Miroslav Sulc

on behalf of OSQAR collaboration

LASER BASED EXPERIMENTS OSQAR

OSQAR

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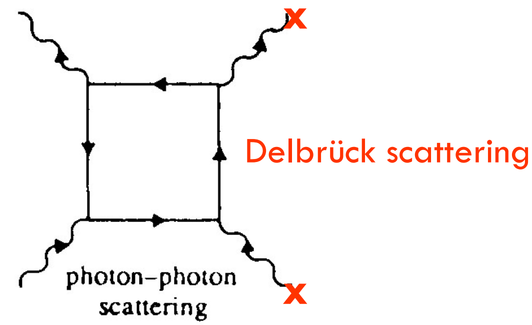
Outline

- Scientific Motivations
- OSQAR experiments
  - LHC magnets
  - Photon regeneration effect
  - Data analysis
  - Vacuum Magnetic Birefringence
  - Cavities preparation
- OSQAR Contributions to International Conferences
- Conclusion
- Perspectives

Scientific Motivations in a Nutshell

(P. Pugnat)

- **To measure for the 1st time the QED Vacuum Magnetic Birefringence** *(Heisenberg & Euler, Weisskopf, 1936) i.e. the vacuum magnetic "anomaly" of the refraction index* "*n-1*" ~ 10^{-22} in 9.5 T



- **To explore the Physics at the Low Energy Frontier** (sub-eV)
  - **Axion** & **Axion Like Particles** *i.e. solution to the strong CP problem (Weinberg, Wilczek, 1978) & Non-SUSY Dark Matter candidates (Abbott & Sikivie; Preskill, Wise & Wilczek, 1983)*
  - **Paraphotons** *(Georgi, Glashow & Ginsparg, 1983)*, **Milli-charged Fermions**
  - **Chameleons** *(Khoury & Weltman, 2003)*
  - ***The Unknown …*** *"Exploring a new territory with a precision instrument is the key to discovery"*, Prof. S.C.C. Ting
- **A New Way of doing Particle Physics** based on Laser beam(s)
- **New very precise and sensitive optical method needed - big challenge**

Theoretical Developments at the Warsaw University

- Detailed arguments and calculations have been presented by Adam Latosinski, Krzysztof A. Meissner and Hermann Nicolai to support their recent proposal that identifies the axion arising in the solution of the strong CP problem, with the Majoron *i.e.* the (pseudo-) Goldstone boson of spontaneously broken lepton number symmetry
- The axionic couplings are found to be fully computable in terms of known SM parameters and the Majorana mass scales. The determination of these couplings is presented involving certain three-loop diagrams, with a UV finite neutrino triangle taking over the role of the usual triangle anomaly.

A. Latosinski, K. A. Meissner, and H. Nicolai, *"Axions without Peccei-Quinn Symmetry"*, http://arxiv.org/abs/1010.5417
A. Latosinski, K. A. Meissner, and H. Nicolai, *"Neutrino Mixing and the Axion-Gluon Vertex"*, http://arxiv.org/abs/1203.3886

OSQAR

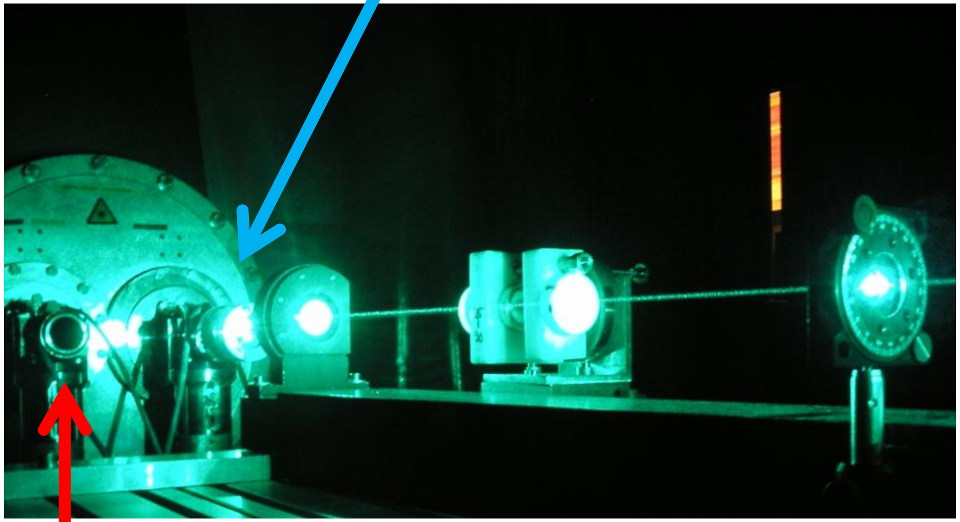
Optical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration

- situated at CERN, magnet test hall SM 18
- purely laboratory laser-based experiment for search of axions and axion-like particles
- it focuses on precision measurements of the magnetic properties of the quantum vacuum

OSQAR experiments

- it combines the simultaneous use of high magnetic field with laser beams in **two** distinct experiments
- two state-of-the-art superconducting decommissioned LHC magnets at CERN with double apertures, 9 T over 2 x 14.3 m

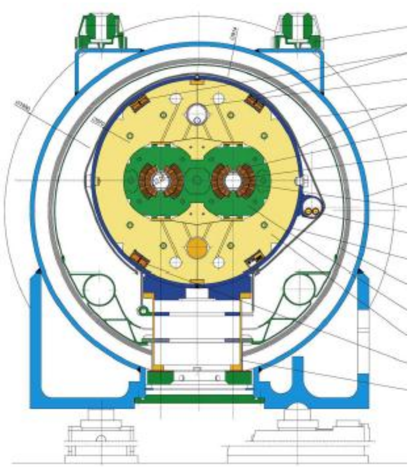
1.Aperture
Photon Regeneration Experiment



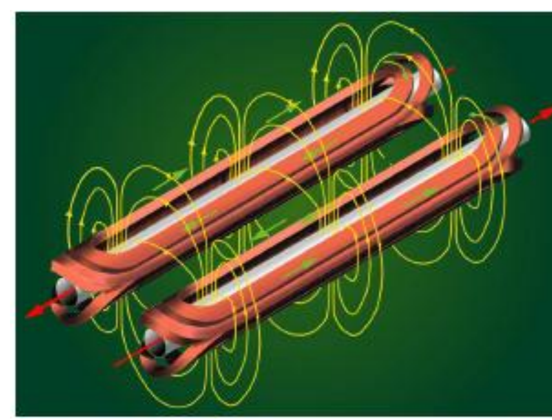
2. Aperture
Vacuum Magnetic Birefringence

LHC magnets

- Standard spare magnets for LHC
- Cooling (1.9 K) and vacuum facilities at CERN SM18 magnet testing hall
- Approximately 6-8 weeks per year for OSQAR experiment
- Absolute priority of LHC experiment



- Magnetic field of LHC dipole 9.5 T
- Effective length 14.3 m
- Filed is perpendicular to the 2 apertures



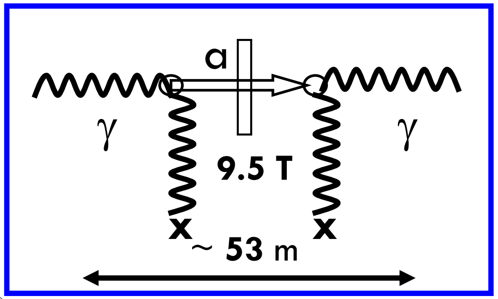
VMB Measurements : Unique opportunity with LHC dipole(s)

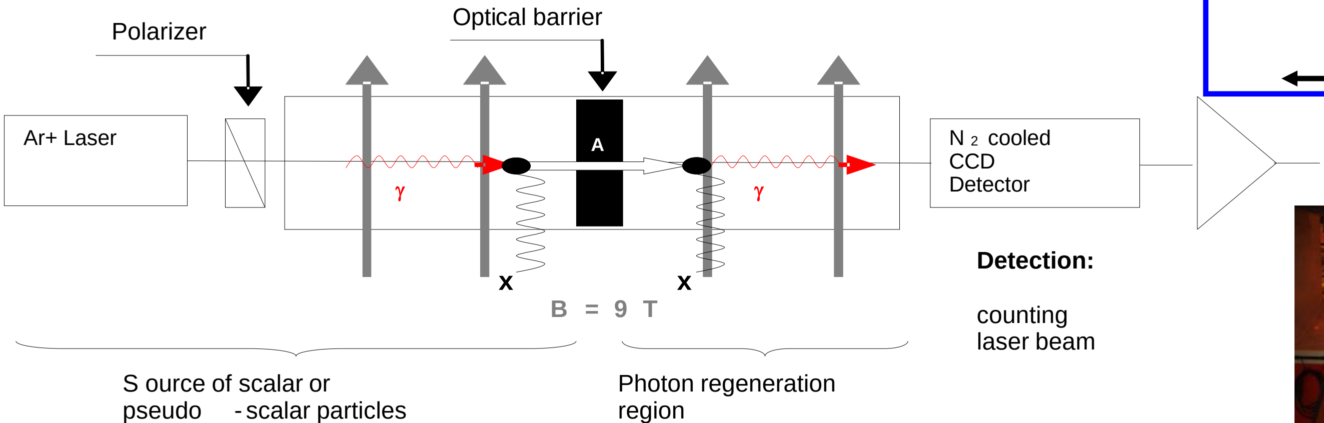
Experiment	**BFRT**	**PVLAS**	**BMV**	**OSQAR**
Status	Terminated	Achieved	Achieved/ Phase-1/Phase-2	
λ (nm)	514.5	1064	1064	**632.8**
Finesse of the FP cavity	N ~250	10^5	$5.10^4/6.10^5/10^6$	**$10^3/10^5$ expected**
Sensitivity (rad/Hz$^{1/2}$)	4.10^{-10}	10^{-11}	$10^{-9}/10^{-10}$	**$10^{-13}/10^{-15}$**
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**

Also Q&A collaboration has reported in 2007 a sensitivity of $4{\cdot}10^{-11}$ rad/$\sqrt{\text{Hz}}$ with a cavity of finesse equal to 30 000 and a modulation frequency of 10 Hz

Photon regeneration effect

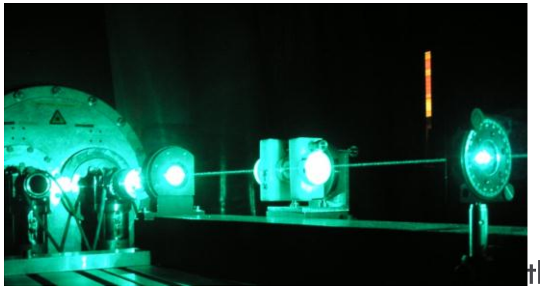
The photon regeneration effect is looked as a light shining through the wall





Two magnets separated by an optical barrier

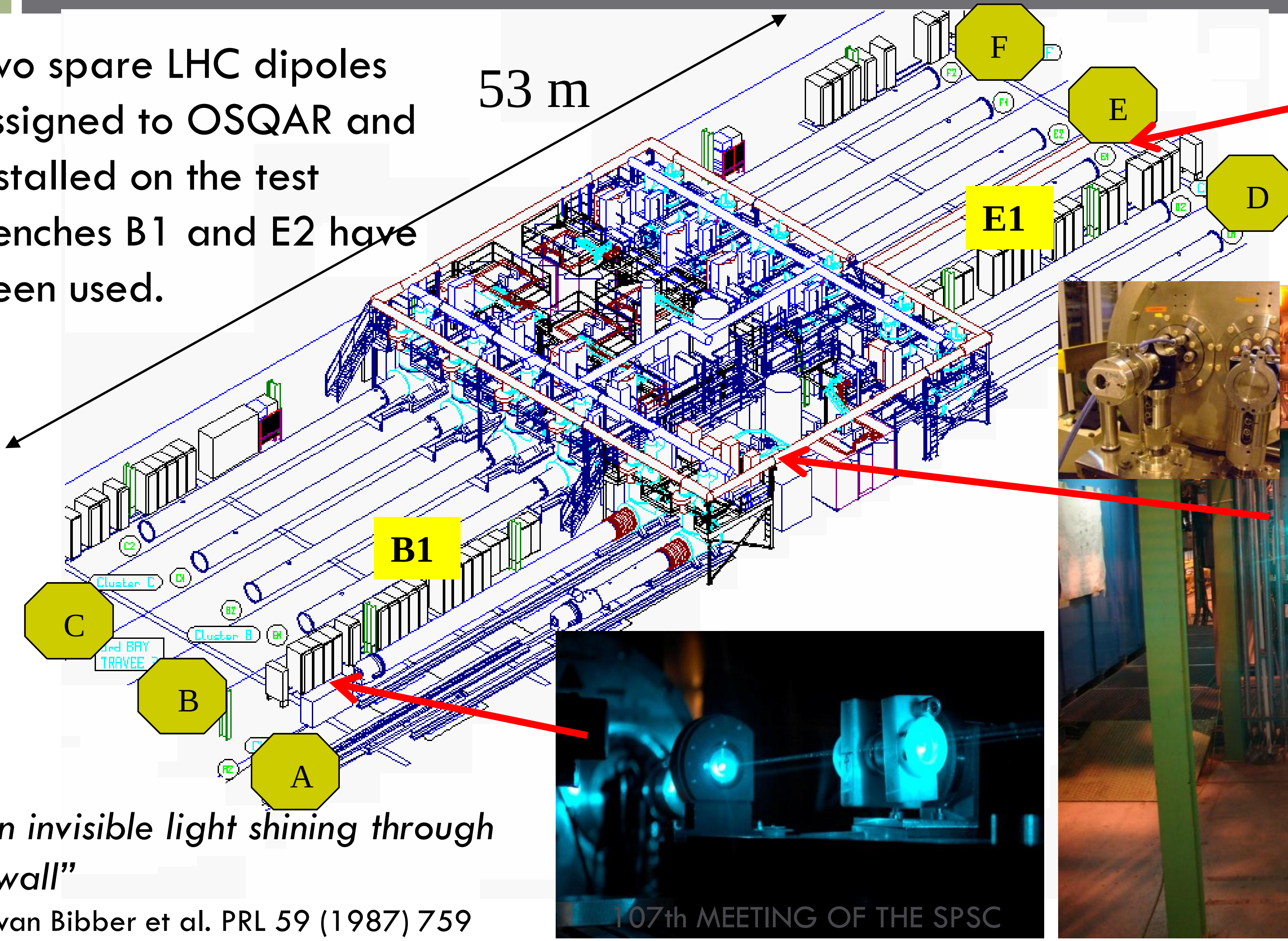
Argon laser is a source of 3-7 W beam

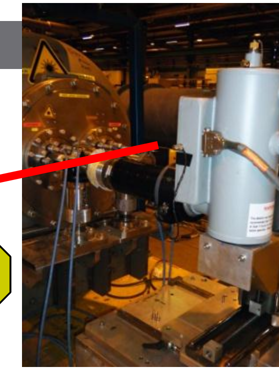


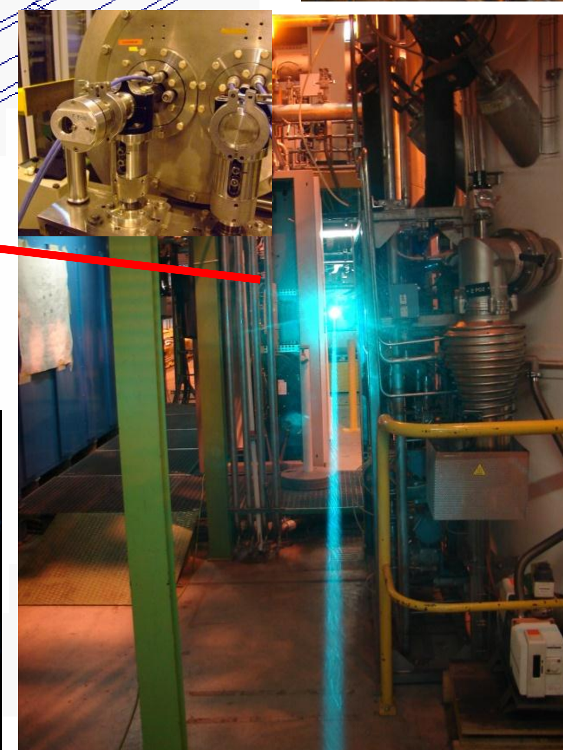
The CCD detector, cooled by liquid nitrogen, measures the laser beam profile by photon counting method

Photon Regeneration Experiment at CERN SM18

Two spare LHC dipoles assigned to OSQAR and installed on the test benches B1 and E2 have been used.



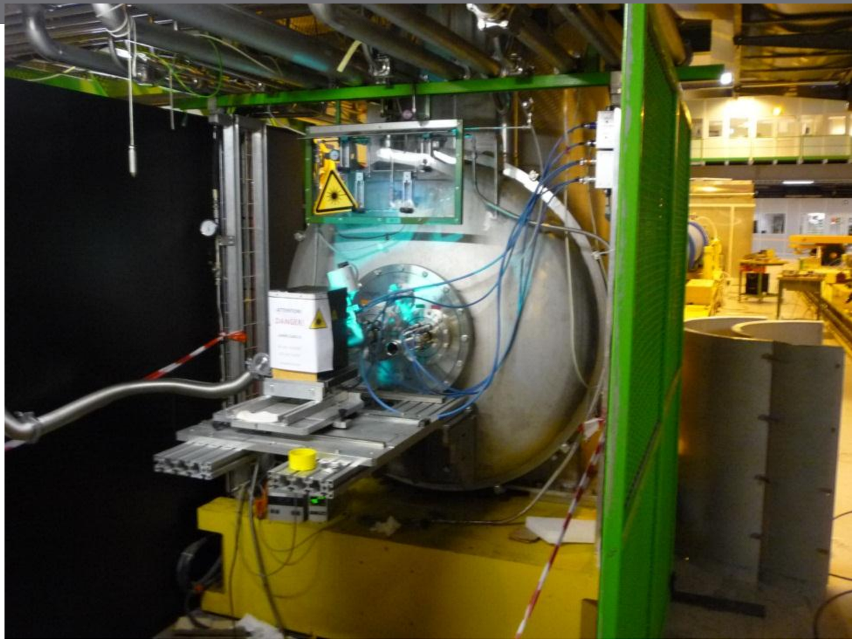




"An invisible light shining through a wall"

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

Light shining through the wall



Argon laser is a source of 3 W beam 488-514 nm, reduced optical power of the laser is limitation

- A typical experimental run started and ended with the beam alignment using absorptive filters to reduce the laser intensity below the saturation level of the LN2 cooled CCD detector
- Wall was inserted
  - The laser beam had a well defined linear polarization parallel to the magnetic field
  - This configuration was suitable for the search of pseudoscalar/axion particles.
  - For scalar particle, a half-wave plate oriented at 45° was inserted at the laser exit to align the polarization perpendicular to the magnetic field.

1-D CCD replaced by new 2-D CCD in 2011

LN/CCD-1024E/1

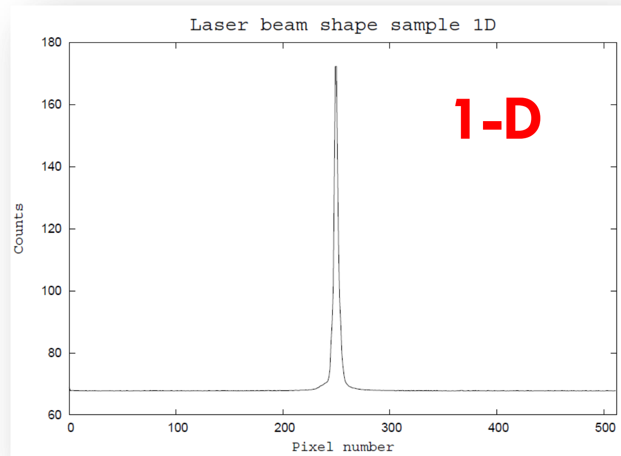
- Lowest read noise in the industry
- Lowest dark current using cryogenic cooling
- QE ~ 30 % at 488-514 nm

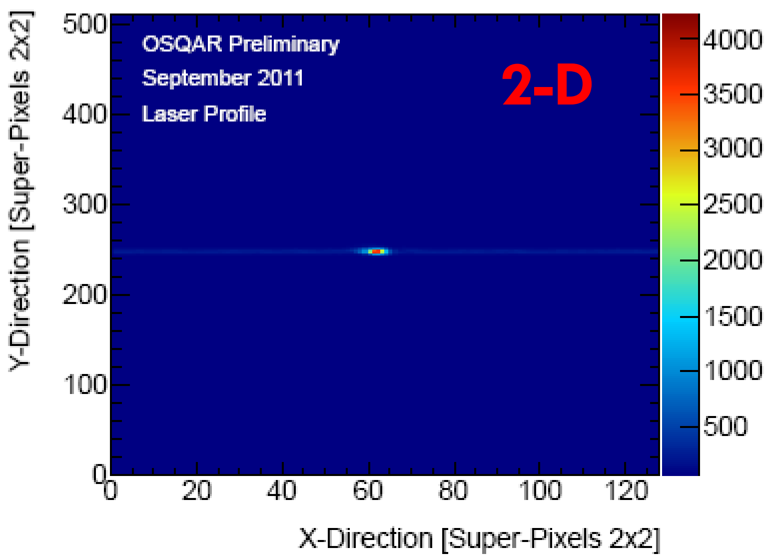
CCD chip, EEV 1024 × 256 square pixels of 26 μm, 26.6 x 6.7 mm

Spurious signals coming from cosmic rays

⇒ Optimisation of the CCD use 1D vs. 2D

⇒ Impact to 1 stripe x pixel



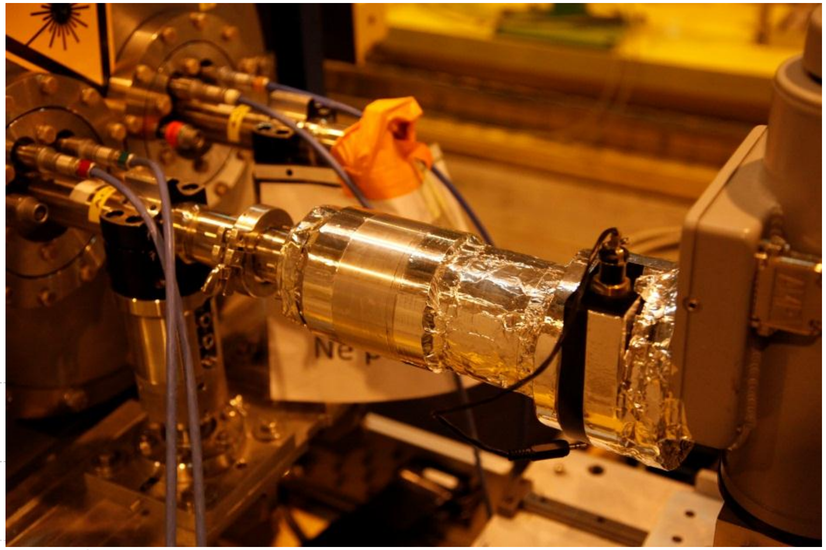


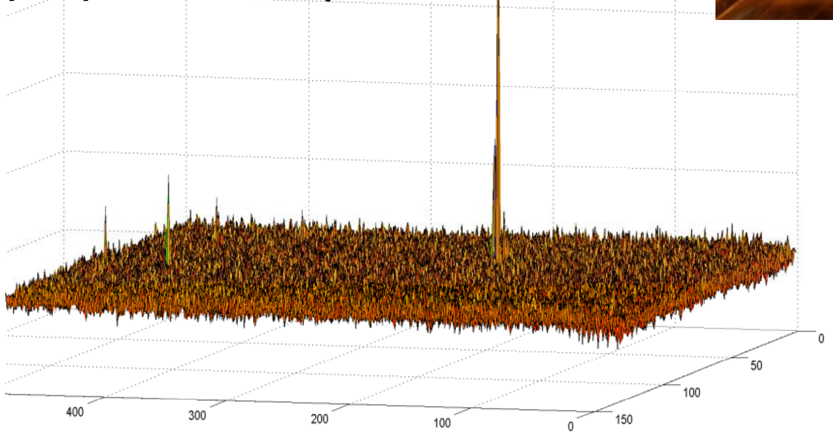
Run in 2012

- Both spare LHC dipoles used for OSQAR experiments have been affected to the LHC and removed from the SM18 test benches
- Two new dipoles have been selected, installed and cold tested
- Alignment tests with the laser beam have demonstrated that the beam pipe geometry of both these new dipoles is suitable for the OSQAR photon regeneration experiment, which is planned to restart in 2013.
- The laser beam has been successfully aligned within the dipole apertures and has reached the CCD detector located at a distance of 55 m
-

Adjustments to improve the experiment

The adjustable beam expander helps to receive appropriate intensity profile at the outer window of the second magnet. It has helped to focus the beam to very small spot on CCD, roughly to one double binning (2x2) superpixel. FWHM was about one superpixel ≈ 60 μm





- light- tightness mechanical connection of CCD camera to anticryostat window
- suppress light background to almost zero level

Laser cooling for photon regeneration

- The laser cooling system has been successfully improved with the installation and the commissioning of a dedicated pressurize unit for demineralized water in 2012
- This new unit allows overcoming the limitation of the total water flow in the SM18 hall

Problem & Solution

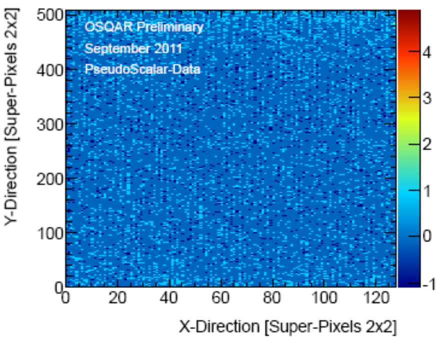
- Unfortunately output power of Ar laser was falling down to 0.3-1.1 W, so next data taking had no sense due a ten times longer time to receive the same statistics, as at previous run

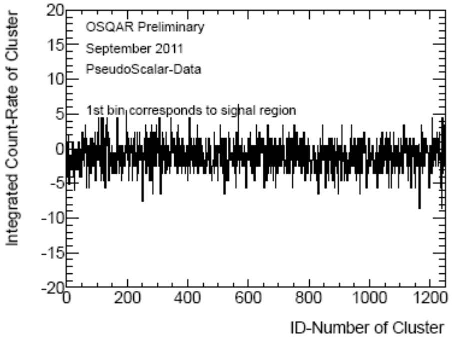
New laser needed

- Two solutions (ongoing)
  - Work in close collaboration with ALPS (discussions well advanced)
  - Rent a new laser from industry or institute

Data analysis from previous run

- The effective beam spot on the CCD was decreased by using an optical lens with a focal length of 100 mm
- It consists of 120 physical pixels, connected to 30 superpixels *(Due to double binning at the readout-step, i.e. summing the recorded entries of four neighbour pixels (2*2) into one superpixel, the spectra have 512*128 values each)*.
- It was measured that the signal shape of regenerated photons is close to the recorded laser spectrum when removing the barrier between the two LHC magnets.

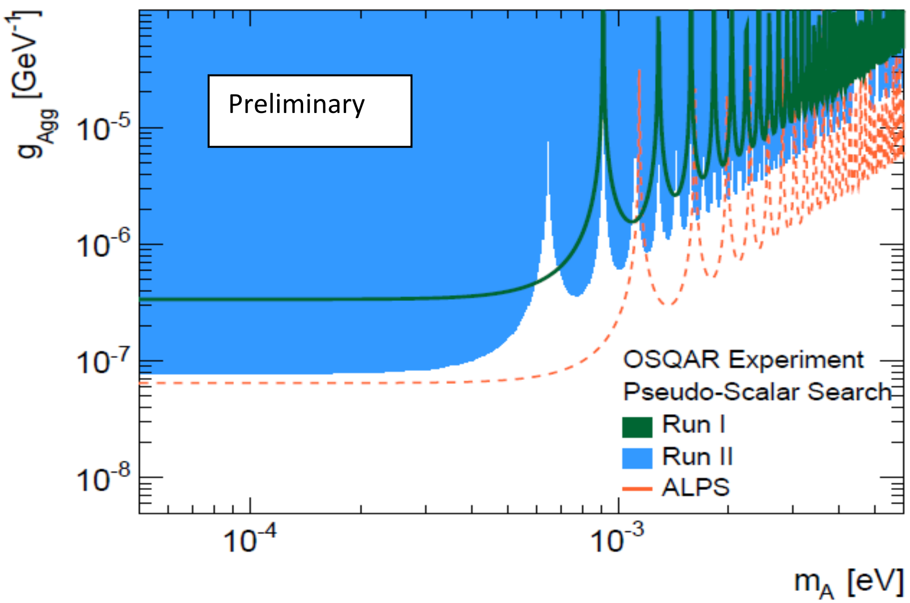




- Cosmic noise (high signal in area smaller than 4 superpixel in width) was removed
- Preliminary results with 2-D CCD leads to **improving of coupling constants exclusion limit 2-3x with respect to our published one**

Data analysis from 2011 in French Institutes (CNRS/UJF-Grenoble1) and at CERN

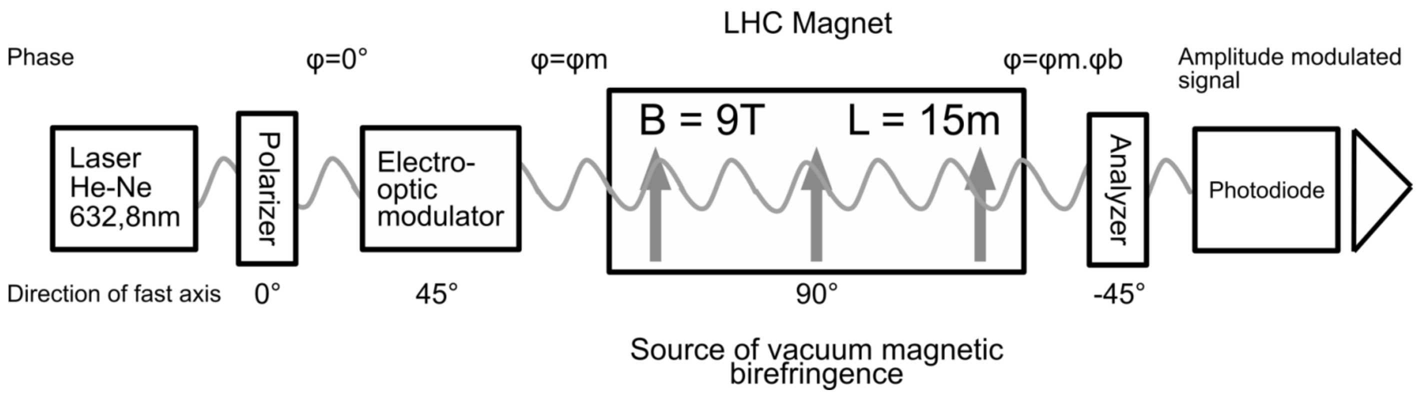
- Exclusion limits confirm the present reference results obtained by the ALPS collaboration
- The preliminary exclusion limits of coupling constants that can be deduced are $7.8 \cdot 10^{-8}$ GeV^{-1} for pseudo-scalar and scalar particle search in the massless limit



Preliminary exclusion limits for the search of new pseudo-scalar and scalar WISPs.

Vacuum Magnetic Birefringence Preparatory phases in Czech Institutes

- This method want to measure the ultrafine Vacuum Magnetic Birefringence
- The change of the light velocity in a background magnetic field is given by QED prediction
- expected value by QED is $\Delta n \approx 3.6\ 10^{-22}$ in 9.5 T field
- axion presence can partially modify this birefringence



Birefringence

- Anisotropy of refractive index, the birefringence δ shown by the vacuum (or gas) after the light has propagated along an optical path L is
- $\delta = 2\pi\, \Delta n\, (L/\lambda) \sin 2\vartheta$ and $\Delta n = C_{CM} \lambda_0 B^2$
- the initially linearly polarized light beam acquires in magnetic field ellipticity
- The predicted VMB effect is very weak so subsequent steps must be done
- VMB experiment starts from measurement magnetic-field-induced birefringence at gases, also known as a Cotton-Mouton, in air, in nitrogen, helium and finely in vacuum

VMB modulation detection techniques

- Noise limitation coming mostly from the shot noise of the photodetector. Signal must be modulated for Signal/Noise optimization.
- The modulation techniques are sensitive with dedicated filtering techniques

Variation of relative directions of electric and magnetic field is needed (or magnetic field pulses….)

Magnetic filed rotation

- Field Modulation at 1-1000 mHz (PVLAS …)

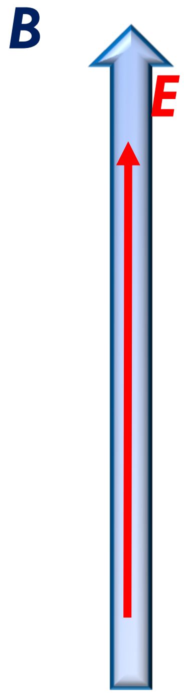
Electric filed rotation

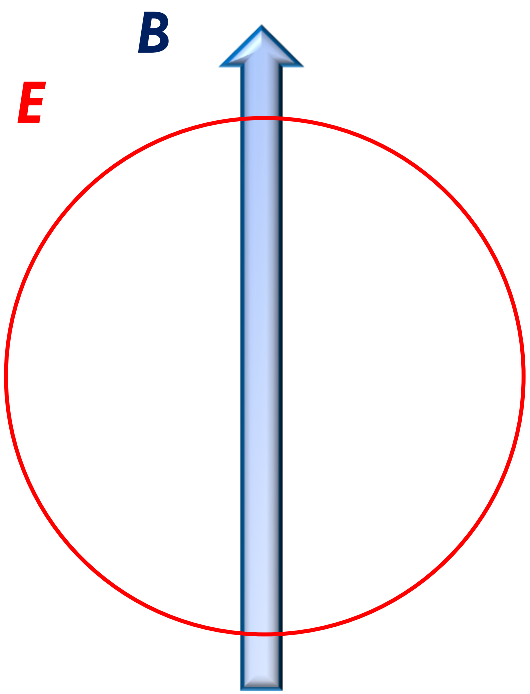
- Half-wave plate ~300 Hz (OSQAR 2007)
- Electro-optical modulator **EOM** ~ 30 MHz

Half-wave plate vs. EOM

Half-wave plate, turning around with ω, rotates electric field with 2 ω

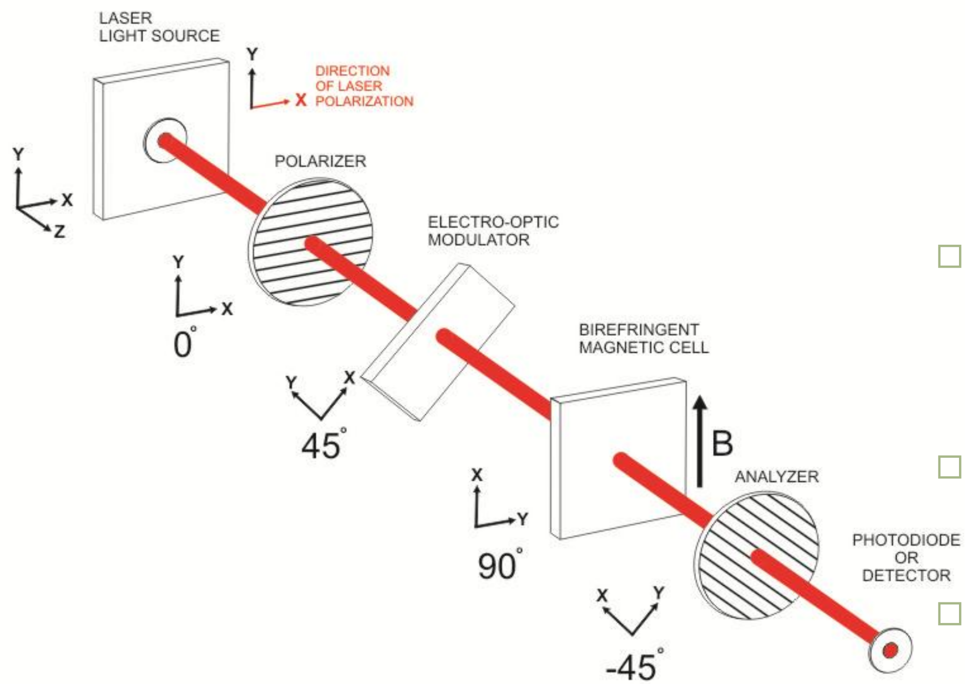
Electro-optical modulator for phase modulation





Standard frequency:
up to
300 Hz 30 MHz

VMB with EOM -experimental set-up



The best orientation of the each successive component in set up is at 45 degree relative to its previous element

- The set of possible configurations of polarized elements was investigated. Calculus with Jones symbolic matrixes was done.
- Laser beam increases degree of polarization by passing Glan-Thomson polarizer prism
- The beam then goes through the electro-optical modulator
- than propagate trough magnetic field where the light acquires an ellipticity from induced anisotropy
- The polarization of the beam is finally analyzed by an analyzer.

Detection in experiment with EOM

The detected intensity I has both constant and time-variable parts, described for amplitude of modulator induced phase shift $T_o > 0.1$ rad by equation

$$I = \frac{I_0}{2}(1 + \delta \sin T)$$

where δ is very small birefringence of the investigated sample, and *sin T* can be expressed by odd Bessel functions J

$$\sin T = 2 \sum_{m=odd} J_m(T_o) \sin m\omega t$$

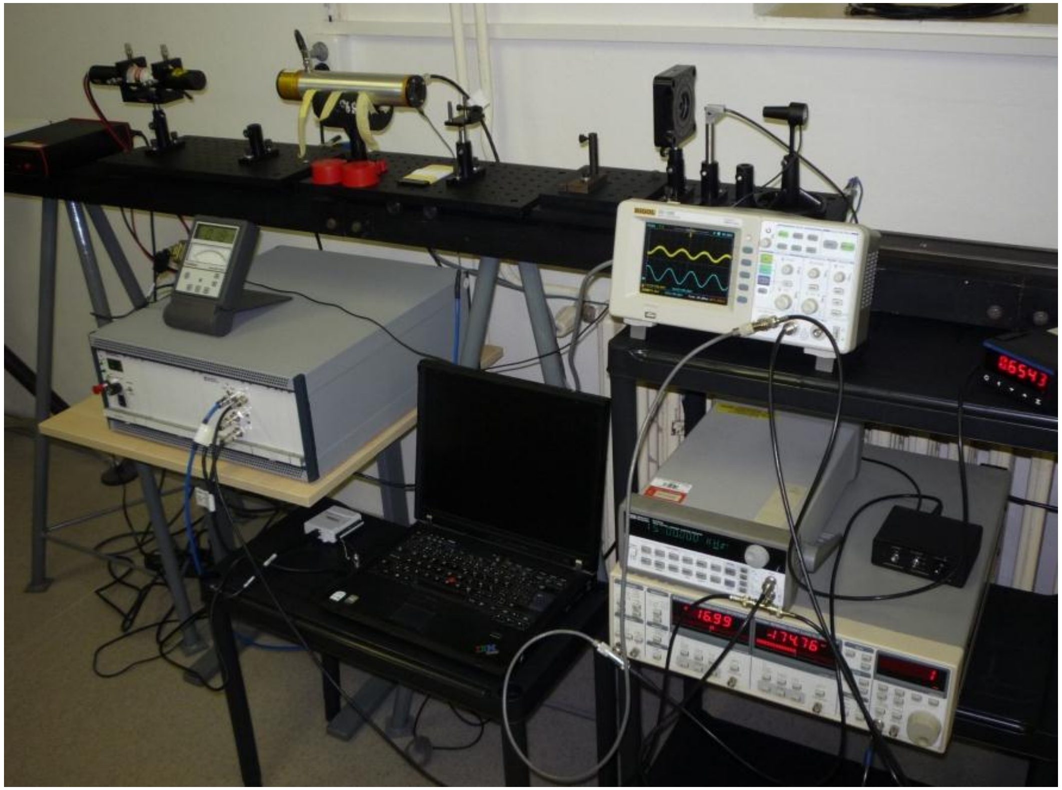
The measured sample birefringence is

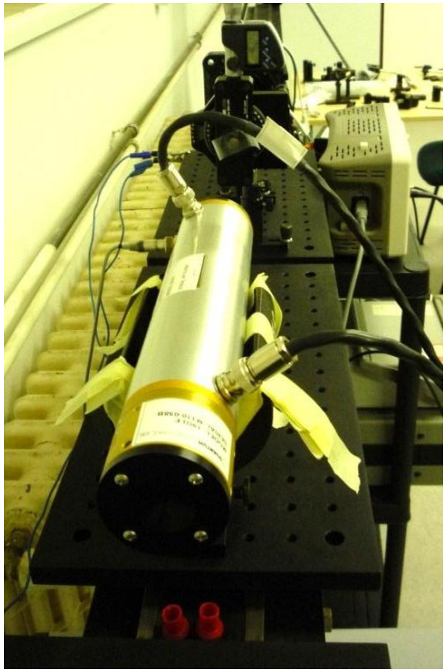
$$\delta = \frac{U_m}{\sqrt{2} U \, J_1}$$

where U is detected constant voltage and U_m is amplitude of alternating voltage of measured signal.

Laboratory test

New laboratory set-up was build in universities laboratories to solve stability problems



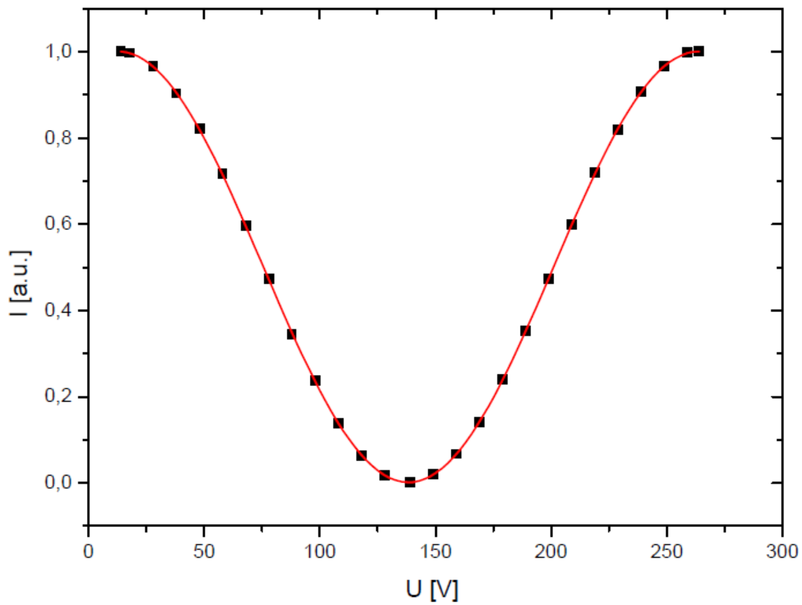


New 50 MHz electro-optical modulator from Quantum Technologies

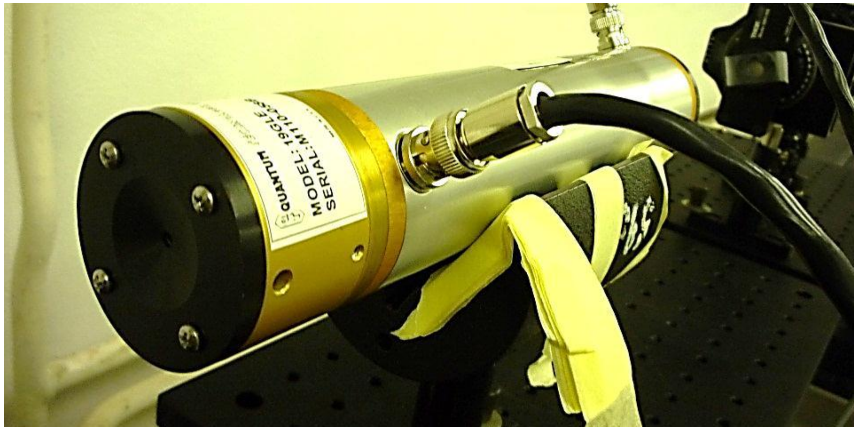
Electro-optical modulator

50 MHz electro-optical modulator from Quantum Technologies

- We check working condition, influence of environment
- We change our set-up from phase modulation to intensity modulation and intensity modulation was measured



Deep modulation 99,5 % , perfect sinusoidal signal (agreement 0.99998), half-wave voltage 125,57 V



Result

- modulator works properly
- it has very good stability

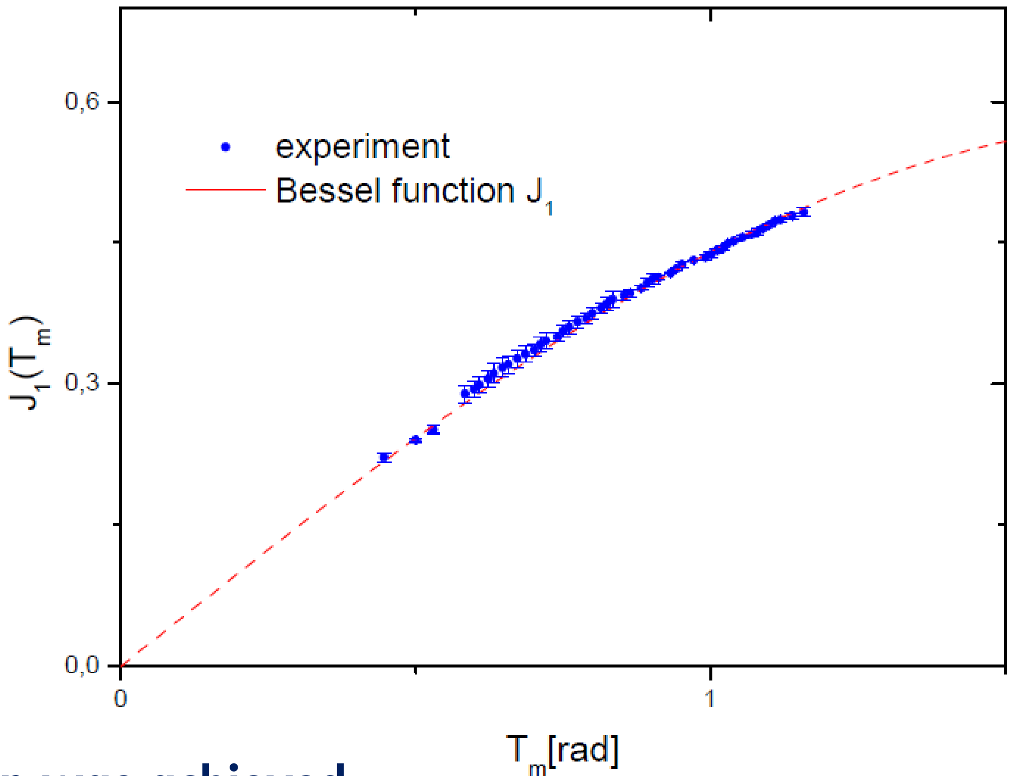
Calibration curve

The EO modulator was calibrated

Detected intensity *I* depends on amplitude of phase modulation T_0 (≈ applied voltage) by equation

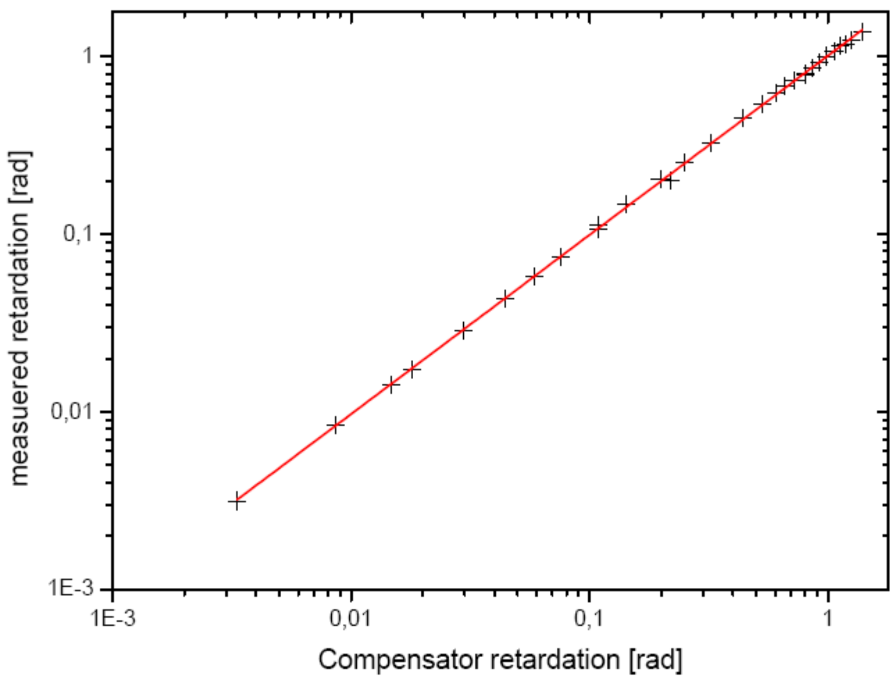
$$I = \frac{I_0}{2}(1 + \sin(T_o \sin \omega t))$$

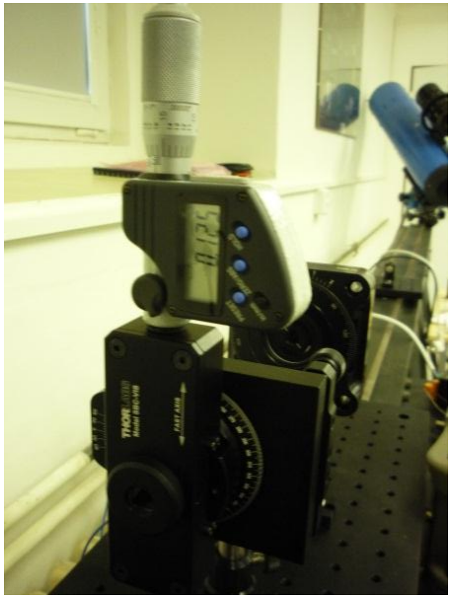
We measure the first harmonic signal, so correlation with Bessel functions J_1 was checked



- **Good agreement with prediction was achieved**
- Due a technical limits of our EOM (maximal applied voltage), it is not be able to work at the maximum of Bessel function (highest signal)
- We work at phase shift amplitude about **1 rad**

Method was checked by Soleil-Babinet compensator measurement





Perfect agreement between adjusted value at S-B compensator and measured values

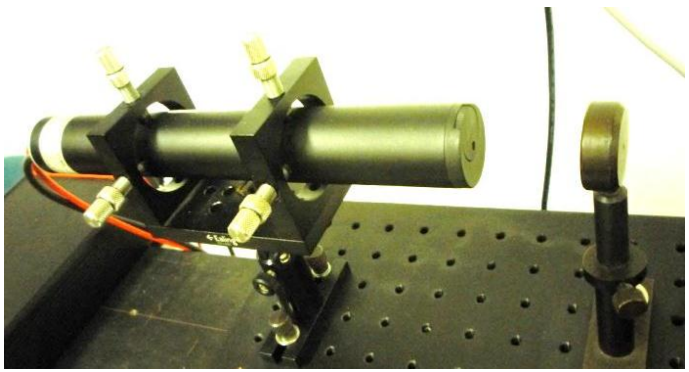
Pearson product-moment correlation coefficient 0.99998

expected sensitivity 10^{-4} rad, with accuracy ~5%

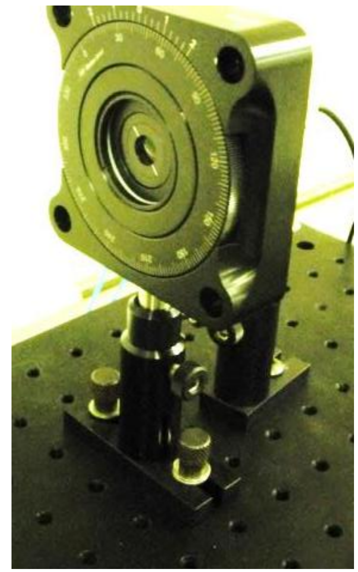
Run in CERN SM18 test hall, August -September 2012

- **Cotton- Mouton constant at nitrogen was measured**
- The new components were used

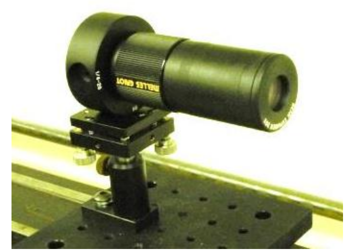
The base element of the set-up was stabilized 1mW He-Ne laser (Melles Griot)



The new beam expanders were used for precision collimation of laser beam inside the LHC magnet pipe

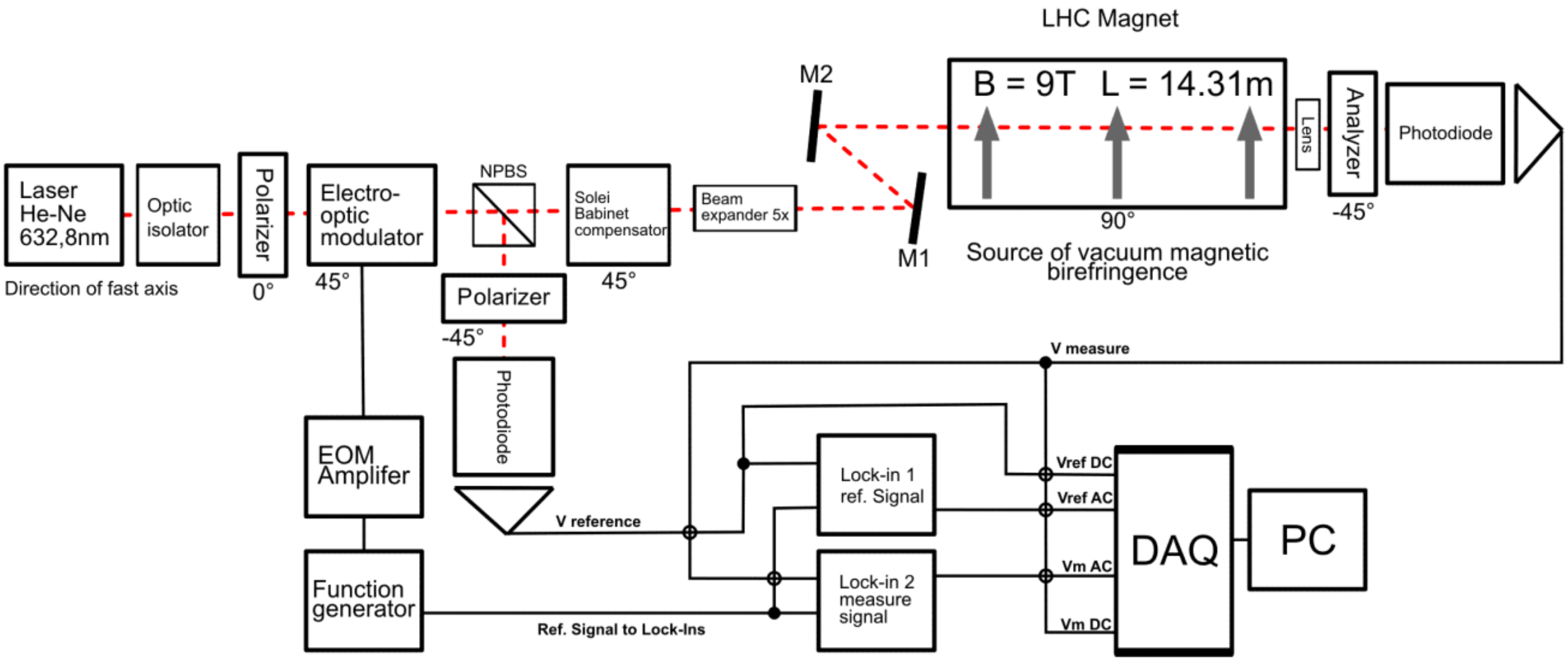


Glan-Thompson prisms (CVI Melles Griot) were used for polarization of light. They provides extinction ratio 1:10000.



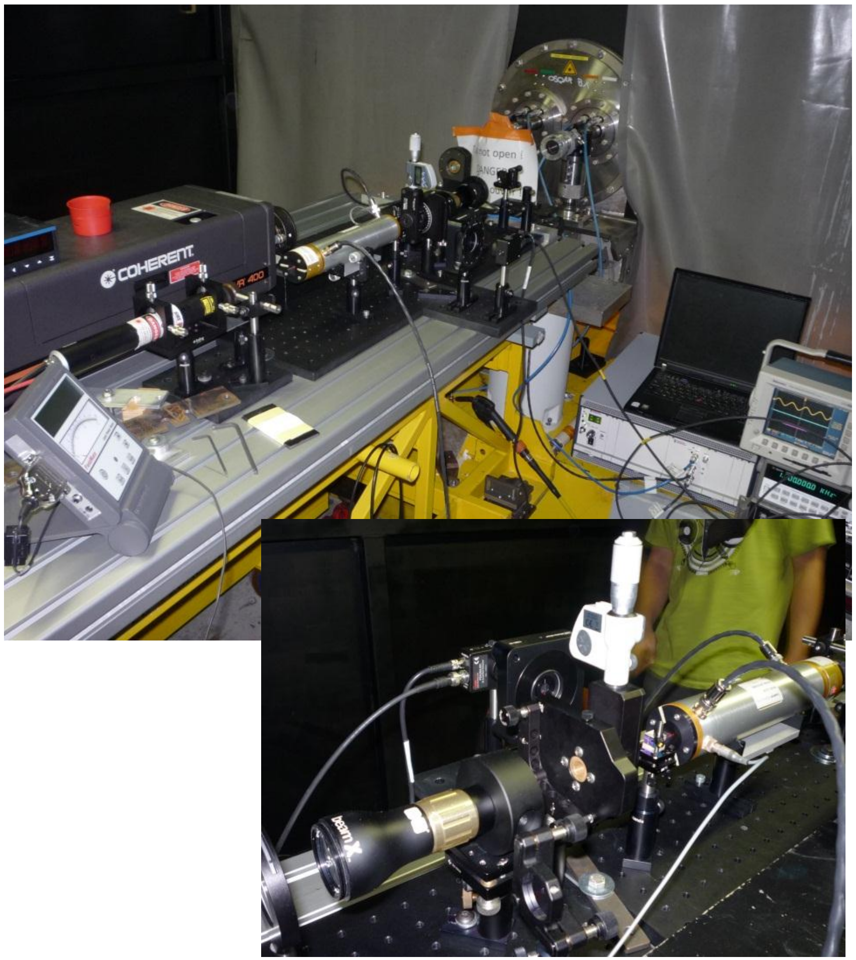
HAMATSU photodiode detector with preamplifier with optical fiber input was used for light detection

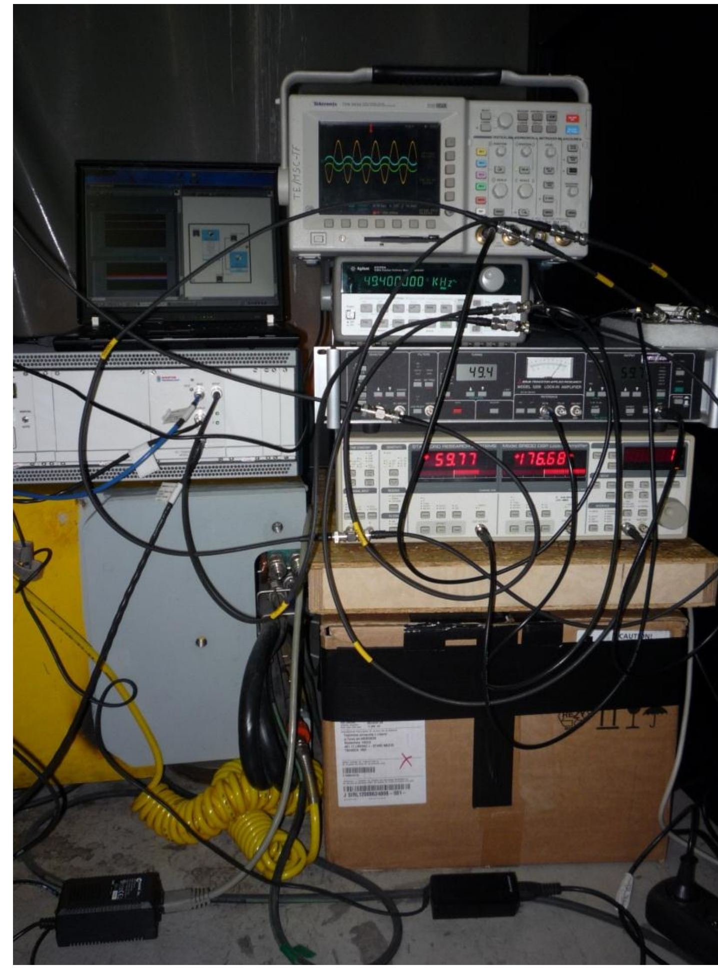
Set-up for the measurement of the Gas Magnetic Birefringence with electro-optic modulator



- AC modulation signal is built up by wave function generator
- System response was analysed by 100 kHz Lock-in amplifier Stanford Research 830 DSP
- New DAQ had took data

Photos of real experiment September 2012



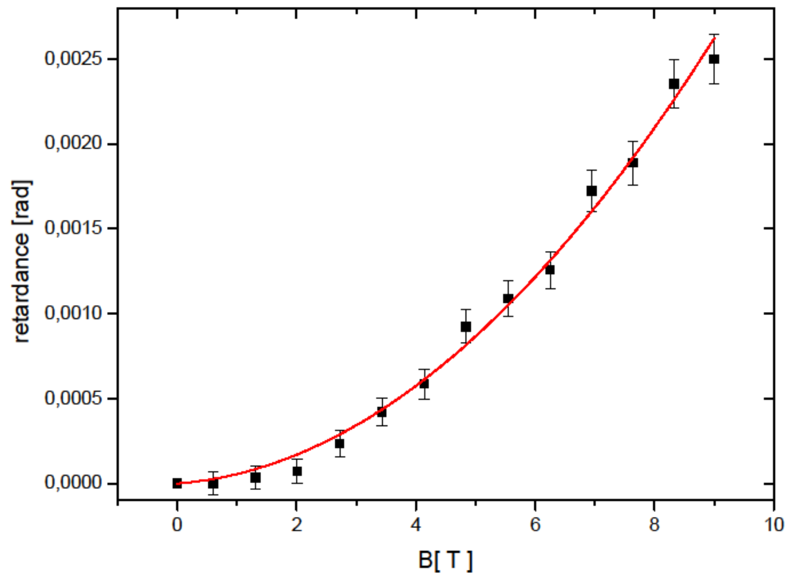


The Cotton-Mouton effect in N_2

- Results of the measured optical retardance δ has been found to increase with the square of magnetic field
- The constant of the Cotton-Mouton effect for N_2 at 1 bar is found to be equal to -$3.6 \cdot 10^{-7}$ rad $T^{-2}m^{-1}$.
- The difference in refractive indices is

$$\Delta n \approx (2.28 \cdot \pm 0.16) \cdot 10^{-13}$$

for N_2 at atmospheric pressure in 1 T field



This result is in good agreement with published values !!!!

Expected OSQAR VMB sensitivity

- Birefringence δ sensitivity of our set-up is extending to 10^{-4} rad now

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

- For He-Ne laser λ= 632.8 nm, and LHC magnet L=14.3 m, the difference $\Delta n \approx 6 \cdot 10^{-14}$ can be measurable
- **Our previous experiments were made without resonant cavities**
- Sensitivity can be significantly increased by an application of high finesse cavities
- It can improve sensitivity by a factor 10^3 - 10^5
- **We are still far from QED prediction, but we are approaching**

Cavities

- Increasing path of the laser beam in the magnetic field
  $\rightarrow$ **using a cavity**
- Magnetic length of LHC magnets of 14.3 m
- Inner tubes are curved – effective aperture is about 23 mm

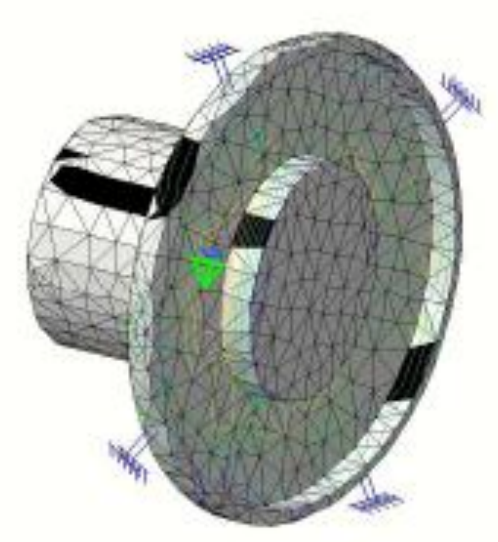
Aim and challenge

- preparation of 2 Fabry-Perot cavities, 19.6 m long, for the photon regeneration run (with Ar+, Nd:YAG laser??)
- completion of full length 19.6 m cavity for VMB, implementation to LHC magnet, for stabilized He-Ne laser, 632.8 nm

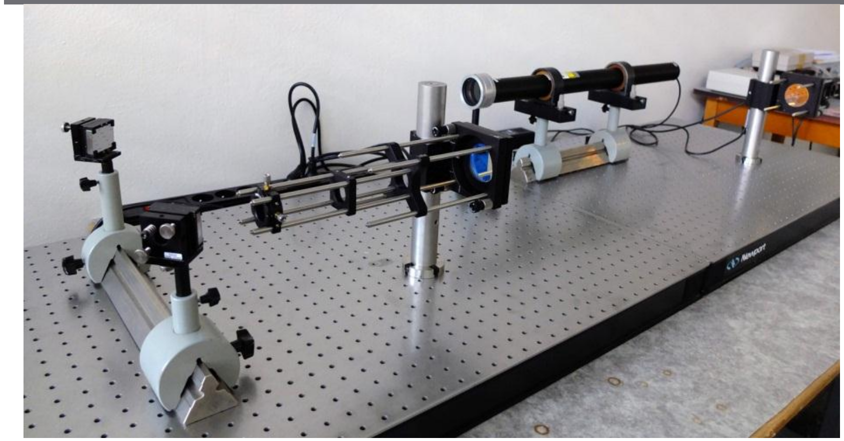
We have new experiences with optical elements mounting, beam alignment and stability from previous runs

Development of high finesse optical cavity

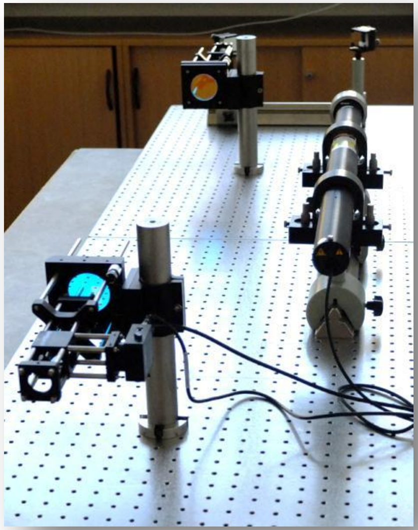
- The preparation of one meter long prototype of the Fabry-Perot cavity started at Czech Technical University , Prague
- The light will be locked inside the cavity by using the Pound-Drever-Hall lock-in technique
- The work was concerning about the design of mirror geometry, parameters of optical reflective layers, calculation of beam matching for optical coupling of the laser beam to the cavity
- The development of a rotating FP cavity to suppress parasitic birefringence of the mirrors



Prototype of 1m long cavity at CTU Prague



THORLABS
PZ631-EC -
Complete System



<u>Planar 2” mirror mount</u>

- Used for locking the cavity‘s resonance frequency
- Adjustable in 5 DOF (two rotation and three translation moves)
- Automated by a close loop controller
- Mirror mount actuated by piezo drivers (Thorlabs)

<u>Concave 2” mirror mount</u>

- Adjustable in 4 DOF (two rotation and three translation moves)
- Automated by a open loop controller
- Mirror mount actuated by piezo drivers
- Vacuum compatible (10^{-9} mbar)

Conclusion

Unexpected circumstances linked to the preparation of the first long shutdown period of the LHC have implied the replacement of both spare LHC dipoles dedicated to OSQAR.

Two new ones have been installed, aligned, successfully tested and commissioned to perform photon regeneration experimental runs.

Photon regeneration

- Several improvements have been implemented (water circuits, optics)
- The results of the 2011 photon regeneration experimental run for pseudoscalar/axion and scalar particle search have been deeply analyzed
- They confirm the results published by the ALPs collaboration and will be submitted for publication

VMB

- Progress toward the measurement of the VMB has been achieved
- The new set-up with electro-optical modulator was tested
- Cotton-Mouton effect in air and nitrogen was measured
- We confirmed that refractive index difference $\Delta n \approx 6 \cdot 10^{-14}$ can be measurable at LHC magnets at CERN without cavity

Cavity

- The building of 1 m long prototype is well advanced

Perspectives & Request

- Two solutions are presently under consideration to perform photon regeneration runs at CERN combining optical power up to 1 kW with the simultaneous use of 2 LHC dipoles, each of them providing a magnetic field of 9 T over 14.3 m.
- This will allow completing the revised program in 2013-14 with as main objectives for the photon regeneration experiment to improve the present reference results
- For 2013, the request from the OSQAR collaboration concerns the possibility to use both dedicated test benches with new dipoles and the required cryogenic cooling capacity at 1.9 K together with dedicated resources.
- **The minimum requirement for run durations at cold conditions in 2013 are: 1 period of 2 weeks and 4 periods of 1 week each.**

OSQAR Contributions to International Conferences

- 20 – 25 May 2012, *12th Pisa Meeting on Advanced Detectors*, La Biodola, Isola d'Elba, Italy, http://www.pi.infn.it/pm/2012/, contribution submitted to *NIMA_PROCEEDINGS-D-12-00275*
- 1 – 8 July 2012, *Advanced Studies Institute – Symmetries and Spin*, Prague, Czech Republic, http://theor.jinr.ru/~praha/2012/, oral contribution, to be submitted to *The European Physical Journal Special Topics*
- 18 – 22 July 2012, *8th Patras Workshop on Axions, WIMPs and WISPs*, Chicago IL, USA, http://axion-wimp2012.desy.de/, oral contribution
- 10 – 12 September 2012, *Open Symposium - European Strategy Preparatory Group*, Krakow, Poland, http://indico.cern.ch/conferenceDisplay.py?confId=175067, contribution ID : 105
- 16 – 18 October 2012, Optics and Measurement 2012, Liberec, Czech Republic, http://oam.kez.tul.cz/, to be submitted to *The European Physical Journal Special Topics*

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THANK YOU FOR YOUR ATTENTION