Laboratory Experiments for Axion Search using Decommissioned LHC Superconducting Dipoles

2005 December 1st

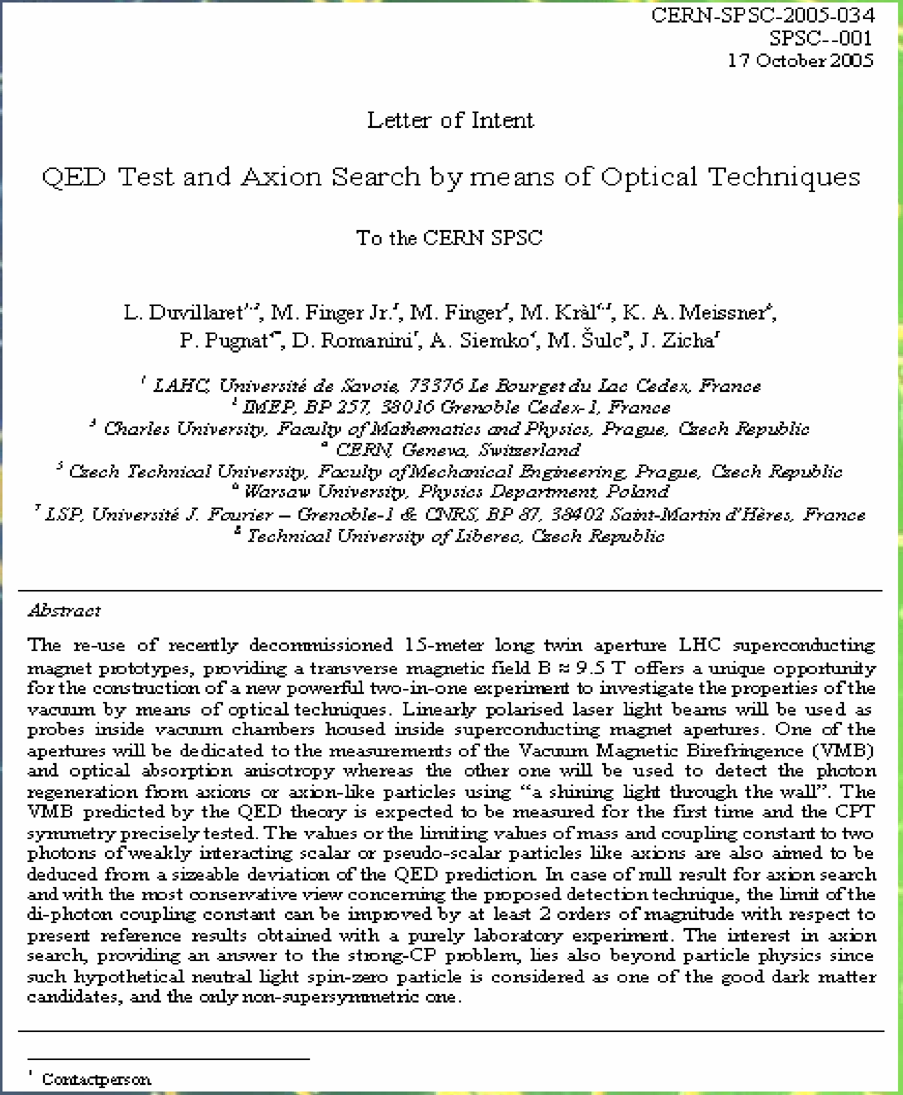
L. Duvillaret[1], M. Finger Jr.[2], M. Finger[2], M. Kràl[3,4], K.A. Meissner[5],
P. Pugnat[3], D. Romanini[6], A. Siemko[3], M. Šulc[7], J. Zicha[4]

[1] *IMEP, INPG – UJF & CNRS, 38016 Grenoble Cedex-1, France*
[2] *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[3] *CERN, Geneva, Switzerland*
[4] *Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic*
[5] *Warsaw University, Poland*
[6] *LSP, Université J. Fourier – Grenoble-1 & CNRS, 38402 Saint-Martin d'Hères, France*
[7] *Technical University of Liberec, Czech Republic*

Introduction

From a Fundamental Question to a LoI

- What is the structure of the Quantum Vacuum?
- From Theory
  - In QED, it is "well-known"
  - In QCD, a non-trivial structure is connected to the strong CP problem;
    a new global symmetry can be introduced (Peccei & Quinn), when spontaneously broken
    ⇒ axions (Weinberg, Wilczek)
- Experimentally,
  - The Quantum Vacuum can be probed with electromagnetic fields



CERN-SPSC-2005-034
SPSC--001
17 October 2005

Letter of Intent

QED Test and Axion Search by means of Optical Techniques

To the CERN SPSC

L. Duvillaret[1,2], M. Finger Jr.[3], M. Finger[3], M. Král[4,5], K. A. Meissner[6],
P. Pugnat[4,*], D. Romanini[2], A. Siemko[4], M. Šulc[8], J. Zicha[5]

[1] LAHC, Université de Savoie, 73376 Le Bourget du Lac Cedex, France
[2] IMEP, BP 257, 38016 Grenoble Cedex-1, France
[3] Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[4] CERN, Geneva, Switzerland
[5] Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic
[6] Warsaw University, Physics Department, Poland
[7] LSP, Université J. Fourier – Grenoble-1 & CNRS, BP 87, 38402 Saint-Martin d'Hères, France
[8] Technical University of Liberec, Czech Republic

Abstract

The re-use of recently decommissioned 15-meter long twin aperture LHC superconducting magnet prototypes, providing a transverse magnetic field B ≈ 9.5 T offers a unique opportunity for the construction of a new powerful two-in-one experiment to investigate the properties of the vacuum by means of optical techniques. Linearly polarised laser light beams will be used as probes inside vacuum chambers housed inside superconducting magnet apertures. One of the apertures will be dedicated to the measurements of the Vacuum Magnetic Birefringence (VMB) and optical absorption anisotropy whereas the other one will be used to detect the photon regeneration from axions or axion-like particles using "a shining light through the wall". The VMB predicted by the QED theory is expected to be measured for the first time and the CPT symmetry precisely tested. The values or the limiting values of mass and coupling constant to two photons of weakly interacting scalar or pseudo-scalar particles like axions are also aimed to be deduced from a sizeable deviation of the QED prediction. In case of null result for axion search and with the most conservative view concerning the proposed detection technique, the limit of the di-photon coupling constant can be improved by at least 2 orders of magnitude with respect to present reference results obtained with a purely laboratory experiment. The interest in axion search, providing an answer to the strong-CP problem, lies also beyond particle physics since such hypothetical neutral light spin-zero particle is considered as one of the good dark matter candidates, and the only non-supersymmetric one.

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[*] Contact person

Preview

- Introduction
- Significance of the proposed experiments
  - QED & the Vacuum Magnetic Birefringence (VMB)
  - Light Pseudo-scalars such as Axions and their contribution to the VMB
  - Photon regeneration experiment
    - Without field, deviation from pure QED *i.e.* paraphoton,
    - With field, photon-axion mixing
  - The 5 different experiment types for the search of "invisible" Axions
- Experimental method for QED Test & Axion Search using decommissioned LHC superconducting dipole magnet(s)
  - Prototyping & integration
  - Measurement principle of the VMB for QED test & Axion search
  - Detection of a "A light shinning through the wall"
  - The Experiments in the "Time-Space" & possible upgrades
- Conclusions

Significance of the proposed experiments

QED prediction for the Vacuum Magnetic Birefringence

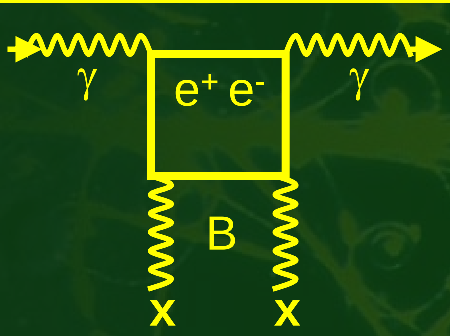
- VMB from the QED Theory: Euler-Heisenberg Lagrangian, *i.e. Taylor expansion of gauge and Lorentz invariants*

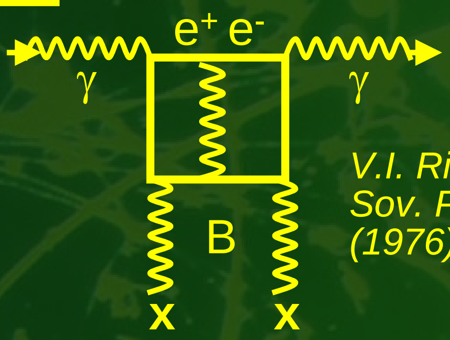
$$L = \frac{\varepsilon_0}{2}\left(E^2 - c^2B^2\right) + \frac{2\alpha^2\hbar^3\varepsilon_0^2}{45\, m^4 c^5}\left[\left(E^2 - c^2B^2\right)^2 + 7c^2\left(EB\right)^2\right] + \ldots$$

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:

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

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

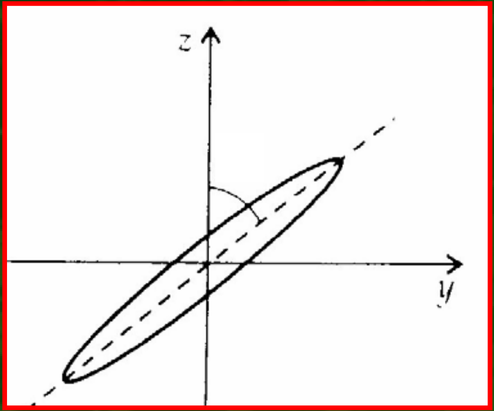
The change of the light velocity in a background magnetic field – “Pure” QED prediction

$$\frac{1}{n} = \frac{v}{c} = 1 - a\frac{\alpha^2\hbar^3\varepsilon_0}{45\, m^4 c^3} B^2 \sin^2\phi = 1 - a\left(1.3\times10^{-24}\right) B^2 \sin^2\phi$$

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

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

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: $\Delta n \approx 3.6\ 10^{-22}$ in 9.5 T field & $\underline{\varepsilon \approx 2.10^{-10}}$ 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.

Significance of the proposed experiments

Beyond the pure QED - Contribution of axions to the VMB

- 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:

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

- A linear polarized laser bean propagating in vacuum is expected to acquire, in presence of a transverse *B* field, a small apparent rotation θ & a small ellipticity ε that can be expressed in Heaviside-Lorentz units *(1T = 195 eV^2 & 1m = 5.10^{-6} eV^{-1}):*

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

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

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

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

Significance of the proposed experiments

Departure from the pure QED prediction with axions

- The so-called “strong CP problem” is connected to the non-trivial structure of the QCD vacuum (‘t Hooft, 1976) and can be summarized by the puzzling question:

  Why QCD does not seem to break the CP-symmetry?

- An elegant solution is the Peccei & Quinn global chiral U(1) symmetry *(1977)* that if spontaneously broken ⇒ Axions *(Weinberg, Wilczek, 1978)*

- “Massive” Axions i.e. O(100 keV) or 1.8 MeV were excluded after extensive search in nuclear transition, particle decays (1978-1987) ⇒ “Invisible” axion models in the range 10^{-6}-10^{-2} eV,

  i.e. **No longer only a HEP problem**…

“Small may also be Beautiful”

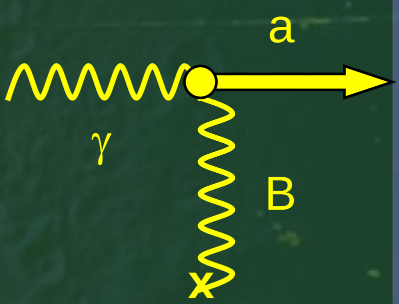
The 5 existing different approaches for the search of “invisible” Axions

- Microwave cavity experiments *(P. Sikivie, 1983)*
  - Resonant conversion of $axion \to \gamma$ in a High-Q cavity + B
- Optical and radio-telescope searches and more recently, with interferometric radio-telescope
- Solar axions:
  - as with telescope, search for thermally produced Axions via Primakoff process i.e. conversion $axion \to \gamma$ (ex. CAST)
- Photon Regeneration Experiment *(K. van Bibber et al. 1987)*
- Polarization Experiments *(L. Maiani et al. 1986)*

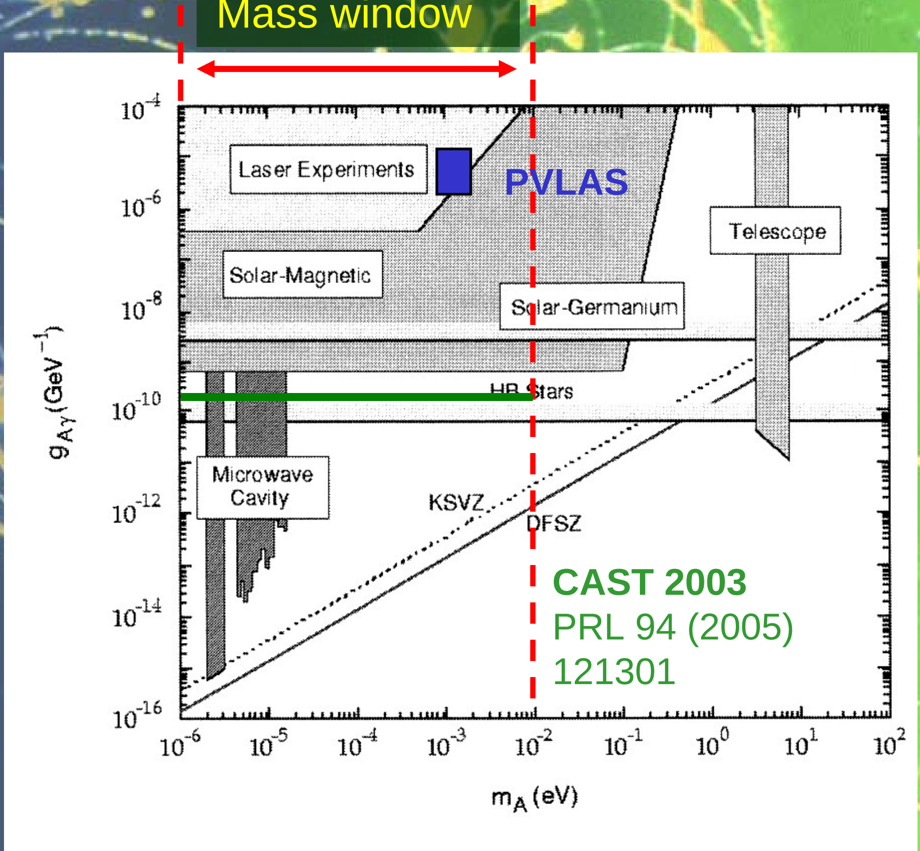
Our Proposal

Sensitivity of various Experiments

- Axions are weakly interacting particles with γ, e^- or Nucleus
- The expected strengths of the interaction are model dependant
- In our case, we are interested to the coupling of axions to 2 γ:
  - $g_{A\gamma} = 1/M$
  - m_A



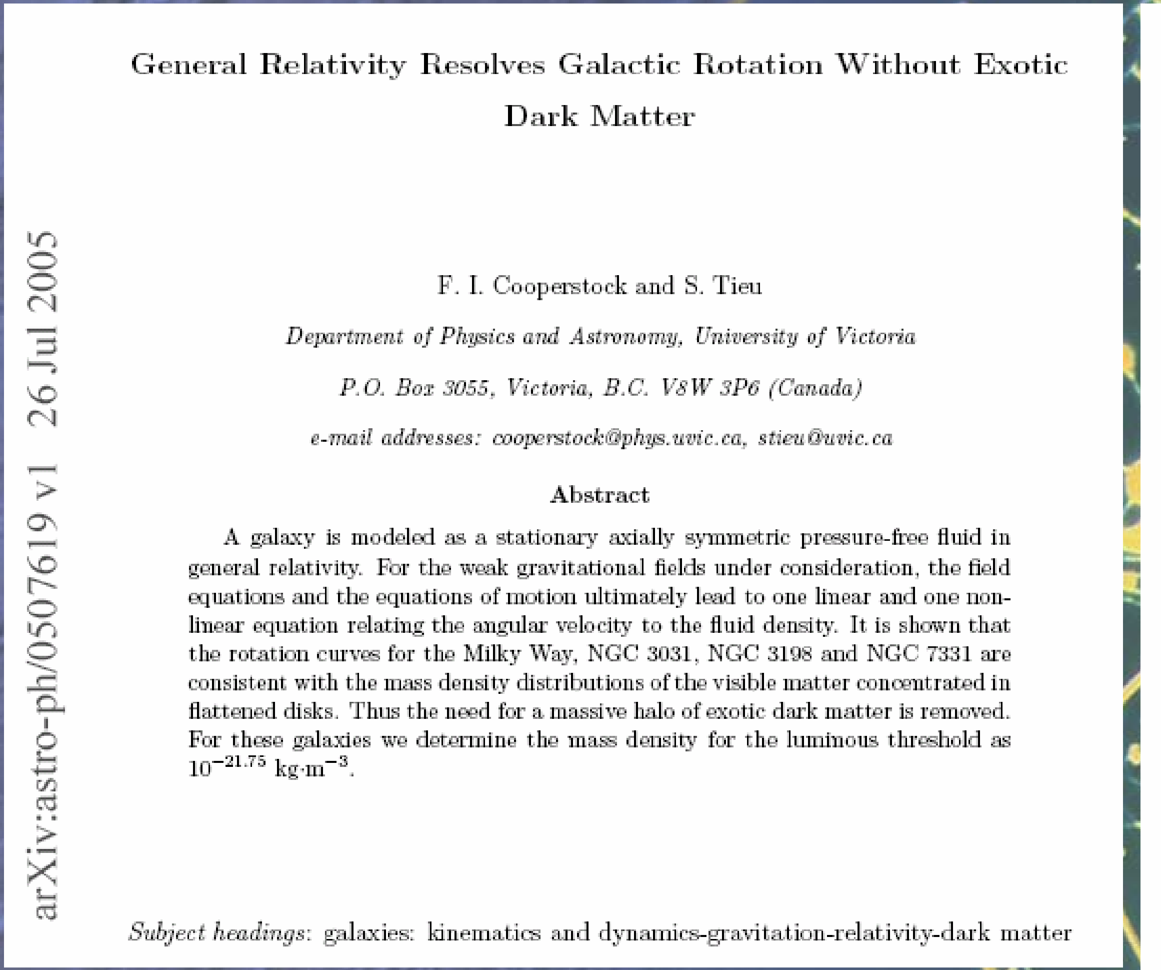
Invisible Axion Mass window



CAST 2003
PRL 94 (2005) 121301

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

Some News about Dark Matter,…



arXiv:astro-ph/0507619 v1 26 Jul 2005

General Relativity Resolves Galactic Rotation Without Exotic Dark Matter

F. I. Cooperstock and S. Tieu

Department of Physics and Astronomy, University of Victoria

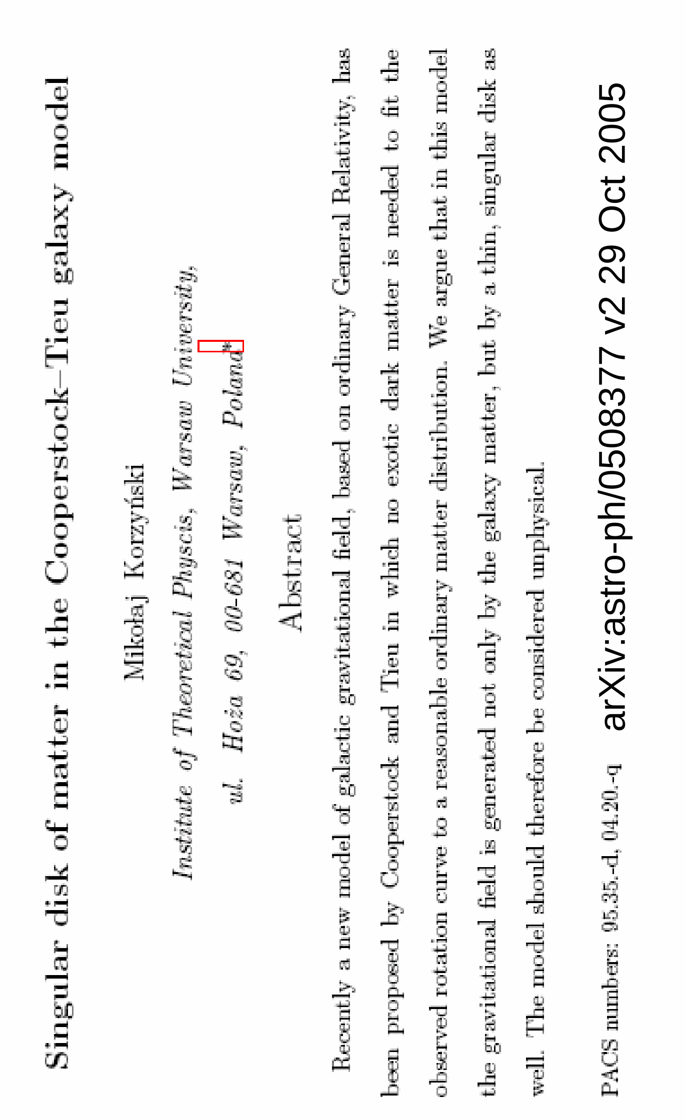
P.O. Box 3055, Victoria, B.C. V8W 3P6 (Canada)

e-mail addresses: cooperstock@phys.uvic.ca, stieu@uvic.ca

Abstract

A galaxy is modeled as a stationary axially symmetric pressure-free fluid in general relativity. For the weak gravitational fields under consideration, the field equations and the equations of motion ultimately lead to one linear and one non-linear equation relating the angular velocity to the fluid density. It is shown that the rotation curves for the Milky Way, NGC 3031, NGC 3198 and NGC 7331 are consistent with the mass density distributions of the visible matter concentrated in flattened disks. Thus the need for a massive halo of exotic dark matter is removed. For these galaxies we determine the mass density for the luminous threshold as $10^{-21.75}$ kg·m^{-3}.

Subject headings: galaxies: kinematics and dynamics-gravitation-relativity-dark matter



Singular disk of matter in the Cooperstock–Tieu galaxy model

Mikołaj Korzyński

Institute of Theoretical Physcis, Warsaw University,

*ul. Hoża 69, 00-681 Warsaw, Poland**

Abstract

Recently a new model of galactic gravitational field, based on ordinary General Relativity, has been proposed by Cooperstock and Tieu in which no exotic dark matter is needed to fit the observed rotation curve to a reasonable ordinary matter distribution. We argue that in this model the gravitational field is generated not only by the galaxy matter, but by a thin, singular disk as well. The model should therefore be considered unphysical.

PACS numbers: 95.35.-d, 04.20.-q

arXiv:astro-ph/0508377 v2 29 Oct 2005

What is new about the production of axions in the sun ? see the presentation of E. Masso

Advantages and Disadvantages of Purely Laboratory Experiments for Axion Search

- Advantages:
  - Experimental approach independent of cosmological assumptions concerning the Axion production or Axion content in the universe,
  - Broad band in mass,
  - Weakly-interacting light scalar particles can also be detected.
- Disadvantages:
  - A "bit short" for the sensitivity required to detect "expected" Axions,

    ⇒ Innovative approach required !

    Key points: optical detection, optical cavity and high-field magnet.

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

- Ideal integration are within a superconducting dipole magnet use in accelerator for HEP

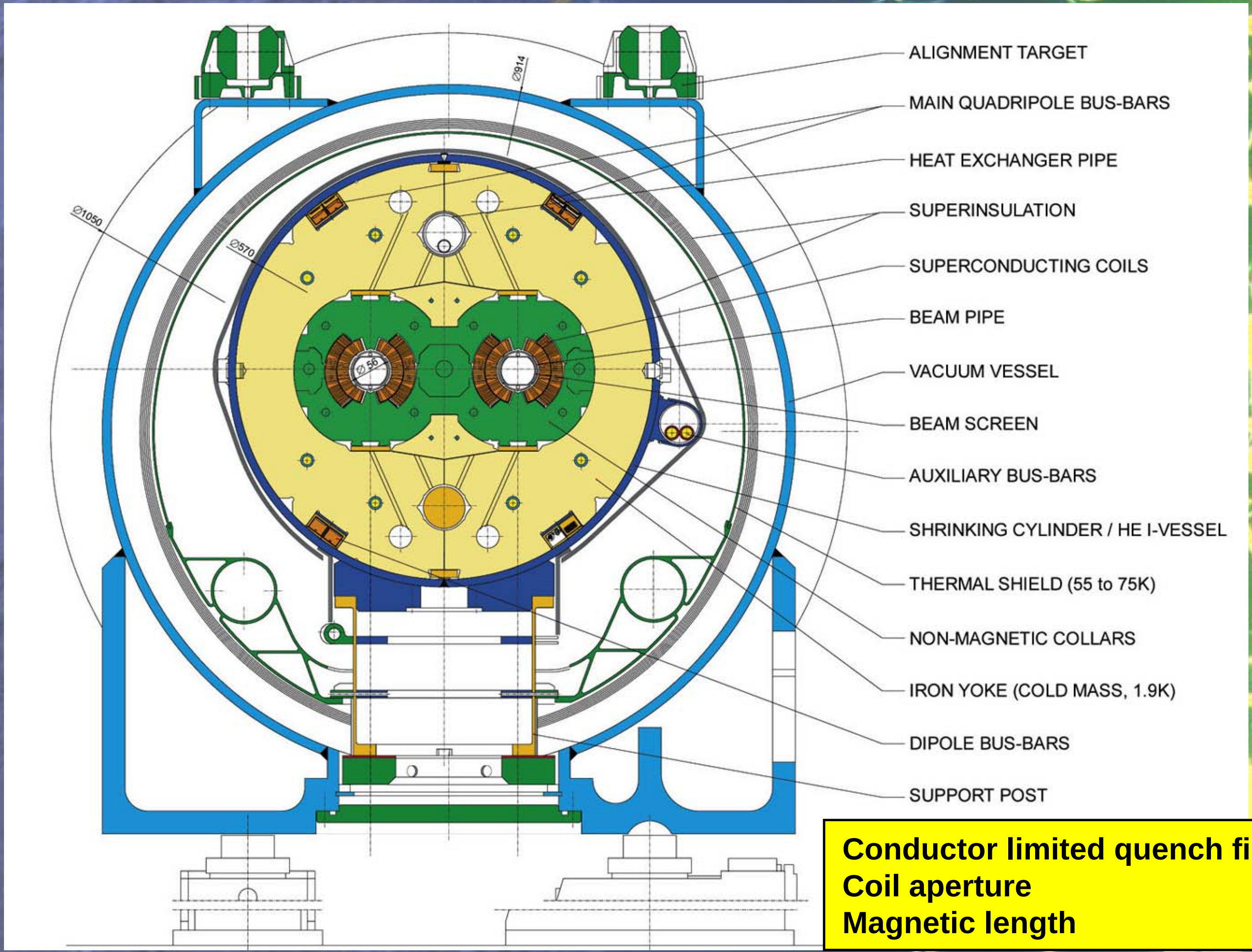
- With this respect, LHC superconducting dipoles *are within the most powerful at present:*
  - $B_{max} \approx 9.76$ T @ 1.9 K
  - Magnetic Length: 14.3 m

    i.e. $B^2 L \approx 1360\ T^2$ m

  $\Rightarrow$ *Big interest in using LHC decommissioned prototypes*

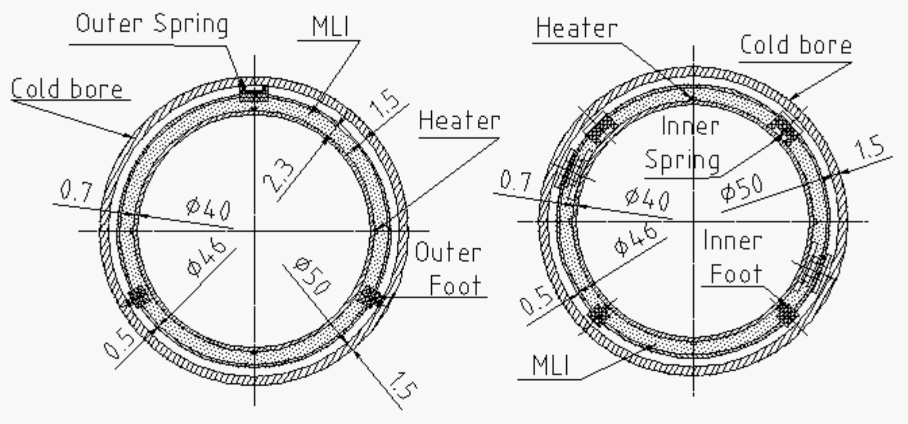
2-in-1 LHC dipole
With transverse B

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**

1st Step of the experiment: *use of warm bores i.e. anticryostats inserted inside cold bores*

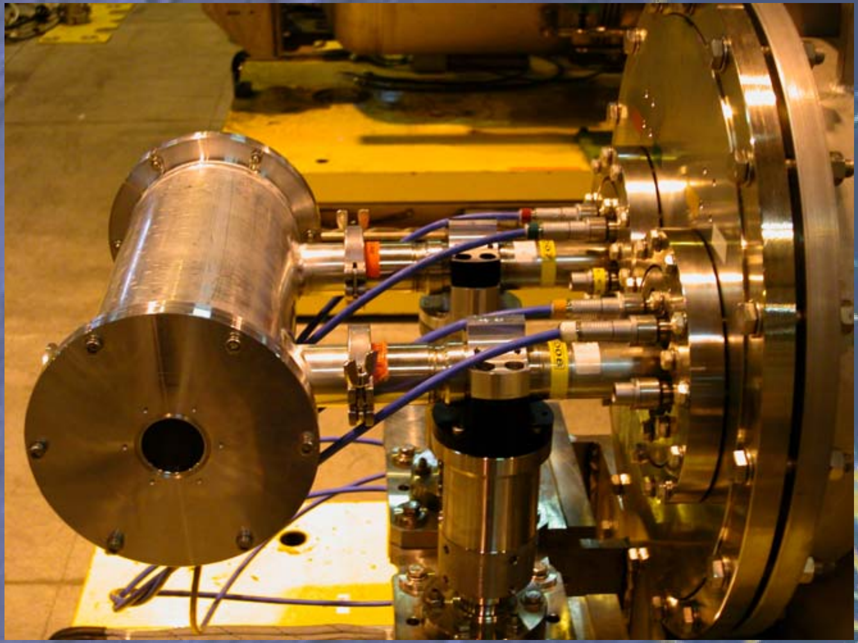


Specially designed for the cold tests of LHC cryomagnets,

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

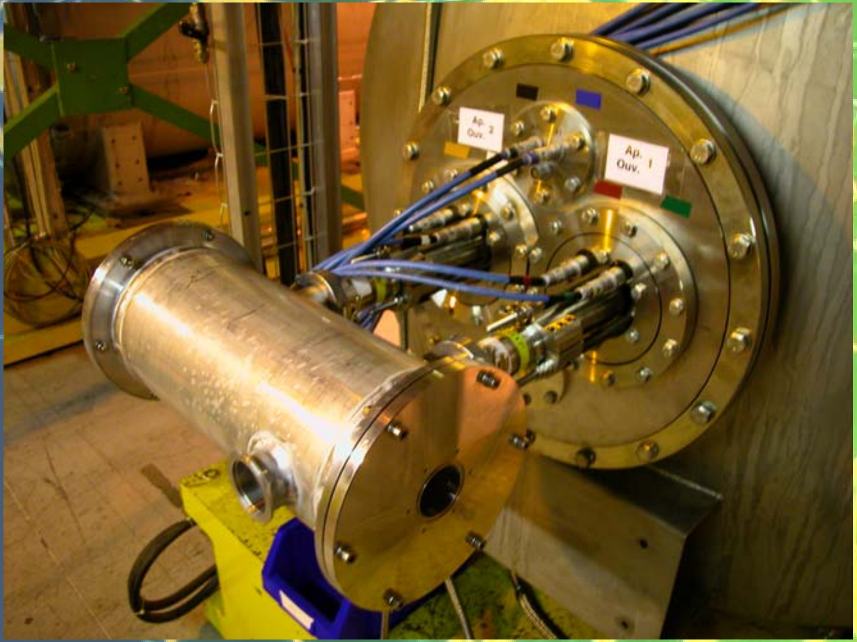


End-caps for housing the optical cavity;

Distance between the mirrors = 19.6 m
⇒ mirror radius for a confocal resonant optical cavity

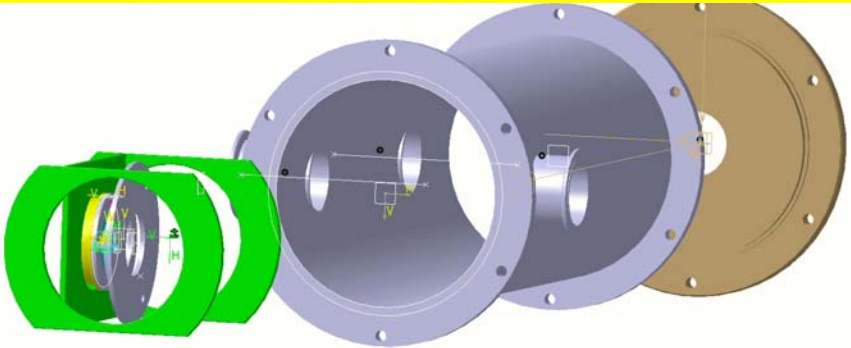
End-caps and connection to the anticryostats - real situation
(Ph-D M. Kràl)

Importance of the mechanical stability

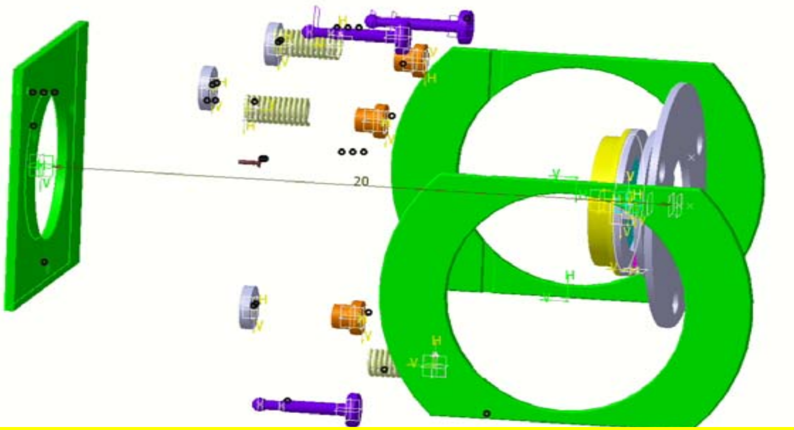


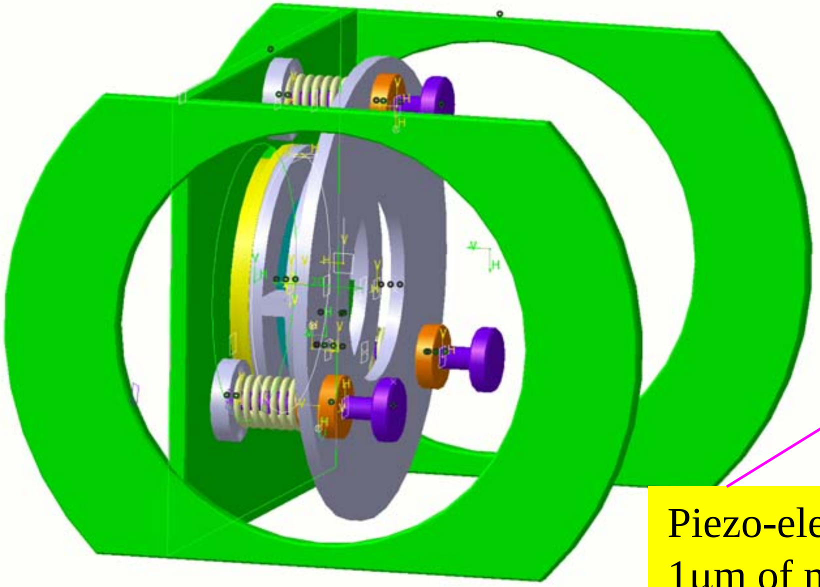
Mirror integration inside the end-caps with precise angular tuning mechanism (Ph-D M. Kràl)

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

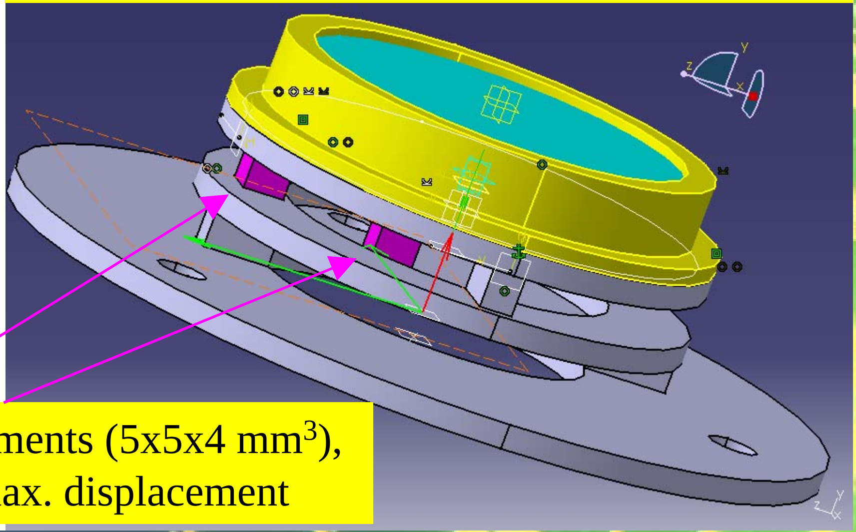


(Ph-D M. Kràl)



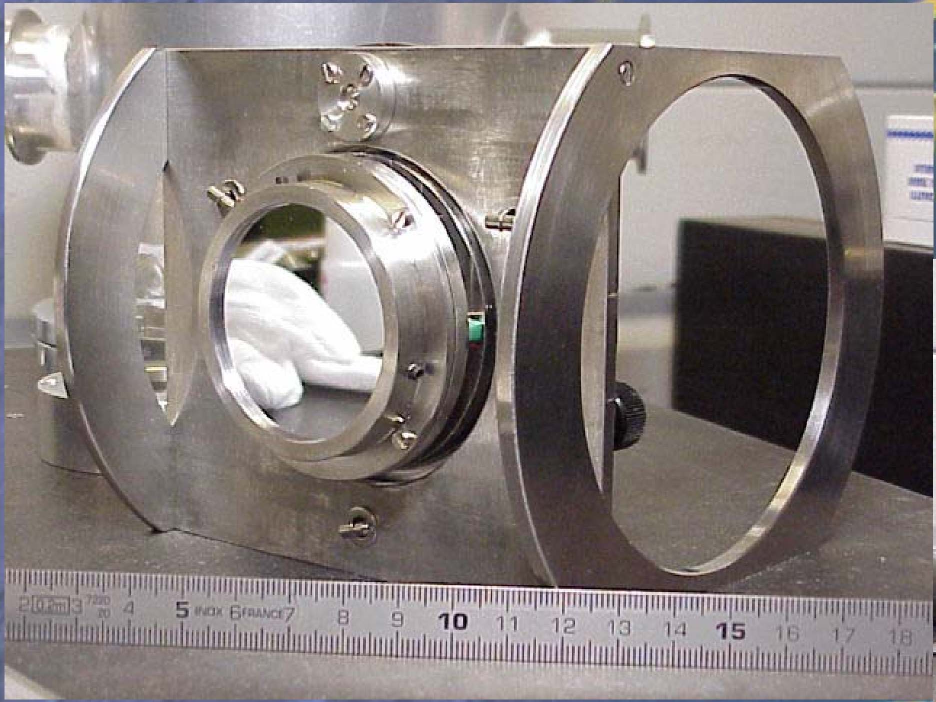


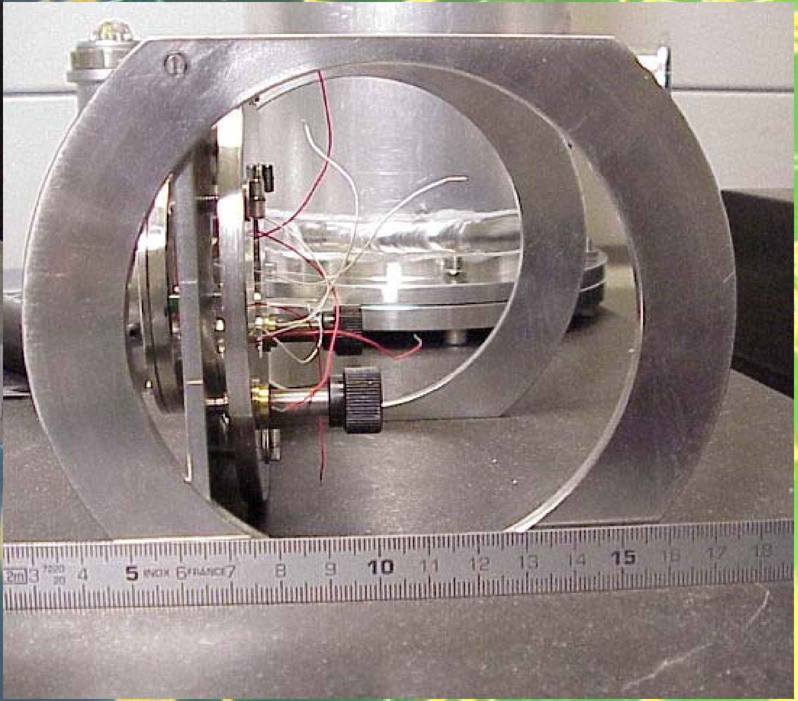
Effective diameter of mirrors is 38 mm



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

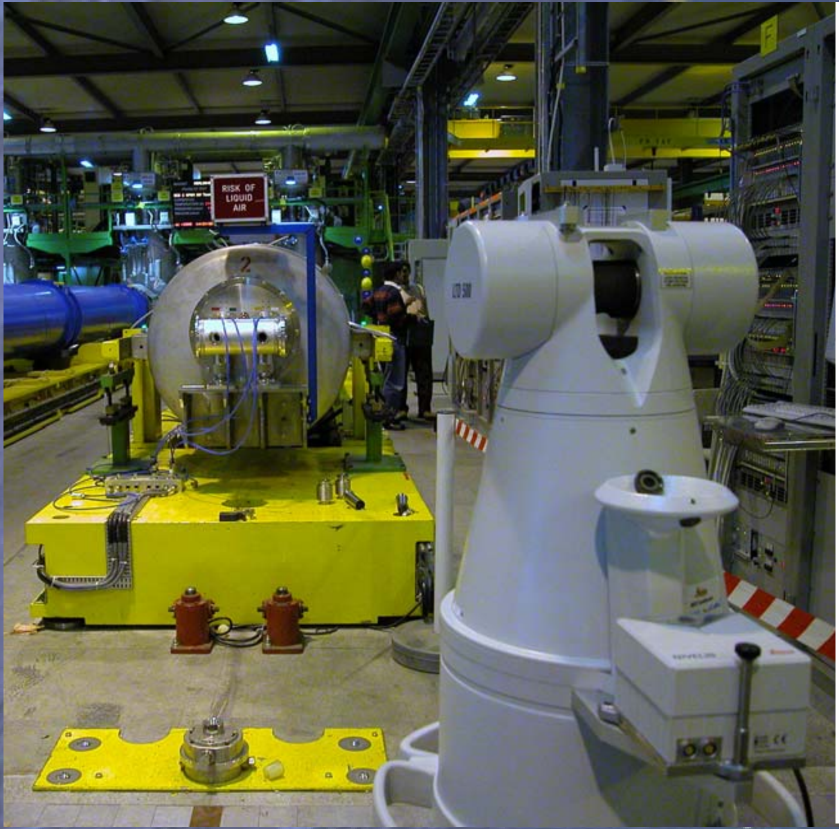
Realization of the 1st prototype of mirror support with precise angular tuning mechanism

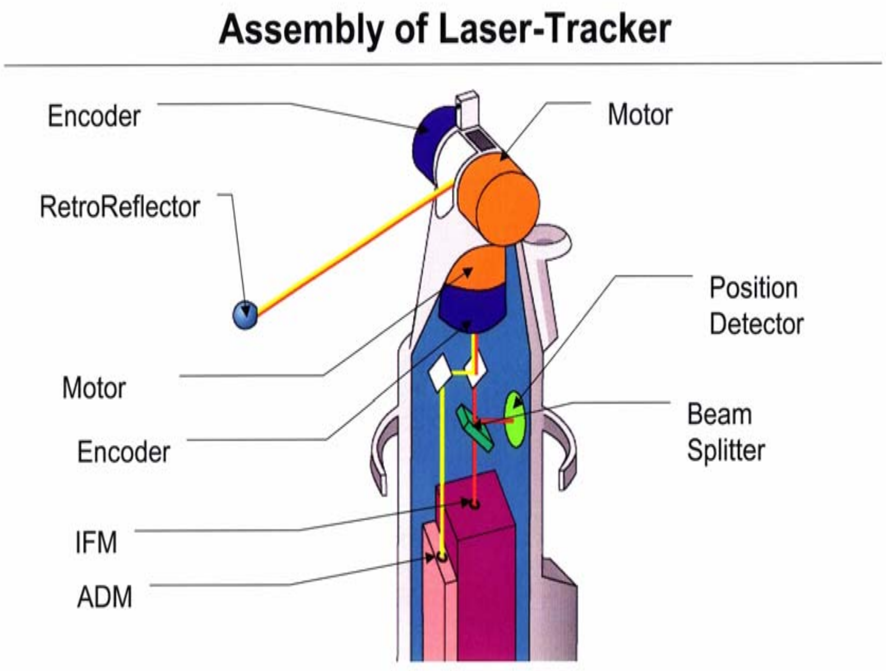




Ph-D M. Kràl

Mechanical vibration studies





Resolution ≈ 1 μm

Results: For magnet in operating conditions, eigen frequencies below 100 Hz, ~ gaussian distribution for vibration amplitudes of end caps with $\sigma_x \approx \sigma_y < 10\ \mu m$ and $\sigma_z \leq 1\ \mu m$;

⇒ Pound-Drever technique to lock the laser frequency with the resonant frequency of the cavity.

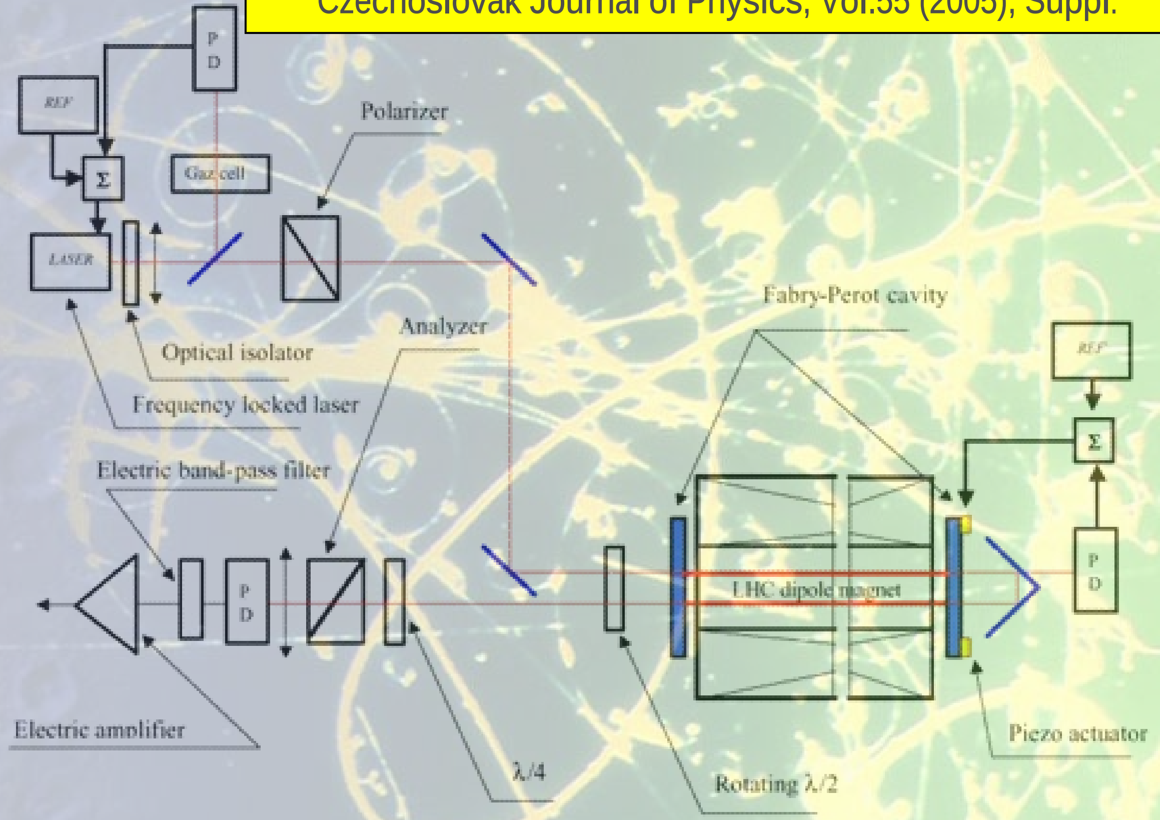
VMB measurements & Axion Search Experiment
Proposed optical scheme

- Axions ⇒ Change of the linear polarisation of a laser beam after propagation in the vacuum with B transverse:
  - Elliptical
  - “Pseudo”-rotation
- 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), Suppl.



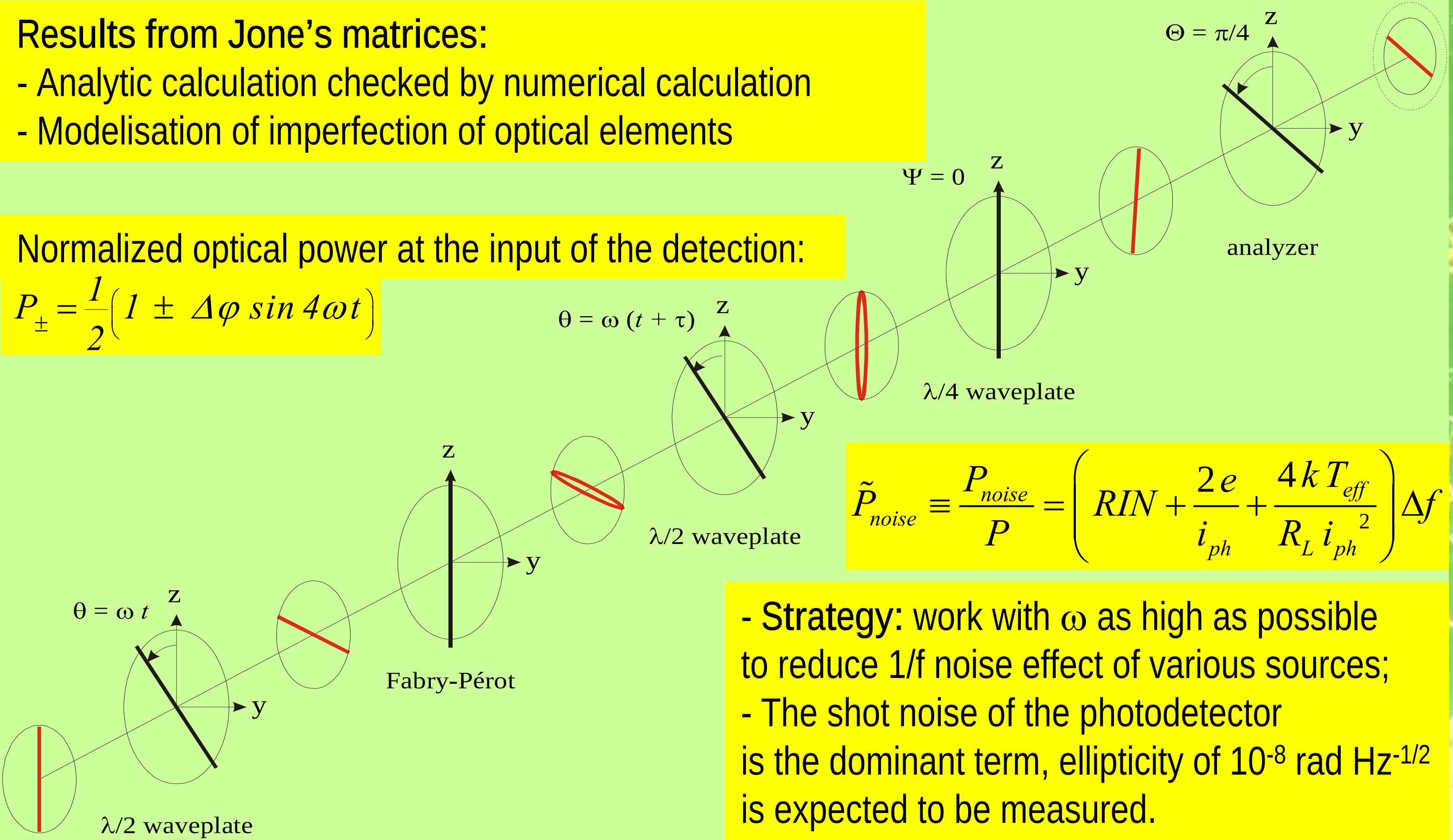
L. Maiani, R. Petronzio, and E. Zavattini, Phys. Lett. 175B (1986) 359

VMB measurements & Axion Search Experiment
Expected results

Results from Jone’s matrices:
- Analytic calculation checked by numerical calculation
- Modelisation of imperfection of optical elements

Normalized optical power at the input of the detection:

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



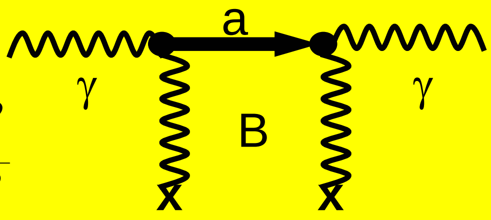
$$\tilde{P}_{noise} \equiv \frac{P_{noise}}{P} = \left(RIN + \frac{2e}{i_{ph}} + \frac{4kT_{eff}}{R_L\, i_{ph}^{2}} \right) \Delta f$$

- **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} rad $Hz^{-1/2}$ is expected to be measured.

Direct Axion Search Experiment

Photon Regeneration

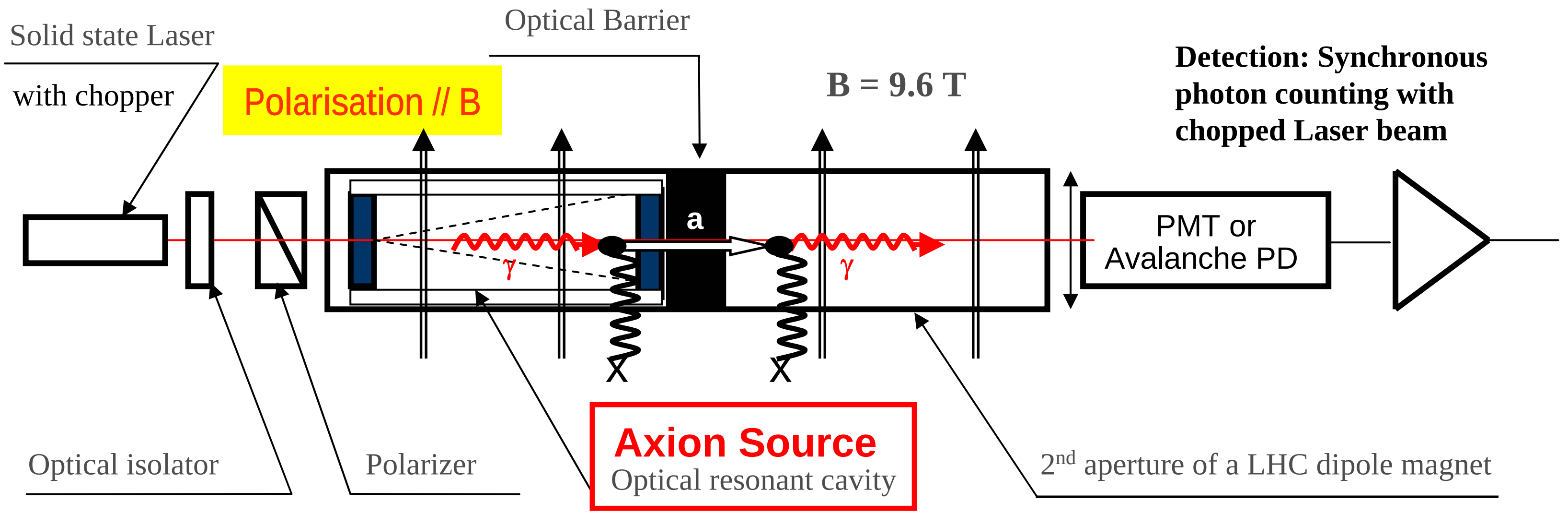
P. Sikivie, PRL 51 (1983) 11415



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

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

K. van Bibber et al. PRL 59 (1987) 759, concept of “a shining light thought the walls”



Solid state Laser with chopper

Optical Barrier

Polarisation // B

B = 9.6 T

Detection: Synchronous photon counting with chopped Laser beam

PMT or Avalanche PD

Optical isolator

Polarizer

Axion Source
Optical resonant cavity

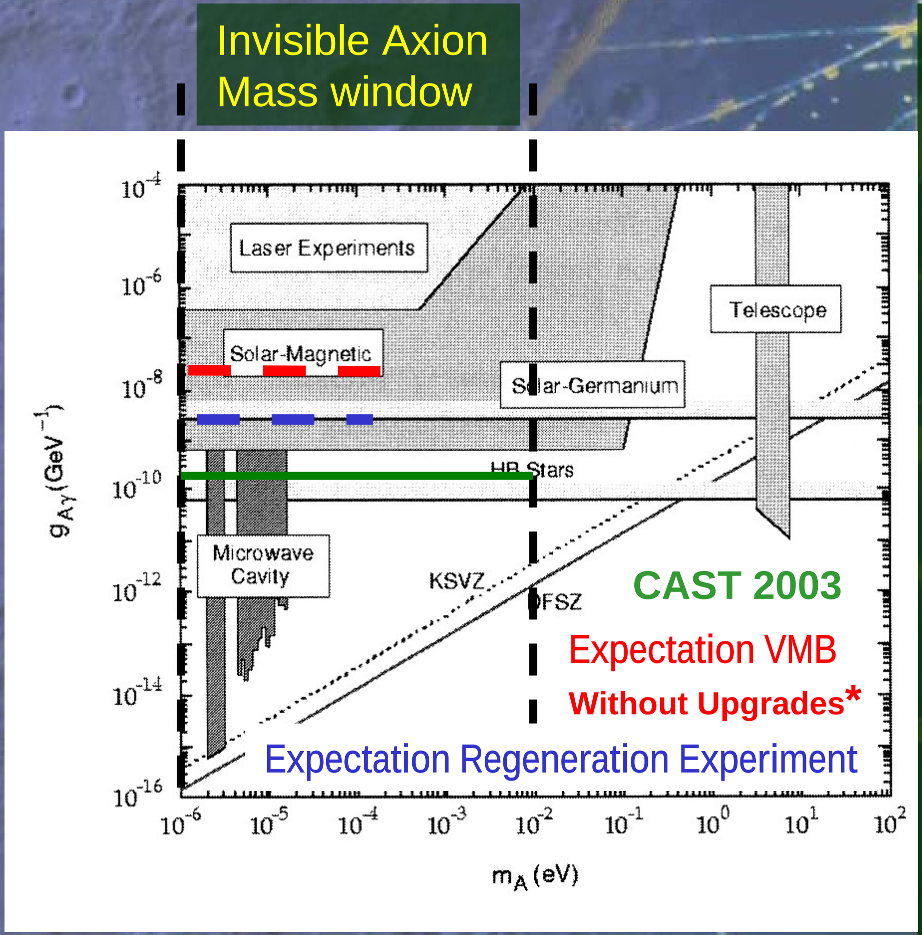
2nd aperture of a LHC dipole magnet

Nd-YAG laser: Power P = 10 - 1000 W
λ = 1064 nm
Optical cavity: F = 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

Axion Search Experiments

Expected results (without upgrades)



- To Confirm the reproducibility of PVLAS results
- To be fully complementary to other type of Axion search experiments:

  A Break through in optical detection technique is required, electro-modulator in MHz range

  &

  Upgrades for the experiments must be anticipated at the earlier stage.

*P. Pugnat, L. Duvillaret, M. Finger, M. Kral , A. Siemko, J. Zicha, Czechoslovak Journal of Physics, Vol.55 (2005), Suppl.

SMTP at CERN will be available when all LHC superconducting magnets will be tested (End of 2006)

The Experiment in the “Time-Space”: Possible Upgrades & Strategy

- Short term - phase-1 :
  - Beginning of 2007: installation at CERN of a LHC prototype dipole for both experiments
    - Start with 1 then 2 optical cavities,
    - 1st version of the optical detection for the VMB (1-50 kHz) + warm bores (P down to ~10^{-8} torr ⇒ parasitic Cotton-Mouton signal coming from residual gas expected below QED prediction);
    - 1st version of the optical detection for the photon regeneration experiment.
  - 1st results expected before the end of 2008.
- Medium term with several possible upgrades - phase-2:
  - VMB:
    - 2nd version of the optical detection with electro-optical modulator (MHz range); in //, R&D to go beyond the sensitivity barrier of 10^{-8} rad $\mathrm{Hz}^{-1/2}$;
    - Increase of the sensitivity of the VMB experiment by improving the vacuum ⇒ solution with cold bores.
  - Photon Regeneration
    - Connection of a second LHC dipole prototype & more;
    - 2nd version of the optical detection with a cold avalanche photodiode;
    - Use of gas to extend the coherence & improve the *axion* → *photon* conversion.

Conclusions 1/2

- The reuse of technology developed at CERN for the LHC project allows the construction of powerful experiments based on optical techniques
  - *to test the CPT symmetry & for the 1st time the QED prediction of the Vacuum Magnetic Birefringence,*

    and

    The physics is in practice guaranteed
  - *to perform direct & indirect search of light scalar or pseudo-scalar particles such as axions that couple to photons.*

    At minimum, improvement by x 10-100 of limits obtained by laser experiment for axion mass & di-photon coupling constant

Conclusions 2/2

In addition to fundamental scientific interests

- This project is expected to impact on optical metrology techniques as well as for the next generation of accelerator technology.

- The Cotton-Mouton effect of gases or liquids can be used to measure the integrated transfer function of accelerator magnets (dipoles & quadrupoles); this optical technique seems particularly suitable for small aperture magnets or/and pulsed type accelerator magnets such as the ones foreseen for
  - The FAIR project at GSI (near Frankfurt)
  - The superconducting SPS at CERN (LHC upgrade)

    see http://care-hhh.web.cern.ch/CARE-HHH/
  - And, The Technology Transfer …

More information

- 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
- 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
- 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/