PBC technology subgroup

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Abstract

Goal of the technology WG set by PBC:

Exploration and evaluation of possible technological contributions of CERN to non-accelerator projects possibly hosted elsewhere: survey of suitable experimental initiatives and their connection to and potential benefit to and from CERN; description of identified initiatives and how their relation to the unique CERN expertise is facilitated.

Keywords

CERN report; Physics Beyond Collider; Beyond the Standard Model; Technology.

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Contents

1 Physics Landscape of Technology sub-group

The initiatives of the "Physics Beyond Collider (PBC) [1] technology working group" tackle exciting physics: the search for Dark Matter, novel forces and precision measurements of Standard Model Physics. Such initiatives can be existing or new experiments. They have in common that they depend little (or not at all) on colliders nor accelerators. However, all of them profit greatly from infrastructure that has been developed or is useful also in the accelerator context. The goal of this study is develop and maintain all kinds of technical synergies between these initiatives and CERN.

Before starting it is important to give the following 'health warning': The initiatives discussed in this document have been presented in public sessions in the PBC general meetings. It should thus be noted that there are often many other initiatives in the same research field, which will not be discussed here. Our aim is to review only the initiatives that have sought to profit via PBC from CERN technology. These initiatives are briefly described in the following and detailed information on these initiatives can be found in Appendix A. On the other hand, we emphasize that the PBC is an open process and that interested groups are always welcome to join discussions.

Technology concerned	benefit from CERN	benefit to CERN	how facilitate?	Exps concerned
Magnet, concretely: high-field, large-bore	availability of strong fields, CERN expertise to build custom magnets	make optimal physics use of magnet resources (spares)	advertise magnet usage times, provide expertise in magnet design, PBC-fellow for IAXO	IAXO, JURA, STAX, VMB@CERN
Optics/Optics sensing, concretely: Fabry Perot, membranes	surface coating, possibility to combine magnet with optics	add local expertise on cavity optics technologies	"optics hub", as described in the document	aKWISP, VMB@CERN, JURA
Radiofrequency cavities, concretely: design for axion searches	experience in design and production	new cavity designs for various physics purposes, tuning and characterization in cryogenic environment	mandate for cavity experts to aid in design	Grenoble initiative, & other Haloscope initiatives operating already at CERN, STAX
Cryogenics, concretely: large-scale: helium, argon, krypton from 120K to mK	availability of cryogenic facilities	participate in research beyond collider	mandate through TE-CRG	DarkSide, aKWISP, VMB@CERN, IAXO
Vacuum, concretely: large-scale leak testing	experience & availability	participate in research beyond collider	mandate through TE-VSC	DarkSide, JURA, aKWISP, CNT

Table 1: Relation between experiments in the PBC technology working group and the relevant technologies.

Most (direct WIMP) Dark Matter searches aim to record the recoil energy of nuclei after scattering with DM particles. One example for this strategy is the **DarkSide** experiment [2]. DarkSide-20k (DS20k), to be placed at LGNS is a direct search of Dark Matter via the detection of WIMPs (Weakly Interacting Massive Particles). It uses a Two-Phase Liquid Argon Time-Projection Chamber with a fiducial mass of 20 tons. When in operation, with an ultra-pure Underground Argon, DS20k will be the first noble liquid detector entirely equipped with photosensors assembled with Silicon Photomultipliers (SiPM), a key enabling technology for next generation WIMP searches.

At lower (sub-GeV) masses one possibility is that DM particles can be detected through electronic recoils. One novel concept is to measure these along **Carbon Nanotubes (CNT)** [3]. Such nanotubes are also considered as DM target in PTOLEMY [4]. PTOLEMY is now aiming to study a series of technologies that would ideally lead in 3-4 years to start to design and build an experiment to detect light dark matter and eventually cosmological neutrinos. The need for large samples of purified detection media can profit from **Cryogenics** and **Vacuum** technologies in use at CERN.

The particle-recoil-strategy is optimal for WIMPs with masses near the GeV-scale but leaves out very light Dark Matter candidates such as the axion. A recent review of the various types of axion searches, that will also play a role in the following, is given in [5].

The axion as Dark Matter is commonly searched for with **Haloscopes** [6]. Most Haloscopes detect axions through their assisted conversion into photons using **Radiofrequency** cavities of high quality factors in strong-field, typically superconducting **Magnets**. Substantial expertise with the Haloscope technique has been gathered in the ADMX collaborations [7], culminating in multiple search results at benchmark QCD sensitivity. In the past recent years, Haloscope implementations at CERN have been set up within CAST, see [8] as well as [9] (the R&D of [9], RADES, eventually aims at using the haloscope technique in IAXO in the future). An initiative for a new haloscope uses a modular hybrid magnet platform would be hosted at the **CNRS/LNCMI-Grenoble, and thus called Grenoble Initiative**.

Without assuming that the axion (or more general, an Axion-like- particle) constitutes Dark Matter, they can be searched for using their direct production in the sun: The ALP/axion from the sun is converted into a photon in the **Magnet** of a “helioscope” [6]. First results of CERN’s CAST helioscope were presented almost 15 years ago [10], using an LHC test-dipole. For the future a custom-made helioscope, called **IAXO** has been proposed [11]. The International Axion Observatory ‘IAXO’ is a fourth generation axion helioscope featuring three large scale subsystems like magnets x-ray optics and detectors, purposely designed for the goal of searching for solar axions with axion-photon coupling down to a few 10^{-12} GeV^{-1}.

In a fully lab-based setting, ALPs can be searched for, using photon beams of various wave-lengths with the light-shining-through-wall (LSW) technique. In the optical, present high power cavities can be ideally operated with 1064 nm. LSW uses two **Magnet-**strings, one before and one behind a light-tight barrier. In the LSW technique, mastering **Optics** technologies is the key to pushing sensitivity. At CERN, the experiment OSQAR is currently providing un-surpassed sensitivity in purely lab-based ALP searches [12]. A “second generation” LSW experiment currently under construction at DESY is ALPS-II [13], aiming to use an advanced optical concept based on resonating cavities, some aspects of which have been already successfully realized [14]. A proposal for a multi-stage experiment of the third generation, is the “Joint Undertaking on Research for Any-light particles” **JURA** which could combine the detector and optics development by ALPS II with dipole magnets existing or under development at CERN. To realize the LSW-technology for ALPs with Tera-Hertz photons is the goal of **STAX** [15].

Another application in which optics are the key technology is the search for novel physics which might take the form of density-dependent fields with **aKWISP** [16]. This experiment constitutes an opto-mechanical detector based on the optical interferometric read-out of a pair of nano-membranes.

In both situations, LSW and aKWISP, besides **Optics** improvements **Cryogenic** environments can push sensitivity. Finally, these tools are also needed for measuring for the first time QED non-linearities in external **Magnetic fields**, as predicted some 80 years ago [17]. Testing the Standard Model in new regimes is a key tool in uncovering new avenues in the exploration of particle physics. A fundamental, outstanding test of QED in the macroscopic regime is the measurement of magnetic vacuum birefringence (VMB). An initiative, called **VMB@CERN** [18], to perform this measurement at CERN is through the combination of optics expertise of several groups already involved in VMB measurement tentatives: **PVLAS** [19], **OSQAR** [20], **Q&A** [21], as well as a contribution from the University of Cardiff, Wales, LIGO group. To finish, having been the promoter in the early 1980's of VMB measurements with optical techniques VMB is one of the many hidden inheritances from CERN [22, 23].

An overview of initiatives, their & relation technology to CERN is given in Table 1.

The document is structured as follows: In Sect. 2, 3, 4, 5, 6 we will discuss the initiatives from the viewpoint of magnet, radiofrequency, optics, vacuum and cryo-aspects, respectively. In Sections 7 we will point at synergies between the projects, and we will finish with some concluding remarks in Section 8.

2 Magnet Technology Landscape

Five out of eight proposed projects require use of superconducting magnets as listed in Table 2. Also 4 out of 6 explicitly request siting at CERN, essentially to use one or more LHC type of dipole magnets including cryo-stating, supply of cryogenics and powering infrastructure.

Id	Initiative Name	CERN siting proposed	CERN requested magnet support
1.	(Baby)IAXO solar Axion search	Eventually	Magnet design, engineering and construction support
2.	Haloscope, Axion search using Hybrid Magnet at Grenoble	No, Grenoble	Magnet expertise
3.	JURA1, Axion search and WISP search	Yes, i.e. B180	8 units 9 T LHC Dipole Magnets if possible depending on LHC operations and availability, Cryogenics and Powering
4.	JURA2, Axion and WISP search	Yes	About 20 units 15 to 16 T FCC type Dipole Magnets, add on to pre-series or 14 units of LHC dipoles
5.	LSW-STAX, Axion search	Yes	2 units 11 T short model Dipole Magnets in 2 cryostats, Cryogenics and Powering
6.	VMB@CERN	Yes	1 high field LHC+ Dipole Magnet, Cryogenics and Powering

Table 2: List of PBC Initiatives that require CERN's Magnet Support and eventually requesting CERN siting.

The Grenoble Haloscope is using the high field hybrid magnet in construction at LNCMI Grenoble and is seeking general magnet support and sharing of expertise from CERN. **IAXO** relies on the design and engineering laboratory at CERN for construction of a large-scale toroid presently aimed at installation at DESY. Since magnet design is almost exclusively covered by CERN and a significant financial contribution to the engineering models and eventually IAXO construction is requested. The first stage of the project for the next 5 years is **BabyIAXO**, a 1/16 scale fully functional model for demonstration and exercising the technology and providing a sensitivity beyond the CAST reach.
The other 4 projects all use LHC or beyond type of dipole magnets. The proposal easiest to realize is

VMB@CERN, requesting operation at CERN of a single 8 to 9 T LHC type of magnet or **babyJURA** with 2 LHC dipoles.
Next is **LSW-STAX** requesting operation at CERN of two 11 T short dipole magnets with proper cryostats.
Much more ambitious is **JURA1** requiring operation at CERN of 4+4, thus some 8 units 8 to 9 T LHC dipole magnets. Given the present limited spare parts of LHC the availability of 8 spare magnets may depend on the operational experience of the LHC and HL-LHC. Realization of JURA2 may require a dedicated low-cost production of some 10 to 20 LHC/FCC type magnets.
Most ambitious in terms of magnet requirements and a long term project is **JURA2**, opting for operation on CERN site of 7+7 LHC dipoles or some 20 fully functional full-size 15 to 16 T class FCC dipole type of magnets for which demonstrator constructions eventually may start in the coming years and obsolete or production add-on units are not likely available before year 2030 or even beyond.

3 Radiofrequency (RF)

3.1 Sharing the CERN Know-How in RF cavity developments

Several initiatives submitted to the PBC technology working group for axion dark matter (DM) searches such as the Grenoble haloscope, IAXO and STAX proposals, require an extensive use of RF technologies. For the resonant photon conversions of axions or ALPs in a strong background magnetic field, the development of resonant cavities of various sizes and shapes with quality factor of 10^5-10^6 could profit from the CERN know-how in RF technologies. To probe axion of mass in the range 0.1 to 800 μeV, the frequency must cover the domain 0.2 to 200 GHz. To fully exploit the conversion volume permeated by the strong magnetic field, multiple cavity schemes could be implemented at high frequency. This implies the production of identical cavities and tuning all of them at the same frequency with dedicated phase matching.

3.2 Improving the performance of the RF detection chain

The development of state-of-the-art quantum amplifiers for the above frequency range is also of prime importance. In the microwave range, the best performances are obtained using cryogenic devices such as high electron mobility transistor amplifiers, SQUID-based amplifiers or parametric devices. To achieve the lowest possible noise temperature, Josephson parametric amplifiers (JPAs) have become the technology of choice for the sub-GHz range and could allow reaching the quantum limit as this was already demonstrated in various laboratory worldwide. RF filter structures are being explored and pursued at CERN within an emerging collaboration between RF specialists and physicists (RADES project). To reduce the thermal noise, all RF equipment including cavities and amplifiers, shall be cooled down below 4K, ideally 40 mK with dilution refrigeration, requiring dedicated cryogenic developments such as the ones already realized for large volumes at CERN and at CNRS Grenoble.

As a summary, the combination of CERN magnet infrastructure with the developments of novel RF structures and ultra-low temperatures can have significant impact on axion DM searches.

4 Optics

Optics and optical techniques have been key to several fundamental advances in science. Very recently and notably with the discovery of gravitational waves, optical detection techniques have come again into the spotlight. Precision physics experiments, where optics often plays an important role, have risen to the forefront in particle physics as tools to investigate and perhaps solve, among others, the Dark Matter and Dark Energy problems.

4.1 Assessment

CERN, as a leading institution in physics research, could act as a catalyst for ideas and techniques exploiting optical detection technologies, while CERN-based activities and also experiments in contact with CERN could benefit from exchange of information and collaboration opportunities. CERN already hosts many groups (KWISP at CAST, OSQAR, several ISOLDE-related groups, MEDICIS, AWAKE, to name just a few) who routinely use optics-based techniques such as (not exhaustively):

- interferometry,
- polarimetry,
- opto-mechanics,
- fiber scintillators and fiber optics,
- laser ranging,
- spectroscopy.

Several research groups (for instance *a*KWISP, ALPS, PVLAS, OSQAR-VMB, Virgo) either participating in the PBC initiative or in contact with CERN, are also involved at various degrees in optics.

4.2 Optics Technology Hub proposal

An “Optics Technology Hub” (OTH) can be set up at CERN, with the goal of supporting and coordinating, especially by exchanging information and stimulating collaboration opportunities, all the advanced optics technologies to be brought to bear now, and in the foreseeable future, in experimental particle physics . The OTH could be structured as a semi-informal working group aiming at:

- following the most recent applications of optics technologies to particle physics experiments sharing information among CERN-based groups employing optics;
- fostering collaborations and synergies on common physics themes which can be attacked using optics technologies;
- keeping contacts with non-CERN activities which use (or may benefit from) optics technologies.

The Virgo collaboration, who already has official ties with CERN in the form of a recognized experiment, will name an observer to follow the activities of the Technology Working Group and to participate in the OTH. Fruitful contacts can be started with DESY and locally based activities, chiefly the ALPS collaboration, who intensively use optics technologies. In particular, DESY hosts a large optics laboratory, has cryogenic facilities and is connected with the LIGO/GEO gravitational wave community. Contacts can also be established with the LNCMI laboratory in France, in particular with the BMV group whose experiment aims at the measurement of VMB using pulsed magnetic fields in conjunction with precision cavity-enhanced polarimetry.

An essential action towards the OTH could be organizing an informal kick-off workshop at CERN. The main aim would be to establish initial ties within the interested community, and to start discussing recently emerging themes, such as the combination of cryogenic and optical techniques where extremely low noise performance is a stringent requirement.

5 Vacuum

5.1 Relation of initiatives to vacuum group expertise

The initiatives of the technology working group require in general an extensive use of the vacuum and surface coating technologies and can profit greatly from the expertise and infrastructures that were developed over the years at CERN. Most of the initiatives require advanced high and ultra-high vacuum systems for the experimental set ups and/or detectors, expertise in vacuum sealing and leak-tightness technology and expertise in dynamic vacuum phenomena.

5.2 Vacuum and surface coating expertise for the initiatives within the PBC technology WG

The advanced high and ultra-high vacuum technologies concern in particular searches like the helioscope IAXO and lab-based experiments using photon beams with the light-shining-through-wall technique like the STAX and the JURA stages. The expertise in vacuum sealing, leak-tightness technology and leak detection techniques for large vacuum systems is of crucial importance for the ARIA facility which is an essential part of the DarkSide experiment. A novel concept for dark matter searches based on the use of the Carbon Nanotubes requires large nanotubes samples of purified detection media. Development of such detection media can profit from vacuum technologies in use at CERN where many relevant and unique expertise exists. This consist in particular of UHV characterization of materials as well as the outgassing and degassing analysis and treatments of materials, including gas analysis by chromatographic techniques. Another potential use of CERN vacuum and surface coating technologies and expertise is pertinent for the searches for novel physics like the aKWISP initiative, which targets the density-dependent fields. The aKWISP can profit from CERN's thin film coating facilities that focus on physical deposition techniques like evaporation, diode and magnetron sputtering, including the XPS quality control for the thin film coatings as well as specific techniques for plasma processing of surfaces, including plasma cleaning and glow discharge. It is of interest of the most of initiatives within the PBC technology WG that CERN facilities can provide the surface cleaning and tailor-made surface treatments for vacuum, brazing and coatings, including numerical simulations of special cases of coatings, vacuum and plasma treatments.

6 Cryogenics

6.1 Relation of initiatives to cryo group expertise

The technological contribution of CERN in the domain of cryogenics can be summarized in a large spectrum of equipment and operating temperature range (from 120 K to mK) mainly focused on helium, nitrogen, argon and krypton facilities coupled to cryogenic test benches, superconducting devices and detectors requiring refrigeration capacity at low temperatures.

Experimental initiatives in the physics beyond colliders domain may certainly take advantage from CERN's already existing cryogenic infrastructure, technological experience and long term reliable operation of such equipment. Benefit to CERN will be the active participation to a sustainable, wide and innovative physics program based on non-accelerator projects.

6.2 Projects and proposals

Regarding the IAXO experiment proposal, a cryogenic study was already conducted and published in collaboration with the Cryogenics group at CERN[1]; the contribution to the BabyIAXO proposal may be focused on the update of the existing study.

In the "advanced-KWISP" initiative the main activity is focused on the cryogenic design and construction of a table-top liquid helium cryostat allowing the cooling down of the combined source-detector device. The procurement and operation of a helium refrigerator system allowing to reach sub-Kelvin temperatures is required.

The DarkSide project has already on-going cryogenic prototyping activities at CERN in the frame of a defined work-package, including the assembly of a one ton liquid argon cryostat and its ancillary liquid nitrogen refrigeration infrastructure to be located in the premises of the Cryogenic Laboratory at CERN, for validation and characterization tests and measurements.

The Grenoble initiative is requiring a dedicated cryogenic refrigeration system at ultra-low temperature (dilution refrigerator of large volume). The JURA 1 proposal will require a complete and very

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[1] Ref. arXiv:1308.2526v1; [physics.ins-det]

large cryogenic helium refrigeration and distribution systems at 4.5 K and 1.8 K temperature range to be coupled to the required 4+4 spare LHC superconducting dipoles magnets infrastructure.

In the frame of the proposal for "Vacuum Magnetic Birefringence" (VMB@CERN) research, helium cryogenics at 1.8 K are required in order to cool down and operate one LHC type superconducting dipole; regarding the required infrastructure, a cryogenic test facility bench at CERN, such SM18, can be considered as potential location. Additionally, expertise may be required for the cooling to cryogenic temperatures of selected critical optical elements.

Always in the same domain of "Measurement of the QED Vacuum Magnetic Birefringence" a much larger project making use of existing LHC superconducting dipole magnets at their ultimate field of future HL-LHC/FCC type magnets will require heavy cryogenic infrastructure and helium refrigeration and distribution systems at 1.8 K and 4.5 K temperature.

The "STAX" proposal, making use in a first phase of an LHC 9 T superconducting dipole, then potentially in a second phase of and HL-LHC 11 T type magnet, will both phases require a dedicated helium refrigeration system at 4.5 K and 1.8 K temperature range.

The "JURA 2" initiative based on the operation of a long string (>10) of high field superconducting accelerator type dipole magnets will require a very large cryogenic infrastructure in terms of helium refrigeration and distribution systems at 4.5 K and 1.8 K temperature range.

7 Synergy Light Shining through Walls + Vacuum Magnetic Birefringence (VMB)

Both LSW and VMB measurements are laser based experiments requiring state of art optics. Both require sending a laser beam through an intense magnetic field. In LSW measurements two (or more) magnets are necessary: the first is to generate the ALPs through the Primakoff effect and the second magnet is used to regenerate light from the ALPs behind a wall separating the two magnets. In VMB measurements linearly polarized light is used and the induced ellipticity after the magnet is measured. To improve the sensitivity in both cases Fabry-Perot resonators are used to increase the interaction time with the magnetic field. The use of such cavities render the optics of these experiments extremely delicate. In this optical domain, very similar magnetic and optical technologies are therefore required for both VMB and LSW. In ALP searches, measurements of both VMB and Vacuum Magnetic Dichroism[2] (VMD) using CERN magnets may also be competitive to LSW efforts. LSW measurements are also being pursued in the micro-wave regime allowing an increased number of input photons. Also in this case the necessary magnetic field is in common with the other initiatives. **This makes these lines of research complementary.**

7.1 VMB@CERN

- The optics necessary for a VMB (due to QED) direct observation using static high magnetic fields seems to be mature. (Static field means that the birefringence signal modulation is *not* due to a modulation of the magnetic field). A first tentative using an LHC magnet was performed by the OSQAR-VMB collaboration in the past, without success due to optics difficulties. **The principal necessity for a VMB detection is to push the field strength to the highest possible values (≥ 9 T) over lengths of $\gtrsim 10$ m.** This implies the use of superconducting magnets, liquid helium and power. At present CERN has working LHC dipole magnets with such a field with the necessary infrastructure, cryogenics and power supplies.
- **VMB may also benefit from top level expertise in cryogenics available at CERN applied to the optics** to reduce thermal noise. Currently thermal noise is limiting the sensitivity of ultra-sensitive experiments like gravitational wave interferometers and VMB experiments. Higher order corrections to VMB may then be achievable. **This is an emerging field and testing is underway in the PVLAS collaboration.**

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[2] Dichroism is a polarization dependent absorption which results in a polarization rotation as opposed to an ellipticity.

7.2 Synergy within LSW (JURA) and with VMB@CERN

- Both VMB and LSW experiments need static magnetic fields as strong as possible.
- In both VMB and LSW it is arguably better to try to limit the length of the magnets. In both cases light must be shone through the bore of a magnet. Problems may arise:

  1) the longer the magnet, the larger the laser beam will need to be thereby needing a larger bore (resulting in a lower field);

  2) to increase the effect under investigation resonant Fabry-Perot cavities can be used but the longer the magnet the narrower the resonances will be thereby **requiring extra mechanical relative stability of the optics at the two ends of the resonator. A single rigid beam/optical bench supporting the optics would be desirable.**
- STAX may overcome some of these difficulties by using high power radio frequency radiation (100 kW) resulting in an increase in the number of photons available for a photon-axion conversion. A drawback may be that the improved sensitivity is for masses below $\sim 10^{-5}$ eV due to the low photon energy. Indeed, the expected KSVZ and DFSZ axion-photon coupling is proportional to the mass of the axion.
- **In PVLAS, OSQAR, BMV, ALPS, STAX etc. there is lots of valuable expertise to bring together.**

7.3 Synergy STAX - JURA

After careful review on the state-of-the-art and all the existing classes of experiments in the field of LSW, it was realized LSW laboratory experiments have never really been optimized so far because of a lack of technology in sub-THz single photon detection, where the highest luminosity sources of photons operate, with fluxes up to 10^{28} photons/s, and the axion production rate can be increased by many orders of magnitude. Furthermore detectors using nano-technology and Quantum Physics could bring a very strong impact if applied to these Fundamental Physics searches.

The STAX project suggests an innovative version of the LSW class of experiments, achieved with the use of extremely intense photon fluxes, obtained moving to the sub-THz region where gyrotrons or klystrons can operate. The novelty of this project will be the first implementation ever of a Transition-Edge-Sensor (TES) single photon detector below the THz region. The implemented solution could, in principle, improve the present laboratory limits on g four orders of magnitude. The STAX facility will rely on two strong dipole magnetic fields of intensity B = 11 Tesla each, and a length L = 150 cm. The suggested magnets consist in two prototypes of the HL-HLC program that fit perfectly these needs.

The OSQAR LSW experiment makes use of two superconducting dipole magnets of the type used in the Large Hadron Collider that contain a vacuum chamber measuring 55 meter in length by 40 millimeters across. To improve the sensitivity a new joint proposal, JURA, is being presented consisting in a multi-dipole LSW experiment, able to strongly increase the BL power, proportional to the amplitude of the photon-axion conversion. STAX and JURA could be synergetic, in a picture where the OSQAR scheme and infrastructure, the SM18 location and the cryogenic system could be used or partially used, moving to the microwaves domain. With a Sub-THz source of photons and a single photon detector like the one proposed by STAX, for instance an ultra-cold TES device, the sensitivity in g would increase by order of magnitudes, allowing the number of magnets and the length of the magnetic path to decrease with an optimization of the cost of the whole set-up. In principle, a very good solution could be to use the OSQAR infrastructure at SM18, replacing the two dipoles with the 11 T HL-LHC prototypes, and a source of 10 to 30 GHz photons like a high power klystron or a gyrotron.

7.4 Summary on Synergy

Within ALP searches, in Table 3 the main characteristics of the different Light Shining through the Wall initiatives and the Vacuum Magnetic Dichrosim initiative are compared. The precursor of ALPS IIc, namely ALPS II, is under construction and will (hopefully) be ready for data taking in 2020. Finally, by using the major achievements of the Large Hadron Collider like the above mentioned superconducting dipoles and test infrastructure as well as future prototype dipoles built for the Future Circular Collider (FCC), CERN is the most promising and best site for such experimental efforts. LSW and VMB bring an opportunity to re-enforce at CERN, and on the long-term basis, the innovative program in the emerging field of laser-based particle physics exploring the promising low energy frontier (sub-eV).

It is worth mentioning that all of the above initiatives can also be conducted in synergy with research and developments performed at CERN on superconducting magnets by exploiting for example statistics on quench occurrence when dipoles will be powered and cycled many times close to their limit to investigate their fatigue behavior and long term stability as this has been already done with spare LHC dipoles used for OSQAR.

	Light Shining through the Wall (LSW)					Dichroism
Status	Approved	Proposed initiatives				
Initiative	ALPS IIc	BabyJURA	JURA 1	JURA 2	STAX	VMB@CERN
Magnet assembly	10 + 10 HERA	1 + 1 LHC	4 + 4 LHC	LHC-FCC	1 + 1 FCC	1 LHC
Field length L_B [m]	94 + 94	$14.3 + 14.3$	$57 + 57$	$100 + 100$ $480 + 480$	$1.5 + 1.5$	14.3
B [T]	5.3	9	9	9 - 15	11	9
Photons/s R [s^{-1}]	$1.6 \cdot 10^{20}$	$1.6 \cdot 10^{20}$	$1.6 \cdot 10^{20}$	$1.6 \cdot 10^{20}$ - $2.7 \cdot 10^{21}$	$1 \cdot 10^{28}$	$2 \cdot 10^{18}$
Photon energy ω [eV]	1.17	1.17	1.17	1.17	1.2×10^{-4}	1.17
N_1	5000	5000	5000	5000	10000	1000
N_2	$4 \cdot 10^4$	$4 \cdot 10^4$	$4 \cdot 10^4$	(4-10)$\cdot 10^4$	10000	n.a.
Background B [s^{-1}]	10^{-4}	10^{-4}	10^{-4}	10^{-4} 10^{-6}	10^{-6}	n.a.
Shot-Noise floor NF	n.a.	n.a.	n.a.	n.a.	n.a.	10^{-12} rad
$g_{a\gamma\gamma}$ [GeV^{-1}]	$< 6 \cdot 10^{-11}$	$2 \cdot 10^{-10}$	$< 6 \cdot 10^{-11}$	$< 3 \cdot 10^{-11}$ $< 1 \cdot 10^{-12}$	$< 1 \cdot 10^{-11}$	$< 1 \cdot 10^{-9}$
m_a [eV]	$< 1 \cdot 10^{-4}$	$< 2.5 \cdot 10^{-4}$	$< 1.3 \cdot 10^{-4}$	$< 1 \cdot 10^{-4}$ $< 4 \cdot 10^{-5}$	$< 4 \cdot 10^{-6}$	$< 2.5 \cdot 10^{-4}$

Table 3: N_1 and N_2 are the amplification factors of the generation cavity and the regeneration cavity, respectively. Regeneration rate signal: $S = RN_1N_2\left(\frac{g_{a\gamma\gamma}BL}{4}\right)^4$. Rotation due to dichroism $\phi = N_1\left(\frac{g_{a\gamma\gamma}BL}{4}\right)^2$. Detection efficiencies of photons have been considered to be ~ 1. Prospect limits on the ALP-photon coupling $g_{a\gamma\gamma}$ have been obtained by setting $S = B$ for the LSW cases and $\phi = NF$ for VMD. Mass limits have been set from $m_a < \sqrt{\frac{4\omega}{L}}$. Everywhere 1 T = $\sqrt{\frac{\hbar^3c^3}{e^4\mu_0}} = 195$ eV^2 and 1 m = $\frac{e}{\hbar c} = 5.06 \times 10^6$ eV^{-1}.

8 Concluding remarks

This document reflects on the discussions and results in the PBC technology sub-group during the years 2017/2018. The goal of the group was to connect initiatives/experiments technology-wise with CERN, even if those experiments are not situated at CERN. Please note that the initiatives that took part in this study do not necessarily give a full representation of their research field: Only experiments that presented themselves during one of the PBC general meetings and were consequently assigned to our working group, are included. The description of these experiments is found in appendix A.

As a main result of our work, we identified several key technologies in which CERN expertise can benefit the experiments, or CERN can profit from technologies developed by the experiments. Those key technologies were superconducting magnets, radiofrequency technologies, optics, vacuum and cryo-aspects, and their relation to CERN are discussed in Chapters 2, 3, 4, 5, 6, respectively. We categorized the needs of new and existing initiatives, and developed recommendations to foster the mutual benefit of CERN and the initiatives respectively.

In addition, experiment synergies were discussed, leading to experiment collaboration in applied technologies and physics reach. Particularly, technological synergies between light-shining-through-walls and QED vacuum-birefringence measurements were discussed in Sect. 7.

In summary, albeit CERN being an accelerator lab, also non-accelerator experiments can profit from CERN expertise and bring further diversity to CERN.

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Appendices

A Experiment questionnaires

A.1 Vacuum magnetic birefringence measurements at CERN: VMB@CERN

Responsible: Guido Zavattini, Pierre Pugnat

A.1.1 Short description of the new initiative, including details of the scientific goal and its significance

Vacuum magnetic birefringence (VMB) is a nonlinear macroscopic quantum electrodynamic effect predicted since 1935, soon after the formulation of Heisenberg's Uncertainty principle and Dirac's equation of the electron. Vacuum can fluctuate, for example, into e^+e^- pairs thereby allowing the interaction between two photons. At a macroscopic level, in the presence of an external field the velocity of light will be less than c and vacuum will become birefringent. This effect is very small and has never been directly observed yet [3]. QED is a very well tested theory but processes with only real photons in the initial and final states is still lacking. The new initiative's goal is to implement a new polarimetric scheme to measure VMB for the first time. For good sensitivity the signal to be measured must be time dependent with a frequency greater than $\sim$ 10 Hz. The new optical scheme being proposed [4] will allow taking advantage of the intense *static magnetic fields* (as opposed to rotating or ramped fields) generated by superconducting magnets available at CERN such as the LHC dipoles which at present produce the highest B^2L value. The necessary modulation of the signal is obtained by modulating the polarization of the probing light. This should allow a first direct detection of vacuum magnetic birefringence. Other new physics may also generate VMB: axions and millicharged particles, for example. Contrary to QED, these will also generate vacuum magnetic dichroism, VMD, (polarisation dependent absorption). The measurement of both VMB and VMD will allow the distinction of the different processes.

A.1.2 Proposed location of the experiment (if known), reasoning for choice

During the preparatory phase, the optics could be developed and tested in a different site from where the magnets are. Currently the PVLAS experiment is running in Ferrara, Italy and the optics will initially be developed there. These tests also include cooling to cryogenic temperatures (LN2 at first) of some of the critical optical elements. With this new optical scheme the most natural site, where the magnets and necessary infrastructures are, is CERN.

A.1.3 Expected number of users

At present the number of people interested in the VMB@CERN collaboration is about 20 from Italy, France, Czech Republic, Wales and Republic of China. Given the size of the experiment this is a congruous number.

A.1.4 Proposed/expected timeline of the experiment

Some preliminary tests will be conducted in an independent way in Ferrara by the end of 2018. A proposal will be submitted to SPSC and funding will then be applied for during 2019. If all goes well I would imagine a 5 year timeline would be long enough after the approval of the experiment in the various institutes.

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[4] G. Zavattini, F. Della Valle, A. Ejlli and G. Ruoso, Eur. Phys. J. C **76**, 294 (2016); *ibid* **77**, 873 (2017)

A.1.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

A Letter of Intent will be presented very soon to the SPSC and a proposal will be submitted by mid 2019. For funding: in Italy the proposal will be submitted to INFN by mid 2019 and a grant will also be applied for from the Italian Ministry for Research (PRIN project); for the Czech Republic funding will be applied for from GAČR (Czech Science Foundation); for France a request will be submitted to CNRS; for the Republic of China funding will come from National Tsing Hua University.

A.1.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

There is experience in using an LHC magnet with an optical setup by the OSQAR collaboration. A collaboration (VMB@CERN) is coagulating including the OSQAR collaborators. Furthermore, the development of more powerful FCC magnets with potentially even higher B^2L is attractive and cryogenic expertise could be necessary if cooling of optical elements will result necessary.

A.1.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

The principle role of CERN would be to supply the infrastructures and the strong dipole magnetic field for the experiment with either an LHC magnet or other prototypes being developed. So, CERN would need to supply power and liquid He for the magnets along with the expertise to run the magnets. Cryogenic expertise may also be necessary for cooling some of the critical optical elements. Finally some infrastructure work will be necessary to construct a single long structure to seismically isolate the optics from ground vibrations.

A.1.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

Support would be needed for both the intense magnetic field and for possible cryogenics to be applied to some optical elements. Development of magnets with even higher B^2L with respect to the LHC magnets would be of immense interest. At CERN this is already ongoing and VMB@CERN could already benefit from prototypes. Using cryogenic optics is a subject in rapid development. This technology at CERN could benefit from this experiment.

A.1.9 Indicate approximative main cost components of the proposal/initiative

A.1.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

- 0.5 MCHF-2 MCHF (Clean rooms for optics, stabilize magnet structure against vibrations, temperature stabilization of apparatus.)

A.1.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

- 0.5 MCHF-2 MCHF

A.2 IAXO

Responsible: Herman ten Kate

A.2.1 Short description of the new initiative, including details of the scientific goal and its significance

The International Axion Observatory ‘IAXO’ is a fourth generation axion helioscope featuring three large scale subsystems like magnets x-ray optics and detectors, purposely designed for the goal of searching for solar axions with axion-photon coupling down to a few 10^{-12} GeV^{-1}. This level of sensitivity is unprecedented. In particular: It goes far beyond previous limits, of CAST and of the strongest astrophysical bounds, by more than 10^4 in signal-to-noise ratio, i.e. more than one order of magnitude in the axion-photon coupling constant. Therefore, it will scan a large portion of the generic axion and ALP parameter space previously unexplored. It probes most of the region hinted by astrophysics: the anomalously high transparency of the Universe to UHE gamma rays and the anomalous cooling rate of stars. For the latter IAXO will test solutions invoking QCD axion models that could also be DM candidates. It explores a large fraction of the QCD axion models above 1 meV mass. In this region IAXO is the only detection technique known with the stated sensitivity to QCD axions. It has relevant sensitivity to additional production channels, as the one mediated by axion- electron coupling, or to alternative hypothetical scalars at the low energy frontier. In addition, the large magnetized volume is available to implement additional setups to search for Dark Matter axions based for example on RF cavities. As a first step, the collaboration envisions the realization of BabyIAXO, a scaled-down version of the full infrastructure, but with dimensions representative of the final systems. Baby-IAXO serves as a fully functional demonstrator of the IAXO subsystems like magnet, optics and detectors, and can lead to significant improvements in the figure of merit of the final IAXO Experiment. At the same time BabyIAXO shall produce new physics outcome, probing a relevant part of the parameter space mentioned above

A.2.2 Proposed location of the experiment (if known), reasoning for choice

The decision on the location is not final, although a highly likely host for IAXO is DESY, Hamburg.

A.2.3 Expected number of users

The IAXO collaboration is in the process of getting consolidated. At the moment 17 institutions have accepted the collaboration bylaws and are therefore formal members of the collaboration. More groups have shown interest since the IAXO Letter of Intent to CERN in 2014 was signed by 90 authors. The collaboration will likely grow in the future as soon as (Baby)IAXO activities get momentum and support from various agencies. The IAXO community will eventually evolve in the coming years to include about 100 scientists.

A.2.4 Proposed/expected timeline of the experiment

BabyIAXO will be designed and built in the next 2-3 years, installed and commissioned in the subsequent 1 year, and then proceed with data taking. By then, the Technical Design Report of the full IAXO Experiment should also be ready, and, funding permitting, construction activities could start in parallel with experiencing data taking with BabyIAXO. Construction of the full IAXO takes 4 years.

A.2.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

The CERN SPSC has reviewed the IAXO Experiment positively in autumn 2013 following a Letter of Intent. It is now in 2017 being reviewed by the Physics Beyond Colliders process. In addition, the IAXO Experiment will be submitted for revision by the Physics Research Committee of DESY in one of its forthcoming meetings, probably in 2018. A number of national funding agencies are reviewing IAXO as well, since several IAXO groups are getting or applying for funding to work on IAXO. To mention are Spain (MINECO), Germany (BMBF), Croatia, France, US (NSF and DOE).

A.2.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

IAXO is the successor of the CAST Experiment that has been active at CERN for more than a decade. The core of the IAXO groups are previous and present members of CAST and they have a long-standing commitment of work at CERN. Although the original research plan of CAST is finished, the experiment is now hosting a number of small-scale prototypes for testing novel concepts or performing R&D. There is potential and there is interest in using CAST infrastructure for providing feedback during the preparatory phase of IAXO, for example, to improve the insight on detector backgrounds.

A.2.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

Both BabyIAXO and IAXO detector magnets are systems of a scale for which CERN's expertise and infrastructure is almost unique. The collaboration expects support and significant participation of CERN, in particular, but not exclusively, with knowledge and expert personnel to the Technical Design Report of the detector magnets and related infrastructure. In addition CERN can participate with providing eventually available tooling and technical follow-up during magnet construction, system integration, test and commissioning, first for BabyIAXO and then for IAXO.

A.2.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

As mentioned above, IAXO crucially relies on CERN's expertise on large-scale superconducting detector magnet design, construction, integration and commissioning. In return, for CERN the IAXO magnet project is a means to maintain and develop its rather unique detector magnets expertise also in view of CERN's mission towards physics experiments at future colliding and non-colliding machines.

A.2.9 Indicate approximative main cost components of the proposal/initiative

A.2.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

- 0.5 MCHF-2 MCHF - for BabyIAXO detector magnet participation,
- 2 MCHF-10 MCHF - for IAXO detector magnet participation.

A.2.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

- 2 MCHF-10 MCHF - for BabyIAXO system,
- $>$ 10 MCHF - for IAXO system.

A.3 DarkSide

Responsible: Livio Mapelli

A.3.1 Short description of the new initiative, including details of the scientific goal and its significance

DarkSide-20k (DS20k) is a direct search of Dark Matter via the detection of WIMPs (Weakly Interacting Massive Particles). It uses a Two-Phase Liquid Argon Time-Projection Chamber with a fiducial mass of 20 tons. When in operation, with an ultra-pure Underground Argon, DS20k will be the first noble liquid detector entirely equipped with photosensors assembled with Silicon Photomultipliers (SiPM), a key enabling technology for next generation WIMP searches.

A.3.2 Proposed location of the experiment (if known), reasoning for choice

Laboratori Nazionali del Gran Sasso (LNGS), a INFN underground laboratory. With 1.4 km of mountains above, it provides the necessary screening from cosmic radiation.

A.3.3 Expected number of users

Of the order of 10 scientist dedicated to DarkSide are already operating at CERN. This number will probably double in 2018.

A.3.4 Proposed/expected timeline of the experiment

DS20k is expected to start data taking at the LNGS in 2021.

A.3.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

DS20k has been scientifically approved and is regularly reviewed by the INFN Commissione Nazionale II (CSN2), the LNGS Scientific Committee and the US National Science Foundation. The DarkSide Collaboration is strong of more than 70 Institutes worldwide[5].

A.3.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

Synergy with activities in the TE-VSC (for vacuum) and TE-CRG (for Cryogentic systems, such as the one of DUNE). Possible synergies with activities and experiments making use of SiPMs.

A.3.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

There are 2 lines of activities in which CERN is currently (1 and 2 below) or might be (3) involved with DarkSide.

1. Purification of LAr of new concept. The Underground Argon coming from a mine in Colorado will be transported to Sardinia, in the Sulcis region, where a purification and Isotopic separation column 350 m tall will be installed in an access well of an unused coal mine (Seruci). The 30 elements of the column are presently individually being tested for leak tightness with the collaboration of the TE-VSC group[6].

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[5] http://arxiv.org/abs/1707.08145v1

[6] CERN Service Agreement KN3155.

2. Cryogenics. The Cryogenic System of DarkSide-20k has a number of innovative solutions. The elements of the system, currently under construction by Institutes of the DS Collaboration, will be assembled early 2018 at CERN in the Cryolab of the TE-CRG group. The system, including a 1 ton cryostat load will undergo a number of validation and characterization tests throughout 2018 with the collaboration of the TE-CRG group[7].
3. SiPM. The read-out and data acquisition systems of DS-20k will be based on modern electronics, including custom SiPM-photosensors currently in advanced state of development by FBK/TIFPA for the DarkSide Collaboration. The most relevant recent results are: 1) readout of a large-area (24 cm^2) SiPM-based tile via a single electronics channel, with a SNR > 13; 2) search of a low-radioactivity (~ 1 mBq/kg) substrate, with a silicon-like thermal expansion coefficient (2.6 ppm/K); 3) R&D on Through-Silicon Via bonding.

A.3.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

Two Groups in the CERN TE Department, TE-VSC (Vacuum, Surface treatment and Coating) and TE-CRG (Cryogenics Group) are providing expertise support and installation sites in two areas:

- Vacuum leak tests. In view of their experience in the quality assurance of cryogenics components and similar accelerator technologies, VSC experts contribute to the pre-construction reviews of ARIA, as well as to the development of quality assurance procedures for leak tests for the ARIA components. Furthermore, they supervise the performance at CERN of leak tests of such components making the necessary testing equipment available. This support is defined via a CERN Service Agreement[8].
- Cryogenics. CRG experts provide support for the assembly, characterization and validation of the cryogenic system of DarkSide-20k as well as an area in the CERN Cryolab. The full validation will be achieved with the installation and on-surface operation of a DarkSide-Prototype consisting of a 1-ton cryostat manufactured with radio-clean steel. The cryostat will contain a prototype Time Projection Chamber. After mechanical and cryogenic validation, the TPC top and bottom planes will be equipped with a small number of SiPM, part of the DarkSide-20k pre-production. The construction of the elements detailed above and their basic functionality tests do not require, in a first phase, low background underground facilities. At the same time, it is on the critical path for the timely completion of the DarkSide-Proto program, which in turn is on the critical path in the overall schedule of DarkSide-20k. We need therefore to guarantee that the on-surface construction and operations are performed at the most convenient location and with expert support. The agreement with CERN is described in a EDMS document[9].

A.3.9 Indicate approximative main cost components of the proposal/initiative

A.3.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

- Not applicable for running initiatives

A.3.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

- Not applicable for running initiatives

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[7] CERN Management Report, EDMS1837551.

[8] CERN Service Agreement KN3155

[9] CERN Management Report, EDMS1837551

A.4 *a*KWISP

Responsible: Giovanni Cantatore

A.4.1 Short description of the new initiative, including details of the scientific goal and its significance

The scientific goal of the *advanced*-KWISP project is to develop a novel opto-mechanical combined source-detector device to investigate Short Range Interactions (SRIs) at separation distances below 1 μm. A detector sensitive to SRIs in this distance region would give access to many yet undiscovered physical processes ranging from the topological Casimir effect[10] to elusive fields such as chameleons, axions, dilatons, and others beyond the current Standard Model paradigm with a direct impact on the Dark Matter and Dark Energy problems[11]. *advanced*-KWISP builds on the experience of the KWISP detector group[12] within the CAST experiment at CERN, where an opto-mechanical detector based on the optical interferometric read-out of a nano-membrane is now searching for solar chameleons[13]. In short, *advanced*-KWISP is a novel small-scale particle physics experiment based on an ultra-sensitive force sensor, where a small investment in terms of funds and manpower could pay large dividends of physics results.

A.4.2 Proposed location of the experiment (if known), reasoning for choice

The ideal location for *advanced*-KWISP is a laboratory having cryogenic facilities, with available access to other advanced technologies such as thin-film coating, precision mechanical fabrication and vacuum. In this respect CERN is certainly the first choice

A.4.3 Expected number of users

10

A.4.4 Proposed/expected timeline of the experiment

The expected timeline of the experiment develops over three 1-year long phases for a total of 3 years:

1. initial room temperature set-up phase
2. low-temperature design and construction phase
3. commissioning and data taking phase

A.4.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

The experiment will be initially reviewed scientifically by the Italian INFN. A CERN review and ERC grant application can also be foreseen. Collaborating Institutions:

- University and INFN Trieste, Italy
- University of Camerino, Italy

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- University of Rijeka, Croatia
- University of Patras, Greece
- University of Freiburg, Germany
- CAPP, Daejeon, Korea
- Bilgi University, Istanbul, Turkey

A.4.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

The KWISP detector group, already involving the Institutions mentioned above, is active in the CAST experiment at CERN. There, it operates a room temperature opto-mechanical detector attempting to sense the direct coupling to matter of solar chameleons. *advanced*-KWISP and KWISP share the same basic force- sensing technology.

A.4.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

Ideally, the *advanced*-KWISP experiment would be located at CERN in a laboratory of relatively modest dimensions with access to cryogenic cooling. This laboratory should be as free as possible from environmental perturbations such as acoustic noise, vibrations and EMI. All the foreseen experimental activities could take place there. The main role of CERN would be to provide expertise, support and infrastructures in the following key areas for *advanced*-KWISP:

cryogenics: design and construction of a table-top liquid helium cryostat to cool the *advanced*-KWISP combined source-detector device; procurement and operation of a refrigerator to reach sub-Kelvin temperatures

thin-film coatings: coating of nano-membranes with thin films of different materials according to custom needs

precision mechanical fabrication and vacuum design and preparation of precision mechanical components to house and manipulate in vacuum nano-membranes

A.4.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

- *Cryogenics* - CERN can provide expertise in the design of a sub-Kelvin cryostat cooled by a liquid-He dilution refrigerator, with special regard to the geometry, the choice of materials and the simulation of the performance. This cryostat must also be able to house a small optical setup inside its cold volume and to interface it with the outside. The technology needed to build and operate such a cryostat is readily applicable, for instance, to cryogenic particle detectors and in precision physics experiments.
- *Thin-film coatings* - Facilities and expertise on metallic thin-film coatings are already present at CERN (for instance in the TE-VSC-VSM group). Coatings of various materials, shapes and thicknesses are essential for *advanced*-KWISP and CERN groups could expand their present experience into dielectric coatings and micro-mechanical fabrication. Devices based on such technologies find widespread application in particle detection, with Transition Edge Sensors (TES) a prime example.
- *Precision mechanical fabrication* - Opto-mechanical devices such as the ones needed by *advanced*-KWISP require high precision mechanical assemblies with very small tolerances. CERN already uses this technology in RF applications, for instance, and could benefit by widening the field of its applicability to other types of devices.

A.4.9 Indicate approximative main cost components of the proposal/initiative

A.4.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

- <0.5 MCHF
  - 300 kCHF, dilution refrigerator and cryostat (if not already available), including vacuum equipment
  - 10 kCHF, thin film coatings

A.4.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

- <0.5 MCHF
  - 40 kCHF, ND:YAG laser
  - 10 kCHF, custom micro-membranes
  - 30 kCHF, vibration-free bench and optical material

A.5 A New Axion Dark-Matter Haloscope based on the Modular Hybrid Magnet Platform in Construction at LNCMI-Grenoble a.k.a. Grenoble initiative

Responsible: Pierre Pugnat

A.5.1 Short description of the new initiative, including details of the scientific goal and its significance

A collaboration between CAPP/IBS KAIST in South Korea, teams from CNRS / Universite Grenoble Alpes and CERN is studying the development of a new haloscope for Axion dark matter search. The superconducting coil under construction at LNCMI-Grenoble will provide a magnetic field of 9 T in a room temperature bore of 812 mm diameter and 1.4 meter high. Combined with resistive magnets, various additional configurations of maximum field and bore diameter will be obtained ranging from 43 T in 34 mm diameter down to 17 T in 375 mm diameter[14]. Each of these magnet configurations will host various types of microwave cavity detectors for the Axion to photon resonant conversion via the inverse Primakoff effect following the Sikivie's detection scheme. These cavities, possibly superconducting, are presently under study at CAPP/IBS and will have a high quality factor $Q \simeq 10^5 - 10^6$. Low-noise microwave amplification of the signal will be ensured by a DC superconducting quantum interference device (SQUID) or Josephson Parametric Amplifiers (JPA) cooled-down to 25 mK by a 3 He/ 4 He dilution refrigerator. This new modular haloscope will be designed to probe QCD dark matter Axions in the mass range of 1-100 eV with unprecedented sensitivity, i.e. the diphoton coupling constant reaching for the first time the theoretical prediction of the Dine-Fischler-Srednicki- Zhitnitsky (DFSZ) model[15].

A.5.2 Proposed location of the experiment (if known), reasoning for choice

The new modular hybrid magnet platform, one of the key ingredients of the new haloscope described here above will be hosted at the CNRS/LNCMI-Grenoble.

A.5.3 Expected number of users

- CNRS-Grenoble: 5
- CAPP/IBS KAIST (South Korean): 5
- CERN: 2
- Others: 1 (retired from CERN)

A.5.4 Proposed/expected timeline of the experiment

The Grenoble hybrid magnet will be in operation from 2019-20 for an expected duration exceeding 10 years. To probe axion in the mass range 1-100 eV, the Grenoble haloscope will use the following hybrid magnet configurations:

- 9 T, 800 mm dia.
- 17 T, 375 mm dia.
- 43 T, 34 mm dia.

The unique modular hybrid magnet platform of LNCMI-Grenoble will be shared between several scientific projects selected from the bi-annual[16] call for proposals of the European Magnetic Field Laboratory.

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[14] P. Pugnat, et al. "Status of the 43-T Hybrid Magnet of LNCMI-Grenoble", IEEE Trans. on Appl. Supercond. 26, 4302405 (2016)

[15] P. Pugnat, R. Ballou, Ph. Camus, F. Caspers, B. R. Ko, N. Roch, and Y. K. Semertzidis, "Preliminary Study for a New Axion Dark-Matter Haloscope", Proceedings of the 12 th Patras Workshop on Axions, WIMPs and WISPs, 20-24 June 2016, Jeju Island, South Korea; https://axion- wimp2017.desy.de/e28952/; https://indico.desy.de/getFile.py/access? contribId=11&resId=0&materialId=slides&confId=13889

[16] https://emfl-users.lncmi.cnrs.fr/SelCom/proposals.shtml

A.5.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

- LNCMI-Grenoble, CNRS.
- European Magnetic field Laboratory (EMFL).
- Institut Néel (IN), CNRS.
- University Grenoble Alpes.
- CAPP/IBS KAIST, South Korea.

A.5.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

- RF technologies including cavities.
- Large superconducting solenoid.
- Cryogenics & ultra-low temperature (dilution refrigerator of large volume).

A.5.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

- Recognized experiment by CERN.
- CERN support in developing RF cavities of various sizes.

A.5.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

A.5.9 Indicate approximative main cost components of the proposal/initiative

A.5.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

- Not applicable.

A.5.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

- Not known yet.

A.6 STAX

Responsible: Paolo Spagnolo

A.6.1 Short description of the new initiative, including details of the scientific goal and its significance

We propose a variation, based on very low energy and extremely intense photon sources, on the well established technique of Light-Shining-through-Wall (LSW) experiments for axion-like particle searches. With radiation sources at 30 GHz, we compute that present laboratory exclusion limits on axion-like particles might be improved by at least four orders of magnitude, for masses ma $\leq$ 0.01 meV. This could motivate research and development programs on dedicated single-photon sub-THz detectors.[17]

A.6.2 Proposed location of the experiment (if known), reasoning for choice

CERN, because of the 11T diploles borrowed from HL-LHC prototypes.

A.6.3 Expected number of users

$\sim$ 30-50

A.6.4 Proposed/expected timeline of the experiment

2020-2022

A.6.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

The review is undergoing in this moment with referees by INFN, Italy. Our goal is to extend outside and create an international collaboration.

A.6.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

Synergy with Magnets group, possible synergy/overlap with Osqar and IAXO.

A.6.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

As mentioned the HL-LHC prototype magnets are of primary importance. As consequence we would need the infrastructure necessary for the cryogenic environment of the dipoles.

A.6.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

As a magnet system, we plan to re-use the existing hardware short models from the CERN 11Tesla magnet program that will be available after completion of the program, and are not planned to be used in any other way. The CERN TE-MSC team will also help in the engineering design of the components of the cryo-assemblies for the two dipoles. Within the high luminosity HL-LHC upgrade project, in the last years several 2 m long models of Nb3Sn dipole magnets with a magnetic length of about 1.5 m and a field intensity of 11Tesla in a 60 mm clear aperture have been built and tested at CERN. The plan consists in using 2 of these short model 11T dipoles together, each of them inserted in its own cryostat. The two cryostated magnets will be then separated by the wall, so that the regeneration part and production part

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[17] `http://www.sciencedirect.com/science/article/pii/S2212686416300085?via\%3Dihub`

of the axion-like particles will be isolated. An external support system will have to be added to fix the distance and the relative alignment between the 2 magnets. Besides, CERN could also provide some high power source of microwave light around 30 GHz, like the Klystron, operating in the KW region, needed for the STAX source.

A.6.9 Indicate approximative main cost components of the proposal/initiative

A.6.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

Cost necessary to realize the cryogenic system for the major equipment of the two 11 Tesla dipoles of the STAX experiment.

- 1 MCHF

A.6.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

- 2 MCHF-10 MCHF

A.7 Carbon nanotubes - CNT

Responsible: Gianluca Cavoto

A.7.1 Short description of the new initiative, including details of the scientific goal and its significance

Directional detection of Dark Matter particles (DM) in the MeV/GeV mass range could be accomplished by studying electron recoils in large arrays of parallel carbon nanotubes (CNT)[18] For instance, in a scattering process with a lattice electron, a DM particle might transfer sufficient energy to eject it from the nanotube surface. An external electric field is added to drive the electron from the open ends of the array to the detection region. We have calculated the anisotropic response of this detection scheme, as a function of the orientation of the target with respect to the DM wind, and concluded that no direct measurement of the electron ejection angle is needed to explore significant regions of the MeV DM mass exclusion plot. We would like to develop and build a compact sensor, in which the cathode element is substituted with a dense array of parallel carbon nanotubes that could serve as the basic detection unit in a large detector for Dark Matter. Recently this idea is being explored in the context of the PTOLEMY project at LNGS (Italy) aiming to develop the technology to detect light DM and eventually the cosmic neutrino relic background[19] .

A.7.2 Proposed location of the experiment (if known), reasoning for choice

Laboratori Nazionali del Gran Sasso (LNGS), a INFN underground laboratory. LNGS is an ideal place for ultra-rare events searches thanks to the low radioactivity of the underground caverns. Currently the LNGS has reserved a space in its overground. R & D activity is also conducted in University and other research centers labs.

A.7.3 Expected number of users

The group involved in the CNT development is of about 10 people. The PTOLEMY project is counting about 50 people from several institutions and countries all over the world.

A.7.4 Proposed/expected timeline of the experiment

The project is now (end 2018) starting. The first R&D phase is expected to last 3-4 years.

A.7.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

The PTOLEMY project is being reviewed by the Scientific committee of LNGS since beginning 2018, when a letter of intent has been sent. The INFN CNS2 is evaluating the official approval of the project in the next months and has already opened a financial line to help the collaboration to start its experimental activity.

A.7.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

Our current R&D activity is related to study very low energy electron scattering process with carbon nanostructures. Eventually we are planning to develop a detector prototype that might be use CNT as

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[18] L. M. Capparelli, G. Cavoto, D. Mazzilli and A. D. Polosa, Phys. Dark Univ. **9-10**, 24 (2015) Erratum: [Phys. Dark Univ. **11**, 79 (2016)] doi:10.1016/j.dark.2015.12.004, 10.1016/j.dark.2015.08.002 [arXiv:1412.8213 [physics.ins-det]]. G. Cavoto, E. N. M. Cirillo, F. Cocina, J. Ferretti and A. D. Polosa, Eur. Phys. J. C **76**, no. 6, 349 (2016) doi:10.1140/epjc/s10052-016-4193-7 [arXiv:1602.03216 [physics.ins-det]]. G. Cavoto, F. Luchetta and A. D. Polosa, Phys. Lett. B **776**, 338 (2018) doi:10.1016/j.physletb.2017.11.064 [arXiv:1706.02487 [hep-ph]].

[19] E. Baracchini *et al.* [PTOLEMY Collaboration], arXiv:1808.01892 [physics.ins-det].

target and avalanche photo-diode or multi-channels plate sensors to detect emerging electrons. Therefore, experience of CERN related to **new material studies** (in particular surfaces characterizations for electron emission) would be very interesting. Experience on sensors developments (photo-diodes) would be interesting as well.

A.7.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

Dark matter detectors of the kind we would like to develop can very much profit from the availability of neutron beams for calibration and testing purposes.

A.7.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

The availability of a **energy tagged neutron beam** with an additional neutron **spectrometer** able to measure the scattered neutron angle would be crucial to study the recoiling particles from the target (CNT in our case).

Some of our tests must be conducted in **vacuum** and CERN might help with the needed vacuum technology (expertise in vacuum components, design of vacuum tight devices, design of electrodes for electric field in vacuum).

CNT and in general 2D material as graphene can be studied with **surface characterization** techniques (XPS, Raman scattering, scattering and transmission electron microscope). CERN experience and facilities for surface characterization would be very valuable therefore.

A.7.9 Indicate approximative main cost components of the proposal/initiative

0.5 MCHF-2 MCHF

A.7.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

Not known yet.

A.7.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

0.5 MCHF-2 MCHF

A.8 JURA

Responsible: Jörn Schaffran, Axel Lindner (both DESY), Pierre Pugnat

A.8.1 Short description of the new initiative, including details of the scientific goal and its significance

Light-shining-through-a-wall (LSW) experiments provide the ideal option to determine WISP-photon couplings in a mostly independent manner. At present the ALPS II experiment based on HERA dipole magnets is being prepared at DESY. Its optics and detector systems could be combined at a later stage with more modern magnets to boost the sensitivity in ALP-photon couplings up to more than an order of magnitude. A new initiative called JURA (Joint Undertaking on Research for Any-light particles) stands for the next steps in LSW experiments. The mandate of the PBC technology group enables to combine different LSW initiative to a new one, leading to fusion of the already existing expertise. The JURA initiative is separated into 3 steps:

1. babyJURA:
   BabyJURA[20] consist of 1 + 1 LHC dipole magnet with a powerful optical system equal to ALPS II.
2. JURA 1:
   Initiative with 4 + 4 LHC dipole magnets[21], which should be realized, if there is a corresponding physics case in view of ALPS II result. JURA 1 would reach sensitivity similar to ALPS II.
3. JURA 2:
   JURA 2 stands for[22] 3rd generation LSW experiment by either using LHC or FCC like magnets. Such an experiment would for example allow to study an ALP detected by IAXO (if its mass is sufficiently low) or even surpass the sensitivity of IAXO if there is a corresponding physics case. The discovery of a WISP would open the window to physics beyond the Standard Model. In such a scenario, it would be of crucial importance to measure properties of the WISP as precisely as possible.

A comparison of the main experimental parameters in the different JURA stages and above mentioned ALPS II experiment is given in table A.1.

Parameter	ALPS II	babyJURA	JURA 1	JURA 2
Magnet aperture [mm]	50	50	50	50-100
Magnetic field B [T]	5.3	9	9	9-13
Magnetic length [m]	189	29	114	200-960
Eff. laser power P [MW]	0.15	0.15	0.15	0.15-2.5
Power-built up Q (behind the wall)	40000	40000	40000	40000-10000
Detector noise DC [s^{-1}]	10^{-4}	10^{-4}	10^{-4}	10^{-6}
Total sensitivity increase (JURA/ALPS II)	1	0.25	1	2-56

Table A.1: Comparision of the ALPS II experiment with the different JURA stages

A.8.2 Proposed location of the experiment (if known), reasoning for choice

The location of the respective experimental stage depends on its length and is therefore not the same for all steps. BabyJURA could be located in the CERN SM18 hall at the OSQAR location and JURA 1 in

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[20] P. Pugnat et al., OSQAR Annual Report 2018, http://cds.cern.ch/record/2641609/files/SPSC-SR-238.pdf

[21] S. Kunc et al., Status and plans of the OSQAR experiments, 131st meeting of the SPSC, 16. October 2018, CERN,

[22] A. Lindner, B. Willke, H. Ten Kate, Future options for searching axion-like particles through light-shining-through-a-wall experiments, PBC-Kickoff-Workshop,6. September 2016, CERN, https://indigo.cern.ch/event/523655/contributions/2246871/attachments/1332644/2003496/LSW.pdf

building 180. JURA 2 is based on the laboratory capable of operating a long string of superconducting accelerator dipole magnets. CERN could be an obvious choice.

A.8.3 Expected number of users

The expected number of collaborators is expected to grow over the years to about 50 participants.

A.8.4 Proposed/expected timeline of the experiment

Naturally, LSW experiments require - due to the accuracy on the ALP-photon coupling improves only with time 1/8 - a short time for data taking. The respective steps have different timelines:

- The preparation phase of babyJURA will start soon and data taking is expected for 2023
- The timeline for JURA 1 is not defined yet. It strongly depends on the progress and results of ALPS II experiment at DESY
- JURA 2 is assumed as a long-term project. The timeline is defined by the availability of LHC or FCC dipoles. Hence a discussion is currently not expected before 2025.

A.8.5 Information on where the experiment is expected to be reviewed scientifically and the names of the institutions involved (if known)

Both DESY and CERN has the expertise and experience to host and therefore review LSW experiments. Obviously, different institutions could be a choice for different stages.

A.8.6 If relevant clarify relations with other related activities at CERN (synergy, overlap)

JURA would benefit from CERNs superconducting magnet technology. Especially commissioning and long-time operation of LHC magnets as the development of new magnet technologies started already for the FCC are an exemplary overlap.

A.8.7 Specify the role that CERN should play in the activities of the proposed experiment. For example, how much of the activities will be located at CERN and what is expected from CERN in terms of the infrastructure and other support

BabyJURA and JURA 1 would definitively profit from the LHC dipoles available at CERN. In addition the impressive cryogenic infrastructure and powering infrastructures are unique for hosting the various JURA stages. JURA 2, in case of FCC magnets will be used, could be an interesting option for a physics experiment exploiting a prototype series of FCC dipole magnets (without inner HTC part to enlarge the aperture). If an FCC is being built, JURA could also be based on the first prototype dipoles produced for the collider. Alternatively or in addition, also depending on ALPS II results, a solution with several LHC magnets (up to 7 + 7) could be taken into account and is than related to the overlaps discussed already for the first two stages above.

A.8.8 Describe in reasonable detail the technology support CERN can provide or the benefit of the technology to be developed

For planning, building up and commissioning magnet strings the cryogenic-, vacuum-, magnet- and optic-technology play a crucial role. JURA can profit from the CERN expertise in this fields and from the experience in hosting and operating large scale experiments.

A.8.9 Indicate approximative main cost components of the proposal/initiative

The cost estimations for investment and operation of JURA have to be considered for all stages separately.

A.8.9.1 Provisional cost estimation incurred by CERN beyond the existing infrastructure and equipment

The main new investments are related to cleanroom, optic, electronic and detector purchase.

Experiment	babyJURA	JURA 1	JURA 2
Costs [MCHF]	0.5-2	0.5-2	>10

Table A.2: Comparision of the investment cost beyond the existing infrastructure and equipment for all JURA stages

A.8.9.2 Expected cost incurred by the collaboration proposing the experiment/initiative including the operation

The main operation costs are related to cryogenic supply.

Experiment	babyJURA	JURA 1	JURA 2
Costs [MCHF]	<0.5	<0.5	<0.5

Table A.3: Comparision of the operation cost for all JURA stages