European Commission

THE EU'S QUANTUM TECHNOLOGIES FLAGSHIP

Taking the lead in the quantum revolution:

an overview of major achievements in 2018 – 2021 (Ramp-Up Phase)

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Executive summary

In autumn 2018, the European Commission launched the Quantum Technologies Flagship, a 10-year initiative with an expected budget of EUR 1 billion. The Flagship is a long-term collaborative initiative that represents a major milestone for quantum technologies in Europe. It is fundamental for European efforts to compete globally in a field of great strategic importance; the Flagship will enable Europe to stay ahead in the second quantum revolution and facilitate the transformation of its economy and society.

The Flagship brings together 236 organisations and over 1500 scientists. The organisations include 77 privately owned companies, 103 universities, and 56 research organisations, kick-starting a competitive European quantum industry. The Flagship is shaped by its Strategic Research Agenda (SRA) and supervised by the Strategic Advisory Board (SAB)[1], which has set out goals for the Flagship's 10-year lifetime. During its ramp-up phase (2018-2021), the Flagship received EU funding of EUR 193 million under Horizon 2020. This phase included 19 R&D projects that started in late 2018 and ended in early 2022, along with two additional projects that started in late 2020 and will end in 2024.

The present report marks the conclusion of the Flagship's ramp-up phase, and the review of these 21 projects in the fields of quantum communication, quantum computing, quantum simulation, quantum sensing and metrology, and basic quantum science, led by independent experts from academia and industry, that was carried out at this point in its lifetime. Their most notable achievements include:

- ***quantum communication***: developed a comprehensive guide to reaching the Flagship's ultimate goal of a quantum internet, and successfully passed the first step: connecting two quantum processors through an intermediate node and establishing shared entanglement between multiple stand-alone quantum processors, forming a proof-of-principle quantum network
- ***quantum computing***: built a quantum computer system of globally competitive performance based on superconducting circuits, as well as conducted very promising work on other computing platforms such as trapped ions and silicon qubits
- ***quantum simulation***: developed two 100-qubit analogue quantum simulators and reached practical quantum advantage in scientific problems involving the study of new materials and phases of matter (e.g. superconductivity, highly entangled systems)
- ***quantum sensing and metrology***: developed some of the world's most advanced quantum sensors based on nitrogen vacancy centres in ultrapure diamond and made significant advances towards improved medical imaging diagnostics and spectroscopy, and ultra-precise clocks
- ***basic quantum science***: made significant advances towards the development of several alternative computing platforms, including photonics-based quantum computing.

In addition, the Flagship's activities have led to the foundation of 25 spin-offs/start-ups; 105 patents have been filed, with 64 already granted, and 1313 scientific papers were published (with another 223 under review). 1961 conferences were attended, and 161 conferences/workshops organised by project researchers.

[1] The SAB is a group of high-level, renowned independent quantum experts who advise the Flagship's other decision-making bodies on any subject of relevance. The SAB consists of 40% industry, 40% academic and 20% research and technology organisation (RTO) representatives.

1. Introduction - Objectives of the Quantum Technologies Flagship

The launch of the Quantum Technologies Flagship in October 2018 was a major milestone for the quantum community 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. It does so by bringing together top research institutions, RTOs, and companies, supporting the best European quantum scientists, and kick-starting a competitive European quantum industry. The Flagship 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[2], 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 computation, quantum simulation, and quantum sensing and metrology, supported by work in basic quantum science (See Fig. 1 below).

Figure 1: An overview of the ramp-up phase of the Quantum Technologies Flagship and the areas of the 21 scientific projects it finances.

[2] The SRA can be found [here](#).

This report considers the 19 R&D projects from the ramp-up phase that commenced in 2018 and ended in early 2022, and two additional R&D projects that started in late 2020 and will be completed in 2024. It also presents the results of the three coordination and support actions (CSAs). The technologies developed during the ramp-up phase will be further matured in subsequent projects, bringing them closer to industrialisation and deployment. This report considers how the Flagship is working towards its broader objectives, as set out in the Horizon 2020 Work Programme 2018-2020 for Future and Emerging Technologies[3]:

- Build a strongly networked European quantum technologies community around the common goals defined in the Strategic Research Agenda.
- Create the European quantum 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 at the same time advancing their fundamental scientific basis, to continuously identify new applications and find better solutions for solving outstanding scientific or technology challenges.

The report is structured as follows:

- Section 2 sets out the achievements of the 21 projects, gathered under each of the five domain pillars. It also reviews the numerous synergies between projects and the overall contribution made by the projects to the aims of the Flagship as a whole.
- Section 3 summarises the key lessons learned during the ramp-up phase, as well as its key collective achievements.
- Section 4 surveys the achievements of the Flagship in the context of European quantum policy, and looks ahead to a number of important new initiatives, including the European Chips Act.
- Section 5 sets out the report's key conclusions and heralds the next phase of the Flagship.
- The Annexes provide more information about the Flagship's governance structure, the start-ups and spin-offs founded, the patents filed by projects, and the Widening Countries involved in this initiative.

[3] 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.

2. THE MAIN ACHIEVEMENTS OF THE FLAGSHIP'S PROJECTS

This section outlines the main achievements of the projects in each research domain, and shows how they have worked towards the Key Performance Indicators for the domain in question. It then identifies the synergies achieved between the projects, before outlining how they have contributed to the objectives of the Flagship as a whole.

2.1 Achievements in Quantum Communication

The internet has been transformational for our society. One of the ultimate goals of the Quantum Flagship is to enable quantum communication between any two points on Earth, hence offering a fundamentally new quantum internet technology. A quantum internet will link quantum processors in synergy with the current "classical" internet to attain unmatched capabilities that are demonstrably not achievable with classical communication.

By creating[4] a common language that unites the highly interdisciplinary field of quantum networking towards achieving the ultimate vision of a world-wide quantum internet, the Flagship has developed a comprehensive guide towards this goal.[5] The guide follows six stages: the first is that of a true quantum network, that allows the end-to-end delivery of quantum bits (or qubits) between any two network nodes, one qubit at a time; the last stage is the long-term goal of connecting large quantum computers on which arbitrary quantum applications can be executed.

The Flagship's researchers have been the first to succeed in realizing the first stage[6]: connecting two quantum processors through an intermediate node and establishing shared entanglement[7] between multiple stand-alone quantum processors. This proof-of-principle quantum network consists of three quantum nodes, at some distance within the same building. For these nodes to operate as a true network, the researchers had to invent a novel architecture that enables scaling beyond a single link. The middle node has a physical connection to both outer nodes, allowing entanglement links with each of these nodes to be established and protected from noise, meaning that they could be used for quantum key distribution, a quantum computation, or any other subsequent quantum protocol. In addition, the developed network announces the successful completion of its (intrinsically probabilistic) protocols with a "flag" signal: this is crucial since, in a future quantum internet, many such protocols will need to be concatenated.

This first entanglement-based quantum network will provide researchers with a unique testbed for developing and testing quantum internet hardware, software, and protocols. While in the lab researchers are focussing on adding more quantum bits to their three-node network and on adding higher level software and hardware layers, testing outside the lab on existing telecom fibres has already started, within a metropolitan-size network. In fact, a major obstacle to the development of long-distance quantum telecommunication systems is that, beyond a few hundred kilometres, photons (the information carriers)

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[4] See project QIA, https://quantum-internet.team/

[5] Quantum internet: A vision for the road ahead, SCIENCE 19, Oct 2018, Vol 362, Issue 6412, DOI: 10.1126/science.aam9288.

[6] See project QIA, https://quantum-internet.team/

[7] Entanglement is a phenomenon observed at the quantum scale, fundamentally connecting particles at small and even at large distances. It provides quantum computers their enormous computational power and it is the fundamental resource for sharing quantum information over the future quantum internet.

are lost, and the signal disappears. Since quantum signals cannot be copied or amplified, the challenge is to find a way of repeating it without altering it by creating 'repeaters' based on quantum memories. By managing to store a photonic qubit in a crystal for 20 milliseconds, Flagship's researchers have set a world record and taken a major step towards the development of long-distance quantum telecommunications networks[8]. The storage time is long enough to allow the construction of a larger network of memories, a prerequisite for the development of long-distance quantum communication.

The investigation of the different protocols that can be run on the quantum internet, together with the systems and components needed to run them, have also been thoroughly investigated, with Flagship's researchers championing the deployment of: continuous-variable quantum key distribution as a means to generate an encryption key with information theoretic security into emerging optical telecommunications networks[9]; one-time programmes, applied in use-cases such as securing digital signatures and message authentication[10]; and quantum oblivious transfer protocol, used in private data retrieval application where clients can download data from a database without the database knowing which information it was[11]. To keep up with the rapid progress in quantum technologies and improvements in the current protocols, the Flagship's researchers are also providing a repository offering a compact and precise review of all the existing quantum communication protocols[12]. Regularly updated to keep track of the advancements, it allows easy communication among computer scientists, engineers, and physicists, enabling them to gain a deeper understanding of how these protocols work and can be deployed.

In the long run, the deployment of a quantum communication infrastructure, such as the EuroQCI, and subsequently of the quantum internet, will need low-cost, reliable, and mass producible components. The Flagship's researchers are at the forefront also in this respect. They have developed certification-ready quantum random number generators (a key component in cryptographic protocols) showing a significant potential for cost and size reductions[13] (with one of the devices based on standard CMOS technology reaching a target cost of the order of EUR 1, being at the same time ready for large-scale production). Finally, new components and devices based on different semiconductor materials have been realized and the modular and miniaturized integration of various systems demonstrated, based on a novel concept extremely well suited to the integration of complex setups, as it allows all elements needed to be incorporated on a single chip[14]. The integration of these quantum devices in existing networks has allowed European researchers to achieve a record-breaking classical data transfer of 11.2 Tb/second in 7-core fibres beside a quantum link.

[8] See project QIA, https://quantum-internet.team/
[9] See project CiViQ, https://civiquantum.eu/
[10] See project UNIQORN, https://quantum-uniqorn.eu/
[11] See project UNIQORN, https://quantum-uniqorn.eu/
[12] See project QIA, https://quantum-internet.team/
[13] See project QRANGE, https://qrange.eu/
[14] See project UNIQORN, https://quantum-uniqorn.eu/

Key performance Indicators: Quantum Communication[15]	
Performance[16]	World record 20 ms quantum memory; low-cost large-scale production ready QRNG; modular and miniaturized integration of various quantum communication systems
European Technical Leadership[17]	World first proof of principle entanglement-based quantum network consisting of three quantum nodes 1.3 km apart
Deployment[18]	2 subsystems ready; EuroQCI roadmap published; national deployment of testbeds; OpenQKD[19] testbed and use case driven sites established
Adoption[20]	5 new EuroQCI services; see also OpenQKD in Action[21] for a list of early testbeds and use cases

2.2 Achievements in Quantum Computation

Despite still being in its infancy, quantum computation is regarded globally as the most promising application of quantum technology. The reason is evident. Our society is creating more and more data, and highly complex problems in many fields require computers that are capable of fully exploiting these large amounts of data. But the computational power of classical computers is stalling: the speed of processors, for example, has hardly increased in recent years. Quantum computers, with their promised greater speeds compared with (even the largest) classical computers and ability to handle at least some of these complex problems, can therefore ease the situation.

The Flagship has been investigating the most promising scalable quantum computing platforms (superconducting, trapped ions, silicon), with the goal of assembling working, EU-made, quantum processors for each of them.

By integrating the whole stack of necessary hardware and software components, the Flagship's researchers have built a quantum computer system of globally competitive performance based on integrated electric circuits made from superconducting metals[22]. This quantum computer, which will be soon made available at Forschungszentrum Jülich (DE), has measurement and cryogenics systems that can hold 100 qubits with state-of-the-art errors in gate operations, and its processor has been already used for a global first in

[15] See https://qt.eu/app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf
[16] Number of complementary subsystems, advancing the state of the art, necessary for Quantum Communications networks or to build a quantum internet.
[17] Entanglement distance in a quantum network based on entanglement distribution and quantum processing, linking processing nodes in two metropolitan networks (average of 20 km) via a quantum repeater backbone (>500 km).
[18] Number of connected European metropolitan areas (and QKD nodes) integrated with a commercial telecom infrastructure, including both terrestrial and satellite QKD links with a secure key rate of at least 100 bit/s.
[19] See project OPEN-QKD, https://openqkd.eu/
[20] Number of quantum communication services that enable commercial adoption for the public as well as private sector.
[21] https://openqkd.eu/openqkd-in-action/
[22] See project OPENSUPERQ, https://opensuperq.eu/

quantum error correction with 17 qubits. A new 25-qubit device in a three-dimensional multi-chip module is showing device performance that is not negatively affected by the high level of integration achieved. Also, a suite of benchmarks from quantum chemistry has been brought forward along with a software stack, making it possible to calibrate and optimize operation of large quantum processors.

A European silicon platform is also in the making[23]. Record coherence time for hole spin qubits, exceeding by an order of magnitude the best values reported worldwide so far, has been measured; in addition, state-of-the-art for two-qubit gates fidelity that put Europe on a par with the best teams in the world has been reached. In the next 18 months the best fabrication process for this platform will be decided on, and the construction started of an actual device.

In addition, prior to the Flagship, no quantum computer was rack-mountable and compatible with industrial standards. Starting from scratch, the Flagship's researchers have developed two 19'' racks supporting up to 50 qubits and installed them in their labs[24]. Their first-of-its-kind 50-qubit trapped ion system required the development and extension of ion-trap quantum processor production, sophisticated control electronics, and ion-addressing capabilities. The control software already includes cloud access, and supports quantum software development kits; furthermore, several algorithms spanning the range from quantum error correction to variational optimizations have been prepared and are available as a suite. One of the most notable features of this system is that it is powered from a single wall-mounted power plug, and it has an extremely low power consumption, which stands at 1.5 kW, or the same amount of energy needed to boil a kettle.

Though still far away from the millions of qubits that will guarantee fully fault-tolerant quantum computing, these superconducting- and trapped ion-based quantum computers (and the semiconductor-based machine, when ready) will both pave the way for the development of the next generation of even more powerful processors in the Flagship's second phase and serve as a training ground for the next generation of European quantum-aware engineers and computer scientists. These is expected to become a highly sought-after workforce (in the EU and globally) in the years to come. To this end, it is crucial to build an early bridge between quantum computing hardware activities and the end-user community as, even more than in classical information technology, quantum computing demands strong cooperation between hardware teams and software users. The Flagship's researchers are already developing complete toolsets that new industrial actors can use to start their own practical investigation, assess the advantage (or lack thereof) of deploying a quantum processor in their specific use case, and share their results[25].

[23] See project QLSI, https://h2020-qlsi.eu/
[24] See project AQTION, https://www.aqtion.eu/
[25] See project NEASQC, https://www.neasqc.eu/

Key Performance Indicators: Quantum Computation[26]	
Performance[27]	Developed platform independent theoretical and experimental tools to verify quantum advantage
European Technical Leadership[28]	25 qubits (superconducting); 50 qubits (trapped ions)
European Impact Leadership[29]	Quantum error correction with 17 qubits implemented. 70 use-cases elaborated with industrial partners ranging from chemistry to machine learning and optimization through to symbolic AI and graph algorithmics[30]
Accessibility[31]	Forschungszentrum Jülich (DE) aims to provide access to a 100-qubit quantum computer building on the OPENSUPERQ results; Forschungszentrum Jülich and GENCI (FR) will also host and provide access to a 100-qubit analogue simulator

[26] https://qt.eu/app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf
[27] The number of unique European quantum computing hardware stack systems/services demonstrating quantum advantage (i.e. outperforming a non-quantum hardware system/service in the solution of the same problem) by an ad-hoc benchmark created for proof.
[28] Largest quantum computing capacity based on a European (or alternatively a widely adopted global) quantum volume benchmark.
[29] Quantum algorithms and use cases created with clear impact orientation in basic science, applied science, industries, and the public sector (aligned with the UN and EU 2030 goals).
[30] See the Quantum Industry Consortium database for quantum computing and simulation use cases.
[31] Number of entities providing public or private access from fully European quantum computing facilities (also based on fully European computing stack) to institutions, academia, research centres and companies.

2.3 Achievements in Quantum Simulation

Fully programmable fault-tolerant quantum computers have still a long way to go before becoming a reality; however, currently available noisy intermediate-scale quantum (NISQ) devices can already simulate[32] systems that could not be simulated by classical computing means or otherwise.

During the Flagship's ramp-up phase, European researchers have developed and perfected, in collaboration with European industrial partners, the building blocks underpinning the next generation of scalable and programmable quantum simulator[33]. As a result of improvements to various cryogenics and atomic/optical techniques and enhancing control of atomic-physics-based platforms using the latest industrial developments, the number of individually addressable atoms/ions increased to above 50 (ions), 300 (tweezer array), and 1500 (optical lattices). This has made it possible to run simulations on these platforms beyond the reach of classical simulation. In particular, in a world-first, practical quantum advantage[34] has been reached in scientific problems involving dynamics of phase transitions and quantum transport in strongly interacting systems.

These results lay the groundwork for the platforms' developments towards practical quantum advantage for real-world problems in the Flagship's next phase, where researchers plan to deliver over 1000 interacting atoms in industry-ready platforms. To be prepared to capitalize on these and future advancements, key European industrial end-users, who have been identifying their demand in terms of quantum simulation (with use-cases multi-parameter quantum metrology, dose optimization in cancer treatment, solving partial differential equations like non-linear Schrödinger equations and the Navier Stokes equation but also problems in combinatorial optimization, machine learning, and big data), have already been presented with the capabilities and opportunities brought by quantum simulation, together with means to use the Flagship's new quantum simulation platforms for "real-world" problems relevant to them.

Two 100-qubit analogue quantum simulators developed within the Flagship are in the process of being installed in the supercomputing and data centres at Forschungszentrum Jülich (Germany) and GENCI (France). This will mark the first step in the deployment of a pan-European hybrid high performance computing and quantum simulation infrastructure that will give researchers and industries access to next generation computing machines.

Key Performance Indicators: Quantum Simulation[35]	
Performance[36]	Optical lattices reached practical quantum advantage in scientific problems involving dynamics of phase transitions and quantum transport in strongly interacting systems

[32] Quantum simulation encompasses several of the most exciting short-term uses of quantum computers, including high-energy physics, quantum chemistry, and simulating the quantum features of particles that are directly relevant to contemporary material science.
[33] See project PASQUANS, https://pasquans.eu/
[34] Quantum advantage refers to the ability of quantum devices of having an advantage (being it faster, better, and/or more cost-efficiently) over classical ones when solving an artificial problem. Practical quantum advantage refers instead to the ability of quantum devices to solve problems of practical interest that are not tractable for traditional supercomputers.
[35] See https://qt.eu/app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf
[36] Number of unique EU quantum simulators (services) outperforming the best-known algorithm running on the best classical computer on at least one relevant real-life computational problem.

Market readiness[37]	Two 100-qubit analogue quantum simulators (PAQUANS/PASQAL) to be installed in Forschungszentrum Jülich (DE) and GENCI (FR)
European Technical Leadership[38]	Number of individually addressable atoms/ions: >50 (ions); >300 (tweezer array); >1500 (optical lattices)

2.4 Achievements in Quantum Sensing and Metrology

The Flagship's researchers have developed some of the world's most advanced quantum sensors based on nitrogen vacancy (NV) centres in ultrapure diamonds[39], which has required advances in their theoretical understanding, material fabrication, engineering of all sub systems involved, and assembly technologies (enabling, for example, the positioning of a diamond within a few 100 µm on top of a tiny optical fibre). A plethora of applications were then developed: a detector with electrical readout and an improved sensitivity surpassing the one obtained with optical readout, a commercial cryogenic scanning probe system with stable operation at low temperature and a spectrum analyser with an extended bandwidth; several new sensing functionalities of NV centres with attractive sensing performances in the optical domain; the demonstration of NV magnetometry under extreme pressures; the possibility of unravelling biochemically relevant reactions with nanoscale spatial resolution; and new scientific applications of the NV-based quantum sensors to advance knowledge on a variety of unresolved topics in modern condensed matter physics.

The Flagship's researchers have also advanced two promising approaches for improving medical imaging diagnostics and spectroscopy by making use of more precise, practical, and efficient nuclear magnetic resonance[40] (NMR). First, they have demonstrated that microscopic spectroscopy is appropriate for (metabolic) analyses of single cells by taking advantage of the unique quantum sensing properties of nitrogen-vacancy centres (NV centres) in nanostructured diamonds to detect NMR signals with 1,000 times better spatial resolution than the current state-of-the-art. The quantum microscope they developed provides researchers with a distinctive tool that significantly advances cell analysis and creates new opportunities for in vitro diagnostics and medical research. Second, they have successfully demonstrated hyperpolarized magnetic resonance imaging (MRI) in practical settings, setting a stepping stone to overcoming the low sensitivity of conventional NMR. The latter is generally limited by the fact that, on average, only one out of several billion nuclear spins is magnetically aligned; this new technique increases the number of aligned spins by several orders of magnitude, thus increasing the strength of the NMR signal by the same factor. This leads to MRI results of equivalent quality, even with a weaker magnetic field and therefore at a fraction of the operating costs.

Ultra-precise clocks are also an important area to which the quantum sensors developed by the Flagship have contributed[41]. The Flagship's researchers have in fact developed the components needed to build a robust, compact, transportable, and easy to use industrial-grade clock, of which the assembly is currently underway (a second design which could lead to more compact and robust optical clocks more suitable for operation on moving platforms has also been developed). These clocks will have a large impact on telecommunication and navigation (e.g. network synchronization, increased traffic bandwidth, GPS

[37] New unique industrial or societal real-life applications (products and services) introduced by EU companies, based on any quantum simulation
[38] The number of qubits or simulated particles of Europe's most advanced non-gate-based quantum simulator.
[39] See project ASTERIQS, https://www.asteriqs.eu/
[40] See project METABOLIQS, https://www.metaboliqs.eu/
[41] See project iqClock, https://www.iqclock.eu/

spoofing and outage resilience, terrestrial navigation with cm precision), geology (e.g. underground exploration, monitoring of water tables, volcanoes or ice sheets), astronomy and space (e.g. low-frequency gravitational wave detection, radio telescope synchronization, deep space navigation), and other fields.

Another promising sensor technology has been developed around atomic vapour cells holding a high number of Rubidium atoms in the vacuum[42], which required the development of a novel fabrication process to produce these cells via a reliable and industrial means based on the same technique used all over the world to produce electronic circuits.

These sensors have then been used to develop several applications: integrated quantum sensor prototypes at high TRL for miniaturized atomic clocks (with superior timing accuracy with respect to high-end quartz-base clocks) and optically-pumped magnetometers (applied in magnetoencephalography for investigating human brain function); a shoebox-sized proof-of-principle demonstrator of an atomic gyroscope for use in the automotive sector; the demonstration of an atomic spectrometer through the imaging of the frequency spectrum of microwave fields; and a method to detect a handful of molecules (nitric oxide, an important tracer gas for inflammatory diseases, like asthma) in a gas of billions of other particles.

In addition, a new technique for imaging THz waves has been realised. THz waves can penetrate many materials, much in the way that X-rays do, but, unlike X-rays, they emit low-energy radiation and therefore safe to use. Through atomic vapour cells, a spatial resolution of 1mm has been achieved with a record-breaking imaging frame rate of 20 thousand frames per second. This will have applications in process monitoring, food safety, security screening and renewable energy technologies.

All the Flagship's developed quantum sensors have the potential to become, in the short to mid-term, compact devices ready for applications, with many more to come.

Key Performance Indicators: Quantum Sensing and Metrology[43]	
Market readiness[44]	3 (clocks; cold-atom gravitometers; NV-centre magnetometers) TRL advancements in all quantum sensors studied: NV-centres in ultrapure diamonds, atomic vapor cells, quantum clocks
Next generation technologies[45]	Increased sensitivity in NMR and MRI; miniaturized atomic clocks, atomic gyroscopes, atomic spectrometers; molecule detectors; THz imaging

[42] See project MACQSIMAL, https://www.macqsimal.eu/
[43] See https://qt.eu/app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf
[44] Number of different (publicly known) product classes or service classes (or use cases) based on quantum sensors developed, implemented and sold by European companies or deployed in the EU.
[45] Number of demonstrated sensing technologies exploiting advanced quantum effects (entanglement, collective coherence etc.)

2.5 Achievements in Quantum Basic Science

The driving force of the R&D projects within the Basic Science section of the Quantum Flagship is to study, develop and exploit novel experimental platforms, which are more exploratory than the usual ones, such as superconducting qubits or laser-driven trapped ions. Such novel platforms may concern trapped ions, but driven by microwaves rather than by lasers; cryogenic set-ups, but involving propagating rather than stored microwaves; also 2D mesoscopic systems, rare-earth ions, and optical systems, but in the perspective of integrated chips, applied to the simulation of complex dynamical systems.

More specifically, during the last four years there has been progress in developing fast and fault-tolerant microwave-driven quantum gates on ions in microtraps, and in the design of scalable components for future multi-qubit quantum processors. For this approach[46], the two-qubit gate fidelity has been increased from ~98% to 99.9%, with an ion transport fidelity of over 99.99999%, and very minor unwanted interactions between ions[47]. This significant progress produced three start-up companies: Universal Quantum (Sussex, UK), EleQtron (Siegen, Germany), and Qudora Technologies (Hannover, Germany). Implementing quantum gates by applying voltages (not laser beams) to microchips, similar to conventional computers, along with the high two-qubit and ion transport fidelity, brings this approach closer to being a viable candidate for building large-scale quantum computers.

Superconducting qubits make extensive use of microwaves, which have quantum behaviour at very low temperatures: frequencies of a few GHz require cooling to milli-Kelvin temperatures. It is then a quite significant technological challenge to propagate and exploit such microwaves in a cryogenic environment. A Flagship project[48] has developed a 6.5 m long superconducting link between two dilution refrigerators and demonstrated quantum teleportation with 55% fidelity over this microwave quantum LAN prototype. Furthermore, a true quantum advantage in a cryogenic quantum radar set-up has been established for the first time. This world-leading position should be pursued towards multi-node microwave quantum LANs and free-space propagating quantum microwaves, with novel protocols promising a more robust quantum advantage.

Another interesting alternative platform for quantum information processing is provided by rare-earth ions, showing potential for scalable quantum computing nodes. Recent achievements[49] include the detection and control of single rare-earth ions as qubits, and the development of device elements required for scalable quantum nodes. A general theoretical framework has been elaborated to describe optically interconnected quantum nodes, and to assess achievable quantum gate fidelities. This led to a comprehensive roadmap for rare-earth-ion-based quantum computing, as well as to first steps towards commercialization.

Mesoscopic physics, which has been awarded several Nobel prizes recently, is a domain where quantum effects play a major and spectacular role, related also to topology. It is therefore worth exploring as a new technological platform for the realization of on-chip quantum components. Within the Flagship[50], this has led to the realization of a new single-photon detector in the THz regime, a novel single-photon detector based on high-temperature superconductors, and superconductivity in twisted bilayer graphene. This is a clear demonstration that this novel class of quantum 2D materials and their heterostuctures are a very promising platform for the development of quantum technologies, where Europe is a clear leader, and where basic science results open the way to applications in novel quantum devices.

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[46] See project MicroQC, https://stelianvitanov9.wixsite.com/my-site

[47] Fidelity is the standard way to measure the quality of a quantum operation, with an ideal value of 1.

[48] See project QMiCS, https://qmics.wmi.badw.de/

[49] See project SQUARE, https://square.phi.kit.edu/

[50] See project 2D-SIPC, https://2d-sipc.eu/about-2d-spic/

Photonic quantum technologies are extremely active worldwide. A Flagship project has contributed to advancing promising platforms[51] in this direction, already well within practical applications, relying on integrated photonic chips and quantum light sources. These chips offer miniaturized architecture, low loss connectivity, and well-developed nanofabrication technology, and they can be used for indistinguishable single photon emission and single photon processing. Quantum technologies in photonic chips are regarded as a major emerging market, by providing better scalability for quantum light sources.

Continuing the theme of light, and regarding the very important issue of quantum simulations, another project has developed a platform for analogue quantum simulations, based on the so-called quantum fluids of light[52]. These coupled light-matter quantum states can be used to simulate the dynamics of quantum mechanical processes in various systems, going as far as astrophysical phenomena. The fundamental understanding of such light fluids, their quantum physics, and their applications, is also a topic where Europe is clearly at the forefront.

There are even more ways to generate and engineer quantum states of light, as a further project has shown by controlling losses in an ingenious way, and by designing new detectors with high resolution in number of photons[53]. This has applications for instance in quantum-enhanced metrology and in the improvement of the frequency stability for commercial atomic clock. Similar techniques may be used for optical routing devices for telecommunication networks, and for simulation of complex dynamical systems.

Overall, the Basic Science projects of the Flagship have advanced into new territories, identifying difficulties, both scientific and technological, but also discovering routes round them, as well as promising new directions. It is clear that such work has been, is, and will remain an essential component in the progress of quantum technologies.

2.6 Coordination and Support Actions (CSAs)

QTEdu

The CSA QTEdu assists the Quantum Flagship with the creation of an education ecosystem necessary to provide the talents and skilled workforce for the quantum industry, ranging from school programmes to master's degrees, and upskilling and reskilling programmes. QTEdu has been successful in:

- organising a pan-European master's degree in quantum technologies
- listing the numerous existing master's programme on the QTEdu website
- preparing materials and tools for training and education[54]
- developing a Quantum Competence Framework[55] to map the landscape of competences and skills in quantum technologies, and facilitate communication and cooperation among different stakeholders in the education ecosystem.

Furthermore, master's degrees in the digital field are being funded under the Digital Europe Programme, and quantum is one eligible area[56]. One of the main activities of the CSA has been connecting the community and providing the reporting infrastructure needed for it to continually update its offerings.

[51] See project S2QUIP, https://www.s2quip.eu/
[52] See project PhoQus, https://www.phoqus-project.eu/
[53] See project PhOG, https://www.st-andrews.ac.uk/~phog/
[54] See, for example, Section "Resources for everyone" on https://qtedu.eu/
[55] See the framework itself here and the corresponding methodology to obtain it there.
[56] See the Funding and Tenders portal.

InCoQFlag

The International Cooperation on Quantum Technologies project (InCoQFlag[57]) aims to identify win-win opportunities to collaborate with countries investing massively in quantum, such as Canada, Japan and the United States. In particular, InCoQFlag has been successful in:

- strengthening connections with Canada, one of the leading countries in the field of quantum technologies. A significant step was the launch of a joint call between the EU and Canada in 2021 in the first Horizon Europe Work Programme, with the overall EUR 8 million budget for collaborative projects gathering European and Canadian academia scientists and industries.
- maintaining a dialogue with Japan, which indirectly contributed to the successful conclusion of the Japan-EU Digital Partnership to advance cooperation on digital issues including establishing modalities of reciprocal access for researchers to supercomputing and quantum computing infrastructures.

QFlag

During the ramp-up phase, the QFlag project provided central support services and acted as a single entry point to the Quantum Flagship. It was critical for the smooth progress of many of this phase's activities, including :

- preparing a community-driven Quantum Flagship Strategic Research Agenda
- building a community with more than 2700 registered participants and community events exceeding 1000 participants (e.g. European Quantum Technologies Conference)
- starting a Quantum Technology Focus Group involving European quantum technology experts in standardisation and IPR
- creating a database of European quantum education programmes and preparation of the first European Quantum Future Academy, with satellite events in all EU Member States, cooperation workshops with US, Japan and Canada, and preparation for the first international cooperation Horizon Europe Quantum calls
- setting up of central communication platforms such as the qt.eu website, and preparing promotional material.

2.7 Synergies within and outside the Quantum Technologies Flagship

Many Flagship projects have demonstrated synergies and cooperation in the course of their activities, as visually summarised in Figure 3. In total 196 scientists from across the 21 projects are involved in collaborations with other Flagship projects.

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[57] InCoQFlag - International Cooperation on Quantum Technologies (qt.eu)

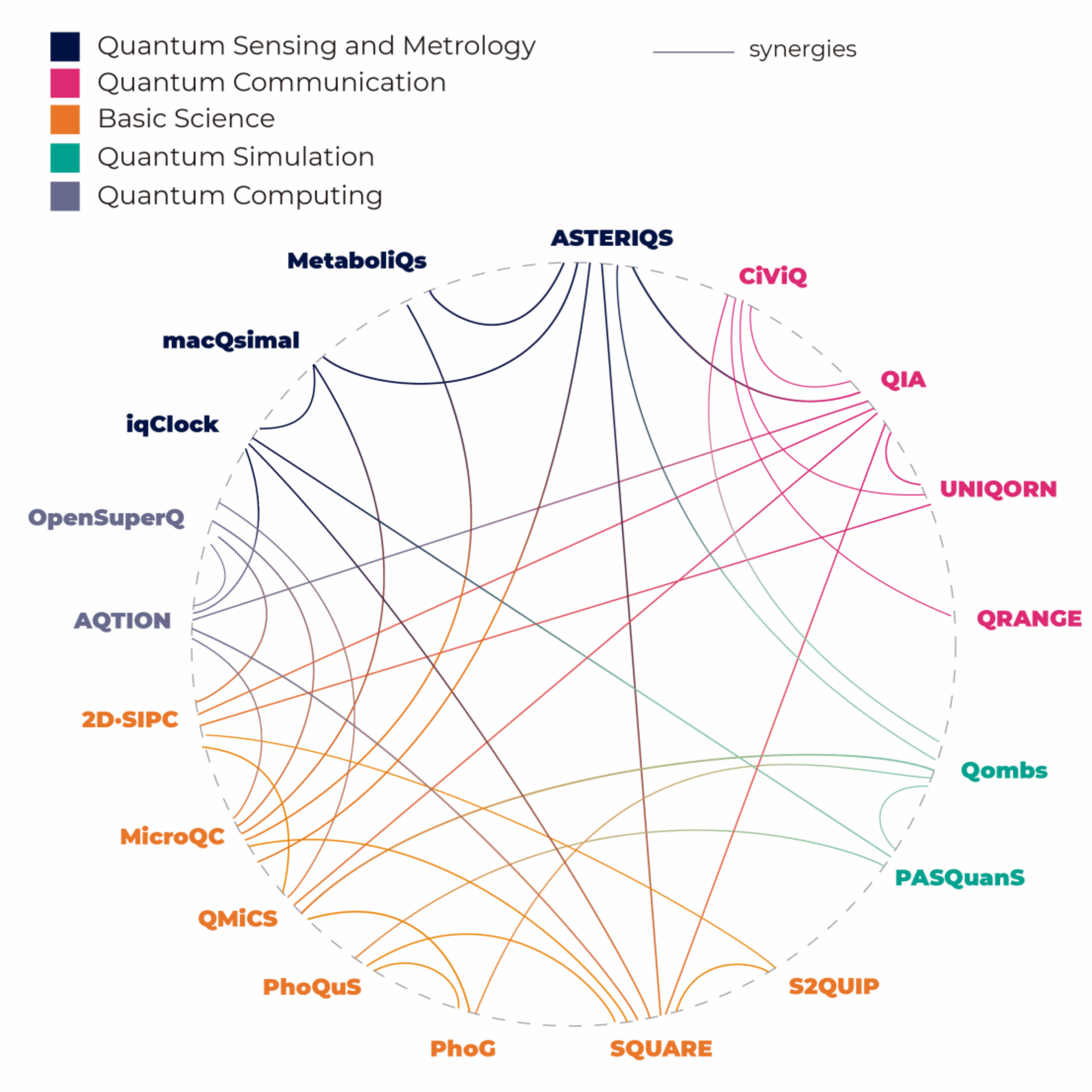


Figure 3: *Visual summarisation of the synergies among QT Flagship projects*

The projects have developed synergies in three main areas, namely Approaches and methods, Use of results in other projects, and Common partners among consortia. These areas are outlined below with some specific examples; synergies beyond the Flagship are then described.

Approaches and methods

Projects have actively communicated and shared the approaches they have used, and learnt from each other. Some specific examples include:

- actively communicate and discuss their similar approach to the engineering of active quantum components based on 2D materials and integrating those into photonics circuits (2D-SIPC, S2QUIP)
- exchanged information on technological approaches and solutions relating to simulation capabilities and the ion-trap architecture (AQTION, PASQUANS)
- coordinated on enabling software (AQTION, OPENSuperQ)
- scientific synergies due to common methodologies and theoretical basis on ion-trap quantum computer (AQTION, IQCLOCK)

- collaboration on methodologies and scientific approaches leading to joint articles (ASTERIQS, MetaboliQs, MACQSIMAL)
- collaborated on trapped ion quantum control techniques (MicroQC, AQTION)
- conducted joint development of the control software stack and collaborated on setting up a new joint start up (OPENSUPERQ, PASQuanS)
- collaborated on simulation of a European quantum network including terrestrial and satellite links (QIA, CiViQ)
- collaborated on single rare-earth ions as quantum processing nodes (QIA, SQUARE)
- collaborated on cryogenic tools (QMiCS, OpenSuperQ)
- information exchanged on technological overlap, leading to articles and proposals (QMiCs, PhoG)
- discussed overlap on technological challenges and conceptual overlap (Qombs, QMiCs)
- worked in a similar area, developing atom ion based platforms (PASQuanS, OPENSuperQ)
- collaborated on fibre cavities, for spin-photon interfaces and readout of quantum bits (SQUARE, S2QUIP)
- technological developments from SQUARE on fibre cavities relevant to other projects (SQUARE, QIA AQTION)
- ongoing interaction on materials development (SQUARE, AQTION)

Use of results in other projects

In several cases, outputs from one project being used as inputs for another. These include:

- development of quantum-grade diamonds in ASTERIQS benefitted MetaboliQs, PASQALS and QIA (ASTERIQS, PASQALS ; MetaboliQs; QIA)
- CiViQ used QRANGE's fast QRNGs specifically tailored for continuous-variable protocols and evaluated squeezed light sources and transimpedance amplifiers from UNIQORN (CiViQ, QRANGE, UNIQORN)
- used developments from ASTERIQS in sensing aspects of project (MetaboliQs, ASTERIQS)
- multifaceted collaboration, including photonic integration where QKD of projects were tested together, leading to joint investigation of the capability of the current network hardware to run QKD post-processing and QRNG post-processing on the embedded CPU (UNIQORN, CiViQ)
- PhoG used photonic chips provided by UNIQORN (UNIQORN, PhoG)
- QRANGE devices implemented in CiViQ and OPENQKD (QRANGE, CiViQ, OPENQKD)
- S2A collaboration for S2QUIP to use SQUARE's open cavity technology has emerged. (S2QUIP, SQUARE)

Common partners among consortia

Some projects have shared personnel and partners, leading to very strong opportunities for sharing of knowledge and for synergies between projects. The sharing of partners also allowed for very natural collaboration between projects. Some examples of shared partners include

- AsteriQs, MetaboliQs
- ASTERIQS, MACQSIMAL, QIA, Qombs, SQUARE
- QIA, AQTION, IQCLOCK, PASQUANS.
- QMiCS, OpenSuperQ,
- QMics, QIA

Synergies beyond the Quantum Technologies Flagship

The projects also had synergies beyond the Flagship. It means that the results of the projects were disseminated beyond the partners involved and increase the impact of the projects in both European and national quantum projects. In most projects, scientists are also involved with:

- QuantERA projects (125 scientists)
- EuroQCI (109 scientists)
- nationally funded quantum projects (761 scientists).

2.8 Overall contribution to the Quantum Technologies Flagship

The Flagship projects have made excellent progress in their contribution to advancing quantum research by, for example, ensuring that European stakeholders will have access to robust atomic simulators (QOMBS), and by demonstrating the potential of propagating microwaves for short-range communication and distributed quantum computing (QMICS), and by enabling technologies for quantum computing, such as an all-European source of quantum-limited microwave amplifiers, control systems, high-density wired dilution cryostat and a firmware stack (OpenSuperQ). The projects have brought industry-oriented and relevant achievements, for example the development of high-precision sensors in MACQSIMAL which will have a wide range of applications in navigation, medicine, communication, and geophysics.

Objectives of the Flagship	**Projects' contribution to the Flagship objectives**
Build a strong networked European quantum technologies community around the common goals defined in the SRA	The projects have engaged in significant dissemination (1313 scientific papers and 223 others under review) and have organised 166 events. The synergies outlined in Section 2.7 demonstrate that the projects are enhancing and developing the community.
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.	The synergies and cooperation evident during the Flagship contribute to creating the European ecosystem, and projects have resulted in 25 spin-offs and 105 patents providing opportunities for commercialisation.
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.	The projects have resulted in prototypes and commercial products. For example, a miniature atomic clock device, a first optically pumped magnetometer and identified opportunities for deployment in industry.

The 21 projects of the ramp-up phase represent 1654 scientists, 13% of whom are female.

Outputs include:

- 25 spin-offs/start-ups, provided in Appendix 1
- 105 patents filed, with 64 already granted, provided in Appendix 2
- 1313 scientific papers published with another 223 currently under review.

The Quantum Flagship has also allowed for more communication of results, with significant involvement in conferences and events, with attendance at:

- 1961 conferences, including presentation at 1624, and organisation of 161 conferences/workshops.

Several Widening Countries were included in the project consortia, and these are listed in Appendix 4.

3. Lessons Learned

This report demonstrates that the 21 scientific projects, including the two still ongoing, have made excellent contributions to the objectives of the Quantum Technologies Flagship, bringing together academia, RTOs, and industry to develop prototypes and marketable products, while significantly strengthening the European quantum community. In this section, the report outlines how the projects have played an important role in achieving the objectives of the Flagship, before going on to outline some of the difficulties or shortcomings, with suggestions on ways to overcome them in any future plans.

The projects have contributed to building the networked European quantum technologies community around the common goals defined in the SRA through strong synergies that arose during the work. As presented above, scientists from across the projects worked in cooperation, shared methodologies, and results, and used results from each other. These synergies should be built upon in future calls for proposals, with more cooperation between projects built into the programme.

The projects have also made progress in creating a 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. This is clear from some of the important breakthroughs that have taken place in cryptography, production of prototypes and marketable products and with the potential contributions that will be made in areas such as telecommunications, medical devices, and navigation. Some specific examples include:

- Important breakthroughs in cybersecurity and cryptography through the quantum cryptography developed in CiViQ and QRANGE
- Identification of the most cost-effective technology for quantum communication for European operators and European governments and citizens (CiViQ)
- The foundation for commercialisation of products by European companies (such as the single photon detector array developed by UNIQORN; and the cryogenic nanometre scale magnetometer developed by ASTERIQS)
- Advances in quantum computing and all-European sources of systems, placing Europe at the forefront of this technology, with quantum-enabled use-cases in European data centres with AQTION and OpenSuperQ.
- Potential improvements for telecommunication, underground exploration, and navigation, through atomic clocks developed in iqClock
- Improvements to medical devices by enabling MRI-based metabolic imaging, through work of MetaboliQS
- Better telecommunications devices achieved by the optical routing devices developed in PhoG.

While these contributions to the Flagship's objectives are significant, the ramp-up phase did see some difficulties and issues, which may be of importance in planning future calls for proposals.

A difficulty commonly cited by the project was the skills gap in quantum technologies, engineering, and computer science that they observed. This caused problems for projects when trying to recruit researchers, as researchers with the appropriate skills proved to be rare or non-existent. For projects that tried to recruit PhD students, similar problems were observed, as there is a shortage of graduates with the skills or background required to take up a PhD in quantum technologies. This indicates a real need at European level to invest not only in research for quantum technologies but also in education and training.

Projects also stated that the increasingly inter- and cross-disciplinary nature of research brings its own challenges: ensuring that teams have adequate numbers of partners across all required disciplines is very important in quantum research, and the Quantum Technologies Flagship has an important role to play in developing those partnerships and consortia.

Moreover, projects also drew attention to the effect of a shortage of European suppliers for quantum components, and delays in design and fabrication from European suppliers. This concern reinforces the need for the Flagship to reduce these gaps and suggests that future proposals should be required to consider supply chain issues explicitly, and offer a clear indication of how these issues will be overcome.

Finally, in many cases, Covid-19 was cited as a significant problem, for reasons including closures of laboratories and experimental facilities, delays in sourcing products and materials, and difficulties in dissemination and networking, given the cancellation of many events during the pandemic. Future calls and projects should consider explicit contingency plans for such events.

4. THE FLAGSHIP IN THE EUROPEAN QUANTUM LANDSCAPE

Cross-cutting achievements

In addition to the Flagship's impressive scientific achievements, excellent progress has also been made towards its targets in the cross-cutting areas that are crucial for the progress of quantum technologies in Europe as a whole.

Key Performance Indicators: Ecosystem[58]	
Investment[59]	National quantum initiatives: EUR 2 billion (Germany), EUR 1.8 billion (France), EUR 670 million (Netherlands)
Lab-to-market [60]	25 university spin-offs/start-ups, with some being the world-leaders in their respective technology
"Lab-to-fab" infrastructure and value chains[61]	1 (QITT); more due with EuroQCI (see also OpenQKD), EuroQCS, and as part of the Chips for Europe initiative
Patent creation and IP retention[62]	105 patents filed (64 already granted)

Key Performance Indicators: Education[63]	
Outreach[64]	https://qt.eu/ established and all relevant social media channels; 7 programmes established/promoted
Education[65]	https://qtedu.eu/ established
Adoption[66]	First pan-European master's degree in quantum technologies; quantum master's programmes eligible area for funding under the Digital Europe Programme

[58] See https://qt.eu/app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf
[59] Total amount of EC investment in the form of venture capital (EU quantum start-ups), corporate seed-funding (EU incubators and accelerators), and EU public investment (EU public-private ventures).
[60] Number of quantum start-ups, spinoffs, incubators, accelerators, as well as public private joint ventures in Europe (given for all pillars, including established EU companies that enter the field).
[61] Number of EU research institutions offering open application labs, testbeds, production cleanrooms, with testing, prototyping and calibration service facilities accessible to European SMEs, covering TRL 2-6.
[62] Quantum-related European patents granted versus distribution of granted patents globally.
[63] See https://qt.eu/app/uploads/2022/04/KPIs-for-QT-in-Europe.pdf
[64] Establish a successful communication and outreach programme to raise awareness of quantum technologies: Number of outreach and training events promoted on the Quantum Flagship website (following the continually updated criteria laid out by the Flagship Coordination and Support Action (CSA)).
[65] Developing an open-source ecosystem of validated and scalable quantum education and training modules: Number of open source, curated (didactically validated) quantum education modules accessible via the Quantum Flagship repository.
[66] Pan-European institutional adoption of the competence framework for planning, conducting and evaluating quantum educational and training efforts: Number of entities (companies, universities and training institutions such as corporate training and vocational) actively using the competence framework in their workforce development and curriculum development efforts.

Diversity and equity[67]	13% of the Flagship's researchers are female; Equality Diversity and Inclusion working group established and first realistic actions identified[68]

Next steps

On the basis of the Flagship's successes, the European Quantum Industry Consortium (QuIC) was founded with the mission of boosting the European quantum technology industry's competitiveness and economic growth, bolstering value creation across the continent, and building a strong, vibrant EU ecosystem comprising SMEs, large corporations, investors, and leading researchers. Thus, Europe has established a solid basis for the Flagship's second phase that will continue to both develop the most promising quantum technologies per pillar and introduce new ones (e.g. photonic quantum computing); and advance quantum basic science, which has been so far pivotal to sustaining the progress of known quantum technologies and introducing ideas leading to new ones.

Furthermore, the deployment of quantum technologies in Europe started already in 2021. The High-Performance Computer and Quantum Simulator hybrid project (HPCQS), supported by the EuroHPC Joint Undertaking69 and running from December 2021 until December 2025 with a total budget of EUR 12 million, aims to integrate two quantum simulators into HPC environments70. The first steps are already being taken towards the deployment of a European Quantum Computing and Simulation (EuroQCS) Infrastructure 71 , which will further integrate quantum computers and simulators based on the technologies developed by the Flagship into the EU's high performance computing infrastructure, with access provided to the Flagship's stakeholders.

Another example of deployment concerns quantum communication technologies and the EuroQCI initiative72, which aims to build a secure quantum communication infrastructure that will span the whole EU, including its overseas territories. The EuroQCI will make use of innovative quantum communication technologies developed by the Flagship.

Finally, coordination of EU- and national-level research is also needed, especially now that the success of the Flagship's ramp-up phase has catalysed the creation of major national initiatives with funding comparable to the Flagship's (Netherlands) or twice as big (France, Germany). Clearly, no single country has the capacity to carry out the complex endeavour required for developing quantum technologies by

[67] Fostering structural integration of equity and diversity initiatives into QT education and training: Number of entities (companies and educational institutions) contributing to the coordinated Quantum Flagship efforts following the guidelines developed in the Coordination and Support Actions (CSAs) (reported into the European Quantum Education Centre (EQEC))

[68] Unconscious bias training in all Flagship's projects; dedicated budget within the CSA to fund individual special assistance to support inclusive participation in congresses, meetings etc.; monitoring of diversity in the quantum community; an inclusive standard for Flagship events and events where Flagship representatives participate plus financing maintenance of a dedicated page in the qt.eu portal to support the implementations suggested; promoting and financing mentoring opportunities; creating and empower a Quantum Diversity Community Network.

[69] The European High Performance Computing Joint Undertaking (EuroHPC JU) is a legal and funding entity, created in 2018 to lead the way in European supercomputing. It is jointly funded by its members, with a budget of around EUR 7 billion for the period 2021-2027.

[70] The French company PASQAL, a start-up that emerged from the Flagship projects PASQuanS, will provide one quantum simulator to GENCIS in France and another to the Jülich Supercomputing Centre in Germany.

[71] https://eurohpc-ju.europa.eu/selection-six-sites-host-first-european-quantum-computers-2022-10-04_en

[72] https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci

itself, and project consortia must capitalize on the strengths of research and industrial groups located in different parts of Europe.

The European Chips Act

Moreover, to fully exploit the Flagship's results and convert them into market innovation, it is essential to support the development and manufacturing of quantum devices through the production of quantum chips. Quantum chips are in fact crucial, in order to facilitate miniaturization of quantum devices; facilitate the integration of quantum devices with other (integrated) devices, including (but not limited to) control electronics and connectivity; and improve fabrication reliability, quantum devices being currently by and large proprietary "hand-made" designs unsuitable for large-scale uptake and mass-market applications.

If Europe does not invest in the specialised facilities needed to produce those quantum chips, key innovations will either fail to reach the market or will receive the finance they need in other world regions. In either case the result will be that the EU's quantum technologies competences will feed the creation of non-EU industrial champions, replicating the current situation of the semiconductor industry[73]. The proposed European Chips Act clearly constitutes a timely action that will serve to mitigate this risk, as it foresees the development of dedicated pilot lines for design, manufacturing and testing quantum chips.

The development of such pilot lines represents a priority in Europe's quantum strategy. Quantum chip innovators need access to both dedicated clean rooms and foundries for prototyping and production[74] as well as testing facilities where those components can be examined and assessed. As for quantum computation and simulation, there are qubit platforms which could build on the well-established fabrication processes of the classical semiconductor industry (which should not only accelerate the capability of the EU for the mass manufacturing of quantum chips in a reproducible way, but also facilitate the integration of quantum devices as sensors or processors within classical microchips). But there are also alternative platforms (such as atoms, ions or photons) in need of ad-hoc innovative and advanced design libraries and fabrication processes. Therefore, the 'advanced technology and engineering capacities for accelerating the innovative development of quantum chips' of the Chips Act, which will bring in the expertise of the semiconductor industry, and 'the open testing and experimentation and pilot production capabilities for quantum technologies' of HE are complementary and both necessary.

The Chips Act will help the Quantum Flagship attain its wider goals, ensuring:

1. **continuity**, as it will help to realise the Flagship's objective of taking the most promising quantum technologies "out of the lab", thus supporting the transformation of European research into commercial applications that make full use of quantum's disruptive potential.
2. **complementarity**, as it will provide the EU with the capacity (not present within the Flagship itself) to move the prototypes delivered by the Flagship research projects up the TRL scale.

Clearly, this effort must be coordinated at EU level. This will ensure that, whatever the origin or technology of an EU quantum device, it will be compatible with the standardised design and manufacturing processes of European manufacturers that will be supported by the Chips Act. National quantum programmes are insufficient for the development of design and manufacturing processes for quantum chips to a level of maturity where they would achieve critical mass or sustainability; therefore, coordinating and bringing

[73] Some EU countries have already signed bilateral cooperation agreements (e.g. FR-NL) and are even negotiating cooperation agreements with third countries (e.g. DE, FR, NL with the US), to better coordinate their quantum activities and find synergies. To avoid fragmentation through the establishment of bilateral agreements across the EU, more coordination at EU level is needed.
[74] Such dedicated clean rooms and foundries make it possible to lower the entry barriers to the development and production of small volumes of quantum components.

together these initiatives under the Chips Act would create scaling effects, rather than dispersing resources in the creation of sub-critical players[75].

[75] Some Member States have already established large national quantum programs with complementary objectives and activities such as the knowledge transfer from the research labs to industrialisation, supporting the emergence of a European quantum industry, including design and production capabilities of quantum chips are common under those programmes. However, each country is specialised for a particular technology to build quantum devices, and a fragmented approach without EU coordination is clearly sub-optimal.

5. CONCLUSION

Quantum technologies will provide unprecedented computing, communication, and sensing capabilities that will benefit the EU, its industry, its citizens but also its security and its autonomy. With the achievements presented in this report, the ramp-up phase enabled Europe to demonstrate once more its excellence in research and development. With these 21 projects, the foundations have been laid for the deployment of quantum technologies that will help Europe to achieve its double transition towards a Green and Digital future. With 25 spin-offs, 105 patents filed and 64 already granted, the impact of the Quantum Technologies Flagship on start-ups and on the potential for the European quantum industry is evident, while the high levels of dissemination resulting from the projects (over 1500 scientific papers) assures the scientific impact of the research conducted. Bringing together 77 privately owned companies with 103 universities and 56 research organisations is an important contribution to the development of a quantum community in Europe, that covers both industry and academia, enabling commercialisation of academic research.

Looking ahead and building on the lessons learnt during the ramp-up phase, under Horizon Europe around 20 new projects will push the boundaries of what quantum technologies can achieve in all four quantum pillars. Aided by a new Coordination and Support Action, the Flagship will move forward towards the maturation of quantum technologies. These efforts will be complemented by other initiatives in production, equity funding, as well as education and training, designed to be as efficient as possible in achieving Europe’s ambitions in this domain, which are encapsulated by the Commission’s “2030 Digital Compass: the European way for the Digital Decade” strategy, which aims to see Europe at the cutting edge of quantum technologies by 2030[76]. This vision, and the way towards it, will be presented in an updated Strategic Research Agenda in 2023.

[76] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021DC0118

Appendix 1 - Governance structure of the Quantum Technologies Flagship

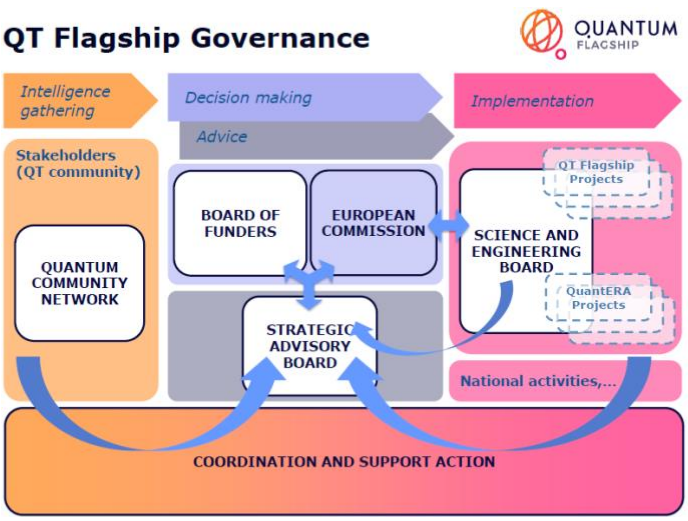
The Flagship's main decision-making bodies are the European Commission and Board of Funders (BoF). The BoF includes the main funders, namely representatives of the Member States and a number of Associated Countries to the Horizon 2020 programme. The work of these decision-making bodies is guided by the 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.

The SAB 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[77] (a leading European network of 39 research funding organisations from 31 countries which supports excellent research and innovation in quantum technologies).

The European quantum community is represented in the Flagship by the Quantum Community Network[78] (QCN), which consists of representatives of all EU Member States and a number of Associated Countries to Horizon 2020. 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.

The CSA QFlag was established in 2017 to implement and launch the Quantum Technologies Flagship, and ensure the best possible implementation and start of the ramp-up phase. It has now been succeeded by the CSA QUCATS.

The figure below shows how the Flagship's governance bodies interact.



[77] QuantERA

[78] More details about the QCN can be found here.

While the above structure proved to be effective during the ramp-up phase, it will be adapted to the new challenges of the second phase of the Flagship, where technology deployment, manufacturing and production, as well as new and ambitious national programmes, must be taken into account.

Appendix 2 - List of start-ups and spin-offs

Pillar	Project	Start-ups and Spin-offs
Communications	CiViQ	Keequant, Luzquanta, Alea Quantum Technologies
Communications	QIA	QBird, WeLinQ
Simulation	PASQUANS	Pasqal, ParityQC, Qruise, planqc
Sensing	ASTERIQS	Diatope, SazonQ, Quantum Technoloiges
Sensing	iqClock	1 in progress (no name provided)
Computation	AQTION	AQT
Computation	OpenSuperQ	Quantum Mads, Atlantic Quantum, Qruise (appears above)
Basic Science	PHOQUS	1 in progress (no name provided)
Basic Science	SQUARE	qlibri
Basic Science	S2QUIP	2 in progress (no name provided)
Basic Science	MicroQC	Eleqtron GmbH Universal Quantum Qudora Technologies GmbH

Appendix 3 - List of Patents

Project	Patent Name	Patent Number
OpenSuperQ	QUANTUM COMPUTER-IMPLEMENTED METHOD FOR SOLVING A PARTIAL DIFFERENTIAL EQUATION	EP3971793A1
OpenSuperQ	QUANTUM COMPUTER-IMPLEMENTED METHOD FOR SOLVING A PARTIAL DIFFERENTIAL EQUATION	WO2022058285A1
OpenSuperQ	QUANTUM PROCESSING UNIT	Confidential
OpenSuperQ	EXTERNAL PORT MEASUREMENT OF QUBIT PORT RESPONSES	WO2020043415A1
OpenSuperQ	ISOLATING AMPLIFIER APPARATUS	Confidential
OpenSuperQ	AN ARBITRARY WAVEFORM GENERATOR WITH ADVANCED COMMAND CONTROL	WO2022002390A1
OpenSuperQ	A FAST CONTROLLER DEVICE FOR CONTROLLING A QUANTUM PROCESSOR	WO2021239215A1
OpenSuperQ	CONFIGURABLE QUANTUM-COMPUTING CONTROL SYSTEM	WO2021204345A1
QIA	PHOTON EXCHANGE BASED QUANTUM NETWORK AND METHOD OF OPERATING SUCH A NETWORK	Not provided
QIA	PHOTON EXCHANGE BASED QUANTUM NETWORK AND METHOD OF OPERATING SUCH A NETWORK	Not provided
ASTERIQS	NANOSCALE THERMOMETRY	EP3951339A1
ASTERIQS	DEVICE AND METHOD FOR USING DIAMOND NANOCRYSTALS HAVING NV COLOUR CENTRES IN CMOS CIRCUITS	WO2021013308A1
ASTERIQS	DEVICE AND METHOD FOR USING DIAMOND NANOCRYSTALS HAVING NV COLOUR CENTRES IN CMOS CIRCUITS	DE102019009133A1
ASTERIQS	Vorrichtungen zur Messung eines Parameters eines Fluids mittels einer Vielzahl von NV-Zentren	DE102020129349A1
ASTERIQS	DEVICE AND METHOD FOR GENERATING AND CONTROLLING A MAGNETIC FIELD STRENGTH	EP3874343A2

ASTERIQS	METHOD AND DEVICE FOR ADDRESSING QUBITS, AND METHOD FOR PRODUCING THE DEVICE	WO2021018654A1
ASTERIQS	Empfänger mit NV-Zentren	DE102021101583A1
ASTERIQS	METHOD FOR GENERATING AT LEAST ONE DETERMINISTIC F-CENTRE IN A DIAMOND LAYER	WO2020260640A1
ASTERIQS	SINGLE CRYSTAL SYNTHETIC DIAMOND MATERIAL	WO2020201208A1
ASTERIQS	Sensoreinheit zum Erfassen eines Magnetfeldes	DE102020211864A1
ASTERIQS	QUANTUM INFORMATION PROCESSING DEVICE, ASSEMBLY, ARRANGEMENT, SYSTEM AND SENSOR	WO2021051163A1
ASTERIQS	SYSTEM FOR THE EVALUATION OF HYPERPOLARIZED MOLECULES IN A BIOLOGICAL SAMPLE	WO2020208103A1
ASTERIQS	Quantum information processing device, assembly, arrangement, system and sensor	AU2020349591A1
CiViQ	A Quantum Random Number Generator	Confidential
CiViQ	Synchronization in Quantum Key Distribution	Confidential
CiViQ	Device and Method for Performing Information Reconciliation in a Quantum Key Distribution System	Confidential
CiViQ	Post-Reception Synchronization in a Continuous Variable Quantum Key Distribution (CV-QKD) System	Confidential
CiViQ	Verfahren und Kommunikationsnetz zur Übertragung von QKD-Signalen	Confidential
CiViQ	Optical communication modules with improved security	Confidential
CiViQ	Quantum Key distribution-based Key exchange orchestration service for quantum-safe data centre and cloud communications	Confidential
CiViQ	A network node, a transmitter and a receiver for quantum key distribution over an optical fibre network	Confidential
CiViQ	A method and a device for carrier recovery	Confidential
CiViQ	High precision estimation of excess noise variance for	Confidential

	continuous variable quantum key distribution	
CiViQ	PCS-1024QAM for Continuous Variable Quantum Key Distribution	Confidential
CiViQ	Joint Classical and Quantum Optical Communications	Confidential
MicroQC	Verfahren zum herstellen einer atomfalle sowie atomfalle	DE102018111220
MicroQC	No name provided	EP3791408
MicroQC	No name provided	US11264220B2
MicroQC	No name provided	PA 006-19/5738
QRANGE	APPARATO DI PRODUZIONE DI FOTONI COMPRENDENTI STATI DI SINGOLO FOTONE IN CORRELAZIONE QUANTISTICA	Confidential
QRANGE	Method and device for quantum random number generation	Confidential
QRANGE	GENERATORE DI NUMERI CASUALI (RNG), IN PARTICOLARE GENERATORE DI NUMERI REALMENTE CASUALI (TRNG) DI TIPO PERFEZIONATO	Confidential

Appendix 4 - List of Partners from Widening Countries

Project	Partner	Widening Country
UNIQORN	Institution of Communication and Computer Systems	Greece
UNIQORN	Cosmote Kinites Tilepikoinonies Monoprosopi	Greece
CiViQ	Univerzita Palackeho V Olomouci	Czech Republic
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