Status of the OSQAR Experiments at CERN

by Andrzej Siemko, Pierre Pugnat & Lionel Duvillaret
on behalf of the OSQAR collaboration

Optical Search for QED vacuum magnetic birefringence, Axion & photon Regeneration

5th PATRAS Workshop on Axions,WIMPs and WISPs
***Durham**, 13-17* July 2009

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

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TUL, Czech Republic — M. Šulc

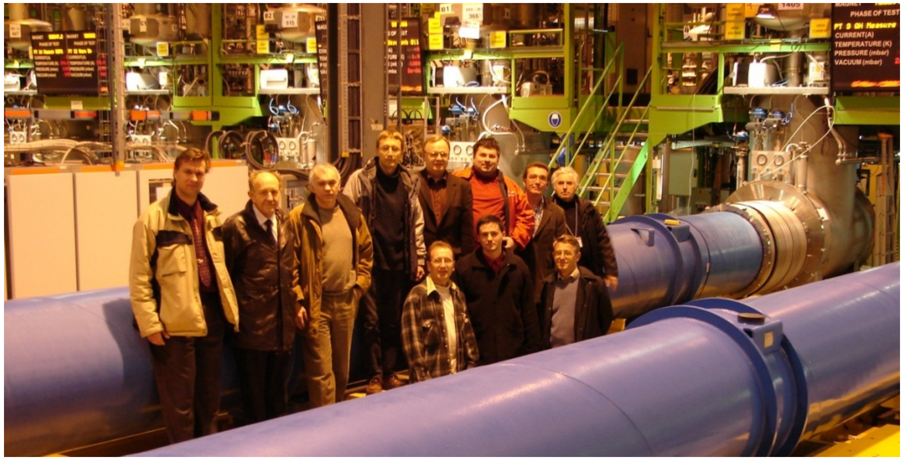
Warsaw University, Physics Department, Poland — A. Hryczuk, K. A. Meissner

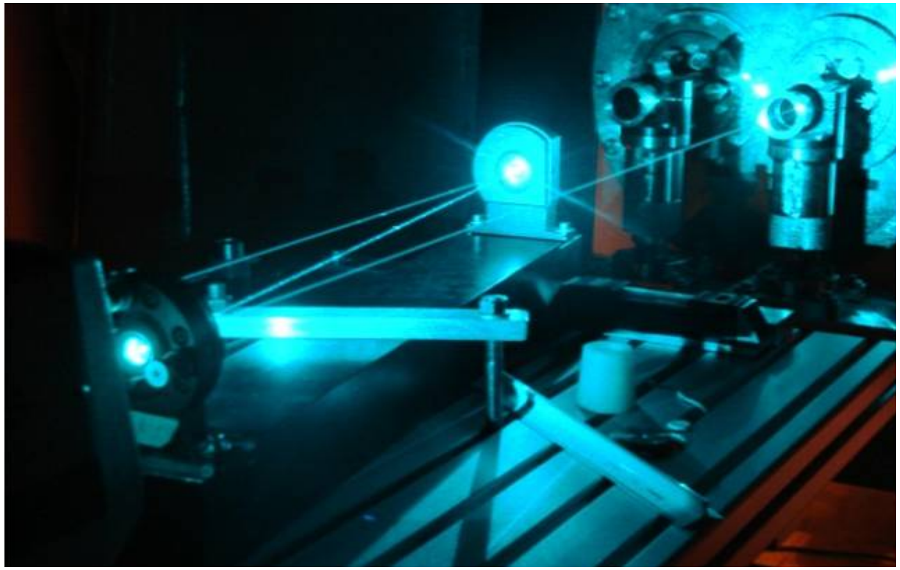
OSQAR Collaboration in Brief

- **2001**, 1st ideas & preliminary works

…

- **22 Feb 05**, 1st OSQAR day at CERN
- **16 Sep 05**, 2nd OSQAR day at CERN
- **17 Oct 05**, LoI submitted to the SPSC
- **6 Nov 06**, 3rd OSQAR day at CERN
- **29 Nov 06**, Proposal submitted to the SPSC
- **7 June 07**, The preliminary phase of OSQAR approved by CERN Research Board
- **9 June 07**, 1st results obtained
- **21 June 07, preliminary results presented** to the 3rd Workshop at Patras (Greece)
- **23-24 Nov 07**, 4th OSQAR days at CERN
- **12-13 May 09**, 5th OSQAR days at CERN





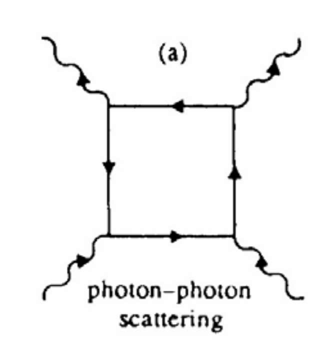
Outline

- Scientific Motivations
- Overview of the OSQAR Experiments
  - Status of Vacuum Magnetic Birefringence Experiment
  - Status of Photon Regeneration Experiment
- Short & Long Term Perspectives
  - R&D
  - Expected results
- Summary & Outlook

Scientific Motivations

To measure for the first time the Vacuum Magnetic Birefringence predicted in QED

(Heisenberg & Euler, Weisskopf, 1936)
i.e. the vacuum magnetic "anomaly" of the refraction index " n-1" ~ 10^{-22} in 9.5 T



- The QED light-on-light scattering produces ellipticity in the linearly polarized light travelling in the magnetic field

$$\Psi = \alpha^2 \omega l B^2 \sin(2\theta) / (15\, m^4) \qquad (\sim 10^{-11} \text{rad for OSQAR})$$

OSQAR

Scientific Motivations

To discover axions/ALPs

- axions ***solve the strong CP problem*** *(Weinberg, Wilczek, 1978)*
- they are ***non-SUSY Cold Dark Matter candidates***

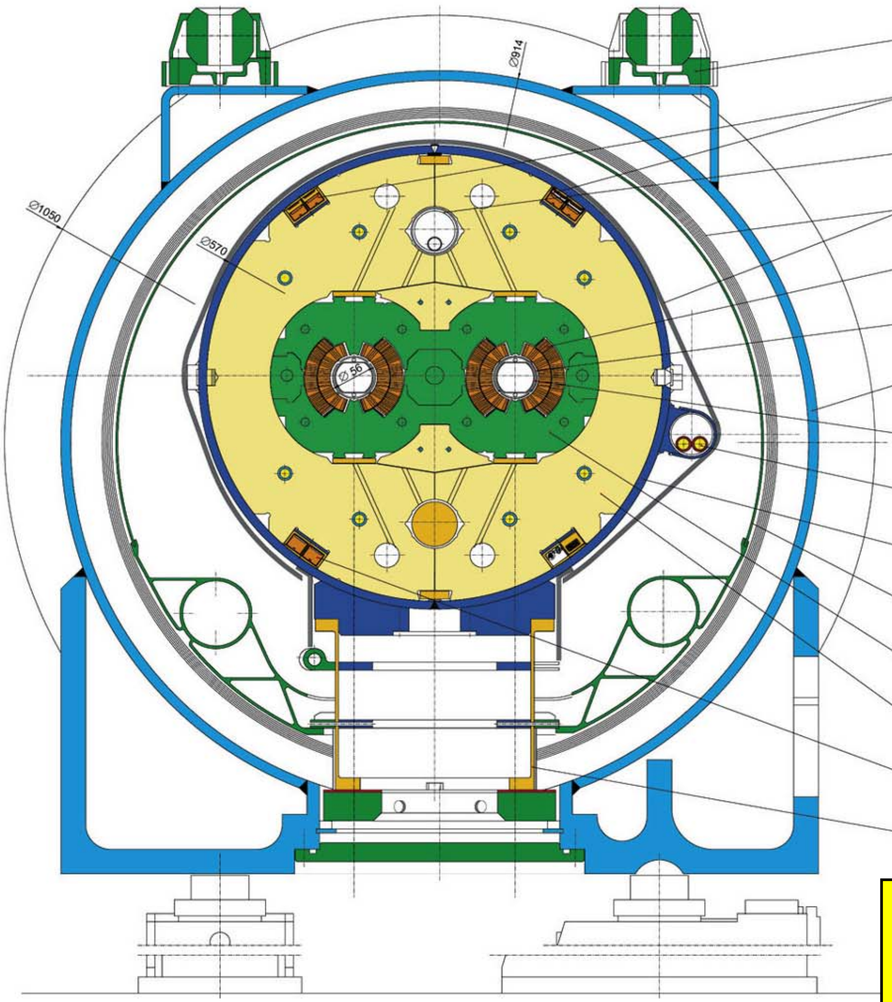
  (Abbott & Sikivie; Preskill, Wise & Wilczek, 1983)
- coupling to photons

$$L = g\, a\, E \bullet B$$

- the coupling induces rotation of polarization and ellipticity for light propagation in the magnetic field
- ,,Shining through the wall'' experiment –

  (laser photon → axion) wall (axion → photon) detection
- the experiment puts bounds on couplings of paraphotons, milli-charged fermions, chameleons,...

Basic Principles of the Experiments: Use of LHC superconducting main dipoles

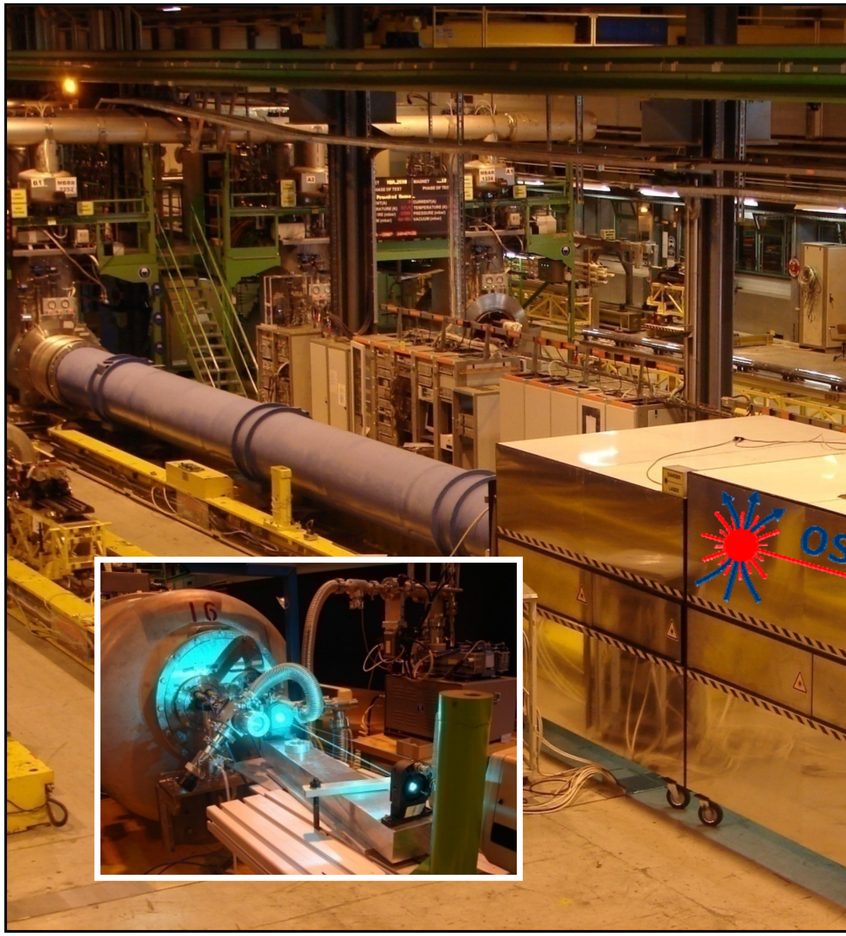


Conductor limited quench field @ 1.9 K	**9.76 T**
Coil aperture	**56 mm**
Magnetic length	**14.3 m**

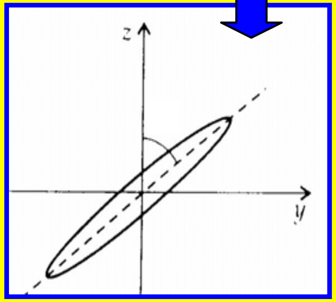
OSQAR

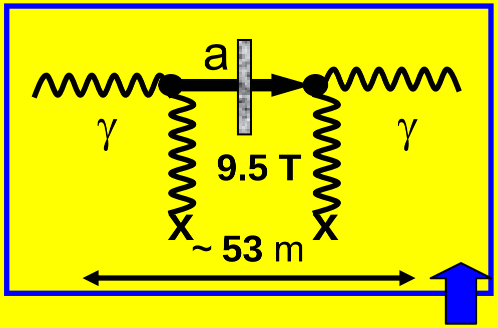
Basic Principles of the Experiments

Use of 1 and/or 2 LHC dipoles for Phase 1&2



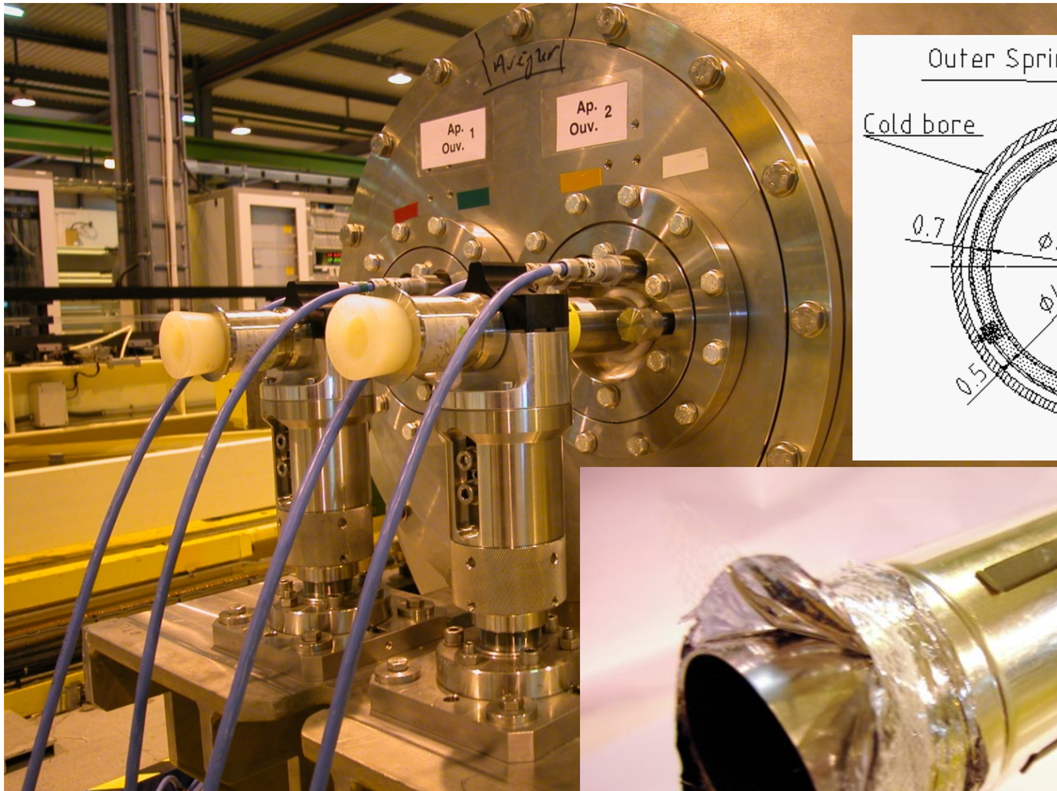
► In one aperture of dipole-1, measurement of the Vacuum Magnetic Birefringence & Dichroïsm

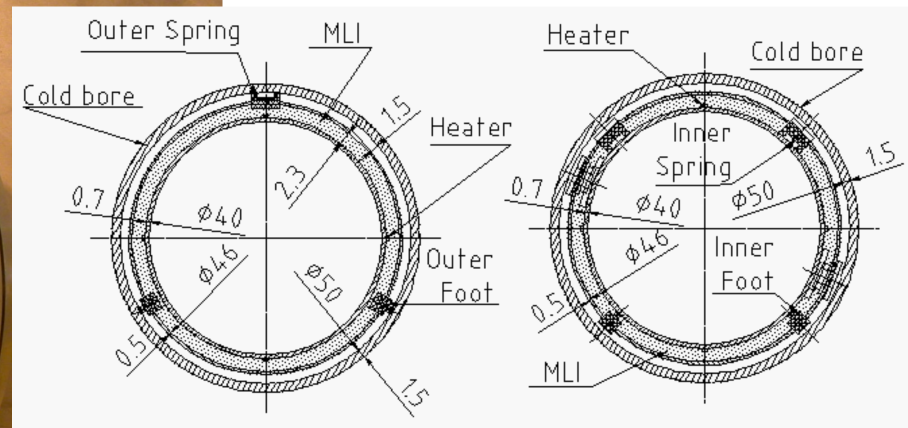




► In the 2[nd] aperture of dipole-1 & one aperture of dipole-2, Photon Regeneration Experiment

Base Line: *use of warm bores - “anticryostats” inserted inside cold bores*





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

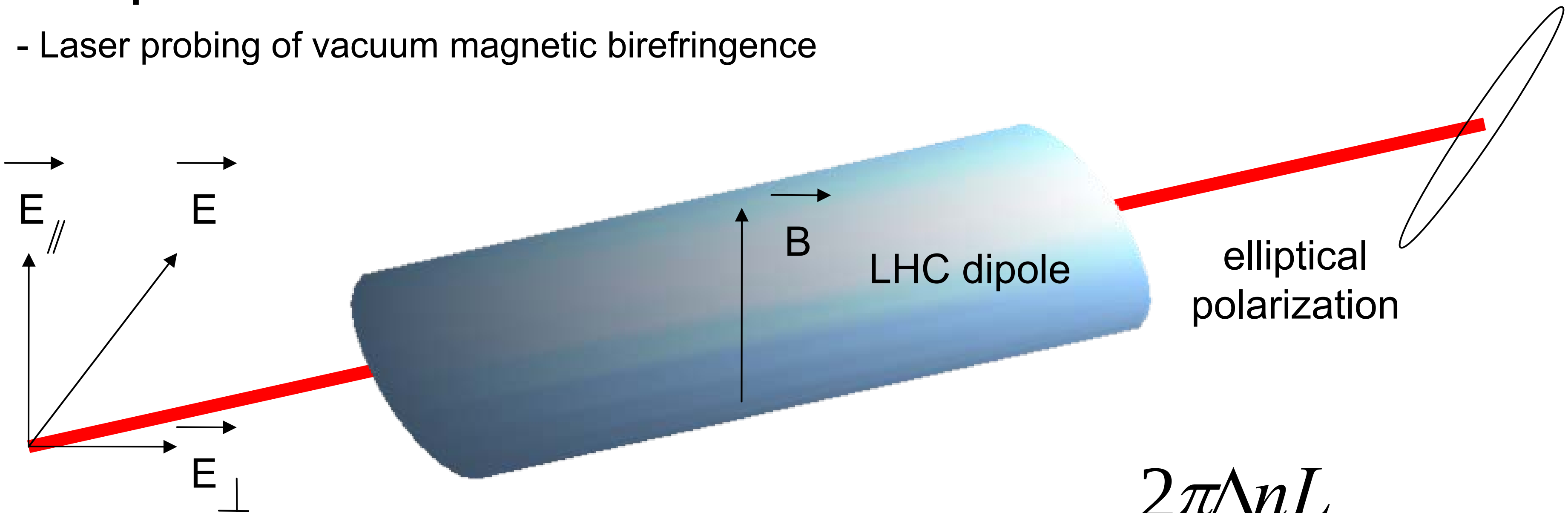
O. Dunkel, P. Legrand and P. Sievers: “A warm bore anticryostat for series magnetic measurements of LHC superconducting dipole and short-straight section magnets”, *CRYOGENICS CEC/ICMC, 2003, Anchorage, Alaska; CERN-LHC-Project-Report-685*

Status of Vacuum Magnetic Birefringence Experiment: from 1st proposal to present

Vacuum Magnetic Birefringence Experiment: From 1st proposal to present

Principle

- Laser probing of vacuum magnetic birefringence



- Signal-to-noise ratio improvement:

$$\Delta\varphi = \frac{2\pi \Delta n L}{\lambda}$$

synchronous detection using a linearly polarized laser beam which polarization is rotated at high frequency → unique signature far from low frequency excess noise

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

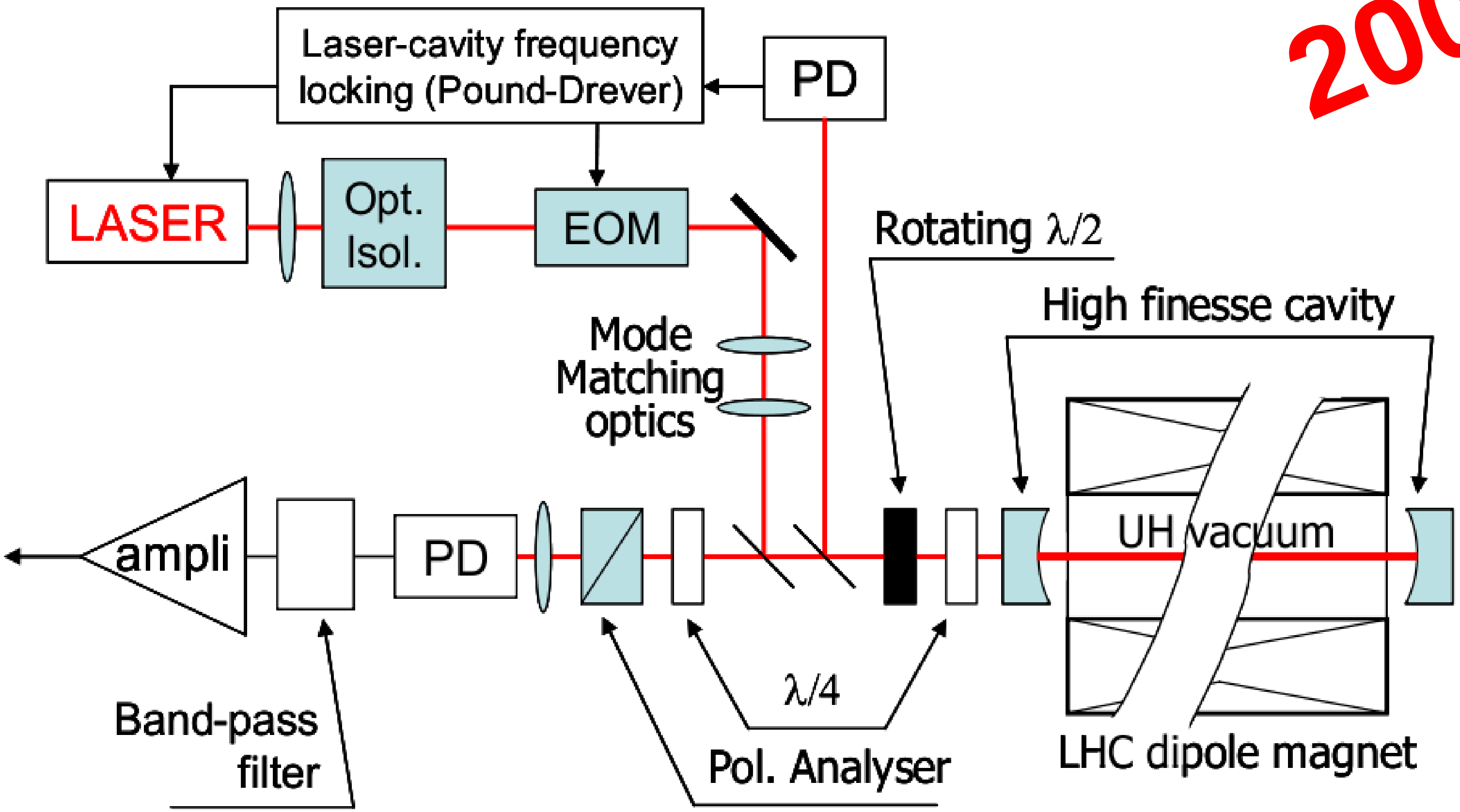
Cotton-Mouton effect measurement in air

- with only one forth and back pass through a LHC dipole

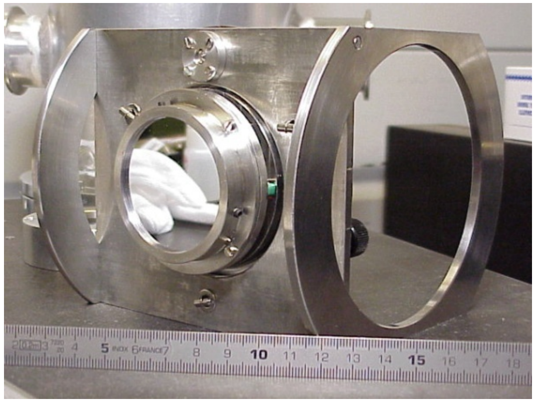
2005

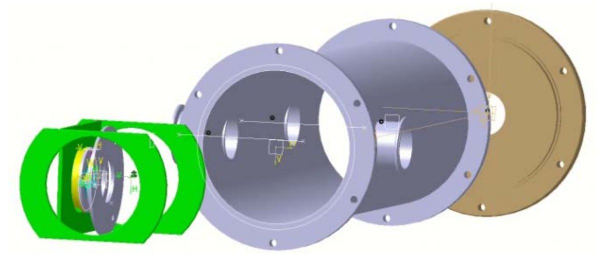
1st proposal

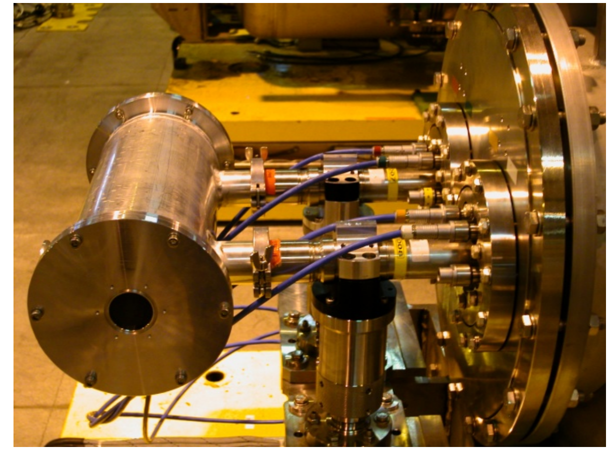
2006



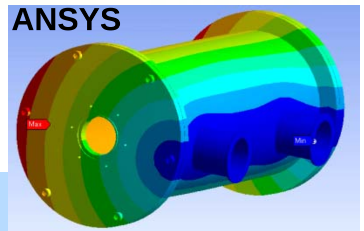
VMB & Dichroism Measurements
Prototyping Phase

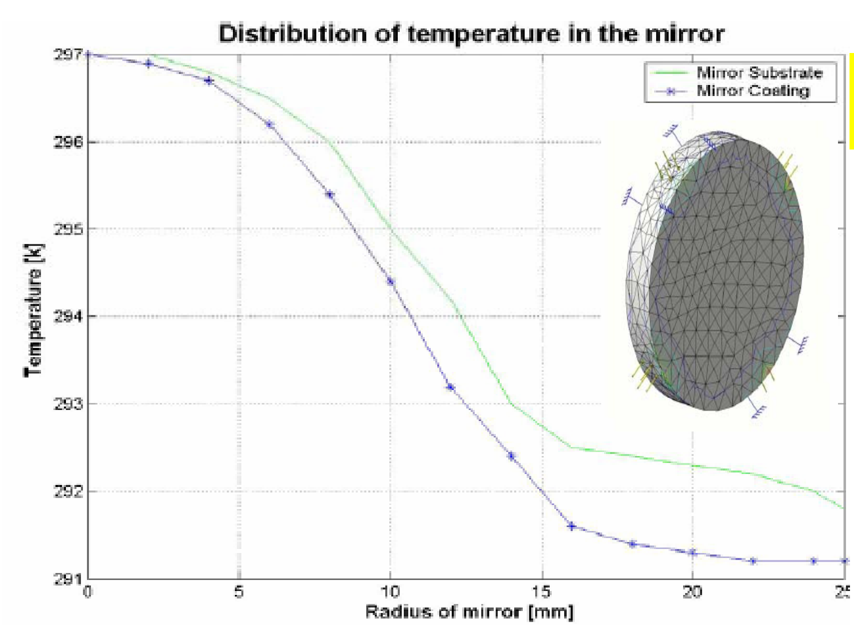




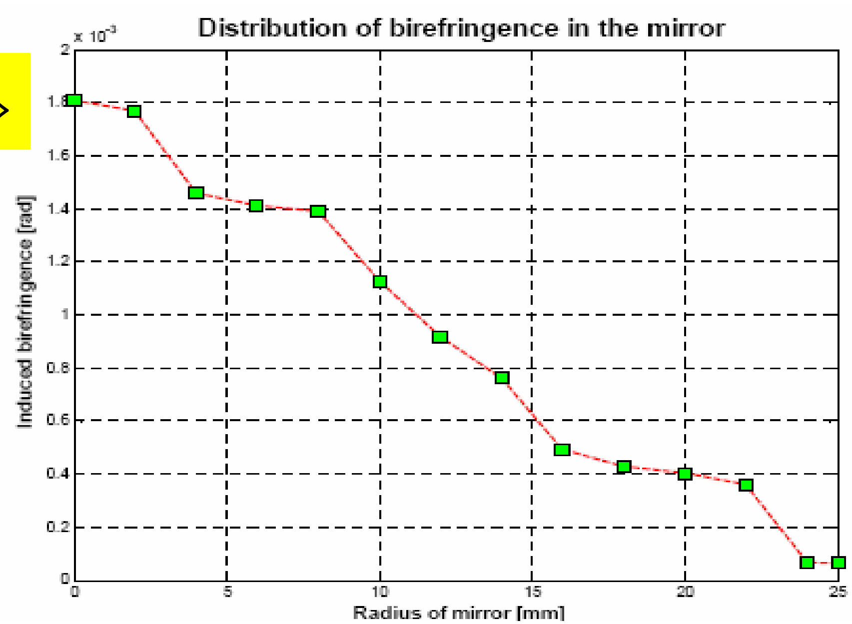


Study of vibration eigenmodes (f, amplitude) →





⇒



Fundamental limit of measurement sensitivity

Signal: $\Delta i = \frac{2\pi \Delta n L}{\lambda} i$

Noise: $\sigma_i = \sqrt{2ei\Delta i}$

Signal to noise ratio: $\frac{\pi \Delta n L}{\lambda}\sqrt{\frac{2i}{e\Delta\Delta}}$

$$\Delta n_{min} = \frac{\lambda}{\pi L}\sqrt{\frac{e\Delta\Delta}{2i}} \approx 10^{-15}\frac{L[m]}{\sqrt{\Delta f[Hz]}}$$

$L = 10^5$ m (high finesse cavity of 10^4) → $T_{acq} > 10^7$ s (3-4 months)

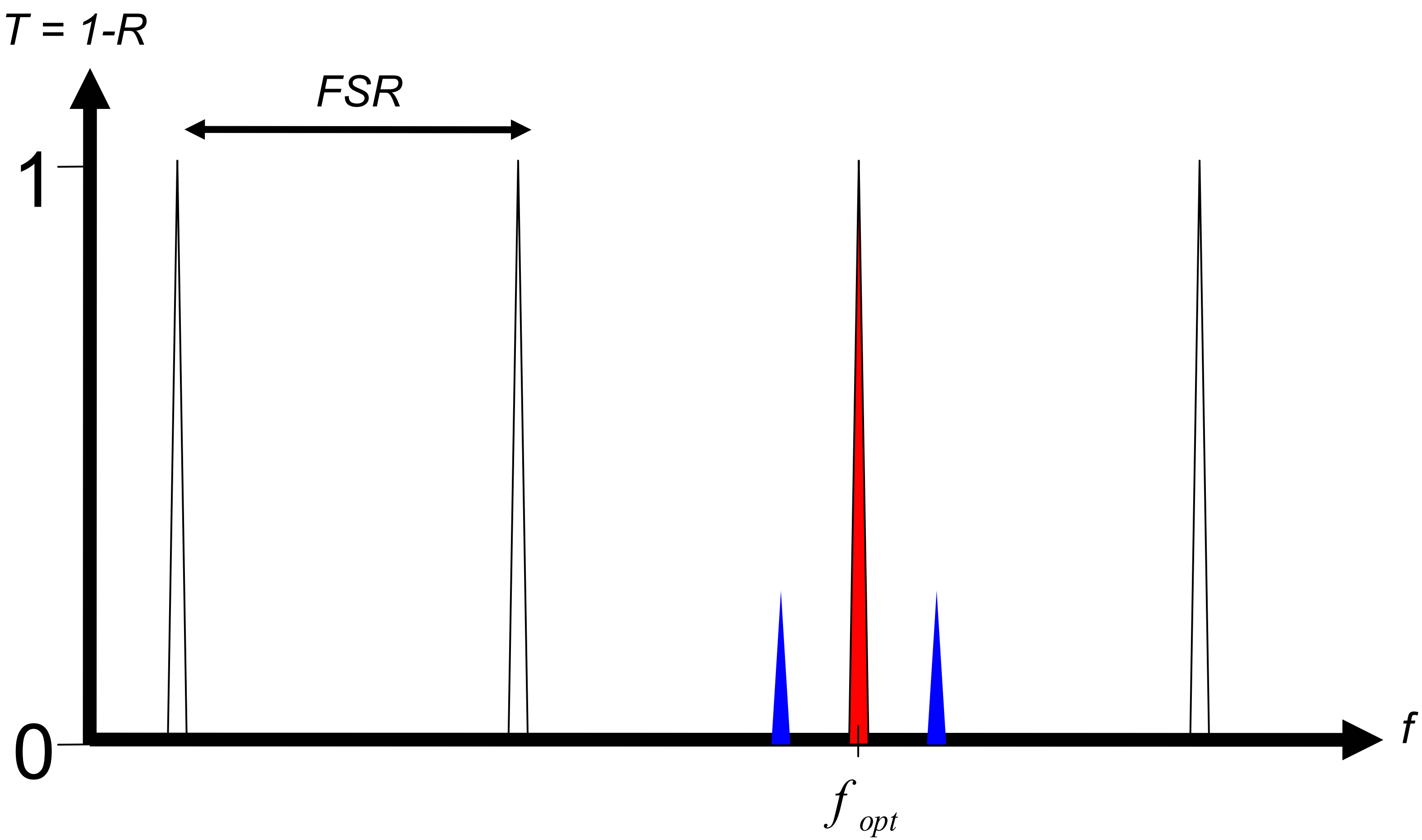
For B = 9.5 T, QED predicts $\Delta n \approx 3.6\cdot 10^{-22}$ **(hardly reachable!)**

How to manage?

Via optical carrier rejection thanks to an ultra resonant optical cavity

- Use of an ultra high finesse tunable Fabry-Pérot cavity

locked onto the optical carrier



Expected gain

Via optical carrier rejection thanks to an ultra resonant optical cavity

$i \rightarrow i$ / 100-1000

S/N ratio → S/N ratio x 30

T_{acq} > 4 days (begins reasonable!)

<u>Further gain is POSSIBLE:</u>

- By keeping only one modulation side lobe (useful information)

- Requires to lock the filtering cavity onto one side lobe

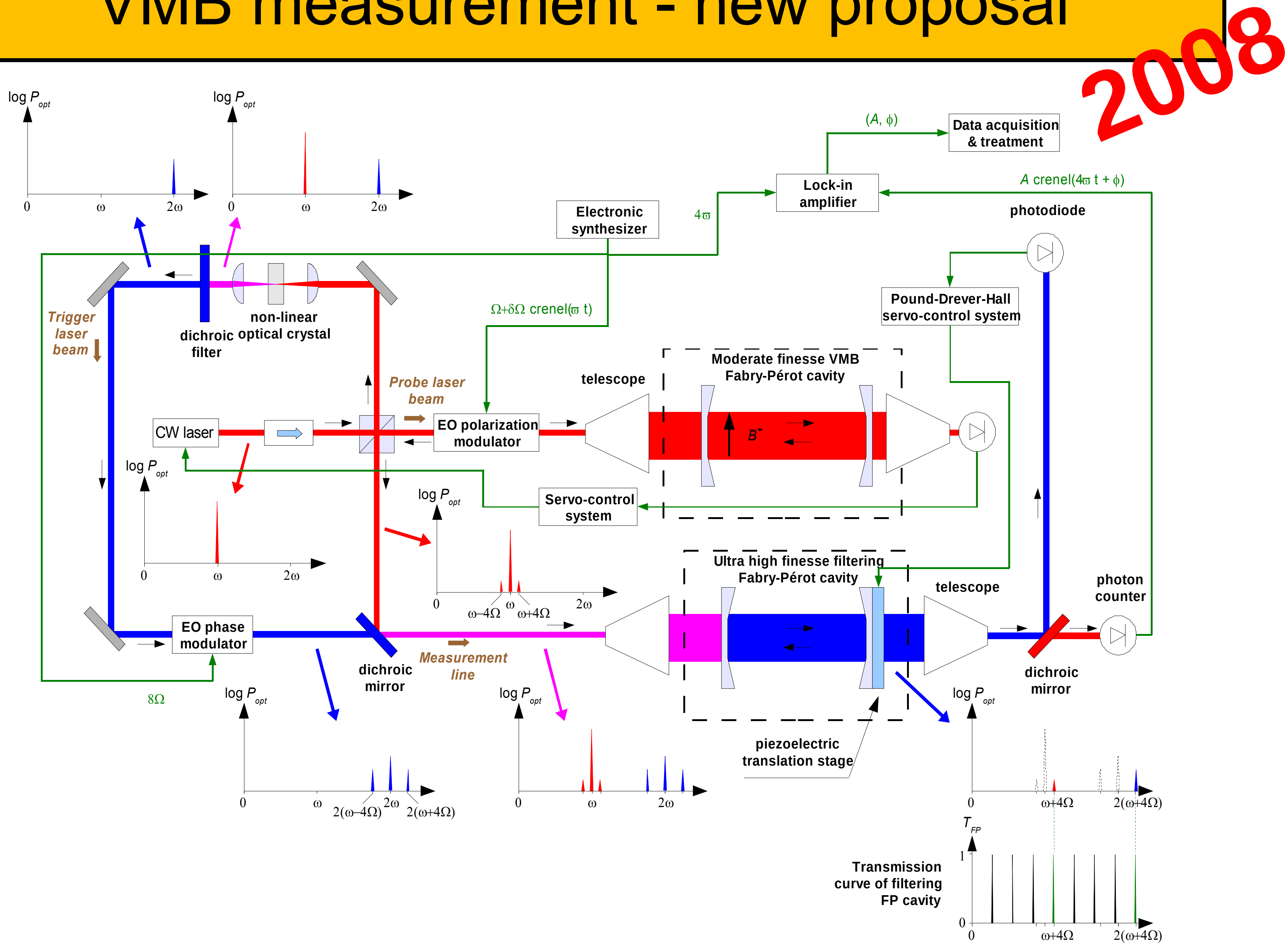
→ off-resonance transmission for the optical carrier ~ $\left(\frac{\pi}{2F}\right)^2$ << 10^{-6}

→ **potential gain: > 10^3** → T_{acq} **reduced to < 1 h!**

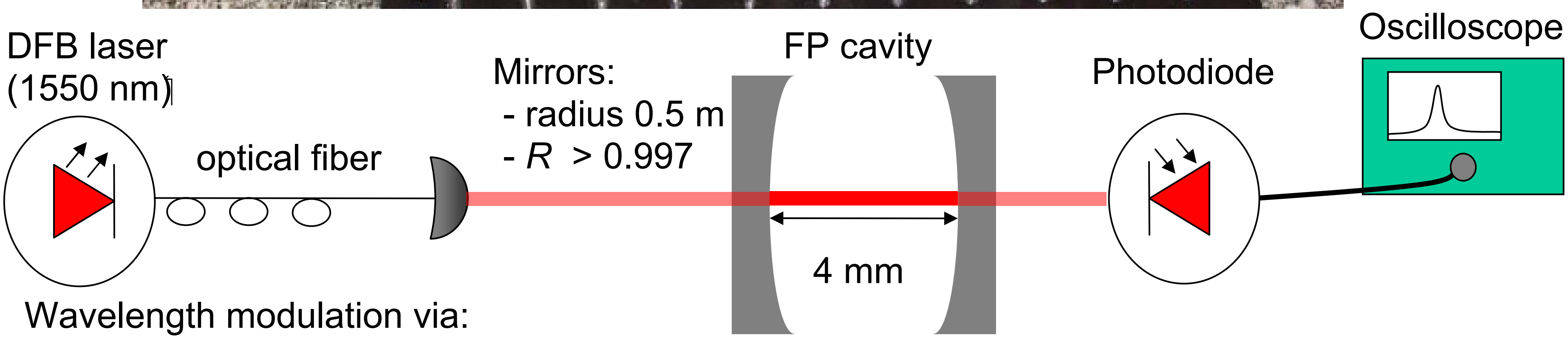
➲ **Major problem: how to lock the FP cavity?**

- Almost no photons in the side-lobe → locking not possible ?

VMB measurement - new proposal

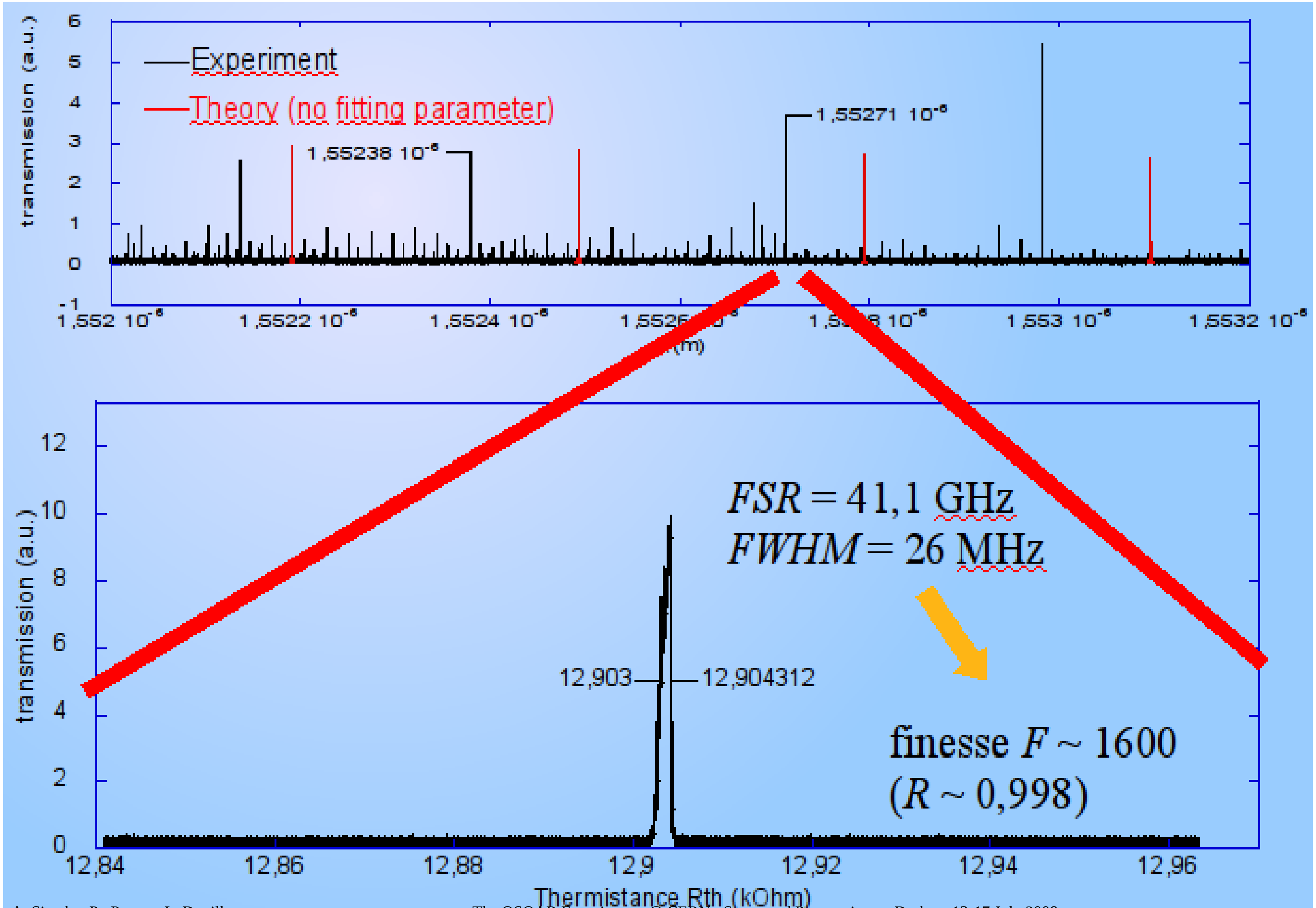


Scale model of the Fabry-Pérot filtering cavity



Wavelength modulation via:
- current (fast modulation > 10 Hz, low accuracy, low wavelength range < 0.5 nm)
- temperature (slow modulation < 0.1 Hz, high accuracy, wide wavelength range ~ 5 nm)

1st results (without servo-control)



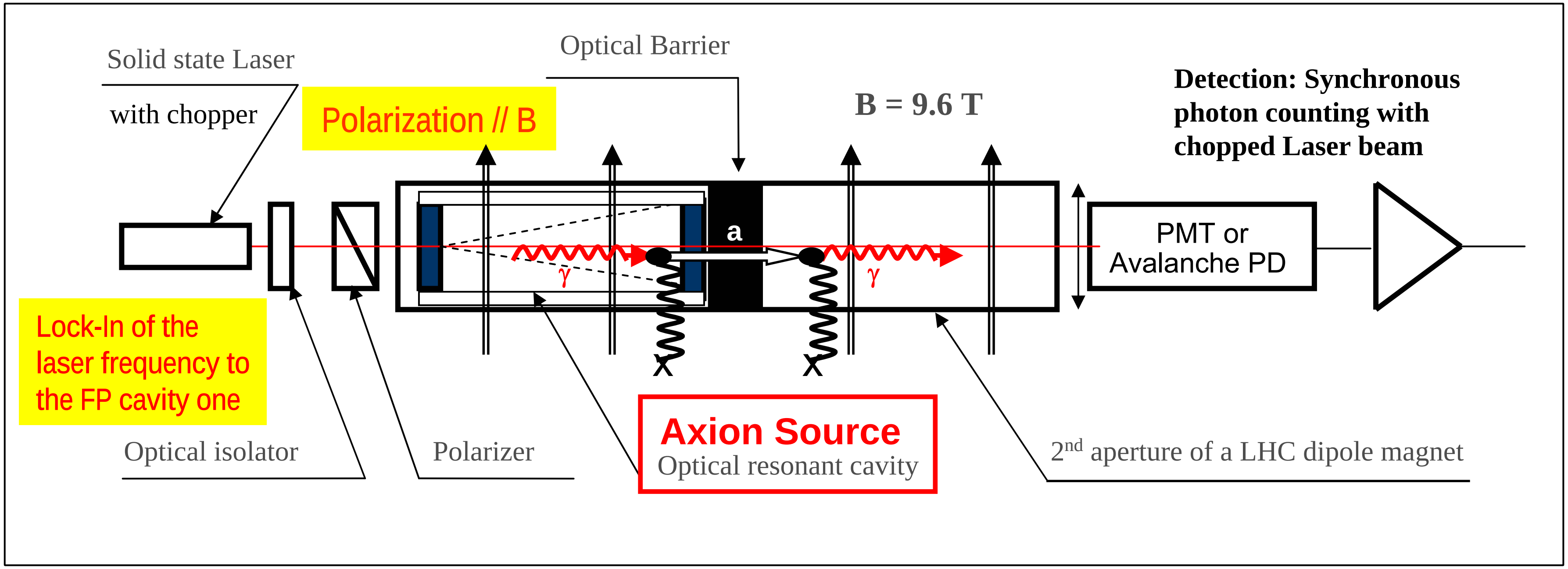
Experiment of photon regeneration from axions or other scalar or pseudo-scalar particles

"An invisible light shining through a wall"

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

Photon regeneration experiment with 1 LHC dipole

Principle



Results

- Published in *Phys. Rev. D*

- Presented to the 3 rd and 4th Patras Workshop on Axions, WIMPs and WISPs

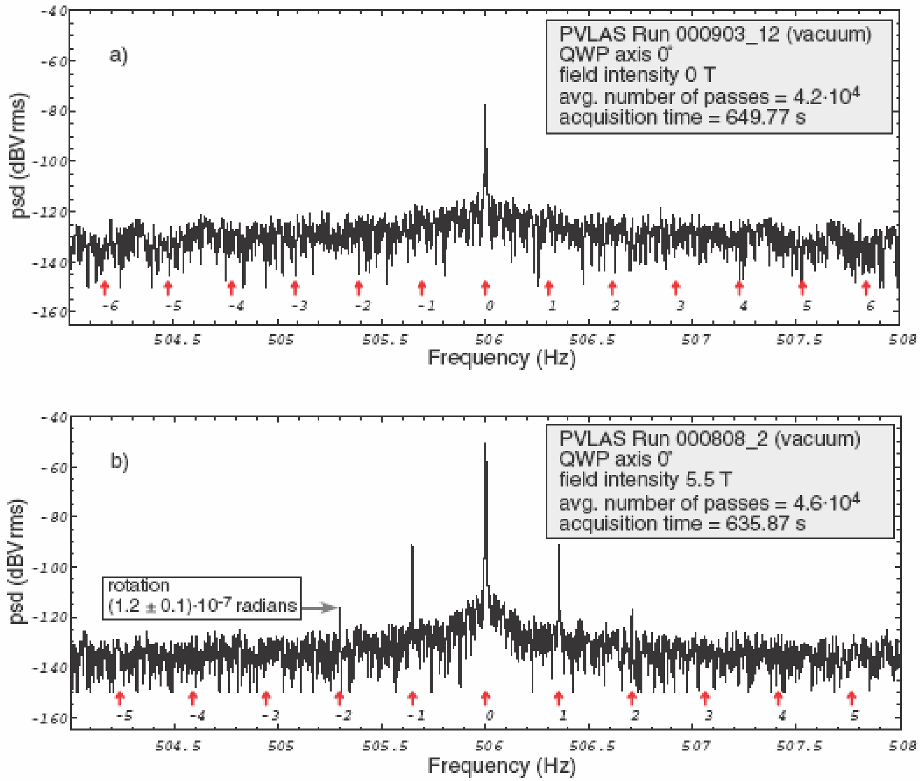
For OSQAR the PVLAS results came at very right moment

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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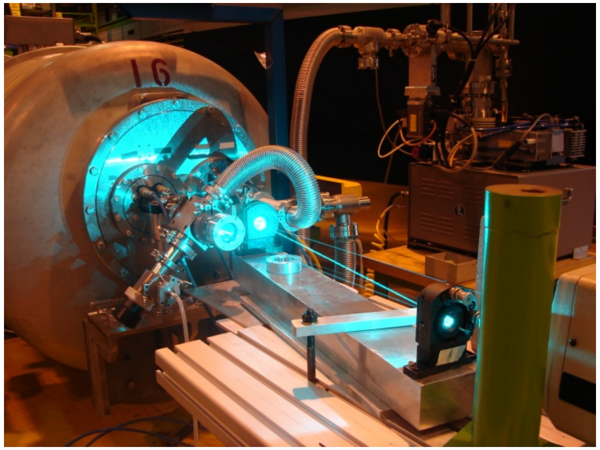
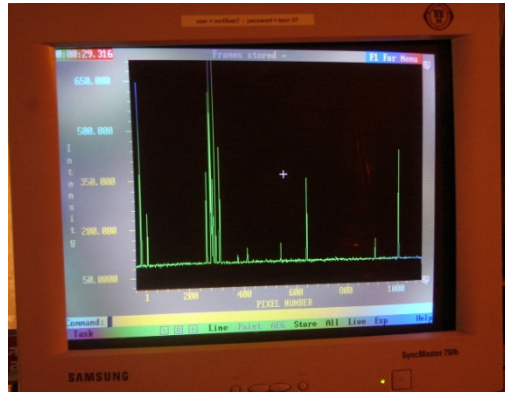
e-mail: lamore@lanl.gov

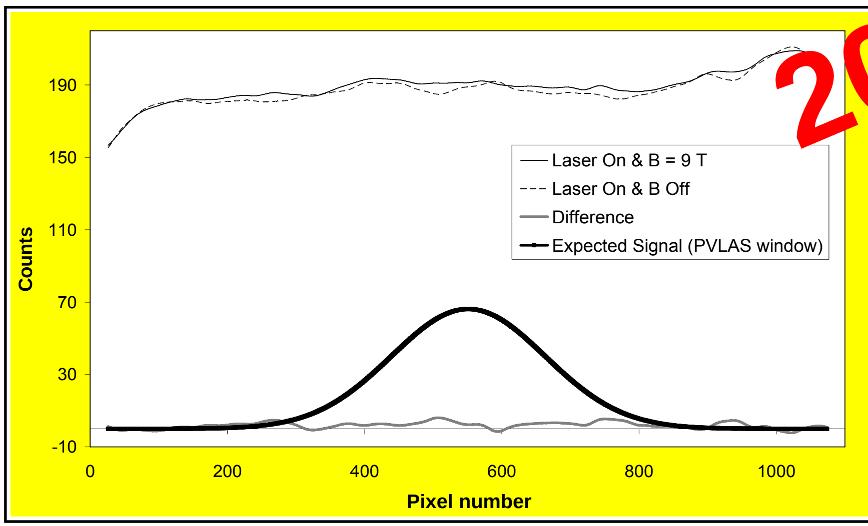
Photon Regeneration 1st results

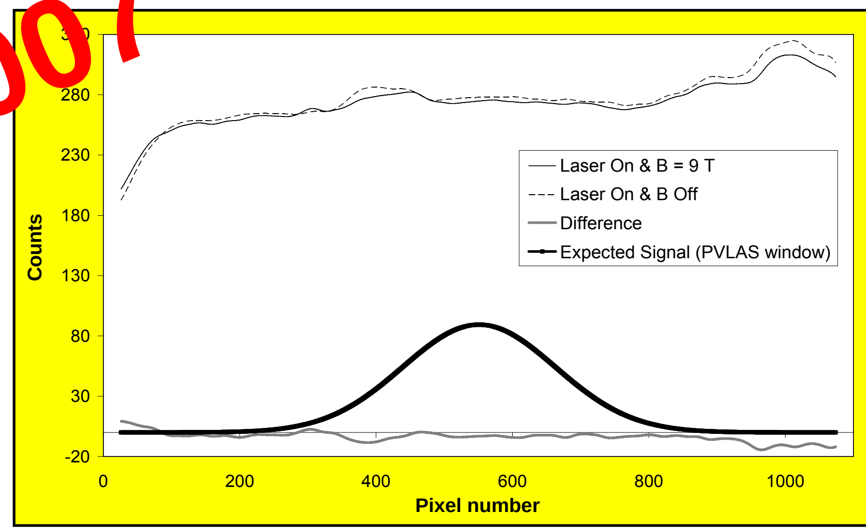
with 18 W Ar+ laser & N_2 gas





2007

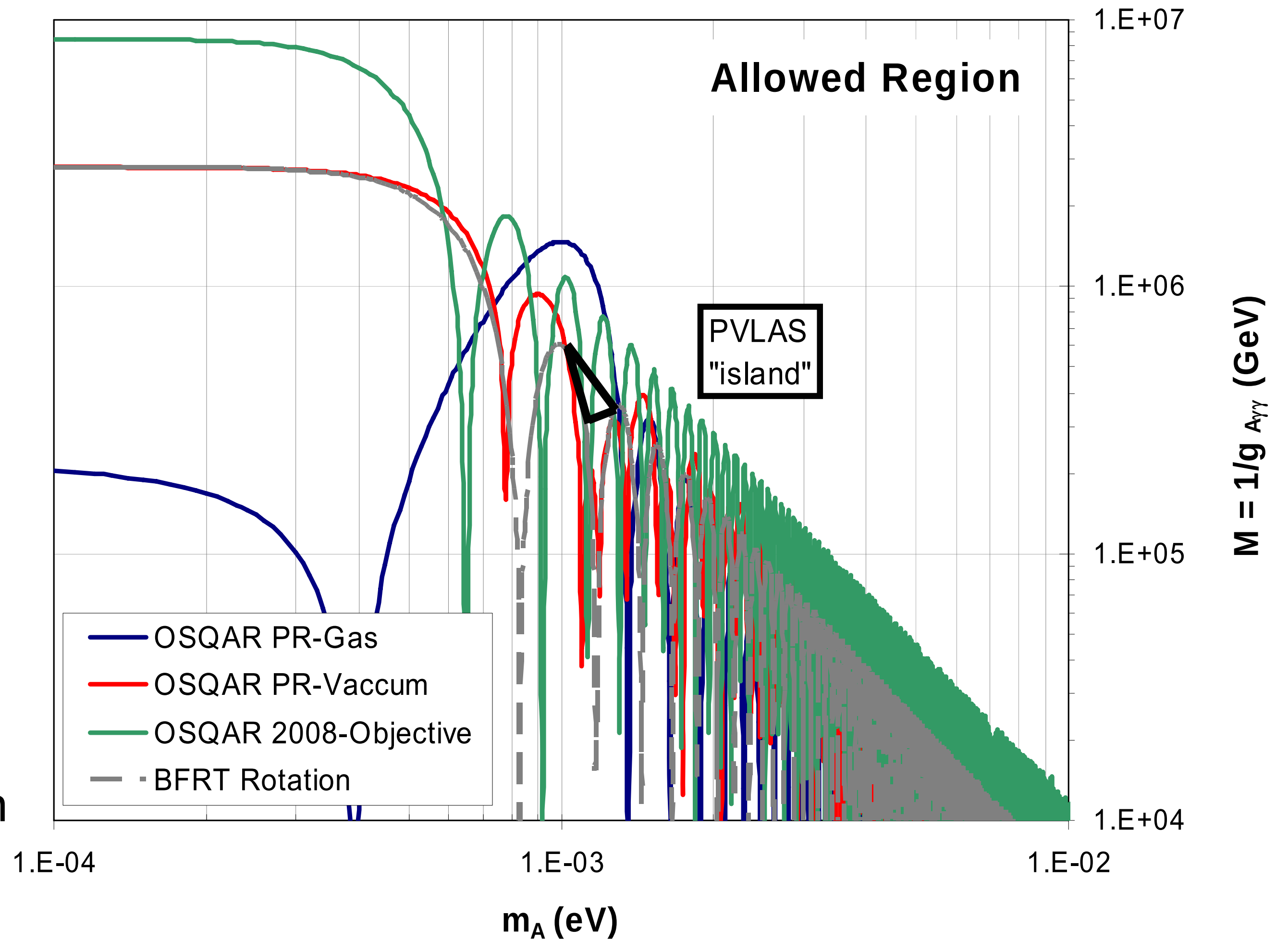




PVLAS result cannot be due to a new light spin-0 particle** (submitted, arXiv: 0712.3362), also reported from **BMV & GammeV

Results Overview including the expected in 2009

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



PHYSICAL REVIEW D, VOLUME 00,

Results from the OSQAR photon-regeneration experiment: No light shining through a wall

Pierre Pugnat,[1,*] Lionel Duvillaret,[2] Remy Jost,[3] Guy Vitrant,[2] Daniele Romanini,[3] Andrzej Siemko,[1] Rafik Ballou,[4] Bernard Barbara,[4] Michael Finger,[5] Miroslav Finger,[5] Jan Hošek,[6] Miroslav Král,[1,6] Krzysztof A. Meissner,[7] Miroslav Šulc,[8] and Josef Zicha[6]

(OSQAR Collaboration)

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[3]*LSP, CNRS/UJF-Grenoble-1, BP 87, 38402 Saint-Martin d'Hères, France*
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[5]*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[6]*Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic*
[7]*Institute of Theoretical Physics, University of Warsaw, Poland;*
[8]*Technical University of Liberec, Czech Republic*
(Received 11 April 2008)

A new method to amplify the photon-axion conversions in a magnetic field is proposed using a buffer gas at a specific pressure in a photon-regeneration experiment. As a first result, new bounds for mass and coupling constant for laboratory experiments aiming to detect any hypothetical scalars and pseudoscalars, which can couple to photons were obtained, excluding with 95% confidence level, the recently withdrawn PVLAS result.

can be easily tuned with gas pressure!

$$P_{\gamma\leftrightarrow A} = \frac{1}{4\beta_A\sqrt{\varepsilon}}(g_{A\gamma\gamma}BL)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2 \qquad q \approx \frac{m_A^2}{2\omega} - (n-1)\omega$$

Unique opportunity with LHC dipoles

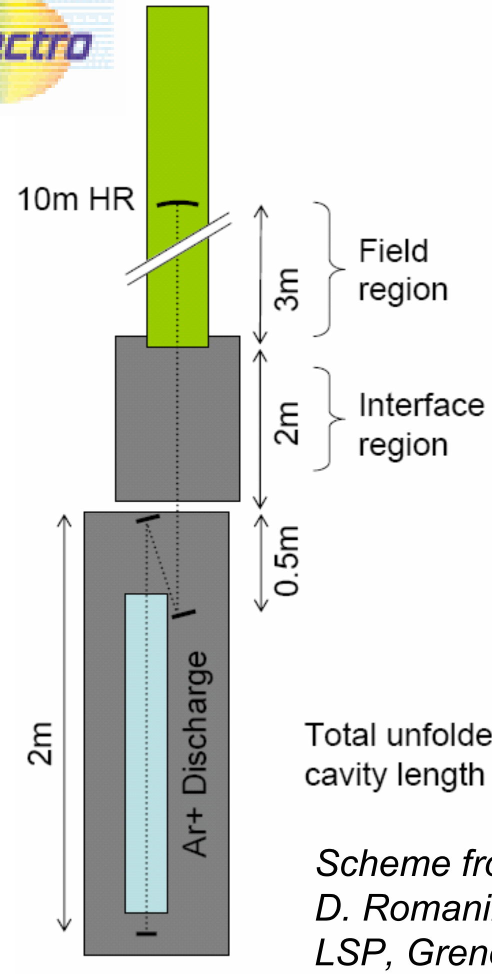
Experiment	**BFRT**	**PVLAS**	**BMV**	**OSQAR**
Status	Terminated	Achieved	Achieved/ Phase-1/Phase-2	Phase-1/Phase-2
λ (nm)	514.5	1064	1064	1550
Finesse of the FP cavity	N ~ 250	120 000	50 000/200 000/ 1 000 000	10 000/1 000
Sensitivity (rad/Hz$^{1/2}$)	10^{-8}	$10^{-6}/10^{-7}$	10^{-8}	$10^{-8}/10^{-10}$
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

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)*

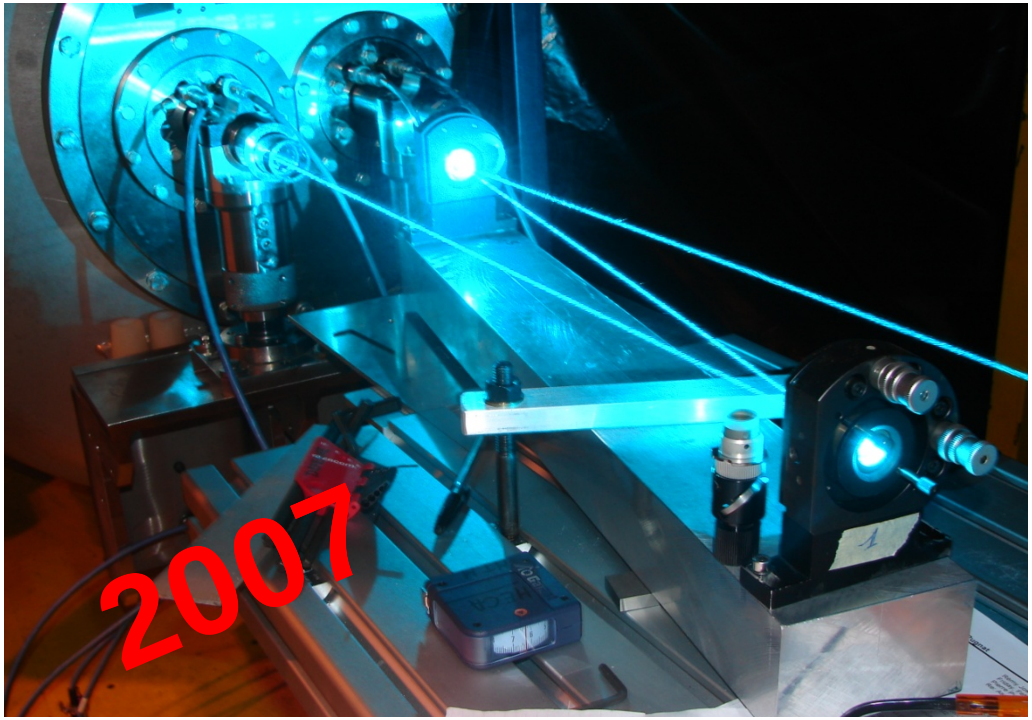
- For Axion/ALP search: Detection with a LN_2 cooled CCD Camera of Princeton Instrument, 1100 pixels of 5 mm height densely packed over 27 mm, QE ≈ 50%, DC/pix ≈ 0.1/mn

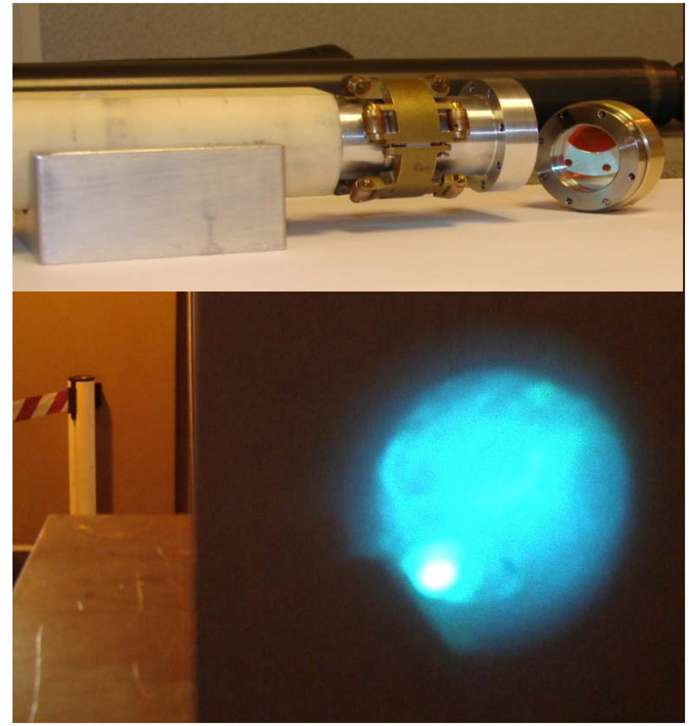


Total unfolded cavity length ~ 8m

Scheme from D. Romanini LSP, Grenoble

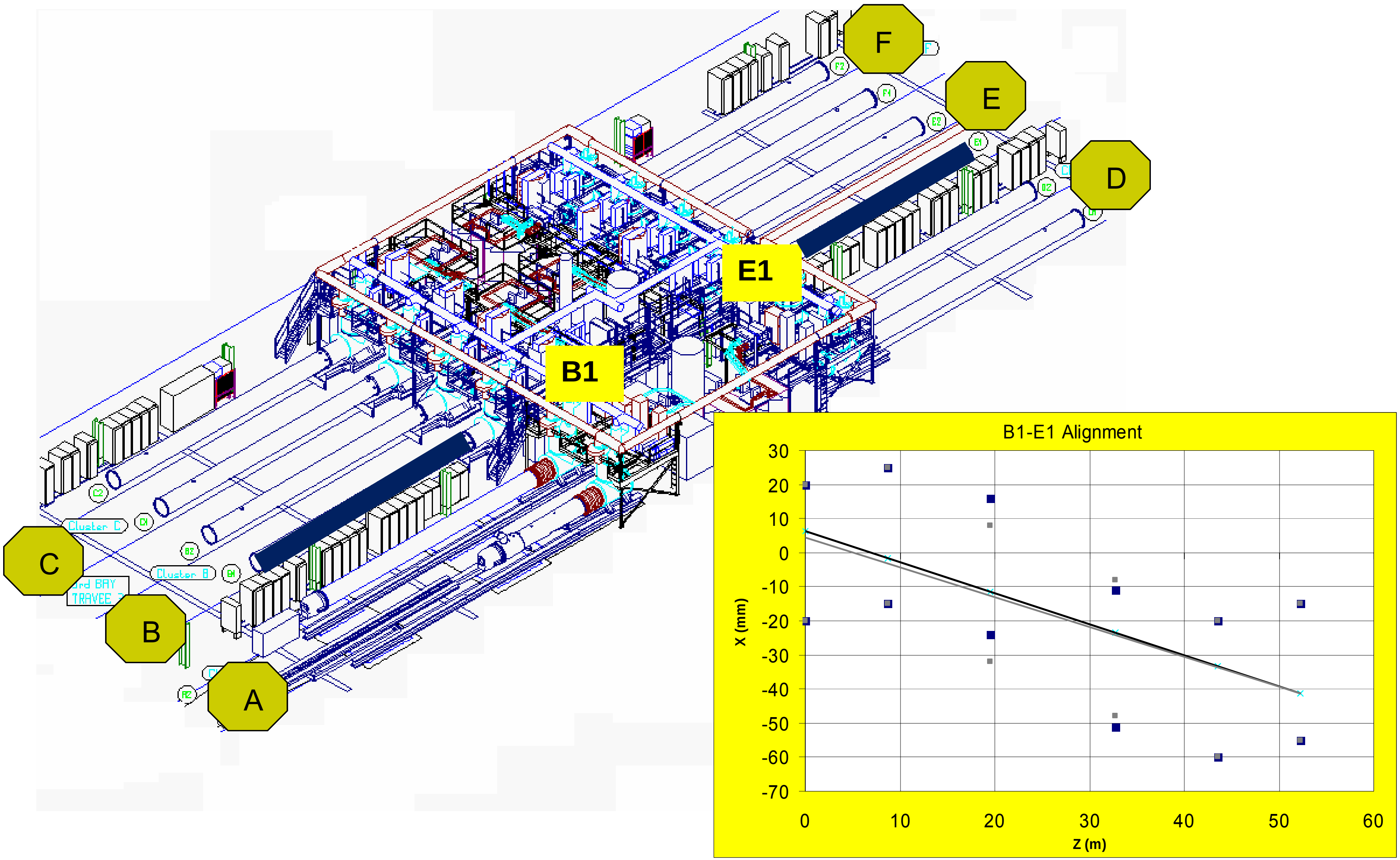
Encouraging results obtained with the extended laser cavity but more R&D required



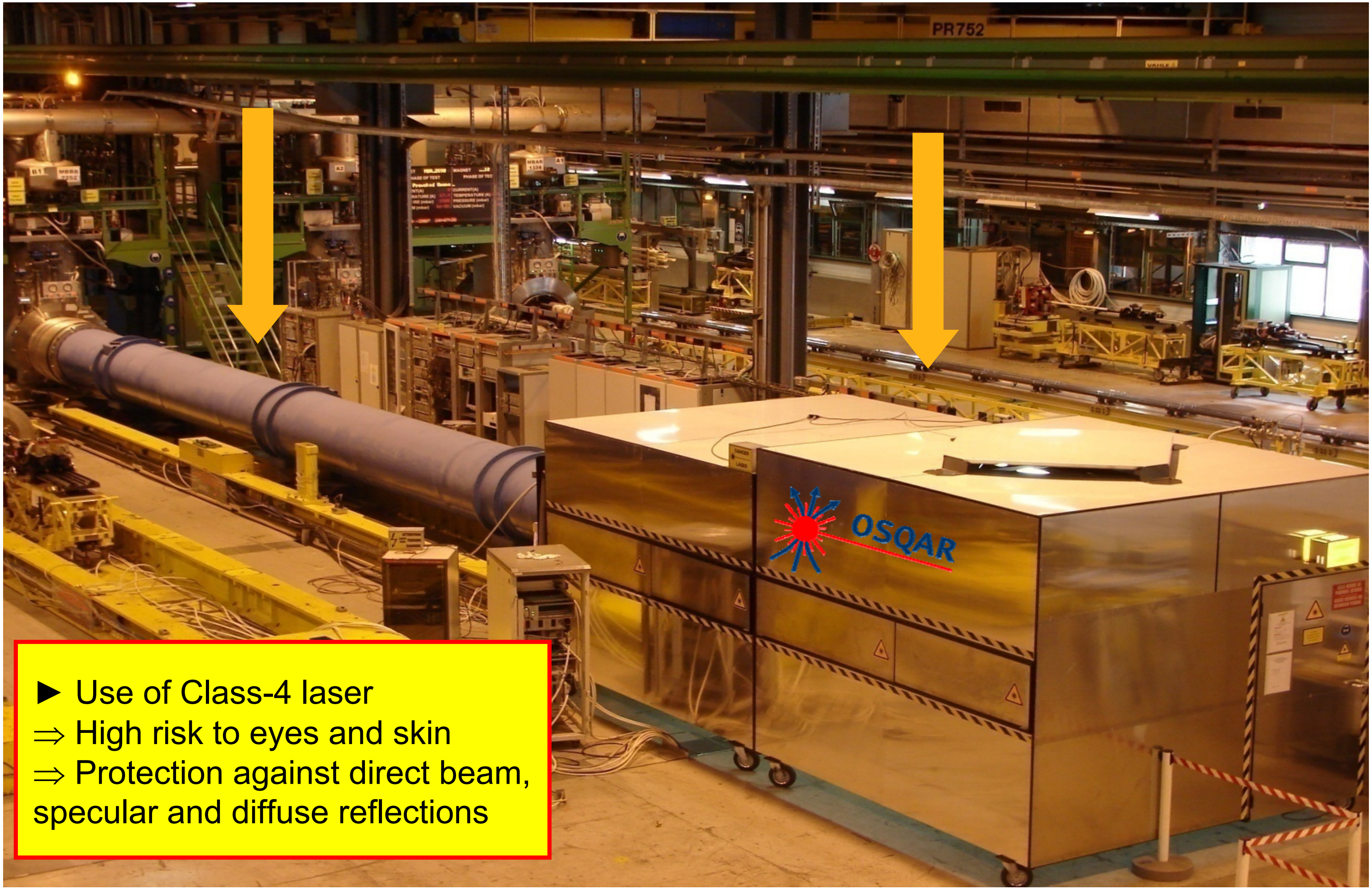


- Laser cavity extended up to 5 m inside the magnet; the intra-cavity CW power obtained was larger than few 100 W
- Problem to align the spot with the CCD detector ⇒ use of 2 dipoles to avoid to develop tricky fine tuning mechanical devices.

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



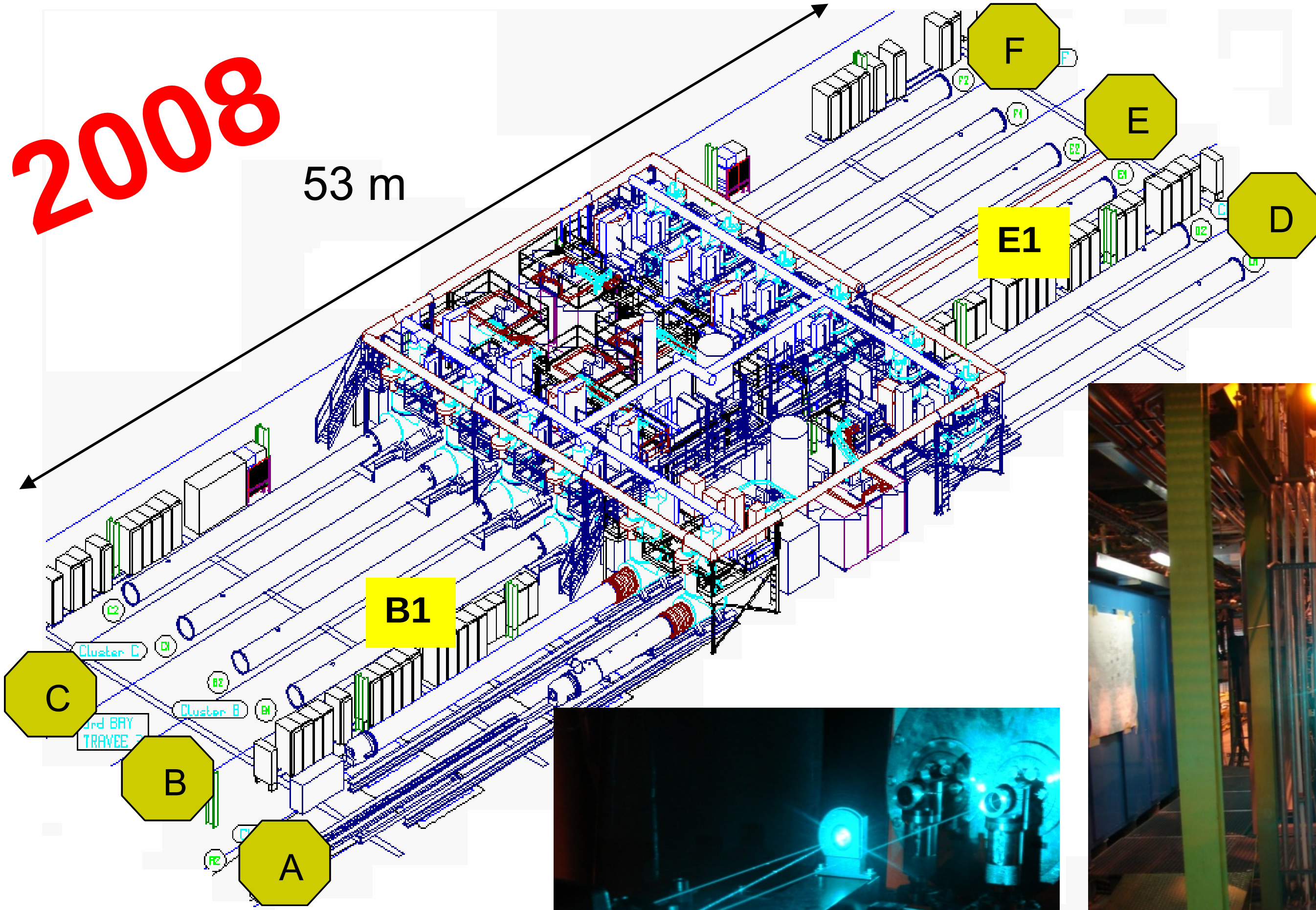
Laser and axion generation chamber

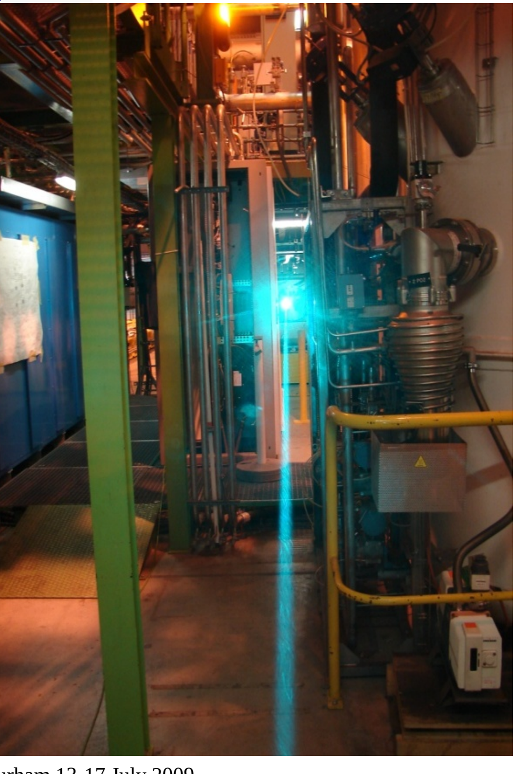


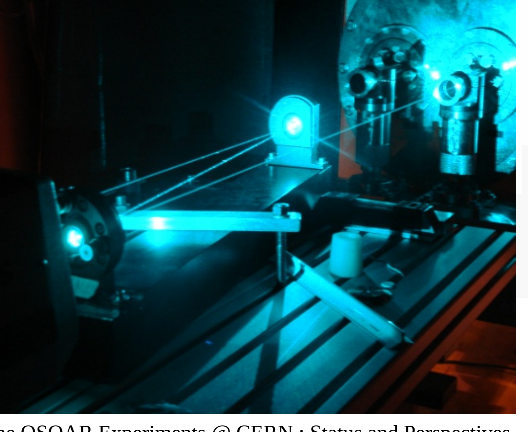
► Use of Class-4 laser
⇒ High risk to eyes and skin
⇒ Protection against direct beam, specular and diffuse reflections

Photon regeneration chamber

Preparation of the phase 2 of the photon regeneration experiment







Summary of the 2008 activities at CERN

- OSQAR 2008 run was approved by the Research Board on 28 May 2008
  - Constraints:
    - Shutdown of the SM18 cryogenic infrastructure from July (lasted till end of September - longer than anticipated)
    - Test co-activities of LHC magnets & RF cavities
  - 2 spare LHC dipoles were connected to the OSQAR test benches & aligned; optimal configuration for the photon regeneration experiment was implemented

    ► Laser beam was successfully aligned within apertures of both aligned LHC dipoles i.e. over 53 m long

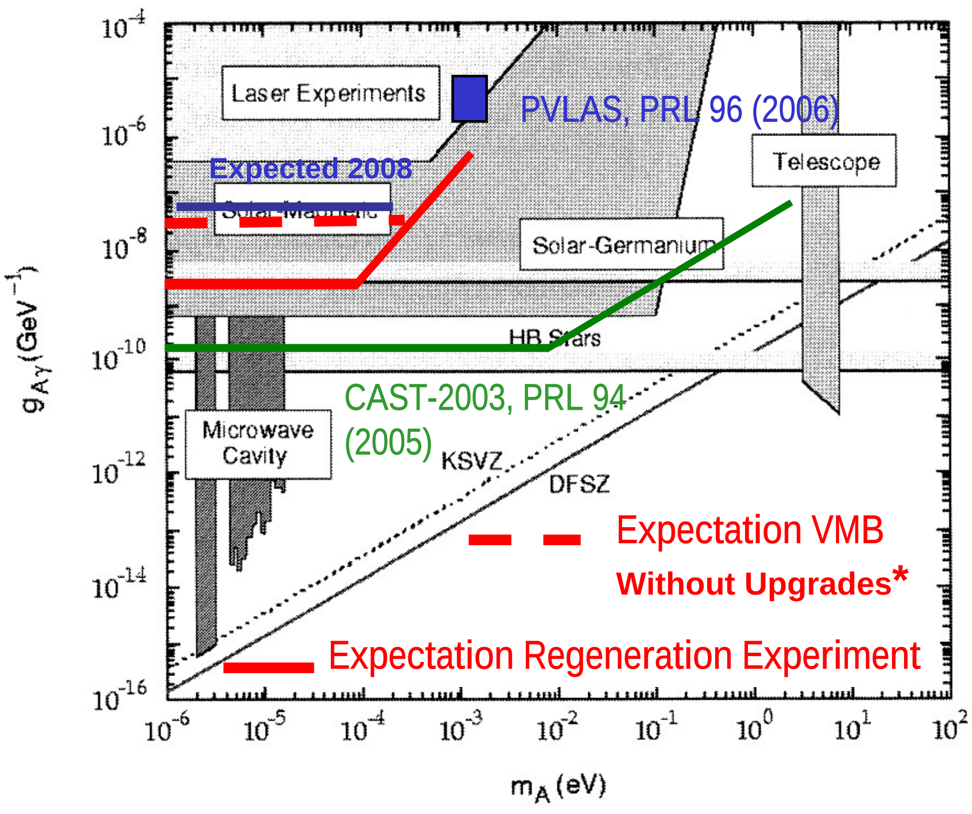
    ► No planned cold runs were performed in 2008

- Incident in the LHC tunnel in September 2008 has stopped the OSQAR experiments, in practice until June 2009

- The 2008 run is postponed till end of 2009
  - VMB: Ar+ Laser within 20-meter long extended cavity (in preparation)
  - Photon regeneration runs with two dipoles (in preparation)

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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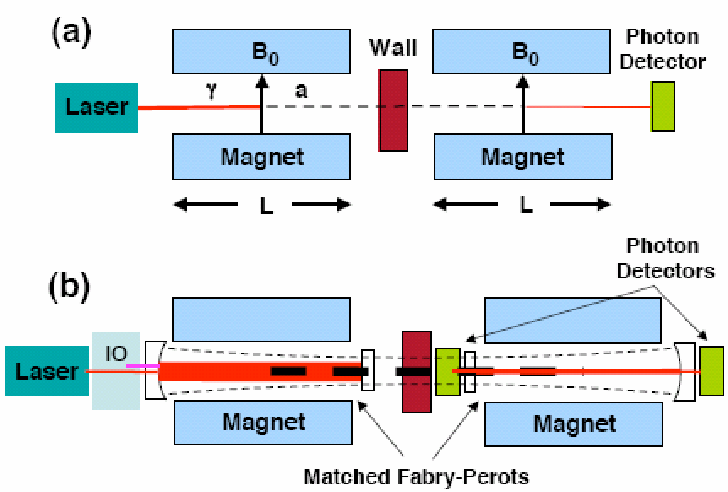

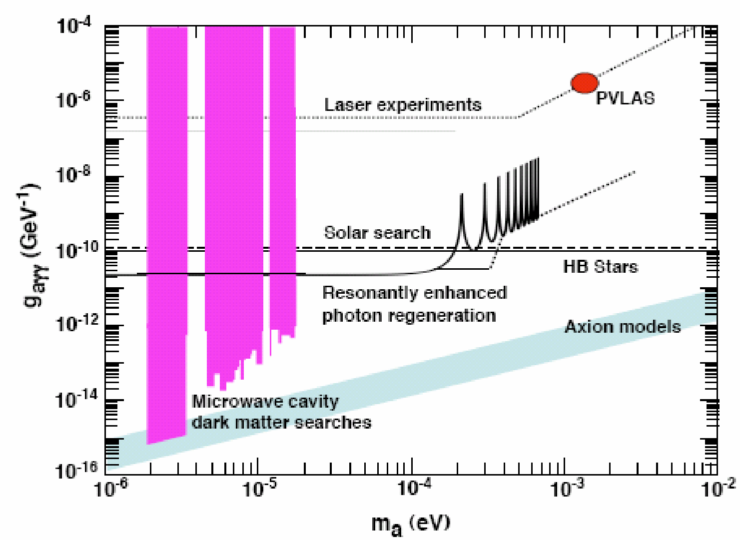

With 4 + 4 LHC Dipoles, i.e. Experiment ~140 m long,…

New proposal

- **Axion detection in the <u>gradient of magnetic field</u>**
  - For a massless axion → symmetry axion-photon (E. *Guendelman 2008*,…)
  - Measurement of the light deflection in the high gradient of the magnetic field Stern-Gerlach like experiment (first order in the axion-photon coupling)
  - use of LHC quadrupole magnets
  - Similar experiment for solar keV axions → novel axion helioscope („new CAST")

Summary

- OSQAR aims to answer to the following questions:
  - *What is the magnetization of the vacuum ?*
    Effects predicted in early QED 70 years ago are for the first time within experimental reach
  - *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 experiments:
  - 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 spin-offs in the domain of metrology of electric & magnetic fields breaking world records in measurements of the rotation of polarization, ellipticity, large optical cavities etc.
  - Emerging field: Laser-based Particle/Astroparticle Physics

Conclusions

- OSQAR activities at CERN were slowed down in 2008 due to unexpected circumstances
- Reconstruction of the experimental set-up for the photon regeneration experiment with two LHC dipoles is in progress
- Preparation for the VMB measurements is progressing well in collaborating Institutes, in particular at IMEP-LAHC
  - An innovative filtering process was proposed & is under development to increase the Signal/Noise ratio,
  - The proof of principle is demonstrated with a small size Fabry-Perot cavity,
  - The development of the full scale 20-meter long cavity & the integration of the innovative filtering techniques will start as soon as the requested founding is obtained.