Quantum Vacuum Magnetic Birefringence

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Does light interact with electromagnetic fields ?

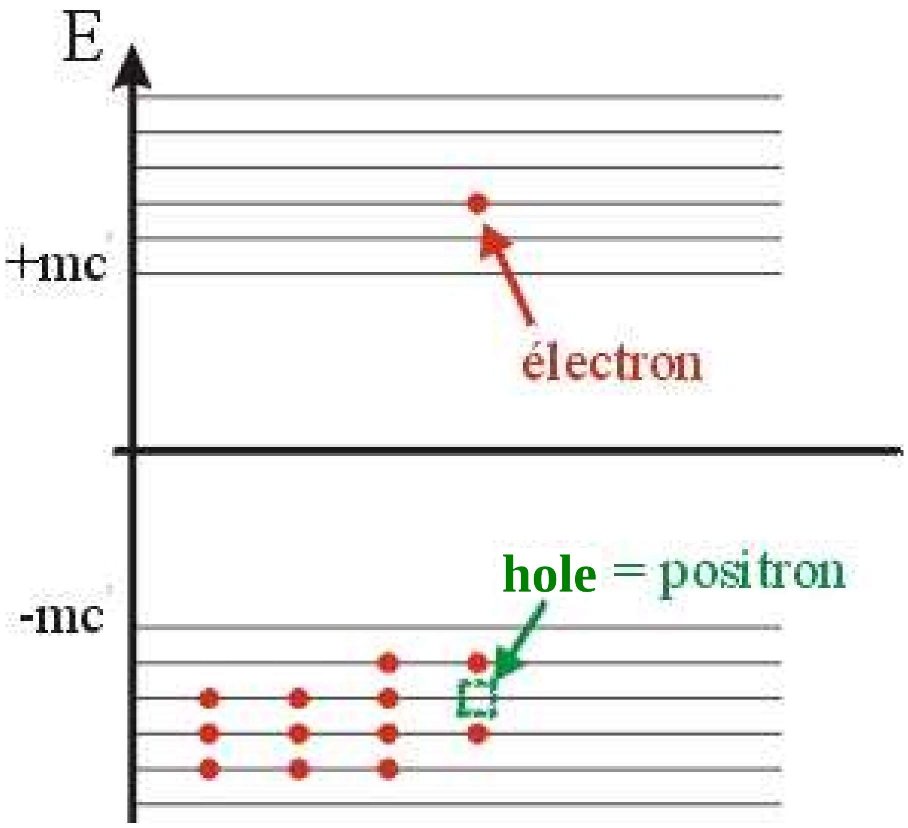
Does the velocity of light change in the presence of electromagnetic fields ?

outline :

Short introduction

BMV Toulouse experiment

1934 Dirac model of quantum vacuum



« Un électron dans un état d'énergie négative est un objet tout à fait étranger à notre expérience, mais que nous pouvons cependant étudier au point de vue théorique; ...
Admettons que dans l'univers tel que nous le connaissons, les états d'énergie négative soient presque tous occupés par des électrons, et que la distribution ainsi obtenue ne soit pas accessible à notre observation à cause de son uniformité dans toute l'étendue de l'espace. Dans ces conditions, tout état d'énergie négative non occupé représentant une rupture de cette uniformité, doit se révéler à l'observation comme une sorte de lacune. Il est possible d'admettre que ces lacunes constituent les positrons ».

P.A.M. Dirac (1902-1984)
(rapport au 7ème conseil Solvay de Physique, 1934)

1934-35 Heisenberg-Euler effective Lagrangian

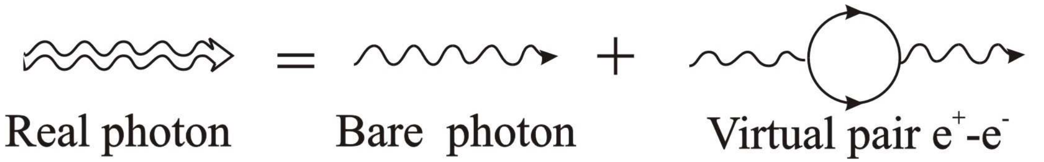
Vacuum is **Lorentz** and **CPT invariant**

$$\mathbf{L} = \frac{1}{2}F + aF^2 + 7aG^2 + \ldots$$

where $F = \left(\varepsilon_0 E^2 - \frac{B^2}{\mu_0}\right)$ and $G = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\vec{E}.\vec{B}\right)$

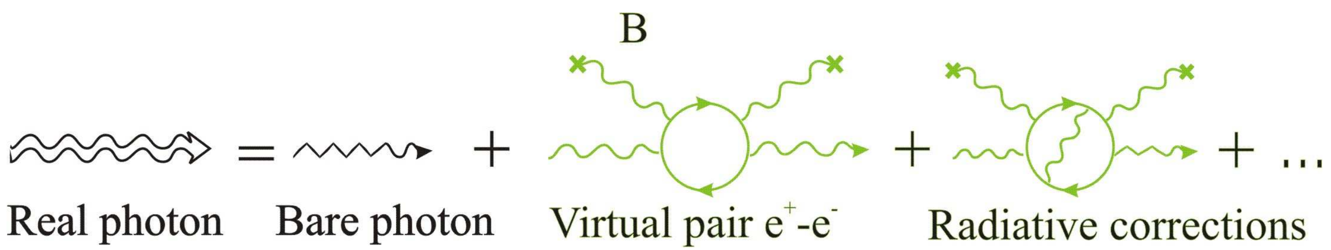
1950 … **Pictorial representation based on Feynman's diagrams**

Without external field:



= c

With external field B:



1970 : C depends on light polarization !

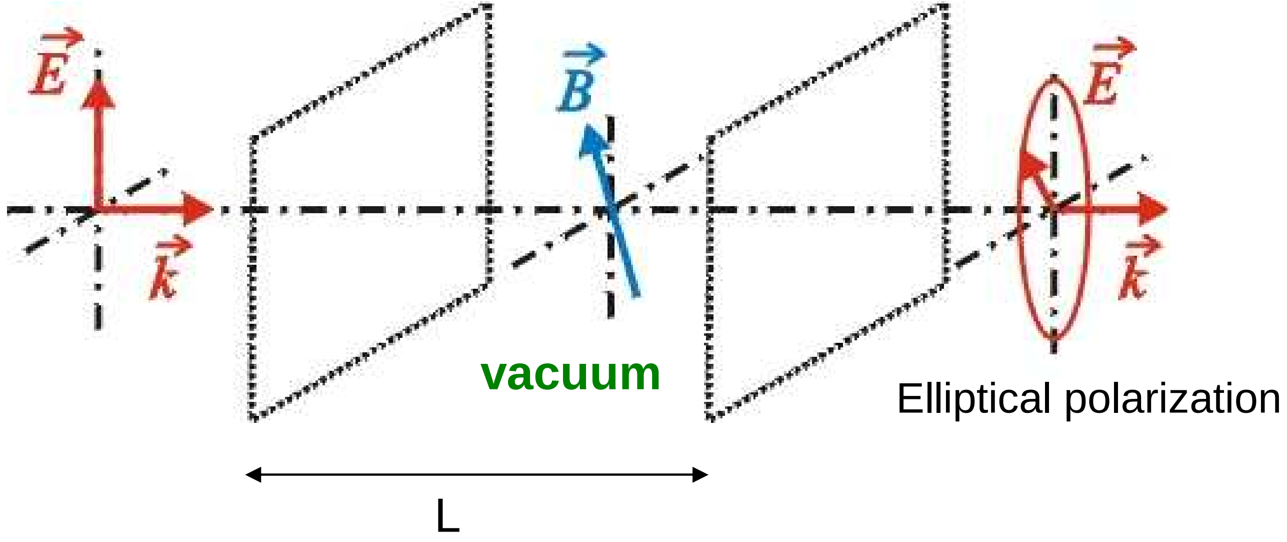
1934 : Vacuum is a non linear optical medium

1970 : The value of the Vacuum linear magnetic birefringence is published

Vacuum Cotton-Mouton effect

$\boxed{\Delta n = 4\ 10^{-24} (T^{-2})}$

Linear polarization



Ψ = ellipticity

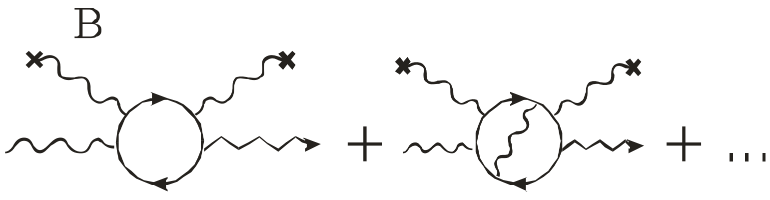
$$\Psi = \frac{\pi}{\lambda} \Delta n \left(\frac{B}{1T} \right)^2 L$$

Angle between **B** and **E** = 45°

Cotton Mouton effect has been discovered in 1901, studied in details since 1904, and it exists in all media.

Δn for helium gas (1 atm, 1 T, 0 °C) is about 2 10 $^{-16}$.

Experimental challenge :



Radiative corrections

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

Fundamental constants : 2006 codata

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

V.I.Ritus, *Sov. Phys. JETP* **42**, 774 (1975) **O(α³)**

O(α⁴) **?**

O(α⁵) **?**

Pure QED test

Theoretical challenge !

Biréfringence Magnétique du Vide

QED tests

S.S. Schweber, *QED and the men who made it*, Princeton;
T.Kinoshita, *Quantum Electrodynamics*, World Scientific

Bound states : **Hydrogène, Muonium, Positronium ….** **Lamb shift**

$p^+ - e^-$ $\mu^+ - e^-$ $e^+ - e^-$

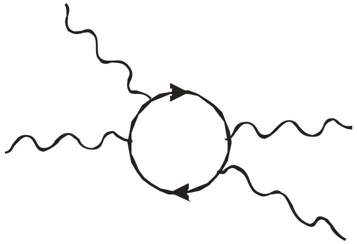
α **Mesurement of the fine structure constant**

Charged particle : **anomalous magnetic moment of e^- et μ^-** **g-2**

Photon : ?

Propagation in external fields (VMB)

Photon-photon collisions



$O(\alpha^2)$

Photon-photon collisions

Four wave mixing

A.L.Hughes et G.E.M.Jauncey, *Phys. Rev.* **36** (1930) 773

R.Karplus et M.Neuman, *Phys. Rev.* **83** (1951) 776

D.Bernard *et al*, *Eur. Phys. J. D* **10** (2000) 141

No signal !

$$\sigma_{\gamma\gamma} \sim 10^{-69}\ \mathrm{m}^2$$

expected for optical photons

Proposal for new very energetic light sources like
Extreme Light Infrastructure (ELI) and
the High Power laser Energy Research system (HiPER)

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI (1927-2007)
CERN, Geneva, Switzerland

Optical cavity to increase the optical path

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

Ellipticity measurement

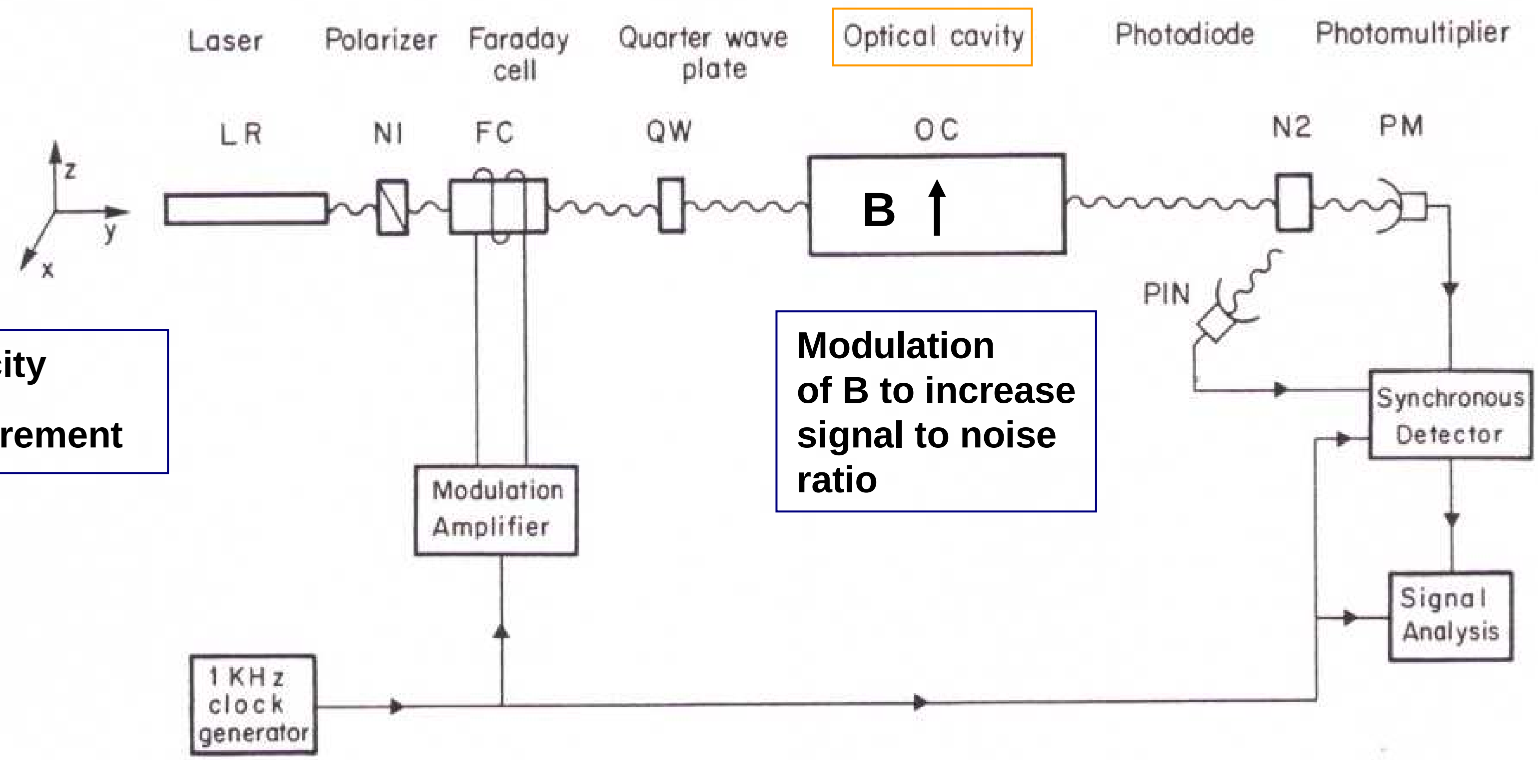


Fig. 3. Principle elements of the experimental apparatus.

Brookhaven National Laboratories, EU

A. Melissinos,
E. Zavattini et al.

Collaboration Brookhaven Rochester FermiLab Trieste (1988-1993)

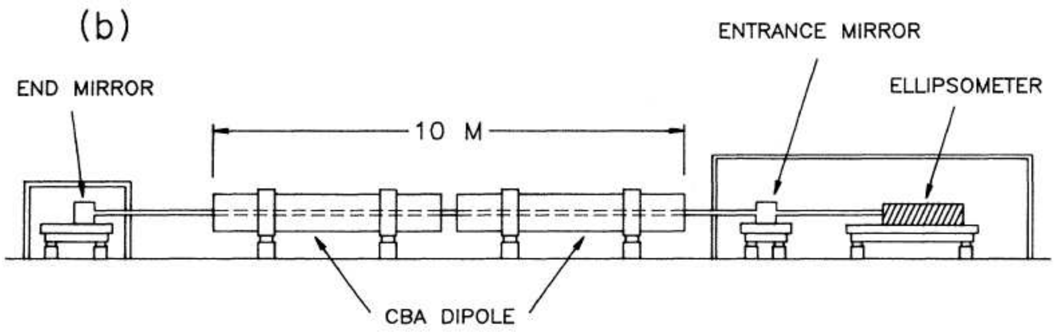


FIG. 4. (a) Schematic view of the ellipsometer; the volume inside the hatched area is evacuated. (b) Layout of the experiment and of the superconducting magnets.

B^2L = 32 T^2m

Superconducting magnet modulated at few mHz

Expected ellipticity from QED prediction : 2.0×10^{-13}

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

Biréfringence Magnétique du Vide

PVLAS (Polarizzazione del Vuoto con LASer) experiment

E. Zavattini

1992 – ….

- Superconducting magnet : 5 T - 1 m.
- Laser λ = 1064 ou 532 nm.
- Fabry-Perot cavity of finesse F ~ 10^5, L ~ 6 m.

Effect modulation by rotation of the whole superconducting magnet

Expected ellipticity :

$\boxed{\mathbf{5 \times 10^{-11}}}$

E. Zavattini et al., PRD **77**, 032006 (2008)

Legnaro Lab, Italy

Q&A (Quantum electrodynamics test & search for Axion)
Center for gravitation and cosmology, National Tsing Hua University of Taiwan

W-T Ni

H.H. Mei et al, arXiv:1001.4325v1
[Mod. Phys. Lett. A (2010)]

Permanent magnet **2,5 T**, **5 m**, rotating at **10 Hz**.
Fabry-Pérot cavity **finesse 100 000**.

Expected ellipticity :

$\boxed{\mathbf{6\times10^{-11}}}$

OSQAR (**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration)

CERN, Geneva Switzerland

Effect modulation by **rotation** of the **polarization** of light

- Laser : λ = 1064 nm
- Permanent magnet : B = 9.5 T

  L_{mag} = 14.3 m
- Fabry-Perot cavity : F ~ 10 000

  L_{cav} = 20 m

P. Pugnat et al., Phys. Rev. D **78**, 092003 (2008)

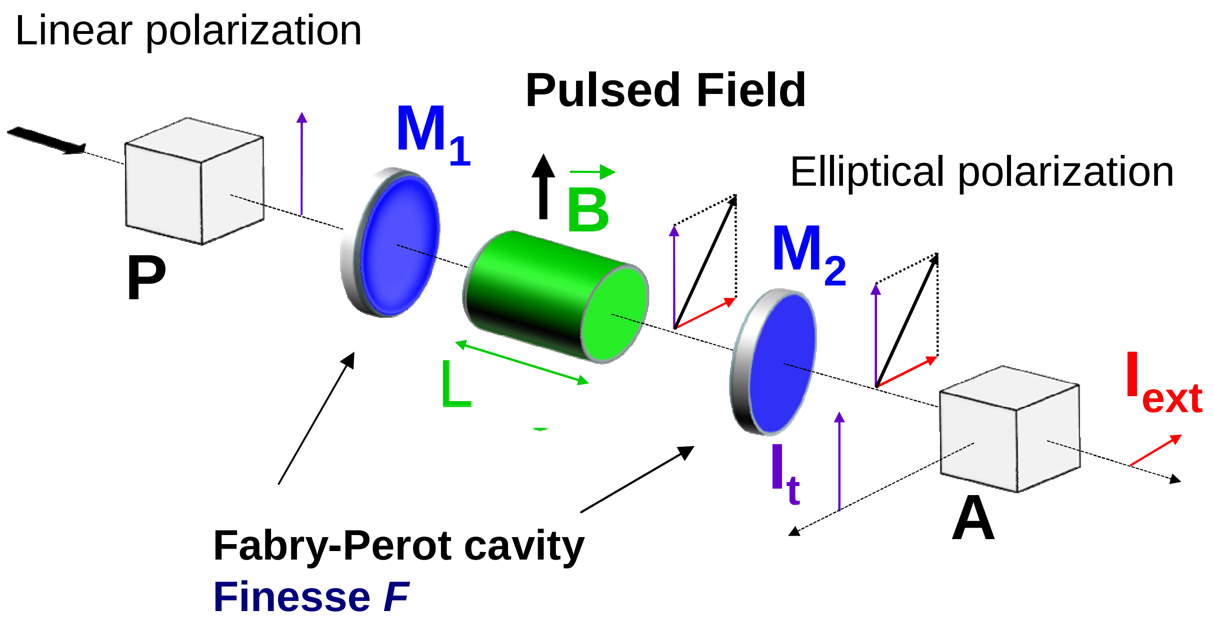
Expected ellipticity :

$\boxed{\mathbf{3\times10^{-10}}}$

P. Berceau, **R. Battesti**, **M. Fouché**, **J. Billette, J. Béard, P. Frings**, **J. Mauchain**, **M. Nardone**, **O. Portugall**, **G. Rikken**, and **C. Rizzo**

Birefringence Magnétique du Vide Experiment

BMV



Ψ = ellipticity

$$\Psi = \frac{2F}{\lambda}\Delta n\left(\frac{B}{1T}\right)^2 \sin(2\theta)L$$

$\Delta n = 4\ 10^{-24}(T^{-2})$

Our choice :
B as high as possible, L as small as possible ⇨ **Table top experiment**

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

$$\boxed{\Psi(t) = \Gamma\sqrt{1 + \frac{I_{ext} - I_t(\sigma^2 + \Gamma^2)}{I_t\Gamma^2}} - \Gamma}$$

with

$$\Gamma = \sqrt{\frac{I_{ext} - I_t\sigma^2}{I_t}}$$

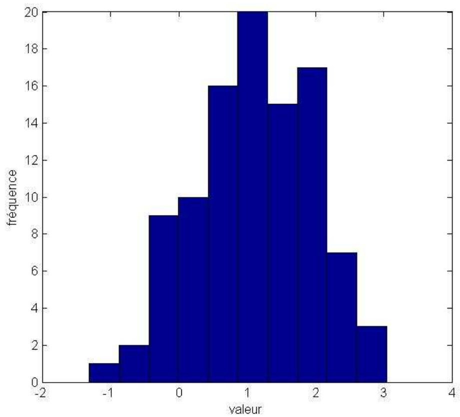
for $\Psi(t) = 0$

Γ ellipticity due to the cavity
$\Psi(t)$ ellipticity to be measured
σ^2 polarizer extinction

$$\Psi(t) = \kappa\, B(t)^2$$

$$\kappa = \frac{\int_0^T \Psi(t)\, B(t)^2 dt}{\int_0^T B(t)^4 dt}$$

several pulses



<κ>

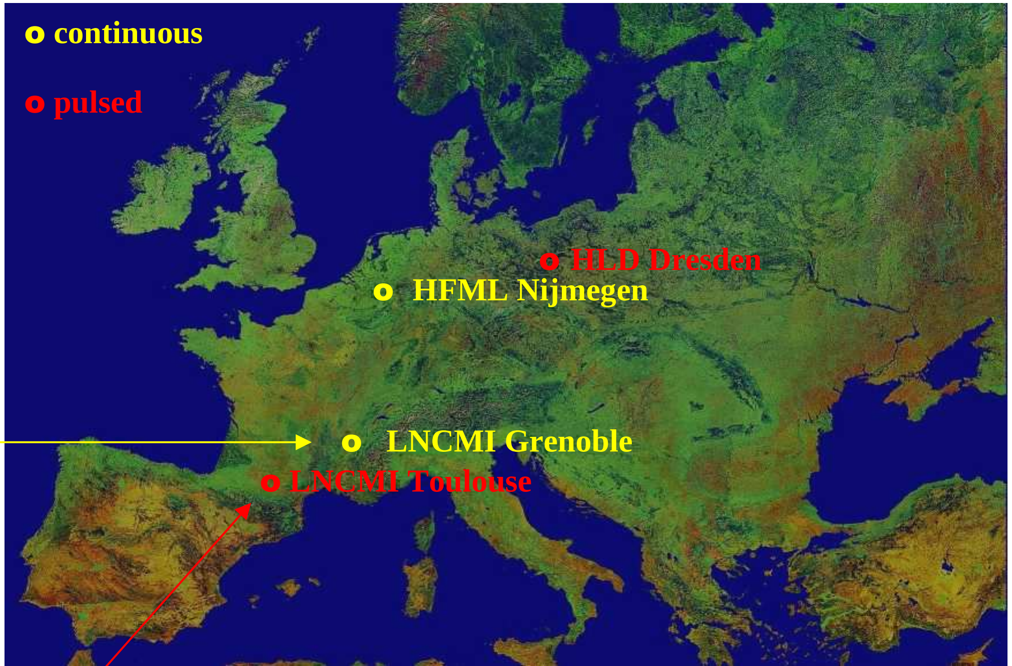
BMV

- **Experimental final goals:**
  - **cavity finesse** F ~ 1 000 000
    LMA (Lyon – IN2P3) mirrors
  - **magnetic field** B^2 L > 600 T^2 m

$\Rightarrow$ **Ellipticity to be measured**

$$\Psi_{QED} \approx 5\times10^{-9}$$

Laboratoire
National des
Champs
Magnétiques
Intenses



Future plans : EMFL

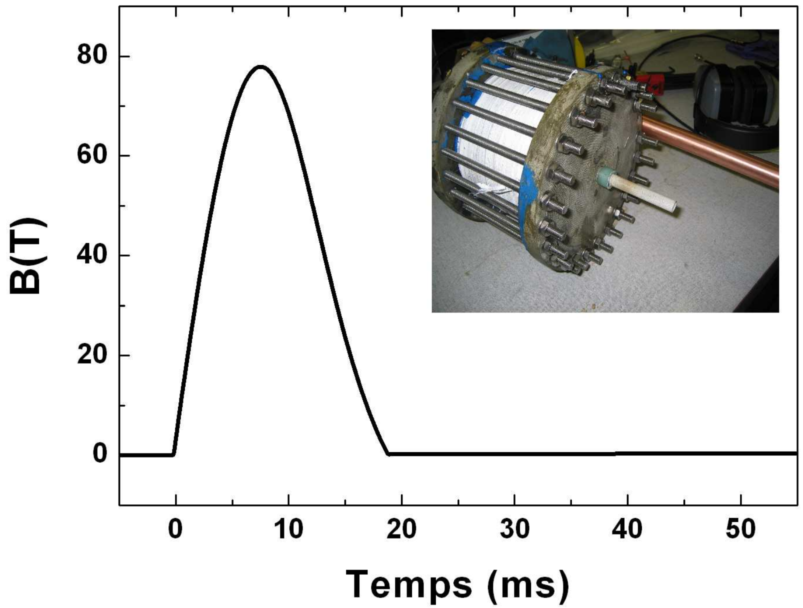
European **M**agnetic **F**ield **L**aboratory
with the HFML of Nijmegen
and the HLD of Dresden.

Laboratoire National des Champs Magnétiques Intenses

LNCMI Toulouse bank of capacitors

14 MJ, 1 GW

Faraday configuration



- MILESTONES :

- Magnetic Field
- Cavity
- Magnetic Field + Cavity
- Gas calibration
- Sensitivity vs Duty Cicle

Intense magnetic fields ?

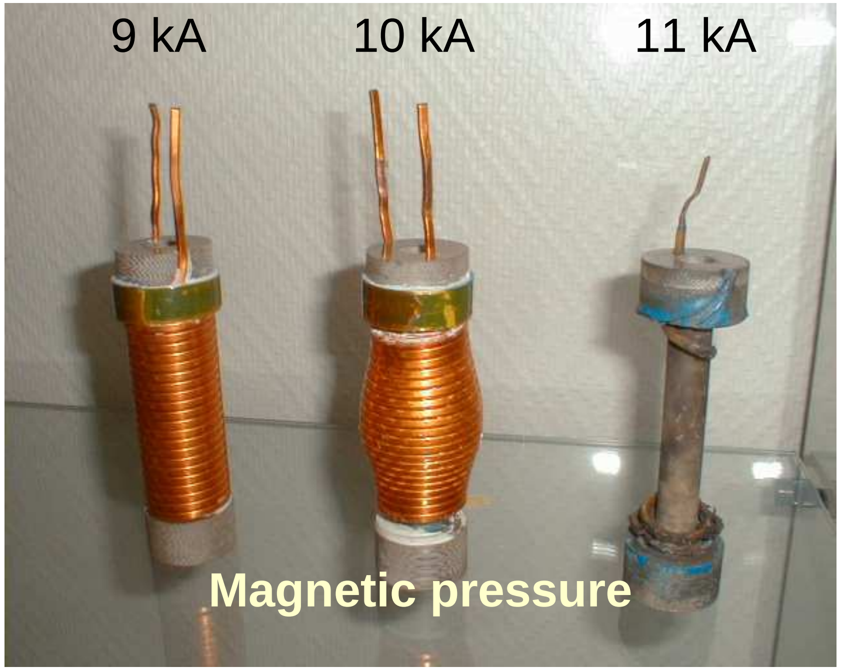
The only method *:* having a strong current circulating into a coil

Two problems :

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

→ Cooling

→ Pulsed field

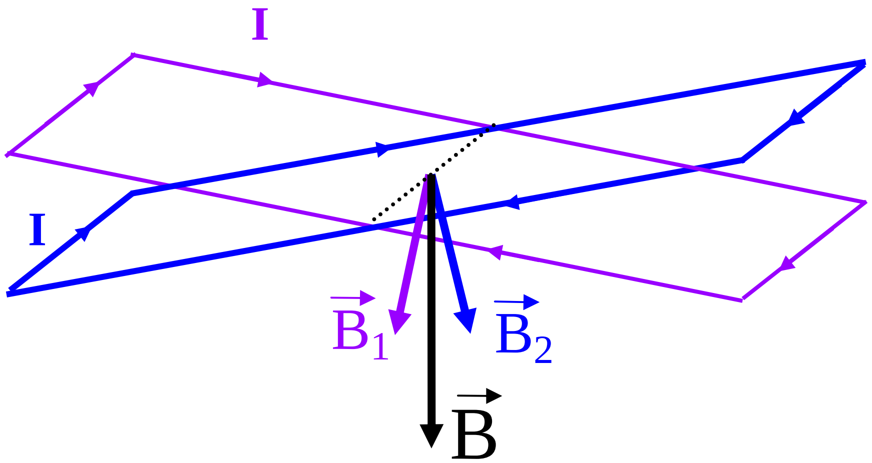


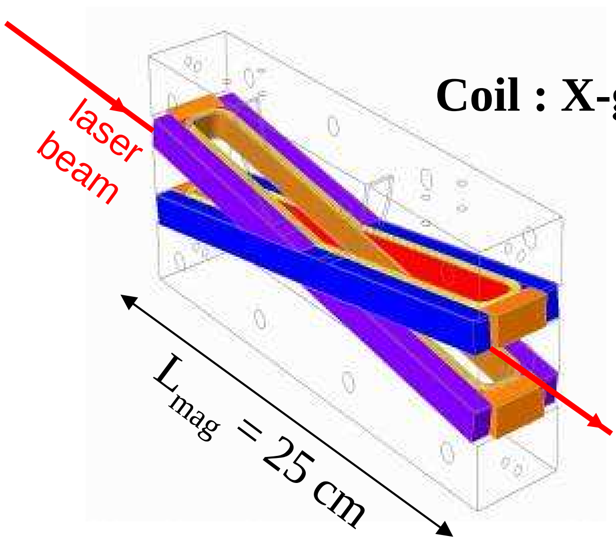
Magnetic pressure ! B^2/μ_0

→ Ultra strong conductors

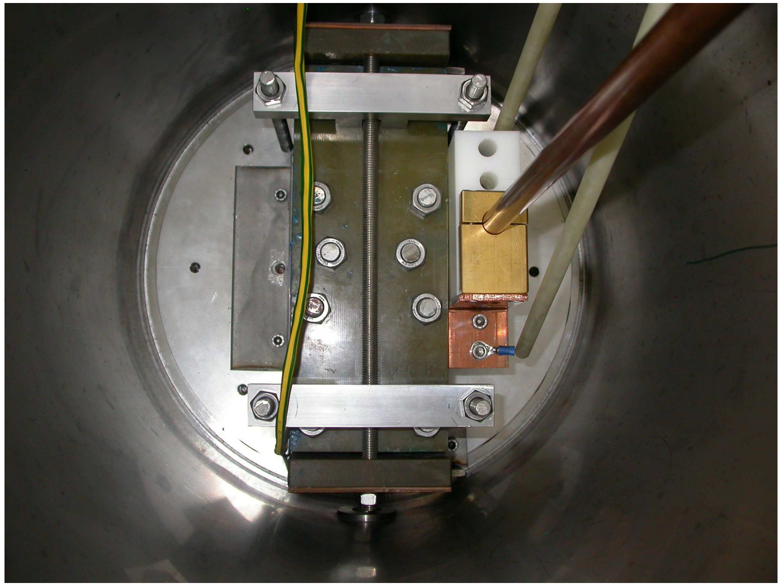
→ External reinforcement

The transverse magnetic field



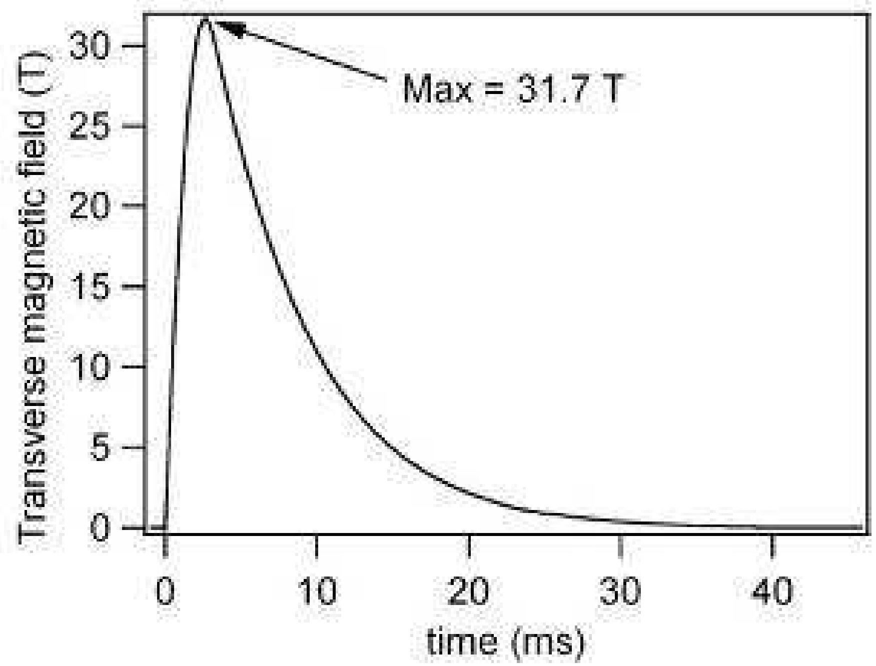


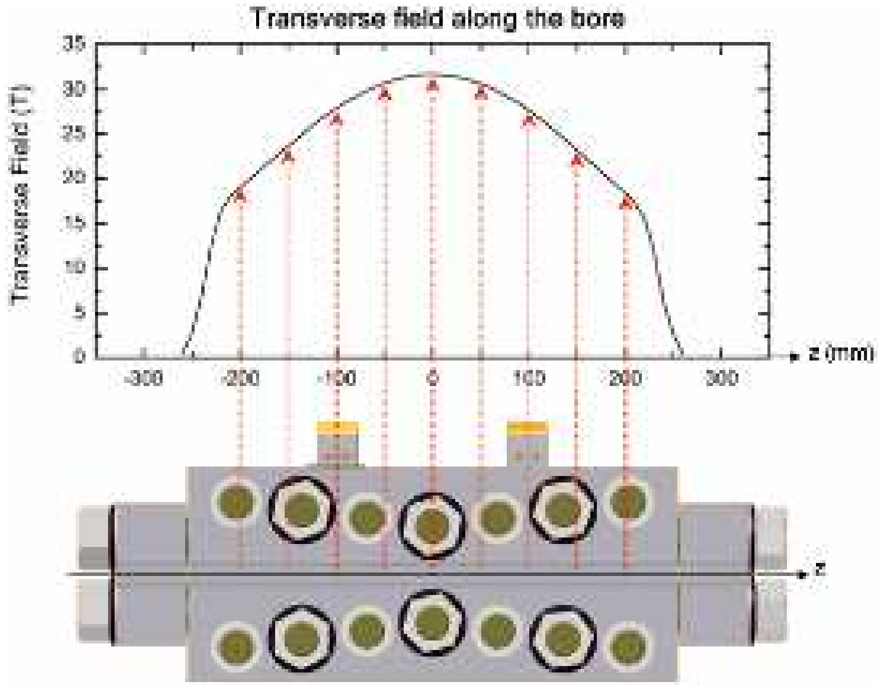
Coil : X-geometry



Coil in its Liquid Nitrogen cryostat

XCoil : 25 T^2m





- XXL-coil :

$I = 27\ 000$ A ➡ **project goal reached**

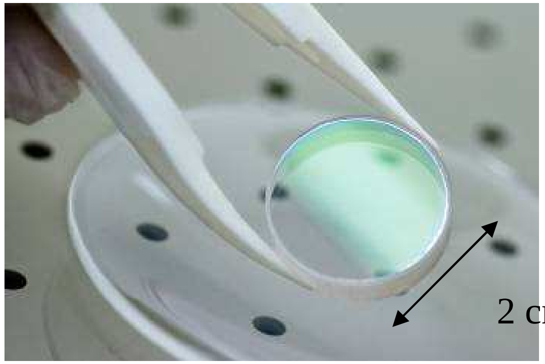
$B = 30$ T

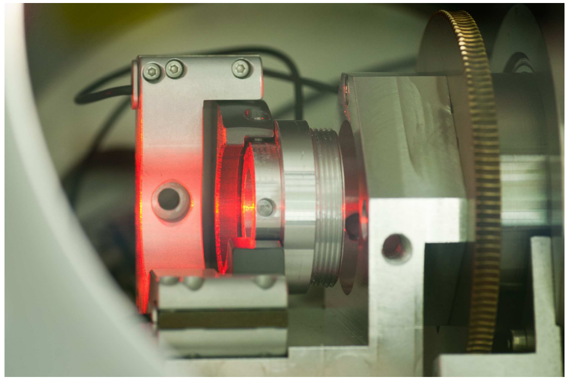
$B^2L_{mag} > 300\ T^2m$ ➡ **two under construction**

The Fabry-Perot cavity

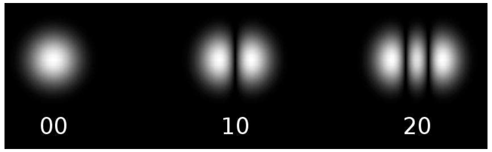
Very high reflectivity mirrors
provided by :

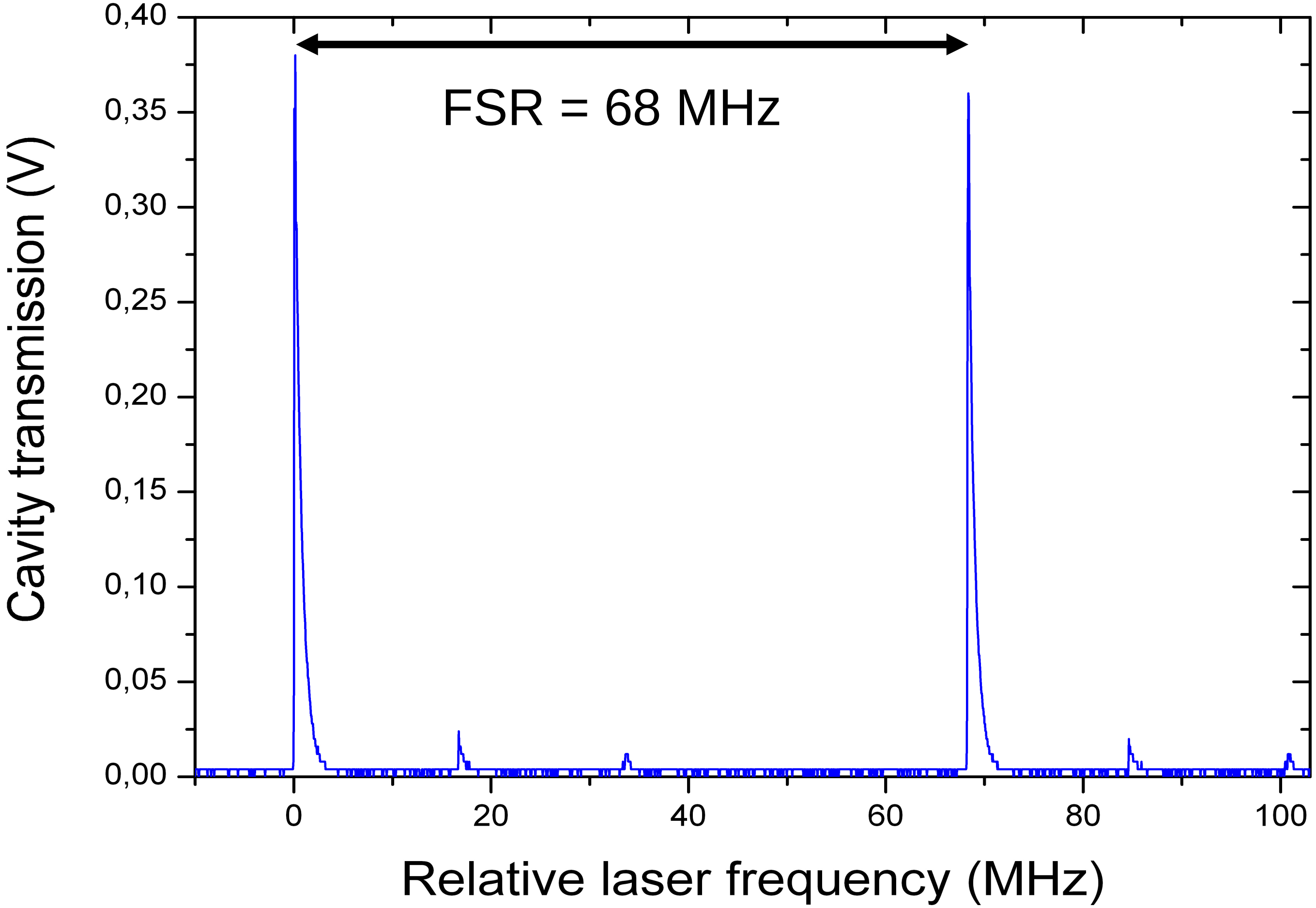
			measured
Firms	- Layertek (Germany)	certified F = 35 000	130 000
	- ATFilms (USA)	certified F = 200 000	490 000
LMA of Lyon (IN2P3)		expected F > 500 000	530 000


2 cm



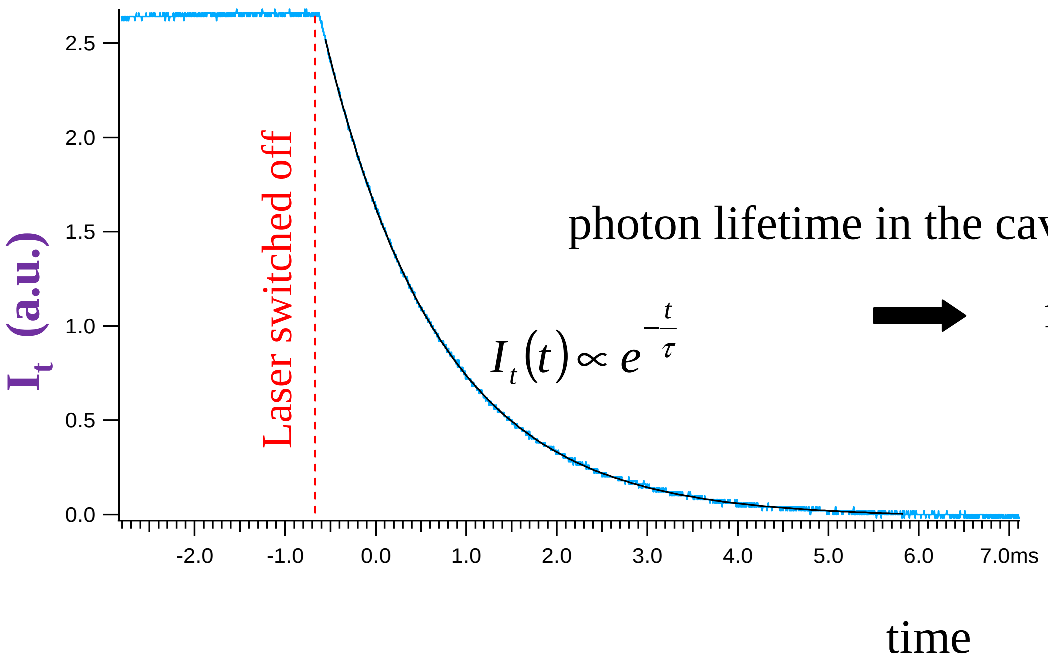
- Cavity length : 2.3 m
- Waist : 1.1 mm





Fabry-Perot cavity

The Fabry-Perot cavity



photon lifetime in the cavity (L_{cav} = 2.28 m long) : **τ = 1.28 ms**

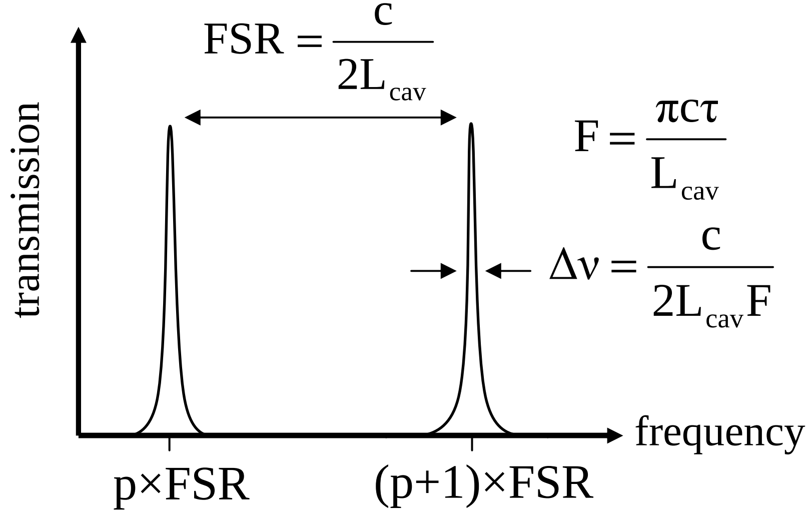
→ flight distance in the cavity **= 384 km**

→ $\mathbf{F} = \dfrac{\pi c \tau}{L_{cav}} = \mathbf{529\ 000}$

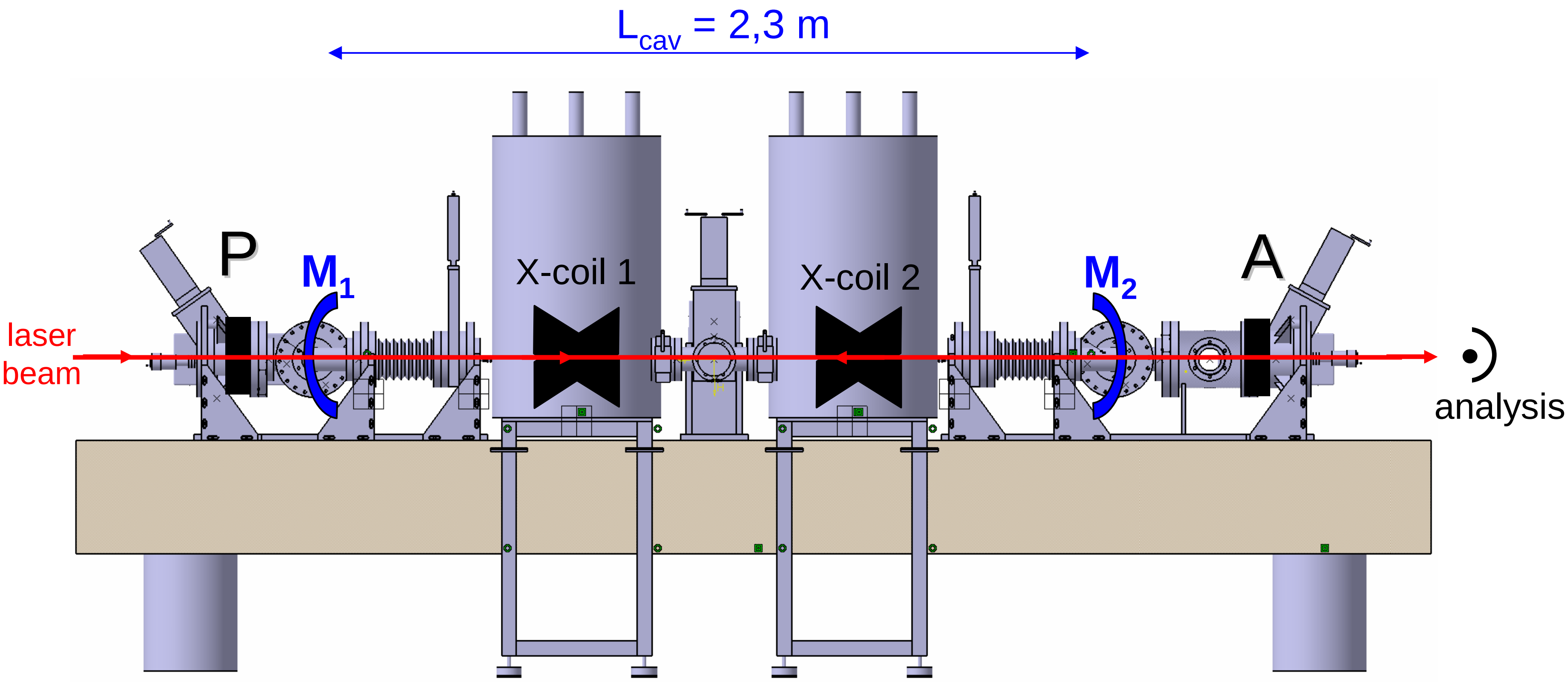
→ **Project goal reached**

The sharpest cavities in the world

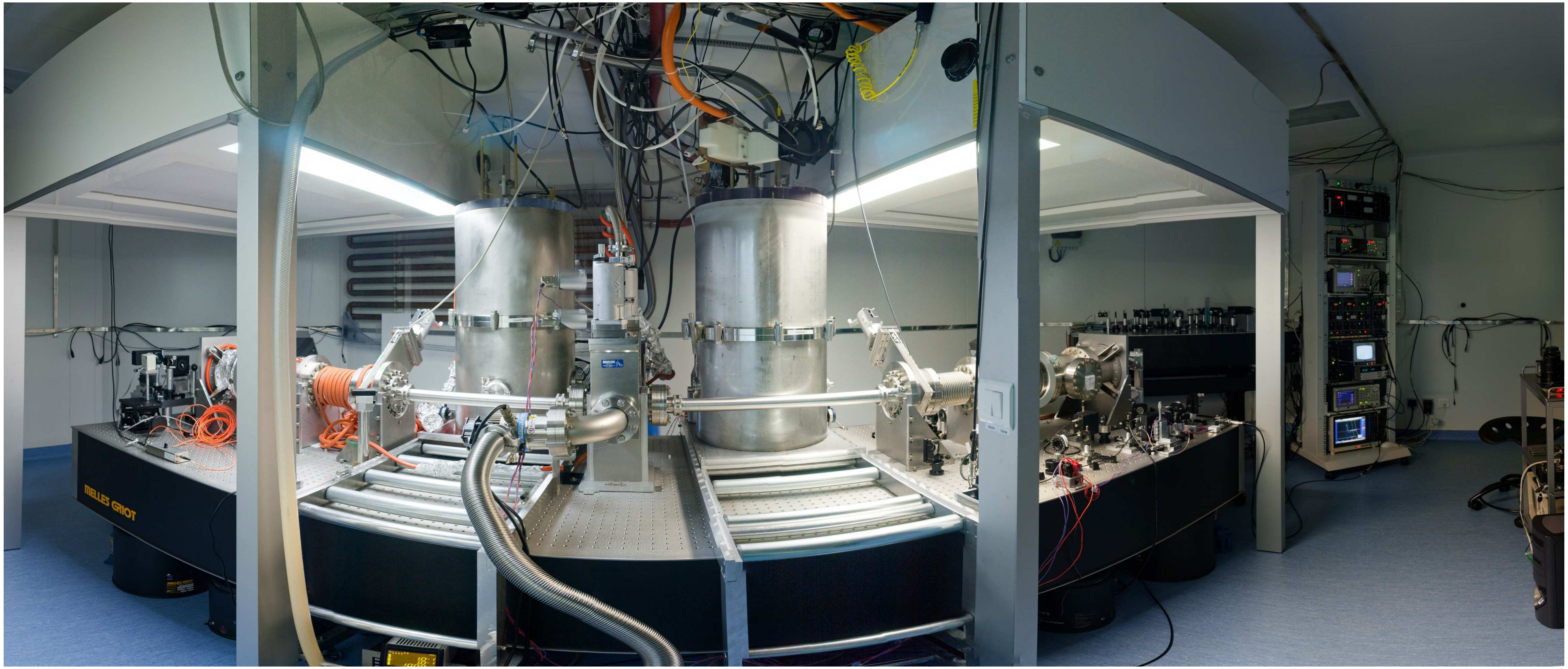
	VIRGO	PVLAS	LIGO	BMV (Biréfringence Magnétique du Vide)	Rempe *et al.* Opt. Lett. 1992
L_{cav}	3 km	6.4 m	4 km	2.3 m	4 mm
τ	159 μs	442 μs	970 μs	1.28 ms	8 μs
F	50	70 000	230	529 000	1 900 000
$\Delta\nu$	1 kHz	360 Hz	164 Hz	124 Hz	20 kHz



Experimental set up

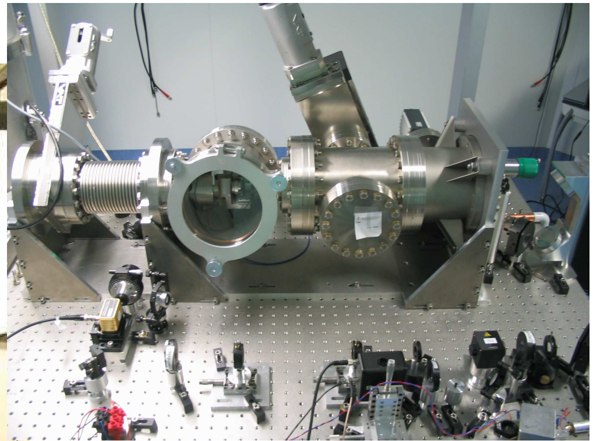
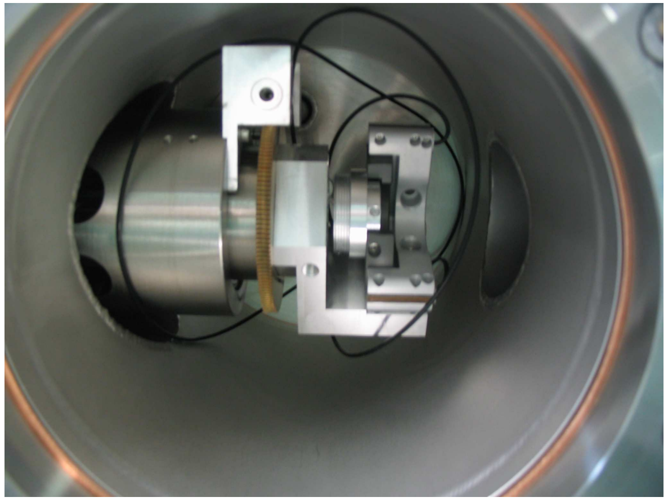


Biréfringence Magnétique du Vide



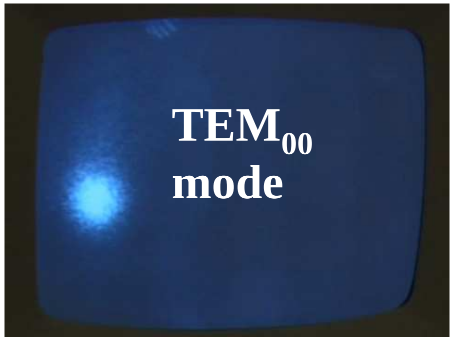
Clean experimental room

11/2010

Mirror alignement

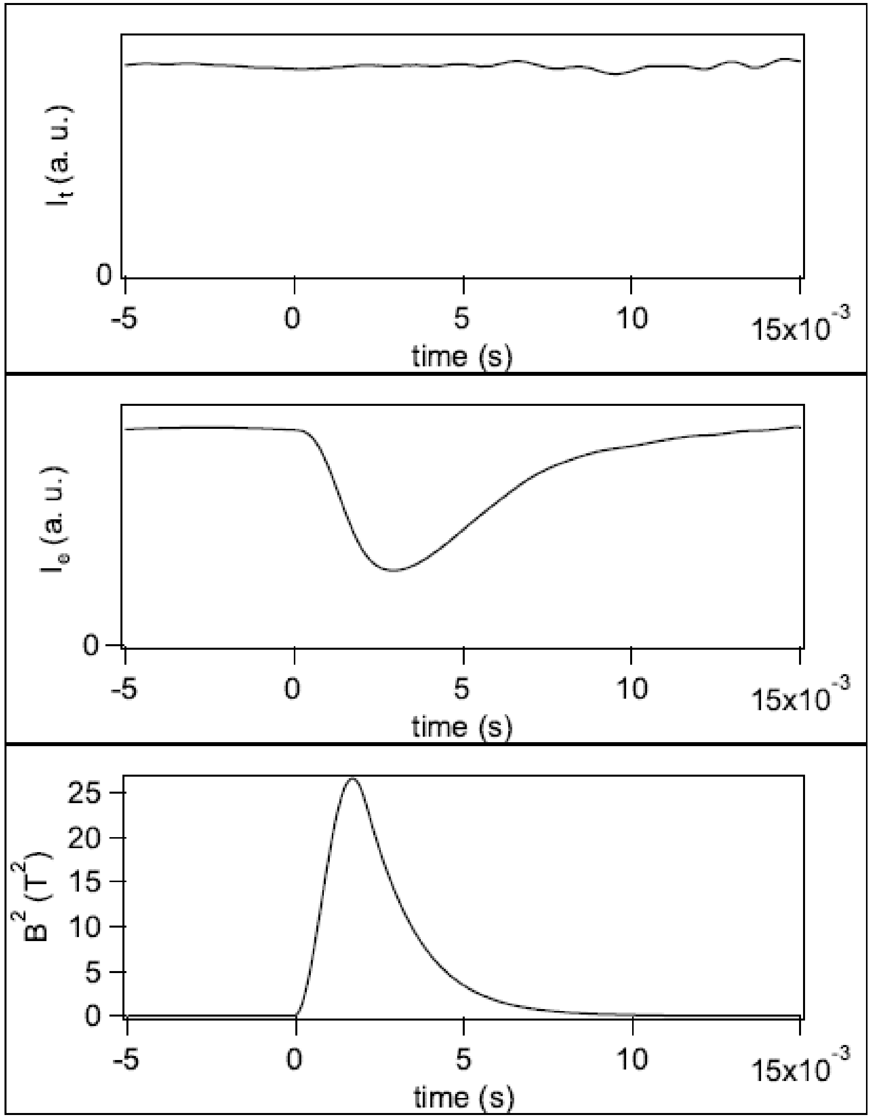
Laser locked
to the cavity



Pulse

Data analysis

Raw signals, 35 mbar of N_2

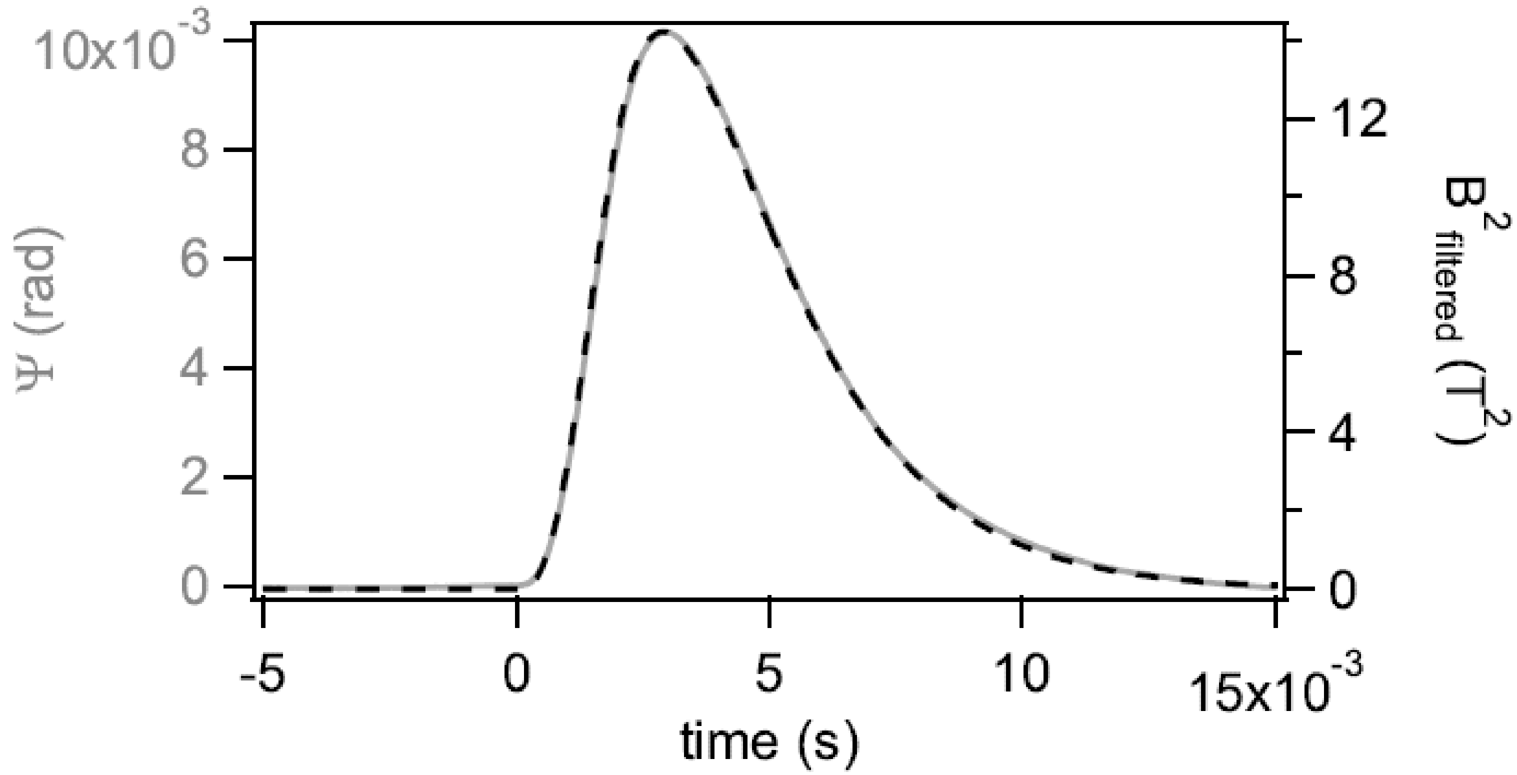


I_t

I_e

I_e does not follow B^2 beacuse of cavity filtering.

B^2



Δn_{max} = 7 10^{-15} (T^{-2})

Δn_{noise} = 10^{-18} (T^{-2})

Few pulses in vacuum give $\boldsymbol{\Delta n_{vacuum} = (4 \pm 50)\ 10^{-20}\ (T^{-2})}$

corresponding to a sensitivity of $\boldsymbol{\Delta n_{sens} = 5\ 10^{-20}\ (T^{-2})\ 1/Hz^{1/2}}$

$\boxed{\textbf{!!}}$

We want to reach Δn_{vacuum} around $4\mathrm{x}10^{-24}$ (T^{-2}) in 1 000 pulses (20 working days).

We need $1\mathrm{x}10^{-22}$ (T^{-2}) **per pulse**

We will gain a factor 100 with new XXL coils ….

Next *big* step

$B^2L > 600\ T^2m$

New cryostat for liquid nitrogen

New power supply

New experimental set up

New experimental room ?

1000 pulses
1 month

QED : $\Delta n = 4\ 10^{-24}\ (T^{-2})$

Biréfringence Magnétique du Vide

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