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Status of the VMB@CERN experiment

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This paper reviews the progress and current status of the VMB@CERN experiment up to 2023. It summarizes the work done since the collaboration was established five years ago and provides an outlook for future measurements of vacuum magnetic birefringence.

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1. Introduction

For nearly a century, physicists have been studying changes in the speed of light in a vacuum caused by a magnetic field. In 1933, O. Halpern described the vacuum as a light-scattering medium [1]. This quantum effect was first described by H. Euler and B. Kockel in 1935 using an effective Lagrangian and was later generalized by H. Euler, W. Heisenberg, and V. S. Weisskopf in 1936 [2,3]. This Lagrangian implies several phenomena, including light-by-light scattering, changes in the speed of light in the presence of an external field, and vacuum anisotropy due to vacuum magnetic birefringence (VMB) [4,5]. The free-field electromagnetic Lagrangian, which describes nonlinear phenomena in vacuum, can be written as equation 1 when the electric and magnetic fields are well below their critical values.

$$\mathcal{L}_{EHW} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] + \cdots, \quad (1)$$

where

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2 \lambdabar_e^3}{m_e c^2} = 1.32 \times 10^{-24}\ \mathrm{T}^{-2}.$$

The parameter A_e describes the nonlinear correction to the Classical Lagrangian. In a vacuum, the index of refraction for light parallel and perpendicular to the magnetic field should differ [4,5]. This difference is determined by the parameter A_e from $\mathcal{L}_{EHW}$.

$$n_{\parallel} - n_{\perp} = \Delta n = 3A_e B_{ext}^2 = 3.69 \times 10^{-24}\left(\frac{B_{ext}}{1\ \mathrm{T}}\right)^2 \qquad (2)$$

For example, at a magnetic field induction of 9.5 T, the birefringence Δn induced by the LHC magnet would be still extremely small, with a value of $\Delta n^{LHC} = 3.6 \times 10^{-22}$. Measuring the VMB would confirm the QED theory, particularly in the low-energy particle region in the eV and sub-eV. Additionally, the VMB can be used to study other phenomena beyond the QED theory, such as Axion-Like Particles [6,7]. Despite numerous experiments and theoretical predictions within quantum electrodynamics, direct measurement of VMB has not yet been achieved. The PVLAS experiment has set the best limit on this phenomenon at 2.5 T [8,9].

$$\frac{\Delta n^{\mathrm{PVLAS}}}{B^2} = (1.9 \pm 2.7) \times 10^{-23}\ \mathrm{T}^{-2} \qquad (3)$$

2. VMB@CERN polarimetry

Birefringence can be determined by measuring the induced ellipticity when linearly polarized light of wavelength λ is passing through a birefringent medium of length L. Assuming the ellipticity is small, it can be expressed as follows:

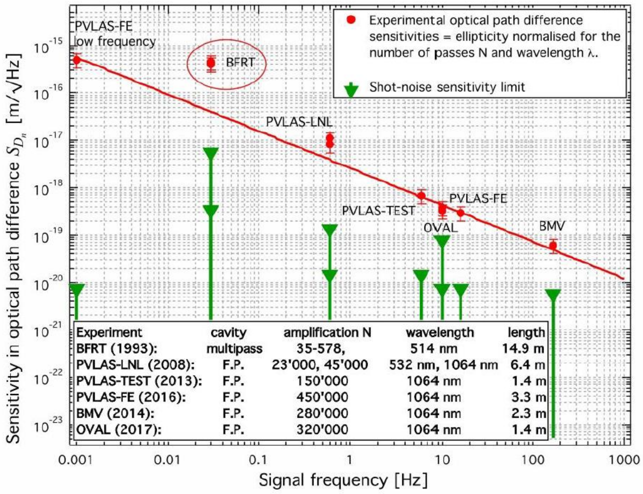
$$\psi = \pi\frac{L}{\lambda}\Delta n \sin 2\vartheta = \psi_0 \sin 2\vartheta \quad (4)$$

The angle between the direction of the magnetic field and the input linear polarization is denoted as ϑ. The measurement attempts for Vacuum Magnetic Birefringence (VMB) began at CERN in

1979 with the proposal of E. Zavattini and E. Iacopini [10]. Subsequent experiments have been conducted since then. Equations 2 and 4 demonstrate that to achieve the maximum induced birefringence in vacuum, it is necessary to ensure the maximum magnetic field strength in the longest possible region. To increase the optical path length in the magnetic field region an effective approach is to use a Fabry-Perot resonator [11]. To enhance the sensitivity of the polarimeter, it is crucial to modulate either the magnetic field intensity or the angle ϑ between polarization and magnetic field direction. There are several options to modulate the magnetic field intensity, such as harmonic filed modulation (BFRT experiment [12]) or pulsed (BMV [13], OVAL [14] experiments). Another option is to modulate the direction of the magnetic field through magnet rotation such as PVLAS I [15], II [8], [9], and Q&A [16]. An alternative approach is to modulate the polarization direction. For noise reduction and signal linearization, one can use a PEM modulator to implement heterodyne measurement. The polarimetry output of such a heterodyne system can be described by the following equation:

$$I_{\text{out}}(t) = I_0\{\sigma^2 + [\psi(t) + \eta(t) + \gamma(t)]^2\} \simeq I_0[\sigma^2 + \eta(t)^2 + 2\psi(t)\eta(t) + 2\eta(t)\gamma(t) + \cdots] \tag{5}$$

The extinction ratio of the polarizers σ^2 and the slowly varying spurious elliptic noise $\gamma(t)$ has a major impact on measurement sensitivity. Using harmonic modulation of the measured signal $\psi(t)$ and the PEM modulation signal $\eta(t)$, the result is well-defined Fourier components corresponding to the measured quantities. The PVLAS [17] and BMV [18] studies have shown that spurious elliptical noise $\gamma(t)$ is a limiting issue in experiments involving high-quality cavities. The origin of the spurious noise is not yet fully understood and therefore cannot be effectively suppressed to achieve the shot noise level as shown in Figure 2.



Experiment	cavity	amplification N	wavelength	length
BFRT (1993):	multipass	35-578,	514 nm	14.9 m
PVLAS-LNL (2008):	F.P.	23'000, 45'000	532 nm, 1064 nm	6.4 m
PVLAS-TEST (2013):	F.P.	150'000	1064 nm	1.4 m
PVLAS-FE (2016):	F.P.	450'000	1064 nm	3.3 m
BMV (2014):	F.P.	280'000	1064 nm	2.3 m
OVAL (2017):	F.P.	320'000	1064 nm	1.4 m

Figure 2: Noise in optical path difference versus working frequency for different polarimeters using cavities (BFRT multi-pass, others - Fabry-Perot) for improved sensitivity.

As mentioned before another method of modulating ellipticity involves altering the direction of the electric field vector, rather than the magnetic field direction. The OSQAR experiment [19] investigated this concept for a magnet from the LHC, but the presence of the static ellipticity of optical elements, such as mirrors and optical windows, has not been resolved. Intrinsic birefringence of mirrors and other optical elements significantly impacts the measured signal and generates an effect many orders of magnitude higher than the VMB. To address this issue, an optical scheme was proposed in 2016 by the PVLAS group [20]. The scheme uses two co-rotating half-wave plates (HWP) to rotate the polarization vector inside the optical resonator. As a consequence of using two HWP the polarization vector on the mirrors is stable and does not affect the measured signal. Figure 3 shows the proposed optical scheme.

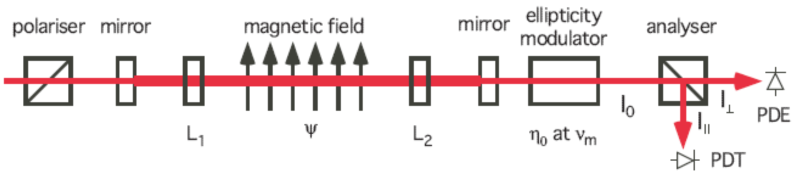


Figure 3: New modulation scheme. L1;2: rotating half-wave plates (HWP). PDE: Extinction Photodiode; PDT: Transmission Photodiode.

To test and implement this scheme within LHC magnets at CERN, the VMB@CERN collaboration was formed in late 2018 [21]. Collaborators from PVLAS, Q&A, OSQAR, and LiGO-Cardif worked together for this purpose.

3. Optical scheme demonstrator

The total ellipticity at the output of the polarimeter in Figure 3 can be described as [22]

$$\psi(t) = N\psi_0 \sin 4\phi(t) + N\frac{\alpha_1(t)}{2}\sin 2\phi(t) + N\frac{\alpha_2(t)}{2}\sin[2\phi(t) + 2\Delta\phi(t)] \qquad (6)$$

where the phase deviations from π for the HWP are denoted by $\alpha_{1,2}(t)$ and their rotation angle is denoted by $\phi(t)$. The relative rotation phase shift between HWP is represented by $2\Delta\phi(t)$ and directly affects the extinction ratio of the polarimeter σ^2. The Fabry-Perot resonator multiplication factor is denoted by N, and the magnetic field in the LHC induces the ellipticity ψ_0 for a single pass. Equation 6 shows that the VMB signal lies at the 4th harmonic frequency of the HWPs rotation $4\upsilon_W$. To proceed with measurements on the LHC magnet, it was necessary to demonstrate the working principle and sensitivity of the newly proposed method on a small lab scale. These measurements were mainly conducted in the laboratory of the former PVLAS experiment in Ferrara [22] and partly in laboratories in Liberec and Cardiff. Equation 6 outlines the basic principles that needed to be demonstrated, including:

- **A:** Synchronous rotation of the HWP to optimize extinction σ^2 - $[2\phi(t) + 2\Delta\phi(t)]$
- **B:** Understand systematic effects at $4\upsilon_W$ and other harmonics - $\alpha_{1,2}(t)$
- **C:** Lock laser to the F.P. cavity with the rotating HWPs Inside - *N*
- **D:** Reach required sensitivity for LHC test in a small lab - noise characterization at $4\upsilon_W$

A: Synchronous rotation of the HWP to optimize extinction σ^2 - $[2\phi(t) + 2\Delta\phi(t)]$

This was the first step in testing the entire system. We gradually selected and tested several types of electromagnetic motors for HWP rotations. Some of them as an entire system, including the control (Thorlabs), and others as individual components with a custom motor control. Two main types of electric motors were tested: brushless and stepper motors. The stepper motor proved to be the better choice, as shown in the graph in Figure 4.

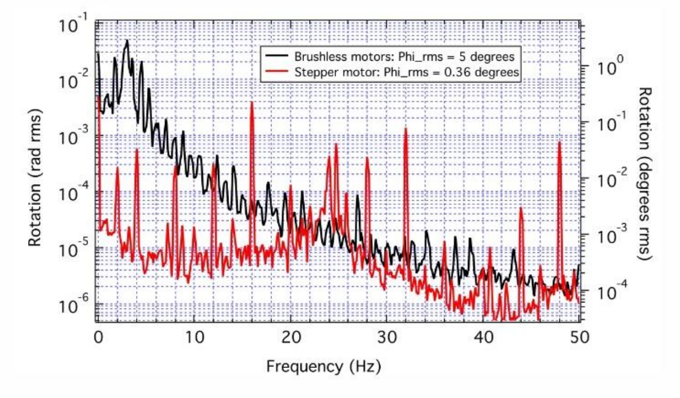


Figure 4: Synchronized rotation of two HWPs.

The extinction coefficient without an optical resonator while rotating was approximately $\sigma^2 \approx 10^{-6}$, which is adequate for the final system implementation with an LHC magnet.

B: Understand systematic effects at $4\upsilon_w$ and other harmonics - $\alpha_{1,2}(t)$

The second step was to investigate and understand how the defects $\alpha_{1,2}(t)$ affect the resulting harmonic frequencies, which are important for the VMB measurement. The goal was to control any possible defects to a reasonable level. This step was already clear from the initial system analyses and the first electric motor tests. It has been found that the impact of HWP on harmonic frequencies is not solely due to HWP defects from manufacturing, but it also encompasses the influence of temperature and the stability of the optical and rotational axis of the system during rotation. HWPs defects to the second order can be described by equation 7 as [22]:

$$\alpha_{1,2}(\phi, T, r) = \alpha_{1,2}^{(0)}(T) + \alpha_{1,2}^{(1)}(r(t)) \cos(\phi(t)) + \alpha_{1,2}^{(2)} \cos(2\,\phi(t)) + \cdots \qquad (7)$$

According to equation 7 and as is shown in Figure 5, the 2nd harmonic is influenced by the wave plate temperature while the 1st, 3rd, and 4th are sensitive to the alignment of the wave plates and the stability of the optical rotation axis.

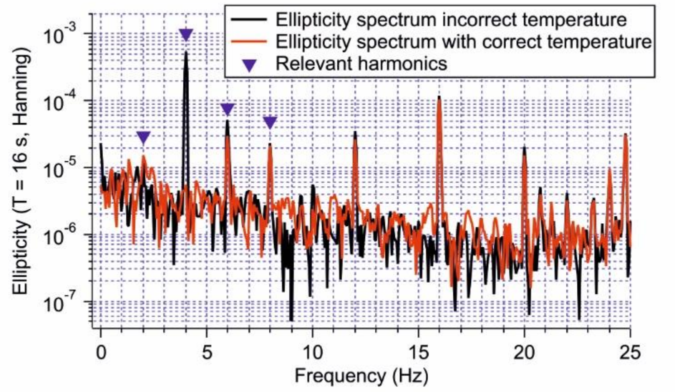


Figure 5: Temperature control of HWPs.

The tests showed that it is not possible to eliminate or control the required frequencies, especially the 4th harmonic frequency where the VMB signal should occur. This posed a serious problem for the final measurements to be done with the LHC magnet, and therefore, it was necessary to consider slow modulation of the magnetic field amplitude to separate the physical VMB signal from the HWP defect effects. Modulation at about 2 mHz is possible with the LHC magnet and has been proven to be the only viable solution.

C: Lock laser to the F.P. with the rotating HWPs Inside – *N*

To achieve stable cavity locking, it is necessary to satisfy the condition $N \cdot \alpha_{1,2} << 1$ with $N \approx 1000$. Otherwise, the phase shift in the resonator would be too large to allow the resonator to lock. The overall phase shift of the HWPs can be mainly influenced by temperature control $\alpha_{1,2}^{(0)}(T)$ and precise adjustment, as shown in Figure 5. These parameters were successfully achieved, and the resonator was locked stably within hours. The strong intensity modulation is due to dust on the wave plates. At this stage, the measurements were performed in the air, and no particular attention was taken to cleanliness.

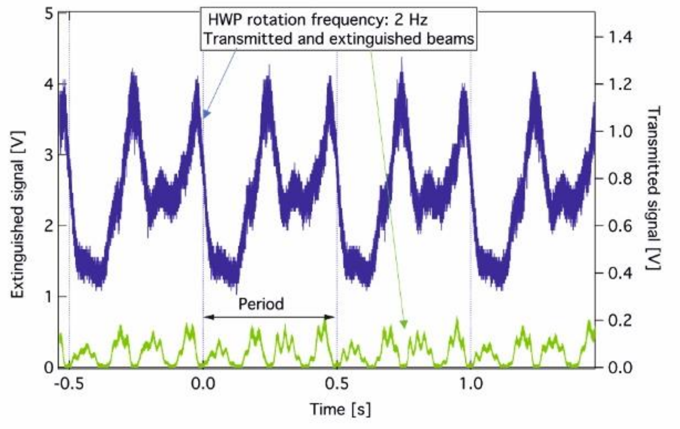


Figure 6: First cavity lock.

D: Reach required sensitivity for LHC test in a small lab - noise characterization at $4\upsilon_w$

In the final stage of testing, it is necessary to determine the level of sensitivity achievable with the system and whether a shot noise limit can be reached. Based on previous tests, it is evident that several parameters must be controlled simultaneously. These include the synchronous rotation to achieve minimum extinction coefficient, and temperature control of HWPs to minimize the 2nd harmonic to prevent resonator unlock. Alignment and stability of the rotation and laser axis with respect to HWPs have the main impact on the VMB signal at 4th harmonics. The following measurements were taken sequentially to reveal the main sources of noise. Sensitivity tests were performed with and without point stabilization, with and without HWPs, and tests with rotating HWPs. The results indicate that shot noise can be achieved by laser-pointing stabilization when the plates are not rotating. These measurements also demonstrate the relationship between the stability of the laser/rotation axis and the elliptical noise of the system. The ratio of the ellipticity to laser beam movement is approximately $10^{-6}/\mu m$. From this value, it can be estimated that the stability of $10^{-9}\ m/\sqrt{Hz}$ is needed to achieve the necessary sensitivity for VMB measurements in the LHC magnet, as shown in Figure 7.

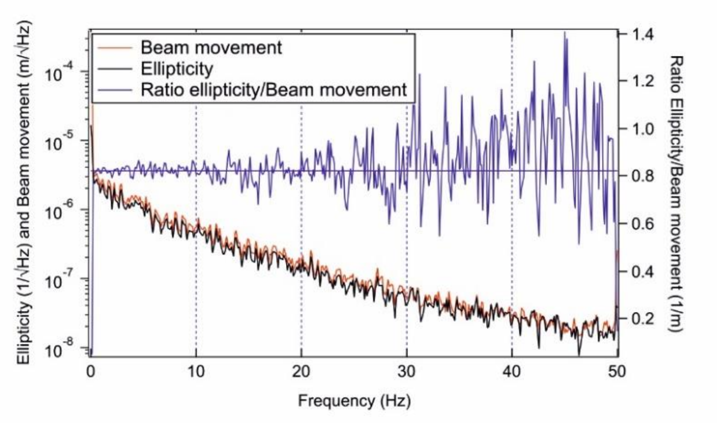


Figure 7: Ellipticity and beam movement measurements.

A test was also conducted without rotating the HWPs inside the resonator, and the shot noise limit was achieved due to the resonator's automatic stability. These tests suggest that the stability of the rotation axis associated with the movement of the HWP through the optical beam is the primary limiting factor in achieving the final sensitivity, as confirmed in Figure 8.

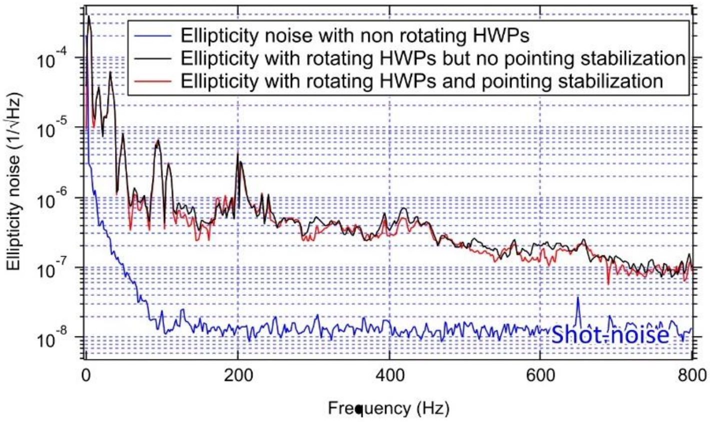


Figure 8: ellipticity noise vs rotation.

4. Conclusion

The tests confirmed that the proposed polarimetric scheme is fully working. It was possible to lock an optical resonator with two rotating half-wave plates (HWPs) inside for the first time. All measurements indicate that the main obstacle to achieving the required sensitivity in VMB@CERN is the instability of the HWP rotation axis. Therefore, it is currently not possible to measure the VMB in the LHC magnet at CERN. However, not all necessary tests have been completed yet, particularly the final test of the HWPs rotation and the locked resonator. Nevertheless, it is possible to improve control over the rotation axes and alignment in real-time by using a laser on the 2nd harmonic. Once the control systems are fully completed, the final testing is expected to take place in 2024. Another possibility is to discover a new method of rotating the polarization vector without the use of mechanical parts or optical elements. This would result in a better ratio of elliptic gradient to displacement. Additionally, the search for new materials and surfaces for the resonator mirrors is being considered, along with a return to the original measurement scheme of PVLAS.

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