Domintating noise sources in PVLAS

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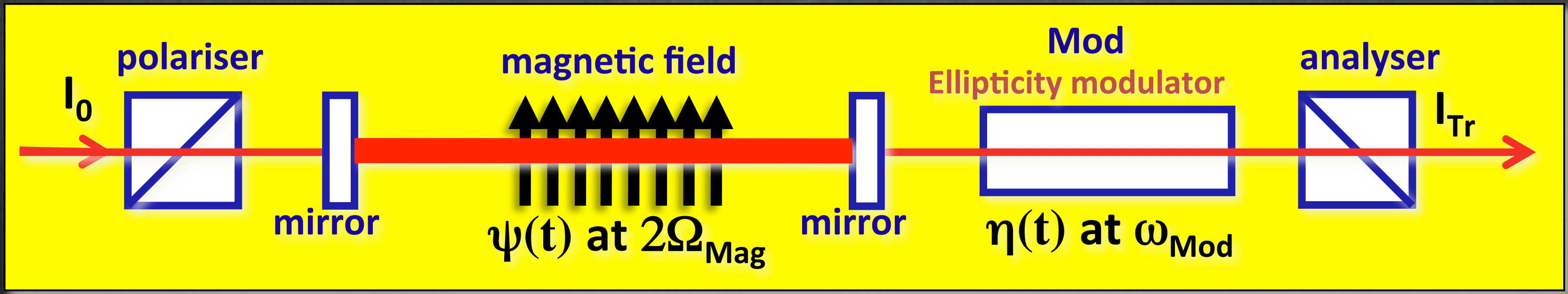
PVLAS scheme

- A Fabry-Perot cavity increases the single pass ellipticity by a factor $N = 2\mathcal{F}/\pi$
- Heterodyne detection linearizes the ellipticity ψ to be measured
- Rotating magnetic fields modulate the searched effect



Frequency components

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

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

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

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

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Sensitivity Goal

Main interest of PVLAS is the Euler-Heisenberg birefringence

- $B = 2.5$ T
- $F = 7 \cdot 10^5$
- $L = 1.6$ m

$\Delta n = 2.5 \cdot 10^{-23}$ ➡ $\psi = 5 \cdot 10^{-11}$

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

⬇

The necessary ellipticity sensitivity is < $5 \cdot 10^{-8}$ 1/√Hz
Birefringence sensitivity < $2.5 \cdot 10^{-20}$ 1/√Hz

Peak shot noise limit = $\sqrt{\frac{e}{I_0 q}} \approx 5 \cdot 10^{-9} \frac{1}{\sqrt{\mathrm{Hz}}}$ for I_0 = 8 mW

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

Actual Sensitivity

Main interest of PVLAS is the Euler-Heisenberg birefringence

- $B = 2.5$ T
- $F = 7\cdot10^5$
- $L = 1.6$ m

$\Delta n = 2.5\cdot10^{-23}$ ⇒ $\psi = 5\cdot10^{-11}$

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

The present ellipticity sensitivity is ≈ $5\cdot10^{-7}$ 1/√Hz

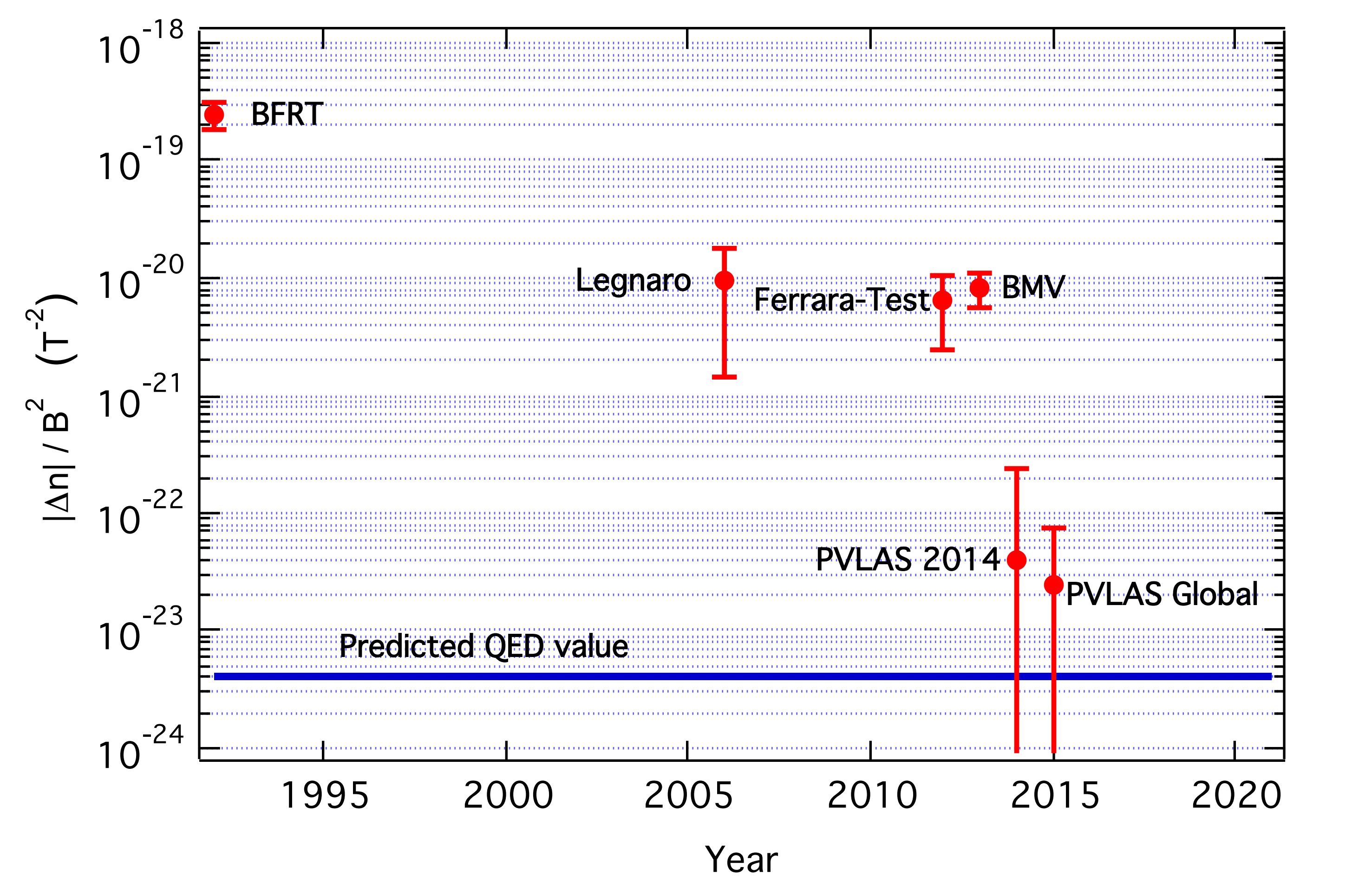
Birefringence sensitivity < $2.5\cdot10^{-19}$ 1/√Hz

Peak shot noise limit = $\sqrt{\frac{e}{I_0 q}} \approx 5\cdot10^{-9}\ \frac{1}{\sqrt{\mathrm{Hz}}}$ for I_0 = 8 mW

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

Present limit

Error bars correspond to 1 σ



$$\Delta n_u = \frac{\Delta n}{B^2} = (-2.4 \pm 4.8) \times 10^{-23}\ \mathrm{T}^{-2}$$

Shot noise

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

$$i_{\rm shot} = \sqrt{2ei_{\rm DC}\Delta\nu} = \sqrt{2eI_0q\left(\sigma^2 + \frac{\eta_0^2}{2} + \alpha_{\rm DC}^2\right)\Delta\nu}$$

- With $\eta_0 \gg \sigma^2, \alpha_{\rm DC}$ the shot noise spectral sensitivity becomes (I_0 = 8 mW)

$$s_{\rm shot} = \sqrt{\frac{e}{I_0q}} \approx 5 \cdot 10^{-9}\ \frac{1}{\sqrt{\rm Hz}}$$

If we were shot noise limited...

- The expected ellipticity for B = 2.5 T, *F* = $7 \cdot 10^5$ and L = 1.6 m is

$$\psi_{\rm QED} = 5 \cdot 10^{-11}$$

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

$$T = \left(\frac{s_{\rm shot}}{\psi_{\rm QED}}\right)^2 = 10^4\ {\rm s}$$

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 $\nu_{\rm Mod}$

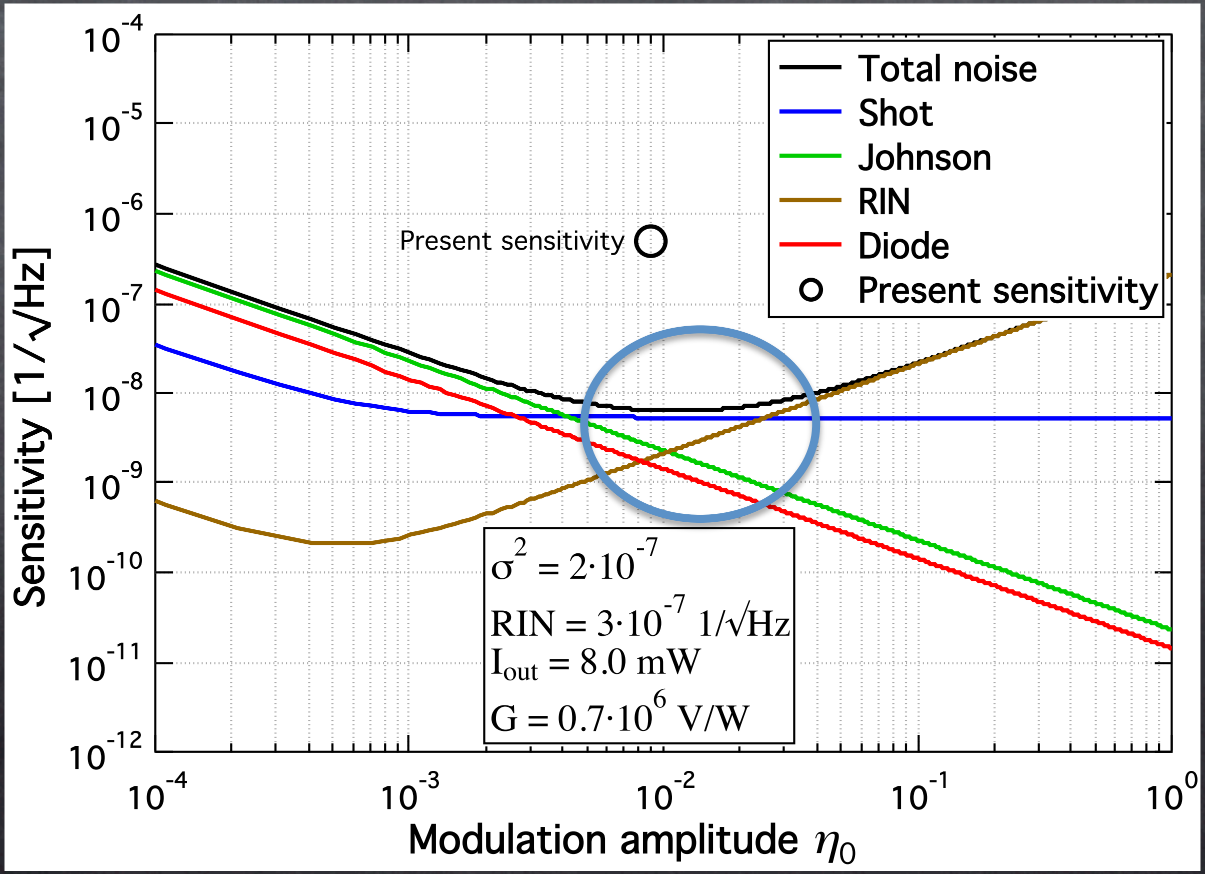
+ all other uncontrolled sources of **time varying birefringences $\alpha(t)$**

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

Calculated noise

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

$F \approx 700000$



Classification

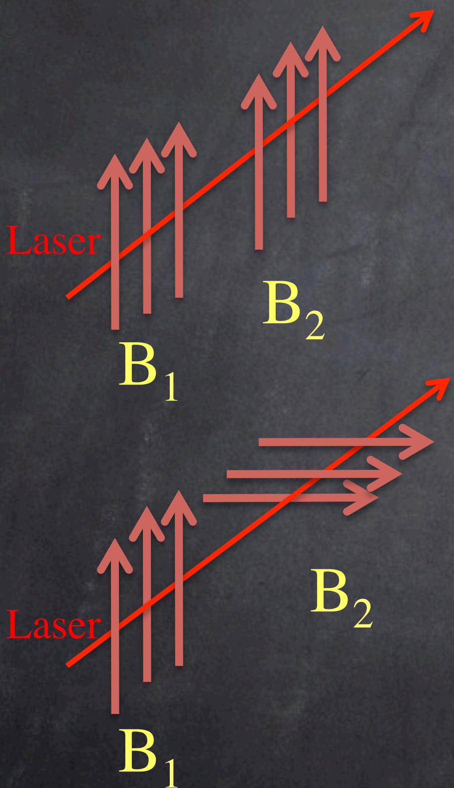
- Noise in phase with the rotation of the magnets
  - Generate peaks
  - Peaks can be at various harmonics
  - Faraday effect at first harmonic
  - <u>Integration is useless until these are eliminated</u>

- Wideband Noise
  - Totally independent from magnets
  - Reduces by integrating in time

IN PHASE NOISE

Two magnets

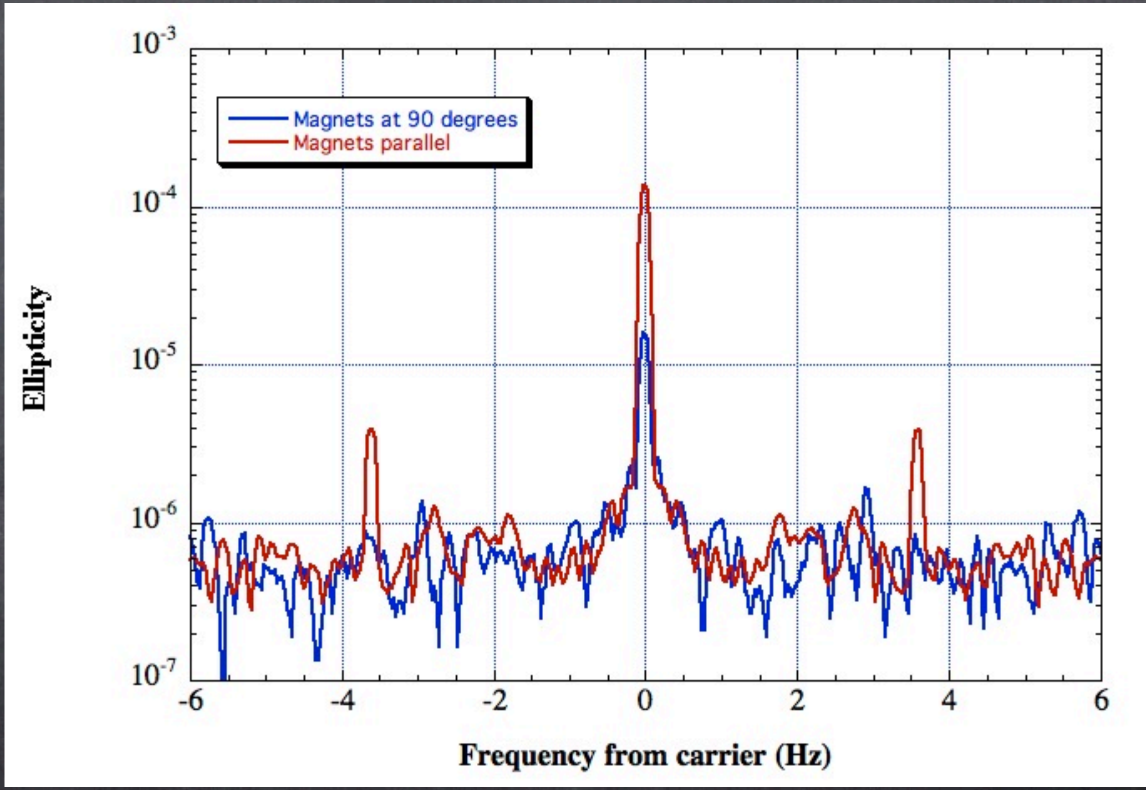
Two magnets system to check that signal is due to magnetic birefringence



$\Psi_{tot} = 2\Psi$

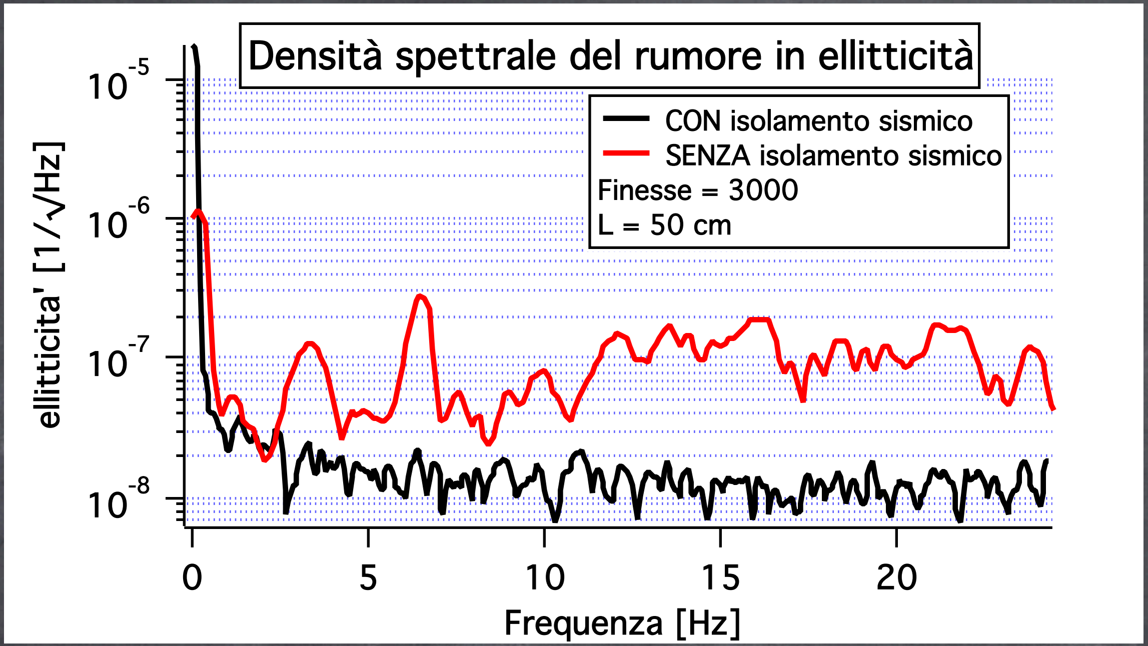
$\Psi_{tot} = 0$

Measurement with 1.3 mbar of air



For a very weak signal this represents a crucial test

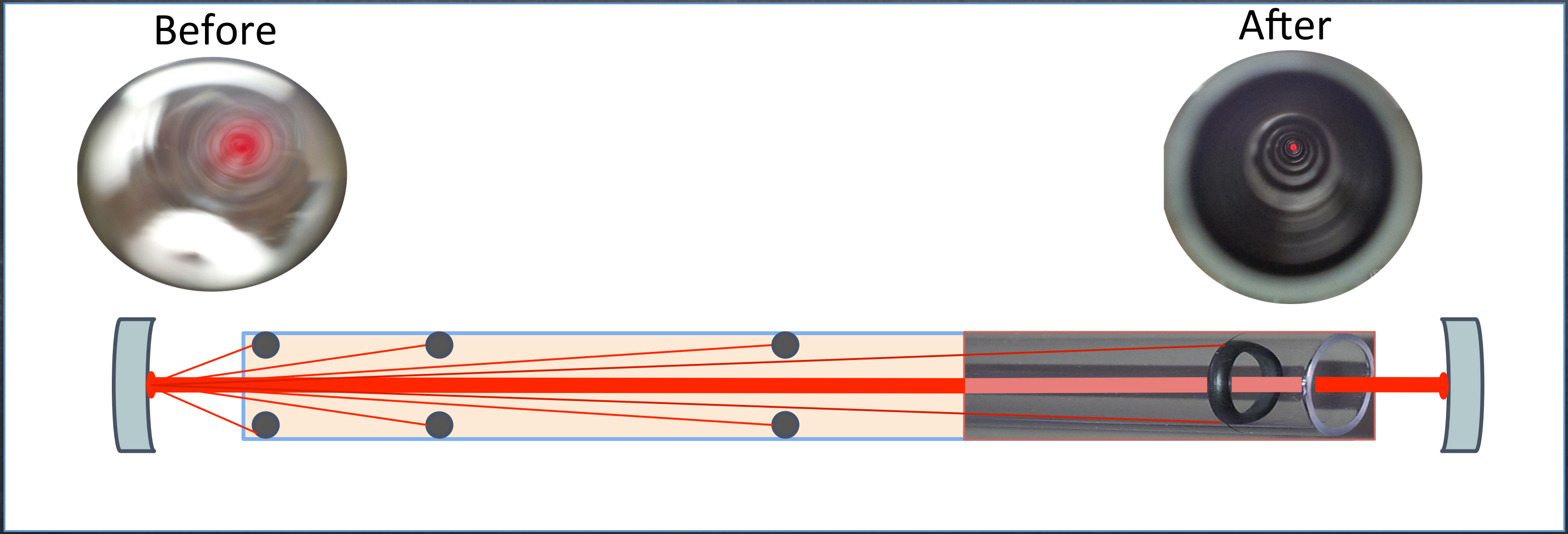
Vibrations



- If rotating magnets shake the optical bench peaks would appear
  - Vibrated bench to determine effect in ellipticity.
  - In phase vibration of the bench with magnets in rotation generate a very small acceleration signal. Not a limiting factor.

Diffused light in tube

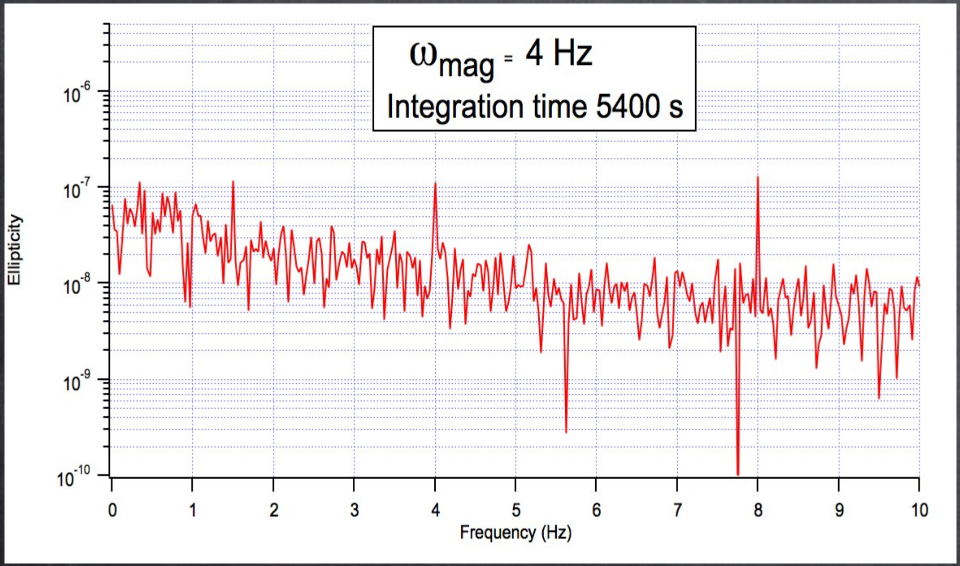
Baffles were mounted in properly spaced positions so that the light scattered from the mirror cannot see the internal surface of the glass tube.



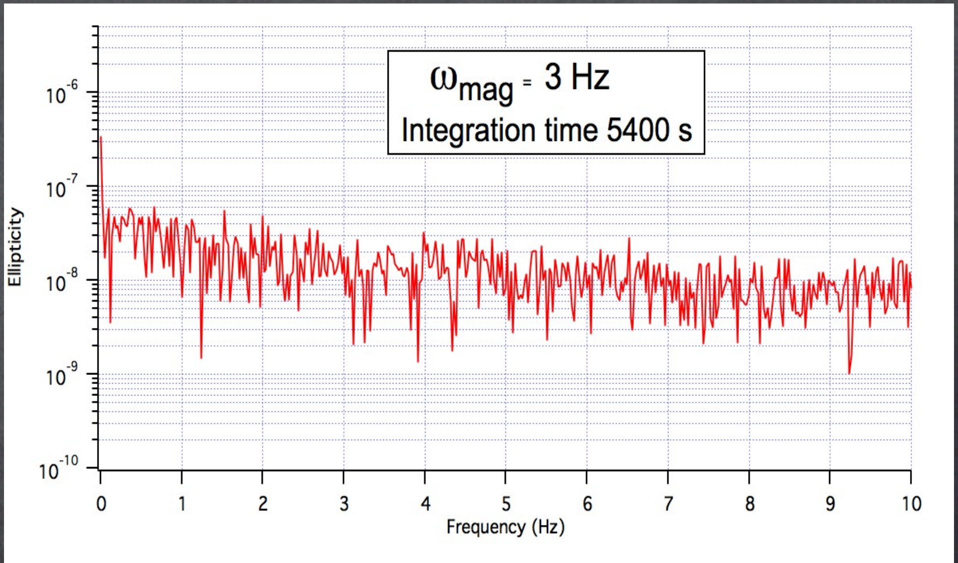
- Not optimal due to rounded edges of the o'rings
- Plan to replace them with baffles with knife-edges
- Black cermamic tube?

Diffused light in tube

- Glass tube without baffles: spurious peaks were present at ω_{mag} and $2\omega_{mag}$
- The peaks depended on the position of the tube in the magnet



- Glass tube with baffles: spurious peaks are no longer present at ω_{mag} and $2\omega_{mag}$



Unfortunately, no improvement in sensitivity

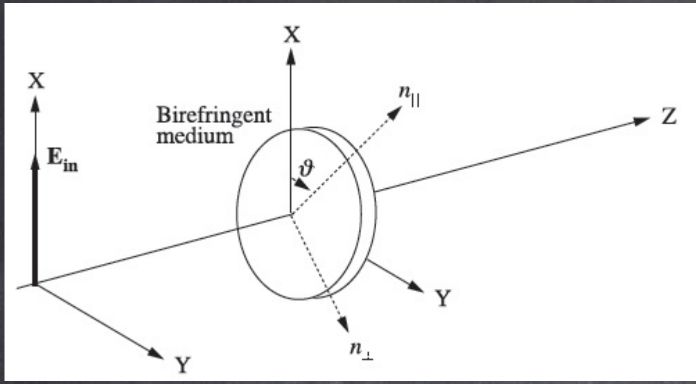
Faraday

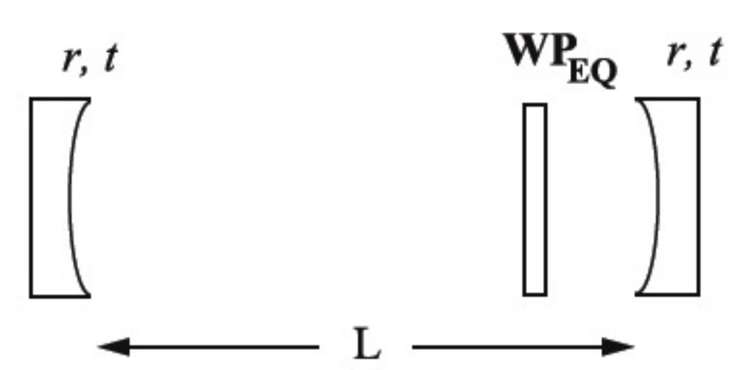
- Faraday effect generates rotations, not ellipticities
  - Variations of the field component parallel to propagation
  - Present in both the gas (calibration) and on the mirrors
  - Linear in the field intensity -> first harmonic (odd harmonics)
  - In principle, not a problem. But …

Cavity birefringence mixes ellipticities and rotations

Mirror birefringence

Fabry Perot cavity mirrors have **intrinsic static birefringence**

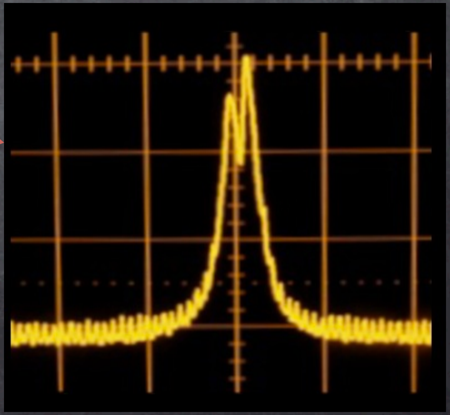




The resulting cavity behaves like a **waveplate.** This results in:

- cavity mode splitting

- increased 1/f noise (?)



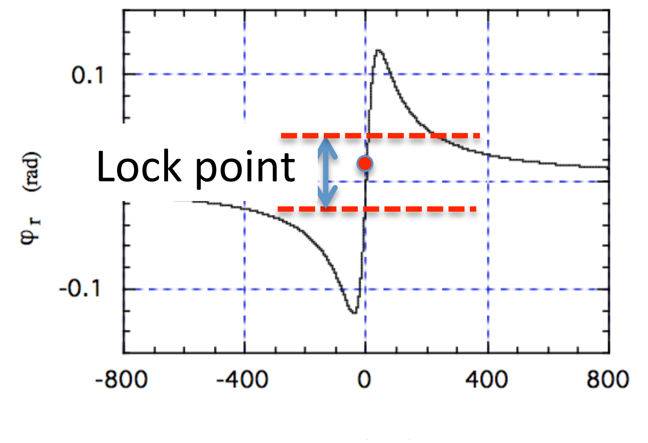
- Cavity mirrors must be rotated to reduce total birefringence
- Polarization must be aligned with one of the equivalent waveplate axes.

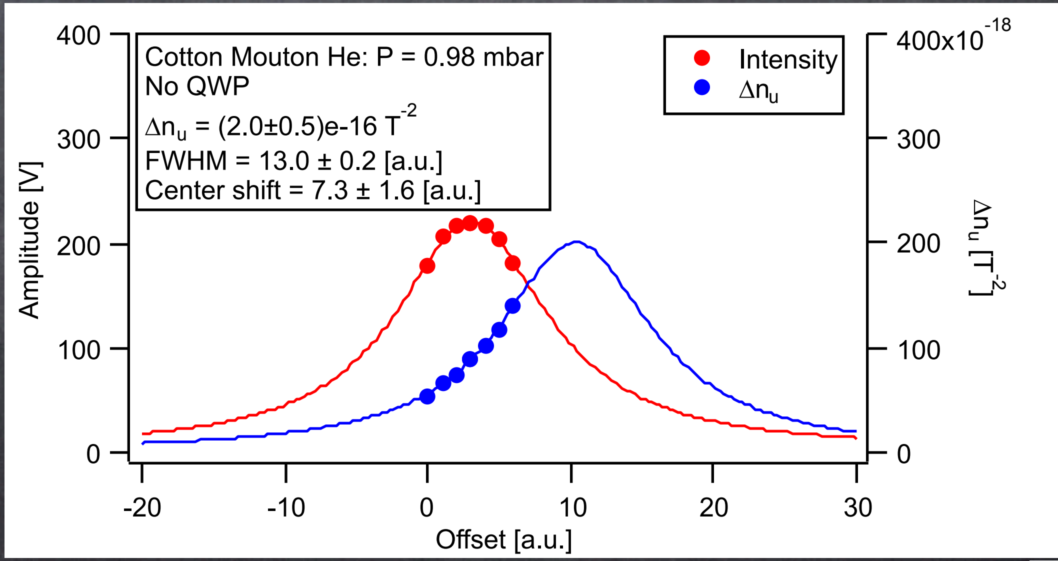
Cavity birefringence

- With He gas at various pressures we measured the ellipticity as a function of feedback offset δ
- The imaginary part of $E(t)$ will beat with the ellipticity of the modulator

$$E(t) = E_0 \left(\frac{2\mathcal{F}}{\pi}\right) i\psi \sin 2\theta \left(1 - i\left(\frac{\alpha_{\mathrm{EQ}}}{2} - \delta\right)\frac{2\mathcal{F}}{\pi}\right)\left(\frac{1}{1 + \left(\frac{2\mathcal{F}}{\pi}\right)^2 \sin^2\left(\frac{\alpha_{\mathrm{EQ}}}{2} - \delta\right)}\right)$$

Error signal





Example with P = 0.98 mbar He

Mirror birefringence

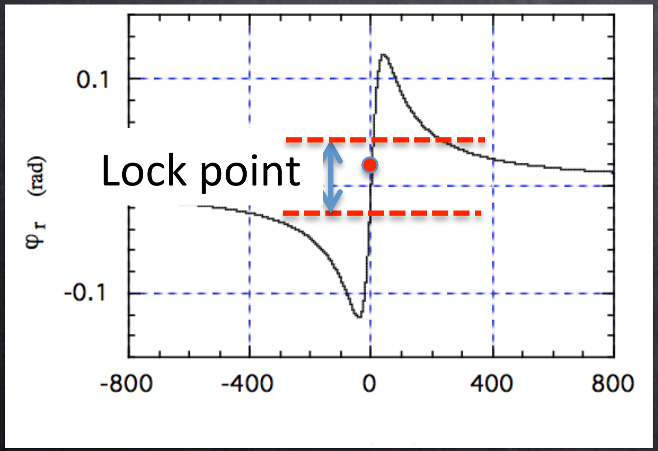
The laser is locked with its polarization along one of the cavity's axis.

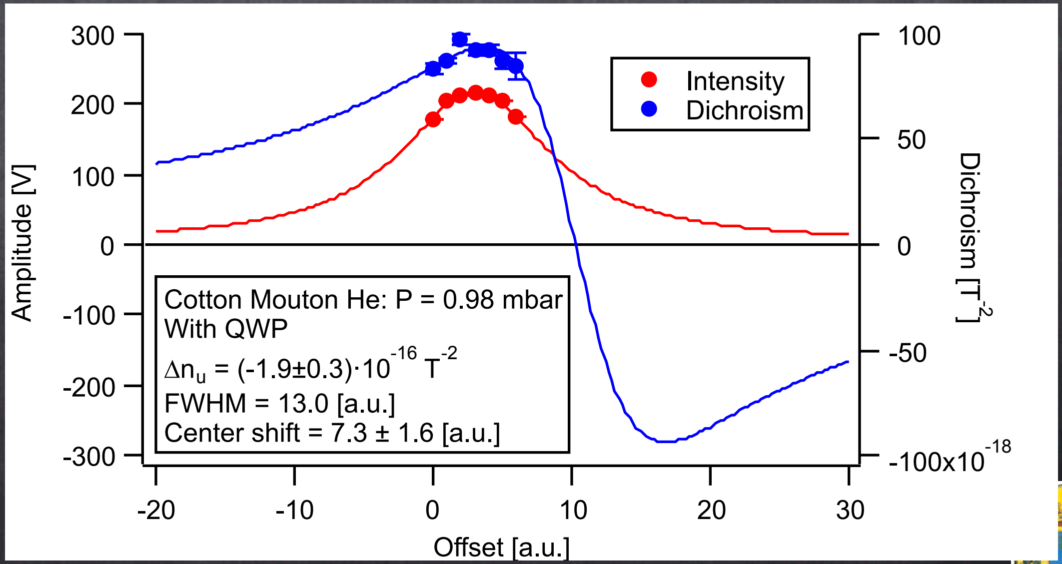
- the perpendicular polarization acquires an extra phase due to the cavity birefringence
- there is also a rotation (real component) [Appl. Phys. B 83, 571-577 (2006)]

$$E(t) = E_0 \left(\frac{2\mathcal{F}}{\pi}\right) i\psi \sin 2\theta \left(1 - i\left(\frac{\alpha_{EQ}}{2} - \delta\right)\frac{2\mathcal{F}}{\pi}\right)\left(\frac{1}{1+\left(\frac{2\mathcal{F}}{\pi}\right)^2 \sin^2\left(\frac{\alpha_{EQ}}{2} - \delta\right)}\right)$$

With a QWP and the ellipticity modulator one can measure the induced rotation.

Error signal



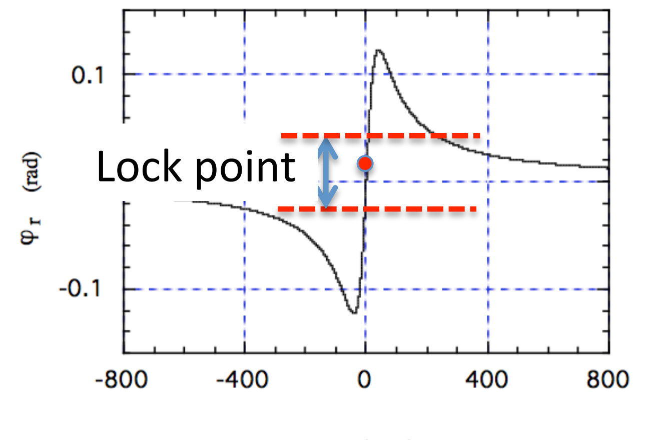


Mirror birefringence

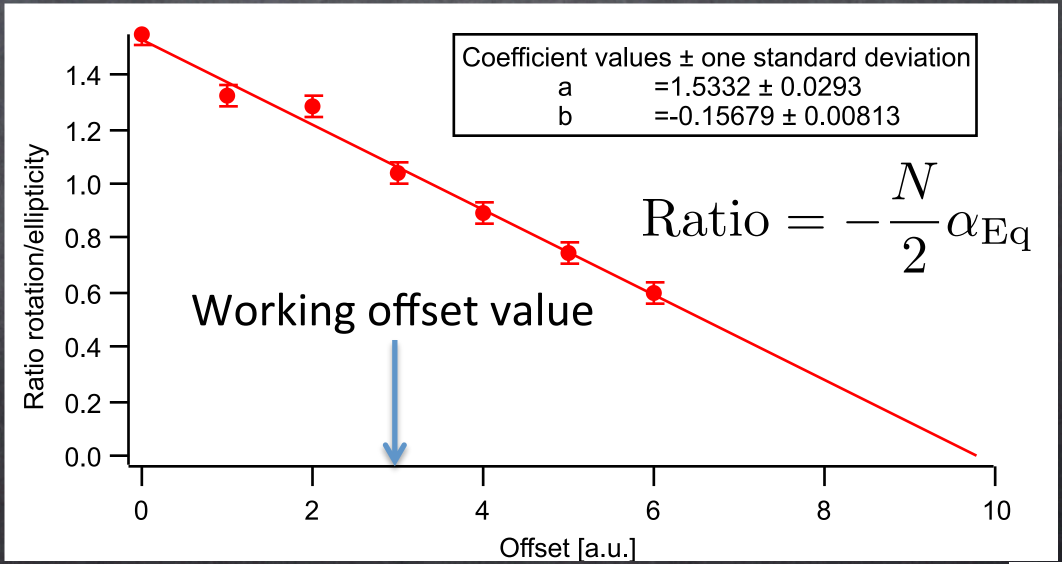
Vice versa if there were a rotation ε induced in the cavity it will partially convert to an ellipticity and beat with the modulator alone

$$E(t) = E_0 \left(\frac{2\mathcal{F}}{\pi}\right) \epsilon \sin 2\theta \left(1 - i\left(\frac{\alpha_{EQ}}{2} - \delta\right)\frac{2\mathcal{F}}{\pi}\right)\left(\frac{1}{1+\left(\frac{2\mathcal{F}}{\pi}\right)^2 \sin^2\left(\frac{\alpha_{EQ}}{2} - \delta\right)}\right)$$

Error signal



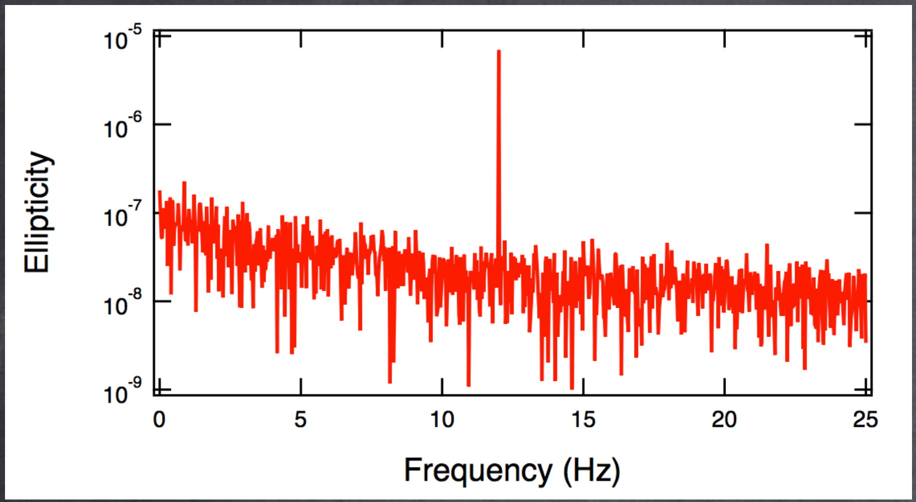
Rotation/ellipticity



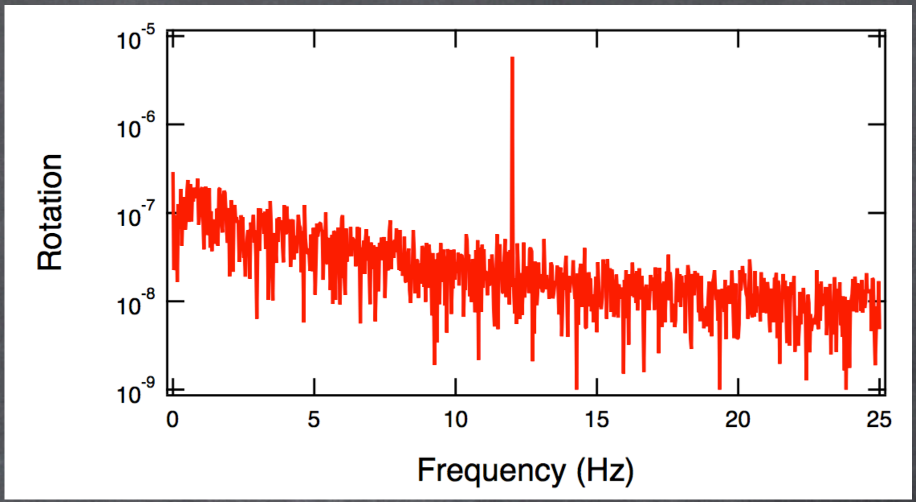
$$\text{Ratio} = -\frac{N}{2}\alpha_{Eq}$$

Mixing

Ellipticity



QWP inserted: Rotation



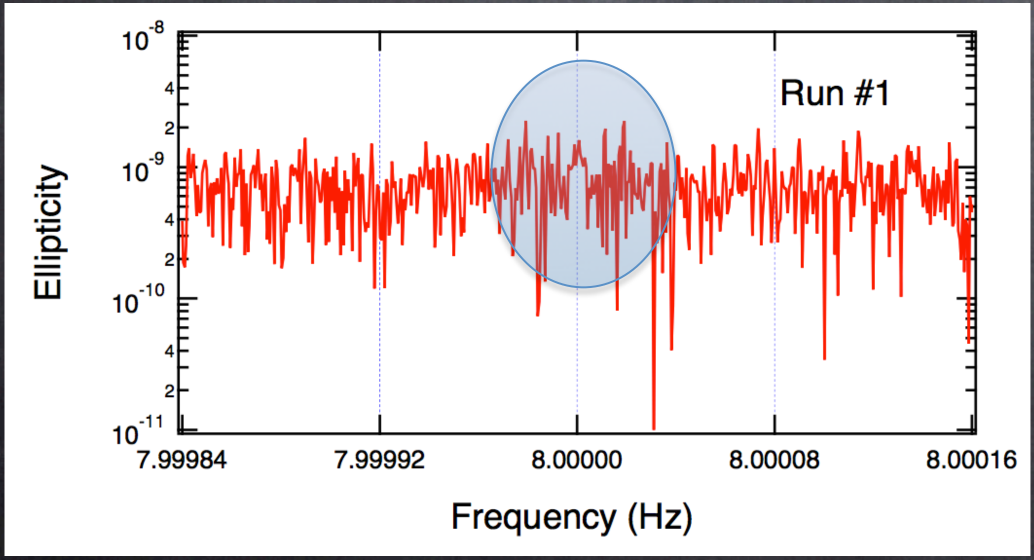
230 μbar Ar. ν_B = 6 Hz, 640 s intgration

In Vacuum

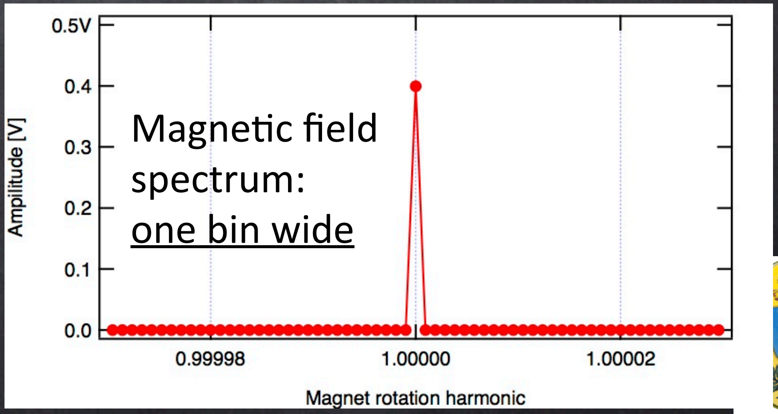
- …. a Faraday rotation will be seen as an ellipticity. In vacuum, we only see a contribution at the first harmonic: signal ≈ 10^{-8}.
- The two magnets give different values and phase in the signal due to slightly different longitudinal component of the field on the mirrors.

In phase noise

- After some effort, we think we have systematic peaks under control. Centering of the glass tube inside the magnet is critical.
- Long integration is possible.
- During some long runs, small drifts change the measurement conditions and small structures appeared around $2\nu_B$ several bins wide in the Fourier spectrum.



P < 10^{-7} mbar. ν_B = 4 Hz
T = 10^6 s intgration
Signal width $\Delta\nu = 10^{-6}$ Hz
Structure > ≈ 10^{-5} Hz



WIDEBAND NOISE

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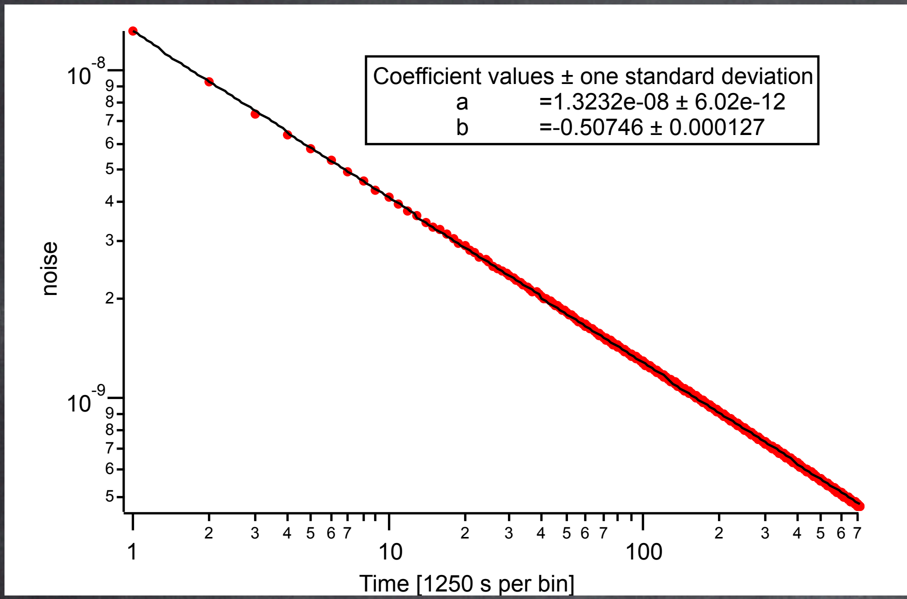
Possible sources

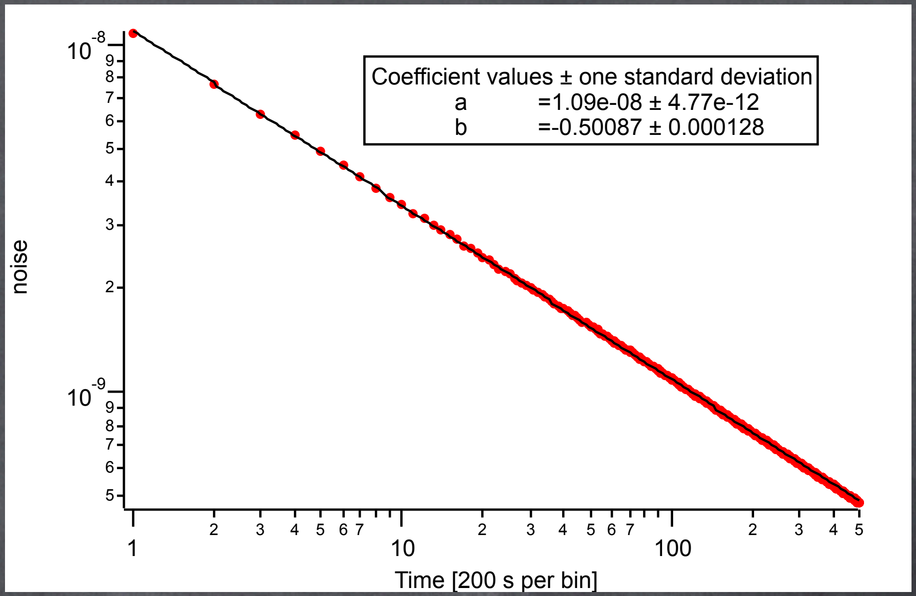
- Thermal effects
- Laser feedback
- Environmental noise
- Diffused light
- Gas
- Mirror birefringence

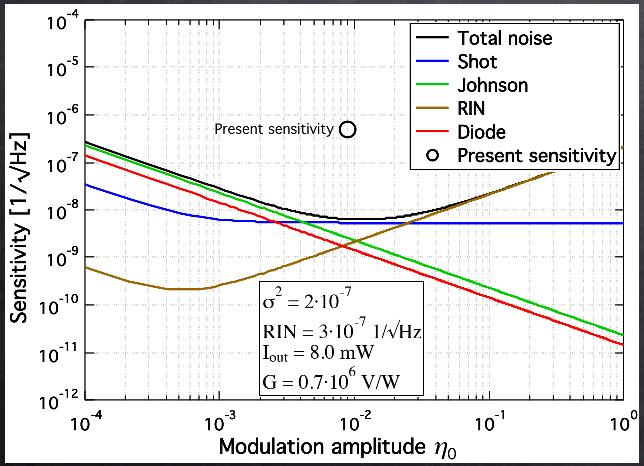
Measured noise

T =8.9· 10^5 s



T = 10^6 s

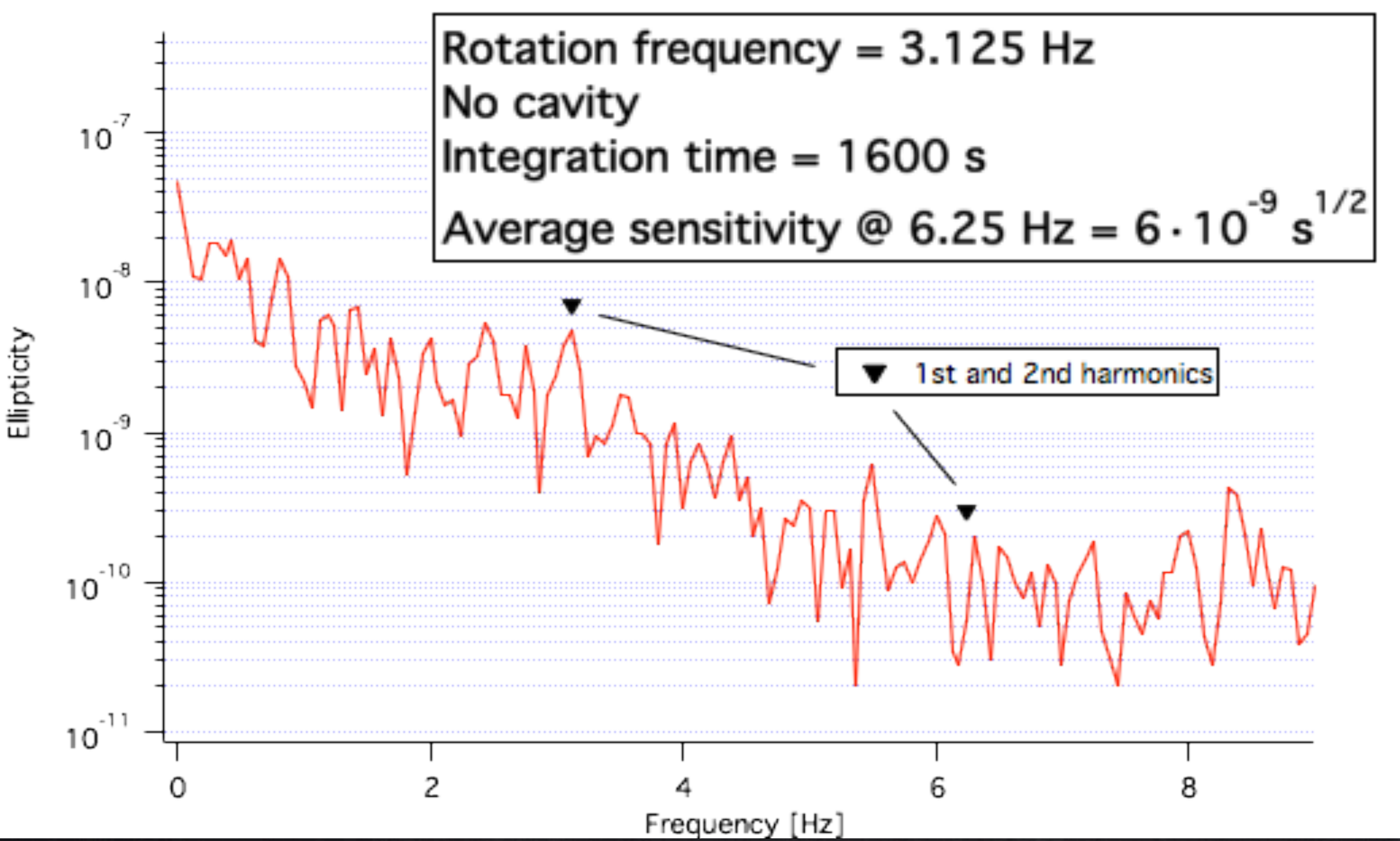




Integrated noise around $2\nu_B$ decreases as $\sqrt{T}$

Performance without cavity

No cavity – reached expected noise level with rotating magnets



No electronically induced signals in the readout system

Thermal effects

- Noise at $2\nu_B$ is independent of laser power
  - Stronger drifts in quasi static ellipticity if power is turned up
  - Effect at much lower frequencies than $2\nu_B$ (6 Hz - 12.5 Hz)
  - After an 'unlock' of the laser there is an ellipticity settling time of several minutes. Does not affect noise a $2\nu_B$.
  - The settling and drifts also depend on how well the polarization is aligned with the cavity birefringence.
  - The contribution of the static ellipticity of the PEM is not neglectable.

Environmental noise

- Possible contribution from conditioning system
  - All electronics has been taken outside of the clean room
  - Temperature stability is better than 0.1 degrees
  - Took two relatively long runs with and without conditioning system => NO DIFFERENCE in sensitivity

Feedback

- Redesigned feedback circuit after 2014
  - Automatic locking
  - Lower noise integrated OpAmps
  - Lower offsets

  No improvement in the wideband noise

- Tried several different locking frequencies
  - Working frequency = 503 kHz: below crystal resonance
  - Tried different frequencies without any improvement in the noise

Feedback 2

- Locking set point can be modulated
  - Modulation generates ellipticity signal at ν_{Mod} and $2\nu_{Mod}$.
  - Conversion Ellipticity => frequency: ≈ 10^{-6} per Hz
  - Output noise from mixer generates noise in ellipticity: ≈ 10^{-9}

Cannot account for observed wideband noise.

Diffused light

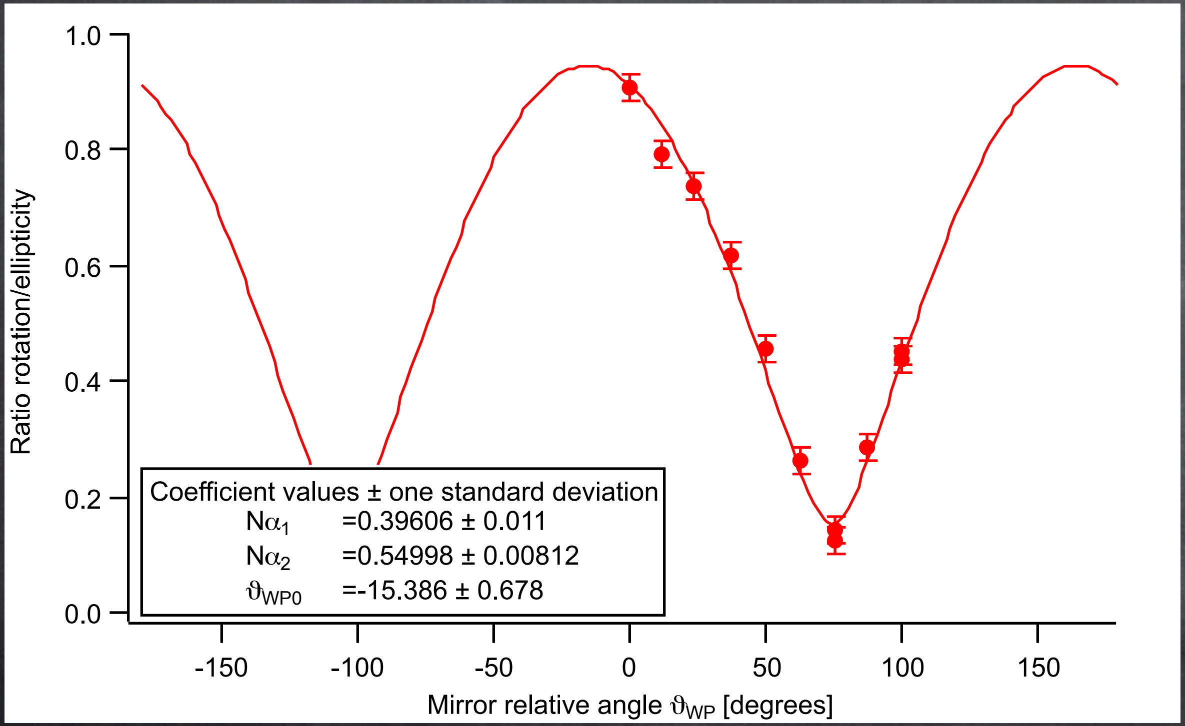
- Installation of baffles and absorbing glass
  - Baffles reduced peaks but had no effect on sensitivity
  - Diaphragm at center of cavity: 5 mm diameter. No effect.
  - Absorbing glass in large vacuum chambers. No effect.

- Changed input polarizer
  - New polarizer with fewer surfaces (Glan-Thompson)
  - Noise improved by factor ≈ 4!
  - May be due to alignment ?

Not really clear..... More testing soon

Mirror Birefringence

- Both mirrors have birefringence with $N\alpha/2 \approx 0.5$
  - Aligned slow axis of one mirror with fast axis of the other



- Unfortunately the alignment drifts slowly with time!
- To be conservative, we considered the worst value.

$$N\alpha_{EQ} = N\sqrt{(\alpha_1 - \alpha_2)^2 + 4\alpha_1\alpha_2\cos^2\vartheta_{WP}}$$

Cooling mirrors

- We are planning to design new chambers for the mirrors which will allow cooling of the mirrors to LN_2.

Thank you

Cotton-Mouton effect

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

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

Gas	Δn_u (T ~ 293 K)
Nitrogen	- (2.47± 0.04) x 10^{-13}
Oxygen	- (2.52± 0.04) x 10^{-12}
Carbon Oxide	- (1.83± 0.05) x 10^{-13}
Helium	(2.2±0.1) x 10^{-16}

Total ellipticity

$$\psi_{\mathrm{gas}} = \frac{\pi L_{\mathrm{eff}}}{\lambda} \Delta n_u B^2 p \sin 2\vartheta$$

To avoid spurious effects the residual gas must be analysed:

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

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

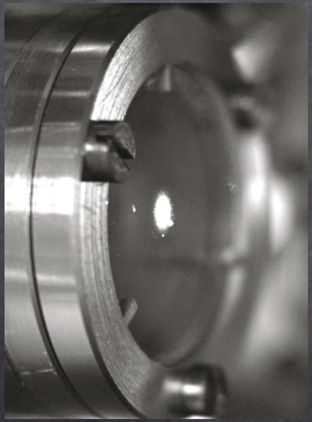
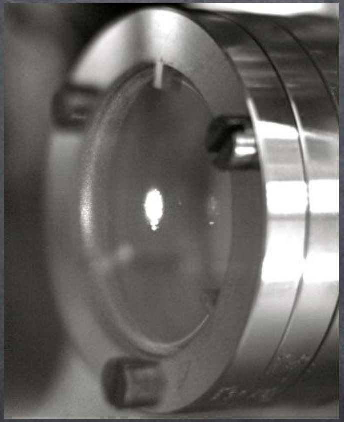
$$\psi = \frac{\pi L_{\text{eff}}}{\lambda} \Delta n(B^2) \sin 2\vartheta(t)$$

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

Problems and how to proeed

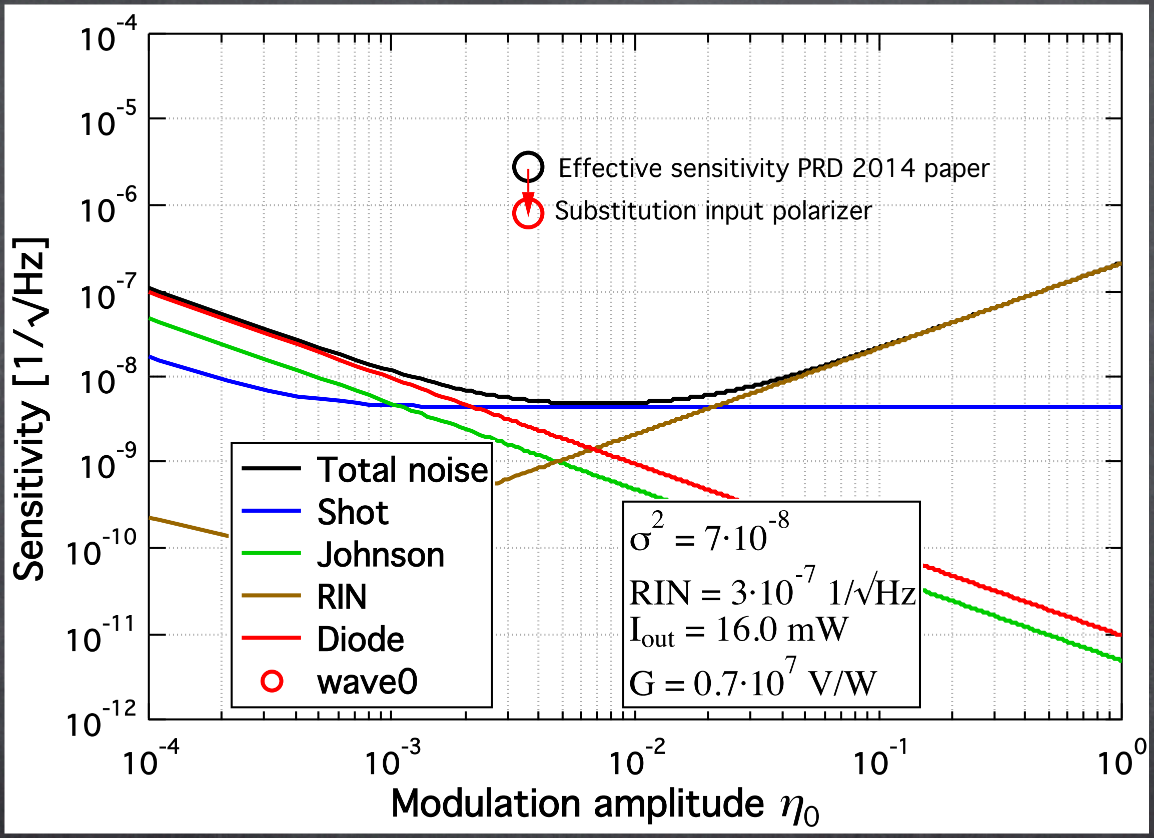
Sensitivity far from expected

- Diffused light in the chambers due to optical elements and from a few dust speckles on the mirrors
- Substituted input polarizer (fewer surfaces) and noise improved by factor 3 …. Clue?

- Ordered wobble-sticks to try to design a cleaning method
- Ordered absorbing glass to cover inner walls of chambers

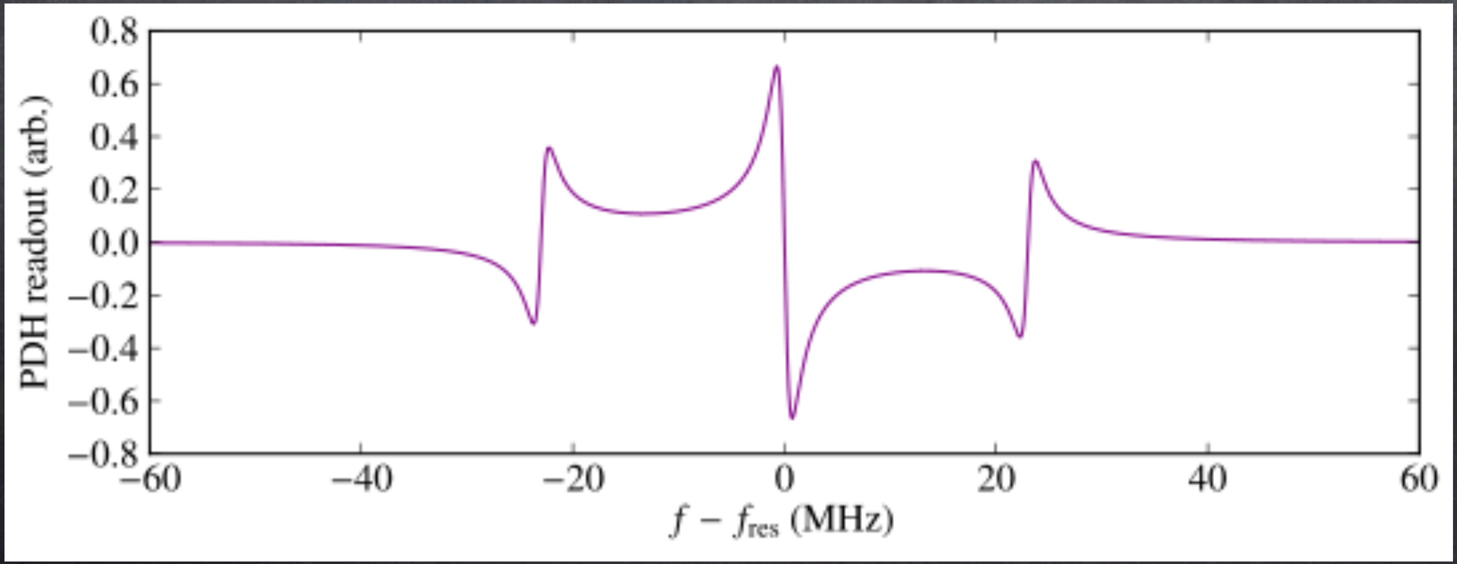
Future



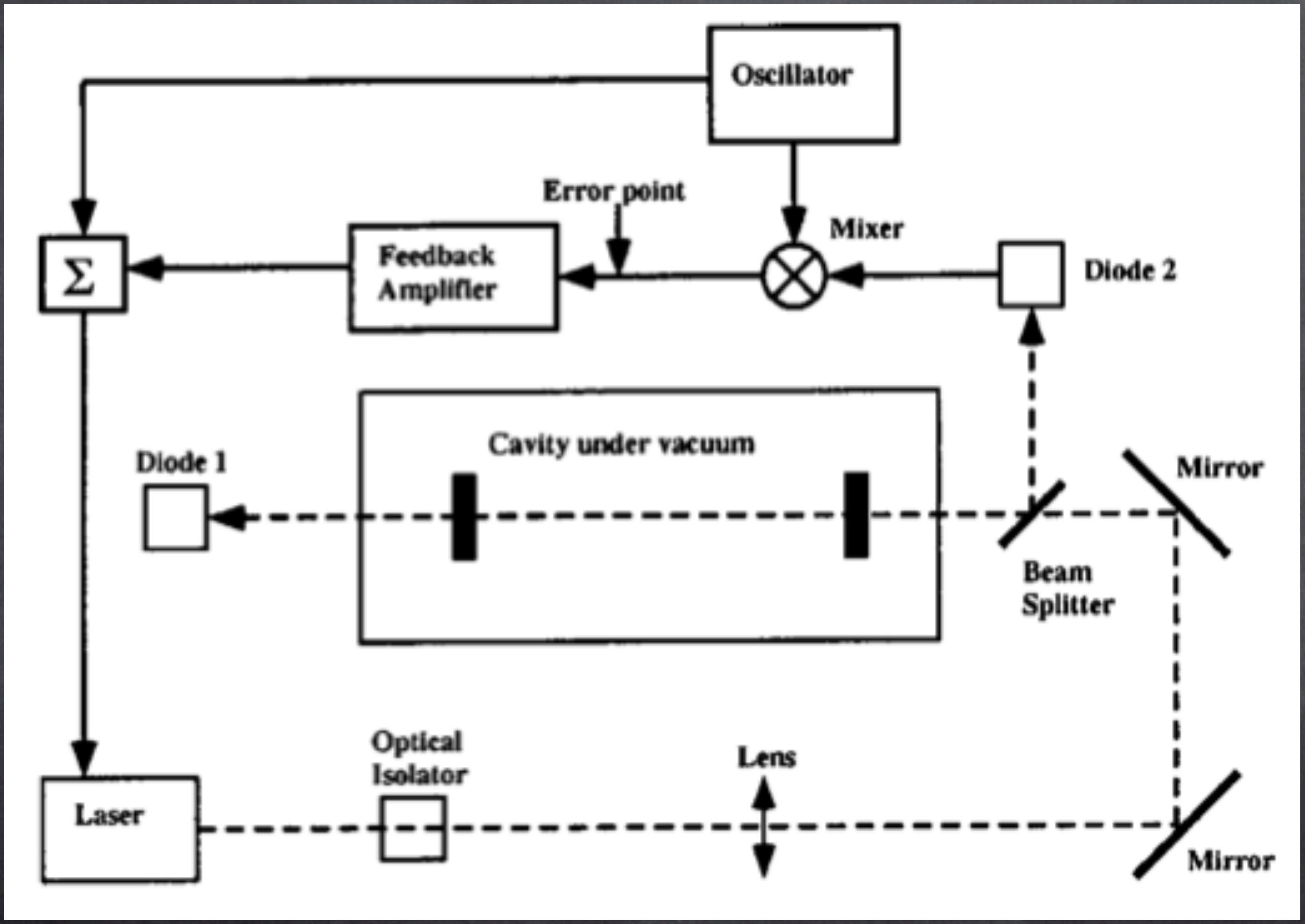
- Starting new data taking with new sensitivity
- QED is still out of reach ....

Laser locking principle

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

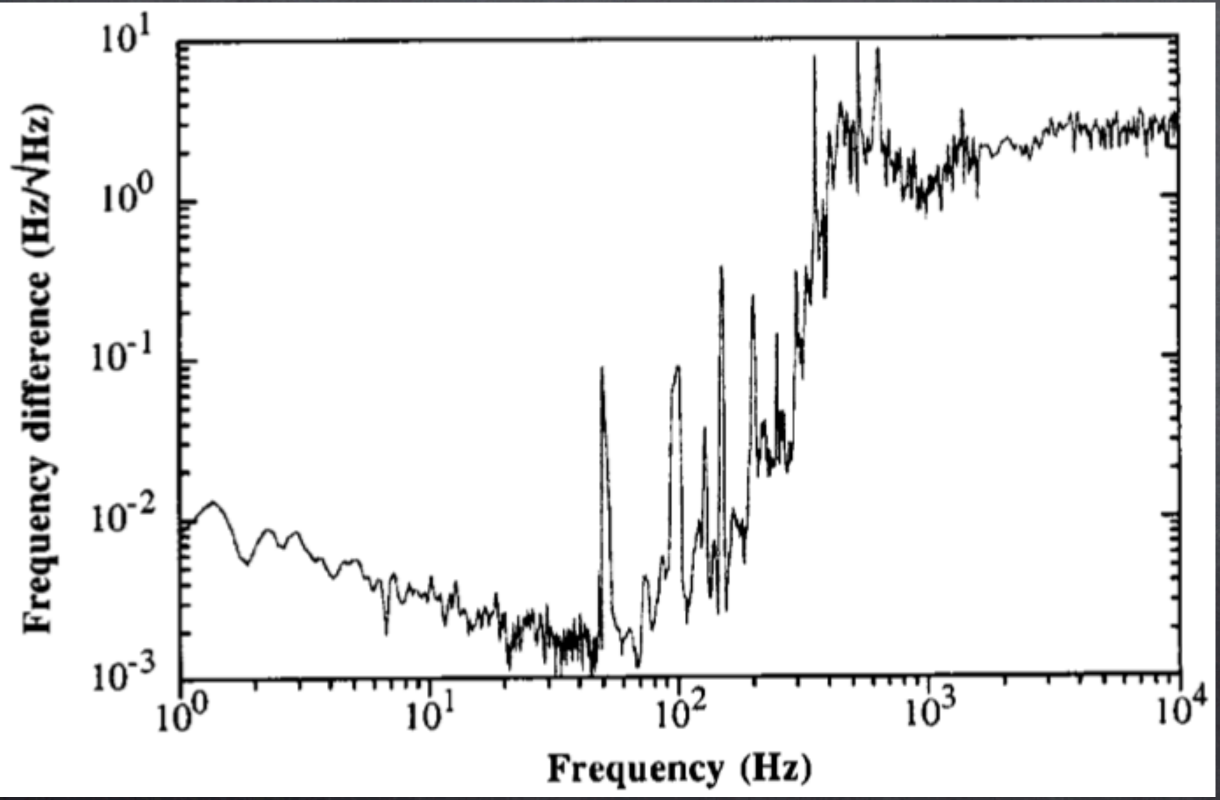


Locking scheme



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

Noise considerations

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

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

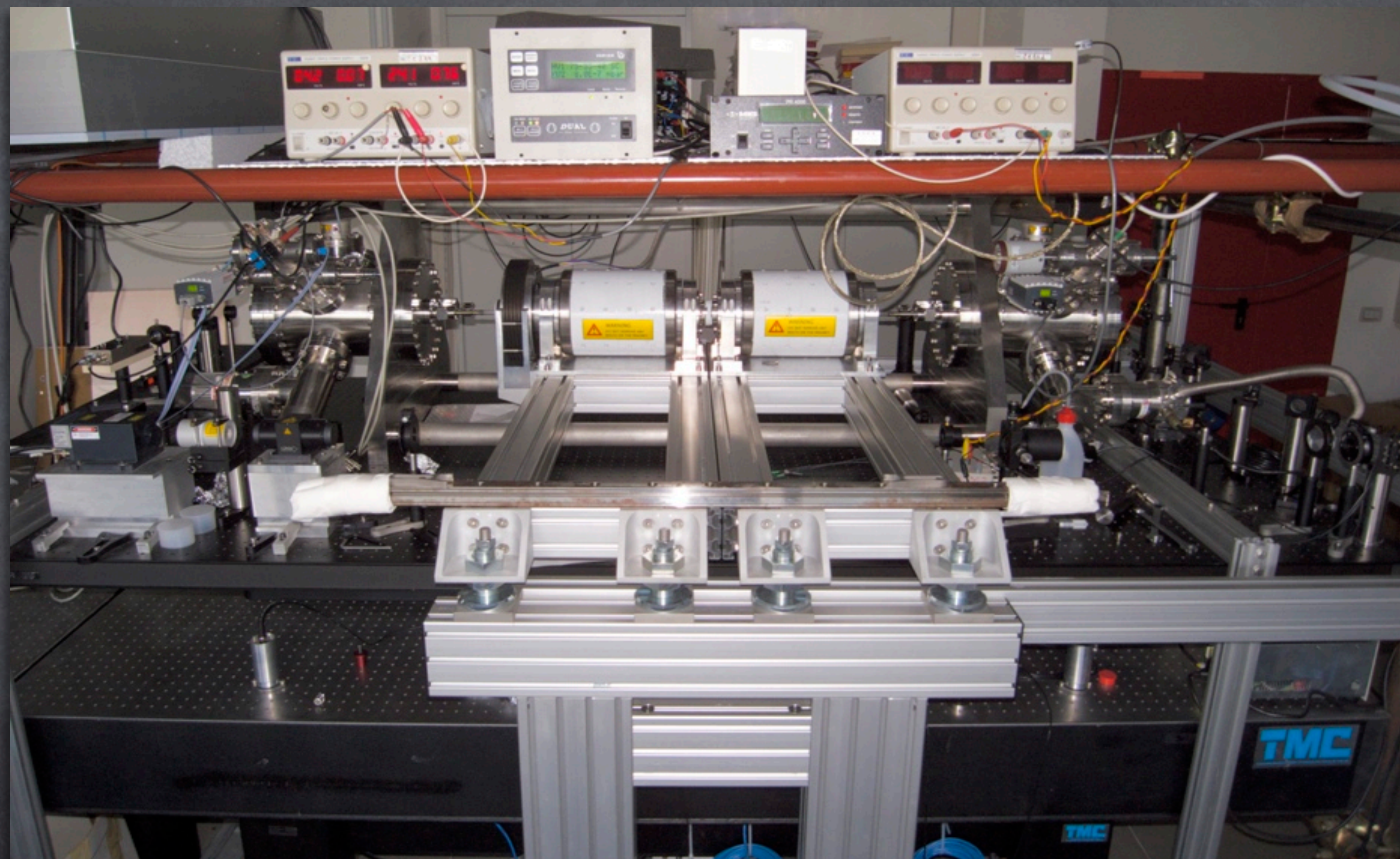
The ellipticity sensitivity spectral density will be

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

Ferrara test setup

- 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**

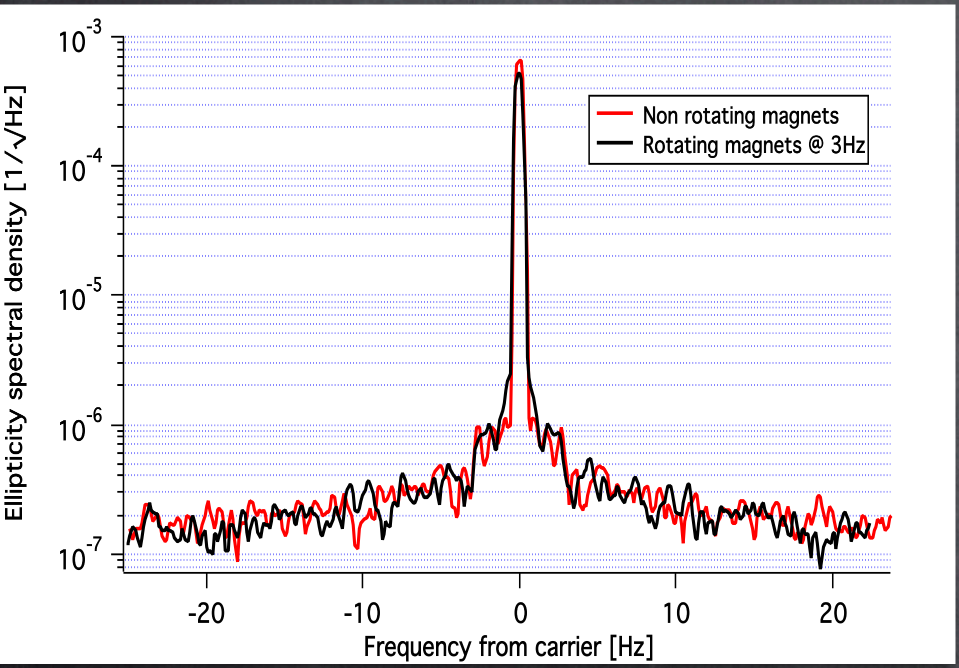
In operation since 2010

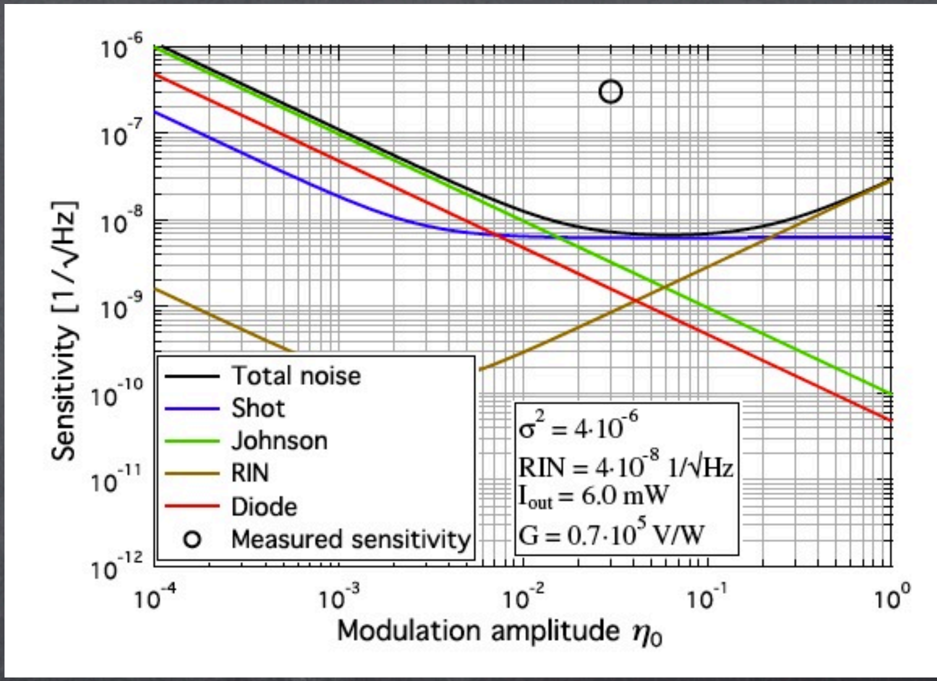


Main limitation: most of the components are **magnetic**

Performance - wideband noise

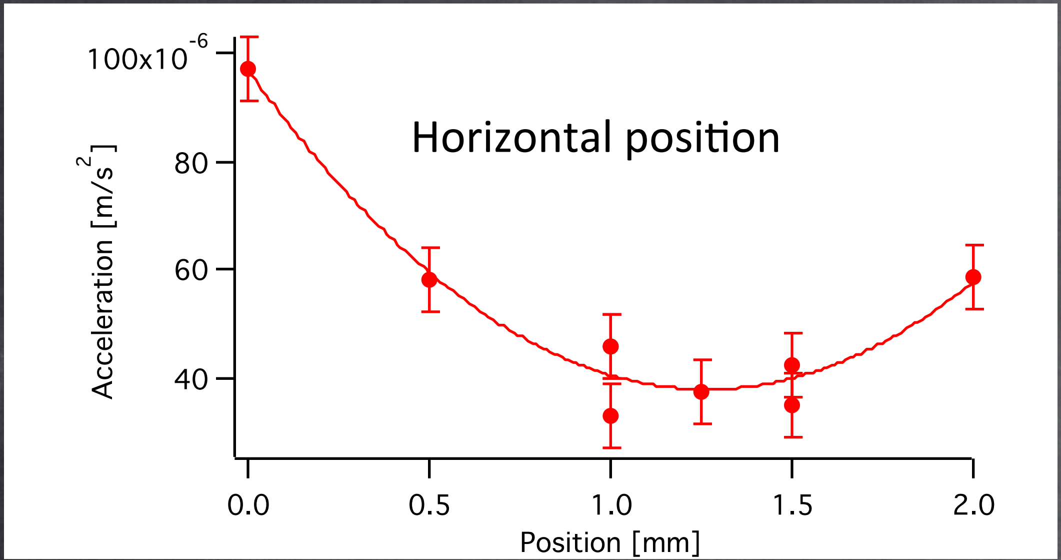
With high-finesse cavity: $F > 400\,000$
Extra wideband noise. Sensitivity worsened – still under study





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

Tube movement



- Placing a 3-axis accelerometer on the glass tube we were able to study its movement as a function of its position
- The glass tube was positioned where the movement was minimum.