Quantum Technologies Flagship Intermediate Report

High-Level Steering Committee
16 February 2017

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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 aims to place Europe at the forefront of the second quantum revolution now unfolding worldwide, bringing transformative advances to science, industry 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 Quantum Technologies will help create a lucrative knowledge-based industry, leading 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 Flagship, the European Commission appointed an independent High-Level Steering Committee (HLSC) consisting of 12 distinguished Academic Members and 12 high-ranking Industry Members, 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 Intermediate Report addresses point (1) and gives options for the discussion of point (2), whereas point (3) will be determined once the implementation model is consolidated following discussions with the European Commission and Member States. The report serves three main purposes: It is an internal guideline in assembling the upcoming H2020 Work Program, a compass meant to inform decision makers and gather their support, and the foundation for future planning through the Strategic Research Agenda, once the Work Program is published.

The Strategic Research Agenda proposed in this document sets the ambitious but achievable goals for the Flagship's ten years' 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 top of 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 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 levels, regional, national and international.

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. 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. Indeed, the largest part of the available QT funding should go to ambitious and at the same time focused and coherent Research and Innovation Projects, selected through a peer-reviewed call for proposals based on the Research Agenda described here, and strategically interconnected by a comprehensive Coordination and Support Action. Training successful "quantum engineers" and more in general a quantum-aware workforce should also be a central objective of the QT program; in addition, further measures are recommended to create better market transparency, to stimulate and support quantum start-ups and to reach out to the public, to stimulate awareness about quantum technologies' opportunities.

2 Context

Currently Europe is at the leading edge in quantum technologies 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 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 Commission 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 European Commission 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 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 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 European Commission appointed an independent High-Level Steering Committee (HLSC) in two steps, announcing the Academic Members in August 2016[4] and the Industry Members in October 2016[5].

[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

[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

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 Future and Emerging Technologies (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.

This Intermediate Report addresses points (1) and (2); point (3) will be detailed in the Final Report.

Since its founding, the HLSC has held two meetings. On 20 September 2016 in Brussels[8], the Committee discussed the core principles of the Strategic Research Agenda, as well as 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. The subsequent second gathering of the HLSC[11] accepted an initial Position Paper, discussed the integration of the issues raised during the QT Workshop, and set the date of the next meeting to 16 February 2017, in conjunction with a Maltese EC presidency event. The HLSC also appointed an Editorial Subcommittee, headed by the Chair of the Committee, staffed with 3 Academic Members and 4 Industry Members[12], and tasked with compiling the upcoming key documents of the QT Flagship.

The results from the consultation process outlined above were distilled by the Editorial Subcommittee and representatives of the EC in their meeting on 19 December 2016 in Berlin, and agreed upon by the HLSC in a further round of internal consultation in January 2017, to be presented hereby as the Intermediate Report of the QT Flagship. The Intermediate Report serves three main purposes. It is an internal guideline in assembling the upcoming H2020

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

[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: https://drive.google.com/file/d/0B8TwJOtGVL5ld0NjdlprdHhqQWM/view

[10] For the results of the consultation process: see https://drive.google.com/file/d/0B8TwJOtGVL5lUlNMSHVSWnFyajA/view

[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 — Prof. Dr. Tommaso Calarco, Prof. Dr. Elisabeth Giacobino, Prof. Dr. Eugene Simon Polzik — Dr. Paolo Bianco, Dr. Michael Bolle, Dr. Daniel Dolfi, Dr. Gregoire Ribordy

Work Program, a compass meant to inform decision makers and gather their support, and the foundation for future planning through the Strategic Research Agenda, once the Work Program is published.

3 Background

Quantum physics was created in Europe in the first decades of the twentieth 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 Quantum Technologies – Communication, Computation, Simulation, Sensing and Metrology – can be expected to produce transformative applications with real practical impact on ordinary people.[13]

[13] The following background information on Quantum Technologies is an 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 in turn may help with multiple applications, ranging from biosensors to magnetic resonance imaging and the detection of defects in metals. Superconducting quantum interference devices are one example of an early quantum technology 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 Program Overview

Goals

The Quantum Technology 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 quantum technologies from basic physics to electronics and computer science. However, to unlock the full potential of quantum technologies, 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 quantum technologies, 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 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:

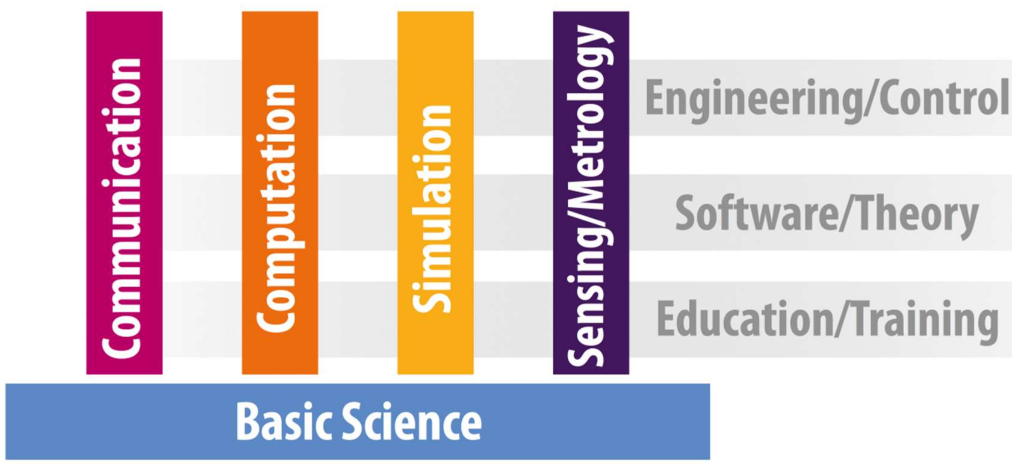
- **Communication**, to guarantee secure data transmission and long-term security for the information society by using quantum resources for communication protocols;
- **Computation**, to solve problems beyond the reach of current or conceivable classical processors by using programmable quantum machines;
- **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 Quantum Technologies 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 quantum technologies 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.



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 quantum 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 quantum technologies programmes, thus ensuring that it is the whole of Europe that contributes to and reaps the benefits of the second quantum revolution.

Concrete measures on how this can be achieved will be discussed in more detail in the Final Report.

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 for making quantum processors with more than 50 qubits will be demonstrated;
- ✔ **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 Y3 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.[14]

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 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

[14] 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”.

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 metrology and sensing 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 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

The previously defined strategic research agenda needs a well-adapted implementation model. Implementation must adhere to a number of frame conditions, among them the regulatory framework of the European Commission and compatibility with existing programs and initiatives. Thus, a detailed discussion with many stakeholders is required - a process which is still ongoing. We present here our preliminary recommendations, still subject to change.

Guiding principles

The implementation of the Flagship program should follow some guiding principles, as suggested in the following.

HOW: In order to put together and coordinate the strengths of Europe in Quantum Technologies the Flagship should operate in a way that is:

- inclusive but rooted in excellence
- efficient and effective in delivering the promised results
- flexible in the implementation, allowing the program 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 program
- closely connected with the existing and planned national and transnational QT programs and taking into consideration the corresponding programs in other parts of the worlds, e.g. in the US and China
- 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 framework for private and institutional investors
- incorporating the lessons learned from the two existing 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
- already in the ramp-up phase, for the high TRL ones, include proof-of-principle and/or demonstrators among their goals
- support the development of a complete supply chain, spanning from Academia to Industry (both Corporaes and SMEs), enabling the transfer of preliminary concepts to products, through increasing levels of engineering and prototyping
- can also include high-risk/high-reward research and developments
- conduct basic research into enabling science and exploration of new concepts and systems
- reinforce the European strength in QT at the international level
- facilitate the creation of a new generation of quantum scientists, engineers, and entrepreneurs and related job positions in Europe
- foster broad support from society for research in QT and ensure societal awareness and acceptance of QT-based applications

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

- include excellent academic and industrial partners (for the application domains at least one member from academia and industry each)
- include partners from different European countries
- focus on impact and strategic benefit for Europe in the global race for QT leadership
- have the ambition to grow, exploit results and invest on their research beyond the duration of their projects
- can allocate part of the budget for inclusion of associated groups outside of the initial consortia to flexibly include emerging players
- are allowed to also include multi-national companies with a broad footprint in Europe, since 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 elements

Preparatory measures preceding the start of the Flagship

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

- Member States are expected to start national support to QT projects as early as possible, preferably already in 2017/18, and undertake joint investments for infrastructure development in terms of user facilities open to the European QT community
- The newly established ERANet QuantERA should be encouraged to take a role in facilitating coordination of national resources in the above directions, similar to the role played by FLAG-ERA in the context of the existing Flagships
- The national metrology institutes, organised in EURAMET, already have strong expertise in QT and should be encouraged to put a focus on next-generation quantum technologies in metrology and sensing
- The European Space Agency should be stimulated to take up an active role on space applications of quantum communication, metrology and sensing
- The HLSC urges the European Commission to stimulate the development of breakthrough technologies in Europe through procurement (with resources from sectors outside the Flagship)

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. Instead of establishing one Core Project for the whole Flagship or for its five domains, the projects funded by the EC contribution should be selected through a Europe-wide peer-reviewed call for proposals, with reviewers both from academia and from industry.

Strategic steering of Flagship focus

- The calls should be structured along the five domains described in section 3
- The balance among the domains should take into account the different needs for strategic development and cost-intensity, which will be reflected in different budgets for each of the different domains
- We recommend that consortia will be required to define both project objectives and long-term (beyond the scope of the proposal) goals. On this basis, the research agenda can be regularly updated

- Throughout the lifetime of the Flagship, there should be open calls to maintain openness to the exploration of challenging new ideas, systems and concepts and flexibility to incorporate these into the strategic research agenda. Early-stage researchers should be explicitly encouraged to submit collaborative 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 industrialisation should be always in focus within proposals addressing the four application domains

Timeline

- Building on the solid basis prepared over the past several years, and to avoid further delay with respect to international competition, the Flagship should already start in its first year with full operational funding
- As ramp-up timeline for the Flagship we suggest the following:
  - September 2017: Final recommendation of strategic research agenda, implementation model and governance structure by HLSC
  - Fall 2017: Announcement of first calls for proposals, by the EC upon advice from the HLSC. Consortia with various focuses and goals get together 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
  - Fall 2018: Evaluation of proposals
  - January 2019: Start of projects with actual Flagship financing
- In the steady-state phase, the number of projects should be reduced via strategic orientation of calls. Initial consortia can be modified, stopped or reorganised. They could evolve into possibly larger, more focused consortia around the most promising and successful routes, from demonstrators to products. Such evolution can be domain-dependent, as each domain has a different maturity level and its own set of timescales.

Review process outline

- We suggest to base the review process for proposals on panels for each of the domains. Their chairs should be appointed by the EC upon recommendation by the HLSC
- The review process could either be organised by the EC itself or by an independent external service provider appointed by the Commission
- The final decisions on consortium partners could be made via a two-step procedure: From among the first-stage short proposals, 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
- The cost reimbursement rate in Flagship-funded projects for industrial partners should be higher than the current H2020 rate of 50%, to stimulate industrial involvement.
- Ongoing projects should be regularly evaluated by clear milestones, but administrative overhead should be kept at a minimum (lean submission forms, work packages self-assessment, light reporting structure, …)
- The ramp-up phase is expected to provide the opportunity of developing coordination and cooperation between academia and industry in order to get projects ready to kick off right in the beginning of the full project phase.

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 member states to also review their engagement in Quantum Technologies. The Flagship will offer mechanisms for smaller European countries to join the program, if they propose their own scientific programs to be included. A close alignment of the Flagship with the national programs' strategies and activities is of highest importance. Measures to achieve this are going to be discussed in more detail in the final report. In case of transnational developments, the contribution of the member states and of the Commission will be coordinated at the European level.

In particular, the Flagship would strongly support infrastructure projects funded through other EC and member state instruments, as all application domains need high-level research infrastructure. These include

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

Education and Training

Quantum technology 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 Flagship program.

- One Executive Board member could be nominated "education & outreach officer" to co-ordinate a focus group on education;
- The Flagship 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 programs, based on PhD and postdocs' excellence (no mobility requirements) including secondment to industry and/or research groups;
- A visitor program for researchers from groups not formally part of a Flagship-funded consortium is also recommended to enable them to work in leading European QT groups.

Further measures

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

- The Flagship could establish a "Quantum Innovation Fund" to provide start-ups in an unbureaucratic way with venture capital and co-fund Quantum Incubators or dedicated QT programs at existing incubators, to make it difficult for foreign corporations to acquire the most successful EU technologies after the extensive Flagship investments
- Several measures should be taken to create market 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 clusters and associations
- Effective outreach activities (such as a web portal, 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

- The Flagship should work closely with existing standardisation institutes (such as the metrology institutes organised in EURAMET) and the European committee for standardisation (CEN-CENELEC and ETSI) to drive standardisation of quantum technologies.
- The Flagship should also 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
- The Flagship should consider establishing a central IP support unit for quantum technologies in order to raise researchers' awareness for IPRs and help them with advice and administration. On demand, the unit would work closely together with the patent attorneys of the inventors' institutes/companies.
- The sensibility and feasibility of generating and protecting a joint patent pool for the European research community and industry should be evaluated, considering also industry's strong interest to keep the IP resulting from their own efforts.

7 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 in QT.

The flagship 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 upon a common basis of Basic Science, and address enabling aspects in: Engineering and Control, Software and Theory, Education and Training.

The strategic research agenda for these 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. The implementation model follows from this strategy, but important aspects are still subject to discussion. It is clear that the largest part of the available QT funding should be allocated to research and innovation projects selected through peer-reviewed calls for proposals based on the above research agenda. The down-selection process for focus topics, IP management and member state coordination are among the aspects still to be detailed, as are further measures, e.g. for education and training, for outreach and for fostering quantum start-ups.

It is now very important to gather feedback from the Member States and the European Commission on the recommendations of this intermediate report, in order to consolidate in particular the proposed implementation model, in synergy with the already running and just starting national QT initiatives. Based on the outcome of this discussion, the HLSC will then propose a further detailed implementation model and a governance model for the Flagship Program. This will on the one hand adhere to the Flagship's guiding principles of transparency and inclusiveness, and on the other hand be as lean as possible to ensure highest effectiveness and efficiency in running the Flagship. These recommendations will be summarized in the Final Report, to be delivered in September 2017.

Appendix I: HLSC members

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