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Letter of Intent

QED Test and Axion Search by means of Optical Techniques

To the CERN SPSC

L. Duvillaret[1,2], M. Finger Jr.[3], M. Finger[3], M. Kràl[4,5], K. A. Meissner[6],
P. Pugnat[4*], D. Romanini[7], A. Siemko[4], M. Šulc[8], J. Zicha[5]

[1] LAHC, Université de Savoie, 73376 Le Bourget du Lac Cedex, France
[2] IMEP, BP 257, 38016 Grenoble Cedex-1, France
[3] Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[4] CERN, Geneva, Switzerland
[5] Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic
[6] Warsaw University, Physics Department, Poland
[7] LSP, Université J. Fourier – Grenoble-1 & CNRS, BP 87, 38402 Saint-Martin d'Hères, France
[8] Technical University of Liberec, Czech Republic

Abstract

The re-use of recently decommissioned 15-meter long twin aperture LHC superconducting magnet prototypes, providing a transverse magnetic field $B \approx 9.5$ T offers a unique opportunity for the construction of a new powerful two-in-one experiment to investigate the properties of the vacuum by means of optical techniques. Linearly polarised laser light beams will be used as probes inside vacuum chambers housed inside superconducting magnet apertures. One of the apertures will be dedicated to the measurements of the Vacuum Magnetic Birefringence (VMB) and optical absorption anisotropy whereas the other one will be used to detect the photon regeneration from axions or axion-like particles using “a shining light through the wall”. The VMB predicted by the QED theory is expected to be measured for the first time and the CPT symmetry precisely tested. The values or the limiting values of mass and coupling constant to two photons of weakly interacting scalar or pseudo-scalar particles like axions are also aimed to be deduced from a sizeable deviation of the QED prediction. In case of null result for axion search and with the most conservative view concerning the proposed detection technique, the limit of the di-photon coupling constant can be improved by at least 2 orders of magnitude with respect to present reference results obtained with a purely laboratory experiment. The interest in axion search, providing an answer to the strong-CP problem, lies also 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.

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[*] Contactperson

1. Introduction

Since its prediction in 1936 by Euler and Heisenberg [1] and independently by Weisskopf [2] 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 the QED theory [3], 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 [4]. After propagating through the vacuum permeated by a transverse magnetic field, the polarization of the laser beam will change to elliptical with parameters of the polarization 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 [5].

In this *Letter of Intent*, which is mainly based on the work reported in references [6], [7] and ongoing study [8], it is suggested to use a decommissioned LHC superconducting magnet prototype providing in two apertures a dipolar magnetic field up to ~ 9.6 T to built a powerful two-in-one laboratory experiment for QED test and axion search by means of optical techniques. Direct and indirect search of axions will be conducted in the same twin aperture superconducting magnet system to cross-check results with independent experimental methods.

As hypothetical weakly interacting scalar or other pseudo-scalar particles like majoron, familon can couple by a two-photon vertex, it is also possible with the proposed experiments to detect their production [5] and the word "axion" is sometimes used loosely in the following as a generic name to include such possibilities.

2. Brief review of some theoretical predictions

2.1. Background

Axions were proposed independently by Steven Weinberg [9] and Frank Wilczek [10] as an extension of the Standard Model to explain why CP violation is observed in weak but not in strong interactions – the so-called strong-CP problem. One of the most striking experimental facts is the neutron electric dipole moment, which, due to a CP-violating term, is calculated to be ten orders of magnitude larger than its measured upper limit [11]. An elegant answer to this problem was proposed by Peccei and Quinn who assumed that the strong interactions Lagrangian has a global $U_{PQ}(1)$ chiral symmetry [12]. Weinberg [9] and Wilczek [10] analysed the consequences of the Peccei-Quinn symmetry and deduced that the spontaneous breaking of a global $U_{PQ}(1)$ chiral symmetry leads naturally to a light pseudo-Golstone boson, called axion interacting with topological charge.

A variety of robust astrophysical arguments and laboratory experiments indicate that axion mass should be lower than 10^{-2} eV [13]. On the other side, a lower bound for axion mass in the range of approximately 10^{-6} eV would be ideal to solve the dark matter problem and the so-called invisible axion is currently referred to the mass range of $10^{-6} \leq m_A \leq 10^{-2}$ eV.

Among various experiments to detect invisible axions, two of them are of purely laboratory type and are the subject of this *Letter of Intent*. Both are based on the assumption that axions can be produced by a polarised laser beam travelling in vacuum in the presence of a strong transversal magnetic field. In the first experiment, axions are supposed, once produced, to modify the polarisation state of the light beam [5] whereas in the second one, they are expected to cross an optical barrier before being reconverted in photons that can be detected [14]. The interest in purely laboratory experiments for axion search is related to the possibility to scan the broad band of the mass spectrum $10^{-6} \leq m_A \leq 10^{-2}$ eV and to be fully independent of the assumptions concerning the axionic content of the universe or the axion production and emission mechanisms in the sun.

2.2. The VMB and optical absorption anisotropy

One of the purely laboratory experimental approach for axion search is of indirect detection type. It is based on the theoretical prediction that scalar or pseudo-scalar particles, due to their coupling to photons, can affect the polarisation of light propagating in vacuum through a transverse magnetic field B [5]. An initially linearly polarized light beam with an angle θ with respect to B is expected to acquire a small ellipticity Ψ and a small apparent rotation Θ due to a linear dichroism. Both effects can be expressed in natural Heaviside-Lorentz units where ħ = c = 1, 1 T = 195 $(\mathrm{eV})^2$ and 1 m = 5 .10^6 eV^{-1} by:

$$\Psi \approx (B^2 l^3 m_A^2 / 96\, \omega M^2) \sin 2\theta \tag{1}$$

$$\Theta \approx (B^2 l^2 / 16\, M^2) \sin 2\theta \tag{2}$$

in the limit $m_A^2\, l / 4\omega << 1$ where m_A is the axion mass, M is the inverse coupling constant to two photons, l the length path in the magnetic field and ω is the photon energy. The polarisation state of the output light beam expressed by (1) and (2) would manifest itself as a sizeable deviation from the initial QED prediction [3] for which no measurable linear dichroism is expected. Photon splitting effect can produce a differential absorption [15] giving rise to a maximum apparent angular rotation of the polarisation of the order of ~ 10^{-33} rad in a 9.5 T magnetic field over a length of 250 km, an angular rotation that is far from being measurable in laboratory conditions. The ellipticity predicted by the QED vacuum-polarisation constitutes the background signal that can be expressed from one loop calculation as:

$$\Psi_{QED} \approx (B^2\, l\, \alpha^2\, \omega / 15\, m^4) \sin 2\theta \tag{3}$$

where $\alpha \approx 1/137$ is the fine-structure constant, ω is the photon energy and m the electron mass. To fix the ideas, the maximum of ellipticity acquired by a laser beam with $\lambda \approx 1550\, nm$ propagating in a 9.5 T field over a length l = 250 km is equal to ~ 2.10^{-10} rad.

2.3. Photons regeneration from “a shining light through the walls”

The second purely laboratory experimental approach to detect axions is of direct type. It is based on the photon regeneration effect using a linearly polarised laser light beam send through an optical absorber [14]. When the polarisation of the light is parallel to the magnetic field, photons of energy ω are expected to be converted to axions with a maximum of probability $P_{\gamma \rightarrow a}$. Such weakly interacting particles can then propagate freely through an 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:

$$CR = \eta\, (P_{\gamma \rightarrow a})^2\, P_L / \omega \tag{3}$$

where $P_{\gamma \rightarrow a} = P_{a \rightarrow \gamma}$, η is the efficiency of the photon detector and P_L the optical power of the laser. In the limit $m_A^2\, l / 4\omega << 1$, the conversion probability $P_{\gamma \rightarrow a}$ is given by [16]:

$$\mathrm{P}_{\gamma \rightarrow \mathrm{a}} \approx B^2 l^2 / 4\, M^2 \tag{4}$$

By rotating the polarisation 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.

It can be added that, according to predictions beyond the pure QED and introducing the mixing with paraphoton, photon regeneration may also occur in the absence of magnetic field [17]. This perspective brings an additional scientific motivation to our project and such a possibility has been considered for the choice of the detection principle for the photon regeneration experiment. One of the consequences of the existence of paraphotons for example, is to provide an explanation for cosmic rays detected with energy above the GZK limit[†].

3. Experimental methods and expected results

3.1. Integration of the 2-in-1 experiments

Because of the strong transverse magnetic field required, an ideal implementation for the VMB and photon regeneration experiments are within long superconducting accelerator magnets such as the ones developed and manufactured for the LHC (Large Hadron Collider) under construction at CERN. Full-scale dipole prototypes have been built to validate the magnet design and will no longer be used for the accelerator. One of the first generation was already decommissioned and is at present in routine operation for the CAST experiment to detect solar axions. Third generation twin aperture superconducting LHC dipole prototypes offer the advantage to have a magnetic field region of length equal to 14.3 m. The maximum field they can reach is around 9.6 T at 1.9 K, which corresponds to the limit of superconducting cables in the peak field region. They have been extensively tested and magnetically characterized in the SM18 facility at CERN which provides the cryogenic environment for cooling large superconducting magnets below the lambda point of liquid He (Fig.1).

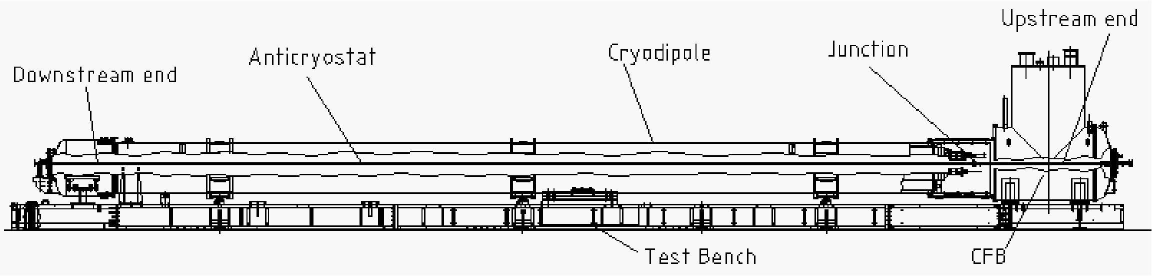

Figure 1: *Layout of a cold test bench for dipole magnets equipped with anticryostats and connected to its Cryogenic Feed Box (CFB). The overall length is equal to 19.6 m.*

The availability at CERN of several decommissioned LHC superconducting magnets offers the opportunity of several upgrades for the proposed experiments, each of them improving the sensitivity by increasing the vacuum light pass in transverse magnetic field with the connection of additional magnets.

[†] The Greisen-Zatsepin-Kuzmin limit is equal to 5.10^{19} eV; It comes from the fact that cosmic rays lose energy through collisions with photons from the cosmic microwave background as they race through space at close to light speed.

3.2. VMB and optical absorption anisotropy experiments

To measure the VMB and absorption anisotropy expressed by (1) and (2) respectively, the experimental approach must focus on two main requirements already addressed in the feasibility study [6], [7], [8]. First, the ellipticity and the apparent rotation of the polarisation acquired by the initially linear polarized laser beam propagating through the vacuum submitted to a transverse B field must be boosted by using an optical cavity (Fig.2). Second, the measurement principle of the extremely small polarisation change must be optimised together with the optical detection technique.

To measure the ellipticity expressed by (1) and (3), a single LHC dipole has $B^2\ l \approx 1290\ \mathrm{T}^2\,\mathrm{m}$ and $B^2\ l^3 \approx\ 263.10^3\ \mathrm{T}^2\,\mathrm{m}^3$ which are respectively about 10 and 20 times larger than the magnetic characteristics of the VMB experimental setup providing the present reference results [18] obtained by the BFRT collaboration (Brookhaven, Fermilab, Rochester, Trieste). Additional gains can be obtained by optimizing the performance of the optical cavity, and of the detection principle [6], [7], [8].

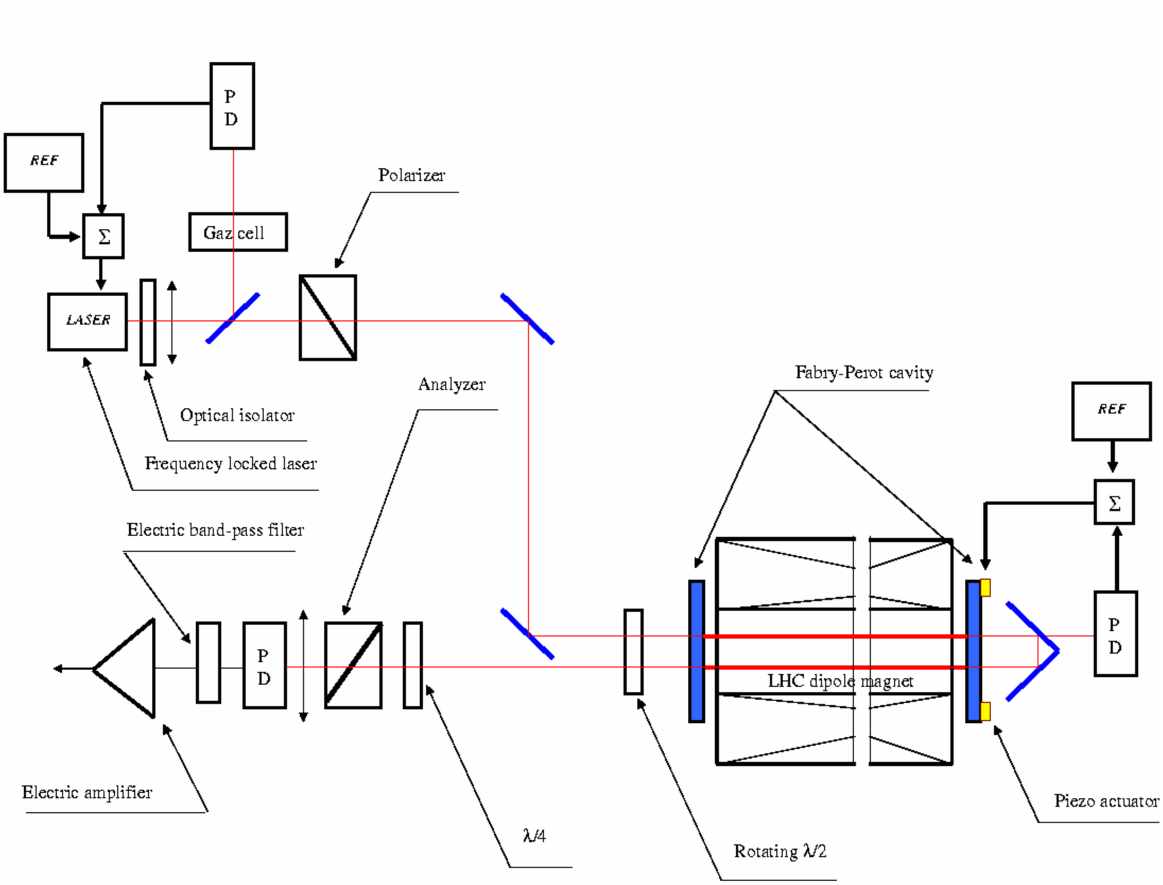

Figure 2: *Optical part of the proposed experiment to measure the VMB.*

A first version of the optical configuration proposed to measure very small optical birefringence is given in Fig.2. It is based on a novel measurement method using a double path of light through a half-wave plate mounted in a high-speed rotation stage. The initial linear polarization state of the laser beam can be modulated typically in the kHz range. After the second pass through the half-wave plate, 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. Then a quarter-wave plate will convert the quasi-linear polarized laser beam coming out from the cavity into a quasi-circular one. Finally, a polarizer will ensure a linear and optimal conversion of the induced ellipticity into a power modulation of the laser beam. A photodiode will be used for the detection. For the phase-1 of this project, an improvement of at least 2 orders of magnitude of the present reference results [18] concerning the VMB and absorption anisotropy is expected together with the measurement for the first time of the QED prediction [6], [7], [8].

By replacing the half-wave rotating plate by an electro-optic modulator, it can be expected to work in the MHz range for the modulation and the detection. This constitutes one of the alternative solutions studied at present to improve the VMB measurements. Several additional upgrades are also currently investigated to further increase the experiment sensitivity. For example, the use of cold bores instead of warm ones will allow improving the quality of the vacuum by reducing the pressure below 10^{-9} torr with the cryopumping effect. This will decrease the background signal coming from the Cotton-Mouton effect of residual gases.

3.3. The photon regeneration experiments

To complement and cross check the VMB measurements, a second experiment is also currently considered. Its aim is to detect the photon regenerations from axions using the concept of “a shining light through the walls” [14]. The realisation of this additional setup is also feasible with a minimum of investment. It is planned to integrate it in the second aperture of the 15-meter long LHC prototype superconducting magnet. The principle of this experiment is schematised on Fig.3. An optical resonant cavity inserted inside a part of the dipole magnetic field region is used as an axion source and a photomultiplier, with a proper magnetic shield, or an avalanche photodiode 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.

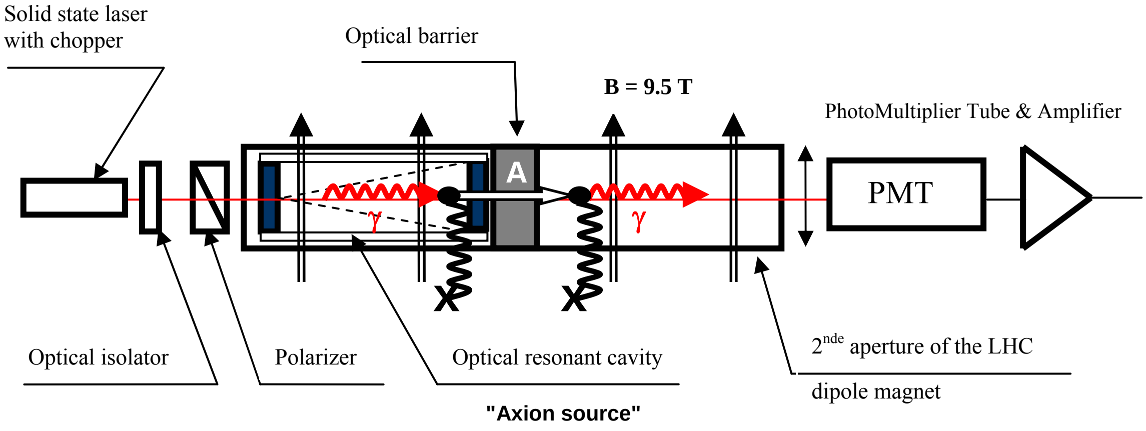

Figure 3: *Principle of the photon regeneration experiment.*

By using a Nd-YAG laser for example, an optical beam power as large as 100-1000 W 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 of the same length.

Assuming the use of a single LHC dipole with a 7-meter long regeneration region and an optical cavity of the same length with a finesse $F \approx 10^5$, the photon counting rate given by (3) can be improved by a factor of 10^7-10^8 with respect to the present reference result obtained with this type of experiment. This corresponds to an upper limit for the coupling constant to two photons $1/M$ down to about 6.10^{-9} GeV^{-1} i.e. an improvement of 2 orders of magnitude with respect to the BFRT results [18].

For this experiment, several upgrades are also currently studied such as the filling of the regeneration zone with a gas to extend the sensitivity to larger axion masses and the connection in series of one, two or more additional 15-m long prototype superconducting magnets to increase the overall experiment sensitivity. At least 6 prototypes superconducting LHC dipoles are stored on the CERN site and could be used for the photon regeneration experiment. That means the upper limit for the coupling constant to two photons could be lowering down to about 10^{-9} GeV^{-1}.

4. The collaboration and the funding

This *Letter of Intent* is the result of an incipient collaboration between 7 institutes. The final list of all participants that will collaborate in this project is under construction.

The re-use of the maximum of developments made at CERN for the LHC and the cold tests of superconducting magnets is considered as a baseline before driving new developments. This concerns, in addition to available superconducting magnet prototypes housed in their cryostat, the vacuum technology, the anticryostats and the test infrastructure at SM18, which includes the cryogenics and the magnet power supply. 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. It is expected that CERN could provide the resources and the funding for the standard services required by the running of experiments.

The part of the project dedicated to the design, integration and support of all optical elements in the anticryostats housed inside the magnet apertures will be realised by the Czech Republic part of the collaboration i.e. between groups from the Charles University and the Czech Technical University of Prague and the Technical University of Liberec (TUL). The mirrors with a radius of 19.6 m required by the optical confocal cavity for the VMB measurements will also be produced by the Czech Republic team of the collaboration.

The optical detection technique 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 the optical ellipsometry techniques [19]. Concerning the development of high quality optical cavity required for the signal amplification of both experiments, the LSP (Laboratoire de Spectrométrie Physique) of the University of Grenoble will provide the essential expertise.

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

Other groups have also expressed their interest to this project such as the group of Dr. B. Barbara and Dr. R. Ballou of the Louis Néel Laboratory of CNRS (Grenoble) as well as the group of Professor A. Morales of the University of Zaragoza (Spain).

The most expensive parts of the project, namely the superconducting magnets, the cryogenic infrastructure, the power supply and the required electronic equipment are already built. An estimate of the cost of the optical instrumentation for both experiments is in progress. Concerning the strategy, it was approved that each national team should address any financial need to their own funding agencies.

5. Concluding remarks

The proposed project offers an exciting opportunity with a broad scientific interest beyond the standard model. This concerns the direct and indirect search of scalar or pseudo-scalar weakly interacting particles such as axions and the possible detection of the mixing of “sterile” photon with paraphoton.

In addition, one of the proposed experiments allows new investigations in a domain of Physics that is guaranteed by the vacuum-polarisation predicted by QED. The test of the QED prediction by measuring an ellipticity of the order of 10^{-10} rad in a 9.5 T magnetic field with the proposed experiment is equivalent, in a sense, to a CPT test at the level of about 10^{-22} that corresponds to the relative change of the vacuum refraction index. To fix the scale, the present best CPT test was obtained with neutral kaon system (K^0, $\underline{K}^0$), at the 10^{-18} level [20] and is model dependent as QCD calculations are required. The birefringence experiment and its QED analysis in terms of CPT test is also model dependent. A third experiment is currently under study to propose a fully model independent CPT test by means of optical techniques.

Concerning light scalar or pseudo-scalar such as axions that couples to photons, at least one of the proposed experiments will improve during the phase-1, by 2 orders of magnitude the present reference results for the limits of axion di-photon coupling constant obtained with an optical experiment. Additional gains are expected during subsequent upgrade phases of the project by improving the vacuum (cold bores approach), the optical cavities, the optical detection and by connecting several LHC superconducting dipoles in series.

Recent results published by the PVLAS experiment [21] provide additional motivation for a purely laboratory axion search experiment that is fully independent of cosmology assumption or solar model. Note that the recent negative result reported by the CAST collaboration [22] and the detection by PVLAS of an apparent rotation of the polarisation generated by a magnetic field of a laser beam propagating in the vacuum [21] are not necessarily inconsistent. Two scenarios were recently proposed for a coherent interpretation of both experimental results by evading the astrophysical bounds [23]. 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 1eV. In the second scenario, the possibility to have a suppression of the Primakoff process for axion production is developed. Such a possibility, if it is confirmed, will modified significantly the present exclusion region diagram for axion mass versus axion photon coupling constant related to various types of experiment [24] and this will provide a strong revival of interest for purely laboratory axion search by means of optical techniques. Laboratory experiments for axion search are in the same continuity line that brought particle physics from cosmic rays to accelerator based experiments. The project proposed in this *Letter of Intent* is complementary to the PVLAS and CAST experiments and can constitute a first step toward a larger scale laboratory experiment such as the one that proposed a "massive" recycling of the HERA's superconducting dipole magnets for axion search [25].

In addition to fundamental scientific interests, laser measurement techniques developed for this project will certainly impact on optical metrology techniques as well as for the next generation of accelerator technology, for instance the part concerning the precise characterisation of field strength and transfer function of magnets for future accelerator projects [26].

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