Workshop on the DRD5 / RD-q Proposal on R&D on quantum sensors

2021 ECFA: roadmap with 6 quantum sensor families

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

2023 ECFA roadmap implementation:

January-March 2023: selection of ~ 2 dozen *conveners* (experts in the 6 quantum sensor families)

April 2023 workshop among *conveners,* with input from their communities and submitted contributions

Identify needs that exceed the possibilities of individual groups, and that would benefit wide communities within the 6 quantum sensor families ➡ candidates for coordinated, global, targeted R&D

List of proto-Work Packages in form of White Paper (https://indico.cern.ch/event/1278425/attachments/2648910/4588936/quantum_ECFA_whitepaper_v0.3.pdf)

⬇

ECFA roadmap implementation (Oct 2023 public workshop): draft proposal (v 0.5)

Oct 2023 open workshop: openly and critically discuss the draft proposal

Workshop focus: Work packages, collaboration structure, organizational and financial issues, organization of work ➡ submission of proposal at end of year

Boundary conditions: format and timeline provided by DRDC and ECFA

The DRD5 / RD-q Proposal on R&D on quantum sensors: Work packages

ECFA: roadmap with 6 quantum sensor families

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

Proposal with 6 high level WP's (each containing sub-WP's)

Sensor family → Work Package ↓	clocks & clock networks	superconduct-ing & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials	
WP1 *Quantum Techniques for Sensing*	X	X	X	X	X		Monday morning
Squeezing							
Entanglement	X	X	(X)	X	(X)		
Back action evasion							
WP2 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)		Monday afternoon
Exotic systems				E,T			
Atom interferometers				X			
Clock & signal distribution	X			X			
WP3 *Quantum Materials*		X X	X X			X X	Tuesday afternoon
0-, 1-, 2-D materials		X	(X)		X	X	
Superconducting devices & electronics at 4K		X				(X)	
WP4 *Large ensembles of quantum sensors*							Tuesday morning
multi-modal systems							
indirect readout							
WP5 *Scaled-up "Quantum for HEP"*		X	(X)	X	(X)	X	Wednesday morning
spin-sensitive devices		X		X		X	
hybrid devices						X	
WP6 *Capacity-driven design*	X	X	X	X	X	X	Wednesday afternoon
schools & training							
networks of expertise							
shared infrastructures							

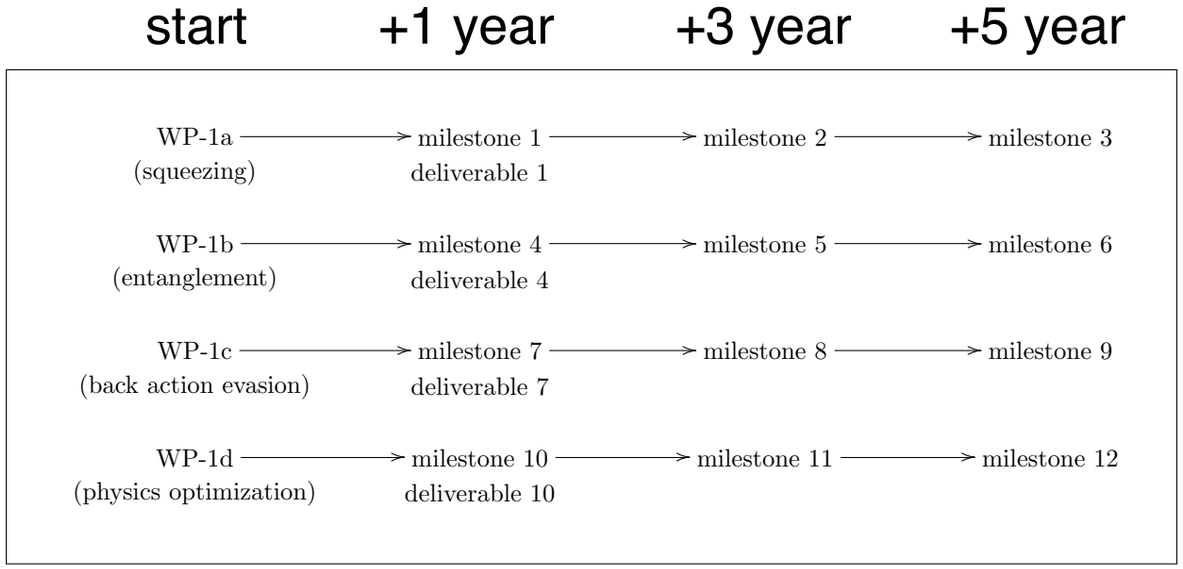
The DRD5 / RD-q Proposal on R&D on quantum sensors:

what do we want to get out of this workshop?

Discussion focus: Work package content, sub-WP focus, organizational aspects

- are we missing important topics, are some topics superfluous (because groups are already working on it), does the text need to be reformulated?

- evaluation by DRDC: milestones, deliverables: how to formulate the specifics of a WP, its goals, its intermediate steps?



- which institutes are involved in which WP? What resources are required?

to submit the proposal, we'll need to show that this initiative is *welcome*
= a list of institutes willing to ***commit*** to work on one or more of the WP's

The DRD5 / RD-q Proposal on R&D on quantum sensors: the names

Conveners (alphabetic ordering)

Hiroki Akamatsu (KEK), Etiennette Auffray (CERN, Geneva, Switzerland), Caterina Braggio, Florian Brunbauer (CERN, Geneva, Switzerland), Shion Chen, Martino Calvo, Marcel Demarteau, Michael Doser (CERN, Geneva, Switzerland), Christophe Dujardin, Andrew Geraci, Arindam Ghosh, Glen Harris, David Hume, Derek F. Jackson Kimball, Jeroen Koelemeij, Georgy Kornakov, Stefan Maier, Gobinda Majumbder (TIFR, Mumbai, India), Alberto Marino, Tanja Mehlstäubler, Alessandro Monfardini, Ben Ohayon (Technion IIT, Haifa, Israel), Nancy Paul, Sadiq Rangwala (RRI, Bangalore, India), Florian Reindl, Mariana Safronova, Swati Singh, Stafford Withington, Steven Worm

WP-1 : QUANTUM TECHNIQUES FOR SENSING

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP 1a (squeezing / optimization)	X			X	(X)	
WP 1b (entanglement)	X			X	(X)	
WP 1c (Heisenberg limit)	X			X	(X)	
WP 1d (optimized exploration)	X	X	X	X	X	

WP-2 : ATOMIC, NUCLEAR AND MOLECULAR SYSTEMS IN TRAPS & BEAMS

WP-2a : Exotic systems in traps and beams

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-2a_a (exotic systems)	E			E	(E)	
WP-2a_b (bound state calculations)				T		

WP-2b : Interferometry

WP-2c : networks, signal and clock distribution

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-2c_a (clock network)	X					
WP-2c_b (portable clocks)	X					

WP-3 : QUANTUM MATERIALS

WP-3a : 0-, 1- and 2-D materials

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-3a_a (tailored materials)		(X)	(X)		(X)	X
WP-3a_b (extended functionalities)		(X)	(X)		(X)	X

WP-3b : Cryogenic systems

work package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-3b_a (4K stage)		X	X			(X)
WP-3b_b (detection)		X				
WP-3b_c (integration)		X				

WP-4 : READOUT OF LARGE ENSEMBLES OF QUANTUM SYSTEMS

WP-4a: Multi-modal devices (e.g. Opto-mechanical systems, transduction)

Scaling up from a small number of sensors to large ensembles: challenge of readout, of optimal mode

Change from one mode (e.g. mechanical, microwave) to another (e.g. interferometry, optical): transduction

Challenges:

- In optomechanical systems the limitations of microwave (GHz) piezo-optomechanical devices need to be overcome to increase their sensitivity.
- Spin-photon interactions can be measured through optical iterrogation of the spin states or through magnetometry.
- Spin defects in 2D materials offer the potential for integration into hybrid quantum systems.
- The relative ease of tuning defects in 2D materials and their heterostructures via stacking, nanoscale patterning, selective doping, and strain engineering make these material systems attractive for the creation of quantum transducers.

WP-4b: Quantum-system-inspired parallel readout

Scaling up from a large number of (HEP) sensors to extremely large ensembles: novel approaches to R/O needed?

Quantum sensors: resonance parameters of a large number of circuits (each with slightly different resonance parameters) are probed in parallel, resulting in a ”forest” of frequencies. A change in one element will change the resonance frequency specific to that element on the time scale of the detector element response: parallel R/O

Global multispectral response of an very large ensemble of detector elements could allow alleviating some of the challenges of existing sequential (readout time) or parallel (number of readout channels, and thus required services) readout approaches, effectively leading to a ”Quantum DAQ”.

Challenges: timing in triggered or collision-linked readout (in the case of High Energy physics accelerator-based systems) ; design of element-specific circuits (in the case elements are not solid-state based)

Work Package	clocks & networks	super-conducting	kinetic sensors	atoms/ions/ molecules	opto-mechanical	nano-engineered / low-dimensional
WP-4a (multi-modal devices)			(X)		X	X
WP-4b (quantum-inspired R/O)		X			(X)	X

WP-5 : SCALING UP “QUANTUM”

WP-5a: Massive spin polarized ensembles

WP-5b: Hybrid devices

WP-5b a: Scintillators

WP 5b b: Ensembles of heterostructures

WP-5b c: Heterodox devices

work package	clocks & networks	supercon-ducting	kinetic sensors	atoms/ions /molecules	opto-mechanical	nano-engineered / low-dimensional
WP-5a (spin ensembles)		X	X	X	X	X
WP-5b (hybrid devices)					(X)	X

WP-6 : CAPABILITY DRIVEN DESIGN

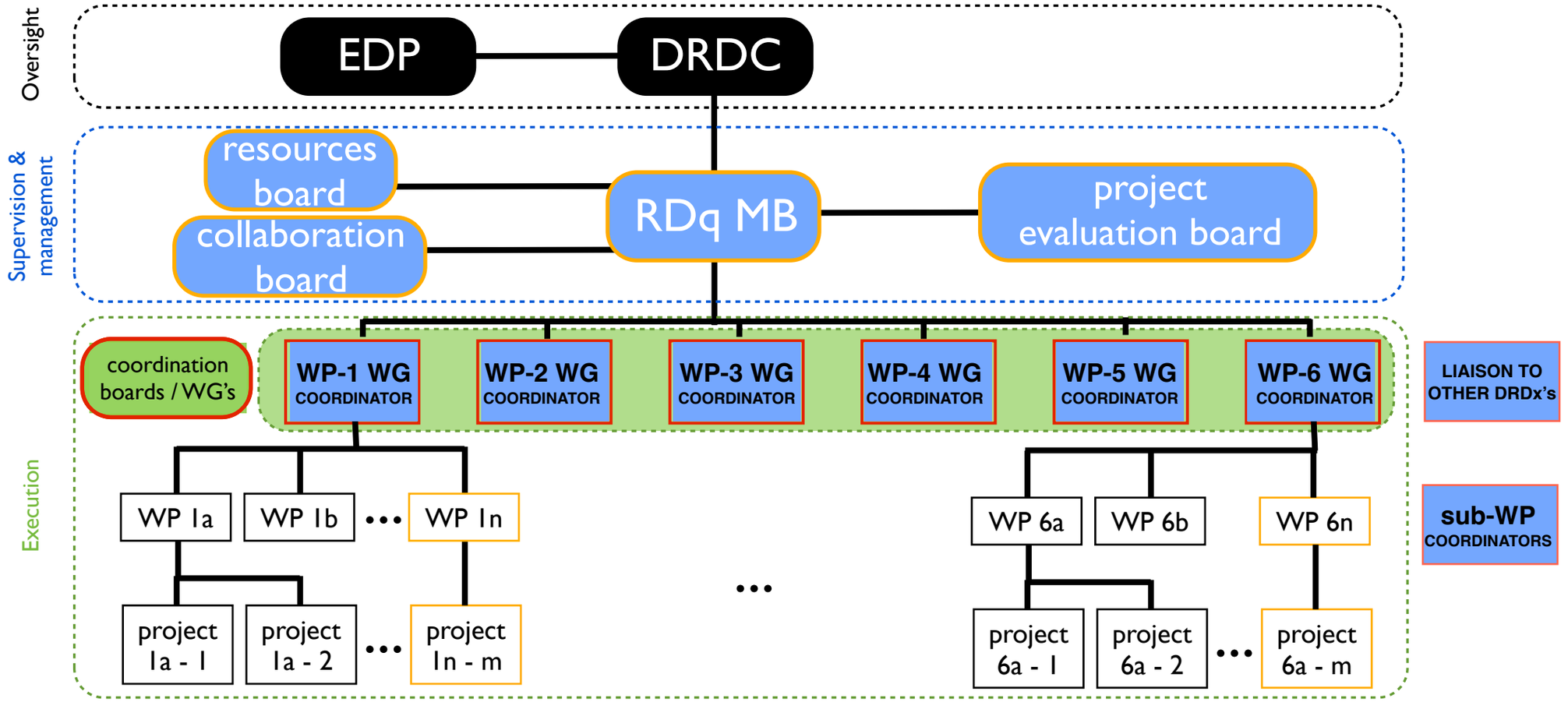
WP-6b: Education platforms (includes WP-6a: Equity, Diversity and Inclusion)

WP-6c: Exchange platforms

WP-6d: Shared infrastructures

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

DRD5 / RD-q : ORGANIZATIONAL STRUCTURE



(platforms may be mono-site or multi-site but carry the responsibility to shepherd the spread-out activities related to their specific WP)

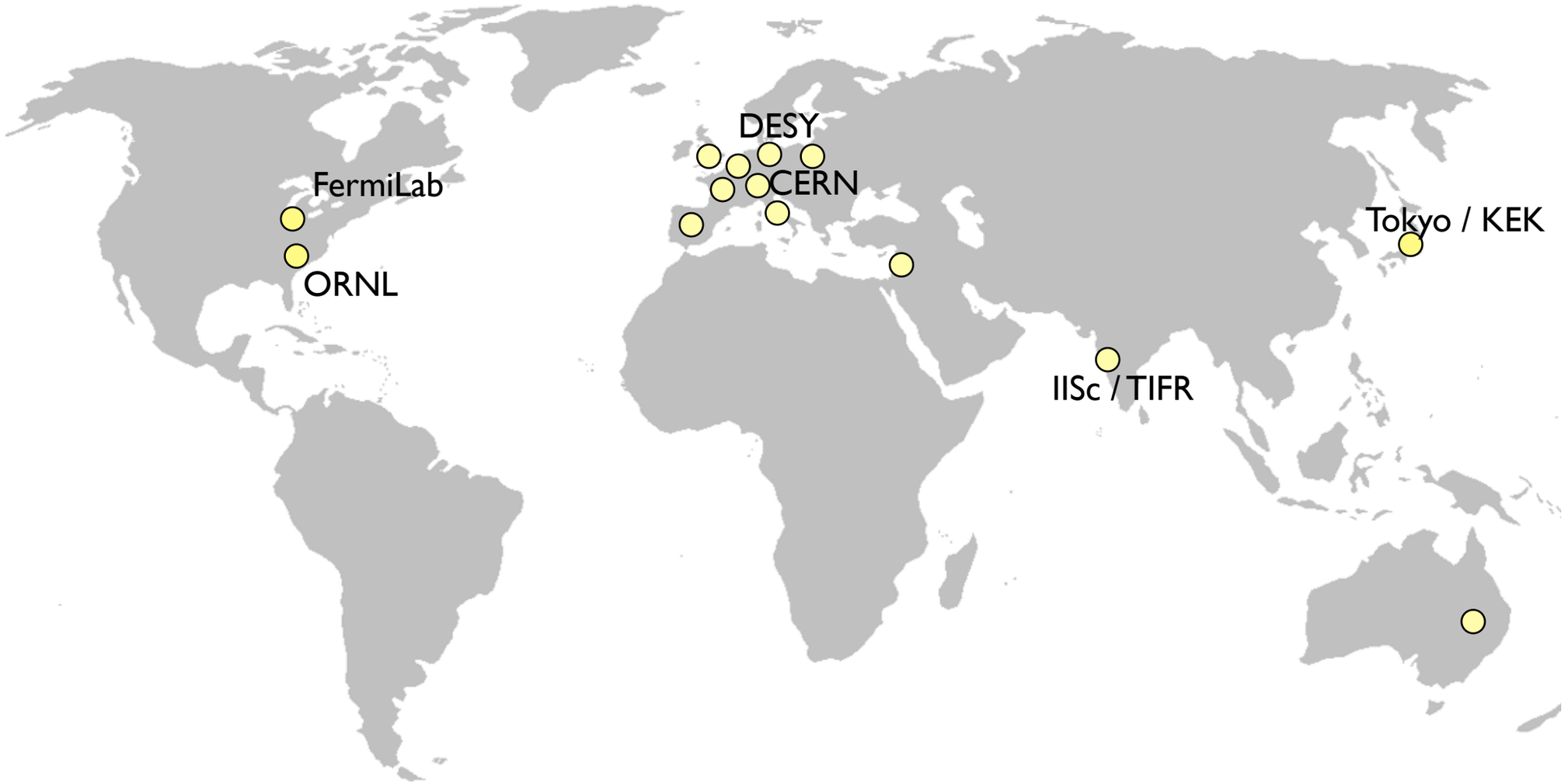
MANAGEMENT BOARD: one spokesperson, one deputy spokesperson, chairs of CB, RB and project evaluation board

COLLABORATION BOARD: WP- and sub-WP coordinators from the 6 Working Groups; ~~an equal number of Quantum Sensor family representatives elected by all participants;~~ one representative / institute

PROJECT EVALUATION BOARD: elected structure consisting of experts from within the Collaboration (can be WG coordinators)

RESOURCES BOARD: ??? TO BE DEFINED ???

DRD5 / RD-q : ORGANIZATIONAL STRUCTURE



ENSURE A WELL-BALANCED DISTRIBUTION OF WP-COORDINATORS, SUB-WP COORDINATORS, SPOKESPERSON NOMINATIONS BY CB and/or SPOKESPERSON; CB SHALL ELECT

LIMITED TERMS OF OFFICE: 1 OR 2 YEARS? RENEWABLE? CB SHALL DECIDE

DRD5 / RD-q : MOU, FINANCIAL ASPECTS, IP

Existing lightweight Memorandum of Understanding (MOU) for the GRADE R&D

Considering that:

CERN as the Host Laboratory and various Institutions and Funding Agencies have expressed their interest in carrying out together long-term quantum sensor-based detector R&D for future particle physics experiments at CERN (e.g. HL- LHC, ILC, FCC, etc.) and elsewhere, which also includes an educational component;

These R&D detector activities share a commonality in that they are generic by nature, potentially comprise initial computer simulations, concept sub-module design, (rapid) detector component prototyping testing and integration, potential end-user need analysis and more, and are to be performed at participating particle physics institutes.

These R&D detector activities ~~at IdeaSquare~~ are known collectively as the "DRD5 / RD-q" Programme whose objective is to explore new quantum sensor-based detector technologies for future particle physics physics experiments at CERN and elsewhere, while engaging students from different fields of interest and industry;

~~If the GRADE Programme proves successful, it may, in due course, result in a formal proposal for larger-scale follow-up programmes or experiments at CERN;~~

Depending on the case, there may be activities involving industrial partners, to be laid down in separate collaboration agreements on terms consistent with this MoU and/or the MoU governing any future follow-up programmes or experiments.

Likewise, there may be opportunities for contributions by students that are not linked to any of the parties, similarly on terms that are consistent with the applicable MoU;

On (*enter date*) the CERN Research Board approved the DRD5 / RD-q Programme, subject to a number of comments concerning governance that are reflected in the terms of this MoU;

Through this MoU (including its Annexes and Amendments) the parties' obligations in the implementation of the DRD5 / RD-q Programme are defined:

Article 1: Purpose

1.1 This MoU defines the terms of participation of the parties in the DRD5 / RD-q Programme, always for non-military purposes only.

1.2 Except as otherwise stated, the implementation of an experiment within the framework of the DRD5 / RD-q Programme is subject to the General Conditions applicable to Experiments at CERN ("the General Conditions"), attached to this MoU as **Annex 2**.

1.3 Experiments are admitted to the DRD5 / RD-q programme on the basis of a proposal submitted to the Director of Research and Computing, who will be advised by a small standing committee that will be convened as appropriate.

1.4 With the exception of Article 7 and **Annex 2**, this MoU is not binding upon the parties, but it is recognised by the parties that adherence to its provisions is fundamental for the success of the GRADE Programme.

2. **Article 2: Parties**

The parties are CERN as the Host Laboratory and the Institutions participating in an R&D activity within the framework of the DRD5 / RD-q Programme and, as the case may be, their Funding Agencies. For each institution a specific Addendum will be drawn up and the parties signing the form set out in **Annex 1** will thereby become a party to this MoU. The current list of such Institutions and/or Funding Agencies and their representatives is given in **Annex 3**.

3. Article 3: Duration

This MoU will remain in force until/inclusive completion of the DRD5 / RD-q Programme, or the ceasing of its approval by the CERN Research Board.

Article 4: Scope of Work

4.1 The scope of activities for each R&D activity within the DRD5 / RD-q Programme, and each party's contribution thereto, which may include modest financial contributions to common expenses, are set out in the Addendum covering that particular institute's activity. The parties to each R&D activity shall agree between themselves on the detailed specifications of the work, which they may decide to define in Annexes to the Addendum.

4.2 Any in-kind contributions shall be deemed to have no financial value.

4.3 A party may withdraw from an experiment, and thereby from this MoU, by giving six months' written notice to the Chairperson of the Collaboration Board of the experiment.

Article 5: Responsibilities of CERN as Host Laboratory

5.1 The obligations of CERN as the Host Laboratory of the DRD5 / RD-q Programme are set out in the General Conditions.

5.2 CERN's specific support as the Host Laboratory includes granting access to the CERN ~~IdeaSquare~~ premises (i.e. shared offices and laboratory space), coordination support across related activities and limited material resources agreed on a case-by-case with t~~he IdeaSquare Program Coordinator and~~ the CERN Director of Research and Computing.

Article 6: Governance

6.1 Each R&D activity within the DRD5 / RD-q Programme shall be managed by a Collaboration Board, consisting of one representative from each party to the experiment, including ~~the IdeaSquare Programme Coordinator, or any other~~ a representative appointed by CERN to represent it as the Host Laboratory.

6.2 Each Collaboration Board shall elect from among its members a Chairperson for that board.

6.3 Each Collaboration Board shall define project milestones for its R&D activity which will be monitored by the standing committee referred to in Article 1.3. CERN's Director for Research and Computing shall annually report progress of the experiments in the DRD5 / RD-q Programme and progress of the DRD5 / RD-q Programme itself to the CERN Research Board.

Article 7: Intellectual Property

7.1 CERN is bound by its Convention to publish or otherwise make generally available the results of its experimental and theoretical work.

~~7.2 Except as otherwise agreed, the parties shall publish and make publicly available all results from the experiments within the DRD5 / RD-q Programme and all proprietary information, whether pre-existing or developed in the course of the experiment, that it has contributed to the experiment. In particular, they shall make software available under Open Source license conditions, hardware designs available under Open Hardware licenses, and results from the experiment available through Open Access publications.~~

ANNEX 1

The European Organization for Nuclear Research (CERN)
as the Host Laboratory of the DRD5 / RD-q Programme

and

…….. participating in the [……..] experiment within the DRD5 / RD-q Programme

declare that this Addendum and the Memorandum of Understanding for providing a framework for the implementation of experiments within the DRD5 / RD-q Programme, govern the implementation of the experiment.

Done in Geneva on …….....

for CERN

by *nnn*
Director of Research and Computing

Done in ……..... on ……

for ……

by [Team Leader]

DRD5 / RD-q : MOU, FINANCIAL ASPECTS, IP

FINANCIAL ASPECTS

Draft Proposal:

No entrance fees, no annual contributions for academic partners.

Tiered annual contributions for industrial partners ? (what rights, which obligations?)

Finally, we foresee a resources review board, whose composition and membership rules are still under discussion, and whose role would be to provide an external viewpoint from among world experts in quantum sensing on the expenditures and sharing of costs of the Collaboration’s R&D and on possible re-prioritizations.

DRD5 / RD-q : MOU, FINANCIAL ASPECTS, IP

Article 7: Intellectual Property

7.1 CERN is bound by its Convention to publish or otherwise make generally available the results of its experimental and theoretical work.

~~7.2 Except as otherwise agreed, the parties shall publish and make publicly available all results from the experiments within the DRD5 / RD-q Programme and all proprietary information, whether pre-existing or developed in the course of the experiment, that it has contributed to the experiment. In particular, they shall make software available under Open Source license conditions, hardware designs available under Open Hardware licenses, and results from the experiment available through Open Access publications.~~

Draft Proposal:

12.4 IP issues and industrial involvement)

With the very rapid progress in the field of quantum sensing, industrial and commercial partners can be expected to be involved either as direct partners with specific collaborating institutes, or as interested participants. We do not foresee that such partners will become collaborators themselves, but do foresee a membership model in which such partners are informed of activities and progress on different detector R&D thrusts. Specific commercial / industrial membership models may in turn be considered in light of their implications for addressing collaborative resource challenges.

At this point in time, the specific details of interaction with industrial/commercial partners are however not yet completely defined, also regarding their voice in potentially shaping some of the research directions. Issues such as patents, interaction with industry, licensing, sharing of IP (prior, created during collaboration, after a group leaves) will be defined 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. Given the worldwide interest in this field, the numerous actors involved, and the very active presence of, and collaboration with, industrial partners, a model relying on open IP is inappropriate to this Collaboration.

DRD5 / RD-q : SUMMARY & NEXT STEPS: DISTRIBUTION OF WORK & RESPONSIBILITIES

Discussion focus: Work package content, sub-WP focus, organizational aspects

- are we missing important topics, are some topics superfluous (because groups are already working on it), does the text need to be reformulated?

- evaluation by DRDC: milestones, deliverables: formulation of the specifics of a WP, its goals, its intermediate steps?

- which institutes are involved in which WP? Which resources are required?

institute	WP-1	WP-2	WP-3	WP-4	WP-5	WP-6
name						

Table 12: Mapping of institutes to Work Packages (expression of interest)

WP	FTE (available)	budget (available, M€)	FTE (additional need)	budget (additional need, M€)
WP-1				
WP-2				
WP-3				
WP-4				
WP-5				
WP-6				

to submit the proposal, we'll need to show that this initiative is *welcome*
= a list of institutes willing to ***commit*** to work on one or more of the WP's

DRD5 / RD-q : SUMMARY & NEXT STEPS: DISTRIBUTION OF WORK & RESPONSIBILITIES

all interested parties should read draft proposal, propose changes to conveners (formulation of the specifics of a WP, its goals, its intermediate steps)

list of conveners & their focus will be circulated and posted on DRD5/RD-q website

for evaluation by DRDC: milestones, deliverables

compact, achievable, time horizon ~ 5 years, mixed (conferences, schools, White Paper, exchange platform - in addition to technical milestones/deliverables)

which institutes are involved in which WP?

institute	WP-1	WP-2	WP-3	WP-4	WP-5	WP-6
name		X	X	X	X	X

Table 12: Mapping of institutes to Work Packages (expression of interest)

which resources are required?

WP	FTE (available)	budget (available, M€)	FTE (additional need)	budget (additional need, M€)
WP-1				
WP-2	2.5	0.15	2.5	0.15
WP-3	2.5	0.15	2.5	0.3
WP-4	2.5	0.15		0.2
WP-5	0.5	0.05		
WP-6				

Table 13: Estimate of annually *available* resources (financial, manpower) within the DRD5 / RDq collaboration and annually *additionally required* needs (financial, manpower) over the next 5 years to tackle the individual WP's.

numbers from all institutes conflated, suggest required ~ available

DRD5 / RD-q : SUMMARY & NEXT STEPS: DISTRIBUTION OF WORK & RESPONSIBILITIES

timeline:

October, November: interaction between interested parties, conveners, M.D & M.D.

regular interactions between DRDC, ECFA, M.D.[2]

end November: version 0.9 of proposal with all currently open questions addressed

in parallel: discussions with CERN, institutes, regarding form & content of MOU

December: formation of proto-collaboration; first meeting of CB to elect officials

in principle aiming to be ready to submit a tentative proposal to the DRDC by end of year