Miroslav Sulc

on behalf of OSQAR collaboration

Laser based experiment OSQAR

OSQAR Experiment

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OSQAR

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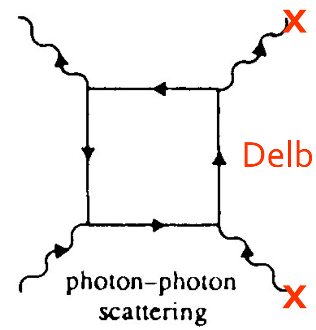
Outline

- Scientific Motivations
- OSQAR experiment
  - LHC magnets
  - Photon regeneration effect
  - Vacuum Magnetic Birefringence
- Cavities preparation
- Conclusions

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**

OSQAR

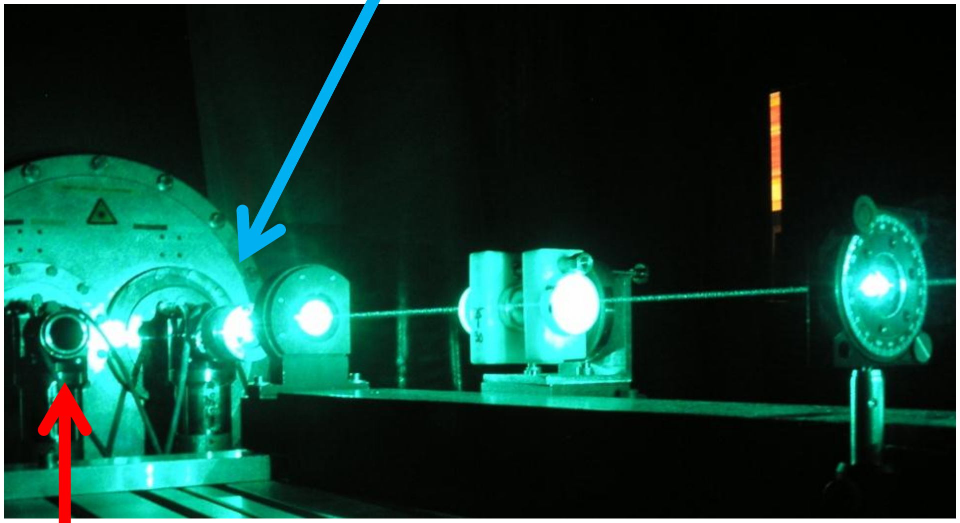
Optical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration

- 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 experiment

- 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

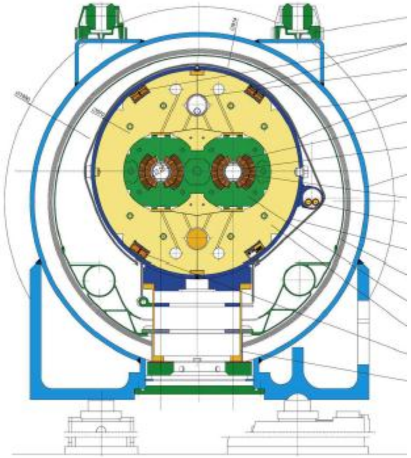
1. Aperture
Photon Regeneration Experiment



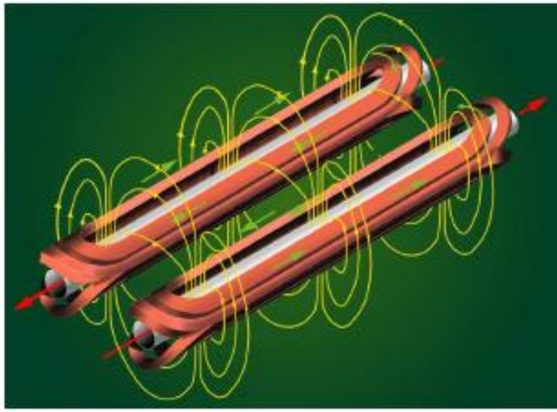
2. Aperture
Vacuum Magnetic Birefringence

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



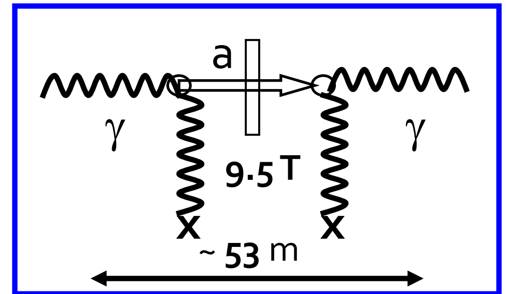
VMB Measurements : Unique opportunity with LHC dipole(s)

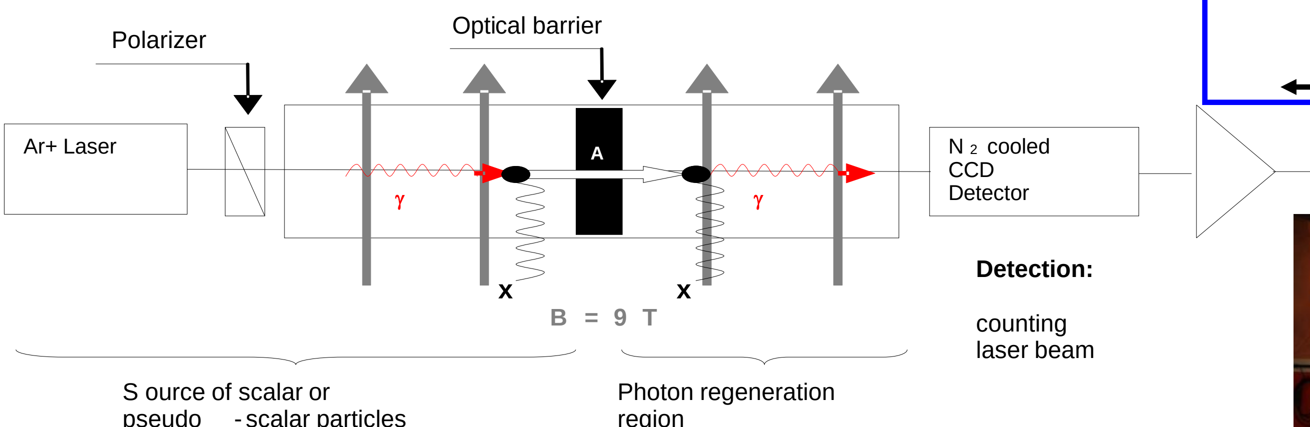
Experiment	**BFRT**	**PVLAS**	**BMV**	**OSQAR**
Status	Terminated	Achieved	Achieved/ Phase-1/Phase-2	
λ (nm)	514.5	1064	1064	**632.8**
Finesse of the FP cavity	N ~250	10^5	$5.10^4/6.10^5/10^6$	**$10^3/10^5$ expected**
Sensitivity (rad/Hz$^{1/2}$)	4.10^{-10}	10^{-11}	$10^{-9}/10^{-10}$	**$10^{-13}/10^{-15}$**
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/√Hz with a cavity of finesse equal to 30 000 and a modulation frequency of 10 Hz

Photon regeneration effect

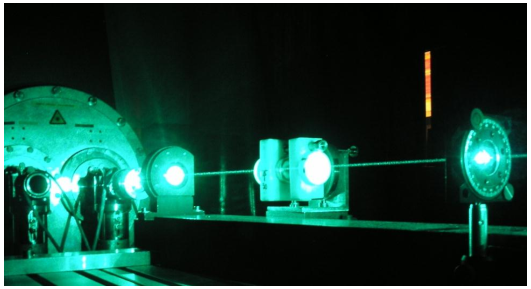
The photon regeneration effect is looked as a light shining through the wall



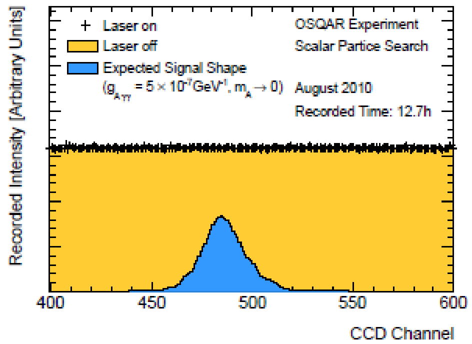


Two magnets separated by an optical barrier

Argon laser is a source of 3-7 W beam

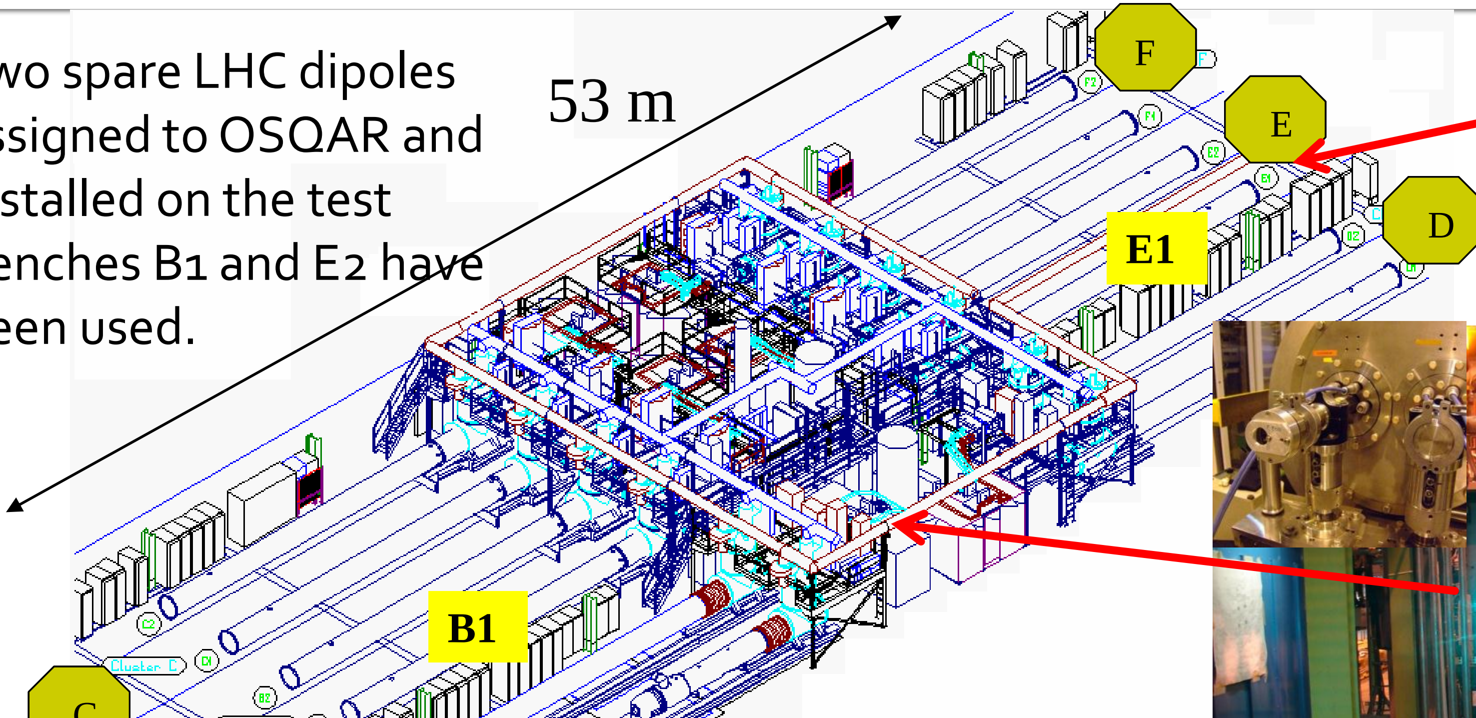


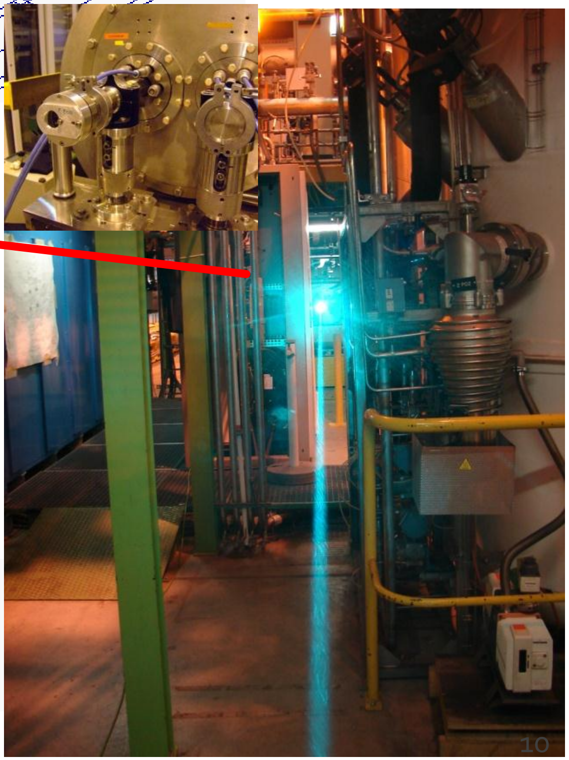
The CCD detector, cooled by liquid nitrogen, measures the laser beam profile by photon counting method

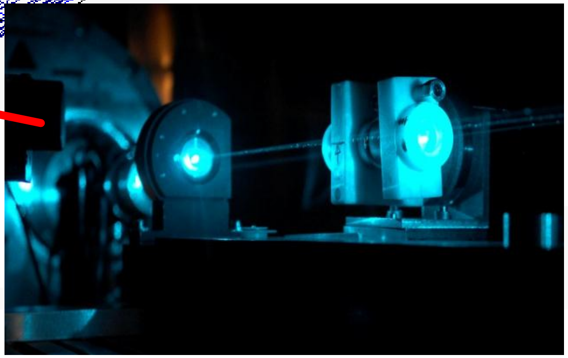


Photon Regeneration Experiment at CERN SM18

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







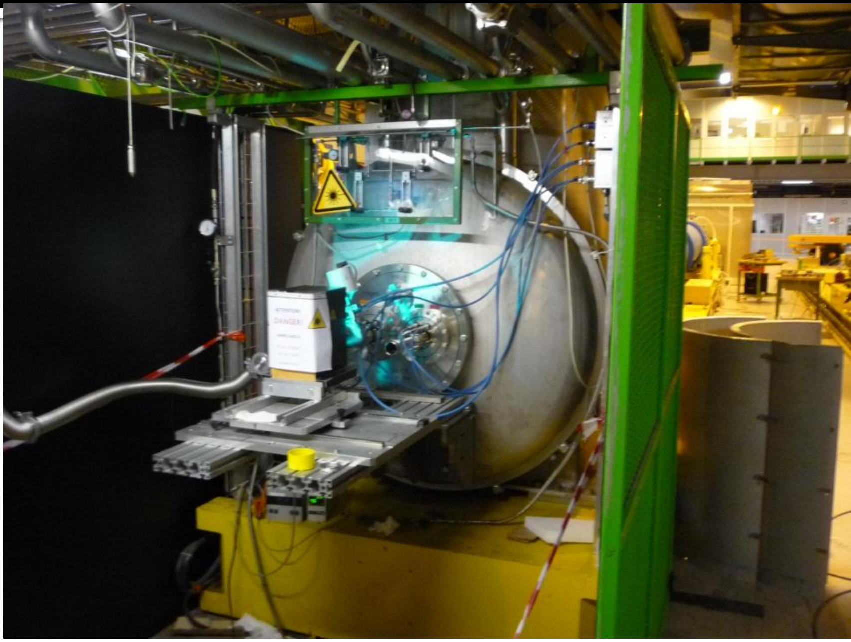
"An invisible light shining through a wall"

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 LN_2 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.

Photon Regeneration results with 1-D CCD camera

- No events above the background were detected during data collection
- The flux detection threshold at 95% of confidence level is equal to 0.013 photon/s for the scalar particle search and 0.033 photons/s for the pseudo-scalar particle search (different data taking time and laser intensities)

$$P_{A\gamma} = \frac{1}{4\beta\sqrt{\epsilon}} g^2 B^2 L^2 \approx \text{const.}\, g^2 B^2 L^2$$

Number of converted photons per time period:

$$N_{axion} \approx \text{const.}\, \eta \frac{P}{\omega} g^4 B^4 L^4 t$$

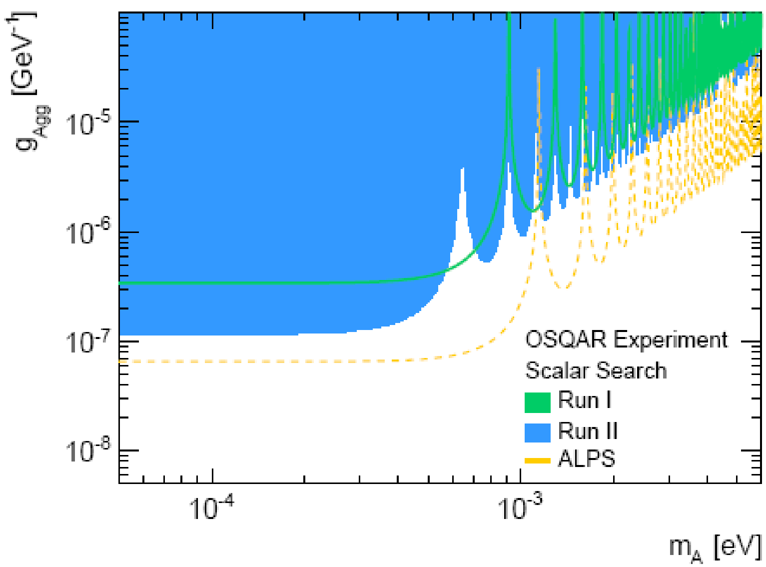
Current parameters

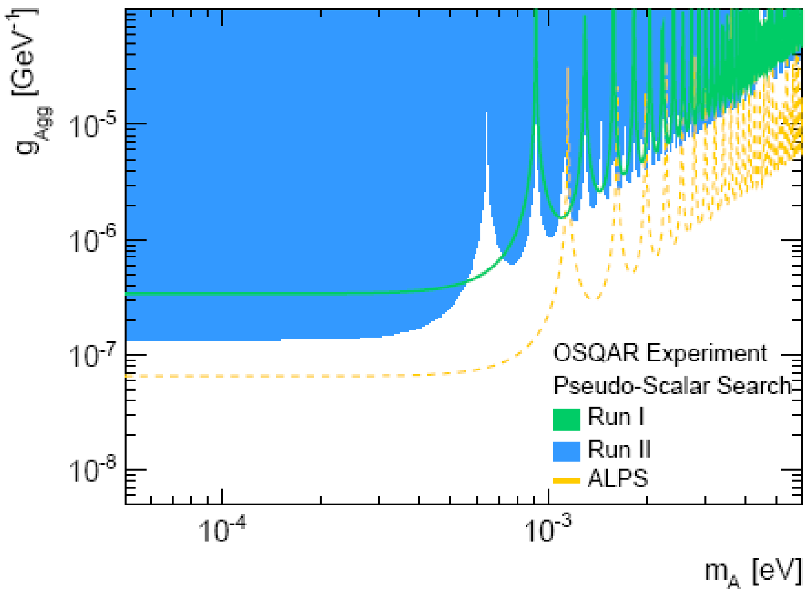
Magnetic field strength: B = 9.5 T
Magnetic field length: L = 14.3 m
Laser power: 2.9 W
Power loss due to reflections: 0.7
Single photon detection efficiency: 0.3

Photon Regeneration exclusion limits

The last published data for OSQAR exclusion limits for scalar ALPs in vacuum.
[arXiv:1110.0774v3]

The results of the ALPs experiment as well as the previous OSQAR results are also indicated





In the limit of massless particles the constraints obtained on di-photon coupling constants are $g_{A\gamma\gamma} < 1.15\cdot10^{-7}$ GeV^{-1} for scalar and $g_{A\gamma\gamma} < 1.33\cdot10^{-7}$ GeV^{-1} for pseudo-scalar particles

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

Princeton Instruments

LN/CCD-1024E/1

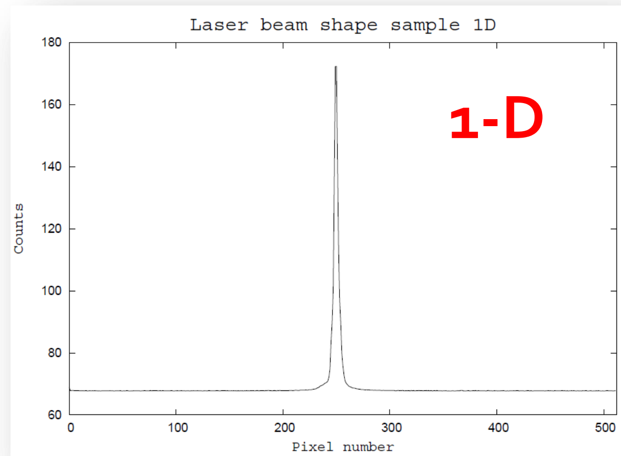
- Lowest read noise in the industry
- Lowest dark current using cryogenic cooling
- QE ~ 30 % at 488-514 nm

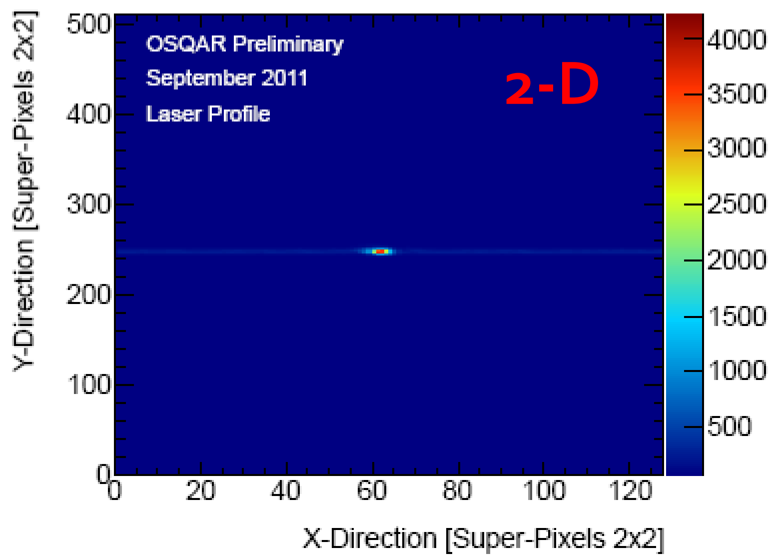
CCD chip, EEV 1024 × 256 square pixels of 26 µm, 26.6 x 6.7 mm

Spurious signals coming from cosmic rays

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

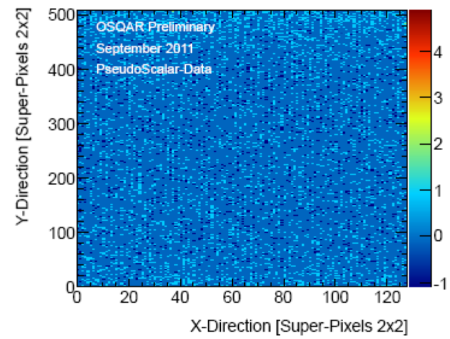
⇒ Impact to 1 stripe x pixel

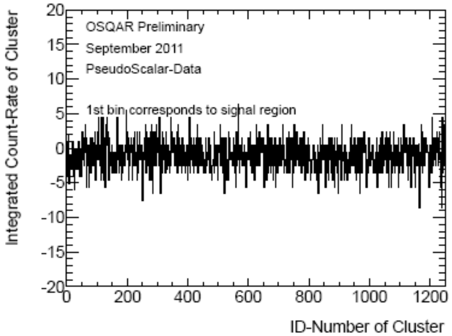




Data analysis

- 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 is assumed that the signal shape of regenerated photons is close to the recorded laser spectrum when removing the barrier between the two LHC magnets.

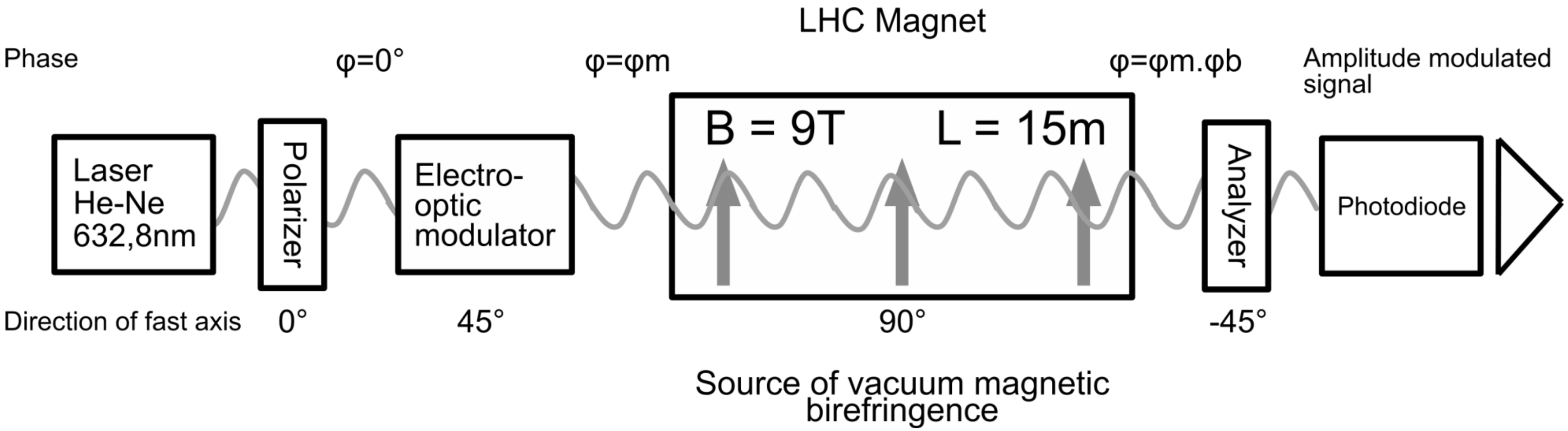




- Cosmic noise (high signal in area smaller than 4 superpixel in width) was removed
- Background was defined and data were analyzed
- Preliminary results with 2-D CCD leads to **improving of coupling constants exclusion limit 2-3x with respect to our published one**
- .

Vacuum Magnetic Birefringence

- 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 about



Birefringence

- Anisotropy of refractive index, the birefringence shown by the vacuum (or gas) after the light has propagated along an optical path *L* is

$$\delta = 2\pi \frac{L}{\lambda} \Delta n \sin 2\theta \qquad n_e - n_o = C_{CM} \lambda_0 B^2$$

- 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 filed pulses….)

Magnetic filed rotation

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

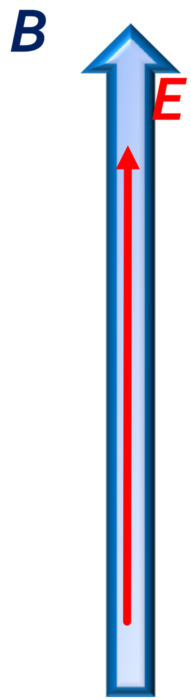
Electric filed rotation

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

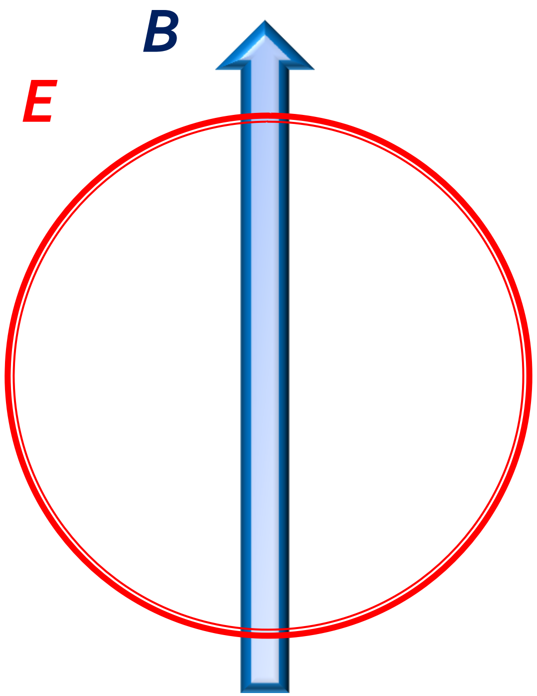
Half-wave plate vs. EOM

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

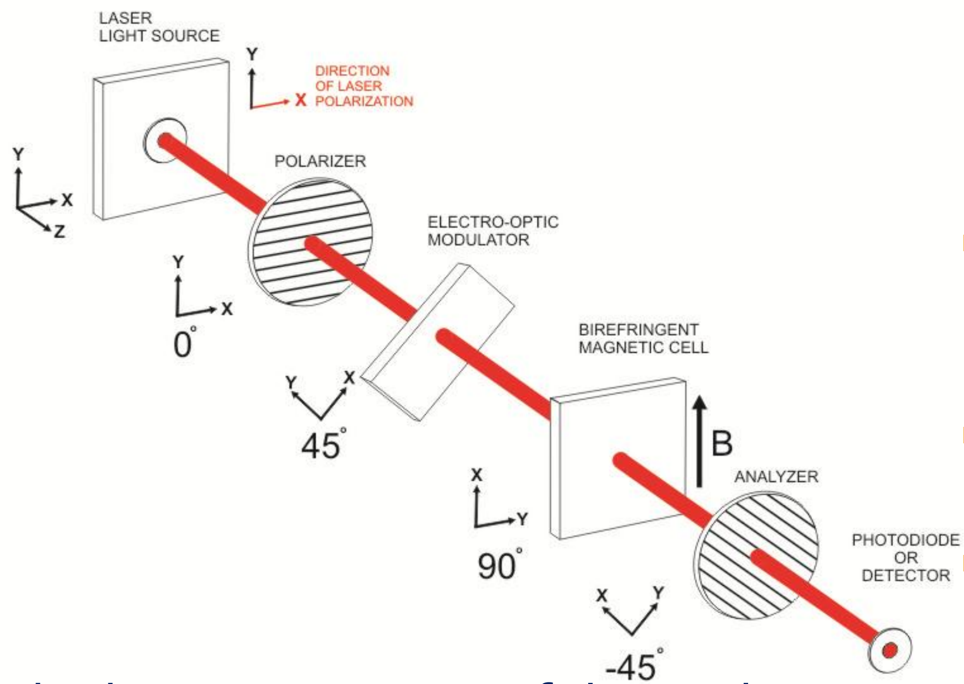
Electro-optical modulator for phase modulation



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

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

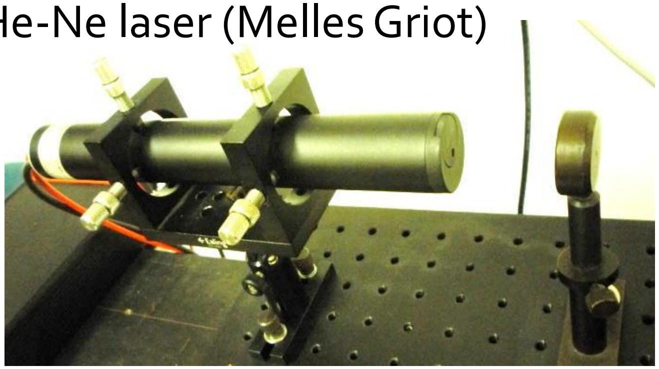
where U is detected constant voltage and U_m is amplitude of alternating voltage of measured signal.

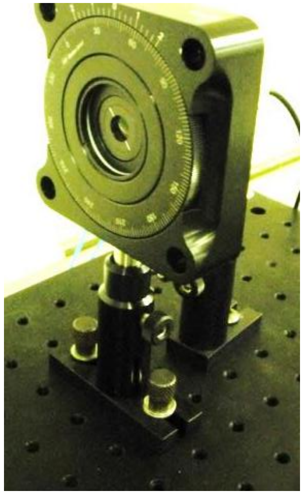
Run in CERN SM18 test hall, December 2011

- Run was realized with **university–made** E-O modulator from $LiNbO_3$ crystal
- **Cotton- Mouton constant at air was measured, but accuracy was not good**

- The new components were used

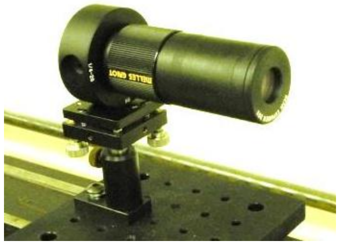
The base element of the set-up was stabilized 1mW He-Ne laser (Melles Griot)





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

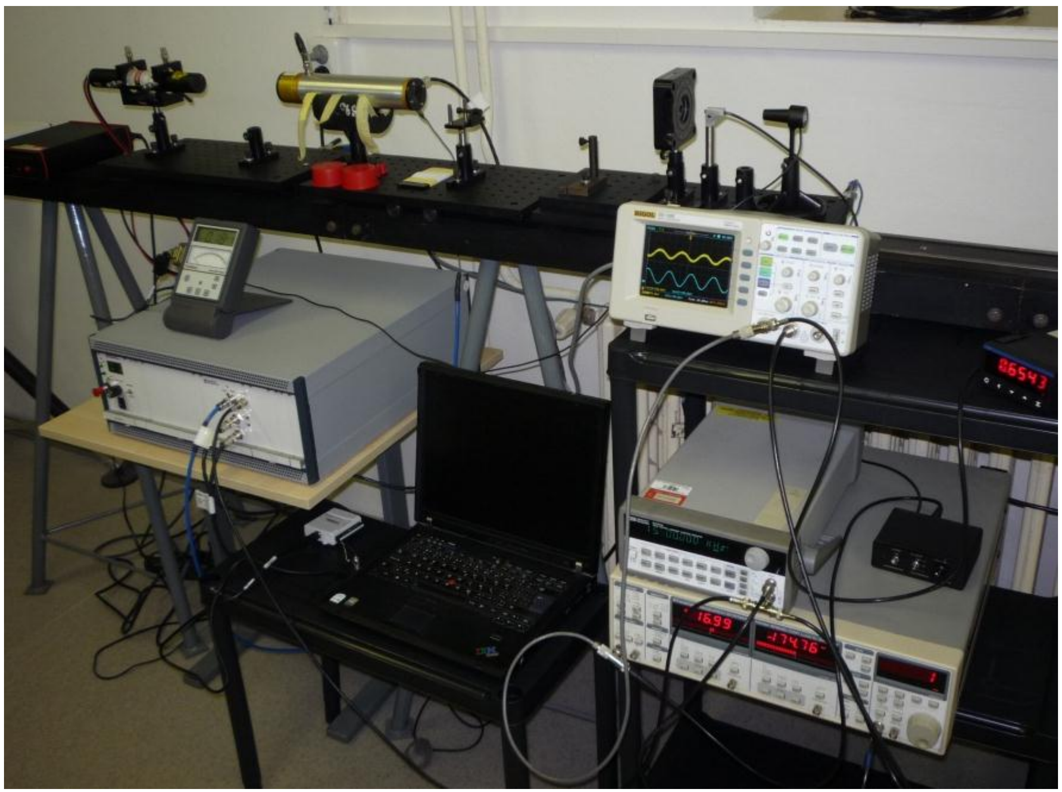
The new beam expanders were used for precision collimation of laser beam inside the LHC magnet pipe

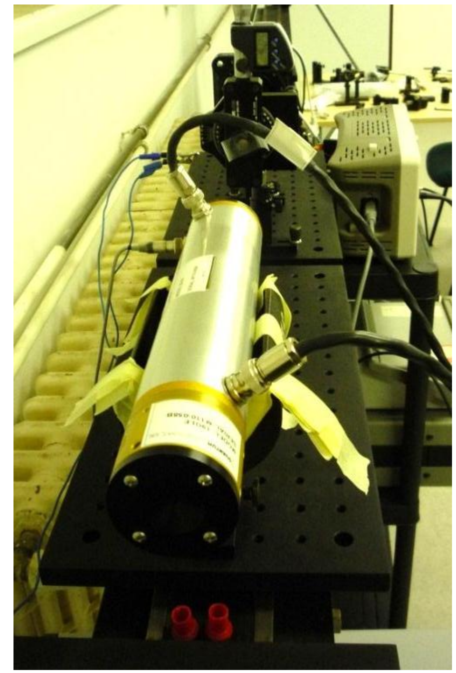


HAMATSU photodiode detector with preamplifier with optical fiber input was used for light detection

Laboratory test

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





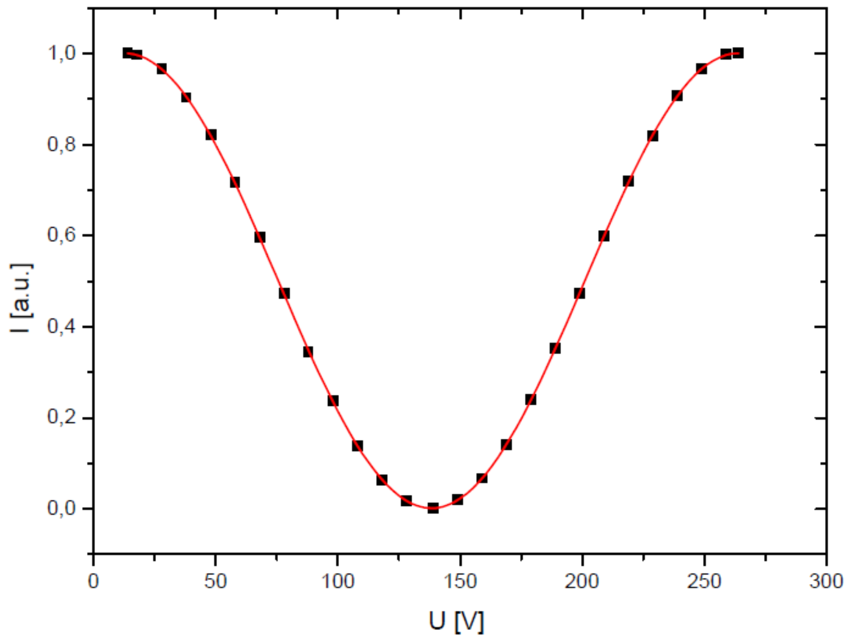
New 50 MHz electro-optical modulator from Quantum Technologies

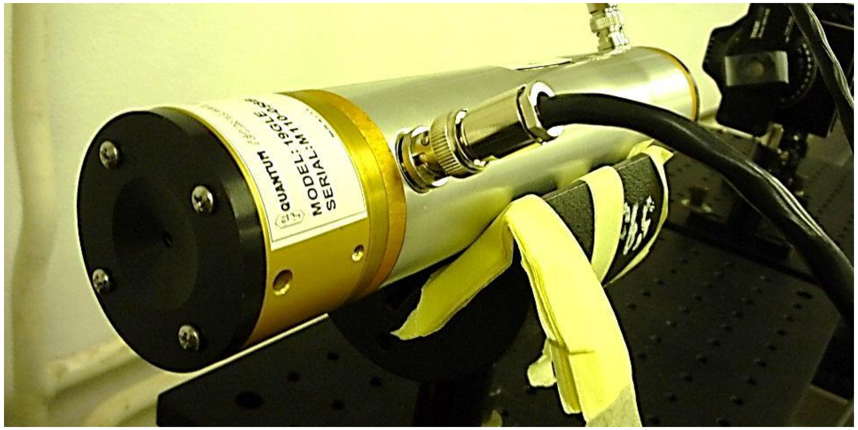
It seems to be much more stable

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

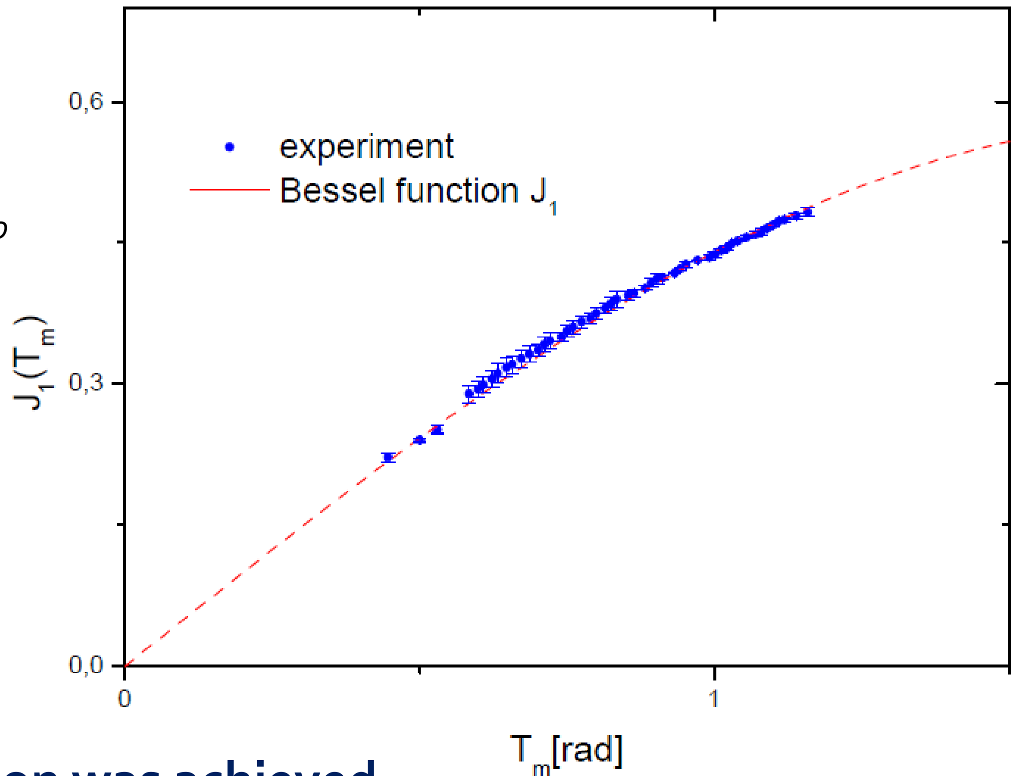
- modulator works properly
- it has very good stability

Calibration curve

The EO modulator was calibrated
Detected intensity *I* depends on amplitude of phase modulation T_o (≈ applied voltage) by equation

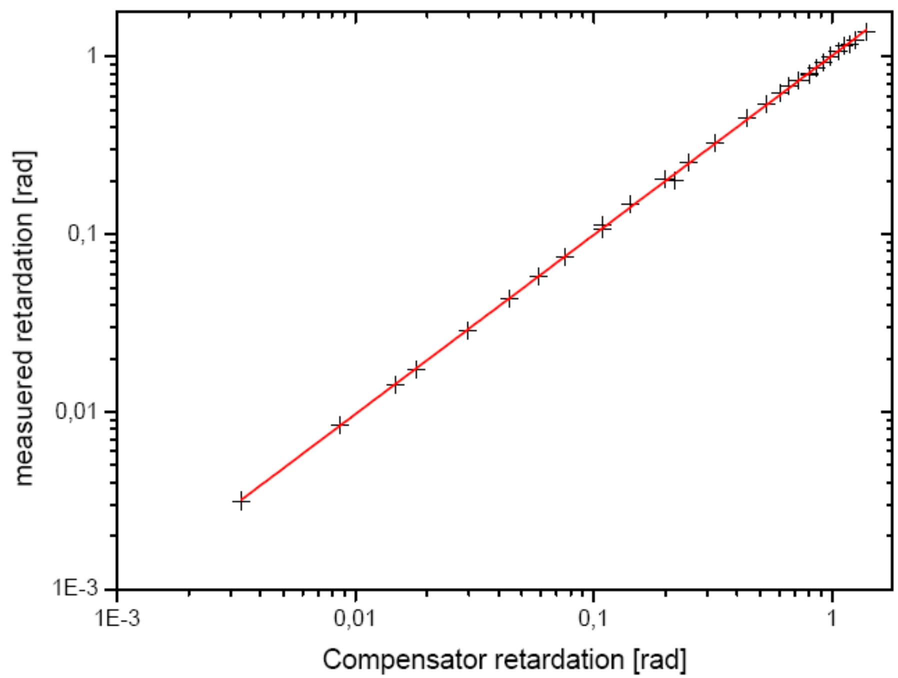
$$I = \frac{I_0}{2}\left(1 + \sin(T_o \sin \omega t)\right)$$

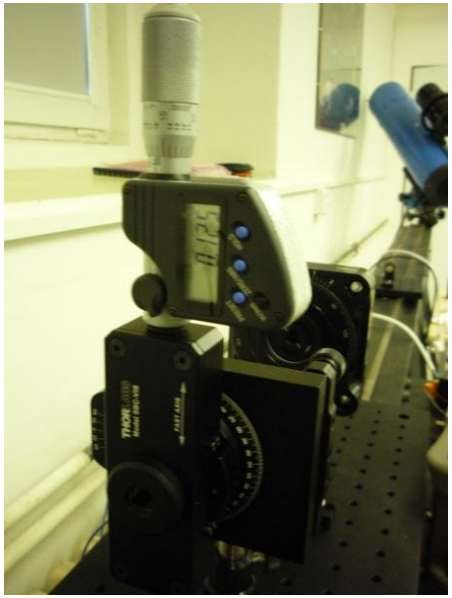
We measure the first harmonic signal, so correlation with Bessel functions J_1 was checked

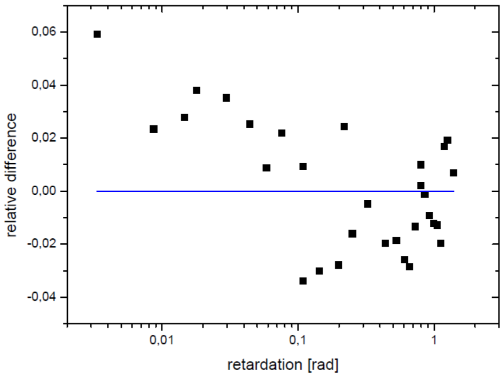


- **Good agreement with prediction was achieved**
- Due a technical limits of our EOM (maximal applied voltage), it is not be able to work at the maximum of Bessel function (highest signal)
- We work at phase shift amplitude about **1 rad**

Method was checked by Solei-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^{-5} rad, with accuracy ~5%

Expected OSQAR VMB sensitivity

- Birefringence δ sensitivity of our set-up is extending to 10^{-5} 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 $\boldsymbol{\Delta n \approx 6 \cdot 10^{-15}}$ 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
  $\longrightarrow$ **using a cavity**
- LHC magnets 14.3 m …. too long ☹
- Inner tubes are curved – effective aperture is about 23 mm ☹

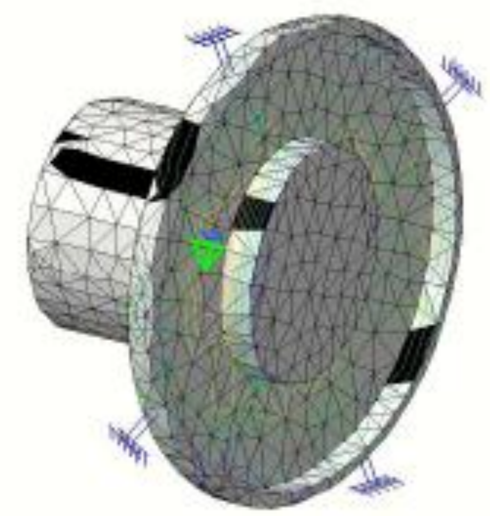
Aim and challenge

- 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

Prototyping of 1 m resonant high finesse 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 into the cavity
- The development of a rotating FP cavity to suppress parasitic birefringence of the mirrors



Cavity with planar - concave mirrors

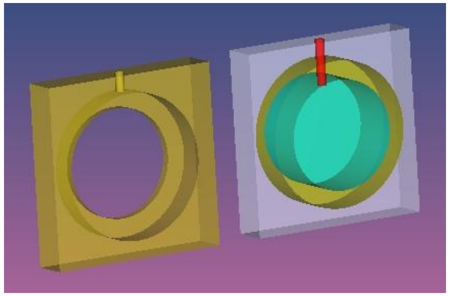
Planar 2″ mirror mount

- 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)

Concave 2″ mirror mount

- 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^{-6} mbar)

THORLABS PZ631-EC - Complete System



Conclusions and Perspectives

Photon regeneration

- Data with LHC magnets and 2-D CCD were taken
- Preliminary results with 2-D CCD leads to improving of coupling constants exclusion limit with respect to previous published one

VMB

- The new set-up with electro-optical modulator was tested
- We suppose that refractive index difference $\Delta n \approx 6 \cdot 10^{-15}$ can be measurable at LHC magnets at CERN without cavity

Cavity

- The building of 1 m long prototype has been started

Thank you for your attention