Review of the PVLAS experiment

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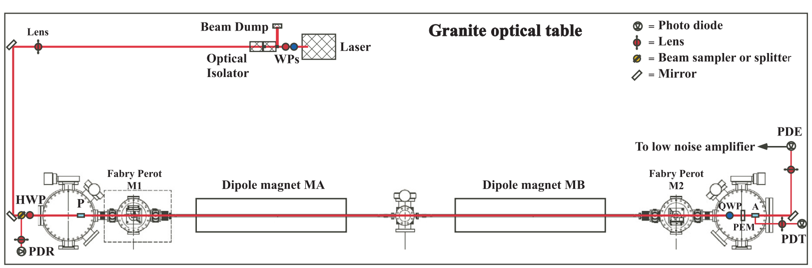
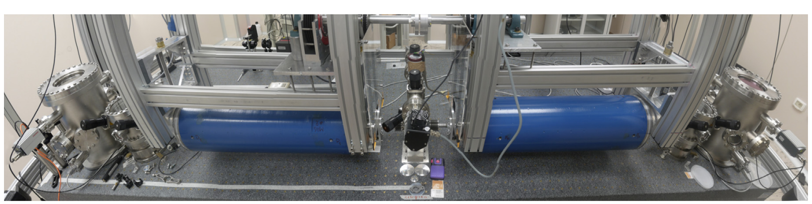
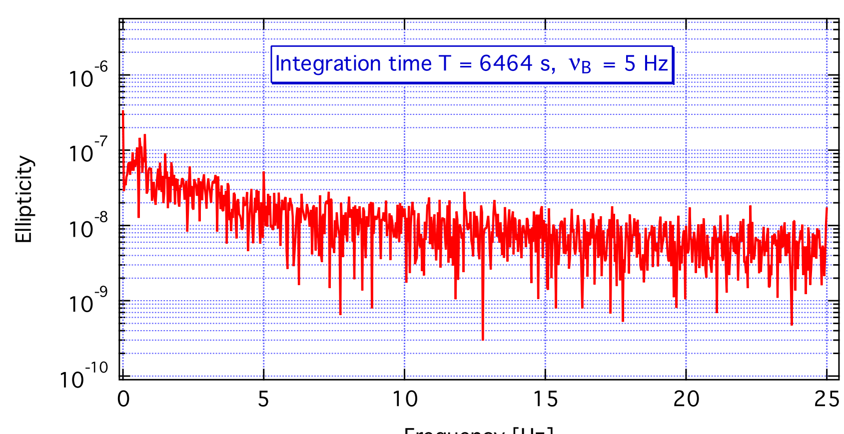
2024/2/16 @Ando Lab Seminar

PVLAS experiment

- Searches for the vacuum magnetic birefringence (VMB) using a linear cavity and rotating magnets
- Analyzes the ellipticity of the transmitted polarization
- Able to also search for the Axion Like Particles
- Research period: 1992-2017
- Result: $\Delta n^{(\mathrm{PVLAS-FE})} \simeq (12 \pm 17) \times 10^{-23}$ @ $B = 2.5$ T
  - ➢A factor of 7 worse than the QED prediction: $\Delta n^{(\mathrm{EK})} = 2.5 \times 10^{-23}$ @ 2.5 T
  - ➢Limiting noise source: thermal birefringence noise of mirror coatings(?)







Reference

◆Review article on the PVLAS experiment

[A. Ejilli et al. Physics Reports 871, 1-74 (2020)]

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The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence

Check for updates

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Lagrangian density in QED

- Lagrangian density for electromagnetic fields in classical vacuum:

$$\mathcal{L}_{\mathrm{Cl}} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right)$$

➡ Maxwell eqs. in classical vacuum

$$\begin{cases} \vec{\nabla}\cdot\vec{E} = 0 & \vec{\nabla}\times\vec{E} = -\dfrac{\partial\vec{B}}{\partial t} \\ \vec{\nabla}\cdot\vec{B} = 0 & \vec{\nabla}\times\vec{B} = \varepsilon_0\mu_0\dfrac{\partial\vec{E}}{\partial t} \end{cases}$$

  - No polarization nor magnetization: $\vec{D} = \varepsilon_0\vec{E}$, $\vec{B} = \mu_0\vec{H}$

- In QED, vacuum has virtual electron-positron pairs
- Lagrangian density with electron-positron fluctuations:

$$\mathcal{L}_{\mathrm{EK}} = \mathcal{L}_{\mathrm{Cl}} + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] \qquad A_e = \frac{2}{45\mu_0}\frac{\hbar^3}{m_e^4 c^5}\alpha^2 = 1.32\times10^{-24}\ \mathrm{T}^{-2}$$

➡

$$\begin{cases} \vec{D} = \varepsilon_0\vec{E} + 4A_e\left(\dfrac{E^2}{c^2} - B^2\right)\varepsilon_0\vec{E} + 14\varepsilon_0 A_e\left(\vec{E}\cdot\vec{B}\right)\vec{B} \\ \mu_0\vec{H} = \vec{B} + 4A_e\left(\dfrac{E^2}{c^2} - B^2\right)\vec{B} - 14A_e\left(\dfrac{\vec{E}}{c}\cdot\vec{B}\right)\dfrac{\vec{E}}{c} \end{cases}$$

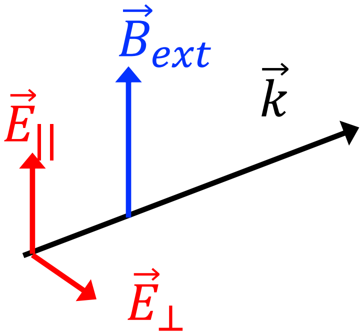
Polarization: $\vec{P}$

Magnetization: $-\mu_0\vec{M}$

Vacuum in QED can be “polarized” or “magnetized”

Vacuum Magnetic Birefringence (VMB)

- Consider an external magnetic field $\vec{B}_{ext}$ perpendicular to a linear polarized beam $\vec{k}$



$$\Rightarrow \begin{cases} \vec{D}_\gamma = \varepsilon_0 \left[\vec{E}_\gamma - 4A_e B_{\text{ext}}^2 \vec{E}_\gamma + 14A_e \left(\vec{E}_\gamma \cdot \vec{B}_{\text{ext}} \right) \vec{B}_{\text{ext}} \right] \\ \vec{H}_\gamma = \dfrac{1}{\mu_0} \left[\vec{B}_\gamma - 4A_e B_{\text{ext}}^2 \vec{B}_\gamma - 8A_e \left(\vec{B}_\gamma \cdot \vec{B}_{\text{ext}} \right) \vec{B}_{\text{ext}} \right] \end{cases}$$

➢ $\vec{B} = \mu_0 \mu(\vec{E},\vec{B})\vec{H},\ \vec{D} = \epsilon_0 \epsilon(\vec{E},\vec{B})\vec{E} \Rightarrow$ refractive index: $n = \sqrt{\epsilon\mu}$

Relative magnetic permeability — Relative dielectric constant

$$\Rightarrow \begin{cases} n_{||} = 1 + 7A_e B_{ext}^2 \\ n_{\perp} = 1 + 4A_e B_{ext}^2 \end{cases} \quad A_e = \frac{2}{45\mu_0} \frac{\hbar^3}{m_e^4 c^5} \alpha^2 = 1.32 \times 10^{-24}\ \mathrm{T}^{-2}$$

➡ Vacuum Magnetic Birefringence (VMB): $\Delta n^{(EK)} = 3A_e B_{ext}^2$

$$= 3.96 \times 10^{-24}\ @\ B_{ext} = 1\ \mathrm{T}$$

Axion-photon interaction in external field

- Axion-photon interaction: Chern-Simons interaction term

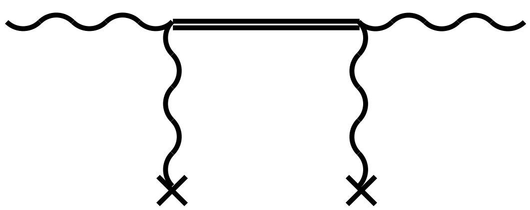
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} a(t) F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a(t) \vec{E} \cdot \vec{B}$$

Electric field parallel to external magnetic field $\vec{B}_{ext}$ can interact with axion

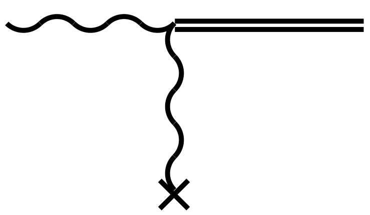
⇒ Difference in the complex refractive indices $\tilde{n}_{||/\perp} = n_{||/\perp} + i\kappa_{||/\perp}$ for the two polarizations in $\vec{B}_{ext}$

Refractive index ($n_{||/\perp}$)   Absorption index ($\kappa_{||/\perp}$)

- $\hbar\omega \ll m_a c^2$ ⇒ Virtual production of axion causes phase delay
  ⇒ Birefringence Δn



- $\hbar\omega \gg m_a c^2$ ⇒ Real production of axion causes photon absorption
  ⇒ Dichroism $\Delta\kappa$



Axion-photon interaction in external field

- Birefringence and dichroism by axion in external field $\vec{B}_{ext}$:

$$\begin{cases} |\Delta n| \simeq \frac{1}{2}\left(\frac{g_{a\gamma}B_{ext}}{2m_a}\right)^2\left(1-\frac{\sin 2\chi}{2\chi}\right)^2 \\ |\Delta\kappa| \simeq \frac{2}{\omega L_B}\left(\frac{g_{a\gamma}B_{ext}L_B}{4}\right)^2\left(\frac{\sin\chi}{\chi}\right)^2 \end{cases}$$

$$\chi \equiv \frac{L_B m_a^2}{4\omega}$$

L_B: optical path inside $\vec{B}_{ext}$

  - Photon energy: small ($\chi \gg 1$) $\Rightarrow$ Δn: large, $\Delta\kappa$: small
  - Photon energy: large ($\chi \ll 1$) $\Rightarrow$ Δn: small, $\Delta\kappa$: large

- Important notes
  - Axion needs not to be the dark matter
  - Static signals for any axion mass m_a
  - Signal$\propto g_{a\gamma}^2$

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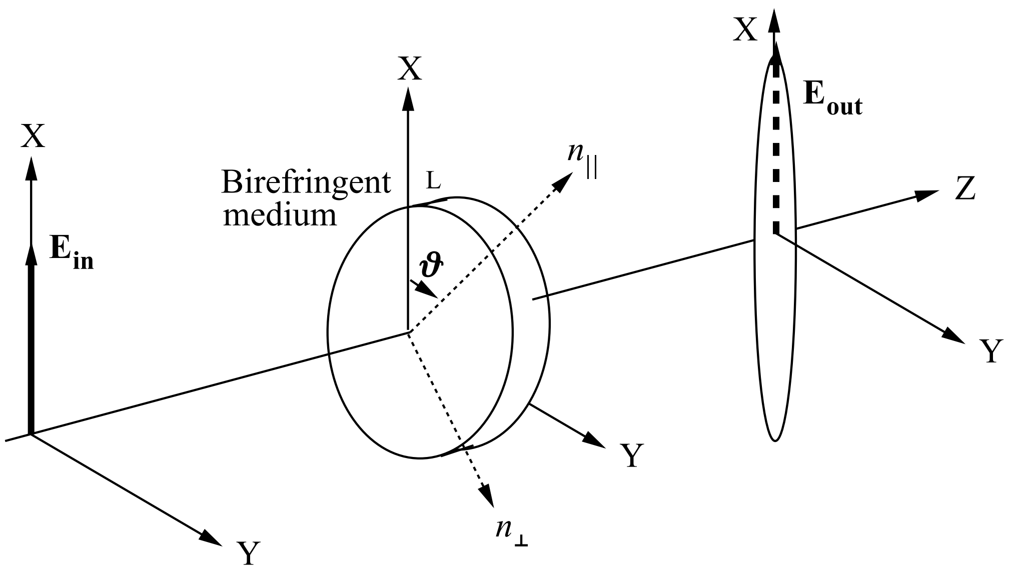
Effect of birefringence Δn and dichroism $\Delta\kappa$

- Consider pure birefringence Δn and input s-pol.:

$$\vec{E}_{in} = E_0 \begin{bmatrix} 1 \\ 0 \end{bmatrix} \Rightarrow \vec{E}_{out} = E_0 \begin{bmatrix} 1 + i\frac{\pi}{\lambda}\Delta D \cos 2\theta \\ i\frac{\pi}{\lambda}\Delta D \sin 2\theta \end{bmatrix} \qquad \Delta D \equiv \int \Delta n(z) dz$$

p-pol. in phase quadrature ⇒ Elliptical polarization

⇒ Ellipticity: $\psi = \frac{\pi}{\lambda}\Delta D \cos 2\theta$



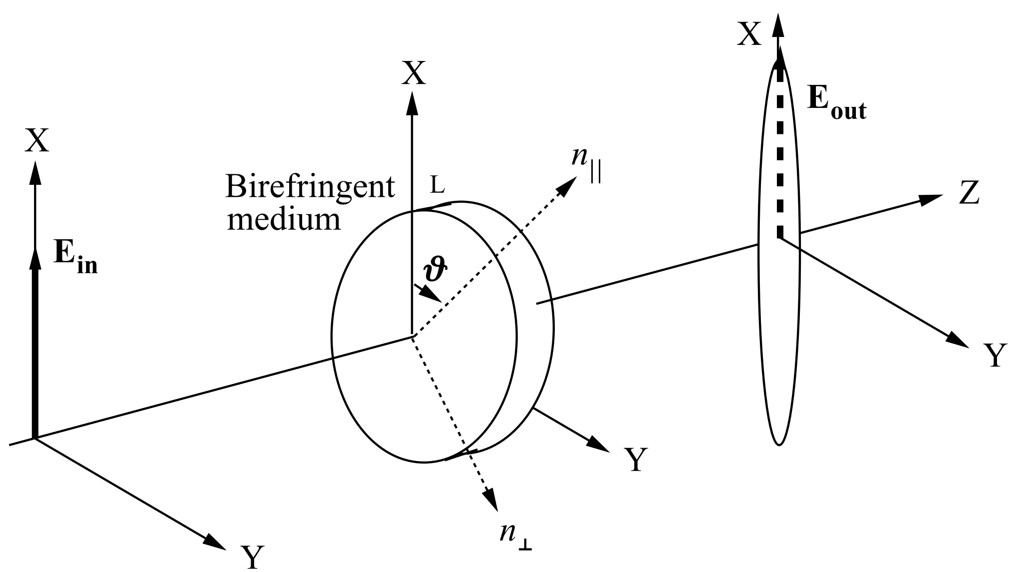
Effect of birefringence Δn and dichroism $\Delta\kappa$

- Consider pure dichroism $\Delta\kappa$ and input s-pol.:

$$\vec{E}_{in} = E_0 \begin{bmatrix} 1 \\ 0 \end{bmatrix} \Rightarrow \vec{E}_{out} = E_0 \begin{bmatrix} 1 - \frac{\pi}{\lambda}\Delta A \cos 2\theta \\ -\frac{\pi}{\lambda}\Delta A \sin 2\theta \end{bmatrix} \qquad \Delta A \equiv \int \Delta\kappa(z) dz$$

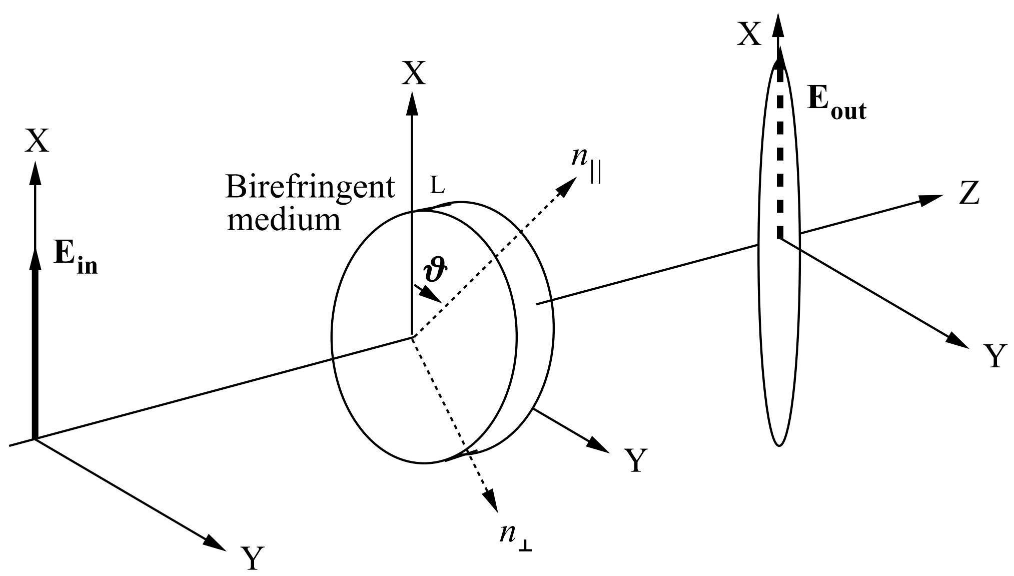
p-pol. in amplitude quadrature ⇒ Rotated linear polarization

⇒ Rotation: $\phi = -\frac{\pi}{\lambda}\Delta A \cos 2\theta$



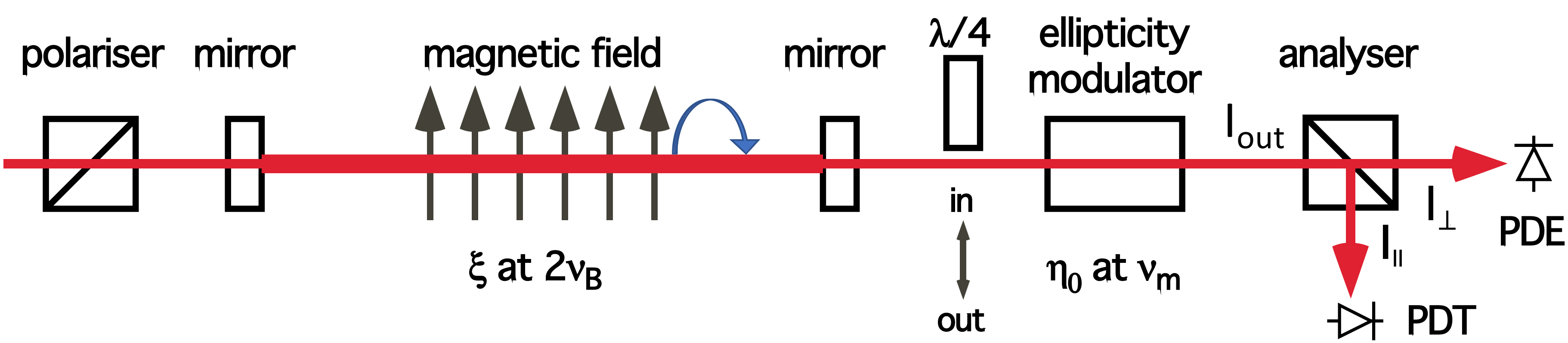
Effect of birefringence Δn and dichroism $\Delta\kappa$

- Important notes on birefringence Δn and dichroism $\Delta \kappa$:
  - Birefringence $\Delta n \Rightarrow$ Ellipticity ψ
  - Dichroism $\Delta \kappa \Rightarrow$ Rotation ϕ
  - VMB signal $\Delta n^{(EK)}$ appears as Ellipticity



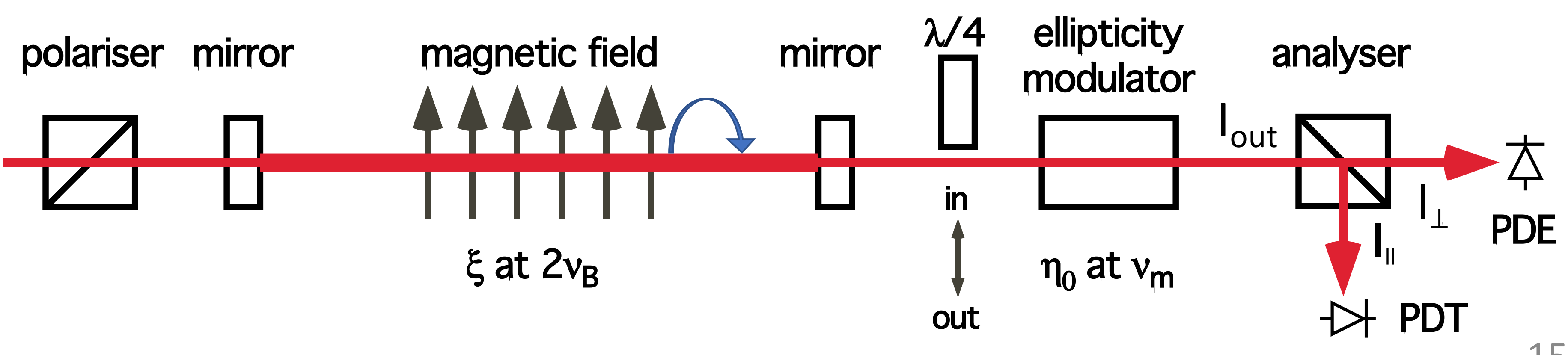
Scheme of PVLAS experiment

- Important components:
  - Rotating permanent magnet
  - Linear cavity
  - Ellipticity modulator
  - QWP for switching ellipticity/rotation measurements
  - PBS and PDs at detection port



Rotating permanent magnet

- Used to generate VMB signal ($\Delta n^{(EK)} = 3A_e B_{ext}^2$)
- Rotated to modulate VMB signal :
  - ➢ rotation at $\nu_B \Rightarrow$ VMB signal appears at $2\nu_B$



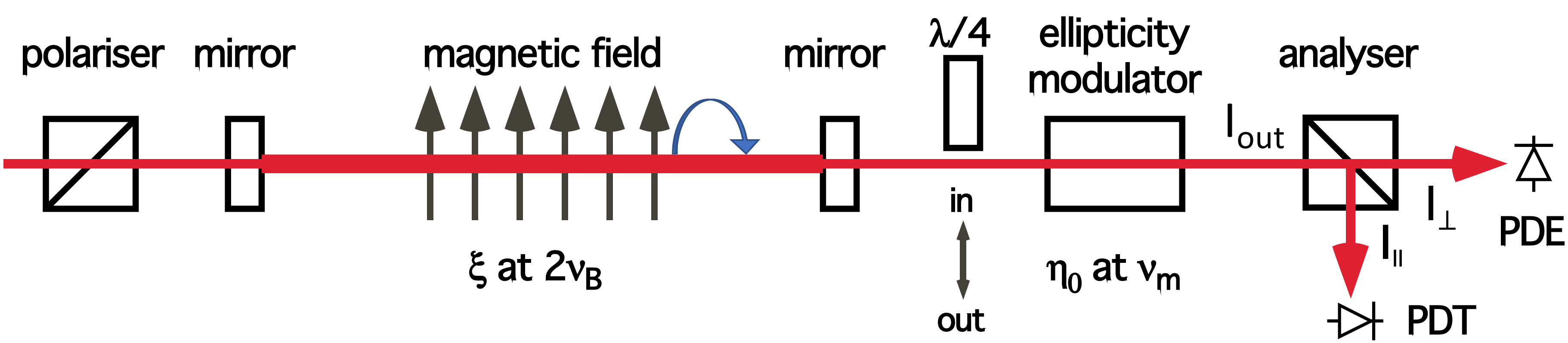
Linear cavity

- Ellipticity ψ and Rotation ϕ inside the cavity can be amplified when simultaneous resonance

$$\vec{E}_{out} = E_0 \frac{T}{1-R}\begin{bmatrix} 1 + N(i\psi + \phi)\cos 2\theta \\ N(i\psi + \phi)\sin 2\theta \end{bmatrix}$$

$N \equiv \frac{2\mathcal{F}}{\pi}$: Amplification factor by finesse

*Birefringence of the mirror coatings can cause the resonant frequency difference between s/p-pols.



Ellipticity modulator

- Transmitted light from the cavity:

$$\vec{E}_{out} = E_0 \frac{T}{1-R} \begin{bmatrix} 1 + N(i\psi + \phi)\cos 2\theta \\ N(\underline{i\psi} + \phi)\sin 2\theta \end{bmatrix}$$

VMB signal

⇒ need local an oscillator to detect the VMB signal in p-pol (phase)

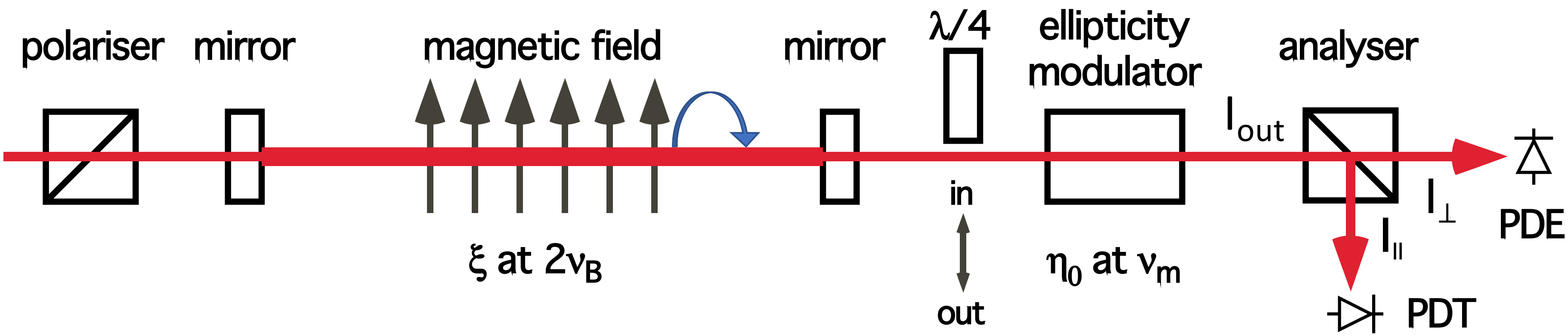
- Use ellipticity modulator:

$$\mathrm{MOD} = \begin{bmatrix} 1 & i\eta_0 \sin 2\pi\nu_m t \\ i\eta_0 \sin 2\pi\nu_m t & 1 \end{bmatrix}$$

  - Able to periodically change the ellipticity at ν_m
  - Using photo-elastic effect

$$\vec{E}_{out} = E_0 \frac{T}{1-R} \begin{bmatrix} 1 + N(i\psi + \phi)\cos 2\theta \\ \underline{i\eta_0 \sin 2\pi\nu_m t} + N(i\psi + \phi)\cos 2\theta \end{bmatrix}$$

LO in phase quadrature (heterodyne detection)



QWP for switching ellipticity/rotation measurements

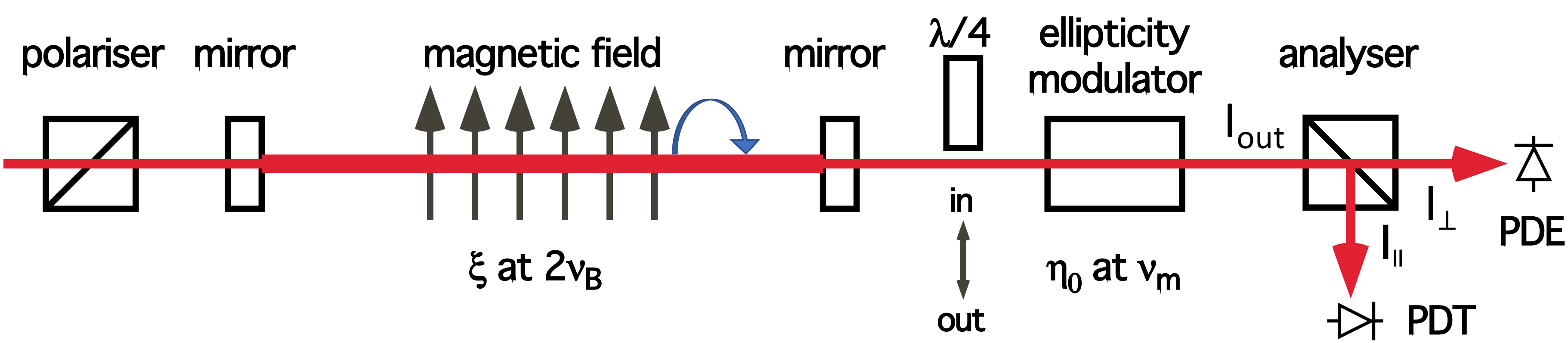
- By inserting QWP before ellipticity modulator, we can switch the measurement modes

  - w/o QWP: Ellipticity measurement (without)

$$\vec{E}_{out} = E_0 \frac{T}{1-R}\begin{bmatrix} 1 + N(i\psi + \phi)\cos 2\theta \\ i\eta_0 \sin 2\pi\nu_m t + N(i\psi + \phi)\cos 2\theta \end{bmatrix}$$

  - w/ QWP: Rotation measurement (without)

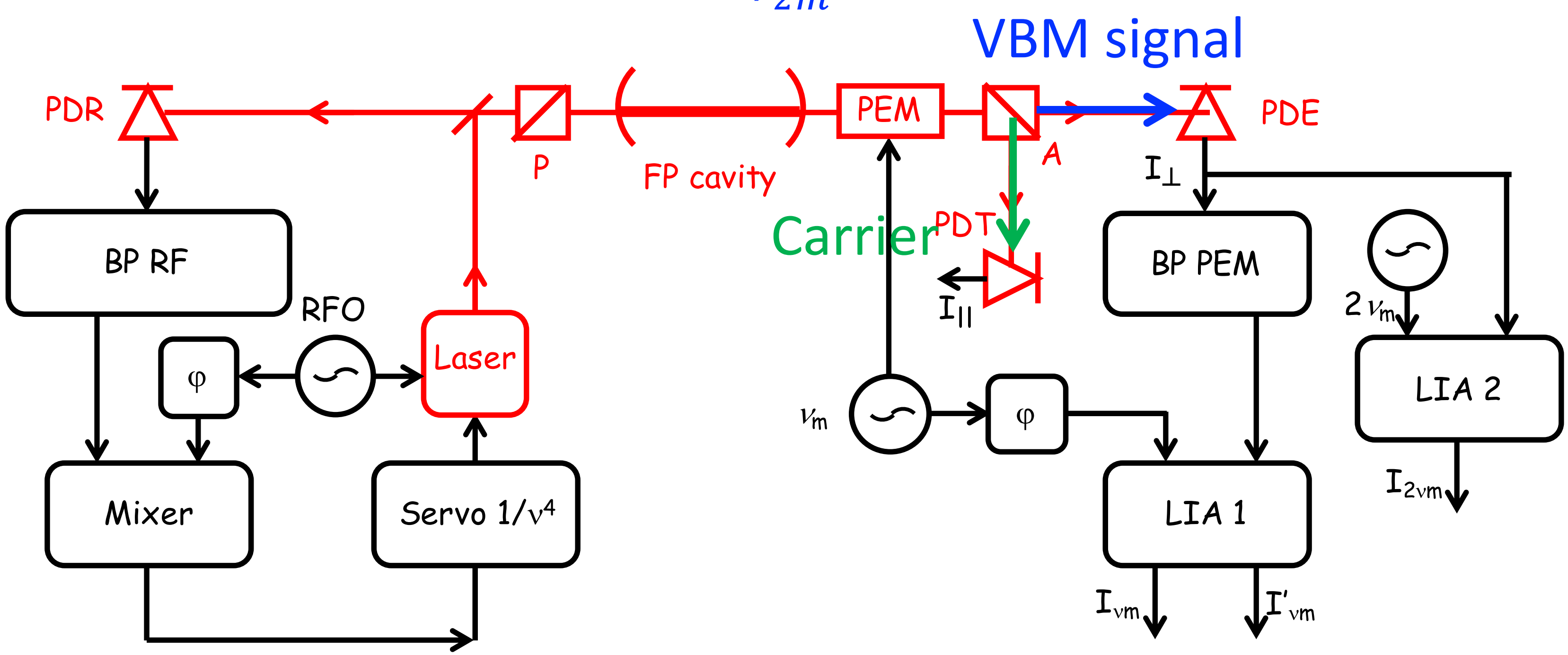
$$\vec{E}_{out} = E_0 \frac{T}{1-R}\begin{bmatrix} 1 + N(i\psi + \phi)\cos 2\theta \\ i\eta_0 \sin 2\pi\nu_m t + N(-\psi + i\phi)\cos 2\theta \end{bmatrix}$$



PDs at detection port

- Transmitted light is split to s- and p- pols. by a PBS
- By demodulating the PD outputs with ν_m, ellipticity signal can be obtained:
- VMB signal peak appears at $2\nu_B$

$$\Psi(t) = \frac{I_{\nu_m}(t)}{I_{\nu_{2m}}} \frac{\eta_0}{4}$$



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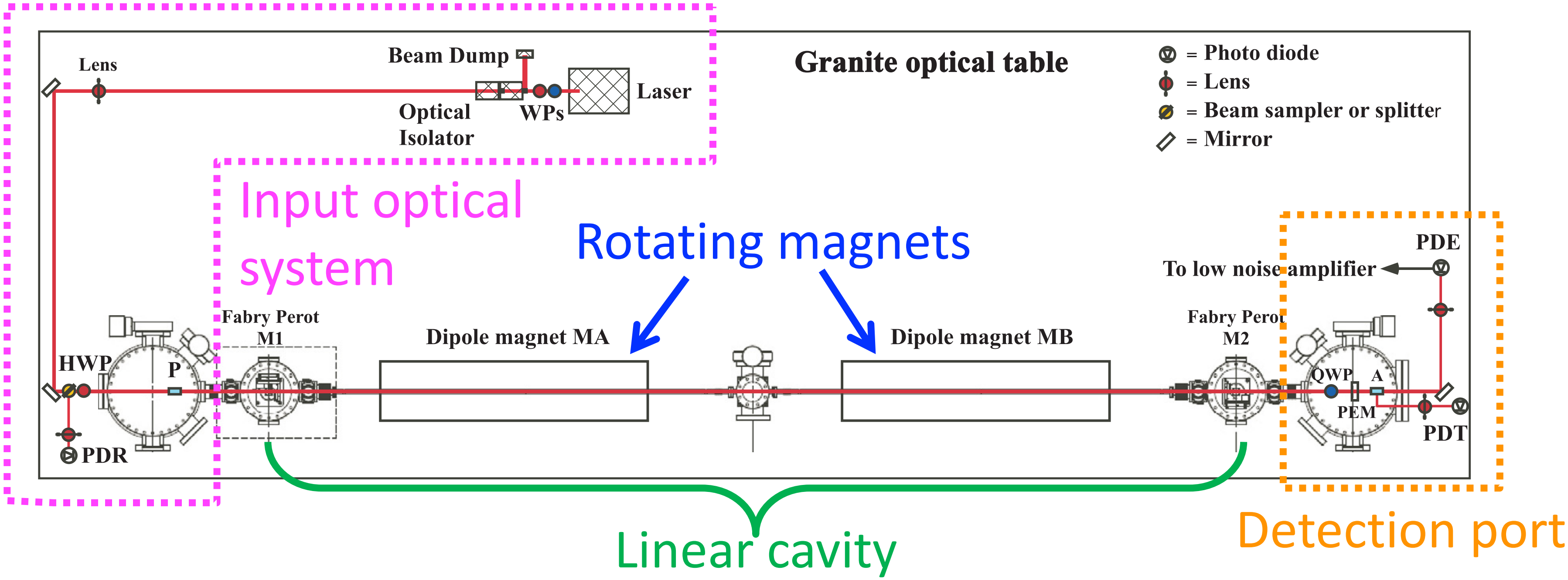
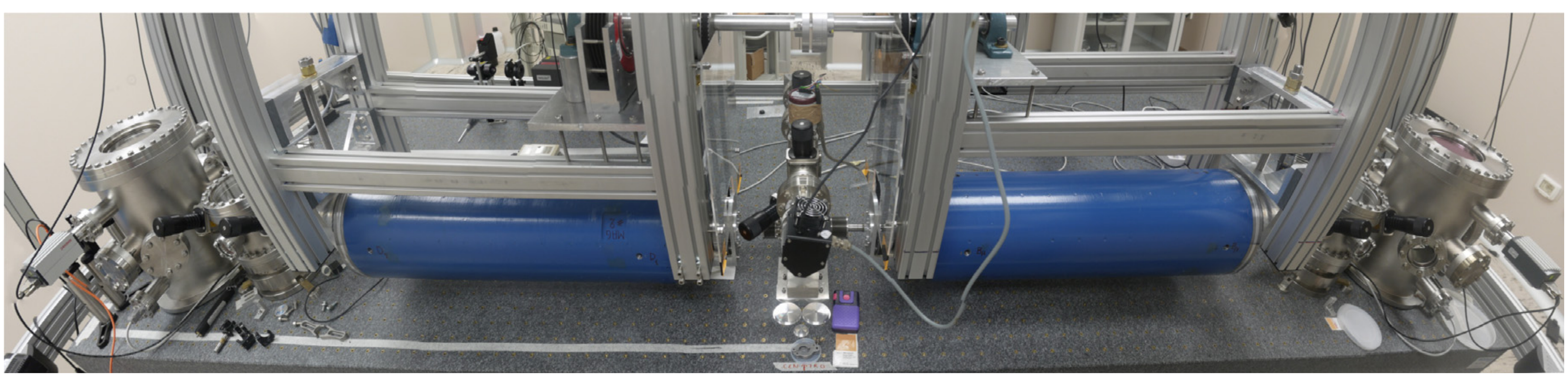
PVLAS-FE

- PVLAS-FE: Final phase of the PVLAS experiment
  - Location: University of Ferrara, Italy

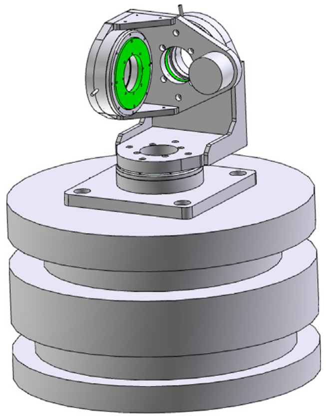


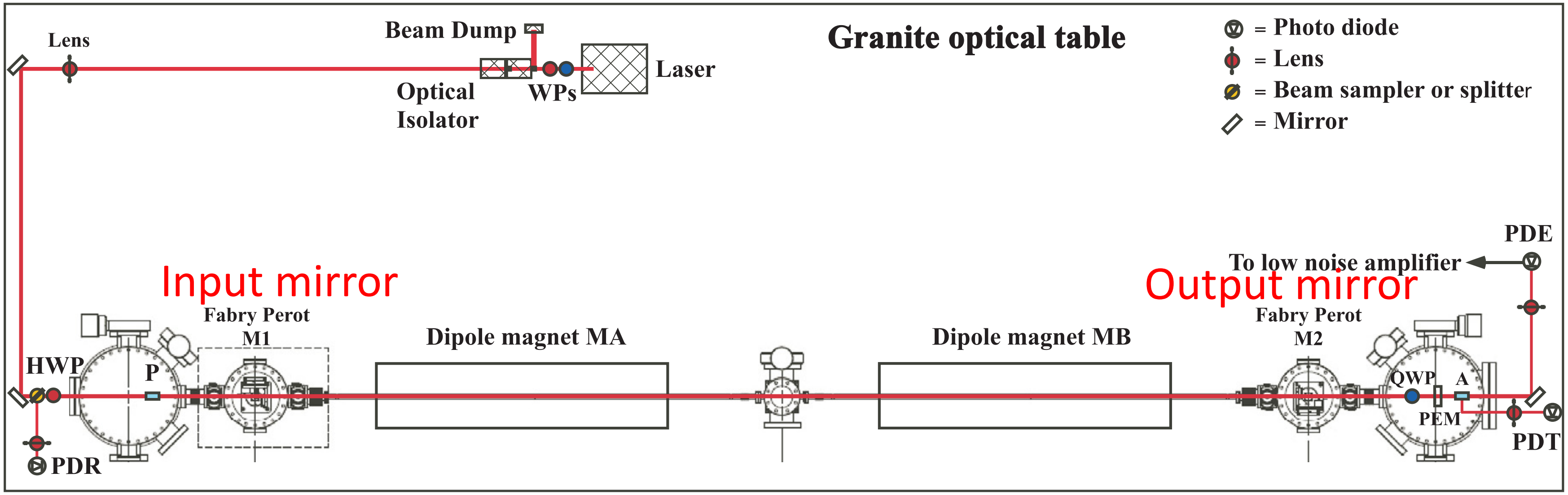


Optical system

- Input optical system
  - Laser: Mephisto 2W (1064 nm)
  - Input power: 50 mW at the maximum
- Cavity
  - Length: 3.3 m (FSR~ 45 MHz)
  - Finesse: $777{,}000 \pm 6000$ (Linewidth~59 Hz)
  - Mirror: $T = 2.4 \pm 0.2$ ppm, $Loss = 1.7 \pm 0.2$ ppm
  - Mirror mount can move in pitch, yaw and roll (for the alignment of the birefringent axis)

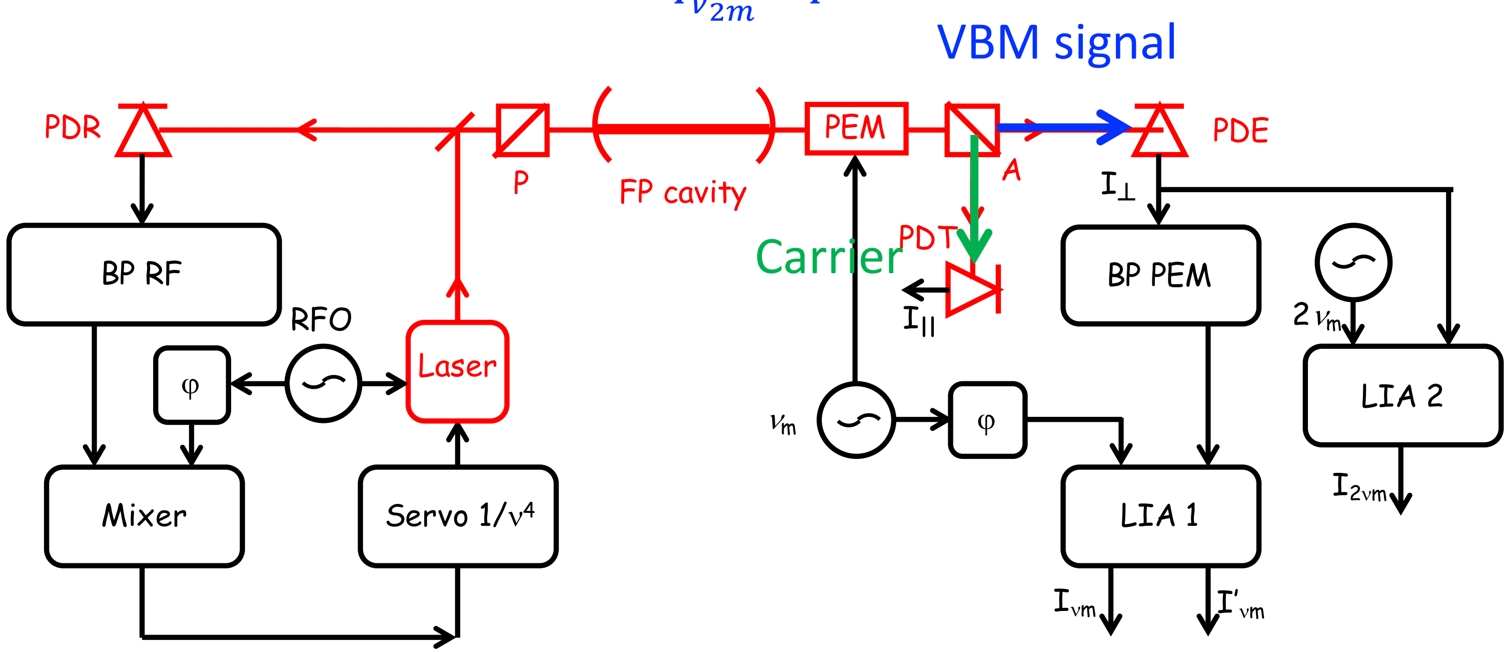
Mount for cavity mirrors





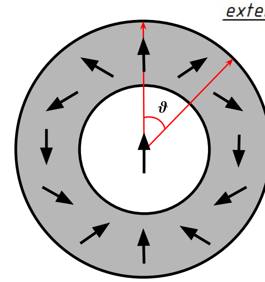
Cavity locking and data acquisition

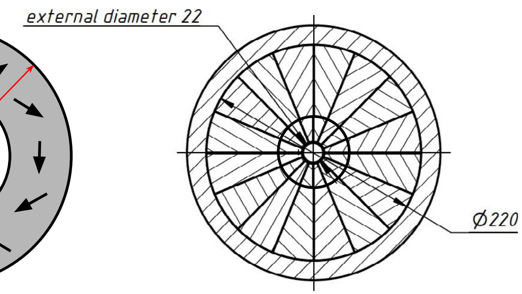
- PDH method was used for the cavity locking
  - 718 kHz sidebands were generated using the PZT inside the laser
- Photo-elastic ellipticity modulator (PEM) for the local oscillator
  - Modulation depth η_0: $3\times10^{-3} - 1\times10^{-2}$
  - Modulation frequency ν_m: $50\ \mathrm{kHz}$
- Outputs of the PD at the detection port were sent to the lock-in amplifier
  - Calibrated ellipticity: $\Psi(t) = \frac{I_{\nu_m}(t)}{I_{\nu_{2m}}}\frac{\eta_0}{4}$



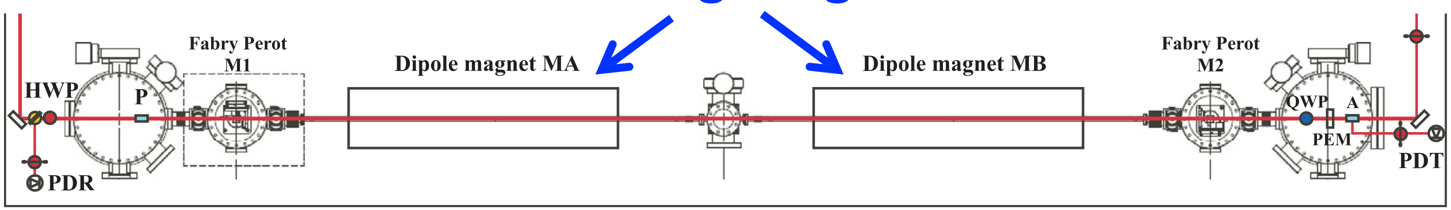
Rotating permanent magnets

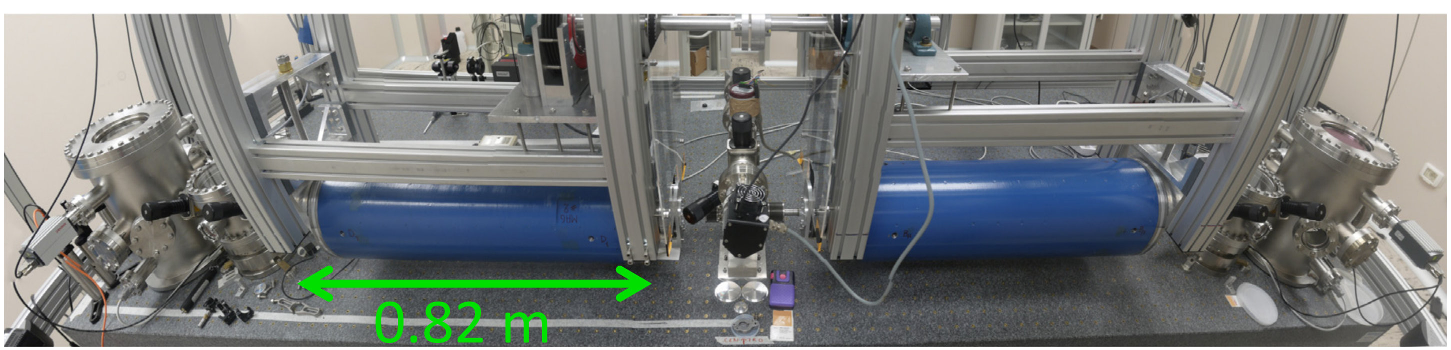
- Nd-Fe-B sintered magnet: 2.5 T
- Halbach configuration
  ⇒ able to cancel the stray magnetic field
- Length: $L_B = 0.82\ \mathrm{m}$
- Rotation frequency: $\nu_B \sim 8\ \mathrm{Hz}$ (depending on the run)
- Used two rotating magnets for the counter check (different ν_B for each magnet)





Rotating magnets

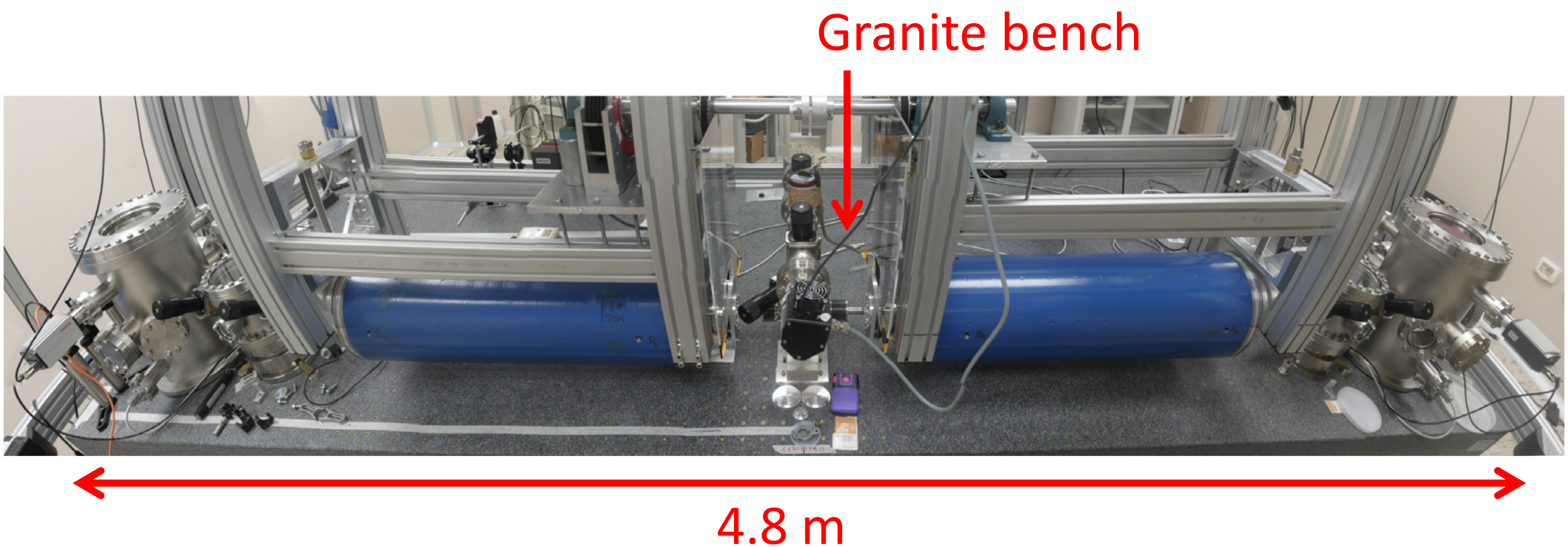




Optical bench and vibration isolation

- Stray magnetic field can produce magnetic force to optical components through eddy current
  ⇒ Used a granite optical bench

- Commercial active vibration isolation is used for the legs
  - BiAir® membrane spring air legs
  - Maintained the position of the bench within 10 μm



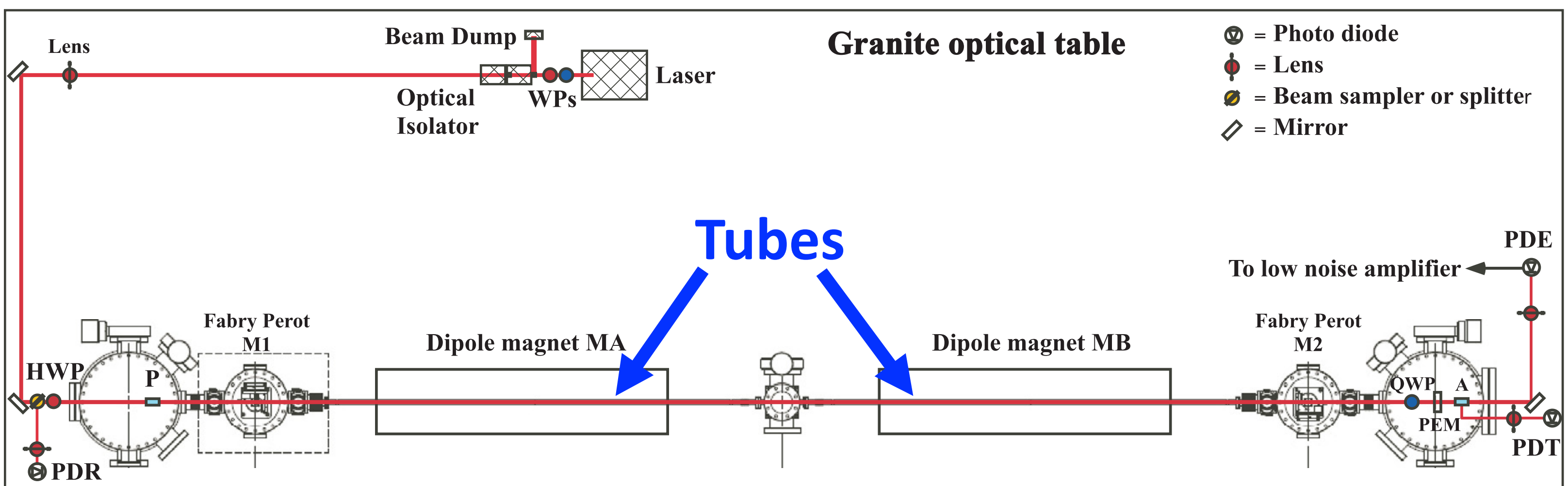
Vacuum tubes

- Gas in the magnetic field can exhibit birefringence: Cotton-Mouton effect (can be used for the calibration)

⇒ Need vacuum to reduce the noise

  - ➢Achieved pressure: 2×10^{-6} Pa

- Two tubes inside the magnets
  - ➢ Made of non-magnetic materials (borosilicate glass, silicon nitride ceramics)
  - ➢Diameter: ~18 mm



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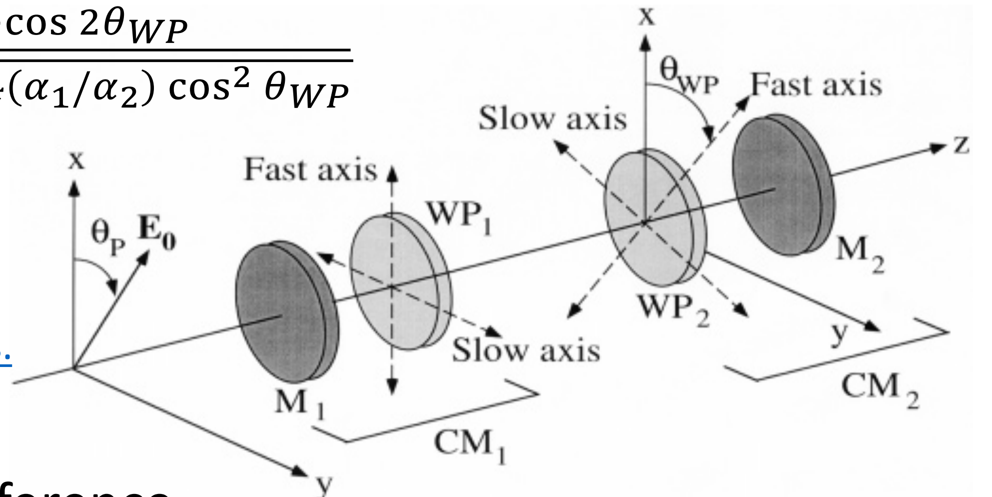
Resonant frequency difference of linear cavity

- Birefringence of mirror coating causes resonant frequency difference even in a linear cavity
  - Birefringence of M_1 and M_2 ⇒ wave plates: WP_1 and WP_2
  - WP_1 and WP_2 ⇒ an effective WP: WP_{EQ}

Phase difference: $\alpha_{EQ} = \sqrt{(\alpha_1 - \alpha_2)^2 + 4\alpha_1\alpha_2 \cos^2\theta_{WP}}$

Angle of axis: $\theta_{EQ} = \frac{\alpha_1/\alpha_2 + \cos 2\theta_{WP}}{\sqrt{(\alpha_1/\alpha_2 - 1)^2 + 4(\alpha_1/\alpha_2)\cos^2\theta_{WP}}}$

F.Brandi et al. Appl. Phys. B 65, 351-355 (1997)



- α_{EQ} causes resonant frequency difference
- θ_{EQ} defines the angle of the eigen linear polarizations in front of M1
- θ_{WP} determines the eigen polarization modes inside the cavity (Linear for $\theta_{WP} = 0, \pi/2, \pi, 3\pi/2$, Elliptic for other values)

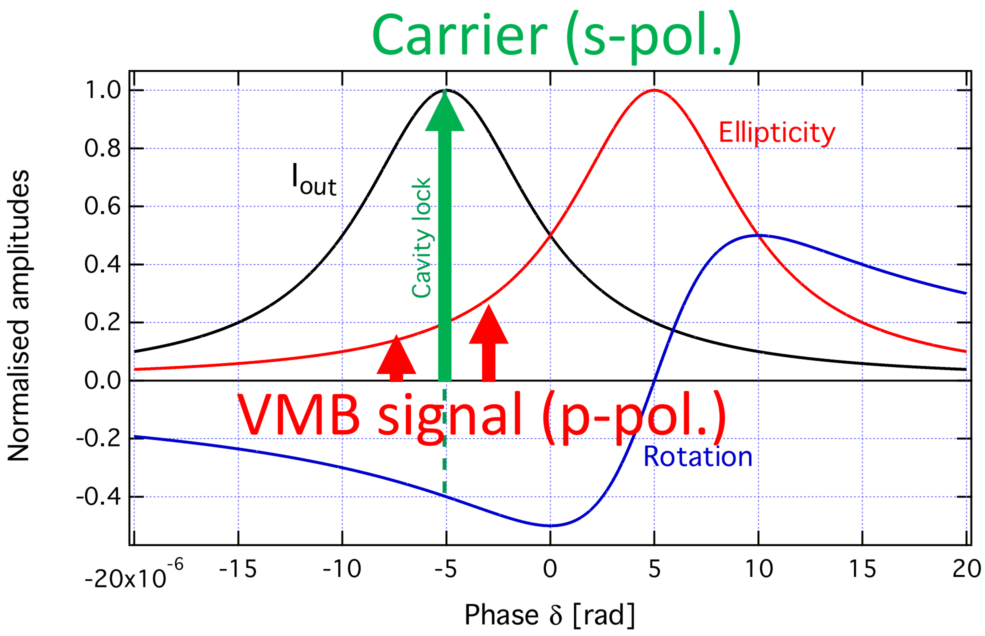
Issues on resonant frequency difference

- Polarization inside cavity needs to be linear to interact with the VMB
- Resonant frequency difference degrades the signal amplification by the cavity like DANCE

Align the slow axis of M1 to the **fast** axis of M2 to cancel out the phase difference α_{EQ}

$\Leftrightarrow \theta_{WP} = \pi/2, 3\pi/2$

How can we align it?



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How to align birefringent axis

- Resonant frequency difference also causes the signal mixing of ellipticity ψ and rotation ϕ due to the detuned cavity:

Actual ellipticity

Measured "Ellipticity": $i\Psi = i\frac{N}{1+N^2\sin^2\alpha_{EQ}/4}\left[\psi + N\frac{\alpha_{EQ}}{2}\phi\right]$

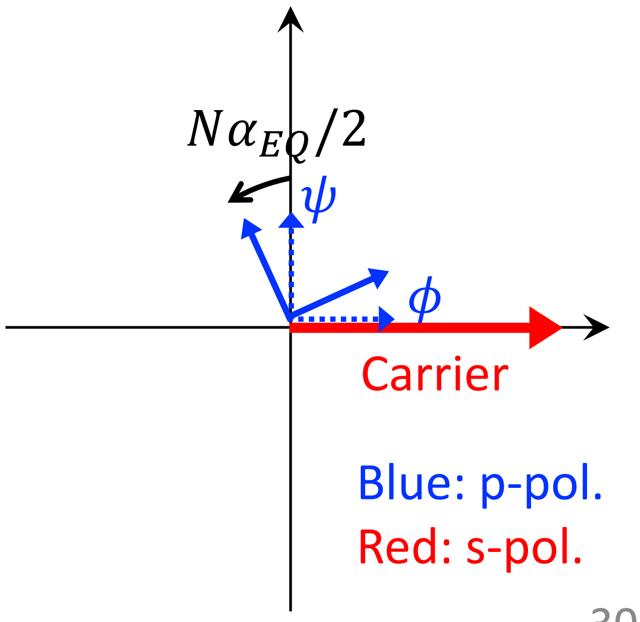
Mixed rotation

Actual rotation

Measured "Rotation": $\Phi = \frac{N}{1+N^2\sin^2\alpha_{EQ}/4}\left[\phi - N\frac{\alpha_{EQ}}{2}\psi\right]$

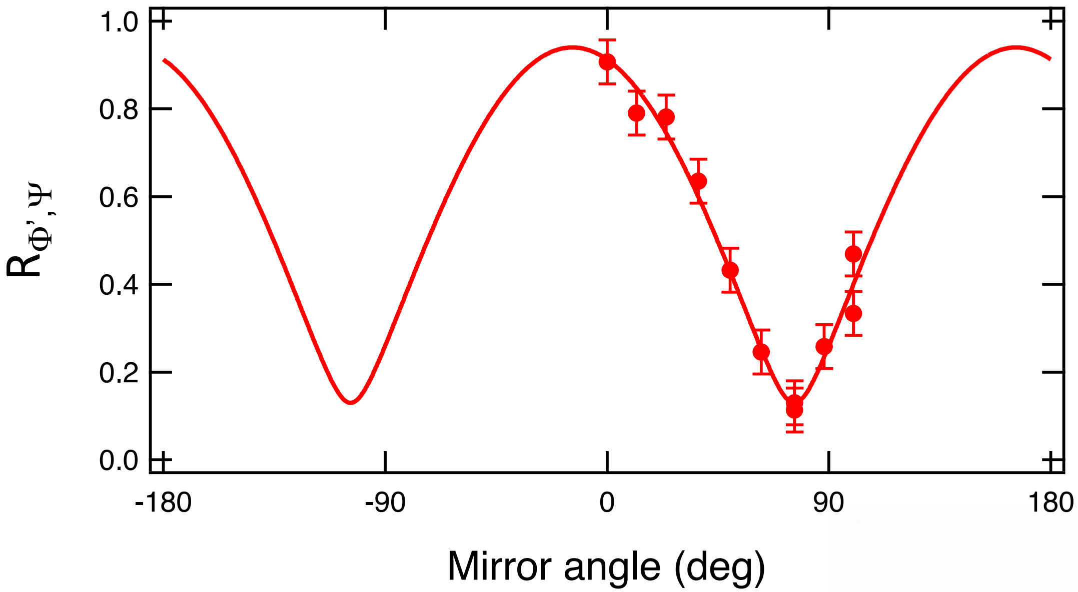
Mixed ellipticity

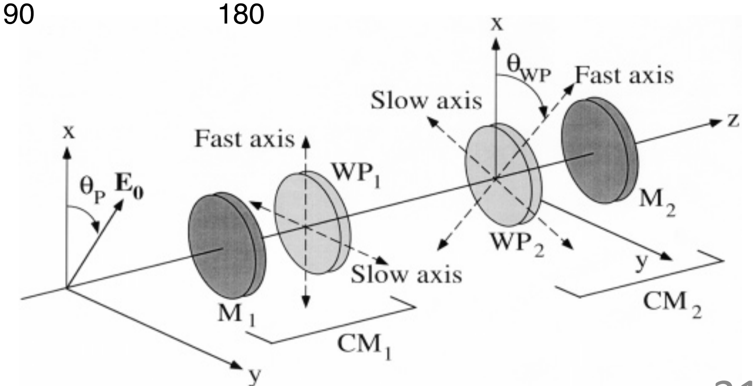
- We can use this mixing to measure α_{EQ}
  1. Prepare intentional birefringence with gas (Cotton-Mouton effect)
  2. Measure its ellipticity and rotation and take their ratio:
     $$R_{\Phi',\Psi} = \Phi/\Psi = \frac{N}{2}\alpha_{EQ}$$
  3. Measure α_{EQ} changing birefringent axis of one of the cavity mirrors



How to align birefringent axis

- Results: $\alpha_{EQ} = 0.6$ µrad - 4.3 µrad
  - DANCE: $\sim$ 10 mrad / mirror (*mechanism is different)
- α_{EQ} was set to 0.6 µrad during the VMB measurement





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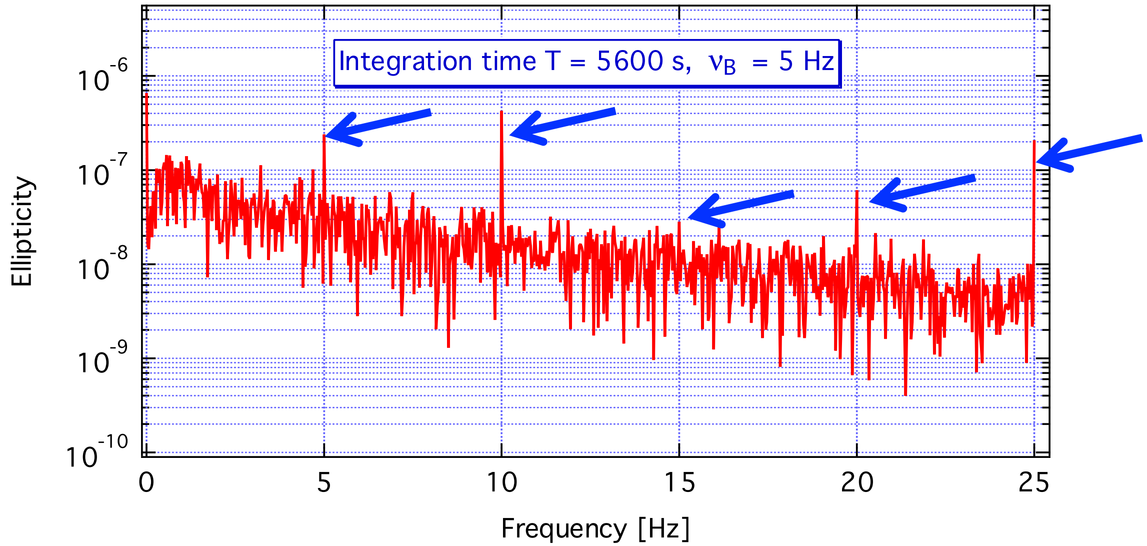
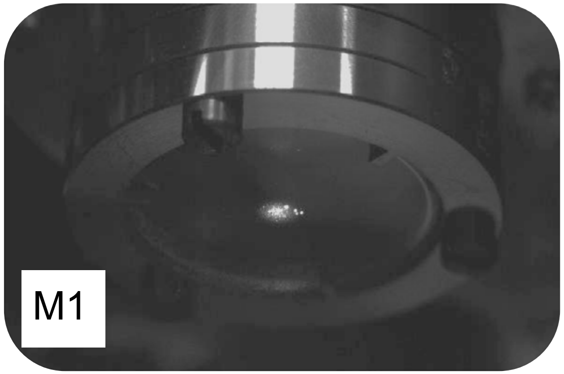
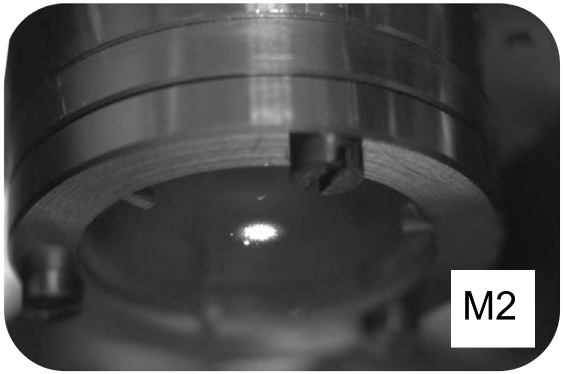
In-phase spurious peak by scattered light

- Signals at harmonics of the magnet rotation (5 Hz) in the ellipticity spectrum

⇒ Scattered light modulated by the oscillation of the vacuum tubes caused these peaks

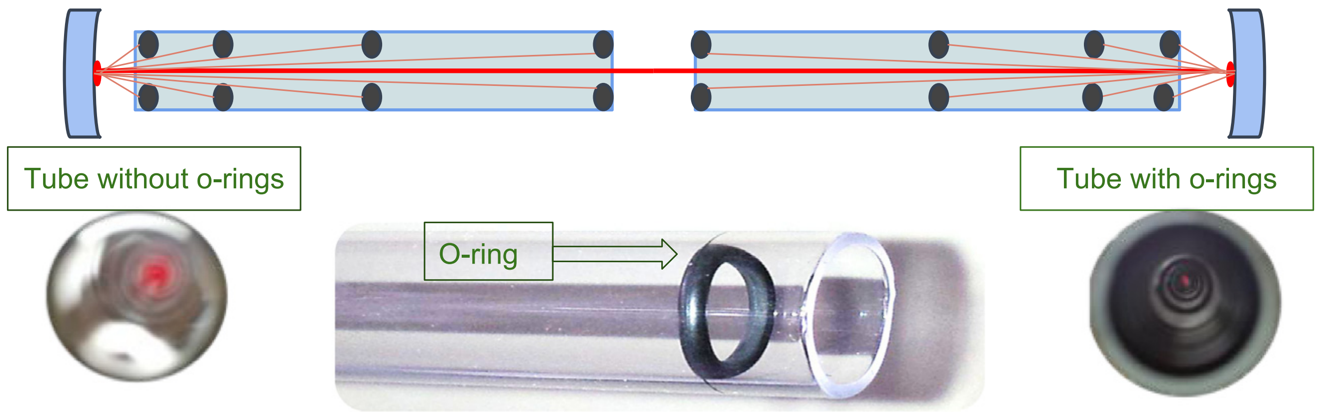




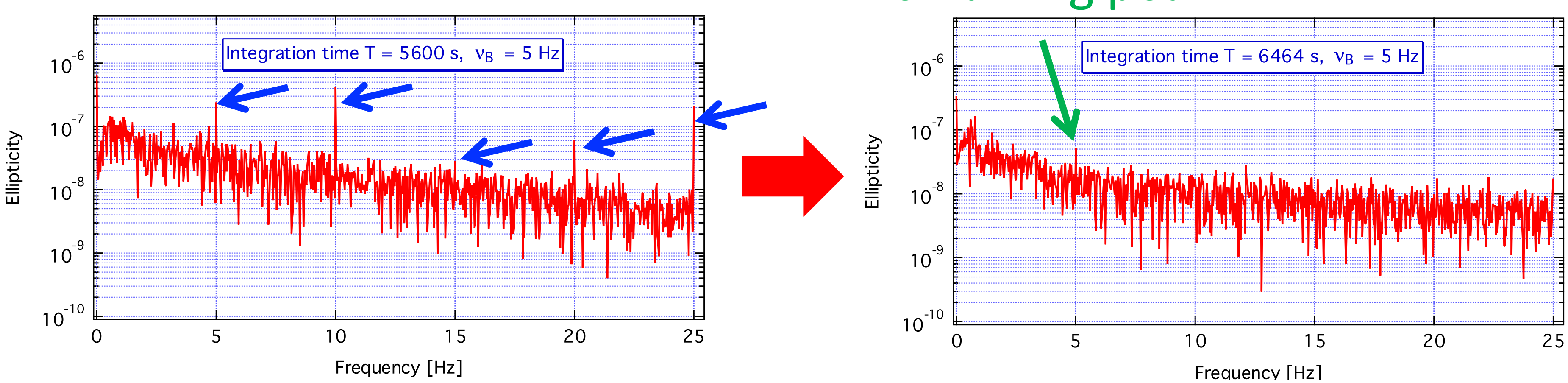


Baffles for prevention of scattered light

- Inserted baffles inside the vacuum tubes
  ⇒ Spurious peaks disappeared greatly except for remaining peak at 5 Hz



Remaining peak



Remaining peak: Faraday rotation by mirror coating

- Remaining peak at 5 Hz does not affect the VMB signal at 10 Hz
- This peak was caused by the Faraday rotation on the mirror coating induced by stray magnetic field:

Faraday rotation: $\Phi_F = N C_{Ver} B_{long}$

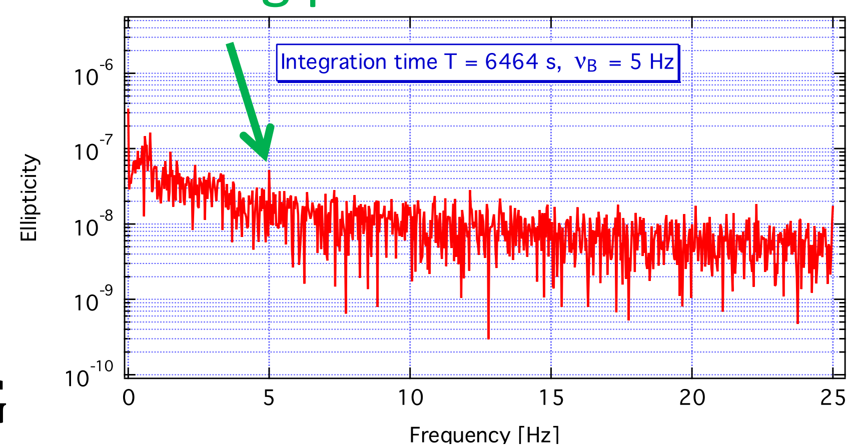
Stray magnetic field along cavity axis

Verdet constant per reflection
($\sim 0.37\times10^{-9}$ rad/G by E.Iacopini et al. Appl. Phys. A 32, 63-67 (1983))

- Estimated stray field along cavity axis from the equation : $\sim 2\times10^{-4}$ G

Plausible from the observed stray field around mirror: < 0.1 G

Remaining peak



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Design and final sensitivities

- Design and final sensitivities at 16 Hz:

Ellipticity spectrum

$S_{\Psi}^{(\mathrm{design})} \simeq 8\times10^{-9}\ /\sqrt{\mathrm{Hz}}$ $\quad$ $S_{\Psi}^{(\mathrm{final})} \simeq 4\times10^{-7}\ /\sqrt{\mathrm{Hz}}$

↕

Cavity length difference between s/p-pols (∼DARM)

$S_{\Delta D}^{(\mathrm{design})} \simeq 6\times10^{-21}\ m/\sqrt{\mathrm{Hz}}$ $\quad$ $S_{\Delta D}^{(\mathrm{final})} \simeq 3.5\times10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

- A factor of ∼50 times worse than the design sensitivity
- Remaining wide band noise is not fully understood
  - ➢Possible cause: Birefringence noise of the mirror coatings induced by thermal fluctuations (Thermoelastic noise)

Thermoelastic noise

- Mechanism and calculation of the thermoelastic noise:
  1. Small volume elements of the mirror coatings have temperature fluctuations, and it causes stress fluctuations
  2. Stress fluctuations causes birefringence fluctuations through photo-elastic effect
  3. Average birefringence fluctuations over the whole volume defined by the beam diameter and the optical depth

$$S_{\Delta\mathcal{D}} = 2d_e\sqrt{2}C_{SO}Y\alpha_{\mathrm{T}}S_T = d_eC_{SO}Y\alpha_{\mathrm{T}}\sqrt{\frac{8k_{\mathrm{B}}T^2}{\pi r_0^2\sqrt{\pi\rho C_T\lambda_T\nu}}} \propto \nu^{-1/4}$$

Fused silica $S_{\Delta D}^{(\mathrm{FS})} \simeq 4\times10^{-21}\mathrm{m}/\sqrt{\mathrm{Hz}}$

Tantala $S_{\Delta D}^{(\mathrm{Ta})} \simeq (1 - 5)\times10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

↑

Plausible compared with $S_{\Delta D}^{(\mathrm{final})} \simeq 3.5\times10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

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Limit on VMB

- PVLAS-FE conducted observation runs from 2014 to 2016
  - ➢Total observation time: $T_{obs} \sim 5 \times 10^{6}\ \mathrm{s} \sim 2\ \mathrm{months}$
- Set the best limit on VMB:

$$\begin{cases} \Delta n^{(\mathrm{PVLAS-FE})} \simeq (12 \pm 17) \times 10^{-23} \ @\ B = 2.5\ \mathrm{T} \\ |\Delta\kappa|^{(\mathrm{PVLAS-FE})} \simeq (10 \pm 28) \times 10^{-23} \ @\ B = 2.5\ \mathrm{T} \end{cases}$$

* QED prediction: $\Delta n^{(\mathrm{EK})} = 2.5 \times 10^{-23} \ @\ B = 2.5\ \mathrm{T}$

⇒ A factor of 7 worse than the QED prediction

- Although longer observation time can improve the SNR, 50 times longer integration (~8 years) is needed to reach SNR=1
- PVLAS-FE ended in 2017 due to the practical impossibility to decrease the wide band noise (thermoelastic noise?)

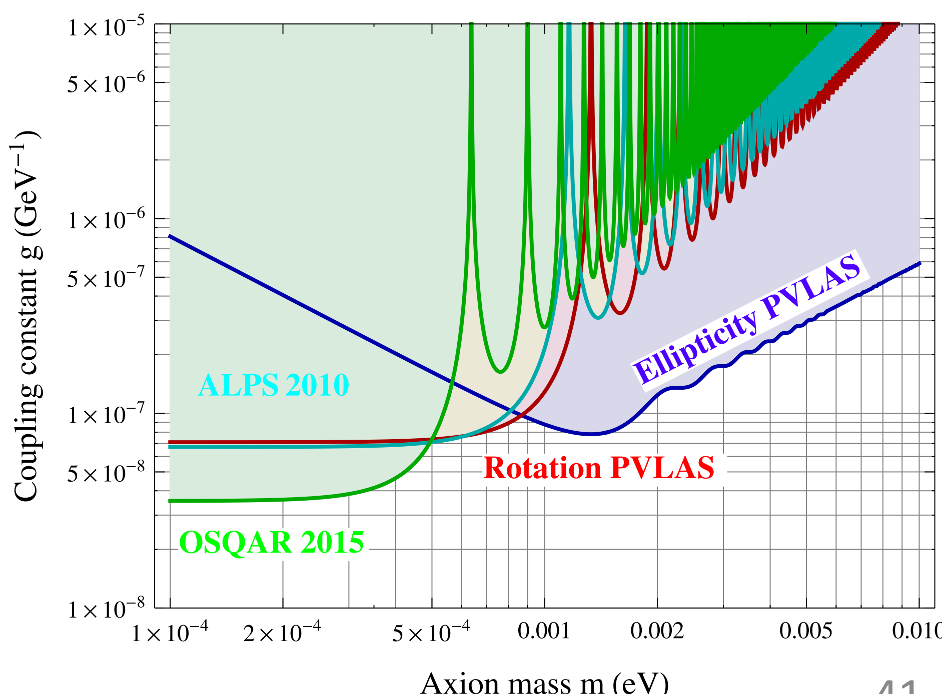
Limit on Axion Like Particles

- Axion Like Particles produce the birefringence and the dichroism in the presence of external magnetic field:

$$\begin{cases} |\Delta n| \simeq \frac{1}{2}\left(\frac{g_{a\gamma}B_{ext}}{2m_a}\right)^2\left(1-\frac{\sin 2\chi}{2\chi}\right)^2 \\ |\Delta\kappa| \simeq \frac{2}{\omega L_B}\left(\frac{g_{a\gamma}B_{ext}L_B}{4}\right)^2\left(\frac{\sin\chi}{\chi}\right)^2 \end{cases} \qquad \chi \equiv \frac{L_B m_a^2}{4\omega}$$

- PVLAS-FE VMB limits
  ⇒ Upper limit on axion-photon coupling constant: $g_{a\gamma}$

- Worse than CAST ($\sim 10^{-10}\ \mathrm{GeV}^{-1}$), but best model-independent limit



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Summary

- PVLAS: experiment for the vacuum magnetic birefringence (VMB) using a linear cavity and rotating magnets
- Analyzes the ellipticity of the transmitted polarization
- Result: $\Delta n^{(\mathrm{PVLAS-FE})} \simeq (12 \pm 17)\times 10^{-23}$ @ $B = 2.5$ T
  - ➢A factor of 7 worse than the QED prediction: $\Delta n^{(\mathrm{EK})} = 2.5\times 10^{-23}$ @ 2.5 T
  - ➢Also set the upper bound for axion like particles
  - ➢Limiting noise source: thermal birefringence noise of mirror coatings(?)