Status of the OSQAR Experiments at CERN

by Andrzej Siemko & Pierre Pugnat (CERN)
on behalf of the OSQAR collaboration

***O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xion & photon **R**egeneration*

***PATRAS Workshop, DESY Hamburg**, 20* June 2008

The OSQAR Collaboration *at present*

▸ *22 Members from 9 Institutes (CZ, FR, PL & CERN)*

CERN, Geneva, Switzerland — P. Pugnat, M. Schott, A. Siemko

Charles University, Faculty of Mathematics & Physics, Prague, Czech Republic — M. Finger Jr., M. Finger

Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic — J. Hošek, M. Kràl, J. Zicha, M. Virius

ISI, ASCR, Brno, Czech Republic — A. Srnka

IMEP/LAHC - INPG, 38016 Grenoble Cédex-1, France — L. Duvillaret, G. Vitrant, J.M. Duchamp

IN, CNRS – UJF & INPG, BP 166, 38042 Grenoble Cédex-9, France — B. Barbara, R. Ballou, Y. Souche

LSP, UJF & CNRS, 38402 Saint-Martin d'Hères, France — R. Jost, S. Kassi, D. Romanini

TUL, Czech Republic — M. Šulc

Warsaw University, Physics Department, Poland — A. Hryczuk, K. A. Meissner

Outline

- Scientific Motivations
- Overview of the OSQAR Experiments
  - "n-1" Experiment *i.e. Vacuum Magnetic Birefringence*
  - Photon Regeneration Experiment
- Preliminary Phase of the OSQAR Photon Regeneration Experiment
  - First results for Axion Like Particle (ALP) Searches
- Short & Long Term Perspectives
  - R&D
  - Expected results
- Summary & Outlook

The Magneto-Optical Properties of the Quantum Vacuum from *QED: The Vacuum Magnetic Birefringence*

- VMB from the QED Theory: Euler-Heisenberg Lagrangian,

  i.e. Taylor expansion of gauge and Lorentz invariants

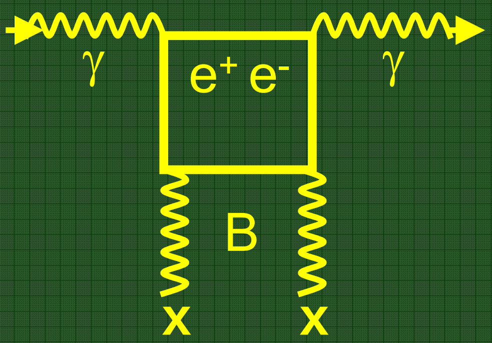
$$L = \frac{1}{2}\left(E^2 - B^2\right) + \frac{2\alpha^2}{45m^4}\left[\left(E^2 - B^2\right)^2 + 7\left(E.B\right)^2\right] + \ldots$$

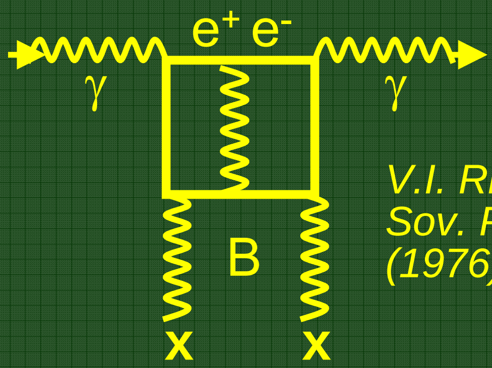
E, B << $m^2/e \sim 10^{18}$ V/m, 10^9 T and ω << m

Heisenberg & Euler, Z. Physik 38 (1936) 314

Weisskopf, K. Danske Vidensk. Selk. Mat.-fys. Medd. 14 n° 6 (1936)

Schwinger, Phys. Rev. 82 (1951) 664





V.I. Ritus, Sov. Phys. JETP 42 (1976) 774

- Tensors of permittivity & permeability of the vacuum:

$$\varepsilon_{ik} = \delta_{ik} + \frac{4\alpha^2}{45m^4}\left[2\left(E^2 - B^2\right)\delta_{ik} + 7B_iB_k\right] + \ldots$$

$$\mu_{ik} = \delta_{ik} + \frac{\alpha^2}{45m^4}\left[2\left(B^2 - E^2\right)\delta_{ik} + 7E_iE_k\right] + \ldots$$

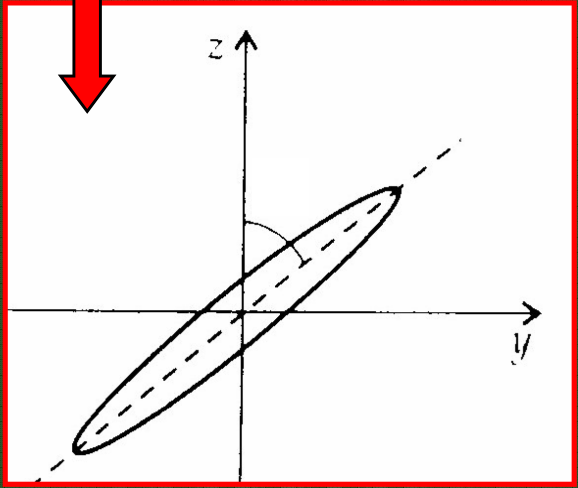
NB: Heaviside-Lorentz units *(1 T = 195 eV^2 & 1 m = 5.07×10^6 eV^{-1})*

"Pure" QED prediction – *The Vacuum Magnetic Birefringence*

$$n_{\perp} = 1 + 7\, A_e\, B^2 \sin^2\phi \qquad n_{//} = 1 + 4\, A_e\, B^2 \sin^2\phi$$

S. L. Adler, Ann. Phys. 67 (1971) 599

As a consequence, a linear polarized light becomes "slightly" elliptical



$$\Delta n = 4.0 \times 10^{-24} B^2$$

$\Delta n \approx 3.6\ 10^{-22}$ in 9.5 T field

$$\varepsilon = \pi \frac{l}{\lambda} \Delta n \ \sin 2\phi = \pi \cdot l \cdot C \cdot B^2 \sin 2\phi$$

Analogue to the Cotton-Mouton effect

$\varepsilon \approx 2.10^{-10}$ for l = 250 km and λ =1.55 μm

2nd order correction to the Lagrangian, i.e.O(α^3), gives a Δn correction of 1.45% with respect to the dominant term.

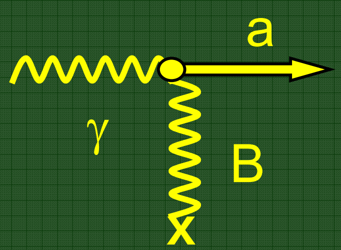
▶ *Measurement of the QED birefringence down to this level is also targeted*

A challenge for optical metrology ⇒ High-field magnet, optical cavity & …

Beyond the pure QED - Contribution of Axions/ALPs to the VMB + Linear Dichroism

- The Euler-Heisenberg Lagrangian can be further extended to include contributions of hypothetical neutral light spin-zero particles that couple to 2-photons such as axions:

$$L_{a\gamma\gamma} = \frac{1}{M}\vec{E}.\vec{B}\ a$$



- A linearly polarized laser beam propagating in vacuum is expected to acquire, in presence of a transverse *B* field, a small apparent rotation θ & ellipticity ε expressed in the limit $m^2\ l\ /\ 4\omega << 1$:

$$\theta \approx \frac{B^2 l^2}{16\ M^2}\ \sin 2\phi$$

$$\varepsilon \approx \frac{B^2 l^3 m^2}{96\ \omega\ M^2}\ \sin 2\phi$$

L. Maiani et al. Phys. Lett. 175B (1986) 359

ϕ is the polarization angle of the light / *B*, *M* the inverse coupling constant, *m* the axion mass & ω the photon energy.

Interest in Axions

- Axions Physics
  - axions are theoretically necessary - the only known solution of the "strong CP-problem"
  - without axions the neutron dipole electric moment is unnaturally small

$$d_n = O(1)\frac{m_u \sin\theta}{f_\pi^2} \approx 10^{-16}\theta \text{ e cm}$$

while experimentally $d_n < 3 \cdot 10^{-26}$

  - axions couple to gluons (solving the strong CP-problem) and to photons (basis of OSQAR experiment)
- "Massive" Axions *(0.1-1.8 MeV)* excluded after extensive search in nuclear transition, particle decays (1978-1987)

$\Rightarrow$ "Invisible" axion models in the range 10^{-6}-10^{-2} eV,

"Small can also be beautiful"

OSQAR - Summary of Scientific Motivations

Results are in practice guaranteed

- Test of QED down to an unprecedented level (i.e. $\Delta n \sim 10^{-22}$) & of Quantum Mechanics
- Axion ?
- New Physics at sub-eV (ALPs, millicharged-particles, paraphotons, Chameleons…) ?
- Identification of the DM component (Non-SUSY) ?

► Also, another way of doing Particle Physics based on Lasers and High Magnetic Field

OSQAR is complementary to CAST…

- Solar observatory: From past to present…

K. Zioutas in CERN Courier of June 2008

- CAST sensitivity for Axion search is x10 better than OSQAR phase-2 but more model dependant,

  Ex. Solar models do not take into account magnetic fields
  $\Rightarrow$ *Are huge solar magnetic fields (up to 100 T & more in bulk) could provide already an efficient axion-photon conversion within the sun ?*

- OSQAR Phase-3 *(not before ~2012)* can be competitive with CAST…

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Optical Precision Measurements for QED Test & Axion Search

The "n-1 Experiment"

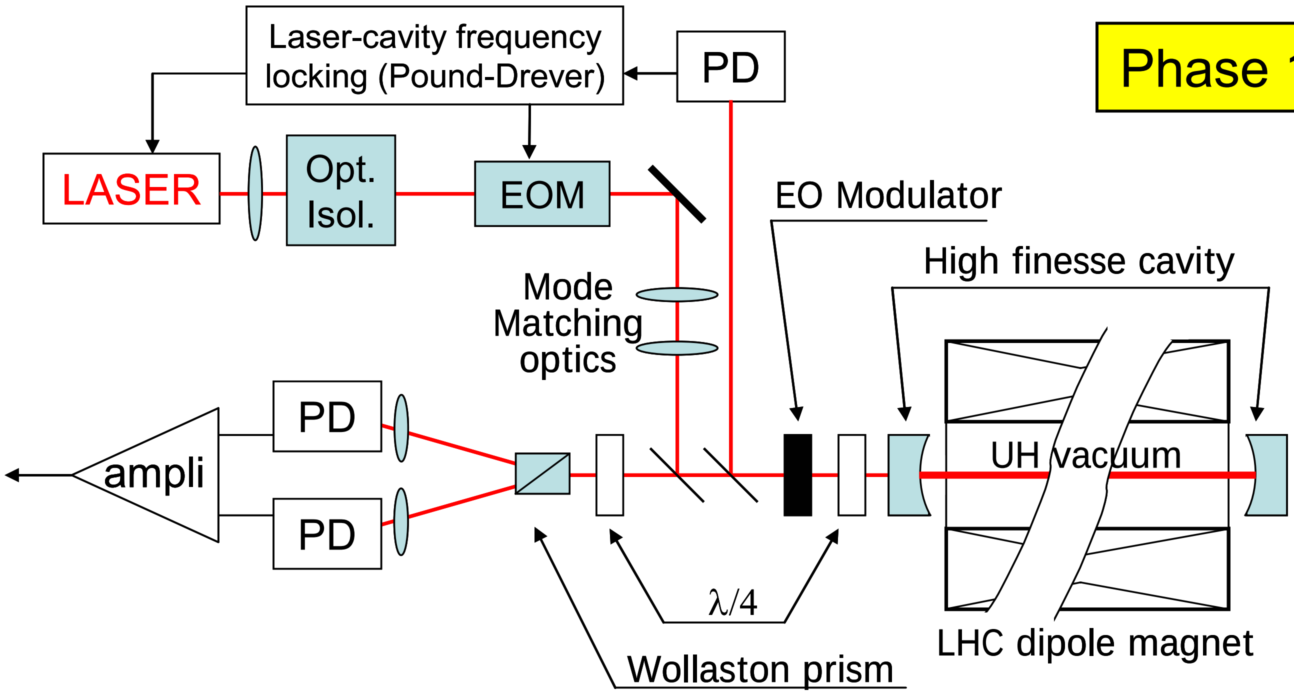
VMB & Linear Dichroism measurements for Axion/ALP Search: *Principle & Proposed Optical Scheme*

- Axions ⇒ Change of the linear polarisation of a laser beam after propagation in the vacuum with B transverse:
  - Elliptical
  - "Pseudo"-rotation
- Background for the ellipticity coming from the QED VMB
  ⇒ Physics is guaranteed
- Very small effects ~10^{-14} rad / T^2 km^3
  ⇒ optical cavity to increase the path in B

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

P. Pugnat, L. Duvillaret, M. Finger, M. Kral , A. Siemko, J. Zicha
Czechoslovak Journal of Physics, Vol.55 (2005), A389;
Optical scheme with inputs from D. Romanini.

Phase 1

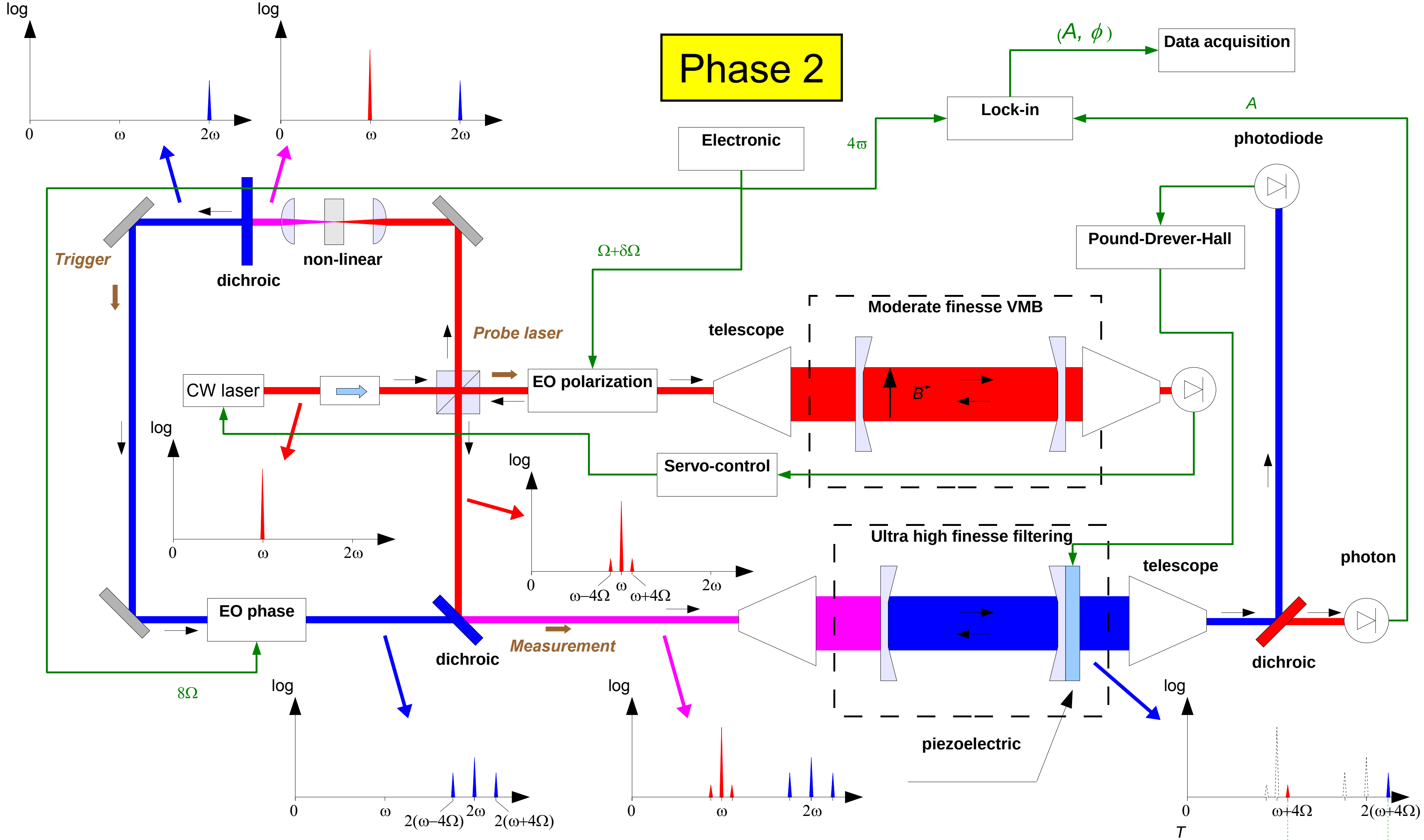


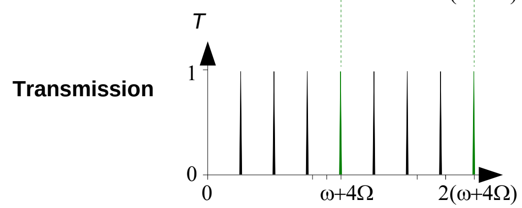
$$\tilde{P}_{opt} \approx 1 + \Psi \sin(4\Omega t + \phi) + \Theta \cos(4\Omega t + \phi)$$

Field Modulation at 1-10 mHz
& dedicated filtering techniques

Metrology,…

From L. Duvillaret, G. Vitrant





"Exploring a new territory with a precision instrument is the key to discovery"

S. Ting, Nobel Prize in Physics (1976)

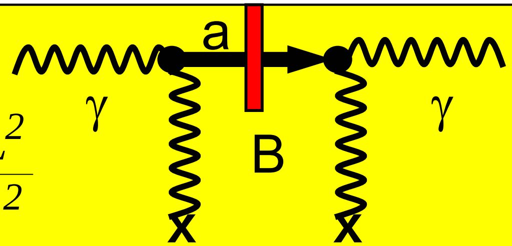
Experiment for Photon Regeneration from Axion or other scalar or pseudo-scalar

“An invisible light shining through a wall”

K. van Bibber et al.
PRL 59 (1987) 759

Direct Axion/ALP Search Experiment
Photon Regeneration

P. Sikivie, PRL 51 (1983) 11415

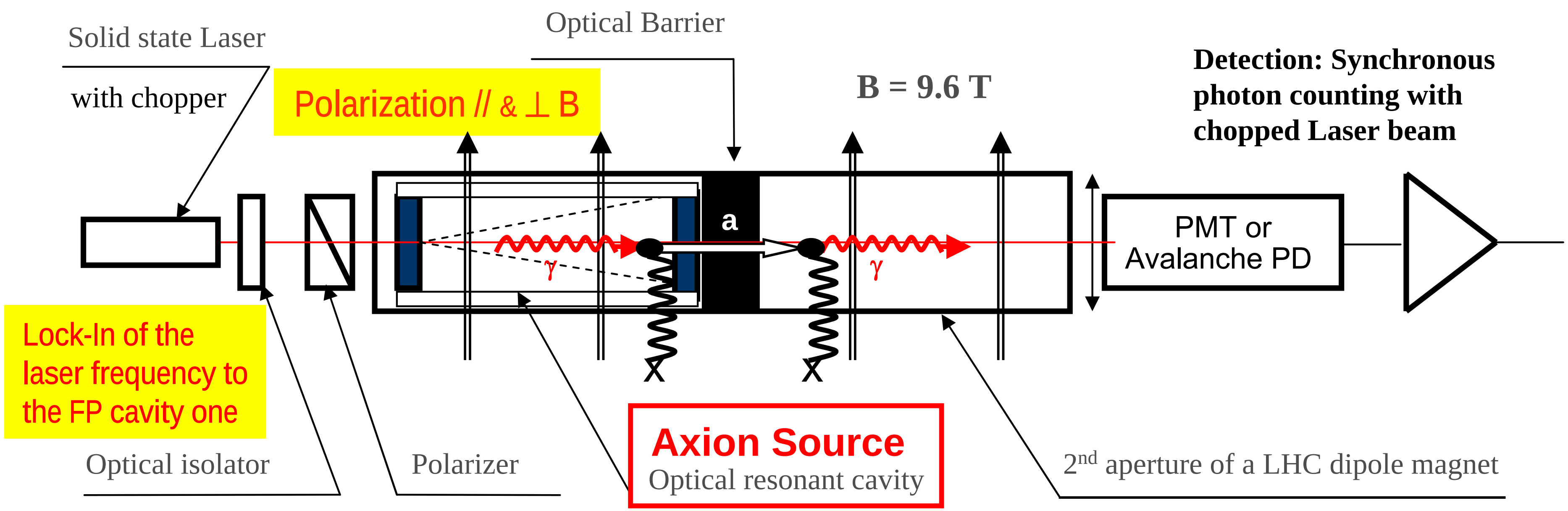


K. van Bibber et al. PRL 59 (1987) 759

In the limit qL<<1

$$P(a \to \gamma) = P(\gamma \to a) \approx \frac{B^2 L^2}{4M^2}$$

$$R \approx \frac{\eta P}{h\nu} \frac{N}{2} \left(\frac{B^2 l^2}{4M^2} \right) \cdot \left(\frac{B^2 L^2}{4M^2} \right)$$



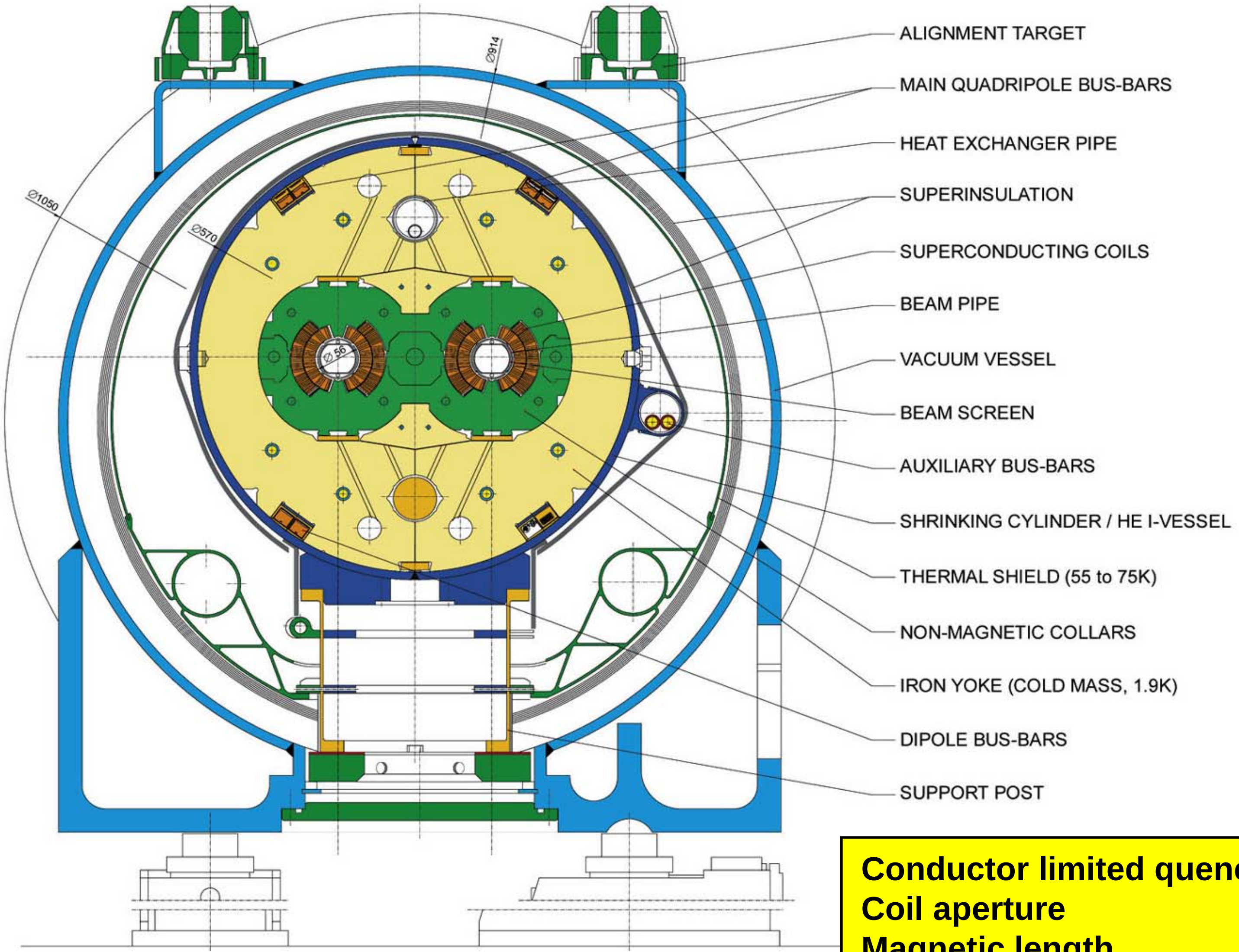
Nd-YAG laser: Power P = 0.1 – 10 kW
λ = 1064 nm
Optical cavity: F = 10^4-10^5, l = 7 m
Detection part: L = 7 m

Expectations: Improvement of the present reference result of Cameron et al. Phys. Rev. D47 (1993) 3707 ~ R x 10^7 with 1 magnet & 100 W

Unique opportunity with LHC dipoles

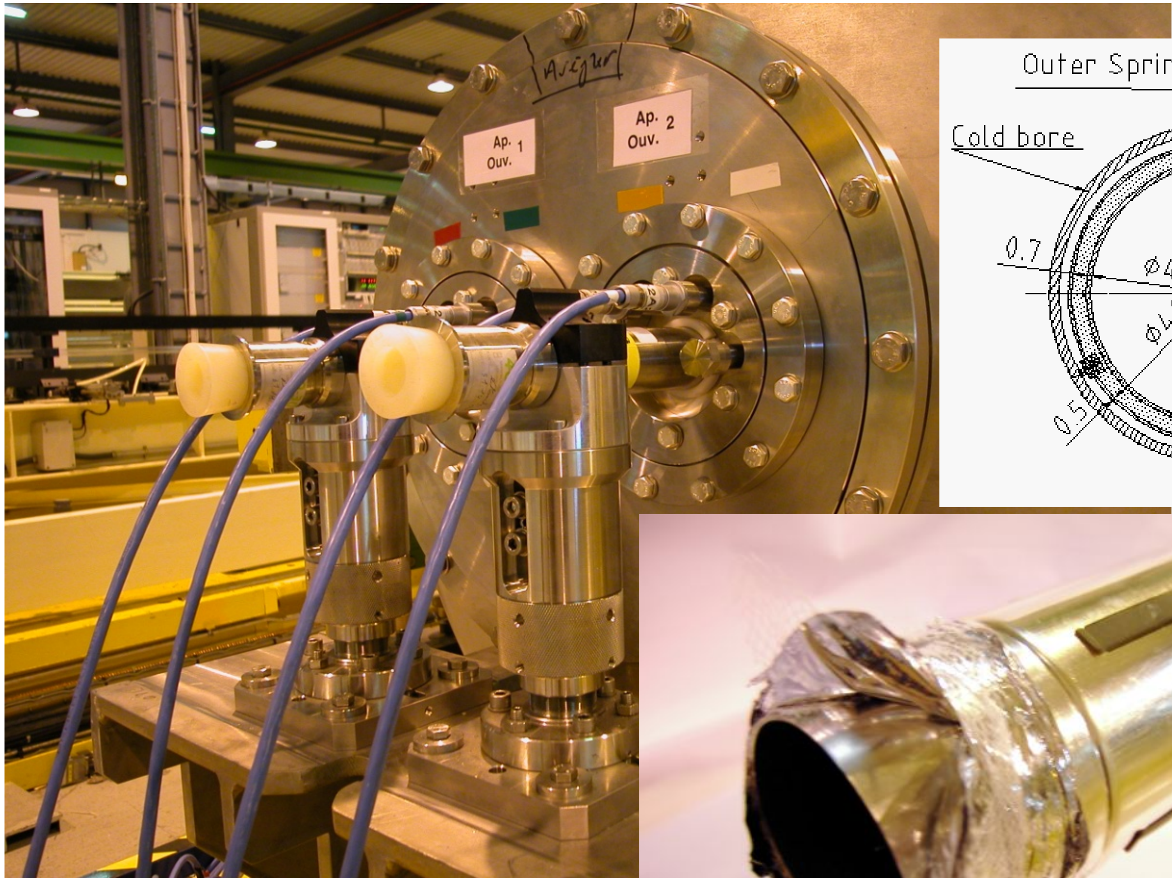
Experiment	**BFRT**	**PVLAS**	**BMV**	**OSQAR**
Status	Terminated	Achieved	Achieved/ Phase-1/Phase-2	Phase-1/Phase-2
λ (nm)	514.5	1064	1064	1550
Finesse of the FP cavity	N ~ 250	120 000	50 000/200 000/ 1 000 000	10 000/1 000
Sensitivity (rad/Hz$^{1/2}$)	10^{-8}	$10^{-6}/10^{-7}$	10^{-8}	$10^{-8}/10^{-10}$
B (T)	4	6	14.3 (during 0.1 s)	9.5
$B^2\,l$ (T^2 m) *for QED Test*	140	36	28	1 290
$B^2\,l^2$ (T^2 m^2) *for ALPs Search*	1 240	36	4	18 460
$B^2\,l^3$ (T^2 m^3) *for ALPs Search*	10 900	36	0.5	263 910
Magnetic duty cycle *(R)**	~1	~1	10^{-4}	~1

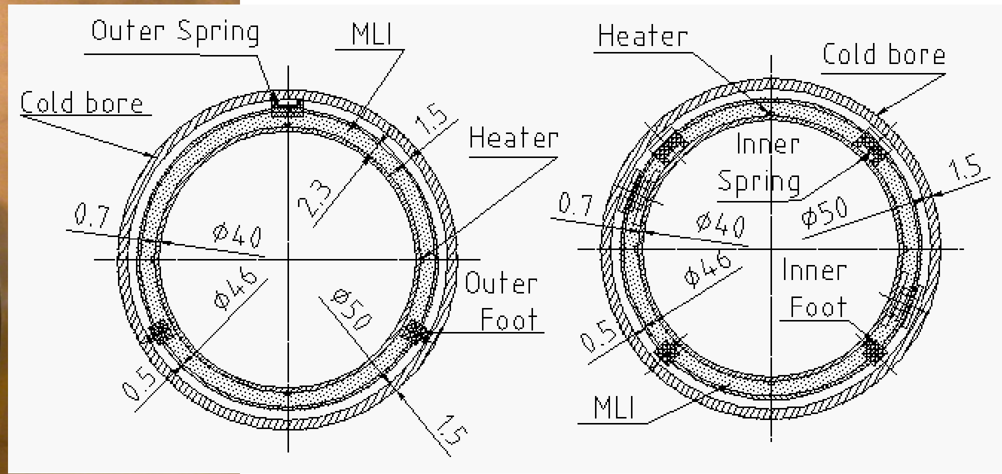
LHC superconducting main dipoles
Cross-section

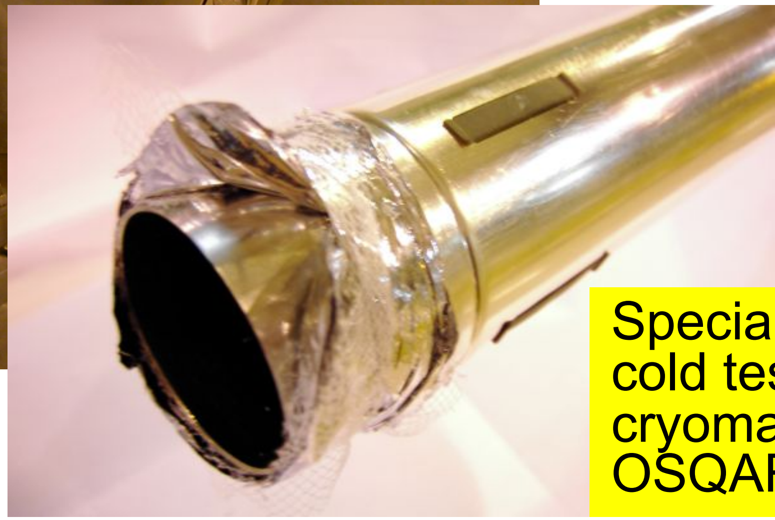


Conductor limited quench field @ 1.9 K	**9.76 T**
Coil aperture	**56 mm**
Magnetic length	**14.3 m**

Base Line: *use of warm bores i.e. anticryostats inserted inside cold bores*



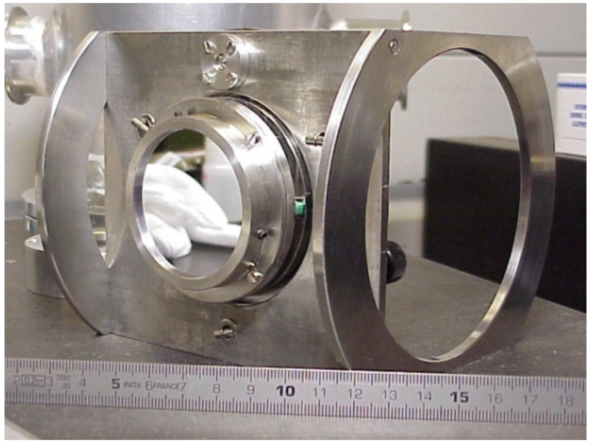


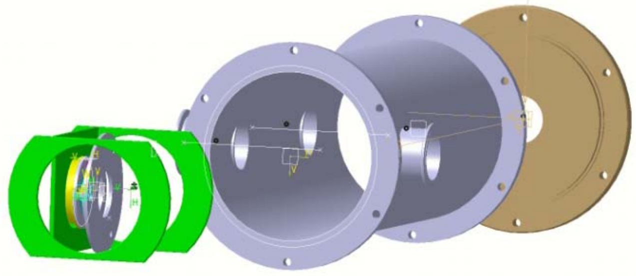


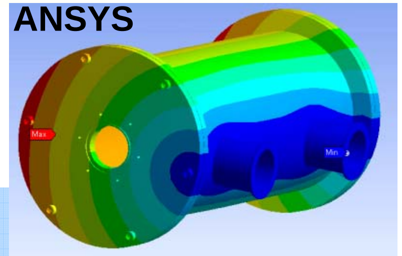
Specially designed for the cold tests of LHC cryomagnets ⇒ is re-used for OSQAR

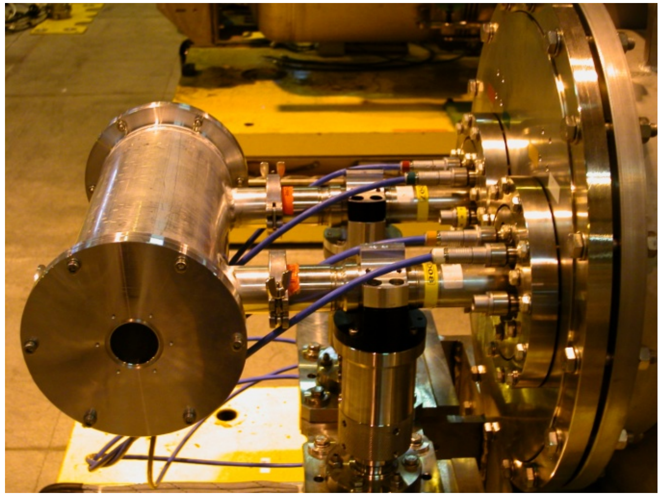
O. Dunkel, P. Legrand and P. Sievers: "A warm bore anticryostat for series magnetic measurements of LHC superconducting dipole and short-straight section magnets", *CRYOGENICS CEC/ICMC, 2003, Anchorage, Alaska; CERN-LHC-Project-Report-685*

VMB & Dichroism Measurements
Prototyping Phase – *PhD M. Král*

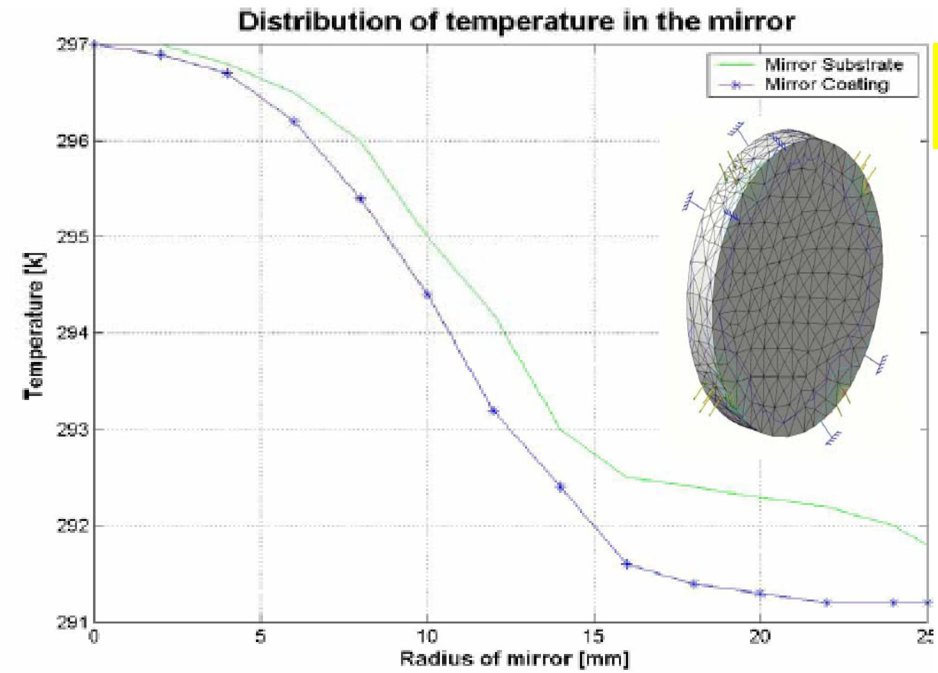




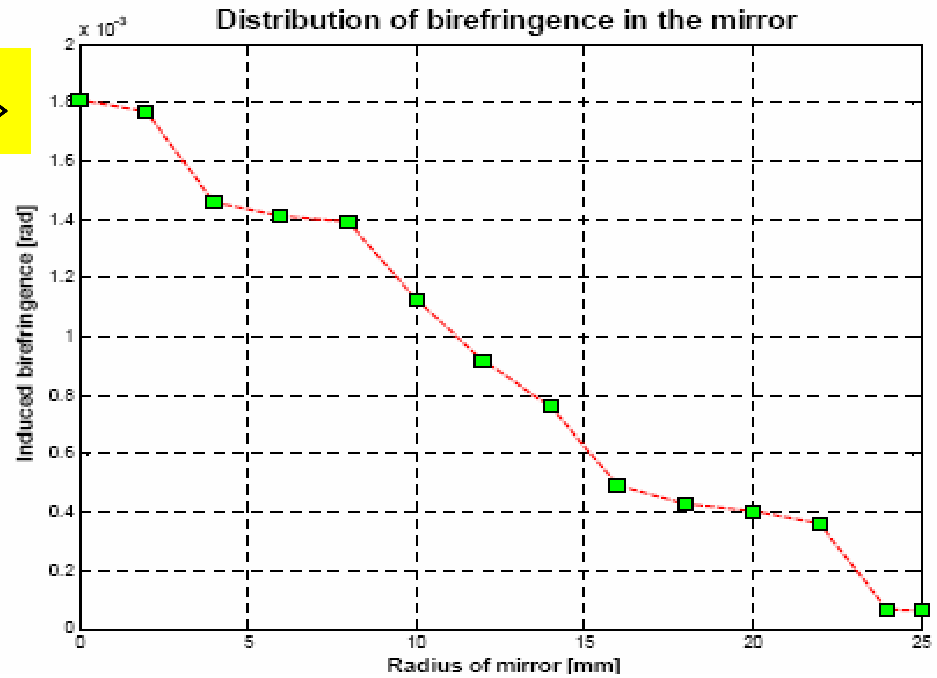




Study of vibration eigenmodes (f, amplitude) →



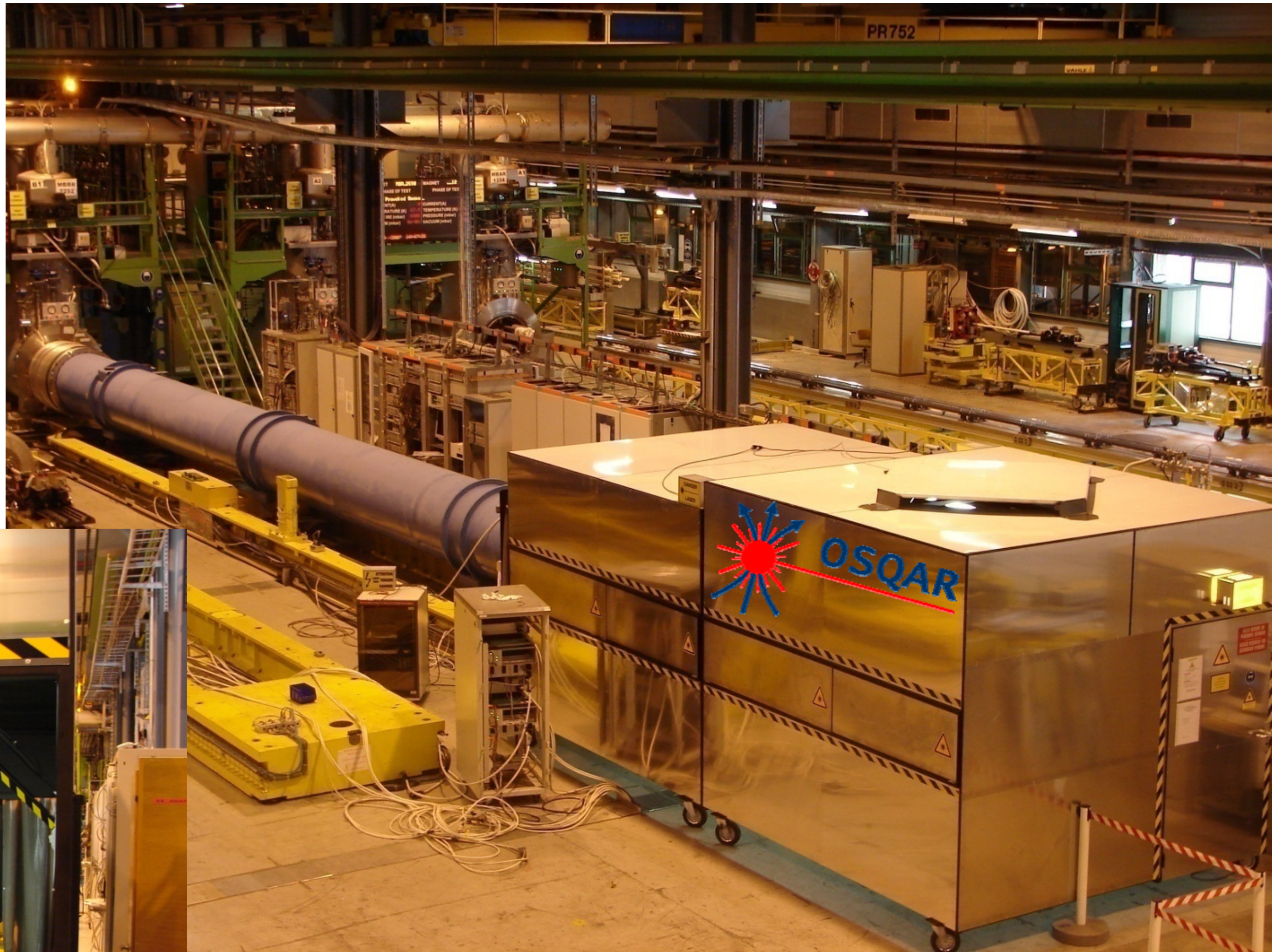
⇒



Re-use a part of the Test Infrastructure of LHC superconducting Magnets

Safety Issues ⇒ Construction of protection chamber against laser radiation (Class-4 laser)

► Use of Class-4 laser
⇒ High risk to eyes and skin
⇒ Protection against direct beam, specular and diffuse reflections



► Also Fire Hazard has to be mastered

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Vol 441| 4 May 2006 nature

PVLAS Results

NEWS & VIEWS

PARTICLE PHYSICS

The first axion?

Steve Lamoreaux

For almost 30 years, the hunt has been on for a ghostly particle proposed to plug a gap in the standard model of particle physics. The detection of a tiny optical effect might be the first positive sighting.

Writing in *Physical Review Letters*[1], Emilio Zavattini and colleagues of the Italian PVLAS collaboration report that a magnetic field can be used to rotate the polarization of a light wave in a vacuum. Although this is the first experimental evidence for such an effect, there is a well-rehearsed, but controversial, explanation for it: the existence of a never-before-seen, chargeless, spinless and near-massless particle — the axion. Has the elusive axion finally allowed itself to be glimpsed?

As befits the potentially revolutionary nature of the PVLAS result, the jury is still out. Such a direct verification would, however, propel it to a place among the most significant in the history of physics. ■

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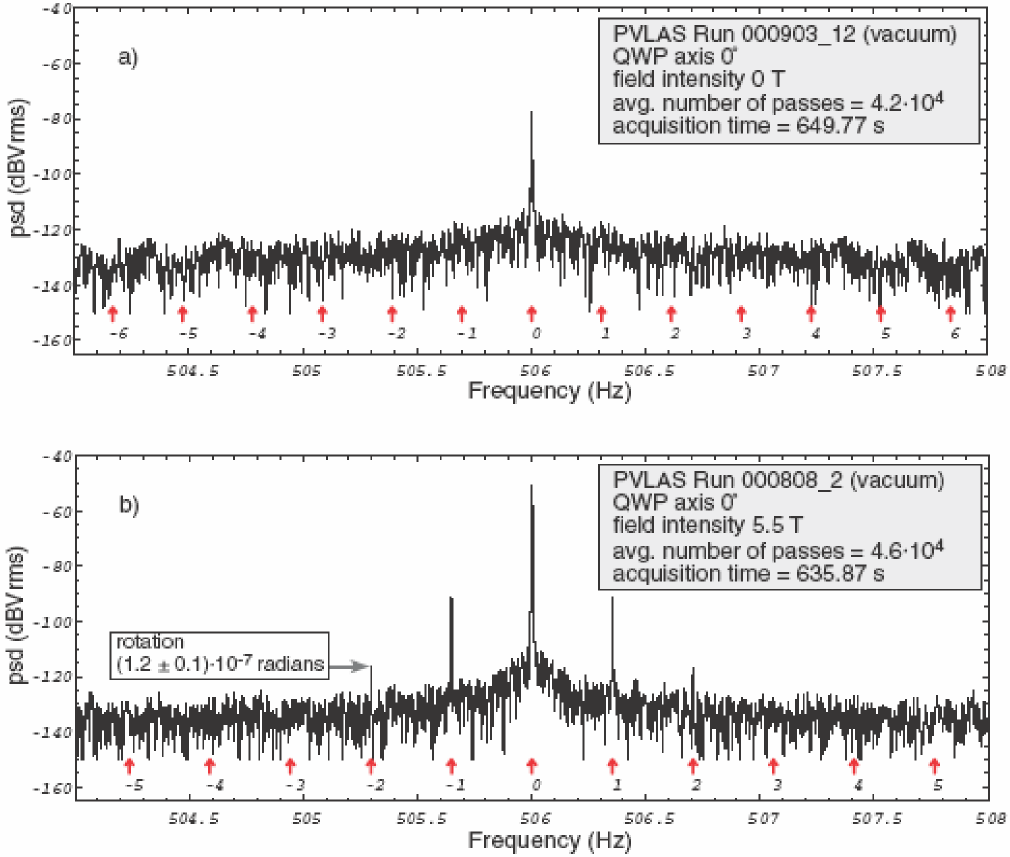
e-mail: lamore@lanl.gov



The one-century old Abraham-Minkowski Controversy

Question: What is the relationship between the energy *E* and the momentum *p* of a photon in a medium of refraction index *n* ?

- Abraham (1909)
  From SR & $p = E\, v/c^2$
  $$p = E / n c$$

- Minkowski (1908)
  From QM & $\lambda = h/p$
  $$p = n E / c$$

"Quite puzzling" knowing the success of QED,… reviewed recently in Nature

Vol 444|14 December 2006 **nature**

NEWS & VIEWS

OPTICS

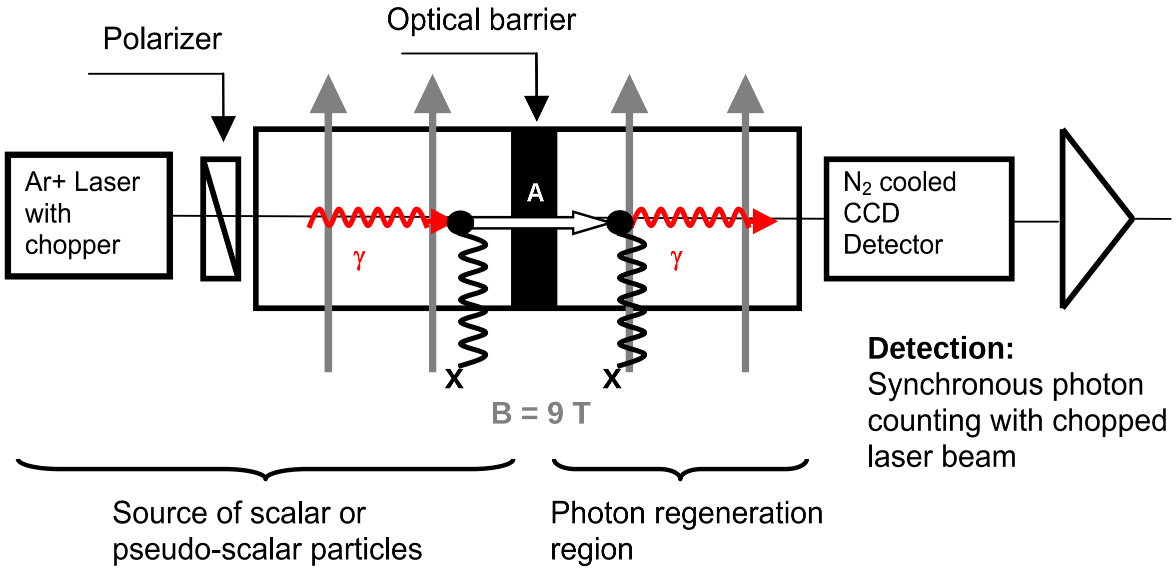
Momentum in an uncertain light

Ulf Leonhardt

How much momentum does light transfer to a material through which it passes? This is a surprisingly opaque matter, contested for almost a century, that is still the object of theory and experimentation.

"Whenever the wave aspects dominate, the Minkowski momentum appears, but when the particle aspects are probed, the Abraham momentum is relevant."

Use of a gaseous amplifier medium for Axion ↔ Photon



$$\frac{dN_\gamma}{dt} = \frac{P}{\omega}\eta\, P_{\gamma\leftrightarrow A}^{\ 2}$$

P. Sikivie, PRL 51 (1983) 11415

K. van Bibber et al. PRL 59 (1987) 759

$$\text{with } P_{\gamma\leftrightarrow A} = \frac{1}{4\beta_A\sqrt{\varepsilon}}(g_{A\gamma\gamma}BL)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2$$

$$\text{and } \ q \approx \left|\frac{m_\gamma^2 - m_A^2}{2\omega^2}\right| \approx \frac{m_A^2}{2\omega^2} - (n-1)\omega$$

⇐ If $k_\gamma = \omega/n$, i.e. Abraham momentum, and not the Minkowski one *i.e.* $k_\gamma = \omega\, n$

"Group velocity Matching"

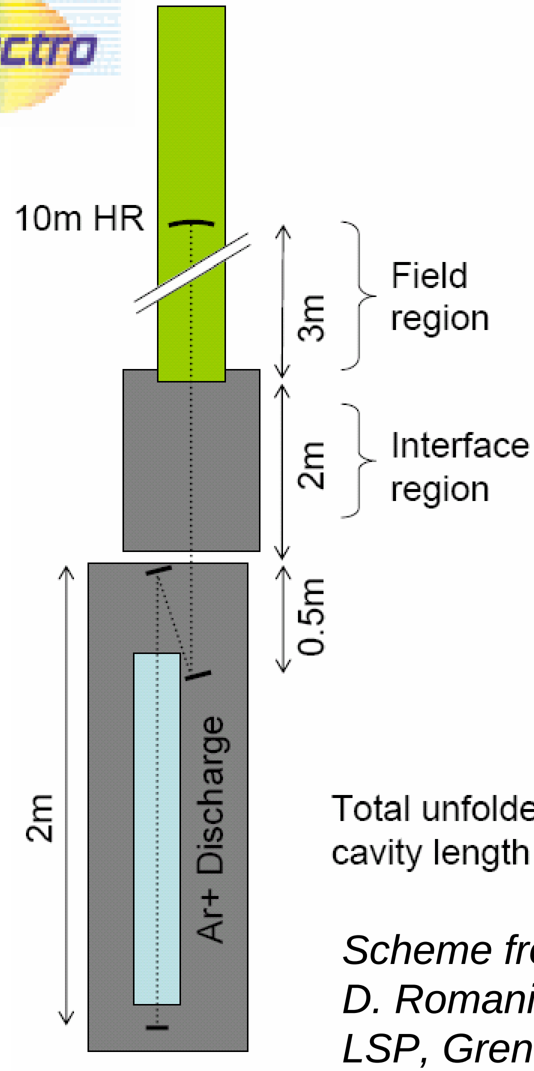
$$\text{Maximum of } P_{\gamma\leftrightarrow A} \text{ for } qL \to 0 \ \ i.e.\ (n-1) = 8.61 \times 10^{-8} \ for\ m_A = 1\ meV\ (PVLAS)$$

$$i.e.\ \ N_2 \text{ gas at the pressure of } 0.31\,\text{mbar}$$

$$\text{With } g_{A\gamma\gamma} = 2 \times 10^{-6} GeV^{-1},\ B = 9\ T,\ L \approx 7.15\ m,\ \eta \approx 32.5\%,\ \frac{dN_\gamma}{dt} \approx 420 \text{ photons/s at } 16\text{ W}$$

Photon Regeneration Experiment using 18 W Ar+ laser
R&D for 0.1-1 kW intra-cavity CW optical power

- Use of Ar+ laser (488 & 514 nm) from the LSP; R&D with R_{max} output coupler (> 99.55 %)
- Mirror integration inside the LHC magnet aperture with a Z-fold cavity (*alternative with a linear one)*
- For Axion/ALP search: Detection with a LN_2 cooled CCD Camera of Princeton Instrument, 1100 pixels of 5 mm height densely packed over 27 mm, QE ≈ 50%, DC/pix ≈ 0.1/mn

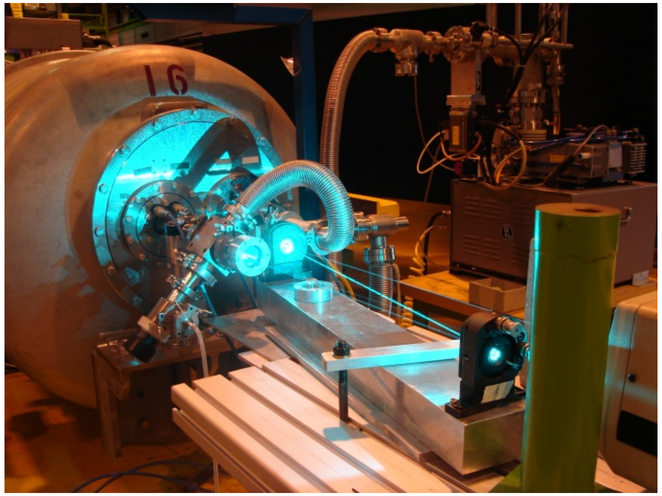


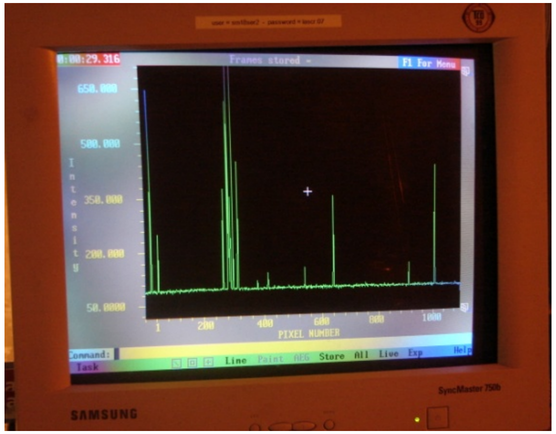
Total unfolded cavity length ~ 8m

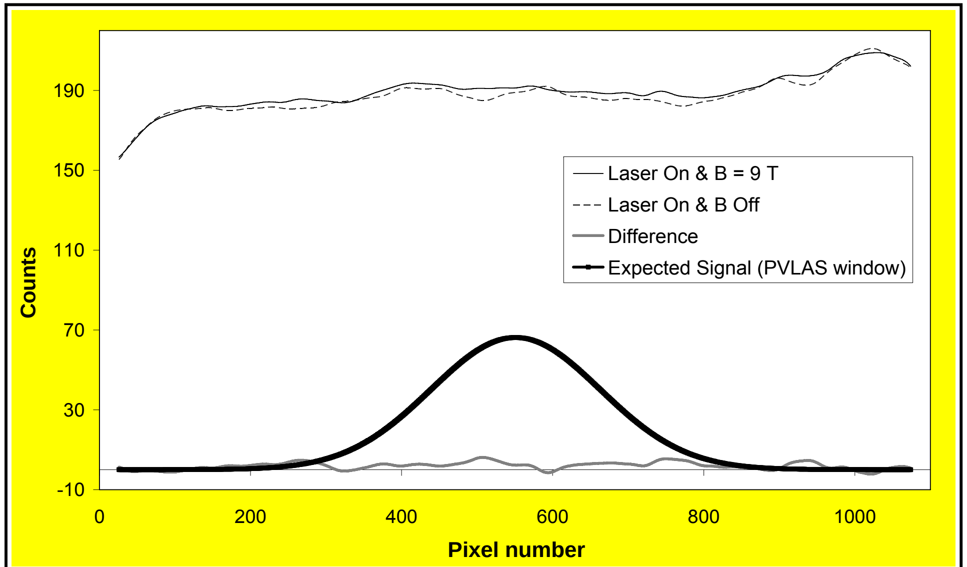
Scheme from D. Romanini LSP, Grenoble

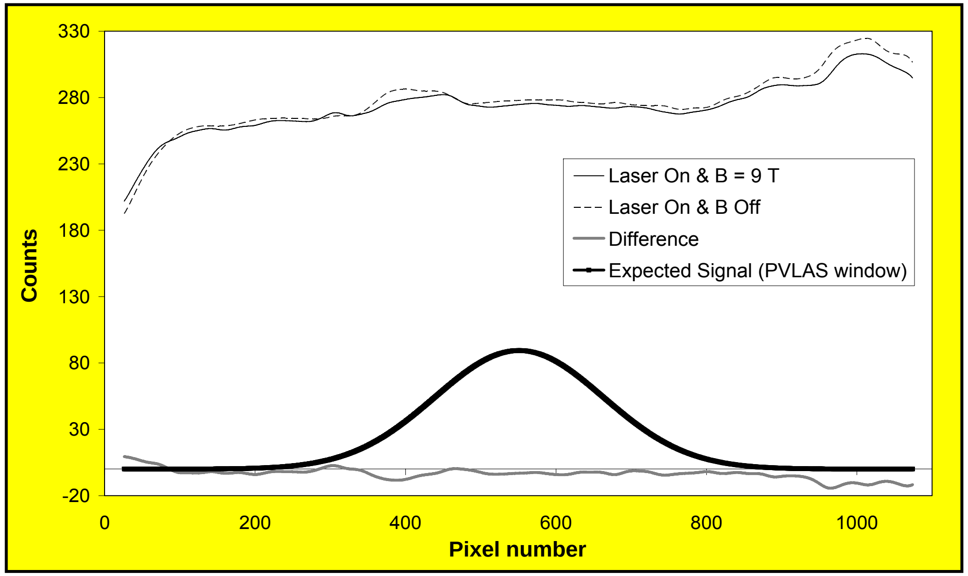
Photon Regeneration 1st results
with 18 W Ar+ laser & N_2 gas

OSQAR



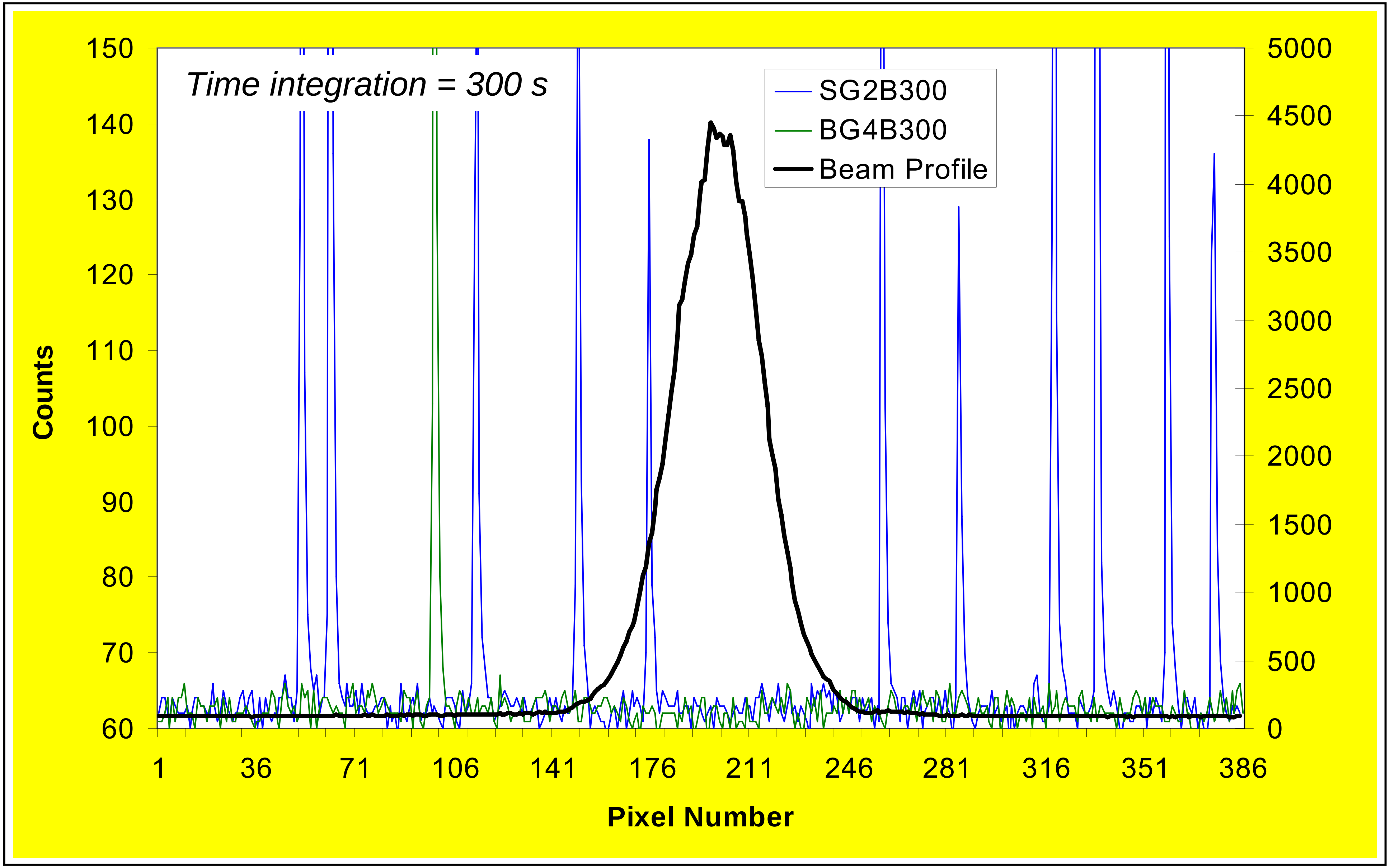






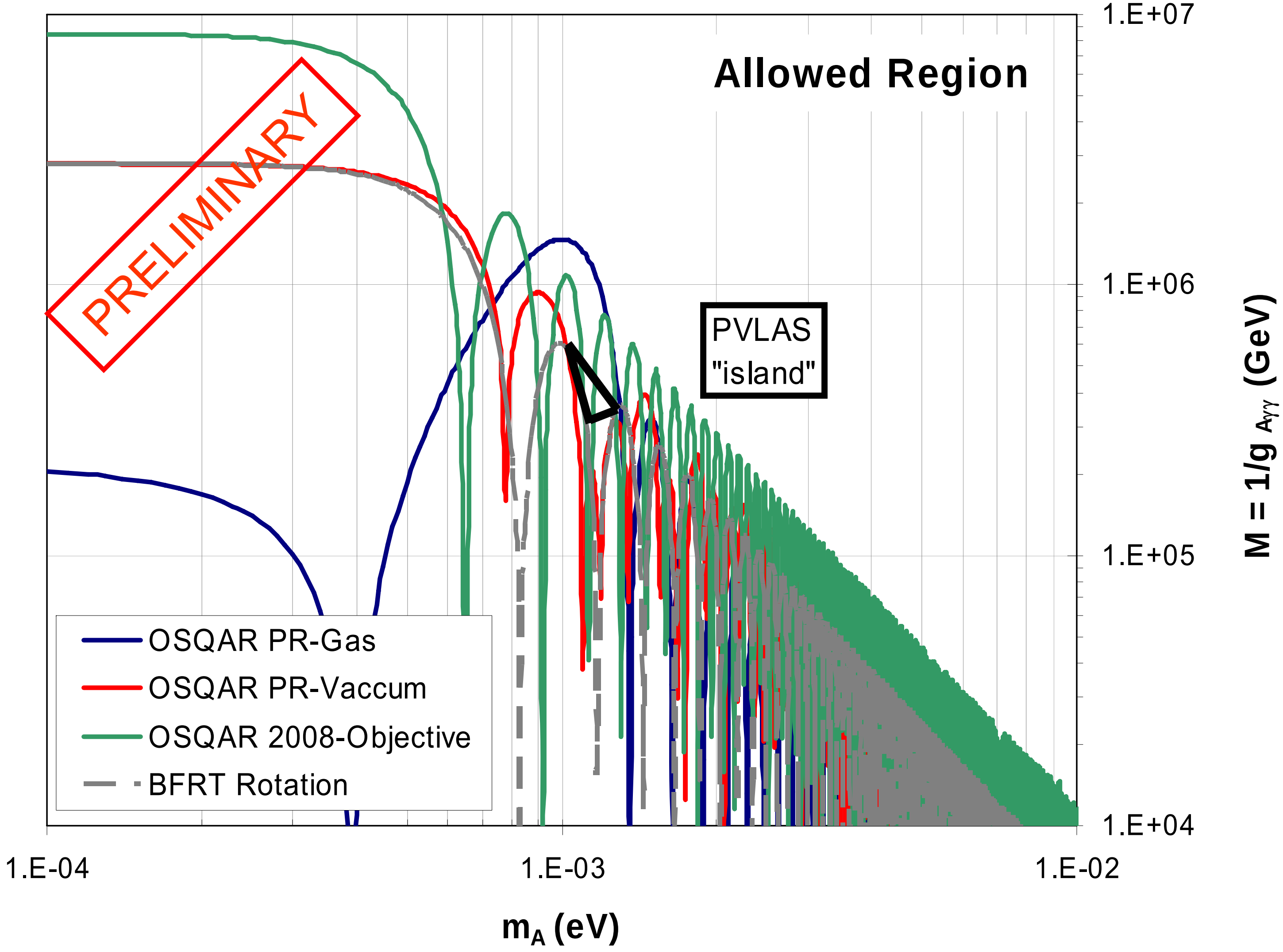
PVLAS result cannot be due to a new light spin-0 particle** (submitted, arXiv: 0712.3362), also reported from **BMV & GammeV

Photon Regeneration Raw Data within vacuum
Polarization // B



Results Overview including the expected in 2008

- PVLAS Results cannot be due to standard Axions
- Our results, as well as the ones of 2 other teams, exclude the interpretation of PVLAS data with the discovery of a new light spin-0 particle,…
- PVLAS retraction arXiv: 0706.3419



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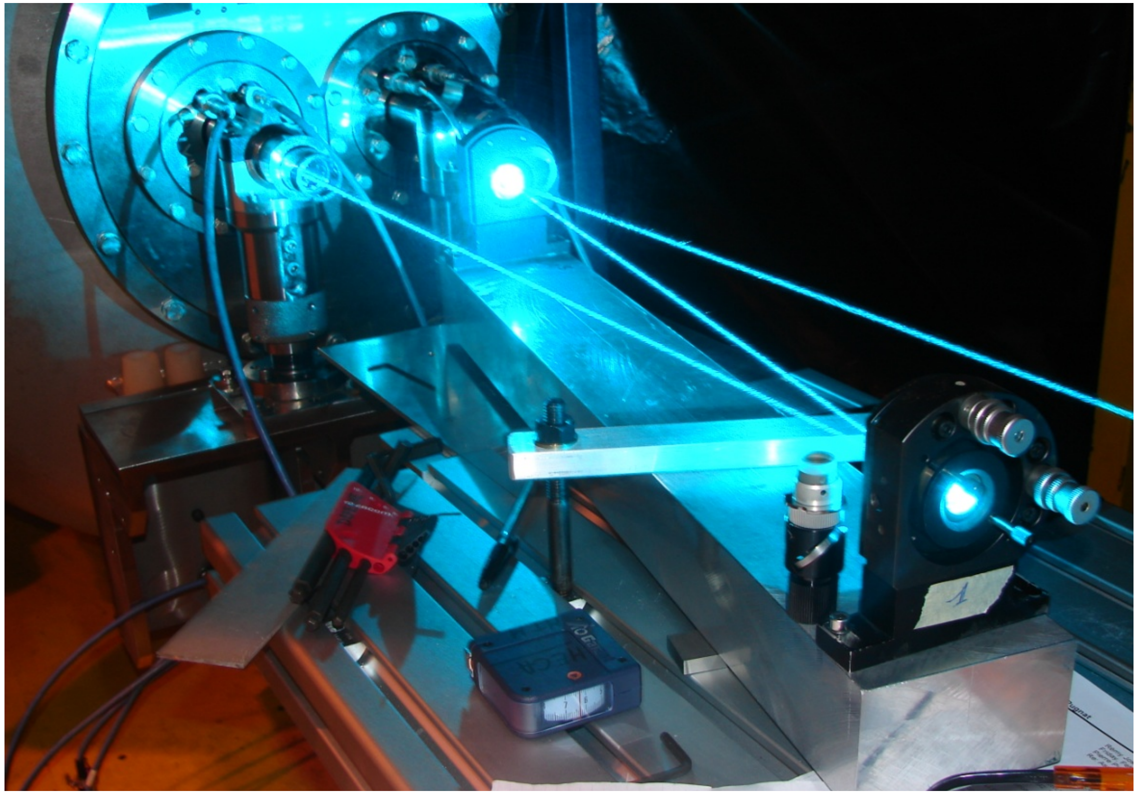
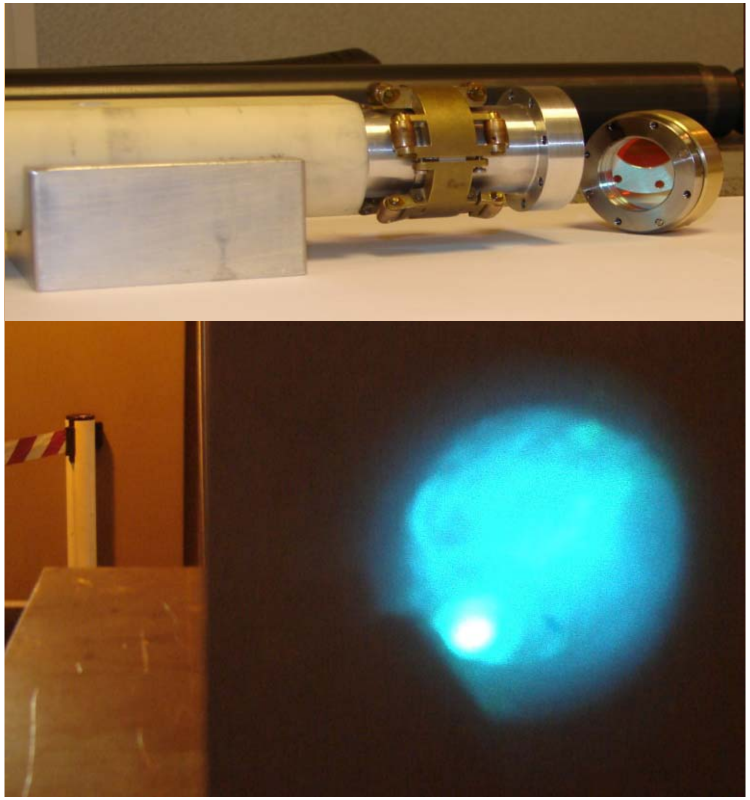
Encouraging results obtained with the extended laser cavity but more R&D required

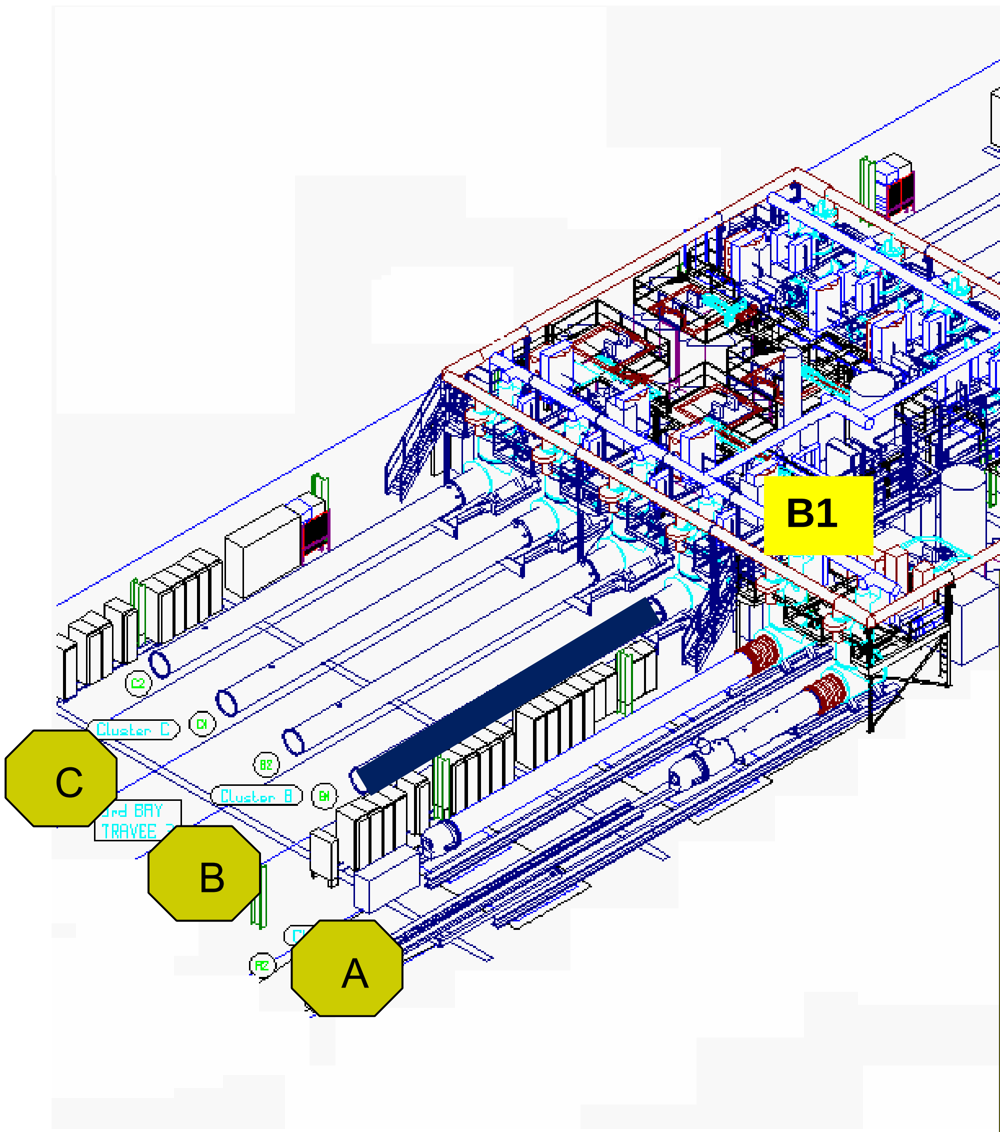


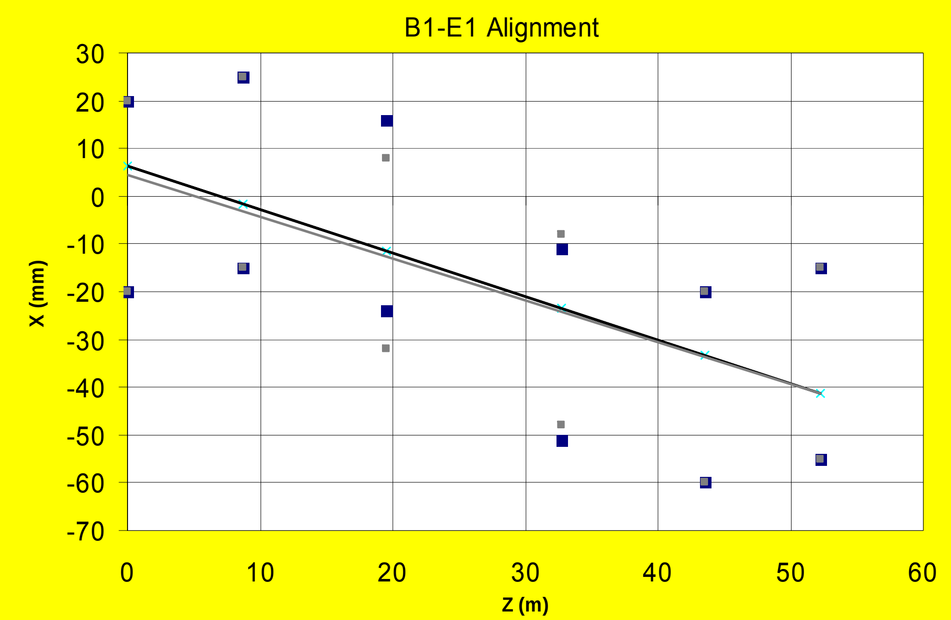
Shortcut to MOV00954.lnk



- Laser cavity extended up to 5 m inside the magnet; the intra-cavity CW power obtained was larger than few 100 W
- Problem to align the spot with the CCD detector ⇒ use of 2 dipoles to avoid to develop tricky fine tuning mechanical devices.

Test benches at SM18 dedicated to the OSQAR photon regeneration runs in 2008



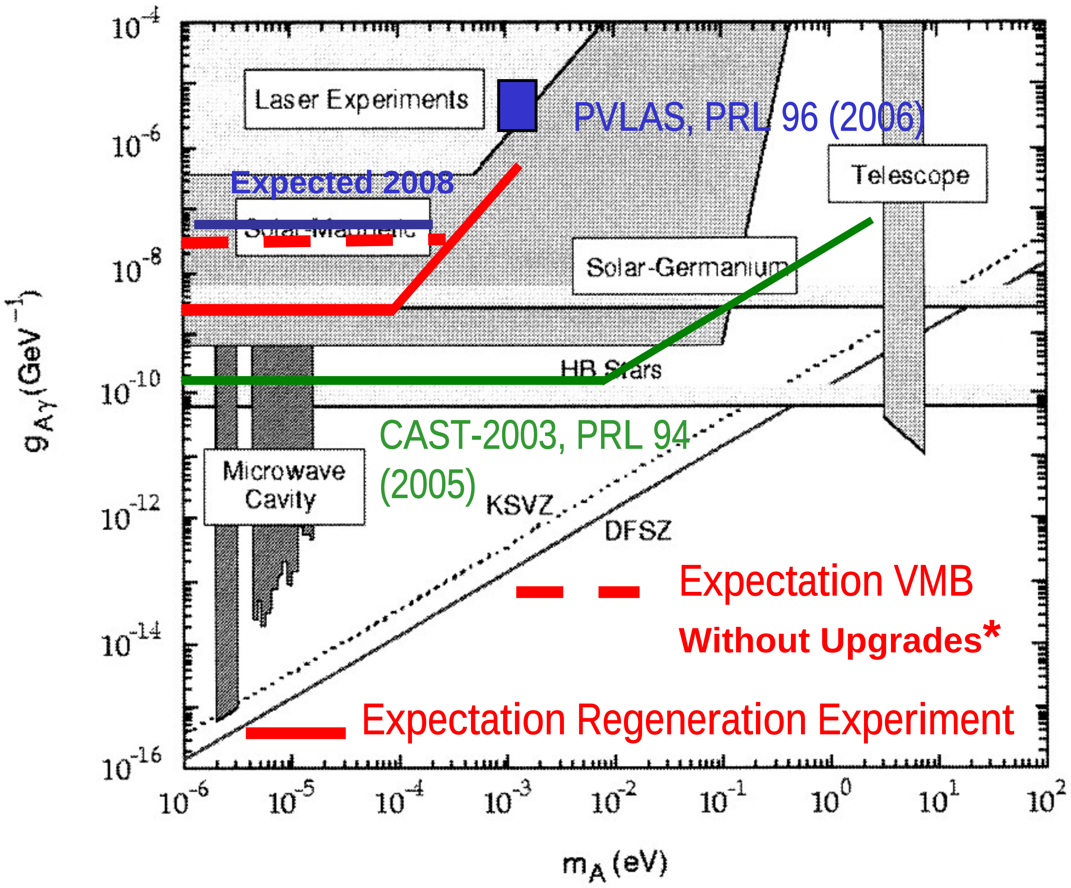


OSQAR Short & "Long" Term Perspectives

	Photon Regeneration Experiment	**VMB Experiment**
Phase 0 *Preliminary Phase*	. 1 LHC dipole . Cross Check of PVLAS result: **done in 2007; negative result & publication submitted**	. 1 LHC dipole . Measurement of the Cotton-Mouton effect of air at ambient pressure as a Proof of Principle: **done in 2005**
Phase 1	. 2 LHC dipoles aligned . Axion source made of Ar+ laser beam of 18 W (CW) within the aperture of one LHC dipole *(**1^{st} milestone** foreseen in 2008)* . Axion source made of Ar+ laser in extended cavity of 19.6 m long, i.e. the length of one LHC dipole, for an expected intra-cavity power of 0.1-1 kW *(**2^{nd} milestone** foreseen in 2009)*	. 1 LHC dipole . Low RIN Laser coupled to a Fabry-Pérot (FP) cavity of 19.6 m long . **Measurement of the 1^{st} order VMB** & combined Analysis with final results of the phase-2 of the Photon Regeneration Experiment for Axion/ALPs searches *(**4^{th} milestone** foreseen in 2011-12)*
Phase 2	. 2 LHC dipoles aligned . Nd:YAG laser of 1-2.5 kW (CW) coupled to a FP cavity of 19.6 m long . Sensitivity approaching the best cosmological constraints *(**3^{rd} milestone** foreseen in 2010-11)*	. 1 LHC dipole . Low RIN Laser coupled to a FP cavity of 19.6 m long + ultra high finesse FP filtering cavity . **Measurement of the 2^{nd} order VMB** *(**5^{th} milestone** foreseen in 2013-14)*

OSQAR Experiments
Expected results

From C. Hagmann, K. van Bibber, L.J. Rosenberg, Physics Lett. B, vol.592, 2004



*P. Pugnat, et al. *Czech Journal of Physics, Vol.55 (2005), A389; Czech Journal of Physics, Vol.56 (2006), C193;*

- **Photon regeneration Experiment**
  - ***Preliminary Phase*** to check PVLAS results; 1 dipole with/without gas *(done)*
  - ***Phase-1***: 2 dipoles, CW laser beam, extra & intra cavity to improve BFRT results *(2008 & 2009)*
  - ***Phase-2***: 2 dipoles, CW laser beam & High Finesse FP cavity *(2010-2011)*
  - ***Phase-3***: more than 2 dipoles to be competitive with CAST
- **"n-1 Experiment" i.e.** VMB & Linear Dichroism
  - ***- Phase-1&2 :*** Measurements of QED prediction in $O(\alpha^2)$ & $O(\alpha^3)$ respectively within 1 dipole *(2012 & 2014)*

Longer term: Towards the "axionic" laser

Phys. Rev. Lett. **98**, 172002 (2007)

Resonantly Enhanced Axion-Photon Regeneration

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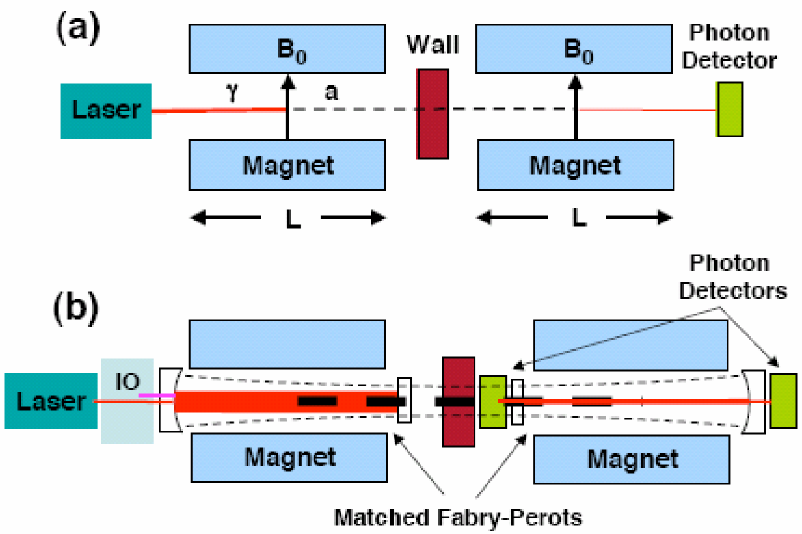

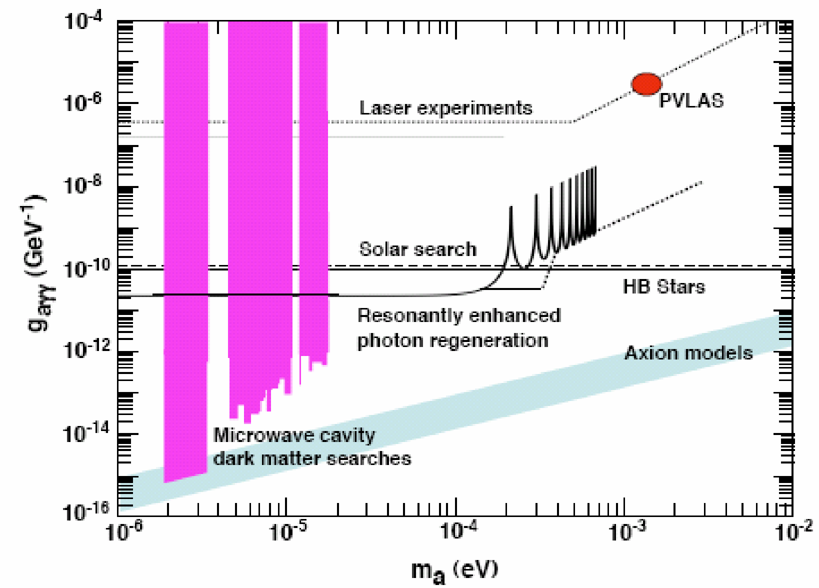

With 4 + 4 LHC Dipoles, i.e. Experiment ~140 m long,…

Summary

- OSQAR aims to answer to both the following questions:
  - *What is the magnetization of the vacuum ?*
    Heisenberg & Euler (1936), Weisskopf (1936), Iacopini & Zavattini (1979), Maiani, Petronzio & Zavattini (1986)
  - *Can a light shin through a wall ?*
    P. Sikivie (1983), K. van Bibber et al. (1987)
- **First results from the photon regeneration experiment: So far no light shinning trough the wall**
- The significance of OSQAR is:
  - to test the QED down to an unprecedented level i.e. $n\text{-}1 \approx 10^{-22}$ -10^{-24}
  - to detect “new” particles beyond the standard model that can couple to photons such as paraphotons, scalar or pseudo-scalar like Axions/ALPs, millicharged fermions,…
  - And also, the spin-off from the development of novel optical techniques for electrical and magnetic field measurements
  - Emerging field: Laser-based Particle/Astroparticle Physics

More information

- *“Feasibility study of an experiment to measure the Vacuum Magnetic Birefringence”, Czech. J. Phys. 55 (2005)* A389-A396, http://doc.cern.ch/archive/electronic/cern/preprints/at/at-2005-009.pdf
- *Letter of Intent*, OSQAR *coll.* , CERN-SPSC-2005-034, 17 October 2005 http://doc.cern.ch//archive/electronic/cern/preprints/spsc/public/spsc-2005-034.pdf
- *“QED test and axion search in LHC superconducting dipoles by means of optical techniques”* , *Czech. J. Phys. 56 (2006)* C193-C202
- *Invited Presentation* to the Workshop “Axions at the Institute for Advanced Study”, IAS Princeton (NJ), 20-22 October 2006 http://www.sns.ias.edu/~axions/schedule.shtml
- *OSQAR Proposal*, CERN-SPSC-2006-035, SPSC-P-331, 9 November 2006 http://doc.cern.ch//archive/electronic/cern/preprints/spsc/public/spsc-2006-035.pdf
- *“Axion Searches at present and in the Near Future”,* R. Battesti, P. Pugnat *et al.* , to appear in the Lecture Notes in Physics (2008), Volume on Axions, (Springer-Verlag) http://arxiv.org/PS_cache/arxiv/pdf/0705/0705.0615v1.pdf
- *“First results from the OSQAR photon regeneration experiment: No light shining through a wall”,* P. Pugnat *et al.* , submitted http://arxiv.org/abs/0712.3362
- *Proposal* submitted in February 2008 by L. Duvillaret on the behalf of the OSQAR collaboration to the French funding agency (ANR Programme Blanc)