QED Test and Axion Search by Means of Optical Techniques

Proposal

By Pierre Pugnat (CERN)

on the behalf of the *OSQAR* collaboration

Optical Search for QED vacuum magnetic birefringence, Axions and photon Regeneration

Tuesday 06 February 2007
80th Meeting of the SPSC

The OSQAR Collaboration *at present*

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

Charles University, Faculty of Mathematics and 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

IMEP, INPG – UJF & CNRS, 38016 Grenoble Cédex-1, France — L. Duvillaret, G. Vitrant

LLN, CNRS, BP 166, F-38042 Grenoble Cedex 9, France — B. Barbara, R. Ballou, Y. Souche

LSP, Université J. Fourier – Grenoble-1 & CNRS, 38402 Saint-Martin d'Hères, France — R. Jost, D. Romanini

TECHNICAL UNIVERSITY OF LIBEREC *Czech Republic* — M. Šulc

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

Preview

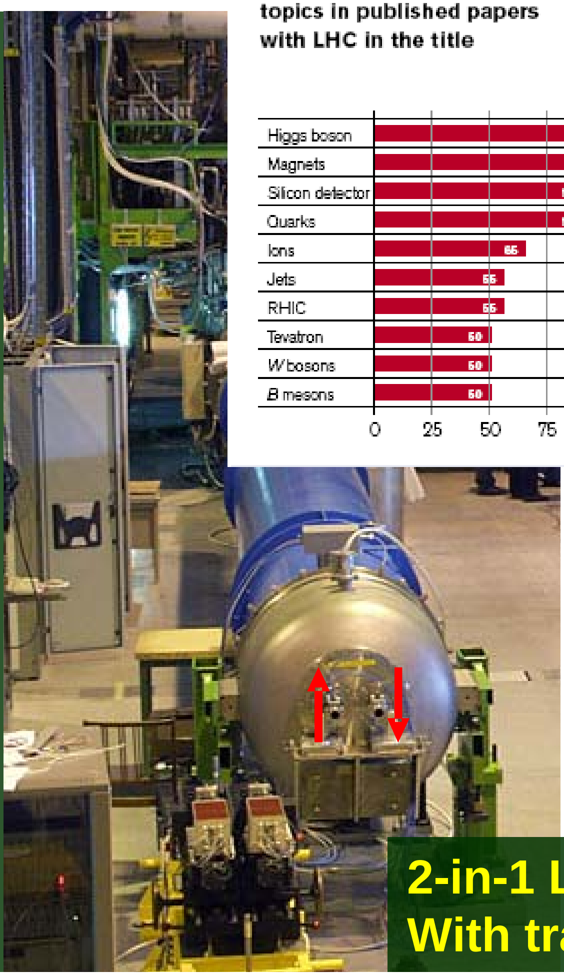
- Introduction
- The Magneto-optical properties of the Quantum Vacuum
- The OSQAR Proposal
  - Optical Precision Measurements for Axion search
  - Photon Regeneration Experiment: *"A light shinning through a wall"*
- Expected Results
- Prototyping, Integration in LHC dipole(s) & CERN infrastructure, Planning
- Summary & Outlook

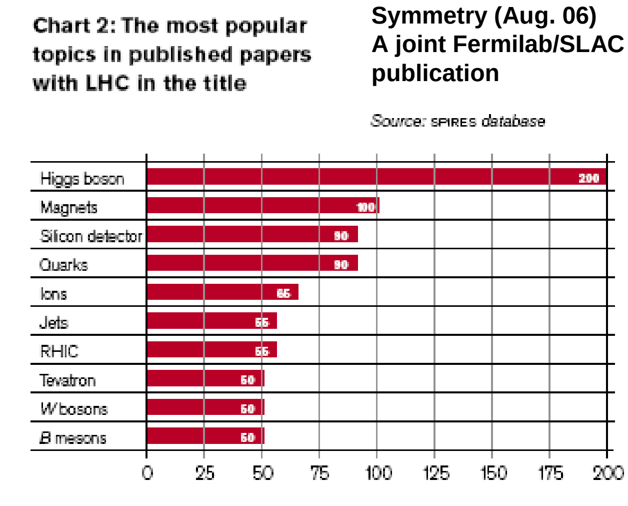
QED Test & Axion Search at CERN using decommissioned LHC superconducting dipole magnet(s)

- Ideal integration are within a superconducting dipole magnet used in accelerators for HEP
- With this respect, LHC main dipoles *are the most powerful at present:*
  - $B_{max} \approx 9.76$ T @ 1.9 K
  - Magnetic Length: 14.3 m

  $\Rightarrow$ the figure of merits of a single dipole, *i.e.* $B^2 L$, $B^2 L^2$ *and* $B^2 L^3$ are 10 – 25 larger than the BFRT magnet system

  $\Rightarrow$ *Big interest in re-cycling decommissioned LHC prototypes*





Symmetry (Aug. 06)
A joint Fermilab/SLAC publication

2-in-1 LHC dipole
With transverse B

The Magneto-Optical Properties of the Quantum Vacuum

Consequences of Dirac's Theory of the Positron
W. Heisenberg and E. Euler in Leipzig[1]
(22 December 1935)

"The fact that electromagnetic radiation can be transformed into matter and vice versa leads to fundamentally new features in quantum electrodynamics… In general, it will be not possible to separate processes in the vacuum from those involving matter since electromagnetic fields can create matter if they are strong enough. Even if they are not strong enough to create matter they will, due to the virtual possibility of creating matter, polarize the vacuum and therefore change the Maxwell equations…"

[1]Translated by W. Korolevski and H. Kleinert, Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany. emails: walja.k@web.de and kleinert.zedat.fu-berlin.de

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

- VMB from the QED Theory: Euler-Heisenberg Lagrangian, *i.e. Taylor expansion of gauge and Lorentz invariants*

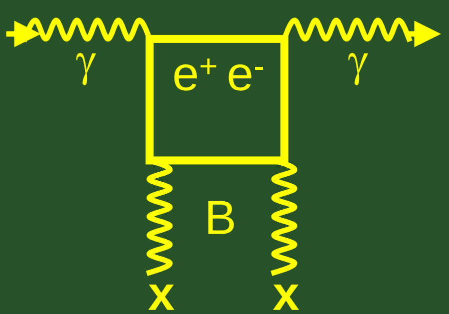
$$L = \frac{\varepsilon_0}{2}\left(E^2 - c^2B^2\right) + \frac{2\alpha^2\hbar^3\varepsilon_0^2}{45\, m^4c^5}\left[\left(E^2 - c^2B^2\right)^2 + 7c^2\left(EB\right)^2\right] + \ldots$$

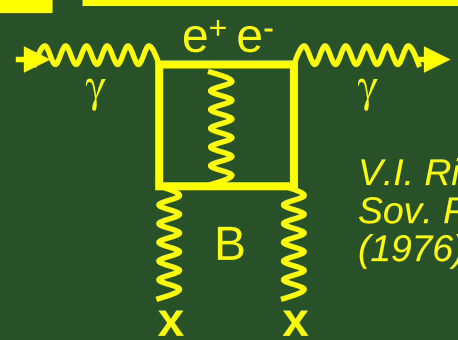
$E, B << m^2/e \sim 10^{18}$ V/m, 10^9 T and $\omega << m$

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 and permeability of the vacuum:

$$\varepsilon_{ik} = \delta_{ik} + \frac{e_G^4\, \hbar}{45\,\pi\, m^4c^7}\left[2\left(E^2 - c^2B^2\right)\delta_{ik} + 7c^2B_iB_k\right] + \ldots.$$

$$\mu_{ik} = \delta_{ik} + \frac{e_G^4\, \hbar}{45\,\pi\, m^4c^7}\left[2\left(c^2B^2 - E^2\right)\delta_{ik} + 7E_iE_k\right] + \ldots.$$

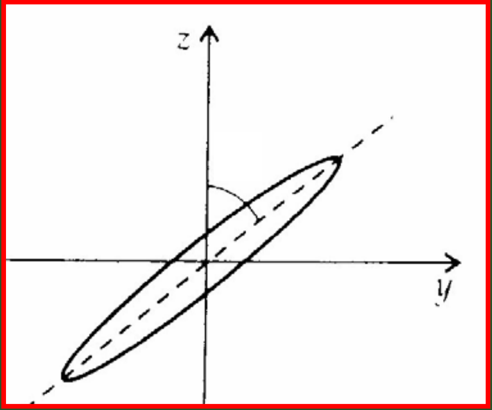
The change of the light velocity in a background magnetic field – the "Pure" QED prediction

$$\frac{1}{n} = \frac{v}{c} = 1 - a\frac{\alpha^2\hbar^3\varepsilon_0}{45\, m^4 c^3} B^2 \sin^2\phi = 1 - a\left(1.3\times 10^{-24}\right) B^2 \sin^2\phi$$

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

$$n_\perp = 1 + 7\, A_e\, B_0^2\, \sin^2\phi \qquad n_{II} = 1 + 4\, A_e\, B_0^2 \sin^2\phi$$

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



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

Analogue to the Cotton-Mouton effect

NA: **Δn ≈ 3.6 10^{-22}** in 9.5 T field & *$\varepsilon \approx 2.10^{-10}$* for *$l$ = 250 km and λ =1.55 μm*

The second order correction to the Lagrangian gives a Δn correction of 1.45% with respect to the dominant term, *i.e.* a measurement of the QED birefringence at the level of few ‰ will provide a test for this term…

A technical challenge from the point of view of optical metrology; High-field magnet, optical cavity are required & …

Polarized Light Propagating in a Magnetic Field as a Probe for Millicharged Fermions

Holger Gies,[1,*] Joerg Jaeckel,[2,†] and Andreas Ringwald[2,‡]

[1]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany*

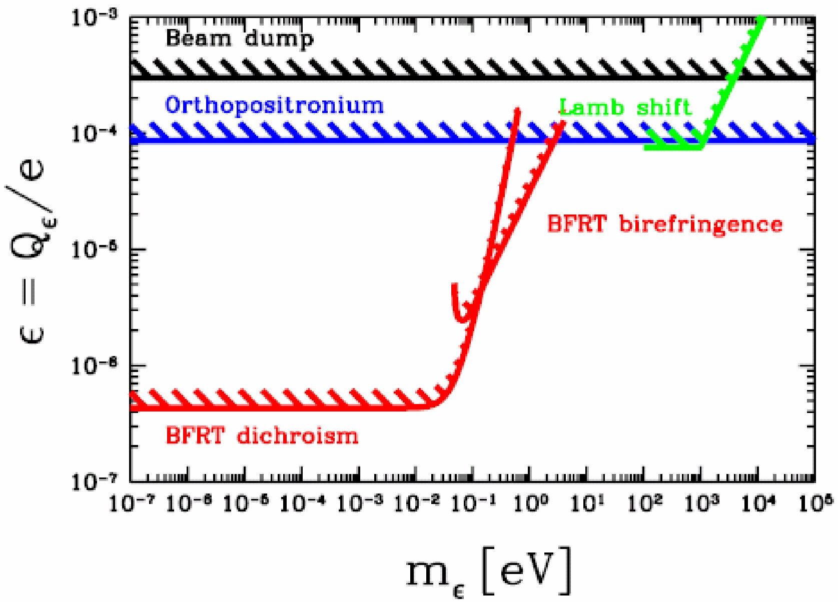
[2]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*

(Received 24 July 2006; published 2 October 2006)

PRL97, 140402 (2006)

Possible extensions of the standard model of particle physics suggest the existence of particles with small, unquantized electric charge. Photon-initiated pair production of millicharged fermions in a magnetic field would manifest itself as a vacuum magnetic (VM) dichroism. We show that laser polarization experiments searching for this effect yield, in the mass range below 0.1 eV, much stronger constraints on millicharged fermions than previous laboratory searches. VM birefringence due to virtual pair production gives a slightly better constraint for masses between 0.1 and a few eV. We comment on the possibility that the VM dichroism observed by PVLAS arises from pair production of such millicharged fermions rather than from single production of axionlike particles. Such a scenario can be confirmed or firmly excluded by a search for invisible decays of orthopositronium with a branching-fraction sensitivity of about 10^{-9}.

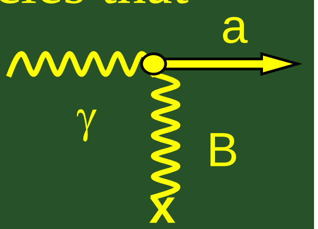
Polarization measurements of laser Beams propagating in transverse magnetic field provide also a very sensitive probe of light millicharged fermions



Beyond the pure QED - Contribution of Axions 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 linear polarized laser bean propagating in vacuum is expected to acquire, in presence of a transverse B field, a small apparent rotation θ & ellipticity ε expressed with Heaviside-Lorentz units *(1 T = 195 eV^2 & 1 m = 5.07x10^6 eV^{-1})* in the limit $m^2\, l\, /\, 4\omega << 1$:

$$\theta \approx \frac{B^2 l^2}{16\ M^2}\ \sin 2\phi \qquad \varepsilon \approx \frac{B^2 l^3 m^2}{96\ \omega\ M^2}\ \sin 2\phi$$

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.

Optical Precision Measurements for QED Test & Axion Search

The “n-1 Experiment” or the “n-ologie”

“g-2 is not an Experiment: It is a way of life”

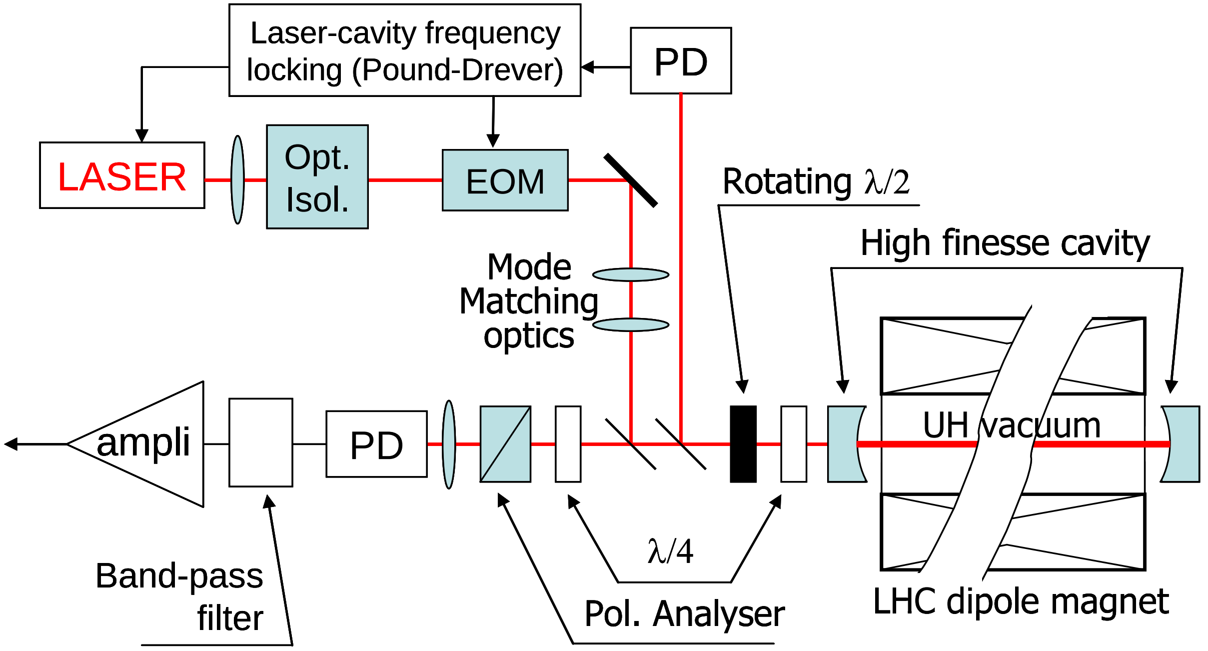
J. Adams (1920-1984)

Former CERN Director-General

VMB & Linear Dichroism measurements for Axion 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
- Very small effects 10^{-14} rad / T^2 km^3 ⇒ optical cavity to increase the path in B
- Background for the ellipticity coming from the QED.

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.



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

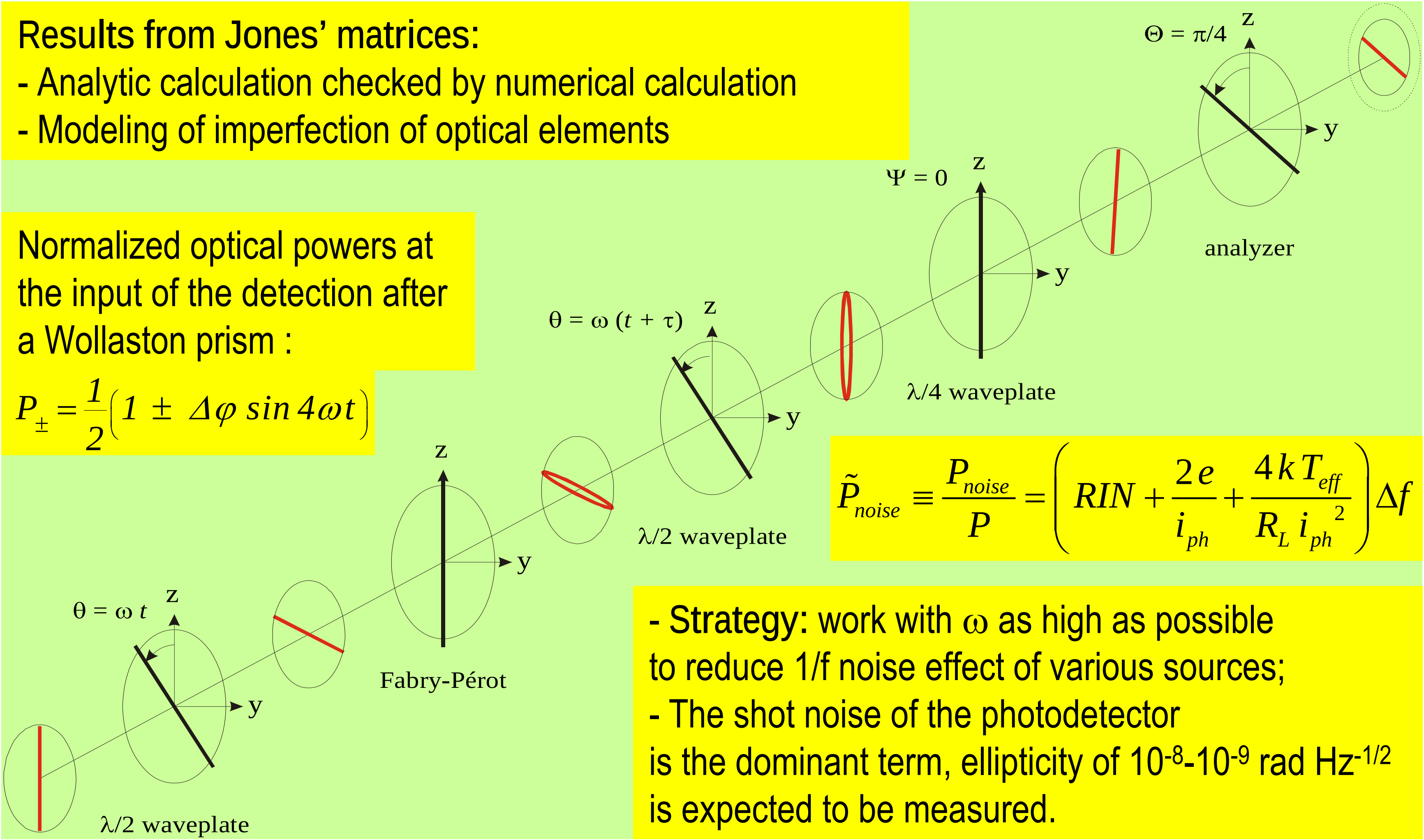
Field Modulation at 1-10 mHz

VMB Measurements
Principle

Results from Jones' matrices:
- Analytic calculation checked by numerical calculation
- Modeling of imperfection of optical elements

Normalized optical powers at the input of the detection after a Wollaston prism :

$$P_{\pm} = \frac{1}{2}\left(1 \pm \Delta\varphi \sin 4\omega t\right)$$



$$\tilde{P}_{noise} \equiv \frac{P_{noise}}{P} = \left(RIN + \frac{2e}{i_{ph}} + \frac{4kT_{eff}}{R_L\, i_{ph}^{2}} \right) \Delta f$$

- **Strategy:** work with ω as high as possible to reduce 1/f noise effect of various sources;
- The shot noise of the photodetector is the dominant term, ellipticity of 10^{-8}-10^{-9} rad Hz$^{-1/2}$ is expected to be measured.

VMB Measurements -“*Proof of concept*” & *Optimization*

- Simulation and calculations based on Jone’s matrix formalism showed the validity of the proposed optical scheme;
- Preliminary measurements of the Cotton-Mouton effect of Air at CERN gave the 2nd proof of concept;
- The sensitivity study of the effects of imperfections of the optical elements have provided key parameters for their specifications.

- Signal/Noise optimization
  - Laser with low RIN
  - 1/f noise limitation coming mostly from the shot noise of the photodetector

$\Downarrow$

Signal must be modulated typically with f > few kHz

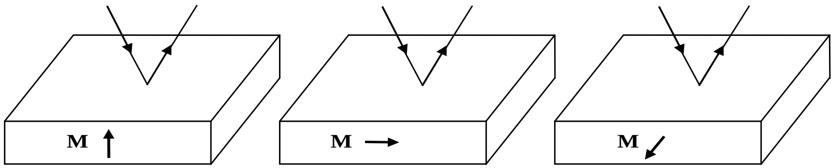
- Two solutions retained:
  - 1st step: rotating $\lambda/2$ wave-plate

  $\Rightarrow$ modulation up to ~20 kHz
  - 2nd step/alternative: Electro-optic

  $\Rightarrow$ modulation up to MHz range

A possible origin for PVLAS like signals

- Magneto-Optical Kerr Effects (MOKE)



Polar, Longitudinal and Transverse

- During the reflection, the magnetization M produces, in general, a birefringence as well as a linear dichroism.

- For normal reflection only a polar MOKE is expected.

- Estimate with a Polar MOKE (like "Faraday effect in reflexion")

- Verdet constant ≈ 4-27 rad $T^{-1}m^{-1}$ for SiO2 type glasses and high-refraction index ones;

- Assuming a mirror thickness of 10 μm, the PVLAS rotation of 3.9×10^{-12} rad/pass can be produced by a transverse spurious B field rotating at 2ω of **0.07 – 0.5 mG !!**

- This numbers can be reassessed once mirror characteristics are known, but the message for all experiments is:

The shielding at the level of mirrors is of prime importance & the residual B **<< 10 μG …**

A comment will be submitted to PRL

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

"An invisible light shining through a wall"

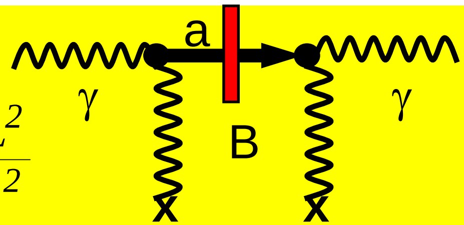
K. van Bibber et al.

PRL 59 (1987) 759

Direct Axion Search Experiment

Photon Regeneration

P. Sikivie, PRL 51 (1983) 11415

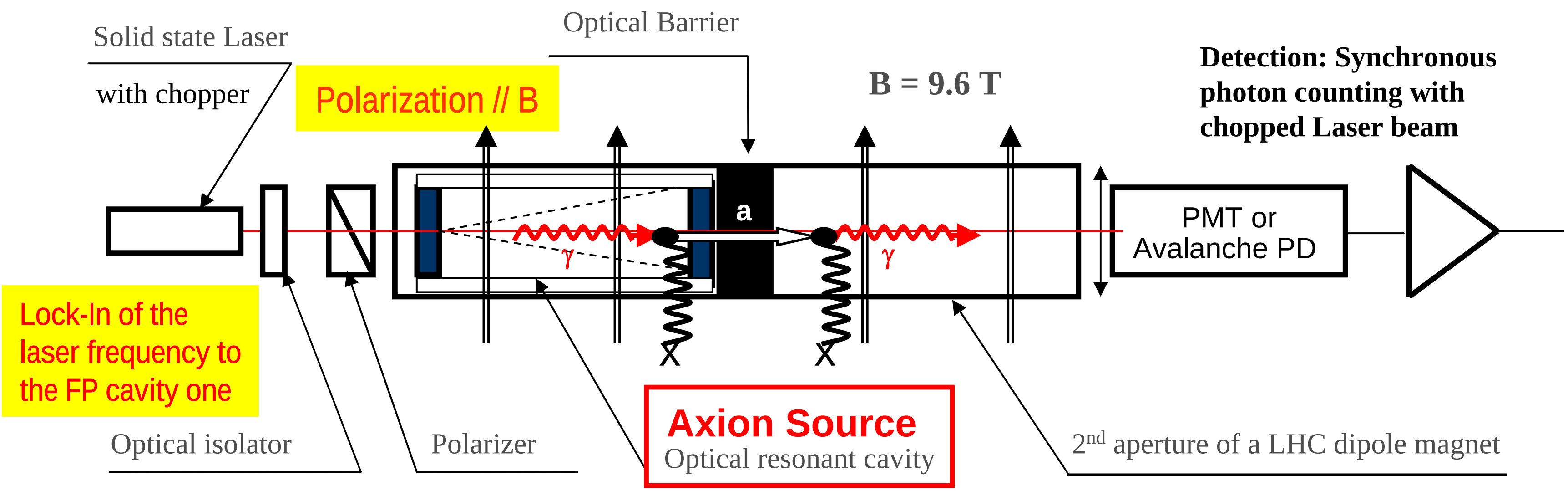


K. van Bibber et al. PRL 59 (1987) 759

In the limit qL<<1

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

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



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

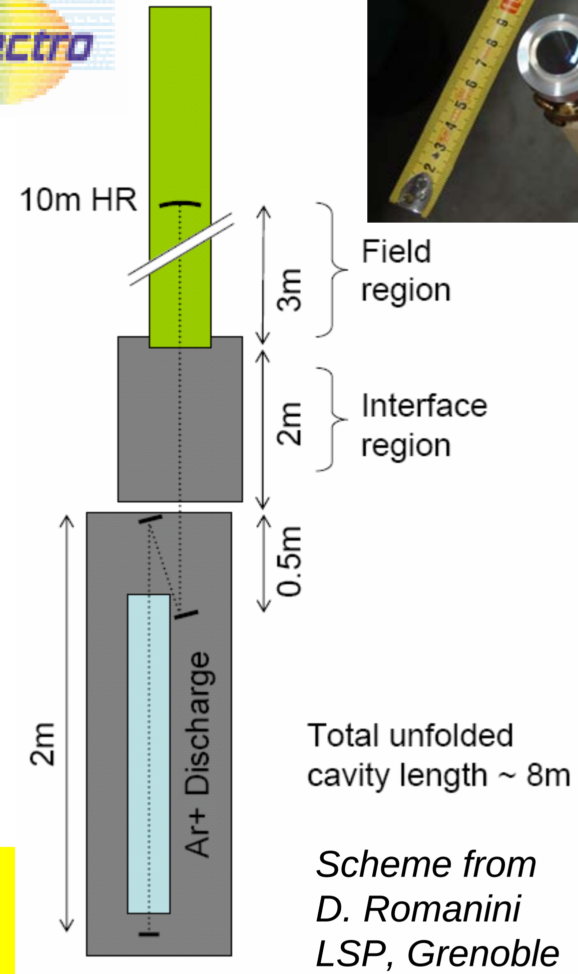
Expectations: Improvement / the present reference result of Cameron et al. Phys. Rev. D47 (1993) 3707 ~ R x 10^7 with 1 magnet & 100 W

But 1 kW inside a cavity of 10^4 gives 10 MW $\Rightarrow$ Optimum Thermal Management

Preliminary Photon Regeneration Experiment using Ar+ laser **with 0.1-1 kW intracavity CW optical power**

- Use of Ar+ laser (488 & 514 nm) from the LSP with R_{max} output coupler;
- Study of the mirror integration inside the LHC magnet aperture **already done** ⇒ 1st choice with a Z-fold cavity (*alternative with a linear one)*;
- **PVLAS results is expected to be checked with less than hour of integration time.**

Detection with a LN2 cooled CCD Camera of Princeton Instrument, QE ≈ 50%, DC/pix ≈ 0.1/mn



Scheme from D. Romanini LSP, Grenoble

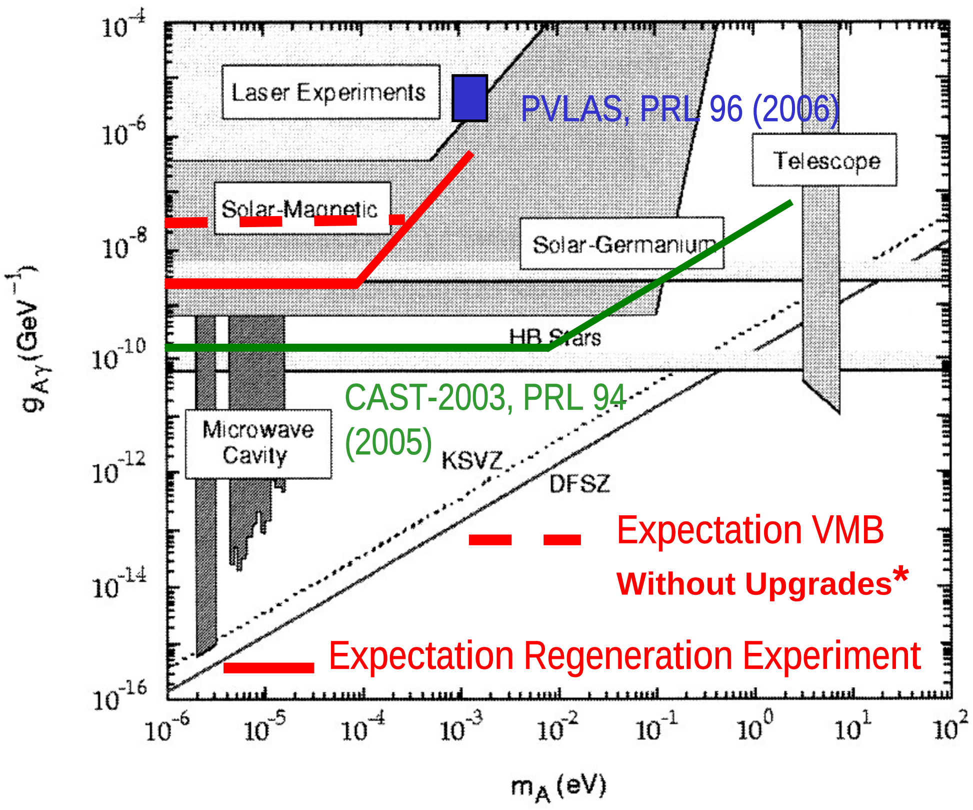
Expected Results

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

S. Ting
Nobel Prize in Physics (1976)
MT19 Conference, Genova 2005

Axion Search Experiments
Expected results (phases-1 without upgrades)

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



- **"n-1 Experiment"**
  - To further improve VMB and dichroism measurements, a breakthrough in optical technique must be achieved: Electro-optical modulator in MHz range & dedicated filtering are required to cross the barrier of 10^{-8} rad/(Hz)$^{1/2}$ $\Rightarrow$ 2nd phase.
- **Photon regeneration Experiment**
  - Preliminary Phase to check a.s.a.p. PVLAS results;
  - Phase-1: 1 dipole with and without gas; CW laser beam & High Finesse cavity;
  - Phase-2: more than 1 dipole ? with pulse laser beam ?

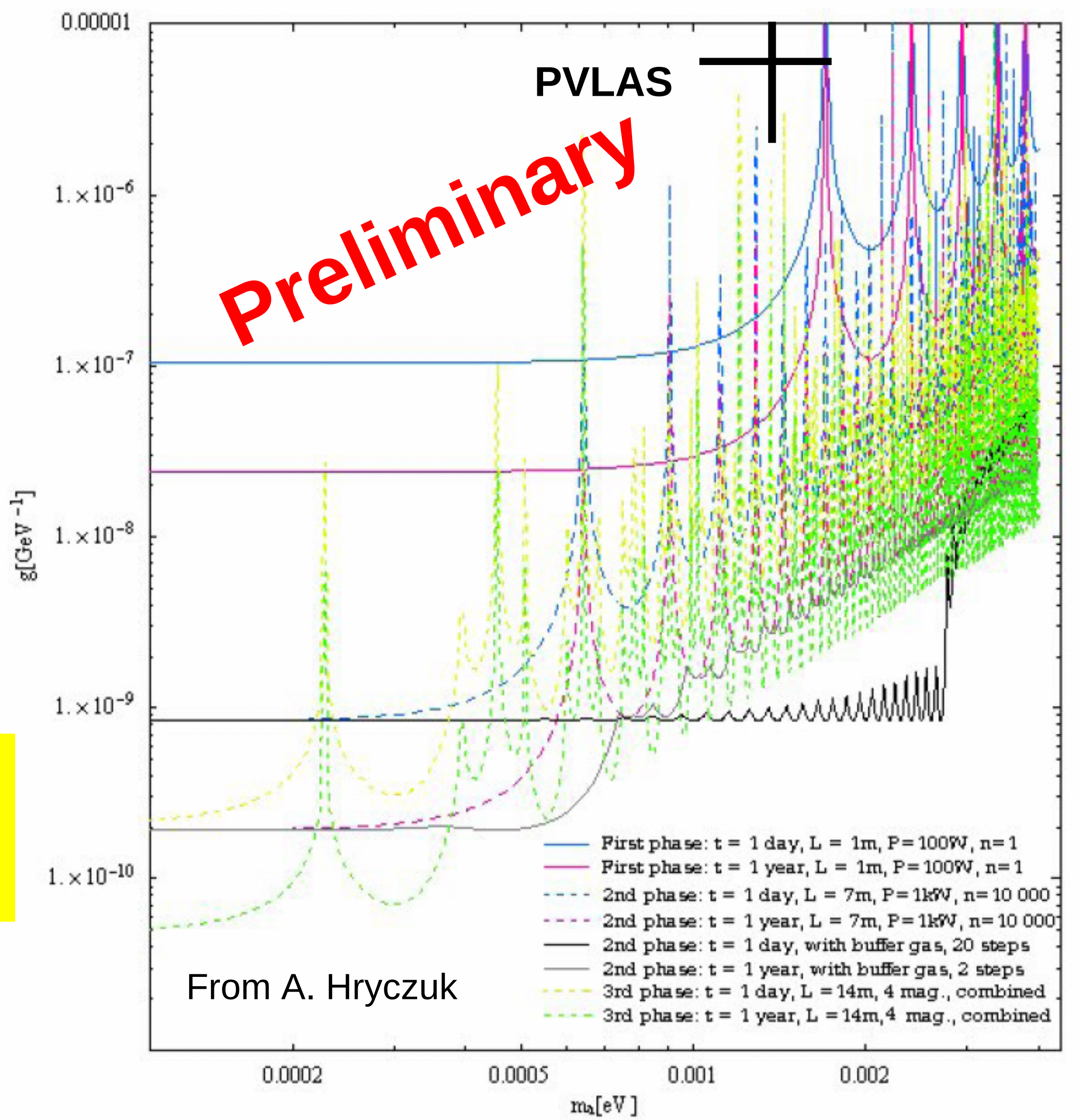
*P. Pugnat, L. Duvillaret, M. Finger, M. Kral , A. Siemko, J. Zicha, Czech. Journal of Physics, Vol.55 (2005), A389; Czech.Journal of Physics, Vol.56 (2006), C193;

Photon Regeneration Experiments with upgrades

Options considered

- ► up to 5 dipoles
- ► to restore the coherence of $\gamma \to a$ oscillation at larger m_a
  - ► fill the magnet aperture with gas;
  - ► alternate polarity of the Magnets.

For g = 1/M, the present CAST limit can be reached with 4 dipoles in total

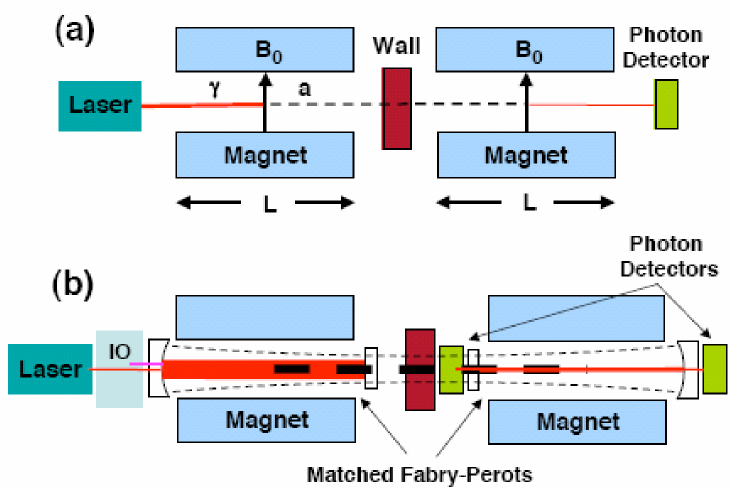


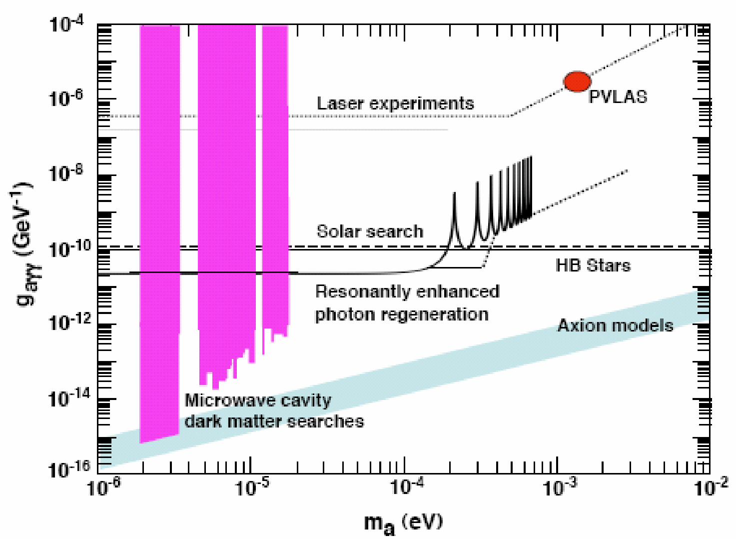
Resonantly Enhanced Axion-Photon Regeneration

P. Sikivie,[a,b] D.B. Tanner,[a] and Karl van Bibber[c]
[a] *Department of Physics, University of Florida, Gainesville, FL 32611, USA*
[b] *Theoretical Physics Division, CERN, CH-1211 Genève 23, Switzerland*
[c] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

We point out that photon regeneration-experiments that search for the axion, or axion-like particles, may be resonantly enhanced by employing matched Fabry-Perot optical cavities encompassing both the axion production and conversion magnetic field regions. Compared to a simple photon regeneration experiment, which uses the laser in a single-pass geometry, this technique can result in a gain in rate of order $\mathcal{F}^2$, where $\mathcal{F}$ is the finesse of the cavities. This gain could feasibly be $10^{(10-12)}$, corresponding to an improvement in sensitivity in the axion-photon coupling, $g_{a\gamma\gamma}$, of order $\mathcal{F}^{1/2} \sim 10^{(2.5-3)}$, permitting a practical purely laboratory search to probe axion-photon couplings not previously excluded by stellar evolution limits, or solar axion searches.

PACS numbers: PACS numbers: 12.38.-t, 12.38.Qk, 14.80.Mz, 29.90.+r, 95.35.+d



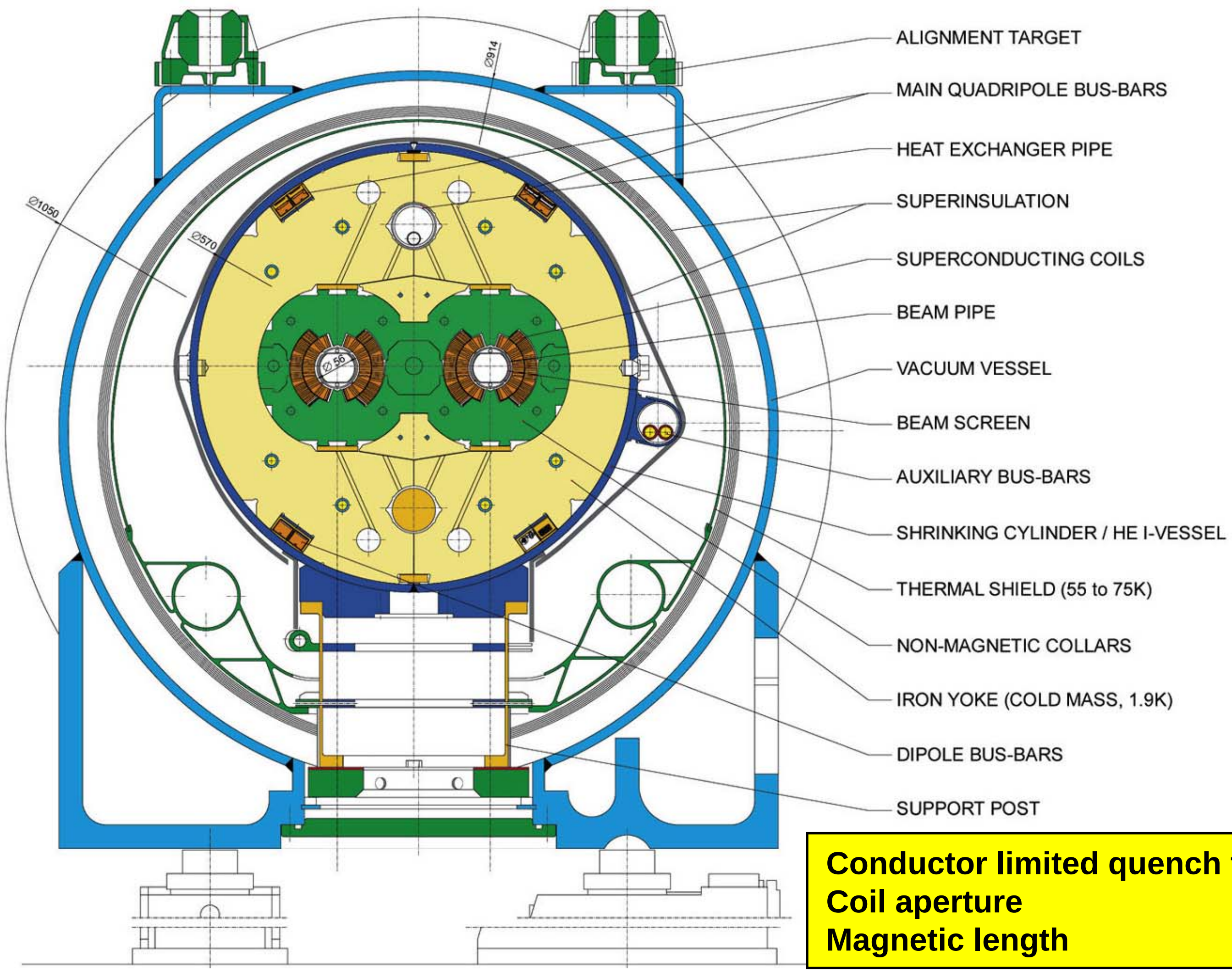


Prototyping

Integration in LHC Dipole(s) & CERN Infrastructure

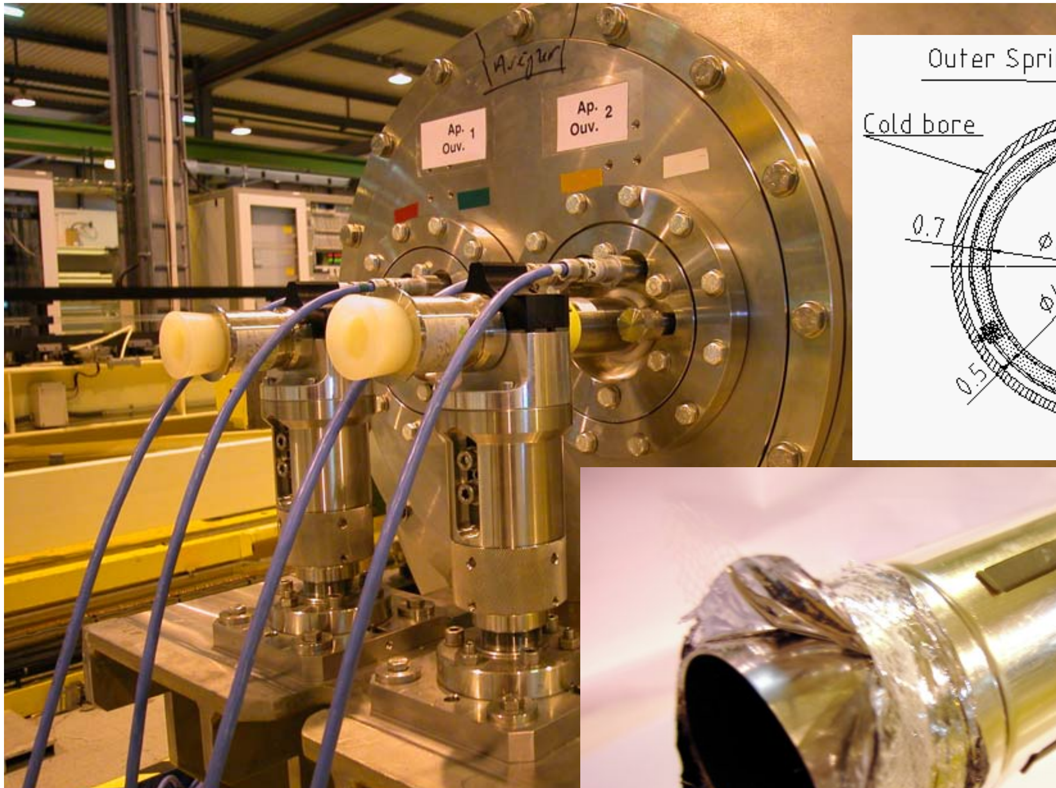
Planning

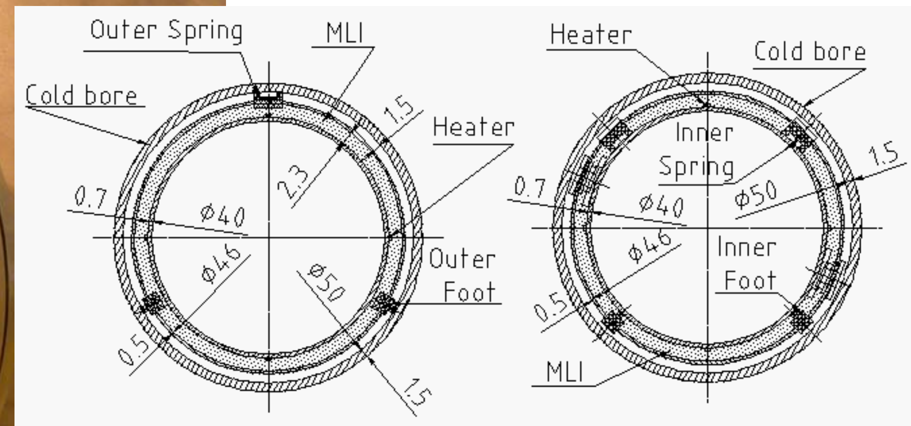
LHC superconducting main dipoles: Cross-section



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*



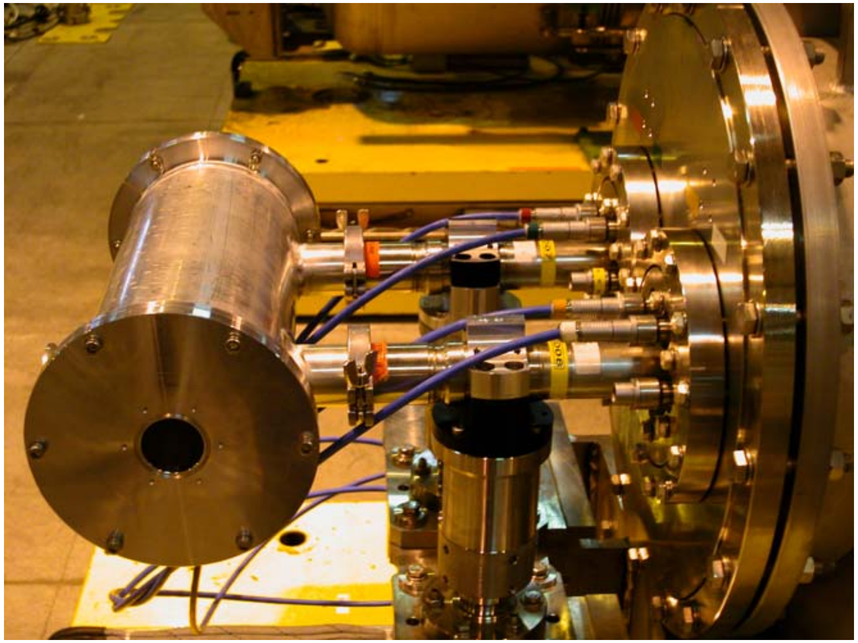


Specially designed for the cold tests of LHC cryomagnets,

They can be used for the core of the optical cavities

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*

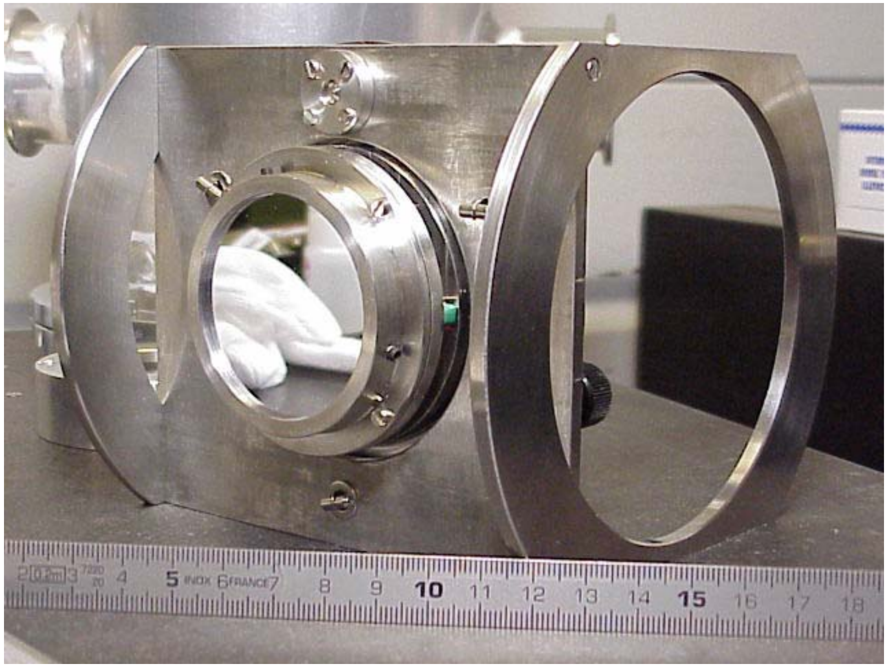
Prototyping for End-caps & mirror support with precise angular tuning mechanism



End-caps for housing the optical cavity;

Distance between the mirrors = 19.6 m
$\Rightarrow$ mirror radius for a confocal resonant optical cavity

End-caps and connections to the anticryostats - real situation

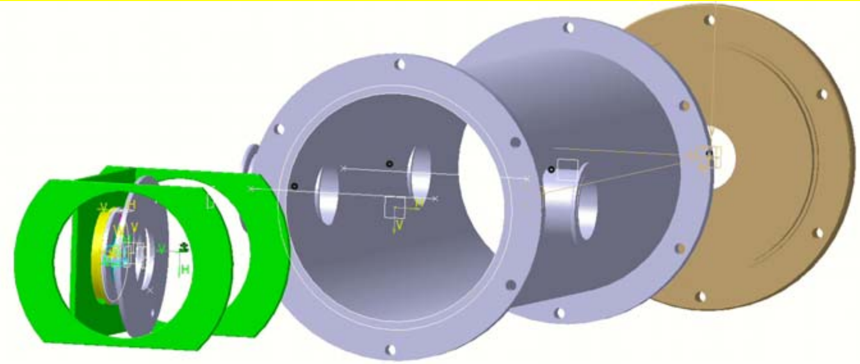


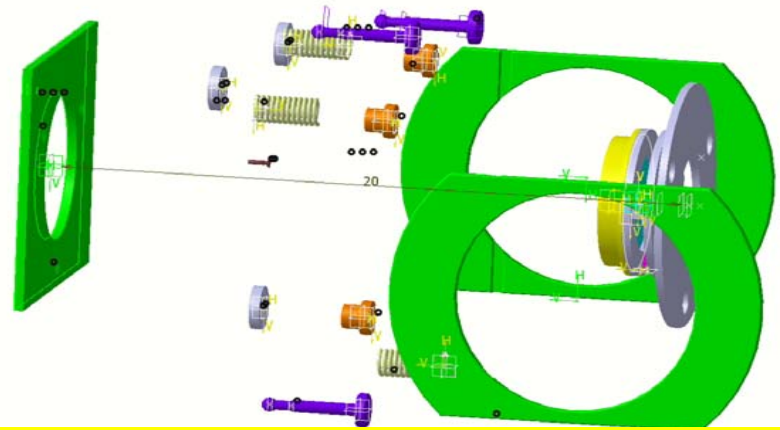
Ph-D M. Kràl

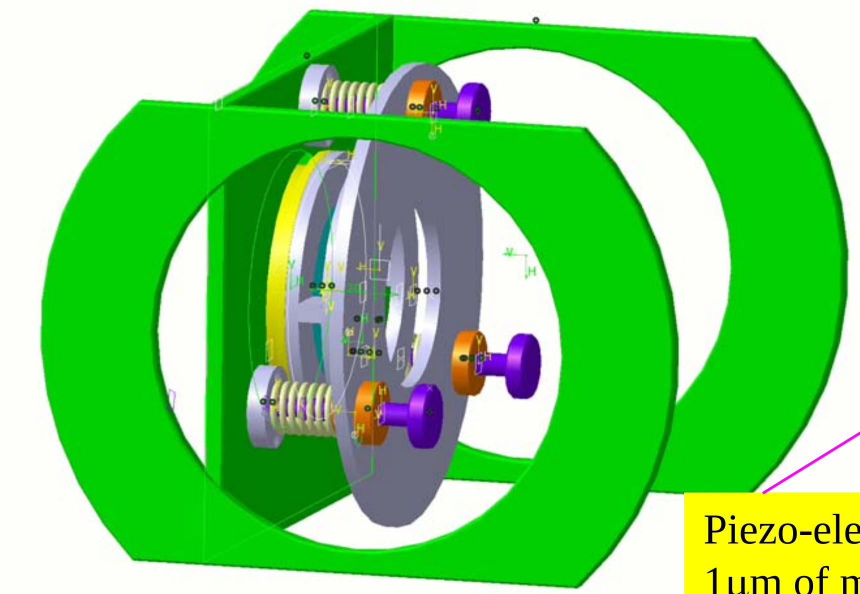
Importance of the mechanical stability

Mirror Integration inside the End-caps with Precise Angular Tuning Mechanism *(Ph-D M. Kràl)*

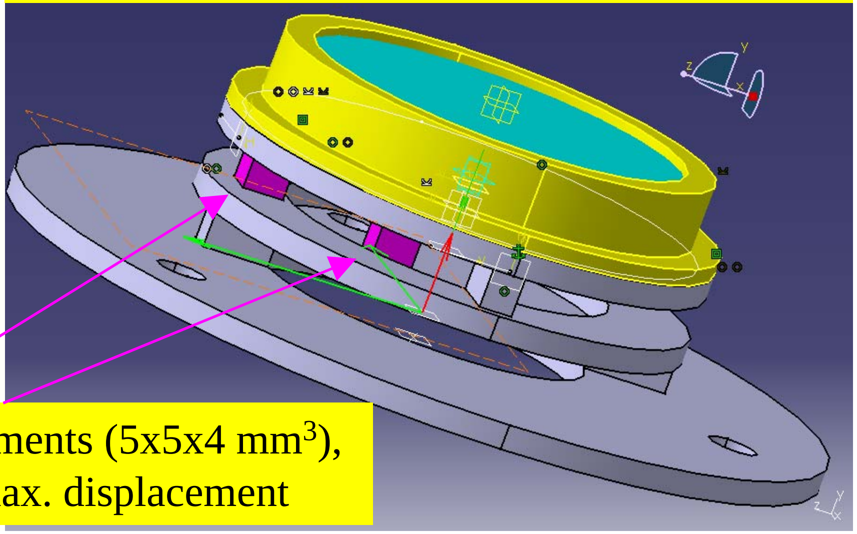
Tuning of mirrors in 2 steps: **1/** by screw $\pm 10^{-4}$ rad; **2/** piezo-ceramics $\pm 5.10^{-6}$ rad







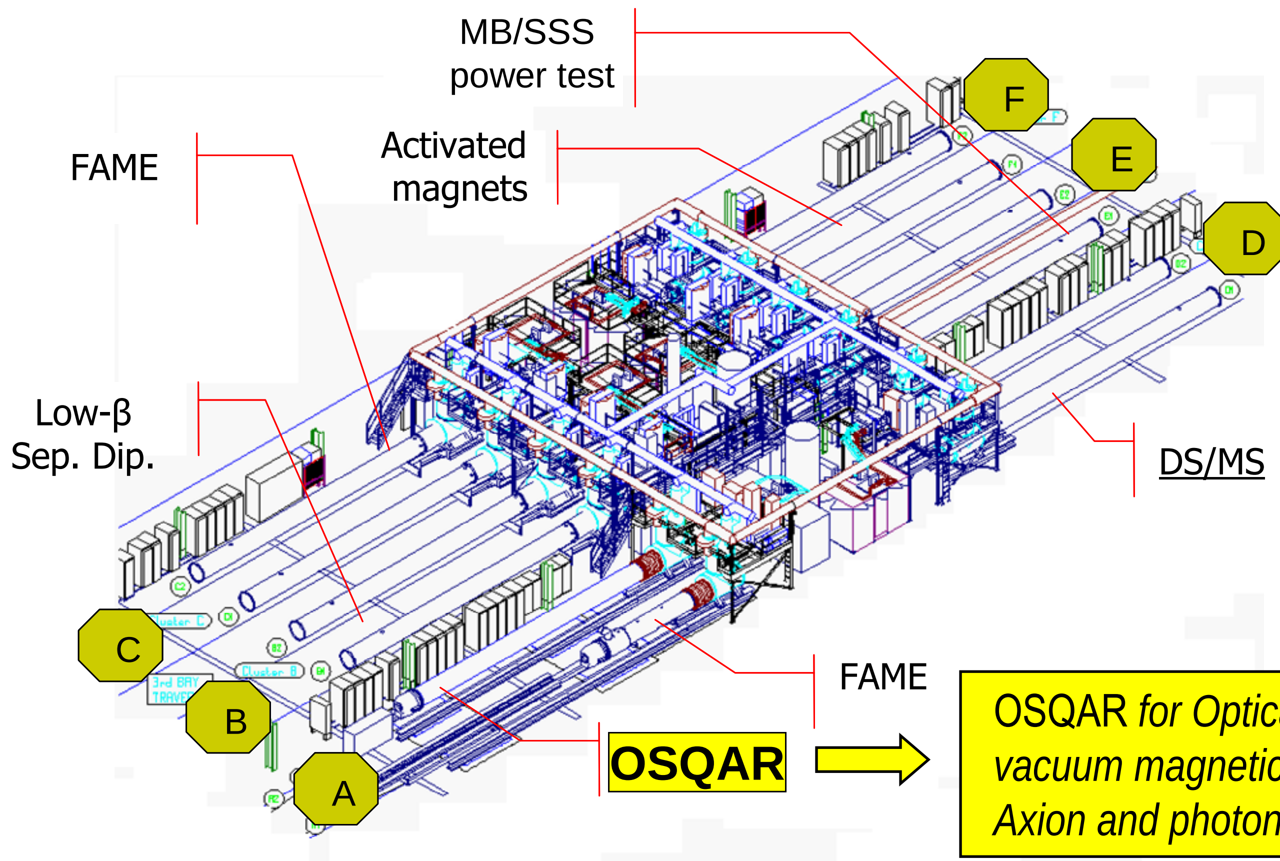
Effective diameter of mirrors is 38 mm



Piezo-elements (5x5x4 mm^3), 1μm of max. displacement

Workshop inside the CERN/AT Department in March 2006

Possible SM18 layout after series tests



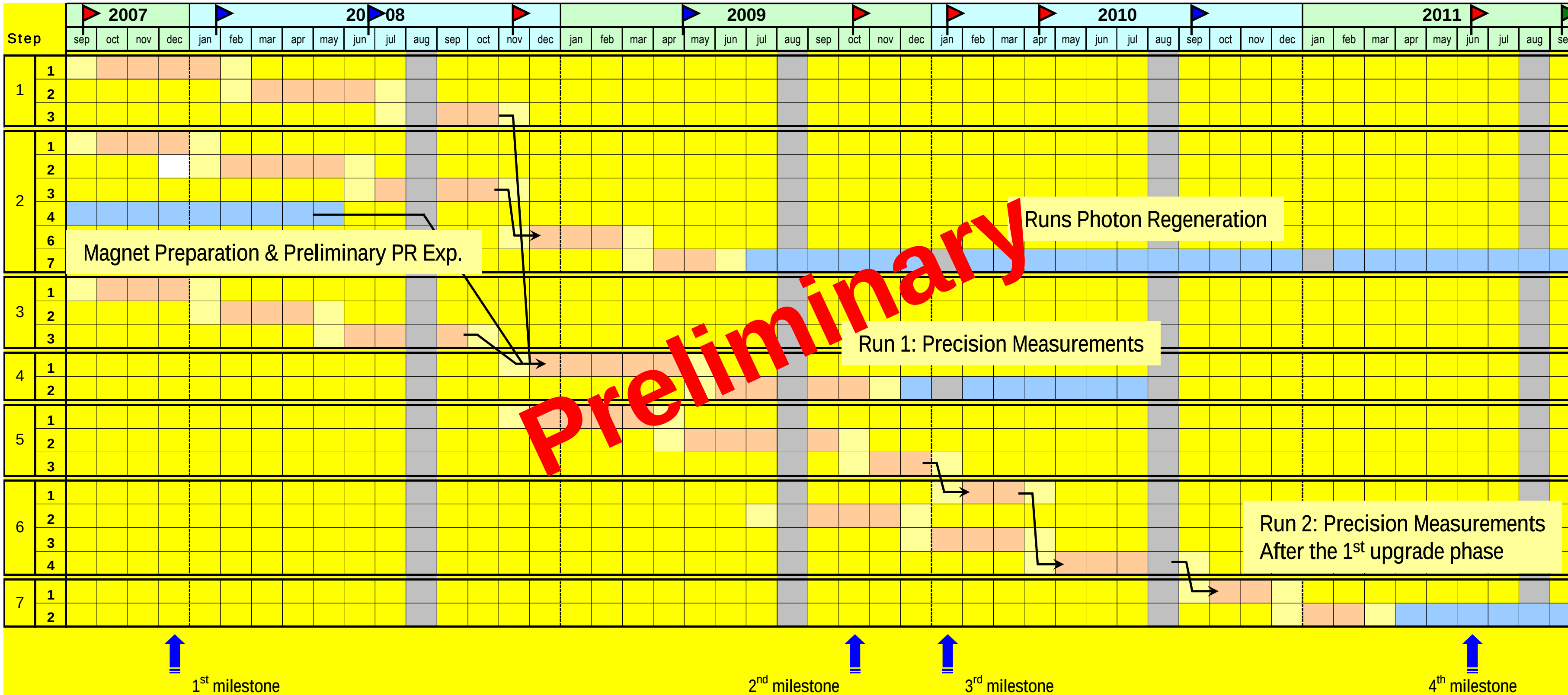
OSQAR *for Optical Search of QED vacuum magnetic birefringence, Axion and photon Regeneration*

Extracted from A. Siemko Presentation: *http://indico.cern.ch/conferenceDisplay.py?confId=1270*

A bench with a fully equipped LHC superconducting dipole **<u>is available today</u>** at SM18 to start the preliminary phase

The Experiments in the "Time-Space"

Strategy & Possible Upgrades



Legend

- **Ramping up or down phases of the activity**
- **Normal running**
- **Additional contributions from CERN concerning the standard services required to install and run the experiments**
- **Coordination meeting between all partners of the collaboration (at the beginning/end of important phases and at the 3 milestones)**
- **Coordination meeting between the partners implied in the corresponding phases**
- **Project Report**

Planning according to present available resources + 2 Post-Docs paid by NFA during 3 years each
Services from CERN is also expected with boundary conditions driven by the LHC construction

Proposal for ANR, CzNFA & CERN-SPSC

Summary

- The objective of OSQAR is to provide the 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 an invisible light shin through a wall ?*
    P. Sikivie (1983), K. van Bibber et al. (1987)

- **The preliminary phase of the photon regeneration experiment does not require significant investments and can start now**…

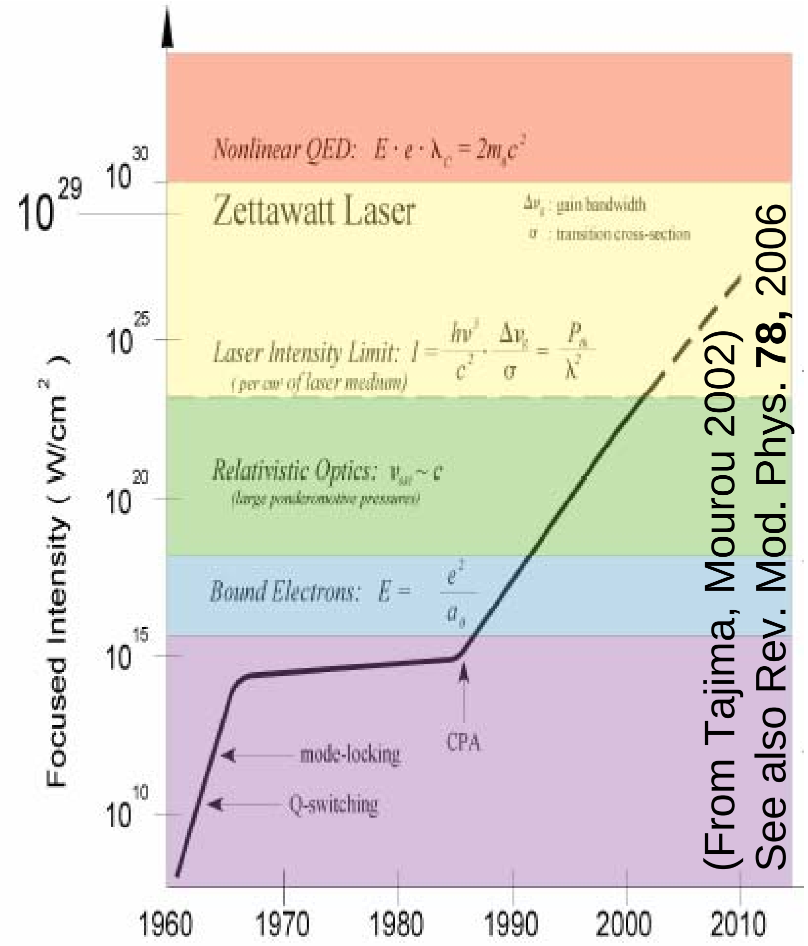
- The significance of the OSQAR proposal is:
  - to test of the QED down to an unprecedented level,
  - to detect "new" particles beyond the standard model that can couple to photons such as paraphotons, scalar or pseudo-scalar like axions, millicharged fermions,…
  - And also, the spin-off from the development of novel optical techniques for electrical and magnetic field measurements

*But as said **R. P. Feynman**:*
"Physics is like sex: sure it has some practical applications, but that's not why we do it"…

Outlook

- Emerging field: Laser-based Particle Physics
  - This proposal focuses on the low field CW regime i.e. E, B << $m_e^2/e \sim 10^{18}$ V/m and low energy $\omega \ll m_e$
  - Present Laser Technology will allow to reach $E/E_{sw} \sim 10^{-2}$ at 1 eV (10^{26} W/cm^2, European Extreme Light Infrastructure)
  - Also XFEL in keV range…

- Photon Regeneration Exp. should also profit from such developments
  - Rabadán, Ringwald, Sigurdson (PRL **96**, 110407, 2006)
  - OSQAR phase-2 ?…



(From Tajima, Mourou 2002)
See also Rev. Mod. Phys. **78**, 2006

More information

- Proposal, CERN-SPSC-2006-035, 9 November 2006
  http://doc.cern.ch//archive/electronic/cern/preprints/spsc/public/spsc-2006-035.pdf
- Presentation given at IAS Princeton (NJ), 20-22 October 2006
  http://www.sns.ias.edu/~axions/schedule.shtml
- P. Pugnat et al., "Axion Searches at present and in the Near Future",
  to appear in the Lecture Notes in Physics, Volume on Axions, (Springer-Verlag)
- P. Pugnat, M. Kràl, A. Siemko, L. Duvillaret, M. Finger Jr., M. Finger,
  K. A. Meissner, D. Romanini, M. Šulc, and J. Zicha, *Czech. J. Phys.* ***56*** *(2006) C193*
- P. Pugnat, L. Duvillaret, M. Kràl, Presentation at the HHH-AMT Workshop on Pulsed Accelerator Magnets, Frascati, 26-28 October 2005; http://ecomag-05.web.cern.ch/ecomag-05/
- L. Duvillaret, M. Kràl, and P. Pugnat, CERN-AT-MTM Internal Note 71, October 2005, CERN-EDMS-Id-672179
  https://edms.cern.ch/cedar/plsql/doc.info?cookie=4169685&document_id=672179&version=1
- Letter of Intent, CERN-SPSC-2005-034, 17 October 2005
  http://doc.cern.ch//archive/electronic/cern/preprints/spsc/public/spsc-2005-034.pdf
- P. Pugnat, M. Kràl, A. Siemko, L. Duvillaret, M. Finger, J. Zicha,
  Czech. J. Phys. ***55*** *(2005) A389*, http://doc.cern.ch/archive/electronic/cern/preprints/at/at-2005-009.pdf