Implementation of the ECFA detector R&D roadmap on quantum sensors: the DRD5/RDq proto-collaboration

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ABSTRACT

The detector R&D roadmap initiated by ECFA in 2020 highlighted the large number of particle physics opportunities that targeted and collaborative R&D in the field of quantum sensors and related technologies can enable. This White Paper is the outcome of a workshop that combined input from the involved communities and from the roadmap's task force 5 (TF5) to, on one hand, establish a list of the most promising areas and define the R&D that would be needed to bring these to the level at which experiments building on them can be envisaged, and on the other hand, define the structure of a collaboration (the DRD5 / RDq collaboration) that would enable such R&D to be pursued at a global scale.

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1. EXECUTIVE SUMMARY

The field of high energy physics has been driven to long-term international collaborative efforts on detector R&D by the numerous challenges posed by the very large and costly devices needed for the relevant experiments. Such a common endeavor that would go beyond numerous field-specific efforts in the hugely diverse, highly dynamic, and rapidly evolving field of quantum sensors, with the goal of advancing a wide range of technologies of great benefit to particle physics on a global scale, appears not to have been attempted yet.

The goal of this White Paper is not to impose a model that, while it may well work for high energy physics, might not be appropriate for the field of quantum sensors, but rather to identify areas within that field where a collaborative effort could lead to advances that individual efforts would not be expected to achieve, to the benefit of both the field of quantum technologies and the field of particle physics.

Instead of addressing the needs of individual areas of particle physics, this White Paper focuses on a set of Work Packages that the authors and the communities that form part of their networks have identified as being potentially specifically and broadly relevant, and that would particularly benefit from targeted collaborative R&D efforts on a global scale.

Finally, in addition to the set of Work Packages enumerated in this White Paper, a proposal for focused efforts to develop an expert workforce through specific university programs and a possible collaborative structure matched to the specific needs of this global effort are presented.

2. INTRODUCTION

In a context of developing or preparing technologies for the upcoming challenges of fundamental research, ECFA initiated a process that culminated in 2021 with the publication of a detector R&D roadmap that laid out the challenges that future particle physics experiments need to address. This roadmap also highlighted the importance of targeted detector R&D in a range of areas relevant to particle physics, among them detectors in the realm of quantum sensors. Six families of quantum sensors were highlighted as particularly relevant to the field of particle physics. In 2022, all areas (represented by the conveners of the respective task forces of the roadmap) were encouraged to implement their respective R&D efforts in the form of dedicated collaborations and to prepare and submit appropriate proposals to a new scientific committee at CERN, the Detector R&D Committee (DRDC). This White Paper represents the proposed path for the implementation of the chapter of the ECFA roadmap dedicated to quantum sensors and related technologies (Chapter 5).

The structure of this White Paper is the following: in the first part, an overview of the most promising areas linked to the ECFA roadmap is provided, while in the second part, collaborative, organizational, and intellectual property-related issues are addressed. First, however, we wish to highlight an aspect that differentiates the implementation of the ECFA roadmap on quantum sensing from those of the other technology areas that form part of that roadmap. While for the latter, there are both pre-existing communities and consensus on which areas are most critically in need of R&D to match requirements for future high energy physics challenges, this is not the case for R&D on quantum sensors for particle physics. Neither are there existing communities that have previously collaborated on R&D at a large scale in the respective areas covered in this White Paper, nor is there a solid consensus on which areas would be most critically in need of a dedicated effort. To address these two points, a workshop including experts from all the areas covered, and incorporating proposals submitted by the wider communities in response to a call sent out 10 weeks prior to the workshop, took place at CERN from Apr. 3-6. This White Paper is the outcome of this workshop.

3. RATIONALE FOR A COLLABORATIVE R&D EFFORT

The field of high energy physics has been driven for decades to long-term international collaborative efforts on detector R&D given the numerous challenges posed by the very large and costly devices needed for the relevant experiments, but also because common standardized solutions that can be scaled up have been central to their conception and construction.

No such common driver has encouraged similar efforts in the hugely diverse, highly dynamic, and rapidly evolving field of quantum sensors. In spite of its track record in tackling technical challenges and in reducing entry costs through standardization in the field of high energy physics, such an approach may not necessarily always be appropriate for the field of quantum sensors, with its often smaller and dynamic groups. However, also within that field, there are challenges where a collaborative effort could lead to advances that individual efforts would not be expected to achieve, and from which both the field of quantum technologies and the field of particle physics can benefit.

We wish to emphasize here that both communities will need to be involved, both intellectually and financially, if such advances that benefit both are to be attempted. Formulating the challenges and the directions of attack coherently can provide funding agencies with a global view that will contextualize individual efforts, will help identify similar and complementary approaches on a global scale, and will provide an exchange point for the sharing of corresponding expertise, workforce, and educational frameworks.

Prior efforts at a national scale have demonstrated that such an approach can result in tangible benefits: the AION collaboration for example has played a pioneering role in defining standardized approaches for detection of gravitational waves and for searches for dark matter using terrestrial vertical atomic interferometric devices. The involved shared engineering effort has resulted in a significant acceleration of building times, in the availability of a set of identical devices at lower cost, and in improved reliability through standardization. The aim of this roadmap implementation is thus to provide a framework within which similarly beneficial detector R&D can be carried out as part of a coordinated global effort within a few overarching sets of related activities (work packages, WP's). Given the global nature of this effort, it is natural that within each of these work packages, a range of complementary activities will take place; what the WP provides is a common framework in which resources, expertise, and goals can be shared and compared.

4. QUANTUM SENSING WORK PACKAGE OVERVIEWS

The ECFA process itself had identified quantum technologies as a promising path for particle physics, and has identified in particular six families of quantum sensors (table 1) as particularly relevant for particle physics. For each of these families, scientific motivations were presented during both the ECFA symposium and in the roadmap itself.

clocks and clock networks	superconducting & spin-based sensors	kinetic detectors	atoms/ions/molecules & atom interferometry	optomechanical sensors	nano-engineered / low-dimensional

Table 1: Families of quantum sensors highlighted in the ECFA detector R&D roadmap

The approach taken in this White Paper is complementary to that of the ECFA roadmap, in that rather than structure the discussions around physics domains and list the most salient challenges in those fields that this roadmap implementation has identified as high-impact targets, we instead list a number of Work Package-like lines of attack, and highlight which areas among the six families of the ECFA roadmap are impacted by focused R&D on them.

We also will not reiterate the physics rationales for the specific quantum sensing families, which are detailed in the ECFA roadmap, chapter 5, as are the potential physics impacts of specific technical advances but instead highlight the technical challenges of the identified high-level work packages, detail the sub-families of technologies and systems that comprise them, and point out areas within them that would best be tackled by a collaborative global approach.

4.1 WP-1 : networks, signal and clock distribution

Numerous individual and locally / nationally linked high precision devices relying on a wide range of quantum sensing systems exist world-wide. In order to achieve the next level of sensitivity, either to transform the individual nodes into a globally linked single detector, or to link heterogeneous devices into a single multi-modal device (allowing to constrain different putative BSM models that affect individual nodes differently) or to provide a global reference signal against which local nodes can be calibrated or compared to, this work package combines collaborative efforts along three lines:

- WP 1a: Large-scale networked atomic clocks and Global sub-ns time stamping
- WP 1b: Portable references and sources

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 1a (clock network)	X					
WP 1b (portable clocks)	X					

Table 2: Quantum sensor families impacted by R&D in WP-1

4.1.1 WP 1a: Large-scale clock network

World-wide efforts towards developing ultra-precise clocks based on a wide variety of systems (different atomic elements, ions or molecules or even nuclei) are pushing the precision of clocks to below 1 part in 10^{18}. At the same time, these different systems have a wide range of different systematics and couplings to putative BSM physics. A dedicated optical frequency and time signal distribution network, that would allow spreading the local clock signals across a multi-nation, continental or international network would greatly benefit the community and would open up significant new parameter space.

High precision temporal comparison of signals from a wide range of quantum sensors at geographically separated positions has multiple benefits. On one hand, it can allow differentiating local glitches from valid signals, while reducing systematics. On the other hand, a distributed set of observations can allow identifying the temporal evolution and direction of a potential source behind these common observations. High temporal-resolution (to O(10 ps)) time stamping on a global scale will result in a set of Earth-sized highly sensitive detectors for all possible types of quantum sensors.

The two aspects (high precision time-stamping to O(10 ps) and distribution of a highly precise continuous clock signal to provide a reference) are closely linked.

Where are we? What do we need to happen?

This WP builds on an existing design study (CLOck NETwork Services) to go beyond current single point-to-point connections between a small number of partners, mainly relying on national initiatives. There is a strong case for cross-national collaborative efforts to extract a higher value out of the individual existing parts and to extend this network towards further institutes. Addressing technical issues (HW for L-band needs to be developed, test dedicated (dark) and existing LCG network fibers, switching bands between countries at borders (cross-border links)) will constitute part of the milestones of this WP.

The interest in time distributions and frequency dissemination over quantum networks has recently increased for both telecommunications applications (fast 5G networks) and scientific applications (ranging from gravitational wave detection to dark matter searches). It has been possible to demonstrate the transmission of quantum information over more than 500 km without the need of any repeaters. Some of these new protocols require sub-nanosecond synchronisation such as the one that can be offered by the CERN technology White Rabbit, currently allowing synchronization at the ns level. It's noteworthy that the European Commission has chosen White Rabbit as a candidate technology for a future EU-wide optical fibre time dissemination network through their programme Alt PNT.

Figure 1: Existing and future trans-national optical clock network

4.1.2 WP 1b: Portable references and sources

While direct distribution of optical frequencies via a trans-national optical clock network is feasible within a geographic region such as Europe, this is much more challenging on a global scale. To tackle the problem of comparing clocks at geographically widely separated stations, an alternative to optical distribution of a reference frequency is to clone a well-established reference, and geographically distribute identical systems. This requires the design and fabrication of standardized portable references, bearing in mind that both neutrals and charged species can play the role of reference clock systems.

Similar distribution needs are also apparent in the case of a generalization of beam-to-trap-to-beam sample ion approaches. Investigations relying on ions of radio-isotopes produced at facilities are currently limited to experiments carried out at the production facilities themselves, which are not necessarily the environments best suited to precision measurements. Portable devices for charged ions would allow transporting moderately long-lived species to a wide range of high-precision measurement devices.

Where are we? What do we need to happen?

For neutral species, magneto-optical traps rely on provision and control of the trapping and probing lasers and of the magnetic field generating infrastructure.

For charged species, either Paul or Penning traps would be suitable, bearing in mind that vacuum limitations may constrain the lifetime of any transported species. Penning-trap based devices relying on superconducting solenoids to address this issue are under construction, while alternate approaches with permanent magnets are still at a conceptual level and their feasibility must be established. Paul trap based devices, in which the RF can help mitigate neutralization of positively charged ions, are limited in the number of different species that can be trapped simultaneously.

In both cases, UHV vacuum systems, uninterruptible power supplies, gate valves, device transportabilty and cost are additional aspects. A standardized approach relying on miniaturization and established readily available components would be greatly beneficial.

4.2 WP-2 : Exotic systems in traps and beams

High sensitivity searches for BSM physics or for violations of fundamental symmetries rely on probing a wide range of systems (trapped atoms, ions, molecules, or beams thereof). While these systems have already led to highly sensitive searches for new physics through precision measurements of masses, transitions or g-factors, it is not clear that these are the optimal systems for specific searches, and it is easy to conceive of many others that have to date not yet been experimentally realized, even in highly active fields (such as that of HCI's, of Ryberg systems, or of radio-isotopes).

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 2 (exotic systems)	X			X	?	

Table 3: Quantum sensor families impacted by R&D in WP-2

Where are we? What do we need to happen?

Exploration of novel production mechanisms (anti-protonic atoms as gateways to trapped, fully stripped nuclei, or to hydrogen-like Rydberg HCI's), of novel species (polyatomic, laser-coolable molecular systems) or extension of existing techniques to all potential systems (e.g. laser-cooling of negatively charged systems, either atomic or molecular) are all needed to enhance the set of available systems for experimental investigation. Which system is optimal for which particular goal is a question covered inter alia in WP 4 (Theory WP), but vice-versa, being able to access a system with highest sensitivity to a particular test of known physics or a specific BSM interaction requires establishing a range of techniques to prepare and manipulate a much wider range of systems than are currently acessible.

A particular category concerns molecules with radionuclides for eEDM searches, with a reach in terms of SUSY sensitivity beyond 10 TeV masses. Given the overlap with WP 5, but also the fact that these mostly (but not exclusively) are investigated in small numbers, this category will be treated here.

What is needed for this category are improvements to existing experiments, new trapping technologies, advanced quantum control (including cooling techniques) of molecules, offline access to species of interest (with production, harvesting and handling on a one day time scale). There are ongoing efforts at ISOLDE, TRIUMF, FRIB on "Beam to beaker to beam". Here, the efforts of WP-1b on portable Penning traps / Paul traps with XUHV are particularly relevant.

4.3 WP-3 : Cryogenic systems

Superconducting technology is essential for observational astronomy for next generation telescopes in the IR$\sim$mm wavelength, but also for x-ray astronomy. Devices consist not only of single (kilo-pixel) detectors but also require complex superconducting electronics. Engineering of superconducting materials to control T_c, but also their other properties (e.g. bi-layers or multi-layers). Very high vacuum is essential for the UHV sputtering processes, as are a number of further performance characteristics of any resulting device. With a focus on the intermediate TRL developments, the following technologies are needed:

- single photon detection (incl. at microwave frequencies)
- ultra-low-noise amplifiers, high temp (4K) ultra-low-noise amplifiers, chip-based systems for generation and detection of squeezed states over microwave to mm wave range.
- solid state superconducting detectors for high-energy photon and massive particle detection and spectroscopy, such as single-electron detection
- development of packaging methods for superconducting electronics (e.g. magnetic field shielding, cosmic ray shielding, stray light shielding, EMI, ...)
- multiplexing technology challenges for superconducting mega-pixel devices
- materials science challenges

These can be grouped into three areas around which the three sub-WP's of the superconducting WP are arrayed:

- Theme 1: superconducting electronics for microwave-mm-wave range
- Theme 2: high-energy particle detection (photons & massive particles)
- Theme 3: characterization and measurement methods (including packaging and screening techniques to stop photons reaching the detector)

As an example for Theme 2, but also for the inter-relatedness of the three themes, we consider the case of R&D on TES/KIDs:

- the optimization of TES/KIDs based light detectors to further enhance their sensitivity (e.g. through the Neganov-Trofimov-Luke effect) and time resolution (through the investigation of novel materials and geometries);
- the development of a compact and radio-pure cryogenic wiring. We underline that, in contrast to TESs, KIDs are currently operated using the same readout as superconducting qubits, i.e., printed circuit boards, SMA connectors, coaxial cables for RF applications, that are known to be intrinsically radioactive, rigid (with potential impact on vibrations) and voluminous.
- the development of a multiplexed readout for TESs, to minimize the number of channels and the heat load on the cryostat. This will not be necessary for KIDs, that are naturally multiplexed, even if a study on the number of detectors that can be coupled to the same feedline without impact on the performance, is still mandatory.
- a new DAQ/storage/trigger system to deal with the much higher data rate of these fast sensors compared to the standard cryogenic calorimeters, and to integrate these data with those obtained from the cryogenic calorimeters.

It should be noted that because of the requisite development / customization costs and a relatively small user base, these developments will not be driven by industry. We also recall that these enabling technologies could have a transformative impact also on other devices, such as superconducting quantum bits, quantum sensors and cryogenic amplifiers.

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 3a (4K stage)		X	X			?
WP 3b (recoil)		X				
WP 3c (integration)		X				

Table 4: Quantum sensor families impacted by R&D in WP-3

4.3.1 WP 3a: The 4K stage

arrays of parametric amplifiers , ASICS at 4K (28 nm), FPGA, tunable circuit elements, material science aspects

ultracold He as an environment and as a detector

SRF, cavity developments,

Where are we? What do we need to happen?

4.3.2 WP 3b: Quantum sensors and exotic beams (particle and high energy photon detection)

New quantum sensing detectors like transition edge sensors (TES) and magnetic microcalorimeters (MMC), and kinetic inductance detectors (KID) open up new possibilities for exotic beam physics because they offer, for the first time, high sensitivity and high efficiency. However, so far these technologies are nascent and have been principally used in metrological situations, and further development is needed to make them broadly and easily applicable to exotic beam physics. For example, first deployment of x-ray TES detectors with muonic [?], pionic [?] , and kaonic [?] beams have shown promising results, but also highlighted the current limitations coming from coincident charged-particle background and limited understanding of the detector response functions.

Where are we? What do we need to happen?

There are 3 tasks to be undertaken to make these new detector technologies compatible with future needs for exotic beam physics:

- Coincidence detectors : Development of a cryogenic charged particle anti-coincidence detector for use with microcalorimeters. This step is essential to reduce beam-induced background and will be useful both for exotic beams like heavy ions storage rings and muon beams, and space-based detectors like the TES detectors that will be deployed in the ATHENA project.
- Metrological calibration lines above 50 keV to 300 keV, needed for high-precision measurements with TES/MMCs whose non-linear response function requires well-known calibration lines close to the transitions of interest. Currently exact line shapes have been obtained for example by using x-ray tubes with crystal spectrometers [?], but currently these highest-precision calibration lines are limited to the few tens of keV regime and limited high precision calibration lines are available in the few hundred keV regime. In principle this can be obtained from both radioactive sources and highly-charged ion transitions measured with crystal spectrometers, but a coordinated effort is needed between the highly-charged ion community and gamma ray sources to provide a dedicated set of calibration lines in the hard x-ray and gamma-ray regime.
- Microcalorimeter detectors are very sensitive thermometers, and any phenomenon that heats the detector arrays can shift the respon function of the detector and introduce systematic shifts. The effect of charged-particle hits has been studied experimentally, but a full modeling of charged particle background from

source to detector would allow to unambigously disentangle this important contribution to the signal and enable more precise measurements. A dedicated full theoretical study would benefit all microcalorimeter detectors and current and future precision studies with charged particle beams.

4.3.3 WP 3c: Resilient integration of superconducting systems

resilience against perturbation (high E,B), noise, packaging, stray-light avoidance, cosmic rays, interfacing

Where are we? What do we need to happen?

4.4 WP 4 : Theory

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 4a (bound states)	X			X	?	
WP 4b (Heisenberg limit)	X			X	?	
WP 4c (optimization)	X			X	?	

Table 5: Quantum sensor families impacted by R&D in WP-4

4.4.1 WP 4a: Bound state calculations

Observables in bound systems such as transition energies and g-factors can be measured with record precision. These observables are responsible for determining fundamental constants and, through redundancy, searching for BSM at the accuracy frontier.

Frontier applications of theory include:

1. Further development of bound-state QED (bsQED). Both the nonrelativistic QED, valid for small Z and so-called all-order methods, best suited for highly relativistic systems. An example of frontier nrQED developments needed is higher-order radiative-recoil effects, which dominate the hydrogen-deuterium isotope shift physics []. A further frontier field is the theory of helium and helium-like atoms [].
2. Further development of the interface between bsQED and low-energy QCD, which manifests as low-energy observables such as electromagnetic moments and their effect on bound-state energy levels. As an example, light-atoms charge radii are limited by our ability to calculate nuclear corrections to muonic atom energy level [].
3. When more equations are available than free parameters, we can search for new physics at the accuracy frontier []. The physics reach is forever at the level of the larger uncertainty between experiment and theory. A consistent, broadband search for new physics must allow for the consistent estimation of fundamental constants in the presence of new physics [].
4. With the advent of quantum technology, a multitude of experiments can be imagined or improved. To choose which of those is worth pursuing, a theory effort is needed in order to identify the most promising systems to search for or constrain new physics model-agnostically.

Where are we? What do we need to happen?

4.4.2 WP 4b: Reaching the Heisenberg limit

Backaction evasion in optomechanical detectors or other sensors among the DRD5 / RDq families of quantum sensors

Squeezed light

Where are we? What do we need to happen?

4.4.3 WP 4c: Resource optimization

Correlation between detector technologies and Physics reach; provide guidance as to the most promising unexplored areas when faced with novel functionality quantum sensors, highlight overlap / complementarity / redundancy between different approaches,

Where are we? What do we need to happen?

4.5 WP 5 : "Bulkification"

Typical quantum sensing systems are at or below the nanometer scale, while at least for High Energy Physics applications, but also for enhanced sensitivity of e.g. levitated macroscopic systems, scaling up to much more massive scales is needed. In this Work Package, the challenge of incorporating quantum systems in large scale devices without losing their quantum behavior will be tackled. This can require manipulating bulk matter (such as NV-diamonds) in such a manner that a very large fraction of the spins are aligned, incorporating individual quantum systems (such as quantum dots) in bulk systems (such as scintillating materials), or constructing or engineering materials at the nano-scale such that local quantum behavior results in desired properties (such as those of engineered multi-layer heterostructures).

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 5a (spin ensembles)		X	X	X	X	X
WP 5b (scintillators)					?	X
WP 5c (planar heterostructures)	?					X

Table 6: Quantum sensor families impacted by R&D in WP-5

4.5.1 WP 5a: Massive spin polarized ensembles

Three overarching categories of massive spin-based detectors have been considered:

- levitated ferromagnetic torque sensors (overlaps with spinor BEC and optomechanical accelerometer)
- molecules with radioisotopes for eEDM
- large volume, high density, highly spin-polarized samples (for HEP and exotic spin-dependent samples, but also magnons)

Where are we? What do we need to happen?

The first category is sensitive to local sources OR ultra-low energy bosonic fields. Spin samples with long coherence times such as ferromagnetic particles (10 micron particulates floated in vacuum at 10 mK) should be many orders of magnitude more sensitive than existing systems (e.g. NVD, BEC). Arrays of these microparticulates should be possible. A consortium of groups in Europe and US collaborators working on this category already exists.

What is needed is development beyond State-of-the-art (superconducting) R/O electronics, much better vacuum, purity/flux trapping of superconductors needed for suspending/levitating the bulk samples. Both the existing community and large-scale HEP labs have quite some expertise in the required areas.

The second category concerns molecules with radionuclides for eEDM searches, with a reach in terms of SUSY sensitivity beyond 10 TeV masses. Given the overlap with WP 3 (exotic systems in traps and beams), this category dealing mainly with small numbers of probed molecules is subsumed under WP 3, although in specific cases, bulk amounts of such spin-oriented molecules are needed.

Thirdly, production of polarized "targets" and CASPEr - like experiments benefit from large compact samples of spin polarized systems. Both going to lower temperatures (from 4K down to 10mK) and to larger sample size (from mm to 10 cm) is important. The following is being looked at and in need of development: expansion of the range of species (other species in addition to para-hydrogen); dynamic nuclear polarization (CASPEr-E with ferroelectric crystals); optical polarization, polarized lXe, lHe_3, naphthalene, and others. In many cases, this requires advances in solid state physics, chemistry, etc., so there is a need to enable supporting developments in neighboring fields and to exchange with them (WP-6a). In this context, the usefulness of bulk polarized materials (such as NV-diamonds) for helicity-sensitive tracking devices, relevant also for nuclear physics, requires further R&D on hyper-polarization, as well as beam tests for establishing proof-of-principle (WP-6b).

4.5.2 WP 5b: Scintillators

Confinement results in artificial atoms, such that nanowires, nano-platelets, mono-layers, Perovskites, quantum dots, quantum wells, and other structures or heterostructures at the few nm scale have well defined properties amenable to nano-engineering. Of particular interest are rapid rise and decay times, narrow-band emission spectra (tailorable via composition, geometry and size), and the breadth of systems that allows optimizing the overall properties of systems incorporating them. Novel active scintillators based on e.g. quantum wells or possibly by coupling quantum cascade lasers to silicon detectors would enable novel functionalities.

Other nanostructured materials with similar potential include metal organic frameworks, aerogel / scintillator hybrid structures (e.g. YAG aerogel with high porosity, supercrystals, optically suspended nanospheres; HfO_2-loaded (high density) water, and many others.

Where are we? What do we need to happen?

Stopping power is important for HEP, so micromachining or engineering of a mix of bulk and nanomaterials is required. Similarly, determining the resistance of any novel materials to radiation is a crucial step in evaluating their potential and suitability for a specific application. Developments both in the field of optics (e.g. metalenses) and large-scale integration (integration of heterostructures) are needed to achieve the transition from small numbers of devices with overall low energy deposit by minimal ionising particles to massive devices with high stopping power.

4.5.3 WP 5c: Ensembles of heterostructures

Composite structures combining low-dimensional materials and nanostructures with established detector technologies can offer unprecedented tunability and improvements in detector sensitivity and performance compared to conventional bulk materials. Work function engineering may allow for increased QE with examples being demonstrated by composite photocathodes with coatings of atomicially thin graphene or BN. Graphene monolayers on photocathodes increase work function (WF) thus enhancing emissivity, while BN can decrease WF and increase QE. Different nanowire systems have been proposed as high efficiency photocathodes owing both to improved geometric emission probability as result of their large surface to volume ratios as well as their reduced dimensionality. In addition to enhanced sensitivity, low-dimensional materials may also be used to tune the response spectrum by either exploiting resonsance effects (e.g. quantum dot size chosen in view of enhanced sensitivtiy to specific wavelength) or using systems that can cover a broad wavelength region such as twisted bi-layer graphene.

In gaseous detectors, low-dimensional materials may be used to fine tune charge transport processes to address limitations of conventional gas-based detectors. This may include the suppression of ion backflow with single- or few-layer suspended graphene membranes acting as selective ion filter while allowing for electrons to pass. Such layers may also be used as physical barrier to separate gas volume allowing for a choice of optimal gases for the sensitive and amplification regions of a detector.

Where are we? What do we need to happen?

While a number of promising materials and structures have been proposed and experimentally evaluated, implementing them in detectors relevant for HEP detection needs poses a number of challenges. Most notably, the mismatch in size scales between nanofabrication techniques and detection areas required for future experimental necessitates dedicated collaborative efforts of material researchers and detector developers. Additionally, compatibility with and stability of low-dimensional and nanostructures materials in environments encountered in HEP detector systems needs to be studied and evaluated. Therefore, a collaborative framework bringing together communities of material scientists and detector developers would be highly beneficial to share knowledge and experience on materials and systems with potential applications for future detection needs. Dedicated meetings and workshops, expert contacts and databases of materials of interest as well as common organisation of measurement campaigns can be valuable aspects to bridge the gap between novel materials and their application in relevant future detection systems.

4.6 WP 6 : Capability driven design

In many of the fields covered by DRD5 / RDq, developments in neighboring engineering and material science fields can open up significant new avenues. To enhance exchanges between quantum sensing efforts and these other fields, exchanges at several levels appear to hold promise and are in some cases essential in the medium term. These consist of:

- Information exchange platforms, where developers of novel materials and their potential users in particle physics can exchange on needs and capabilities;

- Screening and characterization of materials and devices in a systematic / standardized manner (inter alia, testing samples with minimum ionizing radiation) via shared infrastructure and facilities;
- Developing a workforce familiar with the potential and challenges of quantum sensors requires building a educational and development platform

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 6a (Human networking)	X	X	X	X	X	X
WP 6b (Test infrastructure)	X	X	X	X	X	X
WP 6c (Education)	X	X	X	X	X	X

Table 7: Quantum sensor families impacted by R&D in WP-3

4.6.1 WP 6a: Exchange platform

Where are we? What do we need to happen?

4.6.2 WP 6b: Test platform

Where are we? What do we need to happen?

4.6.3 WP 6c: Education platform

Advancements in applications based on the quantum properties of systems require interdisciplinary approaches. Currently, most higher education institutions offer specialization in QT at the postgraduate level of Physics studies. However, the existing education schemes do not adequately prepare engineers and other specialists for the widespread adoption of QT in both frontier science and industry. Without a specialized workforce, the development of the field will be hindered unless appropriate measures are taken. To address these challenges, the following three pillars are considered to be crucial:

- upskilling existing professionals to increase multidisciplinarity
- education based on microcredentials instead of 4 year study plans
- unification of skills in the existing programs

Where are we? What do we need to happen?

4.7 Cross-pollination of Work Packages

The proposed Work Packages are not all orthogonal to each other; in fact, several WP's rely on progress made in other WP's or can enhance the effectiveness of work in them. Table 8 provides a rough indication of such cross-influences.

work package	WP1	WP2	WP3	WP4	WP5	WP6
WP 1 (clocks)		X	X	X		X
WP 2 (exotic systems)	X			X		X
WP 3 (cryogenic)	X			X		X
WP 4 (theory)	X	X	X		X	X
WP 5 (bulkification)				X		X
WP 6 (capacity)	X	X	X	X	X	

Table 8: Work Package cross-influences and impacts

5. FURTHER CONSIDERATIONS

5.1 The importance of Entanglement

In the above Work Packages, entanglement has not played a prominent role, although from exploratory investigations, it is clear that it holds great potential for even more sensitive devices than those whose development is proposed in this White Paper. It must also be said that this topic did not feature prominently in the proposals submitted in the course of the run-up to the DRD5 implementation workshop.

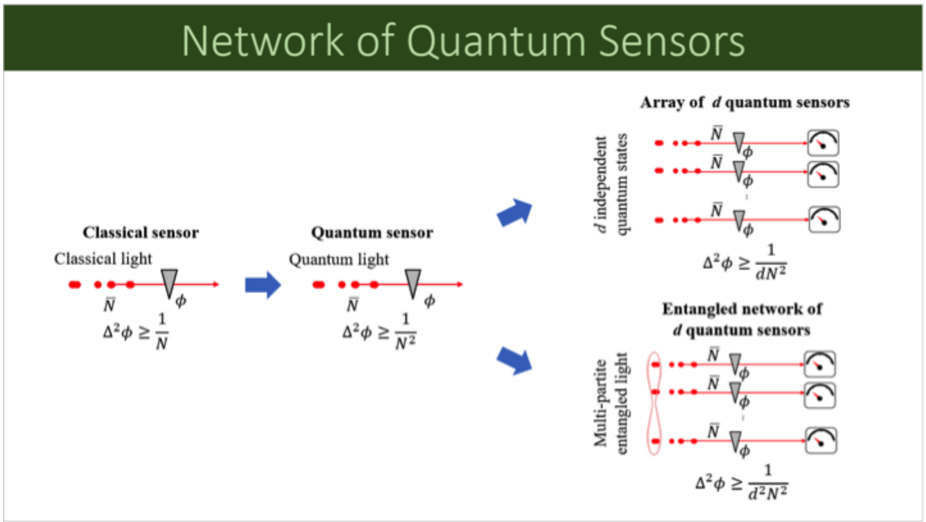

Figure 2: The improvement in sensitivity that entanglement can bring to a set of individual nodes of quantum sensors scales with the number of nodes.

As a consequence, the DRD5 / RDq process should remain open towards potential proposals on how the Work Packages could incorporate developments targeted towards implementing entanglement, given the expected commensurate gains in sensitivity.

5.2 Further technological challenges and projects

6. SUMMARY

7. APPENDIX: THOUGHTS ON COLLABORATIVE STRUCTURE

7.1 Collaborative issues

Standard CERN Collaboration agreements will be used as a starting point in defining the structure of the DRD5 / RDq Collaboration, but with several significant simplifications. Among other,

- no annual membership fees or entrance fees will be raised for academic Collaborators;
- Collaborators can be individual university groups, other Collaborations, laboratories or other academic entities. The status of possible industrial partners will need to be clarified;
- acceptance of membership by an interested party is decided by the Collaboration Board, which is also to be informed in case a party wishes to leave the Collaboration

7.2 Collaboration structure

The structure of a diverse and global collaboration should be as lightweight as possible, while ensuring adequate representation of all involved entities. With six quantum sensing families and six Work Packages (organized around six Working Groups), one possible structure could be a collaboration structure in form of:

- a **Management Board** (one spokesperson, one elected representative from each of the 6 Working Groups); the spokesperson is the interface between the collaboration and the scientific committee on one hand, and represents the Collaboration publicly on the other hand.
- a **Collaboration Board** consisting of overall around 30 elected representatives coming from the 6 Working Groups
- an independent structure consisting of experts from within the Collaboration that forms a **Project Evaluation Board** that has the expertise to evaluate any projects submitted to it by groups of at least 3 collaborating groups for scientific merit and against the overarching goals of the ECFA roadmap

7.3 Issues related to the global scale of the proposal

Given the international scale of this collaboration, and the administrative load of maintaining and coordinating wide-spread efforts, there appears to be a need to have internationally distributed "platforms" or "hubs" for organizational reasons (one per sensor family or Working Group, for a total of six), although their role needs to be defined more precisely.

7.4 IP issues

Interaction with industrial/commercial partners still needs refining, also regarding their voice in shaping some of the research directions. It is definitely recommended to think through issues such as patents, interaction with industry, licensing, sharing of IP (prior, created during collaboration, after a group leaves) in the initial phase of forming this Collaboration, with the base-line understanding that IP created by Collaborators belongs to them and their potential external partners (no common ownership), but that access to IP created in the context of the Collaboration shall remain available to the Collaboration members indefinitely, possibly against minimal licensing fees in the case the Collaborator from whom the IP stems leaves the Collaboration.

7.5 Timeline

The overall process from the start of implementation on January 1, 2023 to the submission of a proposal to the new DRDC scientific committee at the end of 2023 is relatively short; in order to achieve this timeline, the process has been strucutured as follows:

- Recruitment of representative conveners for the six different families of quantum sensors of the ECFA roadmap (about 5 conveners per family). This selection of experts balances geographic spread, expertise, gender and included both theorists and experimentalists. It also tried to balance the representation within the CERN member and associated member states with those of other geographic areas (USA, Japan, Australia);
- a workshop amongst conveners at CERN **(April 2-5, 2023)**;
- until **May 15**: drafting of minutes of this meeting with the identification of potential Work Packages of widespread interest;
- until **May 15**: creation of a set of web pages for registration by interested parties, for information, and to form a proto-collaboration;
- until **June 15**: drafting of a White Paper based on the workshop minutes, through involvement of the conveners and the potentially involved communities;
- until **end of July**: drafting and submission to the DRDC of a Letter of Interest signed by all interested groups, but without any commitments;
- symposium at CERN **(October 2-4)** with the goal of a public discussion and fine-tuning of the LoI to transform it into a proposal to be submitted to the DRDC;
- in parallel, creation of the DRD5 / RDq collaboration;
- **end of 2023:** submission of the DRD5 proposal to the DRDC