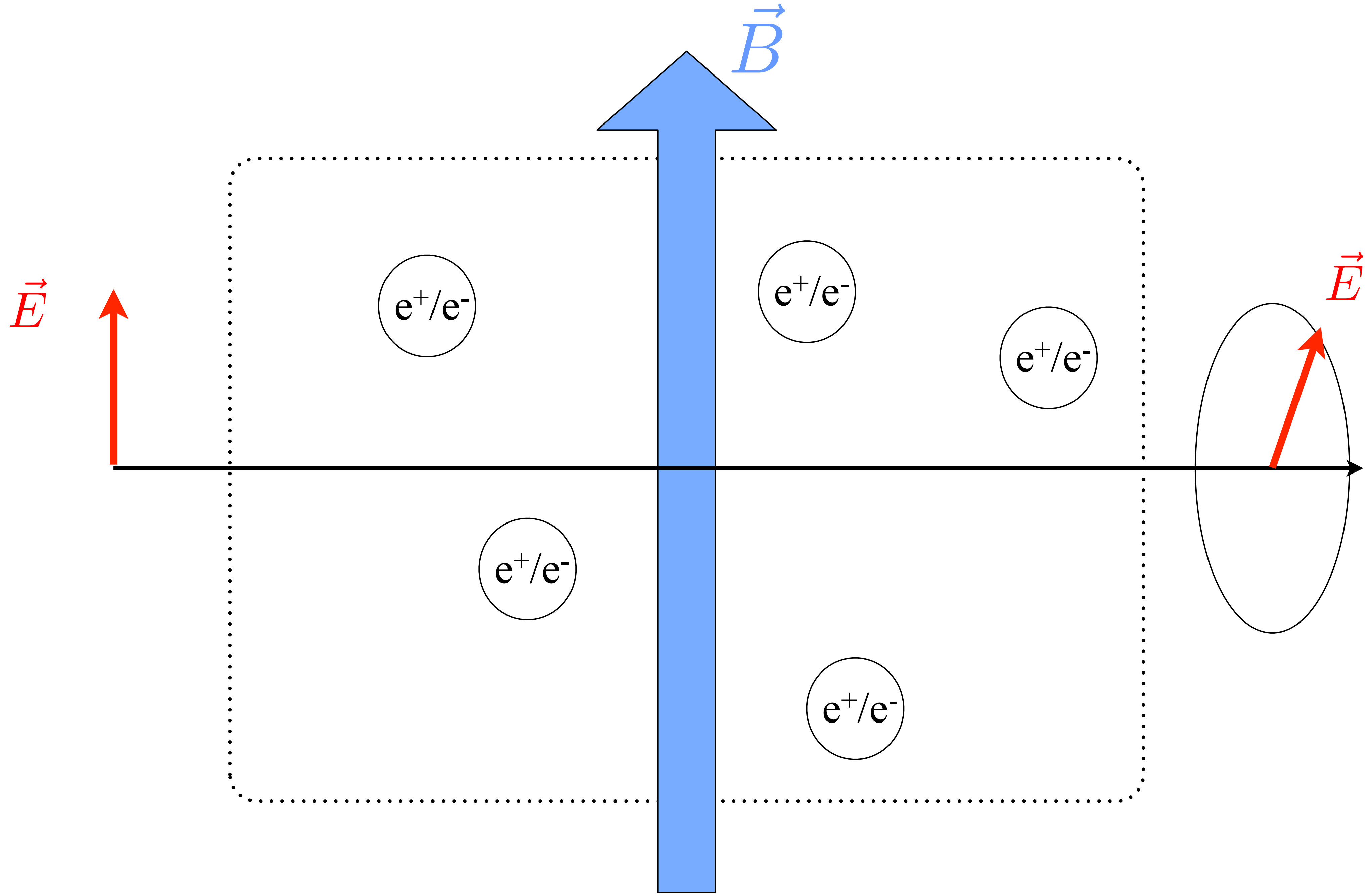
   a. Principle of the measurement

   b. Experimental setup

   c. Magnetic birefringences

Vacuum Magnetic Birefringence

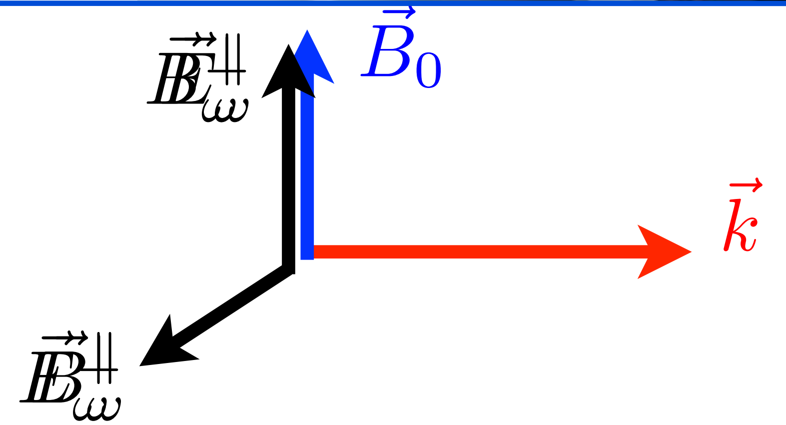
Vacuum...and fluctuations + transverse magnetic field



Vacuum Magnetic Birefringence

$$\mathbf{P}^{CM} = -4c_{2,0}\epsilon_0\frac{B_0^2}{\mu_0}\mathbf{E}_\omega + 2c_{0,2}\frac{\epsilon_0}{\mu_0}\mathbf{B}_0(\mathbf{E}_\omega\cdot\mathbf{B}_0),$$

$$\mathbf{M}^{CM} = 4c_{2,0}\frac{B_0^2}{\mu_0^2}\mathbf{B}_\omega + 8c_{2,0}\frac{\mathbf{B}_0}{\mu_0^2}(\mathbf{B}_\omega\cdot\mathbf{B}_0)$$



$$\epsilon_\parallel = \epsilon_0 - 4c_{2,0}\frac{\epsilon_0}{\mu_0}B_0^2 + 2c_{0,2}\frac{\epsilon_0}{\mu_0}B_0^2$$

$$\epsilon_\perp = \epsilon_0 - 4c_{2,0}\frac{\epsilon_0}{\mu_0}B_0^2$$

$$\mu_\parallel = \mu_0(1 + 4c_{2,0}\frac{1}{\mu_0^2}B_0^2)$$

$$\mu_\perp = \mu_0(1 + 12c_{2,0}\frac{1}{\mu_0^2}B_0^2)$$

$$n_\parallel = \frac{\sqrt{\epsilon_\parallel\mu_\parallel}}{\sqrt{\epsilon_0\mu_0}} = 1 + c_{0,2}\frac{B_0^2}{\mu_0}$$

$$n_\perp = \frac{\sqrt{\epsilon_\perp\mu_\perp}}{\sqrt{\epsilon_0\mu_0}} = 1 + 4c_{2,0}\frac{B_0^2}{\mu_0}$$

$$\Delta n_{CM} = n_\parallel - n_\perp = (c_{0,2} - 4c_{2,0})\frac{B_0^2}{\mu_0}$$

QED

Vacuum Magnetic Birefringence

❑ Birefringence and fondamental constants

$$\Delta n_{CM} = \left(\frac{2\alpha^2\hbar^3}{15 m_e^4 c^5} + \frac{5}{6}\frac{\alpha^3\hbar^3}{\pi m_e^4 c^5}\right)\frac{B_0^2}{\mu_0} = \frac{2\alpha^2\hbar^3}{15 m_e^4 c^5}\left(1 + \frac{25\alpha}{4\pi}\right)\frac{B_0^2}{\mu_0}$$

$$\Delta n_{CM} = k_{CM}\ B^2$$

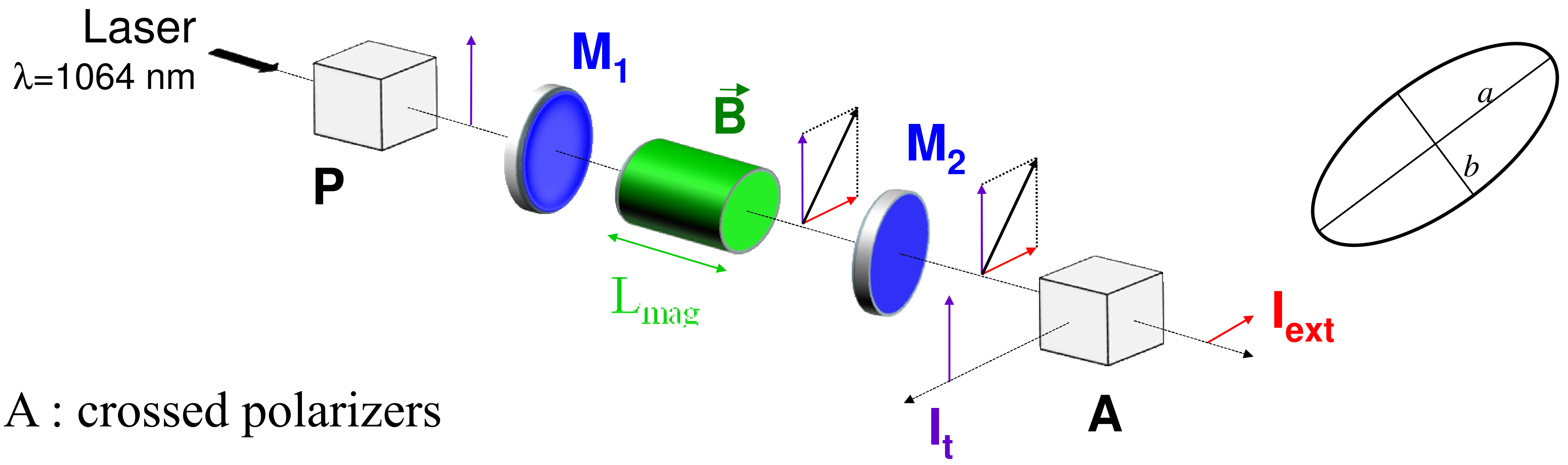
CODATA 2012

$$k_{CM} = (4.0317 \pm 0.0009) \times 10^{-24}\ \mathrm{T}^{-2}$$

great experimental challenge !

Development of a **very sensitive ellipsometer** in order to be able to observe for the first time this QED prediction

Ellipsometer



- P and A : crossed polarizers

- B at 45° from incident polarization

- Ellipticity to be measured $$\Psi(t) = \frac{\pi}{\lambda} k_{CM} \left(\frac{2F}{\pi}\right) B(t)^2 L_{mag} \sin(2\theta_p)$$

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Laboratoire National des Champs Magnétiques Intenses

LNCMI

Intense magnetic fields ?

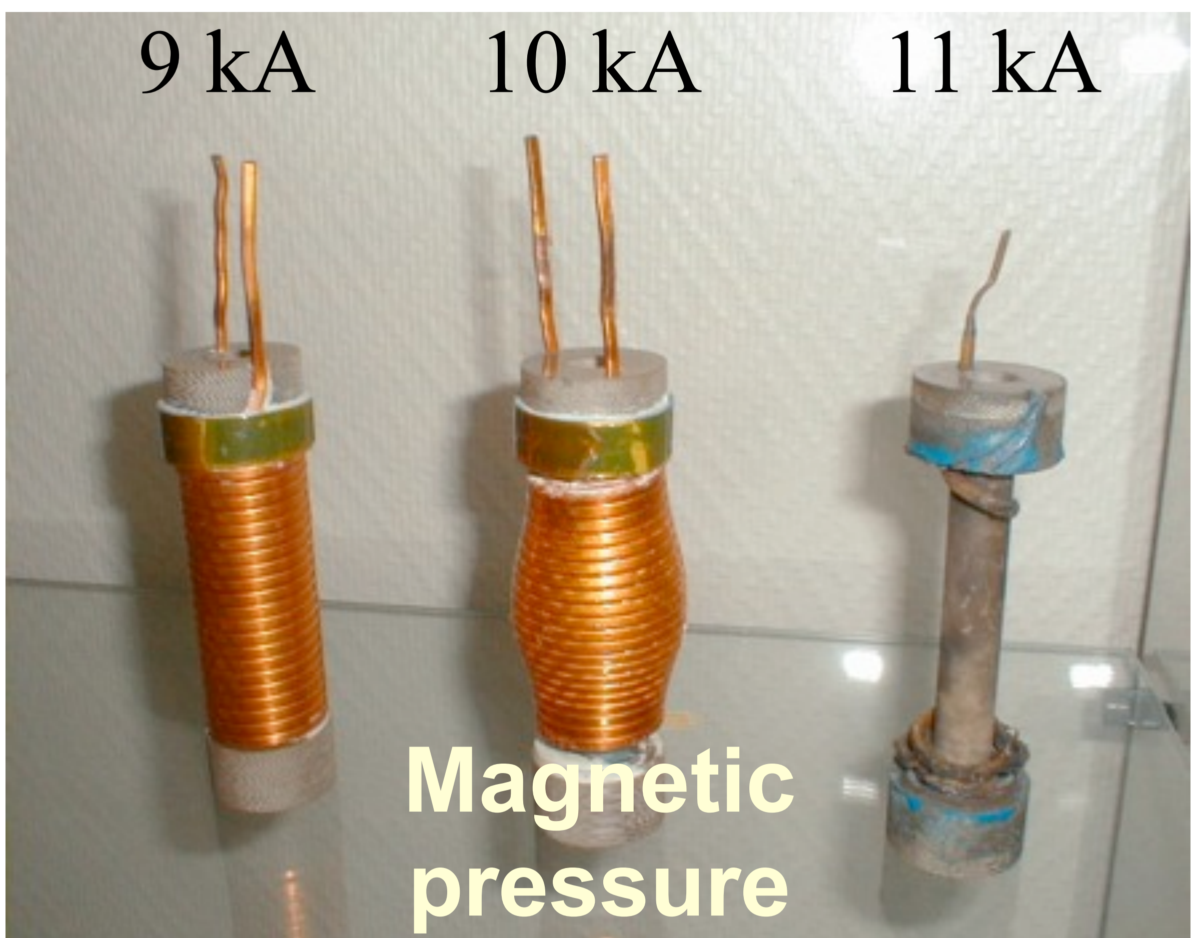
The only method : having a strong current circulating into a coil

Two problems :

Heating ! → Superconductor (limited by B_{crit})

Heating ! → Cooling

Heating ! → Pulsed field

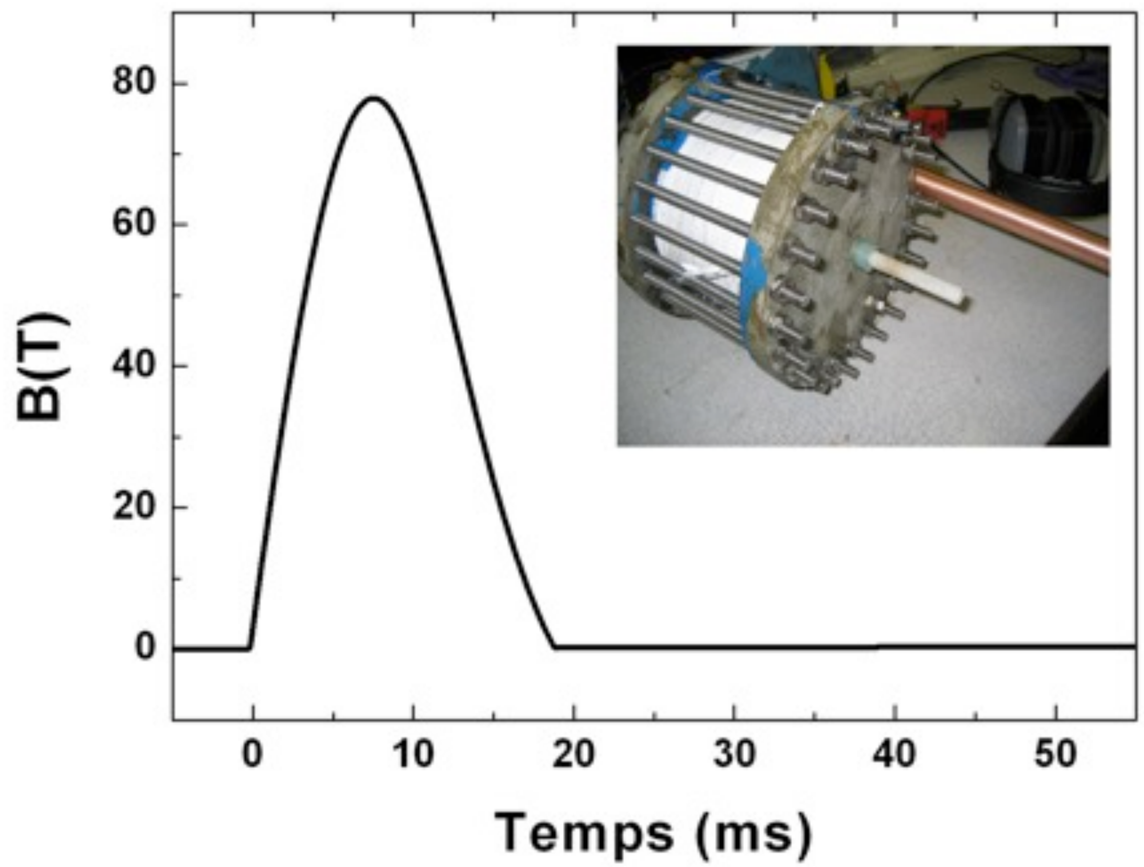


Magnetic pressure ! $\frac{B^2}{\mu_0}$

→ Ultra strong conductors

→ External reinforcement

Faraday configuration

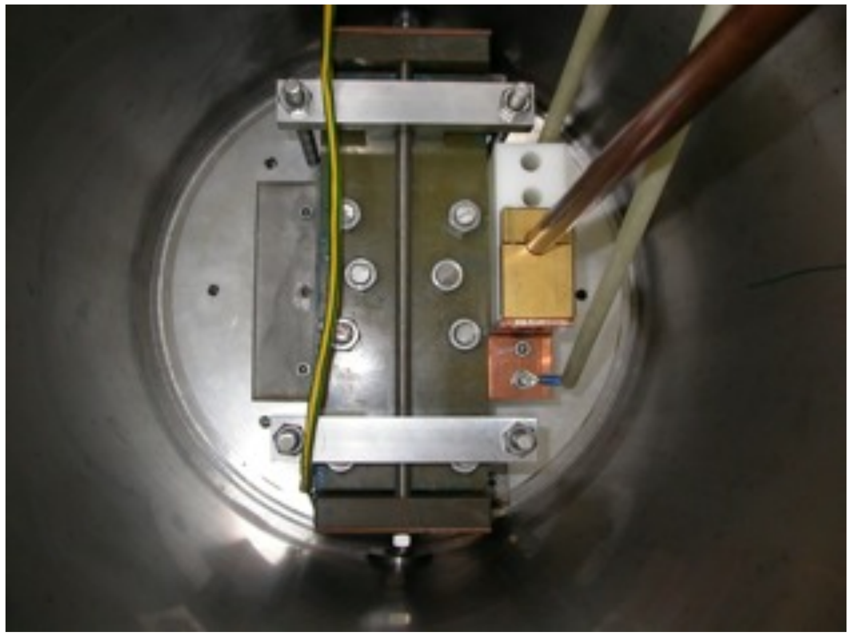


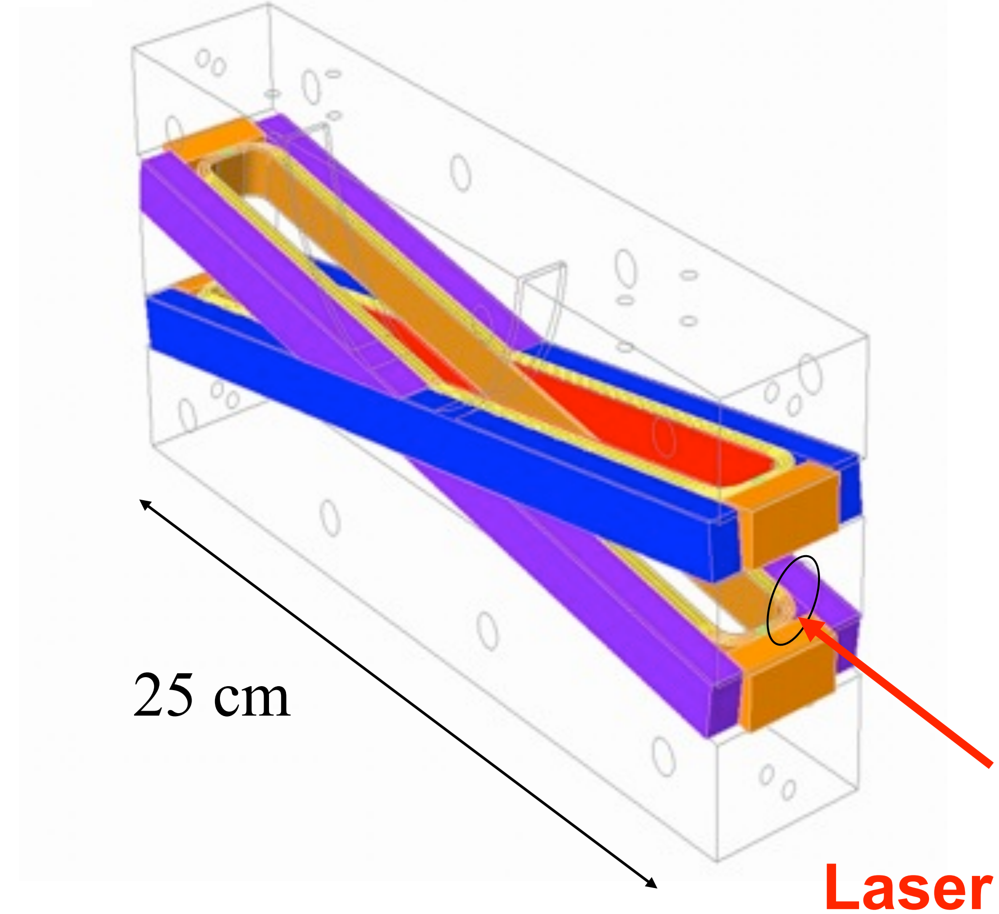
LNCMI Toulouse

14 MJ, 1 GW

Magnetic field : X-Coil

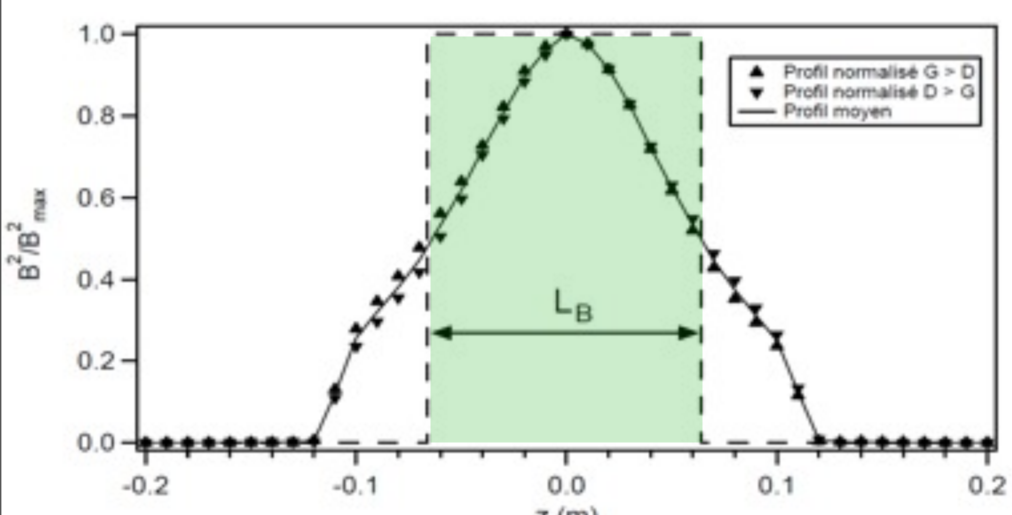
❑ Transverse magnetic field

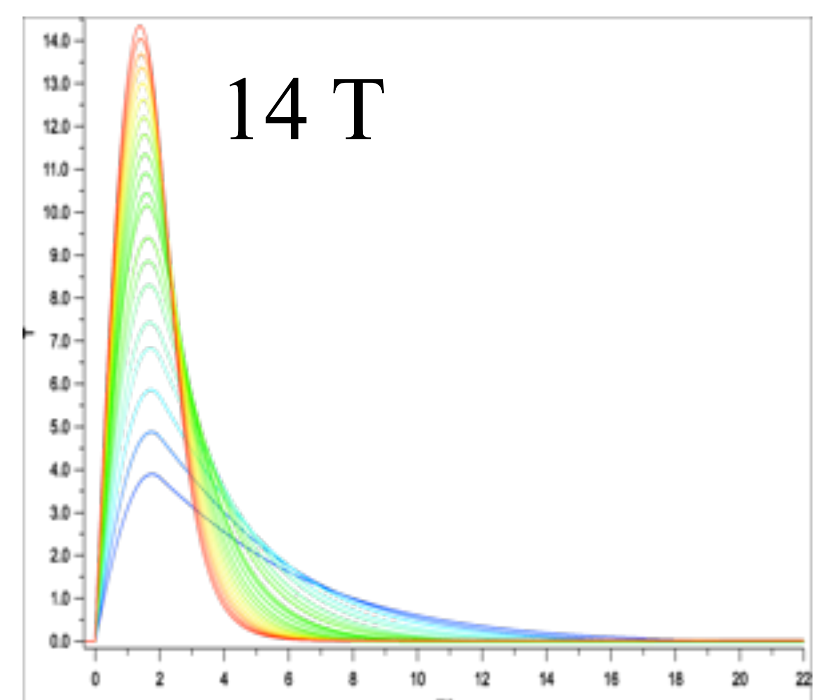




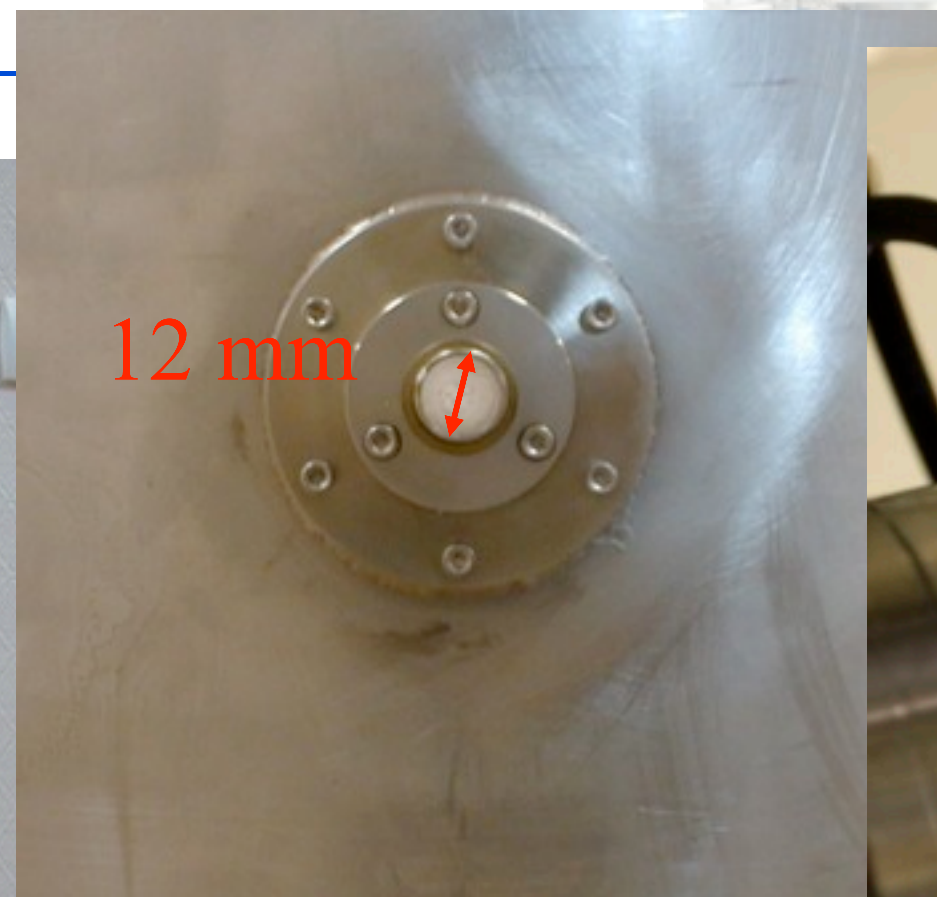
$$B(t)^2 L_{mag} = (6,5\ \mathrm{T})^2 \times 13,7\mathrm{cm}\ = 5{,}7\ \mathrm{T}^2.\mathrm{m}$$

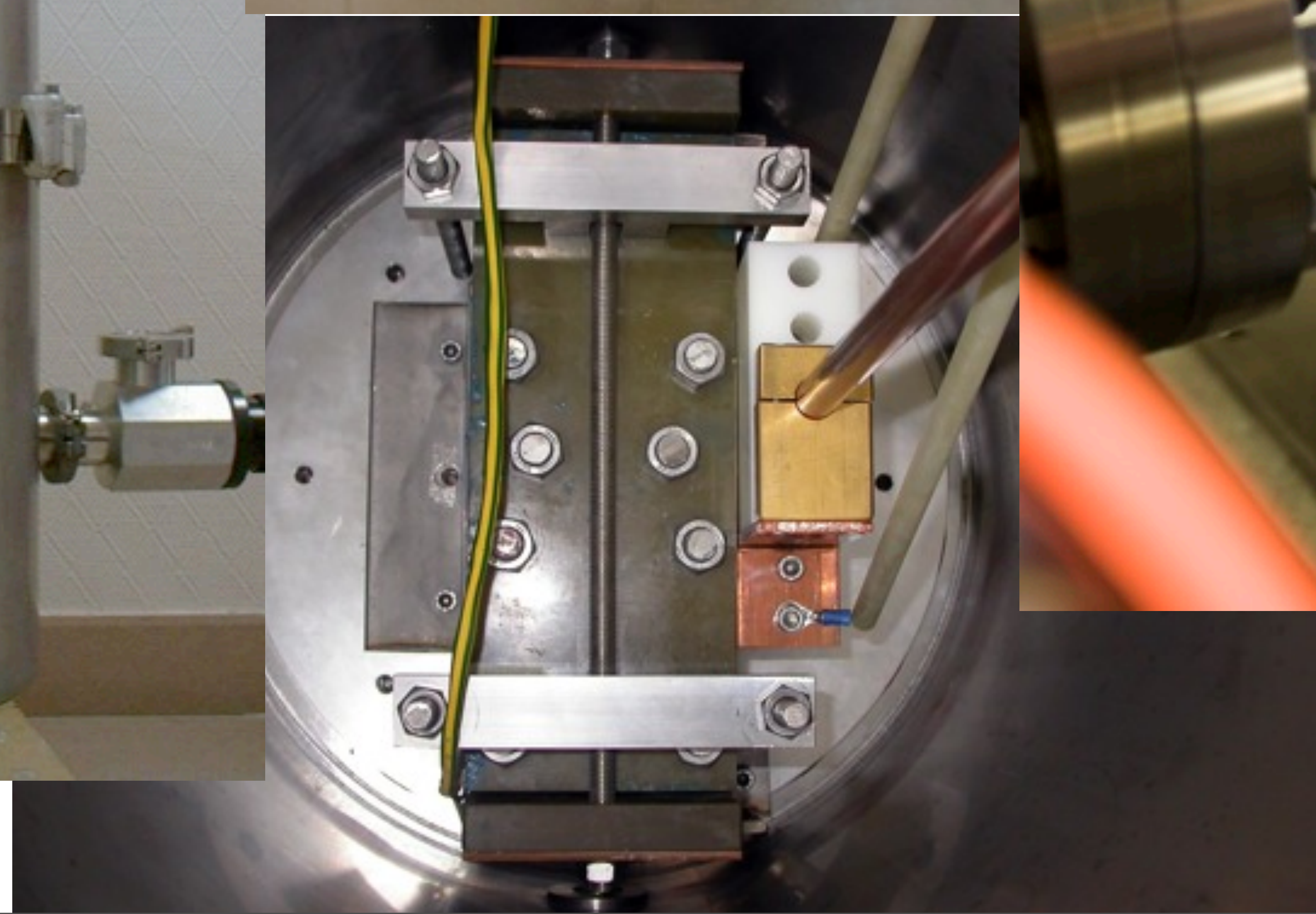
- profil :

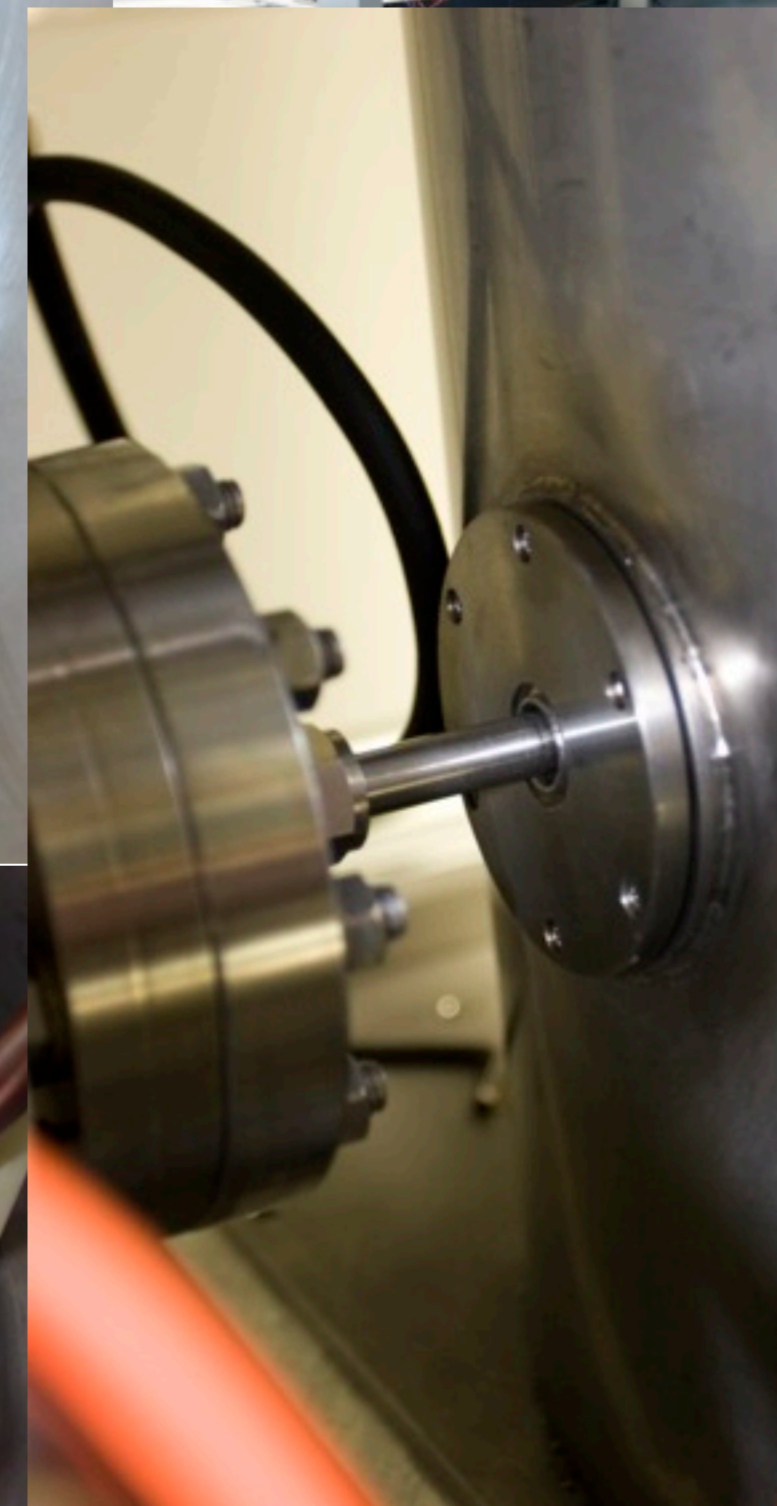




Cryostat







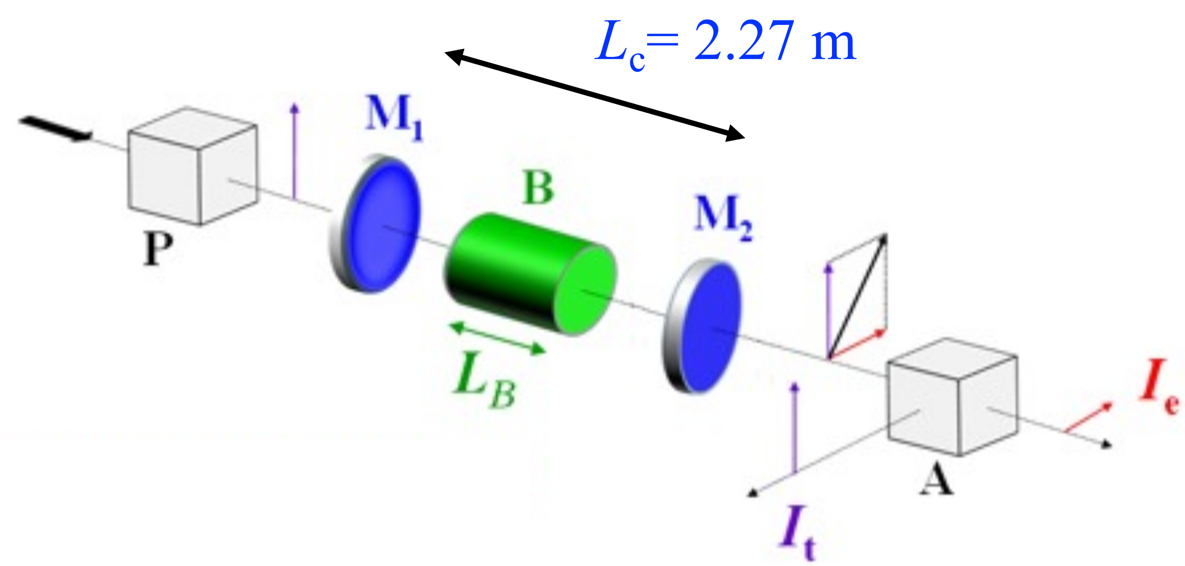
Fabry Perot cavity

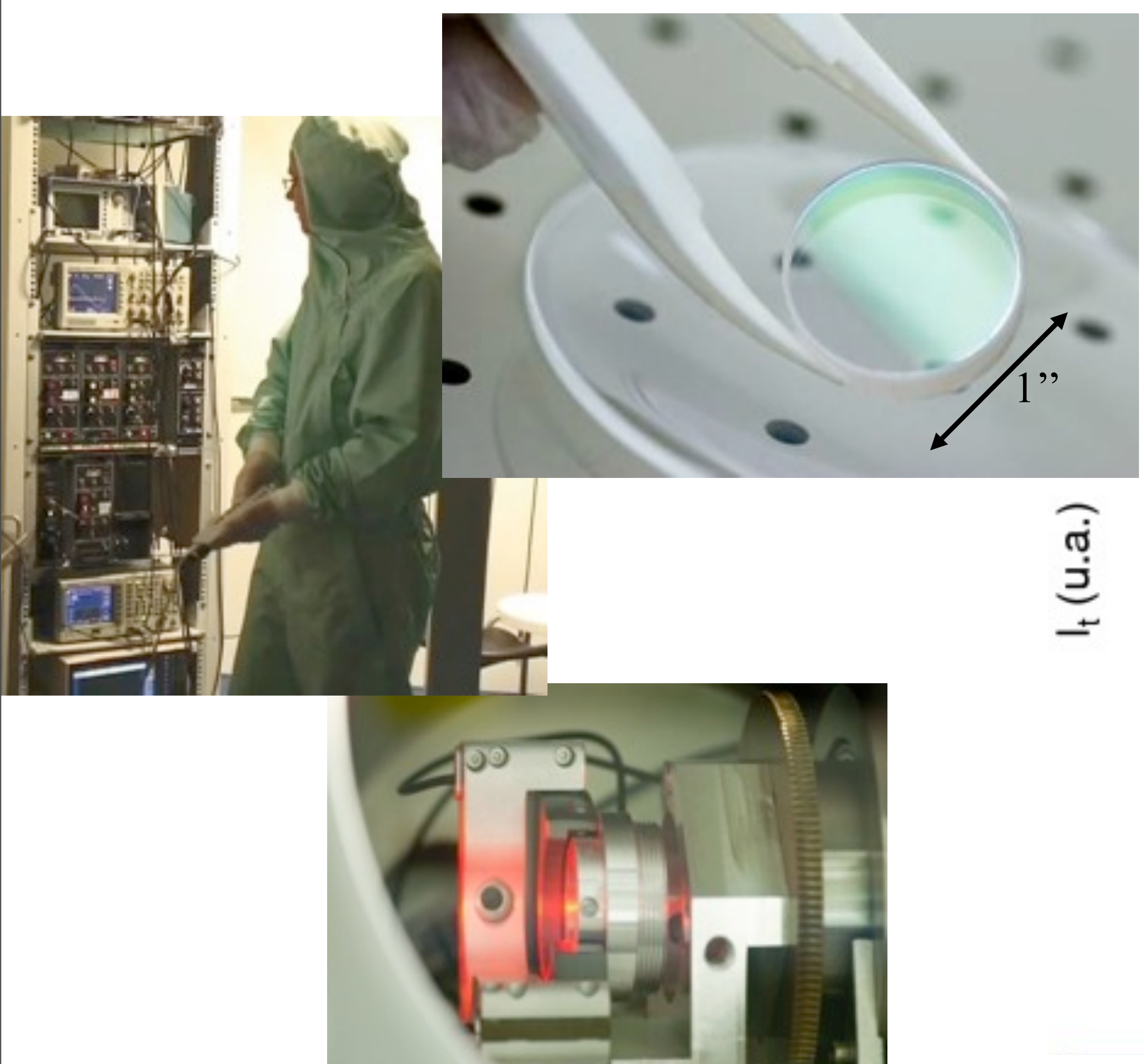
❑ Ellipticity :

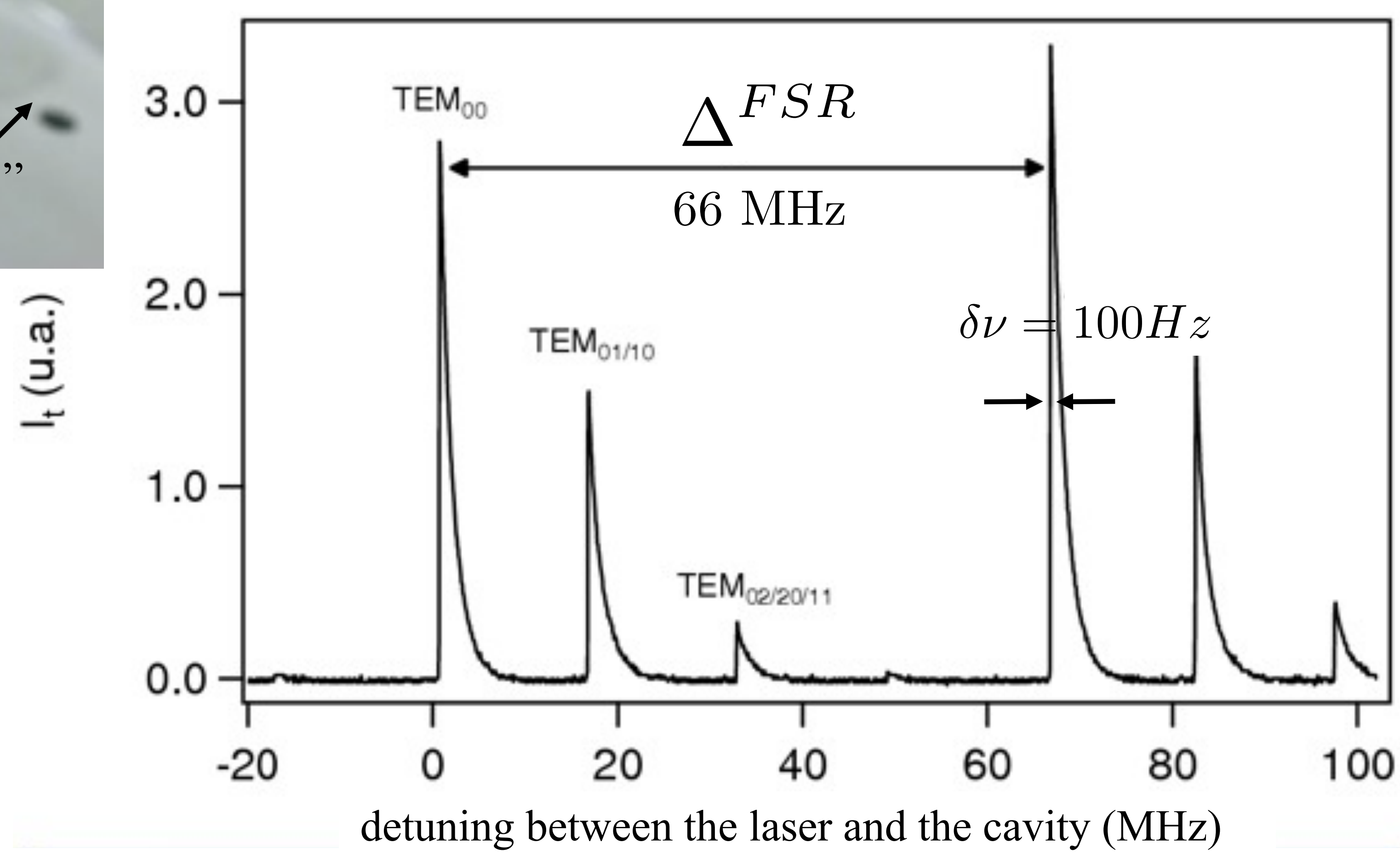
$$\Psi(t) = \frac{\pi}{\lambda} k_{CM} \left(\frac{2F}{\pi}\right) B(t)^2 L_{mag} \sin(2\theta_p)$$

❑ Finesse :

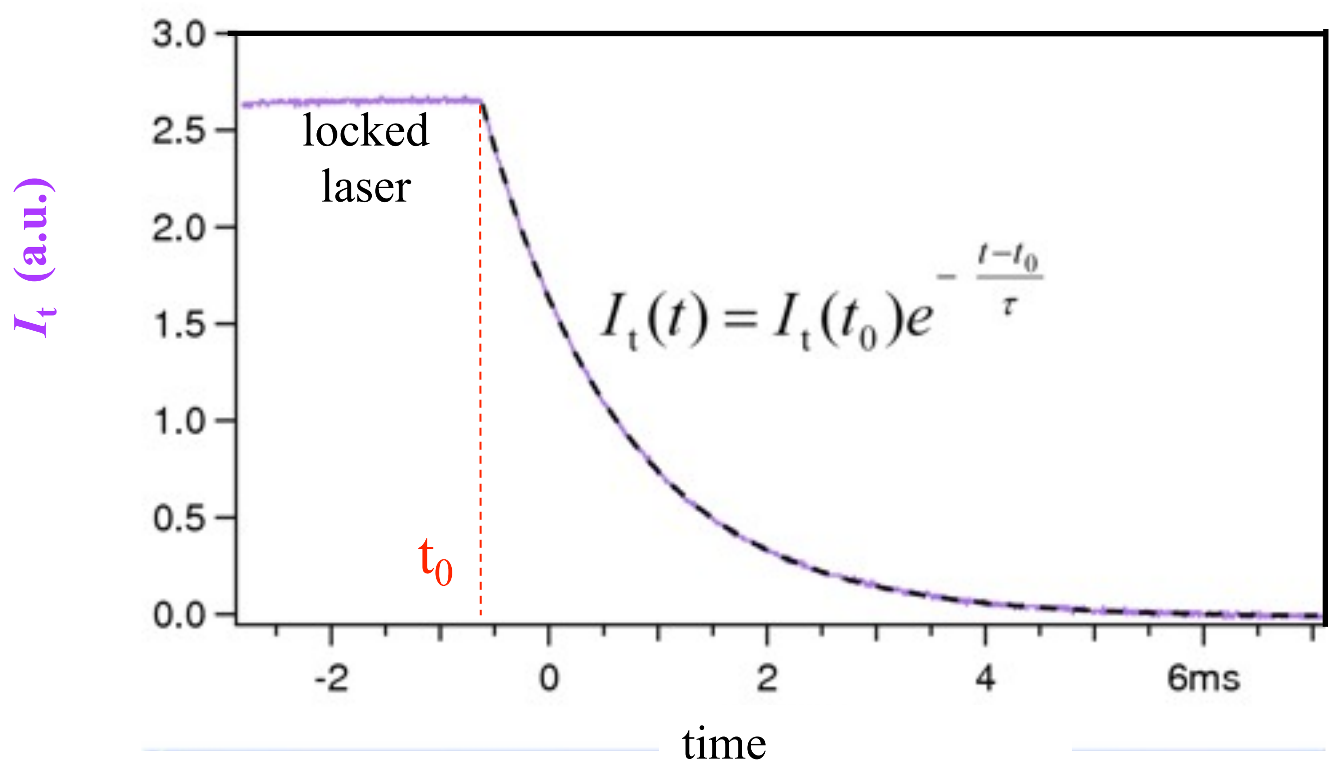
High reflectivity mirrors $\quad \mathrm{F} \simeq 450\ 000$

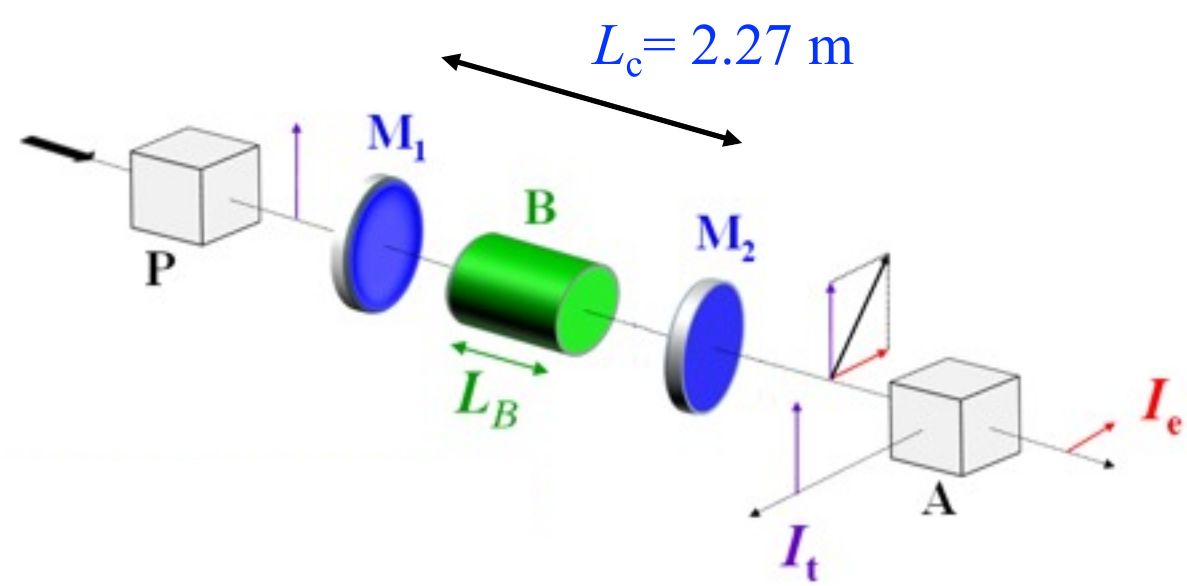






❑ Photon lifetime (τ):





Record :

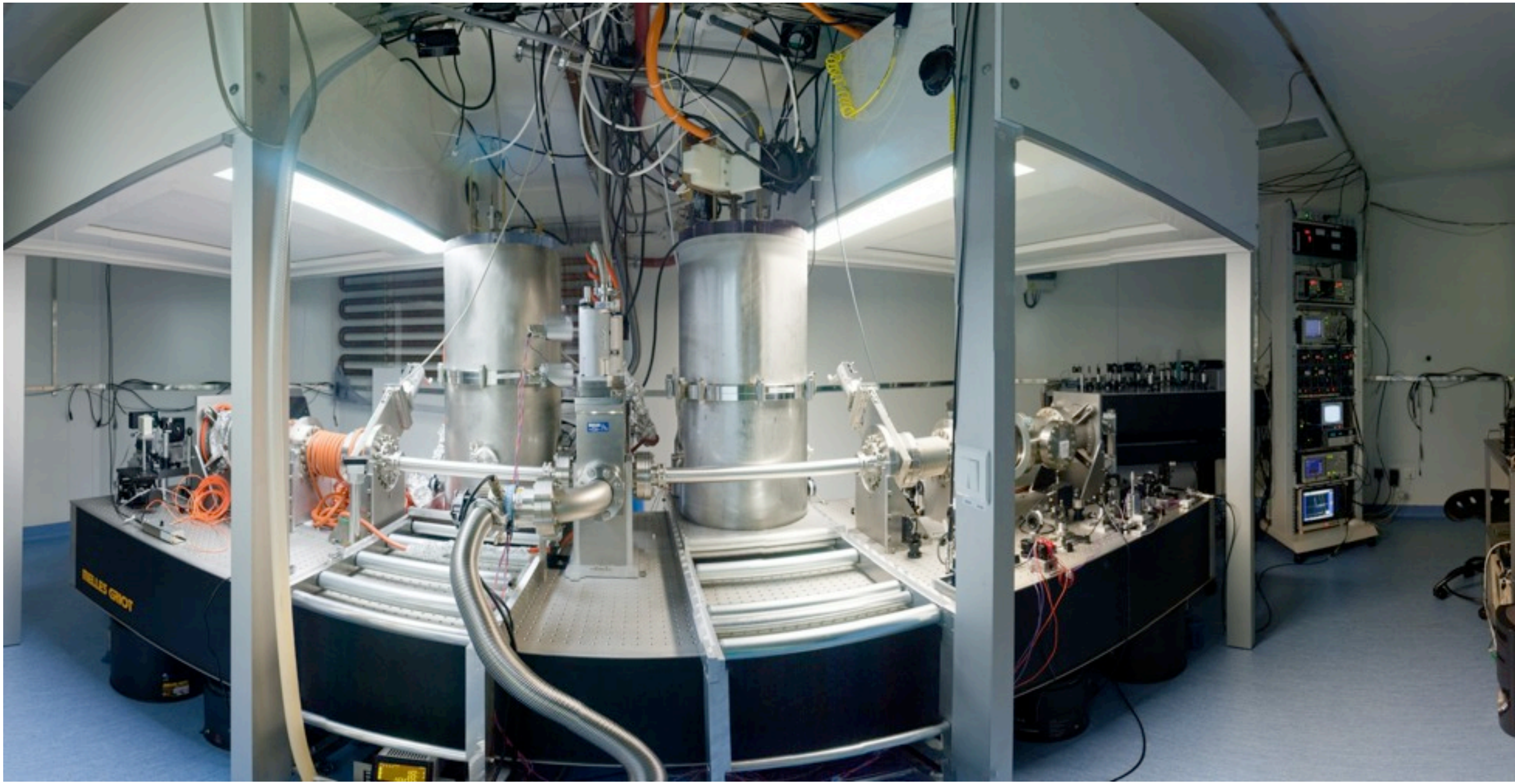
$$\tau = (1.28 \pm 0.03)\ \text{ms}$$

$$F = \frac{\pi c \tau}{L} = 530000$$

Other cavity around the world :

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

Experimental setup in the cleanroom



OUTLINE

1. Quantum vacuum seen by an experimentalist in optics

2. Inverse Cotton Mouton Effect of vacuum

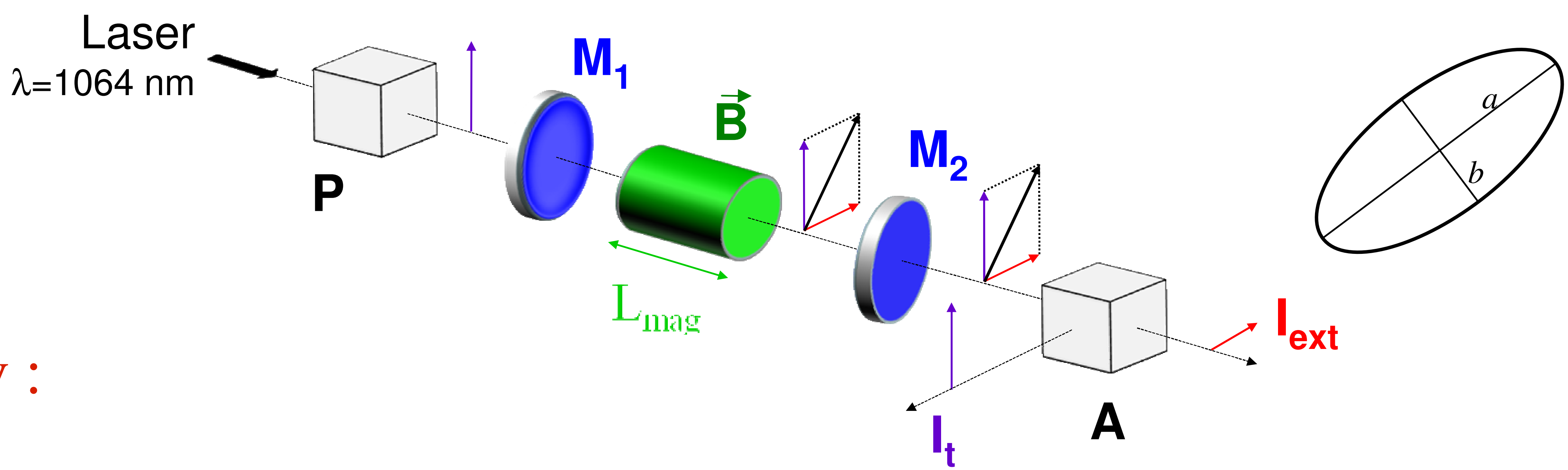
3. Vacuum Magnetic Birefringence

    a. Principle of the measurement

    b. Experimental setup

    c. Magnetic birefringences

Data analysis in gases



❑ Ellipticity :

Cotton-Mouton   Rotation of the major axis of the ellipse

$$\frac{I_e}{I_{t,f}} = \sigma^2 + [\Gamma + \Psi(t)]^2 + [\epsilon + \theta_F(t)]^2$$

Faraday

extinction ratio of polarizers

4.10^{-7}

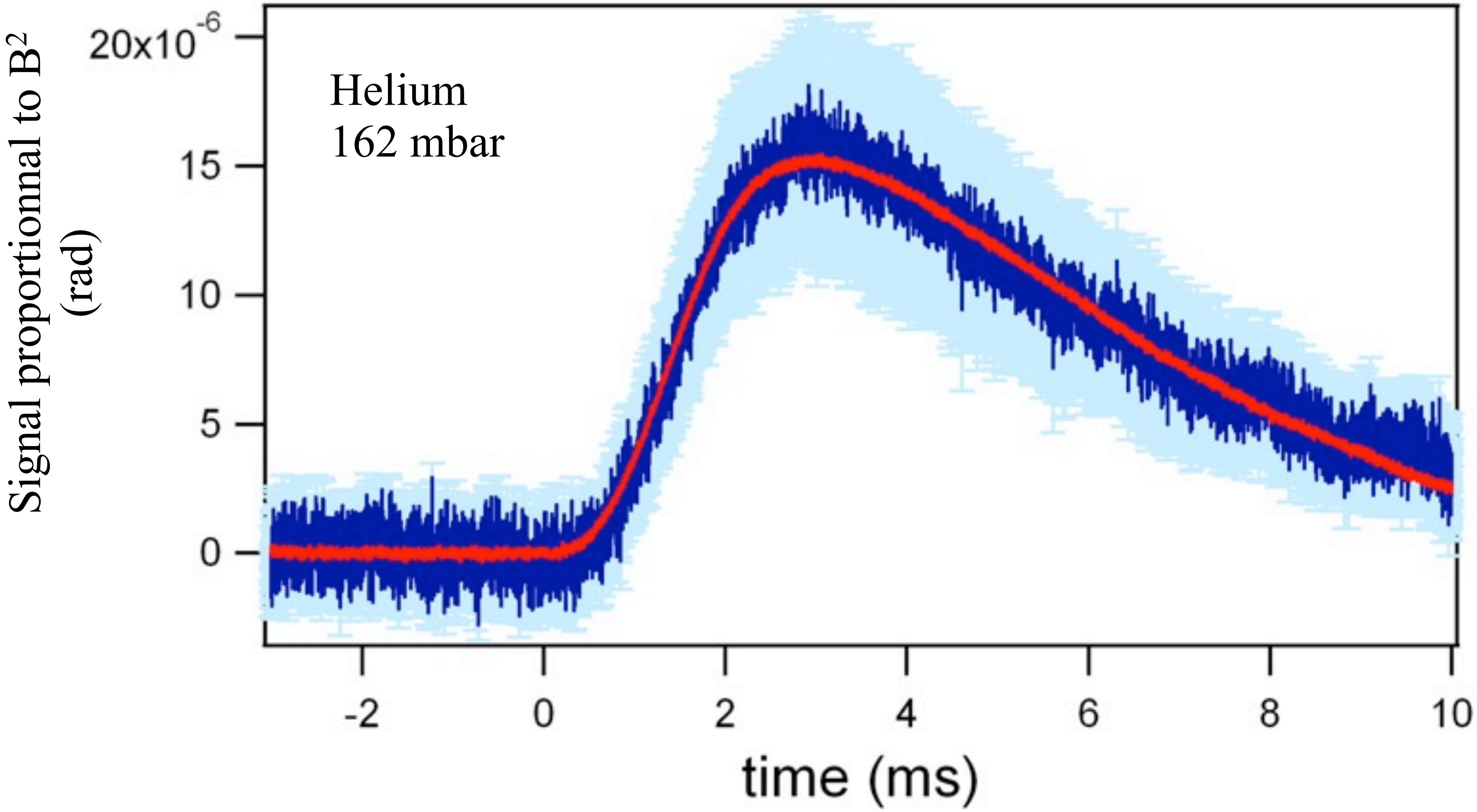
$\Psi(t)$ quantity to be measured
proportionnal to B²(t)

Static ellipticity of mirrors.

Can be tuned from σ value to higher values by turning the mirrors on their own axes

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

Measurements in gases



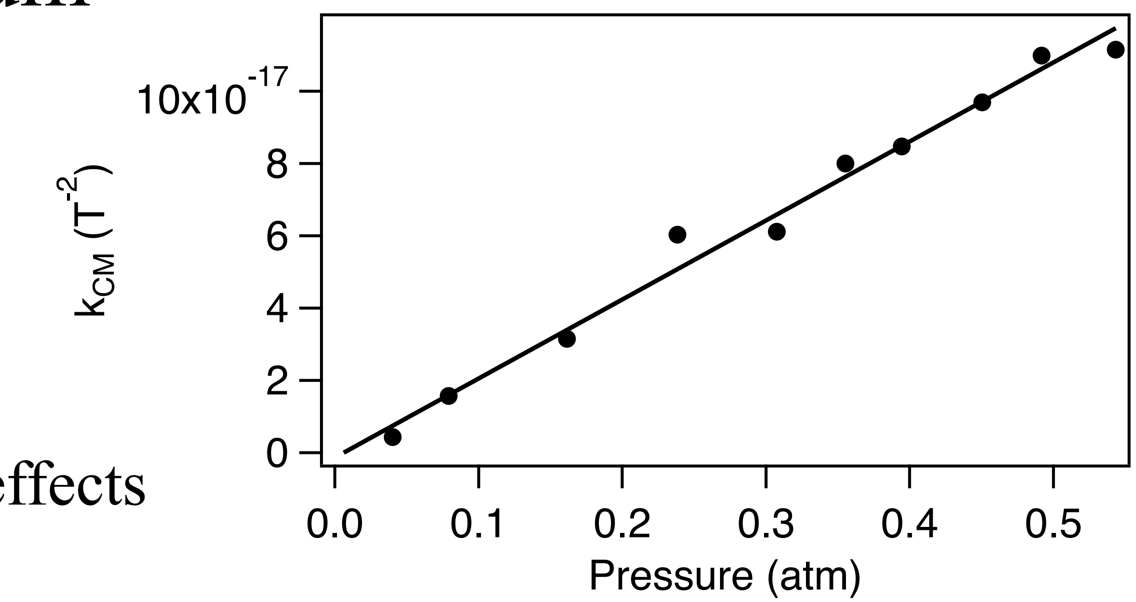
The experimental points (blue) are fitted with a curve proportionnal to B^2 (red).

Cotton Mouton effect in helium

Smallest effect in nature except for vacuum

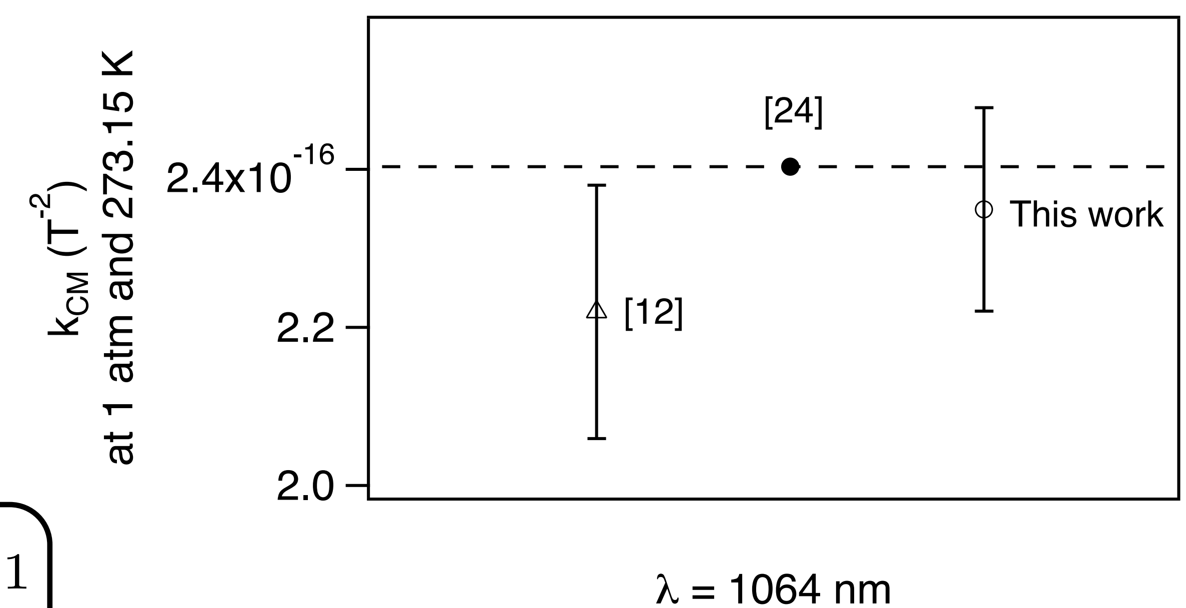
Tight test of our apparatus

Very hard experimental task
(mirrors rotation, Faraday effect cancellation, systematic effects cancellation)



→ A. Cadène *et al*, *Phys. Rev. A* **88**, 043815 (2013)

$$k_{CM} = \frac{\alpha}{4\pi\tau\Delta^{FSR}}\frac{\lambda}{L_B}\frac{1}{\sin 2\theta_p}$$



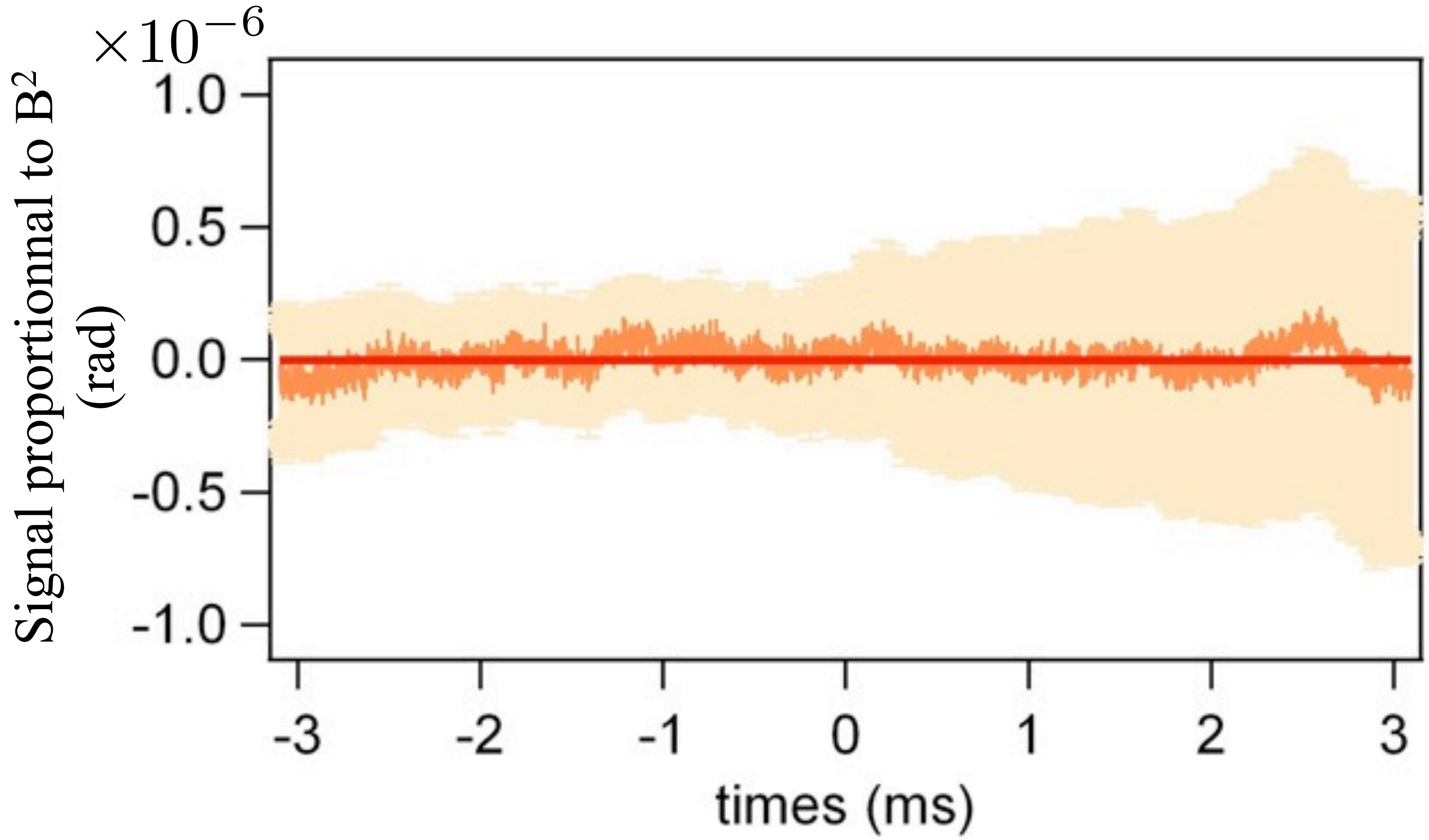
$$\boxed{k_{CM} = (2.35 \pm 0.13) \times 10^{-16}\ \mathrm{T}^{-2}\mathrm{atm}^{-1}}$$

M. Bregant *et al*., *Chem. Phys. Lett.* **471**, 322 (2009)
S. Coriani *et al*., J. *Chem. Phys.* **111**, 7828 (1999)

Measurements in vacuum

More than 100 pulses

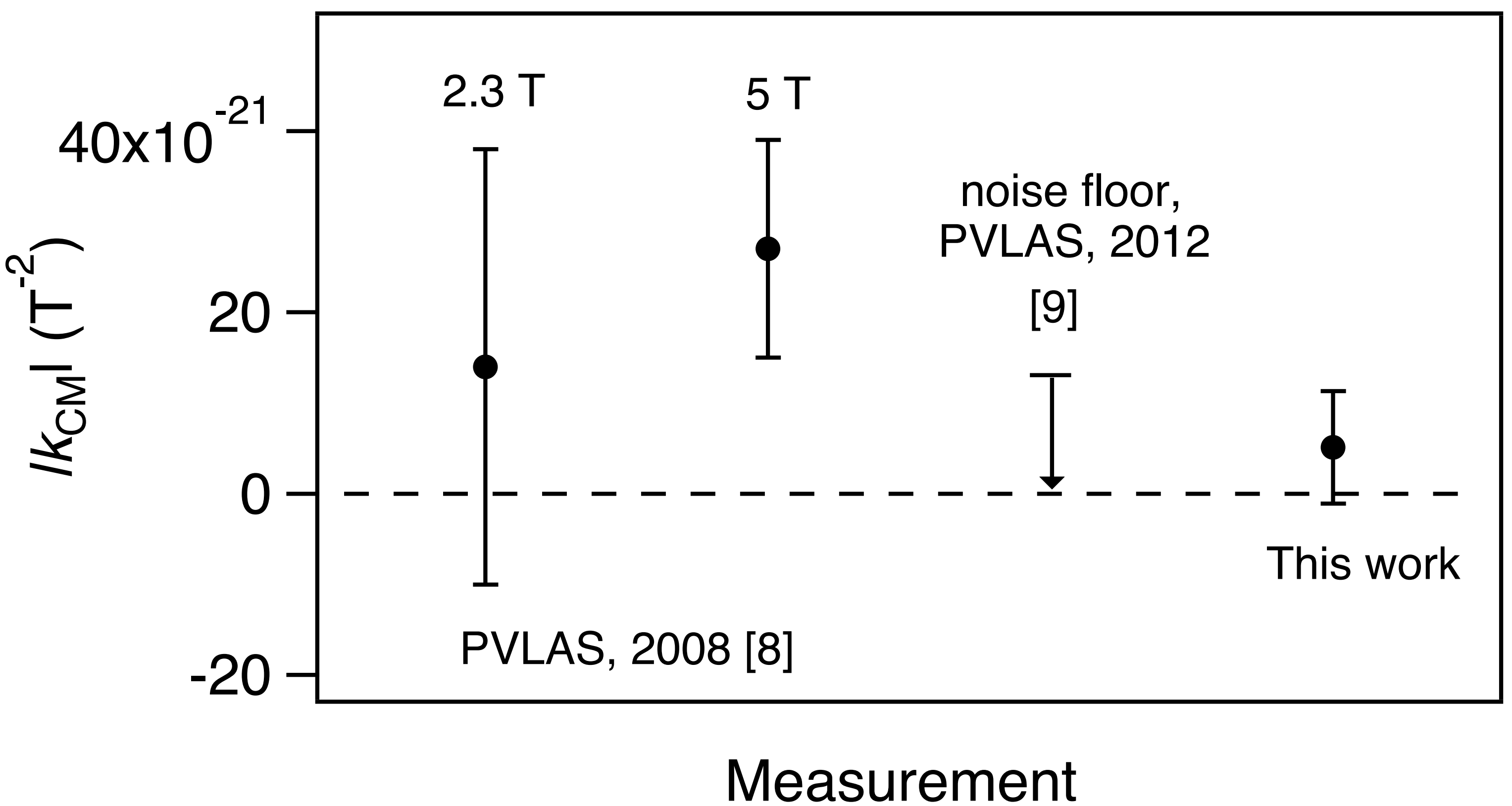
Systematic effects : take into account the symetry properties of the experiment with respect to the sign of B and the sign of Γ.



$$k_{CM} = (5.1 \pm 6.2) \times 10^{-21}\ \mathrm{T}^{-2} \quad \text{at } 3\sigma$$

A. Cadène et al., arXiv:1302.5389v2 (2013), submitted to PRD

Results



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)
A. Cadène et al., arXiv:1302.5389v2 (2013), submitted to PRD

Best measurement ever done in a vacuum

Conclusions

- Developement of a very sensitive ellipsometer for mesuring very small birefringences

- Sophisticated data analysis procedure to overcome systematic effects

- First measurement of Cotton-Mouton effect of helium compatible with theoritical prediction

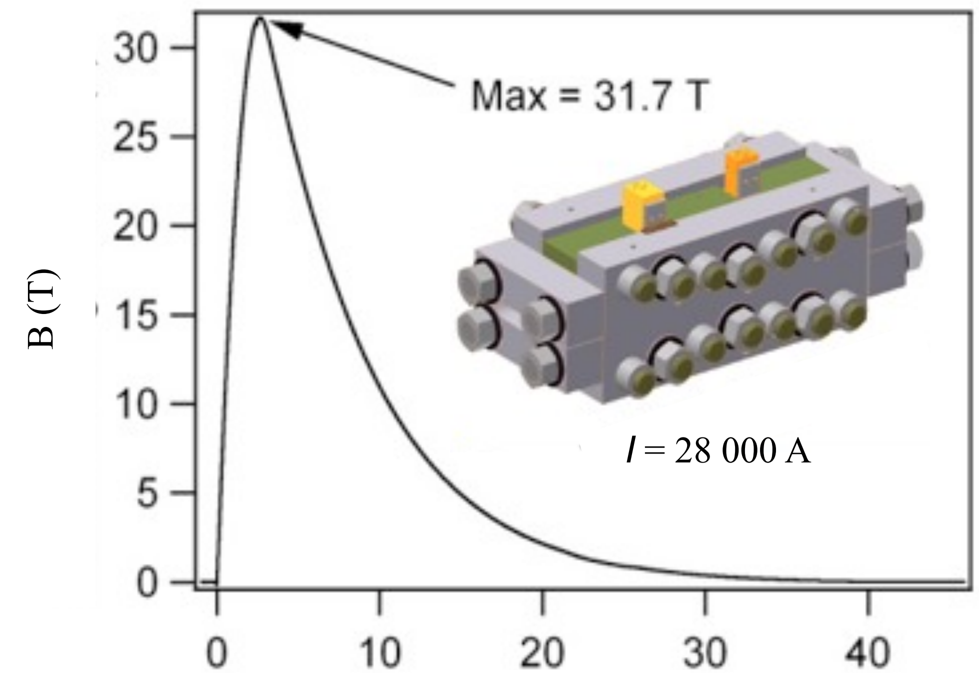
- Best sensitivity ever obtained for VMB experiments

$$\boxed{k_{CM} = (5.1 \pm 6.2) \times 10^{-21}\ \mathrm{T}^{-2}}$$

A. Cadène et al., arXiv:1302.5389v2 (2013), submitted to PRD

Perspectives

- ❑ Magnetic field enhancement : XXL-coils



$$B^2 L_B = 300\ \mathrm{T^2 m}$$

↳ insertion of 2 XXL-Coils

- ❑ New set up design for 2014 with an improvement of the whole optical sensitivity

and what about the magnetic birefringence effect in vacuum ?

More and more realistic 

Acknowledgements

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(ICME project)

Agnès Souquet

Alexandre Bacou

Invited professor

Andrei Baranga

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