The PVLAS experiment: non linear magneto-optical properties of vacuum

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On behalf of the PVLAS collaboration

Summary

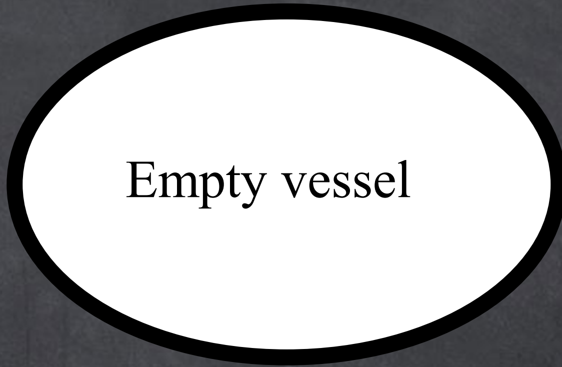
- Introduction
  - Predicted non-linear QED effect
  - Hypothetical millicharged particles
  - Axion search
- Experimental method
  - Heterodyne technique
  - Fabry-Perot interferometer
  - Noise considerations
- Published results
- The PVLAS experiment in Ferrara

Predicted non-linear QED effect

Classical vacuum

The concept and/or existence of vacuum has been disputed for centuries

- One interesting definition by J.C. Maxwell is:



What is left when all that can be removed has been removed (J.C. Maxwell)

Classical vacuum (absence of charges and currents) has no structure and electromagnetic fields are described by the classical Lagrangian density

$$L_{EM} = \frac{1}{2\mu_0}\left(\frac{\mathbf{E}^2}{c^2} - \mathbf{B}^2\right)$$

With the speed of light

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 2.9979 \cdot 10^8 \text{ m/s}$$

Classical vacuum

- The classical Lagrangian density leads to Maxwell's equations

$$\mathrm{div}\,\vec{\mathbf{D}} = 0; \qquad \mathrm{rot}\,\vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

$$\mathrm{div}\,\vec{\mathbf{B}} = 0; \qquad \mathrm{rot}\,\vec{\mathbf{H}} = \frac{\partial \vec{\mathbf{D}}}{\partial t}$$

with

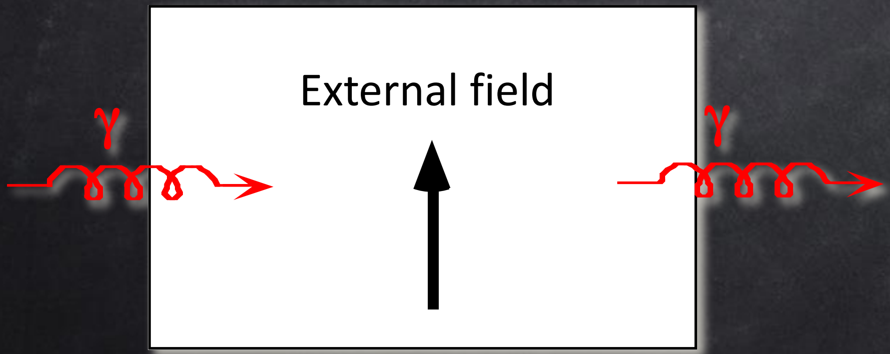
$$\vec{\mathbf{D}} = \frac{\partial L_{EM}}{\partial \vec{\mathbf{E}}}$$

$$\vec{\mathbf{H}} = -\frac{\partial L_{EM}}{\partial \vec{\mathbf{B}}}$$

The superposition principle holds

$$\vec{\mathbf{D}} = \varepsilon_0 \vec{\mathbf{E}}; \qquad \mu_0 \vec{\mathbf{H}} = \vec{\mathbf{B}}$$

Index of refraction $n = 1$



Vacuum

What is left when all has been removed?

Vessel containing field fluctuations

The **Heisenberg uncertainty principle** allows for field fluctuations, thus the fundamental state of systems with finite and infinite degrees of freedom has non zero energy

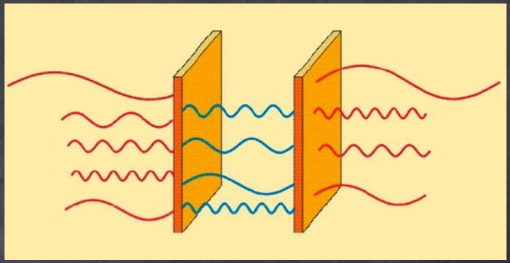
$$DEDt \approx \hbar$$

These fluctuations manifest themselves as **virtual particles**

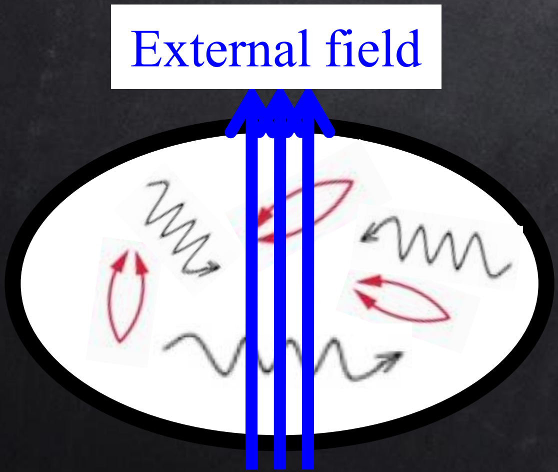
- Vacuum has a structure which can be perturbed and therefore studied

QED tests

- Microscopic tests
  - QED tests in bound systems – Lamb shift
  - QED tests in charged particles – (g-2)
- Macroscipic tests
  - Casimir effect (see C. Braggio's talk)



- QED tests with photons is missing



Macroscopically observable (small) non linear effects have been predicted since 1936 but have never been directly observed yet.

We will concentrate on the **electromagnetic vacuum**

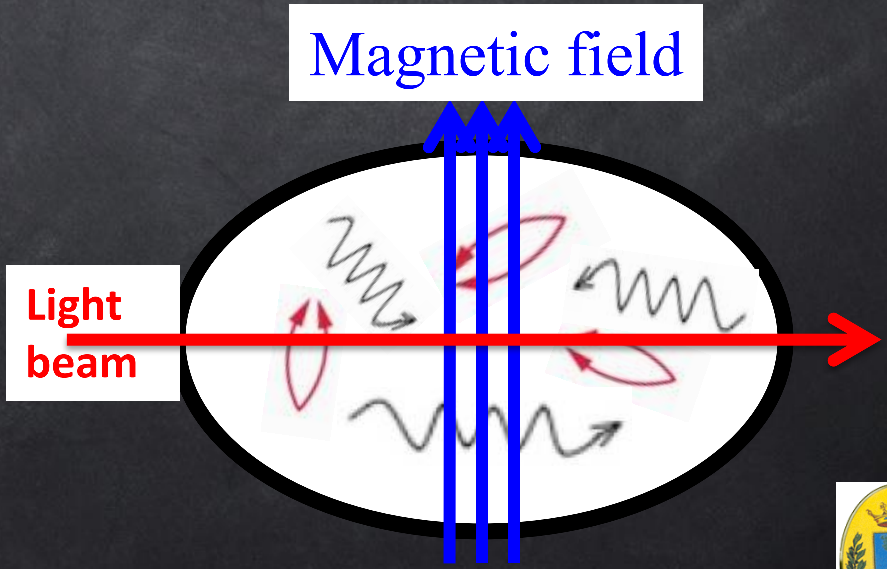
Light propagation in an external field

- Experimental study of the propagation of light in an external field
- General method
  - **Perturb** the vacuum with an external field
  - **Probe** the perturbed vacuum with **polarized light**
  - Extract information on the electromagnetic structure of vacuum

We are aiming at measuring **variations of the index of refraction** in vacuum due to the external **magnetc** field

$$n_{vacuum} = 1 + \left(n_B - ik_B\right)_{field}$$

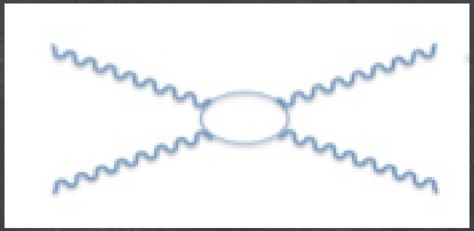
$$n_{media} = \frac{c}{u_{light}}$$



Heisenberg, Euler, Kochel and Weisskopf ('30)

They studied the electromagnetic field in the presence of the **virtual electron-positron** sea discussed a few years before by Dirac. The result of their work is an effective Lagrangian density describing the electromagnetic interactions. At lowest order (Euler – Kochel):

$$L = L_{em} + L_{HE} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{\mathbf{E}}}{c}\cdot\vec{\mathbf{B}}\right)^2\right] + \ldots$$



$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \bar{\lambda}_e^3}{m_e c^2}\right) = 1.32\times 10^{-24}\ \mathrm{T}^{-2}$$

H Euler and B Kochel, *Naturwissenschaften* **23**, 246 (1935)
W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)
H Euler, *Ann. Phys.* **26**, 398 (1936)
V Weisskopf, *Mat.-Fis. Med. Dan. Vidensk. Selsk.* **14**. 6 (1936)

Which is valid for:

1) slowing varying fields
2) fields smaller than the critical value (B << $4.4\cdot10^{9}$ T; E << $1.3\cdot10^{18}$ V/m)

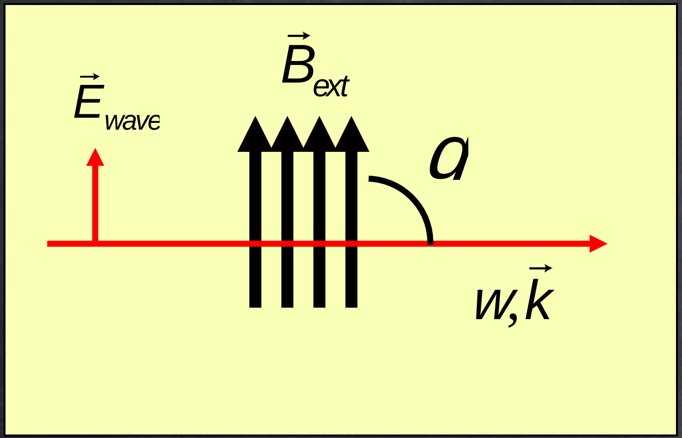
In **the presence of an external field vacuum is polarized**. It became evident that photon – photon interactions could occur in vacuum.

This lagrangian was **validated in the framework of QED by Schwinger** (1951), and the processes described by it can be represented using Feynman diagrams.

Index of refraction

Baier R and Breitenlohner P, *Acta Phys. Austriaca* **25**, 212 (1967); *Nuovo Cimento* 47, 117 (1967);
Bialynicka-Birula Z and Bialynicki-Birula I, *Phys. Rev. D* **2,** 2341 (1970);
Adler S L, *Ann. Phys*. **67**, 559 (1971);

Let us consider our experimental configuration:
linearly polarised light traversing an external transverse magnetic field



$$\hbar\omega \ll m_e c^2$$

$$B \ll B_{cr} = \frac{m_e^2 c^2}{\hbar e} = 4.41 \times 10^9\,\mathrm{T}$$

$$\vec{\mathbf{E}} = \vec{\mathbf{E}}_{Wave} \quad ; \quad \vec{\mathbf{B}} = \vec{\mathbf{B}}_{Ext} + \vec{\mathbf{B}}_{Wave}$$

$$\left|\vec{\mathbf{B}}_{Ext}\right| \gg \left|\vec{\mathbf{B}}_{Wave}\right|$$

$$L = L_{em} + L_{HE} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{\mathbf{E}}}{c}\cdot\vec{\mathbf{B}}\right)^2\right] + \ldots$$

Index of refraction - birefringence

- By applying the constitutive relations to L_{EH} one finds

$$\vec{\mathbf{D}} = \frac{\partial L_{EH}}{\partial \vec{\mathbf{E}}} \qquad \vec{\mathbf{H}} = -\frac{\partial L_{EH}}{\partial \vec{\mathbf{B}}}$$

$$\vec{\mathbf{D}} = \varepsilon_0 \vec{\mathbf{E}} + \varepsilon_0 A_e \left[4\left(\frac{E^2}{c^2} - B^2\right)\vec{\mathbf{E}} + 14\left(\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}\right)\vec{\mathbf{B}} \right]$$

$$\mu_0 \vec{\mathbf{H}} = \vec{\mathbf{B}} + A_e \left[4\left(\frac{E^2}{c^2} - B^2\right)\vec{\mathbf{B}} - 14\left(\frac{\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}}{c^2}\right)\vec{\mathbf{E}} \right]$$

Light propagation is still described by Maxwell's equations in media but they no longer are linear due to E-H correction. **The superposition principle no longer holds.**

Considering linearly polarized light passing through a transverse external magnetic field perpendicular to $\vec{k}$

Index of refraction

$$\begin{cases} \varepsilon_{\parallel} = 1 + 10 A_e \mathbf{B}^2_{Ext} \\ \mu_{\parallel} = 1 + 4 A_e \mathbf{B}^2_{Ext} \\ n_{\parallel} = 1 + 7 A_e \mathbf{B}^2_{Ext} \end{cases} \qquad \begin{cases} \varepsilon_{\perp} = 1 - 4 A_e \mathbf{B}^2_{Ext} \\ \mu_{\perp} = 1 + 12 A_e \mathbf{B}^2_{Ext} \\ n_{\perp} = 1 + 4 A_e \mathbf{B}^2_{Ext} \end{cases}$$

Index of refraction - birefringence

$n_{\parallel,\perp} \neq 1$

$n_{\parallel} - n_{\perp} \neq 0$

- **v ≠ c**
- **anisotropy**

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

$$\Delta n_{(\alpha^2)} = 3A_e B^2$$

$$\Delta n_{(\alpha^3)} = 3A_e B^2 \left(1 + \frac{25}{4\pi}\alpha\right) = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4 c^5}\left(1 + \frac{25}{4\pi}\alpha\right)\frac{B^2}{\mu_0}$$

$$\Delta n = (4.031699 \pm 0.000002)\cdot 10^{-24}\left(\frac{B}{1T}\right)^2$$

$O(\alpha^4)$, $O(\alpha^5)$? Also a theoretical challenge

$\Delta n = 2.5\cdot 10^{-23}$ for B = 2.5 T

Propagation of light

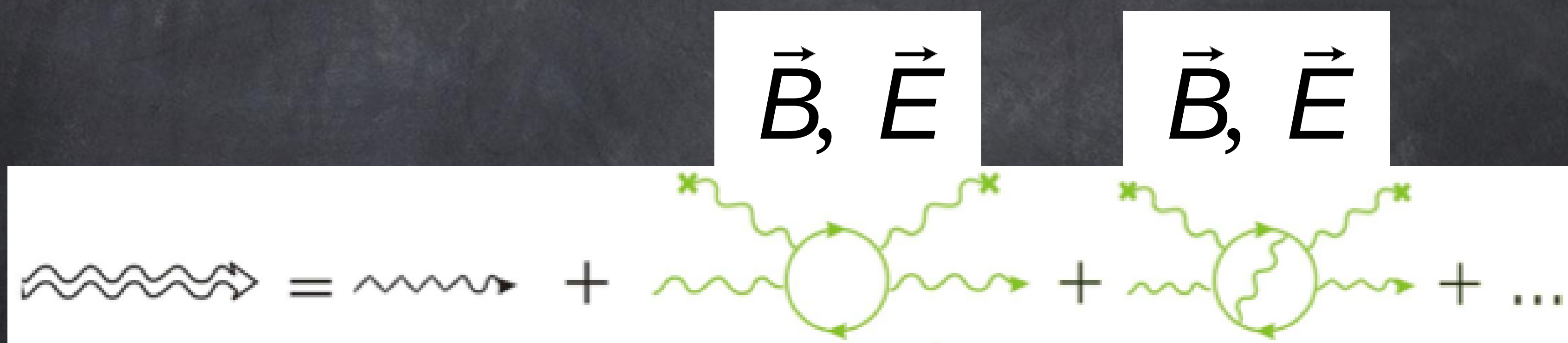
Photon propagation in vacuum as depicted with Feynman diagrams

<u>Without</u> external field

= c

Real photon | Bare photon | Virtual pairs

<u>With</u> external field



Real photon | Bare photon | Virtual pairs | Radiative corrections

- c depends on the external field!
- c depends on light polarization!

Index of refraction vs scattering

$$n = 1 + \frac{2p}{k^2} N f\left(0, E_g\right)$$

Optical theorem

$$\frac{ds_{gg}}{dW}\left(J, E_g\right) = \left| f\left(J, E_g\right)\right|^2$$

Both related to the scattering amplitude with $f(\vartheta, E_g) \propto A_e$

Two principle methods for detecting light-light interaction:

- Direct scattering
- Index of refraction measurements

Light-light scattering

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

For non polarized light: $$s_{gg}^{[*]} = \frac{973 m_0^2}{20p} \frac{E_g^6}{\hbar^4 c^4} A_e^2$$

From Euler-Heisenberg Lagrangian (S.I. units)

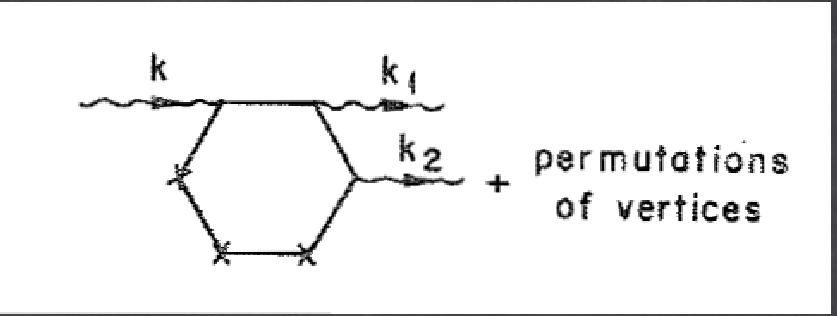
- For light at 1064 nm this predicts a value of **$\sigma_{\gamma\gamma}$ = 1.8·10^{-65} cm^2**
- Experimentally Bernard et al.[**] have published **$\sigma_{\gamma\gamma}$ < 1.5·10^{-48} cm^2 from a direct scattering experiment**
- From birefringent measurements on finds **$\sigma_{\gamma\gamma}$ < 1.2·10^{-58} cm^2**

*Duane et al., Phys Rev. D, vol 57 p. 2443 (1998)

**Bernard D. et al., The European Physical Journal D, vol 10, p. 141 (1999)

Index of refraction - absorption

S. Adler (1971) calculated the absorption due to QED which is of next order and connected to the phenomenon known as **photon splitting**



$$a_{\left\{\begin{smallmatrix}\perp\\\parallel\end{smallmatrix}\right\}} = \frac{4\pi}{\lambda} k_{\left\{\begin{smallmatrix}\perp\\\parallel\end{smallmatrix}\right\}} = \left\{\begin{matrix}0.51\\0.24\end{matrix}\right\} \left(\frac{\hbar\omega}{m_e c^2}\right)^5 \left(\frac{B\sin\theta}{B_{cr}}\right)^6 \text{cm}^{-1}$$

Expected values

$$n_{vacuum} = 1 + \left(n_B - i k_B\right)_{field}$$

$$n_{\left\{\begin{smallmatrix}\perp\\\parallel\end{smallmatrix}\right\}} = 1 + \left\{\begin{matrix}4\\7\end{matrix}\right\} \times \underline{1.32\times10^{-24}} \left(\frac{B}{1\,\text{T}}\right)^2 - i\left\{\begin{matrix}0.24\\0.51\end{matrix}\right\} \times \underline{4.0\times10^{-91}} \left(\frac{\lambda}{1\,\text{m}}\right)\left(\frac{B}{1\,\text{T}}\right)^6 \left(\frac{\hbar\omega}{1\,\text{eV}}\right)^5$$

$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \bar{\lambda}_e^3}{m_e c^2}\right)$$

Unmeasureably small

Linear birefringence

- A birefringent medium has $n_{||} \neq n_{\perp}$
- A linearly polarized light beam propagating through a birefringent medium will acquire an **ellipticity** ψ

If the ligh polarization forms an angle ϑ with respect to the magnetic field **B** the electric field of the laser beam before and after can be expressed as

$$\vec{E}_\gamma = E_\gamma e^{\imath\xi}\begin{pmatrix}1\\0\end{pmatrix}$$

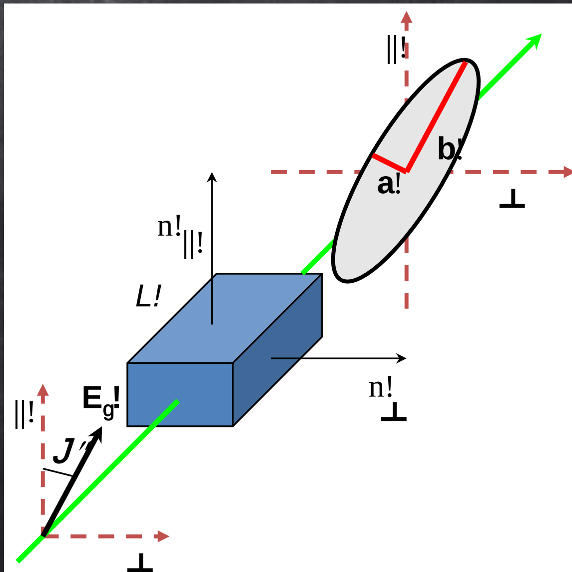
After a phase delay ϕ of the component parallel to **B** with respect to the component perpendicular to **B** by ϕ

$$\phi = \frac{2\pi}{\lambda}(n_\parallel - n_\perp)L$$

$$\vec{E}_\gamma = E_\gamma e^{\imath\xi}\begin{pmatrix}1+\imath\left(\frac{\phi}{2}\right)\cos 2\vartheta\\ \imath\left(\frac{\phi}{2}\right)\sin 2\vartheta\end{pmatrix}$$

Ellipticity

$$\psi = \frac{a}{b} = \frac{\left(\frac{\phi}{2}\right)\sin 2\vartheta}{\left|1+\imath\left(\frac{\phi}{2}\right)\cos 2\vartheta\right|} \approx \frac{\pi\Delta n L}{\lambda}\sin 2\vartheta$$



Linear dichroism

- A dichroic medium has different extinction coefficients: $\kappa_{||} \neq \kappa_{\perp}$
- A linearly polarized light beam propagating through a dichroic medium will acquire an apparent **rotation** ε

If the ligh polarization forms an angle ϑ with respect to the magnetic field **B** the electric field of the laser beam before and after can be expressed as

$$\vec{E}_\gamma = E_\gamma e^{\imath\xi}\begin{pmatrix}1\\0\end{pmatrix}$$

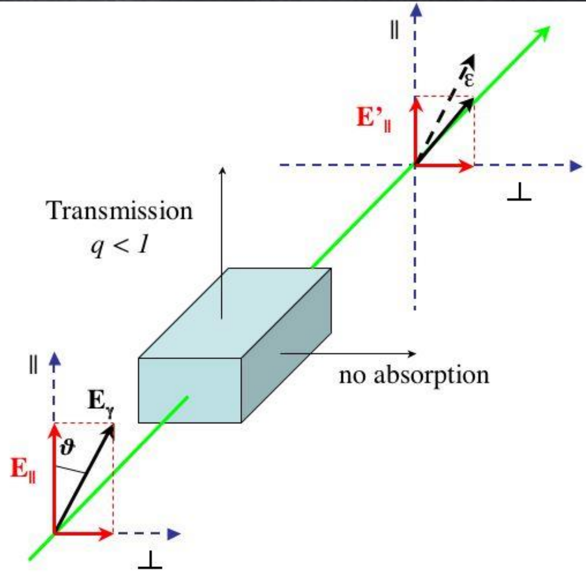
After a reduction of the field component parallel to **B** with respect to the component perpendicular to **B** by

$$q-1=\frac{2\pi}{\lambda}(\kappa_{\parallel}-\kappa_{\perp})L$$

$$\vec{E}_\gamma \approx E_\gamma e^{\imath\xi}\begin{pmatrix}1+\left(\frac{q-1}{2}\right)\cos 2\vartheta\\ \left(\frac{q-1}{2}\right)\sin 2\vartheta\end{pmatrix}$$

Apparent rotation

$$\epsilon = \frac{\left(\frac{q-1}{2}\right)\sin 2\vartheta}{1+\left(\frac{q-1}{2}\right)\cos 2\vartheta} \approx \frac{\pi\Delta\kappa L}{\lambda}\sin 2\vartheta$$



Hypothetical Millicharged particles

Millicharged particles

- Vacuum fluctuates and therefore, in principle, will do so into any particle virtual pairs compatible with vacuum
- These could be fermions or bosons with electric charge εe and mass m_ε
- As with the E-H Lagrangian light propagation depends on its polarization (perpendicular or parallel to the magnetic field)
- Two regimes exist:

$\hbar\omega \ll 2m_\epsilon c^2$ Laser energy below the particle mass

$\hbar\omega \gg 2m_\epsilon c^2$ Laser energy above the particle mass

Millicharged particles

- If $\hbar\omega \ll 2m_\epsilon c^2$ virtual pair production will occur
  - The polarized virtual pairs induce a birefringence and will cause a differential phase delay in the light propagation through the magnetic field depending on its polarization.
- If $\hbar\omega \gg 2m_\epsilon c^2$ both virtual pair production and real pair production will occur
  - Again vacuum will become birefringent due to virtual pair production.
  - Real pair production will cause an intensity reduction dependent on the light polarization => dichroism (I will not discuss this subject)
- The complex index of refraction also depends on a dimensionless parameter χ

$$\chi \equiv \frac{3}{2}\frac{\hbar\omega}{m_\epsilon c^2}\frac{\epsilon e B_{\rm Ext}\hbar}{m_\epsilon^2 c^2} = \frac{3}{2}\frac{\hbar\omega}{m_\epsilon c^2}\frac{B_{\rm Ext}}{B_{\epsilon,{\rm crit}}}$$

Millicharged particles - fermions

- It can be shown that, in the case of fermions, the birefringence induced in the presence of an external magnetic field is

$$\Delta n^{\mathrm{Df}} = \begin{cases} 3A_\epsilon B_{\mathrm{ext}}^2 & \text{for } \chi \ll 1 \\ -\frac{9}{7}\frac{45}{2}\frac{\pi^{1/2}2^{1/3}\left(\Gamma(\frac{2}{3})\right)^2}{\Gamma(\frac{1}{6})}\chi^{-4/3}A_\epsilon B_{\mathrm{ext}}^2 & \text{for } \chi \ll 1 \end{cases}$$

with

$$A_\epsilon = \frac{2}{45\mu_0}\frac{\epsilon^4\alpha^2\lambda\!\!\!^{-}{}_e^3}{m_\epsilon^2 c^2}$$

For χ << 1 this leeds to the predicted QED case

Millicharged particles - bosons

- It can be shown that, in the case of bosons, the birefringence induced in the presence of an external magnetic field is

$$\Delta n^{\mathrm{sc}} = \begin{cases} -\frac{6}{4} A_\epsilon B_{\mathrm{ext}}^2 & \text{for } \chi \ll 1 \\ \frac{9}{14}\frac{45}{2}\frac{\pi^{1/2} 2^{1/3} \left(\Gamma(\frac{2}{3})\right)^2}{\Gamma(\frac{1}{6})} \chi^{-4/3} A_\epsilon B_{\mathrm{ext}}^2 & \text{for } \chi \ll 1 \end{cases}$$

with $$A_\epsilon = \frac{2}{45\mu_0}\frac{\epsilon^4 \alpha^2 \bar{\lambda}_e^3}{m_\epsilon^2 c^2}$$

- With respect to fermions the birefringence has an opposite sign

Axion-like particles

One can add extra terms [*] to the E-H effective lagrangian to include contributions from hypothetical **neutral light particles interacting weakly with two photons** (Heaviside – Lorentz units)

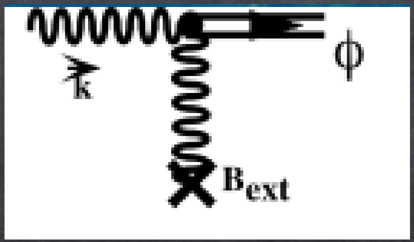
$$L_\phi = g_{\mathrm{a}}\phi\left(\vec{E}_\gamma \cdot \vec{B}_{\mathrm{ext}}\right)$$

pseudoscalar case: Interaction if polarization is perpendicular to B_{ext}

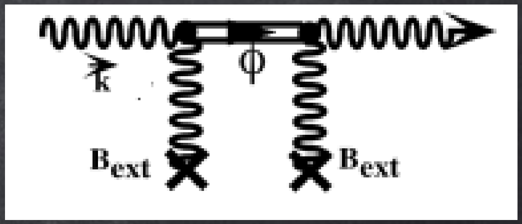
Effects on photon propagation

The photon will oscillate with the axion

Absorption



Dispersion



DICHROISM

BIREFRINGENCE

$$L_\sigma = g_{\mathrm{s}}\sigma\left(\vec{B}_\gamma \cdot \vec{B}_{\mathrm{ext}}\right)$$

scalar case: Interaction if polarization is perpendicular to B_{ext}

g_a, g_s are the coupling constants

[L.Maiani, R. Petronzio, E. Zavattini, Phys. Lett B, Vol. 173, no.3 1986]
[E. Massò and R. Toldrà, Phys. Rev. D, Vol. 52, no. 4, 1995]

Axion-like particles

- Dichroism induces an apparent rotation ε

$$\epsilon = -\sin 2\vartheta \left(\frac{g_{\mathrm{a,s}} B_{\mathrm{ext}} L}{4}\right)^2 N \left(\frac{\sin x}{x}\right)^2$$

N = number of passes through the magnetic field

- Birefringence induces an ellipticity ψ

$$\psi = \sin 2\vartheta \frac{g_{\mathrm{a,s}}^2 B_{\mathrm{ext}}^2 kL}{4 m_{\mathrm{a,s}}^2} N \left(1 - \frac{\sin 2x}{2x}\right)$$

Units

$$1\ \mathrm{T} = \sqrt{\frac{\hbar^3 c^3}{e^4 \mu_0}} = 195\ \mathrm{eV}^2$$

$$1\ \mathrm{m} = \frac{e}{\hbar c} = 5.06 \cdot 10^6\ \mathrm{eV}^{-1}$$

Where $x = \frac{L}{2}\left[\frac{m_{\mathrm{a,s}}^2}{2k}\right]$ and *k* is the wave number

- Both ε and ψ are proportional to N
- Both ε and ψ are proportional to B^2
- ε depends only on $g_{a,s}$ for small x
- **the ratio ψ / ε depends only on $m^2_{a,s}$**

Both $g_{a,s}$ and $m_{a,s}$ can be disentangled

University of Ferrara

Aim of PVLAS

The PVLAS experiment was designed to obtain experimental information on vacuum using optical techniques.

The full experimental program is to detect and measure

- **LINEAR BIREFRINGENCE**
- **LINEAR DICHROISM**

acquired by vacuum induced by an external magnetic field **B**

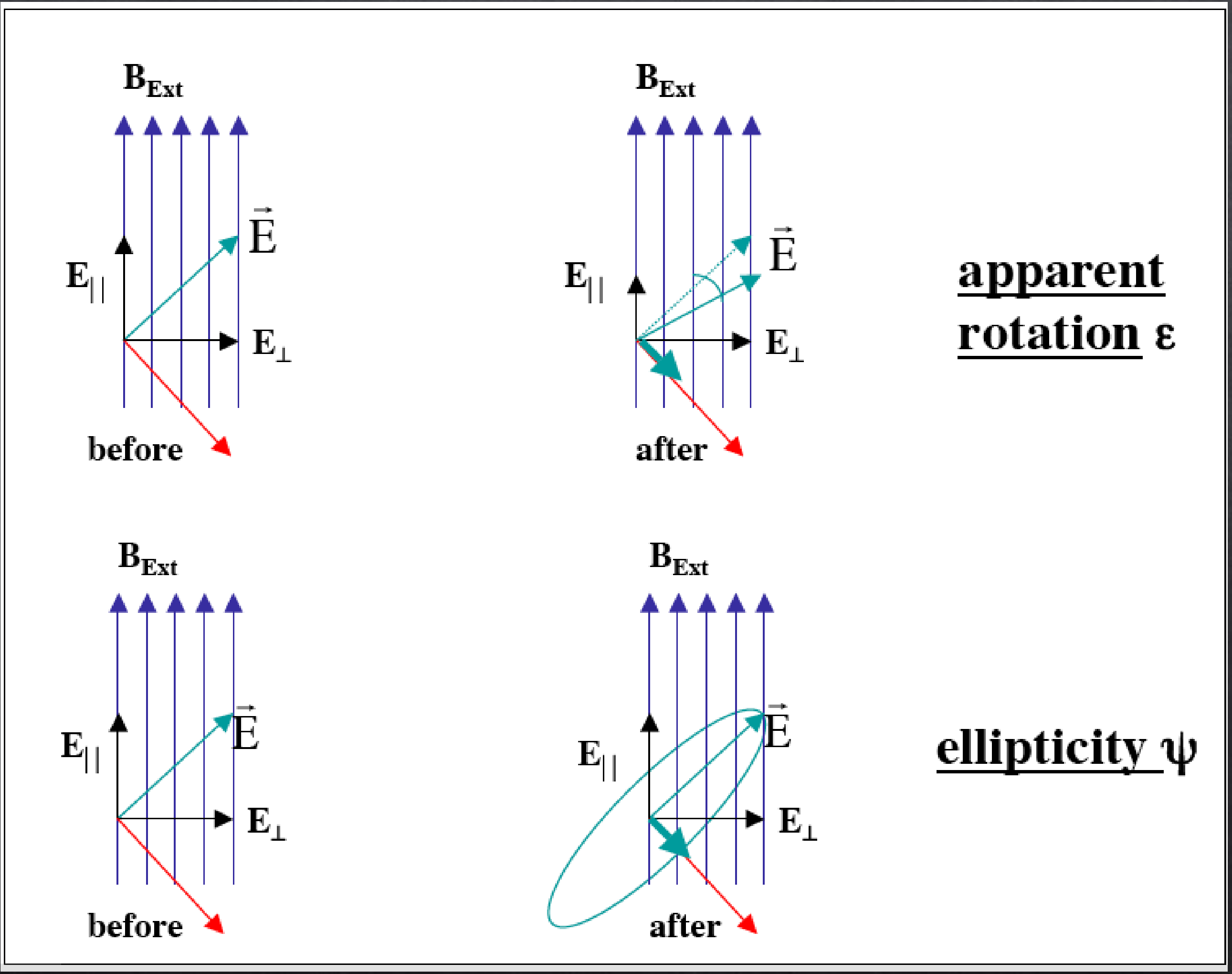
Summing up ...

Dichroism $\Delta\kappa$

- (Photon splitting)
- Real particle production
- MCPs

Birefringence Δn

- **QED dispersion**
- Virtual particle production
- MCPs



Both Δn and $\Delta\kappa$ are defined with sign

Calibration

A gas at a pressure p in the presence of a transverse magnetic field B becomes birefringent. Δn_u indicates the birefringence for unit field at atmospheric pressure

$$\Delta n = n_{\parallel} - n_{\perp} = \Delta n_u \left(\frac{B[\mathrm{T}]}{1\mathrm{T}} \right)^2 \left(\frac{P}{P_{atm}} \right)$$

Total ellipticity

$$\psi_{gas} = N\pi \frac{L}{\lambda} \Delta n_u B^2 p \sin 2\vartheta$$

Gas	Δn_u (T ~ 293 K)
Nitrogen	$-(2.47 \pm 0.04) \times 10^{-13}$
Oxygen	$-(2.52 \pm 0.04) \times 10^{-12}$
Carbon Oxide	$-(1.83 \pm 0.05) \times 10^{-13}$

To avoid spurious effect the residual gas must be analysed:

Ex. $p(O_2) < 10^{-8}$ mbar

Experimental method

Key ingredients

Experimental study of the quantum vacuum with:

- magnetic field perturbation
- linearly polarised light beam as a probe
- changes in the polarisation state are the expected signals

Ellipticity

$$y = \frac{pL_{eff}}{l} Dn \sin 2J$$

- high magnetic field
  - rotating high field permanent magnet
- long optical path
  - very-high finesse Fabry-Perot resonator: $N = {}^{2F}\!/_{p}$
- ellipsometer with heterodyne detection for best sensitivity
  - periodic change of field amplitude/direction for signal modulation

Numerical values

Main interest is the Euler-Heisenberg birefringence

- B = 2.5 T
- $F = 4\cdot10^5$ $\Delta n = 2.5\cdot10^{-23}$ ⇨ $\psi = 3.7\cdot10^{-11}$
- L = 2 m

If we assume a maximum integration time of 10^6 s (= 12 days)

⇩

Ellipticity sensitivity of $< 3.7\cdot10^{-8}\ 1/\sqrt{\text{Hz}}$

Birefringence sensitivity $< 2.5\cdot10^{-20}\ 1/\sqrt{\text{Hz}}$

Present sensitivity in $\Delta n = 1.8\cdot10^{-18}\ 1/\sqrt{\text{Hz}}$

$$\text{Shot noise limit} = \sqrt{\frac{e}{I_0 q}} = 1.5\cdot10^{-9}\frac{1}{\sqrt{\text{Hz}}} \quad \text{for } I_0 = 100\ \text{mW}$$

(I_0 = output intensity reaching the analyzer, q = 0.7 A/W)

Jones vectors

- With coherent polarized light the Jones matrix formalism may be used. The electric field can be written as a column vector (x = vertical, y = horizontal)

$$\vec{E} = \begin{pmatrix} E_x(t) \\ E_y(t) \end{pmatrix} = \begin{pmatrix} E_{0x} e^{\imath \phi_x} \\ E_{0y} e^{\imath \phi_y} \end{pmatrix}$$

- Each component will have an amplitude and phase
- Example: A linearly polarized beam along the x axis

$$\vec{E} = E_{0x} e^{\imath \phi_x} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Jones vectors

- The x and y components of a beam linearly polarized at 45° will have equal amplitudes and phases

$$\vec{E} = E_0 e^{\imath\phi} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

- We can simplify this expression by keeping track of only the phase difference between the x and y components

$$\vec{E} = E_0 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

- A right-circularly polarized beam will have

$$\vec{E} = E_0 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ e^{-\imath\frac{\pi}{2}} \end{pmatrix} = E_0 \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -\imath \end{pmatrix}$$

Jones matrices

- The intensity of a beam can be then calculated as

$$I = \vec{E}^T \cdot \vec{E}^*$$

- Any Jones vector can then be transformed by a 2x2 complex matrix. Some useful examples:

$$A = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Polarizer along y - Analyzer

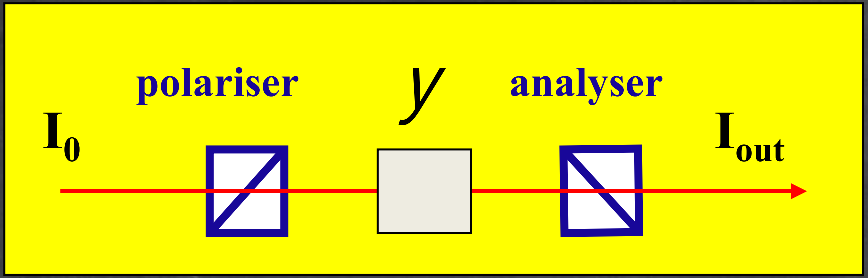
$$P = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Polarizer along x - Polarizer

$$BRF = \begin{pmatrix} 1 + \imath\psi \cos 2\vartheta & \imath\psi \sin 2\vartheta \\ \imath\psi \sin 2\vartheta & 1 - \imath\psi \cos 2\vartheta \end{pmatrix}$$

Birefringent medium of ellipticity ψ (ψ << 1)

Jones matrices



Two crossed polarizers with birefringent medium:

$$\vec{E}_{\rm BRF} = E_0 \cdot BRF \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} 1 + \imath\psi/cos2\vartheta \\ \imath\psi \sin 2\vartheta \end{pmatrix}$$

and after the analyzer

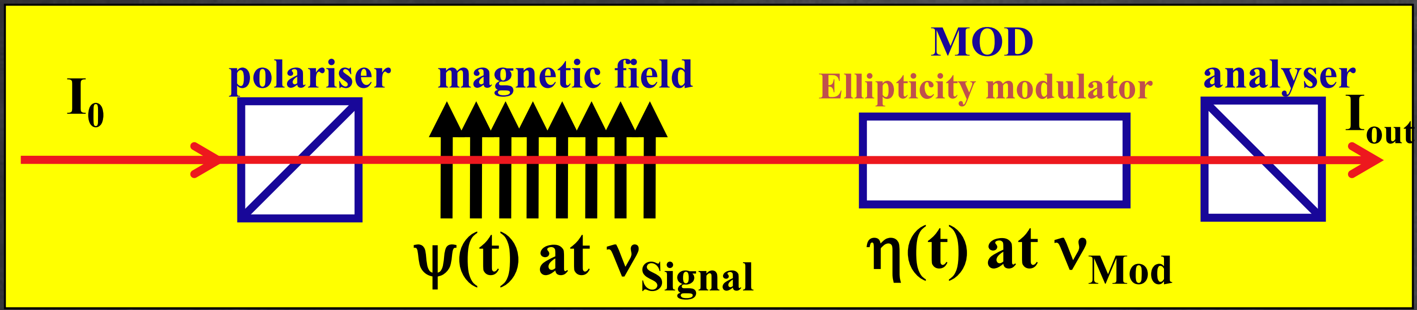
$$\vec{E}_{\rm out} = E_0 \cdot A \cdot BRF \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} 0 \\ \imath\psi \sin 2\vartheta \end{pmatrix}$$

Finally the intensity will be

$$I_{\rm out} = I_0 |\imath\psi \sin 2\vartheta| = I_0 \psi^2 \sin^2 2\vartheta$$

The output intensity is proportional to ψ^2: very small!

Heterodyne detection



- Let us add a known ellipticity with a time dependent modulator placed with $\vartheta = 45^\circ$

$$MOD = \begin{pmatrix} 1 & \imath\eta(t) \\ \imath\eta(t) & 1 \end{pmatrix}$$

- Keeping only first order terms

$$\vec{E}_{\text{out}} = E_0 \cdot A \cdot MOD \cdot BRF \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} 0 \\ \imath\psi \sin 2\vartheta + \imath\eta(t) \end{pmatrix}$$

Ellipticities add up algebraically. The intensity

$$I_{\text{out}} = I_0 |\imath\psi \sin 2\vartheta + \imath\eta(t)|^2 \simeq I_0 \left[\eta(t)^2 + 2\eta(t)\psi \sin 2\vartheta \right]$$

is now linear in ψ

Heterodyne detection

- ψ can also be modulated by either rotating the magnetic field or by ramping it. In PVLAS we have permanent magnets and therefore rotate them.
- By modulating both η and ψ the double product leads to frequency sidebands around the η carrier frequency.
- The $\eta^2(t)$ term results at twice the carrier frequency and is used to measure η directly.
- In practice slowly varying spurious ellipticities $\alpha(t)$ are also present and the crossed polarizer-analyzer pair transmit a fraction σ^2 (at best $\sigma^2 \approx 10^{-7}$) of I_0.
- The expression PVLAS is based on is

$$I_{\text{out}} = I_0\left[\sigma^2 + \eta(t)^2 + \alpha(t)^2 + 2\eta(t)\psi\sin 2\vartheta(t) + 2\eta(t)\alpha(t)\right]$$

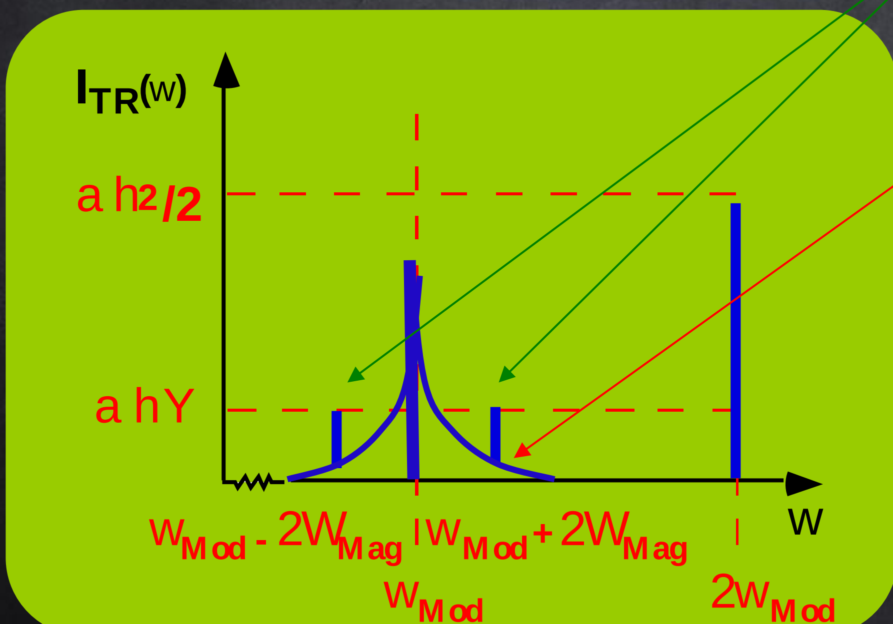
- Inserting a quarter wave plate before the modulator allows rotation measurements
- Ellipticities and rotation do not mix and are independent
- In practice, nearly static rotations/ellipticities 〈 generate a 1/f noise around ω_{Mod}.

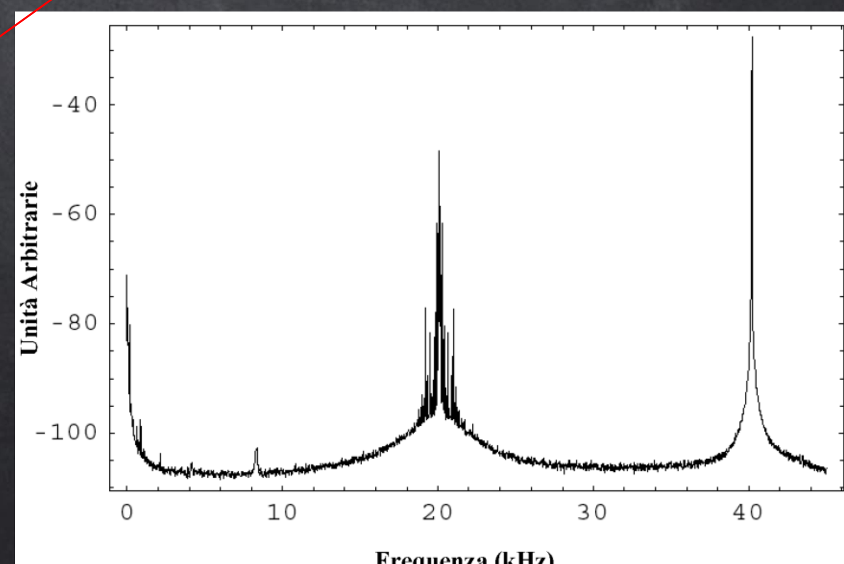
$$\psi \sin 2\Omega_{Mag} t \; \eta_0 \sin \omega_{Mod} t = \psi \eta_0 \frac{1}{2} \left[\cos\left(\omega_{Mod} - \Omega_{Mag}\right)t - \cos\left(\omega_{Mod} + \Omega_{Mag}\right)t\right]$$

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

$$= I_0 \left[\sigma^2 + \left(\eta(t)^2 + 2\psi(t)\eta(t) + 2\alpha(t)\eta(t) + \dots\right)\right]$$

signal noise





Ellipiticity vs Rotations

- Ellipticities have an imaginary component whereas rotations are real

$$ROT = \begin{pmatrix} 1 & -\varphi \\ \varphi & 1 \end{pmatrix}$$

Small rotation

$$MOD = \begin{pmatrix} 1 & \imath\eta(t) \\ \imath\eta(t) & 1 \end{pmatrix}$$

Birefringence

$$\vec{E}_{\text{out}} = E_0 \cdot ROT \cdot MOD \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} 1 - \imath\varphi\eta \\ \varphi + \imath\eta \end{pmatrix}$$

- After the analyzer the intensity will be

$$I_{\text{out}} = I_0 |\varphi + \imath\eta|^2 = I_0(\varphi^2 + \eta^2)$$

- Rotations do not beat with ellipticities

Optical path multiplier

Optical path multiplier

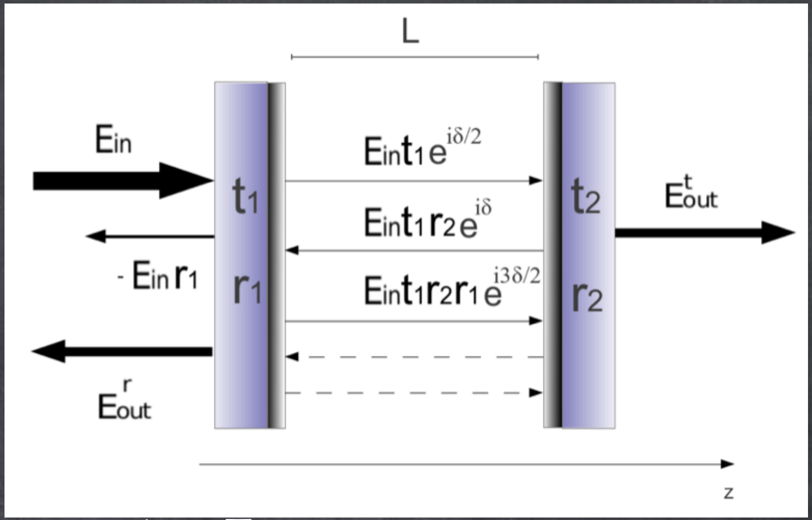
- The ellipticity induced by a birefringence is proportional to the path length in the magnetic region
- A Fabry-Perot interferometer is used to increase the path length by a factor of about 300000. A magnet 1 meter long becomes equivalent to 300 km!
- Very high reflectivity mirrors with very low losses are used
- A standing wave condition is maintained with a feedback system applied to the laser

Fabry-Perot

t and *r* are the reflection coefficients of the electric field

Let us assume $t_1 = t_2$ and $r_1 = r_2$.

Ideally $t^2 + r^2 = 1$



The roundtrip phase of a wave is $\delta = \dfrac{4\pi L}{\lambda}$

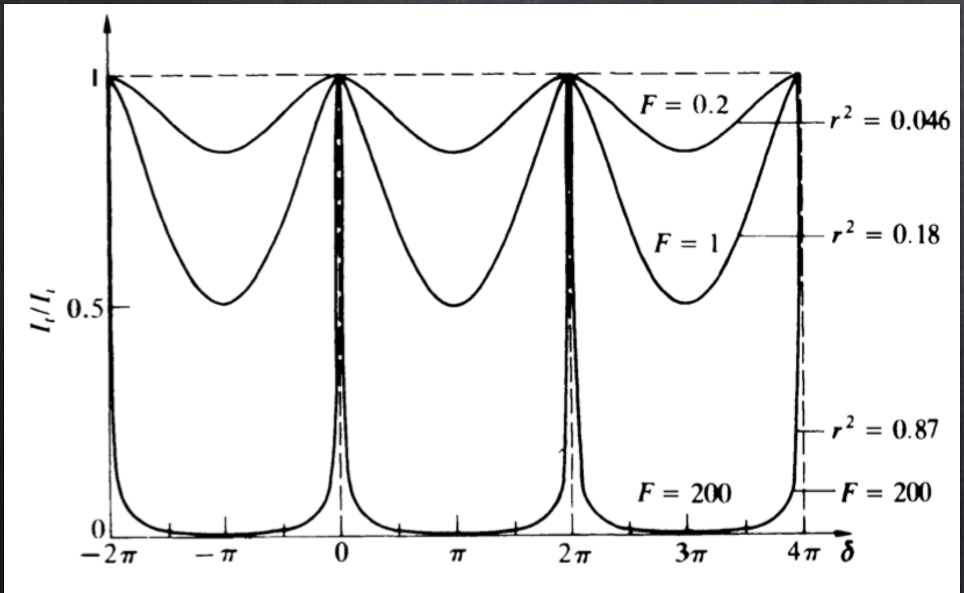
The electric field at the output of the system will be

$$E^t_{\text{out}} = E_{\text{in}} t^2 e^{\imath\frac{\delta}{2}} \sum_{n=0}^{\infty} r^{2n} e^{n\imath\delta} = E_{\text{in}} t^2 \frac{e^{\imath\frac{\delta}{2}}}{1 - r^2 e^{\imath\delta}}$$

Fabry-Perot

- The intensity at the output of the interferometer is

$$I^t_{\text{out}} = \frac{1}{1 + \frac{4r^2}{(1-r^2)^2}\sin^2\frac{\delta}{2}}$$



$\delta = 2\pi$ defines the free spectral range:

$$\nu_{frs} = \frac{c}{2L}$$

The δ corresponding to a FWHM defines the finesse

$$\mathcal{F} = \frac{\nu_{fsr}}{\Delta\nu_{FWHM}} = \frac{\pi\sqrt{r^2}}{1 - r^2}$$

Fabry-Perot example

- Given an infrared beam at 1064 nm and a cavity of length L = 3 meters with finesse *F* = 300000

$$\nu_{laser} = \frac{c}{\lambda} = 2.8 \cdot 10^{14}\ \mathrm{Hz} \qquad \nu_{fsr} = \frac{c}{2L} = 50\ \mathrm{MHz}$$

$$\Delta\nu_{cavity} = \frac{\mathcal{F}}{\nu_{fsr}} = 166\ \mathrm{Hz}$$

- Very very narrow resonances compared to the frequency of the incoming light.
- Feedback on laser is necessary to maintain resonance
- The cavity has a lifetime $\tau = \dfrac{\mathcal{F}L}{c\pi} \simeq 1\ \mathrm{ms}$

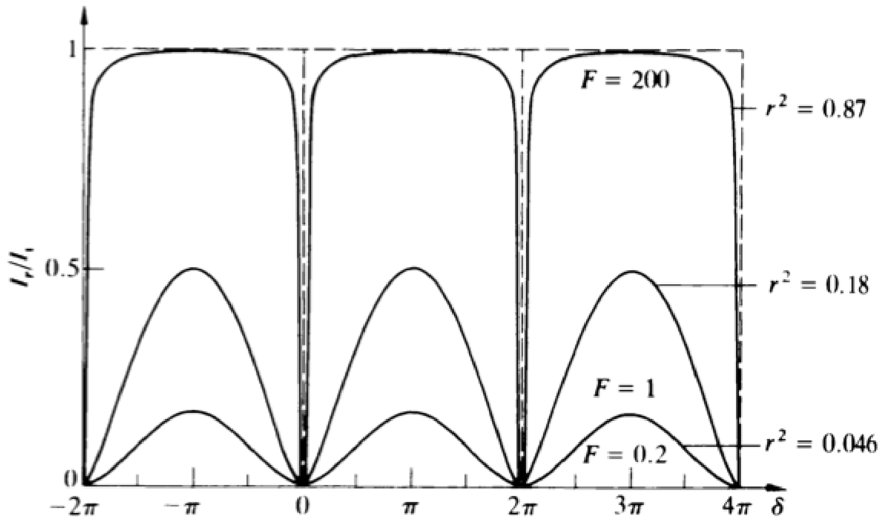
Fabry-Perot in reflection

- If all the light is transmitted at the output, in reflection there must be none. Indeed the reflected field is

$$E^r_{\text{out}} = -E_{\text{in}} r + E_{\text{in}} t^2 r e^{\imath\delta} \sum_{n=0}^{\infty} r^{2n} e^{\imath n\delta} = -E_{\text{in}} \frac{r(1-e^{\imath\delta})}{1-r^2 e^{\imath\delta}}$$

which yields for the intensity

$$I^r_{\text{out}} = \frac{\frac{4r^2}{(1-r^2)^2}\sin^2\frac{\delta}{2}}{1+\frac{4r^2}{(1-r^2)^2}\sin^2\frac{\delta}{2}}$$



Fabry-Perot in reflection

- A real Fabry-Perot always has some losses indicated with *p* such that $r^2 + t^2 + p = 1$
- The reflected electric field and its phase will then be

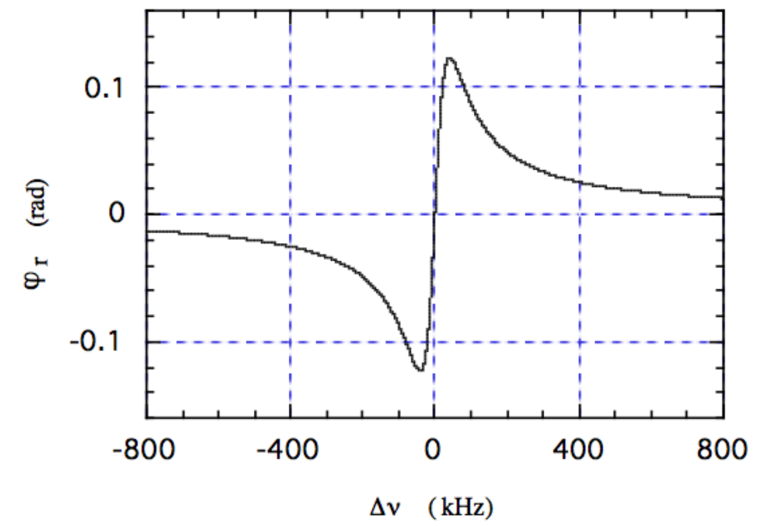
$$E^r_{\text{out}} = -E_{\text{in}} \frac{r(1-(1-p)e^{\imath\delta})}{1-r^2 e^{\imath\delta}}$$

$$\tan\varphi_r = -\frac{(1-r^2-p)\sin\epsilon}{(1+r^2-r^2p)-(1+r^2-p)\cos\epsilon}$$

where $\epsilon = \delta - \delta_{\text{max}} = \frac{4\pi L}{c}\Delta\nu$

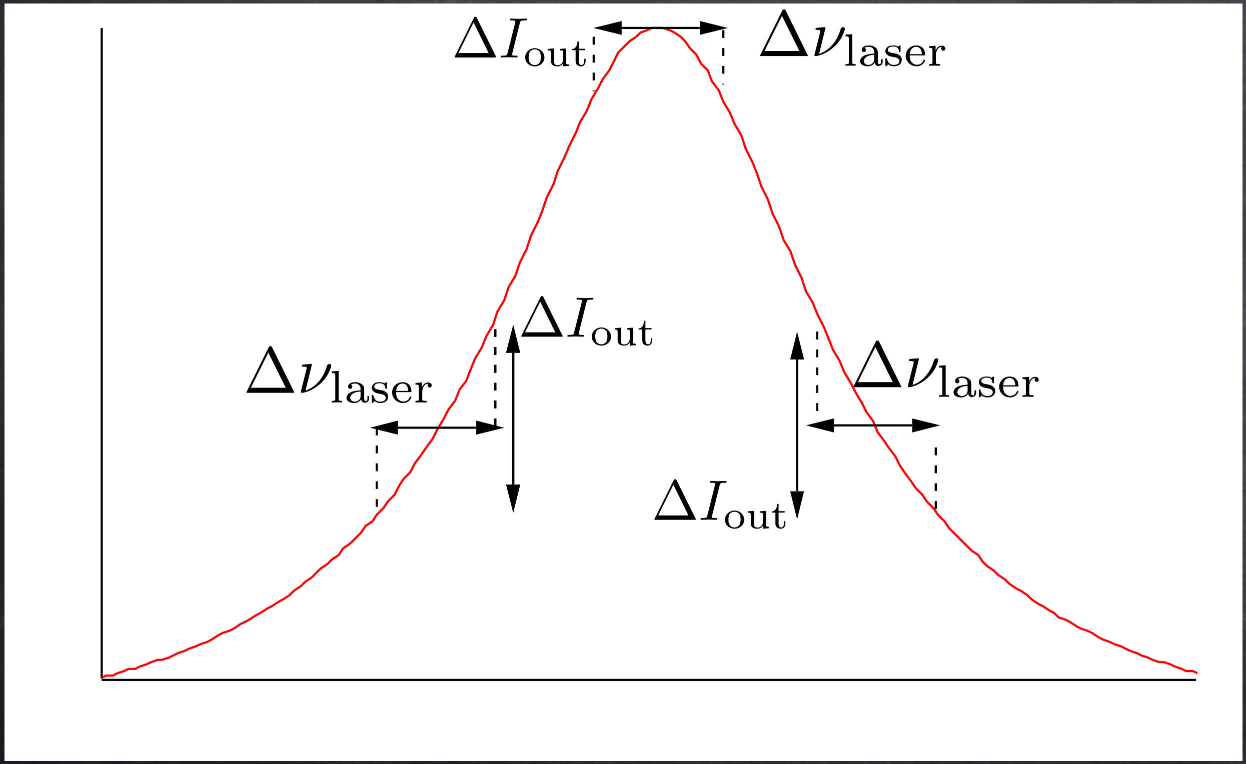
For a small ε

$$\tan\varphi_r = -\frac{(1-r^2-p)\epsilon}{(1-r^2)p} \propto \Delta\nu$$



Laser locking principle

- For locking a laser to a cavity an error signal is necessary proportional to $\nu_{\text{laser}} - \nu_{\text{cavity}}$.



Left: ΔI_{out} in phase with $\Delta\nu_{laser}$ at same frequency

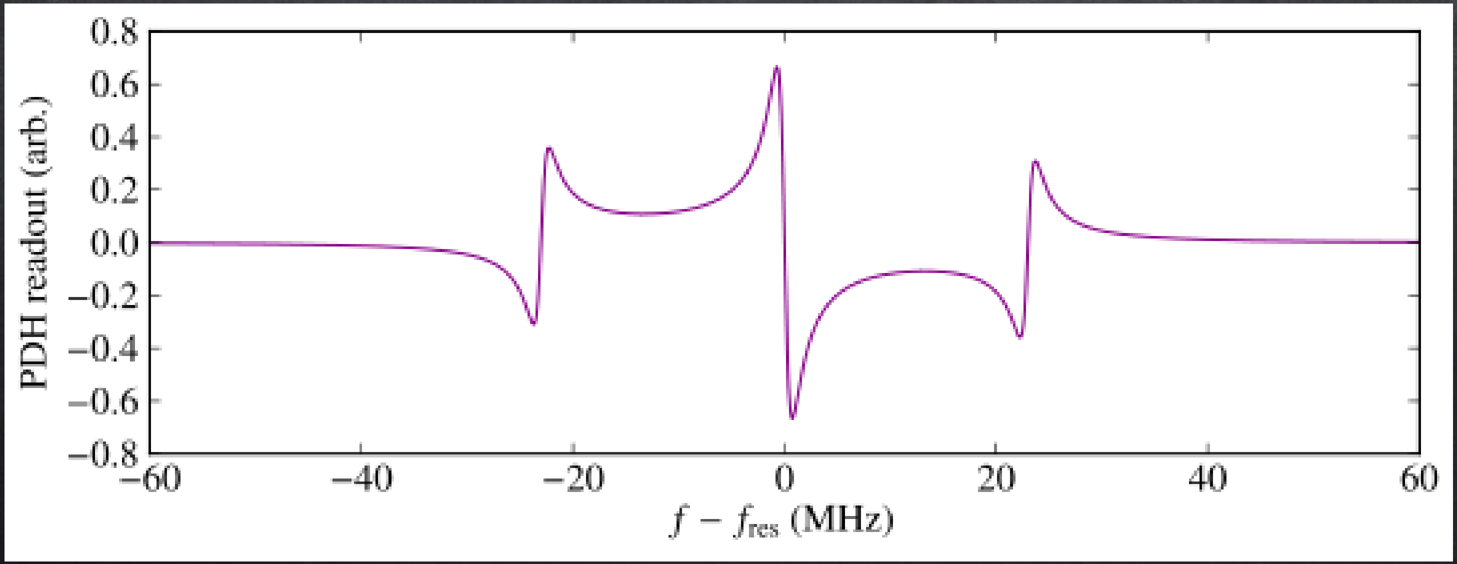
Right: ΔI_{out} has opposite phase with $\Delta\nu_{laser}$ at same frequency

Center: ΔI_{outr} at second harmonic. First harmonic is zero

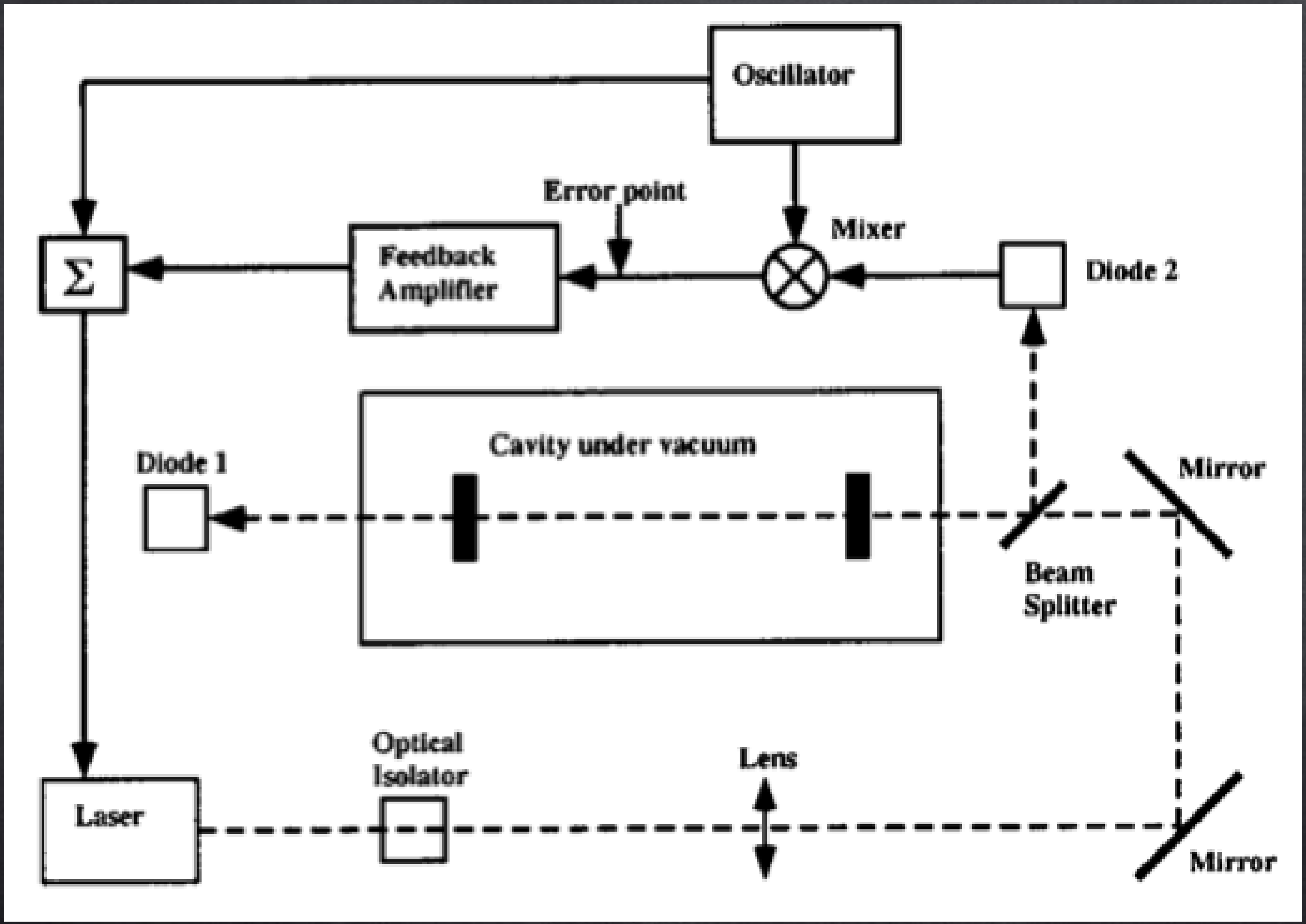
- Modulating the laser frequency modulates the output intensity. First harmonic is proportional to $\nu_{\text{laser}} - \nu_{\text{cavity}}$

Laser locking principle

- In practice the laser is modulated at a frequency greater the the resonance width
- The reflected light is detected and demodulated at the modulation frequency
- An error signal is obtained. The central part is linear

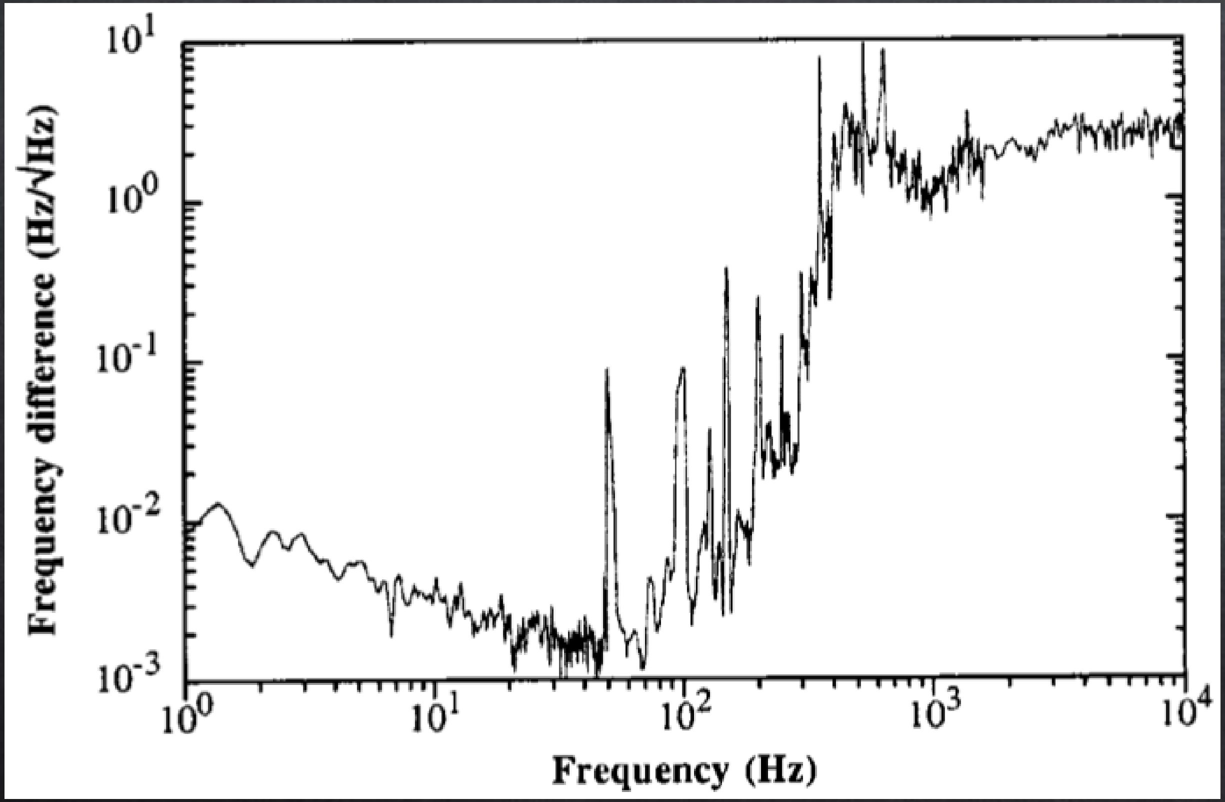


Locking scheme



Locking scheme

Noise spectral density of the error signal during lock. This indicates the frequency **difference** between the cavity and the laser.



Cavity finesse = 45000
Cavity width = 3800 Hz

Signal amplification

- How much will the Fabry-Perot will increase the effective path length ?
- With the Jones formalism one can also describe the cavity including internal and external birefringences

$$CAV = A \cdot SP \cdot MOD \cdot t^2 e^{\imath\delta} \sum_{n=0}^{\infty} \left[BRF^2 r^2 e^{\imath\delta}\right]^n \cdot BRF$$

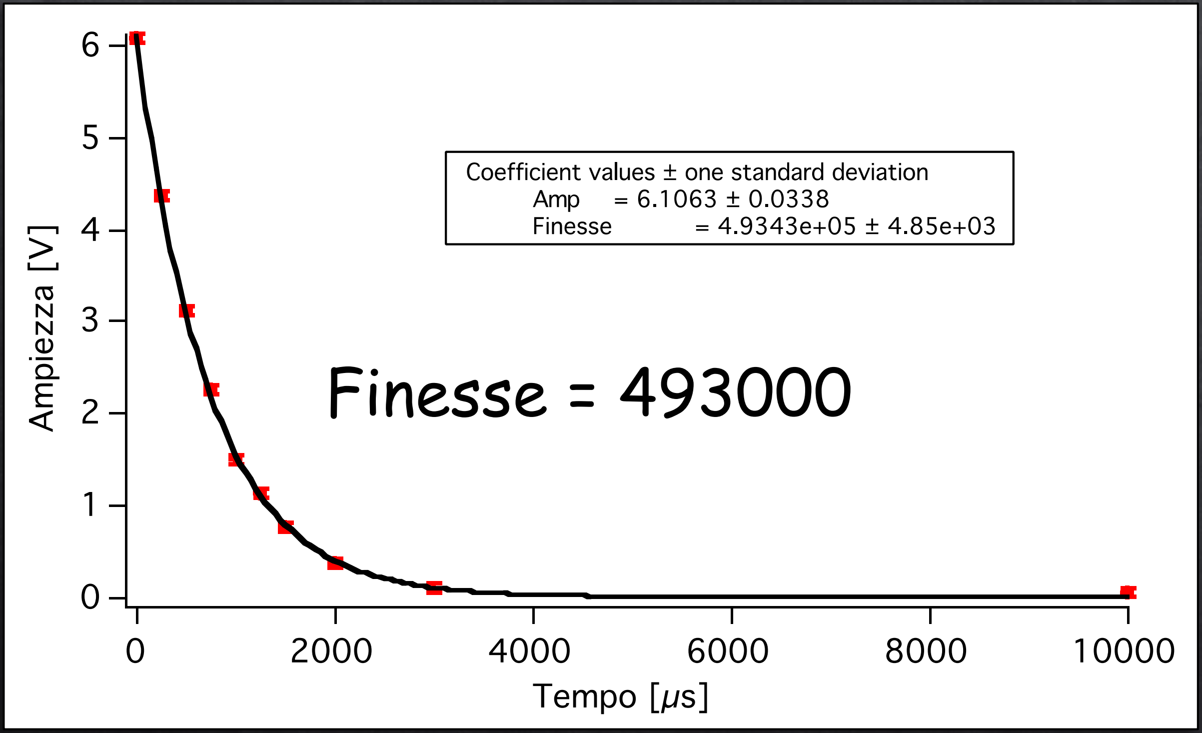
- The ellipticity ψ is multiplied by $N = \frac{1+r^2}{1-r^2} = \frac{2\mathcal{F}}{\pi}$

$$\vec{E}_{\text{out}} = E_0 \cdot CAV \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$= E_0 \frac{t^2}{t^2+p} \begin{pmatrix} 0 \\ \imath\alpha(t) + \imath\eta(t) + \imath \frac{1+r^2}{1-r^2}\psi \sin 2\vartheta(t) \end{pmatrix}$$

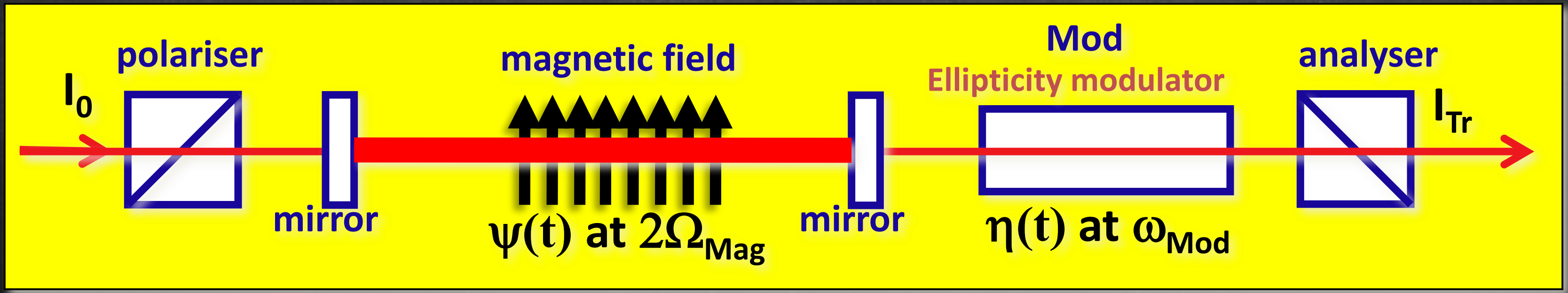
Best measured finesse

- Decay curve of light for a 1.4 m long cavity.
- Decay time = 730 μs



PVLAS scheme

- The cavity will increase the single pass ellipticity by a factor N
- The heterodyne detection linearizes the ellipticity ψ to be measured
- The rotating magnetic field will modulate the searched effect



Frequency components

Frequency	Fourier component	Intensity/I_{out}	Phase
dc	I_{dc}	$\sigma^2 + \alpha_{\text{dc}}^2 + \eta_0^2/2$	$-$
ν_{Mod}	$I_{\nu_{\text{Mod}}}$	$2\alpha_{\text{dc}}\eta_0$	θ_{Mod}
$\nu_{\text{Mod}} \pm 2\nu_{\text{Mag}}$	$I_{\nu_{\text{Mod}} \pm 2\nu_{\text{Mag}}}$	$\eta_0 \frac{2\mathcal{F}}{\pi}\psi$	$\theta_{\text{Mod}} \pm 2\vartheta_{\text{Mag}}$
$2\nu_{\text{Mod}}$	$I_{2\nu_{\text{Mod}}}$	$\eta_0^2/2$	$2\theta_{\text{Mod}}$

The signal amplitude can then be calculated from the two sidebands:

$$\Psi = \frac{1}{2}\left(\frac{I_{\nu_{\text{Mod}}+2\nu_{\text{Mag}}}}{\sqrt{2I_{\text{out}}I_{2\nu_{\text{Mod}}}}} + \frac{I_{\nu_{\text{Mod}}-2\nu_{\text{Mag}}}}{\sqrt{2I_{\text{out}}I_{2\nu_{\text{Mod}}}}}\right)$$

All sources of noises contributing to the spectral density of the photodiode signal at $\nu_{\text{Mod}} \pm 2\nu_{\text{Mag}}$ will limit our sensitivity

Noise considerations

Indicating with $R_{\nu_{\mathrm{Mod}}+2\nu_{\mathrm{Mag}}}$ the noise spectral density at the signal frequencies and assuming

$$R_{\nu_{\mathrm{Mod}}+2\nu_{\mathrm{Mag}}} = R_{\nu_{\mathrm{Mod}}-2\nu_{\mathrm{Mag}}}$$

The ellipticity sensitivity spectral density will be

$$s = \frac{R_{\nu_{\mathrm{Mod}}+2\nu_{\mathrm{Mag}}}}{\sqrt{4 I_{\mathrm{out}} I_{2\nu_{\mathrm{Mod}}}}}$$

Shot noise

INFN Istituto Nazionale di Fisica Nucleare

- The ultimate limit will be the rms shot noise i_{shot} of the current i_{DC} (q = photodiode efficiency ≈ 0.7 A/W, $\Delta\nu$ = bandwidth).

$$i_{\text{shot}} = \sqrt{2ei_{\text{DC}}\Delta\nu} = \sqrt{2eI_{\text{out}}q\left(\sigma^2 + \frac{\eta_0^2}{2} + \alpha_{\text{DC}}^2\right)\Delta\nu}$$

- With $\eta_0 \gg \sigma^2, \alpha_{\text{DC}}$ and substituting

$$R_{\nu_{\text{Mod}}+2\nu_{\text{Mag}}} = i_{\text{shot}}/(q\sqrt{\Delta\nu})$$

the shot noise spectral sensitivity becomes (I_0 = 100 mW)

$$\boxed{s_{\text{shot}} = \sqrt{\frac{e}{I_{\text{out}}q}} = 1.5 \cdot 10^{-9}\ \frac{1}{\sqrt{\text{Hz}}}}$$

If we were shot noise limited…

- The expected ellipticity for B = 2.5 T, *F* = $4\cdot 10^5$ and L = 2 m is

$$\psi_{\rm QED} = 3.7 \cdot 10^{-11}$$

- The necessary integration time to reach a signal to noise ratio = 1

$$T = \left(\frac{s_{\rm shot}}{\psi_{\rm QED}}\right)^2 = 1600 \text{ s}$$

Other known noise sources

$$s_{\rm dark} = \frac{V_{\rm dark}}{G}\frac{1}{I_{\rm out} q \eta_0}$$

Photodetector noise. Reduce contribution by increasing power or improving detector

$$s_{\rm J} = \sqrt{\frac{4k_{\rm B}T}{G}}\frac{1}{I_{\rm out} q \eta_0}$$

Johnson noise. Reduce contribution by increasing power

$$s_{\rm RIN} = {\rm RIN}(\nu_{\rm Mod})\frac{\sqrt{(\sigma^2 + \eta_0^2/2)^2 + (\eta_0/2)^2}}{\eta_0}$$

Laer intensity noise. Reduce contribution by reducing σ^2, stabilize power, increase ν_{Mod}

+ all other uncontrolled sources of **time varying birefringences α(t)**

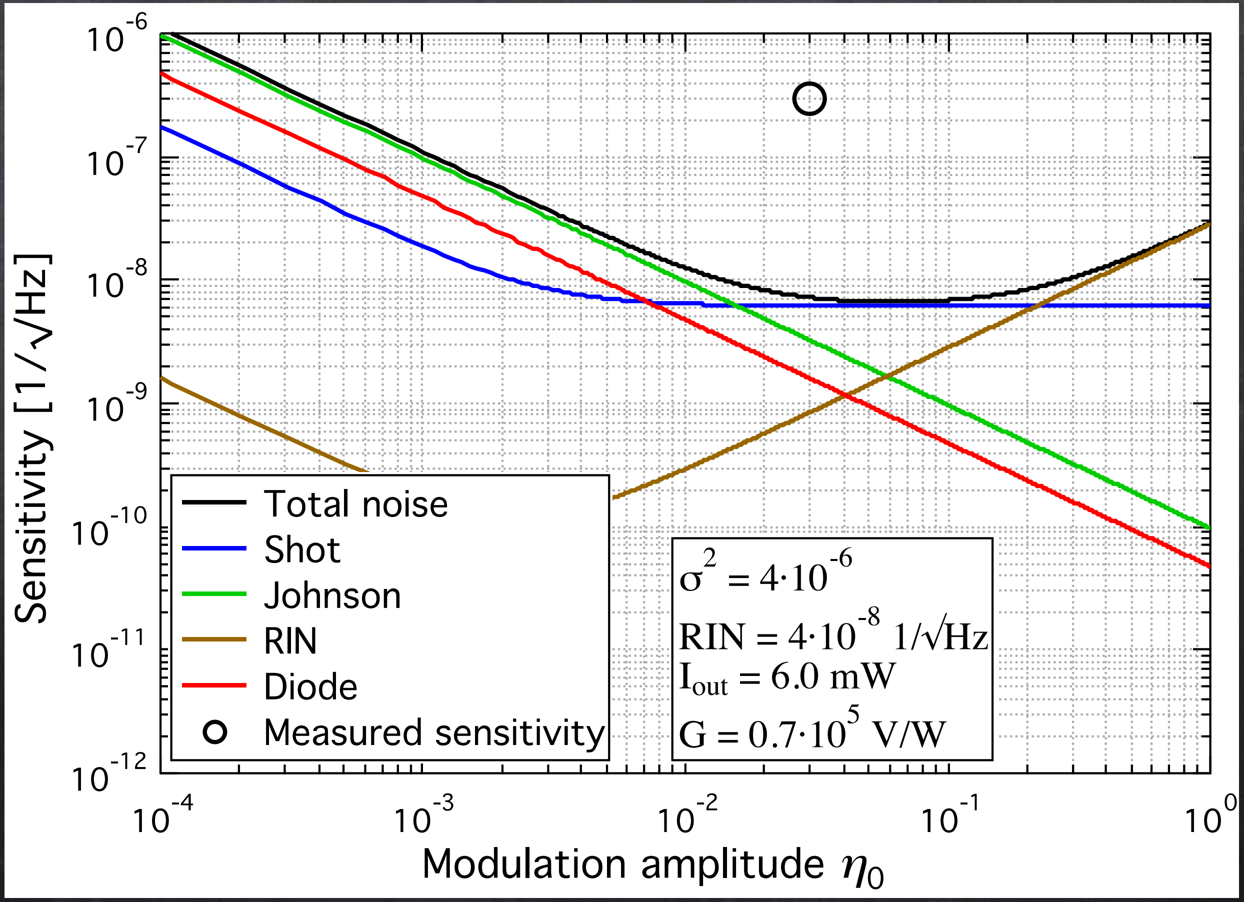
1/f noise: increase ν_{Mag}

High finesse cavities are a strong source of 1/f birefringence noise

Calculated and measured noise

- Contribution of the various noises as a function of the modulation amplitude η_0 compared to the measured sensitivity.

$F \approx 400000$



Ferrara test setup

Limitations of the previous apparatus

- Superconducting magnets produce stray fields when operated at high fields (saturated iron)
- Running time very limited due to liquid helium consuption
- Short term sensitivity for ellipticity about 2-3 10^{-7} 1/√Hz,
  but long term 1 10^{-6} 1/√Hz
- Observed correlation between seismic noise and ellipticity noise. The Legnaro apparatus is large and therefore difficult to isolate seismically.
- No zero measurement possibile with field turned ON.

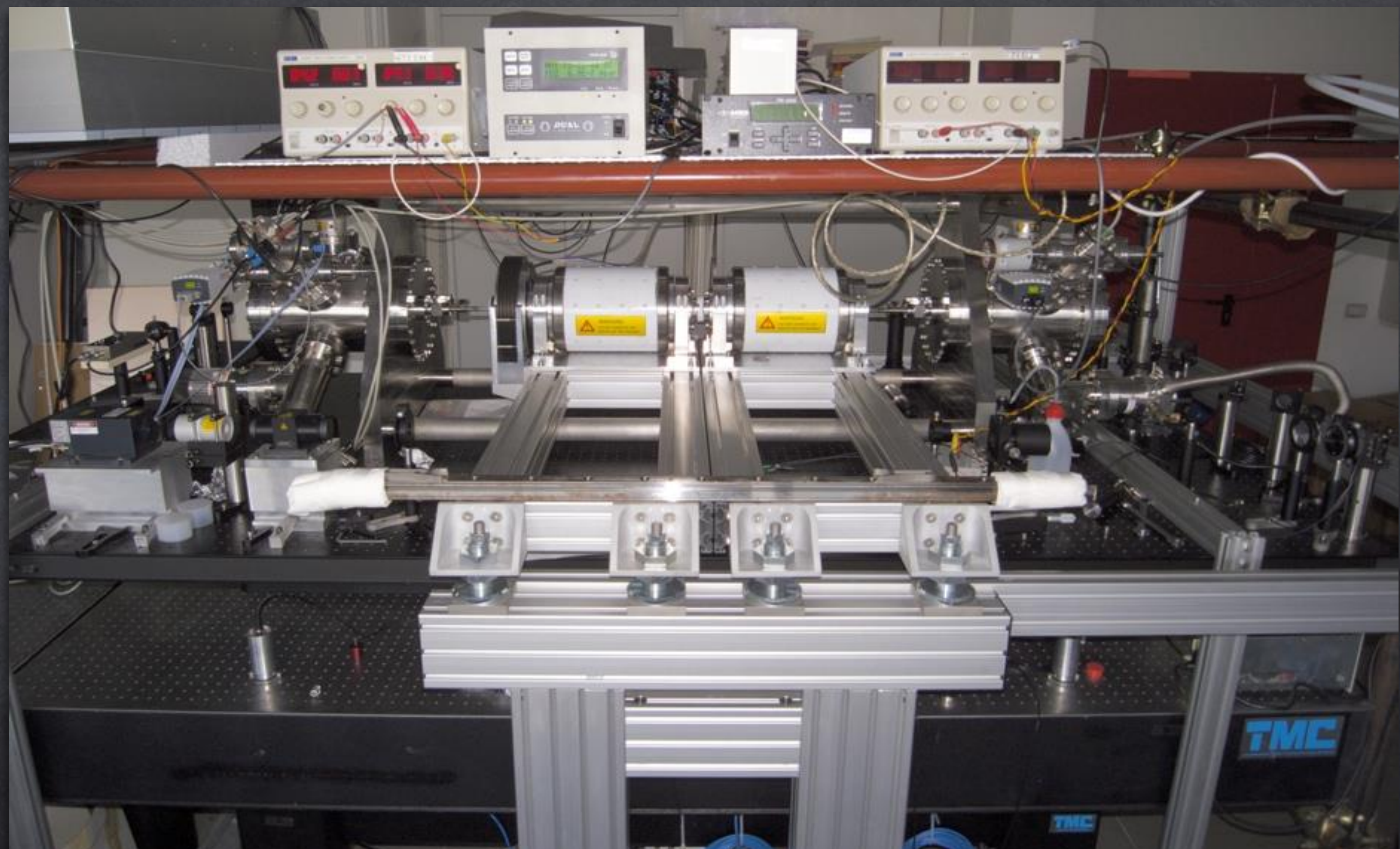
Development strategy

- Reverse the logic of designing the apparatus
  - Old - get the highest magnetic field and build the optical system around it
  - New - **build up an ellipsometer with best sensitivity and find a suitable magnetic source** - the problem is the optics
- New magnetic sources available: **permanent dipole magnets** with 2.5 T field almost on shelf, up to 3 - 3.5 T for special orders
- Build up a test apparatus to **improve sensitivity** for an ellipsometer coupled to **very high finesse Fabry-Perot cavity**
- Design the system with built-in capability of **bad signal rejection** (Two magnet system)

Ferrara test setup

In operation since 2010

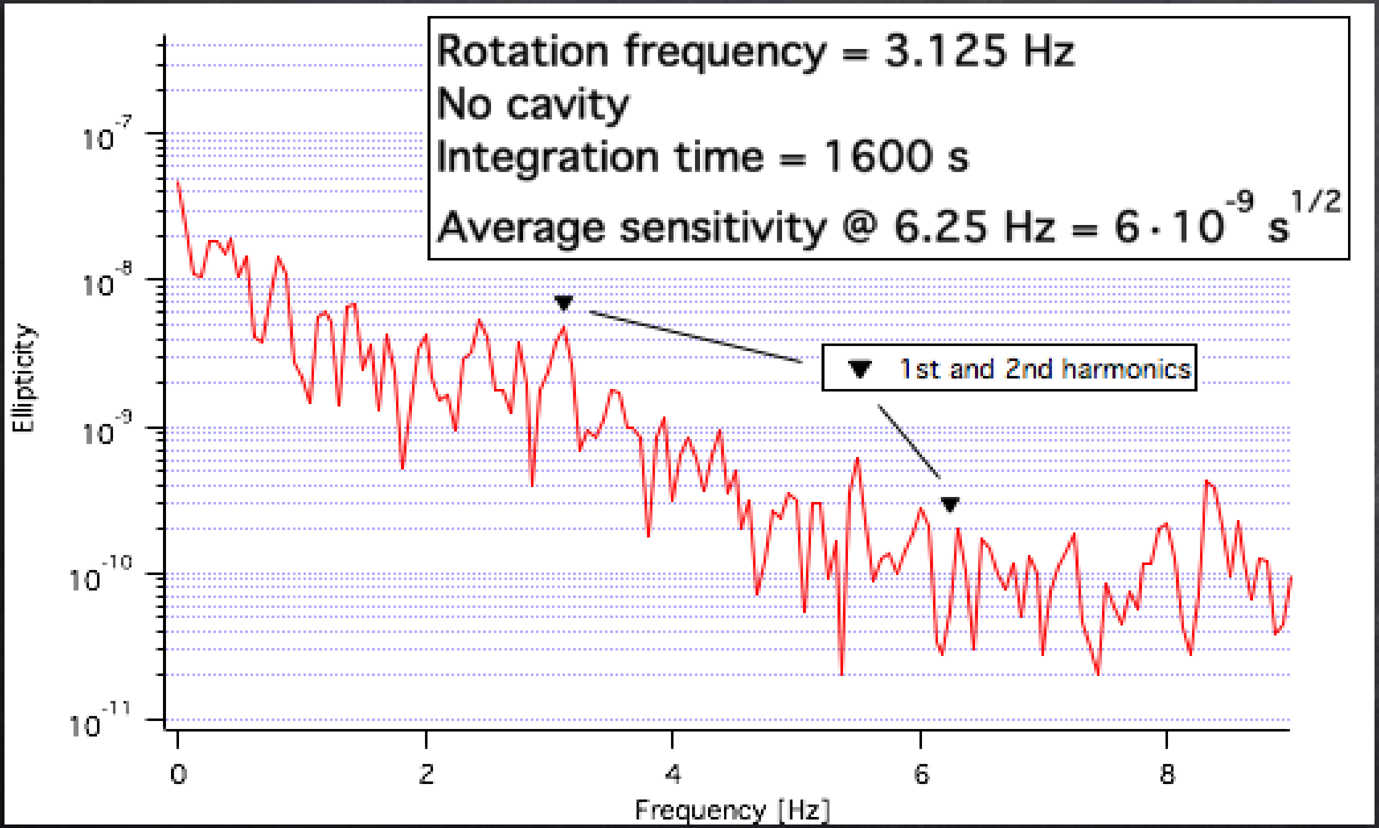
- Ellipsometer and optical cavity on **single optical table**
- Optical table with **active suspension system**
- **Two magnets**
- **High rotation frequency for the magnetic source**
- **High frequency polarization modulator**



Main limitation: most of the components are **magnetic**

Performance

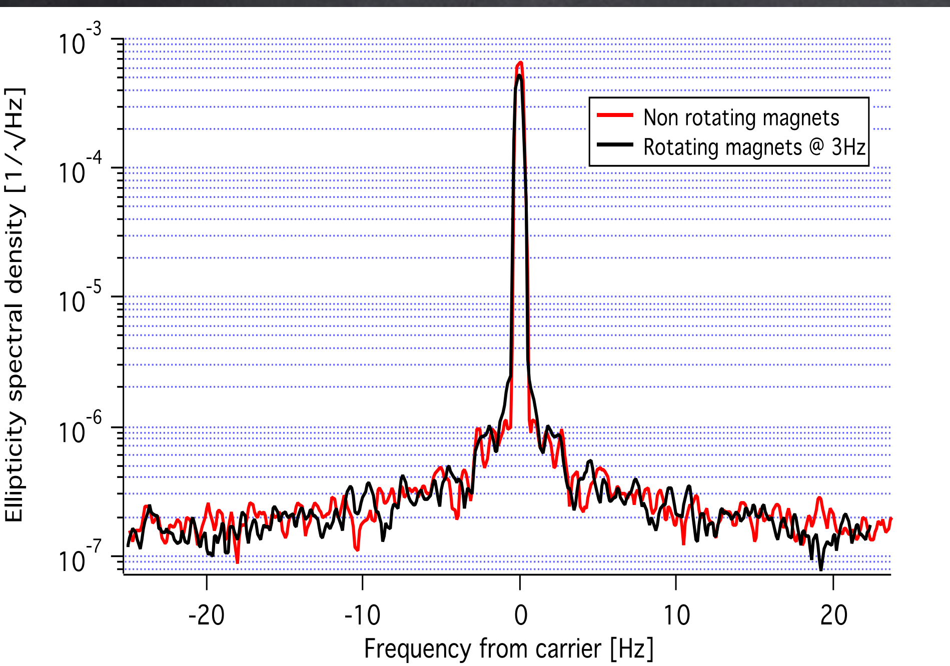
No cavity – reached expected noise level with rotating magnets

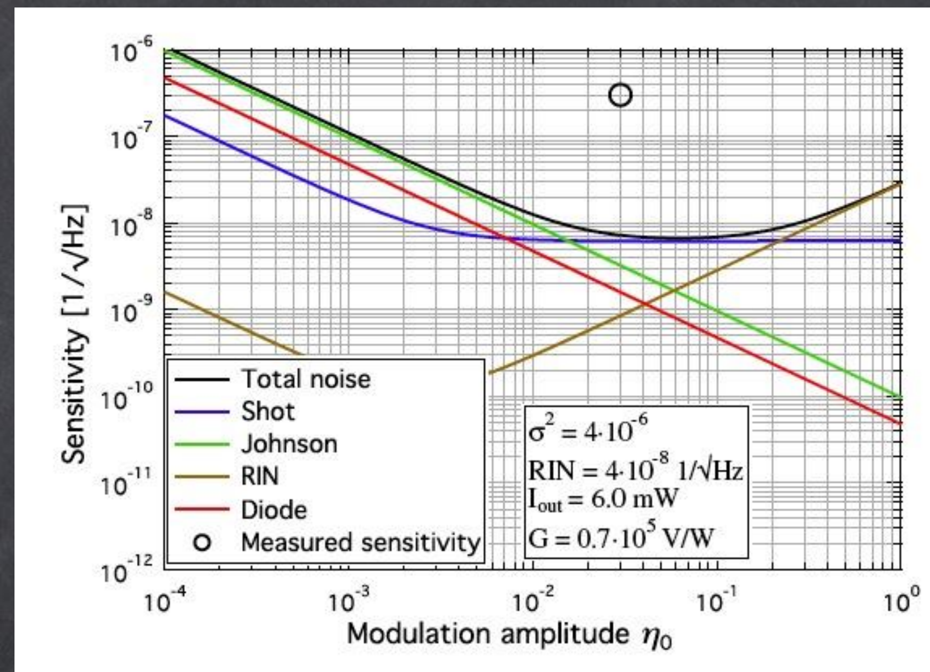


No electronically induced signals in the readout system

Performance - wideband noise

With high-finesse cavity: $F > 400\,000$
Extra wideband noise. Sensitivity worsened – still under study



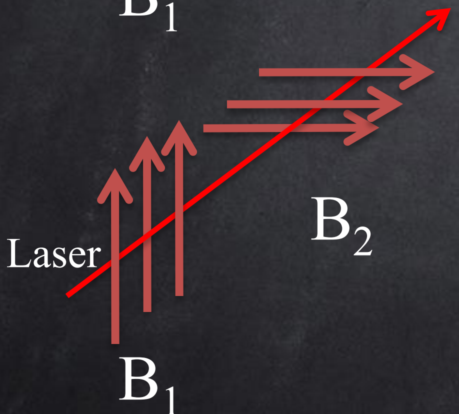


s_{total} (6 Hz) ~ 3 10^{-7} 1/√Hz
s_{total} (20 Hz) ~ 1.5 10^{-7} 1/√Hz

Performance - excluding peaks

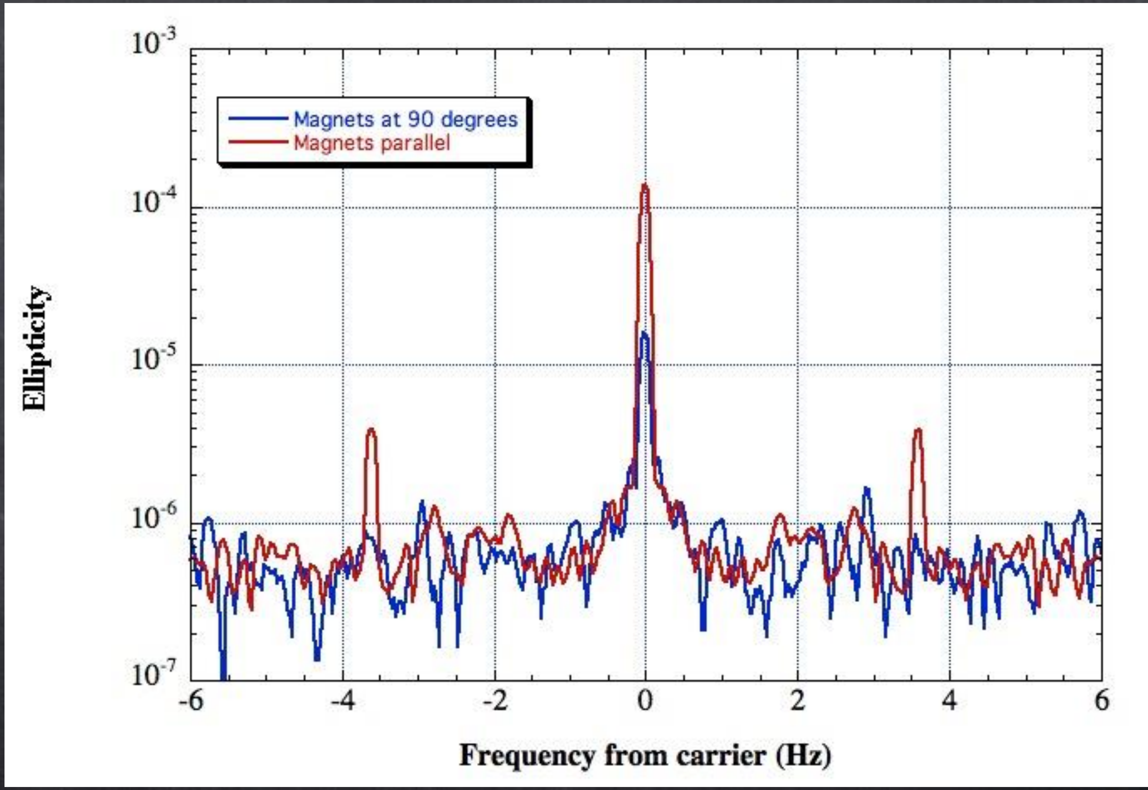
Two magnet system to check that signal is due to magnetic birefringence
Peak magnetic field intensity = 2.3 T. Average field = 2.15 T

$$\Psi_{tot} = 2\Psi$$



$$\Psi_{tot} = 0$$

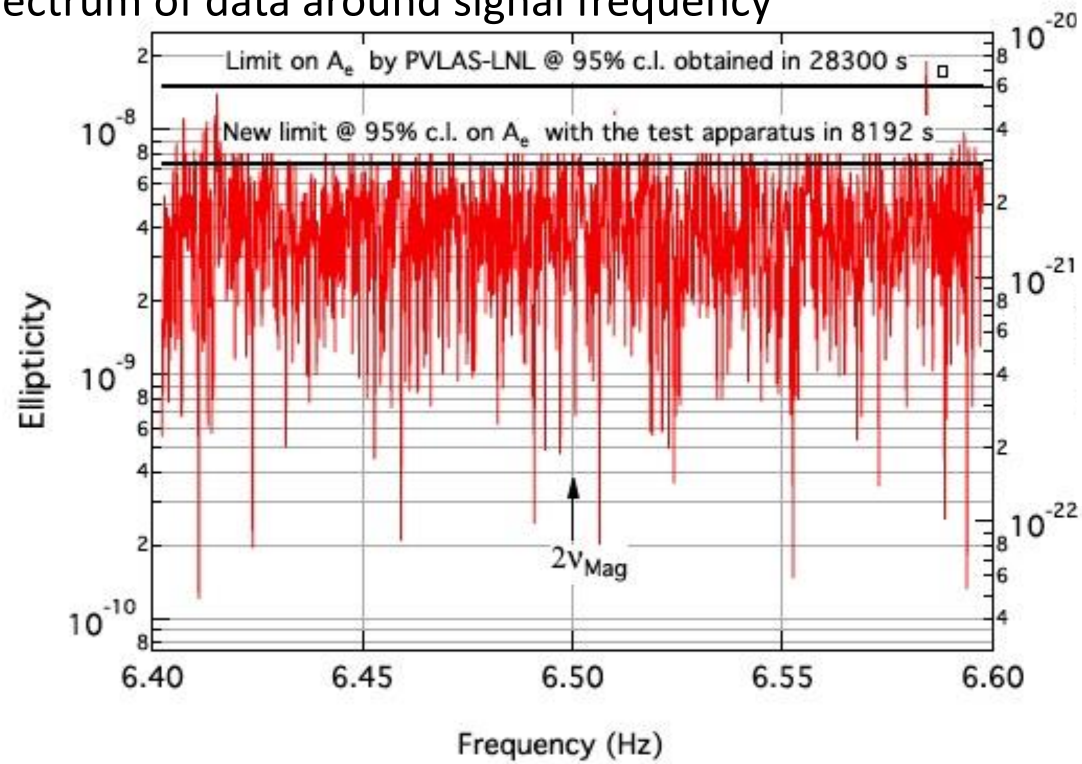
Measurement with 1.3 mbar of air

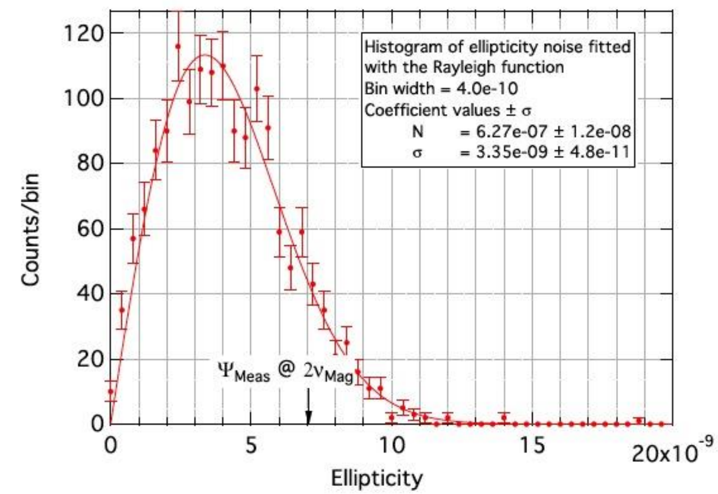


For a very weak signal this represents a crucial test

Vacuum test measurement

Spectrum of data around signal frequency





Distribution of noise

Rayleigh function

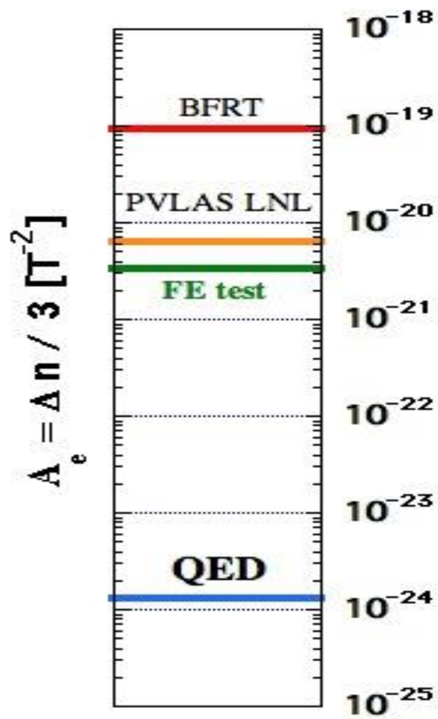
$$P(r) = N \frac{r}{s_y^2} e^{-\frac{r^2}{2s_y^2}}$$

$\sigma_\psi = 3.35\ 10^{-9}$

$\Delta n < 4.5\ 10^{-20}$ [95% C.L.]

$A_e < 3.3\ 10^{-21}\ T^{-2}$ [95% CL]

$$\Delta n = 3 A_\mathrm{e} B_\mathrm{ext}^2$$



Limits on new physics - ALP

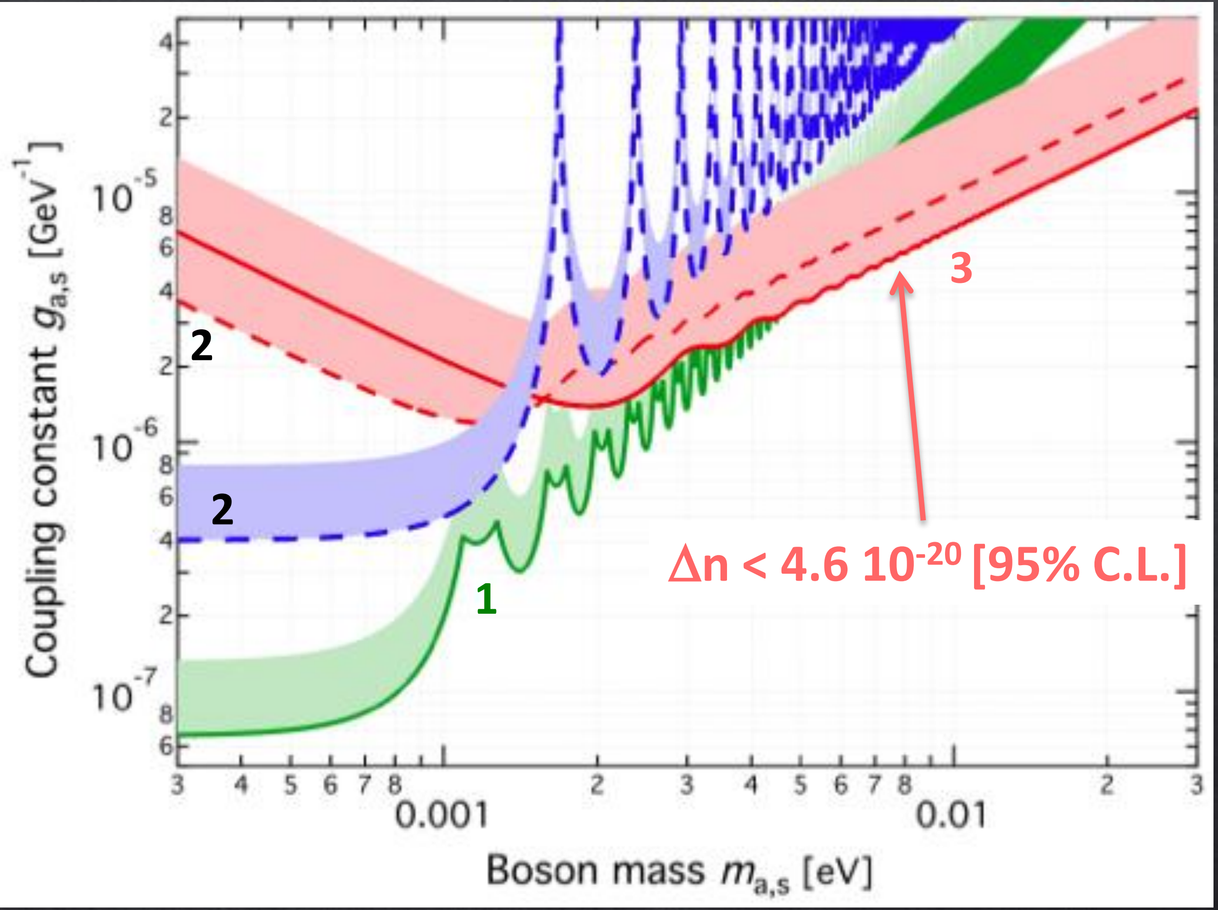
Limits on Axion Like Particles from ellipticity measurements with the Ferrara test setup

Integration time = 8192 s

$B^2L = 1.85\ T^2\ m$

F = 240 000

Magnet rotation @ 3.25 Hz

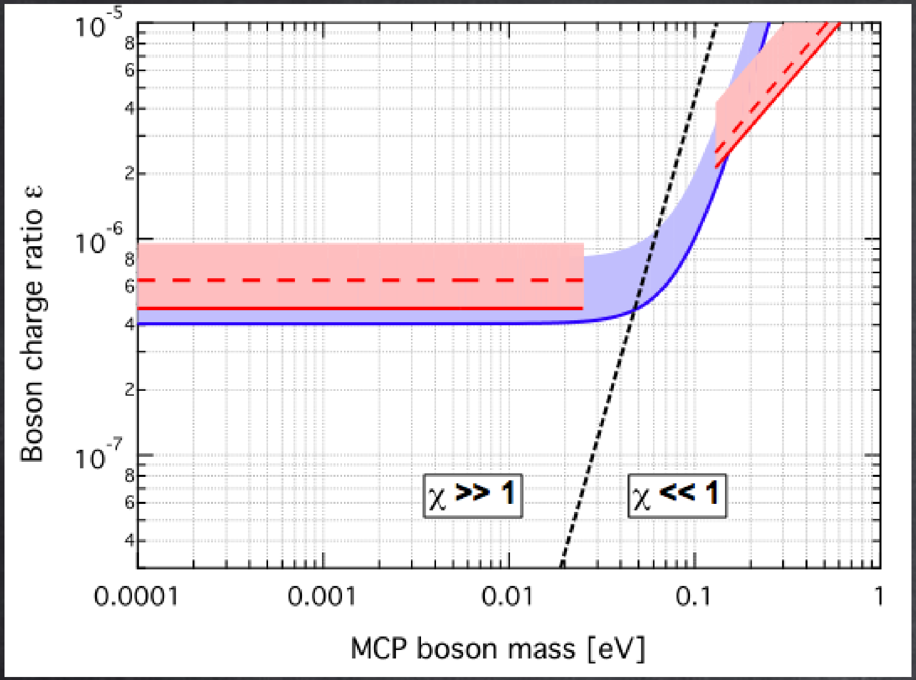


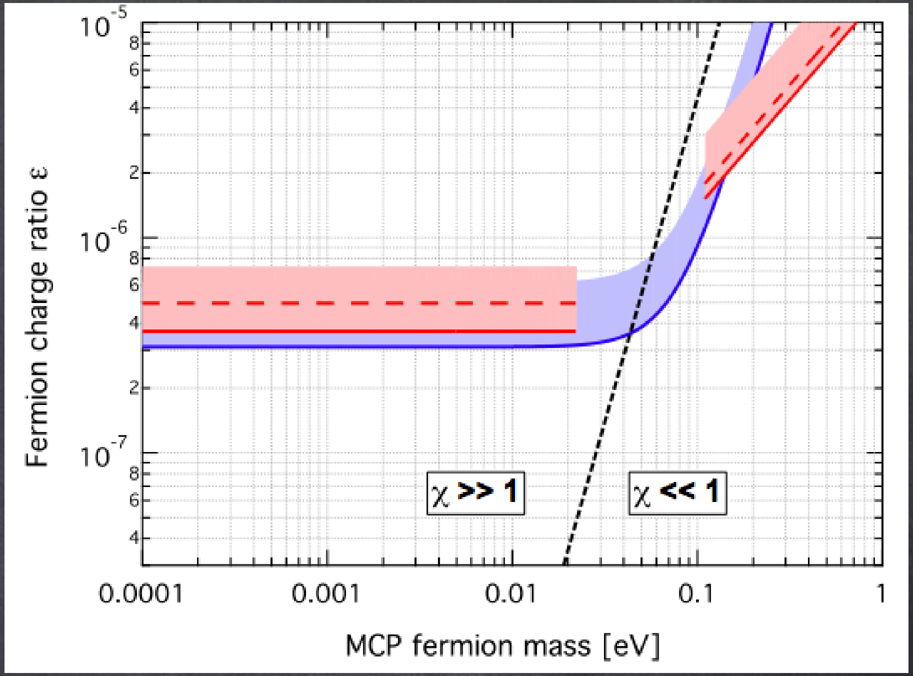
1 . Ehret K et al, Physics Letters B 689, 149 (2010)

2 . Zavattini E et al, Phys. Rev. D 77, 032006 (2008)

3 . Della Valle F. et al, New J. Phys. 15, 053026 (2013)

Millicharged particles





Boson

Fermion

- Exclusion plots for the existence of millicharged particles derived from ellipticity measurements
- Other more stringent laboratory results exist

PVLAS in Ferrara

Laboratory - clean room

Pro
Clean room class 10000

Possible temperature stabilization system

Con
Environment with human noise sources during day

Optical bench

Actively isolated granite optical bench

4.8 m length, 1.2 m wide, 0.4 m height, 4.5 tons

Compressed air stabilization system for six degrees of freedom
Resonance frequency down to 1 Hz

Bench installed

Fortunately survived the May 20 2013 earthquake

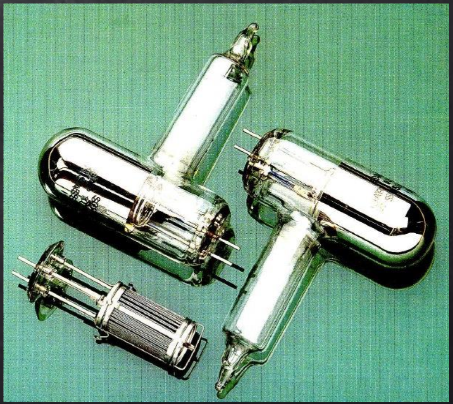
Vacuum and pumping

- All components of the vacuum system and optical mounts made with **non magnetic materials** (at best)
- Vacuum pipe through magnet made in **Pyrex** to avoid eddy currents
- Pyrex pipe surrounded by **Carbon fiber tube** to avoid interaction of scattered light with magnets
- Motion of optical components inside vacuum chamber by means of **piezo-motor**
- Low pressure pumping by using getter - NEG pumps – **noise free, magnetic field free**

Vacuum chambers

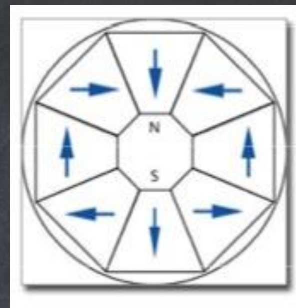
Linear translator

Getter pumps



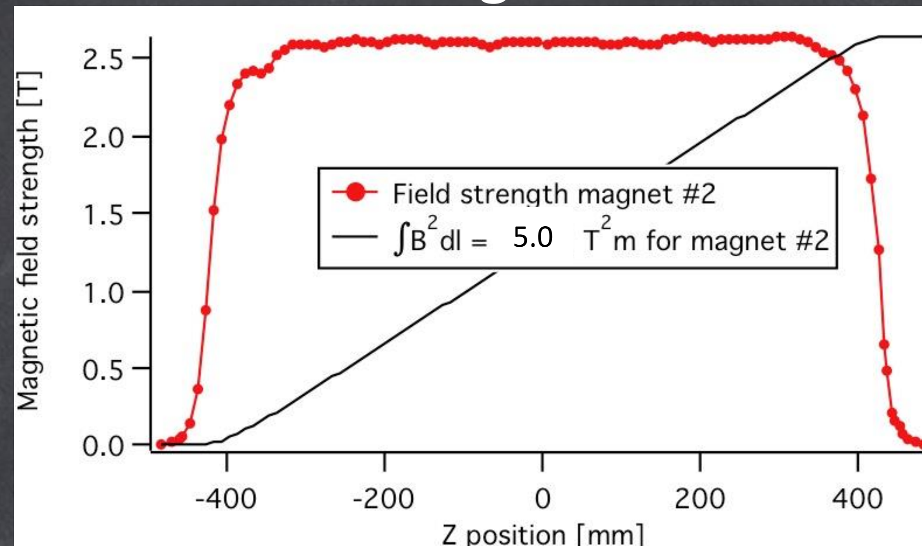
The magnets

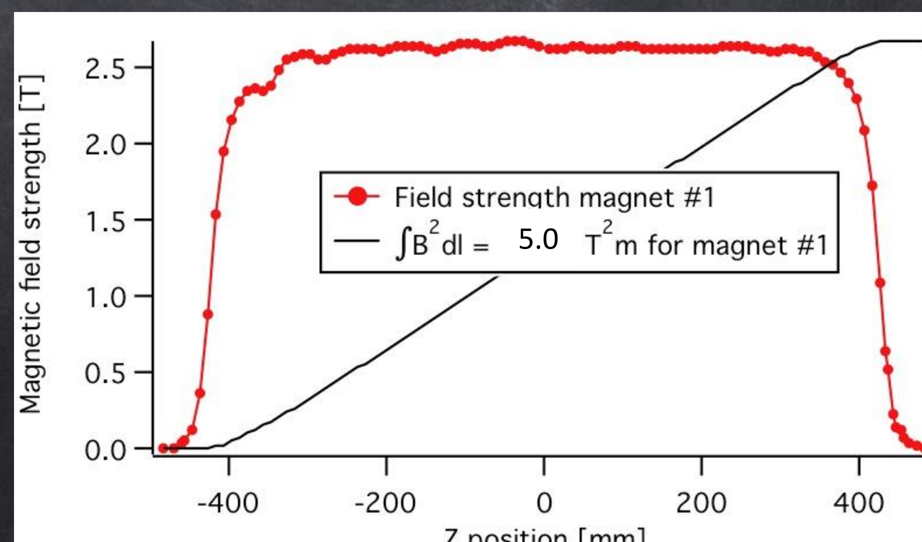
Halbach configuration



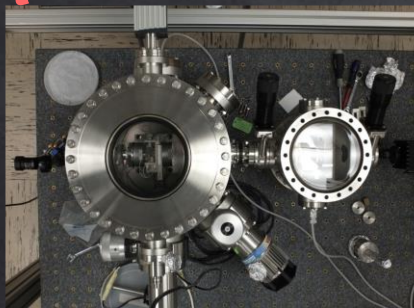
Magnets have built in **magnetic shielding**
Stray field below 1 Gauss on side

Total field integral = 10.0 T^2 m

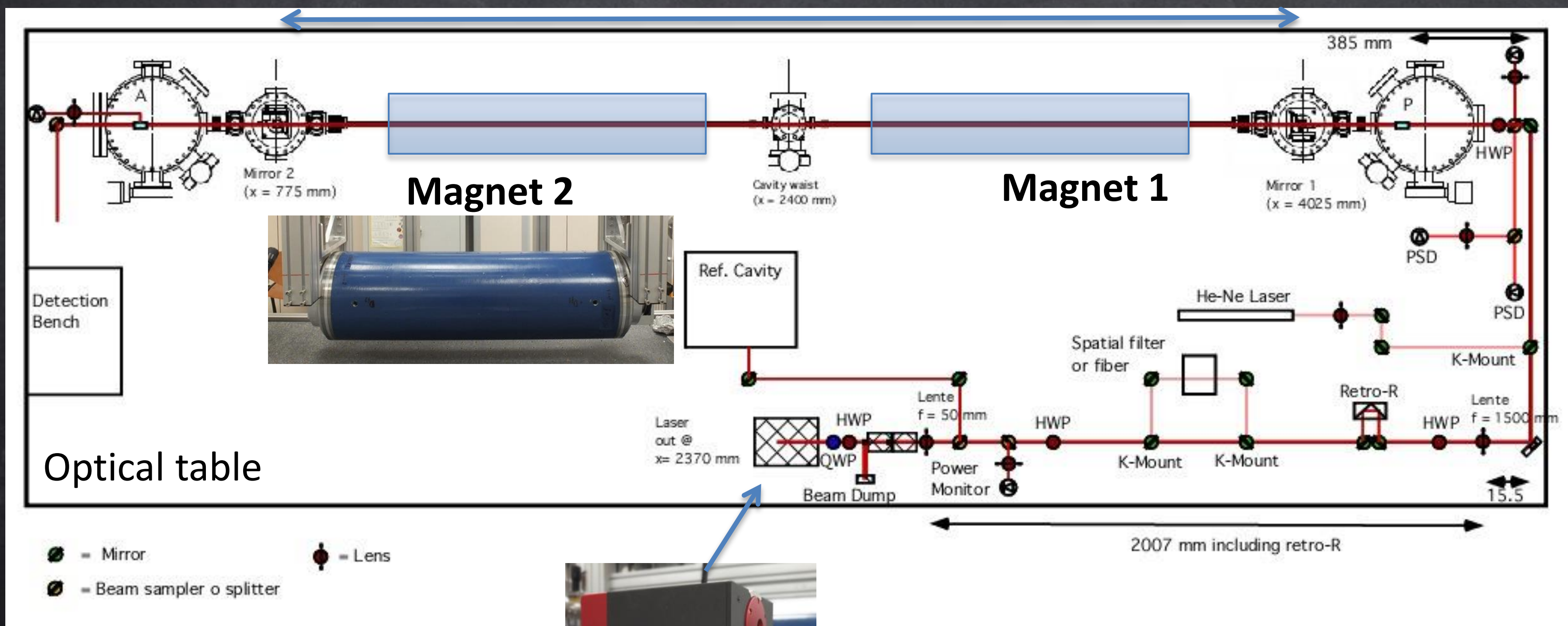




Optics layout



3.25 m long Fabry Perot cavity



2 W NPRO Nd:Yag Laser

λ = 1064 nm

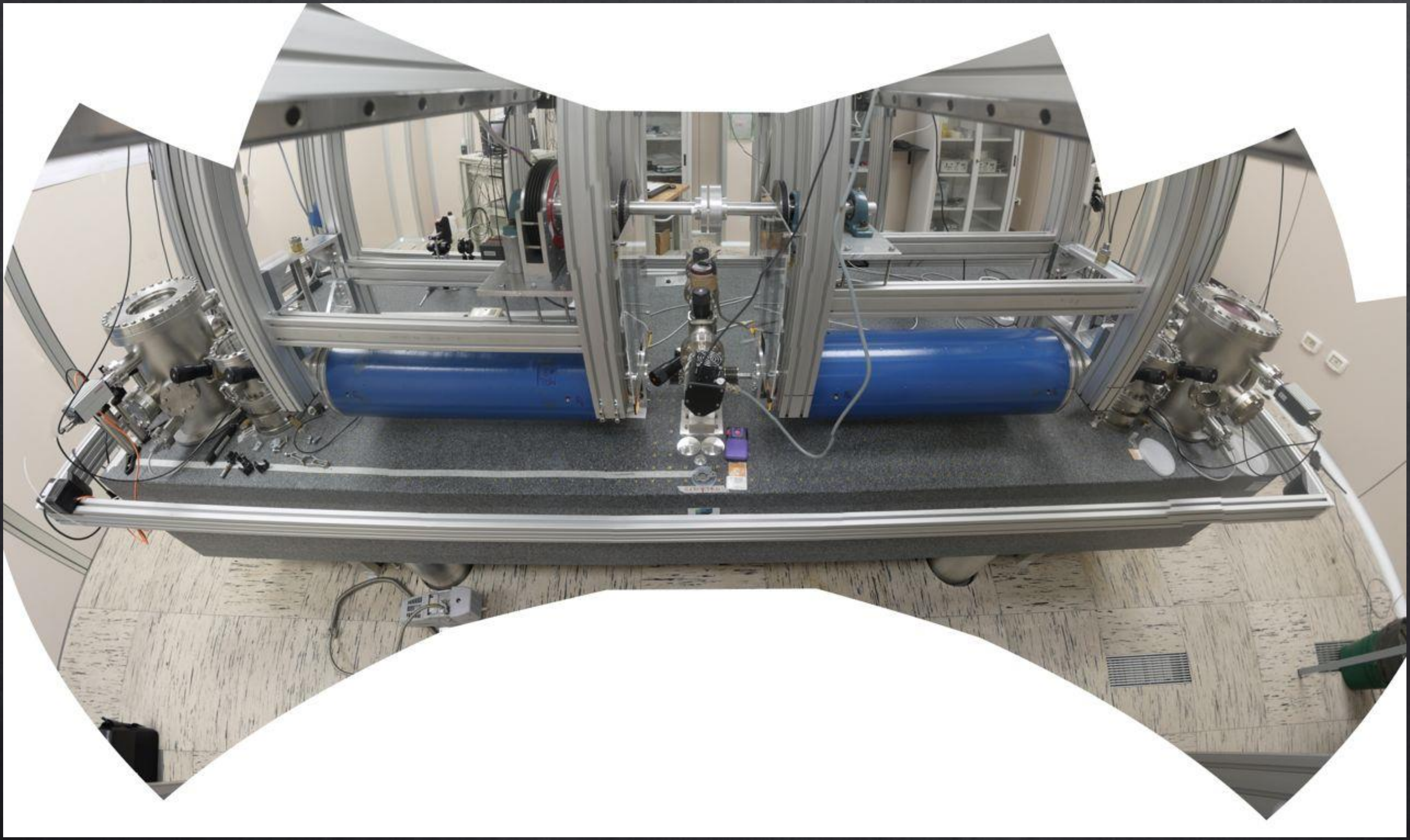
University of Ferrara

Rotating magnet

The compact structure of the permanent magnets allows for very high modulation frequency

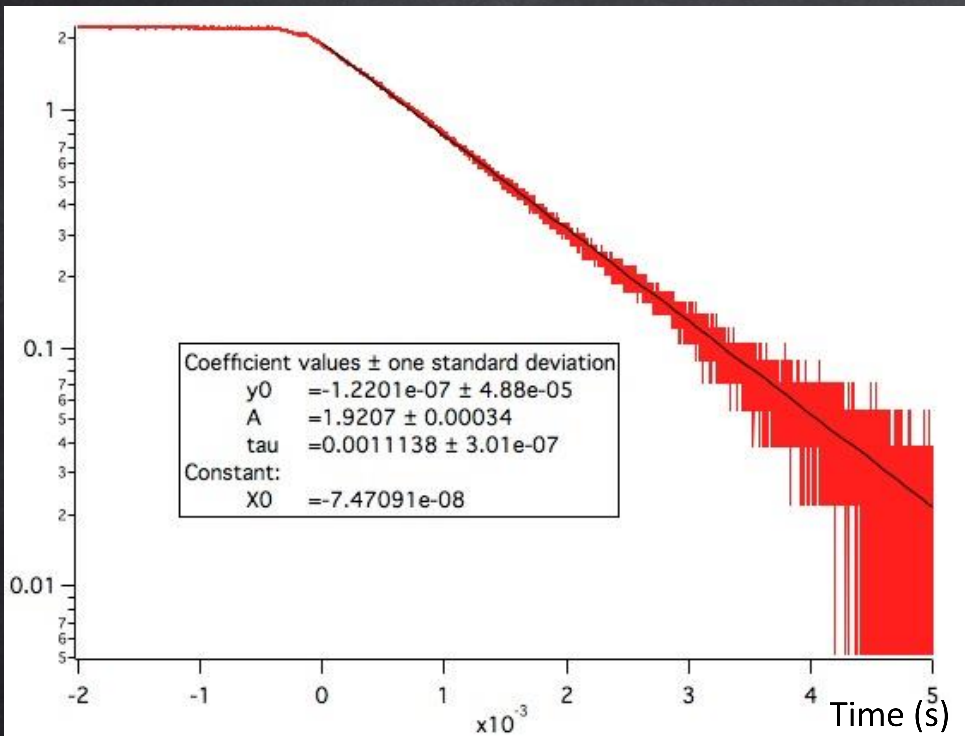
Magnet rotating at 4 Hz – target: 10 Hz

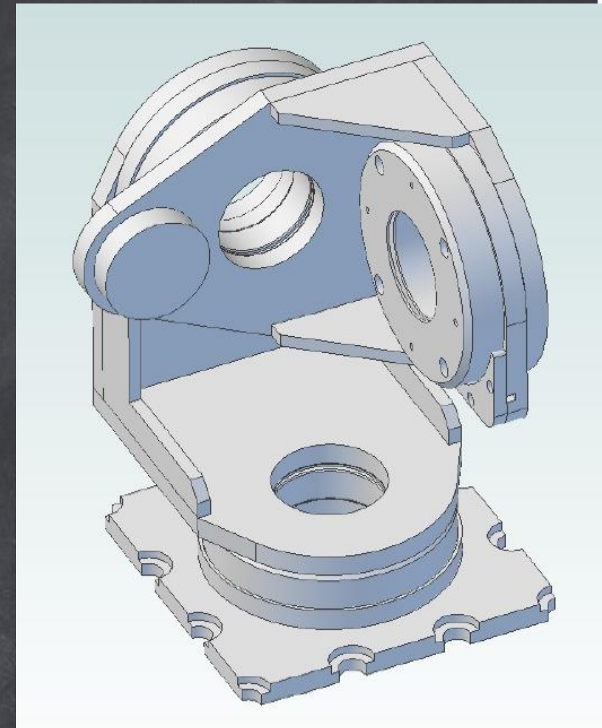
The mounted apparatus



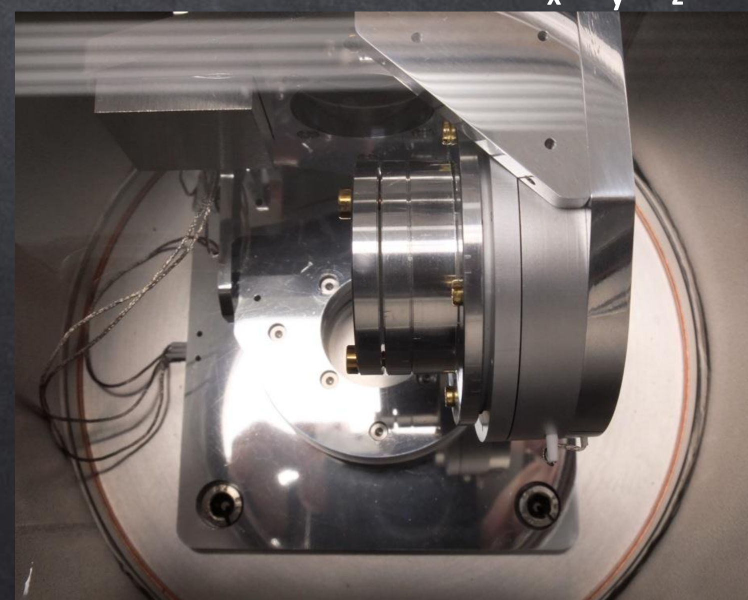
Cavity

Fabry Perot cavity with low finesse and high finesse mirrors
Spherical mirror with r = – 2 m





3-Motor Mirror tilter, θ_x, θ_y, θ_z



Transmitted power = 200 mW

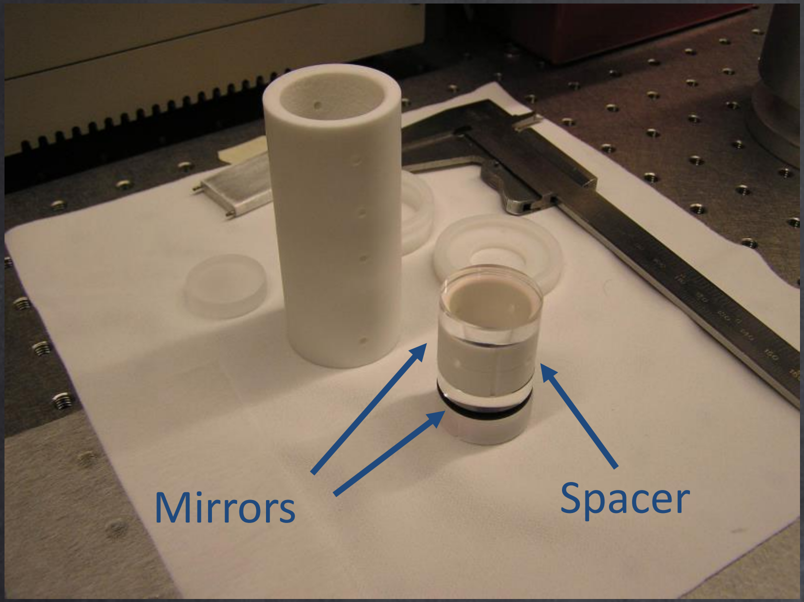
τ = 1.1 ms , d = 3.25 m

Finesse = 325 000 N = 207 000

Circulating power = 40 kW

Mirror test facility

Test cavity

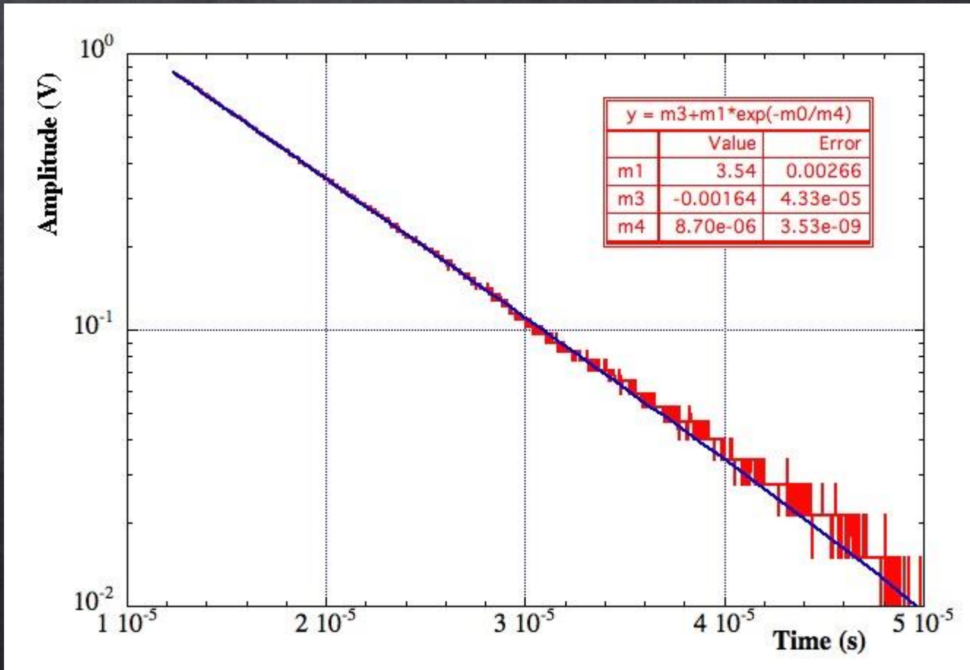


Short Fabry Perot resonator to test mirrors

Spacer with d = 1.7 cm

Holder and spacer made in MACOR

Cavity decay curve

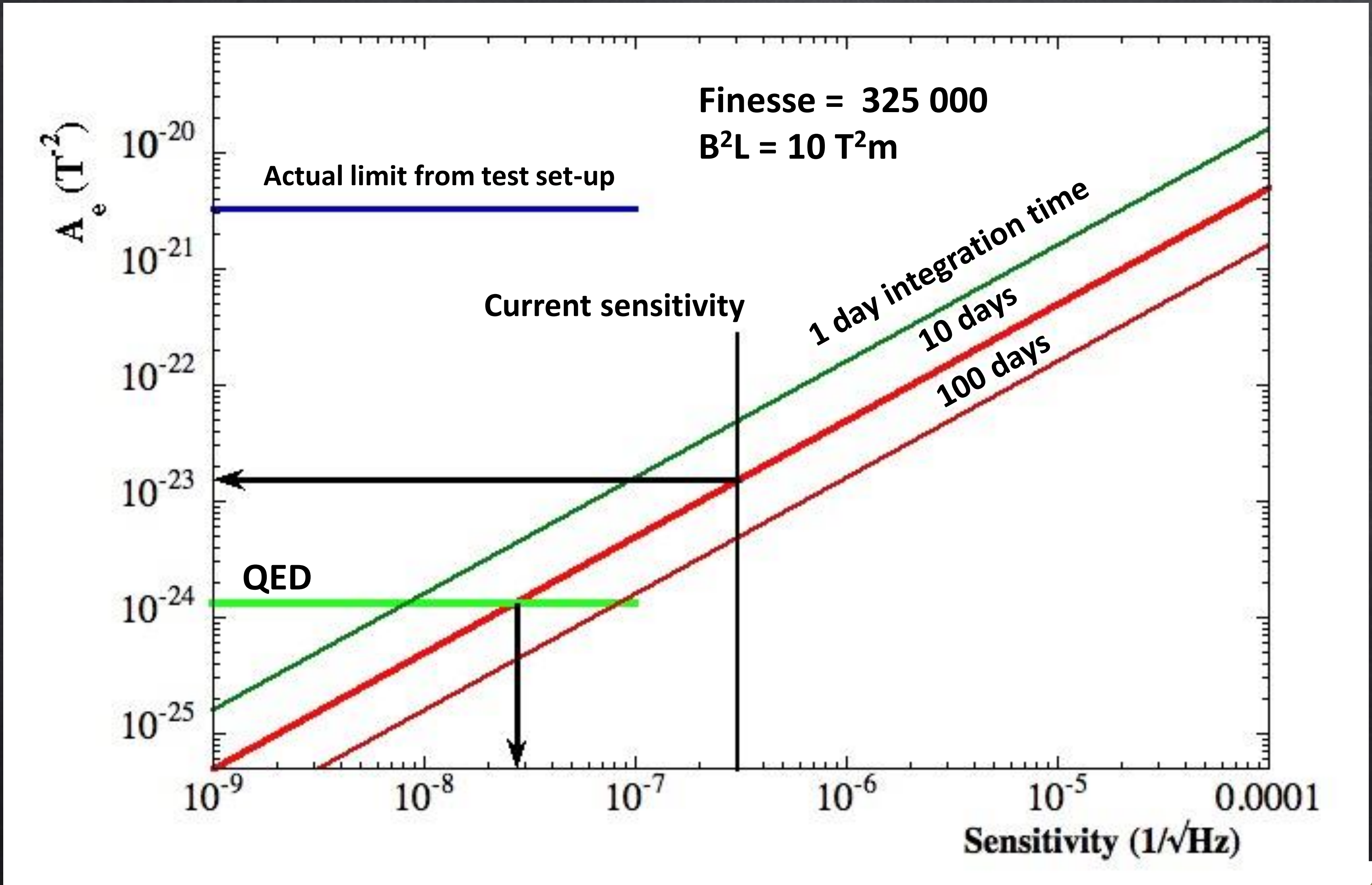


Cavity can be operated in air and low vacuum
System to test cleaning procedure

With best mirror we have

T = 8.7 μs → **F = 480 000**

Perspective



Other efforts

- **BMV experiment (Toulouse, France)**
  Pulsed magnet with very high field (>20 T), but short time (3 ms), L_{eq} = 0.14 m
  Limited repetition rate (~ 10 minutes)
  High finesse Fabry Perot with F ~ 500 000, d = 2 m
  Actual sensitivity a little bit worse than Ferrara test set-up

- **Q & A Experiment (Taiwan)**
  Permanent magnet 2.3 T, 1.8 m long (Possible acquisition of 2nd magnet)
  Heterodyne detection scheme with magnet rotating
  High finesse Fabry Perot with F ~ 100 000
  Separate optical benches
  Poor sensitivity

- **OSQAR experiment (CERN)**
  Decommissioned LHC magnet 15 m long, 10 T
  Fabry Perot cavity 20 m long but low finesse
  Separate optical benches
  Magnet modulation via current modulation (?)
  Real sensitivity not clear

Comparison

Experiment	PVLAS	Q & A	BMV
Status	Achieved/planned	Achieved/planned	Achieved/planned
Wavelength (nm)	1064	1064/532	1064
Magnetic dipole	Permanent	Permanent	Pulsed
$\int B^2\,\mathrm{d}L$ (T^2 m)	1.85/10	3.2/19	25/600
Average B_{ext} (T)	2.15/2.5	2.3/2.3	14/30
Finesse	$2.4 \times 10^5 / > 4 \times 10^5$	$3 \times 10^4/1 \times 10^5$	$5 \times 10^5/1 \times 10^6$
QED ellipticity (equation (31))	$3 \times 10^{-12}/3 \times 10^{-11}$	$7 \times 10^{-13}/3 \times 10^{-11}$	$9 \times 10^{-11}/5 \times 10^{-9}$
Detection scheme	Heterodyne	Heterodyne	Homodyne
Effect mod. freq. f_{mod}	6 Hz/20 Hz	26 Hz	500 Hz
Duty cycle D_t	~ 1	~ 1	3×10^{-6}
s @ f_{mod} ($\mathrm{Hz}^{-1/2}$)	$3 \times 10^{-7}/3 \times 10^{-8}$	$1 \times 10^{-6}/1 \times 10^{-8}$	$5 \times 10^{-8}/7 \times 10^{-9}$
s_{eff} @ f_{mod} ($\mathrm{Hz}^{-1/2}$)	$3 \times 10^{-7}/3 \times 10^{-8}$	$1 \times 10^{-6}/1 \times 10^{-8}$	$3 \times 10^{-5}/4 \times 10^{-6}$
Δn_{eff} sensitivity ($\mathrm{Hz}^{-1/2}$)	$1.7 \times 10^{-18}/2.5 \times 10^{-20}$	$3.0 \times 10^{-17}/7.4 \times 10^{-21}$	$2.6 \times 10^{-16}/3.0 \times 10^{-18}$
A_e sensitivity ($\mathrm{T}^{-2}\,\mathrm{Hz}^{-1/2}$)	$1.2 \times 10^{-19}/1.3 \times 10^{-21}$	$1.8 \times 10^{-18}/4.7 \times 10^{-22}$	$4.4 \times 10^{-19}/1.1 \times 10^{-21}$
Time for SNR = 1	260 yr/12 d	63×10^3 yr/1.4 d	3.6×10^3 yr/8.3 d

Della Valle F. et al, New J. Phys. 15, 053026 (2013) (Free access journal)

Other proposals-ideas

INFN Istituto Nazionale di Fisica Nucleare

Using Gravitational Wave interferometers

PHYSICAL REVIEW D VOLUME 19, NUMBER 8 15 APRIL 1979

Testability of nonlinear electrodynamics

A. M. Grassi Strini, G. Strini, and G. Tagliaferri

Eur. Phys. J. C
DOI 10.1140/epjc/s10052-009-1079-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Probing for new physics and detecting non-linear vacuum QED effects using gravitational wave interferometer antennas

Guido Zavattini[1,a], Encrico Calloni[2]

Modern Physics Letters A, Vol. 6, No. 40 (1991) 3671–3678
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TEST OF QUANTUM ELECTRODYNAMICS USING ULTRA-HIGH SENSITIVE INTERFEROMETERS

WEI-TOU NI,* KIMIO TSUBONO,† NORIKATSU MIO,† KAZUMICHI NARIHARA,‡ SHEN-CHE CHEN,* SUN-KUN KING,* and SHEAU-SHI PAN*

EPL, **87** (2009) 21002
doi: 10.1209/0295-5075/87/21002

Interferometry of light propagation in pulsed fields

B. Döbrich[(a)] and H. Gies

Using frequency measurements techniques instead of polarimetry

PHYSICAL REVIEW A, VOLUME 62, 013815

Measurement of mirror birefringence at the sub-ppm level: Proposed application to a test of QED

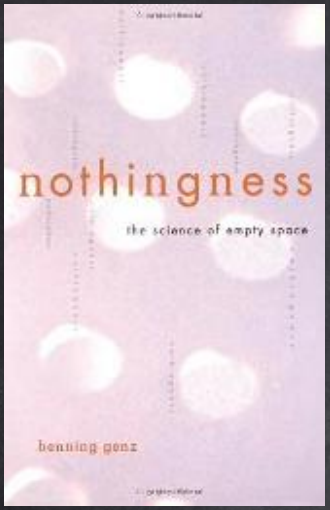
John L. Hall,* Jun Ye,* and Long-Sheng Ma†

REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 033105 (2010)

Highly sensitive frequency metrology for optical anisotropy measurements

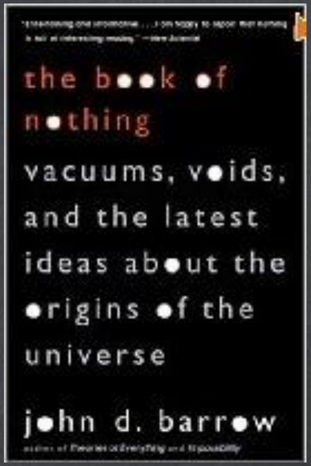
Gilles Bailly,[1,2] Raphaël Thon,[1,2] and Cécile Robilliard[1,2,a)]

Reading



Henning Genz
Nothingness

John D. Barrow
The book of Nothing



IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. **76** (2013) 016401 (23pp) doi:10.1088/0034-4885/76/1/016401

Magnetic and electric properties of a quantum vacuum

R Battesti and C Rizzo

IOP Publishing — Journal of Physics A: Mathematical and Theoretical

J. Phys. A: Math. Theor. **41** (2008) 164039 (11pp) doi:10.1088/1751-8113/41/16/164039

External fields as a probe for fundamental physics

Holger Gies