Miroslav Sulc

on behalf of OSQAR collaboration

PROGRESS OF THE LASER-BASED EXPERIMENT OSQAR

Outline

- OSQAR short presentation
- Scientific Motivations
- OSQAR experiments
  - LHC magnets
  - Photon regeneration effect
  - Photon regeneration data analysis
  - Vacuum Magnetic Birefringence
  - Cavities preparation
- Conclusion

OSQAR

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

- 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
- Situated at CERN, magnet test hall SM 18

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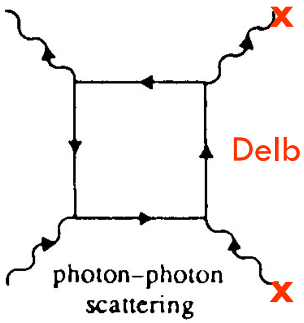
Scientific Motivations in a Nutshell
(P. Pugnat)

- **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
- **To measure for the first 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



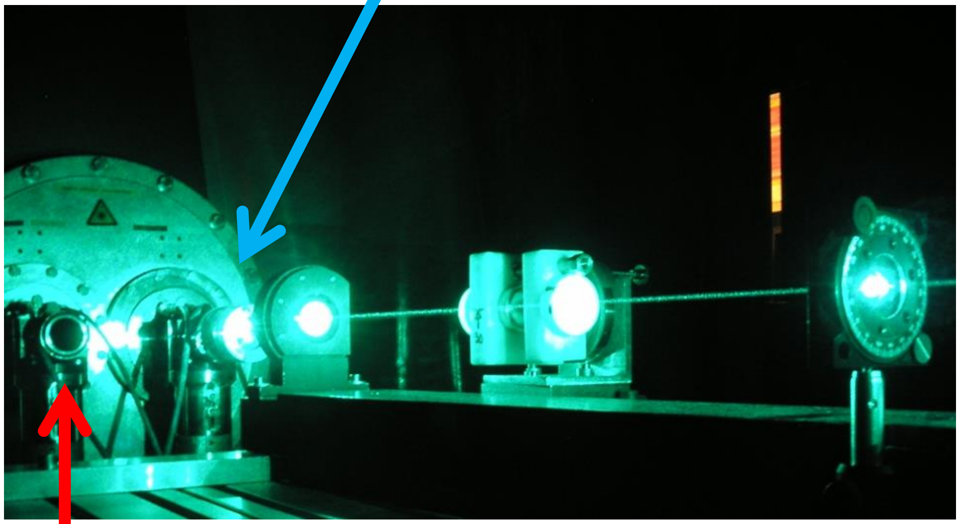
Delbrück scattering

- **A New Way of doing Particle Physics** based on Laser beam(s)
- **New very precise and sensitive optical method needed - big challenge**

OSQAR experiments

- OSQAR 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, 9.5 T over 2 x 14.3 m

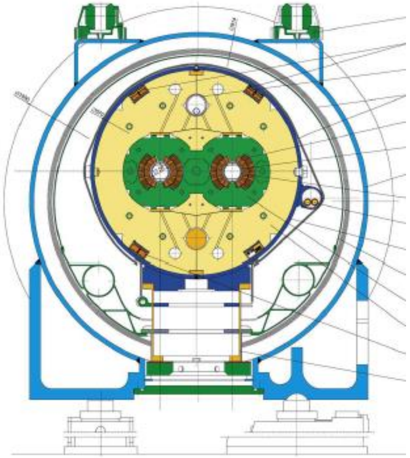
1.Aperture
Photon Regeneration Experiment



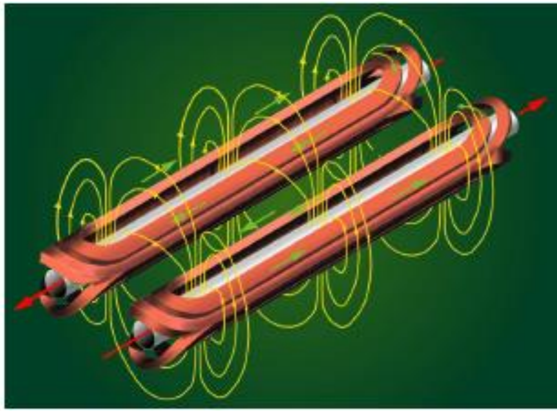
2. Aperture
Vacuum Magnetic Birefringence

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

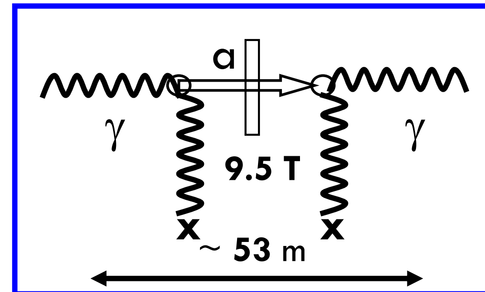


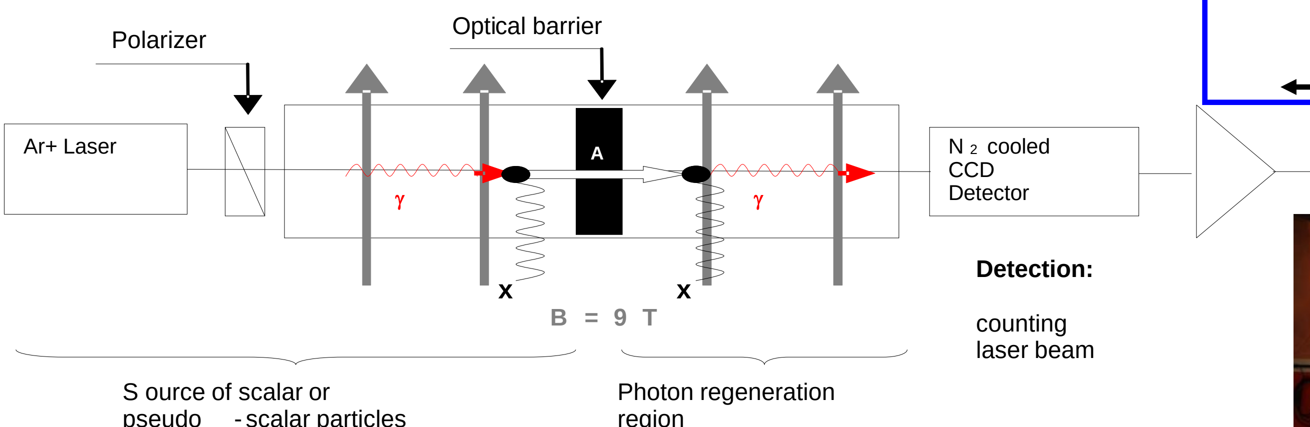
- Magnetic field of LHC dipole 9.5 T
- Effective length 14.3 m
- Filed is perpendicular to the 2 pipes



Photon regeneration effect

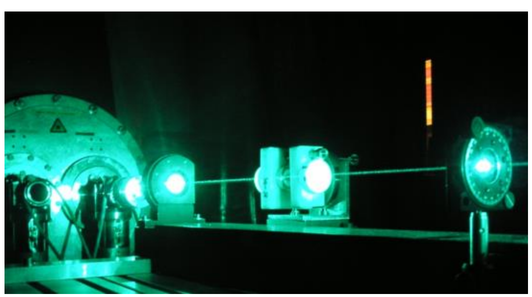
The photon regeneration effect is looked as a light shining through the wall





Two magnets separated by an optical barrier

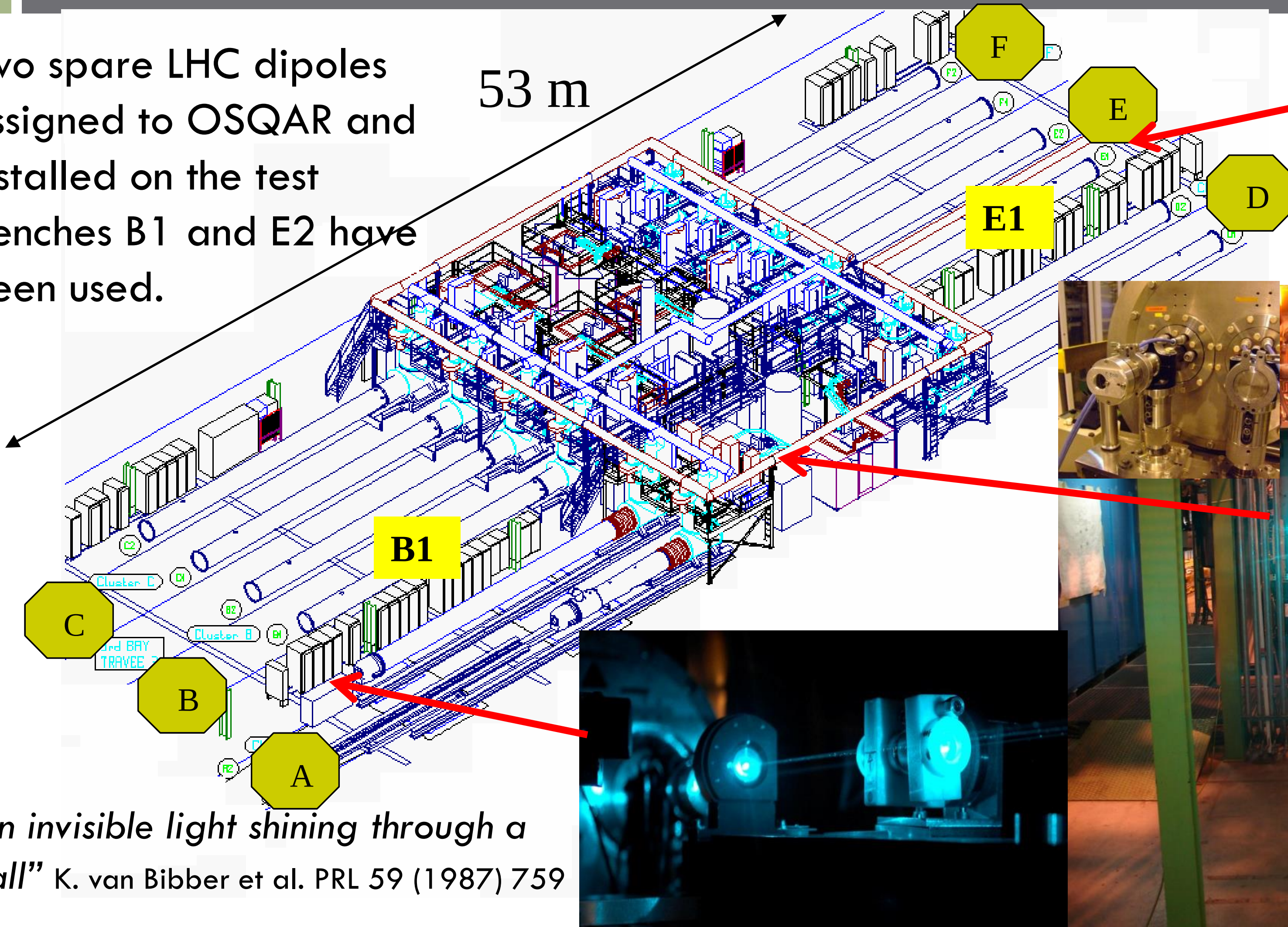
Argon laser is a source of photons

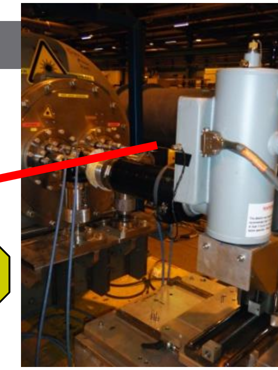


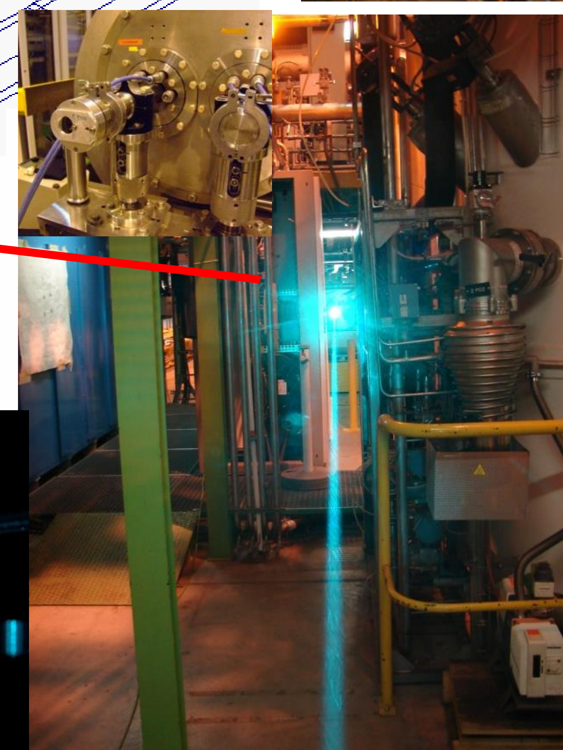
The CCD detector, cooled by liquid nitrogen, measures the laser beam profile by photon counting method

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.

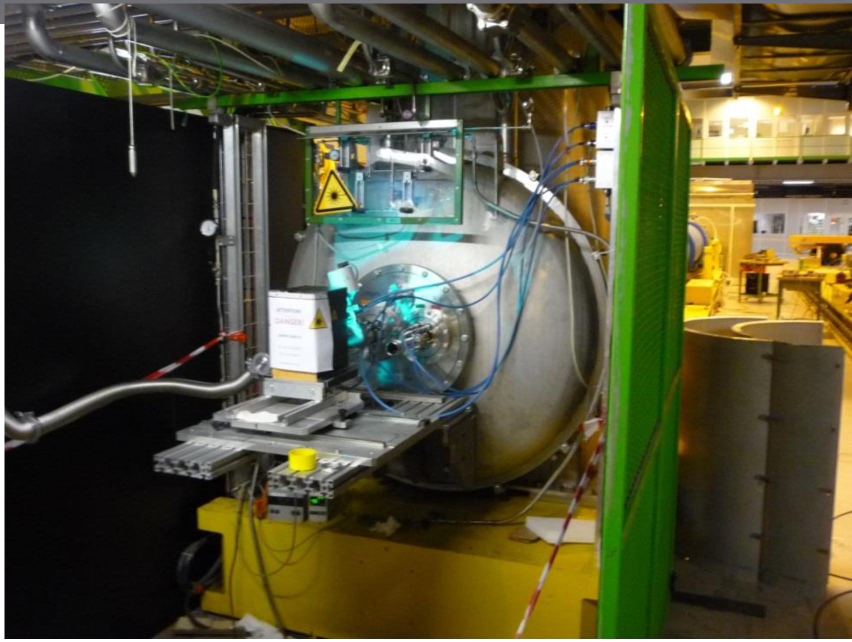






"An invisible light shining through a wall" K. van Bibber et al. PRL 59 (1987) 759

Light shining through the wall



Ar$^+$ laser is a source of 3 - 25 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.

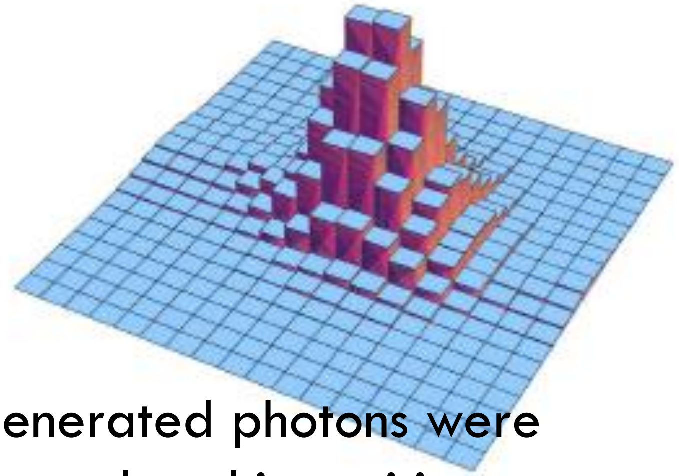
CCD detector

LN/CCD-1024E/1

- Low read noise 3.4 e^-
- Low dark current 0.5 e^-/pixel/hour
- cryogenic cooling
- QE ~ 30 % at 488-514 nm

CCD chip, EEV 1024 × 256 square pixels of 26 μm, 26.6 x 6.7 mm
Pixels were binned to 2x2 superpixels

- the effective beam spot on the CCD was decreased by using an optical lens with a focal length of 100 mm
- spot consists from 30 superpixels

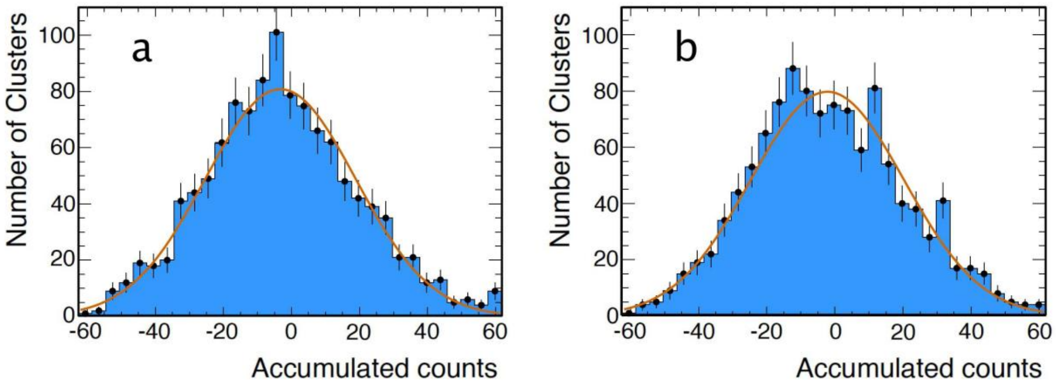


- Regenerated photons were expected at this position

Method of signals filtering was applied

- Cosmic cleaning procedure was applied systematically to each 2D image
- average recorded count-rate per super-pixel was treated as a constant bias or offset and therefore subtracted from each spectrum
- Alternatively the subtraction of the background acquisition frame to each spectrum acquired for WIPs search gives no significant difference
- scalar and pseudoscalar particles spectra have been added separately
- The cosmic cleaning procedure has been applied a second time in order to identify hot cells, which were rejected from further study
- the final data spectrum has been clustered to optimize the experimental sensitivity to a rectangle of 4×5 super-pixels
- The integrated signal of each cluster is defined by the sum of all recorded counts of the corresponding 20 super-pixels.
- Resulting histograms were made

Gaussian distribution



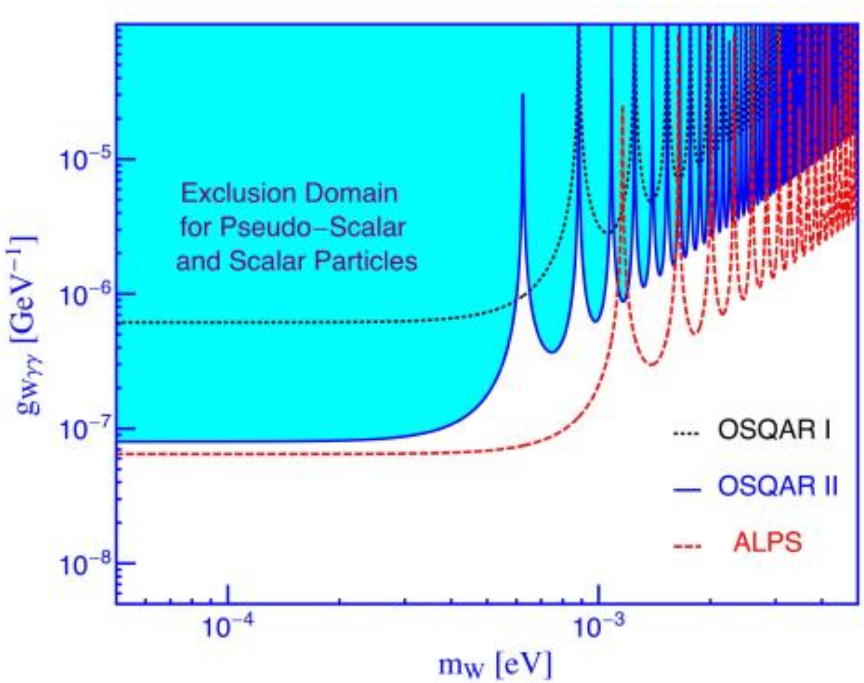
Histograms of the accumulated counts from clusters of super-pixels of the CCD for a) pseudoscalar and b) scalar

We have statistic from only 21/23 hours with 1.6 W power because in 2012 run
laser was falling down to 0.3-1.1 W

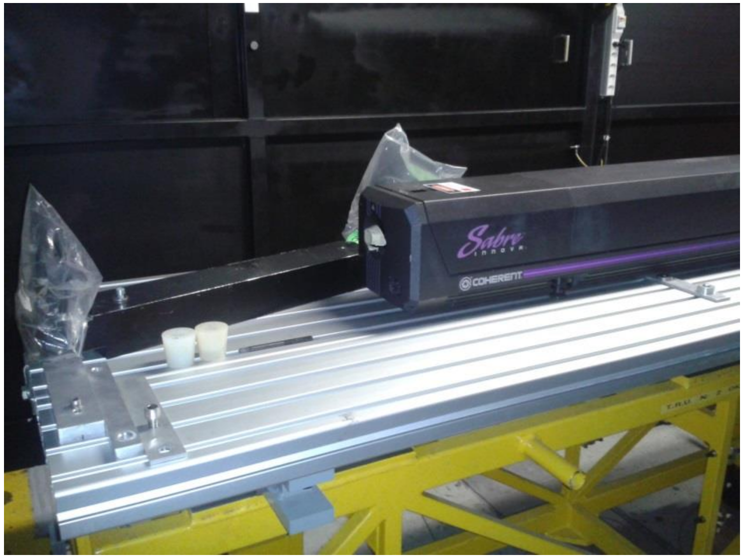
It corresponds to 137 cluster counts and gives a limit to the sensitivity of 6.32 photon/h or 1.76×10^{-3} photon/s.

Results from data analysis

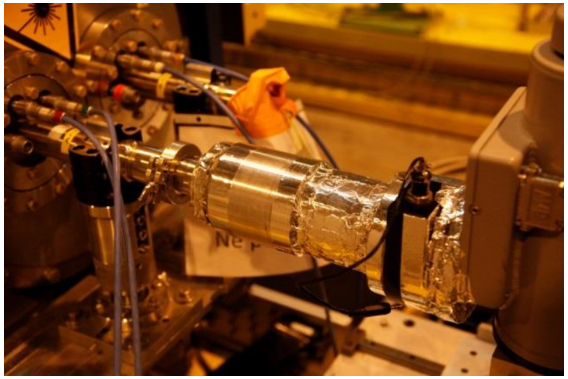
- The exclusion limits of coupling constants that can be deduced are $8 \cdot 10^{-8}$ GeV^{-1} for pseudo-scalar and scalar particle search in the massless limit
- Exclusion limits confirm the present reference results obtained by the ALPS collaboration



Run in August/September 2013

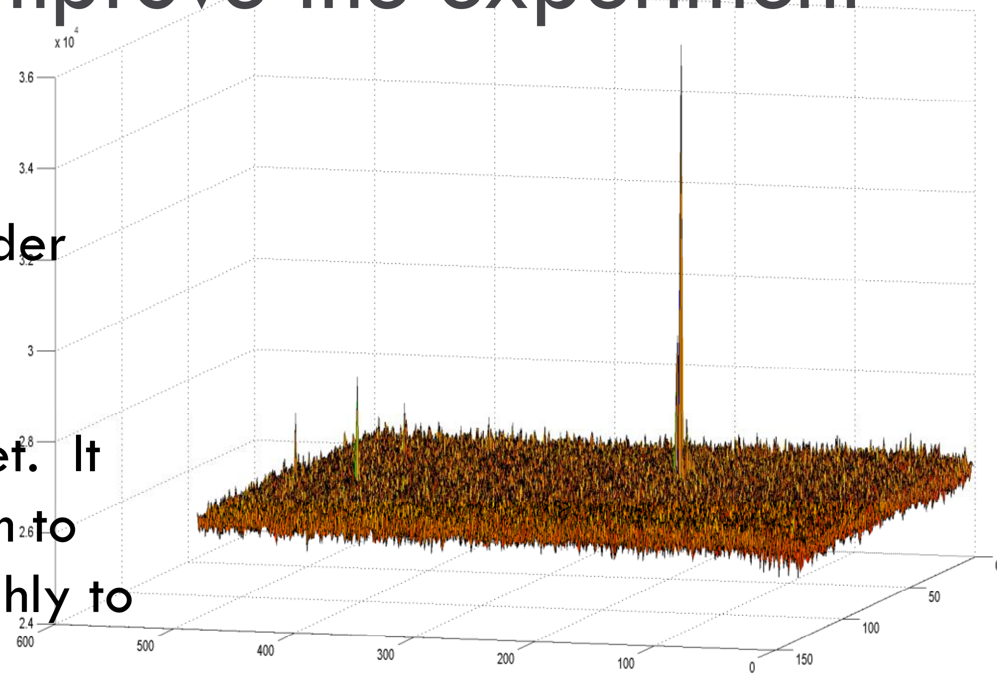


- 25 W argon laser will be used
- Around 200 hours for both scalar and pseudoscalar measurement



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

Aadjustments to improve the experiment



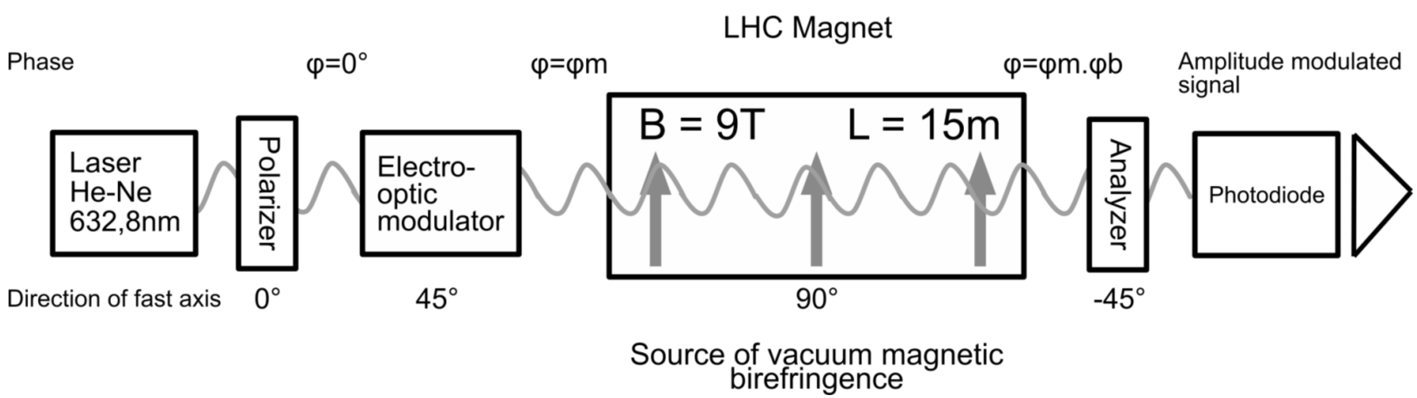
The adjustable beam expander helps to receive appropriate intensity profile at the outer window of the second magnet. It has helped to focus the beam to very small spot on CCD, roughly to one double binning (2x2) superpixel. FWHM was about one superpixel ≈ 60 μm

- Still better statistics method can be used

We want to extend exclusion limit to $2 \cdot 10^{-8}$ GeV^{-1} for pseudo-scalar and scalar particle search in the massless limit

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



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

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

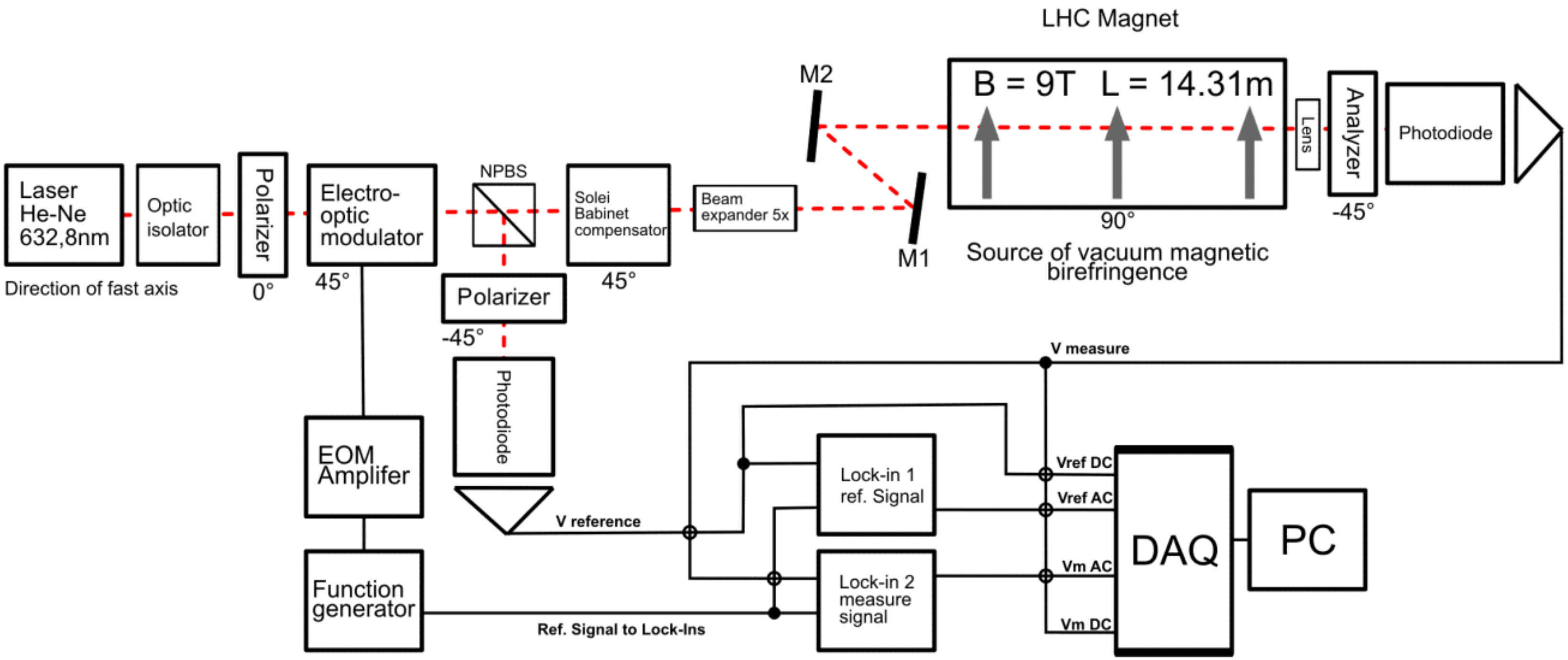
Magnetic filed rotation or modulation

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

Electric filed rotation

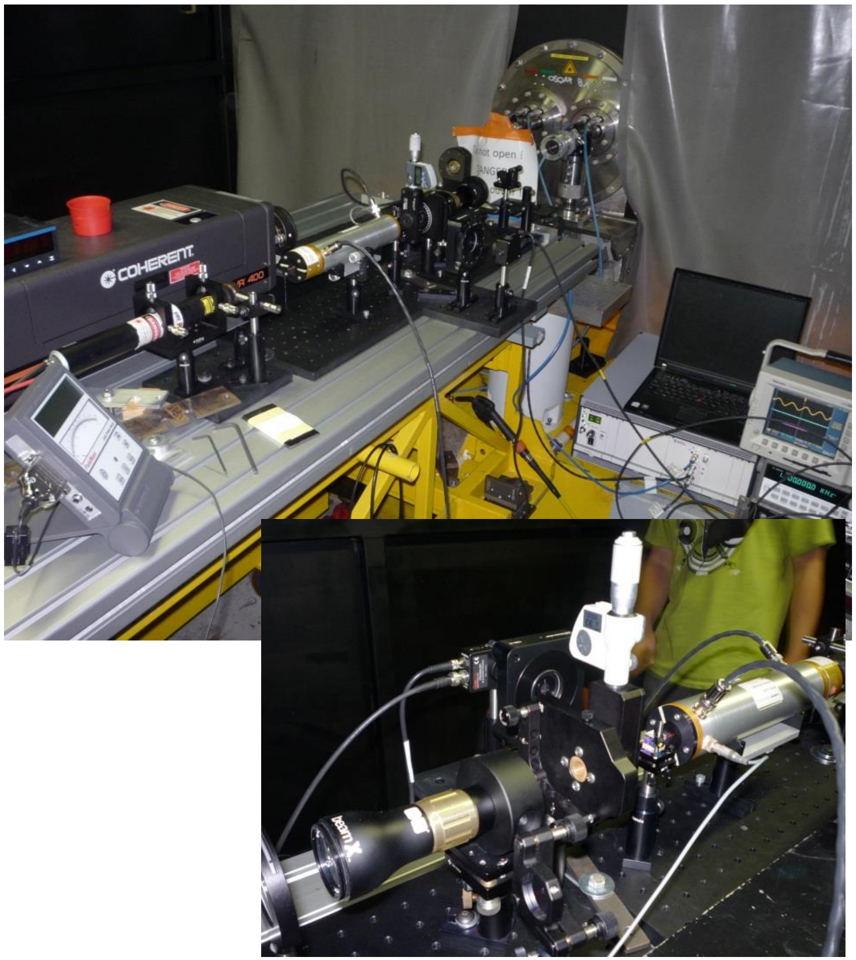
- Half-wave plate ~300 Hz (OSQAR 2007)
- Electro-optical modulator **EOM** ~ 30 MHz

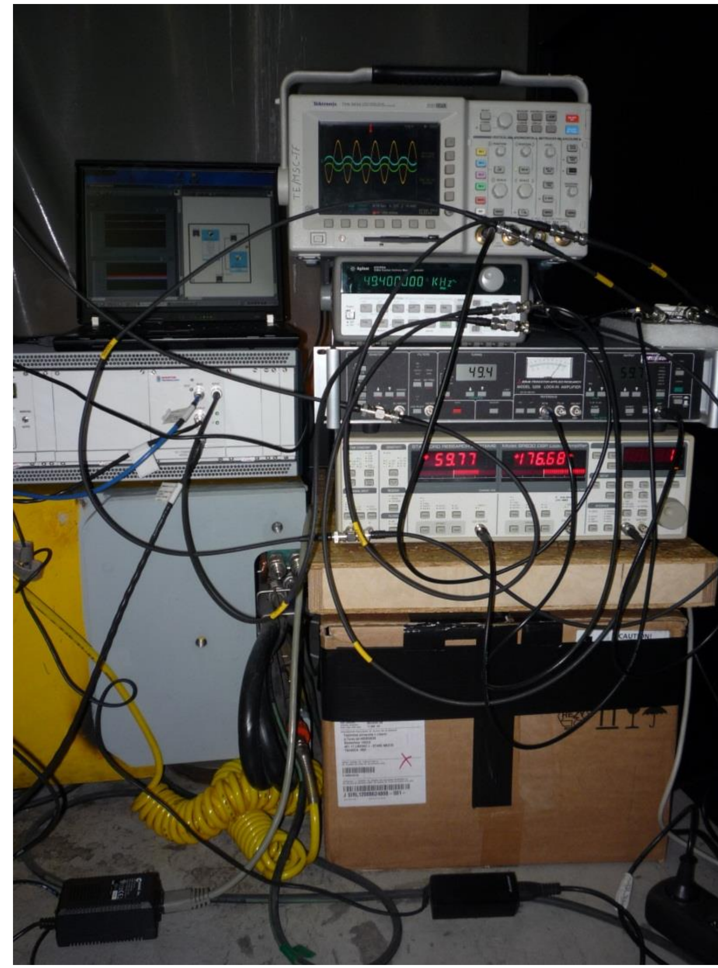
Set-up for the measurement of the Gas Magnetic Birefringence with electro-optic modulator



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

Photos of real experiment September 2012



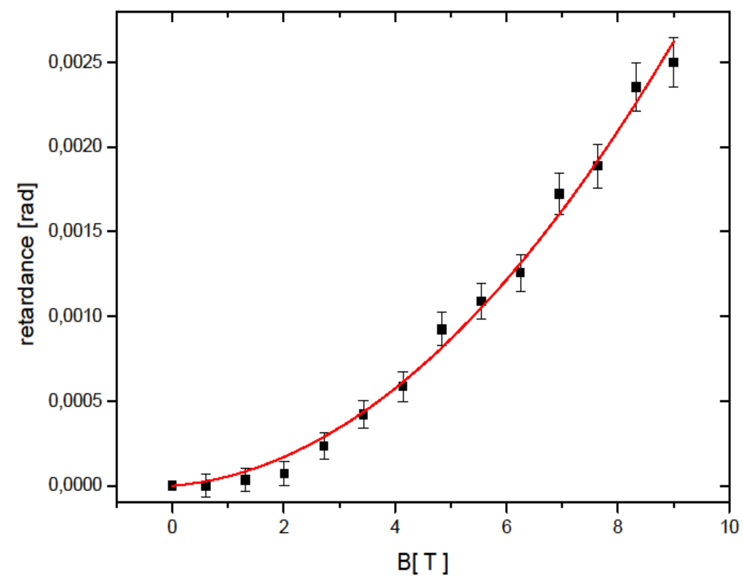


The Cotton-Mouton effect in N_2

- 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 $-3.6\cdot10^{-7}$ rad $T^{-2}m^{-1}$.
- The difference in refractive indices is

$$\Delta n \approx -(2.28\cdot\pm0.16)\cdot10^{-13}$$

for N_2 at atmospheric pressure in 1 T field



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

Expected OSQAR VMB sensitivity

- New PID controller has been created for stability improvement of an electro-optic modulator (EOM) in 2013
- New method was tested in 2013 with higher accuracy
- Birefringence δ sensitivity of our set-up is extending to $2 \cdot 10^{-4}$ 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 $\boldsymbol{\Delta n \approx 1.3 \cdot 10^{-12}}$ can be measurable
- **Our previous experiments were made without resonant cavities**
- Cavity can improve sensitivity by a factor 10^3
- **We are still far from QED prediction, but we are approaching. We will be able to measure the Cotton-Mouton effect for helium**

Cavities

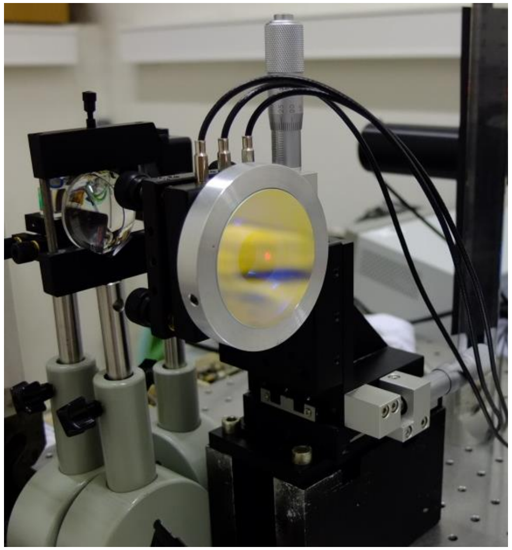
- Aim – to increase path of the laser beam in the magnetic field $\rightarrow$ **using a cavity**
- Magnetic length of LHC magnets is 14.3 m
- Inner tubes are curved – effective aperture is about 23 mm

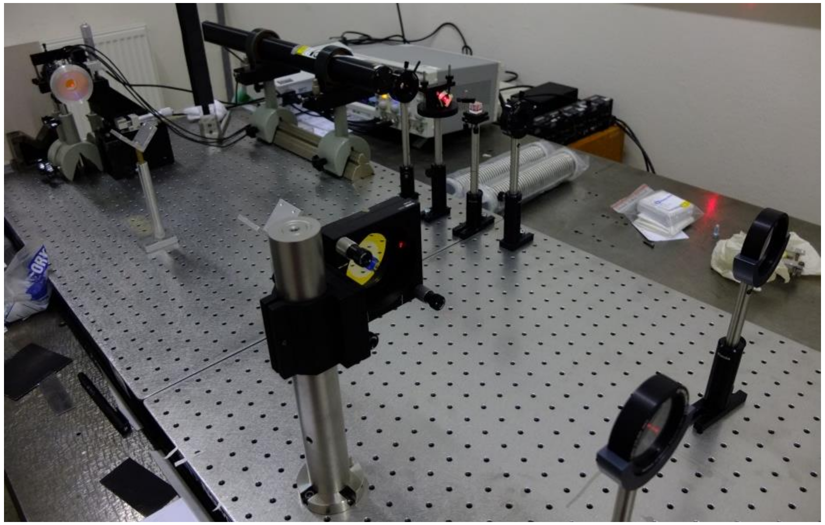
Aim and challenge

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

Development of high finesse 1 m long optical cavity

- The one meter long prototype of plano-concave resonator cavity was finished at Czech Technical University , Prague
- The light was locked inside the cavity by using the Pound-Drever-Hall lock-in technique
- Cavity finesse was 300



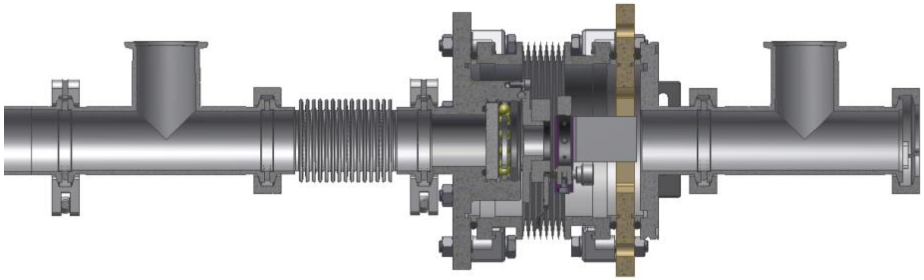


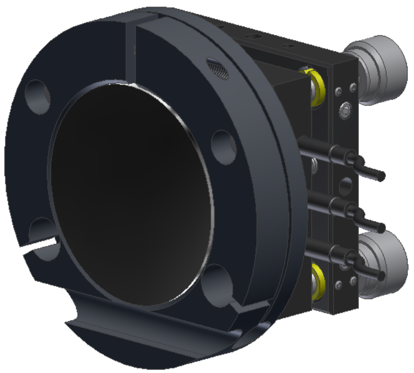
- We have new experiences with beam alignment and beam cavity mode matching for optical coupling of the laser beam to the cavity

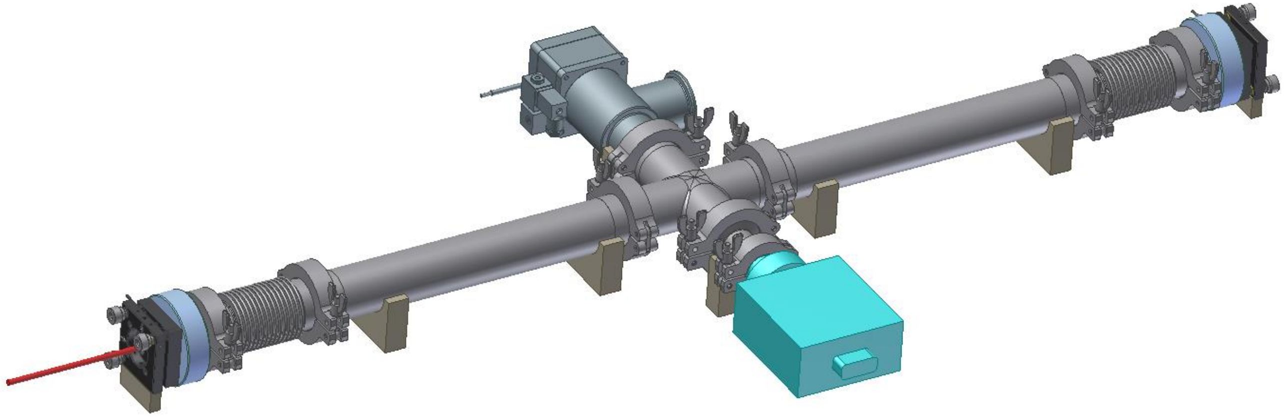
Full length 19.6 m cavity for VMB, stabilized He-Ne laser, 632.8 nm

Cavity was designed on the base of the prototype
- to be compatible with LHC vacuum system,
- isolated from vibrations

It is almost complete now

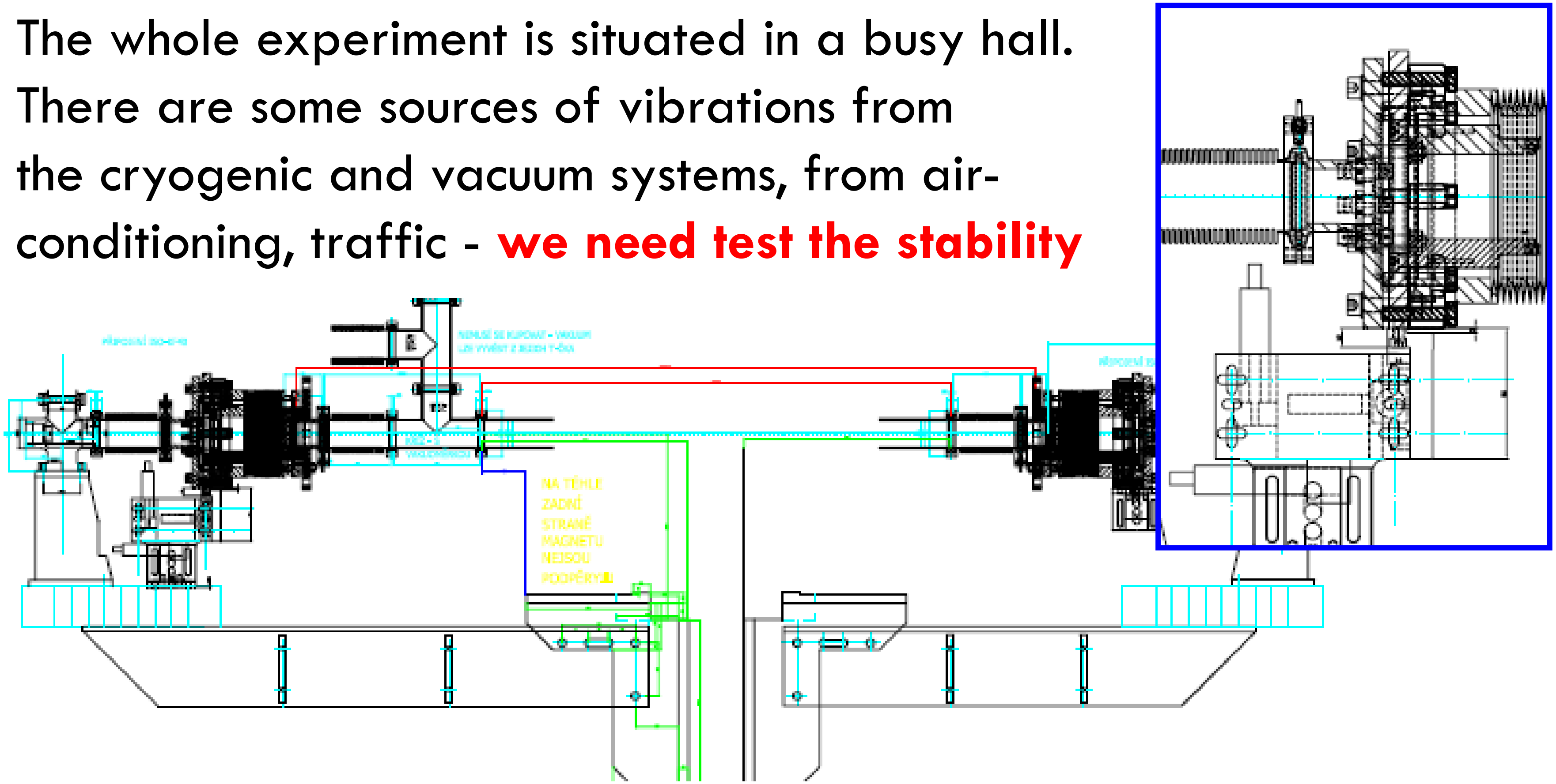






Implementation to LHC magnet in CERN SM18 hall

The whole experiment is situated in a busy hall. There are some sources of vibrations from the cryogenic and vacuum systems, from air-conditioning, traffic - **we need test the stability**



The first tests and implementation will be at September 2013

Cavity for Photon Regeneration

- Aim - to profit from the large laser intracavity optical power
- Based on the same mechanics, vacuum and electronic parts as for VMB
- High quality mirror layers are necessary
- The implementation of the resonantly-enhanced conversion scheme* with two long length cavities is challenging
- technical difficulties resulting from the design and realization of active locking systems for two high-finesse Fabry-Perot cavities

* P. Sikivie, D. B. Tanner, and Karl van Bibber, Phys. Rev.Lett. 98, 172002 (2007).
* G. Mueller, P. Sikivie, D.B. Tanner and K. van Bibber, Phys. Rev. D 80, 072004 (2009).

Conclusion

Photon regeneration

- The data from previous photon regeneration run for pseudoscalar/axion and scalar particle search have been deeply analyzed
- They confirm the results published by the ALPs collaboration
- New OSQAR run is prepared to extend exclusion limits about factor four

Vacuum Magnetic Birefringence

- Cotton-Mouton effect in nitrogen was measured with electro-optical modulator set-up
- The VMB sensitivity is suitable for the Cotton-Mouton effect at helium measurement

Cavities

- The 1 m long prototype cavity was built
- New cavity will be prepared to 2013 VMB measurement

THANK YOU FOR YOUR ATTENTION