XAX / BMV experiments

Rémy Battesti

Laboratoire National des Champs Magnetiques Intenses - Toulouse

Outline

- The X- AXions experiment :

  Oscillations of X-photons into massive particles : the X-AXions (XAX)

- The BMV experiment :

  Measurement of the Vacuum Magnetic Birefringence predicted by Quantum ElectroDynamics theory

Fabienne Duc

Paul Frings

Jean-Pierre Nicolin

Rémy Battesti

Thomas Roth

Carsten Detlefs

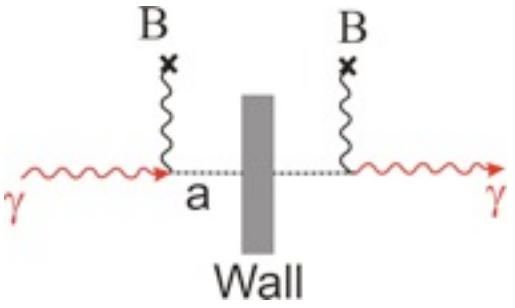
Carlo Rizzo

Paul Berceau

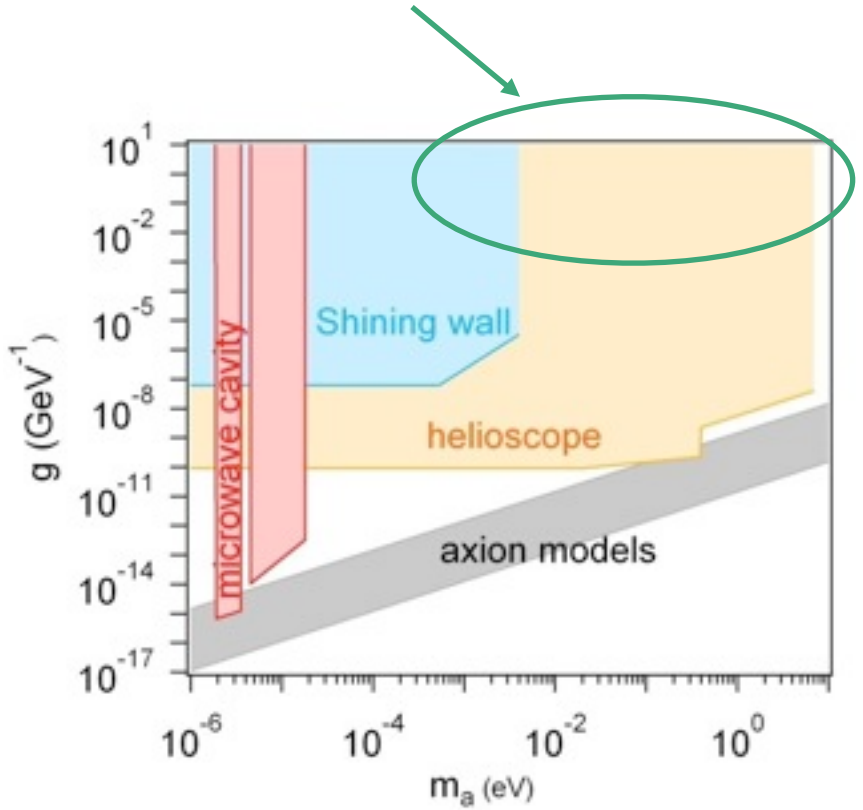
Marc Nardonne

…

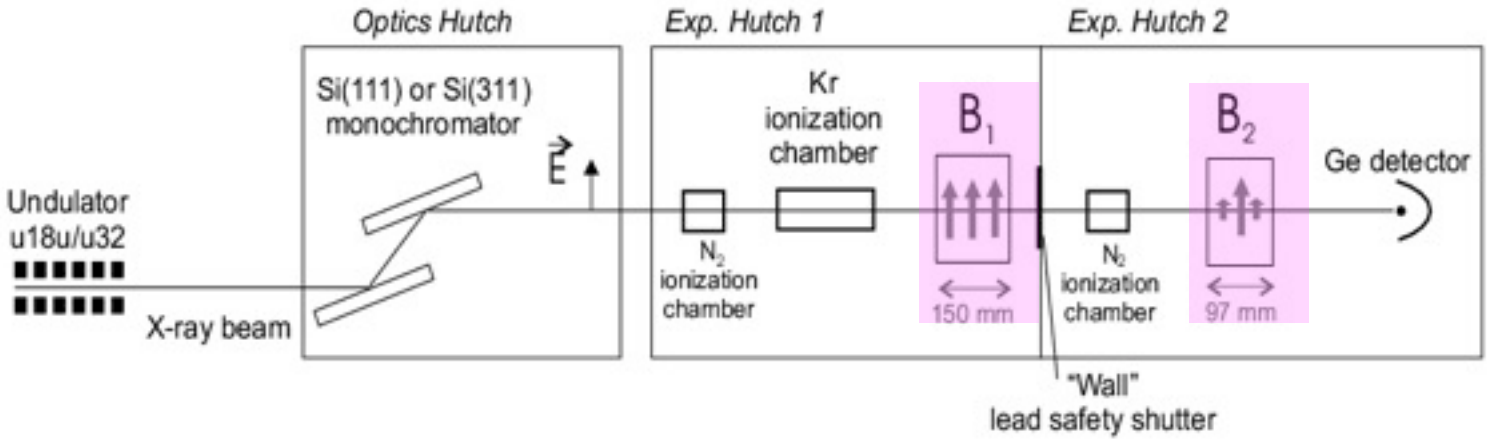
An X rays experiment at ESRF



- Shining wall experiment
- Search for higher mass ➡ **photons with higher energy : X rays**



Experimental setup



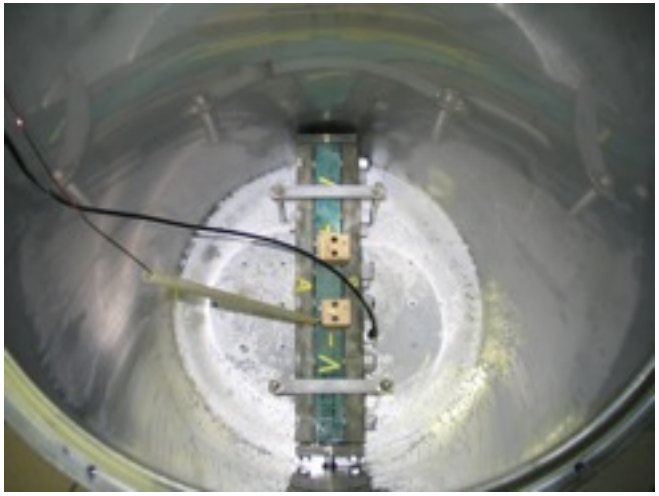
Number of regenerated photons :

$$N_{RP} = \eta \times N_i \times \left(g \frac{B_1 L_1}{2} \right)^2 \mathrm{sinc}^2 \left(\frac{m_a^2 L_1}{4\omega} \right) \times \left(g \frac{B_2 L_2}{2} \right)^2 \mathrm{sinc}^2 \left(\frac{m_a^2 L_2}{4\omega} \right)$$

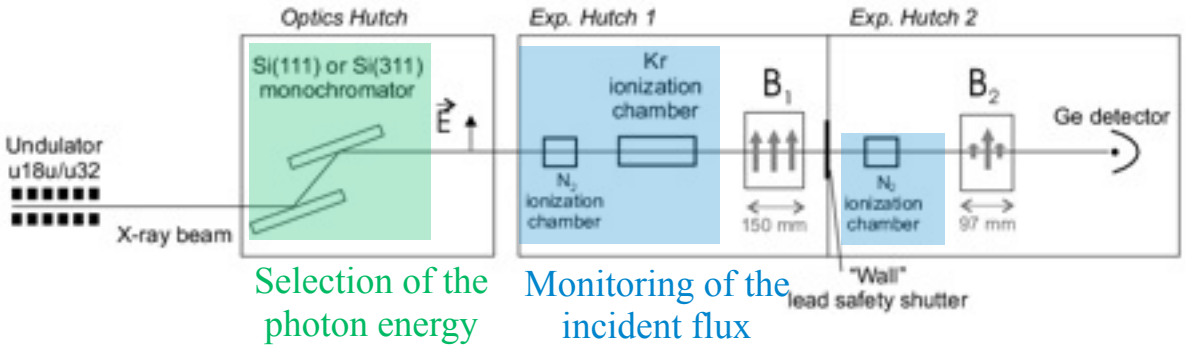
Coils

- First magnet : superconducting magnet
  B_1 = 3 T over L_1 = 150 mm

- Second magnet : pulsed Xcoil
  B_2 = 12 T over L_2 = 365 mm



Experimental setup



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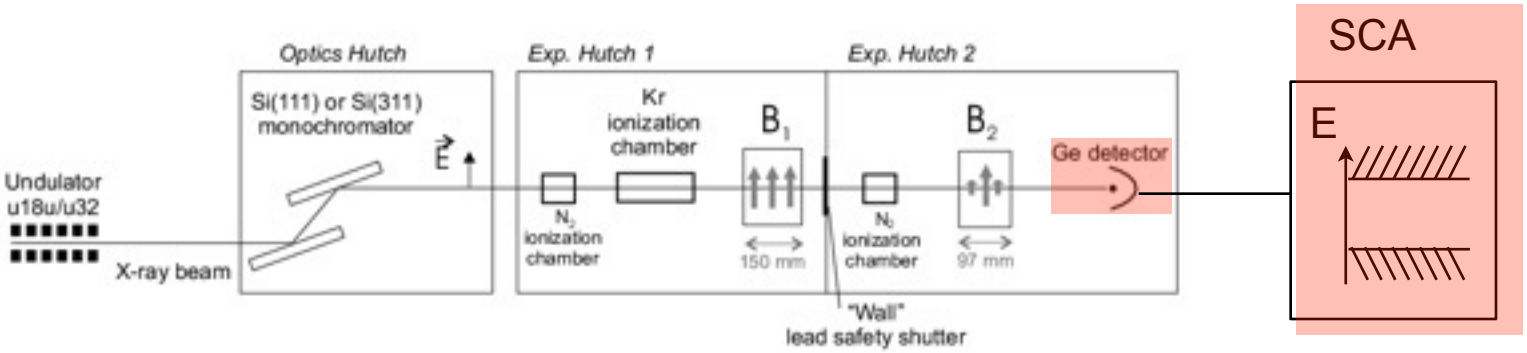
$N_i = 1.2 \times 10^{12}$ photons/s at $\omega = 50.2$ keV

$N_i = 3.1 \times 10^{10}$ photons/s at $\omega = 90.7$ keV



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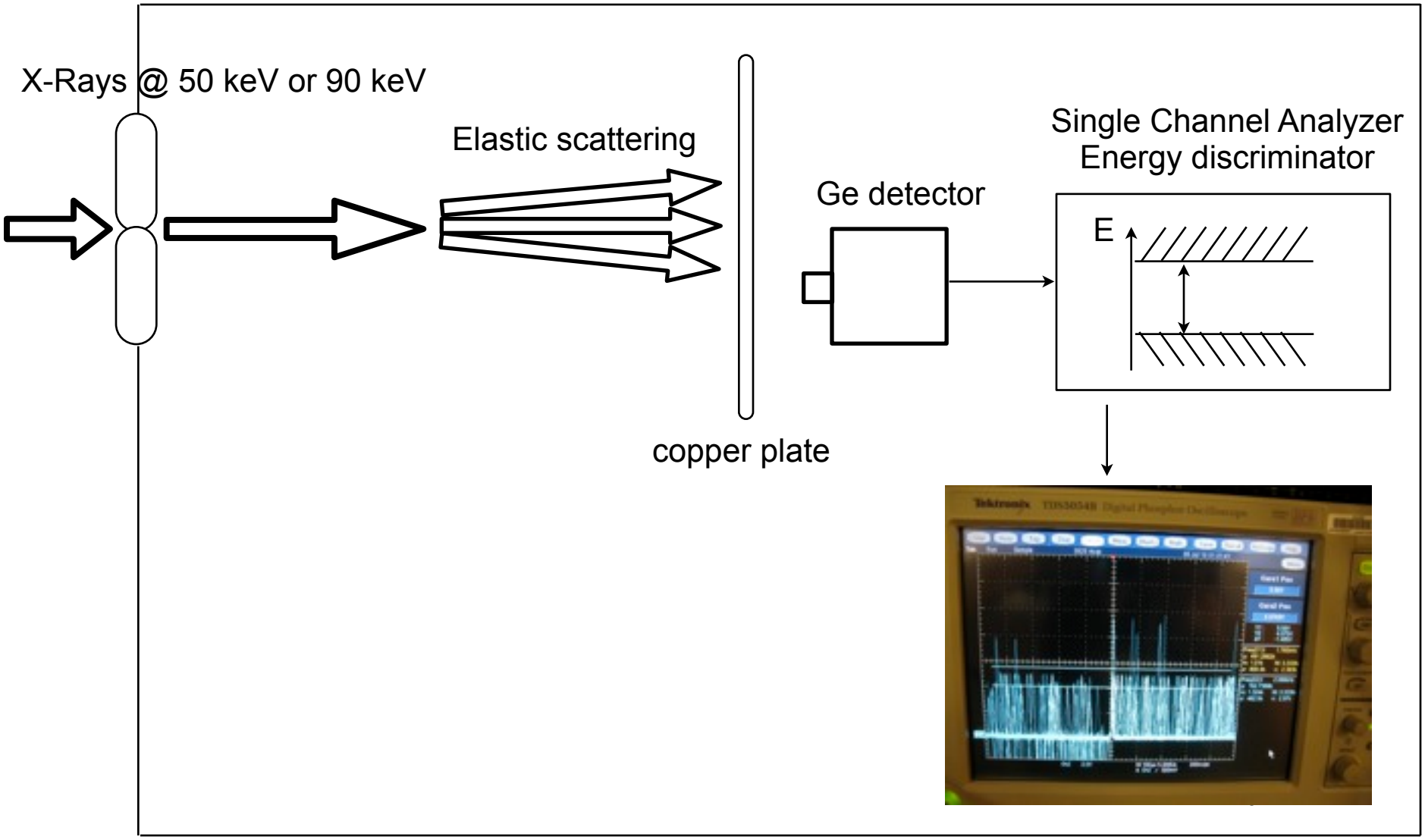
- 5 mm thick Ge detector cooled with liquid nitrogen
- η = 99.98 % at ω = 50.2 keV
- η = 84 % at ω = 90.7 keV
- background = (7.2 +/- 0.7) x 10^{-3} Hz

- Signal filtered to reject events that do not correspond to the incident photon energy

Detector alignment



❑ Expected :

- Monday & Tuesday : transportable generator installation
- Tuesday evening : Test of the X-Coil - 12 T
- Wednesday : Start of the experiment

  4 magnetic pulses per hour 24/24h
- Sunday : Stop of the experiment

  At least : 300 pulses

❑ Reality :

- Monday & Tuesday : transportable generator installation
- Tuesday evening : magnetic field slowly increased

  19h17 : XCoil resistance = 50 Ω instead of 150 mΩ
- Wednesday : XCoil resistance = 50 Ω ⇒ **Xcoil broken**

  Replaced by a superconducting magnet – 3 T over 97 mm

  Nitrogen filling
- Thursday : Try Helium filling ⇒ **fail**

  magnet heating

  23h30 : end of nitrogen filling
- Friday & Saturday : Experiment with a wall inside the first magnet ⇒ **background to high**
- Sunday : Helium filling ⇒ **18h50 : OK**

  evening : ω = 50.2 keV
- Monday : ω = 90.2 keV

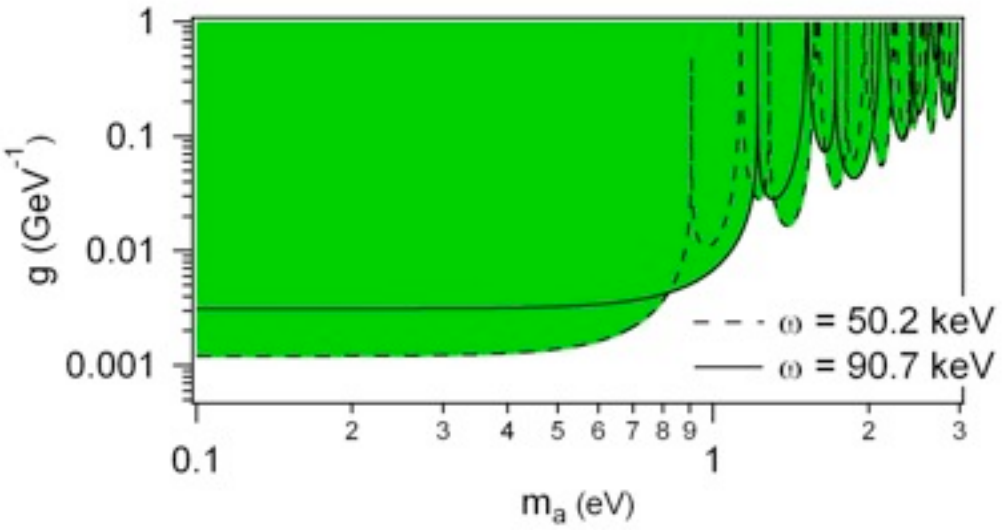
  19h19 : end

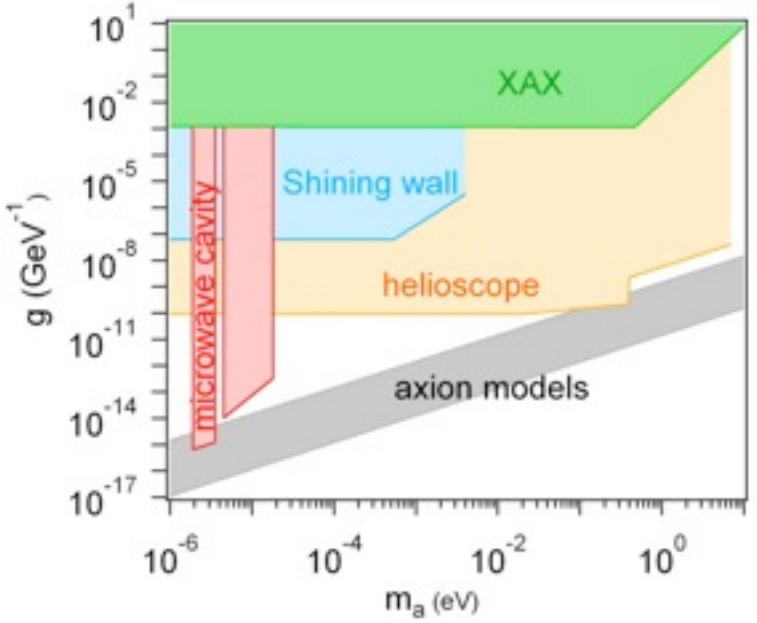
Results

X-ray beam	Magnets	ω (keV)	t_i (s)	N_{inc} (Hz)	Count rate (Hz)	N_p (Hz)
OFF	OFF		13913	0	$(7.2 \pm 0.7) \times 10^{-3}$	
ON	OFF	50.2	7575	1.2×10^{12}	$(5.7 \pm 0.9) \times 10^{-3}$	
ON	ON	50.2	7276	1.2×10^{12}	$(6.2 \pm 0.9) \times 10^{-3}$	$(0.5 \pm 2.6) \times 10^{-3}$
ON	OFF	90.7	7444	3.2×10^{10}	$(7.9 \pm 1.0) \times 10^{-3}$	
ON	ON	90.7	7247	3.1×10^{10}	$(8.1 \pm 1.1) \times 10^{-3}$	$(0.2 \pm 3.0) \times 10^{-3}$

➡ No regenerated photon detected

➡ Extension of exclusion limits for existence of axion :





R. Battesti et al., Phys. Rev. Lett. ***105****, 250405 (2010)*

Conclusion

- Photoregeneration using X-Ray

  widening of the energy window of purely terrestrial experiment

  ⇒ But axion is still running

  Opens a new domain of experimental investigation of photon propagation in magnetic fields

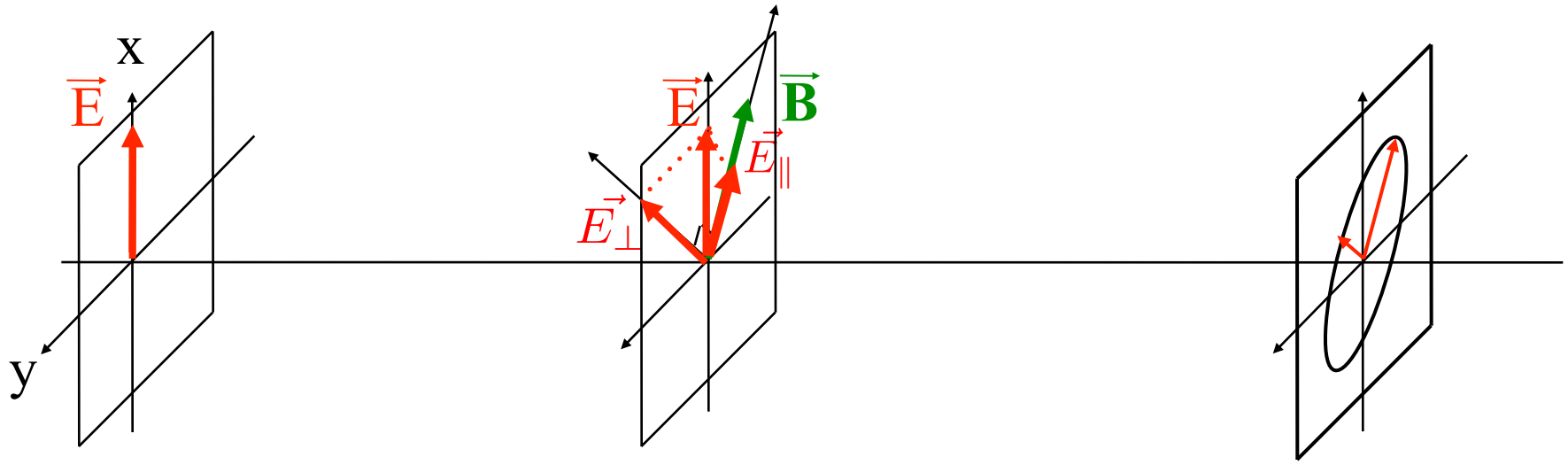
- Perspectives
  - Photoregeneration using periodic magnetic fields

    ⇒ enhancement at a given axion mass
  - Ellipticity measurements : vacuum magnetic birefringence

The BMV experiment

Biréfringence Magnétique du Vide

Vacuum Magnetic Birefringence



Linear polarization

Elliptic polarization

Induced magnetic birefringence :

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

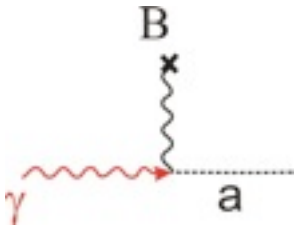
- This effect exists in **any** medium, even in **vacuum**
- From **QED theory** : $\Delta n = 4\times10^{-24}\ \mathbf{B^2} = \Delta n_u \times \mathbf{B^2}$

Very challenging !

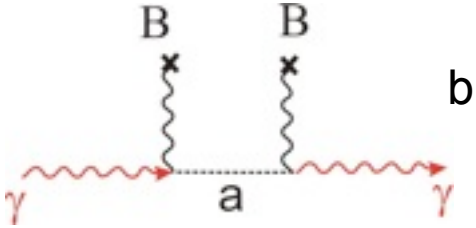
Z. Bialynika-Birula et al., Phys. Rev. D ***2,*** *2341 (1970)*

W. Heinsenberg et al., Z. Phys. ***38,*** *714 (1936)*

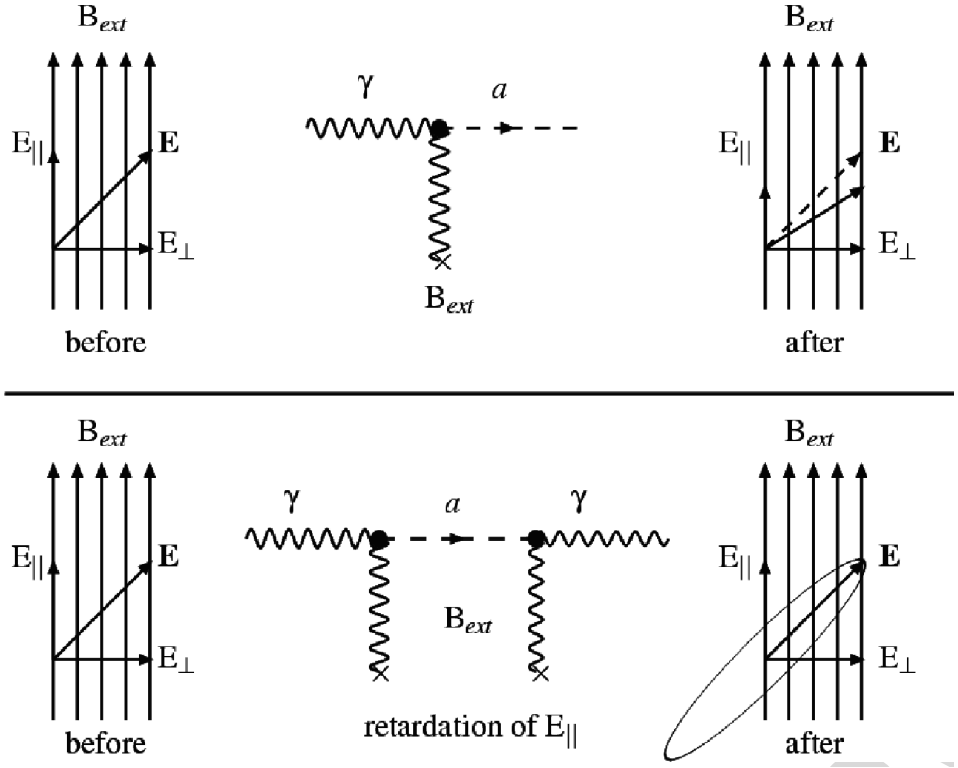
- ALP test (BMV) :



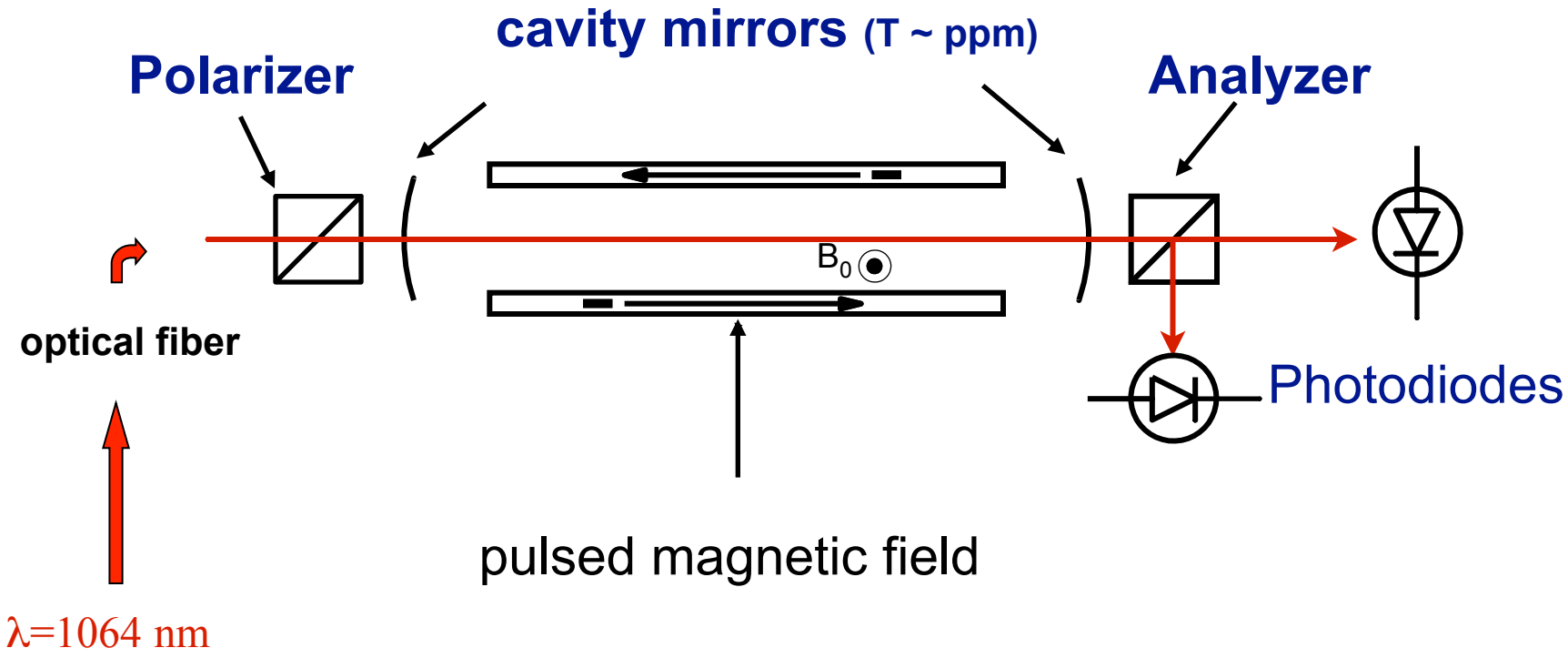
dichroïsm



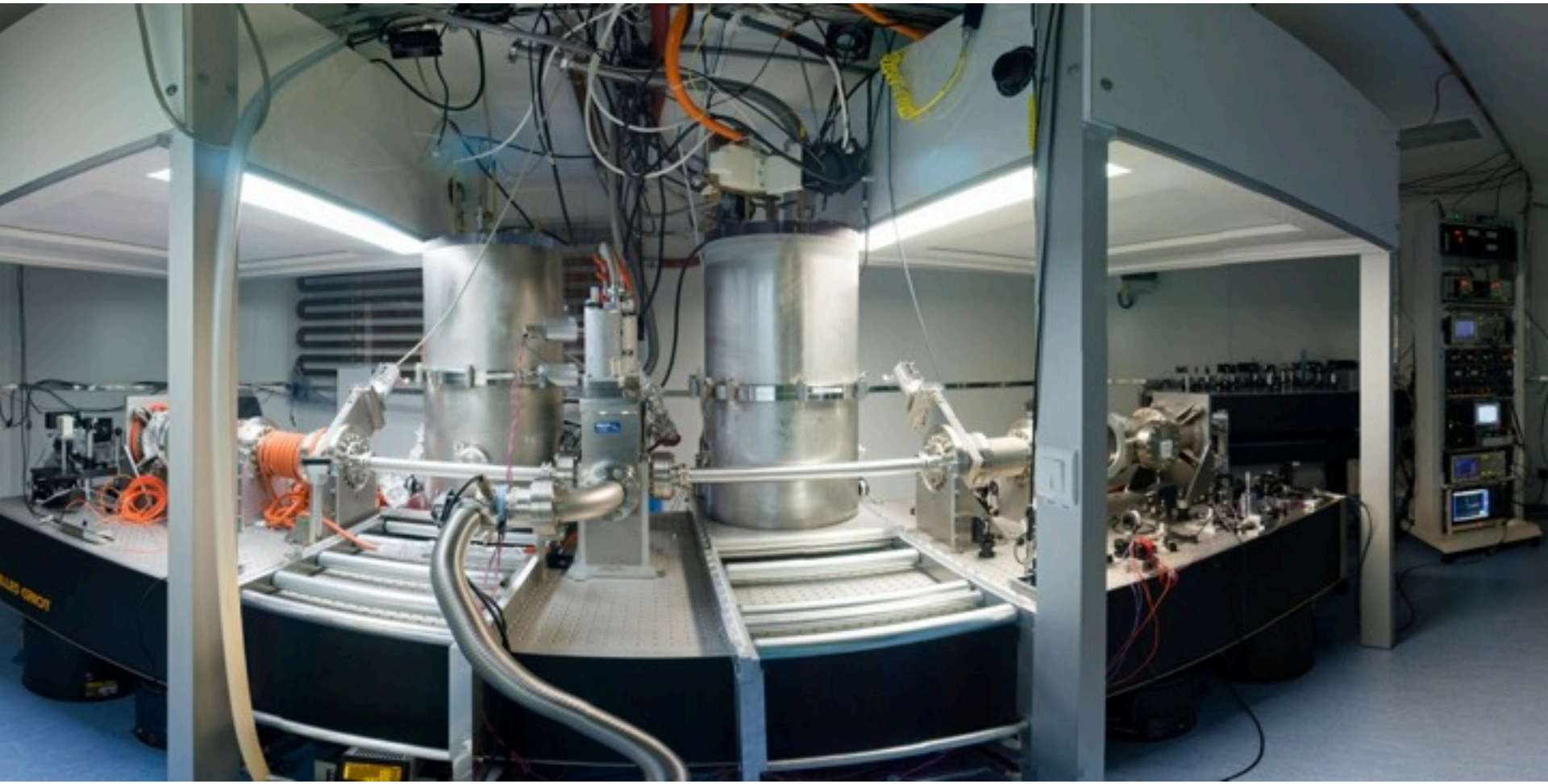
birefringence

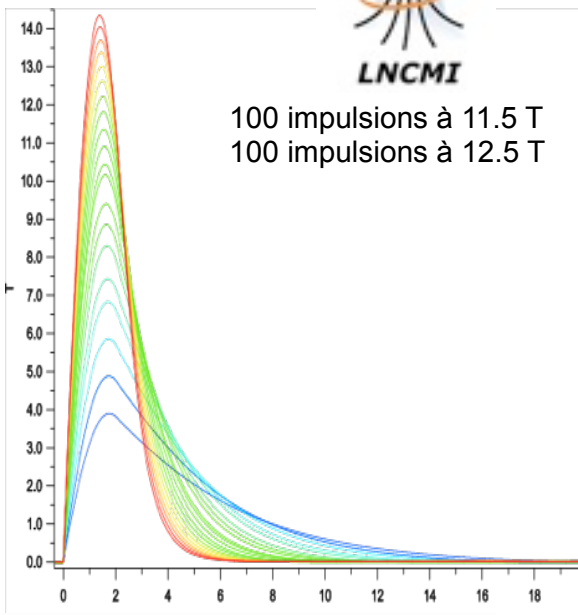


Experimental set up based on Iacopini and Zavattini idea (1979)

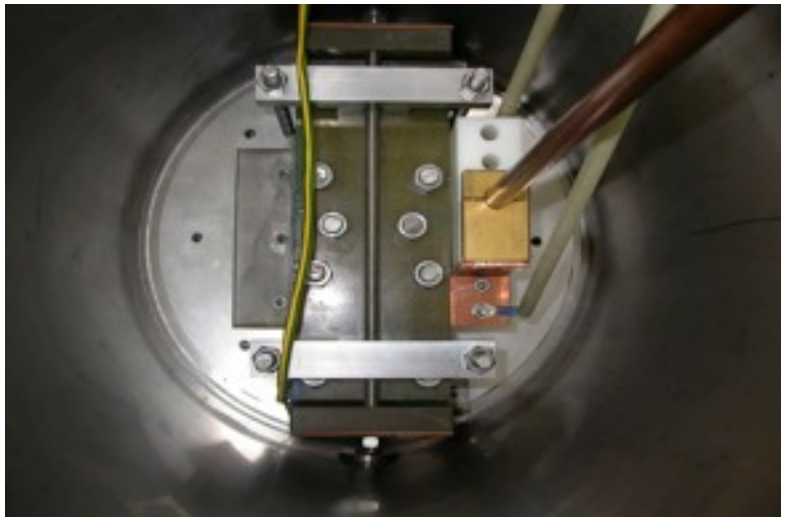


$$\psi = \frac{\delta}{2}\sin(2\theta) \longrightarrow \psi(t) = \frac{\pi}{\lambda}\Delta n_u \left(\frac{2F}{\pi}\right)\left(B^2 L_{mag}\right) sin(2\theta)$$



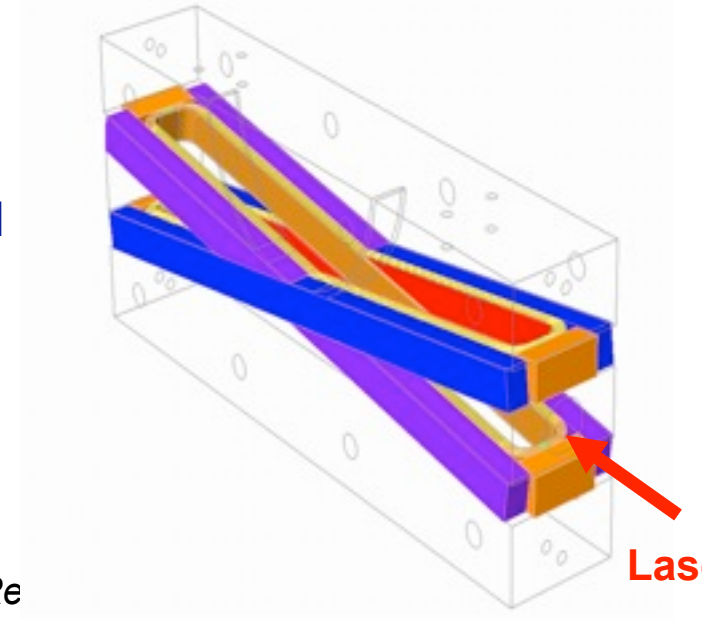


LNCMI Toulouse bank of capacitors 14 MJ, 1 GW



Xcoil

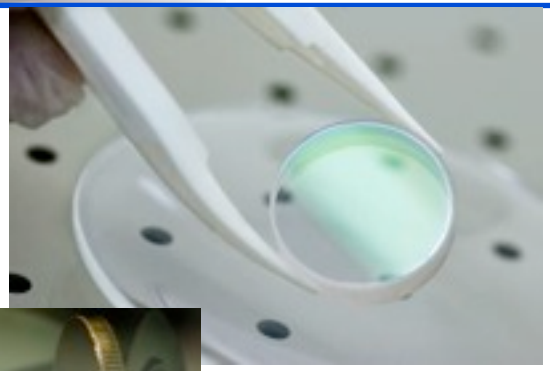
Transverse field

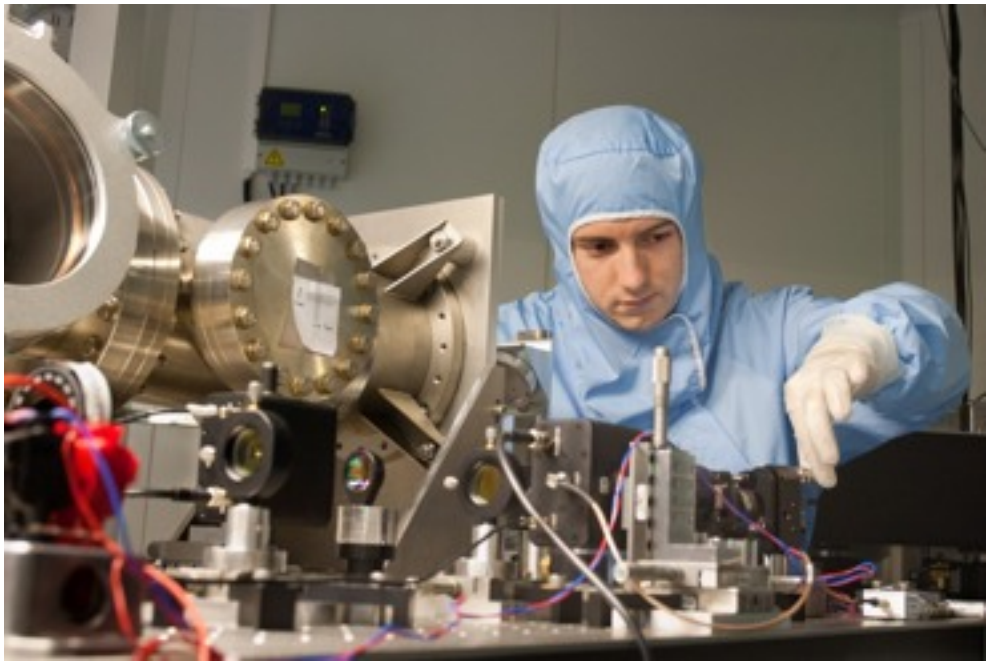


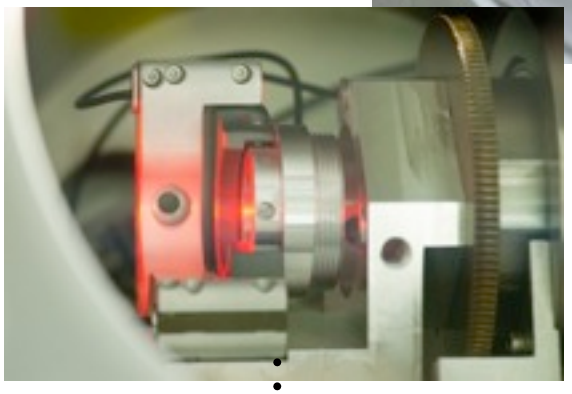
B = 14,3 T	8300 A
B^2L = 28 T^2m	**t ~ 5 ms**

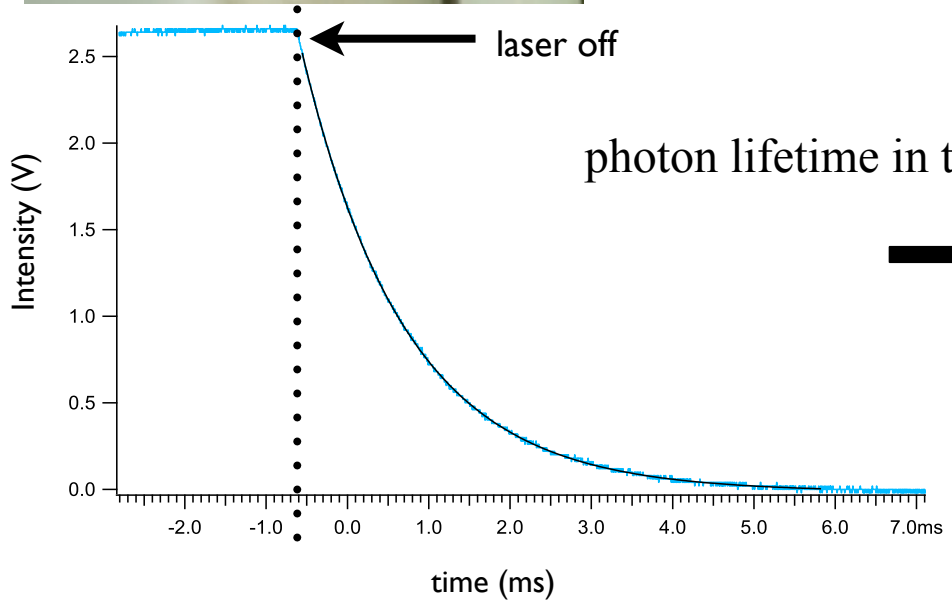
Re
5 pulses per hour

Designed for BMV at the LNCMI in 2002









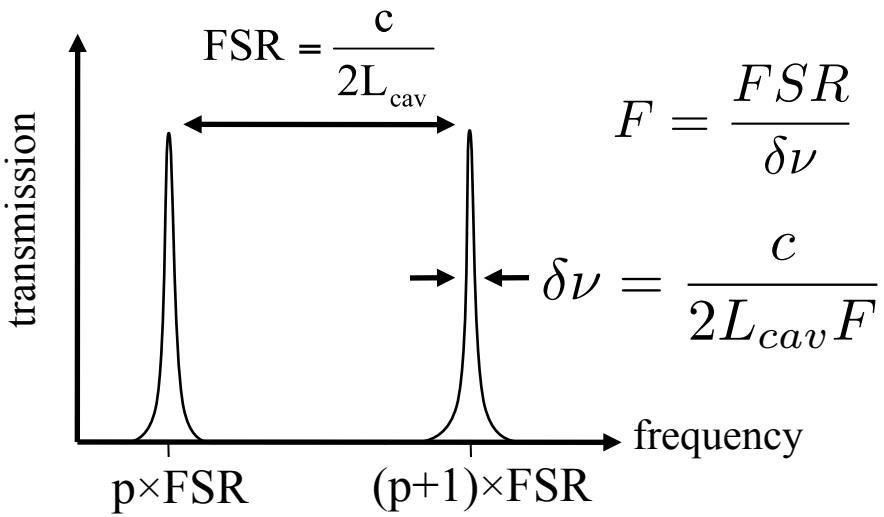
photon lifetime in the cavity (L_{cav} = 2.28 m long) : τ = **1.28 ms**

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

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

The sharpest cavity of the world

	VIRGO	PVLAS	LIGO	BMV	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



$$F = \frac{FSR}{\delta\nu}$$

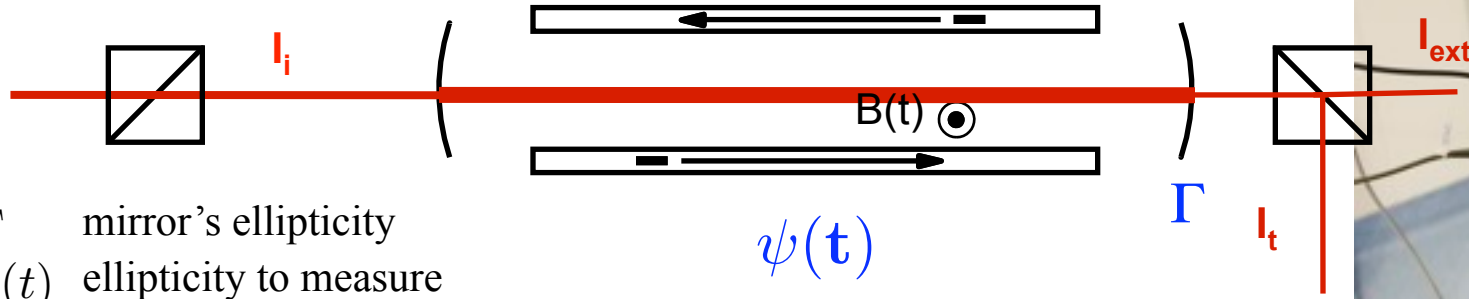
$$\delta\nu = \frac{c}{2L_{cav}F}$$

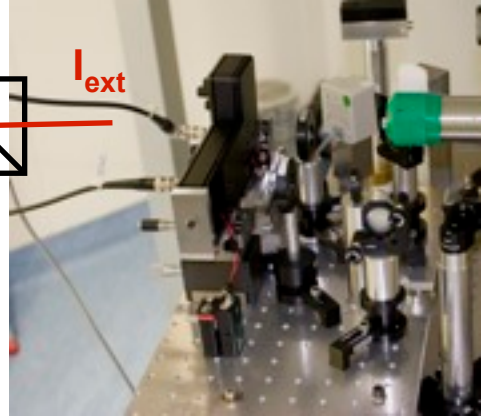
$$\psi(t) = \underbrace{\frac{2\pi c}{\lambda} \times \frac{\tau}{L_{cav}} \times L_{mag} \times \Delta n_u \times \sin(2\theta)}_{\alpha} \times B^2$$

$$\alpha \downarrow \Delta n_u$$

Expected values

- $\Delta n_u(air) \simeq 7,5 \cdot 10^{-13}\ \mathrm{T}^{-2}$
- $\Delta n_u(He) \simeq 2 \cdot 10^{-16}\ \mathrm{T}^{-2}$
- $\Delta n_u(vacuum) = 4 \cdot 10^{-24}\ \mathrm{T}^{-2}$



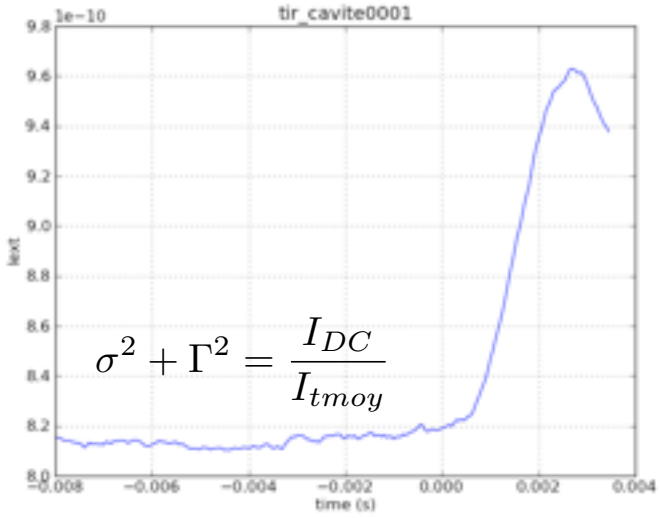


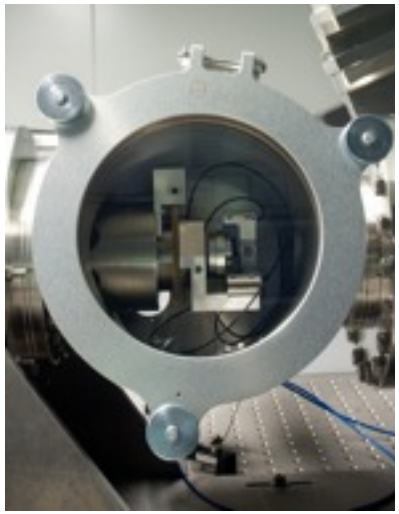
Γ mirror's ellipticity
$\psi(t)$ ellipticity to measure
σ^2 extinction of polarizers

Battesti et al, *Eur. Phys. J. D* **46**, 323–333, 2008

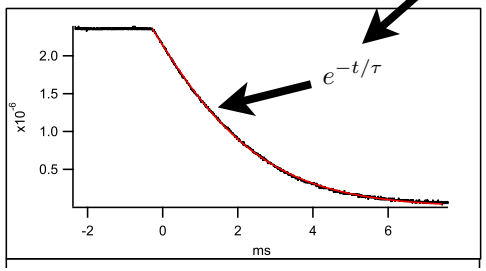
$$I_{ext} = I_t\sigma^2 + I_t\left(\Gamma + \psi(t)\right)^2 = I_t\left(\sigma^2 + \Gamma^2\right) + 2I_t\Gamma\psi(t) + I_t\psi(t)^2$$

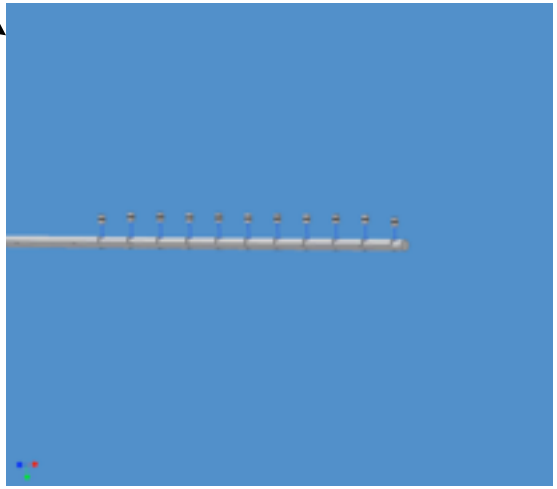
$$\Psi(t) = -\Gamma + \sqrt{\frac{I_{ext}}{I_t} - \sigma^2}$$

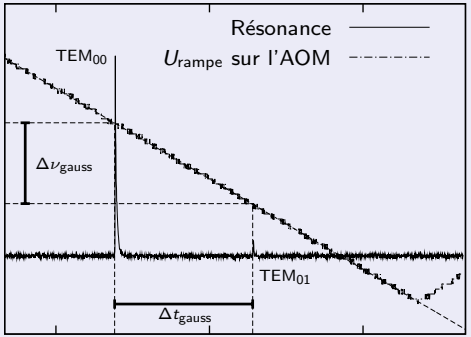




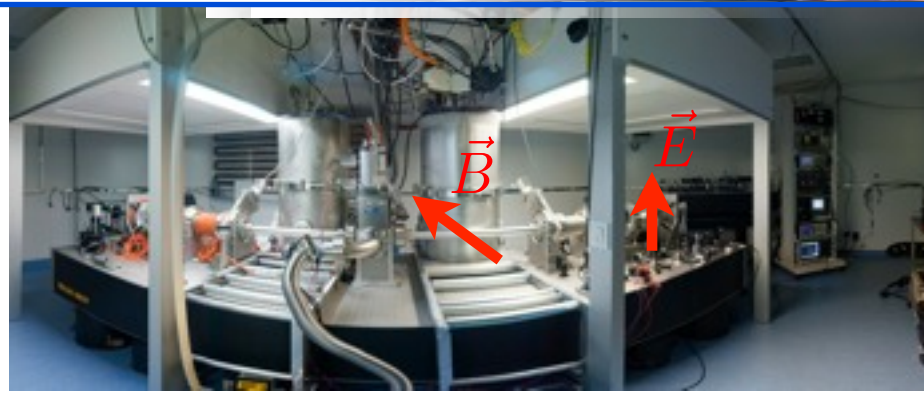
$$\psi(t) = \frac{2\pi c}{\lambda} \times \frac{\tau}{L_{cav}} \times L_{mag} \times B^2 \times \Delta n_u \times \sin(2\theta)?$$



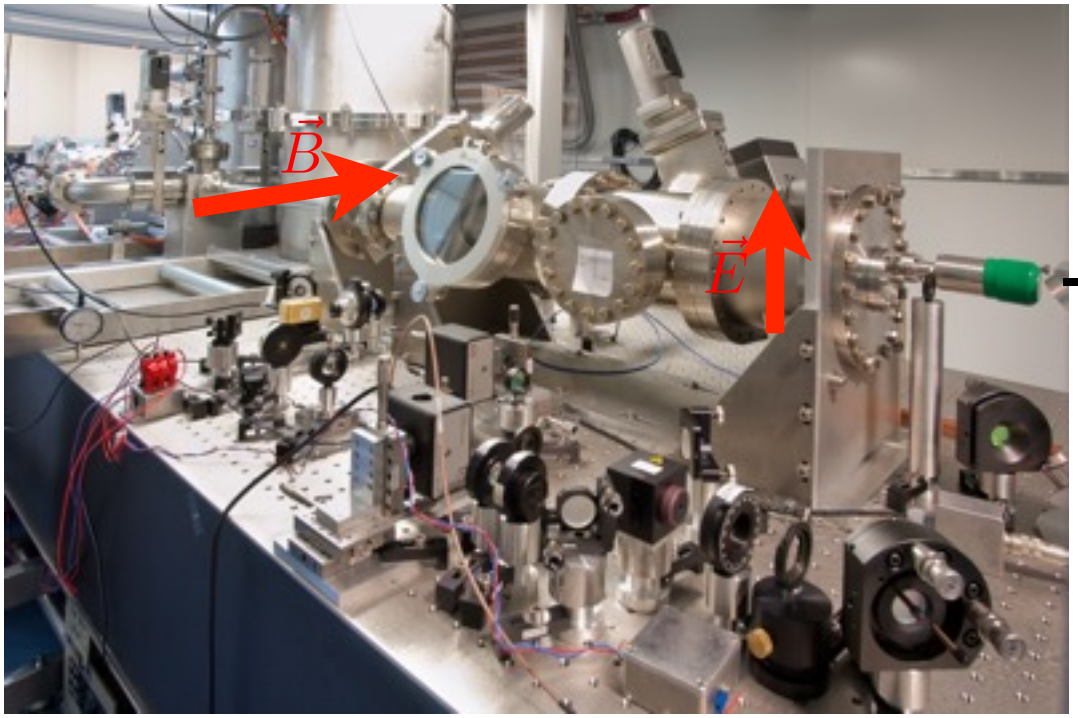




$$\frac{\delta(\sin(2\theta))}{\sin(2\theta)} < 1\% \Rightarrow \delta\theta < 3^\circ$$

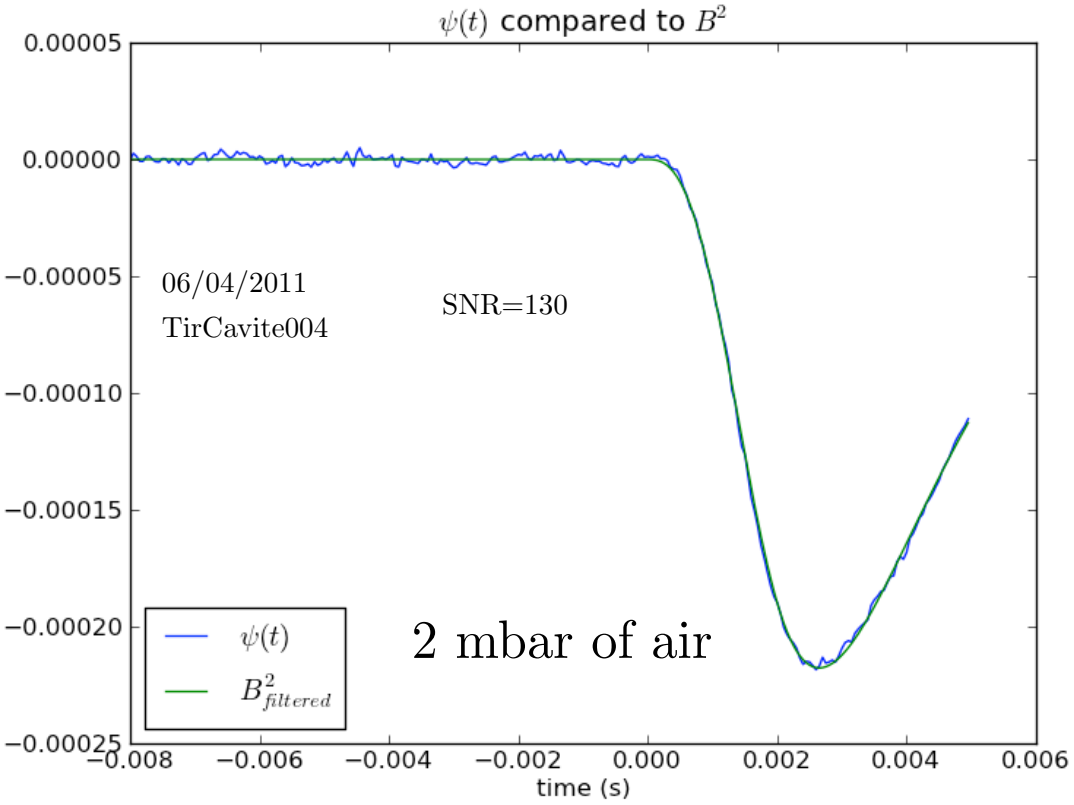


- Mechanical alignment : we evaluate θ within $\pm 5^\circ$



rotation : 1 turn = 2,4°

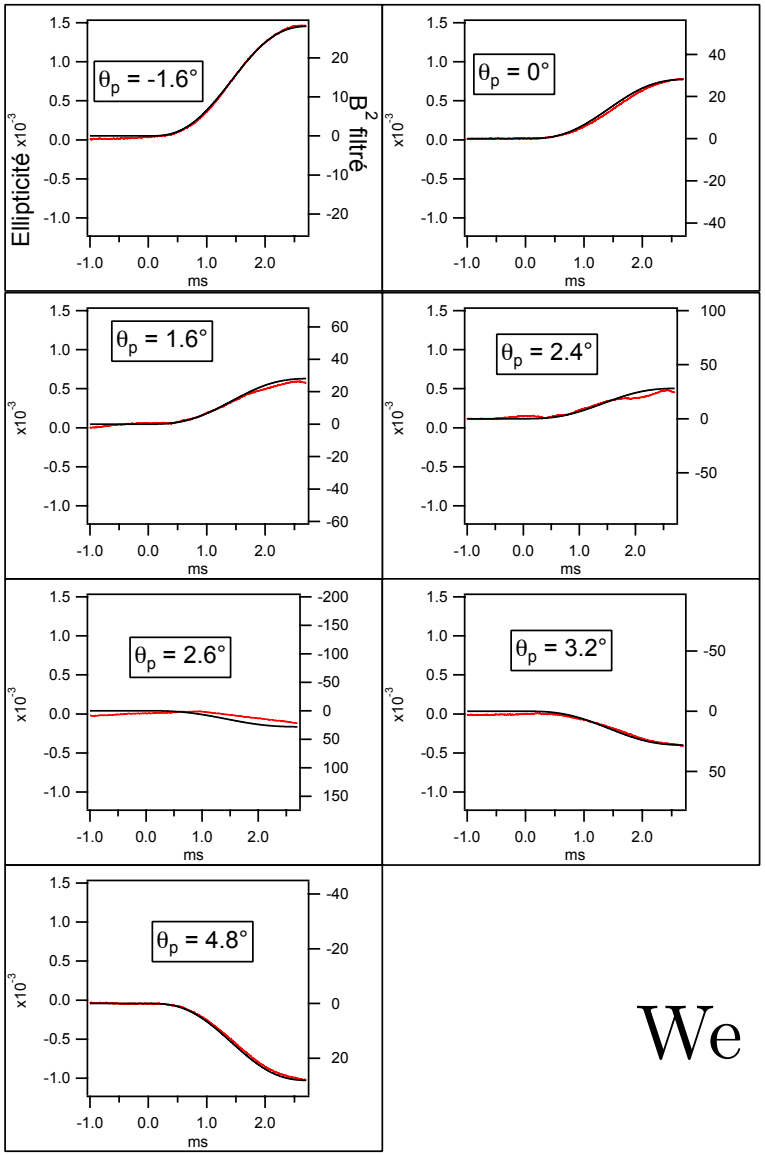
$$\psi = f(\theta_p)$$



$$\Delta n_{fit} = \Delta n_{corr} = -8 \cdot 10^{-17}$$

$$\Downarrow$$

$$\theta = 2^\circ$$



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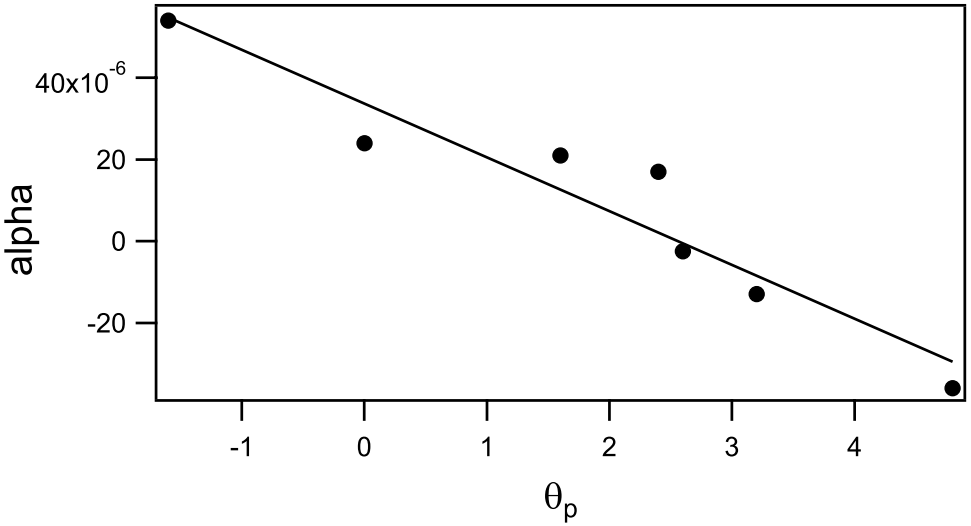


$$\text{We put } \theta = (2,6 \pm 0.2)^\circ$$

Conclusions and perspectives

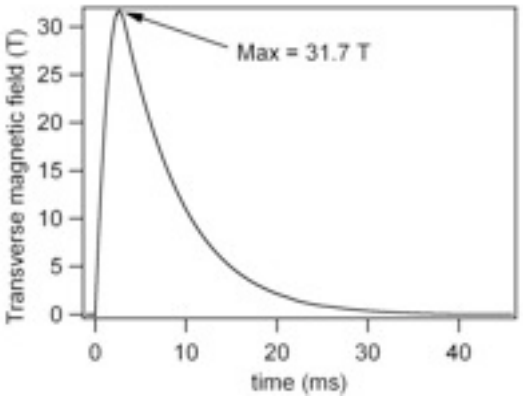
- Already done :

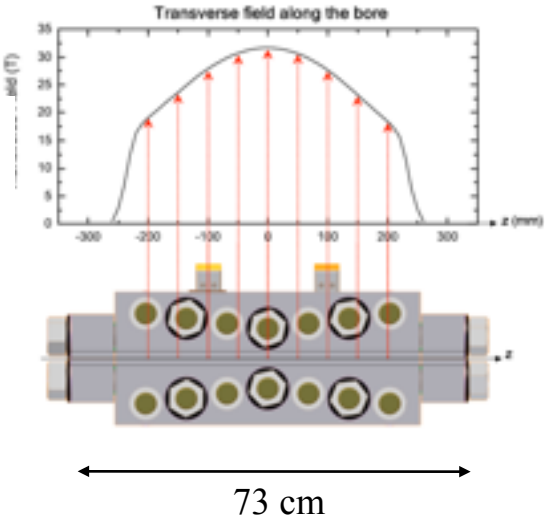
  Coupled high magnetic field and the best Fabry-Perot cavity

- Future :

  - **Increase** of the transverse magnetic field : new XXL-coil :

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





Conclusions and perspectives

- Our smallest measured Δn_u is 4×10^{-17} T^{-2} per pulse with a SNR of 60.

  ➡ Our best sensitivity is **6.6×10^{-19} T^{-2} per pulse**

- insertion of 2 XXL-coils on a new setup

  $\Rightarrow B^2 L_{mag} = 300\ T^2m$
- improvement of **Γ^2** (10^{-7})
- decrease **σ^2** (10^{-8})
- stabilisation of our locking system

➡ Improvement of the sensitivity :

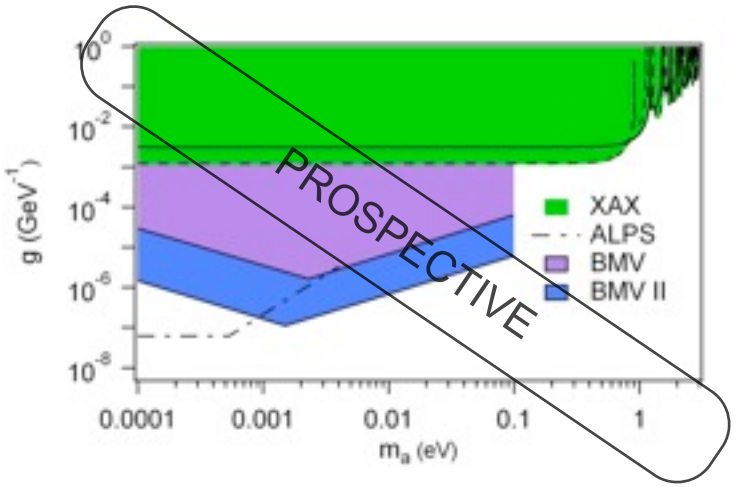
2.6×10^{-21} T^{-2} per pulse

- **Vacuum measurement**

  5000 pulses (2 months)

➡ QED : $\Delta n = 4.10^{-24} B^2$

➡ New axion terrestrial limits



XAX / BMV experiments

Rémy Battesti

http://www.toulouse.lncmi.cnrs.fr/

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