Midterm Report of the Quantum Technologies Flagship

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1 Executive summary

Since the autumn of 2018, the Quantum Technologies Flagship has been supporting world-leading research in quantum technologies, strengthening Europe's quantum community, and laying the groundwork for a European quantum industry capable of transforming research results into products and applications that will have a major economic and societal impact. In its three-year ramp-up phase, the Flagship is supporting 19 projects in four research and innovation domains that represent the major applied areas in the field – quantum communication, quantum computing, quantum simulation, and quantum sensing and metrology – and in basic quantum science.

Now that the Flagship has reached the halfway point of its ramp-up phase, it is time to survey the progress it has made so far. This report reviews the specific goals for quantum communication, quantum computing, quantum simulation, quantum sensing and metrology, and basic quantum science set out in the Flagship's Strategic Research Agenda, and highlights the major achievements of the projects working in each of these areas. These achievements can be summarised as follows:

Communication (four projects)
Projects have made world-leading advances in continuous variable quantum key distribution (QKD) technologies to be used in telecom infrastructures; achieved breakthroughs towards high efficiency and multiplexed quantum memories technologies, enabling the storage of quantum information, quantum money, QKD, digital signatures and secure quantum cloud computing; specified, modelled and validated construction technologies for three different types of quantum random number generation,; and developed advanced components systems for quantum communication for use in several different areas, including QKD and quantum networks.

Computing (two projects)
Projects have developed a proof-of-concept for building a scalable European quantum computer based on trapped ion technology and following widespread industry standards, assembled a quantum computer demonstrator with 10 qubits; and demonstrated an operational prototype of racked 50 qubits; concerning superconducting qubits, achieved fidelity of above 99 % for two-qubit gates and assembled a seven-qubit machine, a stepping-stone to much larger machines.

Simulation (two projects)
Projects have developed the next generation of atomic-based programmable quantum simulators, investigating investigated applications to scientific problems and quantum advantage; and made progress towards demonstrating that quantum simulation can be useful for optimising real devices.

Sensing and metrology (four projects)
Projects have progressed towards the development of quantum sensors based on NV-diamond centres for applications e.g. in the automotive industry, and medical instrumentation; made advances in quantum metrology and sensing through MEMS (microelectromechanical systems) technology using five different types of sensors; achieved homogeneous layers of ultra-shallow NV centres to build sensors that will enable much safer and more accurate medical imaging; and made progress toward the next generation of extremely accurate integrated/compact optical quantum clocks.

Basic science (seven projects)
Projects have discovered a multitude of novel 2D opto-electronic materials, achieved world record tune-ability of photon emitters for quantum communication, and developed new single photon

detectors, showing how these technologies could be integrated into industrial systems; developed and implemented high-fidelity conditional quantum gates with microwave-driven ions, with the goal of building a scalable quantum computer; made progress towards the fabrication of compact entangled photon-based light sources (photon guns) for photonic applications and imagery; made progress towards real-life applications of propagating quantum microwaves for communication and sensing; performed advanced nanofabrication of 2D materials to enable reconfiguration of photonic circuits using MEMS; and carried out detection and control of single rare earth ions (REI) as qubits (cerium, erbium) and development of growth techniques for REI-doped thin films for optimal photonic integration, to be the fundamental building block of a quantum computer.

Coordination of the Flagship activities (one project)
A coordination and support action has ensured the smooth running and further development of the Flagship and raised the profile of its activities and of quantum technologies in general, updating the Flagship's Strategic Research and Innovation Agenda.

The report also makes an assessment of synergies achieved between the projects, including plans for future collaboration, and a brief survey of the difficulties that some projects have encountered. It is clear that, over the past 18 months, the Flagship has helped Europe's quantum technologies community to build new and fruitful connections.

The report then provides some reflections on the progress collectively made by the Flagship so far, and looks ahead to the further developments that can be expected between now and the end of the ramp-up phase, both by the projects themselves, and in the cross-cutting areas of engineering/control, education/training and software/theory, as well as in activities in innovation, international cooperation, and gender equality.

An annex concludes the report with detailed summaries, based on submissions from the projects themselves, of their activities, the main results they have achieved so far, and any results that are of broader interest beyond the immediate scope of the project.

2 Introduction

2.1 Objectives of the Quantum Technologies Flagship

The launch of the Quantum Technologies Flagship in October 2018 was a major milestone for quantum in Europe. The aim of this long-term, collaborative initiative is to enable Europe to stay ahead in the second quantum revolution and the transformative advances it will bring to science, the economy and society, by bringing together top research institutions and companies, supporting the best European quantum scientists, and kick-starting a competitive European quantum industry. It is fundamental to European efforts to compete globally in a field of great strategic importance.

The Flagship's activities are shaped by its Strategic Research Agenda (SRA), originally drafted in 2017 and updated in early 2020,[1] under the supervision of the Flagship's Strategic Advisory Board (SAB) and with input from over 2000 experts. It surveys the current state of play in quantum research and sets ambitious but achievable goals for the Flagship's ten-year lifetime, with a focus on its initial three-year ramp-up phase. It structures the Flagship's work around four mission-driven research and innovation domains, representing the major applied areas in the field: **quantum communication**, **quantum computing**, **quantum simulation**, and **quantum sensing and metrology**, supported by work in **basic quantum science** (and by cross-cutting actions in engineering/control, education/training and software/theory).

In the Flagship's ramp-up phase, 20 projects are being funded, among them a Coordination and Support Action (see Figure 1 below). Now, after 18 months, this phase has reached its halfway point, and it is time to monitor the projects' progress and consider the synergies developing among them, as well as to identify challenges faced and ways in which those could be addressed collaboratively within the Flagship. It is also the moment to consider how the Flagship as a whole is working towards its broader objectives, as set out in the Horizon 2020 Work Programme 2018-2020 for Future and Emerging Technologies:[2]

- Build a strongly networked European quantum technologies community around the common goals defined in the Strategic Research Agenda
- Create the European ecosystem that will deliver the knowledge, technologies and open research infrastructures and testbeds necessary for the development of a world-leading knowledge-based industry in Europe, leading to long-term economic, scientific and societal benefits
- Move advanced quantum technologies from the laboratory to industry with concrete prototype applications and marketable products while advancing at the same time the fundamental science basis, in order to continuously identify new applications and find better solutions for solving outstanding scientific or technology challenges.

[1] http://ec.europa.eu/newsroom/document.cfm?doc_id=42721; https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=65402

[2] The Flagship projects were selected from proposals submitted to the FETFLAG-03-2018 call, part of the Horizon 2020 Work Programme 2018-2020 for Future and Emerging Technologies.

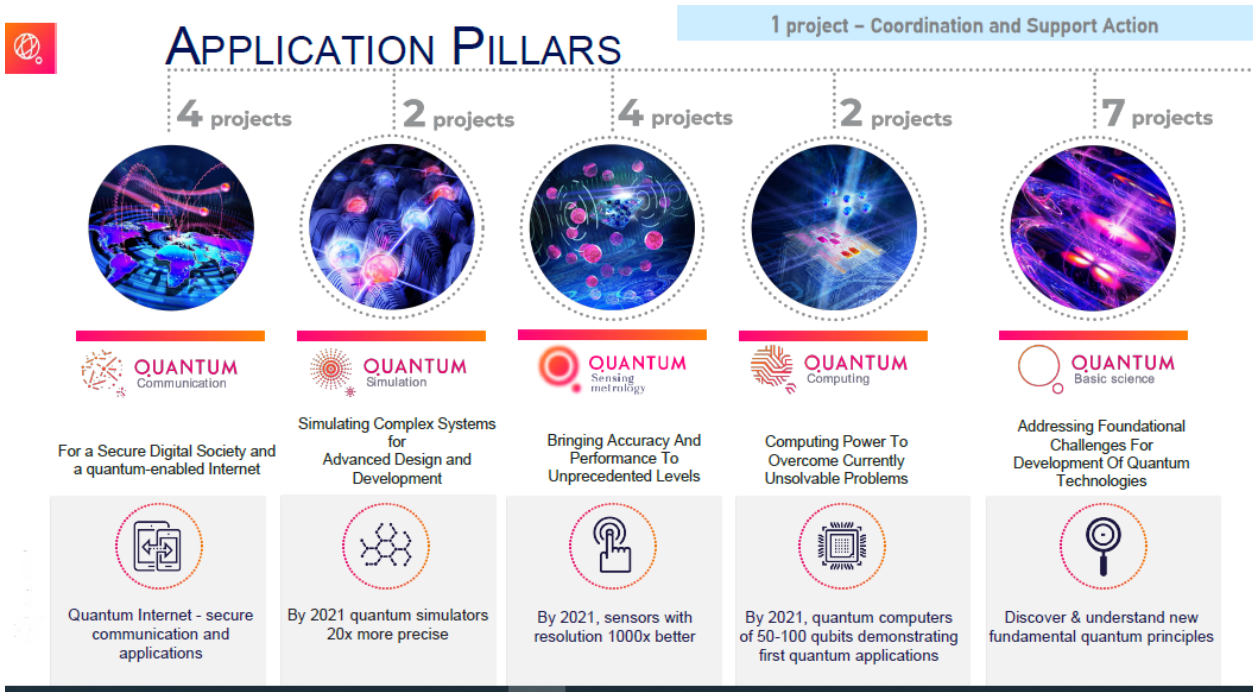

Figure 1: An overview of the ramp-up phase of the Quantum Technologies Flagship and the areas of the 20 projects it finances.

2.2 Governance structure of the Quantum Technologies Flagship

The Flagship's main decision-making bodies are the European Commission and Board of Funders. Their work is guided by the Strategic Advisory Board (SAB), which brings together independent high-level quantum experts to set the direction for the Flagship, monitor its overall progress, and oversee its Strategic Research Agenda. It is complemented by the Science and Engineering Board (SEB), whose role is to coordinate the projects' activities, bringing together the project coordinators and representatives of QuantERA. Finally, the European quantum community is represented in the Flagship by the Quantum Community Network (QCN), which consists of representatives of all EU Member States and countries associated to the Flagship. These representatives are experts in the field with a high profile in their national quantum communities, and they provide a link between these communities and the Flagship, promoting the involvement of national stakeholders and ensuring that the Flagship's activities complement national quantum programmes.

Figure 2 below shows how these bodies interact.

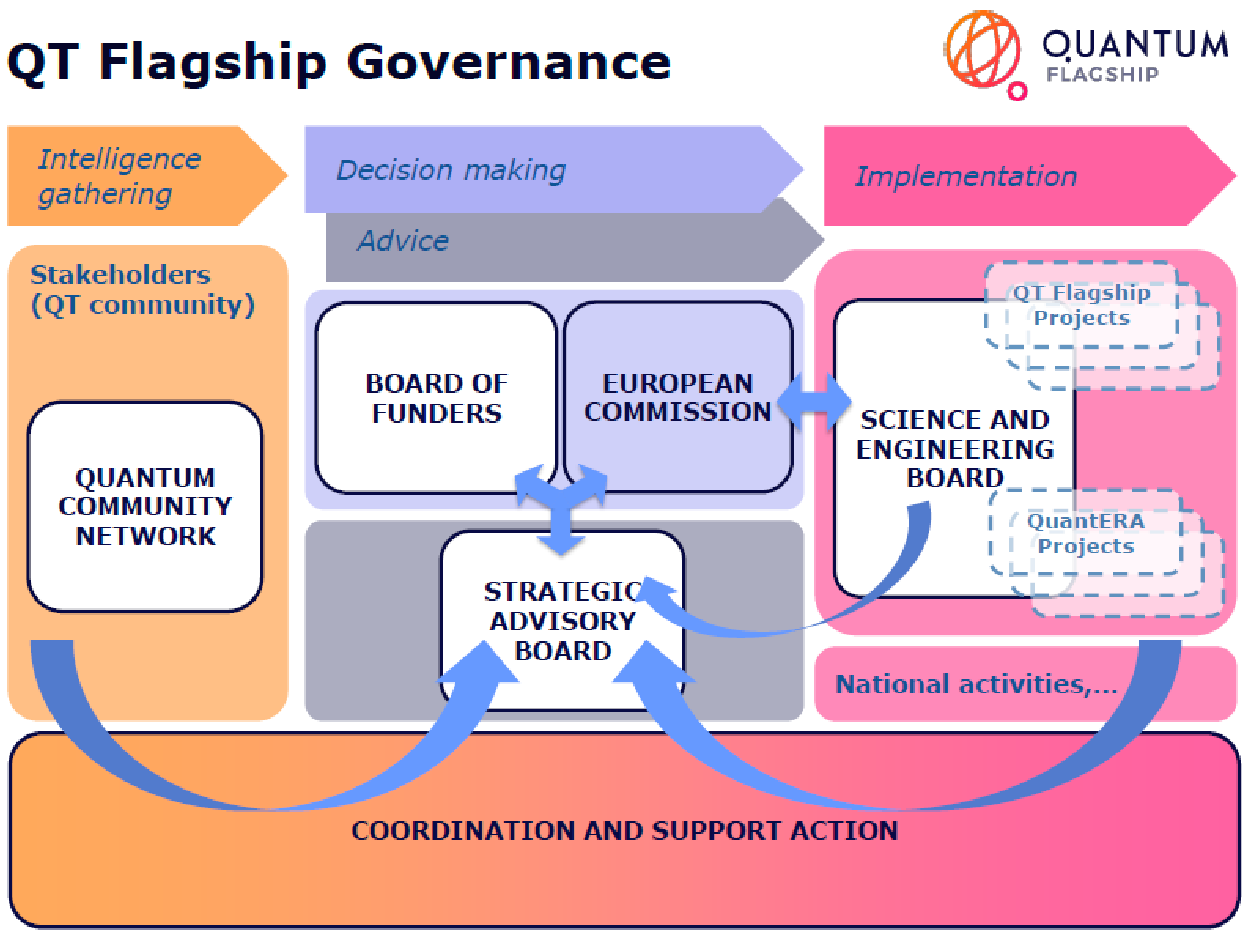

Figure 2: the governance structure of the Quantum Technologies Flagship

2.3 Overview of the progress of the Quantum Technologies Flagship

The main body of this report details the main results of each individual project and also the results achieved with a potential impact beyond the project itself. It then identifies the synergies that are being achieved between the projects, as well as areas where difficulties have emerged over the last 18 months. However, *the goals for each research and innovation domain over the first three years of the Flagship specified in the SRA*, and the progress made by the projects towards these goals over the last eighteen months, will be summarised first.

Communication (four projects)

The long-term success of quantum communication is reliant on pursuing both the immediate need for commercial ready QRNGs [quantum random number generators] and QKD [quantum key distribution] systems and demonstrating their operation in real-world networks, but also for the next generation of devices and systems to ensure European leadership in quantum internet technology. Academic and industrial work promoting standardisation and certification should be addressed at every stage, as well as active participation in European and international standardisation bodies.

Current Flagship projects have:

- achieved advancements in continuous variable QKD technologies, allowing integration into emerging telecommunication networks, becoming a *world leader in continuous variable QKD* (**CIVIQ**)
- achieved *breakthroughs towards high efficiency and multiplexed quantum memories technologies*, enabling storage of quantum information, QKD, digital signatures and secure quantum cloud computing (**QIA**)
- specified, modelled and validated construction technologies for *three different types of QRNG* for many applications, in particular cryptography, games and quantum simulation **(QRANGE**)
- developed *advanced components systems for quantum communication* in areas such as QRNG, QKD systems and quantum networks (**UNIQORN**)

Computing (two projects)

In three years, several experiments should have reached "quantum advantage", i.e., demonstrate a processor in the NISQ regime with a sufficient number of qubits (around 50) and an error rate low enough so it cannot be classically simulated. From there, the main challenge will be to solidly corroborate this regime and approach a first generation of applications while steadily improving the capabilities of the hardware. With this, it is important that a supply chain is developed bottom up, from the current needs in terms of performance and reliability of hardware and engineering science, to interfacing to, and meeting the needs of, software developments. This applies particularly for suppliers of photonics, cryogenics, control, and manufacturing of qubit hardware.

Current Flagship projects have:

- developed a proof-of-concept for building a *scalable European quantum computer* based on trapped ion technology using a European supply chain and industry-standards such as 19'' racks; assembly of a *quantum computer demonstrator with 10 qubits*, now available in the cloud, and demonstration of an operational prototype of racked 50 qubits (**AQTION**)
- achieved *fidelity of above 99 % for two-qubit gates*, assembled a *seven-qubit machine*, ramped up a computing laboratory based on superconducting qubit technology (**OPENSUPERQ**)

Simulation (two projects)

The perspectives for quantum simulation are concentrated around learning properties of physical systems and making use of programmable quantum simulators to solve near-term problems of end-users. Applications can be identified in solving practical routing and scheduling problems, and in offering cloud services in the quantum simulation of strongly correlated quantum systems and materials. There is also a need to develop a comprehensive and strategic patent portfolio to protect innovations in the field of quantum simulation and to provide information about the IPRs that are open to licensing.

Current Flagship projects have:

- developed the *next generation of atomic-based programmable quantum simulators* (100 atoms in tweezer arrays, 50 ions in ion trap, 20 Rydberg atoms in arrays), identified use-cases and developed validation methods also applicable to computing and metrology that require entanglement as a resource (**PASQUANS**)
- made progress towards a first demonstration that quantum simulation can be useful for *optimising real devices* (**QOMBS**)

Sensing and metrology (four projects)

The objectives for Quantum Sensing and Metrology include quantum sensors, imaging systems and quantum measurement standards demonstrated in a laboratory environment outperforming classical or current state-of-the-art counterparts in one of the following criteria: size, operating environment, sensitivity, specificity, statistical or systematic uncertainty, calibration intervals, lifetime, traceability. The TRL of different types of quantum sensors spans a large range from devices that have already started penetrating the market (e.g. magnetic field sensors based on squids, atom gravimeters, microwave clocks) to laboratory prototypes.

Current Flagship projects have:

- progressed towards the development of *quantum sensors based on NV-diamond centres* for room temperature devices applications e.g. for the automotive industry, and medical instrumentation (**ASTERIQS**)
- made advances in quantum metrology and sensing through MEMS (microelectromechanical systems) technology using *five different types of sensors*, as well as innovative integration and packaging technologies (**MACQSIMAL**)
- achieved homogeneous layers of ultra-shallow NV centres with excellent coherence time and sensing/polarisation efficiency that lead to (7x) *improved imaging sensitivity* (**METABOLIQS**)
- made progress toward the *next generation of integrated/compact optical quantum clocks*, 100x more stable than standard microwave atomic clocks commercially available today (**IQCLOCK**)

Basic science (seven projects)

Basic Science has the goal to explore and understand the science underlying all quantum technologies, both theoretically and experimentally. While remaining exploratory, basic science … should aim to explore new quantum effects and gain new understanding that are not limited to the pillar activities and which may contribute to new quantum technologies and applications in the long term.

Current Flagship projects have:

- discovered a *multitude of novel 2D opto-electronic materials*, achieved world record tune-ability of photon emitters for quantum communication, developed new single photon detectors and integrated them into photonic circuits compatible with industrial systems (**2D-SIPC**)
- developed and implemented high-fidelity conditional quantum gates with microwave-driven ions that are *highly robust against various error sources* (**MICROQC**)
- made progress towards the fabrication of *compact entangled photon-based light sources* (photon guns) for photonic applications and imagery, e.g. super-resolution microscopy **(PHOG**)
- made progress towards the development of different types of *photonic platforms for quantum simulations*, with a theoretical framework useful for other platforms (**PHOQUS**)
- made progress towards real-life applications of propagating quantum microwaves used for communication (microwave QKD, free-space quantum microwaves and Quantum radar) and sensing (QMICS)
- performed *advanced nanofabrication of 2D materials* to enable reconfiguration of photonic circuits using MEMS (microelectromechanical systems) for low power consumption (**S2QUIP**)

- carried out detection and control of *single rare earth ions (REI) as qubits* (cerium, erbium) and development of growth techniques for REI-doped thin films for optimal photonic integration (SQUARE)

Coordination of the Flagship's activities (1 project)

The role of the QSA coordination and support action (CSA) and its follow-up QFLAG is to foster a community of quantum stakeholders in Europe and to link the Flagship's activities to national quantum programmes. It also supports the efficient governance of the Flagship and monitors its progress, and coordinated the update of its Strategic Research Agenda.[3] It has played a major role in publicising the work of the Flagship both in the scientific community and to the general public.

3 Synergies within the Quantum Technologies Flagship

3.1 Overview

Several of the QT Flagship projects seem to be collectively moving towards common aims. Their complementarity and developing synergies are already revealing some cross-cutting themes and success stories. The reported existing and potential synergies are visually summarised in Figure 3, while some highlights follow immediately below.

[3] https://ec.europa.eu/digital-single-market/en/news/new-strategic-research-agenda-quantum-technologies

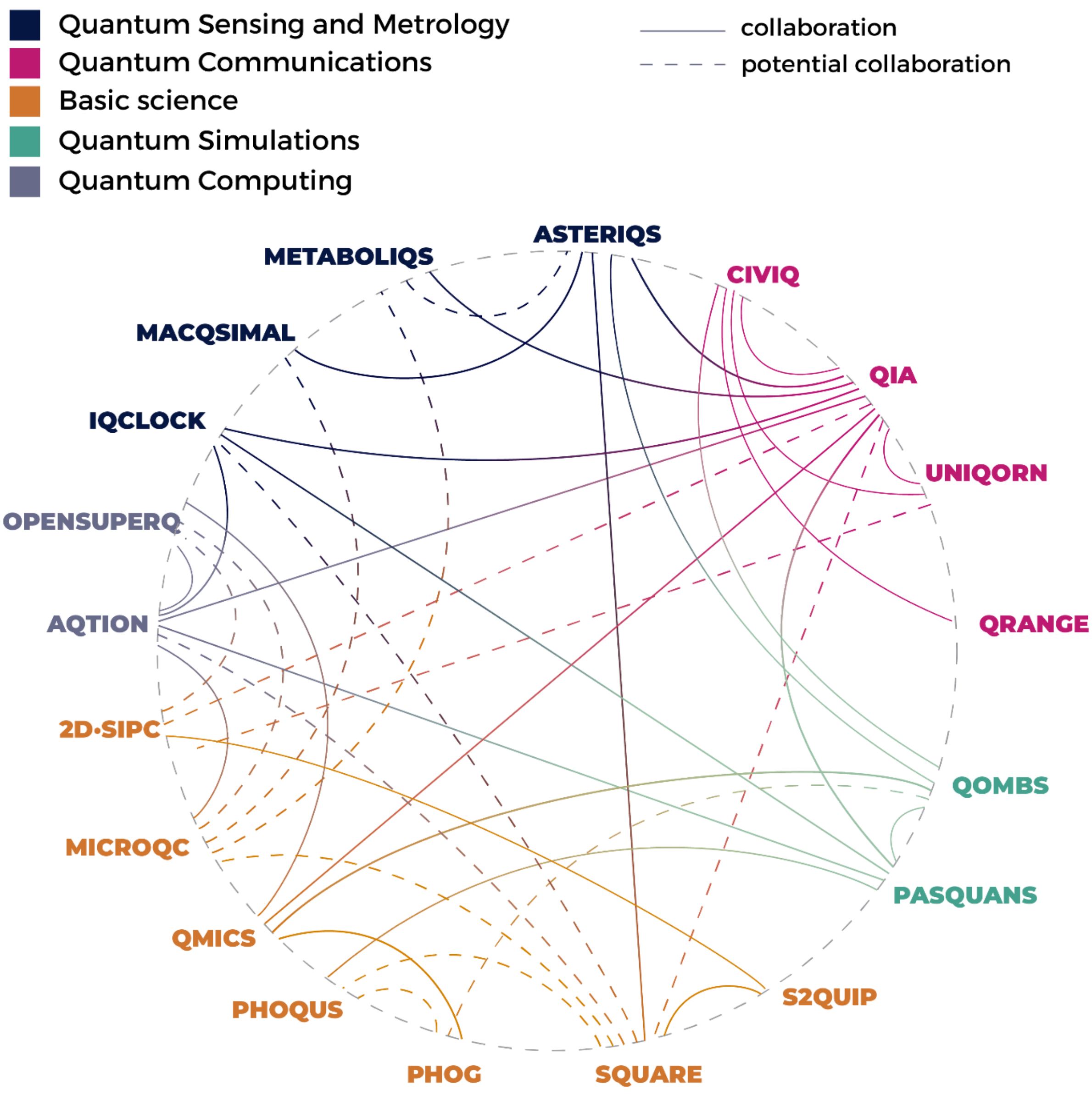

Figure 3: *Visual summarisation of the existing and potential synergies among QT Flagship projects*

3.2 Specific synergy categories

Approaches and methods
2D-SIPC, **S2QUIP:** actively communicate and discuss their similar approach to the engineering of active quantum components based on 2D materials and integrating those into photonics circuits.
AQTION, PASQUANS: exchange on technological approaches and solutions relating to simulation capabilities and the ion-trap architecture
AQTION, OPENSUPERQ: coordinate on characterisation methods
AQTION, IQCLOCK: discuss routines and methods relating to the operation of an ion-trap quantum computer, which can be considered as an extension of an atomic clock
MicroQC, AQTION: various collaborations between the two groups have been running for several years.
QIA, **CIVIQ:** collaborate on phase stabilisation of distant lasers, as required for creating efficient entanglement between remote nodes
QIA, **SQUARE:** collaborate on single rare-earth ions as quantum processing nodes
QMiCS, **OpenSuperQ:** collaborate with the synergy extending to the experiment; there is an active collaboration between a QMiCS experimental partner and an OpenSuperQ theory partner on optimal control
QMiCS, QIA: collaborate on the basis of a similar theoretical problem description
QMiCs, PhoG: discuss quantum communication protocols
Qombs, QMiCs: discuss overlap and differences in the challenges regarding free-space propagating quantum signals and collaborate on a feasibility study of a low-loss free-space quantum communication system with long-wavelength radiation (infrared-microwaves)
Qombs, CiViQ: collaborate on the study and implementation of a continuous-variables quantum communication protocol
SQUARE, S2QUIP: collaborate to fabricate better cavities for off-chip and on-chip coupling and the generation of indistinguishable photons – to make a fiber cavity setup available for 2D material and quantum dot single photon sources
SQUARE, PhoQus: discuss the possibility for using CO2 laser machining used for fiber cavity production to create high-quality cavity potentials for photon BECs
SQUARE, iqClock: discuss the use of fiber cavities for an atomic clock
SQUARE, AQTION, OpenSuperQ, QIA: schemes and protocols developed by AQTION, OpenSuperQ and QIA guide the way for SQUARE.

Use of results in other projects

CiViQ, QRANGE, UNIQORN: CiViQ will use QRANGE's fast QRNGs specifically tailored for CV protocols and will evaluate squeezed light sources and transimpedance amplifiers from UNIQORN

UNIQORN, CIVIQ: multifaceted collaboration, including already employing the TIA designed in UNIQORN together with a balanced detector from CIVIQ; other possibilities include the fully developed balanced receiver from UNIQORN to be used for CIVIQ systems, the squeezed light sources from UNIQORN to be employed for CV quantum communication applications developed in CIVIQ, system designers and developers in CIVIQ benefiting from the simulation tool devised in UNIQORN

OpenSuperQ, AQTION: working to make the compilation infrastructure of AQTION compatible with OpenSuperQ

QRANGE, CIVIQ, OPENQKD: QRANGE devices will be implemented in CIVIQ and OPENQKD

S2QUIP, 2D·SIPC: collaborate to provide 2D·SIPC with on-chip cavities

S2QUIP, SQUARE: S2QUIP will adapt SQUARE's open cavity technology as a characterisation tool, speeding up their investigation of 2D materials' properties

Common partners among consortia

AsteriQs, MetaboliQs: have several partners in common, as both projects exploit NV centres in diamond and technologies for sensing, which leads to strong synergy without redundancy.

ASTERIQS, **MacQsimal**, **QIA**, **Qombs, SQUARE**, share some common partners, which, according to ASTERIQS, "brings a natural way for collaboration".

QIA shares partners with **ASTERIQS**, **METABOLIQS**, **SQUARE**, **AQTION**, **IQCLOCK**, **PASQUANS**.

QMiCS has intrinsic collaborations with the superconducting quantum computing project **OpenSuperQ** via two joint partners, and with the quantum communication project **QIA** via one joint partner.

Synergy possibilities to be further explored

2D-SIPC, **QIA, UNIQORN QMICS**, **OPENSUPERQ:** the quantum devices and photonic circuits and detectors developed by 2D-SIPC could be of interest to the other projects.

MicroQC identifies possibilities to collaborate with the large superconductor-based quantum computing project **OpenSuperQ**, as well as with projects using microwave technologies such as **OPENQSUPERQ**, **MacQsimal**, **ASTERIQS**, **METABOLIQS**.

PASQuanS is exploring synergies with:

- **PhoQus**, which aims at exploring analogue quantum simulation of various systems ranging from condensed matter to astrophysics with photonic and polaritonic platforms; a particular common aspect is the quantum simulation of dissipative models or dissipation used as a resource.

- **AQTION** and **iqCLock** on the problem of stabilisation of lasers for high fidelity single atom manipulations.
- **iqClock** on the generation of entanglement for quantum enhanced metrology; tailored preparation and characterisation of the states is a common theme in quantum technologies (computing, metrology and simulation)
- **Qombs**, the other quantum simulation project, on development of cold-atom platforms.

PhoG is looking for cross-fertilisation with projects **Qombs** and **PhoQus**, as the extended version of PhoG (larger quantum networks effectively combining two to many basic PhoGs) will be useful for quantum simulations and other different applications in Quantum Technologies and beyond.

PhoQuS, **PASQuanS**: are exploring collaborations on the topic of engineering specific Hamiltonians.

PhoQuS, SQUARE: Potential collaborations can be developed to improve fabrication and performances of open microcavities used in both consortia

SQUARE, QIA: SQUARE's developed theory is of direct relevance for entanglement distribution in quantum networks could be specifically relevant for QIA

UNIQORN, QIA: collaboration on the control and management stack for quantum (QKD) networks is expected.

Synergies beyond the QT Flagship
ASTERIQS has several synergies with QuantERA projects such as **MICROSENS**, **NanoSpin** and **Q_Magine**, on diamond and SiC material. Several **QMiCS** partners are involved in QuantERA projects, such as the QuCos project to develop cat codes or the project QuantHEP.

4 Conclusions

The Quantum Technologies Flagship projects are progressing well towards the objectives set out for the Flagship as a whole. Around 1400 scientists are directly involved in the Flagship's projects. They represent a total of 236 organisations: one third (77) are privately-owned companies, and the rest universities (103) and research organisations (56). Of the companies, 23 are start-ups. The projects expect that, during their lifetime, around 20 further spin-off companies will be created.

In the less than two years since it was launched, the Flagship has also made a significant contribution to expanding and uniting Europe's quantum community, not least via major events in Vienna (Austria) in 2018, and in Grenoble (France) and Helsinki (Finland) in 2019.[4] In addition, scientists working on the projects have already attended more than 1000 conferences and workshops. The projects themselves have organised events attended by more than 12,000 quantum experts.

[4] https://qt.eu/newsroom/flagship-kickoff-in-vienna/; https://eqtc19.sciencesconf.org/; https://qt.eu/engage/community/quantum-flagship-event-helsinki-2019/.

Many of the stakeholders of the Quantum Flagship are also actively involved in other quantum programmes in Europe, either those organised by QUANtera (35 stakeholders) or national programmes (133 stakeholders).

The Flagship projects are also progressing towards the common goals for the application areas and the fundamental science domain that were set out in the Flagship's original Strategic Research Agenda and the updated version of 2020 – this update was an opportunity to take stock and reflect on how things have changed since 2017, and was accomplished by close cooperation between the SAB, the SEB and the QCN. The projects in the four research and innovation domains have made progress in the specification, modelling and validation of construction technologies, in the development of integration methodologies, and in advancements of already existing quantum technologies, making these technologies more efficient and more compact. These advances stretch from the discovery of new materials and proofs-of-concept to reaching higher levels of technology-readiness and the building of infrastructures.

The groundwork for a pan-European ecosystem that will enable a world-leading quantum technology industry in Europe has been laid. End-users in key application areas have been involved in the Flagship from the beginning, with a notable positive impact on its results – this involvement could even be expanded over the last 18 months. To complement this, the basic science projects have made many discoveries that will potentially be of great use in application areas. In some cases, they, like their counterparts in the other four domains, have made enough progress to file patents. For instance, the QIA project achieved the set-up of the world's first multi-node processor network, and world record memory efficiencies towards the development of quantum repeaters. In total, two thirds of the Flagship's projects have filed at least one patent application so far, generating 60 applications altogether. 16 patents have already been granted.

The numerous scientific results achieved by the projects have also been published in in over 500 articles, of which about 80% are fully peer-reviewed journal articles, while another 160 articles are currently under review. 50 of these published articles were the result of collaboration between two or more Flagship projects. Indeed, all the projects are benefiting from synergies in approaches and methods, and the use of results. Joint workshop have been organised by some projects. Several projects share common partners, which can help to identify synergies and avoid duplicated work. The synergies within the Flagship are constantly being monitored and further developed: at the most recent SEB meeting, topics were identified where deeper collaboration between projects could be beneficial. Coordinators for each topic were chosen to coordinate the work between all interested projects. This will also help the Flagship to continue its good record of helping projects to overcome their difficulties with techniques developed by another project.

In the next 18 months, greater progress can be expected also in the cross-cutting areas of engineering/control, education/training and software/theory, as well as in the complementary overarching activities in innovation and international cooperation, and gender equality. For optimal support, two additional Coordination and Support Actions are starting their activities in September 2020: one concentrating on the coordination of International cooperation with the US, Canada and Japan, the other initiating the development of quantum technologies education programmes in secondary education, tertiary education and industry training.