Quantum Technologies Flagship Final Report

High-Level Steering Committee
28 June 2017

1 Executive Summary

The first quantum revolution – understanding and applying the physical laws of the microscopic realm – resulted in ground-breaking technologies such as the transistor and the laser. Now, our growing ability to manipulate quantum effects in customised systems and materials is paving the way for a second quantum revolution.

In April 2016, the European Commission announced the Quantum Technology (QT) Flagship, which will be managed as part of the FET program and is expected to be a large-scale initiative similar in size, timescale and ambition to the two ongoing FET Flagships.

The QT Flagship initiative is very important and urgent to place and keep Europe at the forefront of the second quantum revolution now unfolding worldwide, bringing transformative advances to science, economy and society. It will create new commercial opportunities addressing global challenges, provide strategic capabilities for security and seed yet unimagined applications for the future. In the past, Europe has missed the opportunity to capitalize on major technology trends (e.g. digital platforms); this could well happen again if Europe does not take decisive action now. Developing Europe's capabilities in QT will help to create lucrative knowledge-based start-ups, foster further growth of SMEs and industry and thus lead to long-term economic, scientific and societal benefits.

The long-term horizon is a "Quantum Web": quantum computers, simulators and sensors interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement. On the corresponding time scale – which is in fact longer than the flagship's expected duration of ten years – the performance enhancements resulting from quantum technologies will yield unprecedented computing power, guarantee data privacy and communication security, and provide ultra-high precision synchronization, measurements and diagnostics for a range of applications available to everyone locally and in the cloud.

To prepare the QT Flagship, the European Commission appointed an independent High-Level Steering Committee (HLSC) consisting of 12 distinguished Academic Members and 12 high-ranking Industry Members (from both large multi-nationals and SMEs), as well as one observer. The main tasks of the HLSC are to deliver (1) a Strategic Research Agenda, (2) an Implementation model and (3) a Governance model. This Final Report addresses these by containing (1) as already published in the Intermediate Report, as well as detailing recommendations for point (2) and (3), enhanced by discussions with the European Commission and Member States.

The Strategic Research Agenda (SRA) proposed in this document sets the ambitious but achievable goals for the Flagship's ten-year lifetime, and details them for the initial three-year ramp-up phase. To work towards these goals, the QT Flagship should be structured around four mission-driven research and innovation domains, representing the major applied areas in the field: Communication, Computation, Simulation, as well as Sensing and Metrology. These application domains should be built on a common basis of Basic Science, with top research institutions and companies spread across Europe assisting their objectives by delivering novel ideas, tools, methods and processes. The enabling aspects addressed in each domain belong to one of these three categories: Engineering and Control, Software and Theory, Education and Training.

Key to the initiative's added value is its pan-European dimension. This would allow an optimal integration of the diverse expertise of academic, SME and industry partners across Europe, promote international collaboration, exchange and networking of people and information, integrate national and European metrological and standardisation institutes in developing quantum-based standards, and, finally, align existing Member States strategies and activities ensuring that funding is spent in the most efficient way at all level: regional, national and international.

The HLSC proposes a set of guiding principles in the Implementation on how to combine and coordinate the strengths of Europe, which sort of projects and activities to fund, and how to assemble the most suitable consortia to achieve the goals of the QT Flagship. To remain at the forefront and take a strategic lead, the implementation of the QT initiative needs to start as early as possible. Preparatory actions should already take place in 2017/2018, to have the first Flagship-funded projects start in 2019. The summary of these measures is followed by recommendations on the strategic steering, the timeline, the evaluation and review process, the international cooperation and the possible intellectual property rights issues of the research and innovation projects that will receive the largest part of the available funding. Where appropriate, we have distinguished between the ramp-up phase (first three years) and the in general more consolidated steady-state phase. Training successful “quantum engineers” and more generally a quantum-aware workforce should also be a central objective of the QT program; in addition, further measures, e.g. for outreach to the public, are recommended to be implemented across all research and innovation projects. The section on Implementation is wrapped up by a mix of qualitative and quantitative key performance indicators for the evaluation of the overall success of the initiative.

The Governance Model proposed by the HLSC serves as the basis to ensure that the overall strategy of the QT Flagship will have the broadest scientific, economic and societal impact. It sketches a simple organizational structure for effective and efficient coordination between the projects and between the domains of the initiative. It also provides for close alignment of the Flagship’s strategy with the EC and national funding agencies and QT programs, while maintaining transparency of operational and decision-making processes and open feedback channels for the QT community.

A global race for technology and talent has started to profit from the promising future of quantum applications. As governments and companies worldwide, including Google, IBM, Intel, Microsoft and Toshiba, are investing substantially to unleash the QT potential, there is a strong urgency for Europe to start fast with real focused and consolidated efforts to keep up with global developments. By defining the Strategic Research Agenda, as well as the cornerstones of Implementation and Governance for the QT Flagship in a joint effort of academia and industry with extensive political and community support, the Final Report provides solid foundations for and beyond the 10-year programme cycle, setting the stage for Europe to spearhead the second quantum revolution.

2 Context

Currently Europe is at the leading edge in QT worldwide. According to McKinsey's data[1], over 50 percent of academic papers in the field come from European scholars. In the period of 2013-2015, 2455 authors of quantum physics papers came from the EU, compared to 1913 from China and 1564 from North America.

The European Commission (EC) also had its fair share in supporting QT over the last 20 years, with a cumulative investment reaching €550M. Within Horizon 2020, the EU Framework Program for Research and Innovation, the EC is already actively supporting QT notably from the FET Work Program for 2016-2017. [2] Thanks to these efforts, Europe has a well acknowledged world-class scientific and technical expertise, leading in many areas.

Quantum research in Europe reached a watershed moment in April 2016, marking the publication of the Quantum Manifesto[3], endorsed by over 3500 stakeholders from a broad scientific and industrial community in Europe, as well as the EC Communication on the European Cloud Initiative proposing the launch of the QT Flagship. The support of the EC was reaffirmed by Commissioner Günther H. Oettinger at the "Quantum Europe: A New Era of Technology" conference in Amsterdam, and subsequently confirmed by the Competitiveness Council's 26 May 2016 session on "Digital Single Market Technologies and Public Service Modernization" in Brussels.

The QT Flagship will be managed as part of the Future and Emerging Technologies (FET) program. It is expected to be a large-scale initiative similar in size, timescale and ambition to the two ongoing FET flagships, the Graphene Flagship and the Human Brain Project Flagship. Their experiences and best practices, as well as lessons learned from the FET will be included in the QT Flagship. It will be partly financed from H2020 and its successor FP9 and from different other sources at EU and national levels, for instance national funding organisations and research institutes, stimulating investment by industrial partners as well. The additional sources for its financial support, its leadership and governance will be defined as part of the preparation process. Following the Amsterdam conference, the EC appointed an independent High-Level Steering

[1] As presented by Dr. Gustav Kalbe, EC Head of Unit for High-Performance Computing and Quantum Technologies: The new Flagship on Quantum Technologies. State of Play. Brussels, 20 June 2016 https://www.flagera.eu/wp-content/uploads/2016/02/05-EC-QT-Flagship-State-of-Play-30-June-2016.pdf

[2] For further information, context and announcements see: https://ec.europa.eu/digital-single-market/en/quantum-technologies
Commission Staff Working Document on Quantum Technologies accompanying the "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: European Cloud Initiative Building a competitive data and knowledge economy in Europe – COM (2016) 178" https://ec.europa.eu/digital-single-market/en/news/commission-staff-working-document-quantum-technologies

[3] For the full document: see QUROPE Quantum Manifesto endorsement – http://qurope.eu/manifesto

Committee (HLSC) in two steps, announcing the Academic Members in August 2016[4] and the Industry Members in October 2016[5].

Thus, the HLSC consists of 12 distinguished Academic Members and 12 high-ranking Industry Members of the European QT field, as well as one observer, linking the HLSC to the FET flagship interim evaluation panel.[6] The main tasks of the HLSC, as outlined in the Terms of Reference[7], are to deliver

(1) **a Strategic Research Agenda**, taking into account industrial aspects. It should include a long-term roadmap for the flagship as well as a more detailed agenda for the H2020 ramp-up phase that should start as of 2018;

(2) **an Implementation model**, which describes a concrete implementation approach both for the short-term ramp-up phase within H2020 as well as for the longer term beyond H2020;

(3) **a Governance model**, including both the internal governance of the flagship, as well as the relations with Member States, with the EC and with the relevant funding agencies.

The HLSC has held four live meetings, with several tele-conferences in between. On 20 September 2016 in Brussels[8], the Committee discussed the core principles of the Strategic Research Agenda, as well as cornerstones of the Implementation and Governance models. It also agreed to initiate a participatory, non-discriminatory consultation phase with the QT community, including academia and industry. Hence, a community-wide workshop was organized on 10 November 2016 in Berlin[9], preceded by an open online consultation[10], providing the broadest possible range of stakeholders with the opportunity to give input on the HLSC discussions. Subsequently, the HLSC[11] accepted an initial Position Paper at its second gathering, discussed the integration of the issues raised during the QT Workshop, and appointed an Editorial Subcommittee[12]

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[4] EC Digital Single Market: Expert Group on Quantum Technology Flagship now set up. 5 August 2016 https://ec.europa.eu/digital-single-market/en/news/expert-group-quantum-technology-flagship-now-set

[5] EC Digital Single Market: 12 industrial members join the Expert group on Quantum Technology Flagship. 13 October 2016 https://ec.europa.eu/digital-single-market/en/news/12-industrial-members-join-expert-group-quantum-technology-flagship

[6] For the complete list of the Members of the HLSC: see Appendix I

[7] Register of Commission Expert Groups: Internal Rules of Procedure, Terms of Reference: http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=24516&no=1

[8] Summary of Results of the first meeting of the HLSC, 20 September 2016, Brussels: http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=26107&no=2

[9] QT Flagship Community Consultation Workshop Minutes, 10 November 2016, Berlin: http://qurope.eu/system/files/QT%20flagship%20workshop%20minutes_QUROPE.pdf

[10] For the results of the consultation process: see http://qurope.eu/system/files/Comments%20from%20online%20consultation.pdf

[11] Summary of Results of the second meeting of the HLSC, 10 November 2016, Berlin: http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=27828&no=2

[12] Members of the Editorial Subcommittee: Chair: Prof. Dr. Jürgen Mlynek — Academic Members: Prof. Dr. Tommaso Calarco, Prof. Dr. Elisabeth Giacobino, Prof. Dr. Eugene Simon Polzik — Industry Members: Ing. Paolo Bianco, Dr. Michael Bolle, Dr. Daniel Dolfi, Dr. Grégoire Ribordy

tasked with compiling the key documents of the QT Flagship. The third meeting took place on 16 February 2017 in Malta[13] in conjunction with a Maltese EC presidency event. Here the HLSC officially adopted the Intermediate Report, containing the Strategic Research Agenda and a set of recommendations for the Implementation model. The Governance structure, as well as further measures for the Implementation were the focus of the fourth HLSC event held on 21 April in Brussels[14].

The results from the consultation process outlined above were distilled by the Editorial Subcommittee and agreed upon by the HLSC in June 2017, to be presented hereby as the Final Report of the QT Flagship. The document will be officially handed over to representatives of the EC in the Fall of 2017.

3 Background

Quantum physics was created in Europe in the first decades of the 20th century by a generation of young physicists who are now familiar names: Bohr, Planck, Einstein, Heisenberg, Schrödinger, Pauli, Dirac, Curie, De Broglie and others. It has fundamentally changed our understanding of how light and matter behave at extremely small scales, showing that objects can be in different states at the same time (superposition) and can be deeply connected without any direct physical interaction (entanglement). It has also vastly impacted our daily life: Ground-breaking technologies resulting from this first quantum revolution were, for example, the transistor and the laser, without which current computers, mobile phones and the Internet would be unthinkable.

One hundred years on, our ability to use previously untapped quantum effects in customised systems and materials is paving the way for a second quantum revolution. This will add a new stage to the already staggering impact of conventional information and communication technologies, by providing a novel and fresh conceptual platform within which a family of next-generation disruptive technologies, varying from products with a relatively short time to market to revolutionary new technologies that may require more than a decade of research, can be conceived, developed, tested and commercialized.

The developments in the leading domains of QT – Communication, Computation, Simulation, Sensing and Metrology – can be expected to produce transformative applications with real practical impact on ordinary people.[15]

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[13] Summary of Results of the third meeting of the HLSC, 16 February 2017, Malta: http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33046&no=3

[14] Summary of Results of the fourth meeting of the HLSC, 21 April 2017, Brussels: http://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33051&no=4

[15] Excerpt from the Quantum Manifesto

About Quantum Communication

Communication security is of strategic importance to consumers, enterprises and governments alike. At present, it is provided by encryption via classical computers, which could be broken by a quantum computer. This motivates the development of post-quantum cryptography, that is, encryption methods that quantum computers could not break. Secure solutions based on quantum encryption are also immune to attacks by quantum computers, and are commercially available today, as is quantum random number generation – a key primitive in most cryptographic protocols. But they can only function over distances up to 300 km: quantum information is secure because it cannot be cloned, but for the same reason it cannot be relayed through conventional repeaters. Instead, repeaters based on trusted nodes or fully quantum devices, possibly involving satellites, are needed to reach global distances. The advantage of trusted-node schemes is that they provide access for lawful intercept, as required by many nation states, and they are already being installed. The advantage of quantum repeaters, exploiting multimode quantum memories, lies in extending the distances between trusted nodes.

The building blocks for fully quantum repeater schemes are twofold: a small quantum processor and a quantum interface to convert the information into photons similar to the optoelectronics devices used in today's internet, but with quantum functionality. These building blocks have already been demonstrated in the lab, but years of R&D are still needed for them to reach the market. As soon as this happens, true internet-wide quantum-safe security could become a reality.

About Quantum Computation

Quantum computation is among the most far-reaching and challenging of quantum technologies. Based on quantum bits that can be zero and one at the same time and instantaneous correlations across the device, a quantum computer acts as a massive parallel device with an exponentially large number of computations taking place at the same time. There already exist many algorithms that take advantage of this power and that will allow us to address problems that even the most powerful classical supercomputers would never solve.

Quantum computers using different platforms have been demonstrated over the last two decades. The most advanced are based on trapped ions and superconducting circuits, where small prototypes for up to 10-15 quantum bits have already run basic algorithms and protocols. Many platforms and architectures have demonstrated the basic principles of quantum computing based on solid-state systems and on atomic and optical systems.

Due to technological interest and the evident limitations of existing approaches, referred to as the "end of Moore's Law" of computational scaling, global IT companies have been taking an increased interest in quantum computing in the last decade. Advances in quantum computer design, fault-tolerant algorithms and new fabrication technologies are now transforming this "holy-grail" technology into a realistic programme poised to surpass classical computation by ten to twenty years in some applications. With these new developments, the question companies are asking is not whether there will be a quantum computer, but who will build and profit from it.

Realising quantum computing capability demands that hardware efforts should be complemented by the development of quantum software to obtain optimised quantum algorithms able to solve application problems of interest.

About Quantum Simulation

The design of aircraft, buildings, cars and many other complex objects makes use of supercomputers. By contrast, we cannot yet predict if a material composed of few hundred atoms will conduct electricity or behave as a magnet, or if a chemical reaction will take place. Quantum simulators based on the laws of quantum physics will allow us to overcome the shortcomings of supercomputers and to simulate materials or chemical compounds, as well as to solve equations in other areas, like high-energy physics.

Quantum simulators can be viewed as analogue versions of quantum computers, specially dedicated to reproducing the behaviour of materials at very low temperatures, where quantum phenomena arise and give rise to extraordinary properties. Their main advantage over all-purpose quantum computers is that quantum simulators do not require complete control of each individual component, and thus are simpler to build.

Several platforms for quantum simulators are under development. First prototypes have already been able to perform simulations beyond what is possible with current supercomputers, although only for some particular problems.

This field of research is progressing very fast. Quantum simulators will aim to resolve some of the outstanding puzzles in material science and allow us to perform calculations that would otherwise be impossible. One such puzzle is the origin of high temperature superconductivity, a phenomenon discovered about thirty years ago, but still a mystery in terms of its origin. The resolution of this mystery will open the possibility of creating materials able to conduct electricity without losses at high temperatures, with applications in energy storage/distribution and in transportation.

About Quantum Sensing and Metrology

Superposition states are naturally very sensitive to the environment, and can therefore be used to make very accurate sensors. As a result of steady progress in material quality and control, cost reduction and the miniaturisation of components such as lasers, these devices are now ready to be carried over into numerous commercial applications.

Solid-state quantum sensors, such as nitrogen vacancy centres in diamond, have been shown to be useful for measuring very small magnetic fields. This may help with multiple applications, from biosensors to magnetic resonance imaging and detection of defects in metals. Superconducting quantum interference devices are one example of an early QT now in widespread use, in fields as diverse as brain imaging and particle detection.

Quantum imaging devices use entangled light to extract more information from light during imaging. This can greatly improve imaging technologies by, for example, allowing higher resolution images through the use of squeezed light or creating the ability to produce an image by measuring one single photon which is entangled with a second, differently coloured and entangled photon that is being used to probe a sample.

Atomic and molecular interferometer devices use superposition to measure acceleration and rotation very precisely. These acceleration and rotation signals can be processed to enable inertial navigation devices to navigate below ground or within buildings. Such devices can also be used to measure very small changes in gravitational fields, magnetic fields, time or fundamental physical constants.

Quantum metrology employs intrinsically quantum mechanical features such as coherence and the Josephson and quantum Hall effects to perform precise measurements of e.g. time, frequency, voltage, current and resistance in quantum standards. Tremendous progress in this field over the past years culminates in an expected redefinition of the SI unit system in 2018. With this step, quantum standards will directly profit from advances in quantum technology with impact on a large range of commercial applications and society.

4 Flagship Initiative Overview

Goals

The QT Flagship represents a strategic investment enabling Europe to lead the second quantum revolution, building on its scientific excellence, on an established and growing interest from major industries, and on ecosystems of high-tech SMEs occupying leading positions in their specific markets.

Top research institutions and companies spread across Europe cover all aspects of QT from basic physics to electronics and computer science. However, to unlock the full potential of QT, accelerate their development and be first in bringing commercial products to domestic and international public and private markets, the QT Flagship will have to:

- Consolidate and expand European scientific leadership and excellence in quantum research, including training the relevant skills;
- Kick-start a competitive European industry in quantum technologies to position Europe as a leader in the future global industrial landscape;
- Make Europe a dynamic and attractive region for innovative research, business and investments in QT, thus accelerating their development and take-up by the market.

Towards those goals, a solid engineering base needs to be developed in Europe. Focused programmes fostering ecosystems of scientists, engineers and companies should work on shared mission-driven technology roadmaps and develop and standardise tools and software. This in turn requires the QT Flagship to have a strong scientific foundation, through investment in excellent collaborative scientific projects across Europe.

Structure

The QT Flagship program should be structured in five **domains**, each of which should be reflected in a call for proposals. Four vertical domains (not necessarily of the same size in terms of allocated resources) address vital application areas of a future knowledge-driven industry:

- **Communication**, to guarantee secure data transmission and long-term security for the information society by using quantum resources for communication protocols;
- **Computation**, to solve problems beyond the reach of current or conceivable classical processors by using programmable quantum machines;
- **Simulation**, to understand and solve important problems, e.g. chemical processes, the development of new materials, as well as fundamental physical theories, by mapping them onto controlled quantum systems in an analogue or digital way;

- **Sensing and metrology**, to achieve unprecedented sensitivity, accuracy and resolution in measurement and diagnostics, by coherently manipulating quantum objects.

Basic Science will be a horizontally fully cross-cutting domain, to develop novel ideas that can have a major impact on the four application domains, ranging from theoretical and experimental fundamental science to proof-of-principle experiments, capable of delivering the concepts, tools, components, materials, methods and processes that will enable the flagship objectives to be realised.

An integral part of each application domain will be common enabling aspects in the following categories:

- **Engineering and Control**: Advancing the understanding, design, control, construction and use of new technologies and driving their transition from concepts, theories, one-off and proof-of-principle experiments, to devices suitable for use in applications and eventually for products, by facilitating materials fabrication and miniaturised or integrated solutions for low-cost, robust, high-yield and scalable devices and systems applicable to diverse technology platforms;
- **Software and Theory**: Developing quantum algorithms, protocols, and applications, and connecting to tools for control and certification that understand and profit from the quantum advantage;
- **Education and Training**: Specific programmes for training a new generation of skilled technicians, engineers, scientists and application developers in QT and fostering ecosystems for them to work on shared mission-driven technologies and to develop and standardise tools and software. This includes a strong dissemination work towards society, to allow new and senior professionals, and the public in general, to understand the potential of QT and their benefits.

Projects should be positioned within one of the domains, and may link to other domains. They should always address Education and Training as well as at least one of the other two enabling aspects.

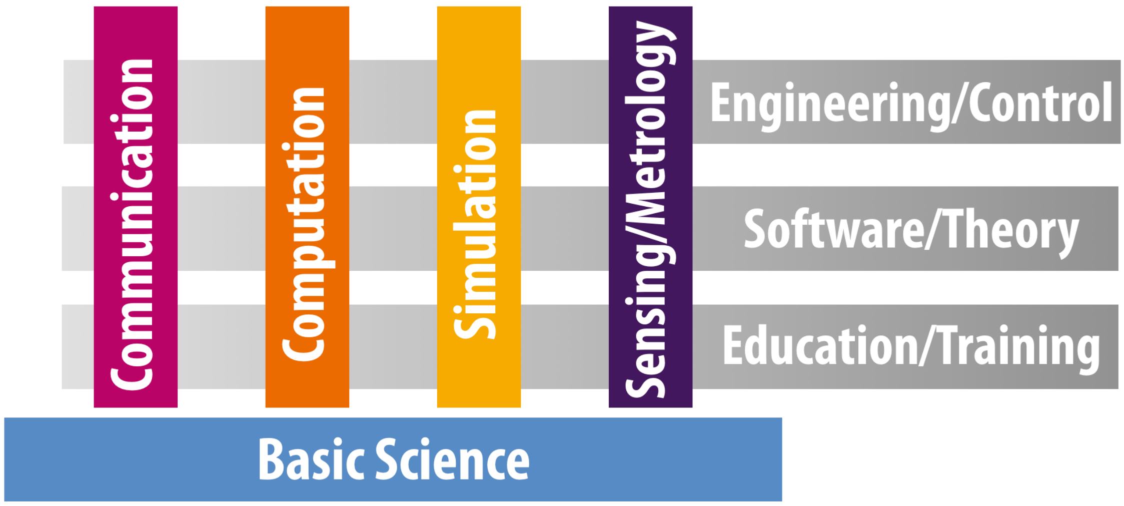

Figure: Structure of the Strategic Research Agenda

Added Value

Key to the initiative's added value is its pan-European dimension that will allow to:

- Combine the strength and flexibility of a broad, de-centralised programme with the clustering and coordination of focused initiatives;
- Harness capabilities and ideas from multiple academic and industry partners across Europe;
- Promote international collaboration, exchange and networking of people and information between different centres, and across academia and industry, thus fostering mobility and knowledge exchange;
- Integrate national and European metrological and standardisation institutes in developing quantum-based standards for the most mature technologies;
- Promote the integration of and collaboration between education, science, engineering and innovation.

In addition, the QT Flagship should also:

- Align existing Member States strategies and activities, ensuring that there is an optimized organisation of efforts and that funding is spent in the most efficient way at all levels: regional, national and in the important context of international cooperation;
- Assist nascent national QT programmes, thus ensuring that it is the whole of Europe that contributes to and reaps the benefits of the second quantum revolution.

5 Strategic Research Agenda

Quantum Communication

Quantum communication involves generation and use of quantum states and resources for communication protocols. Typically, these protocols are built on quantum random number generators (QRNG) for secret keys and quantum key distribution (QKD) for their secure distribution. Its main applications are in provably secure communication, long-term secure storage, cloud computing and other cryptography-related tasks, as well as in the future a secure “quantum web” distributing quantum resources like entanglement and connecting remote devices and systems.

Quantum Communication milestones

- **In 3 years**, development and certification of QRNG and QKD devices and systems, addressing high-speed, high-TRL, low deployment costs, novel protocols and applications for network operation, as well as the development of systems and protocols for quantum repeaters, quantum memories and long distance communication;

- **In 6 years**, cost-effective and scalable devices and systems for inter-city and intra-city networks demonstrating end-user-inspired applications, as well as demonstration of scalable solutions for quantum networks connecting devices and systems, e.g. quantum sensors or processors;

- **In 10 years**, development of autonomous metro-area, long distance (> 1000km) and entanglement-based networks, a "quantum Internet", as well as protocols exploiting the novel properties that quantum communication offers.

Academic and industrial work promoting standardisation and certification should be addressed at every stage.

Application goals

3 years: autonomous QKD systems over metropolitan distances will address low deployment costs, high secure key rates (> 10Mbps) and multiplexing (medium TRL). Certification and standards for quantum communication devices and systems will be established, as required by the security community, industry, ESA and government organisations (high TRL). QRNGs e.g. for use as components of cheap devices will be developed targeting high-volume markets (high TRL) or high-speed systems, including entropy source and application interface (medium TRL). QRNG and QKD devices and systems should address issues of practicality, compactness, high-rates, or include novel approaches that address security vulnerabilities or certification challenges. Preparatory actions for QKD beyond the direct communication distance limit (> 500km) will exploit trusted nodes or quantum repeaters, possibly integrated on high-altitude platforms

(HAPs) or satellites (low TRL). Quantum repeater and multipartite entanglement-based network building blocks (low TRL) will demonstrate (quantifiably) improved performance for core technologies: efficient and scalable quantum memories and interfaces; frequency conversion; teleportation; entanglement distillation; error correction; sources of single photons and entanglement, and detectors (medium TRL). Practical protocols and efficient algorithms for quantum networks, e.g. digital signatures, position based verification, secret sharing, oblivious data searching (medium TRL) will be developed. Solutions that use both classical and quantum primitives should be explored (medium TRL).

6 years: Targeted actions supporting QKD in test-bed networks, demonstrating long distances via trusted-nodes, HAPs or satellites, as well as multi-node or switchable intra-city networks, in conjunction with infrastructure projects (high TRL). Autonomous QKD systems suitable for low-cost volume manufacturing (high TRL) as well as systems targeting increased (> 100Mbps) secure key rates over metropolitan distances (medium TRL) will be sought. Quantum repeaters and entanglement-based networks beating direct communication distances (low TRL) will be demonstrated. Hardware and software for entanglement-based networks will be developed, including multipartite and device-independent-inspired protocols, with explicit and demonstrable assumptions about security, e.g. for QRNG as well as QKD over > 10km (medium TRL).

10 years: The final objectives include generalised use of autonomous QKD systems and networks (high TRL); device independent QRNG systems and QKD over metro-area distances (medium TRL); quantum cryptography over > 1000km (medium TRL); protocol demonstrations, e.g. cloud computing, on photonic networks connecting remote quantum devices or systems (low TRL).

Enabling tools

Enabling tools include: a) theory and software development of protocols and applications that build on, or go beyond, standard QRNG- and QKD-based primitives, as well as novel approaches for their certification, including methods to test and assess the performance of quantum networks; more efficient algorithms and security proofs targeting practical systems, including the combination of classical and quantum encryption techniques for holistic security solutions and expanding the potential application market. b) Engineering and control solutions that enable scaling and volume manufacturing, e.g. development of high-speed electronics and opto-electronics, including FPGA/ASIC, integrated photonics, development of dedicated fiber systems, packaging, compact cryo-systems and other key enabling technologies.

Education and training aspects are common across all domains, and are addressed globally in the Implementation Elements section below.

Types of projects (ramp-up phase)

Projects must clearly address the challenges for well-identified applications in quantum communication. Projects should identify current and targeted TRL levels in 3 years as well as a clear 6-10-year vision. It is envisaged that projects will include multidisciplinary teams addressing theory, experiment and technology development, as well as academic and industrial partners relevant to the targeted TRLs of the applications. For the challenge of quantum communication over > 500km, the projects should be of a preparatory action form aimed at defining the framework for large scale deployment. The number of partners and budget for any project should reflect the ambition and breadth of the targeted objectives.

Quantum Computing

The goal of quantum computing is to complement and outperform classical computers by solving some computational problems more quickly than the best known or the best achievable classical schemes. Current applications include factoring, machine learning, but more and more applications are being discovered. Research focuses both on quantum hardware and quantum software – on building and investigating universal quantum computers, and on operating them, once scaled up, in a fault-tolerant way.

Quantum Computing milestones

- ✔ **In 3 years**, fault tolerant routes will be demonstrated for making quantum processors with eventually more than 50 qubits
- ✔ **In 6 years**, quantum processor fitted with quantum error correction or robust qubits will be realized, outperforming physical qubits;
- ✔ **In 10 years**, quantum algorithms demonstrating quantum speed-up and outperforming classical computers will be operated.

Application goals

After **3 years**, the most promising quantum computing platforms and scale-up strategies will be identified after a review of the ability of runner-up platforms to prove their potential and overcome their current roadblocks. The leading platforms shall demonstrate an algorithm with quantum advantage or fault tolerance with >10 qubits, develop scale-up science as needed and map out a path to >50 qubits and beyond, including an architecture where unit cells can be scaled and mass manufactured either locally or connected through a quantum network. To get there, an advanced demonstrator will show the full technology chain from device to user such that properly instructed non-experts can try it (low TRL), including compilers and small-scale applications. The quantum software side will provide few-qubit applications and advanced tools to validate and verify quantum computation and processors, advance the theory of fault-tolerance and explore alternative computational models to inform architecture development. The viability of the primitives for distributed quantum computing, to form larger quantum computing clusters out of few qubit processors, will be tested in order to inform future platform choices.

After **6 years**, logical qubits are expected to outperform their constituent physical qubits by repetitive error correction, and infrastructure for hundreds of qubits will be developed. Quantum computer prototypes will be operated under human supervision and, if successful, deployed to data centres for first field tests (low-medium TRL). In parallel, algorithms and applications will be developed that make use of these larger systems.

After **10 years**, fault tolerant implementations of technologically relevant algorithms will be demonstrated in a scalable architecture, and will be ready to reach hundreds of qubits with the perspective for user-friendly quantum computers to be operated by staff at data centres (medium TRL).

Enabling tools

Enabling tools include a) quantum software and theory: verification and validation, more efficient error correcting codes and architectures, fault tolerance, discovery of new algorithms, compilers, architectures, resource optimisation, evaluation of non-circuit based computational models, connection to quantum simulation; b) engineering and control: further development of optimal control schemes and suitable hardware, materials, cryogenics, lasers, electronics including FPGAs and ASICs, microwave sources, detectors, low-level software.

Types of projects (ramp-up phase)

The leading quantum computing platforms (demonstrated algorithms with more than 5 qubits, high gate fidelities, no principal obstacles to scaling – low-medium TRL) are currently trapped ions and superconducting qubits. Industrial efforts also support spins and topological qubits in solid state. To reach year three goals, projects will integrate the efforts of several groups, include experimental and theoretical work as required and may explore the use of foundries and outsourcing. Projects will include experimental as well as theoretical studies, including development of quantum software/compiling/algorithms/control and efficient error correcting codes.

Leading quantum computing platforms should demonstrate quantum advantage or fault tolerance with more than 10 qubits, as well as the potential to scale systems to a useful size.[16]

Other promising platforms not meeting all the above criteria can be funded in smaller, focused projects. To be selected in the evaluation, they must show basic single-qubit operations and coherent qubit-qubit coupling, and the proposal must demonstrate more attractive scaling potential. These could be spins in solid state (e.g. electrons in quantum dots, defects and impurities), clusters and molecules, linear optics, neutral atoms, and topological quantum states. These focused projects will need to identify the main roadblock and show a focused effort to overcome them after three years.

Smaller targeted projects for clearly identified challenges shall also be possible.

Quantum Simulation

The goal of quantum simulation is to solve important quantum problems by mapping them onto controlled quantum systems in an analogue or digital way. Compared to computing where the aim is to have a fully fault-tolerant and universal quantum computer, simulations are more specialised and require neither fault-tolerance nor

[16] The term “quantum supremacy” is often used when referring to quantum devices outperforming classical devices, especially in the US quantum computing community. Throughout this report we prefer to use the term “quantum advantage”.

universality, hence allowing earlier and more efficient scaling through quantum software specialised and optimised for these simulators. Problems addressed by quantum simulators have initially been academic in nature but can now also lead to crucial technological applications, e.g. in ubiquitous optimization problems including routing and machine learning.

This goal is approached from two distinct ends: Starting from readily large controlled quantum systems based on *lattices*, atomic and otherwise, certain problems can be studied, including condensed-matter lattice models describing novel materials, quantum field theory, and quantum annealing which can address classically hard optimization problems of relevance, e.g., for neural networks and artificial intelligence. They are already at the verge of outperforming classical supercomputers and need to be brought closer to industrially relevant questions in fields such as image recognition and deep learning. Other simulators (based on specialised, non-fault-tolerant quantum *processors*) are also within reach, e.g. to develop better methods for problems motivated by chemistry and biology (electronic structure, reaction kinetics, energy conversion with applications for instance in catalysis and fertilizer development).

In contrast to quantum computing, where the quest for the “winning platform” is reasonable, different platforms of quantum simulations (superconducting qubits, atoms and molecules in optical lattices, trapped ions, atoms near nano-structures, arrays of cavity QED systems etc.) complement each other and need to be developed in a parallel manner.

Quantum Simulation milestones

- ✓ **In 3 years**, experimental devices with certified quantum advantage on the scale of more than 50 (processor) or 500 (lattices) individual coupled quantum systems;
- ✓ **In 6 years**, quantum advantage in solving important problems in science (e.g. quantum magnetism) and demonstration of quantum optimisation (e.g. via quantum annealing);
- ✓ **In 10 years**, prototype quantum simulators solving problems beyond supercomputer capability, including in quantum chemistry, the design of new materials, and optimisation problems such as in the context of artificial intelligence.

Application goals

After **3 years**, certified quantum advantage on the scale of more than 50 (processor) or 500 (lattices) individual quantum systems (corresponding to higher than 2^{50} or 2^{500} dimensions in Hilbert space, depending on the platform) will be reached for scientific simulation problems in lattices or arrays of localised sites, with adequate local control capabilities. A small-scale processor for other types of simulations will also be realised. Certification will be based on theoretical tools developed for this task and comparison to supercomputer calculations, likely based e.g. on tensor networks and quantum complexity theory. Both approaches will map out scaling strategies up to the goals of year ten. The breadth of applications for quantum simulators will be expanded and realistic approaches for simulation of quantum chemistry would be put forward (low TRL).

After **6 years**, quantum solutions will be demonstrated for a class of optimization problems on a programmable lattice and medium-scale non-lattice problems on the scale of hundreds or thousands of individual quantum systems, depending on the platform. Theory will continue to develop new applications and algorithms with quantum advantage (e.g. quantum learning theory), and address questions of error correction in simulation (low-medium TRL), as well as to benchmark simulators as compared to classical devices.

After **10 years**, materials-science based problems beyond supercomputer capability will use quantum simulators, non-lattice problems with more than 100 individual quantum systems will be simulated (medium TRL), and new optimization-related applications from outside the domain of physical sciences, for instance in artificial intelligence, will be run on these simulators.

Enabling tools

Enabling tools include: a) Theory: designing novel types of simulators and annealers, assessing the fundamental computational power of quantum simulation, certifying/error correcting simulations, finding new simulation paradigms, as well as development of classical and quantum software to validate quantum simulators, including quantum Monte Carlo, exact diagonalisation, tensor network methods and a variety of mean field and perturbation techniques. b) Engineering and control: improvement of techniques to site-address lattice-based simulators (in control and measurement), high-fidelity control and programming of interactions, minimisation and/or engineering of dissipation, as well as challenges similar to those of computing.

Types of projects (ramp-up phase)

Physical platforms that have shown either more than 50 interacting quantum units and/or full local control should be developed – likely optical lattices, Josephson arrays, quantum dot arrays, linear optical networks, and arrays of traps. These projects need to be closely integrated including theory support in development of protocols, validation schemes and control and classical simulation software well adapted to these goals. Proposals should aim at delivering operational demonstrators and a route, ranging from hardware control and software to complexity considerations, to outperforming classical computers should be outlined in proposals submitted to the ramp-up call. Physical platforms for these processor-type simulations are those proposed for quantum computing.

Similar to quantum computing, smaller targeted projects for clearly identified challenges shall also be possible.

Quantum Sensing and Metrology

Quantum sensing and metrology attempts to reach and overcome limits of classical sensing by means of suitable, often non-classical, states. Sensing beyond standard quantum limits (SQL) has been achieved in laboratory. Quantum sensing, not necessarily beyond SQL, is now seriously pursued in industry. The objective is the full commercial deployment of the *first generation* of quantum sensors and metrology devices exploiting coherent quantum systems. Low TRLs are targeted in the short term (3 years), medium TRLs in the medium term (6 years), up to high TRLs in the longer term (10 years). *Second generation* quantum sensors, based on entangled quantum systems, will be demonstrated at the end of the flagship (medium TRL).

Sensors will be developed using different platforms, including, but not limited to: photonics, warm and cold atomic sensors, trapped ion sensors, single-spin or ensembles of solid-state spins, electrons and superconducting flux quanta in solid state, optomechanical and opto-electromechanical sensors, as well as hybrid systems.

The activities in the Quantum Sensing and Metrology domain will lead to much improved existing applications and also new applications in the areas of medical diagnosis, material analysis, navigation, civil engineering, network synchronization, a faster internet, and metrology standards. The new quantum sensors also will be part of a quantum-enhanced Internet of Things. Quantum sensors are particularily interesting where all improvements of classical sensors have been exploited.

Quantum Sensing and Metrology milestones

- ✓ **In 3 years**, quantum sensors, imaging systems and quantum standards that employ single qubit coherence and outperform classical counterparts (resolution, stability) demonstrated in laboratory environment;
- ✓ **In 6 years**, integrated quantum sensors, imaging systems and metrology standards at the prototype level, with first commercial products brought to the market, as well as laboratory demonstrations of entanglement enhanced technologies in sensing;
- ✓ **In 10 years**, transition from prototypes to commercially available devices.

Application goals

3 years: Enhanced measurement and metrology of current, resistance, voltage and magnetic fields. Prototypes of integrated compact field sensors for e.g. chemical and materials analysis, medical diagnostics, labelling, trace element detection, enhanced imaging with very low light intensity. Sensors of gravity, gravity gradient and acceleration, e.g. for civil engineering and navigation. Optical clocks for timing and network synchronisation. Radio-frequency, microwave and optical signal processing for e.g. management of the frequency spectrum in communication applications. Improved optical sensing and imaging using entanglement, e.g. super resolution microscopy beyond the current limits with minimum exposure. (The application of optical clocks should target medium TRL levels up to technical validation in relevant environment, all other applications should demonstrate low TRL levels up to experimental proof of concept.)

6 years: Inertial sensors and clocks (microwave and optical) will be available as compact, autonomous, field-usable systems (medium TRL). Sensor networks for earth monitoring and tests of fundamental physics will be available (low to medium TRL). Optical interferometers, e.g. for gravitational wave detection, will operate with optimised squeezed states (low TRL, experimental proof of concept). Compact, integrated solid-state sensors will address applications such as healthcare or indoor navigation (low to medium TRL). Spin-based sensors and entanglement-based sensors will address e.g. life-science, including Nuclear Magnetic Resonance (NMR) down to single molecule, Electron Paramagnetic Resonance, hyper-polarised NMR and Magnetic Resonance Imaging (low TRL). Optomechanical sensors will allow developing force sensing, inertial positioning devices, microwave-to-optical converters (low TRL). Sensors based on electrons and flux quanta in solid state devices will allow shot-noise-free ultra-sensitive electrical measurements and hybrid integration of different quantum devices (low to medium TRL).

10 years: Commercial sensors and large-scale sensor networks, including the required infrastructure such as a European frequency transfer network, (up to demonstration in operational environment, high TRL) will provide earth monitoring beyond the capabilities of classical systems and improve bounds on physics beyond the Standard Model. Solid-state and atomic sensors will allow development of commercial biosensors and universal electrical quantum standards (up to high TRL). Sensors employing entanglement will outperform the best devices based on uncorrelated quantum systems (medium TRL).

Enabling tools

Enabling tools include a) Theory and Software**:** multiparameter estimation algorithms in the presence of noise, precise understanding of quantum advantage in specific implementations of quantum metrology, optimised exploitation of entanglement, fundamental theory of usefulness of mixed quantum states and imperfect quantum operations for metrology, design of novel precision measurement and sensing schemes, design of novel tests of fundament physics; b) Engineering and Control: synthesis and growth of materials, single atom doping techniques, fabrication and integration, photonic platforms, compact microwave sources, nano-mechanical devices, advanced NMR and coherent control techniques.

Types of projects (ramp-up phase)

The projects should address the above challenges, with adequate TRL and timing, as well as the long-term vision. Possible technological or scientific roadblocks for the different platforms should be identified early on to be addressed in the next phase. All projects should clearly identify which aspect(s) of already available sensors, such as temporal/spectral/spatial resolution, sensitivity, accuracy, compactness or field deployability will be improved. Projects are encouraged to include industry and academic partners from theory, experiment, and engineering in a well-balanced interdisciplinary team. Small projects are possible as well as larger projects when integration of competences are necessary or if big infrastructures are concerned.

Basic Science

For the success of the four application domains, the development of new scientific tools and concepts must be kept active and running. In fact, while some quantum technologies have reached a significant level of maturity and are ready for the transition to industry applications, it is crucial to pursue the study of open scientific questions – both experimental and theoretical – in order to develop more applications, and to ensure flexibility in the evolution of the flagship. This will require the combined competencies of quantum and classical arenas to develop the tools, components, materials, processes that will enable the mission-driven objectives to be realised. This process is expected to work both ways: new science provides new ideas for quantum technologies, but also developing quantum technologies stimulate new questions to be answered by new science.

This effort will be organised along a transverse domain of Basic Science, which will be broad and ambitious in its spirit and its goals, and will generically concern several if not all domains. As a consequence, it would be impossible to give a prescriptive and exhaustive list of topics. Rather, this domain should be left open to any topic of basic quantum science, possibly including research on the societal impacts and ethic components of QT. The following are a few examples of research directions and goals among those that can be addressed.

Quantum Information Science

Its aim is to identify and experimentally explore the laws and the ultimate limits governing any information process based on quantum effects as well as to develop feasible protocols. This includes for instance instrumental theories and methods to understand the resources needed for quantum information processing tasks, such as number of qubits, entanglement, coherence, various aspects of secrecy and quantum cryptography, randomness, or channel capacities, and quantum measurement, and how to use them for the construction of algorithms and protocols. It also includes applications of QI concepts to other fields: quantum chemistry, biology, high-energy physics, quantum thermodynamics, mathematics and computer science.

Quantum Foundations

The main objective is to understand what makes quantum theory special and how it differs from classical physics, and it involves both theoretical and experimental developments. It is a powerful force to push technology forward, as it has been demonstrated by the recent “loophole-free” tests of Bell’s inequalities, which can also be seen as the best-so-far sharing of high quality entanglement between remote sites. Examples of research goals for the next years are no-go theorems for classical systems with experimental demonstrations, verification and testing of quantum systems, novel forms of causality in quantum physics and relativistic quantum information, or high precision measurements for exploring the limits of quantum mechanics.

Open Quantum Systems and Decoherence

The general objective is to understand the mechanism for decoherence and to devise methods that achieve a given task in the best possible way, in the presence of experimental imperfections and potentially detrimental effects of the surroundings. For this purpose, theoretical, numerical and experimental investigation of open-system dynamics and studies of the quantum-to-classical transition and quantum effects in macroscopic systems need to be conducted in many different platforms. As an outcome, practical methods to fight decoherence (error correction, dynamical decoupling, reservoir engineering, quantum control) need to be developed.

Types of funding instruments (ramp-up phase)

This transverse domain does not call for large heavily funded collaborations, but rather for small focused projects, fulfilling SMART criteria and goals (i.e. being Specific, Measurable, Achievable, Relevant, and Time-bound) relevant for the long-term vision of the QT Flagship. However, it might be also possible to envision larger, less focused networks with moderate funding, mostly in relation with clearly defined research and training objectives.

6 Implementation

Implementation of the QT Flagship will significantly differ from the two previous Flagship projects, as the QT Flagship will not have a single core consortium, but will be run as a set of individual but closely connected research projects all addressing the Strategic Research Agenda. The projects funded by the EC will be selected through a Europe-wide peer-reviewed call for proposals. Non-research/innovation actions, such as outreach, education or alignment with national QT initiatives, will be coordinated and to some degree implemented by a Coordination and Support Action (CSA).

The EC-funded Flagship activities of the ramp-up phase (first three years) must adhere to the H2020 rules for participation and calls for proposals and those of the steady-state phase to the FP9 ones. In the following, we include some recommendations whose future implementation will depend on the relevant FP9 rules.

Guiding principles

The HLSC suggests the following guiding principles for the implementation of the QT Flagship initiative.

HOW? In order to combine and coordinate the strengths of Europe in QT, the Flagship should operate in a way that is:

- inclusive but rooted in excellence and potential impact on European society
- efficient and effective in delivering the promised results
- flexible in the implementation, allowing the initiative to focus and adapt to the evolution of the field
- open to involving emerging actors, attracting and retaining the best talents also from other fields
- transparent in the development process for each aspect of the Flagship
- closely connected with the existing and planned national and transnational QT programmes (including QuantERA) and taking the corresponding programmes

in other parts of the world (e.g. the USA, Canada, China, Australia and Japan) into consideration
- providing equal opportunities for all qualified teams in Europe to contribute
- accountable to the community, Member States and the wider society
- creating an easily accessible and lean way to stimulate exchange between universities and companies, and helping universities to spin off start-up companies
- incorporating the lessons learned from the two existing FET Flagship initiatives

WHAT? The Flagship should fund projects and activities that:

- have strong perspectives for application and engineering focus and aim at societal impact and commercial exploitation
- have demanding but achievable goals, measurable key performance indicators (KPIs) and intermediate milestones
- include proof-of-principle and/or demonstrators among the goals of the high TRL milestones already in the ramp-up phase
- support the development of a complete research and innovation value chain, spanning from academia to industry (both large companies and SMEs), enabling the transfer of preliminary concepts to products, through increasing levels of engineering and prototyping
- should also include high-risk/high-reward research and developments and conduct advanced research into basic science and the exploration of new concepts and systems
- reinforce the European strengths in QT at the global level
- facilitate the creation of a new generation of quantum scientists, engineers, entrepreneurs and related job positions in Europe
- garner broad support from society for QT research, ensuring the awareness and acceptance of QT-based applications

WHO? We recommend that the consortia that will lead the selected projects:

- include excellent academic, SME and industrial partners, but can allocate a limited part of the budget for inclusion of associated groups outside of the initial consortia, to flexibly include emerging players
- focus on impact and strategic benefit for Europe in the global race for QT leadership
- have the ambition to grow in investment volume, exploit results and invest in their research beyond the duration of their projects
- are allowed to also include non-European companies. Such companies should only be funded if (a) they are investing in research in Europe and producing revenue in Europe as a result of their investment and (b) their participation is deemed essential for carrying out the action (e.g. due to outstanding competence/expertise, access to research infrastructure or data). However, some IP restrictions should apply (see below). International collaboration is essential to maintain European competitiveness in quantum research. The Flagship should establish a continuous dialogue with leading research centres and companies from third countries that could eventually join cofunding schemes.

Implementation model

Preparatory measures preceding the start of the Flagship

Due to very strong international competition, it is highly recommended to start timely preparatory actions already before the launch of the first Flagship-funded projects in 2019.

- Member States are expected to start the national support of QT projects as early as possible, preferably already in 2017/18, and undertake joint investments for infrastructure development of user facilities open to the European QT community
- The newly established ERANet QuantERA should be encouraged to take a role in facilitating the coordination of national resources in the above directions
- The national metrology institutes, organised in EURAMET, already have strong expertise in QT and should be encouraged to put a focus on next-generation QT in sensing and metrology
- The European Space Agency should be encouraged to take up an active role on space applications of quantum communication, sensing and metrology
- The HLSC urges the EC, Member States and Associated Countries to stimulate the development of breakthrough technologies in Europe through procurement (with resources from sectors outside the Flagship). An example could be funding the implementation of a QKD testbed, followed by the procurement of a QKD backbone.

Calls for research and innovation projects

The largest part of the available funding of the Flagship should be used to fund ambitious and at the same time focused and coherent research and innovation projects.

Strategic steering of Flagship focus

The strategic steering of the Flagship should be done i.e. by formulating work programmes. The work programmes and calls should be published by the EC, based on a clear and explicit Strategic Research Agenda (which should be updated regularly based on advice by the Steering Board) as well as the status of the ongoing funded projects.

We recommend to structure the calls along the five domains of the QT Flagship as described in the SRA. The balance among the domains should take the different needs for strategic development and cost-intensity into account, which will be reflected in different budgets for each domain. We also recommend that consortia will be required to define both project objectives and long-term goals (beyond the scope of the proposal). On this basis, and with additional input from the research community, the SRA can be updated regularly.

We recommend to require the presence of academic and industrial partners in projects within the application domains.

In the steady-state phase, the number of projects should be reduced via a strategic orientation of calls. Initial consortia can be modified, reorganised or dissolved. They could evolve into possibly larger, more focused consortia around the most promising and successful routes, from demonstrators to products. Such an evolution can be domain-dependent, as each domain has different maturity levels and its own set of timescales. At the same time, throughout the lifetime of the Flagship, there should be open calls to maintain openness to the exploration of challenging new ideas, concepts and flexibility to incorporate these into the SRA.

Regardless of how it will be organized, as a matter of principle, particularly early-stage researchers and SMEs should be explicitly encouraged to submit proposals. This would allow their development and integration into the community, and later into strategic projects, should they be successful. TRL advances and exploitation towards commercialisation should always be among the main goals of proposals addressing the four application domains.

Inclusiveness is a major goal of the QT Flagship. We therefore encourage the research community to include excellent small groups and excellent groups from smaller countries in their consortia.

Ramp-up timeline

Building on the solid basis prepared over the past several years, and to avoid further delay in combatting international competition, the Flagship should already start in its first year with full operational funding.

We suggest the following ramp-up timeline for the QT Flagship:

- Fall 2017: announcement of the first calls for proposals by the EC upon advice from the HLSC. Consortia with various focuses and goals assemble and prepare their proposals
- Spring 2018: deadline for submission of first-stage short proposals, if 2-step proposal process is chosen (see below)
- Summer 2018: deadline for submission of final proposals
- Late 2018: evaluation of proposals
- Early 2019: start of projects with actual Flagship financing

Evaluation and review process outline

We suggest to base the evaluation process for proposals on panels for each of the domains with representatives from both academia and industry. The final funding recommendations on consortium partners could be made via a two-step procedure. From the short proposals submitted in a first-stage evaluation, the review panels could select a smaller number for invitation to full proposal submission, corresponding to a success rate of at least 30% in the second stage. Evaluation criteria should follow the WHAT and WHO guiding principles outlined at the beginning of this section.

Ongoing projects should be regularly reviewed by clear milestones, but administrative overhead should be kept at a minimum (lean submission forms, work packages self-assessment, light reporting structure etc.).

The ramp-up phase is expected to provide the opportunity of developing coordination and cooperation between academia and industry and to develop SMEs in order to have projects fully operational in the steady-state phase.

Collaborations with international corporations and other institutes

The core principle of the QT Flagship has to be the focus on developing innovation, creating value and wealth and exploiting results in Europe. However, the QT research community is internationally connected and several of the major industrial QT players are non-European. This leads to the question to what degree international cooperation with non-European partners should be foreseen within the Flagship.

We recommend that international cooperation on the scientific level should be stimulated according to the standard H2020/FP9 rules, but cooperation with companies should be subject to restrictions. In particular, for companies with headquarters outside of the European Union or Associated Countries only R&D departments that are located within the EU wil be funded by the flagship and Associated Countries and only if they agree not to transfer intellectual property rights outside the EU (see also the next paragraph).

Intellectual Property Rights (IPR)

Generally, the underlying IPR guidelines for R&I activities are defined by the EC and recorded in grant agreements. This includes the obligation to define the pre-existing IP, knowhow, knowledge or any additional data that is "needed for carrying out the project"[17] (the so-called "background") that the consortia members will bring to the project by creating a positive list. Furthermore, consortia should assess and agree on what "needed" in this regard means, and make sure that any information needed for the smooth running of the project is accessible to all project partners.

In principle, project results belong to the partner who generated them. Yet, given the nature of collaborative projects it is possible that several partners will be involved in fostering project results. In this case "joint ownership" of results may arise. Consortia should determine certain provisions, including those for a potential transfer of ownership, in the consortia agreement or in a separate joint ownership agreement. We recommend that joint ownership is proposed to be transferred to the involved industrial partner for exploitation, with a non-exclusive, royalty-free right of use and a fair and reasonable compensation for the other partners owning the IP.

The sensibility and feasibility of generating and protecting a joint patent pool for the European research community and industry should be evaluated, considering also the industry's strong interest to keep the IP resulting from their own efforts. European companies should always reserve the "right of first refusal" and "right of first use" for all IP generated within the QT Flagship.

Member States alignment

Several Member States (e.g. UK, Netherlands, Germany, Austria, France, Italy, Denmark) have already launched or are planning to launch a national QT initiative. We strongly support this and urge all other MSs to also enhance their engagement in QT. Strong national commitment to QT is important and will send a clear signal. There is a broadly recognized need for aligning national programmes' strategies and activities and those of the Flagship with each other. To achieve this, a periodic review of the Flagship's

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[17] European Commission: Guide to Intellectual Property Rules for FP7 projects. Version 3. http://ec.europa.eu/research/participants/data/ref/fp7/89593/ipr_en.pdf

SRA is necessary, as is maintaining an intense dialogue between the QT Flagship's Steering Board and the national programme responsibles. Small countries should be able to profit from inclusion in the strategic alignment of programmes and the coordination of supporting activities, such as outreach.

In case of transnational initiatives, such as QuantERA, the projects should be synchronized with the undertakings of the QT Flagship by including them in the cross-project coordination activities (see SEB in the governance section).

All application domains need high-level research infrastructure and we would strongly recommend the Flagship R&I projects to make use of infrastructure projects funded through other EC and MS instruments. On the other hand, we urge those infrastructure projects to be open to Flagship projects, in particular to grant access to:

- (micro- and nano-) fabrication facilities for materials and devices
- critical materials such as isotopically purified elements, compounds and Helium
- communication testbed environments
- supercomputing infrastructure for theoretical efforts

This openness will foster exchange of knowledge and will be of mutual benefit for both sides.

Education and Training

QT is at the intersection of physics, engineering, computer science and related fields of study. Training successful "quantum engineers" and more generally a quantum-aware workforce should be a central objective of the QT Flagship initiative.

The possibility to nominate an "education & outreach officer" should be considered, to coordinate a focus group on education with both representatives from the funded projects and the community. This focus group should aim to influence teaching curricula of physics, engineering and information science departments at European universities, but also the curricula of schools, supporting the creation and distribution of teaching material.

We recommend QT training programmes, funded by the RIAs and based on PhD and postdocs' excellence (no mobility requirements) including secondment to industry and/or research groups. A visitor programme for researchers from groups not formally part of Flagship-funded consortia is also recommended to enable them to work in leading European QT groups.

Further measures

To ensure that all goals of the QT Flagship are addressed adequately, additionally to the calls for research and innovation projects, a variety of further measures are recommended, to be coordinated by the CSA.

- Strive to create market growth and transparency, and match technology offers with market demands, such as academia-industry workshops, application market studies, a pan-European conference/trade show, networking of quantum industry groups and associations

- Support the large number of European SMEs for adoption of QT, and consolidation through private European investment funds
- The Flagship could establish a “Quantum Grand Challenge”. This initiative could award cash prizes to the winners of competitions in the four application areas. This prize would encourage wider regional participation from individuals, teams and organizations from various backgrounds and communities
- Effective outreach activities for reaching the wider public (such as a web portal, presence in social media, exhibitions for the wider public for example in science museums, public events and conferences, pro-active use of news on all available communication channels) are recommended to ensure broad support from society for research in QT and increase acceptance of QT-based applications
- A continuous consultative forum should be provided for the QT community to gather input for the SRA, but also to collect feedback on the Implementation and Governance as perceived from outside the QT Flagship
- The Flagship should work closely with metrology institutes (organised in EURAMET) and European and international organizations for standardisation (e.g. CEN-CENELEC and ETSI) to drive the standardisation of QT
- The Flagship should liaise with the European Space Agency to develop appropriate plans and actions for the deployment of QT in space, especially in the fields of communication and sensing

Key Performance Indicators

We recommend monitoring the Flagship’s progress by regularly evaluating a set of key performance indicators (KPIs). These KPIs have to include a mix of qualitative and quantitative options, differentiating between the evaluation of the overall success and the performance of particular domains/projects.

For each funded research and innovation activity, there will be project-specific milestones and KPIs defined - a well-established component of H2020 project evaluations. These should be both on a technical level, highlighting world-first achievements and records, and on a formal/management level (e.g. number of papers published). The latter should be uniform for all Flagship activities to enable aggregation.

Examples for technical KPIs include:

Quantum Communication

- Maximum distance for a ground quantum communication line with at least a certain qbits/sec rate
- Maximum transmission rate for quantum communication to a stationary satellite

Quantum Computing

- Number of qbits in a quantum processor
- Number of qbits with quantum error correction in a quantum processor
- Quantum speed-up in a quantum computer

Quantum Simulation

- Number of lattices or processors in a quantum simulator
- Number of problems solved beyond supercomputer capability

Quantum Sensing and Metrology

- Number of commercial quantum sensors
- Number of commercial quantum gravimeters

Operation and manufacturing

- Constraints in space: best miniaturization achievable, e. g. number of qubits in a standard 19” rack
- Mean time between maintenance (MTBM) (considering system preparation as a maintenance)
- Production scaling capability
- Usage of existing industrial processes vs need to invent new processes (and their costs)

For qualitative KPIs, we recommend to collect success stories of technical and socio-economic achievements made possible by the QT Flagship. Additionally, we recommend quantitative compound KPIs for the QT Flagship as a whole to evaluate how well it is fulfilling its strategic goals. A report on these KPIs, as well as the aggregated project-specific KPIs should be compiled annually by the central support unit of the initiative.

The recommended quantitative compound KPIs are:

Strategic goal	KPI
Foster collaboration	Number of co-written publications between (a) different partners participaging in one or more Flagship funded projects and (b) academia and industry
	Number of new collaborations, stimulated through FS activities, leading to joint projects/publications/patents/funding
	Funding from MS leveraged, compared to funding from EC
Stimulate innovation	Funding from industry / venture capital raised, compared to public funding
	Number of patents filed
	Number of demonstrators (TRL 4) and prototypes (TRL 6) built
	Number of spin-offs founded + those surviving the first 5 years
Ensure scientific excellence	Number of papers published in peer-reviewed journals and citations therof
Train quantum aware workforce	Number of PhDs and master students graduated, funded by Flagship
Outreach	Number of positive articles/mentioning in public media
Gender diversity	Number of females in management / WP leaders / PhD students / …

At the current stage it is hard to estimate targets for most of these KPIs, as they depend on the number and size of the funded projects and partly also on the achievement of some technical milestones which are crucial for the success of some innovation fields. We recommend that targets for the KPIs are developed in the first year of the ramp-up phase. Also, they might be adjusted and expanded to have a (sub-)set of KPIs that is common to all Flagships in order to compare them better with each other.

7 Governance

As already noted in the Implementation section, before detailing the proposed Governance model, it is important to accentuate that there is a paradigm shift in the collaboration model of the QT Flagship. There will be no core consortium implementing the QT Flagship (as is the case of the other two running Flagships, Graphene and the Human Brain Project). Instead the QT Flagship will be implemented by a limited number of projects that will contribute to the SRA. These projects will be selected via peer-reviewed calls for proposals, published by the EC. These projects will then be asked to closely coordinate their activities and collaborate on R&I tasks (especially when they cover related research areas). Additionally, all projects will be required to contribute to jointly agreed cross-project activities as outlined in the previous section.

The Governance of the QT Flagship needs to ensure:

- Definition and update of an overall strategy to have the broadest possible societal impact of the initiative as a whole
- Strategic, well coordinated advice to the EC, which will implement the Flagship through peer-reviewed calls for proposals and potentially other measures in the steady-state phase
- A simple and efficient organizational structure differentiating between funding agencies vs. the EC part of the QT Flagship inititative
- Effective and efficient coordination and cooperation between the projects of the QT Flagship
- Transparency of operational and decision-making processes and open feedback channels for the QT community to contribute to the strategy definition process
- Close alignment of the Flagship's strategy with national QT programmes
- Effective implementation of further measures, not covered by R&I calls (outreach, market evaluation, driving of standardization and norms etc.)

Overview

The governance should be as effective and compact as possible on all levels, from stakeholder representation to the scientific, advisory, supervisory and executive bodies, including efficient feedback loops. Decisions should be taken at the lowest possible level to have short control cycles. The QT Flagship Governance model should include three decision-making levels:

- **Operational level:**

(i) RIAs: Every-day decisions required to coordinate within a RIA and to reach project milestones are to be taken within the funded QT Flagship projects.

(ii) CSA action and FCO: Every-day decisions regarding outreach, education, innovation and community involvement activities should be taken by the Flagship Coordination Office (FCO) of the CSA action

- **Coordination level:**

(i) RIAs: Discussions for coordination between different RIAs funded by the QT Flagship including decision making e.g. for joint development of common technologies or joint use of infrastructures is to be done by the SEB.

(ii) The FCO should monitor the alignment of national QT initiatives with the QT Flagship, gather input for updating the Strategic Research Agenda and do an overall coordination of outreach, education, innovation and community involvement activities. For the success of the Flagship, a consensus has to be reached whenever possible between SEB and FCO before liaising with the SB.

- **Strategic level:**

(i) Advice for strategic decision-making, with long-term impact across the whole initiative (e.g. focus areas for R&I) is to be provided by the Steering Board (SB). Such advice is made available to the EC and to the BoF, which are the ultimate decision-making bodies of the QT Flagship.

[Optional] The SB members could be further advised by an (international) Scientific Advisory Board (SAB), made up by few highly esteemed quantum scientists (e.g. Nobel laureates) and industrialsts (e.g. company CEOs / CTOs).

The Governance model should be reviewed after the ramp-up phase by the SB, EC and the BoF and changes possibly be made to provide a leaner structure by further streamlining processes. Measures to deal with conflict of interest, as well as accountabilities and overlapping functions need to be established. The EC will also hold an independent interim assessment of the QT Flagship, in due time.

An overview of the proposed governance structure is presented in the following figure.

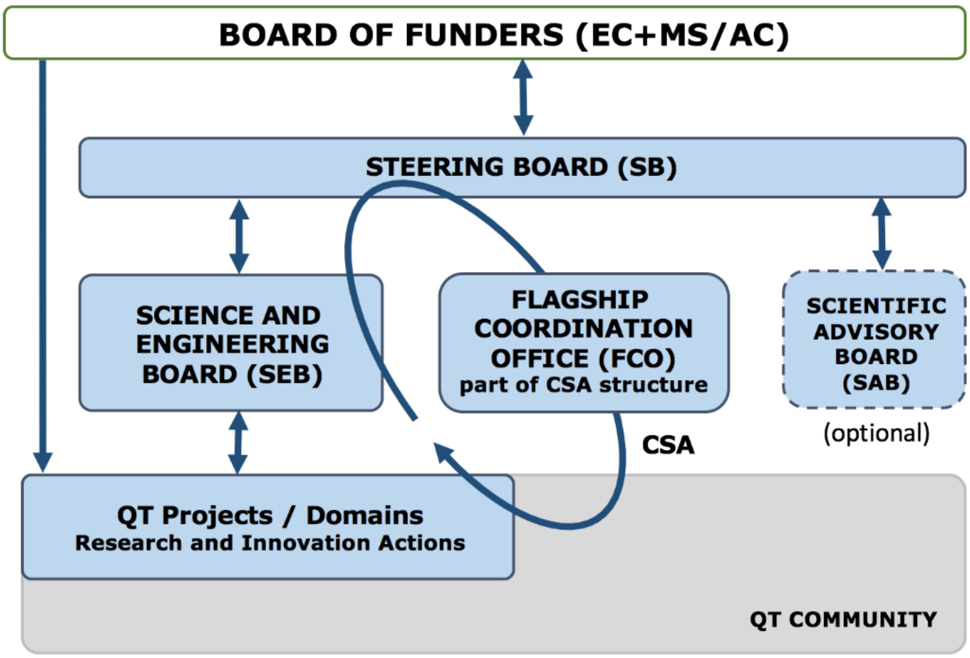

Figure: Overview of the governance structure

Governance bodies

In the following, we describe the role and responsibilities of each governance body.

Board of Funders

The Board of Funders (BoF) is a well-established governance body for all Flagships. It brings together the main funders of the Flagship initiatives, namely representatives from the Member States and Associated Countries of Horizon 2020 and the EC with the purpose of programming activities in support of the Flagships. The main role of the BoF is to discuss and possibly plan the financial support to the Flagships for their whole duration.

We recommend to establish a QT Working Group within the BoF that consists of BoF members with competence and/or interest in QT. This group could meet more frequently than the BoF and prepare the BoF sessions with specific discussions on QT matters. In addition it would help spreading information about the QT Flagship within the MS/AC governments, as well as provide information about QT Flagship relevant government initiatives in each country.

We recommend to also include representatives of QuantERA in this working group and in the BoF in general.

Steering Board

The Steering Board (SB) should be accountable for preparing and updating the Strategic Research Agenda based on the input received from the SEB and the FCO. It should monitor the Flagships's progress towards both its research and innovation goals and its non-technical goals, such as education and outreach. For this, it should propose KPIs for the Flagship's output and impact and regularly evaluate them. The SB should regularly report to the BoF and recommend actions to close the identified gaps.

The SB should have around 20 members, including its chair and one or more vice-chairs, who should be appointed by the EC. The members should come from academia, industry and RTOs with an equal share of academia and industry representatives. It should meet between two and four times per year, as needed, and may decide to define working groups who could meet more often, as deemed necessary.

To fulfil its tasks, the SB needs to interact closely with both the SEB and the FCO. The chair of the SEB and the FCO Director should therefore be permanent invitees without voting rights. Logistical support should be provided by the FCO staff.

Measures to deal with conflicts of interst (CoI) need to be established. To ensure maximum transparency, the best option would be that SB members leave the SB if their research group is directly awarded Flagship funding. Since the number of QT industry and SMEs is limited, care should however be taken not to shift the balance towards academia by such rules.

Science and Engineering Board

The Science and Engineering Board (SEB) is responsible for overseeing the implementation progress of the Flagship's work plan and ensure the coordination of the research and innovation activities between the different EU-funded projects and between the Flagship domains. In particular, it should identify and coordinate cooperation between the funded consortia, for example for jointly developing technologies or sharing infrastructure. It should advise the SB with focus on the running projects and propose changes to the SRA taking into account scientific and technological advances or roadblocks encountered in the funded projects.

The SEB should report to the SB and to the EC and the BoF on the overall performance and progress of the Flagship projects. For this, it will be supported by the FCO to gather and compile all relevant information.

The SEB will be composed of the project coordinators of all EU-funded Flagship projects and representatives of the QuantERA projects, selected by the QuantERA project coordinators among themselves.

We recommend that the SEB members elect a chair and seven representatives among themselves for the five Flagship domains and the two cross-cutting topics Engineering/Control and Software/Theory. To the extent possible, an equal representation from academia and industry should be sought. The SEB will meet as frequently as required (ideally, bi-monthly). We recommend that the FCO Director will be permanently invited to these meetings to ensure close alignment.

The Coordination Support Action and its Flagship Coordination Office

The Coordination Support Action (CSA) and its Flagship Coordination Office (FCO), led by an FCO Director, will have the role to coordinate the QT Flagship activities that are not part of the RIA projects. In particular, it should act as an intermediary among governance bodies, community, national initiatives and QT-relevant trade associations and strive to reach consensus between them on the relevant aspects concerning future developments of the Flagship, to ensure a strong common vision supporting the way forward for the whole initiative. It will also ensure promotion, dissemination and outreach for the QT Flagship, for example by running a web portal, ensuring the QT Flagship presence in the social media, organizing conferences, workshops, concertation events, etc. The FCO will coordinate the education and training efforts of the Flagship and link them to education initiatives of the QT community. It will also facilitate QT standardisation.

The CSA action and its FCO will also support the SEB and SB in their work by providing data and analysis. For this, it will gather KPIs, project outcomes and results, and channel feedback from the QT community, especially on the SRA. They will also support the SB logistically. Finally, they will propose relevant benchmarks to consider for the RIAs of the QT Flagship by considering those of other existing quantum research initiatives, at national or international level.

The FCO should be managed by a team of well-connected senior members of the QT community. We foresee the team to be lead by an FCO Director, who will dedicate most of his time to the Flagship. Arrangements will be made to avoid possible conflicts of interest. The FCO should be supported by a staff of full-time employees, ideally with experience in research, industry, project management and communication. We estimate that in the ramp-up phase, a staff of ten full-time employees is required, which could become larger in the steady-state phase. The SEB and the FCO should be very closely aligned and try to seek consensus before interacting with the SB. For this, meetings will need to be organized between the FCO and the SEB. A constant flow of information and discussion between the two bodies is highly recommended.

Scientific Advisory Board (optional)

The Scientific Advisory Board (SAB) could be set up with the aim of providing independent scientific advice to the SB, especially in areas where the SB may lack expertise. Another important role of the SAB is to bring an international perspective into the QT Flagship.

The SAB could be composed of up to ten international, highly respected QT experts, e.g. Nobel laureates, directors of other large-scale QT initiatives and industry CEOs/CTOs. They must not have any involvement in Flagship funded projects to avoid conflicts of interest. They could meet at least annually with the SB, and on request by the SB possibly more often.

8 Conclusions and Outlook

The QT Flagship initiative has the ambitious goals to unlock the full potential of quantum technologies, accelerate their development and ensure that Europe will be among the first to bring commercial products to the market, by consolidating and expanding European scientific leadership and excellence in quantum research, by kick-starting a competitive European quantum industry, and by making Europe a dynamic and attractive region for innovative business and investments.

The Strategic Research Agenda for the domains outlined in this document is based on a comprehensive QT roadmap which has been developed over the last decade and has been adapted to the Flagship's goals. It is proposed to be structured around four vertical domains representing the application areas in the field: Communication, Computation, Simulation, as well as Sensing and Metrology. These vertical domains are rooted in the horizontal domain of Basic Science, and address enabling aspects in Engineering and Control, Software and Theory, as well as Education and Training.

The Implementation model and the Governance structure are designed to translate this strategy in the most effective and efficient way, while keeping the QT Flagship open to new ideas and participants. Though we believe that we have addressed all relevant implementation issues, many details will be determined only during the actual ramp-up phase. A call for a Coordinating and Support Action with the aim of putting the HLSC recommendations into practice has been already published by the EC. The first call for research and innovation actions will have been launched as part of the H2020 Working Programme 2018/19 at the time this document is officially handed over. Also, the successor programme FP9 is still in the making and might set new cornerstones for the Implementation and Governance of the QT Flagship, which should be carefully reviewed at the end of the ramp-up phase.

The Final Report is a comprehensive blueprint on how to combine and coordinate the strengths of Europe to stay at the helm of the global race for new scientific horizons. It synthesizes effectiveness, transparency and inclusiveness for realizing ambitious research and innovation projects with highest impact. Much as the spirit of the HLSC, we believe that the cooperation coming to life in the flagship framework will exert decisive influence on the future of quantum technologies.

Appendix I: HLSC members

Chairman

Prof. Dr. Jürgen Mlynek
Humboldt University of Berlin

Academic members

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University of Innsbruck

Prof. Dr. Vladimir Bužek
Slovak Academy of Sciences, Bratislava

Prof. Dr. Tommaso Calarco
University of Ulm

Prof. Dr. Per Delsing
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Prof. Dr. Marek Kuś
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Prof. Dr. Eugene Simon Polzik
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Dr. Michael Bolle
Robert Bosch GmbH

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Observer

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Appendix II: Index of abbreviations

AC	Associated Countries of The European Union
ASIC	Application Specific Integrated Circuit
BoF	Board of Funders
CSA	Coordination and Support Action
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CoI	Conflict of Interests
EC	European Commission
ERA	European Research Area
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EU	European Union
EURAMET	European Association of National Metrology Institutes
FCO	Flagship Coordination Office
FET	Future and Emerging Technologies
FP9	Research, Technological Development and Demonstration Framework Programme of the European Union for 2021-2027
FPGA	Field Programmable Gate Array
H2020	Horizon 2020 European Framework Programme for R&I
HAP	High-Altitude Platform
HLSC	High-Level Steering Committee - Commission Expert Group on QT
KPI	Key Performance Indicator
MS	Member States of the European Union
NMR	Nuclear Magnetic Resonance
R&D	Research and Development
R&I	Research and Innovation
RIA	Research and Innovation Action
RTO	Research Technology Organisation
QED	Quantum Electrodynamics
QKD	Quantum Key Distribution
QRNG	Quantum Random Number Generator
QT	Quantum Technology
SAB	Scientific Advisory Board
SB	Stakeholder Board
SEB	Science and Engineering Board
SMART	Specific, Measurable, Achievable, Relevant and Time-Bound
SQL	Standard Quantum Limit
SRA	Strategic Research Agenda
TRL	Technology Readiness Level
WP	Work Programme of the European Commission