OSQAR

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

QED vacuum birefringence workshop
1 - 3 November 2015
DESY Hamburg

Štěpán Kunc on behalf of OSQAR collaboration

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Outline

- OSQAR experiment overview
- VMB experiment
- Future plans of OSQAR

CERN Globe of Science & LHC dipole

Collaboration

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Scientific Motivations of OSQAR

- **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, 2004)* ***Dark Energy candidate***
  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)

- **Spin-offs** in the domain of the metrology of electric & magnetic fields

Three distinct experiments in strong magnetic field

- **The photon regeneration effect**
  looks as a Light Shining through the Wall . OSQAR has the best exclusion limit for axions and axion like particles nowadays.

- **The Vacuum Magnetic Birefringence**
  OSQAR is developing of accurate method for this experiment, but it is able to measure only similar stronger effect in diluted gases till now.

- **Chameleon search**
  looks as measurement of afterglow of light, as the photons convert to trapped chameleons and reconvert back to photons. OSQAR did hte preparatory phase for 2015 run.

Brief history of OSQAR

2007 - start of OSQAR collaboration
2007 - 2008 - VMB I measurements - CM in air
- double pass, rotating wave plate

2010 - start of LSW measurements
- 3W laser , CCD QE 30%

2012 - 2014 - VMB II measurements - CM in N2, argon
- EOM modulated ellipsometer
- single pass

2013 - LSW measurements
- 15W cw laser, CCD QE 50%
- first optical cavity test

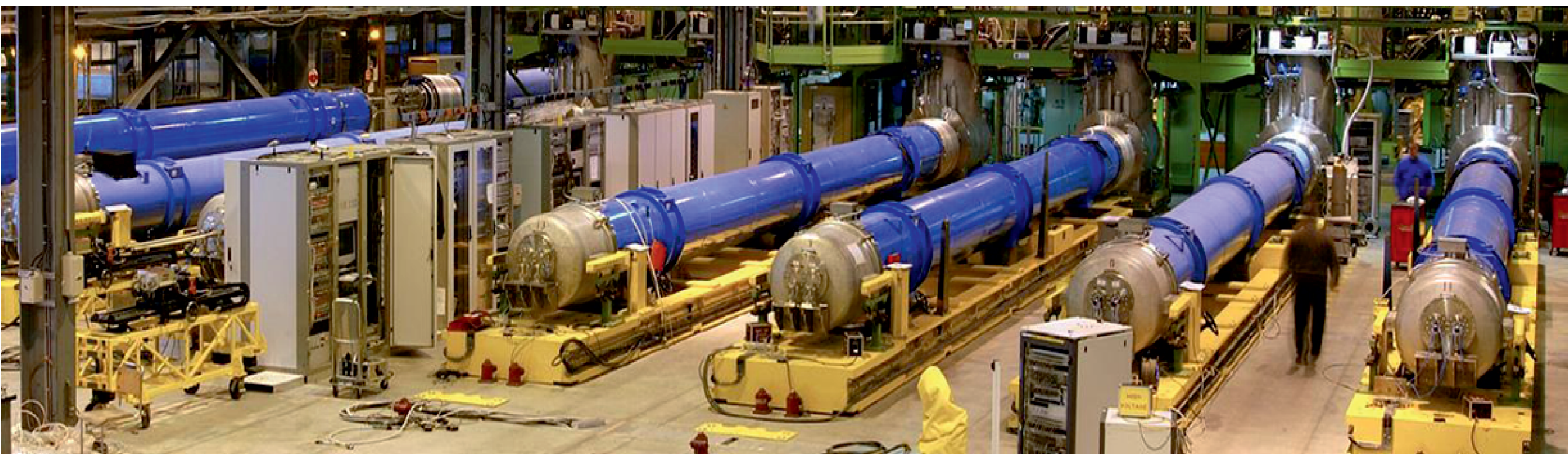
2014 - LSW measurements
- 18.5W cw laser, CCD QE 86%

2014 - Set - up testing for Chemeleon run
2015 - Chameleon measurements

Organisation of OSQAR experiment

- OSQAR is operated in CERN in SM18 hall
- SM18 - test hall for all LHC magnets - complete infrastructure
- Preparation and test are made in home institutes
- Data taking in CERN, one per year - 6 weeks duration
  - 5 weeks (LSW,Chameleons)
  - 1 week VMB
- Data analysis in home institutes

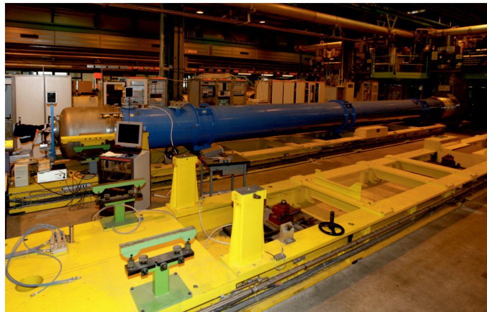
Sm18 Hall - Test Banches



OSQAR experiment in SM18

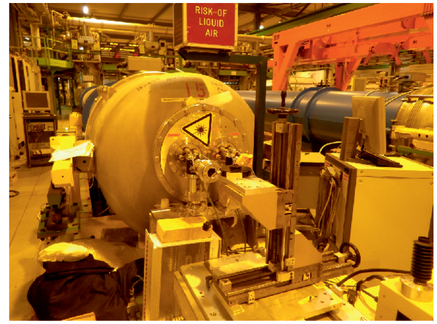
2 dipoles in line for ALPSs measurements

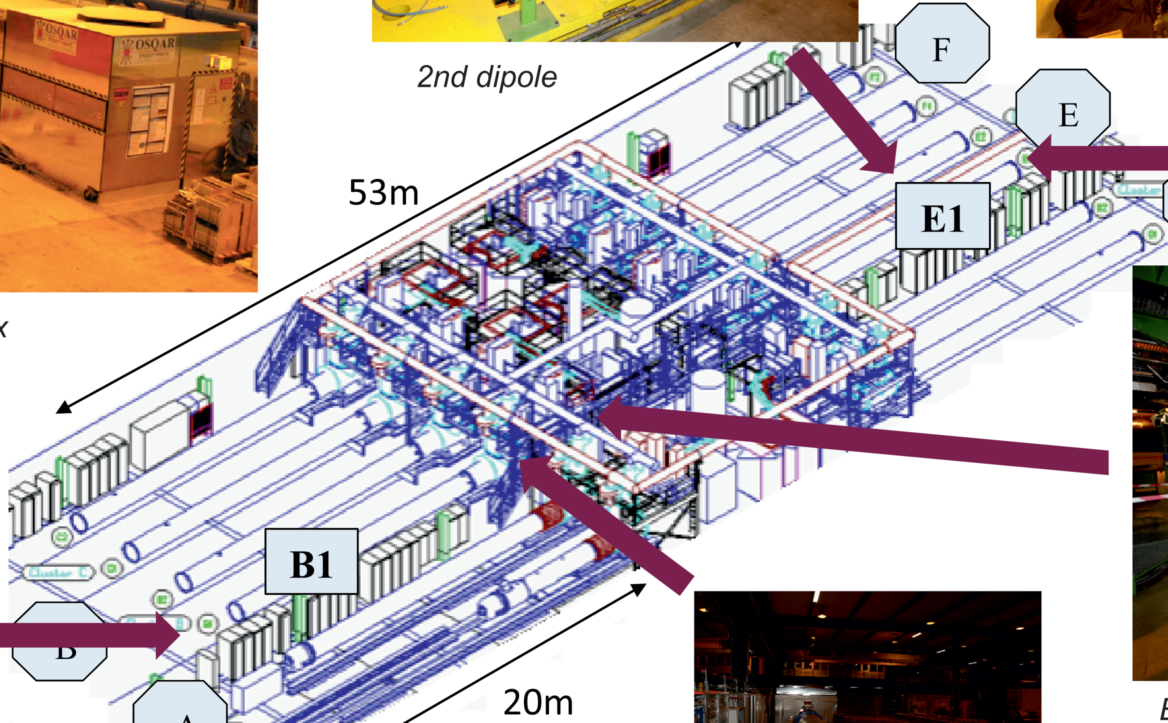
OSQAR box

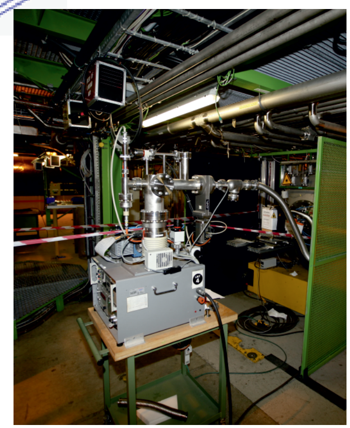


2nd dipole

End of 2nd dipole







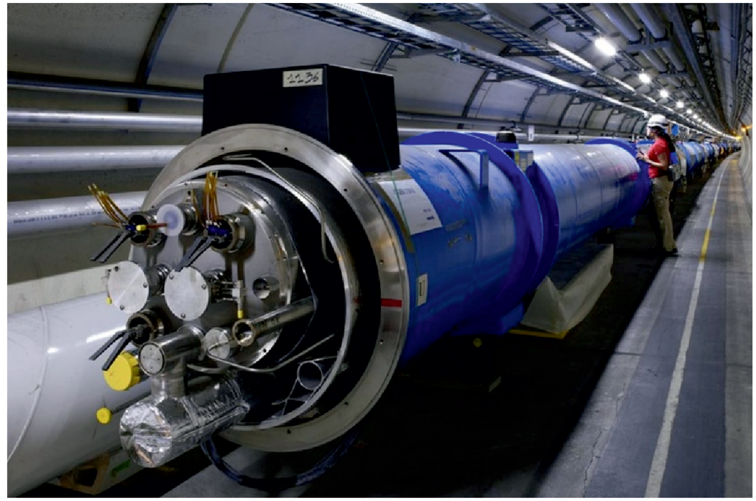
End of 1st dipole

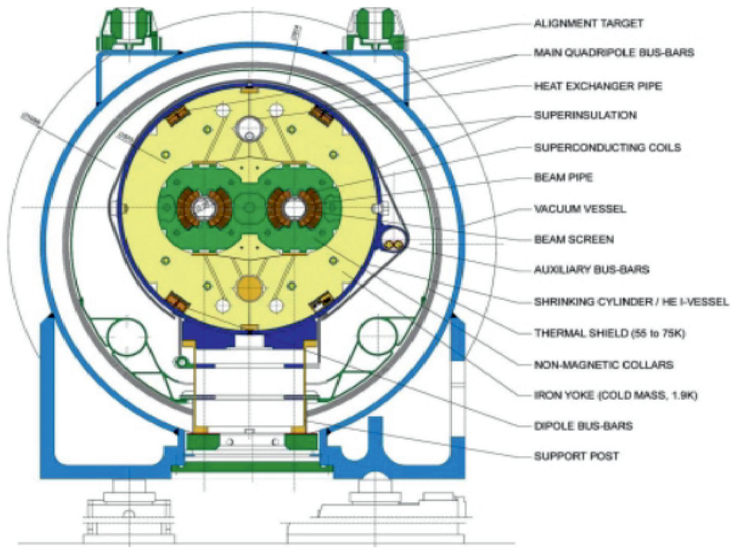
1st dipole

1 dipole for VMB & Chameleons measurements

LHC Magnets

- Standard spare magnet for LHC
- Cooling(1.9K) and vacuum
- Effective Magnetic field of
  B = 9.0T (12850 A)
  length L = 14.31m
  B^2L = 1158 T^2m
- ramping rate **50 A/s** (safe)
  modulation **2mHz**
  maximum ramping rate **100A/s**
  maximum modulation **4mHz**
- free aperture **D = 25mm**





Vacuum Magnetic Birefringence

- W.Heisenberg and E.Euler:
  Consequences of Dirac's Theory of the Positron
- Prediction of Vacuum Magnetic Birefringence
- Vacuum magnetic "anomaly" of the refraction index

$$\Delta n = 4.0\times10^{-24}B^2$$

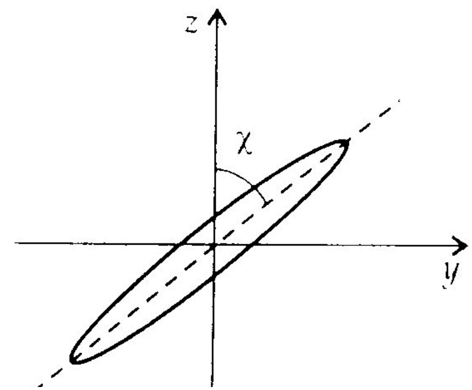
- Coresponding ellipticity induced in a laser beam polarized linearly at 45° to the magnetic field in is

$$\Psi_{QED} = \Delta n \pi N L/\lambda$$

- For the conditions of OSQAR experiment
  $N = 1$, $B^2 = 81\ T^2$, $L = 14.31$ m, $\lambda = 633$ nm

$$\boldsymbol{\Delta n = 3.24\times10^{-22}}$$

$$\boldsymbol{\Psi_{QED} = 2.3\times10^{-14}\ rad}$$



Cotton - Mouton effect

- Cotton–Mouton effect - birefringence in liquids and gases in the presence of a transverse magnetic field

- Weakest in gases - $\Delta n($ B/1T$^2 \cdot$ P/1atm)

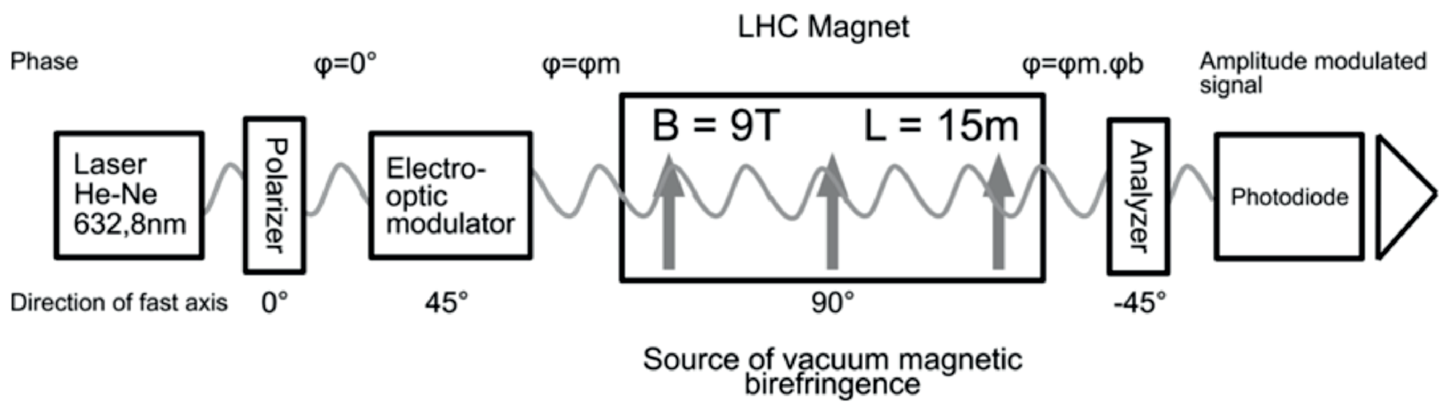
  O2 - $\Delta n \approx -(2.5) \cdot 10^{-12}$
  N2 - $\Delta n \approx -(2.28) \cdot 10^{-13}$
  Ar - $\Delta n \approx (5) \cdot 10^{-15}$
  He - $\Delta n \approx (2.4) \cdot 10^{-16}$

- **Cotton – Mouton effect is the same effect as VMB, therefore we use it for testing of ellipsometer.**

- Cotton – Mouton effect shows linear dependence on gas pressure.
  – Residual gas is one of possible sources of fake signal

The measurement principle and setup

- experiment uses a polarization modulation techniques for measuring optical birefringence
- higher sensitivity compared to static methods
- Polarization modulation using an electro - optic modulator at 49KHz

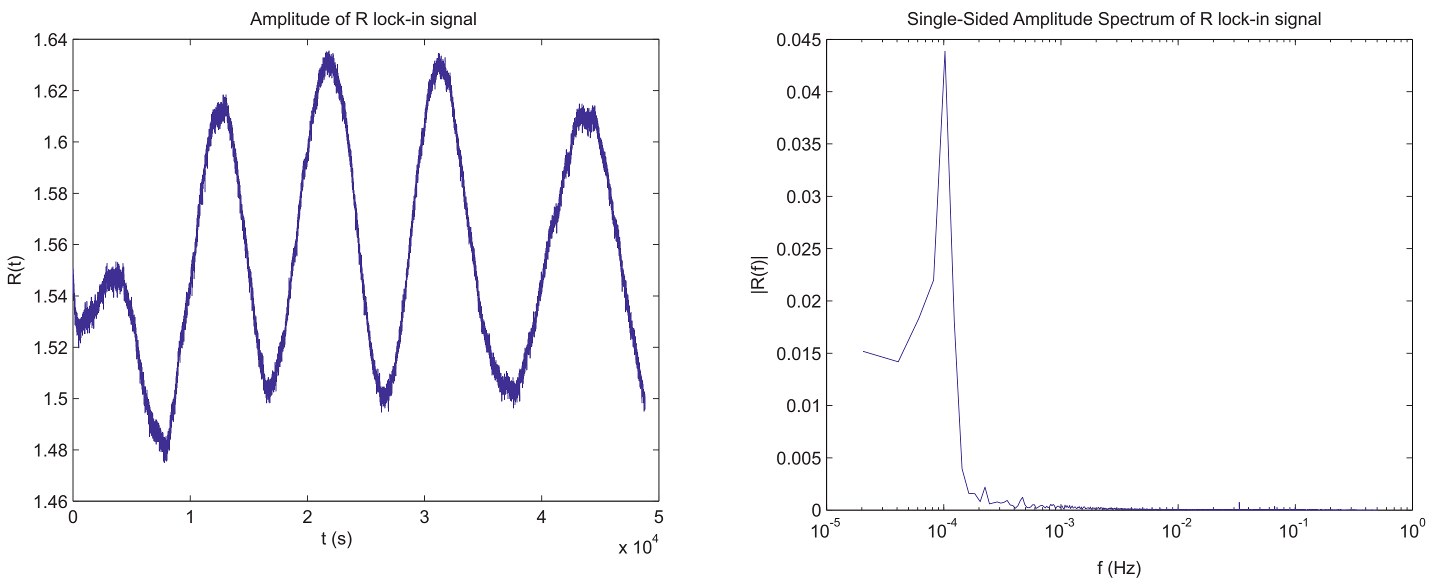


$$I_m = I_0 / 2(1 + \sin(\delta) \sin T), \quad \sin(T_0 \sin \omega t) = 2 \sum_{m=odd} J_m(T_0) \sin(m\omega t)$$

Low frequency noise in birefringence signal

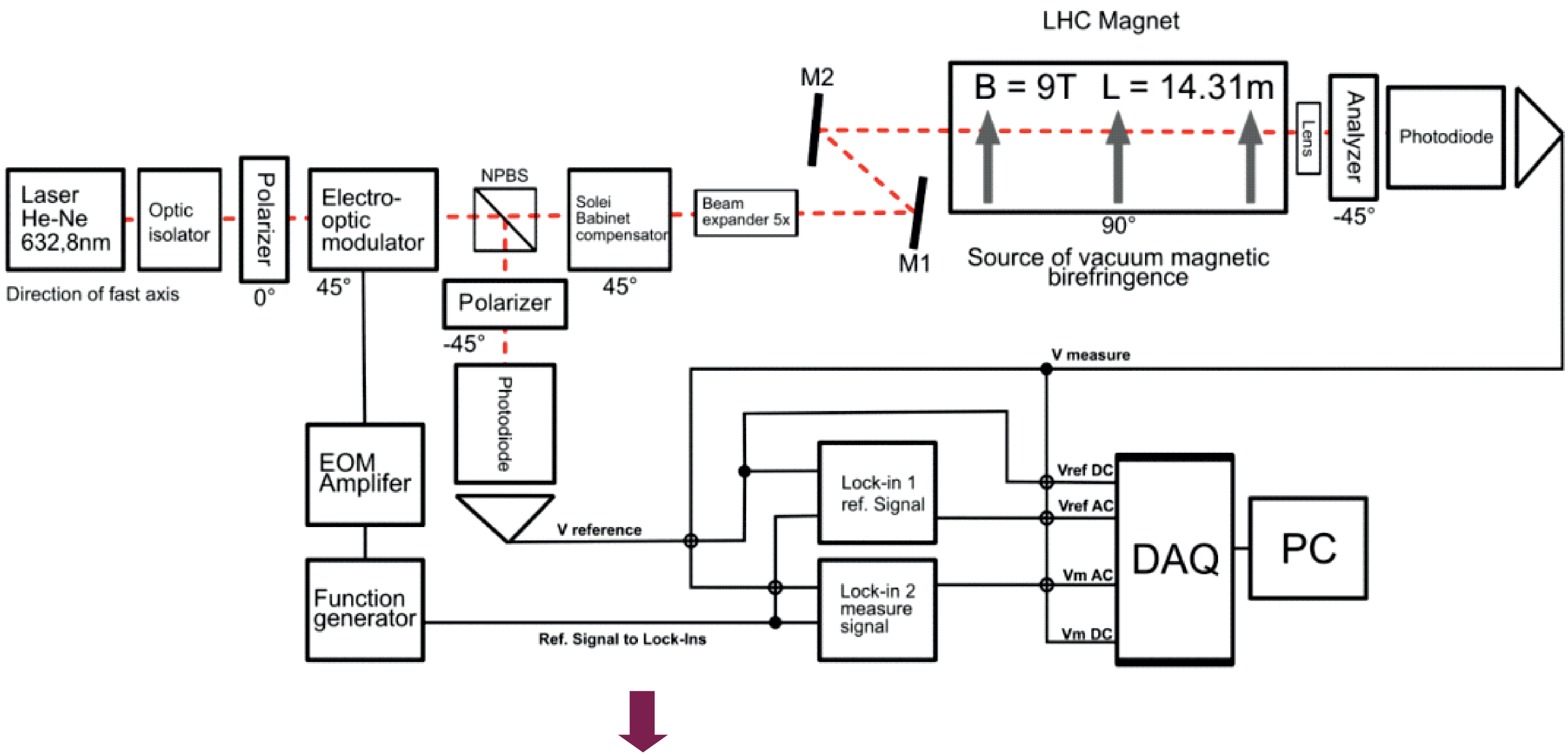
- homodyne measurement
- due to lack of magnet modulation
- low frequency noise around 0.1 mHz

R signal from Lock-in at 49 KHz



- small changes in birefringence of optical elements
- instability of electro-optic modulator
- Amplitude instability of laser

Setup of Cotton - Mouton measurement



The reference branch is used to control sporadic signals

Birefringence calculation

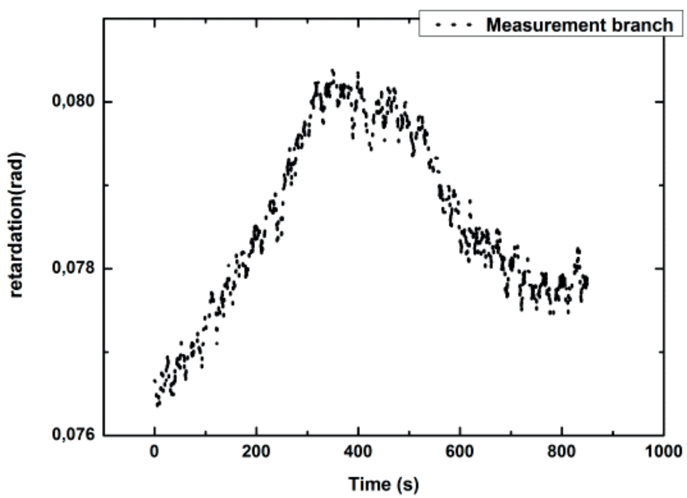
$(\delta + \text{noise}) = \arcsin(\sqrt{2}V_{1fm}/V_{DCm}2J_1(T_0))$ measurement branch

$\text{noise} = \arcsin(\sqrt{2}V_{1fr}/V_{DCr}2J_1(T_0))$ reference branch

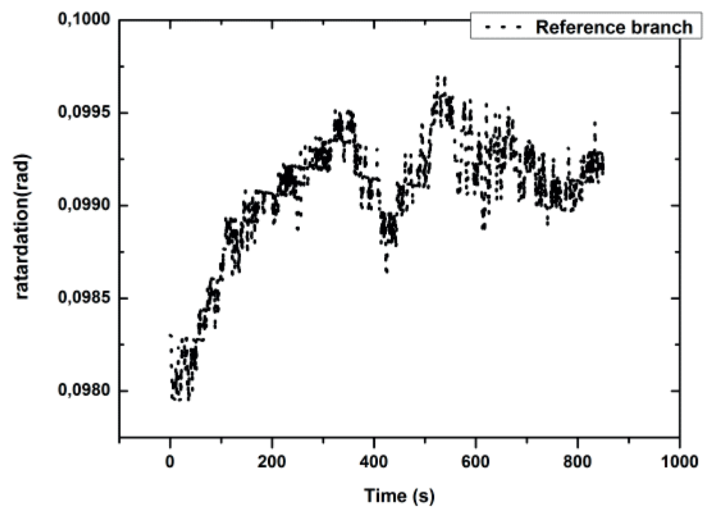
$\text{final} = (\delta + \text{noise}) - \text{noise} = \delta$

V_{1f} - R value of from lock -in amplifier at 49KHz
V_{DC} - DC voltage of signal
T_0 - 72° J_1(maximum at 105°)

Birefringence signal in measure branch



Birefringence signal in reference branch

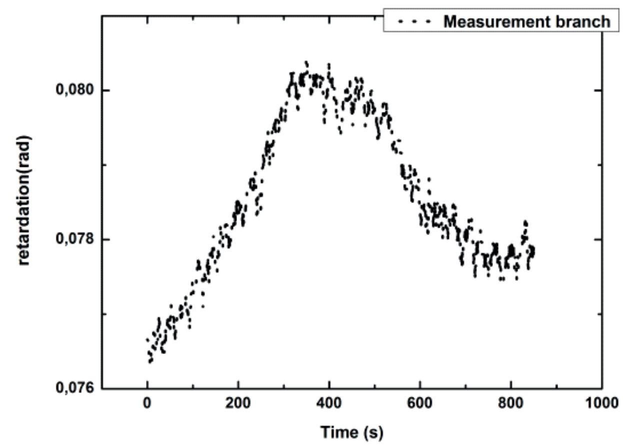


Measurements in N2 gas 1bar 0-9T

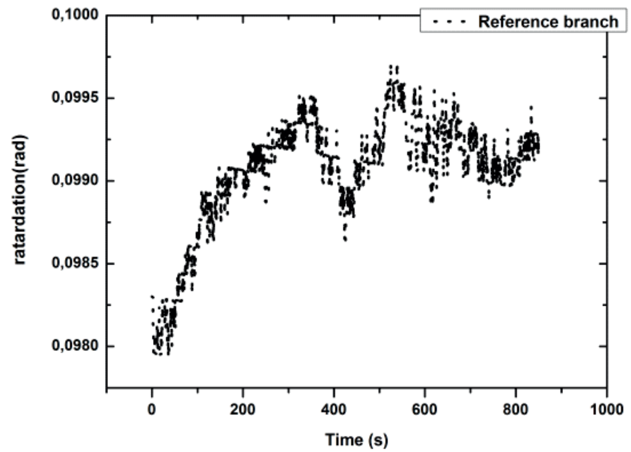
The results of measuring Cotton - Mouton in N2

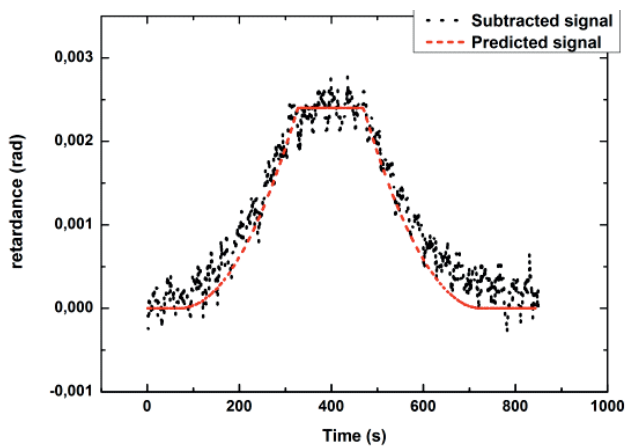
Measurements in N2 gas 1bar 0-9T

Birefringence signal in measure branch

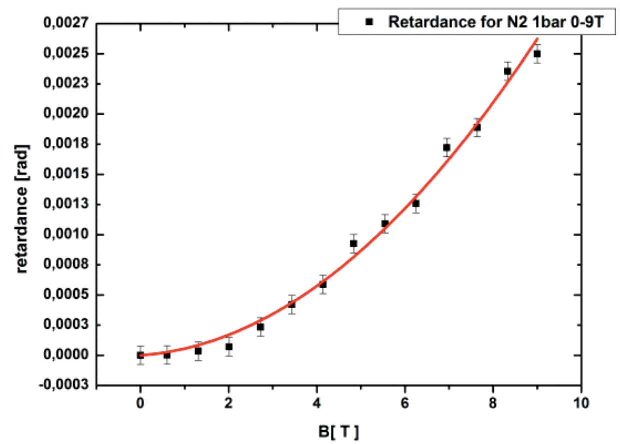


Birefringence signal in reference branch





subtracted signal as function of time

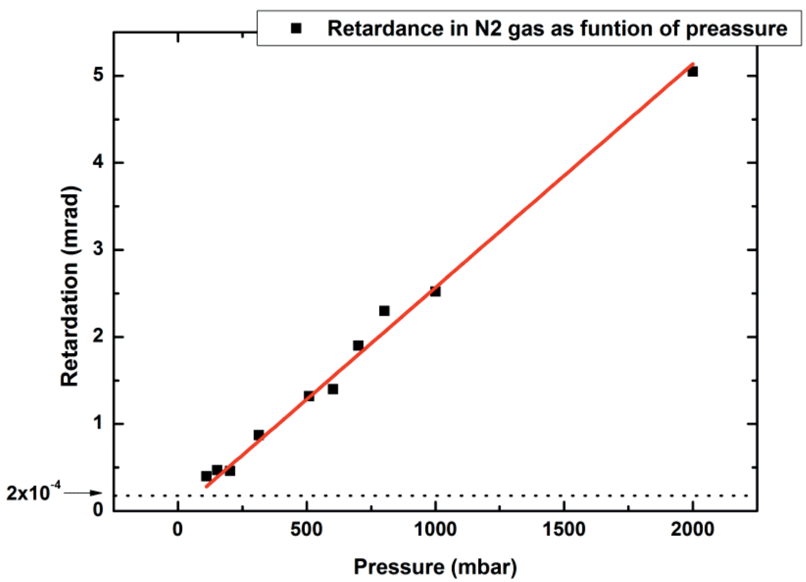


subtracted signal as function magnetic filed

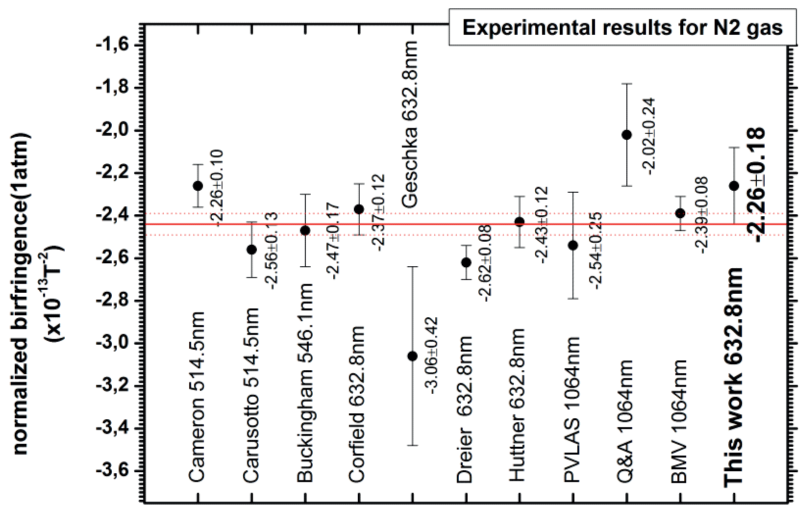
The results of measuring Cotton - Mouton in N2

Measurements as function of pressure 100 - 2000 mbar

Birefringence as function of pressure



Comparison with other experiments



Conclusion of birefringence measurement

- The lowest measurable value of birefringence for one passage LHC magnet is **2×10^{-4} rad**

- For the He-Ne laser and 14.3 m long LHC magnet is the lowest measurable difference in refractive index **$\Delta n \approx 1.8 \times 10^{-14}$ in 9T field**

- **All previous measurements were realized without the use of optical cavities a magnet modulation**

- **Optical cavity may increase the sensitivity by a factor of 10^3**

How to improve OSQAR experiment Future plans

1. Optical cavity

- longer path in magnetic field
- beter signal stability
- First test in 2014 whit 3m long prototype

4. Magnet modulation - 2 mHz

5. More LHC dipoles

6. Different setup of ellipsometer

7. Different measurement principle