PVLAS

Guido Zavattini,
Università di Ferrara and INFN-Ferrara

"Hands holding the void"
Alberto Giacometti

Summary

- Experimental aim and technique
- Published experimental results
- Discussion - comments - criticisms
- What questions can be answered
- Physics results

Legnaro
U. Gastaldi (g)
G. Ruoso (l)
G. Petrucci (h)

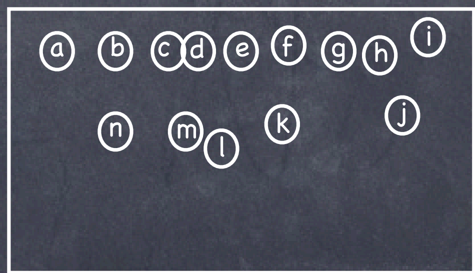
Trieste
M. Bregant
F. Della Valle (j)
G. Cantatore (e)
M. Karuza (m)
E. Milotti (b)
G. Raiteri
E. Zavattini (c)

Ferrara
G. Di Domenico (k)
G. Zavattini (n)

Pisa
E. Polacco (a)
S. Carusotto

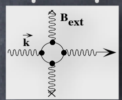
Frascati
R. Cimino (d)

Technical support
S. Marigo (f)
A. Zanetti (i)
G. Venier



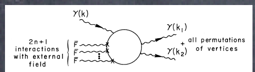
Theme

- Theme
  - Vacuum is a physical state and can be treated as a "material medium"
  - **Perturb** the vacuum with an external magnetic field
  - Use a polarized light beam as a **probe** to measure the effect of the magnetic field
  - Extract information about the **structure** of vacuum
    - QED interactions
    - other interactions?
- Aim
  - Macroscopic properties can be deduced from effective lagrangians
  - Measure the magnetically induced linear birefringence and linear dichroism (optical rotation) of vacuum
  - Possible contributions to macroscopic properties
    - photon-photon scattering →

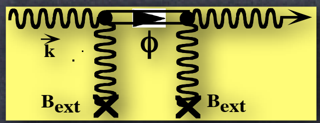


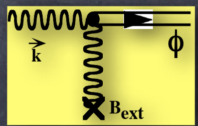
+ diagrams of order higher than α^2

    - photon splitting



    - production of:
      - neutral bosons
      - mcp
      - .....

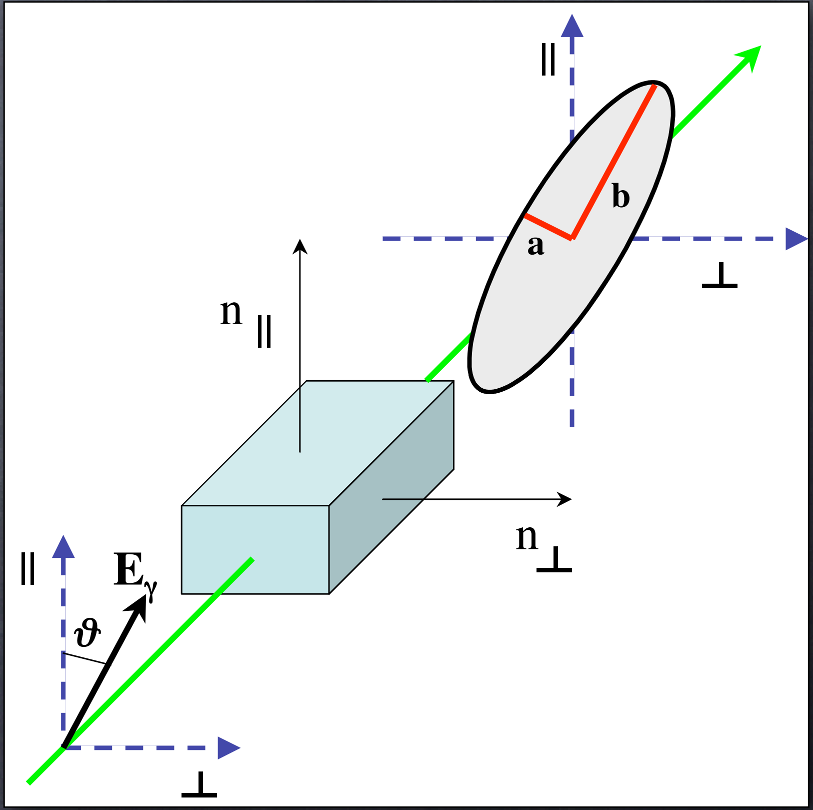




Linear Birefringence

- A birefringent medium has $n_{||} \neq n_{\perp}$
- A linearly polarised light beam propagating through a birefringent medium will acquire an <u>ellipticity</u> Ψ

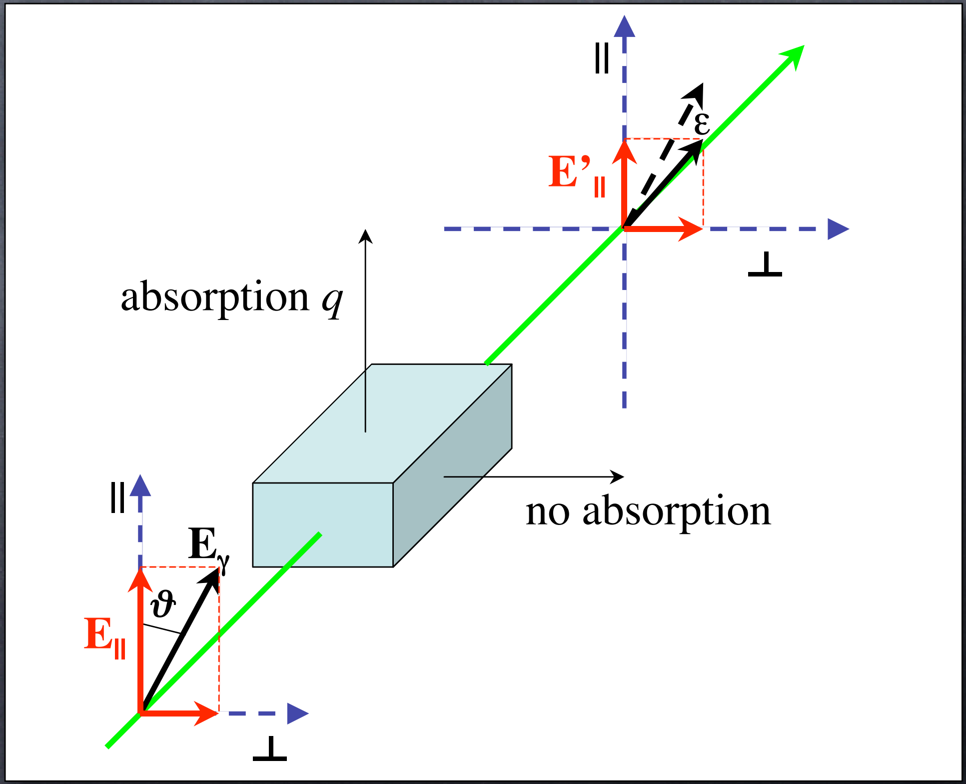
$$\psi = \frac{a}{b} = \frac{\pi L}{\lambda}\left(n_{\parallel} - n_{\perp}\right)\sin 2\vartheta$$



Linear Dichroism

- A dichroic medium has a selective absorption of a polarization component
- A linearly polarised light beam propagating through a dichroic medium will acquire a (apparent) rotation ε

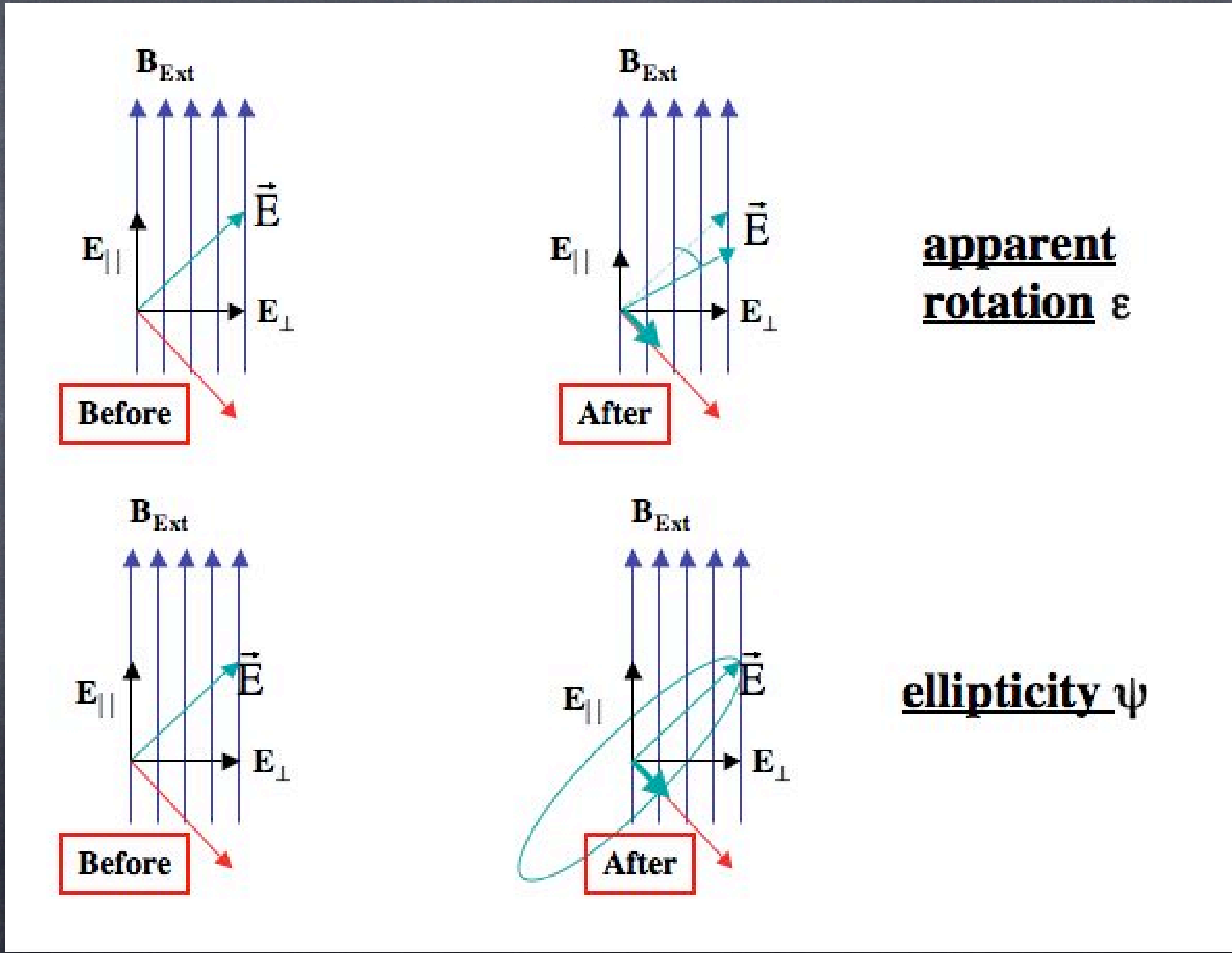
$$\varepsilon = \left(\frac{1-q}{2}\right)\sin 2\vartheta$$



Measured quantity

Dichroism

Birefringence



Electromagnetic vacuum

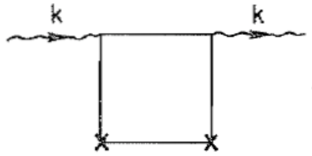
$$\mathcal{L}_{EM} = \frac{1}{8\pi}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{A_e}{4\pi}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}\right)^2\right]$$

$$A_e = \frac{1}{90\pi}\left(\frac{\alpha^2 \lambda\!\!\!^-{}_e^3}{m_e c^2}\right) \approx \frac{4}{3}\cdot 10^{-32}\ \frac{\mathrm{cm}^3}{\mathrm{erg}}$$

W Heisenberg and H Euler, *Z. Phys*. **98**, 714 (1936)
H Euler, *Ann. Phys*. **26**, 398 (1936)

- Light propagation through magnetized vacuum is still described by Maxwell's equations in matter. They are no longer linear.
- Linearly polarized light passing through a transverse magnetic field B_0 will acquire an ellipticity due to magnetically induced birefringence
- Adler (1971) also calculated photon splitting

Vacuum birefringence



+ permutations of vertices

$$\begin{cases} \varepsilon_{||} = 1 + 10 A_e B_0^2 \\ \mu_{||} = 1 + 4 A_e B_0^2 \\ n_{||} = 1 + 7 A_e B_0^2 \end{cases} \qquad \begin{cases} \varepsilon_{\perp} = 1 - 4 A_e B_0^2 \\ \mu_{\perp} = 1 + 12 A_e B_0^2 \\ n_{\perp} = 1 + 4 A_e B_0^2 \end{cases}$$

$\Delta n = 3 A_e B_0^2 \Rightarrow \Delta n = 1.2 \cdot 10^{-22}$ for $B_0 = 5.5\text{T}$

$$\psi_{PVLAS} = 2.1 \cdot 10^{-11}$$

- $v \neq c$
- anisotropy

A_e can be determined by measuring the magnetic birefringence of vacuum.

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

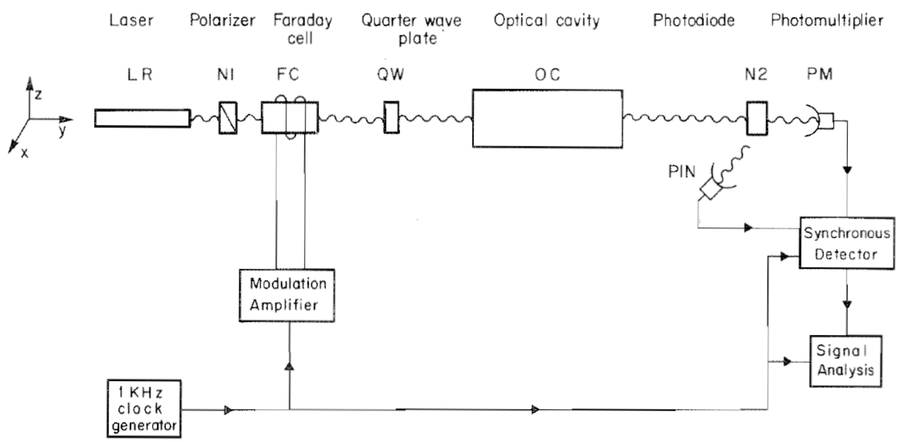


Fig. 3. Principle elements of the experimental apparatus.

First experimental scheme to measure magnetically induced vacuum birefringence with ellipsometric techniqes

Photon splitting

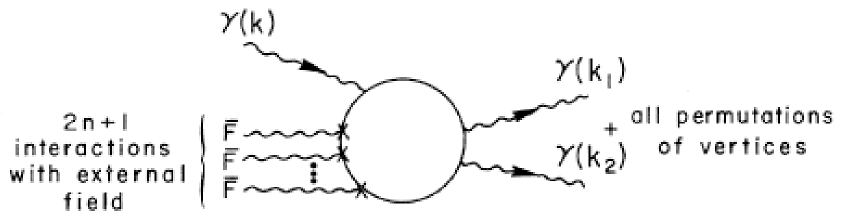


FIG. 1. Ring diagram for photon splitting involving $2n+1$ interactions with the external field.

$$\kappa[(\parallel)\to(\parallel)_1+(\parallel)_2]=\frac{\alpha^3}{60\pi^2}\left(\frac{48}{315}\right)^2\left(\frac{\omega}{m}\right)^5\left(\frac{\bar{B}\sin\theta}{B_{cr}}\right)^6 m=0.39\left(\frac{\omega}{m}\right)^5\left(\frac{\bar{B}\sin\theta}{B_{cr}}\right)^6\ \mathrm{cm}^{-1},$$

$$\kappa[(\parallel)\to(\perp)_1+(\perp)_2]=\frac{\alpha^3}{60\pi^2}\left(\frac{26}{315}\right)^2\left(\frac{\omega}{m}\right)^5\left(\frac{\bar{B}\sin\theta}{B_{cr}}\right)^6 m=0.12\left(\frac{\omega}{m}\right)^5\left(\frac{\bar{B}\sin\theta}{B_{cr}}\right)^6\ \mathrm{cm}^{-1},$$

$$\kappa[(\perp)\to(\parallel)_1+(\perp)_2]+\kappa[(\perp)\to(\perp)_1+(\parallel)_2]=2\kappa[(\parallel)\to(\perp)_1+(\perp)_1].$$

With B=5.5T and ω/m = 1/511000 one finds $\Delta k \approx 6\cdot10^{-83}$ cm^{-1}

With L_{eff} = 60 km => Dichroism induced rotation $\approx 2\cdot10^{-76}$ rad

Particle induced dichroism and ellipticity

[Maiani, Petronzio and Zavattini, Phys. Lett B, 175, no. 3 (1986)]

In this example there is an interaction if $B_{Ext} \parallel E$

Dichroism

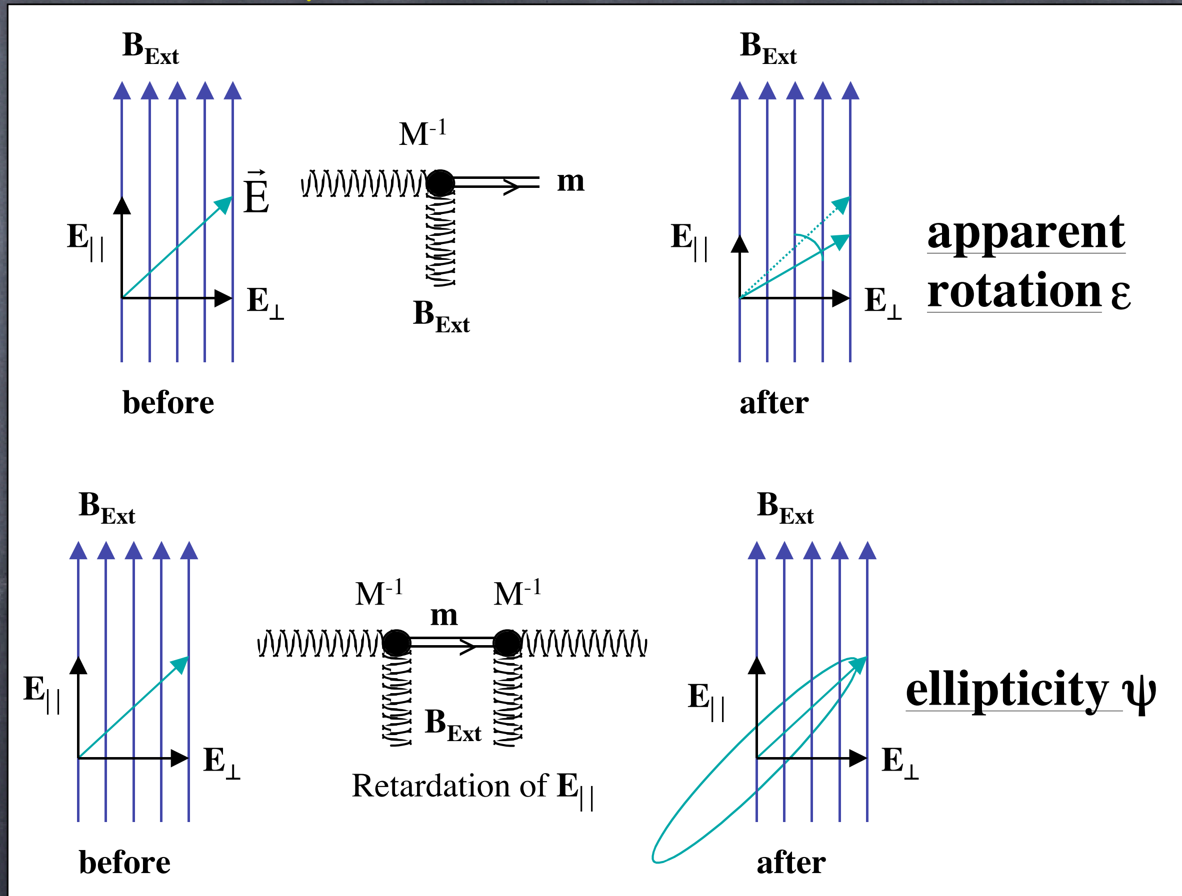
$$\varepsilon = \sin 2\vartheta \left(\frac{BL}{4M}\right)^2 N \left(\frac{\sin x}{x}\right)^2$$

Birefringence

$$\psi = \sin 2\vartheta \frac{kB^2 L}{4M^2 k_m^{\ 2}} N \left(1 - \frac{\sin 2x}{2x}\right)$$

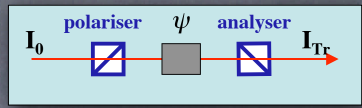
$$x = \frac{L}{2}\left[\frac{k_m^{\ 2}}{2k}\right]$$

$$k = \frac{2\pi}{\lambda};\ N = \frac{2F}{\pi};\ k_m = \frac{mc}{\hbar}$$



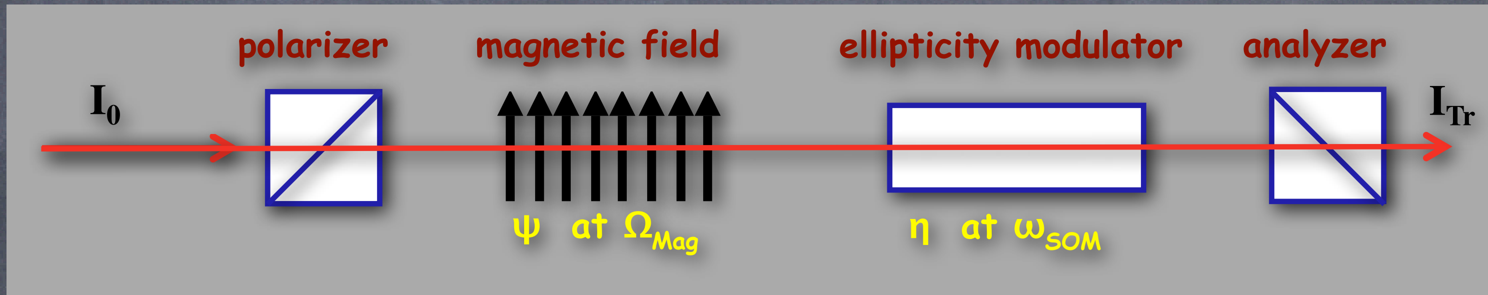
Ellipticity Measurement

- Static measurement is excluded



$$I_{tr} = I_0\left[\sigma^2 + \psi^2\right]$$

- Modulate the field and add a carrier signal at ω_{SOM}
- Rotating the field at Ω_{Mag} produces a signal at $2\Omega_{Mag}$



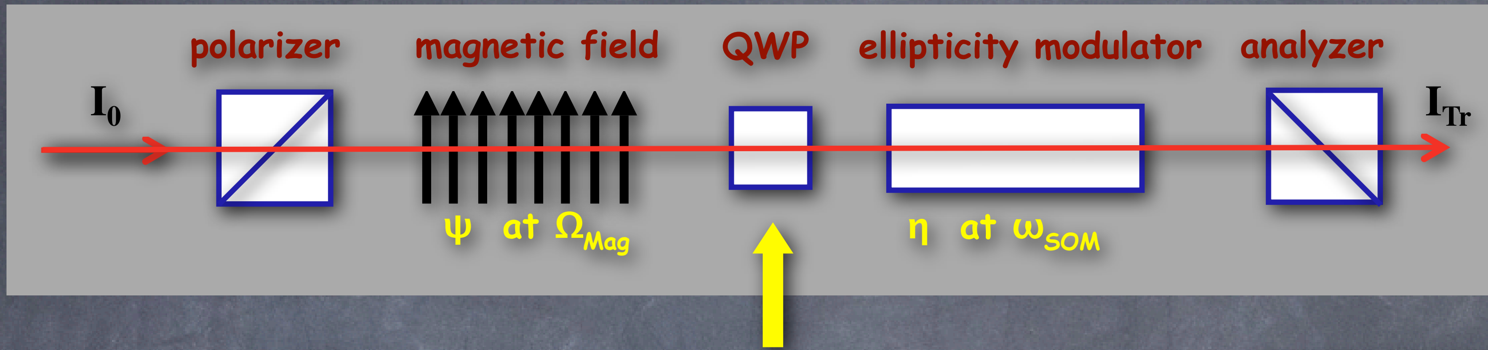
Ideally,

$$I_{Tr} = I_0\left[\sigma^2 + \left(\psi(t) + \eta(t)\right)^2\right] =$$
$$= I_0\left[\sigma^2 + \left(\psi(t)^2 + \eta(t)^2 + 2\psi(t)\eta(t)\right)\right]$$

The main frequency component appears at

$\omega_{SOM} \pm 2\Omega_{Mag}$ and $2\omega_{SOM}$

Rotation Measurement



A QWP can be inserted to transform a rotation into an ellipticity with the same amplitude. Two positions for the QWP slow axis: 0° and 90°.

$$\varepsilon(t) \quad => \quad \begin{cases} \Psi(t) & \text{for } \vartheta_{QWP} = 0^\circ \\ -\Psi(t) & \text{for } \vartheta_{QWP} = 90^\circ \end{cases}$$

The main frequency component appears at

$\omega_{SOM} \pm 2\Omega_{Mag}$ and $2\omega_{SOM}$

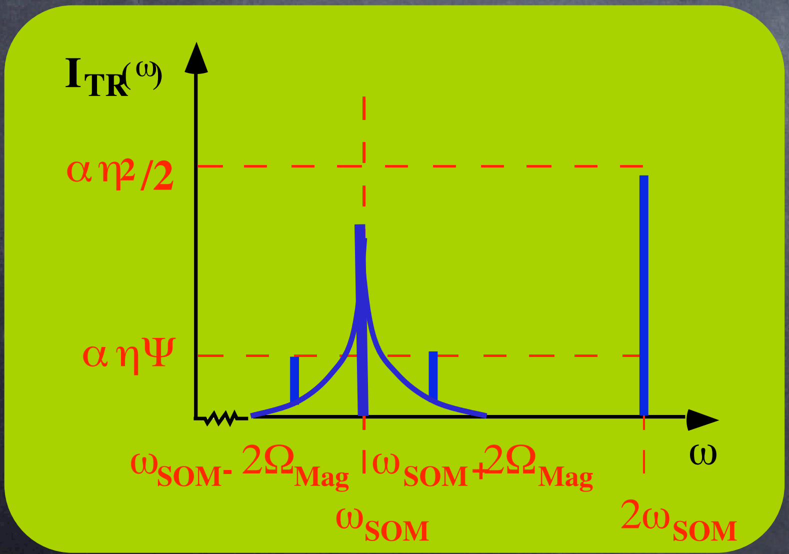
In practice, nearly static rotations/ellipticities α_s generate a 1/f noise around ω_{SOM}.

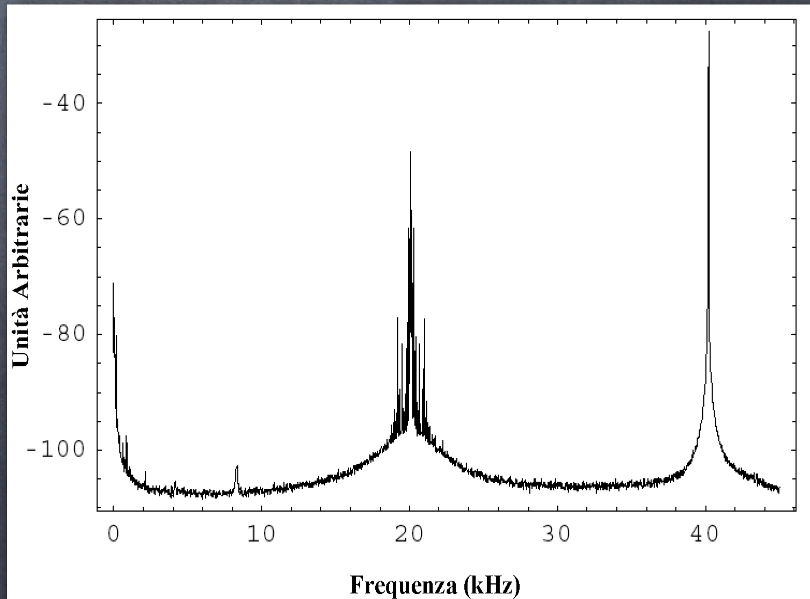
$$I_{Tr} = I_0\left[\sigma^2 + \left(\Psi(t) + \eta(t) + \alpha_s(t)\right)^2\right]$$
$$= I_0\left[\sigma^2 + \left(\eta(t)^2 + 2\Psi(t)\eta(t) + \underline{2\alpha_s(t)\eta(t)} + \ldots\right)\right]$$

Normalization

Desired signal

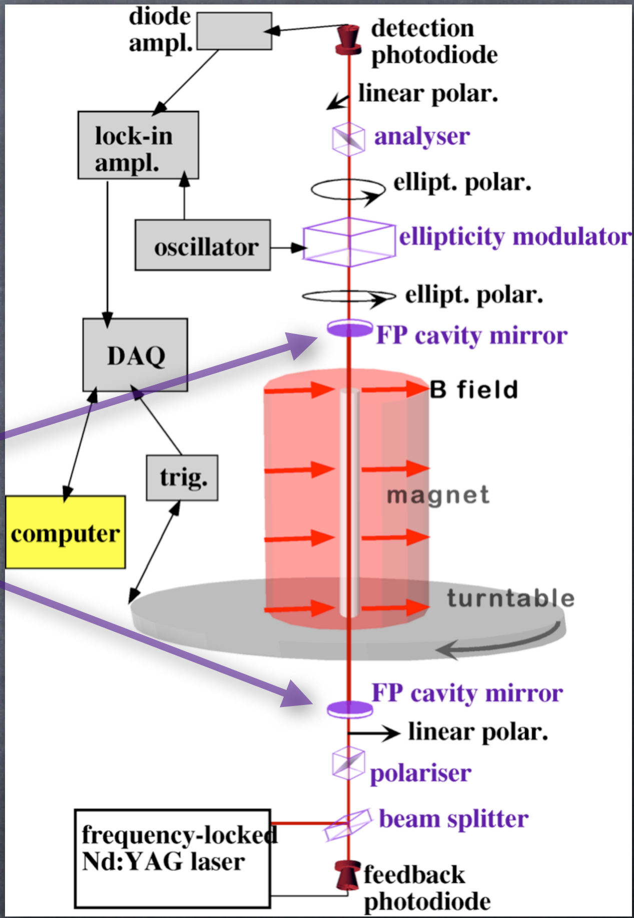
Birefringence noise





Particle production

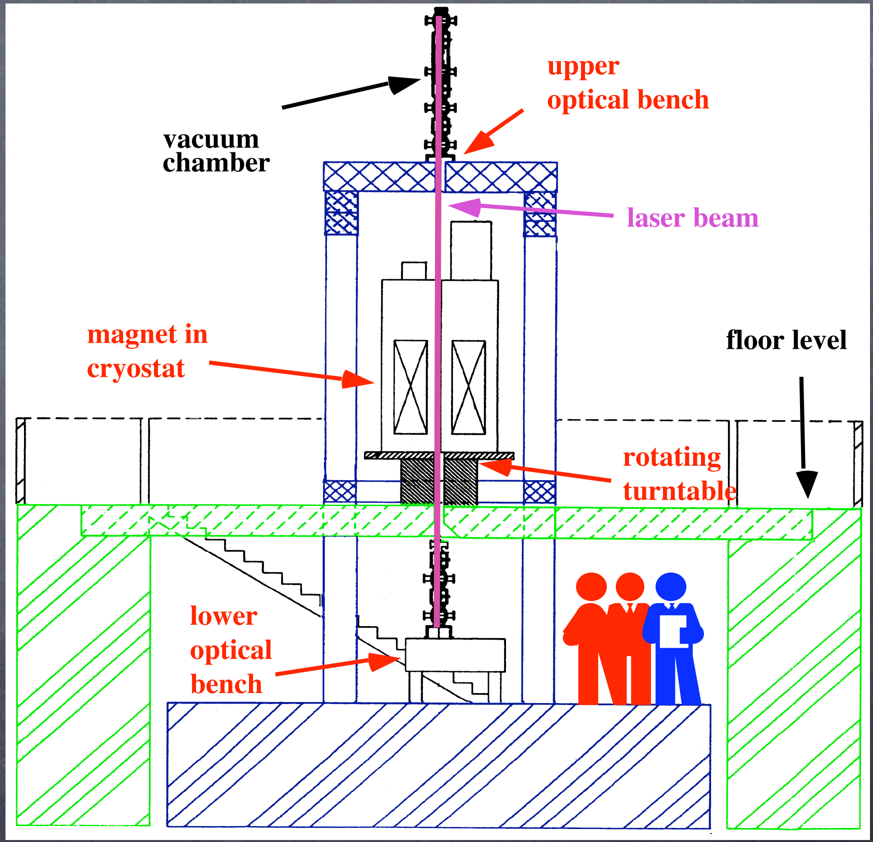
- Main parameters of the apparatus
  - magnet
    - dipole, 5.5 T, temp. 4.2 K, 1 m field zone
  - cryostat
    - rotation frequency ~300 mHz, sliding contacts, warm bore to allow light propagation in the interaction zone
  - laser
    - 1064 nm, 100 mW, frequency-locked to the F.-P. cavity
  - Fabry-Perot optical cavity
    - 6.4 m length, finesse ~100000, optical path in the interaction region ~ 60 km
  - heterodyne ellipsometer
    - ellipticity modulator (SOM) and high extinction ($\sim 10^{-7}$) crossed polarisers + Quarter Wave Plate (QWP)
    - time-modulation of the effect
  - detection chain
    - photodiode with low-noise amplifier
  - DAQ
    - Slow: demodulated at low frequency and phase-locked to the magnetic field instantaneous direction
    - Fast: high sampling frequency direct acquisition



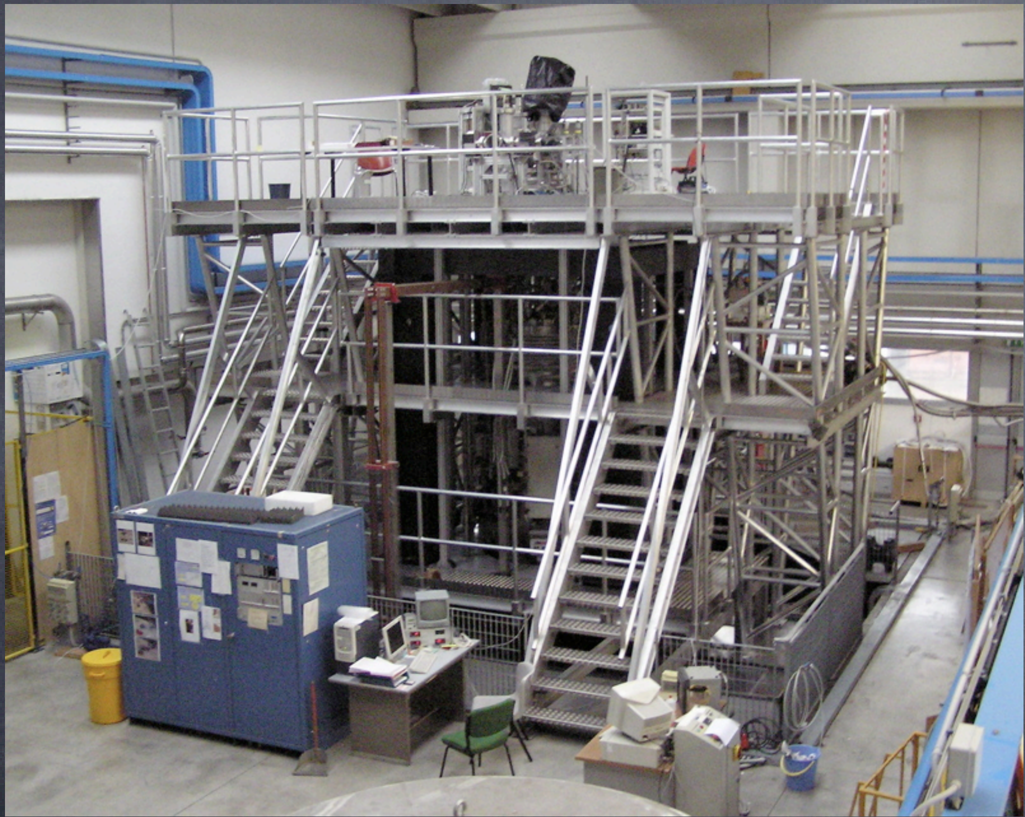
PVLAS: Schematic drawing

- The granite tower (blue in the drawing) supports the upper optical bench and is mechanically isolated from the hall (in green)

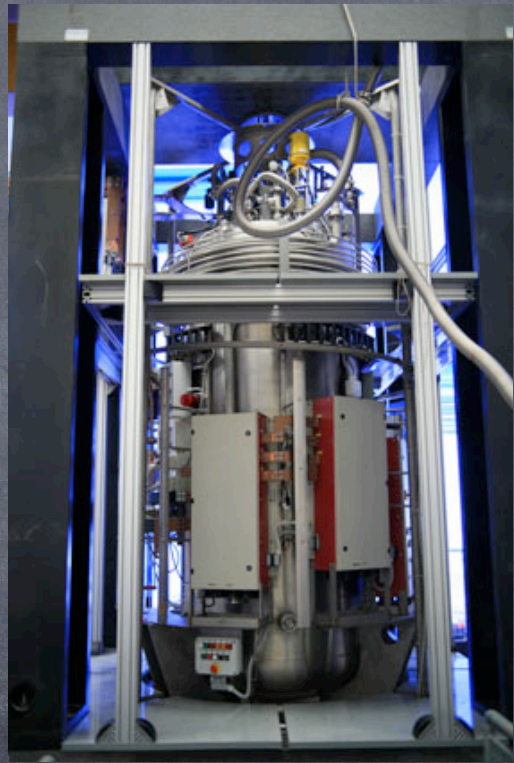
- The turntable, holding the magnet, rests on a beam fixed to the floor of the hall (green in the drawing)



PVLAS setup



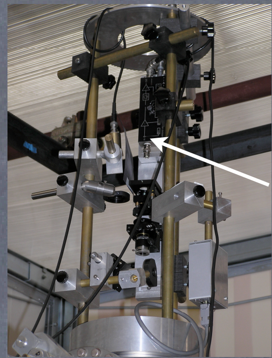
Experimatal hall



Warm bore cryostat for magnet

Optical benches

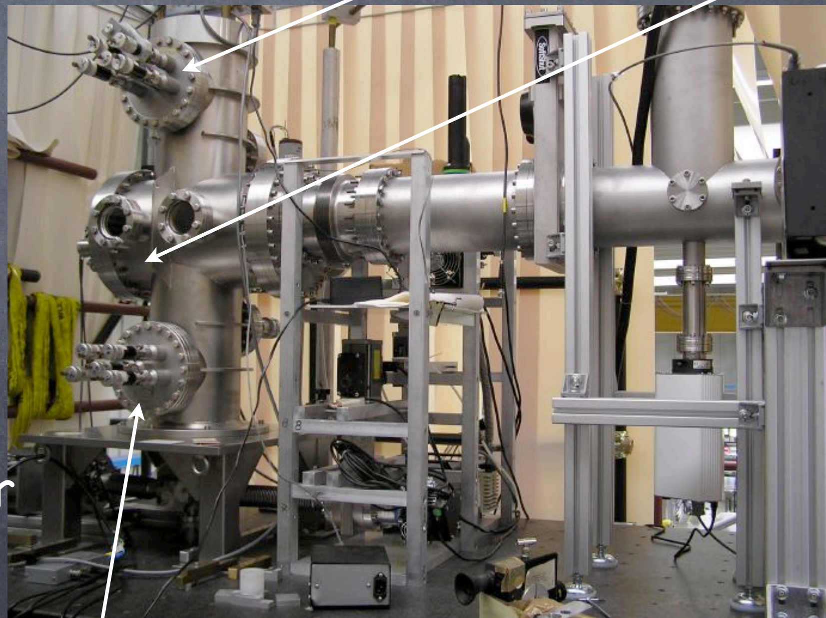
Upper optical bench



Photodiode

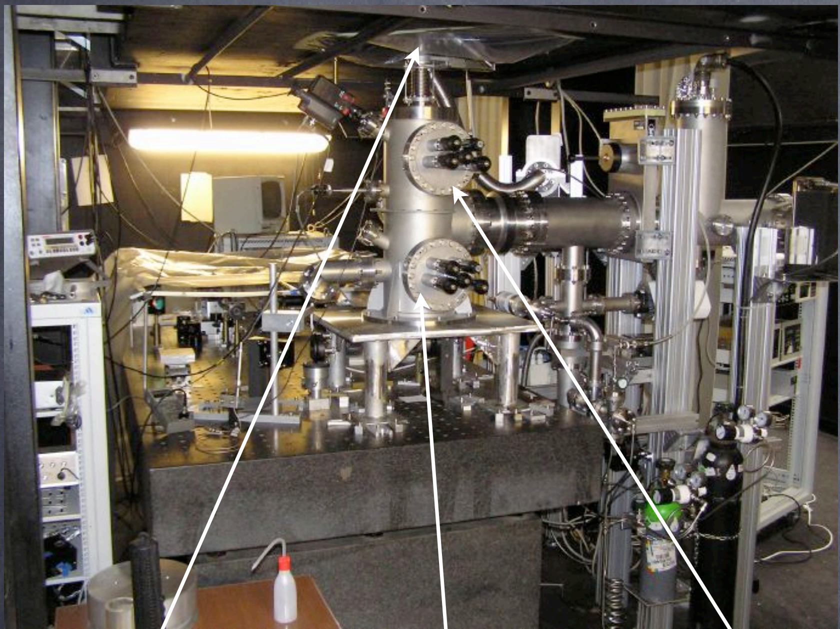
Analyzer

Modulator



Top mirror

Lower optical bench



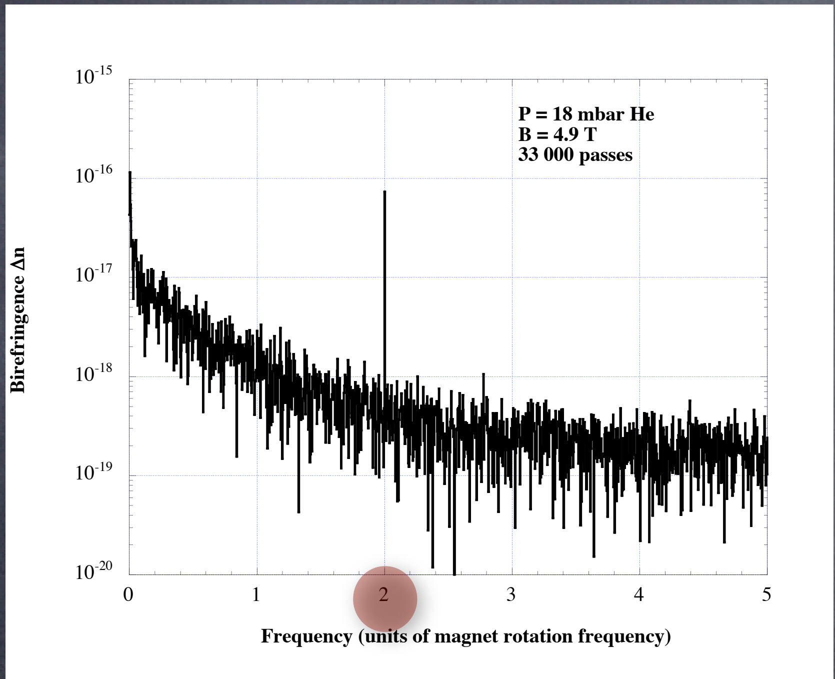
Quartz tube

Polarizer

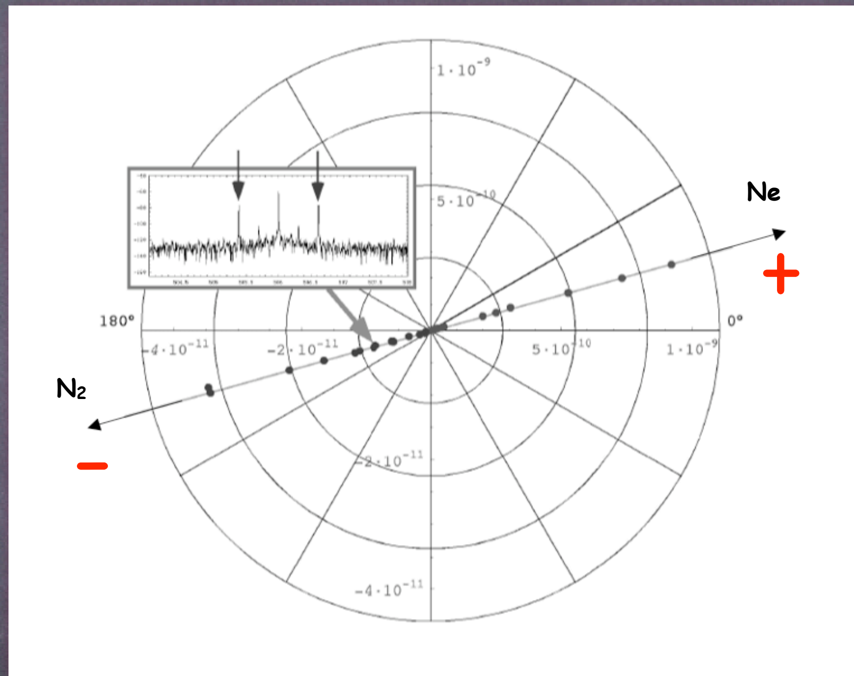
First mirror

Gas phase and amplitude calibration

- Signal amplitudes given by the ellipsometer can be checked by measuring the magnetic birefringence (Cotton-Mouton effect) of gases
- Signal phases are checked by plotting data in a phase-ampitude polar plane: points corresponding to different gas pressures must lie on a straight line

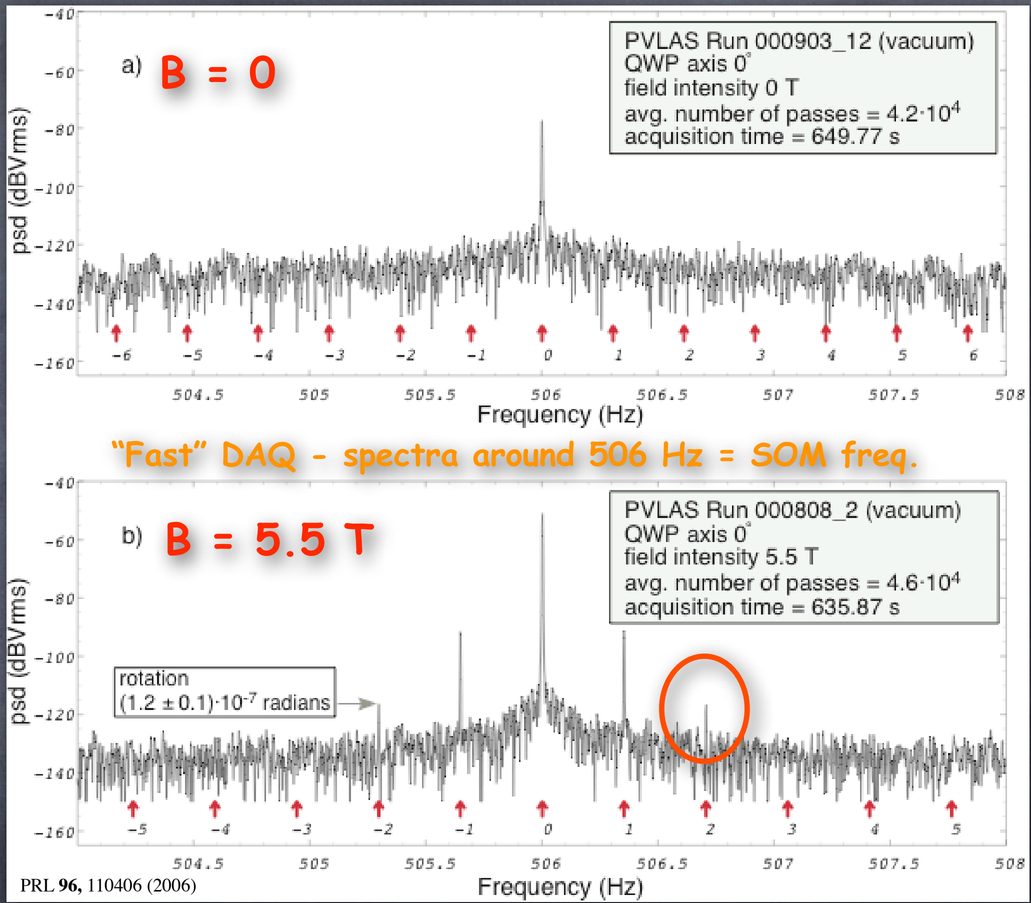


The expected signal (magnetic birefringence of a gas in this case) appears at twice the magnet rotation frequency (here 0.6 Hz)



Data points (taken at several pressure values <mbar for N_2, 1-20 mbar for Ne) align along a straight line determined by the apparatus geometry and by the position of the initial polarisation

Vacuum rotation measurements (amplitude)

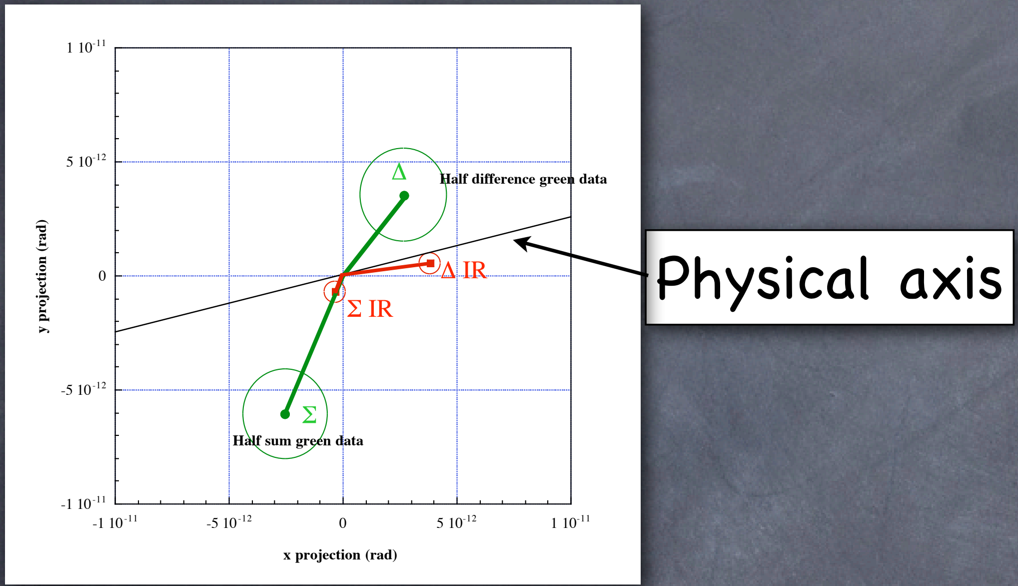


- Signal observed in Vacuo with B ≠ 0 and cavity present
- Data clusters in polar plane change sign under a QWP axis exchange
- The average rotation vector lies along the physical axis

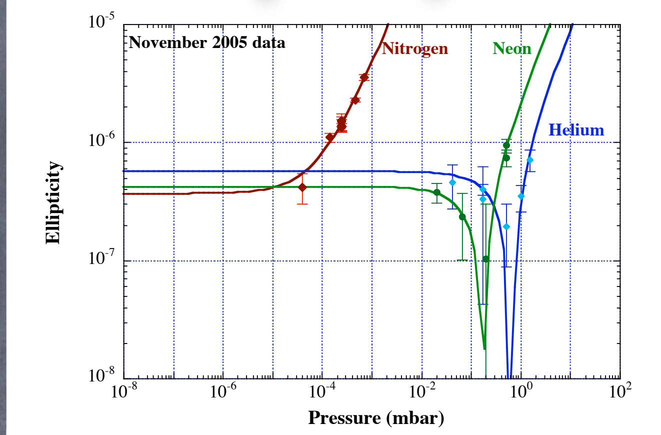
The signal corresponds to a "true" rotation (dichroism) with amplitude ± 3σ $(3.9\pm0.5)\times10^{-12}$ rad/pass

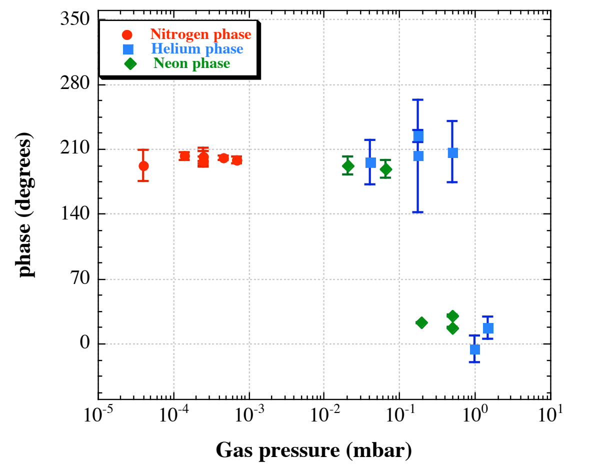
Summary of results

Dichroism



Ellipticity





	1064nm	532nm
Dic 10^{-12}rad/pass; 3σ	? 3.9±0.5	+ 6.3±3.1
Ell 10^{-12}/pass; ; 3σ	- 3.4±0.9	- 6.0±1.8

Vacuum has **opposite** ellipticity to Ne

Discussion I

- QED vacuum birefringence
  - Expected signal @ 5.5 T and 50000 passes: $2 \cdot 10^{-11}$
  - **Observed** ellipticity signal
    $(3.0 \pm 0.9) \cdot 10^{-7}$ @ 532nm; $(1.7 \pm 0.5) \cdot 10^{-7}$ @ 1064nm
  - **4 orders of magnitude larger** than expected and with **wrong sign**
  - Possibile QED-QCD interference?
    (J. Rafelski in "Frontier Tests of QED and Physics of the Vacuum" E. Zavattini, D. Bakalov, C. Rizzo Eds. Heron Press, Sofia, 1998)
- Photon Splitting induced dichroism
  - Theoretically expected rotation: $\approx 10^{-76}$ rad!
  - **Observed** dichroism induced rotation signal
    $(3.2 \pm 1.5) \cdot 10^{-7}$ @ 532nm; $(2.0 \pm 0.3) \cdot 10^{-7}$ @ 1064nm
  - **Directly** tried to detected photons from 532 nm splitting: noise level **200 times below expected value** (assuming $3.2 \cdot 10^{-7}$ rad rotation)

Discussion II

- Photon-boson oscillation
  - Model predicts both **ellipticity** and **rotation** (same signs)
  - Observed **both** phenomena => mass and coupling
  - Deduced mass in allowed range: 1 meV
  - Does not contradict BFRT experiment
  - Coupling constant (≈ $4 \cdot 10^5$ GeV) much too large: **> 4 orders of magnitude compared to limits from CAST**
  - Measured parity from ellipticity and rotation are **inconsistent**
- Millicharged Particle model
  - Observed both predicted effects

M. Ahlers et al. hep-ph/0612098

	$n_\parallel > n_\perp$	$n_\parallel < n_\perp$
$\pi_\parallel > \pi_\perp$	ALP 0^- or MCP $\frac{1}{2}$ (small χ)	MCP $\frac{1}{2}$ (large χ)
$\pi_\parallel < \pi_\perp$	MCP 0 (large χ)	ALP 0^+ or MCP 0 (small χ)

⇔

	1064nm	532nm
Dic 10^{-12}rad/pass; 3σ	? 3.9±0.5	+ 6.3±3.1
Ell 10^{-12}/pass; 3σ	- 3.4±0.9	- 6.0±1.8

Criticisms/Problems

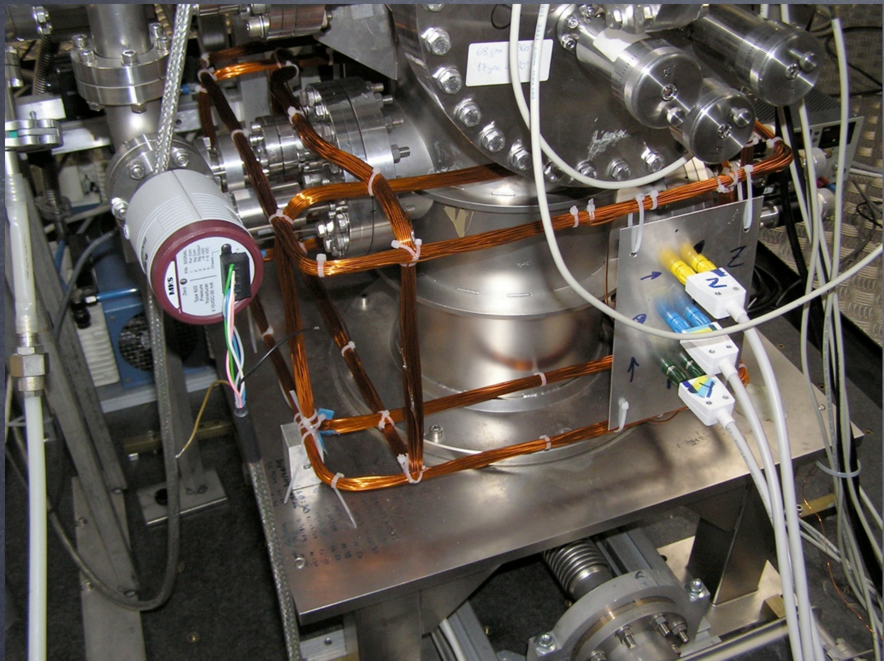
- Dichroism measurement is a **disappearance** measurement prone to systematics
- A signal is also present a $1\Omega_{mag}$ and is still to be understood
- Data are not as clean as desired

- Our signal at $2\Omega_{mag}$ is NOT directly generated by the $1\Omega_{mag}$ signal
- NO DIRECT artifact explanation for either peaks at $1\Omega_{mag}$ or $2\Omega_{mag}$ but both are due to the presence of the **cavity**
- We are working on **INDIRECT** effects from fringe fields present when running with fields above 2.5 T

Physics strategy

- Appearance measurements
  - Particle regeneration
  - Photon splitting detection
- Systematics: try to eliminate peaks and reduce noise
  - Reduce fringe field
    - Active field compensation on mirrors
    - Run at 2.5 T
    - Turn to permanent magnets: 3 meters, 2.3 T
  - Use fiber optics to move laser and feedback circuit far from magnet
- Interesting physics results
  - Direct photon splitting limit
  - Photon - photon scattering limit

Field compensation



- Most sensitive elements to a magnetic field are the cavity mirrors: lab measurements
- Generate field to study effects of field on mirrors with cavity
- Direct Faraday rotation is NOT responsible for $1\Omega_{mag}$ rotation peak
- Field sensor very near mirrors allows feedback system to compensate dynamically the stray field on the mirrors

Regeneration

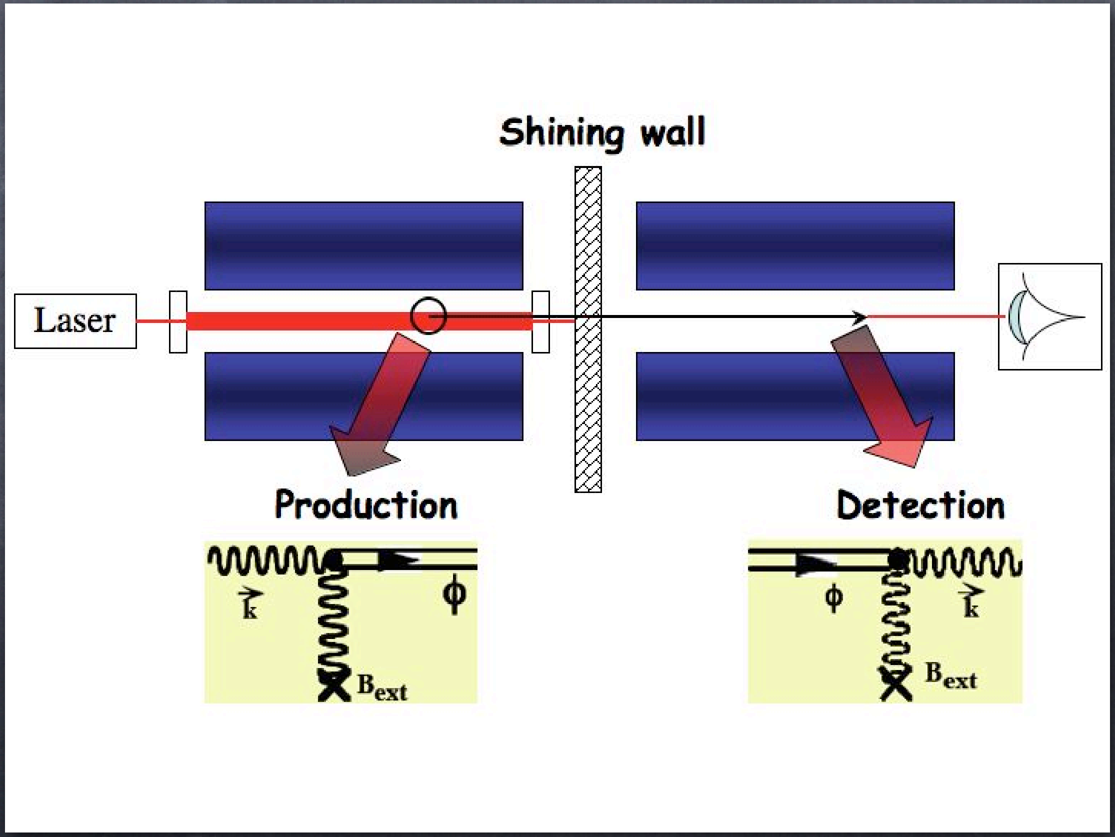
Photon regeneration plans:

Name	Place	Laser	Flux of initial γ's	Magnets	$P_{\gamma\phi\gamma}\|_{(g,m_\phi)\mathrm{PVLAS}}$
PVLAS	Legnaro/I	$\lambda = 1064$ nm, $\omega = 1.17$ eV $P = 20 - 800$ mW, cw $N_r = 5 \times 10^5$	3×10^{22}/s - 1×10^{24}/s	$B_1 = 5$ T $l_1 = 1$ m $B_2 = 2.2$ T $l_2 = 0.5$ m	$\sim 10^{-23}$
LIPSS	Jlab/USA	$\lambda = 900$ nm, $\omega = 1.38$ eV $P = 3 - 10$ kW, cw $N_r = 0$	1×10^{22}/s - 5×10^{22}/s	$B = 1.7$ T $l = 1$ m	$\sim 10^{-23.5}$
ALPS	DESY/D	$\lambda = 1064$ nm, $\omega = 1.17$ eV $P = 1$ kW, cw $N_r = 0$	1×10^{22}/s	$B = 5$ T $l = 4.21$ m	$\sim 10^{-19}$
BMV	LULI/F	$\lambda = 1053$ nm, $\omega = 1.18$ eV 4 pulses of 1500 J/day $N_r = 0$	8×10^{21}/pulse	$B = 11$ T $l = 0.25$ m	$\sim 10^{-21}$
APFEL	DESY/D	$\lambda = 32$ nm, $\omega = 38.7$ eV 8×10^3 pulses of 50μJ/sec $N_r = 0$	8×10^{12}/pulse	$B = 2.24$ T $l = 6$ m	$\sim 10^{-19.5}$
????	CERN/CH	$\lambda = 1064$ nm, $\omega = 1.17$ eV $P = 1$ kW, cw $N_r = 0$	1×10^{22}/s	$B = 9.6$ T $l = 7$ m	$\sim 10^{-17}$

A. Ringwald (DESY) IDM 2006, Rhodes, Greece

Verify particle interpretation

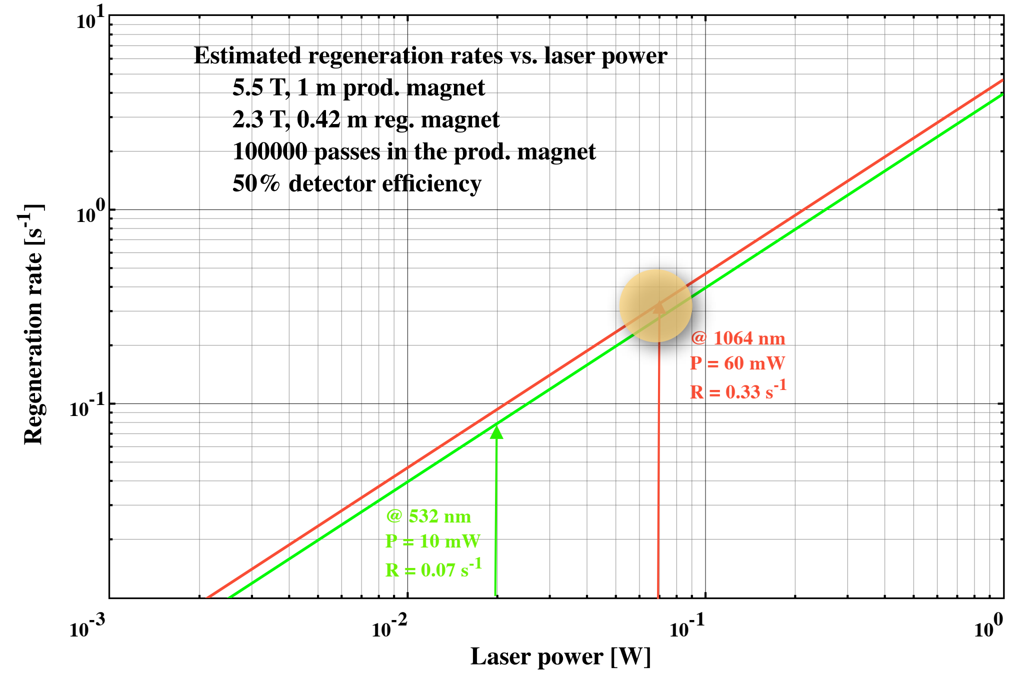
Need an APPEARANCE measurement



Rates and measurement times

$$R = \frac{W}{\omega}\frac{N}{2}\left(P_{\gamma\leftrightarrow a}\right)^2 = \frac{1}{16}\frac{W}{\omega}\frac{N}{2}\left(\frac{B_0 L}{M}\right)^4\left(\frac{\sin(x)}{x}\right)^4$$

- Scenario
  - 1064 nm laser, ~60 mW at FP output
  - 1 m, 5.5 T superconducting magnet for <u>production</u>
  - 42 cm, 2.3 T permanent magnet for <u>regeneration</u>
  - particle parameters
    - M = 3.8·105 GeV
    - m = 1.1 meV

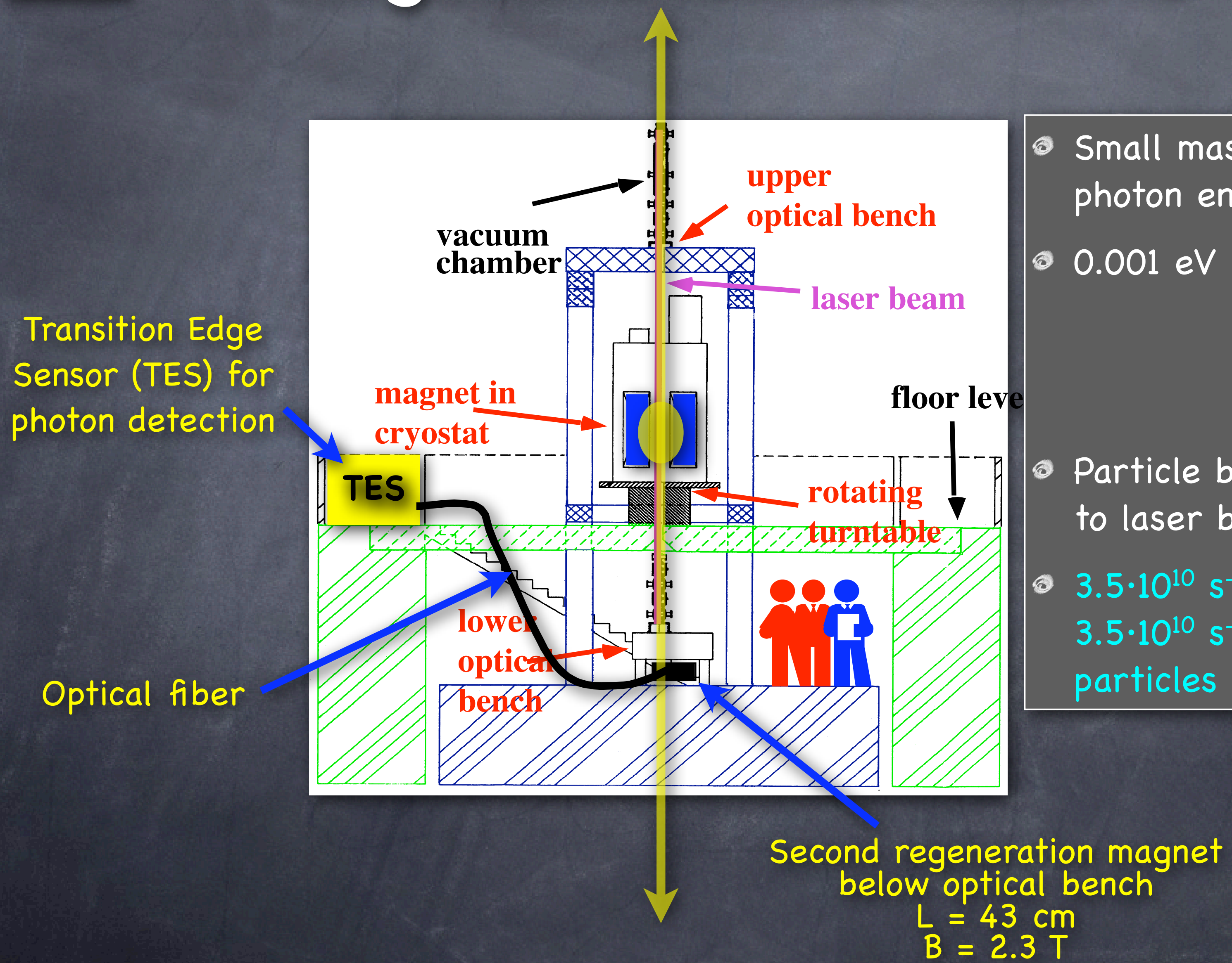


regeneration rate ~ **0.33 ph/s**

assume: 0.01 Hz background, 0.3 efficiency

<u>**Measuring time with TES to have SNR = 1: ~ 10 s**</u>

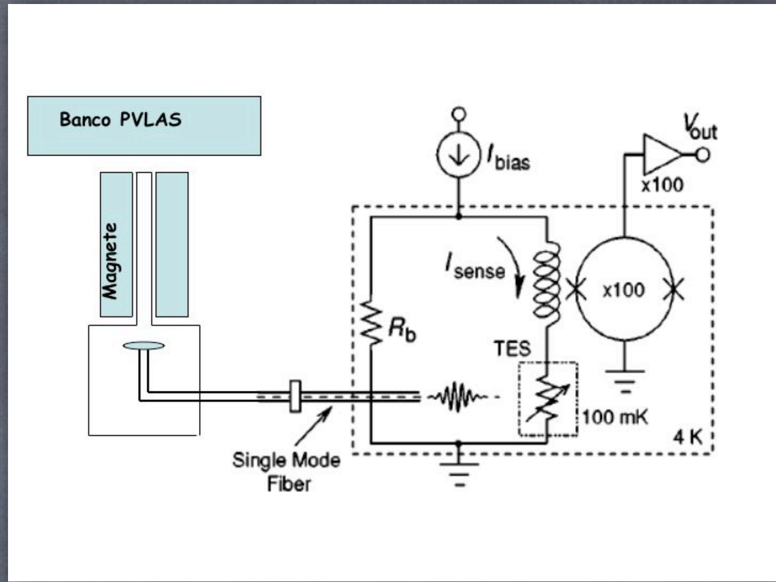
Regeneration at PVLAS

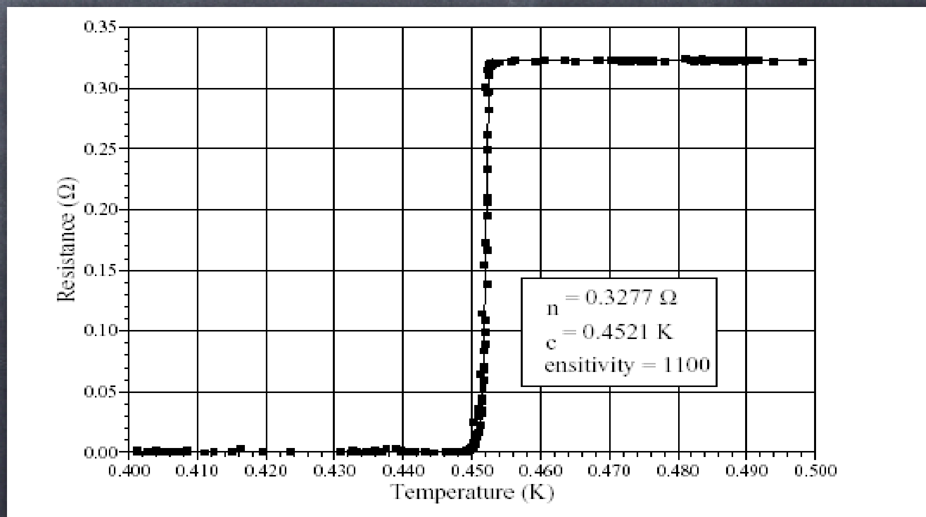


- Small mass compared to photon energy
- 0.001 eV << 1.17 eV
- Particle beam collinear to laser beam:
- $3.5 \cdot 10^{10}$ s^{-1} up going and $3.5 \cdot 10^{10}$ s^{-1} down going particles

TES detector

- Transition Edge Sensor
  - works as a bolometer
  - cryogenic temperatures (~100 mK)
  - potentially no background
  - spectroscopic ability
- Photon transport
  - fiber optic
  - 1064 nm interferential filter
- TES developed and provided by Genova INFN group led by F. Gatti

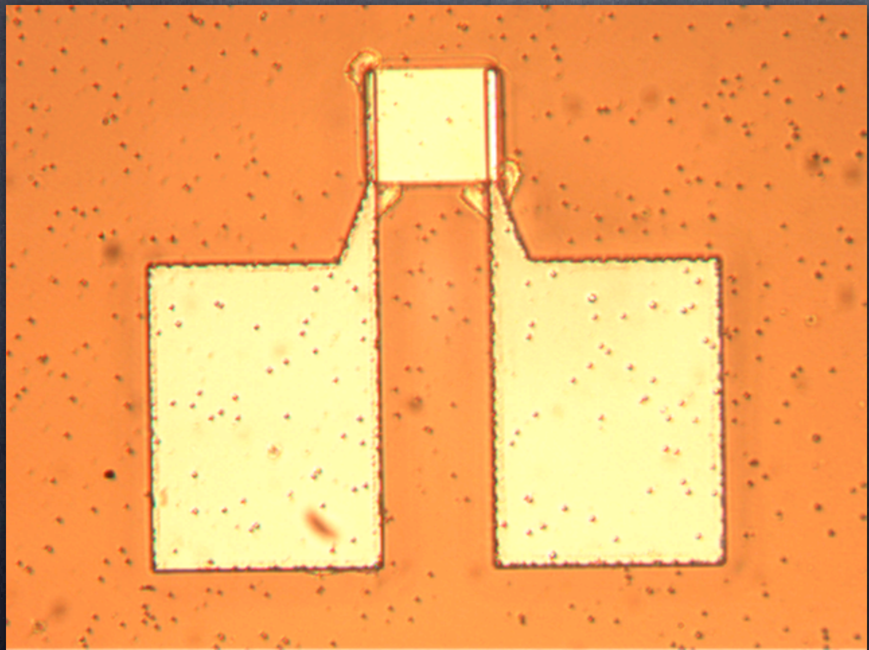


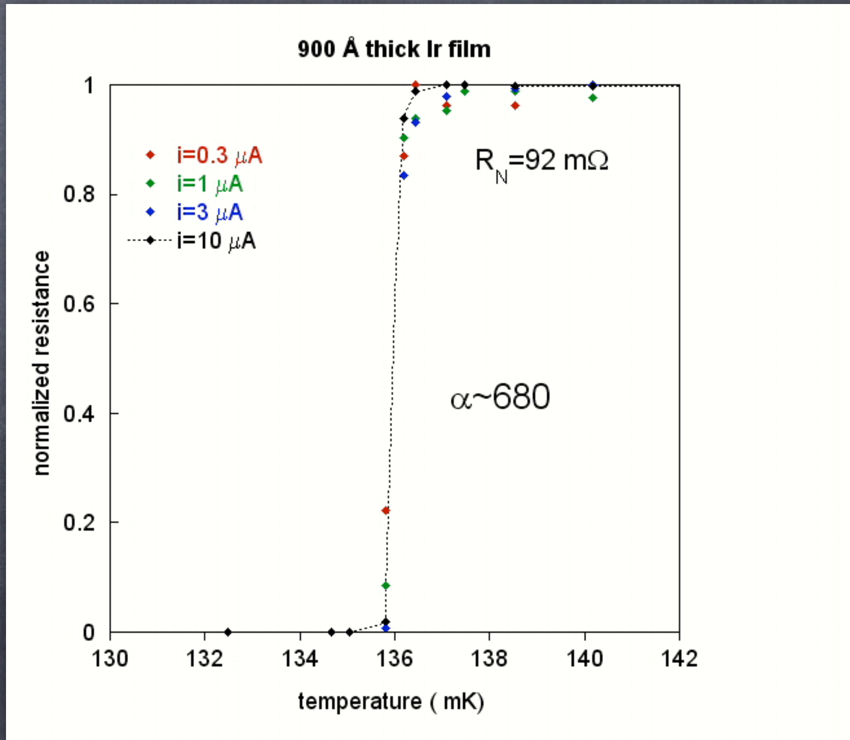


Rivelatore TES per PVLAS

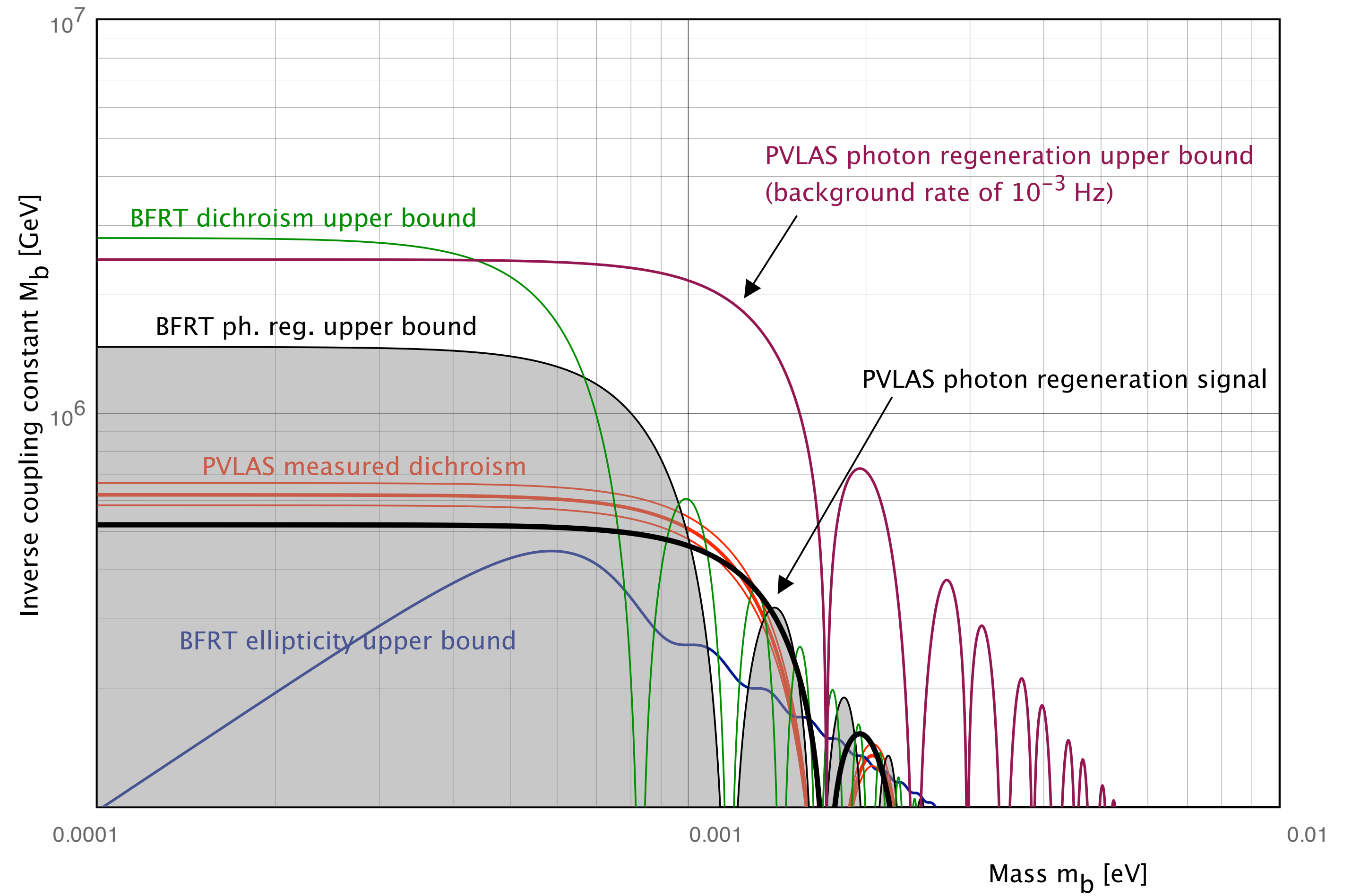
(Genova group - F. Gatti)

- Detector size (25 μmx25 μm)
- Characterized at low temperature
- Tests are beginning with photons





Regeneration: if No signal



Some physics bounds

Photon splitting

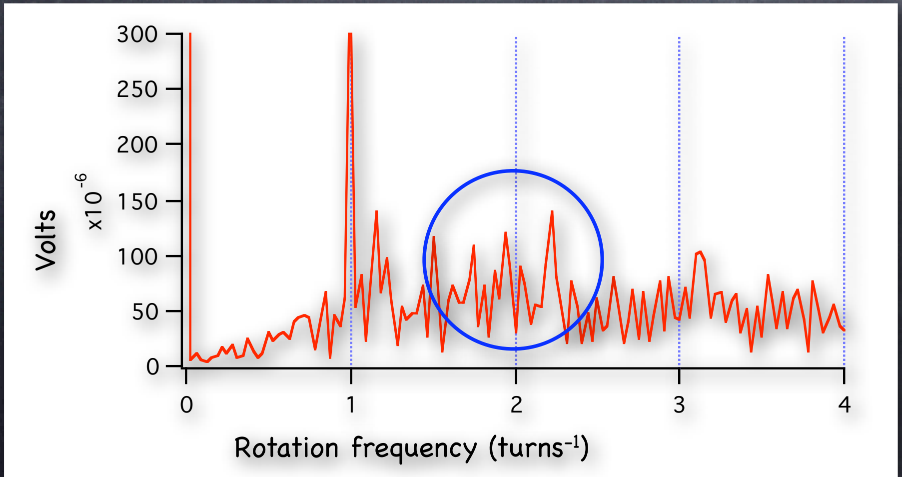
Measured rotation: ≈ $2 \cdot 10^{-7}$

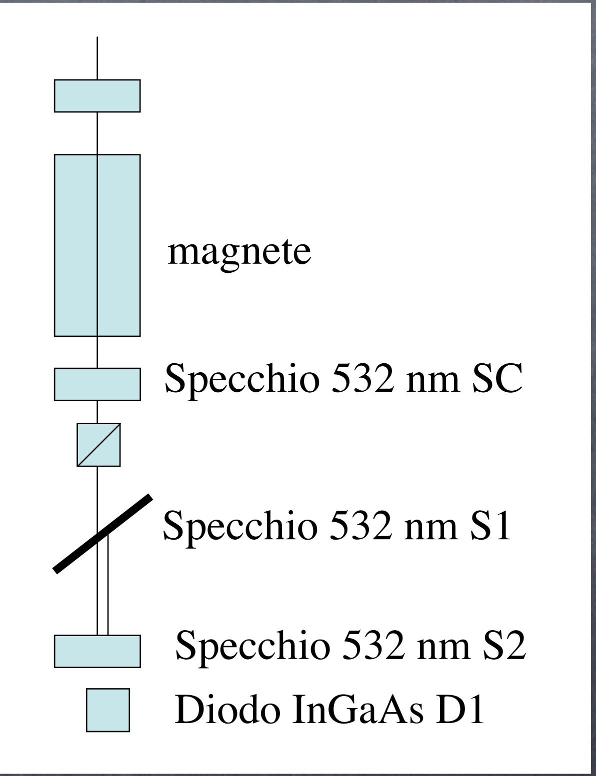
⇓

Escaping fraction of power: 10^{-7}

Highest probability is to split into two 1064 nm photons

With a gain of $6.5 \cdot 10^{8}$ V/A we expected a ≈ 20 mV peak at $2\Omega_{mag}$





$\Delta k < 2 \cdot 10^{-17}$ cm^{-1}

Light by light scattering

Very low energy photon-photon scattering is proportional to A_e^2

$$\sigma_{\gamma\gamma}^{[*]} = \frac{1}{(45)^2}\frac{973}{5}\frac{\alpha^4}{\pi}\left(\frac{\hbar\omega}{m_e c^2}\right)^6\left(\frac{\hbar}{m_e c}\right)^2 = \frac{4\pi}{5}973 E_\gamma^{\ 2} k_\gamma^{\ 4} A_e^2$$

For E_γ = 1.17 eV (1064nm) this predicts a value of $\sigma_{\gamma\gamma} = 1.9\cdot10^{-65}$ cm^2

Experimentally Bernard et al.[*] have published $\sigma_{\gamma\gamma} < 1.5\cdot10^{-48}$ cm^2 @ 0.8 eV

Assuming our ellipticity result is systematic:

$$\Delta n = 3A_e B_0^2 < 1.5\cdot10^{-18}$$

$$A_e < 1.7\cdot10^{-28} \text{ erg/cm}^3$$

$\sigma_{\gamma\gamma} < 2.7\cdot10^{-57}$ cm^2 @ 1064 nm

Conclusions

- We have given a clear answer that our signal is NOT photon splitting
  (very recent paper suggests different splitting mechanism: E. Gabrielli et al. hep-ph/0702197)
- We will try do give a clear answer to the question: Are we generating an unknown particle?
- A regeneration (APPEARANCE) measurement is underway
- We are still working on systematics:
  - INDIRECT fringe field effects