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Proposal

Optical Search for QED vacuum magnetic birefringence, Axions and photon Regeneration (OSQAR)

Submitted to the CERN SPSC

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"Exploring a new territory with a precision instrument is the key to discovery"

S. Ting, Nobel Prize in Physics (1976)
MT19 Conference, Genova 2005

Abstract

Since its prediction in 1936 by Euler, Heisenberg [3] and Weisskopf [4] in the earlier development of the Quantum Electrodynamic (QED) theory, the Vacuum Magnetic Birefringence (VMB) is still a challenge for optical metrology techniques. According to QED [5], the vacuum behaves as an optically active medium in the presence of an external magnetic field. It can be experimentally probed with a linearly polarized laser beam [6]. After propagating through the vacuum submitted to a transverse magnetic field, the polarization of the laser beam will change to elliptical and the parameters of the polarization are directly related to fundamental constants such as the fine structure constant and the electron Compton wavelength. Contributions to the VMB could also arise from the existence of light scalar or pseudo-scalar particles like axions that couple to two photons and this would manifest itself as a sizeable deviation from the initial QED prediction [7]. On one side, the interest in axion search, providing an answer to the strong-CP problem lies beyond particle physics since such hypothetical neutral light spin-zero particle is considered as one of the good dark matter candidates, and the only non-supersymmetric one. The cosmological problems concerning dark matter and dark energy could then profit from results obtained from the purely laboratory experiment proposed in this document. On the other side, the domain of physics that will be investigated with this project is guaranteed by the QED vacuum polarization. The test of QED by measuring a predicted ellipticity of the order of 2×10^{-11} rad for a light beam propagating over ~ 25 km in a 9.5 T field constitutes the best test of a theory never achieved so far i.e. at the level of $\sim10^{-22}$ that corresponds to the absolute relative change of the vacuum refractive index.

To measure both magnetic birefringence and linear dichroism of the vacuum, the experimental approach must focus on two main requirements, a strong transverse magnetic field and an efficient tool for the optical metrology. This project focuses on the development of the required optical measurement technique for which a breakthrough is expected to be achieved with respect to the present state of the art. Today, optical techniques enable to reach a sensitivity for ellipticity measurement of the order of $\sim10^{-8}$ rad/(Hz)$^{1/2}$. With this project a limit value below $\sim10^{-10}$ rad/(Hz)$^{1/2}$ is aimed to be achieved. One of the key idea of the proposed detection scheme is based on a high frequency modulation of the polarization of the laser beam that will probe the vacuum under high transverse magnetic field, leading to the creation of two sidebands far enough from the optical carrier. Then, with a hyper selective optical filter centred on one of the two sidebands, the optical carrier can be strongly rejected and consequently the modulation depth of the signal to measure will be increased by the same ratio. The development of this rejection filter which does not affect the sideband containing the relevant information will be one of the innovative achievements of this project. Concerning the strong transverse magnetic field required to obtain measurable effects from the polarized vacuum, one of the ideal implementations for the experiment is within long superconducting accelerator dipolar magnets such as the ones developed and manufactured for the Large Hadron Collider (LHC) under construction at CERN. This possibility was already addressed in the feasibility study published in two parts [36] and a *Letter of Intent* [1] was submitted to the CERN-SPSC committee to propose a re-use of long LHC prototype magnets providing a magnetic field up to 9.5 T over 14.3 meters long as well as existing CERN infrastructure. The feasibility study and the technical proposal was also presented during five international conferences or workshops - the later one being hosted at the Institute for Advance Study at Princeton - and received each time a positive feedback from the scientific community.

In addition to fundamental scientific interests, laser measurement techniques developed for this project will impact on optical metrology techniques and a patent is aimed to be registered. Various scientific domains could profit from this development such as the precise characterisation of field strength, field angle and transfer function of magnets in general, and in particular those dedicated to future accelerator projects [32]. The characterisation of plasmas that will be produced by ITER or the W7-X stellator could also profit from the novel optical metrology techniques developed for this project. Let us also notice that with this technique, coupled to pigtailed electro-optic or magneto-optic probes, a wide field of applications can be considered.

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1 Introduction

In this technical proposal, which constitutes formally the follow-up of the Letter of Intent submitted to the CERN SPSC in October 2005 [1], two new generation of purely laboratory experiments for axion search will be presented. They are foreseen to provide complementary results to CAST [2] and other similar experiments. Whereas CAST probes axions supposed to escape from the sun before to be converted to photons in a high transverse magnetic field via the so-called Primakoff effect, *i.e.* $A + \gamma_{virtual} \rightarrow \gamma$, both proposed experiments are expected to produce axions from linearly polarized laser beams propagating in the transverse magnetic field. They can be viewed roughly as being of fixed target type, with low energy polarized photon beams colliding with virtual photons provided by the magnetic field *i.e.* $\gamma + \gamma_{virtual} \rightarrow A$. With this respect, purely laboratory experiments for axion search are in the same continuity line that brought particle physics from cosmic rays to accelerator based experiments. In addition, this proposal is not only focused on the axion search but offers also a broad band of scientific interests starting from a precise new test of the QED up to the search of any scalar, pseudo-scalar or other particles, like paraphotons or milli-charged particles, that can couple to photons.

This technical proposal is divided in three main parts. In the first one, the significance of the proposed experiments will be highlighted starting from the theoretical point of view, then with respect to past and existing purely laboratory experiments probing the quantum vacuum and finally from the point of view of potential applications of the optical techniques which aimed be developed. A special focus will be given to the recent PVLAS results and possible interpretations. The second part will be devoted to the experimental methods addressing the challenge of optical techniques. By pushing the optical detection techniques up to the present state of the art during the phase-1 and beyond in the phase-2, a significant enlarged domain of axion mass and axion di-photon coupling constant not yet explored with laser based experiments is expected to be probed with photons typically in the energy range 1-3 eV. The expected sensitivity for both experiments in their phase-1 and phase-2 will be given as well as a preliminary analysis of the random and systematic errors and their control. In the third part, the proposed plan as well as a preliminary cost estimate and schedule will be given. The re-use of the maximum of development made at CERN for the LHC and the cold tests of the superconducting magnets is considered as a baseline before driving new developments. In particular, it should be emphasized that LHC main superconducting dipoles, among them the five full scale prototypes of the last generation which were decommissioned, constitute at present the state-of-the-art in magnet technology for such type of experiments.

2 Significance of the Proposed Experiments

2.1 From Theory

2.1.1 Overview

Since its prediction in 1936 by Euler and Heisenberg [3] and independently by Weisskopf [4] in the early development of the Quantum Electrodynamic (QED) theory, the Vacuum Magnetic Birefringence (VMB) is still a challenge for optical metrology techniques. According to the QED theory [5], the vacuum behaves as an optically active medium in the presence of an external magnetic field. It can be experimentally studied by using as a probe, a linearly polarized laser light beam [6]. After propagating through the vacuum submitted to a transverse magnetic field, the polarization of the laser beam will change to elliptical with polarization state parameters directly related to fundamental constants such as the fine structure constant and electron Compton wavelength.

Contributions to the Magneto-Optical Properties of the Vacuum, i.e. birefringence and linear dichroism, could also arise from the existence of light scalar or pseudo-scalar particles like axions that couple to two photons and this would manifest itself as a sizeable deviation from the pure QED prediction [7].

More recently, it was proposed that the study of the Magneto-Optical Properties of the Vacuum can give competitive constraints on milli-charged fermions, most notably in comparison to other laboratory searches [8], and this could constitute a way for "illuminating the hidden sector of string theory by shining light through a magnetic field" [9]. Milli-charged particles also arise naturally in so-called paraphoton models from some small mixing angle between the kinetic terms of photons and paraphotons [10].

2.1.2 Magneto-Optical Properties of the Vacuum in QED

i) One Loop contribution

The pioneering works of Euler, Heisenberg [3], and Weisskopf [4] have shown that the classical electromagnetic theory must be corrected by nonlinear terms due to the probability of electron-positron pair creation i.e. the vacuum polarization effects. This is generally expressed by corrective terms in the classical expression of the Lagrangian density $L^{(0)}$ of the vacuum submitted to an electrical field $\boldsymbol{E}$ and a magnetic field $\boldsymbol{B}$. Omitting terms of the order of α^3 which will be introduced in the next paragraph, the Euler-Heisenberg-Weisskopf (EHW) effective Lagrangian density can be written as:

$$L_{eff}^{EHW} = L^{(0)} + L_{eff}^{(1)} = \frac{1}{2}(E^2 - B^2) + \frac{2\alpha^2}{45\, m_e^4}\left[(E^2 - B^2)^2 + 7(E\cdot B)^2\right] \qquad (2.1)$$

where the natural Heaviside-Lorentz units are used with $\hbar = c = \mu_0 = \varepsilon_0 = 1$ and the fine structure constant $\alpha = e^2/4\pi \approx 1/137$, and m_e is the electron mass. The expression (2.1) can be considered as the first terms of a development in power series of the only two Lorentz- and gauge-invariant combinations of second order in the fields containing no derivatives. It is valid in the limit $E, B << m_e^2/e$, for a photon frequency $\omega << m_e$ and corresponds to the one loop contribution of the light-by-light scattering (Fig.1). For the case which is considered here, it can be shown that the EHW terms are much more important than the corrections that involve field derivatives [11].

From the derivatives of the EHW effective Lagrangian density with respect to $\boldsymbol{E}$ and $\boldsymbol{B}$, the components of the electric and magnetic relative permeability tensors of the vacuum can be deduced:

$$\begin{aligned}\varepsilon_{ij} &\approx \delta_{ij} + \frac{4\alpha^2}{45\, m_e^4}\left[2(E^2 - B^2)\delta_{ij} + 7(B_i B_j)\right]\\ \mu_{ij} &\approx \delta_{ij} + \frac{4\alpha^2}{45\, m_e^4}\left[2(B^2 - E^2)\delta_{ij} + 7(E_i E_j)\right]\end{aligned} \qquad (2.2)$$

In the following, the restriction to the special case of the vacuum perturbed by a magnetic field and a linearly polarized light probe is considered. In that case, the first order correction to the velocity of the light can be expressed as [12]:

$$v/c \approx 1 - a\ B^2 \sin^2\theta_B\, (\alpha^2 / 45\, m_e^4) \qquad (2.3)$$

where θ_B is the angle between the direction of the photon propagation and the ***B*** field and a is a constant equal either to 8 or 14 for photons polarized perpendicular and parallel to ***B,*** respectively. The quantum vacuum behaves as a birefringent medium when submitted to a magnetic field. This type of induced birefringence has been known in material optical science since 1905 as the Cotton-Mouton effect [13]. When the light beam propagates perpendicularly to the magnetic field, the refractive index difference between light polarized parallel and perpendicular to ***B*** is given by:

$$\Delta n = (n_{//} - n_{\perp}) \approx (6\,\alpha^2 / 45\, m_e^4)\, B^2 \tag{2.4}$$

and for example corresponds to a value $\Delta n \approx 3.6 \times 10^{-22}$ in a 9.5 T field, which is indeed really challenging to measure. A possibility to observe the photon-photon interaction due to the QED vacuum is to measure the ellipticity ψ_{QED} acquired by a laser light beam, initially linearly polarized, after its passage through the vacuum submitted to a transverse magnetic field [6]. This ellipticity is equal to:

$$\psi_{QED} = \pi\, \Delta n\, (L/\lambda) \sin 2\theta \tag{2.5}$$

where L is the length of the optical path in the magnetic field region, λ is the light wavelength and θ is the angle between the light electrical vector and the applied field ***B***. An important point is that the ellipticity is cumulative upon reflection so the effect can be accumulated by making the light travel back and forth in the magnetic field region of length l i.e. $L = N\, l$. To fix the ideas, the maximum of ellipticity acquired by a laser light beam with $\lambda \approx 1.55\, \mu m$ propagating in a 9.5 T field over a length $N\, l$ = 25 km is equal to ~ $2\text{x}10^{-11}$ rad, i.e. at the limit of what can be measured at present. It should be emphasized that the ellipticity (2.5) is a function of the experimental environment whereas the relevant physical characteristic which can be deduced from this experiment is the difference in the refraction index Δn produced by the magnetic field.

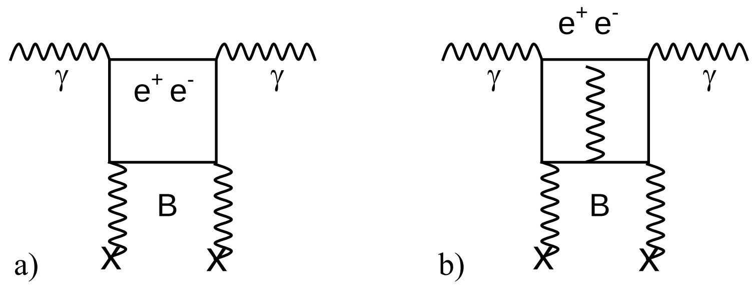


Fig. 1 : *Feynman diagrams for light-by-light scattering producing the magnetic birefringence of the vacuum due to the photon dispersion; a) the dominant term and b) one of the second order diagrams with radiative correction.*

ii) Two Loop contribution

The first and one of the second order Feynman diagrams for the light-by-light scattering are given in Fig.1. The effect of the dominant term on the polarization of light traveling in vacuum in a transverse magnetic field was presented in the previous paragraph and here the effect of the second order diagram with radiative correction is briefly introduced. The two loop effective Lagrangian proportional to α^3 was derived by Ritus [14] and the result can be written in a similar form as the dominant first order one (2.1) but with different coefficients:

$$L_{eff}^{(2)} = \frac{\alpha^3}{\pi\, m_e^4}\left[\frac{16}{81}(E^2 - B^2)^2 + \frac{263}{162}(E \cdot B)^2\right] \qquad (2.6)$$

This term (2.6) produces a second-order QED correction to Δn with the same field dependence, which is predicted to be 1.45 % of the dominant term (2.4) [14]. Such an effect is also targeted to be measured with one of the proposed experiments after its upgrade phase.

The so-called g-2 experiments on electrons represent at present the most stringent test of QED at the level of $\sim 10^{-12}$ and require high-precision calculations involving for example 891 eight-order Feynman diagrams [15]. In comparison, the change of the refraction index of the vacuum in presence of magnetic field i.e. "the magnetic *n-1* vacuum anomaly", require much less calculations to probe QED down to the 10^{-22} level and this constitutes a well motivated challenge for experimentalists. Any additional contribution to the vacuum anomaly would be extremely significant indicating new physics or problems with QED theory and/or general symmetry principle like Lorentz or CPT invariance.

2.1.3 Physics beyond the Standard Model

i) Photon mixing with light scalar or pseudo-scalar particles

The EHW effective Lagrangian density can be further extended to include contributions of hypothetical neutral light spin zero particles that couple to two photons such as axions [7]. In this case, the initially linearly polarized light beam with an angle θ with respect to B is expected to acquire a linear dichroism characterised by a small apparent rotation Θ and a small ellipticity Ψ due respectively to the absorption and dispersion processes induced by the production of spinless particles. Both effects can be expressed in natural Heaviside-Lorentz units where 1 T = 195 (eV)^2 and 1 m = 5 *x* 10^6 eV^{-1} by:

$$\Theta \approx N \frac{B^2 l^2}{16\, M^2} \sin 2\theta \qquad (2.7)$$

$$\Psi \approx N \frac{B^2 l^3 m^2}{96\, \omega\, M^2} \sin 2\theta \qquad (2.8)$$

where M is the inverse coupling constant to two photons, m is the hypothetical particle mass, N the number of passes in the cavity, l the length of the magnetic field region and ω is the photon energy. The polarization state of the output light beam, characterised by (2.7) and (2.8) in the limit $m_A^2\, l\, /4\omega << 1$, would manifest itself as a sizeable deviation from the pure QED prediction [7] for which no measurable linear dichroism is expected. Photon splitting effect can produce a differential absorption [12] giving rise to an apparent angular rotation of the polarization of the order of $\sim 10^{-34}$ rad in a 9.5 T magnetic field over a length of 25 km, an angular rotation that is far from being measurable in laboratory conditions, except if the coupling with scalar/pseudo-scalar particles enhances significantly this effect [16].

Another experimental approach to probe the coupling of photons with scalar or pseudo-scalar particles is to perform the so-called photon regeneration experiment [17] which is of double oscillation type. A linearly polarized laser light beam propagating in a transverse magnetic field is sent through an optical absorber. When the polarization of the light is parallel to the magnetic field, photons of energy ω are expected to be converted to axions due to the mixing effect with a maximum of probability $P_{\gamma \rightarrow A}$. Such weakly interacting particles can then propagate freely through the absorber before being regenerated in the magnetic field sitting in the other side of the absorber. The expected counting rate (CR) of the detector due to the photon regeneration is:

$$CR = \eta\, N\, (P_{\gamma \to A})^2\, P_L / 2\omega \tag{2.9}$$

where $P_{\gamma \to A} = P_{A \to \gamma}$, η is the efficiency of the photon detector and P_L the optical power of the laser. In the limit of coherent oscillation with $m_A^2\, l / 4\omega << 1$, the conversion probability $P_{\gamma \to A}$ is given by [18]:

$$P_{\gamma \to A} \approx B^2 l^2 / 4 M^2 \tag{2.10}$$

It can be added that by rotating the polarization of the laser light beam by 90º i.e. to be orthogonal to the magnetic field direction, the experimental condition is optimised for the search of light scalar particles.

Whereas the precision measurements of the magneto-optical properties of the vacuum can probe the photon absorption to produce axions or axion-like particles (Fig.2a), the photon regeneration experiment is expected to detect directly the photon to axion followed by the axion to photon conversions (Fig.2b). In both cases, the requirement of coherence between the photon and axion fields introduces a limit on the mass of the axions which can be produced.

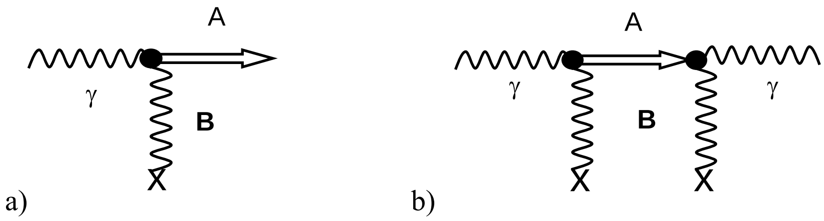


Fig. 2 : *Feynman diagrams for a) axion production and b) axion exchange.*

The axions are the consequence of the absence of CP violation in QCD (Quantum Chromodynamics) and was predicted independently by S. Weinberg [19] and F. Wilczek [20] from the breaking of the Peccei and Quinn symmetry [21]. The interest in such hypothetical neutral light spin-zero particles lies beyond particle physics since they are considered now as good dark matter candidates [22] and the only non/supersymmetric ones. The development of a pure laboratory experiment for the production and the detection of possible dark matter candidate offers the opportunity to perform a experimental study fully independent of astrophysical and cosmological assumptions.

ii) Photon mixing with paraphotons

The photon regeneration experiment can be performed without magnetic field to search for possible mixing of photons with paraphotons. According to the model of L.B. Okun [10], oscillation could occur between the non-interacting massive photon or paraphoton (γ_p) and the massless interacting one with the probability:

$$P_{\gamma \to p} \approx l^2 m_p^4 \sin\phi / 16\, \omega^2 \tag{2.11}$$

where ϕ is the mixing angle and m_p the paraphoton mass.

iii) Photon coupling with millicharge particles

Recently the interest in precision measurements of the magneto-optical properties of the vacuum was extended to the case of the coupling of photons with milli-charged particles that are predicted from possible extensions of the standard model [8], [9]. Photon can initiate pair production of milli-charged fermions in an external magnetic field and this would manifest itself as a vacuum magnetic dichroism whereas the dispersion effect would provide, like in QED, a magnetic birefringence. In the sub-eV energy range the limits already inferred from the pioneering BFRT experiment (Brookhaven, Fermilab, Rochester, Trieste) [23] are more than two orders of magnitude better than the ones obtained by other purely laboratory experiments.

2.2 From Past and Existing Experiments

2.2.1 An overview

The idea to probe the QED vacuum polarization using a laser beam propagating in a transverse magnetic field was first proposed at CERN by I. Iacopini and E. Zavattini [6]. Later, L. Maiani, R. Petronzio, and E. Zavattini [7] proposed to extend the interest of such type of experimental approach to investigate the possible coupling to photons of any scalar or pseudo-scalar particles.

The present reference results concerning the magneto-optical properties of the vacuum and the photon regeneration experiment were obtained by the BFRT collaboration [23]. An overview concerning the limits of axion mass and di-photon coupling constant can be found in [24] and on the summary plot describing excluded regions (Fig.3). These limits on axion parameters obtained by various experiments must be interpreted with prudence as the results are not based on the same "degree of confidence". For example, it should be emphasized that laser-based experiments are the only ones that give limits independent of solar model, astrophysical and cosmological assumptions.

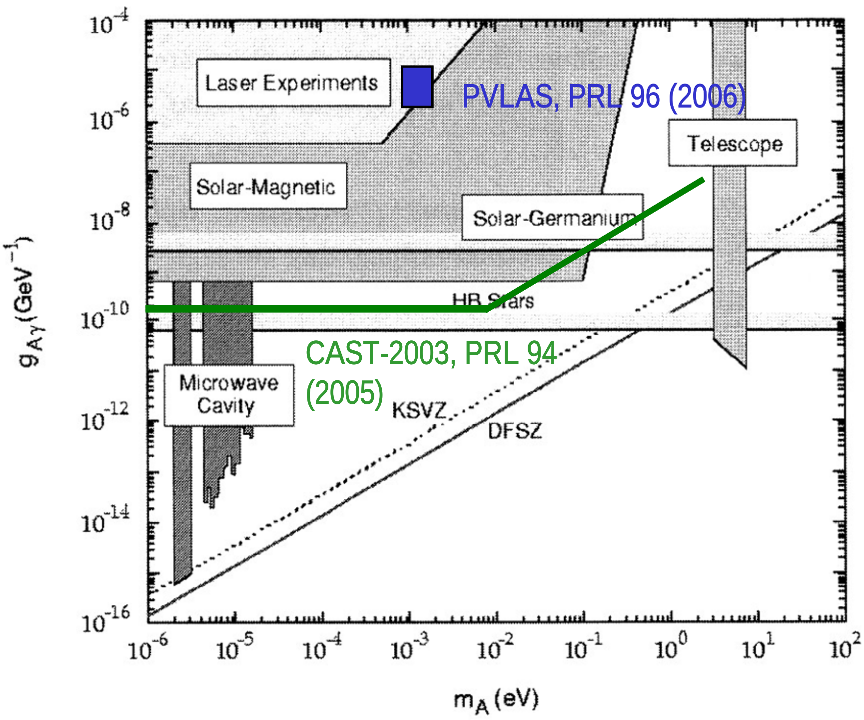


Fig. 3: *Limits of axion mass and di-photon coupling constant from various axion search experiments extracted from [24]. The recent results of PVLAS and CAST collaborations are also added.*

2.2.2 PVLAS Results

Recent results published by the PVLAS collaboration [25] shown in Fig.3, provide additional motivation for a purely laboratory axion search experiment. The apparent rotation of the polarization generated by a magnetic field and measured by PVLAS on a laser beam propagating in the vacuum is not necessarily inconsistent with the negative result reported by the CAST collaboration [2]. Two scenarios were initially proposed for a coherent interpretation of both experimental results by evading the astrophysical bounds [26]. In a first one, a trapping mechanism involving paraphotons is discussed but seems at present not consistent with a transparent universe at low temperature i.e. below 1 eV. In the second scenario, the possibility of a suppression of the Primakoff process for axion production is developed. The later scenario, if it is confirmed, will modify significantly the present exclusion region diagram for axion mass versus axion photon coupling constant related to various types of experiments (Fig.3). It has already provided a strong revival of interest for purely laboratory axion search by means of optical techniques [27]. At present it is clear that the results of PVLAS cannot be interpreted with standard axion models and the terms of Axion-Like-Particules (ALP) was introduced to enlarge “l’horizon des possibles”. New theoretical possibilities were considered recently in two additional models aiming to reconcile PVLAS and CAST results [28], [29] but this appears as a challenge for the theory.

More recently, several interpretations were suggested to interpret PVLAS results without considering axions or ALPs. There is for example, a possibility of coupling of photons with milli-charged fermions [8] as already mentioned in the paragraph 2.1.3. It was also shown, within the context of the first QED correction, expressed by the Euler-Heisenberg-Weisskopf Lagrangian, that the effect of the slowly rotating strong magnetic field could explain PVLAS results without the need of a low mass intermediate particle such as axion [30]. However this last result seems to be based on ad hoc hypotheses and the birefringence and linear dichroism are predicted to be one order of magnitude larger than PVLAS results. If this result is correct and assuming that a rotating magnetic field produces the same effect as a rotating polarization in a fix magnetic field orientation, the BFRT collaboration should also have seen such an effect…

From the pure experimental point of view, it cannot not be excluded that “unknown, albeit very subtle, instrumental artefacts” can explain the PVLAS results. For example, it is suggested in a comment [31], to check whether a tiny fringe field component of the rotating magnetic field is present at the level of the mirror(s) of the Fabry-Pérot cavity and can produce a magneto-optical Kerr effect, which may be at the origin of the observed rotation of the polarization of the light.

2.3 The spin off from the development of novel optical methods for magnetic and electrical field measurements

The experimental methods and more precisely the modulation and the filtering techniques which are proposed in the next paragraph to measure the fine magneto-optical properties of the vacuum in transverse magnetic field can be adapted to any electric or magnetic field measurements. For electric fields, the optical detection system can be coupled with a Pockels cell whereas for magnetic fields a precise magnetometer can be obtained using magneto-optical sensors.

The Cotton-Mouton effect observed in gases and liquids can also offer several possibilities to characterize for example superconducting accelerator magnets, i.e. magnets with transversal field orientation. As this was already addressed [32], the detection scheme proposed in Fig.6, with only one reflecting mirror instead of a Fabry-Pérot cavity, can be used to measure the magnetic axis of quadrupoles, the magnetic field angle of dipole magnet or the integrated transfer functions of dipoles and quadrupoles. For the determination of the magnetic axis of quadrupoles, a simultaneous transversal motion of the reflecting mirror and of the laser beam is required to find the minimum of the signal received by the photodiodes. Concerning the measurement of the integrated transfer functions, an axial displacement of the reflecting mirror and a precise position control is needed to determine the field strength. This can be achieved using a laser tracker system such as the one provided by Leica™. For field angle measurements, a Cotton-Mouton cell and magnet system providing a reference field angle are required. Only relative small development effort seems to be needed to put in practice the Cotton-Mouton effect to characterize accelerator magnets. This new measurement method using a “light-wire” in a gas or a liquid is very promising and seems particularly suitable for pulsed magnets as well as for magnets with small apertures.

It can be added that the measurement principle shown in Fig.6 is also suitable for the Faraday effect when the magnetic field is parallel to the laser light beam. Therefore in principle, the three components of magnetic fields can be measured and such a possibility could also be very useful in plasma physics for example, for which the magneto-optical diagnostic is of major interest as it can provide a robust measurement of the line integrated current density. This characterization of plasma is of special importance for long pulse operation expected in future machines such as ITER or the W7-X stellator developed to study the nuclear fusion [33].

3 Proposed Experimental Methods

3.1 The Magnet System

A detailed presentation of the LHC main dipoles can be found in [34] and the two dimensional cross-section is shown in Fig.4. The two most important magnet characteristics for this proposal are the maximum operating field[1] and the magnetic length which are equal to 9.5 T and 14312 mm respectively. The figure of merits of the magnet system for this proposal can be defined from formulas (2.5), (2.7) and (2.8). Relevant values are reported in Table 1 for a LHC dipole, the BFRT and PVLAS superconducting magnets. The LHC dipole has figure of merits between 9 and 24 times larger than the ones of the BFRT collaboration. The PVLAS experiment compensates the low performance of its magnet by using a powerful optical cavity with finesse in the range 10^4-10^5. It should be emphasized that the overall figure of merits of the experiment should also take into account additional gains obtained by the detection principle and the optimization of the signal over noise ratio. These points are addressed in the paragraph 3.2.

	B_{max} (T)	$B_{max}^2\,l$ (T m)	$B_{max}^2\,l^2$ (T^2 m^2)	$B_{max}^2\,l^3$ (T^2 m^3)
BFRT	4	140	1240	10 900
PVLAS	6	36	36	36
A single LHC dipole	9.5	1290	18 460	263 910

Table 1: *Comparison of the figure of merits of the magnet system for BFRT, PVLAS and this proposal.*

To control the field quality and to measure the transfer function of LHC superconducting dipoles, field measurements were performed with rotating coils [34] kept at room temperature by sliding warm fingers inside the apertures called anticryostats [35]. They have a 40 mm aperture and a length of 19.6 m to go through the Cryogenic Feed Box (CFB) and have been used opened at both ends or closed and pumped down. In order to operate the optical cavity at room temperature, the anticryosats will be used as a part of the vacuum chamber with end-caps at both extremities. The mirrors of the cavity will be integrated inside end-caps well outside the magnetic field to avoid spurious effects. The tuning of the orientation of the mirrors will be done using piezoelectric actuators. First prototypes for end caps and support of the mirrors were

[1] The limit of the superconducting cables at 1.9 K allows to reach a maximum field of 9.75 T.

already produced and are shown in Annex 1. A general layout of a superconducting dipole on a test bench connected to its CFB and fitted with anticryostats is shown in Fig.5.

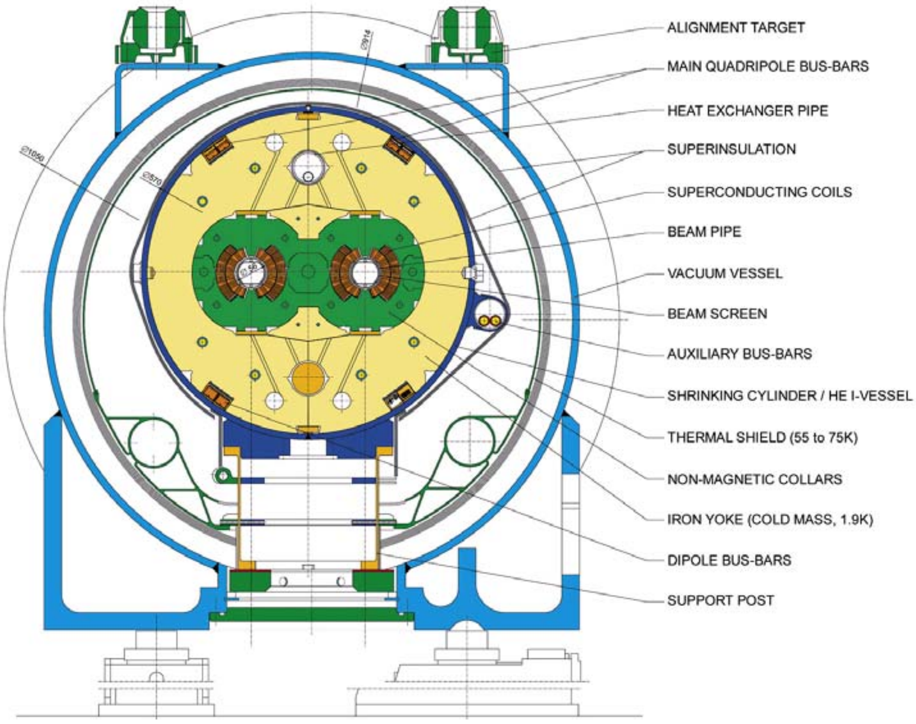


Fig. 4: *Cross-section of a LHC superconducting main dipole magnet housed inside its cryostat.*

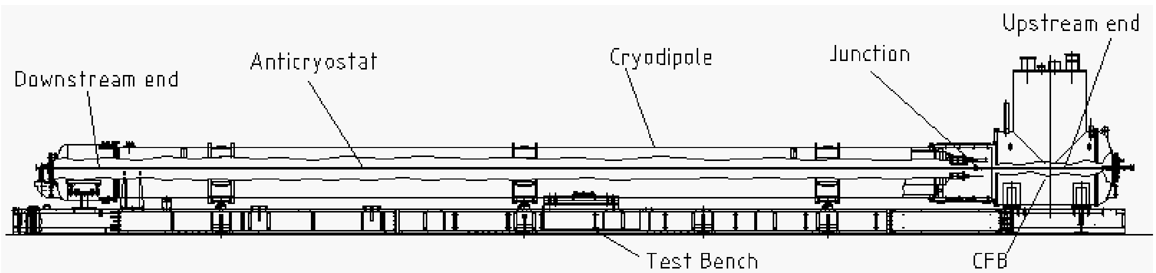


Fig. 5: *Layout of a cold test bench for dipole magnets equipped with anticryostats and connected to its Cryogenic Feed Box (CFB). The overall length is equal to 19.6 m.*

3.2 The "*n-1* experiment" to probe the Magneto-Optical Properties of the Quantum Vacuum

3.2.1 Measurement Principles

i) Phase-1

To measure the VMB and absorption anisotropy expressed by (2.5), (2.7) and (2.8) respectively, the experimental approach must focus on two main requirements already addressed in the feasibility study [36]. First, the ellipticity and the apparent rotation of the polarization acquired by the initially linearly polarized laser beam, propagating through the vacuum submitted to a transverse *B* field must be amplified with an optical cavity. Second, the optical detection technique should reduce the noise down to a "manageable" signal over noise ratio. One of the most important drawbacks of the amplification of the light path in the magnetic field within a cavity concerns the systematic errors introduced. Any birefringence of the mirrors of the cavity will also be amplified. Such point is one of the most important ones. It will be treated in the special paragraph 3.2.3 devoted to the control of the systematic errors and will required a modulation of the magnetic field. It can be also added that to cope mostly with possible systematic effects amplified by the optical cavity affecting birefringence and linear dichroism measurements, the cavity finesse considered in the following was limited in the range 10^3-10^4.

The first version of the optical configuration proposed to measure very small optical birefringence is sketched in Fig.6. This version does not contain neither the Fabry-Pérot (FP) filtering cavity nor post optical amplification that will be implemented in the phase-2. It is based on a novel measurement method using a double path of light through a specific electro-optic modulator used to produced a very high speed rotation (up to several MHz) of the plane of polarization of the outcoming linearly polarized laser beam. After the second pass through the electro-optic (EO) modulator, the laser beam will retrieve, to the first order, its linear polarization state with the small VMB rotation angle induced by the vacuum submitted to the transverse B field inside the optical cavity. Several improvements in the optical diagram given in Fig.6 were added with respect to the previous version published in [1], [36]. In particular to be able to measure simultaneously the birefringence and the linear dichroism of the vacuum, a λ/4 wave plate was added after the rotating λ/2 wave plate.

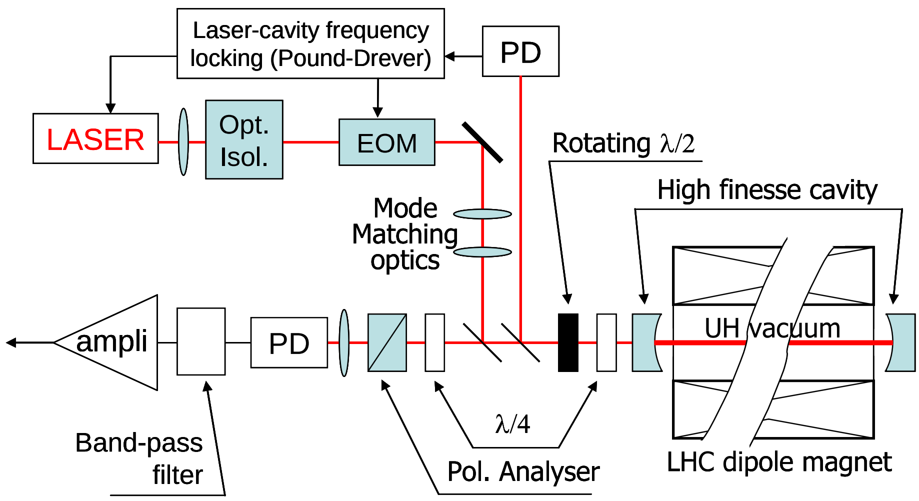


Fig. 6: *Proposed optical scheme for the measurements of the vacuum magnetic birefringence and linear dichroism.*

The modelling with the Jones' matrices formalism introduced in Annex 2, was cross-checked with numerical calculations. Assuming perfect optical elements, the result obtained gives to the 1st order, an output optical power modulated at 4ω, ω being the angular modulation frequency of the incoming linear polarization. The normalised optical power can be written as:

$$\tilde{P}_{opt} \approx 1 + \Psi \sin(4\omega t + \phi) + \Theta \cos(4\omega t + \phi) \qquad (3.1)$$

where Ψ is the birefringence, Θ the apparent rotation or linear dichroism, and ϕ the phase of the 4ω component mostly related to the disorientation of the magnetic field with the analyzer. The details of the calculations when the hypothesis of perfect optical elements is relaxed, is given in Annex 2. A Wollaston prism, with a 45° orientation of its dielectric axes with respect to the orientation of the incoming linear polarization of the laser beam, will separate the laser beam into two perfectly balanced secondary beams in absence of birefringence and linear dichroism. The ultra small birefringence and linear dichroism induced by the vacuum will produced a high frequency, ultra small unbalanced optical power received by the two photodiodes. The difference of the signals delivered by these photodiodes will lead to the power modulation of the laser beam that is directly related to the magneto-optic properties of the vacuum. Moreover, such a differential detection will drastically reduce, by a few orders of magnitude, the laser relative intensity noise (RIN) contribution to the limitation of the signal-to-noise-ratio of the experiment.

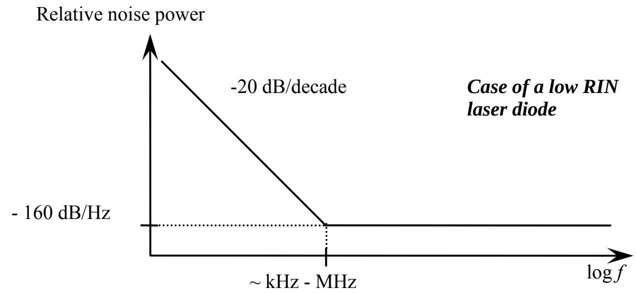
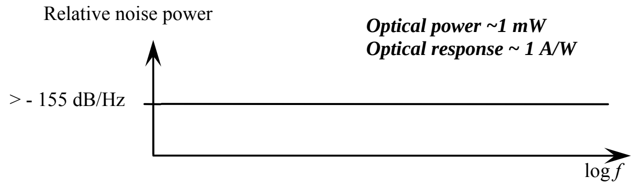
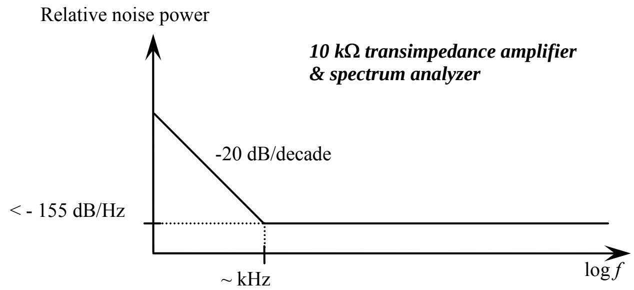
Noise source	Principal characteristics
Laser RIN	
Photodiode shot noise	
Electronic unit noise	
Acoustic vibrations	Especially detrimental below ~ kHz
Temperature fluctuations	Especially detrimental below ~ Hz
Intrinsic noise	From active optical elements if any.
Fluctuations of laser polarization state	Of first importance only if the measurement of the vacuum magnetic birefringence is based on the magnetic field induced variation of the laser polarization. Possible suppression by use of high-grade polarizer(s) with the drawback of converting polarization fluctuations into intensity fluctuations.

Table 2: *Overview of the various sources of noise impacting the measurements of the magneto-optical properties of the vacuum.*

A summary of the main results obtained in [36] concerning the analysis of the noise and the expected sensitivity is now given. Table 2 shows the different noise sources that contribute to the limitations of the experimental sensitivity for the measurement of extremely small birefringence. The three main sources of noise affecting measurements are:

- the RIN of the laser,
- the shot-noise of the photodiode, and
- the Johnson noise of the effective load resistance of the photodiode.

By summing all these contributions, the following expression for the total relative noise power can be obtained:

$$\tilde{P}_{noise} \equiv \frac{P_{noise}}{P} = \left(RIN + \frac{2e}{i_{ph}} + \frac{4kT_{eff}}{R_L \, i_{ph}^{\;2}} \right) \Delta f \qquad (3.2)$$

where k is the Boltzmann constant, i_{ph} is the photodiode average current, R_L represents the load resistance of the photodiode and $T_{eff} > T_{amb}$ and Δf are the effective temperature and bandwidth of the detection system respectively. Table 1 has been built using typical maximum ratings of photodiode characteristics and the best laser diode in terms of RIN. Above a few kHz, Table 2 shows that the relative noise power coming from the three main noise sources are very close, even if the shot noise gives the main contribution. Above a few kHz, the relative noise power coming from the three main noise sources are very close, even if the shot noise gives the main contribution. For an acquisition time of a few seconds ($\Delta f \sim 1$ Hz), the relative variation of the electrical power delivered by the photodiode should be at least -150 dB to distinguish the effect of the VMB from the noise. This implies a modulation depth of at least $3\text{x}10^{-8}$ for the photodiode current i_{ph}, i.e. a minimal ellipticity Ψ of the same order of magnitude. ψ_{QED} given in (2.5) is achievable considering $\Delta f \sim 1$ mHz (acquisition time of a few tens of minutes) and a finesse $F \sim 1000$ for the optical cavity, these two values being realistic. One order of magnitude can be probably gained via a simultaneous increase by a factor of 10 of the acquisition time (to reach a few hours) and of the optical power impinging on the photodiode (few 10 mW). However, long acquisition time brings a lot of drawbacks due to long term drifts of electronics and temperature and the increase of the finesse of the cavity is an alternative solution to consider but with a control of systematic errors introduced by the magneto-optical properties of the mirrors of the cavity (see paragraph 3.2.2).

ii) Phase-2 and beyond

To gain several additional orders of magnitude in the measurement sensitivity necessary to study the VMB down to the level of the second order QED prediction, a breakthrough should be achieved to overcome the shot noise limit. The shot noise constitutes a strong limitation because the VMB and the linear dichroism induce an exceedingly slight modulation of the optical power. Thus, the suppression of the constant part of the optical power should improve the situation. In electronics for example, a direct current can be suppressed by inserting a capacitance in the circuit. Based on this analogy, a novel optical detection scheme is under development. It consists in the transposition of the modulated laser beam to a frequency far away from the optical carrier frequency. With optical filtering, the constant part of the optical power (i.e. the optical carrier) would be strongly suppressed and this will dramatically increase the modulation depth of the laser beam impinging on the photodiode. Moreover, a post-amplification using an optical amplifier will permit to retrieve the optical power prior to the filtering. However, the sensitivity gain obtained by this technique will be slightly reduced due to the noise factor of the optical amplifier. Nevertheless, considering a 100-factor rejection of the optical carrier, a gain in sensitivity of the order of 50 could be achieved using a low noise optical amplifier. Coupled to the use of a cooled photodiode and 1^{st} electronic amplification stage, a gain of at least two orders of magnitude is expected, all the other parameters (F, Δf) being unchanged.

iii) Summary

A new optical detection method was proposed and optimised to measure for the first time the Vacuum Magnetic Birefringence predicted by the QED using a LHC superconducting dipole. During the phase-1 of this experiment, the sensitivity for ellipticity and linear dichroism measurements will reach the present state-of-the-art ~10^{-8} rad/$(\mathrm{Hz})^{1/2}$ whereas in the phase-2 an improvement by at least 2 order of magnitude is expected.

The working principle of the "*n-1* experiment" was proved with preliminary measurements of the Cotton-Mouton effect of air in a LHC superconducting dipole magnet [32] using a half-wave plate mounting on a moderate speed rotation stage instead of the EO modulator. The optical bench and the measurement results are presented in the next paragraph.

3.2.2 Results of preliminary measurements of the Cotton-Mouton effect of air as a first proof of principle

i) Measurements of the Cotton-Mouton Effect of air

To validate the concept of modulation of the polarization for birefringence measurement based on a double optical path in a λ/2 rotating wave plate, preliminary measurement of the Cotton-Mouton effect of air was performed inside one aperture of a LHC superconducting dipole without using an optical cavity.

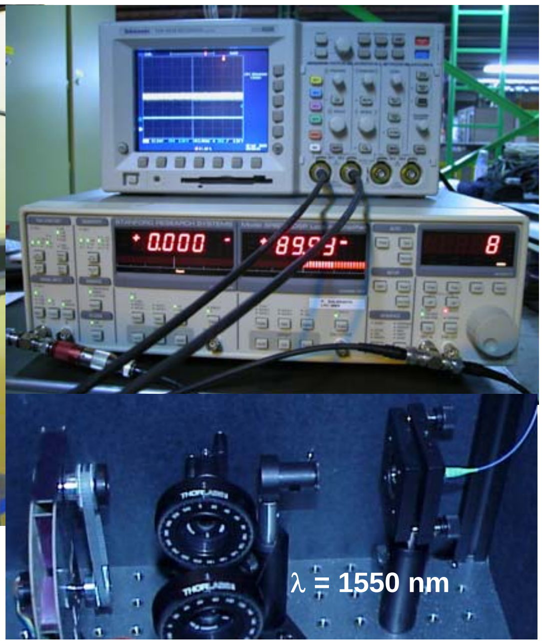


Fig.7: *Optical bunch and lock-in detection used to measure the Cotton-Mouton effect of air in a LHC superconducting dipole. For the double paths of the laser beam inside the magnet aperture, a mirror was positioned outside at one of the magnet extremities.*

The optical bench used is shown in Fig.5. The λ/2 wave plate was rotated by a small electrical motor via a belt. Obviously this rotating system is not optimized but it was sufficient to give a first proof of principle concerning the modulation and detection of the signal foreseen. The birefringence of air was measured at low modulation frequencies (80 and 46 Hz) as a function of the magnetic field amplitude and the Cotton-Mouton constant of air was deduced knowing the magnetic length of the dipolar magnet equal to 14312 mm. The value deduced for air at the pressure of 1 atm and at T = 300 K is equal to $1.12 \pm 0.02\ 10^{-6}$ rad T^{-2} m^{-1}. It is in good agreement with the result of 1.13 10^{-6} rad T^{-2} m^{-1} obtained by combining data from Ref. [37] for N_2 and O_2.

For the precise measurement of the magnetic birefringence of the vacuum, much higher modulation frequency will be obtained and an electro-optical modulator will replace the $\lambda/2$ rotating wave plate. This possibility was also demonstrated and is discussed in the next paragraph.

ii) Improved solution for the modulator

A phase modulator made from a $LiNbO_3$ crystal, was used to modulate the polarization of a He-Ne laser beam (623 nm). Crystal's dimensions were 2 x 3 x 40 mm^3, with optical axis perpendicular to the beam. A full rotation of the polarization of the laser beam was obtained up to 80 kHz with a half-wave voltage amplitude of 165 V. For a light with a wavelength of 1550 nm, the voltage should be increased up to ~400 V. Other electro-optical crystals requiring lower voltage are now under test.

3.2.3 Control of Systematic Effects

i) Cotton-Mouton Effect of residual gases

To avoid problems related to thermal contraction effects such as uncontrolled misalignment of optical elements, the warm bore approach making use of anticryostats is at present considered as the baseline for the first phase of the *n-1* experiment. In that case, the optimum vacuum which can be obtained will have a minimal pressure in the range 10^{-8}-10^{-9} torr with a residual gas mostly composed of water vapor [38]. The background signal coming from the Cotton-Mouton effect is proportional to the pressure of the residual gas and can be estimated to be at least two orders of magnitude lower than the 1st order QED vacuum magnetic birefringence (2.5). To be able to test the second order QED correction, i.e. the term coming from the 2 loop contribution (2.6), the vacuum should be improved down to the level of ~10^{-11} torr. This is planned for the phase-2 of the experiment. One of the most direct ways to reach such a residual pressure is to use cold bores to profit from the cryo-pumping effect. Other solutions are also currently under consideration with the constraint of warm bores. To give a limit, 12 meter long LEP vacuum chamber was pumped down to 10^{-12}-10^{-13} torr with non-evaporable getters [39].

To close this paragraph, it should be added that before proceeding to the measurements of the magneto-optical properties of the vacuum, precise measurements of the Cotton-Mouton effect will be performed for various gases as a function of the pressure and temperature. A focus will be given to the residual gases which are expected to remain at the end of the pumping phase.

ii) Intrinsic birefringence and linear dichroism of the Fabry-Pérot cavity

A fully isotropic Fabry-Pérot cavity should give, in principle, no birefringence and no linear dichroism signals. However, in most practical cases at least one of the components of the cavity is slightly anisotropic, inducing some birefringence or/and dichroism. A dedicated choice of the mirrors and of the coating will be made to reduce these effects and a careful characterization of the optical cavity, once built, will be performed. A specific Soleil-Babinet compensator will be used to minimize first order parasitic effects in zero magnetic field. It is a modulation of the field of the superconducting magnet, typically at 1-10 mHz, which mostly will allow to detect only the field dependant birefringent and dichroic signals. As this will be discussed in the next paragraph, it is of prime importance to assure that no spurious systematic effects are presents in these field-dependant signals.

iii) MOKE of the mirrors of the Fabry-Pérot cavity

With the presence of a fringe magnetic field at the level of the mirrors, one of the Magneto-Optical Kerr Effects (MOKE) resulting from the diamagnetic magnetization of the dielectrical mirrors of the cavity could produce, at each reflection, a linear dichroism as well as a birefringence. In general, three different MOKE, can be distinguished as a function of the orientation of the magnetization of the mirror (Fig.8). The polar one can be viewed as a Faraday effect with one reflection and in normal incidence, there is in principle no longitudinal and no transverse Kerr effects [40]. In other words, the polar MOKE is the only expected linear effect in magnetic field which could produce, as already mentioned in the paragraph 2.2.2 [31], a PVLAS like signal.

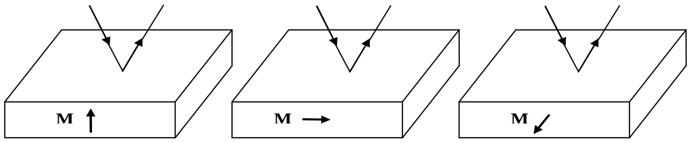


Fig.8: *The three different configurations of Magneto-Optic Kerr Effects (MOKE) as a function of the orientation of the magnetization* ***M****; a) polar, b) longitudinal and c) transverse.*

To estimate the magnitude of the magnetic field which can produce an optical rotation of the same order of magnitude as the PVLAS result [25], the Verdet constants of diamagnetic materials can be used as a starting point. They are typically in the range 4-27 rad T^{-1} m^{-1} for SiO_2 type glasses and high-refraction index ones respectively [40]. With such numbers and assuming a mirror thickness of about 10 μm, a value of 8-54 10^{-12} rad/mG can be obtained. Compared to the PVLAS rotation of 3.9 10^{-12} rad/pass and converted to the same angle but by reflection, a second harmonic magnetic field component, i.e. oscillating at twice the magnet rotation frequency ω_M, perpendicular to each mirror and with a value in the range 0.07-0.5 mG can produce the optical rotation observed. As a consequence, the screening of the fringe field at the level of the mirrors should give a resulting magnetic field typically lower than 10 μG. In this proposal, no oscillating magnetic field at $2\omega_M$ can be generated around the mirrors. In addition to cope with the second order effect coming from non linear MOKE, dedicated shielding chambers using mu-metal are foreseen to be integrated inside the end caps.

iv) Imperfections of other optical elements

The study of the effects of the imperfections of optical elements other than the optical cavity was performed for the case of birefringence measurements i.e. Cotton-Mouton effect and QED Vacuum Magnetic Birefringence, the later being considered as the benchmark. The modeling of the imperfections as well as the calculation details [32] are given in Annex 2. The most important results of this study were to show that:

- the use of optimized optical components (but far from the state-of-the-art) gives access to the measurement of ultra low birefringence corresponding to a magnetic induced dephasing $\Psi = \beta/2$ in the range of 10^{-10} rad;
- the method offers some flexibility to reduce the effect of imperfections of optical elements down to a level which was calculated to be of the order of 3.10^{-13} rad.

3.3 The Photon Regeneration Experiment

3.3.1 Measurement Principles

To complement and cross-check the VMB measurements, the photon regeneration experiment will be integrated in the second aperture of the 15-meter long LHC superconducting magnet. The principle of this experiment is schematised in Fig.9. A cavity inserted inside a part of the dipole magnetic field region is used as an axion source and a Photo-Multiplier Tube (PMT) or an Avalanche Photo-Diode (APD) for example, as an optical detection system. The optical barrier will intercept all photons not converted into axions and the detection of any photon at the same wavelength as the laser beam can be interpreted as an axion to photon reconversion inside the regeneration region. A chopper can be used for a synchronous photon counting with the chopped laser beam to improve the background rejection. When the magnetic field is switched off, the same measurements can be repeated to detect the possible mixing effect between photons and paraphotons. It can be noticed that contrary to the vacuum *n-1* experiment, the photon generation does not required vacuum in the beam pipe. It can be filled with a gas at known pressure and temperature to restore the coherence of the axion-photon oscillation [41].

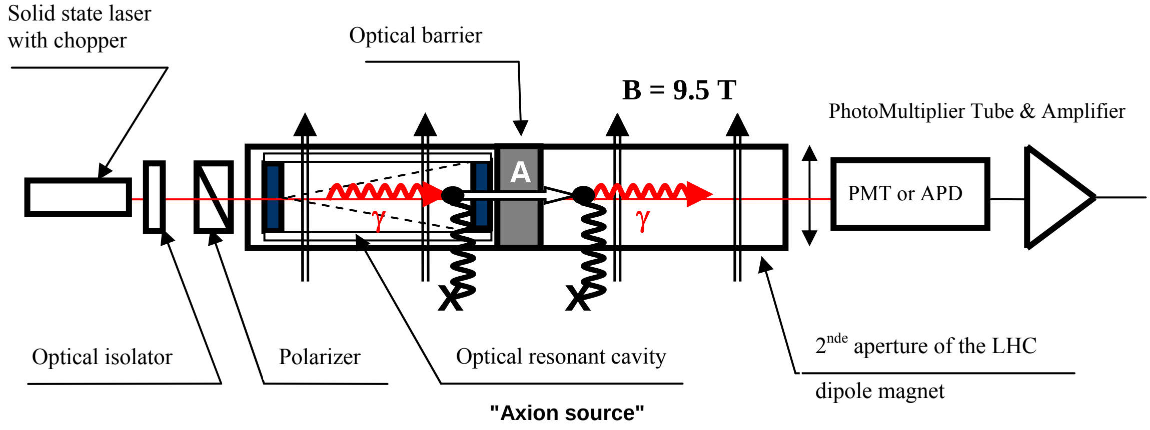


Fig. 9: *Principle of the photon regeneration experiment.*

3.3.2 Preliminary Phase

For an optimum photon regeneration experiment, a high finesse Fabry-Pérot cavity should be used together with a powerful laser and the coupling between both should be optimized. Typical performance which can be obtained with today state-of-the-art optics is discussed in the next paragraph for the phase-1 and 2 of this experiment. However, as for the *n-1* experiment, the laser and the Fabry-Pérot cavity should be locked to each other and an active feedback is required to tune either the cavity length or the laser frequency to keep both in resonance at one frequency. One of the most popular techniques is the so-called Pound-Drever-Hall technique [42] schematized in Fig. 6. The practical application of such a technique with long cavities cannot easily be achieve in less than 1 year and to be rapidly competitive in the “cross-check” of the PVLAS results [25], it was decided to add a preliminary phase for the photon regeneration experiment.

Two different solutions are presently considered for this preliminary phase. The first one is based on the use of the laser with a Z-fold cavity shown in Fig. 10 and Annex 3. This Nd:YVO_4 laser pumped by a laser diode was developed at the *Laboratoire de Spectrométrie Physique* (LSP) of the University of Grenoble [43]. A maximum stable intra-cavity optical power around 150 W can be obtained at wavelength of 1064 nm. Preliminary tests with this solid state laser allowed to identify the origin of the limitation of the optical power. It is mostly due to the heating of the crystal surfaces and the thermal lensing effect. The integration inside the magnet aperture of the cavity arm containing the planar mirror M4 can be realized as a first step, with the distance d5 taken equal to 3 m to obtain a 1 meter long cavity immersed in the magnetic field. To reach larger optical power typically up to 1 kW, the second solution under consideration consists in using the ionized argon laser (Ar+) of the LSP which can provid its maximum of power at 540 nm. The study of such a possibility together with the integration inside the magnet aperture of the cavity arm containing one of the mirrors is now on-going. The linear Ar+ laser cavity must be extended up to about 3 m. This later solution is considered at present as the preferred one as in addition, much more efficient optical detectors can be found for this wavelength.

For the photon regeneration experiment, a special attention should be devoted to the choice of the photo-detector which should work in the photon counting mode. For this preliminary phase, the first choice concerns at present a LN2 cooled CCD (Charge-Coupled Device) camera. One of the major interests to use a matrix detector is to allow a 1 or 2 dimensional mapping of the laser beam profile or to establish some spatial correlations for the "real-photon counting". This provides, in addition to the temporal correlation which will be based on the chopper frequency, a powerful discrimination to reject dark counts. The LSP can provide a LN2 cooled CCD (Princeton Instrument) with a quantum efficiency around 50 % at 540 nm and a dark count rate below ~0.1 /minute.

The minimal expected performances for this preliminary photon regeneration experiment are given in Fig.11 for 1 hour and 1 year of integration times. For this calculation, 100 W of optical power were considered in 1 m long cavity immersed in 9.5 T field. The length of the photon regeneration zone is assumed to be equal to 13.3 m and the lost of the coherence of the axion-photon oscillation was taken into account. This preliminary estimate shows that with the foreseen configuration of the Ar+ laser, the PVLAS results can be checked in less than 1 hour (Fig.11).

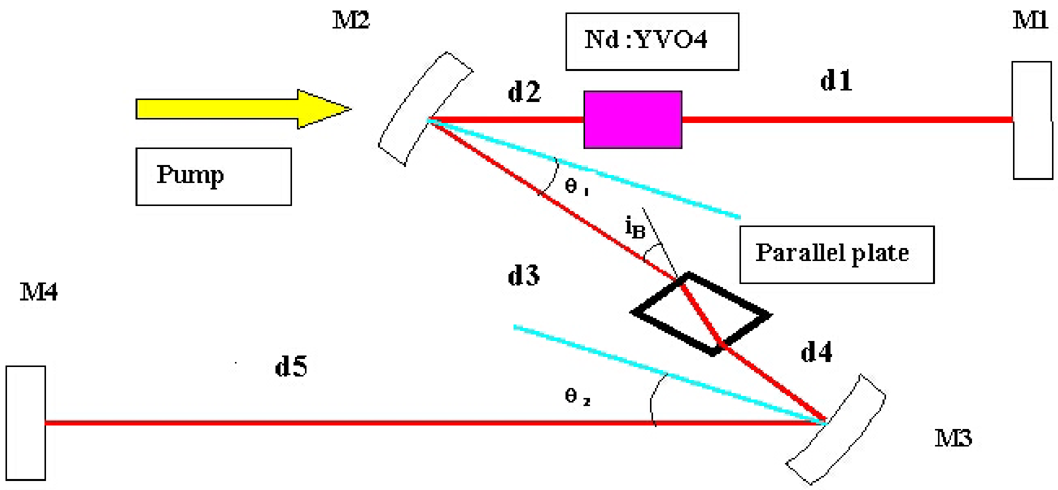


Fig. 10: *Schematic diagram of a Z-fold cavity of the Nd: YVO_4 laser. The Nd:YVO_4 crystal is the laser gain medium whereas the Brewster plate is used to polarize the light beam.*

3.3.3 Phase-1, Phase-2 and beyond

With a Nd:YAG laser, an optical beam power as large as 1-10 kW [2] can be obtained at the wavelength λ = 1064 nm. The optimum for the photon regeneration experiment is obtained for an optical cavity and a regeneration region both immersed in the same magnetic field integral. Assuming as a first step the use of a single LHC dipole with a 7-meter long regeneration region and an optical cavity with a finesse of 10^4-10^5 of the same length, the photon counting rate

[2] For example, the firm Toshiba (Toshiba Corporate Manufacturing Negineering Center) succeeded to perform with six modules pumped with laser diodes within a linear cavity to make a Nd:YAG laser which can delivered up to 11 kW in continuous mode with an efficiency of the electrical to optical conversion of ~20%.

given by (2.9) can be improved by a factor of about 10^8 with respect to the present reference result obtained by the BFRT collaboration [23]. This corresponds to a limit for the coupling constant to two photons *1/M* of about 10^{-9} GeV^{-1} i.e. an improvement by more than 2 orders of magnitude with respect to the BFRT results. The lost of coherence in the axion to photon conversion will prevent to probe axion with mass typically larger that 0.5 meV at the lower value of *1/M*. By filling the magnet aperture with a gas and tuning the plasma frequency, which provides an effective mass to the photon, to be equal to m_A, the coherence effect can be restored to probe axion with larger mass [41].

Optimum detectors in the near infrared are of solid state type. They are based either on semiconductor technology (Si, Ge or InGaAs) or on the superconducting one and are of bolometer type i.e thermal type detectors. J.-Cl. Villégier from the CEA-Grenoble was contacted to study the possibility to use superconducting bolometers working at 4 K with quantum efficiency larger than 20 % at 1064 nm and dark counts below 0.1 s^{-1} [44]. The preferred solution at present concerns, as for the preliminary phase, a LN2 cooled CCD (Charge-Coupled Device) camera[3] with a quantum efficiency of ~18 % at 1064 nm and dark counts of 0.1 electron/pixel/s. A significant input from the results of the preliminary phase is expected concerning the optimum choice of the laser and of the photo-detector.

3.4 Expected Results

3.4.1 Measurements of the Magneto-optical Properties of the Quantum Vacuum

As already mentioned in the paragraph 3.2, the first QED correction expressing the vacuum magnetic birefringence is considered as a first benchmark for the *n-1* experiment. For the search of axion or axion-like particles, this experiment will be less powerful than the photon regeneration one, mostly because of the lower photon flux used, and the minimal coupling which can be reached will be in the range of 10^{-8}-10^{-9} GeV^{-1}, i.e. a gain of 2 orders of magnitude with respect to BFRT results [23].

3.4.2 Photon regeneration experiment

The results expected from the photon regeneration experiment are given in Fig.11 for the various options considered starting from the preliminary phase with the A+ laser inside a Z-fold cavity, then for the phase-1 with a cavity of finesse 10^4 coupled to 1 kW laser and finally for the phase-2 and beyond using up to 1+4 magnets with alternate polarities. The efficiency of the detector was assumed to be equal to 75 % and even if the efficiency of the photon detection at 1064 nm will be typically in the range 20-40 %, all results can be scaled by increasing the integration time accordingly. Calculations were made with vacuum inside the beam pipe excepted for two of them where a buffer gas was considered. It is interesting to notice that the sensitivity of CAST can be reached during the phase-1 of this experiment for axion mass covering the so-called invisible window i.e. the plausible mass range for dark-matter axions.

[3] http://www.roperscientific.de/pixis.html

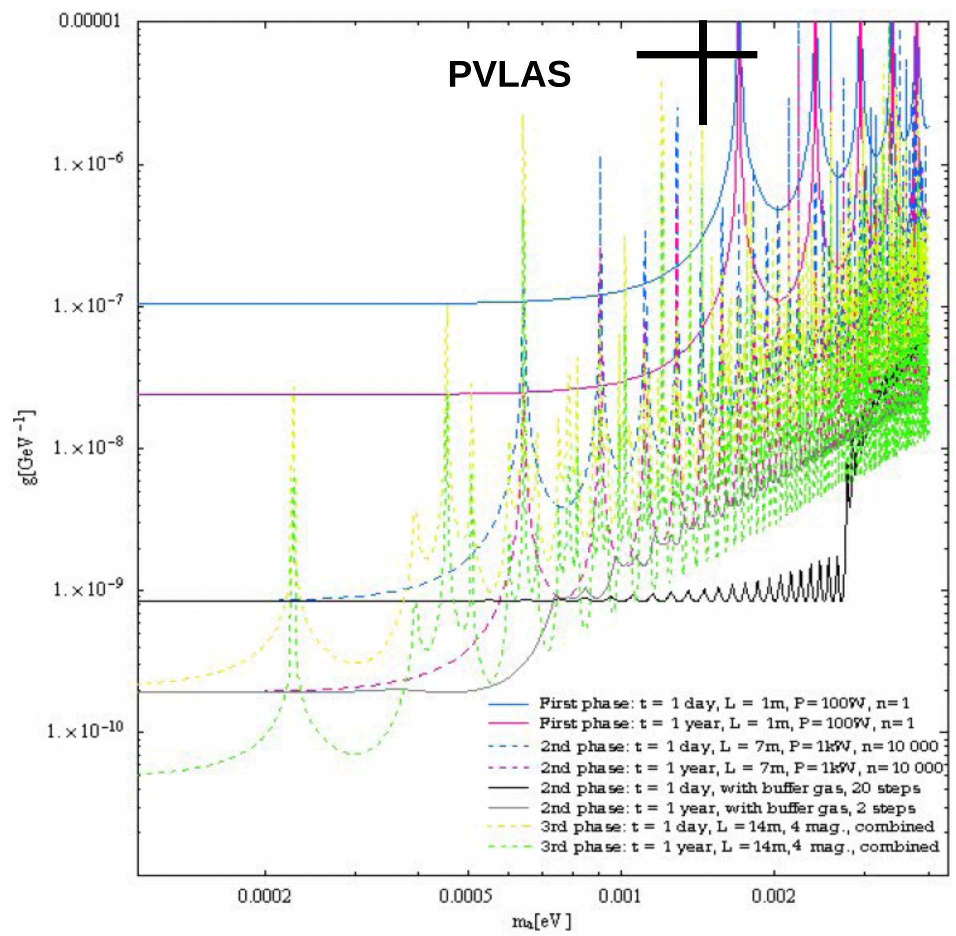


Fig. 11: *Expected results for the photon regeneration for the different cases considered*

3.4.3 Both combined Experiments

The simultaneous investigation of the magneto-optical properties of the vacuum and of the photon regeneration is of prime importance for the result interpretation and for the control of systematic errors. In case of an axion or axion-like particle signature, both experiments can provide sound results via mutual cross-checks.

4 Strategy, Preliminary Cost Estimate and Schedule

4.1 Proposed Plan

This multidisciplinary project is based on the international collaboration including at present eight Institutes and Laboratories with the required and recognized expertise in various domains relevant for this proposal (Annex 4).

The re-use of the maximum of research and development made at CERN for the LHC and the cold tests of superconducting magnets in particular is considered as a baseline before driving new development work. This concerns, in addition to available superconducting magnet prototypes housed in their cryostat, the vacuum technology, the anticryostats and the test infrastructure at SM18 test facility, which includes the cryogenics, the magnet power supply, the powering and electronic racks for the magnet protection [34]. These components already built will be re-use and will constitute the most expensive part of the project (≥ 4 M€). When all LHC superconducting magnets will be cold tested at the end of 2006, at least one of the twelve fully equipped test benches could be dedicated to the proposed experiments without interfering with the LHC project. Such a possibility was already addressed in an internal review of the AT department aiming to prepare the future activities that will take place in the SM18 test hall [45]. With this scenario and in a similar way that it is done for the CAST experiment, CERN should provide the expertise, the resources and the funding for the standard services required by the running of the proposed experiments.

Concerning the realisation of high quality optical cavities required for the signal amplification and the filtering of the three experiments, the LSP of the University of Grenoble will provide the essential expertise. The design, integration and support of all optical elements in the anticryostats housed inside the magnet apertures will be realised in collaboration with the Czech Republic part of the collaboration i.e. between groups from the Charles University (CU) and the Czech Technical University (CTU) of Prague and the Technical University of Liberec (TUL). The hyper polished substrates of the mirrors with a radius higher than 10 m required by the optical resonant cavity for the VMB measurements could also be produced by the Czech Republic teams of the collaboration.

The optical source for the VMB and linear dichroism experiment and the optical detection systems will be developed by a group from the IMEP (Institute of Microelectronics, Electromagnetism and Photonics) and will profit from the latest development in the field of optical ellipsometry techniques.

The theoretical support for the proposed experiments, analysis of the results and for the required simulation will be assured by a theoretical group of the Warsaw University.

4.2 Overall Cost Estimate of the Project (Phase-1 & 2)

Concerning the strategy, it was agreed that each collaborating Institutes will address its own financial need to its funding agencies according to the strategy defined in the paragraph-4.1. A preliminary cost estimate is given here below for each partner and a synthetic view can be found in Annex 5.

Partner 1: CERN

CERN is expected to provide for this project one of the available LHC prototype dipoles and one available fully equipped bench of the SM18 test facility including cryogenics, vacuum, power supply, instrumentation racks and control systems (cost estimate > 4 M€, but already existing). From the functioning cost of a similar experiment at CERN such as CAST, a first estimate of the overall cost can be given. For the running of both experiments of this project during the period 2008-10, the total cost for the exploitation is estimated to be about 850 k€. Of course this cost depends mostly of the future use of the SM-18 Superconducting Magnet Test Plan (SMTP). A preliminary review was organised in the CERN/AT department showing the necessity to have several test benches in operation during the running of the LHC [45]. The exact number of test benches is not yet defined but if CERN decides, as this will be most probably the case, to maintain few benches in operation for the LHC, the running cost of both proposed experiments will be drastically reduced. In the Annex 6, the proposed slot in the SM-18 test hall is shown for the proposed experiments together with the other requirements for the LHC operation. The choice of the test bench was driven by the possibility to use a most powerful power converter, i.e. 20 kA and 60 V, which will allow a field modulation at frequencies typically in the range 1-20 mHz.

Partner 2: Czech Republic Team

The Czech Republic Team will be mainly in charge of all mechanical elements and in particular those requiring micro-mechanisms. It will also contribute to the running of the experiments as well as to the data analysis and interpretation of the results in collaboration with all other teams.

- **Charles University (equipments & running costs: 35 k€ / missions: 35 k€)**
  - Two end-caps to close both pipes and transparent window to ensure the transition from Ultra High Vacuum (UHV) chambers and end caps housing the mirrors; piezo-actuators cannot easily be used in UHV.
  - Missions (to CERN and for international conferences): 8.75 k€/year → 35 k€
- **Czech technical University (equipment & running costs: 75 k€ / missions: 35 k€)**
  - Two specially developed anticryostats for UHV.
  - Missions (to CERN and for international conferences): 8.75 k€/year → 35 k€
- **Technical University of Liberec (equipment & running costs: 35 k€ / missions: 35 k€)**
  - Four mirror supports with precise tuning mechanism using piezo-actuators.
  - Missions (to CERN and for international conferences): 8.75 k€/year → 35 k€

Partner 3: French Team

- **IMEP (human resources: 140 k€ / equipment & running costs: 165 k€ / missions: 35 k€)**

IMEP will be mainly in charge of the optical source and the detection system for the VMB and linear dichroism experiment. IMEP will be also mainly in charge of the source and detection for the photon regeneration experiment:

  - Complete high power laser source for the photon regeneration experiment (tunable laser source, optical table, mode matching optics for the FP cavity, laser-cavity locking system of Pound-Drever-Hall [42]): 50 k€
  - Complete source (ultra low RIN laser, optical isolator, specific Soleil-Babinet compensator and EO modulator for the high speed rotation of the linear polarization of the laser beam, mode matching optics, synthesizer, …) for the VMB and linear dichroism experiment: 55 k€
  - Optical detection system for the photon regeneration experiment (with full electronics and opto-mechanical integration in the LHC dipole): 15 k€
  - Whole optical detection system (except filtering FP cavity) for the VMB and linear dichroism experiment (optical amplifier, telescope, Wollaston prism, high power photodiodes, lock-in amplifiers, …): 45 k€
  - Missions (to CERN and for international conferences): 8.75 k€/year → 35 k€
    Concerning human resources, the strong implication of IMEP for phases 1, 5 & 6 implies that a full time post-doc position must be maintained over 3 years (end of 2006 up to the end of 2009): full cost of 3 x 46.7 k€.

- **LSP (human resources: 140 k€ / equipment & running costs: 105 k€ / missions: 35 k€)**

The LSP will be mainly in charge of the design, realization and characterization of the 3 FP cavities required for the project. The funding request related to these 3 FP cavities is the following:

  - State of the art, highly reflective, lossless multilayer dielectric coating made by Layertec – Germany: 5 k€/coating batch (~10 x 1” diameter mirrors/run) x 3 coating runs → 15 k€
  - Whole opto-mechanics for the 3 FP cavities: 60 k€
  - Whole locking system for the VMB and linear dichroism experiment (special electronics required): 30 k€
  - Missions (to CERN and for international conferences): 8.75 k€/year → 35 k€

Concerning human resources, the strong implication of the LSP for phases 2, 3 & 6 implies that a full time post-doc position must be financed over 3 years (end of 2006 up to the end of 2009) : full cost of 3 x 46.7 k€.

- **LLN (equipment & running costs: 30 k€ / missions: 35 k€)**

The LLN will be mainly in charge of the test at the GHMFL (Grenoble High Magnetic Field Laboratory) facility of the different optical elements and materials used for the design of both experiments under very high magnetic field. It will be also in charge of the shielding of the magnetic field around the mirror of the moderate finesse FP cavity for the The funding request for the LLN is the following:

  - Use of the very high magnetic field of the GHMFL facility: 1 k€/hour x 15h → 15 k€
  - Ultra low magnetic field chamber housing mirrors: 15 k€
  - Missions (to CERN and for international conferences): 8.75 k€/year → 35 k€

Partner 4: Polish Team

- **Warsaw University (human resources (1/2 PhD): 70 k€ / missions: 35 k€).**

The Warsaw University will be mostly in charge of the interpretation of the results starting from the raw data.

4.3 Schedule and Yearly Milestones

Based on the proposals that will be submitted to the French and Czech funding agencies for a first duration period of 4 years, this project can be split in 7 main steps which include the achievement of the phase-1 of both experiments as well as the development required for their 1st upgrades needed for the running of the phase-2. Assuming that the construction and development of the whole experimental apparatus will be ensured by a maximum of ~8 FTE (Full-Time Equivalent Scientist), no more than 4 parallel tasks have been considered in our preliminary schedule.

In addition, first results to check the PVLAS result from a preliminary photon regeneration experiment presently under study are expected by the end of 2007 (1st milestone) and this task is integrated inside the preparatory phase, sub-step 2.4 of the planning (Annex 7). This preliminary phase can be realised with no material investments as all optical devices will be provided by the French and the Czech national teams.

Step 1 (Sep 07 – Nov 08 at LSP & CERN): Optical Fabry-Pérot cavities for the photon regeneration experiment and the 1st phase of VMB and linear dichroism experiment (without FP filtering cavity and post amplification)

- Conception (1.1), realization (1.2), test and characterization (1.3) of two optical cavities, the one for the VMB and linear dichroism measurements (19.1 m, moderate finesse) and the other for the photon regeneration experiment (7 m, high finesse). The conception phase will take into account the constraints of the CERN experimental environment and will profit from the design and integration study already performed during the years 2002-2005 (1 Ph-D, Annex 1).

Step 2 (Sep 07 – Jun 09 at CERN & IMEP; Run of the Photon Regeneration Experiment from July 2009):

- Conception (2.1), realization (2.2), test and characterization – in terms of noise for the detection – (2.3) at IMEP & CERN of both optical source and detection system that will be implemented at CERN for the photon regeneration experiment. The design and realization of the laser-cavity locking system will be done by LSP.

- Mid 2007: installation at CERN (2.4) of a LHC prototype cryodipole for both experiments without interfering with the LHC project; installation of the preliminary photon generation experiment described in the paragraph 3.3.2 to check rapidly PVLAS results (**1st milestone**)
- Construction of the photon regeneration experiment with state of the art optics at CERN from November 2008: Installation (2.6 conditioned by 1.3 and 2.3) of the FP optical cavity in the LHC dipole; test, characterization and feedback on the experiment (2.7) up to June 2009.
- **Start of the 3rd version of the photon regeneration experiment from July 2009: results expected in October 2009** with a confirmation or not of the PVLAS results (**2nd milestone**). From this date, depending on the results obtained, feedback on the experiment and study for further improvements (optimized optical detection with a cold avalanche photodiode, use of a gas to extend the coherence and to improve the axion-photon conversion).

Step 3 (Sep 07 – Oct 08 at IMEP): Source for the VMB and linear dichroism experiment

- Conception (3.1), realization (3.2), test and characterization (3.3) at IMEP of the optical source delivering a large beam required by the optical FP cavity with a very high quality of its linear polarization. The specific electro-optic modulator used for the high frequency rotation of the polarization will be made by Photline Technologies - Besançon (a first prototype has been already delivered by this company and its characterization is on going at IMEP). The specific Soleil-Babinet compensator used for the compensation of the mirror birefringence will be made by Optique Fichou - Paris.

Step 4 (Nov 08 – Nov 09 at CERN): 1st version of VMB and linear dichroism experiment in the second magnet aperture

- Construction of the VMB and linear dichroism experiment at CERN from November 2007: Installation (4.1 conditioned by 1.3, 2.4 and 3.3) of the FP optical cavity in the LHC dipole, test, characterization and feedback on the experiment (4.2) up to November 2008. For this 1st version, the rotation frequency of the linear polarization induced by the EO modulator will be in the range 10-100 kHz and warm bores will be used; for a pressure below ~10^{-8} torr, the parasitic Cotton-Mouton effect coming from residual gas is below the QED prediction.
- **Start of the 1st version of the VMB and linear dichroism experiment (without FP filtering cavity and post amplification) from December 2008: first results expected before January 2010 (3rd milestone)**

Step 5 (Nov 08 – Jan 10 at LSP): Optical Fabry-Pérot cavity for the 2nd step of VMB experiment.

- Conception (5.1), realization (5.2), test and characterization (5.3) of the optical cavity (~ 1 m, ultra high finesse) for the filtering cavity concerning the 2nd step of VMB and linear dichroism measurements.

Step 6 (Jul 08 – Sep 10 at LSP & IMEP): Overall detection system for the 2nd step of VMB and linear dichroism experiment (with FP filtering cavity and post amplification)

- Test (6.1 conditioned by 5.3) of the overall detection system (filtering FP cavity + optical amplifier) using an EO modulator to simulate experimentally the VMB and linear dichroism signals. Design (6.2), realization (6.3), test and characterization (6.4 conditioned by 6.1) of the control system used to lock the centre frequency of the filtering cavity onto the laser optical carrier.

Step 7 (Sep 10 – Mar 11 at CERN): 2^nd version of VMB and linear dichroism experiment (with FP filtering cavity and post amplification)

- Stop of the running of the VMB and linear dichroism experiment (4.2), installation (8.1 conditioned by 7.4) of the new detection system, test, characterization and feedback on the experiment (8.2) up to March 2011.
- **Start of the 2^nd version of the VMB and linear dichroism experiment from April 2011: first results expected in June 2011 (4^th milestone)**

Prospects for improvements of the 2-in-1 developed experiment are expected after the 4^th milestone such as e.g. connection of several LHC dipoles in series.

5 Concluding remarks

The proposed project offers an unprecedented and unique opportunity for a QED test down to a record level as well as for a broad experimental investigation beyond the standard model of particle physics. The later includes the possibility to test some extensions of the QED with paraphotons or millicharge particles as well as the coupling to photons of any scalar or pseudo-scalar particles such as axions. The search for axions is motivated by at least three main components. First, axions are the most attractive solution of the strong CP-problem as this was, for example, pointed out recently by E. Witten during a workshop on axions at the Institute for Advance Study at Princeton [46]. Second, they constitute the only non-supersymmetric candidate for the dark matter. Third, axions and axion-like particles are abundant in string theory and their discovery may indirectly provide a clue to physics at extreme (Planck) scales. It can also be added that the purely laboratory experiments of this proposal are complementary to the CAST experiment, as the results which can be obtained are fully model independent.

Concerning more specifically the *n-1* experiment to measure the magneto-optical properties of the vacuum, the objective is challenging and well defined. It is shown in this proposal, that by using simultaneously the state-of-the-art in optics and one LHC superconducting dipole, the first order QED prediction for the Vacuum Magnetic Birefringence can be measured for the first time. This effect is considered as a benchmark before to go further. From this point and as for all experiments of metrological type, any progress will be very demanding and will require significant investments for a deep understanding of each part of the experimental set-up.

The photon regeneration experiment is much easier to achieve especially for its preliminary phase for which no substantial funding is required. Whatever will be the first result of this preliminary phase, it will bring rapidly a significant contribution to the interpretation of PVLAS results. For the phase-1 of this experiment a powerful DC laser will be associated with a high finesse cavity to amplify the optical path in the magnetic field. With such a configuration, the BFRT result [23] is expected to be improved by 2 orders of magnitude. For subsequent upgraded phases, more superconducting dipoles could be progressively connected to further increase the magnetic length but also, additional improvements will be possible using the state of the art in pulse laser technology [47]. This could bring the opportunity to lunch at CERN a new long term research program in the emerging field of laser particle physics.

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Annex 1:
Prototyping Phase for End-Caps and Mirror Supports

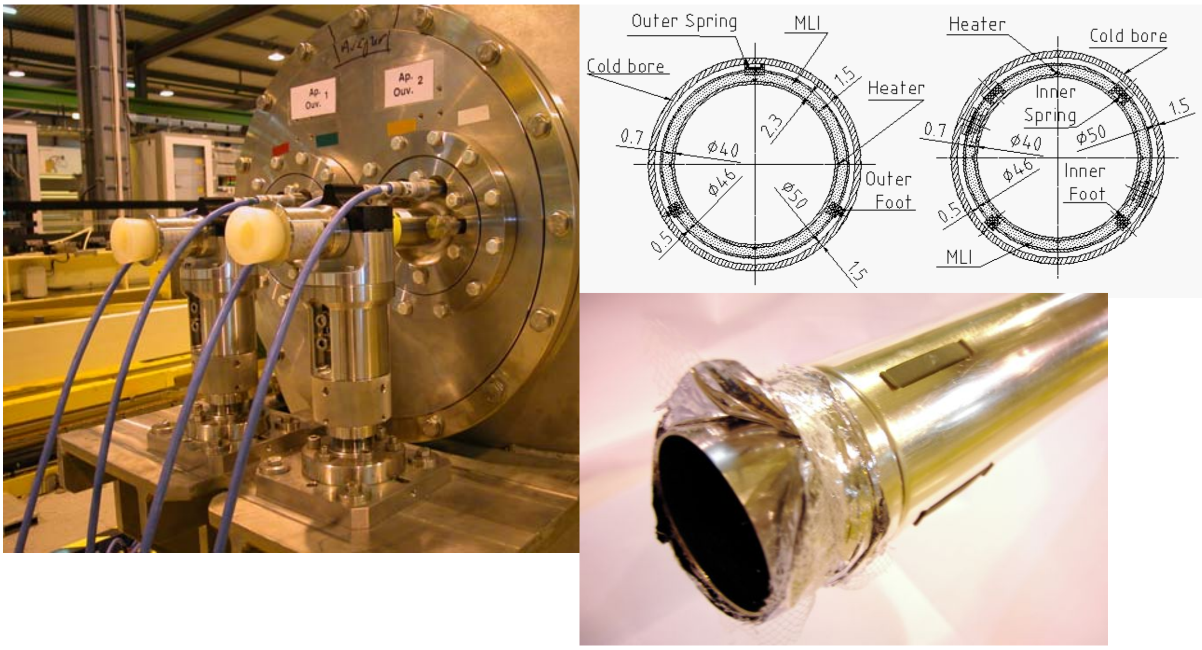


Fig.1-A1: Anticryostats mounted inside a LHC cryodipole

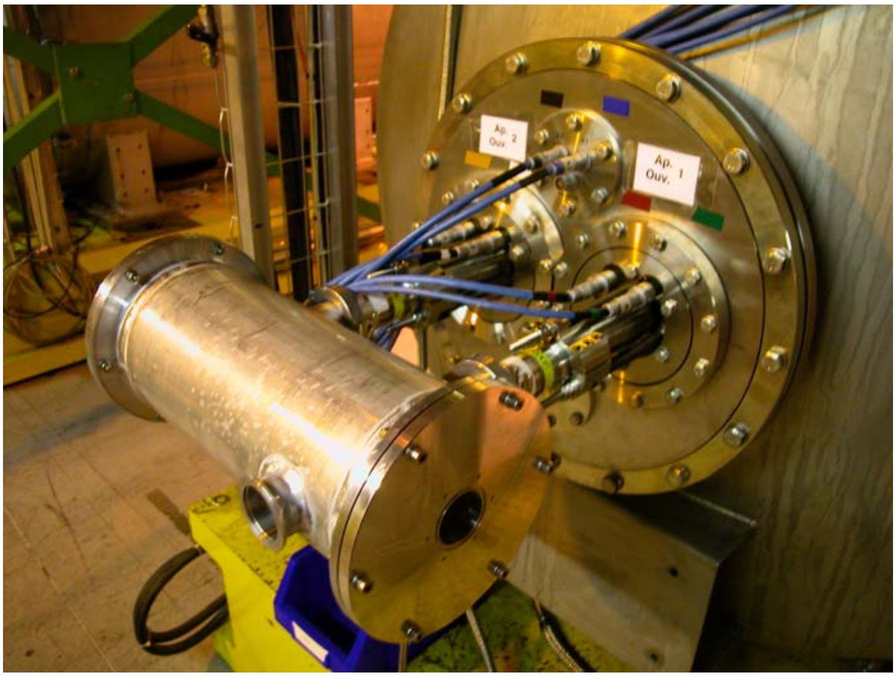


Fig.2-A1: Prototype end-caps connected to the Anticryostats

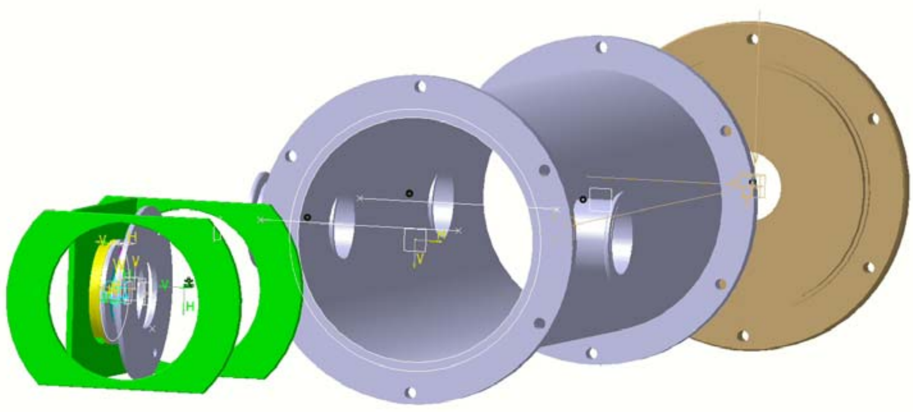


Fig.3-A1: Integration of the mirror support inside the end-cap.

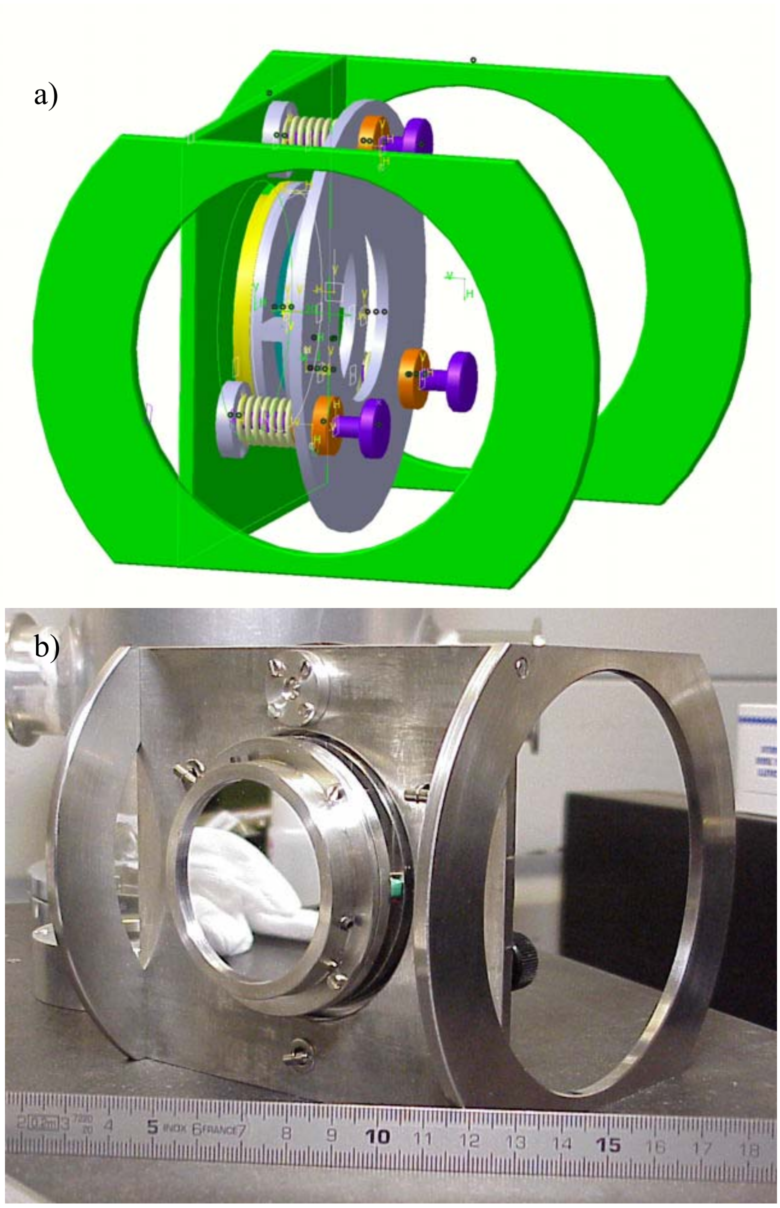


Fig.4-A1: Mirror support a) drawing, b) first prototype

Annex 2: Study of the systematic effects coming from the imperfections of optical elements other than the optical cavity

Simplified experimental set-up:

In the framework of the feasibility study of a new experiment at CERN using LHC decommissioned dipole prototypes to test the Quantum Electrodynamics and to search Axions, a dedicated optical experimental setup was proposed to measure the Vacuum Magnetic Birefringence (VMB). To reduce the detrimental effects of mechanical vibrations and the excess of noises encountered at low frequency in both laser source and electronic detection system, the measurement method should take benefit of a modulation of the optical signal at high frequency. The proposed solution is based on a half wave plate mounted on a high speed rotation stage (Fig. 1-A2) to modulate the polarization state of the laser beam in the kHz range. By replacing the half-wave rotating plate by an electro-optic modulator, it can be expected to work in the MHz range for the detection, and this constitutes one of the alternative solutions currently studied. To measure the Cotton-Mouton effect of some gases, only a double pass in the magnetic cell is foreseen in a first step, whereas for the VMB project a much longer pass in the magnetic field region will be realised using an optical cavity obtained with the addition of a mirror just after the rotating half wave plate.

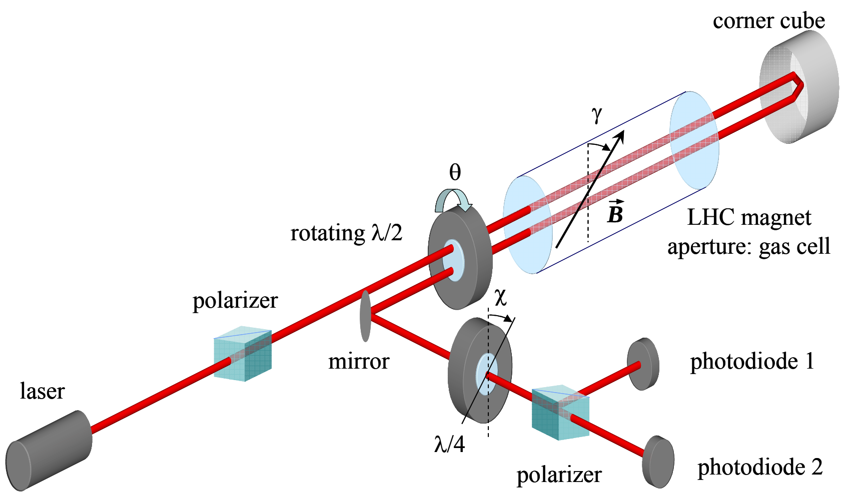


Fig. 1-A2: *Simplified experimental set-up*

Optical calculations with Jones' matrices:

The proposed experimental setup (Fig.1-A2) constitutes the first step for the project concerning the measurement of the very small Vacuum Magnetic Birefringence (VMB) i.e. a magnetic induced dephasing β of the order of 10^{-10} rad in a 9.5 T field. It is crucial to estimate the effect on the birefringence signal of all major experimental imperfections in addition to noise problem related to various sources (laser RIN, photodiode shot noise, Johnson noise and detection noise factor) and already addressed in the core of this proposal (paragraph 3.2).

The main imperfections of the optical elements are summarised in Table 1-A2 with an estimate of their order of magnitude first, for classical low cost components, and second for optimised ones. For example, using a standard rotation stage, δχ can get value as low as

1'~ 3.10^{-4} rad. Concerning ε and δ linked to the offsets of the phase retardation of the half and quarter wave plates, values as low as 5.10^{-4} can be reached using zero order wave plates. In case of optimised components all values can be reduced down to about 10^{-5} rad, whereas for state of the art components an additional reduction by at least a factor 10 is possible. In addition, ε and δ can be further reduced with a proper adjustment of the laser wavelength.

Parameters	$2\pi\delta$	$2\pi\varepsilon$	$\delta\chi$	γ
Description	offset of phase retardation of the λ/2 waveplate	offset of phase retardation of the λ/4 waveplate	misalignment of the λ/4 waveplate	misalignment of the analyser with respect to **B**
Typical values (in rad) for classical components	$2\pi \times 5.10^{-4}$	$2\pi \times 5.10^{-4}$	3.10^{-4}	3.10^{-4}
Typical values (in rad) for optimised components	$2\pi \times 10^{-5}$	$2\pi \times 10^{-5}$	10^{-5}	10^{-5}

Table 1-A2: *Main imperfections of the optical elements with their order of magnitude estimate.*

The Jones' matrices formalism was used to calculate the output optical power. Each optical element appearing in Fig.1-A2 produces an effect on the light beam polarization that can be described by a matrix:

$$M_{\lambda/n} = \begin{pmatrix} \exp(-i\pi/n) & 0 \\ 0 & \exp(i\pi/n) \end{pmatrix} \quad (1)$$

$$R_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad (2)$$

$$M_{CM} = \begin{pmatrix} \exp(-i\beta/2) & 0 \\ 0 & \exp(i\beta/2) \end{pmatrix} \quad (3)$$

$M_{\lambda/n}$ and M_{CM} are the Jones' matrices in the eigen referential of the optical element of a λ/*n* wave plate and the gas cell –in which the Cotton-Mouton effect occurs– respectively. R_θ is the rotation matrix that allows going from the eigen referential of one optical element to the eigen referential of the following optical element. The initial polarization state –in the laboratory referential– of the laser beam after its crossing of the first polarizer, represented by the two components of its normalized electric field, is given by the Jones vector:

$$E_{in} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (4)$$

The polarization state of the laser beam impinging onto the second polarizer will be given by:

$$E_{out} = R_{-\chi} \cdot M_{\lambda/4+\delta\lambda} \cdot R_{\chi-\theta-\delta\theta} \cdot M_{\lambda/2+\varepsilon\lambda} \cdot R_{\theta-\gamma+\delta\theta} \cdot M_{CM} \cdot R_{\gamma-\theta} \cdot M_{\lambda/2+\varepsilon\lambda} \cdot R_\theta \cdot E_{in} \quad (5)$$

where all possible offsets of phase retardation of the half and quarter wave plates ($2\pi\varepsilon$ and $2\pi\delta$, respectively) have been taken into account. The rotation δθ of the half wave plate during the double pass of the laser beam through the gas cell was also considered. Considering a pulsation of the order of 750 $rad.s^{-1}$ and a physical length of ~ 40 m, δθ will be of the order of

10^{-4}. In absence of any imperfection of optical element and in the limit of very low λ/2 rotation speed (i.e. $\varepsilon = \delta = \delta\theta = 0$), it is obvious to show, from relation (5), that the normalized optical powers received by the two photodiodes present at the same time the highest linearity and the highest sensitivity in the case where χ= π/4. These normalized optical powers are given by the square of the modulus of the two components of E_{out} and for χ = π/4 and $\varepsilon = \delta = \delta\theta = 0$:

$$P_{opt_{1,2}} = \frac{1}{2}\left(1 \pm \beta \sin\left(2\gamma - 4\theta\right)\right) \tag{6}$$

with $\theta = \omega t$. Consequently, the magnetic induced dephasing β of the gas is easily obtained from the difference of the two optical powers received by the photodiodes:

$$P_{opt_1} - P_{opt_2} = \beta \sin\left(2\gamma - 4\omega t\right) \tag{7}$$

Using a lock-in detection with a reference signal at 4 ω, the value of β can be directly measured. The different noise sources encountered in the experiment will lead to a minimum measurable value of β around 10^{-8}-10^{-9} rad / $\sqrt{Hz}$.

In a first step, the parasitic effects of the imperfections of optical elements and of the misalignment of the quarter wave plate, i.e. $\chi = \pi/4 + \delta\chi$, will be considered. From the product of the matrices given in (5), a Taylor expansion up to the 4th order in ε, δ, δθ and δχ, and to the 2nd order in β has been made analytically using Mathematica™. The output optical power was expressed in terms of Fourier components keeping only the lowest order terms:

$$\begin{aligned} P_{opt_1} &= P_0 + P_{2\omega}\cos\left(2\omega t - \varphi_{2\omega}\right) + P_{4\omega}\cos\left(4\omega t - \varphi_{4\omega}\right) \\ &+ P_{6\omega}\cos\left(6\omega t - \varphi_{6\omega}\right) + P_{8\omega}\cos\left(8\omega t - \varphi_{8\omega}\right) \end{aligned} \tag{8}$$

with

$$\begin{cases} P_0 \cong \frac{1}{2} - \pi\delta + 2\delta\chi\left(\delta\chi - 2\delta\theta\right) \\ P_{2\omega} \cong 2\pi\varepsilon \\ P_{4\omega} \cong \sqrt{\frac{\beta^2}{4} + 16\pi^4\left(\pi^2\delta^2 + \delta\chi^2\right)\varepsilon^4 + 4\pi^2\beta\varepsilon^2\left(\delta\chi\cos 2\gamma - \pi\delta\sin 2\gamma\right)} \\ P_{6\omega} \cong \frac{\pi\beta\varepsilon}{4}\sqrt{\beta^2 + 64\left(\pi^2\delta^2 + \delta\chi^2\right) - 16\beta\left(\delta\chi\cos 2\gamma - \pi\delta\sin 2\gamma\right)} \\ P_{8\omega} \cong \frac{\beta^2}{4}\sqrt{\pi^2\delta^2 + \delta\chi^2} \end{cases} \tag{9}$$

and

$$\begin{cases} \varphi_{2\omega} \cong \arctan\left(\delta\theta\right) - \frac{\pi}{2} \\ \varphi_{4\omega} \cong \arctan\left(\frac{8\pi^2\delta\chi\varepsilon^2 + \beta\cos 2\gamma}{8\pi^3\delta\varepsilon^2 - \beta\sin 2\gamma}\right) - \pi \\ \varphi_{6\omega} \cong \arctan\left(\frac{8\delta\chi\cos 2\gamma + 8\pi\delta\sin 2\gamma - \beta\cos 4\gamma}{8\pi\delta\cos 2\gamma - 8\delta\chi\sin 2\gamma + \beta\sin 4\gamma}\right) - \pi \\ \varphi_{8\omega} \cong 4\gamma + \arctan\left(\frac{\delta\chi}{\pi\delta}\right) - \pi \end{cases} \tag{10}$$

The limit of ultra-low magnetic birefringence can be defined from:

$$\{\delta,\delta\chi\}\,\varepsilon^2 \ll \beta \ll \{\delta,\delta\chi\} \tag{11}$$

where Eq. (8) becomes:

$$\begin{aligned} P_{opt_1} &= \frac{1}{2} - \pi\delta + 2\delta\chi\left(\delta\chi - 2\delta\theta\right) \\ &-2\pi\varepsilon\cos\left(2\omega t - \arctan\left(\delta\theta\right)\right) \\ &+\frac{1}{2}\beta\sin\left(4\omega t - 2\gamma\right) \\ &-2\pi\beta\varepsilon\sqrt{\pi^2\delta^2+\delta\chi^2}\cos\left(6\omega t - \left(2\gamma + \arctan\left(\frac{\delta\chi}{\pi\delta}\right)\right)\right) \\ &-\frac{1}{4}\beta^2\sqrt{\pi^2\delta^2+\delta\chi^2}\cos\left(8\omega t - \left(4\gamma + \arctan\left(\frac{\delta\chi}{\pi\delta}\right)\right)\right) \end{aligned} \tag{12}$$

In principle, the values of ε, δ, δχ, β and γ can all be extracted from measurements of the amplitudes and phases of the different Fourier components of the optical signal received by the photodiode:

$$\begin{cases} \varepsilon \cong \dfrac{P_{2\omega}}{2\pi} \cong \left\{\dfrac{P_{4\omega}P_{6\omega}}{4\pi P_{8\omega}}\right\} \\ \sqrt{\pi^2\delta^2+\delta\chi^2} \cong \dfrac{P_{6\omega}}{2P_{2\omega}P_{4\omega}} \cong \left\{\dfrac{1}{4P_{8\omega}}\left(\dfrac{P_{6\omega}}{P_{2\omega}}\right)^2\right\} \\ \left\{\dfrac{\delta\chi}{\pi\delta} \cong \tan\left(2\varphi_{6\omega}-\varphi_{8\omega}\right) \cong \tan\left(\varphi_{8\omega}-2\varphi_{4\omega}\right)\right\} \\ \gamma \cong \dfrac{\varphi_{4\omega}+\pi/2}{2} \cong \left\{\dfrac{\varphi_{8\omega}-\varphi_{6\omega}}{2}\right\} \\ \beta \cong 2P_{4\omega} \cong \left\{\dfrac{4P_{2\omega}P_{8\omega}}{P_{6\omega}}\right\} \end{cases} \tag{13}$$

One of the key interest of the proposed method results from the fact that all the unknown parameters ε, δ, δχ, γ and β are each given by two independent equations and the known parameter δθ can also be retrieve from the measurement of the phase $\varphi_{2\omega}$:

$$\delta\theta \equiv \frac{\omega L_{eff}}{c} \cong -\frac{1}{\tan\left(\varphi_{2\omega}\right)} \tag{14}$$

Indeed, the rotation δθ of the half wave plate during the double pass of the laser beam through the gas cell can be very accurately estimated from the physical length L_{eff} followed by the laser beam between its two crossings of the half wave plate. Obviously, the validity of relations (13) and (14) implies that the condition (11) is fulfilled.

Estimates of the order of magnitude:

From the estimates given in Table 1 for classical optical elements, the relation (11) expresses for β a value ranging from 2.10^{-7} up to 2.10^{-5}. Let us now calculate the orders of magnitude of the Fourier components of the optical signal received by the photodiode before the simplifications that have led to relations (9). Table 2-A2 gives the summary of the results for different values of β.

β	$P_{2\omega}$	$P_{4\omega}$	$P_{6\omega}$	$P_{8\omega}$
$2\ 10^{-5}$	$3\ 10^{-3}$	10^{-5}	10^{-10}	$2\ 10^{-13}$
$2\ 10^{-6}$		10^{-6}	10^{-11}	$2\ 10^{-15}$
$2\ 10^{-7}$		10^{-7}	10^{-12}	$2\ 10^{-17}$

Table 2-A2: *Orders of magnitude of Fourier components*

If the signal over noise ratio is now considered (laser RIN, shot noise, Johnson noise and detection noise factor), the Fourier components $P_{6\omega}$ and $P_{8\omega}$ are not measurable in a reasonable time as the minimum achievable modulation depth is of the order of 10^{-8}-10^{-9} $Hz^{-1/2}$. Moreover, the situation is worse if a better control of the parasitic effects lead to lower values of δ, ε and δχ. It can also be noticed that $P_{8\omega}$ presents a quadratic behavior with β (see Eq. 9) and as a consequence is certainly not a good candidate for β measurement. As a summary, the relations appearing in (13) that are not usable are put between brackets.

Expected performances and proposed strategy:

Fig.2-A2 shows the only usable relation leading to β (see last relation of (13) involving $P_{4\omega}$) versus γ for different values of β ranging from 10^{-7} to 2.10^{-5}. It has been obtained using the Fourier components of the optical signal received by the photodiode before their simplifications that lead to relations (9). As it can be seen, the maximum of discrepancy increases rapidly with the decrease of the β value and vanishes for some specific values of γ. It can be added that such specific values of γ do not exist anymore as soon as β is lower than $\sim 1.5 \times 10^{-8}$ in the present case. As a consequence, this very simple method that requires only the measurement of a single frequency component is only valuable for the characterization of large magnetic birefringences when classical optical elements are used. Otherwise, this method requires high quality optical elements with a crucial control of all the parasitic effects in order to lower their spurious effects down to the noise limit. Indeed, values of δ, ε and δχ ten times lower than the ones considered in Fig. 2-A1 lead to exactly the same curves if the value of β is divided by 1000. Therefore, the use of optimised components (far from the state of the art) gives access to the measurement of ultra low birefringence corresponding to a magnetic induced dephasing β in the range of 10^{-10} rad, thus demonstrating the hardiness of the proposed method. The simultaneous measurement of $P_{2\omega}$ gives us a precious indication of the limit of validity of the method as it directly leads to ε:

$$\min(\beta) \approx 2\ P_{2\omega}^{\ 2}\sqrt{\pi^2\delta^2 + \delta\chi^2} \approx P_{2\omega}\ P_{6\omega} / P_{4\omega} \tag{15}$$

This limit of validity that requires the measurement of $P_{6\omega}$, can be easily determined under high magnetic field with a gas at atmospheric pressure as this latter will exhibit a well precise measurable Cotton-Mouton effect. Moreover, the optimization of the system can be done by a simultaneous measurement and minimization of the two Fourier components $P_{2\omega}$ and $P_{6\omega}$. At low magnetic birefringence, the optimization of the experimental setup can still be partially ensured as the laser wavelength can be servo-controlled on the minimum of $P_{2\omega}$.

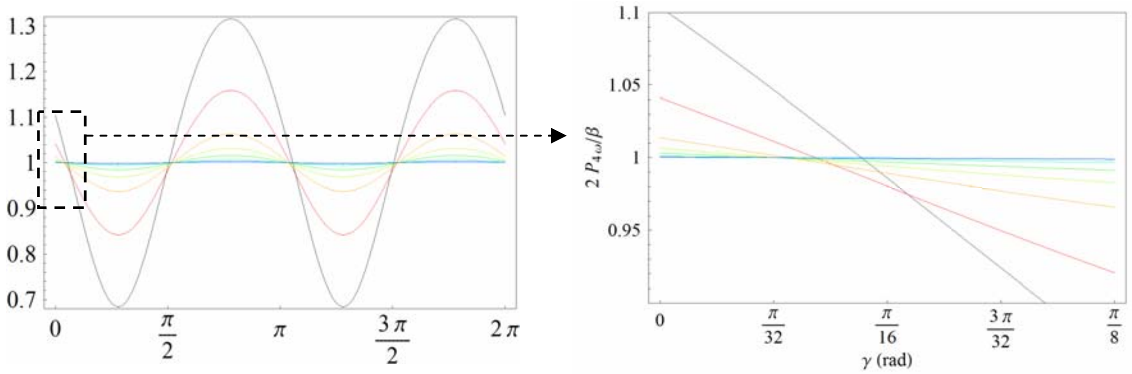


Fig.2-A2: *The ratio $2P_{4\omega}/\beta$ as a function of γ for $\delta = \varepsilon = 5.10^{-4}$, $\delta\theta = 10^{-4}$ and $\delta\chi = 3.10^{-4}$. The plots with decreasing maximums correspond to the values of $\beta = 10^{-7}$, 2.10^{-7}, 5.10^{-7}, 10^{-6}, 2.10^{-6}, 5.10^{-6} and $> 10^{-5}$ respectively.*

Table 3-A2 summarizes the proposed experimental method with its limit of validity. As a general remark, simultaneous measurements of the three Fourier components $P_{2\omega}$, $P_{4\omega}$ and $P_{6\omega}$ are required and this can be done with a commercial lock-in amplifier.

Proposed experimental method	
Expression of β	$2P_{4\omega}$
Required conditions	$P_{2\omega}$ and $P_{6\omega}$ must be minimized by a fine tuning of the laser wavelength.
Limit of validity	$\beta \geq 8\pi^2\varepsilon^2\sqrt{\pi^2\delta^2 + \delta\chi^2} \approx P_{2\omega}\, P_{6\omega} / P_{4\omega}$ for classical optical components $\beta \geq 3.10^{-8}$ rad optimised components $\beta \geq 3.10^{-13}$ rad

Table 3-A2: *Characteristics of the proposed experimental method*

Concluding remarks:

The proposed optical scheme for the VMB experiment allows an optimised strategy to measure magnetic birefringences over an ultra wide range of magnitudes (giving access to magnetic induced dephasing β as low as 10^{-10} if optimised optical components are used). To study the Cotton-Mouton effect, fine tuning of quarter wave plate orientation and laser wavelength can be used to reduce spurious effects coming from the imperfection of the optical elements. As the Cotton-Mouton effect is proportional to the gas pressure, the proposed experiment allows its measurement for a pressure range covering at least 7 orders of magnitude. This is an important step for the VMB project as the Cotton-Mouton effect of residual gases, such as water vapor, is expected to be one of the main background signal components.

Annex 3:

The Nd:YVO4 laser in operation (λ = 1064 nm)

Annex 4:

Matrix of the Domains of Expertise and Responsibilities

	Quantum & Particle Physics	Experiment Area, Sc Magnet & Vacuum	Optics Cavities	Optics Detection	Optics Micromechanics & Integration	Magnetic Materials and Magneto-optics
CERN*	√	√*			√	√
Charles University**	√			√		
Czech Tech. University*				√	√	
IMEP***				√*		
LLN*	√					√*
LSP*			√*	√		
Tech. Univ. of Liberec*				√	√*	
Warsaw University***	√*					

* Thematic Responsibility
** National Team Coordination

Spokespersons *K. A. Meissner, P. Pugnat*

Technical coordinators *L. Duvillaret, A. Siemko*

National Team Leaders Czech Republic: *M. Finger*; France: *L. Duvillaret*; Poland: *K. A. Meissner*

Thematic Team Leaders Quantum & Particle Physics: *K. A. Meissner*; Experiment Area, Sc Magnet, & Vacuum: *A. Siemko*; Optical cavities: *D. Romanini*; Optical detection: *L. Duvillaret*; Optical micromechanics: *M. Šulc*; Magnetic Materials and Magneto-optical properties: *Y. Souche*

Annex 5:

Preliminary estimate of Cost and Human Resources required on the 4 year basis

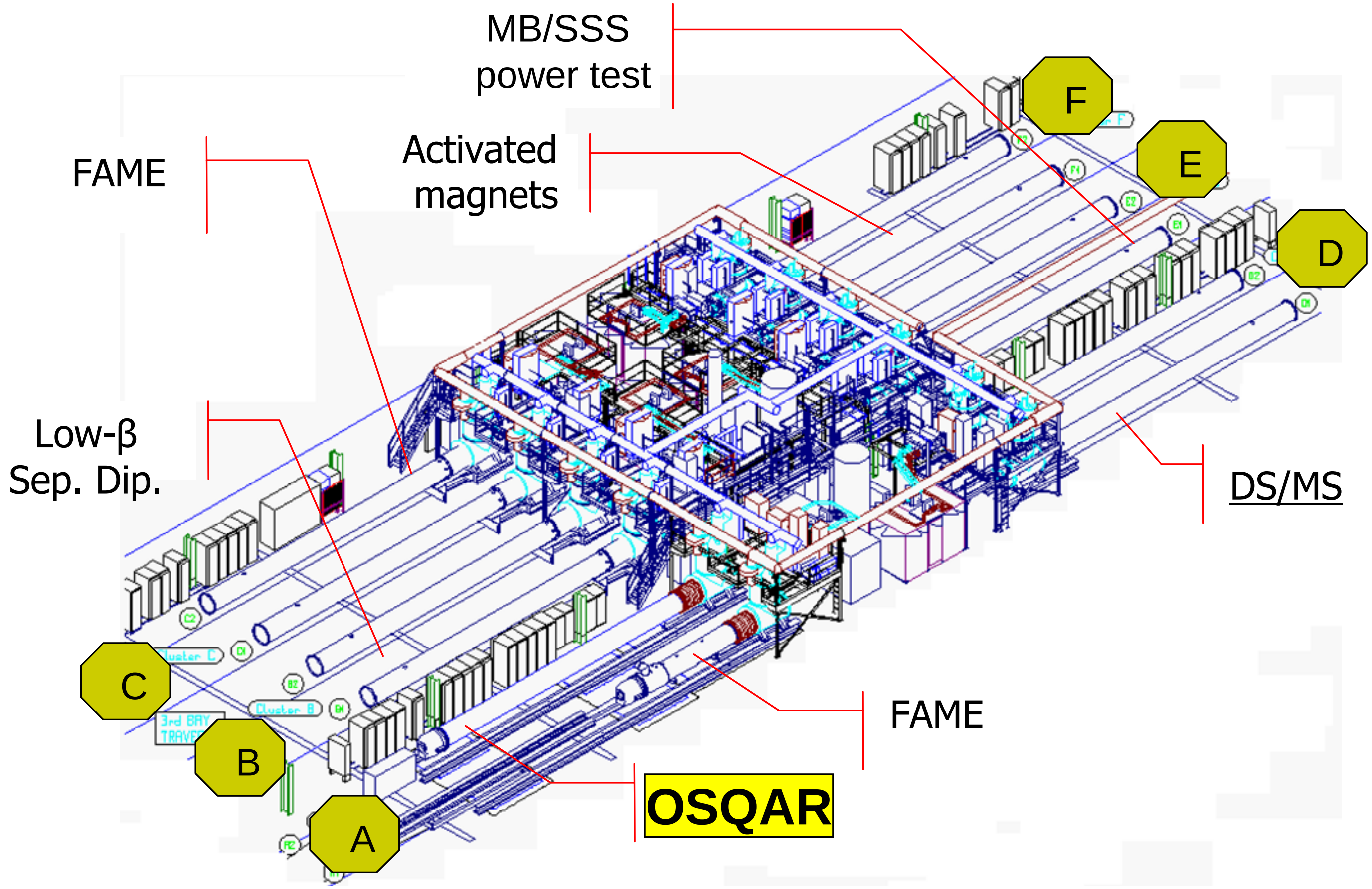
	Number of Physicists	**Full Time Equivalent (FTE)**	**FTE to be recruited****	**Equipments & Running Costs*****
CERN	2	2x0.25		<< 425 k€/year of running
Charles University	4	4x0.2		70 k€
Czech Tech. University	2	2x0.25		110 k€
IMEP	4 + 1	0.5 + 3x0.25 + 0.1	0.75	200 k€
LLN	3	3x0.1		65 k€
LSP	4 + 1	3x0.2 + 0.25	0.75	140 k€
Tech. Univ. of Liberec	3	0.5 + 2x0.25		70 k€
Warsaw University	1 + 1	0.25 +0.5	0.5	35 k€
Total	26*	6.05	2	690 k€ without CERN running cost

* This number is larger than the number of co-authors of this proposal as physicists such as Ph-D students not yet involved were count.

** 1 Post-Doc is expected to be funded by the French ANR agency during the first 3 years and another by the Czech funding agency; as an alternative it is also considered to find a French collaborator with an expertise either in optical cavity or in optical detection; a Ph-D in Theory is also foresee to contribute in the interpretation of results.

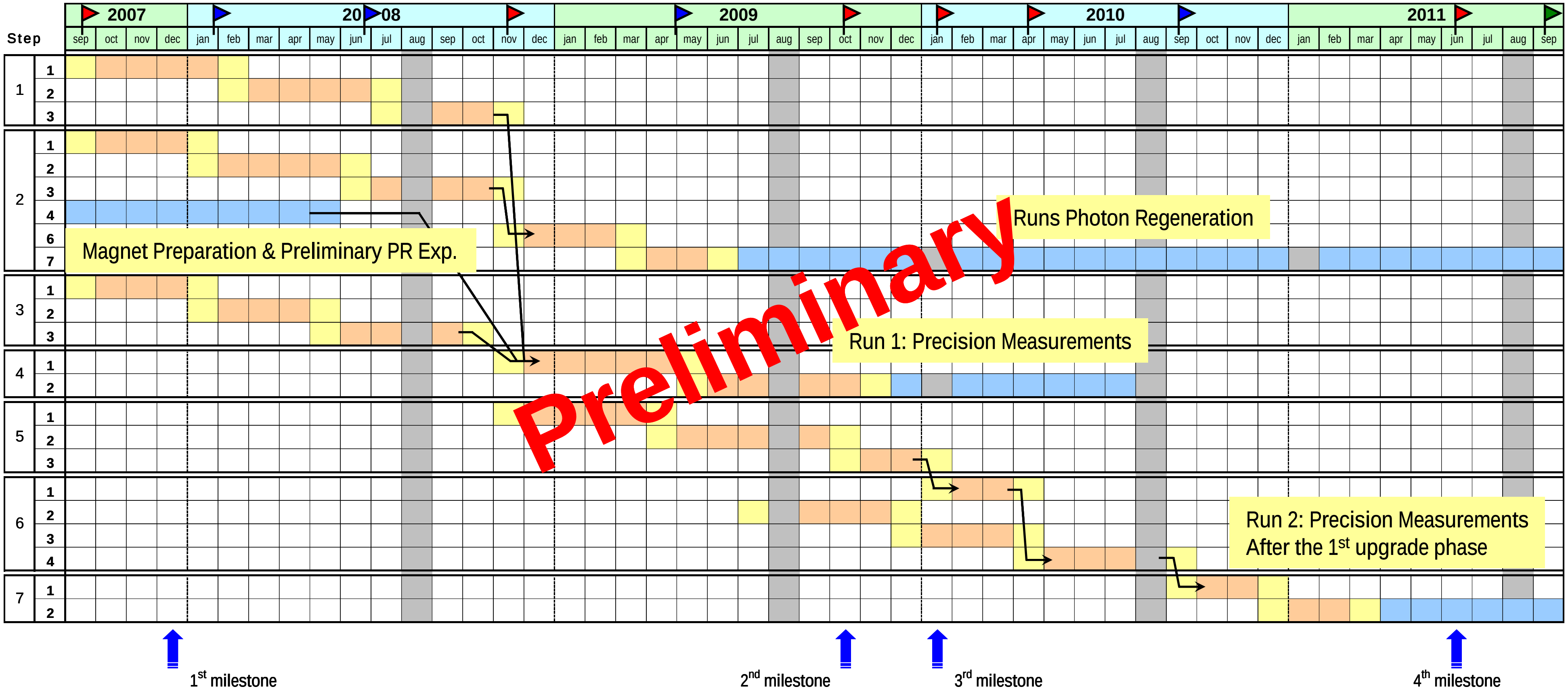
*** See paragraph for 4.2 for more details.

Annex 6: Layout of the Superconducting Magnet Test Plan in the CERN SM-18 Hall with the possible slot for the proposed experiments



Adapted from: http://indico.cern.ch/conferenceDisplay.py?confId=1270

Annex 7: Preliminary Planning



Legend

- **Ramping up or down phases of the activity**
- **Normal running**
- **Additional contributions from CERN concerning the standard services required to install and run the experiments**
- **Coordination meeting between all partners of the collaboration (at the beginning/end of important phases and at the 3 milestones)**
- **Coordination meeting between the partners implied in the corresponding phases**
- **Project Report**

Planning according to present available resources + 2 Post-Docs paid by NFA during 3 years each
Services from CERN is also expected with boundary conditions driven by the LHC construction

NFA : National Funding Agencies

Annex 8:

Publications and Reports

L. Duvillaret, M. Finger Jr., M. Finger, M. Kràl, K. A. Meissner, P. Pugnat, D. Romanini, A. Siemko, M. Šulc, and J. Zicha , Letter of Intent, CERN-SPSC-2005-034, 17 October 2005
http://doc.cern.ch//archive/electronic/cern/preprints/spsc/public/spsc-2005-034.pdf

P. Pugnat, M. Kràl, A. Siemko, L. Duvillaret, M. Finger, J. Zicha,
Czech. J. Phys. 55 (2005) A389; http://doc.cern.ch/archive/electronic/cern/preprints/at/at-2005-009.pdf

L. Duvillaret, M. Kràl, and P. Pugnat, *CERN-AT-MTM Internal Note 71, October 2005, CERN-EDMS-Id-672179*; https://edms.cern.ch/cedar/plsql/doc.info?cookie=4169685&document_id=672179&version=1

P. Pugnat, M. Kràl, A. Siemko, L. Duvillaret, M. Finger Jr., M. Finger, K. A. Meissner, D. Romanini, M. Šulc, and J. Zicha, *Czech. J. Phys. 56 (2006) C193*

P. Pugnat et al., "Axion Searches at present and in the Near Future",
to appear in the Lecture Notes in Physics, Volume on Axions, (Springer-Verlag)

P. Pugnat, Comments on "Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field", submitted to *Phys. Rev. Lett.*

Invited Presentations of the Project to Workshops and Conferences

"Feasibility study of an experiment to measure the Magnetic Birefringence in Vacuum", M. Kràl, *"Symmetries and Spin" Conference*, Prague, 5-10 July 2004, (SPIN-Praha-2004) http://thsun1.jinr.ru/~praha/2004/

"QED Test & Axion Search in a LHC Superconducting Dipole By Means of Optical Techniques", P. Pugnat, *"Symmetries and Spin" Conference*, Prague, 27 July - 3 August 2005, (SPIN-Praha-2005) http://thsun1.jinr.ru/~praha/2005/

"On the Cotton-Mouton Effect & its Possible Application to Characterise the Magnetic Field of Accelerator Magnets", P. Pugnat, *Workshop CARE Ecomag05*, *HHH-AMT Workshop on Pulsed Accelerator Magnets,* Frascati, 26 - 28 October 2005, http://ecomag-05.web.cern.ch/ecomag-05/Proceedings/WG3/WG3_Pugnat.pdf

"Laboratory Experiments for Axion Search using Decommissioned LHC Superconducting Dipoles", P. Pugnat, *1st Joint ILIAS-CAST-CERN Axion Workshop*, CERN, 30 November - 2 December 2005; http://agenda.cern.ch/fullAgenda.php?ida=a056218

"Laser-based Experiments using LHC Superconducting Dipoles for Axion Search at CERN", P. Pugnat, *2nd Joint ILIAS-CAST-CERN Axion Workshop*, University of Patras, Greece, 18-19 May 2006; http://indico.cern.ch/conferenceDisplay.py?confId=1743

"Laser-based Experiments in High Magnetic Field for QED Test and Axion Search at CERN", P. Pugnat, *Workshop "Axions at the Institute for Advanced Study"*, Princeton, 20-22 October 2006, http://www.sns.ias.edu/~axions/schedule.shtml