Strategic Research Agenda

QUANTUM FLAGSHIP

Strategic Research Agenda

The European Quantum Flagship has received financial support by the European Commission in the scope of the Coordination and Support Action "Quantum Technology Flagship Coordination and Support Action" (Grant Number 820350).

Published by:

European Quantum Flagship

CSA project coordinator:

VDI Technologiezentrum GmbH
VDI-Platz 1
40468 Düsseldorf, Germany
Phone: +49 211 6214 665

e-mail: info@qt.eu
Website: www.qt.eu
Twitter: twitter.com/QuantumFlagship
LinkedIn: www.linkedin.com/company/quantum-flagship/

Special thanks to:

Robert Thew, University of Geneva, for the overall coordination and Head of content creation.

Steven Randall, design and layout, ocean-design.com

Brussels, Düsseldorf, March 2020.

Table of contents

Executive Summary **7**
Introduction **11**
Quantum Communication **20**
- Socio-economic challenges 22
- Research and innovation challenges 24
- Quantum Communication roadmap 34

Quantum Computing **36**
- Socio-economic challenges 39
- Research and innovation challenges 39
- Quantum Computing roadmap 46

Quantum Simulation **48**
- Socio-economic challenges 51
- Research and innovation challenges 52
- Quantum Simulation roadmap 56

Quantum Sensing and Metrology **58**
- Socio-economic challenges 61
- Research and innovation challenges 63
- Quantum Sensing and Metrology roadmap 68

Scientific and Technological Resources **70**
- Scientific Resources 72
- Technological Resources 74
- Scientific and Technological Resources roadmap 79

Innovation **80**
- Use cases and requirement specifications 83
- Infrastructure and supply chain 83
- Trained and educated workforce and users 85
- Supporting and promoting the development of new products and services 85
- Innovation roadmap 88

International Cooperation **90**
- Quantum Technologies: a major disruptive sector calling for a worldwide research and innovation 92
- A clear framework to benefit from international collaboration 93
- Addressing the IP issue: Making Europe stronger to benefit from an open world 95

Gender Equality **99**
- Increasing gender diversity at senior levels 100
- Approach to gender equality in the Quantum Flagship 102
- Conclusion 103
- Gender Equality roadmap 105

Education and Training **106**
- Current status 108
- Conclusion 109
- Education and Training roadmap 110

Appendix **112**
- Evolution of the Strategic Research Agenda 112
- Strategic Advisory Board 112
- Strategic Research Agenda Work Group 113
- Innovation Work Group 113
- Gender Equality Work Group 113
- Glossary 114

Executive Summary

Executive Summary

It is now widely understood that the mastery of deep technologies will determine the future prosperity of countries and regions across the world. Sovereignty over these technologies will become the critical building block for the future economic development and digital self-determination of societies. Quantum technologies have a special role to play in this regard, as their disruptive potential is outstanding and will have fundamental implications for society and the economy as a whole. The use of quantum technologies will make it possible to solve societal problems that are considered simply insoluble today, whether in the development of entirely new medicines, the optimisation of traffic flows or financial strategies, the development of new materials that are still unimaginable today or the use of unbreakable secure communication.

By moving towards a digital society, data is increasingly becoming the lifeblood of our economy. Those who master the relevant technologies can use the data for industrial exploitation and, if necessary, protect it from unwanted access. It is therefore of the highest European interest to be at the forefront of international competition in quantum technologies. The European Quantum Technology Flagship, established in 2018, is a large-scale, long-term initiative that brings together research institutions, industry and public funders, expanding European leadership and excellence in this field. It will foster the development of a competitive quantum industry in Europe, making the results of quantum research available as commercial applications and disruptive technologies. The Flagship will run for ten years, with an expected budget of EUR 1 billion.

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. The Quantum Flagship initiative is targeted at keeping Europe at the forefront of the second quantum revolution now unfolding worldwide. The long-term vision for the Quantum Flagship initiative is for a "Quantum Internet": quantum computers, simulators and sensors interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement to secure our digital infrastructure. 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 synchronisation, measurements and diagnostics for a range of applications available to everyone locally and in the cloud.

The Strategic Research Agenda (SRA) at hand was prepared under the supervision of the Quantum Flagship Strategic Advisory Board. More than 2000 quantum experts across Europe have been consulted in an open and transparent process over the last 18 months to set a clear direction for the future development of quantum research and innovation in Europe. This SRA sets the ambitious but achievable goals for the Quantum Flagship, and details them for the next three years, with an outlook for six to ten years. To work towards these goals, the QT Flagship is structured around four research and innovation domains, representing the major applied areas in the field: Communication, Computing, Simulation, as well as Sensing and Metrology. These application domains are anchored 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. These are supported by cross-cutting areas covering: Engineering and Control, Software and Theory, Education and Training and further complemented by overarching activities in Innovation and International Cooperation as well as Gender Equality.

1. Quantum Europe – Engage all stakeholders/create an innovative ecosystem!

The implementation of this SRA will require significant investments, both private and public, and efficient cooperation between all parts of the European innovation system. The main challenge is to move quickly from early research to industrial exploitation. In the private sector, the emerging quantum industry must work closely with traditional industrial sectors to identify first use cases and to develop quantum enabled solutions for tomorrow's digital world. The European Commission and national governments must closely coordinate their resources, policies and investments to achieve not only a critical mass of investment, but to create the innovation-friendly framework conditions for a digital Europe. Quantum scientists must work even more closely with engineers and with industry in order to raise technology readiness levels.

2. Financing the growth – Build a sustainable Quantum industry!

A key issue for Europe towards the industrial deployment of quantum technologies is how it can promote and provide the access to financing for the development of a sustainable "Quantum industry". In contrast to the US risk capital approach and China's state-capitalism system, Europe has not yet found its own way to meet this challenge. While Europe is getting better at setting up innovative start-ups – around 50 Quantum start-ups have been set up in recent years – the subsequent growth financing for these often hardware companies remains a major problem as it is very cost-intensive and does not offer a quick return on investment. European venture capital companies, unlike their American counterparts, and traditional banks are rarely making such investments. The future growth financing for these start-ups must be made possible in Europe, without US venture capital money luring them to California or state-controlled companies buying majority shares. It may be a task of the European Investment Bank to remedy this obvious market failure, which is not specific to quantum but applies to the entire deep technology sector.

3. From lab to fab to market – Provide the necessary infrastructure!

To further develop this area as a whole, including commercially, these research and innovation priorities need to be accompanied by major European infrastructure investments such as those for Quantum Communications, Quantum Computers and Simulation or Quantum Sensing and Metrology, which are currently under discussion or already being implemented. These infrastructure programmes represent a golden opportunity to facilitate access to technology to accelerate and strengthen engagement with industry, as well as seeding the growth of the necessary supply chains and providing a training ground for a future quantum-aware work-force. Early industrial involvement will be critical for a successful transition from lab to fab to market and to facilitate the early development of industry standards with our international partners. The SRA captures this expanded vision of the Quantum Flagship initiative.

4. Strengthening Europe – Create a European IP and standardisation strategy!

For the implementation of the Quantum Flagship it will be vital that a dedicated IP and standardisation strategy is pursued to safeguard Europe's interests. The Flagship will on the one hand work closely with the European Patent Office to monitor the development of IP in this field and on the other hand pursue a coordinated approach in cooperation with the relevant standardisation bodies. The Flagship focus will be on coordinating the different activities as the standardisation itself is a primary task for the industry.

5. Education and outreach – Train a quantum-aware workforce and society!

Education, while one of the cross-cutting activities, also has a more general dimension, and is of central importance beyond research. The creation of a learning ecosystem embracing the concepts of quantum physics at all levels ranging from school up to the working environment is required, not just for a quantum-ready workforce to emerge, but for a well-informed society with knowledge and attitudes towards the acceptance of quantum technologies. On a shorter time-scale, we are already observing a clear shortage of quantum experts in this early phase, especially in engineering. It must therefore be a priority for the Member States and the EU Commission to significantly increase the number of trainees in this sector in order to meet the foreseeable demand. In order to prepare industry for the development of quantum technology products and services, a flow of students from science to industry is required. Educational workshops in collaboration with industry can help boost this flow of talented people. In addition, young entrepreneurship professionals and students should be trained and prepared to bring quantum technologies to market through start-up companies. Tackling the challenges of equality, equity and integration in quantum technologies as we begin to structure this emerging industry is a great opportunity. Europe has not yet sufficiently understood how to significantly increase the number of women in STEM subjects. Thus, we have a large untapped potential as we know that the effects of women's participation generally contribute to increasing the quality, societal relevance and competitiveness of research and innovation.

Europe has all the elements to become a world leader in quantum technologies and its industrial exploitation. Our goal is to establish a quantum industry and develop quantum enabled strategic value chains across European key sectors. More specifically our ambition is to become a global leader in quantum computing through the development of cutting edge computing platforms; that we have established a working critical communication infrastructure that protects against cyber threats and is used by governments as a first user to ensure the long-term protection of critical government data and infrastructures, and that we develop and market quantum-based sensing and metrology solutions that give European industries a competitive quantum advantage.

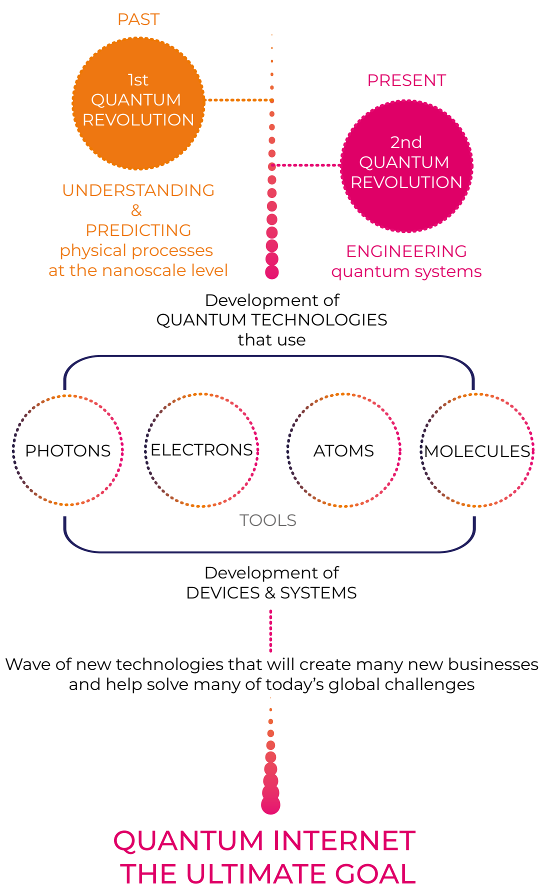
Introduction

The long-term vision is to realise a Quantum Internet; quantum computers, simulators, and sensors, interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement, to provide European citizens with more secure telecommunications and data storage, improved healthcare, and better performing computation.

Introduction

The First Quantum Revolution shaped the world we live in today; without mastering quantum physics, we could not have developed computers, telecommunications, satellite navigation, smartphones, or modern medical diagnostics. Now, a second quantum revolution is unfolding, exploiting the enormous advancements in the ability to detect and manipulate single quantum objects (photons, electrons, atoms, molecules), something that even Einstein considered impossible.

Due to the huge potential, large strategic initiatives and investments are currently being made by governments and corporations around the world to capitalise on the potential of the second quantum revolution to gain a competitive advantage over competitors.



The Ultimate Goal – Developing a Quantum Internet

Building on its scientific and technology excellence, Europe launched the FET Flagship Initiative on Quantum Technologies (Quantum Flagship) in April 2016. Through its ramp-up phase under Horizon 2020, the European Commission supported 20 projects with 152 million euros. In the up-coming Research Framework Programme Horizon Europe (2021–27) the European Quantum Flagship Initiative will become fully operational with a total investment of 1 billion euros.

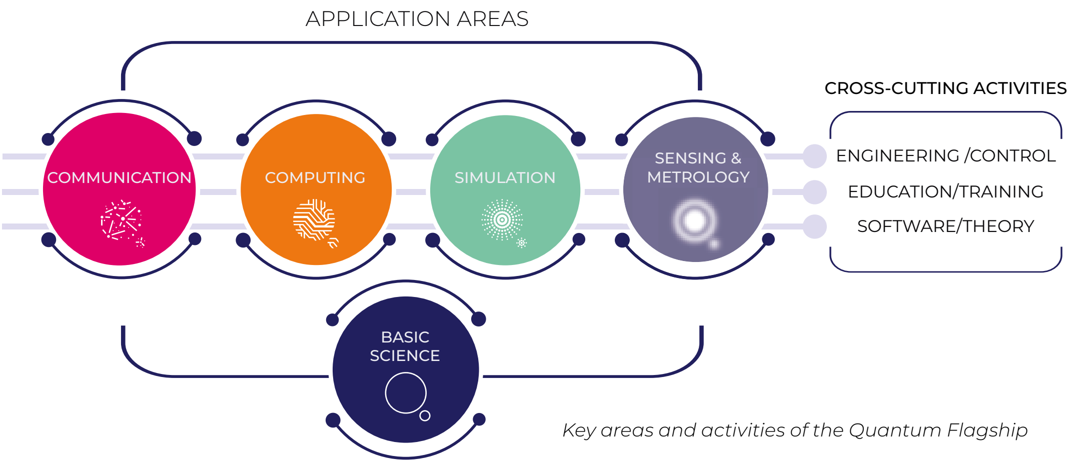
With this investment, Europe will seize the opportunities offered by the second quantum revolution in all possible fields, for the benefits of its citizens, industries and of the digital economy. The long-term vision is to realise a Quantum Internet; quantum computers, simulators, and sensors, interconnected via quantum networks distributing information and quantum resources such as coherence and entanglement, to provide European citizens with more secure telecommunications and data storage, improved healthcare, and better performing computation. To this end, quantum technologies are an essential building block for Europe's technological sovereignty.

The Quantum Flagship strategy is structured around four distinct but interconnected application domains

Communication, Computing, Simulation as well as Sensing & Metrology, which are complemented by a Scientific and Technological Resources area, which encompasses Basic Science and cross-cutting activities – Engineering, Control, Software and Theory.

Quantum Communication

Networks based on quantum technologies will help protect the increasing amounts of citizens' data transmitted and stored digitally, for instance health records and financial transactions. Quantum networks use photon-based quantum states that are compatible



Key areas and activities of the Quantum Flagship

with the current digital infrastructure. If anything intercepts even a small amount of light in such a quantum state, it will be noticed, meaning that with quantum technology we can achieve the most secure form of communication known, especially in the case of long-term security. Terrestrial quantum communication can well cover metropolitan areas, while longer (including inter-continental) distances can be covered by space-based links, possibly leveraging existing satellite networks or making use of dedicated ones. For point-to-point communication this is already on the market today and will be developed further to also provide a diverse and multi-functional quantum network – a quantum internet consisting of mutually connected quantum

A second quantum revolution is unfolding, exploiting the enormous advancements in the ability to detect and manipulate single quantum objects (photons, electrons, atoms, molecules)

←

"Algorithms for quantum computers have been developed already that outperform their classical computing counterparts."

computers that allow for advanced protocols, including certification, secure signatures and identification of all communication partners. Many other applications of quantum networks are already known theoretically, such as access to remote quantum computers in the cloud for simulations on proprietary new drugs without disclosing their design.

Quantum Computing

Quantum computers are based on qubits – quantum bits – built on various platforms (trapped ions, quantum electronic circuits, individual atoms, photons, nuclear spins, or electron spins) and exploit phenomena such as superposition and entanglement, making enormous computing power available to solve problems we could never solve otherwise. Algorithms for quantum computers have been developed already that outperform their classical computing counterparts. These include, for example, the computation of properties of material and chemicals and their dynamics, the solution of equations and mathematical problems (such as the factorisation of large numbers, essential in the context of encryption for secure communications), and pattern recognition. In the future, universal quantum computers will be widely applicable, including for process optimisation, machine learning, artificial intelligence, business process optimisation, finance and inventory management, dynamic systems and digital simulation of quantum many body systems as they appear in different fields of physics, chemistry, biology, drug design and material science.

Quantum Simulation

Closely related to quantum computers, and realisable even earlier, are quantum simulators. They will be key to the design of new chemicals, from drugs to fertilisers for future medicine and agriculture, and of new materials, such as high-temperature superconductors, e.g. for energy distribution without loss. Others imitate the idea of a wind tunnel, where small models are used to understand the aerodynamics of cars or planes: some quantum simulators use simple model quantum systems to understand systems that would be much more difficult, or even impossible, to compute or to experiment with.

Quantum Sensing and Metrology

Quantum sensors will provide the most precise and accurate measurements in many fields, boosting the performance of consumer devices and services, from medical diagnostics and imaging, high-precision navigation, earth observation and monitoring, to future applications in the Internet of Things. Quantum sensors exploit quantum coherence, superpositions and entanglement emerging in individual quantum systems, such as single photons, electrons, ions, or atoms. Exploiting quantum light or quantum detectors will also improve the performance of imaging system (e.g. in terms of resolution,

sensitivity or noise), with applications in the life science and healthcare sector, extending fundamental limits of medical imaging e.g. by imaging deeper into tissue, with broader spectral ranges and higher speeds. Quantum metrology uses these quantum technologies to realise highly reproducible and universal measurement standards within the International System of units for e.g. time-keeping or electrical measurements, with a high impact on industry, economy and society in general (competitiveness of industry, fair trade, security of consumers). Quantum metrology also plays a key role in developing measurement methods for standards.

Scientific and Technological Resources

This encompasses Basic Science and the cross-cutting activities: Engineering; Control; Software, and Theory. 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 and ensure the long-term impact of quantum technologies. The addition of quantum technologies in space will also require both the development of new theoretical tools and the achievement of substantial experimental and technological breakthroughs. Combined with these cross-cutting activities, this will bring together the combined competencies of quantum and classical arenas to develop the tools, components, materials and processes that will enable the mission-driven objectives to be realised. This process is expected to work in

Quantum sensors will provide the most precise and accurate measurements in many fields including future applications in the Internet of Things.

© Melpomenem / iStockphoto.com

> "The goal of the Quantum Flagship is to build strategic value chains in Europe in this emerging industry in each of the main application areas."

two important ways: **new science provides new ideas for quantum technologies, but also developing quantum technologies stimulates 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 generally concern several if not all domains, providing the Scientific Resources for the future. 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 also including research on the societal impacts and ethical components of quantum technologies. The cross-cutting activities will provide the technological resources needed to ensure efficient and coherent development across all application areas.

For each of these applications areas, strategic Quantum Flagship projects will be started under the Horizon Europe framework programme. However, this effort requires the well-aligned interplay of various activities, from research and innovation projects, to making the necessary infrastructure available, and integrating quantum technologies in Europe's space and metrology programs, to creating valuable education, training and networking measures. The goal of the Quantum Flagship is to build strategic value chains in Europe in this emerging industry in each of the main application areas; Quantum Flagship funding activities will focus on Technology Readiness Levels 1–5 including research, development and early innovation activities. These will be complemented by coordinated investments in European infrastructure through the Digital Europe Programme. Here, too, close cooperation is sought with the European member states' activities, as is already the case with the European Quantum Communication Infrastructure (EuroQCI)[1] and the Quantera[2] projects.

Under the leadership of the Quantum Flagship's Strategic Advisory Board[3], the European quantum community – with currently over 2000 experts from research and industry – has drawn up this Strategic Research Agenda. It is intended to give the European Commission and member states, as well as research organisations and companies, a better insight and understanding of the strategic directions for coordinated future investments in this area.

Similar to a naval flagship, coordinating the activities of a whole fleet of independent ships, the Quantum Flagship will take this role for the "Quantum Fleet" in Europe. To this end, it will bring together and steer the European activities in quantum technologies for the benefit of European citizens. Europe's goal in this field should be ambitious and challenging, e.g. building and operating the first quantum computer in Europe, outperforming classical computers and solving mathematical and also applied problems; deploying a pan-European secure quantum communication network; establishment of a fibre backbone at selected reference points for time and frequency dissemination; realising ultrasensitive (point of care) diagnostics for healthcare, exploiting next generation of quantum sensors for the metrological certification of both classical and quantum technologies, and enabling more accurate autonomous driving through enhanced satellite and inertial navigation.

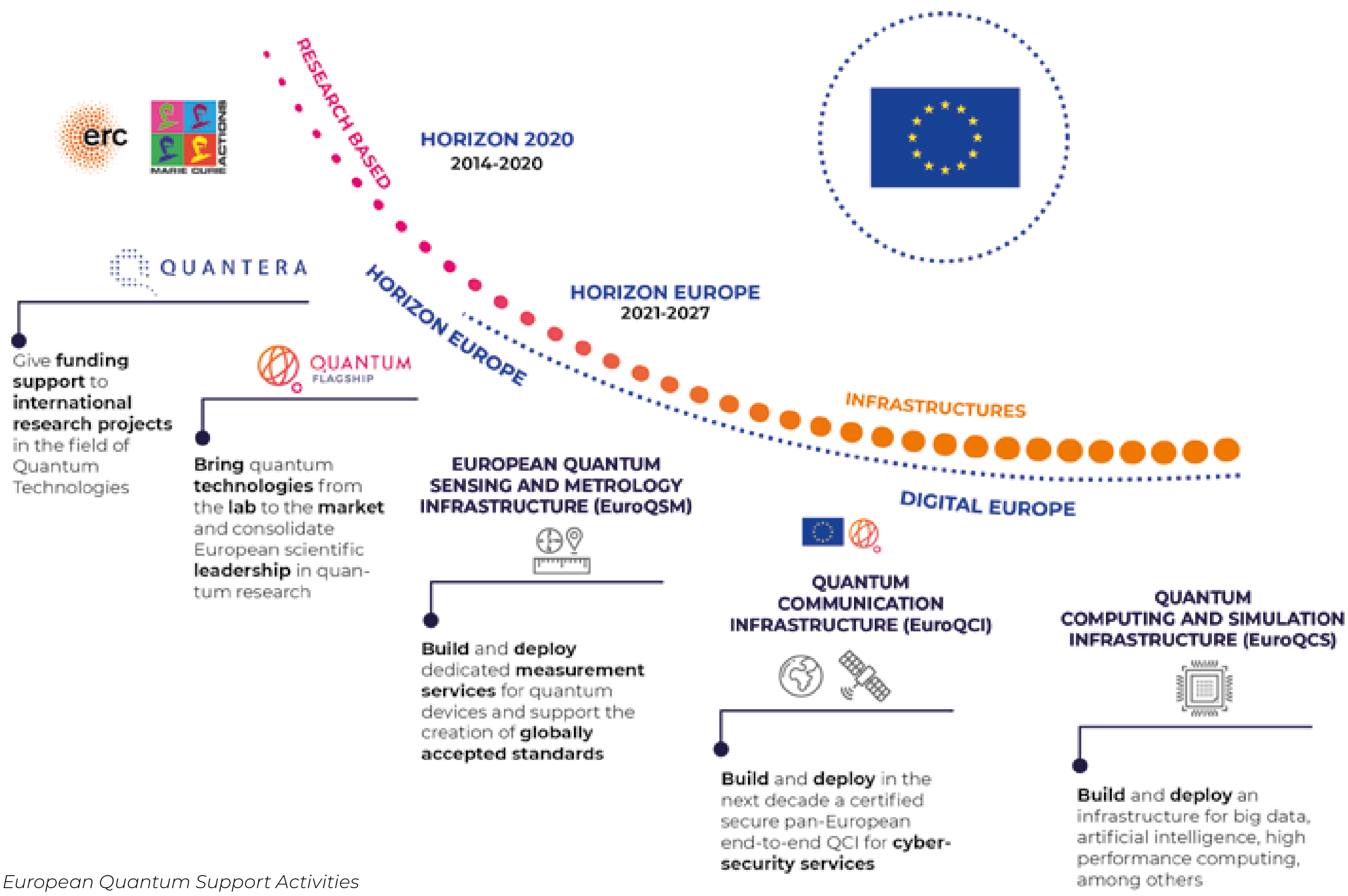
Developing a competitive quantum industry in Europe

The development of an innovative quantum industry requires the creation of an innovative ecosystem in Europe, involving start-ups,

[1] https://ec.europa.eu/digital-single-market/en/news/future-quantum-eu-countries-plan-ultra-secure-communication-network
[2] https://www.quantera.eu/
[3] Governance of the Quantum Flagship: https://qt.eu/about/structure-and-governance/

established small, medium and large enterprises, as well as research and technology organisations. This is particularly crucial for the space segment of the Quantum Internet, where the high technological and budgetary demands of space missions require a pan-European effort. To build a flourishing quantum industry, Europe needs to protect its ideas and strategically build up intellectual property to compete with other regions. Although the significance of statistics is limited, it would be alarming to see Europe falling behind in the race for IP in quantum technologies while US and China have become the dominant countries in this field. Europe will leverage partnerships with strong international partners of complementary expertise, to jointly develop the field and create clear scientific and economic win-win opportunities.

Irrespective of the fact that Europe has a very strong scientific position for commercialising quantum technologies, access to capital is a crucial factor for nurturing a quantum industry in Europe. The commercial development of quantum devices is costly, time-consuming and risky. It is known from other deep-technology industries that European venture capital companies are often more risk averse than American counterparts – who are a key driver for growing innovative companies in the US – and generally make smaller investments. At the same time, European banks often shy away from investments in deep-tech companies, especially if they are small companies or start-ups. In contrast to the venture capital backed system in the USA, China pursues a state capitalism model to build and protect its deep-tech

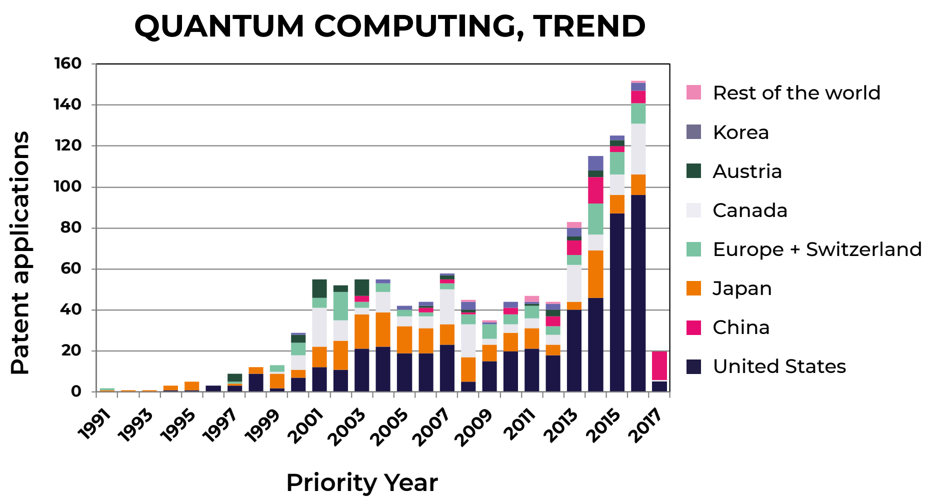


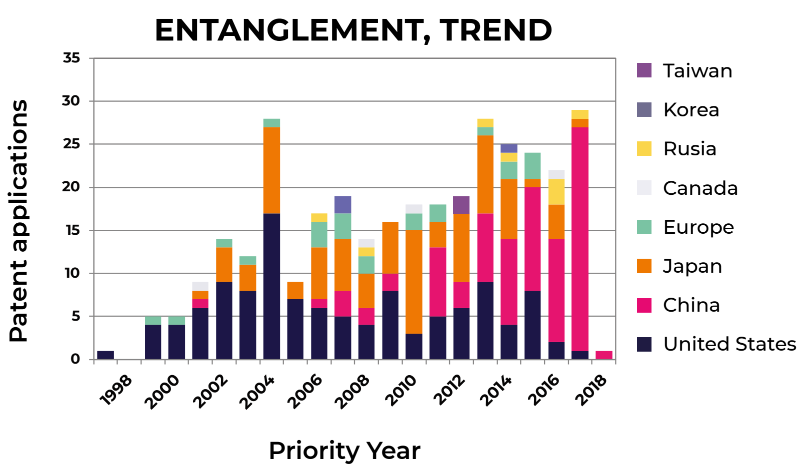
European Quantum Support Activities

> **"At the heart of a European strategy in a deep-tech sector such as quantum technologies, besides defining research and innovation priorities, is the training of young people to drive innovation."**

industry. Europe still needs to find its way to overcome the bottleneck in providing financing to deep-tech companies, to build a competitive industry.

At the heart of a European strategy in a deep-tech sector such as quantum technologies, besides defining research and innovation priorities, is the training of young people to drive innovation. Only a pan-European approach can bring the necessary changes. The Quantum Flagship will analyse the situation in the European countries and develop corresponding recommendations. Particular attention will also be paid to **education and training**, as well as **gender equality**, and in general, equity in the field, where, as for STEM – science, technology, engineering and mathematics – areas in general, this is currently problematic. The long-term goal of the Flagship is for equity across the quantum technologies domain, from academia to industry and at all levels. The implementation of the Quantum Flagship Strategic Research Agenda is a European task of industry, research, national ministries and the EU Commission alike. Joining all European forces to develop, apply and commercialise quantum technologies will create great benefits to European citizens, for Europe's economic development and for the major challenges facing society.

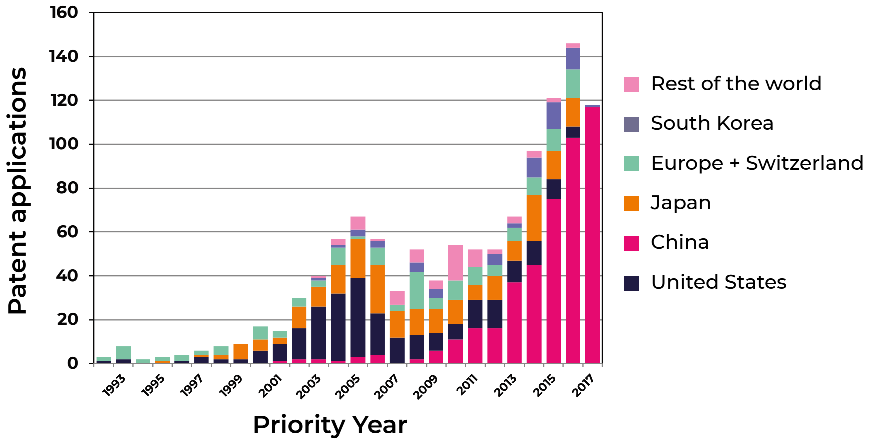




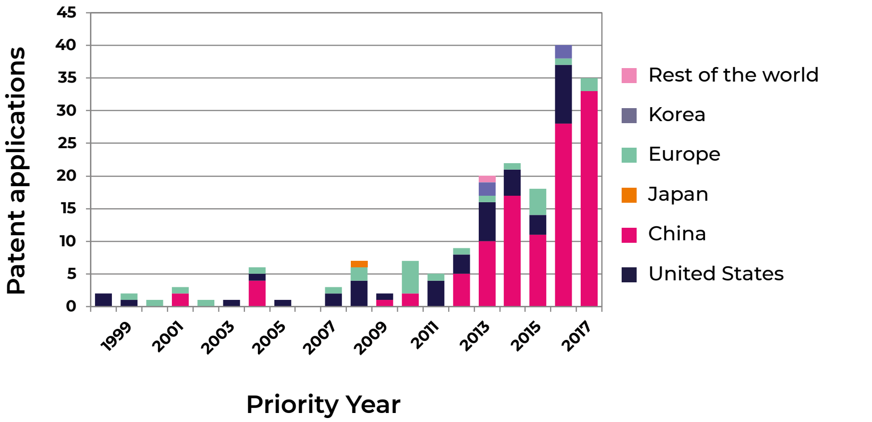
Patent analysis of selected Quantum technologies; Joint Research Centre; European Union 2019[4]

[4] http://publications.jrc.ec.europa.eu/repository/bitstream/JRC115251/patent_analysis_of_selected_quantum_technologies_1.pdf

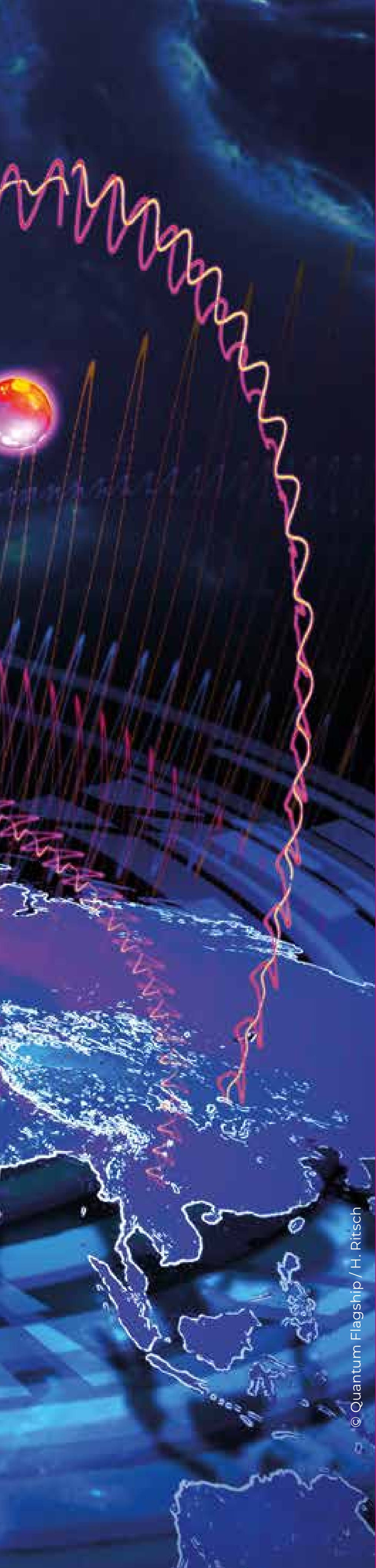
QUANTUM KEY DISTRIBUTION, TREND



COLD ATOM INTERFEROMETRY, TREND



Quantum Communication


© Quantum Flagship / H. Ritsch

Quantum communication will build on the current digital infrastructure to distribute and connect quantum resources for improved security and functionality. This will address challenges such as the long-term security of health records, to connected quantum clock networks and eventually enabling secure connection to quantum computers in the cloud.

Quantum Communication

Quantum communication involves the generation and use of quantum states and resources for communication protocols in order to bring radically new applications and increased cybersecurity to European citizens. At present, the most advanced applications of quantum communication are in cryptography, in which it can enable fully future-proof security, even if an attacker has a quantum computer. Although it may take many years for a large-scale quantum computer to be realised, quantum security techniques are important today for protecting information that must remain confidential for many years, such as industrial secrets of companies or the genome data and medical records of individuals. However, eventually it will extend to new domains, such as remote connection to quantum computers solving complex optimisation problems or improved clock synchronisation by producing entanglement between different end-nodes in the network.

First generation technology for quantum cryptography has already reached a high TRL, with commercial products and prototypes for quantum random number generation (QRNG) and quantum key distribution (QKD) already available. Furthermore, fibre optic networks for QKD have been built in several countries including Europe, US, China and Japan and a quantum communication satellite has been launched. However, much more work is needed to further improve upon these technologies, as well as to integrate them into useful cryptographic systems and communication networks.

Current fibre-based QKD schemes are limited to direct transmission distances of around 400km, extendible via trusted nodes to continental scales and even planetary scales using satellite-based transmission. Quantum repeaters are necessary for distributing resources such as entanglement for more complex applications. Significant R&D is needed in order to build such quantum repeaters, as well as to develop the technology to connect them to other quantum systems such as quantum processors or sensors.

The long-term vision is to develop a Europe-wide quantum network that complements and expands the current digital infrastructure, laying the foundations for a quantum internet. To achieve this, the objective is to advance quantum communications in three essential directions:

1. Performance: Increasing bit rates, fidelities, link distances, robustness etc of all types of quantum communications.
2. Integration: Combining quantum communications with conventional network infrastructures and applications.
3. Industrialisation: Realising technology that is manufacturable at an attractive price point and which generates wealth and jobs in Europe.

Socio-economic challenges

Quantum cryptography provides protocols whose security can be proven directly from information-theoretic principles and the laws of quantum mechanics, and which do not require any assumptions about the computational resources available to an adversary. Information-theoretic security will be important for data confidentiality in the future when we can expect more powerful computers and new algorithms to be at the fingertips of our digital foes. Of particular concern is the advent of quantum computers that can be used to launch efficient attacks on conventional techniques, such as the Diffie–Hellman–Merkle key exchange algorithm.

The near- to medium-term applications of quantum communications are expected to be in cryptography, where it can be used to generate high entropy random numbers and to distribute secret digital keys, as well as

perform several other important primitives. In the longer term, we may see many other applications in networked sensing, timing and computing, such as the secure use of a remote quantum computer for simulating properties of a new material, without disclosing its structure.

The main challenge that quantum communication-based technologies may face at the current stage of development is the lack of appropriate economic and human resources. The amount of investment needed to develop both the infrastructure that will allow the deployment of these technologies, and the development of new components and systems that will unlock the full potential of a quantum internet is significant. There will, however, be a direct benefit to the European economy, delivered by the multi-billion euro business for quantum cryptography expected to develop over the next decade. Several studies have predicted sales of quantum key distribution systems and services to grow strongly. Indeed, a robust and secure communication infrastructure based on quantum security will be essential to protect European sovereignty and its economy in the face of increasing cybersecurity challenges. It will benefit a wide range of users in the financial, healthcare, government and corporate sectors, and underpin many millions of jobs across Europe.

A necessary condition for Europe to have a major share of this growing market is to ensure the engagement of existing European quantum communication industry partners, enable new-comers and the emerging start-ups, facilitate the development and growth for QKD network services, related software, system integration and certification services, as well as for the supply chain of associated quantum photonic components.

To ensure the development of new technologies and systems, innovation platforms that enable innovators to develop new products and solutions are needed. The launch of the QKD testbed and forthcoming possibility of the European Quantum Communication Infrastructure (EuroQCI) could provide the ideal testing-ground where innovators (e.g. research institutions, software developers, hardware industry, internet service industry, security professionals) can get access to technology-testing, where new standards, procedures, protocols and security policies can be examined and tested both for QKD technology and beyond towards the realisation of a quantum internet. It can also serve as a platform where the quantum and the conventional communication communities can find a common ground. Enabling an open innovation ecosystem will allow for spin-off developments that will bring applications that may not yet be envisioned. There is also a

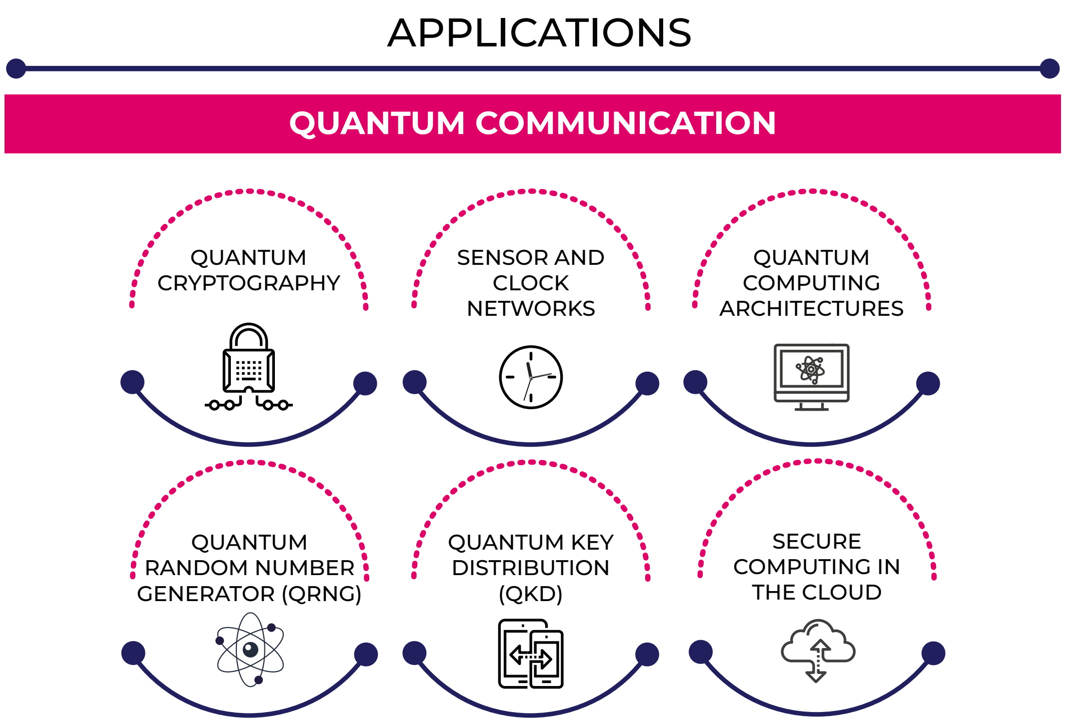
> **"The future of Europe's digital infrastructure will require the incorporation of quantum-safe solutions to ensure its integrity in the face of the risks to cryptographic systems presented by quantum computers."**

need to ensure the European work force will have adequate skills to exploit these new technologies. This would facilitate the technology adoption by a broader sector of society.

Some challenges in this area are the protection of critical infrastructure, such as energy services, service networks, repositories of personal information, security of data transmission between remote industrial and/or chemical plants, security of smart living environments in smart cities of the future. Quantum-safe cryptographic solutions for critical infrastructure represents a major challenge to the resilience of services and needs to be addressed in an holistic manner, by combining adapted solutions including QKD. To enhance the autonomy and security of a digital Europe and to strengthen trust, we need to raise awareness about this issue. There are also implications for the security of financial transactions as well as long-term security of health records and the uptake of e-government and e-services. The extension of such platforms to genuine global-scale networks through quantum repeaters and ground-to-satellite quantum communication will enhance the societal impact of quantum communication technologies and help maintain European information security infrastructures in the quantum era.

Research and innovation challenges

The future of Europe's digital infrastructure will require the incorporation of quantum-safe solutions to ensure its integrity in the face of the risks to cryptographic systems presented by quantum computers. To ensure technological leadership in the future, it is also necessary to remain at the forefront of R&D towards building a quantum internet. Digital infrastructure can also take advantage of new functionalities afforded by emerging quantum technologies to connect small quantum processors, or sensor and clock networks, using photonic links and entanglement. To keep pace with this,



there is a need to ensure a robust and sustainable supply chain of both people and technologies to build a European quantum industry. The following challenges need to be addressed to ensure a strong quantum future for Europe.

1) Quantum security The privacy, security and integrity of data, at rest and in transit, as well as quantum-secure access to it, is an essential part of the strategic vision for Europe and quantum technologies need to be an integral part of this and its subsequent development. Investment in infrastructure, including pre-commercial procurement, is required immediately and on a European level to kick-start the quantum security ecosystem in both the public and private sectors. Programmes for acquainting industry with quantum security and its implications are also required.

2) Quantum networks of the future offer long-distance and end-to-end quantum communication, further building on secure network functionality as well as connecting distributed quantum processors or sensor networks, which would enable radically new applications. Investment in R&D is required to ensure Europe's technological leadership in the future. In addition, R&D testbeds are needed to bring such technology out of the lab, as well as support to set future quantum internet standards by ensuring early adoption of, and training in, using European technology world-wide. The terrestrial and space segments will have different demands in terms of technological requirements and timescales, which will need to be coordinated and mutually harmonised.

3) Supply chain To grow a dynamic and robust quantum industry there is a need to invest in people, technologies, and commercial-scale fabrication facilities. Investment in new concepts and component development, ranging from basic science to engineering is essential to build the necessary innovation ecosystem. This needs to be complemented by inter-disciplinary education and training programmes to ensure a quantum aware workforce from academia to industry and decision makers. The development of applications, protocols and quantum software are also of paramount importance. SMEs throughout Europe must be supported to ensure that they can access fabrication and other facilities necessary to build quantum devices without the associated large-scale investment, reducing risks to investors, catalysing the growth of a new generation of quantum SMEs throughout Europe, and boosting the high-tech manufacturing sector in Europe.

Protection of data networks, health records, secure computing in the cloud

© sasun1990 / iStockphoto.com

1 Quantum security

Quantum cryptography is arguably one of the most advanced quantum technologies, with commercial products and prototypes for quantum random number generation and quantum key distribution already available. However, despite this, significant barriers to its widespread adoption remain. Challenges include reducing the cost of the technology, improving performance and closer integration in cybersecurity systems and communication networks. QKD pilot networks are needed to address these integration issues and to act as testbeds for the development of new applications and industrial standards. These are essential steps for the pan-European quantum network incorporating both terrestrial and satellite-based links envisaged in the Quantum Communication Infrastructure (EuroQCI) declaration signed in June 2019.

Quantum Random Number Generation

(QRNG) is one of the most practical quantum technologies, with diverse applications in cryptography, electronic gaming and numerical simulations. Given the pervasiveness of the deployment of random numbers, poor quality or compromised generators can result in significant long-term economic damage that is very hard to reverse. As quantum physics provides the only true source of randomness in nature, it can provide a very attractive solution for the generation of random bit streams. It is very likely therefore that QRNG will be one of the first quantum technologies exploited at scale.

It is envisaged that a variety of quantum approaches will be deployed in different scenarios. For example, high security cryptographic applications, numerical simulation and modelling will require high-rate, high-quality QRNG, while for IoT or mobile phone applications, low cost, size, weight and power will be the main considerations.

Quantum random number generators are already available commercially. However, they deliver relatively low bit rates (of the order of a few Mb/s) and are relatively expensive compared to competing non-quantum approaches. Fortunately, new schemes are emerging from the lab that can offer much higher bit rates in the Gbps regime. Furthermore, integrated photonics are providing a route to significantly reduce the cost of QRNG. The generation of high-quality random numbers relies also on the theoretical techniques needed to extract the entropy in the raw bit stream deriving solely from quantum effects, as well as the ability to implement these on different platforms and to integrate devices seamlessly into IT systems.

Looking to the longer term, device-independent QRNG, and its many variants that were born out of fundamental tests of nonlocality (Bell tests), can overcome some of the implementation security challenges and allow self-testing devices. Further theoretical and experimental research is required to improve the efficiency of these device-independent schemes.

Realising the full economic and societal benefit of QRNG will require Europe to establish a process for security evaluation and certification of devices, as this is essential for their use in many cryptographic applications.

Quantum Key Distribution

(QKD) offers a provably secure way to establish a secret key between distant parties, which can subsequently be used in various cryptographic applications.

The past decade has seen increasingly impressive demonstrations of fibre-optic-based QKD, as well as the first demonstration of QKD between a ground station and a low earth orbit satellite. Despite this progress, there remain a number of scientific and engineering challenges to be overcome before QKD can make a wide-ranging impact on everyday life. The challenges, described below, may be summarised as reducing cost, improving performance, integration with current systems, establishing a certification processes for quantum security devices and developing new techniques and protocols, which can expand the current functionality.

One of the central challenges for both fibre and free-space QKD systems is to lower the cost of the technology. This might be achieved by using new innovative designs that simplify the system, or by exploiting photonic integrated technologies, where components may be mass-manufactured cheaply on a semiconductor wafer. Chip-based QKD can also drastically reduce the size, weight and power requirements, which is important for many free-space applications, including satellites, and can enable new deployment scenarios such as in IoT.

Secure key rates may be improved through higher clock rates, more efficient components or protocols, or by multiplexing multiple quantum channels in parallel. This is important for both fibre optic systems where network deployment results in the secure rate being shared between many users, and for satellite QKD for which optical losses tend to be high.

Another important challenge is to extend the distance of a secure QKD link. Current technology allows fibre links of a few hundred kilometres using practical thermo-electrically cooled semiconductor detectors and up to 400km with low temperature superconducting detectors. Improvement in photon detection technologies is required to further extend the range of practical systems, as are the development and implementation of new protocols that can allow operation over 500km and beyond. However, since quantum signals cannot be amplified in the same way as classical signals to compensate the losses of the transmission channel, research on quantum relays and repeaters, discussed in more detail below, may eventually allow communication over longer distances. For satellite QKD, operation should be extended from low earth orbit to high earth orbit, as well as QKD between deployed satellites and their interoperability with terrestrial systems.

Ultimately QKD should operate as a component within a secure system, such as a secure communication infrastructure used in telecommunications or critical infrastructure. Realising fully integrated solutions that can operate in appropriate environments reliably is a considerable engineering challenge. Satellite based QKD systems present particularly extreme re-engineering challenges to cope with being launched into space and operating there.

Another important challenge to be addressed is the integration of quantum and algorithmic techniques to realise complete cryptographic solutions. This may include the combination of QKD and QRNG with other algorithm-based methods of quantum-safe cryptography. Although the resulting composites may not be information-theoretically secure, they may still provide long term security advantages over current methods. Collaboration between quantum and classical cryptographers should be encouraged to stimulate new quantum-safe applications.

The security of all cryptographic systems is based on a set of working assumptions. The unique feature of quantum cryptography is that none of these assumptions depend on the capabilities of an adversary. This is a highly desirable feature as assumptions about the adversary are difficult to test and impossible to control. On the other hand, the security of QKD does rely on the assumptions made about the QKD equipment and, in particular, how closely a real system implements the theoretical model. Research on the security of implemented systems (both fibre and free-space), including methods of attacking QKD systems and how to prevent such

"Europe must take the lead in developing standards for quantum networks, e.g. by utilising the QKD Industry Specification Group in ETSI together with the certification bodies and security agencies in each country."

attacks, is therefore very important. This should be used to establish a third-party security evaluation and certification process for QKD equipment in Europe.

Device-independent (DI) QKD is an alternative approach to implementation security using verification procedures which are independent of the device and its implementation. Fully DI protocols are based on Bell tests. They offer strong security but their experimental implementation is very demanding. Semi-device independent protocols have been developed to mitigate this. Some notable examples are measurement-device-independent (MDI) and detector-device-independent schemes that overcome attacks and manipulation of the QKD system's detectors, as well as the Twin-Field (TF) approach that combines aspects of MDI with the possibility of extending the point-to-point QKD distance. Although very promising, more research is required on protocols that can be implemented practically. Another avenue of investigation is to develop theoretical tools to handle a wider variety of DI-inspired protocols or better suited Bell tests, going beyond what has been demonstrated in laboratory settings.

QKD networks realised to date have mostly been distinct from the conventional telecom network and deployed on dark fibre carrying no other signals. To reduce the deployment cost, work is required on different schemes for multiplexing quantum and classical signals onto common fibres, as well as deployment on typical telecom architectures, such as point-to-point and point-to-multipoint links and with typical network components.

Realising a network for key distribution requires the development of a protocol stack for generation, routing and storage of key material. More research is required on different approaches to quantum networking, and, in particular, for efficient implementation of large-scale networks. There should also be an investigation of how QKD may be implemented in dynamic software-defined networks. Collaboration between quantum and conventional cryptographers will be important to ensure the overall system security.

Current QKD networks work under the assumption that an adversary is unable to access the intermediate nodes, as well as the end points. Although eventually quantum repeaters (discussed below) may allow this assumption to be relaxed, practical deployment requires investigation of how classical techniques (such as secret sharing) may be used to reduce the need for trust in the intermediate nodes. Practical implementations of MDI-QKD and TF-QKD will allow network deployments in which some of the nodes can be placed in untrusted locations and provide insight into the challenges faced for fully entanglement-based networks.

Quantum networks may also be extended using satellite QKD links to connect different metropolitan areas together. A first goal is to implement satellite-based QKD in low orbit to be used for governmental and commercial purposes. This will pave the way to the adoption of space-based QKD facilities by Europe. In order to complement and support such efforts, research and development is needed in interdisciplinary topics. Some of the challenges to be addressed include increasing performance, operation during daylight and bad weather, the development of cost-effective ground stations and the interfacing of ground stations and fibre optic networks. Longer-term goals include higher orbit and inter-satellite schemes.

To date, quantum cryptography has focussed mainly upon random number generation and key distribution. Although these are important primitives, from which many other cryptographic tasks and applications can be derived, there should be more research to discover new quantum crypto primitives, especially in a network context, as well as experimental work on implementations. Examples include quantum-secure authentication, digital signatures, bit commitment, position-based cryptography and everlasting secure storage, for example in securing genome information over multiple generations. These all require quantum and classical cryptographic techniques, as well as close collaboration with network engineers, system operators and end-users to ensure end-to-end security.

Europe must take the lead in developing standards for quantum networks, e.g. by utilising the QKD Industry Specification Group in ETSI together with the certification bodies and security agencies in each country. This is essential for ensuring interoperability of different components within a quantum network, which is important for fostering competition and stimulating the market, as well as ensuring that networks are implemented securely.

2 Quantum networks

The objective of realising quantum networks is to go beyond short distance QKD links and fully exploit the potential of quantum communication. The ultimate objective is to realise a global quantum internet. Here the current focus lies mainly on the first two challenges of realising quantum communication, namely to increase distances, and enable advanced application functionality for the end-user. However, many key elements developed for Quantum Security that improve accessibility (specifically, low loss switches or cheap photonic clients) also form key ingredients for large scale quantum networks.

Quantum networks that provide end-to-end entanglement offer advantages beyond those provided by short-range QKD networks. This could allow for long-distance quantum communication, which avoid intermediate trusted nodes, where necessary. Moreover, such networks unlock a host of other opportunities such as Bell-based fully DI QKD to build applications in the domain of security, or new application in metrology, sensing, distributed systems, and even secure access to a remote quantum computer in the cloud, for example to perform simulations of proprietary materials without disclosing the material design.

On a high level, realising a fully-fledged quantum network requires advances in several key technologies in an interdisciplinary effort between physics, computer science and engineering. First, a quantum repeater is needed in order to generate entanglement over arbitrary distances. Several candidate technologies (and hybrids thereof) exist for such repeaters ranging from multiplexed quantum repeaters using quantum memories (e.g. systems using quantum memories based on rare earth ions and atomic gases), repeaters which hope to ultimately create highly entangled cluster states to send information by forward error correction (e.g. using quantum dots), to quantum processing nodes, which next to storing quantum information, also function as quantum computers (e.g. Nitrogen Vacancy (NV) centres in diamond, Ion Traps or Neutral Atoms, Rydberg atoms, single rare-earth ions, …).

Quantum repeaters for long-distance communication (hundreds to thousands of kilometres), and in the quest for higher bit rates (leading ultimately to deterministic entanglement distribution), several scientific as well as technological gaps have to be filled. This effort spans from fundamental research to pure engineering challenges and can build on the trusted-node networks that are starting to take shape. While still being at an early technology readiness level (TRL), quantum repeater technology, including quantum memories for light, quantum light sources, single photon detectors and interfaces between light emitted from different sources, have over the past decade moved from theory to a wide range of proof-of-principle demonstrations with encouraging results for the future that may be needed to develop a fully-fledged quantum network that will allow secure multipartite communication over long distances. Three approaches are explored to implement such a network, the first one, based on quantum memories (e.g. rare earth memories, atomic gases), and more recent approaches based on large photonic entangled states for forward error-correction (e.g. using quantum dots). Finally, quantum processing nodes as used in end-node systems (see below) can also function as repeaters.

End-nodes that connect to a quantum network, and on which applications are executed, can range from simple photonic devices as in QKD, quantum processing nodes using noisy qubits, to fully fledged quantum computers with an optical interface (e.g. NV in diamond and other colour centres, trapped ions, neutral atoms, single rare-earth ions in solids) in a series of intermediary network development stages, where each stage unlocks further applications that can be run on such networks. We also need to interface end nodes and quantum repeater systems to enable maximum functionality of the network.

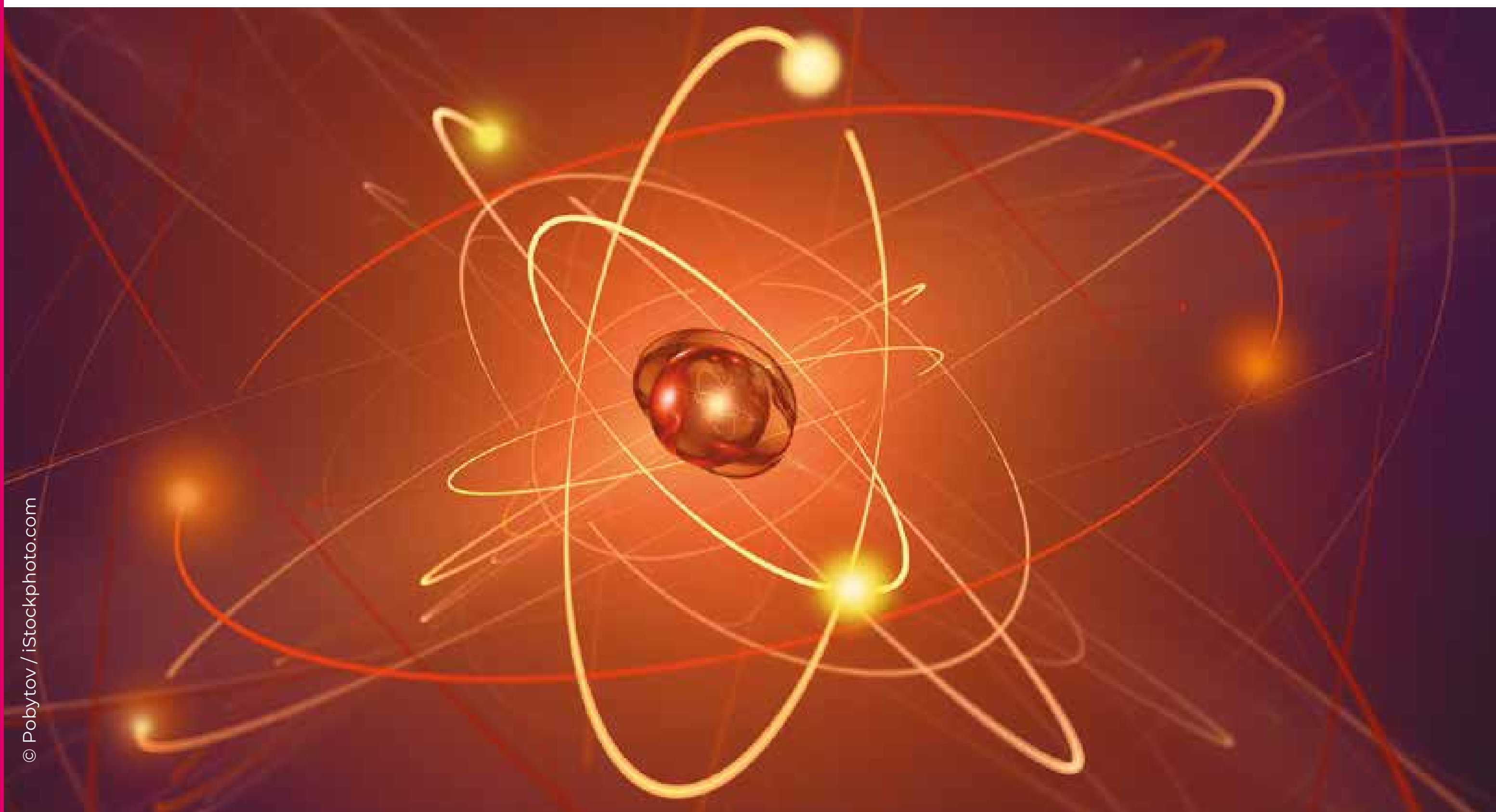
Quantum processing will increase the speed of calculation times and be used by quantum computers for the future quantum internet.

Enabling technologies

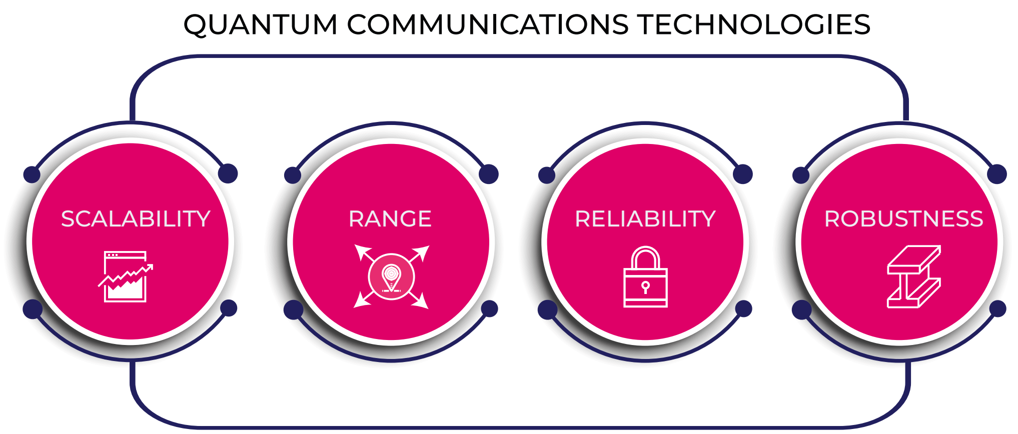
From a hardware perspective several key enabling technologies will also be required such as more efficient conversion to telecom wavelengths or between different quantum nodes, connections between satellite and ground-based systems, low-loss optical switches, and enabling technologies such as robust phase stabilisation. From a software perspective, this includes software to test and benchmark the performance of network developments.

Network architectures and control plane

Due to fundamental differences between classical and quantum communication, as well as technological considerations such as the limited lifetime of quantum memories, we also need a new fast and reactive control plane in order to scale such networks. This calls for resilient protocols and architectures that can mitigate errors in practice, as well as the development of a flexible quantum network stack that orchestrates the interplay between applications and hardware. Such a stack for entanglement-based schemes has



© Pobytov / iStockphoto.com



very different requirements than trusted-node-based quantum networks. These differences arise from performing genuinely quantum communication end to end, as well as timing requirements to combat limited memory lifetimes. A first such stack and early control protocols have recently been suggested in Europe, showing great promise to determine efficient control of large networks in the future led by European technology.

Software stacks are essential to ensure users can run present and future applications in an easy manner on such a network. This includes the development of a software stack for programming such networks in order to run arbitrary applications in platform independent software.

New applications and use-cases are to be developed to maximise the benefit of quantum network development to European Citizens. Importantly, for new, as well as some existing applications, it will be essential to determine precise requirements for feeding into the design process of early networks to be deployed.

Advancing quantum networks requires an extensive long-term and focused engineering effort in synergy with advancements in physics and computer science. To ensure the development of these new technologies and systems, platforms that enable innovators to develop and test new products and solutions are needed. The software industry could benefit from these testbeds by being able to develop new products without the need to invest in quantum hardware and fibre infrastructure themselves. The hardware industry could also establish interoperability between different physical systems and platforms.

3 Supply chain

The issues of scale, range, reliability, and robustness that are critical for quantum communication technologies cannot be resolved by incremental improvements, but rather need to be addressed by making them the focal point of the strategic research agenda. In addition, the form of ultimate solutions is far from known, and a large variety of possible approaches and technologies are presently pursued in parallel. As such, it is essential to perform an extensive requirements study, and significantly advance performance of all enabling technologies underlying quantum communication.
As appropriate for the requirements of quantum network systems, this study can include a targeted advancement of supply chain components including light sources, interfaces, quantum memories, and single

"The long-term success of quantum communication is reliant on pursuing both the immediate need for commercial ready QRNGs and QKD systems and demonstrating their operation in real-world networks."

photon detectors, while ensuring their interoperability. This includes making classical support technology — stable lasers, cryogenics, etc. — cheaper, smaller, more robust and more user-friendly, which will also benefit non-quantum applications based on the same devices and hence boost Europe's competitiveness in non-quantum technologies. The development of materials, single integrated solutions or hybrid integrated solutions that are miniaturised and scalable, fabrication and packaging solutions, are also key challenges, as is the development of new protocols, applications and software. All aspects of the supply chain components need to be studied, ranging from fundamental properties to engineering quantum devices and systems to interfacing these with integrated photonics, fast (classical) opto-electrical and FPGA systems, always with a view towards end-user applications and their operation in communication networks.

Essential supply chain components for Quantum Communication include the following:

Photon sources are key enabling technologies with important properties including stringent wavelength and bandwidth requirements, as well as purity and efficiency specifications, which characterise the brightness of the source and its usefulness for coupling the generated light into other systems. A range of directions that span different technologies and theoretical approaches need to be explored according to quantum network requirements, including probabilistic, heralded or deterministic source operation; generation of single photon states, entangled photon pairs, and multi-photon entangled states such as graph or cluster states; encoding in discrete or continuous variables of light; chip-based techniques for scaling up quantum photonic sources. Approaches to engineer the generated states of light and to optimise the amount of information carried by the single or entangled photons will also be useful.

Quantum memories, interfaces and switches typically involve light-matter coupling and provide an interface between quantum information carriers (quantum states of light) and quantum information storage and processing devices (atoms, ions, solid state systems). They are an integral part of a full-scale quantum information system. Improving the efficient interconversion between flying and stationary quantum systems, multiplexing the memory and interfacing with other physical systems, or other bandwidth regimes, will be crucial for advanced quantum networks. This also includes appropriate interfaces between ground and space networks.

Photon detection technologies need further improvements in single photon detection efficiency in conjunction with lower dark count rates, smaller timing jitter and higher detection rates. For continuous-variable systems, developing coherent receivers with properties compatible with high-speed operation in the quantum regime is necessary. It is increasingly important to maximise performance for all parameters in one device, nonetheless devices optimised for specific applications or operating conditions—e.g. cryogenic or room-temperature operation, on the ground or within a satellite—should be considered. Size and cost need to be addressed in relation to the target applications.

Analysis of applications, protocols and software is a key ingredient for secure and multi-functional quantum networks. For instance, QKD protocols exploring different photonic degrees-of-freedom (frequency, time bins, polarisation, path, orbital angular momentum), discrete modulation for continuous-variable schemes, DI protocols, or protocols exploiting relativistic effects, with the prospect of enabling affordable and practical services, well integrated into current networks and providing the highest security guarantees. In all such cases of protocol development, it will be necessary to set concrete security benchmarks and take into account realistic devices. Furthermore, classical cryptographic protocols and functionalities need to be incorporated into the larger quantum internet framework. Applications and use-cases need to be developed in close cooperation between industry and academia. As in the classical information and communication technology field, quantum software developments can be expected to become much richer and more dynamic in the long run, enabling an extended quantum software supply chain.

A comprehensive technological environment will be crucial for putting in place a sustainable supply chain for quantum communication. Research and development are needed in interdisciplinary topics. These include the development of high-rate QKD satellite payloads, space compatible components, advanced pointing and tracking systems, low-loss space-to-ground and inter-satellite links using adaptive optics, high bandwidth electronics, advanced data processing, optical devices such as efficient, low-loss modulators, low linewidth, stable lasers, and cryogenics. Scaling up quantum photonics will also require facilitating access to state-of-the-art foundry and packaging services and reducing the runtimes for efficient and cost-effective system characterisation. Furthermore, access to optical ground stations and management centres will be necessary for developing space-based networks.

In addition to the developments required for forming the technological basis of the quantum communication supply chain, it will also be crucial to develop related education and training, as for all quantum technologies but with a special focus for such applications.

Education and training

Developing and deploying quantum communication technologies requires a highly diverse skill set. New undergraduate and Masters programs for physics, computer science and engineering and space engineering students should be created in European universities, with a broad and interdisciplinary basis, involving electromagnetism and optics as well as quantum physics, as well as a foundation in computer science including network systems, cryptography and security. Also network technicians need training in such new technologies to ensure their deployment and maintenance. Both of these education trajectories greatly benefit from open development infrastructures.

Already at the high school level, students should be engaged with modern didactic methods to explain the concept of a qubit, teleportation, and to explore quantum technologies in simple programming exercises. With this, they can understand QRNG, QKD and more general quantum protocols, which in turn helps in the long run to establish quantum communication as common knowledge. This will increase trust of the society in this technology.

For the integration of quantum communication technology into existing network infrastructures, it is important to engage classical security, network and infrastructure experts. Open test and development infrastructures, as well the dissemination of quantum technologies at classical network conferences and communities (e.g. the IETF) greatly benefit such education.

Hackathon types of events for the development of quantum internet protocols are also a means of popularising these concepts among students and practitioners.

roadmap

Quantum Communication

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

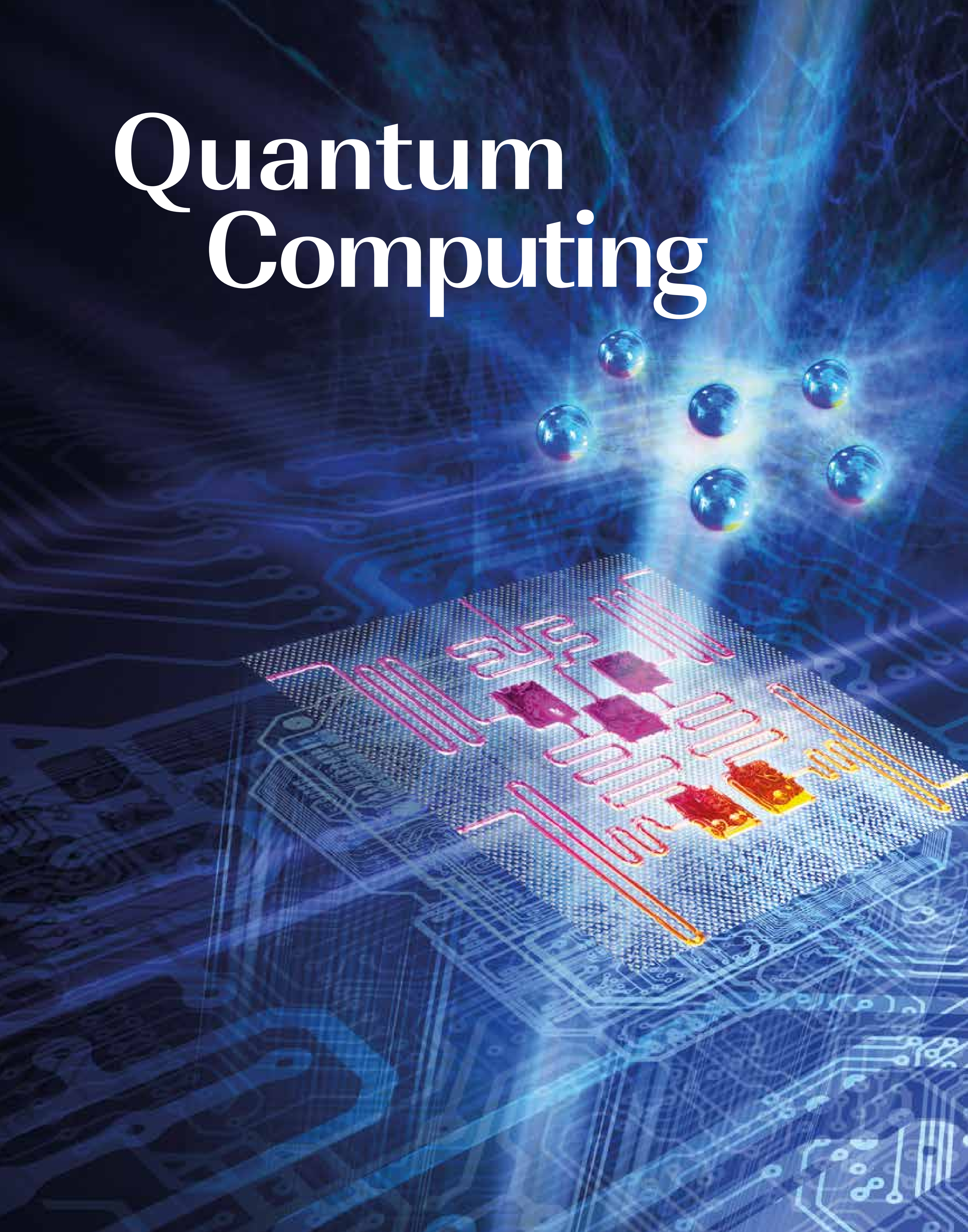
3 year vision

- Development of use-cases and business models, cost-effective and scalable devices and systems for inter-city and intra-city, as well as software stacks, including key management and application interface, for end-to-end security in the context of the European Quantum Communication Infrastructure (EuroQCI).
- Develop trusted-node network functionality and interoperability for fibre, free-space and satellite links.
- Develop satellite-based quantum cryptography for world-wide secure key-distribution using QKD protocols and networks with trusted nodes.
- Standards (even for low TRL devices and systems) and a means to engage wide spread adoption, certification methodologies for QRNG and QKD, in an engagement with stake-holders such as EURAMET, ETSI, CEN-CENELIC and DIN.
- Development of test suites for network performance, applications, protocols, and software.
- Demonstration of key critical components for satellite-based communication. A coordinated action at ESA/EU level for the components required for development of satellite QKD and preparatory actions for standardised QKD satellites and ground station components is needed.
- Advances in QKD, QRNG and quantum-secure authentication systems should demonstrate readiness for critical infrastructure, IoT and 5G. Trusted-node network functionality and interoperability for fibre, free-space and satellite links. End-to-end security over trusted nodes between EU countries.
- Improved device and component performance addressing parameter benchmarks of relevance for cryptography and network applications.
- Demonstration of an elementary link as a building block for a future quantum repeater.
- Demonstration of application protocols, including protocols on a network of at least two quantum processor nodes in platform-independent software.
- Demonstration of a platform-independent software and network stack on a quantum network consisting of at least two quantum nodes with memory.
- Launch of education activities engaging classical security and network practitioners and Masters courses in quantum technologies, including quantum communication, in universities throughout Europe.

6–10 year vision

- Demonstration of a chain of physically distant quantum repeaters enabling quantum communication over at least 800km using telecom fibres.
- Demonstration of a quantum network node of at least 20 qubits connected to a quantum network.
- Demonstration of quantum network applications in platform-independent software in the quantum memory stage of network development, or above.
- Demonstration of Device-independent-inspired QRNG and QKD.
- Demonstration of entanglement generation using satellite-based links.
- Open development infrastructure to educate and engage a future workforce, as well as classical security and network professionals and industry.
- Clear progress towards a robust supply chain for quantum communication.

Quantum Computing




© Quantum Flagship / H. Ritsch

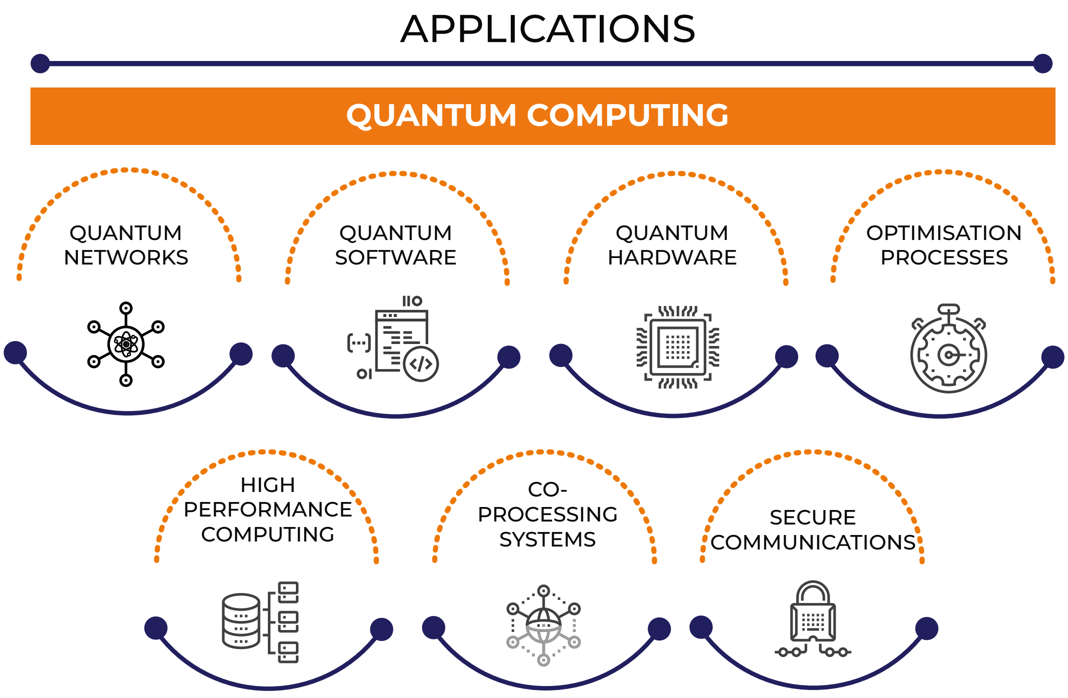
Quantum computers have the potential to solve tasks that we don't even dare dream of today and that classical computers can never solve. Completely new solutions for drug development, material design or areas such as financial services and transport will be possible.

Quantum Computing

A quantum computer is a device that harnesses the laws of quantum mechanics to solve certain tasks using therefore fewer computational resources than classical computers. The primary objective of system and hardware research is to fully develop such computers and to demonstrate their quantum advantage on a system level. Further objectives include the development of theory, quantum system software and dedicated algorithms to solve specific tasks, and the creation of interfaces between quantum computers, communication systems and classical computers. The construction of universal quantum computers with thousands of error corrected quantum bits would have a tremendous impact. It would allow us to solve problems that the most powerful supercomputers are not, and probably never will be, able to handle.

The basic building blocks of quantum computers have been prototyped and demonstrated with many different technologies, including trapped ions, superconducting devices, spins in semiconductors, neutral atoms, photons, and NV-centres in diamonds. As these technology platforms have different strengths and weaknesses with respect to the requirements for quantum computing, they merit, in part, continuous study, comparison and re-evaluation within the Flagship.

The development of commercially relevant products will start with intermediate scale devices without full quantum error correction, which will be engines for application development and used by a variety of stakeholders in industry, national labs and academia. Applications discovered for such intermediate devices (for example in approximate methods for quantum chemistry) will help support the development of larger-scale processors with error correction for universal quantum computing. Universal quantum computers will be widely applicable, including process optimisation, machine learning, business process optimisation, finance and inventory management, dynamic systems and digital simulation of quantum many body systems as they appear in different fields of physics, chemistry and material science.



Socio-economic challenges

The ability to process data fast will be a key driver for the future economy, where even marginal technological differences lead to valuable competitive advantages. As progress of traditional computing technologies is coming to its physical limits in size and power density, new paradigms are sought after. Quantum computing is a post von-Neumann architecture and post-Moore computing paradigm with the potential to provide substantial acceleration of selected computational tasks.

Europe has pioneered the key elements of quantum computing and its research groups are globally competitive. It is a focal point of the Flagship to transform this starting position into competitive complete systems and applications. This includes to play out and enhance specific European strengths such as institutional support, academia, research and technology organisations (RTO) and small and medium enterprises (SME), but also large companies and the European research programs. Research topics need to be combined with targeted training and funding for system integration as well as ensuring close collaboration between quantum hardware, system development and software specialists. The high demands on system integration of universal quantum computers requires fundamental research on quantum computing and a whole new hardware ecosystem with opportunities for spin-offs in areas including optics, solid state physics, electronics and computer science related topics. In this ecosystem, seed funding for both, small- and large-scale undertakings is a pivotal instrument.

Research on quantum theory, algorithms and application software is needed to discover new quantum algorithms and link quantum algorithms to use-cases in different fields. Research on algorithms is suited to engage with user communities, including industry and academic applications, for supplying and exchanging ideas and expertise for use-cases and to support start-ups to emerge with manageable risk and investment. On the academic side, quantum algorithm and software research are carried out at a few very visible research centres in computer and data science and in physics. As a consequence, quantum computing research needs to be fostered as a strong focus of computer science research within Digital Europe. This is an important step for the central challenge of training quantum-aware programmers and user communities.

Research and innovation challenges

One of the most challenging functions of the Strategic Research Agenda is to monitor the technology developments, both in terms of current performance and also future potential for scalability. In the first stage, the Flagship selected two technologies, trapped ions and superconducting qubits, to implement computing devices and platforms. Semiconductor and photonic qubit technologies appear now as further potential technologies to implement devices. One of the main challenges to achieve an efficient quantum computer is to increase the fidelity of the qubits and the gates. Another key area of development is the link between hardware, algorithms and applications.

A general objective is to create a healthy industry which has four key components: hardware, system integration, software, and the user communities. On the software side, there are two aspects, on one hand is the need for the development of an entire software stack that interfaces the system integration of quantum computing into an existing computing environment; and on the other hand, dedicated back-ends are required to efficiently control gates and access qubits. Ideally, the user software

"Research on quantum theory, algorithms and application software is needed to discover new quantum algorithms and link quantum algorithms to use-cases in different fields."

and its interfaces will be platform agnostic and system integration includes the dedicated error correction schemes and hardware.

Future directions of quantum computing research include the following main challenges:

1) Technologies, devices and platforms The development of candidate quantum computing platforms to understand key characteristics and explore ways to improve systems performance is essential for the European strategy on quantum computing. Improvements of materials and fabrication processes to enhance coherence of quantum systems; development of control systems for qubit initialisation as well as qubit and gate manipulations and qubit read-out; investigation of error correction methods; and new architectures and interfaces between quantum computers, communications systems and quantum memories are integral parts of this vision.

2) Software / algorithms / use cases The development of new quantum algorithms and its mapping to problems where quantum computers outperform classical computers is a major goal. This includes investigations on: theory of quantum algorithms and their complexity; development of software stacks to integrate quantum computing into current computing environments, and deployment of algorithms to characterise and benchmark different quantum computing platforms.

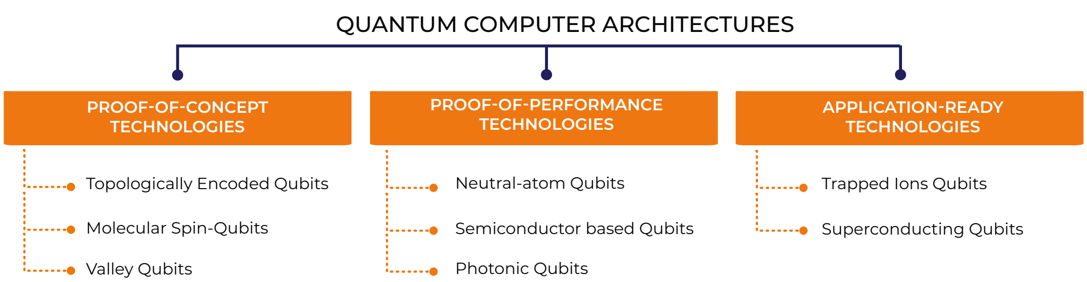
3) Supply chain Quantum computers rely on a broad spectrum of classical technologies where the European high-tech industry is world leading and offering an ideal starting point to create the required new ecosystem. However, the industry relies on seeding in areas such as education and training, standardisation, technology foundries and investment capital.

1 Technologies, devices and platforms

There are currently two leading quantum computing platforms in the Flagship based on different device technologies: Trapped ions and superconducting qubits. These two technologies satisfy the five required criteria for quantum computing defined by DiVincenzo:

1. A scalable physical system with well characterised qubits;
2. The ability to initialise the state of the qubits to a simple fiducial state;
3. Long relevant decoherence times;
4. A "universal" set of quantum gates;
5. A qubit-specific measurement capability.

Further qubit and platform types including impurity spins in solids, neutral Rydberg atoms, topological qubits and photonic qubits, which need to be considered as future candidates for quantum computing and require further development.



The respective quantum computing architectures can be roughly grouped into three categories:

a) Those technical approaches that show theoretical merit to be pursued for several reasons, yet have not satisfied the DiVincenzo criteria,

b) those systems that have fulfilled the DiVincenzo criteria, yet need to improve on system size and system control to find applications in advanced quantum algorithms, and;

c) quantum architectures that are at the threshold of fault-tolerant quantum computing with sufficiently large quantum registers to realise logical qubits for large-scale quantum computation.

a) Proof-of-concept technologies. Researchers come up with entirely new approaches to encode and manipulate quantum information – developments that are necessary and may lead the field in the years to come. Given the fundamental research nature of these investigations, these technologies are generally not yet mature. Technologies in this category look promising and, partially, have realised first steps to encode and manipulate quantum information – yet still require significant additional efforts to go beyond a conceptual stage. Technically, they have not in practice met all of DiVincenzo's requirements yet.

b) Proof-of-performance technologies. Quantum computing architectures in this category have demonstrated the necessary capabilities to implement quantum algorithms. A sufficient level of control has been achieved to initialise a quantum register, manipulate it with a gate-set compatible with universal quantum computation, as well as the capability to read out the register at the end of the computation. These technologies generally focus on improving the level of control regarding initialisation, manipulation and readout, as well as increasing the number of qubits they control. Technically, these have qualitatively met DiVincenzo's requirements, but need improvements in quantitative performance.

c) Application-ready technologies. Only a few quantum technologies have realised a level of control yet with error rates below 1 in 100 quantum gate operations and individual control of qubits in quantum register consisting of 20 and more qubits. These quantum computing architectures are employed to evaluate and implement the first applications of quantum computers. Furthermore, these technologies are the most likely to achieve a quantum advantage within the next few years.

A brief description of the respective technologies is provided below in alphabetical order:

Molecular spin-qubits

The ability to manufacture controlled magnetic molecules that put spins at a well-defined distance provides an attractive chemical platform for quantum computing. On the one hand, one can use hollow molecules such as the Buckminster-Fullerene C-60 as cages to trap electron spins, on the other hand one can prepare magnetic molecules with electron spins at well-defined positions and thus perform solid-state electron spin resonance. While this idea promises to solve the initialisation problem of spin resonance, fabrication and operation are still early in their development.

Neutral-atom qubits

Neutral atoms have been used successfully in optical lattices or tweezer arrays (with Rydberg atoms) for some of the largest scale quantum simulations to date, with promising applications also for quantum computing. Next to long coherence times and single atom addressability, they offer direct scalability towards 103-104 particle size systems. Today, they have already enabled some of the most complex and advanced quantum simulations with applications from material science, high-energy physics to statistical physics, and in many cases, already in computationally intractable regimes.

Photonic qubits for quantum computing

Integrated quantum photonics has enabled the generation, processing, and detection of quantum states of light in high component density, pro-grammable devices, supporting multi-qubit operations. With low decoherence properties, photonics provides routes toward Noisy Intermediate Scale Quantum (NISQ) era machines that outperform classical computers in solving industrially relevant problems. Manufacturing a fault tolerant universal quantum computer in photonics is now being pursued commercially. Single photon sources and photon-photon interactions, mediated through light-matter interaction, provide significant reductions in overheads in this compelling model.

Semiconductor based qubits

Semiconductor-based qubits make use of today's electronics technology. Employing nanofabrication techniques, quantum dots have been defined in which individual electrons can be confined. Also, isolated donors have been positioned in semiconductor substrates and used to trap individual electrons. In both cases, the spin of one or more electrons is considered the most promising qubit representation, since spin coherence is longer than the coherence of charge states or other degrees of freedom. These devices can be measured and controlled fully electrically, again much like transistors in today's digital electronics.

Superconducting qubits

Superconducting qubits are applied world-wide by many research groups and demonstrated at very different levels, from two qubit gates to integrated systems with 20 qubits and full software support. The technology is ready for small systems integration of quantum computing in quantum sensing or quantum communications applications. In the context of quantum computing in a NISQ regime, combined with an error mitigation scheme, chemical simulation has been demonstrated with results at very high precision.

Topologically-encoded qubits

Topologically protected qubits are prominently developed in semiconductor nanowires hosting Majorana zero modes at their edges but are also being pursued in other platforms. While the existence of Majorana Fermions seems experimentally established, operating them and meeting all of DiVincenzo's criteria is a current frontier. It is believed that owing to their topological stability, once this is met, high performance can be reached with little overhead. Several other platforms for topologically protected qubits are being pursued, including Strontium Ruthenate, Fractional Quantum Hall Systems, and Josephson Junction arrays.

Trapped ions

Trapped ion set-ups have been the first successful platform for the demonstration of quantum information processing (including Shor's algorithm for factoring numbers and quantum chemistry), with long qubit coherence times and high fidelities demonstrated for state preparation, single-, two-and multi-qubit gates, and state detection. All building blocks for initialisation, manipulation and readout have been demonstrated at the fault-tolerant threshold.

Valley qubits

Charge-carriers in 2D crystals have an additional electronic degree of freedom, the valley-index, characterised by a distinct momentum and quantum valley number. This quantum valley number can be used as a qubit to encode information when the electrons are in a minimum energy valley. Valley polarisation can be engineered in silicon.

Regardless of the status and category of a respective quantum architecture, all systems focus on the same three essential goals: more qubits to be controlled, with an ever-increasing level of control, and improved coherence time of the qubits relative to the quantum gate time.

Larger quantum registers are necessary to implement user-driven use-cases for quantum computing. State of the art systems have between 20 to 50 qubits, yet the challenges to achieve 1000s of qubits are yet to be solved.

Increased level of control, in particular the initialisation, manipulation, and readout of qubits with error rates notably below 1%. Such a high level of control will allow quantum researchers and engineers to push towards fault-tolerant quantum computing as well as scalable quantum control.

Improve coherence time relative to the gate time is probably going to be one of the most challenging aspects for quantum computing. The time quantum information can be stored in current system is generally limited. In order to implement, as long as possible, quantum algorithms, one will have to increase the storage time and/or increase the speed at which information can be processed. Ideally these tasks will be tackled while maintaining, preferably increasing, the level of control of the entire quantum register.

Research and development on these three areas – which can and ought to be pursued regardless of the architecture and category – will result in the following targets and milestones that give European quantum technologies a natural advantage compared to other nations:

Scalable quantum computing will require a collective effort in Europe to realise quantum registers that are not only suitable for 50 to 100 qubits, but show a clear-cut path towards 1000 qubits. The implementation of such a register, paired with a sufficient level of control, would set Europe apart on a global scale.

Fault tolerant quantum computing represents a collective research, engineering and quantum software challenge. Achieving fault-tolerance relies on choosing a quantum error correction code which is suitable for the dominant noise model in the system, and a level of control such that error accumulation can be effectively suppressed using quantum-compatible feedback routines. Finally, the routines need to be implemented sufficiently fast such that errors do not increase during the computation. The biggest likely challenge in this field will be to show a universal gate-set, the hallmark for arbitrary quantum computing, employing two logical qubits. While highly demanding, this achievement is nothing short of the equivalent to being the first nation to land on the moon.

Large-depth quantum computing, meaning the implementation of quantum algorithms with hundreds of gate operations, will be necessary to implement most customer-driven use-case realisations of quantum computing. These realisations will require a sophisticated application of error suppression, potential error correction, error-indication (with some post-selection) as well as tremendous efforts with respect to engineering suitable quantum architectures and control systems. While large-depth quantum computing might not seem as interesting from a scientific point of view, the realisation of a set of customer-driven use-case implementations would represent the rocket-launcher to initiate a quantum computing industry based in Europe.

These three targets can and should be paired seeing that several techniques developed in one branch complement research in another area, e.g. fault-tolerant encoding, error correction as well as error suppression techniques developed for fault-tolerant quantum computing will influence the achievements accessible in large-depth quantum computing.

2 Software / algorithms / use cases

Europe has a strong pre-existing theoretical expertise in quantum information processing. It is necessary to maintain and expand this know-how in order to create the necessary interfaces connecting the quantum computing hardware to the future general user communities. In the next years, numerous software advancements need to take place. First, designing novel quantum algorithms will play a pivotal role, since they define which problems can obtain an advantage through a quantum solution. Moreover, the algorithms need to be mapped to, and optimised for, specific use-cases, which is the interface for the user communities. In order to increase the users' base and ensure systems integration, a general-purpose, platform agnostic, software inter-face will be necessary. In the near term, hardware will operate in a NISQ regime, and thus dedicated control software is essential for optimal performance. For universal quantum computing architectures, fault-tolerant schemes need to be developed. The required error correction methods depend on the qubit platform technology and clearly belong to the hardware-close part of the future software stack. The close Europe-wide cooperation between theory and experiment as well as academia and industry, are essential to build a functional quantum computer, including algorithms, software environments and user interfaces.

Quantum error correction and fault-tolerant computing

Quantum computers will remain rather demanding devices, susceptible to disturbances and errors. Fortunately, methods have been developed to protect such devices against disturbances and imperfections, as long as these are small enough. Such devices already allow quantum computing in the Noisy Intermediate Scale Quantum regime, where "Noisy" stands for the not perfectly controllable qubits in an "Intermediate Scale" hardware consisting of ten to a few hundred qubits. These methods are constantly being improved and refined. However, for universal quantum computing, further development is needed.

Compilers & system stack

There is a big challenge on investigating and developing optimised compilers for quantum computing, in particular, ones that take advantage of the properties of each specific platform and minimise the required resources (number of qubits, circuit depth) for running a quantum computation. These compilers need to allow for hybrid algorithms where a part of the code will be addressed by a quantum processing unit while the remaining is performed by classical processing units (CPU, GPU, etc.). This is a necessary requirement in order to integrate quantum computing in a common computing infrastructure. Further, quantum computing needs to be transparently integrated in today's middle-ware stack.

Quantum algorithms and application areas

Initial proofs of principle, for example in quantum chemistry and optimisation have been successfully demonstrated. The community has, and continues, to develop a good number of quantum primitives to provide quantum advantages and many academic papers addressing quantum algorithms and their implementation on simulators and on NISQ hardware have been published. One of the challenges is to exploit and apply these techniques to practical and industrial use-cases. For the future, it is also important to establish criteria both on classical computers as well as on quantum computers in order to assess for which computational or industrial problems quantum computers offer an advantage. Such methods enable the quantum computer as an accelerator in a classical computing environment.

Some application areas have been identified, for example, the quantum simulation of energy versus bond-length for small molecules. Such calculations will potentially deliver the first short-term applications demonstrating an advantage of quantum computing, even in the NISQ regime. Other fields where quantum computing in the NISQ regime is applied include process optimisation, machine learning, business process optimisation, finance and inventory management and quantum many body systems as they appear in different fields of physics, chemistry and material science, as well as confinement calculations of quarks and gluons within QCD. It is important to have a close cooperation with industry and the large European research facilities in order to assess their computational needs and co-develop quantum algorithms.

Benchmarking quantum computers

For quantum computing it is important to go beyond the number of qubits. Benchmarking, verification and certification for different qubit hardware platforms typically considers a full range of critical parameters that influence the current and future capabilities of a physical quantum processor architecture. Such parameters include gate fidelities (not just in isolation, but also considering cross-talk), overall gate speed, qubit connectivity (e.g. large-scale arrays with nearest-neighbour couplings vs coupled nodes with all-to-all intra-node couplings), as well as metrics like qubit density and manufacturability. In the near- and in-termediate-term, the most practical benchmarks will likely derive from demonstrated performance of certain applications. To avoid optimising devices for a specific benchmarking method, a standardised suite of algorithmic benchmarks needs to be developed which takes different resource demands into account (e.g. number factored, molecule size). These benchmarks should allow one to address both, the current NISQ regime as well as fault-tolerant universal quantum computing, with a resolution that allows characterisation on a device, platform, or full system level. Benchmarking of quantum computers requires a global effort that integrates international research groups, industries and standards bodies.

3 Supply chain

Enabling technologies will be the "picks and shovels" (one of the most commercially successful economic branches during the gold rush) of quantum technologies. Leadership in quantum technologies hinges as much on these enabling technologies as it does on integrating systems for entirely new applications.

Technical areas

It is of crucial importance to ensure access, within Europe, to the key enabling technologies and a suitable, reliable supply chain. This includes photonics (lasers, light-distribution, fibre-technology), electronics (in particular high-speed phase-coherent control of RF and microwave fields), coherent interconnects operating at the single photon level (e.g. opto-mechanical interconnects between superconducting circuits and photonic networks; to a large extent as integrated cryogenic electronics), high-capacity cryogenics, as well as micro- and nano-fabrication capabilities for several materials to realise semiconductor quantum dots, single photon emitters, novel ion-traps, atom chips, as well as superconducting systems. This also includes quantum software development capabilities for both low-level (hardware-close) control software as well as industrial use-cases on the application level.

The ecosystem

The successful creation of spin-offs or engaging small companies for quantum computing platform developments is a challenging task which needs to be considered by the research programs. Small entities rely on access to research facilities and infrastructure, investment capital and open foundries. The motivation for large companies to join research programs relies on institutional actions (European and national programs) and communication. A dedicated quantum computing infrastructure initiative would address these challenges and accelerate the development of an innovative ecosystem and training ground.

"Benchmarking of quantum computers requires a global effort that integrates international research groups, industries and standards bodies."

roadmap

The roadmap has two stages. The first one describes milestones to be reached within the next three years. The second stage contains medium-term milestones which are expected in the timeframe of six to ten years.

Quantum Computing

3 year vision

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

Some specific challenges include:

- Demonstrate practical strategies for a future fault tolerant universal quantum computer.
- Identify algorithms and use cases where quantum computing has an advantage.
- Enhance the NISQ processing regime with error mitigation methods, enabling deeper algorithms.
- Engage chip foundries and other hardware providers, public or industrial, as well as the software industry, existing companies and start-ups.
- Initiate academic and industrial research contribution on quantum device physics, qubit and gate control, leveraging optimal control theory for faster and more robust gates, photonics, RF-electronics, cryo- and superconductor electronics, system engineering, integration and device packaging,
- Develop HW-agnostic benchmarking of NISQ based systems, quantum application and algorithm theory, software architecture, compilers and libraries, as well as Electronic Design Automation (EDA) and simulation tools.
- Coordinate industry, foundries and other infrastructure entities on quantum computing.
- Stimulate EU-wide joint actions with other fields such as material science, theoretical physics, cryo-physics, electrical engineering, mathematics, computer science and high-performance computing.
- Address standards bodies (EU, international).
- Develop educational tracks on quantum technologies and its applied fields at universities.

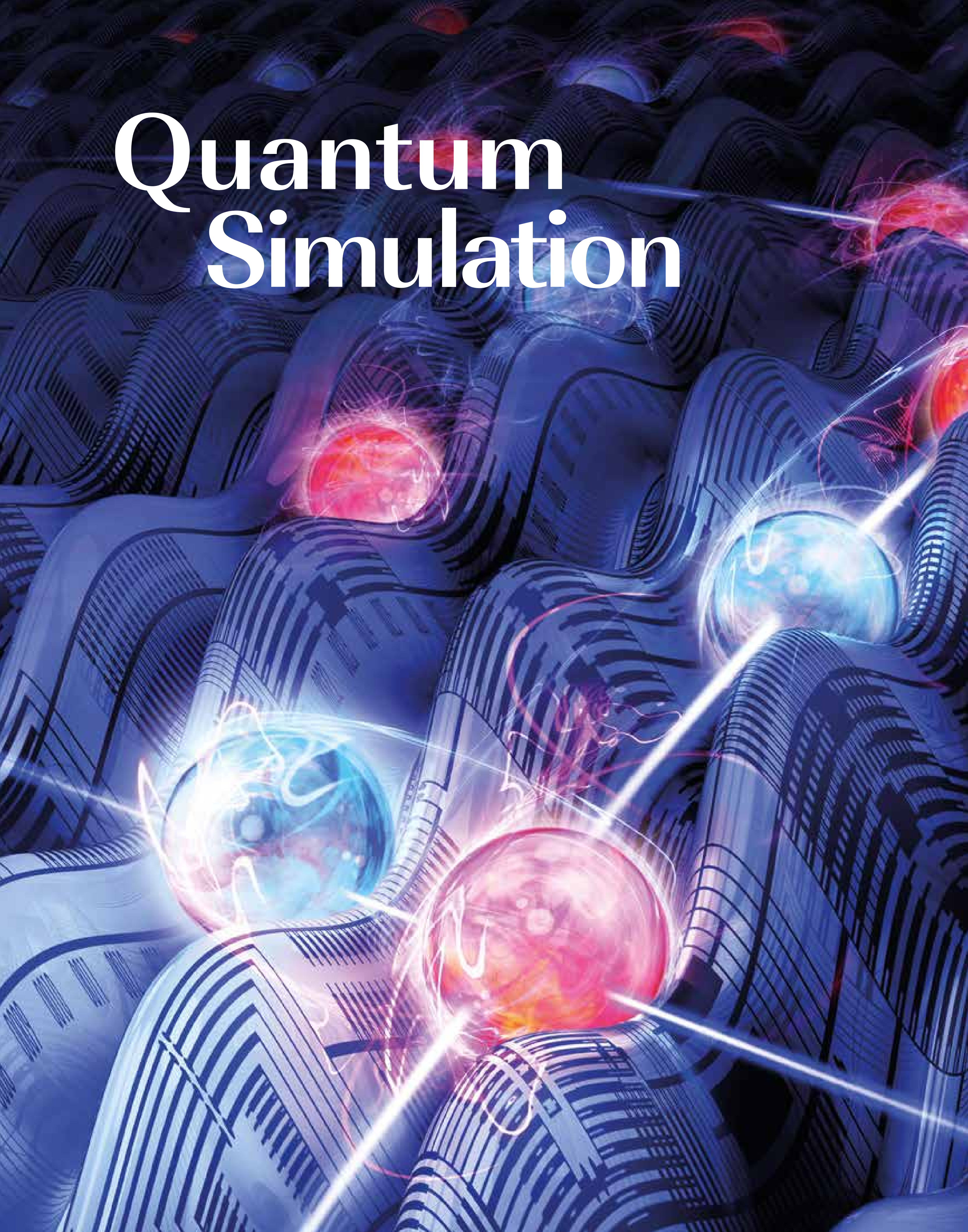
6–10 year vision

Scalability is seen as a key for the medium-term. The systems integration will require a stronger ecosystem which is able to deliver components, including assembly and package technology, device and systems development, and integration. For this integration task a European-wide approach for facilities and a strong involvement of engineering capabilities are absolutely required. In this time, a transition from NISQ to error corrected universal quantum computing regime is expected. This requires a massively higher number of qubits, built-in quantum error-correction and even more theoretical investigations on algorithms.

Some specific challenges include:

- Demonstration of quantum processors fitted with quantum error correction and robust qubits with a universal set of gates to outperform classical computers.
- Demonstration of quantum algorithms with quantum advantage.
- Establishing foundries able to manufacture the required technology, including integrated photonics, cryogenic and superconducting electronics. as well as
- Supporting established and new instrument builders and software companies.
- Coordination of research, development and integration on materials, quantum device physics, qubit and gate control, quantum memories, photonics, RF-, cryo- and supercon-ductor-electronics, system engineering and device packaging.
- Expanded suite of quantum algorithms for software and hardware-agnostic benchmarking, including digital error corrected systems, and optimising compilers and libraries.
- Demonstrate automated system control and tune-up.
- Develop an integrated tool-chain (design to processing) and module libraries for integrated optics, cryo- and superconductor electronics, including coherent optical-electronic converters.
- Coordinate EU-wide joint actions with other fields, such as material science, theoretical and cryo-physics, electrical engineering, mathematics, computer science, and increasingly, scientists working in potential application fields and industry (small, medium and large entities).
- Address standards bodies (EU, international)
- Integrate industry (SME and large companies) and foundries.
- Engage with the EU infrastructure, the large labs and programs, and the research and technology organisations (RTO).

Quantum Simulation




© Quantum Flagship / H. Ritsch

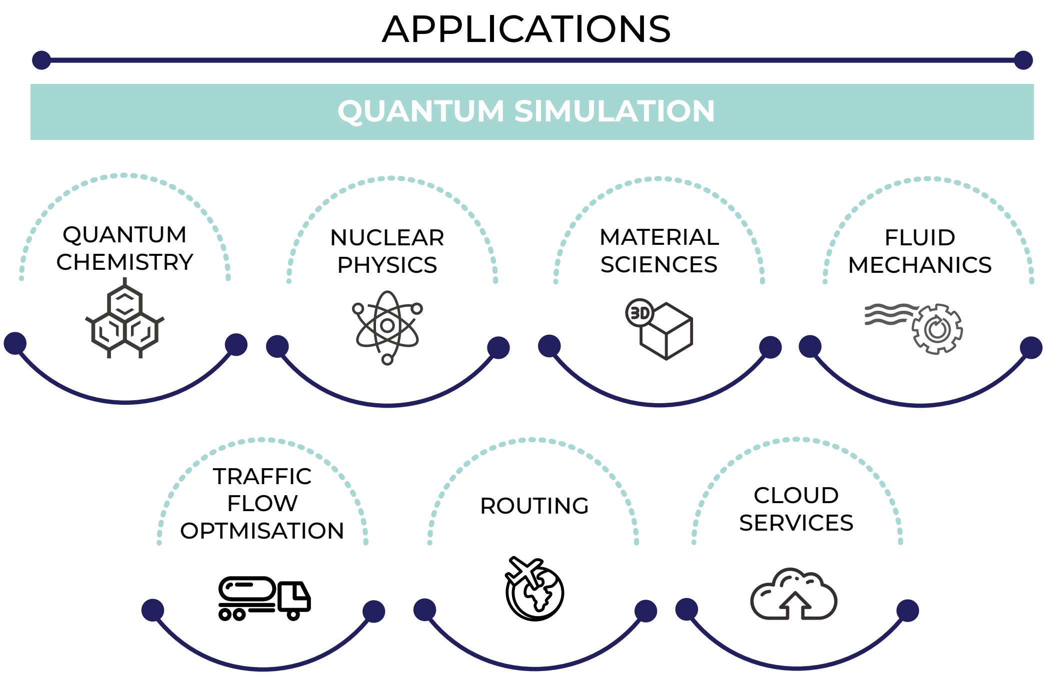
Quantum simulators promise novel insights into strongly correlated quantum matter and at the same time offer near-term perspectives of tackling computational problems on quantum devices without quantum error correction.

Quantum Simulation

Quantum simulators are highly controllable quantum devices that allow one to obtain insights into properties of complex quantum systems or solve specific computational problems inaccessible to classical computers. The basic ideas go back to the work by Richard Feynman, who noticed that precisely controlled quantum systems could serve as simulators even in situations intractable for classical devices. Generally speaking, quantum simulators allow one to solve complex quantum problems with very high levels of accuracy. It allows one to predict static and dynamical properties of complex quantum materials or to solve optimisation problems. In contrast to full fault tolerant quantum computers, quantum simulators are devices that are anticipated to operate largely without the necessity of quantum error correction

The notion of *tuneable* or *controlled* quantum systems is at the heart of a functioning simulation platform, rendering efforts towards an increasing level of control a central focus of current research activities. With the recent technological advances, reliable large-size systems can be realised, e.g., systems of ultracold atoms in optical lattices with ten thousand or more constituents interacting with each other, arrays of Rydberg-excited atoms in optical tweezers, or single photons propagating in arrays of waveguides or nonlinear resonators. On these platforms, quantum states can be precisely initialised as well as being evolved under the action of quantum operators to create entangled resources. In this way, e.g., properties of quantum mechanical ground states can be characterised, or the dynamics of interacting systems out of equilibrium can be controlled and probed in a way that is beyond the reach of known classical algorithms.

Today's quantum simulators are already well developed. They solve specific scientific problems, which go beyond the currently classically accessible limit. One severe limitation of classical approaches is the required memory to encode quantum states with increasing constituent numbers, making already a system size of about 40 constituents hard to compute. A key step is to leverage this potential for near-term applications with significant impact on the scientific and commercial sector.



The Quantum Flagship provides the framework for this task. Important targets for the empowerment of quantum simulators are to achieve:

(a) higher levels of control,

(b) higher state-preparation fidelities,

(c) large-size systems, and

(d) programmability at lowest entropies.

For these future developments, quantum simulator capabilities will range from the approximate solution of optimisation problems to the solution of problems in quantum chemistry, nuclear and high-energy physics, or materials science. Furthermore, quantum simulators have by nature a general scope; they can be used for general problems as long as these can be mapped into an equivalent physics model.

Different approaches to quantum simulation can be classified as follows:

- **Digital quantum simulators** approximate local quantum dynamics in a stroboscopic fashion, involving a variant of the Trotter formula. Digital quantum simulators are intrinsically programmable due to the approximation of the target dynamics starting from a few basic building blocks.
- **Analogue quantum simulators** emulate other quantum systems under precisely controlled thermodynamic and interaction conditions. In particular, these simulators go beyond a computational paradigm based on qubit systems, for example, by working directly with fermionic particles. This makes them less general, but significantly reduces the over-heads and the requirements in terms of control.
- **Heuristic quantum devices** such as programmable quantum simulators, annealers, variational optimisers, or variants of quantum approximate optimisers and other noisy intermediate-scale quantum (NISQ) devices aim at providing approximate solutions to optimisation problems. Here, often both a classical and a quantum component comes into play in hybrid schemes operating without quantum error correction. The potential of these devices for technological application is high, but a significant amount of ground work is still required to understand their potential.

It is important to realise that in view of the fact that efficient quantum computing with fault tolerant error correction and scalable gate operations remains a scientific and technological challenge, the development of quantum devices focuses on the use of imperfect moderate size quantum processors without error correction, yet with a quantum advantage. Quantum simulators are such devices without error correction. In this sense, there is an overlap between quantum computing and quantum simulation. While quantum simulation feels naturally inclined towards analogue quantum simulation, it includes naturally a part of universal digital quantum computing. While the division between these two pillars remains fuzzy, the interferences and overlaps between these fields are being managed and creatively employed.

Socio-economic challenges

The efforts in quantum simulation are expected to have a major impact on several socio-economic challenges.

- Europe has a strong chemical and pharmaceutical industry. This industrial base is extremely important for many key technological challenges of the future. Industries in Europe can greatly benefit not only from improved possibilities to simulate material properties to enhance their performance but also from shaping novel synthetic quantum materials with no equivalent in nature. Therefore, connecting the Quantum Simulation pillar to industrial customers can further boost European innovation.
- The efforts on quantum simulation contribute to making Europe an attractive

"Quantum simulators are expected to provide unprecedented insights into complex quantum systems and materials with potentially important applications for end-users."

region for highly innovative research and business, accelerating their development and take-up by the market. This applies in particular to mid-term devices that promise to offer solutions to problems of end-users in optimisation, routing, and scheduling. The potential of applications is expected to contribute to a competitive European industry, both in hardware and software, and to position Europe as a leader in these fields.

- These efforts are expected to consolidate European scientific leadership in a field of re-search and development where it has already achieved a world leading position. This leadership is also expected to have a decisive, positive impact on training activities. It will bring the concepts of quantum mechanics closer to the centre of society, which by itself has the potential to spark new ideas and approaches to problem solving.

Challenges are arising from establishing a closer contact with the end-users to find the most promising applications for near-term devices. This especially applies to the currently most developed non-qubit based, simulators. To maintain the leading position Europe has established, and in order to bring efforts to a new level, there is a need to ensure a sustainable supply chain of both technologies and human resources to contribute to building a European quantum industry.

Research and Innovation Challenges

Europe is particularly well placed internationally to take a leading role in the development of quantum simulators, given the impact it has had on the field so far. Quantum simulators are expected to provide unprecedented insights into complex quantum systems and materials with potentially important applications for end-users. For this to be possible, significant research progress is required, in a highly competitive environment.

In the following we will summarise some of the main challenges that need to be addressed.

1 Platforms and implementations

Quantum simulators naturally cover a large variety of platforms. There are not only platforms to implement digital quantum simulation and heuristic quantum devices, but also different platforms for realising analogue quantum simulation. As the latter aim at directly mimicking the target system, the spectrum of platforms is large.

Ultra-cold atomic and molecular quantum gases constitute one of the most prominent and promising platforms for quantum simulators. There are a number of architectures being developed with increasing ability to tackle complex problems. These include systems of ultracold atoms in optical lattices with short- and long-range interactions, and continuous systems confined in atom chips. Recent key achievements have been the realisation of the superfluid-to-Mott-insulator transition, entanglement propagation in spin systems of dipolar atoms, and the first quantum simulations of the Fermi-Hubbard model. Besides dipolar atoms, strong coherent interactions spreading over long distances have recently been created in reconfigurable arrays of individually trapped cold atoms, excited to Rydberg states. This platform allows for programmable analogue and digital quantum simulators. Moreover, their fast data rate renders them also prime candidates for the implementation of heuristic quantum approaches. Future work will aim at higher levels of control, larger systems, and better read-out techniques, beyond what is possible with present quantum gas microscopes. Another outstanding challenge is the need for lower entropy, i.e. higher fidelity, initial state generation.

Trapped ions are a second key platform for realising state-of-the-art quantum simulators. The extraordinary level of control of motional and internal quantum states enables the realisation of prototypes of both digital and analogue quantum simulators, featuring programmable short-range and long-range interactions. Rydberg states can also be realised in systems of trapped ions. A key challenge is to scale up the system size – possibly using segmented traps – and to improve coherence times. Recent efforts include verifiable variational quantum simulations, opening up perspectives of achieving near-term programmable quantum devices.

Superconducting qubits offer a wide range of applications in quantum simulation. It has become clear that superconducting devices allow for quantum simulations under highly controlled conditions, specifically when realising qubits in a one-dimensional chain with adjustable coupling between every pair of qubits of a superconducting-qubit architecture that allows for a tuneable qubit-qubit coupling platform. For this type of quantum simulation platform, system sizes are comparably small, but at the same time offering large degrees of control.

Photonic simulators make use of single photons in complex networks to generate many body entangled states. These single photons are generated by single photon sources or emerge from strong non-linearities in lattices of resonators. These simulators are scalable and integrated platforms, some compatible with the most advanced opto-electronics and nanotechnologies. Solid state, 2D materials, as well as atomic single photon sources and non-linear resonators required for such applications are rapidly reaching maturity.

There are a number of other prominent quantum simulation platforms being developed and refined, including architectures of polariton condensates in semiconductor nanostructures, circuit-based cavity quantum electrodynamics, arrays of quantum dots that already have commercial applications in quantum annealing, and photonic platforms. Other prominent architectures include spins in solids such as ensembles of colour centres in diamond or the use of colour centres to control other electron or nuclear spin ensembles for the purposes of quantum simulation.

Figures of merit and benchmarking

There are several figures of merit for the success of quantum simulations depending on the specific path used. For digital quantum simulators and variational approaches, figures of merit of average gate fidelity of individual quantum gates apply similarly to quantum computation. For circuits as a whole, the quantum volume gives rise to a good heuristic figure of merit in its combination of connectivity, number of qubits, average gate fidelity and number of gates. For analogue quantum simulators, different figures of merit can be relevant depending on whether the application is more simulation- or solving-oriented. These include e.g. coherence, speed of entanglement propagation, and local or global entropy.

The validation and verification of quantum simulators requires benchmarking against classical methods, such as tensor-network methods, brute-force simulations, or techniques to derive lower bounds to ground-state energies. Another way to verify quantum simulators is a direct comparison of simulation results from different platforms.

2 Exploitation and use-cases

Key applications connected to the three types of simulators are:

Analogue quantum simulators offer Analogue quantum simulators offer unprecedented insights into strongly correlated quantum systems. They have the ability to account **for complex interparticle interactions, e.g. the long-range and anisotropic interactions, relevant for quantum magnetism or to mimic biological-relevant cases. Furthermore, they allow for tests of novel situations by engineering correlations and entanglement among particles**. One can distinguish between static and dynamical quantum simulators. The former assesses static properties, i.e. ground state or thermal properties, such as ground state properties of the fermionic Hubbard model that promises in-sights into the functioning of high-temperature superconductivity, which remains one of the big mysteries in solid-state physics. Dynamical quantum simulators explore how quantum states evolve, such as out of equilibrium properties of many-body localised systems that violate expectations of quantum statistical physics. Both problems are outside the reach of classical computers.

Digital quantum simulators will focus, in the short-term, on algorithms that require only a small number of operations. This is necessary because these universal simulators are currently relatively error-prone, and each operation is performed error-free only with a certain probability (fidelity). Gate fidelities of 99.5% – 99.95% appear realistic and are required for various applications.

Hybrid quantum simulators are based on algorithms that require a close interaction

Applications include traffic flow optimisation, aspects of computational fluid mechanics or the approximation of solutions to routing and scheduling problems.

© Britus / iStockphoto.com

between quantum and classical computers. Here, the quantum system is used as a sub-module of an otherwise classical algorithm. While it remains to be established in what precise way these quantum simulators can have a quantum advantage, the integration with classical numerical methods allows the optimal preparation for the material problem; the separation into an efficiently classically-treatable part and one that isolates the quantum mechanical complexity in the form of strong electronic correlations. Methods of this kind are also available in limited form in current quantum chemistry. For example, the CASSCF (complete active space self-consistent field) method is well known. The defined active space is severely limited on classical computers. On quantum simulators, however, significantly larger spaces can be selected. This promises substantial improvements in the accuracy of material simulations. Current methods allow at most for a qualitative study which substantially limits the application of simulation methods in material development. Higher accuracy that allows for quantitative predictions could have a vast impact in the development of new functional materials and drugs.

Programmable near-term quantum simulators, coherent quantum annealers, and near-term devices without quantum error correction promise applications in solving or approximating solutions to optimisation problems and may be helpful in realising instances of quantum machine learning. Approximate solutions to optimisation problems may computationally outperform classical computers. This includes applications for traffic flow optimisation, aspects of computational fluid mechanics or the approximation of solutions to routing and scheduling problems.

In general, the efforts to develop controlled quantum simulators provide an alternative viewpoint on many relevant problems and has the potential to lead to important new scientific discoveries and technological advances.

3 Supply chain

The key to success in quantum simulation is related to enabling technologies. Indeed, a European leadership in quantum simulation can be maintained if such enabling technologies can be put into good use in new applications of quantum technologies. Given that for quantum simulation, various architectures are being considered, the relevant supply chains largely depend on the platform chosen. The supply chains include the development of novel photonic components, of innovative fast and efficient detectors, of techniques for the manipulation of ultracold atoms and ions, of electronics, high-capacity cryogenics, and optimal control techniques. It also includes capabilities for fabrication of the most advanced materials (i.e., quantum dots, layered materials, colour centres) when it comes to solid-state based platforms of quantum simulators. On the side of soft-ware and compiler development, new ideas of variational eigen-solvers and of quantum-classical hybrids are part of the supply chain, in order to fully develop the potential of quantum simulators without quantum error correction in its use in mid-term practical applications. A quantum computing and simulation infrastructure initiative would provide an excellent and timely focal point for all of these challenges. This could allow simulation as a service in a testbed environment, not only for technological development but also for seeding and consolidating the supply chain, as well as facilitating a broader contact with end-users to further expand the application portfolio, and providing a training ground for a wide range of stakeholders.

roadmap

3 year vision

Quantum Simulation roadmap

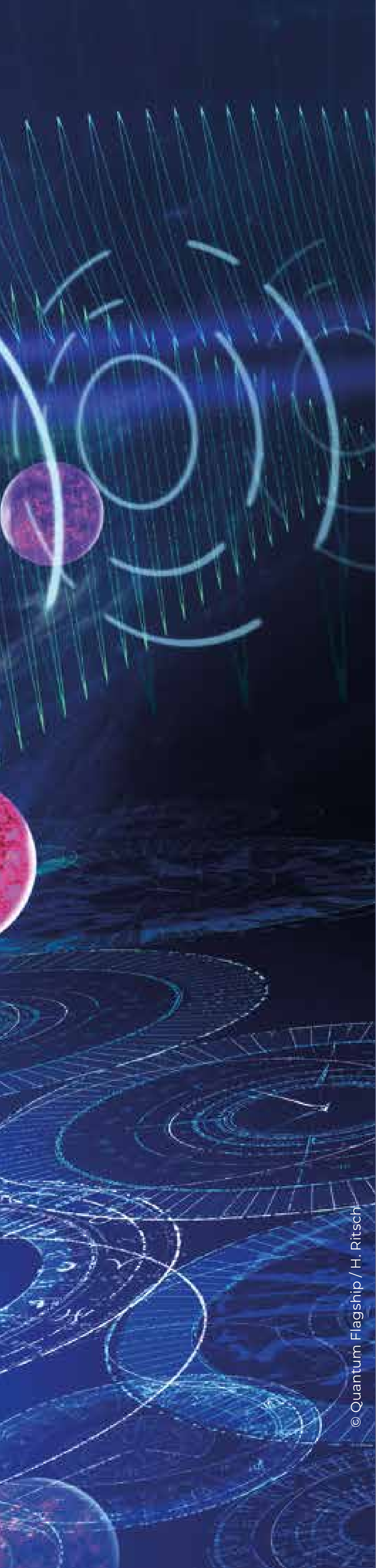
The perspectives for quantum simulation are concentrated around learning properties of physical systems and making use of programmable quantum simulators to solve near-term problems of end-users. Applications can be identified in solving practical routing and scheduling problems, and in offering cloud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

- Demonstrate the "quantum advantage" in simulation for a range of tasks – this is seen as an important milestone, but not an application as such.
- Notions of quantum machine learning are widely regarded as highly exciting and fit quantum simulation goals and also the interest of end-users. Here, near-term programmable devices and quantum simulators promise to offer a speedup in instances of machine learning problems, including quantum kernels and quantum classification schemes.
- Overall, there is a need to improve levels of control and scalability, achieve a further entropy reduction in various platforms, and explore the potential of programmability of quantum simulators. There is an imperative to develop quantum-classical hybrid architectures and to bring various platforms of quantum simulators to a level so that they can be accurately compared on the same test problems.
- In order to develop a vision for the coming three years, it is important to consider the precise needs of industrial partners and end-users. Stakeholders should contribute to identify the problems that are interesting for them to justify better scope and key goals of quantum simulators. For this, close interaction with industrial partners is key; efforts should be close to the needs of companies with quantum simulation applications. All stakeholders should be brought together to identify further applications in the study of complex quantum systems and end-user applications.
- Efforts to expand and strengthen the supply chain, the development of key enabling technologies and improving notions of control of quantum simulators as well as entropy reduction and interaction engineering should be supported throughout.
- It is widely acknowledged that notions of certification are again key to a good functioning of quantum simulators. As in all other applications of quantum technologies, certification, benchmarking and tomographic recovery seem highly important.

6–10 year vision

- The most important element of a sustainable vision for the field of quantum simulation is to establish a close link to end-users and to develop more practical applications. Quantum simulators are very well-placed to achieve this aim. Fault-tolerant quantum computers offer a wide range of applications, but they will most likely not be available within this time frame.
- Programmable quantum simulators and other near-term devices without error correction, in contrast, are expected to offer near-term practical solutions. This requires significant research and development, especially on the hardware side to achieve quantum simulators offering a higher degree of control and programmability.
- From the perspective of learning physical properties, applications in quantum chemistry are among the most exciting. The demonstration of quantum simulation platforms unambiguously outperforming classical computers, solving problems in complex quantum systems and materials science with quantum simulators should be supported. It is also generally acknowledged that a close and sustained dialogue with companies is required to generate and maintain an interest in investing in quantum simulation.
- The efforts on hardware development are accompanied by software developments with notions of computer science that are expected to play a greater role also in research and innovation. Indeed, close interactions with material science and the study of complex quantum systems on the one hand and of algorithmic developments in optimisation problems on the other, are anticipated.
- A number of quantum software companies have emerged within Europe; it is an important incentive to realise quantum algorithms and algorithmic components on near-term programmable quantum devices that can be seen as being quantum simulators. It is important to build a bridge between the industry and research on quantum simulation and computing. It is key to translate the problems of industry in the language of our computing and simulation paradigms. In this context, it is emphasised how important it is to create an industry-targeted roadmap.

Quantum Sensing and Metrology



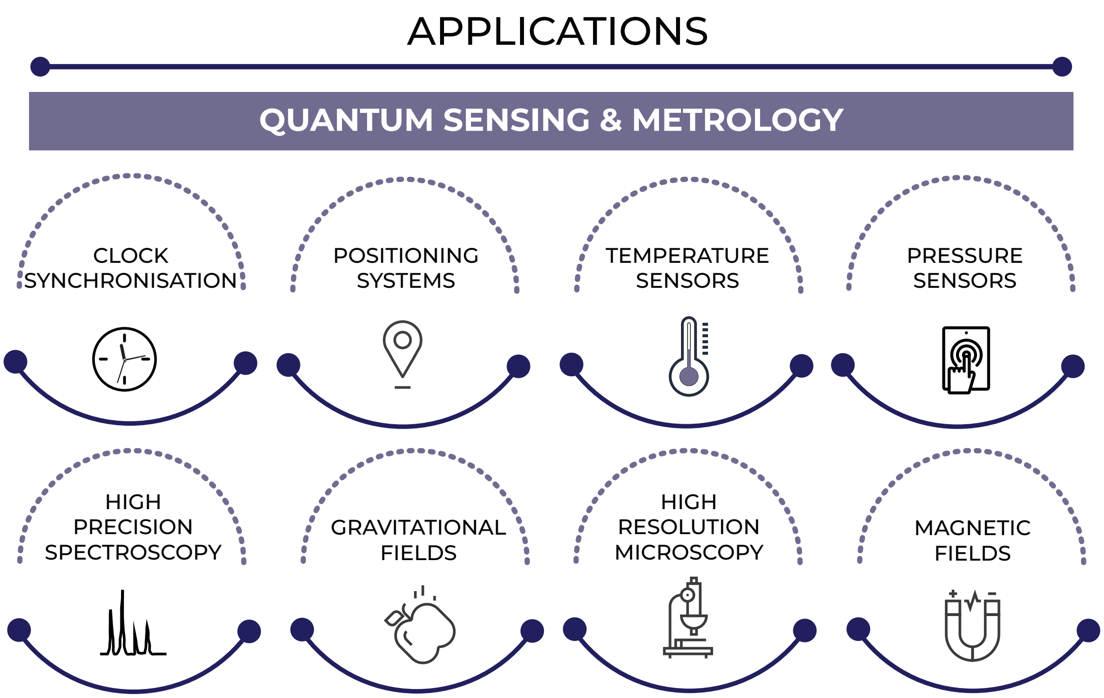
The second Quantum Revolution will result in quantum sensors that outperform existing sensors in many aspects, such as size, operating environment, sensitivity, specificity, statistical or systematic uncertainty, traceability, calibration intervals, lifetime, power consumption, reliability, or security, unleashing a wealth of novel applications.

Quantum Sensing and Metrology

The impact of quantum sensing and metrology technologies is broad and considerable, with many applications in every-day life. Technologies range from positioning systems, clocks, gravitational, electrical and magnetic field, force, pressure, and temperature sensors, quantum electrical measurement standards, nuclear magnetic resonance (NMR), ultra-high-precision spectroscopy and microscopy, to optical resolution beyond the wavelength limit. Sensing and metrology will be enhanced in many ways by quantum technologies: better accuracy and stability, as well as novel traceability chains to the revised International System of Units (SI), and will yield enhanced sensitivity when exploiting quantum-enhanced precision well beyond the classical and standard quantum limits (SQL)

Important use-cases can be identified in the fields of: medicine; physics; chemistry; biology; geo-physics; climate science; environmental sciences; mobility; defence, and data storage and processing. Novel imaging sensors will have a large impact in the medical sector, e.g. magnetometry to image brain activity. Many applied and fundamental experiments in physics will profit enormously from the increased use of quantum sensing and metrology. Geophysics and climate change will profit for example from improved gravitational sensors for the detection of oil, gas, minerals as well as the monitoring of sea levels and ground water on a global scale (ESA GOCE – Gravity field and Ocean Circulation Explorer – follow-up). Defence systems and autonomous mobility and navigation will profit from long-term stable rotation and acceleration sensors based on quantum technologies.

The central concept of a sensor is that a probe interacts with a system that carries the property of interest, which then changes the quantum state of the probe. Measurements of the probe may reveal the parameters of this property. Quantum-enhanced sensors either take advantage of the absence of classical noise processes, using a quantum algorithm for extracting the relevant information, or even employ probes that are prepared in



particular non-classical states. Control over all relevant degrees of freedom and long coherence times enables quantum-limited resolution, even beyond the standard quantum limits (SQL). To achieve this type of control and generate non-classical or even entangled states in noisy real-world scenarios, novel theoretical foundations, tailored materials and experimental techniques are necessary. It should be stressed that the character of coherence and entanglement as resources are explored by the resource theories which examines the laws of quantification, manipulation and interconversion of such resources in order to establish optimal operating conditions and optimal use of resources for quantum sensors. Besides going beyond the SQL performance, quantum sensors offer advantages in terms of their size, operating environment, being drift free, and potentially having a simpler traceability to the new SI unit system compared to classical measurement devices. Indeed, the new SI unit system, often dubbed “quantum SI”, having direct links to fundamental physical constants, benefits from quantum measurement standards that are expected to greatly simplify calibration and measurement services for the new quantum devices in general, and for quantum sensors in particular.

Because of the wide range of prospective applications and their specificity, a broad range of physical platforms needs to be considered, including (but not limited to) trapped ions, ultra-cold atoms, warm and hot atomic vapours, nano- and micro-mechanical oscillators and opto-mechanical systems, superconducting and semiconducting nano-circuits, artificial systems such as quantum dots and spin defects in solid-state, as well as all-optical set-ups involving non-classical states of light. In a first step, quantum sensors employ and will exploit single particle quantum coherence on a variety of different platforms leading to new functionalities, improved performance or easier conditions of use. These applications have perspectives for reaching the level of a demonstrator in the near-term, while some are already at the production stage.

In a second step, the size, cost, robustness and reproducibility of these initial devices and systems will be improved. Quantum sensors will emerge that exploit the full properties of “exotic” quantum states to achieve performances surpassing those of classical counterparts. Ultimately, networks of quantum sensors may enable novel applications e.g. in Earth monitoring and environmental science. Initially, high-performance sensors for specific applications are expected to drive development, and in the future, these technologies are expected to have a relevant position in the mass market. This position, however, will be gained only once proper quality assurance and standardisation has been developed, underscoring the need for engaging in these activities.

Socio-economic challenges

Over the past decades, sensors have become a key element in everything from cars to washing machines to smartphones. The market for sensors is a multi-billion euro domain with a projected annual growth rate approaching 10% for the next 5 years. The reality is that without sensors a large part of the automotive and mobile economy would not have been able to grow. A number of European actors (including large companies and SMEs) are already among the market leaders, making Europe a competitive actor in the field.

By addressing the demand for high performance sensing and metrology tools for applications in healthcare, security, electronics industry, and research, quantum-technology-based solutions promise to further grow this market. In this context, quantum sensing and metrology will address a number of socio-economic challenges, summarised below.

Market identification

Europe has the potential to become an attractive region for innovative research, business and investments in quantum technologies, but to achieve this it is necessary to accelerate the development and take-up by the market, which would be further enhanced through dedicated standardisation and certification efforts. The identification of successive niche applications to progressively drive the European production capabilities to scale, and the definition of standards and certification to allow large scale deployment across different segments, are needed. These are fundamental steps to kick-start a competitive European industry in quantum technologies and to position Europe as a leader in the future global industrial landscape. Quantum metrology activities are also well placed to support this both as a measurement service and by exploiting quantum sensing technologies to reach new operating regimes.

Development of healthy and competitive ecosystem

This requires two key initiatives. Firstly, an improved supply chain, bringing together key actors in Europe and supporting actions to fill in the gaps such that quantum sensing and metrology can strengthen Europe's competitivity and leading role in the field, as well as ability to develop critical components of key 21st century technologies within Europe. Secondly, a well-developed ecosystem is crucial and quantum sensing and metrology can support start-ups and SMEs as well as contribute to increasing awareness of the potentialities of quantum-based technologies within larger companies to nurture the ecosystem and maximise success through exchange of ideas or partnerships. A large-scale pan-European infrastructure initiative for sensing and metrology would greatly assist in this endeavour.

Environment and healthcare to improve the quality of life of European citizens

Quantum sensing technologies can help address environmental challenges of the 21st century through greenhouse gas monitoring, precise measurements of pollution in urban areas, and monitoring of sea level rise and ice sheet shrinkage. There are also quantum metabolic tools for ultrasensitive sensing targeting healthcare challenges like aging, neurodegenerative diseases and cancer. This includes diagnostics and personalised treatment. Quantum sensors are also enabling autonomous driving, including navigation and brain machine interfaces, and in security, sensing technologies related to the detection of minor traces of explosives, poisons etc.

Earth sensing and observation

In light of the extreme effects of the climate crisis, Earth observation is one of the most important scientific endeavours of our times. As of today, the study of global mass transport phenomena via satellite gravimetry provides important insights for the evolution of our planet and climate changes by improving our understanding of the distribution of water and its changes. Atom interferometry will play an instrumental role to improve satellite-based measurements for space-geodesy. Classical electrostatic accelerometers used so far in gravity missions exhibit increased noise at low frequency and long-term drifts pose severe limits. This is particularly true for the ability to faithfully reconstruct the earth gravity field at low degrees and even more for precise models of its temporal fluctuations. Atom-interferometric quantum sensors offer far superior long-term stability and higher sensitivity.

Dissemination

Quantum Sensing and Metrology will contribute to making available to society new products with direct impact on healthcare, quality of life, security, and the development of an energy-efficient economy, as well as supporting certification, standardisation and quality assurance through novel or improved calibration and measurement services. Specifically, within the Quantum Flagship, it is expected that quantum sensing and metrology will provide a large variety of technologies and solutions. We can identify two main product categories: small and inexpensive quantum sensors for mass-market applications and high-performance, high-cost quantum sensors for selected niche applications and a smaller market. In this second category, we can also consider quantum measurement standards and calibration services devoted to certification of these novel quantum devices and systems.

Research and innovation challenges

Quantum sensors are both presenting new technologies to address current sensing tasks more effectively and going beyond the boundaries of what can be detected with present day technologies. Therefore, any quantum sensor should outperform existing sensors in at least one of the following criteria: size, operating environment, sensitivity, specificity, statistical or systematic uncertainty, traceability, calibration intervals, lifetime, power consumption, reliability, security. Benchmarking against existing reference systems and/or standards for verification is necessary.

To achieve the central goal of "demonstration quantum sensing beyond classical capabilities for real-world applications" the following central challenges need to be addressed:

- Develop techniques to achieve full control over all relevant quantum degrees of freedom and to protect them from environmental noise and malicious interventions.
- Identify correlated quantum states that outperform uncorrelated systems in a noisy environment and methods to prepare them reliably.
- Leverage interdisciplinary expertise and join forces with other fields, such as the signal processing community to further advance the limits of sensors sensitivity and resolution and to implement the best control protocols, statistical techniques (e.g. Bayesian) and machine learning algorithms.

Commercial applications require the development of miniaturised, integrated, cost efficient and user-operable quantum sensors. To achieve this, the following technological challenges need to be addressed, wherever possible jointly with the other pillars:

- Improved fabrication, material, integration and packaging solutions.
- Improved access to facilities, e.g. integrated photonics and electronics.
- Electronic and optics integration into sensor platforms.
- Miniaturised laser and vacuum systems.
- Exploitation of micro-electro-mechanical systems (MEMS), opto-mechanical systems, and micro-machining.
- Definitions for standard interfaces between components.
- Common open source control software platforms.

The challenges facing quantum sensing and metrology can be addressed in two phases. The first phase is focused on near-term applications, where first-principle devices and systems are developed in parallel to advancing longer-term concepts. During the second phase, these first devices should go beyond proof-of-principle towards higher TRLs to be ready for market uptake, in the case of space-based sensors, this could target an Earth-Venture-like mission as a pathfinder for in-orbit validation. In parallel, emerging approaches should be matured and evolved towards proof-of-principle demonstrators. In the following we elaborate on these with respect to the near- and longer-term application potential.

"Quantum Sensing and Metrology will contribute to making available to society new products with direct impact on healthcare, quality of life, security, and the development of an energy-efficient economy."

1 Near-term applications and developments

First application targets here are for enhanced measurement and metrology of current, resistance, voltage and magnetic fields, as well as prototypes of integrated compact field sensors for e.g. chemical and materials analysis, medical diagnostics, labelling, trace element detection, enhanced imaging and spectroscopy with very low light intensities. Other approaches include sensors of gravity rotation, gradient and acceleration, e.g. for civil engineering, Earth observation and navigation.

The large-scale deployment of miniature and low-cost quantum clocks would enable a more efficient network synchronisation and new Global Navigation Satellite System (GNSS) applications.

Optical clocks for timing and network synchronisation provide critical enhancements for infrastructure as well as having synergies with quantum communication networks by using the same fibre- and free-space-based infrastructures for their comparison. The large-scale deployment of miniature and low-cost quantum clocks would enable a more efficient network synchronisation and new Global Navigation Satellite System (GNSS) applications. Exploring technologies for improved and new space-based time and frequency transfer (TFT) techniques capable of going beyond current ESA missions (such as ACES -Atomic Clock Ensemble in Space) and achieving better performance could positively impact navigation and Earth monitoring applications.

Quantum-enhanced radiofrequency, microwave and optical signal processing and detection are important for example in the management of the frequency spectrum in communication applications. Improved optical sensing and imaging will be achieved using non-classical or entangled light, e.g. for super-resolution microscopy or entangled two-photon spectroscopy. Similarly, improved single-photon detectors and arrays, or cameras, for optical spectroscopy, imaging and LIDAR, will have an impact not just here, but across the Flagship and beyond.

© 3DSculptor / iStockphoto.com

The strong effective optical nonlinearities provided by opto-mechanical coupling allow the implementation of sensing-relevant on-chip architectures, e.g. for acceleration measurements, low-noise amplification of electromagnetic signals, optical detection of single microwave quanta, and on-chip generation of squeezed light. Application domains include medicine (e.g. MRI imaging), security (e.g. Radar and THz monitoring), positioning, as well as timing and navigation (oscillators).

In addition, we can expect a continuous development on additional techniques, concepts and enabling support technologies, e.g. Rydberg ion electric & magnetic field sensors, quantum engineered slow light structures, chip-based magnetic levitation of superconducting or magnetic particles for future matter-wave interferometry with massive, levitated objects, etc.

Nitrogen vacancy centres in diamond and other colour centres will measure temperature, electric and magnetic fields, pressure, forces and optical near-fields with nanometre resolution. In particular, magnetic field sensing comes naturally for such spin sensors and is of crucial importance for several fields of science including chemistry, biology, medicine and materials science. Such centres can also be embedded in living cells. We will see them incorporated into lab-on-a-chip devices for ultrasensitive NMR and attached to particular proteins, combining their sensing ability with functionalities such as drug delivery devices or markers for ultra-sensitive MRI.

Squeezing and the creation of non-classical states, e.g. Bell states, which are insensitive to global field fluctuations but sensitive to gradients, can further enhance the sensitivity. Such sensors will allow the exploration of quantum error correction protocols and of decoherence-free subspaces to reach longer coherence times. Applications may include the elucidation of structure and dynamics of single biomolecules, and ultrasensitive metabolic imaging in a wide range of scales, from sub-cellular imaging to medical MRI.

2 Medium and longer term applications

As control and understanding of quantum sensing and metrology technologies improve we will look at more advanced application solutions. Inertial sensors and clocks (microwave and optical) will be available as compact, autonomous, field-usable systems (medium to high 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 and/or quantum-based detection (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 molecules, electron paramagnetic resonance, hyper-polarised NMR and magnetic resonance imaging, and sensing conformational changes of single molecules under physiological conditions (low TRL). Ion based sensors may be used for radio-frequency and microwave amplification and detection. Opto-mechanical sensors will allow for 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). Entangled two-photon absorption in atomic and molecular systems demonstrating quantum advantage of non-classical states of light for spectroscopy and imaging in chemistry, biology or in-vivo, as well as prototypes for quantum LIDAR and RADAR, (low TRL). There will be electric, magnetic, temperature and pressure sensors based on artificial atoms (e.g. colour centres, quantum dots, ...) or opto-mechanical and -electrical systems (medium TRL) and Atom Trap Trace Analysis detecting rare radioisotopes for age dating in earth and environmental science (low TRL).

Commercial sensors and large-scale sensor networks, including the required infrastructure such as a European frequency transfer network, (up to demonstration in operational environments, high TRL) will provide Earth monitoring beyond the capabilities of classical systems and improved constraints on physics theories 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).

3 Supply chain

Leadership in quantum technologies hinges as much on enabling technologies as it does on combining systems for entirely new applications. Enabling technologies will be one of the first markets of and for quantum technologies in the foreseeable future. It is therefore of crucial importance to ensure that Europe develops its own supply chain of key enabling technologies for quantum sensing and metrology. This includes photonics (high-stability lasers, light-distribution and

First application targets here are for enhanced measurement and metrology of current, resistance, voltage and magnetic fields. →


© sakkmesterke / iStockphoto.com

-control, fibre-technology, chip-scale optical frequency combs), electronics (in particular high-speed phase-coherent control of RF and microwave fields and integrated circuits for low cost sensors), single photon microwave to optical frequency conversion, improved single and few-photon detectors, cryogenics, as well as micro- and nano-fabrication capabilities for diverse materials including photonic and electronic integration, e.g. to realise novel ion-traps, micro-fabricated cells, atom chips, opto-mechanical oscillators. It is also important to develop tailored materials that host colour centres and single crystal materials with minimal residual impurities (below one part per billion level) and the availability of isotopic engineering.

This also includes the development of quantum-aware sensor-specific software and hardware as well as industrial use-cases for quantum sensors. Since the initial markets are expected to be small in many cases, it is of paramount importance to support small companies and the creation of spin-offs, as well as industrial use-cases for quantum sensors. For resources, we should en-sure that all critical components are available in Europe, in particular taking advantage of existing foundries and large-scale infrastructure, such as the Laser-Lab Europe and other large-scale national and international research initiatives including the European Metrology Network for Quantum Technologies (EURAMET) and COST actions. We also need a better synergy between technology platforms and to optimise the coordination between big RTO platforms complying to long-term roadmaps and smaller academic platforms having more flexibility.

The supply chain may also include things like characterisation, measurement and calibration facilities, including microgravity facilities, standardisation activities and also theory aspects like the development of control methods that achieve enhanced robustness and sensitivity at the same time, optimal experiment design as well as signal processing methods (post-processing) for optimal extraction of information from measured time series.

Human resources represent an important element in the supply chain and there are several key challenges to address in terms of education and employment. We need to strengthen the connection between leading-edge research in quantum metrology, and quantum hardware development (materials, sensors and control systems) in European academic and research institutions and the European industrial and entrepreneurial ecosystems. This could be facilitated by the creation of specific academic curricula to address the skill sets necessary for the development of a competitive, world class critical mass of Quantum Technologies professionals. This would facilitate the training of highly qualified engineers, technicians, as well as business developers and sales force with exposure to quantum concepts, increasing competitive job profiles for Europe's brains.

A quantum sensing and metrology infrastructure could bring together a wide range of competencies relevant for addressing installation, operation, maintenance and management of devices and systems to provide coordinated services and solutions exploiting the next generation of quantum sensors and the metrological certification of both classical and quantum technologies. This could look to build on and synergise with recent efforts of EURAMET and the creation of the European Metrology Network for Quantum Technologies (EMN-Q), a network of European Metrological and non-Metrological Institutions, which aims at the development of dedicated measurement services for quantum devices and apparatuses and to support the creation of globally accepted standards that are perceived fundamental for the take up of the quantum technologies market.

"We need to strengthen the connection between leading-edge research in quantum metrology, and quantum hardware development."

roadmap

Quantum Sensing and Metrology

The objectives for Quantum Sensing and Metrology include quantum sensors, imaging systems and quantum measurement standards demonstrated in a laboratory environment outperforming classical or current state-of-the-art counterparts in one of the following criteria: size, operating environment, sensitivity, specificity, statistical or systematic uncertainty, calibration intervals, life-time, traceability. The TRL of different types of quantum sensors spans a large range from devices that have already started penetrating the market (e.g. magnetic field sensors based on squids, atom gravimeters, microwave clocks) to laboratory prototypes. Thus, there are individual roadmaps for each type of quantum sensor and platform. In the following, overarching milestones are presented together with a few more specific examples, grouped into near- and medium-term objectives.

3 year vision

- Evolution of key enabling technologies and materials, supported by spin-off companies, and establishment of a reliable, efficient supply chain including first standardisation and calibration efforts.
- Development of chip integrated photonics, electronics and atomics, miniaturised lasers, traps, vacuum systems, modulators and frequency converters.
- Engineering of materials using nanofabrication, functionalisation and chemical modification of surfaces, e.g. for biosensing; synthesis of ultra-pure materials (e.g. diamond, SiC), doped nanoparticles, colour centres.
- Establishment of standardisation, calibration and traceability for new sensor technologies.
- Prototypes of compact quantum electrical standards with enlarged application ranges.
- Prototypes of transportable optical clocks and their comparison over large distances as well as atomic gravimeter and gyroscopes surpassing existing (classical) devices in statistical and systematic uncertainty.
- Prototypes of transportable electric, magnetic, temperature and pressure sensors based on artificial atoms (e.g. colour centres, quantum dots) or quantum opto-mechanical and -electrical systems.
- Table-top prototypes of quantum-enhanced, super-resolved, and/or sub-shot noise microscopy, spectroscopy, and interferometry, as well as quantum LIDAR and RADAR.
- Laboratory demonstration of the practical usefulness of engineered quantum states (such as entangled states) in more and more real-world applications, supported by theoretical modelling of real-world noise scenarios and the identification of noise-immune quantum states and algorithms, e.g. by employing machine-learning algorithms, Bayesian inference and quantum error correction for sensing.

6–10 year vision

- Continued evolution of enabling technologies and material engineering to increase TRL and promote quantum sensors to the market.
- Integration of quantum measurement standards for self-calibration in instrumentation.
- Establishment of foundries on key technologies to provide access to innovations for a larger basis of researchers and companies.
- Fabrication of optically and electronically integrated lab-on-a-chip platforms based on functionalised materials for biomedical applications or integrated atom chips for sensing electric and magnetic fields.
- Laboratory prototypes of quantum-enhanced measurement and imaging devices, entangled clocks, inertial sensors and quantum opto-mechanical sensing devices.
- Commercial products, such as magnetometers improving MRIs, quantum-enhanced super-resolved and/or sub-shot-noise microscopes, high-performance optical clocks and atom interferometers, quantum RADAR and LIDAR.
- Development of networks of quantum sensors as well as space-borne quantum-enhanced sensors, including optical clocks, atomic and optical inertial sensors.

Scientific and Technological Resources


© Quantum Flagship / H. Ritsch

The Scientific and Technological Resources area can provide maximum flexibility for the attribution of scientific and technological resources: on the scientific side, it provides an ‘entrance door’ for new ideas or themes, and on the technology side, it exploits synergies and sharing of resources.

Scientific and Technological Resources

In order to build up the long-term viability of a European industry based on quantum technologies, the Quantum Flagship requires a well-supported and dynamic effort for developing Scientific and Technological Resources. In the sections above covering the four core quantum technology application domains, a number of common themes, requirements and challenges have naturally emerged. They range (in TRL) from foundational issues in basic science, up to technological resources to practically manufacture, scale up, operate, and deploy quantum technologies. Therefore, in order to fully and coherently exploit synergies across the flagship application areas and thus ensure success, it is required to support and develop:

- Basic scientific resources for novel concepts, leading to more advanced technologies.
- Technological resources – starting from the underpinning components and going up to systems engineering, benchmarking & verification, theory, software, and control.

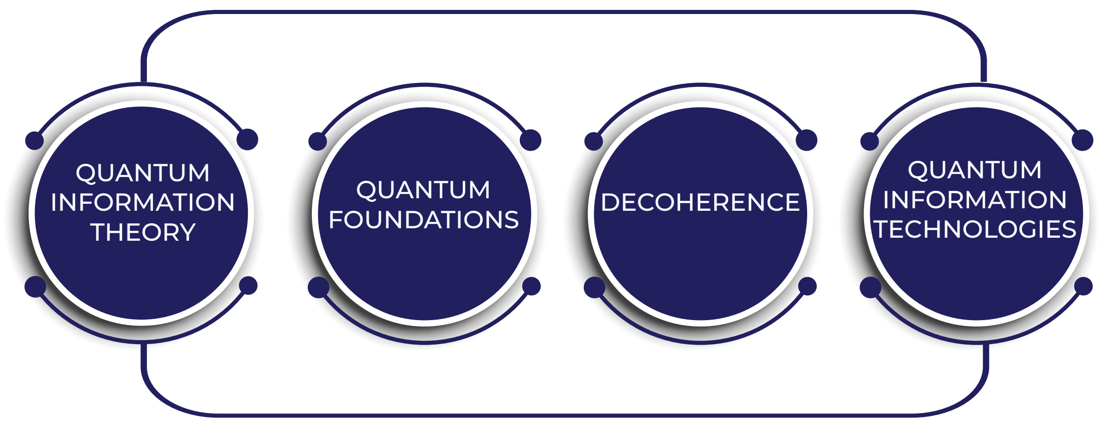
It is expected that focussed projects within each application area will include targeted efforts at developing some of the relevant science and technology. Nevertheless, there are broader and/or generally cross-cutting activities, to be supported and coordinated within a Scientific and Technological Resources programme.

In addition, being open-minded towards new ideas, possibly stimulated by growing social and economic impact of quantum activities, is likely to foster and catalyse the development of currently unforeseen quantum technologies. All these potential contributions are important and needed for a healthy long-term vision for the field.

Scientific Resources

Basic science has the goal to explore and understand the science underlying all quantum technologies, both theoretically and experimentally. While remaining exploratory, basic science within Scientific and Technological Resources should aim to explore new quantum effects and gain new understanding that are not limited to the pillar activities and which may contribute to new quantum technologies and applications in the long term. This effort includes both scientific activities that are transversal across several applications areas, as well as those that are sufficiently foundational that their impact in existing or new applications lies well in the future. This aims to ensure the long-term success of the four application domains, by providing constant development of new scientific tools and concepts. In fact, while some quantum technologies have

SCIENTIFIC RESOURCES



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 in two ways: new science provides new ideas for quantum technologies, but also developing quantum technologies stimulates new questions to be answered by new science as well as experimental guidance for new theoretical developments.

This requires Basic Science to be broad, ambitious and open in its spirit and its goals. As a consequence, it not possible to give a prescriptive and exhaustive list of topics, and the following are a few examples of research directions and goals among those that can be addressed.

Quantum information theory

As its classical counterpart, quantum information theory aims at identifying the laws and the ultimate limits governing any information process based on quantum effects. Many results in the field are phrased in terms of different resources, such as classical and quantum
bits, randomness, secret bits, entanglement or non-local correlations. Results here are often transversal and find applications in different pillars. For instance, inter-conversion laws between classical and quantum bits can be used to simplify the experimental implementation of many protocols. Another objective of the field is the development of certification methods for quantum technologies. Complex quantum systems, e.g. multipartite quantum networks, or medium-size quantum computers and simulators that are being prepared in many experimental labs. Finding efficient and scalable ways of certifying their quantum properties and correct performance is crucial for the development of quantum technologies. This necessarily includes methods for the estimation and classical simulation of complex quantum systems beyond brute-force approaches.

Quantum foundations

Here the main objective is to understand what makes quantum theory special and how it differs from classical physics. It involves both theoretical and experimental developments, and any gap between the classical and quantum formalism is a potential resource for a new quantum information protocol. One is therefore interested in obtaining new no-go theorems for classical systems and demonstrating them in the lab. It is a powerful force to push technology forward, for instance as it has been demonstrated by the recent “loophole-free” tests of Bell’s inequalities that not only represent seminal quantum foundation experiments, but also open new avenues for device-independent protocols. At the same time, the concept of quantum information provides new insights to gain a better understanding of quantum physics and how it differs from other theories, including theories that go beyond the quantum laws. Fundamental concepts such as causality or relativity theory change when combined with quantum phenomena.

Decoherence

The main challenge for any practical device based on quantum information is decoherence. Under its presence, quantum effects disappear, the systems under study start behaving classically, and any quantum advantage is lost. Therefore, understanding the mechanisms behind decoherence and how to mitigate, or even exploit, their effects is a fundamental research line transversal to all pillars. The main objective is to develop methods for the theoretical and experimental investigation of open-system dynamics. These

> **"The development of many quantum technologies at scale requires access to industrial-grade micro- and nano-fabrication facilities, providing the necessary resources for the manufacture and packaging of quantum devices."**

can be used, e.g., for the study of the quantum-to-classical transition. Of particular relevance is pushing the boundaries at which quantum effects can still be observed and see how to experimentally prepare and maintain, in a controlled way, macroscopic systems in coherent or even entangled quantum states. Understanding decoherence is also fundamental for the development of methods to fight against it, such as error correction, dynamical decoupling, or reservoir engineering.

Quantum information technologies

While much of the quantum device and component technologies will be addressed in the main application areas, there remain significant basic science challenges to advance these across the Flagship. These can range from single photon sources with optimised wavelength, bandwidth, purity and efficiency to conversion of light at the quantum (single photon) level to/from telecoms wavelengths, or single photon detectors with lower dark-count rates, smaller timing jitter, and higher detection rates (near unity efficiency). Similarly, for: quantum memories; photonic cavity/emitter devices; novel ion-traps and atom chips, and opto-mechanical systems.

Many of these relate to materials and fabrication, however, the work required here is focused for example on: spectroscopy, e.g. for solid state quantum memories; atom, ion, and molecular implantation; new materials and fabrication, e.g. for detectors, integrated circuits, or spin systems. However, this also addresses new regimes of operation, from generating increasingly complex quantum states to optimally controlling coherence in diverse physical systems. This is equally valid for hybrid systems that interface different technologies or operating regimes, e.g. addressing the conversion between photonic and microwave systems, or the interface between terrestrial and satellite communication systems. This should focus on novel ideas and approaches with potential impact for the Flagship. The development of more mature component technologies, in general, will be addressed within the application areas, or for more cross-cutting devices and systems, in Technological Resources.

Beyond quantum information technologies

Concepts and tools developed for quantum information technologies also find application and provide new useful insights in other scientific disciplines. This a very broad research line, ranging from biology and thermodynamics to condensed matter or high-energy physics as well as in a broad range of applications. In fact, quantum technologies are reaching many regimes where new theoretical developments are necessary. For example, technologies involving long distances such as quantum communications in space or very high precision measurements including atomic clocks and atom interferometry reach situations where gravity can no longer be described by Newtonian physics and relativity kicks-in. New regimes are also within reach in thermodynamic processes. Thermodynamic laws are usually applied at the macroscopic scales including many particles where fluctuations are irrelevant. However, quantum technologies allow the study of thermodynamic effects at the quantum scale, where entanglement and coherences appear, and fluctuations become relevant. Similar considerations arise in the presence of quantum effects in biology and life sciences. A question of growing interest is to determine if biological processes exploit quantum effects such as entanglement, coherence and squeezing. Finally, quantum technologies are also facing new challenges in the preparation of complex many-body systems. This requires exploring novel phases of matter from a quantum information perspective and for quantum information purposes, including the characterisation of many-body systems with topological properties.

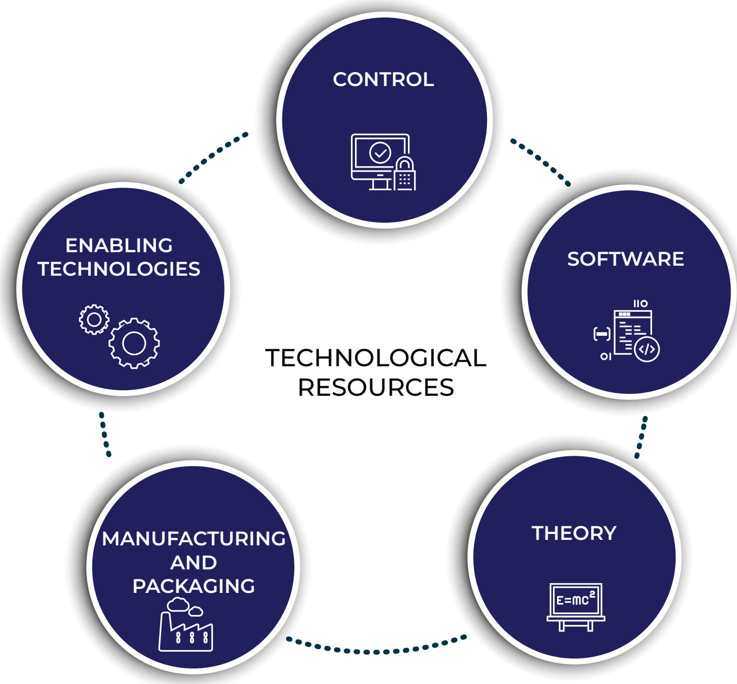
Technological Resources

The cross-cutting activities of the quantum flagship represent and provide technological resources to ensure a coherent and efficient exploitation of concepts, tools, technologies and people across the flagship. These activities include: manufacturing & packaging; enabling technologies; control; software, and theory. In the following we highlight some of the key challenges in these areas.

Manufacturing and packaging

The development of many quantum technologies at scale requires access to industrial-grade micro- and nano-fabrication facilities, providing the necessary resources for the manufacture and packaging of quantum devices. Closer integration between quantum and classical devices (e.g. electronic, RF & microwave, optical) will be needed, which will require leveraging expertise in existing facilities and manufacturing centres, such as large-scale facilities like IMEC and LETI for photonics, semiconductors and atom/ion trap chips as well as smaller foundries such as IPHT/VTT for superconductors, among others. Much of the development in quantum technologies has thus far been performed in university cleanrooms, and even the most advanced of these will be unable to support the manufacture of quantum devices at the scale and complexity required by a mature industry. We need to develop ways for communities to come together to ensure an efficient use of resources and a scalable development path for the future.

Some manufacturing methods are not yet industrialised but offer unique capabilities, such as high-precision deterministic single ion implantation, STM-based lithography, laser-writing of optical defects and advanced crystal growth techniques. Access to all such resources for quantum technologies is fragmented, and the quantum technologies community should identify key process technologies and materials to help federate competencies that already exist – see also the Innovation section. This will be further complemented by the development of accessible integrated circuit libraries, for circuit elements with quantum-levels of performance and functionalities, and intermediate-scale



prototyping centres for multi-wafer projects, as a way to manage development costs. In some cases, material purity needs to be further increased, or non-standard materials developed, such as isotopically enriched substrates, and these need to be incorporated into industrial fab lines.

Further development of high-purity/precision optical materials with engineered impurities/colour-centres is needed, not just in diamond but also other hosts such as SiC and wide band-gap materials. Similarly, for packaging, e.g. of specialty chips, there is a need to bring people together from different areas, e.g. ions and integrated optics, superconducting circuits, semiconductor quantum devices, and cryo-electronics. The need to operate at cryogenic temperature may introduce non-standard requirements for the packaging. Dedicated support in these areas will help accelerate development and lay the foundation of a scalable industry. Overall, harnessing such manufacturing and packaging capabilities will increase the yield, uniformity and reproducibility of quantum devices, as well as drive down their cost. Satellite-based quantum technologies will additionally require extra qualifications to meet the high demands in terms of weight, mass, integrability and reliability, which are required by every space mission.

Enabling Technologies

A wide variety of conventional components are needed, together with the quantum devices, to deliver complete systems. In many cases, such components require further development in key metrics in order to meet the levels required by the quantum technology. Such components include: low-loss optical switches; enablers for robust phase stabilisation; stable and narrow linewidth lasers; efficient low-loss modulators; optical fibre technology; chip-scale optical frequency combs; ultrafast laser technologies using fibre lasers; high-efficiency photonic integrated circuits; nano-engineered micro-cavities; miniaturised vacuum systems with the potential for integrated optical and EM traps; RF and microwave sources (especially high-speed phase-coherent multi-channel; FPGAs optimised for quantum control; cryogenic systems with increased cooling power. In many cases, the systems (laser, cryostats) are already available in lab settings, but need to be made cheaper, more compact, robust and user-friendly. The size and cost per-channel for signal generators needs to be driven down substantially to assist with the practical scale-up of most key qubit technologies. Common requirements across hardware platforms e.g. the use of AWGs in all areas) will help increase the drivers to invest in development of these technologies. While these technologies should all be developed in the context of improving quantum technologies, it is worth noting that such developments in components may also impact other (non-quantum) areas and thus boost Europe’s competitiveness more broadly.

Control

Quantum technology requires the precise control over multiple small quantum sub-systems (e.g. atoms), but at the same time have to be capable of operating efficiently in a noisy and decoherence-inducing environment. Indeed, decoherence and the lack of robust quantum control protocols is one of the reasons that have limited the potential impact of quantum technologies, i.e. transitions from the laboratory to the commercial market, while it must be noted that several quantum products and devices have already been commercialised. Therefore, there is a demand for new high-precision quantum control schemes in theory and experiment that have the capacity to outrun decoherence. These control schemes must be insensitive to experimental imperfections in the lab and especially, in the future, also to imperfections outside the lab when quantum technologies move to the commercial market. The theoretical studies, as well as the experimental development, of new control schemes are key technological resources, particularly for quantum sensors, quantum repeaters and quantum simulators.

Successful implementations of quantum technologies face the challenge to preserve the relevant non-classical features at the level of device operation. Quantum optimal control provides toolboxes that allow one to identify the performance limits for a given device implementation, and it provides the protocols for realising device operation within those limits. Quantum control addresses two fundamental questions, that of controllability, i.e., what targets are accessible, and that of control design, i.e. how can a target be reached. Approaches for control design can be open-loop or closed-loop. In the latter case, the specific nature of quantum measurements needs to be taken into account. The combination of quantum control and quantum measurements is still in its infancy, and some challenges are: extending the understanding of controllability from closed to open quantum systems, in particular those with non-Markovian dynamics and from single quantum systems to ensembles; developing and deploying efficient numerical techniques for optimal control of open systems; improving the connection to experiments and developing standard interfaces between experiment and theory; understanding control complexity, in particular scaling with system size, and developing easy to use optimal control algorithms and software packages.

In the long term, control schemes need to be made scalable. Meeting this challenge will make quantum control a basic building block of every quantum technology and ensure, at the same time, its proper functioning in a world where quantum effects are diluted by decoherence at the macroscopic level. Qubit controls should be robust with respect to the influences of the rest of the architecture they are placed in. Independent of a specific platform, error correction at large, for instance by toric codes, is one of the strategic long-term goals that is expected to benefit from control techniques, given recent advances of randomised benchmarking. To this end, system-identification protocols matched with optimal control modules will be of importance. In short, quantum control will be the means to get the most performance out of an imperfect system and combine challenging physics at the few-qubit level with engineering at the multi-qubit level.

The long-term goal of quantum optimal control is to develop a software layer enhancing the performance of quantum hardware for computing, simulation, communication, metrology and sensing, beyond what is classically achievable, and demonstrating a clear quantum advantage.

Software

Practical quantum technologies will require complete software that simulates or pre-dicts to some extent the quantum simulation or computation results, and can provide guidance and verification of the correct functioning of the stacks, whether for programming quantum hardware or at an application level. Classical algorithms based, e.g., on tensor network methods shall emulate communications systems, quantum computers, quantum simulators or quantum sensor systems. Such software will need to be developed, standardised, and integrated into existing computing environments, with software back-ends to provide such a layer to the whole computation infrastructure. Implementing this level of software often needs to leverage the realtime capabilities and the integration of different platforms. The community should develop ways to provide these, in part by managing and coordinating a git-type library, by training programmers (often physicists) in good coding practice and by funding dedicated, open-source, open-stack, software projects that fill strategic cross-pillar and cross-platform gaps. The openness needs to be balanced with the need for developing IP portfolios.

There is also a need to contribute to documentation of interfaces, standardisation

and interoperability. From a signal-processing perspective, we envisage greater use of machine learning and Bayesian inference in the interpretation of quantum sensor data, or results from qubit measurements, while software for automated calibration and tune-up protocols will become increasing crucial as quantum devices scale up. For a successful quantum computing industry, one needs to consider both hardware and software as well as the end-users. The control software should cooperate closely with control hardware and to achieve it, there should be an effort of API and architecture standardisation to provide interoperability of equipment and software components between vendors.
There are already well-established, quantum-application dedicated, open-source control systems on the market so such an approach already works, but needs investment to increase their TRL.

Theory

At the heart of the whole quantum technology field are quantum states and transformations as mathematical objects, so it is very important to explore theory for its own sake, first in Basic Science, but also for key technologically-oriented questions.
For example, finding the right approaches to encode information in a quantum state; understanding the computational complexity of tasks with quantum states; determining which parts of a quantum computation or error-correction procedure actually need to be quantum; contributing to new schemes for quantum devices and protocols, including communications protocols; and developing algorithms to enhance quantum sensor performance (both sensitivity and resolution).
In addition, theory has a key role to play in the verification and benchmarking of devices and systems (see above).

3 year vision

Scientific resource objectives

- Further development of the concept of hybrid devices that combine at least two different systems in order to combine strengths and reduce weaknesses.
- Improved understanding of the quantum-classical transition and decoherence mechanisms.
- Explore novel concepts and systems where quantum technologies can be an advantage, e.g. in biology, chemistry and thermodynamic systems as well as across the established application areas.
- Demonstration of novel quantum information technologies, transferring them to the application domains or opening up new areas or research and innovation.

Technological resource objectives

- Demonstrate performance from quantum devices fabricated in industrial-grade facilities which is comparable to state-of-the-art from specialised (e.g.) university cleanrooms.
- Improve the yield and uniformity of quantum devices through the use of established fabrication facilities.
- Improve access to, and streamlining of, fabrication and packaging facilities.
- Improve critical performance metrics of key enabling technologies, as well as reducing cost, size, etc.
- Control of open quantum systems, decoherence control.
- Develop control calibration methods for non-trivial pulse shapes.
- Analytical design of control schemes and development of efficient descriptions thereof in order to facilitate both analytical and numerical design and improvements.
- Convergence of numerical optimal control and experimentation in many platforms, including handling of calibration uncertainties and other experimental constraints.
- Establish a framework for software stacks across the quantum technologies applications domains.
- Develop classical software to benchmark and verify quantum simulation and computation results and to individuate their limits.

6–10 year vision

Scientific resource objectives

- The long-term objective is to continue to work towards opening up new avenues for potential growth in the field of quantum technologies.
- Develop scalable methods for the certification of complex many-body and multi-partite quantum systems.

Technological resource objectives

- Demonstrate systems, manufactured at scale, which fully integrate quantum devices with a range of classical (optical/electronic) devices.
- Develop schemes to stabilise and control complex entanglement-based networks.
- Modular approach from simple to complicated control pulses in theory and improved pulse shaping in experiments.
- Implement reliable strategies for the control of mesoscopic systems.

Innovation


© yucelyilmaz / iStockphoto.com

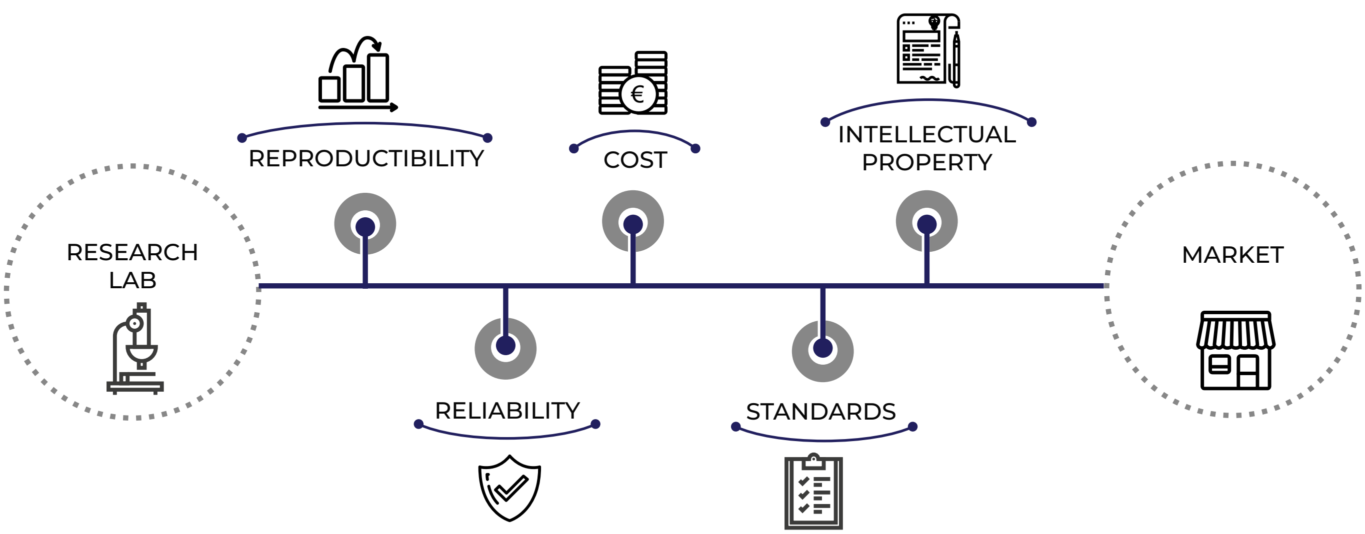
Addressing the challenges of scaling up from lab to products and services, raising awareness and bringing key stakeholders together, are all essential to develop the dynamic innovation ecosystem that will put Europe at the forefront of the emerging quantum technologies industry.

Innovation

The quantum flagship is application-oriented, and it expects to bring economic and societal benefit from quantum technologies throughout the lifetime of the programme and beyond. To achieve this goal, it is necessary that the outcomes of research meet a need in order to bring new products, which is the definition of innovation. Therefore, innovation is a central concern of the quantum flagship that involves the contribution of all stakeholders from research laboratories to industry, and the future users of quantum technologies. On one hand, research laboratories can propose new concepts and new outcomes of their work. On the other hand, industry and more generally anticipated and unanticipated future users, having a detailed knowledge of their needs, can define specific use-cases where quantum technology-based products can bring new solutions or new functionalities that do not exist classically.

Taking a research result up to a product-ready level is a long endeavour and the laboratory demonstration is only one step in the innovation process. As the work progresses towards the product, other considerations have to be taken into account such as reproducibility, reliability, cost, definition of standards, intellectual property management, etc. The umbrella under which these aspects converge is called the TRL scale. The TRL scale has proven its effectiveness for many different new technologies and therefore new products based on quantum technologies should comply with it. The TRL scale would give potential end-users and investors a transparent way of validating the technology by monitoring the development rates and its readiness. It will allow the identification of bottlenecks that can limit the transfer from research to product and can help in setting the agenda for possible improvements or solutions.

Based on discussions with relevant academic groups, RTOs and representatives from industry, an inventory was made of challenges and needs for developing new products and services based on quantum technologies. These challenges and needs can be grouped into 4 main categories: use-cases & requirement specifications; infrastructure & supply chain; educated personnel & users, and support & promotion.



Use cases and requirement specifications

The identification of use-cases for new products and services based on quantum technologies is an essential step when bringing new concepts from research to the application phase. Quantum technologies should bring improved performances of existing products or services, or make them easier to use. Quantum technologies should even foster the emergence of entirely new use-cases. In general, tackling big problems in energy, health and security are the main drivers behind the development of a technology and quantum technologies are potentially the ultimate disruptive technology. Some more specific short-term-based use-cases in material science have already been identified, such as the measurement of magnetic fields at the nanometre scale with application to spintronics or high-density storage disks, but more use-cases are necessary to expand the quantum technologies applications portfolio.

Identifying new use-cases arises through discussions where a solution meets a problem. This can happen at meetings and conferences, during discussions between scientists, R&D engineers and potential users. Therefore, conferences and workshops involving all of these stakeholders are very useful. This process can be fostered by organising workshops dedicated to use-cases with specific brainstorming sessions. Several industry workshops and use-case workshops have already been organised in the framework of the Flagship and this activity will be increased. Further options are meetings with stakeholders such as financial institutions, governmental organisations, product developers, computer gamers, security agencies and defence, etc., aimed at sharing information about quantum technologies and at exploring new use-cases.

Another way to identify new use-cases is to exploit existing software tools that have been developed for this purpose. This requires the identification of connections between scientific and technical capabilities (through technology licensing, patents or publication databases) with technical or societal needs. A preliminary test of such a platform has already been made in the framework of the recent coordination and support action QSA (see www.qt.eu), however, this has to be further investigated and requires a more systematic effort to be validated.

Based on the identified use-cases, requirement specifications have to be defined for the new products and services based on quantum technologies. The requirement specifications set targets for the science and R&D communities. These targets can be used to bridge the gap between the state-of-art performance and the user-required performance of new concepts.

Infrastructure and supply chain

The Role of RTOs in new products and service development

As in other high-tech sectors, there is a need for an innovation roadmap, to guide industry, such as the highly successful, decades-long, ITRS Innovation Roadmap for Semiconductors[5], or more general technology mapping forums[6]. Innovation roadmaps should be coordinated at a European level, focussing on cooperation between universities, RTOs, industry and governments to bring new quantum technology to society as fast as possible.

To create quantum technology-based products and services requires repeatable a nd reliable manufacturing of quantum technology devices and systems. Setting KPIs (Key Performance Indicators) for quantum

[5] https://irds.ieee.org/editions
[6] https://worldtechnologymappingforum.org/

technology devices as well as standardisation of quantum technology systems will stimulate a modular approach. This approach guarantees that components can be developed in parallel paths, reducing time to market. RTOs can carry out repeated fabrication and are familiar with the modular (system engineering) approach of prototypes and products, which would be of great help to industry. RTOs, universities and industry need to find ways to form quantum-centred consortia comparable to EUROPRACTICE[7] or other Multi Project Wafer (MPW) prototyping and packaging services, so that designs can be easily exchanged.

As it takes a very long time and/or large financial investment to develop radically new products, it is crucial to develop easily accessible services that assist developers of quantum technologies-related products and services in identifying available infrastructures and facilities (e.g. clean-rooms) that can help to accelerate their development. The very long time needed to set up a new production facility (10 years for new SMEs) can also be reduced with the help of RTOs. To bring SMEs, RTOs and universities together, one can think of creating a platform like Actphast[8]. The platform provides a webpage with information on capabilities, services and prototypes to SMEs developing photonics technologies.

Identify critical infrastructure and facilities

An inventory is needed of what infrastructures and facilities are required by SMEs and start-ups to develop new quantum technology-based products. This means that these infrastructures and facilities should be easily available as they may not have the means (financially or the right contacts/entry points) to access them. This inventory of critical facilities should also include measurement and metrology facilities and not just focus on manufacturing and production. Obviously, this is important for a broader field of deep-tech companies. The whole landscape from SME to large industry should be investigated. Furthermore, the presence of high-level specialists is required, who can translate the needs of industry and match this with the available infrastructure and facilities.

Already identified as a critical need are EU-based infrastructure initiatives for quantum computing and simulation, quantum sensing and metrology, as well as communication, that can be used for developing services by industry, as well as bringing all stakeholders together to develop and strengthen supply chains and innovation ecosystems.

Another critical issue that needs to be addressed is how to scale prototype production to 100 – 1000 products. More generally, the transfer from laboratory to industry (even small production) has to be addressed as well as the question of having sufficient capabilities to suddenly ramp up production if necessary. An example of how this can be solved is making use of pilot-lines (e.g. PICs4life, PIXapp, InPulse, etc.).

Identify critical suppliers

An inventory is needed of what critical suppliers are required by industry to develop new quantum technology-based products. Already known to be critical is the performance of current cryogenic systems, optic systems as well as electronic measurement & control systems. These systems are currently a limiting factor for the development of quantum technology-based products and services. A group representing cryogenic, optic and electronic industry should be created based on the various ecosystems to support the quantum technologies R&D activities. The integration of

[7] http://www.europractice.com
[8] https://actphast.eu/

subsystems and components is an essential step in going from prototype to product. Platforms for photonic integration are now maturing and might be ported to quantum technologies integration steps.

Trained and educated workforce and users

Train personnel for working in the quantum industry

In order to make industry ready for developing quantum technology-related products and services, a flow of students from academia to industry is required. Educational workshops in partnership with industry can help to kick-start this flow of talented people. Furthermore, young professionals and students should be trained about entrepreneurship and prepared to take quantum technologies to market via start-up companies. Developing a library of information documents such as application notes like "PICs for quantum technologies", as has been done for other fields[9], or short presentations of recent results in quantum technologies. This information should be aimed at professionals that are currently working in relevant sectors of the industry and could be publicised at workshops or disseminated widely through various channels.

Organise workshops to raise awareness on capabilities and needs of industry

In order to translate the potential of quantum technologies to a language industry can relate to, using advisors or intermediators is an option. Identification of specialists who can act as brokers between the quantum R&D community and industry is needed. Those specialists need to be able to act as interpreter between the needs of the industry and the offer from the quantum R&D community. To be able to help with developing quantum technologies that is relevant and more focused to address specific problems, an in-depth understanding of the barriers the different sectors encounter is needed. Participation in industry-oriented conferences is required, in particular those dedicated to start-ups. Workshops are needed, either with specific industries, such the automotive industry, but with a broad quantum theme, or alternatively, workshops focused around a specific quantum theme such as quantum for cyber-security. Other ways of identifying the needs of industries is through targeted visits to companies, or by partnering for hackathons or open challenges, as well as focused workshops for industry.

Supporting and promoting the development of new products and services

The Flagship is oriented towards applications and aims at improving the transfer from research to applications. At the moment, only a relatively small number of industries are involved in quantum technologies. Several directions can be investigated to try to improve this situation.

Funding and investments

The investment in development of European quantum technologies has to be strengthened. Compared to the situation in the US, there are far fewer investors in quantum technologies in Europe. There are a few examples going in the right direction, but they are limited. A significant effort should be put towards bringing investors and investment into the field of quantum technologies. What is important for VCs is to show the long-term potential of a technology. It may not be less important if there is no return on investment within 3 years, but it would be critical to show that the potential market will be very large. Quantum

> "The investment in development of European quantum technologies has to be strengthened."

[9] http://pics4all.jeppix.eu/documents/application-notes.html

technologies have a large potential market even if it may not be in the short term. It is therefore important to bring new things out of the box with potentially significant applications.

Special instruments are needed to support the emerging start-up scene. The nature of the start-up companies in the quantum technologies field is that their technologies are still mostly low TRL. This is due to the fact that quantum technologies represent an emerging field and that many ideas still need to be proven, both technically but also, which market need they could fulfil. Because of this, start-up companies can't find suitable funding. Most SME instruments are unsuitable because funding is provided for a much higher TRL. Special instruments could be organising possible EU support for large investment e.g. when facilities are required or promoting EU projects that support engagement of start-ups with investors. Some existing instruments might be suitable for investing in quantum technology development. An inventory of all national support funds devoted to incubators for early stage SMEs should be made available.

One other important aspect is to inform potential investors of the possibilities offered by quantum technologies. Most of them are not aware of the potential applications of quantum technologies. It is therefore very important to create a link between researchers and investors. All tools that can help fostering those connections are welcome. In particular, person to person meetings with decision makers are very useful to create awareness. The Flagship should promote work-shops for investors to introduce

Patenting is an important tool for protection for quantum technology stakeholders.

© Melpomenem / iStockphoto.com

them to the technology and its opportunities. Trying to develop fund raising from private funders should be a central activity of the flagship. The Flagship should address the communication barrier between investors and scientists by helping to train scientists to speak to investors. Another way to inform potential investors is setting up a service that could make the connection between investors and quantum technology companies.

Standardisation

Standardisation is an essential point to allow transfer from research to industry. The absence of standards will preclude any massive investment in the development of a technology. This question has to be addressed at the start of the technology development and can then evolve as the technology matures. An effort on standardisation has been ongoing at ETSI for several years in the field of quantum communication. One of the more recent initiatives comes from CEN-CENELEC which organised a dedicated meeting in Brussels in March 2019. These sorts of activities should be further pursued and become a regular activity.

IP strategy

It is important to raise awareness of the quantum technology stakeholders of the importance to protect their results. Patenting is one tool for that, while protection as a trade secret and using contractual obligations are other tools. It is part of a virtuous circle were researchers can valorise their results and make the transfer of their results to industry, which will then produce new products which generate new income and a return on investment for the researchers. An action has already been started by the European Patent Office to promote patenting and this should be continued in the next phase of the flagship to ensure a strategically-relevant IP portfolio within Europe. In addition to raising awareness, there could be a proactive action, such as an agency, to help and support academia and SMEs to file and licence IP rights.

Technology transfer significantly varies between institutions, which can be a barrier for companies. It is suggested that the Flagship should provide some guidelines to technology transfer offices to make engagement easier. Equally, the Flagship should examine international best practice on dealing with technology transfer offices and guidance should be provided in the context of the European Technology Transfer Block Exemption Regulation to encourage in-licensing of inventions from other companies and research groups. Furthermore, when groups of research institutes and companies are involved in joint projects, packages of licensing rights and common licensing policies should be constructed to simplify the licensing process.

roadmap

3 year vision

Innovation

- The identification of use-cases for quantum technologies represents a system for identifying emerging research result and are an important tool in promoting innovation. The tools for managing this and channels for promotion and dissemination should be key targets for accelerating innovation and growing ecosystems.
- Identifying enabling technologies developed for quantum technologies but that can be used by other fields would provide added value to the Flagship initiative.
- Defining and processing benchmarks and KPIs that can evaluate the added value of quantum technologies will be needed.
- Concerted and coherent mapping of quantum technologies to the existing EU TRL scale, which can provide a guide to industry.

6–10 year vision

- Demonstration and promotion of functionalities achieved with quantum technologies that are not achievable classically and that fulfil identified use-cases.
- Development of schemes for the evaluation of quantum technologies and the continued updating and improvement of benchmarks and KPIs.
- Promotion of new enabling technologies and products that facilitate the development of quantum technologies and that find applications outside of the fields of quantum technologies.
- Evaluation of the impact of those products outside of the field of quantum technologies and the progress of quantum technologies according to the TRL scale.

International Cooperation


© RomoloTavani / iStockphoto.com

Quantum technologies have a huge potential for innovation that may revolutionise the information economy. Europe can play a leading role through strategic international cooperation to develop competitive collaborations that represent a win-win for Europe and the field.

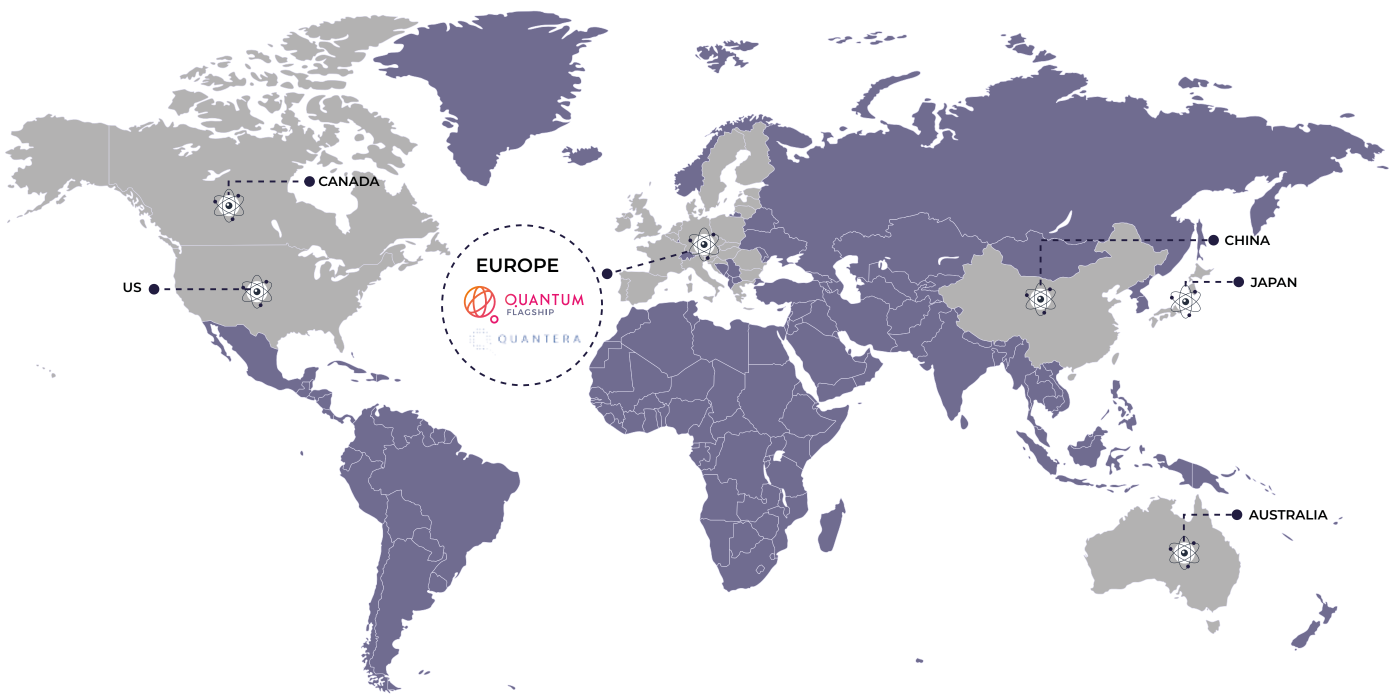
International cooperation

Europe has world-leading researchers in most domains of quantum technologies but it would be unrealistic to maintain such a strong position in isolation. To further strengthen Europe's position, it is crucial to (1) foster international scientific and education cooperation, in a framework ensuring that this is a winning partnership for Europe, avoiding brain, ideas and IP drain, and (2) support communication and coordination between European academic and research organisations and their top-level counterparts outside Europe.

Quantum technologies: a major disruptive sector calling for a worldwide research and innovation

Quantum technologies are one of the most disruptive R&D sectors as they present a game-changer for the entire information and data value chain from sensing, to communication, sorting, simulating, predicting and computing. The second quantum revolution is emerging from decades of major discoveries in quantum physics. This basic research activity is developing best in an open research spirit based on international collaborations.

The second quantum revolution is now entering into a new phase of technological developments. However, the key characteristic of the present technological developments is that they are still strongly "entangled" with fundamental research since the engineering race is launched at a very low maturity level while major conceptual issues are still unsolved. Even if at the international level the efforts to develop the quantum technologies are considerable, in many cases, the race might be a long and arduous one as fundamental research is a key player that needs time to go through complex issues. The required conceptual and technological breakthroughs are calling for a worldwide research and innovation effort.



Quantum technologies are developing fast through open research and global, public and private, cross-community efforts. The exchange of ideas in this exploratory research and development is the groundwork of the present expansion of the field.

A clear framework to benefit from international collaboration

Europe has world-leading researchers in most quantum technology domains but its competitors such as China, US, Canada, Japan and Australia are strong and are massively investing to develop quantum technologies. It would be difficult or even unrealistic to maintain such a strong position in isolation. Up to now, collaboration and open exchange of ideas with leading researchers all around the world has contributed to build the European leadership. Isolating Europe or putting illsuited barriers between Europeans and their international collaborators would in fact slow down Europe and weaken its positions.

At the same time, the disruptive potential of quantum technologies may give a substantial advantage to future owners of quantum technologies and applications and thus Europe should be agile in the competition for the creation of economic value in order to protect its main interests. quantum technologies can also raise issues of sovereignty that can change the reasoning about international collaborations. Therefore, it is crucial to foster international scientific cooperation, in a framework that ensures that this is a winning partnership for Europe, avoiding brain, ideas and IP drain.

Economical support from the European Commission in R&D gives an amazing opportunity for its European members to generate new market opportunities. European R&D collaborations participate actively in the creation of valuable and competitive products and/or services. In the global economy Europe is considered as a real contender against world superpowers, such as the USA and China. The European R&D is highly valuable and as anything valuable it needs to be protected, otherwise it may be easily copied or even stolen.

The European R&D Community support has a tremendous positive impact in the overall competitiveness of European companies. However, the European Community also has the responsibility to protect the generated added value, such as the Intellectual Property, the know-how, the patents and the copyrights. Strategic European R&D developments in networking security such as in quantum technologies need to be highly secure among the European members. Cooperation between the member states will eventually lead to the creation of expertise in new countries within the EU and lead to a European leadership in Quantum Technologies. By doing so, the EU also guarantees technological independence and minimises IP/ideas drains by foreign powers. International collaboration is crucial for the economic growth of European companies. IP rules are an important issue while constructing International collaborations on quantum technologies, and should be questioned in a global context.

To avoid any free access to technological progress or IP/ideas drain from foreign countries, projects and partnerships that benefit from European funds should be closely monitored. As a matter of fact, in the last phase of the Quantum Flagship, companies from foreign countries (outside the EU) were also included in some European consortiums. In the US and China, the information about public/defence R&D projects and partnerships are carefully protected by authorities. Thus, ideas, IP and information should be carefully handled by European authorities as well during the R&D phases to avoid any crucial information leak.

"Europe has world-leading researchers in most quantum technology domains but its competitors such as China, US, Canada, Japan and Australia are strong and are massively investing to develop quantum technologies."

An appropriate IP framework shall be drafted in the next years for quantum technologies to take care of the economical concern. But this should not prevent the EU from strengthening scientific collaborations outside Europe. Building strong European regulations in order to protect IP is not contradictory with engaging for structuring future international collaborations. While the first enables the protection of key competencies and attracts partners seeking new markets through complementarities, the second is a resource for worldwide solutions on major societal challenges, such as health, energy and security.

This is the win-win approach that we recommend to be conducted in parallel while discussing with countries that are investing massively in academic and industrial research on quantum science.

Preparing Europe for the international competition

As far as brain drain is concerned, the first key element is to provide an attractive environment in Europe for key researchers and start-ups to be able to develop their ideas and activities. Considering the global picture, providing a very competitive and attractive European ecosystem in quantum technologies is the best way to prepare Europe for international competition.

In particular, it has been made clear[10] that reaping the benefits of the second quantum revolution requires a consistent strategy not only in research and development, but also in the following key areas:

- Education and training both for researchers, technology developers, and for future users.
- Technology transfer and start-up support to stimulate economic value creation.
- Creation of a European supply chain on critical technologies to ensure technological sovereignty.
- Development of standards and regulations which are efficient tools in international competition.
- Public procurements and more generally, development of use-cases, and stimulation in Europe to accelerate the development and dissemination of quantum technologies.

With these assets in hand, Europe can be well prepared to face international competition and to derive the best benefit from the cooperation it will set up.

Two additional issues need to be addressed: the IP and innovation protection policy and the co-operation policy in terms of regions and countries. The IP protection is a key issue but due to its complexity and its possible political dimension, it will be treated in a separate section, below. A first strategy could be to minimise the IP issues by collaborating first on basic research or general issues for which the main deliverable will be open publication. As far the foreign affairs dimension of this topic of international collaborations is concerned, this is mainly a political issue treated at the commission and EU countries government level. In the recent EU call for a Coordination and Support Action on international collaborations, three countries have been specifically targeted: US; Canada, and Japan.

Cooperation in research and innovation: complementarity and critical mass

The overall criteria for an international cooperation in research and innovation is that Europe should benefit at least as much as its partners from the international cooperation within the project.

Practically, this corresponds to cases where:

- The expertise of partners complements each other in such a way that the European

[10] Such as the Quantum Technologies Flagship Final Report written by the High-Level Steering Committee appointed by the European Commission (report delivered on 28 June 2017).

partner would not be able to pursue the same objectives with the same ambition or at the same speed without the establishment of the international cooperation.

- The expertise of partners is of similar levels, and combining forces is likely to lead to the critical mass needed to cope with the targeted challenges. However, this is more prone to follow-on competition and should be treated carefully. For example, this is the case if EU researchers are stronger at lower TRL and other non-EU researchers are faster in creating start-ups.
- The partners share themselves the challenges to resolve the difficulties and progress faster.

In such cases, it is likely that part of the generated IP would not have been obtained at all, or not in the same timescale, without setting up the international cooperation.

The way suggested to implement consistently these criteria is the following:

First, one is to determine – prior to calls for projects – the scientific and technological areas where collaboration with countries outside Europe is a winning case and to restrict the call for international collaborations to this list of topics. As this approach may be too slow for some research areas and preclude the establishment of a specific and very fruitful collaboration, either on a specific topic, or with a specific international group, one could combine it with an open call with potentially different (stricter) evaluation criteria.

Then one is to determine, for each given project, if the proposed collaboration is beneficial to Europe. Indeed, scientists and their peers are well placed to analyse the complementarity or the critical mass effect of the international partners. Thus, the evaluators would then assess – project-by-project and on the basis of the case made by the proposers – the need, relevance, and win-win scheme of the international cooperation. Besides the funding programs, one could dedicate a group of evaluators to assess the potential achievement of a critical mass with the proposed collaboration.

International collaborations in education and training

The overall criteria to develop international collaborations in education and training should be the same as in research activities: Europe should benefit at least as much as its partner from the international cooperation. Therefore, either European students can learn skills abroad that they cannot acquire in Europe, or European institutes attract the best talents from abroad to be educated and later work in Europe (a reverse brain-drain). As relevant activities may include joint education programmes, joint courses, joint PhDs, professor exchanges… the primary indicator of success is enrolling the best students in the program. In terms of evaluation criteria, this means that a lot of emphasis should be put on the visibility to be achieved by the program to be implemented.

The collaboration for training and education could be a way to develop common 'language' and cultures such as best practices which are a determinant to build fruitful cooperation.

The collaboration in large public communication and engagement, such as conferences, social media, radio, tv…, can also be the best way to maximise the public awareness about quantum technologies similarly to what is done in the large-scale international collaborations such as space, astrophysics, particle physics and fusion energy.

"Discussing market needs with key international partners and selected early adopters could also help identify new use-cases in which quantum technologies will bring added value."

Implementation – strategy sharing, exchanges of best practices, identification of use-cases

A successful international cooperation is built through strong mutual understanding, and, in the rapidly changing and challenging field of quantum technologies, there is a strong rationale to share views on best strategy and practices with high-level counterparts from governmental organisation, academics and industry (e.g. USA, Japan, Canada). Also, there are benefits for all players to set up at the earliest convenience the necessary working groups to define global standards for quantum technology-based products and devices. Practically, this may be pursued through specific – bilateral or trilateral – workshops gathering high-level representatives from research agencies, research institutions, government organisations and industrials active in quantum technologies.

Setting up the framework for relevant research collaborations may specifically benefit from such strategic workshops. Part of this activity is supported by the international cooperation task proposed in the QFLAG CSA. The research workshops could also participate to part of the objectives targeted here at the level of broader research communities.

Discussing market needs with key international partners and selected early adopters could also help identify new use-cases in which quantum technologies will bring added value. Use-cases and early adopters can be seen as one of the possible strategic discussions with key international partners. Indeed, high-tech domains such as forefront research, space exploration or health, energy and environment issues are already fields of strong international collaborations with some specific countries. Those fields could also be interesting domains to develop early applications of quantum technologies within the existing collaborations.

Addressing the IP issue: Making Europe stronger to benefit from an open world

The delicate equilibrium between IP protection, free trade, and open research & innovation

Quantum technologies have a huge potential for innovation which may revolutionise the information economy, shaking all businesses and disrupting the technological context of key elements of sovereignty. The mastery of IP issues is thus strategic both at the economical level, and in some cases, at the sovereignty level. These two issues should guide the partnership policy.

The IP protection calls for a global policy throughout its entire life from the creation of new IP to its licensing and transformation into new businesses including its future when those businesses evolve. Indeed, the simplest way to capture IP is to buy the company owning the IP or a license to exploit it. Moreover, large companies are international and are implanted in different countries either directly or through subsidiaries or joint ventures. Thus, the reflection about a consistent IP protection policy should not only evaluate the pros and cons of open innovation versus restricted collaborations, but it should also consider the targeted equilibrium between protectionism and free trade. None of these issues are specific to quantum technologies. Nevertheless, the huge impact foreseen from quantum technologies make them, maybe, a more burning issue.

There is also a need to raise awareness about "immaterial IP" with European academics: Researchers are usually driven in thinking that the subject of their research is the key container of all the IP they are generating. But, intangible IP can make the difference between a successful work or product. One shall raise awareness among European researchers about the fact that IP protection starts with the whole R&D process, including minor issues solved to achieve the process. The only way of protecting this is through self-discipline: whilst it is important to cooperate, it is also important to avoid lingering on aspects that aren't in the scope and are not relevant to the cooperation subject. Strengthening IP protection within the flagship remains an important requirement and a daily task.

Specific protection when sovereignty is involved

Quantum technologies may impact areas of sovereignty for Europe or for some European countries. Sovereignty may lead to a country dependent policy and to specific development[11] and protection[12] programs. Many European countries have such schemes.

This question of sovereignty should be addressed in each country, probably relying on a permanent exchange of information between the community and their government representatives in order to monitor and analyse the progress and evolution of quantum technologies. A joint vision of this question at the European level would help to smoothly manage it in the flagship.

Favour the strengthening of European research, innovation and business

As far as research, innovation or economy are concerned it is important to recall that barriers have often proved to be counterproductive. Indeed, barriers work both ways and, if they provide protection, they also reduce the flow of information and opportunities that feed Europe and boost its economy, its research and innovation dynamics. The best option appears to keep the system open, and to obtain the needed protection, not through barriers and limitations, but through the strengthening of the European research, innovation and business ecosystem; A soft power strategy.

The first point is to have a clear and strong IP policy. Taking patents and other relevant IP protection measures (such as trade secrets and contractual relationships) should be strongly encouraged or required in EU or MS grants, and by relevant institutions[13]. In the framework of research projects resulting from calls opened to international cooperation, consortium agreement should ensure equilibrated rights of exploitation and use of the generated IP, so that EU can benefit from each project. Patents are good, but a coherent and strategic portfolio of patents would be more effective. EU could help in connecting and exploiting patents from different projects and different entities as part of a coherent portfolio[14]. Finally, we should avoid the need to negotiate multiple licences to exploit technologies. Licencing is the path towards business creation and licencing should be carefully done in order to ensure the best possible IP management. Sharing good practices and issuing guideline could be part of the setting up of relevant IP protection. Also, joint agreements between academics, SMEs and larger companies could be a way to help the filing of patents and fund their support throughout their lifecycle. Funds need to be dedicated in advance to filing patent applications not just in local countries, but to ensure that the portfolio is built at least in the "Big Five" countries (Europe, US, China, Japan and Korea) and to maintain the portfolio for several years (at least five) to allow technology licenses to be developed.

---

[11] e.g. targeted research and development programs could be financed at European or members state level.
[12] e.g. a legislation allowing states to prohibit or frame the acquisition of a company active in a strategic field by a foreign investor could be generalised.
[13] In some cases, a conscious decision could also be taken not to file a patent, in order to keep crucial knowledge secret. In these cases, Non-Disclosure Agreements need to be put in place.
[14] This might be specifically useful when patents are filed by small, even if highly innovative, research institutions since their patent portfolio might be too small to ensure the best possible valorisation dynamics.

A second point, providing an immense soft power and implicitly keeping Europe at the most advanced level with benefit to business, is for Europe to lead the (global) international working groups defining the needed technical standards for practical implementation (as it was back at the beginning of mobile communication). This will prevent the largest players from developing their own and force the other players to catch up. At the same time, it will provide the necessary technical stability that European industrial players would like to see as one of the conditions for large-scale investments and provide a level playing field as a basis for fair competition.

Other actions, beyond research and research management, are needed, and are cited below. They correspond to policies already implemented by EU and member states, but maybe not to the desirable extent. These actions are part of a successful innovation policy, which cannot rely only on research and research management, but also depends on a consistent set of measures and an overall favourable context.

One point could be to (further) foster the emergence of strong European investment funds able to support the early stages of start-up growth, and their transformation into mid-size companies. One way, already implemented in some countries and planned on a European level as part of the European innovation council (EIC), is to keep an eye on progress with the possibility to act on the evolution of start-ups and companies, which would require direct government investment in their capital. These European public investments funds would reinforce the impact of European private investment funds. It would have a leverage effect on European private investments.

A second approach could be to make Europe more attractive, to avoid the displacement of innovative industries to other countries and even to attract foreign companies to Europe. In particular, EU and member states could further support the emergence of strong local quantum technology innovative ecosystems, where companies will find a combination of public research (University, RTO…), industry, high quality workforce and platforms to pursue their development.

Following the leading role in coordinating the global definition of standards and the investment in facilities that have already been made, Europe could focus one or more (better more) of such local ecosystems as a “go to place” for test, verification and validation of products based on quantum technology.

Gender Equality

Tackling the challenges of equality, equity and inclusion in the quantum technologies domain as we begin to structure this emerging industry represents a timely opportunity. In particular, the impact of the participation of women generally contributes to increasing the quality, societal relevance and competitiveness of research and innovation.

© Vectorig / iStockphoto.com

Gender Equality

Equality, or more generally, Equity, and diversity issues are wide-ranging and include age, living location, gender, gender orientation, sexuality, religion, indigenous status, cultural and linguistic background, race, disability, mental and physical health, pregnancy, parenting, and other responsibilities related to care of dependents. While the strategy should initially focus on the challenges related to gender, solutions and the implicit change towards a more diverse and tolerant culture could also have a more positive impact on these other areas. It is important to mention that when talking about gender, it is important to understand that this is far more complex than the traditional binary male-female concept.

Quantum physics and technologies represents a special case in terms of gender equality. This is because:

1. Women are in clear minority in the quantum technologies field where the number of women in quantum physics and technologies is lower than average in science, technology, engineering, and mathematics (STEM) and
2. This is a potentially high-growth area that will have a significant effect on the demographic of scientists in the EU.

Overall, women represent 20% of the physics graduates and doctorates[15] and 13% of the engineers[16] in STEM. This is a problem that needs to be fully assessed, for which statistics focused on the quantum physics and technologies fields are needed that give a better reflection of the ecosystem in a quantitative and qualitative way, alongside a battery of measures directed to correct the imbalance. The quantum community needs (additional) resources, including dedicated funding allocated to gender equality, and a dedicated CSA for gender equity in the quantum community.

Despite the progress that has been made in getting women into science at the university level, there remains a challenge to ensure the promotion of women to senior positions, increase their representation as conference presenters, chairs, PI of important grants, and, in general, their equal treatment. The impact of the participation of women is overall positive, contributing to increasing the quality, societal relevance and competitiveness of research and innovation[17]. Furthermore, according to a new research from the McKinsey Global Institute, to the improvement of the global economy, stating that by advancing women's equality, $12 trillion could be added to global GDP by 2025[18]. It is thus that the work on gender equality is of such significant strategic importance that it should have a place alongside science, innovation, industry, education etc. in the Strategic Research Agenda.

Increasing gender diversity at senior levels

In the overall realm of STEM careers, which include all disciplines within science, technology, engineering and mathematics, there has been progress in getting women into science. The share of women at the top level of an academic career rose from 18% in 2007 to 21% in 2013. The share of women heads of higher education institutions rose from 15.5% in 2010 to 20% in 2014[19]. These numbers are across STEM, and for the quantum technologies field evidence suggest that these are even lower. Evidently there remains a challenge to ensure the promotion of women to senior positions, increase their representation as conference presenters,

[15] Women in Physics and Astronomy, 2019, American Institute of Physics
[16] Roberta Rincon, Ph.D., Manager of Research, SWE https://alltogether.swe.org/2018/09/swe-research-update-women-in-engineering-by-the-numbers/
[17] http://www.ciencia.gob.es/stfls/MICINN/Organismos_Intermedios/FICHEROS/Guidance_to_facilitate_the_implementation.pdf
[18] https://www.mckinsey.com/mgi/overview/in-the-news/the-economic-benefits-of-gender-parity
[19] https://eige.europa.eu/sites/default/files/mh0716096enn.pdf

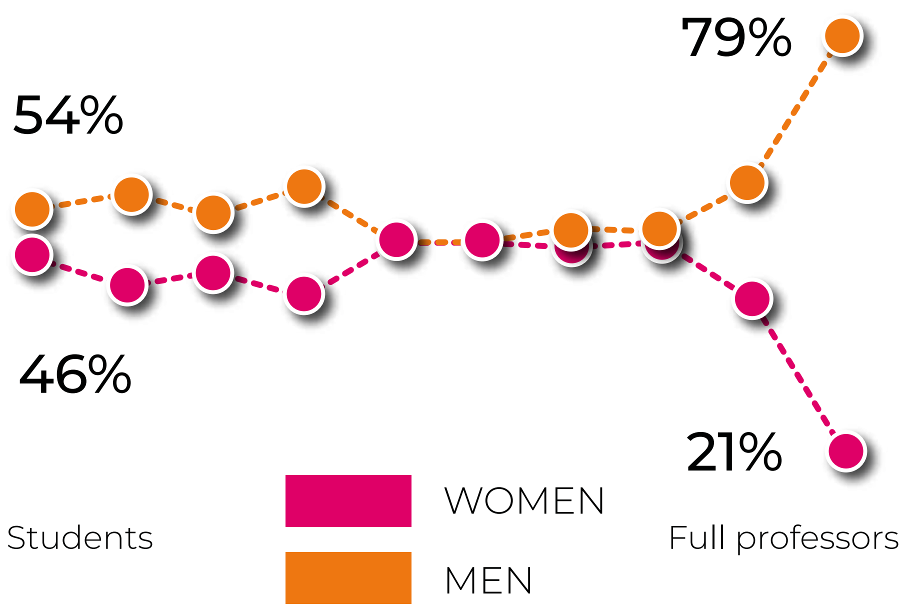


Figure adapted from www.ciencia.gob.es

chairs, PI of important grants, and, in general, their equal treatment. Many countries, institutions and national research initiatives have developed programmes to help support women in STEM areas which have a good overlap with the diverse fields involved in Quantum Technologies. In industry, we see similar challenges. One of the most marked problems facing gender equality in quantum science, and STEM in general is that we seem to be able to reach reasonable numbers of female undergraduate students but as their careers progress through post-graduate studies and towards full professorships, the ratio tips significantly towards men. The graphic[20] here is for all sciences (in Spain). However, in quantum technologies we are generally struggling to even come close to 50% for the undergraduate stage. Reasons why this is like that, could depend on many factors, such as (unconscious) bias, low visibility of female scientists, as well as structural challenges in academia that often work against work-life balance and family-friendly policies. While issues like unconscious bias and the visibility of women can be approached from the quantum community perspective, others need local and institutional involvement to change human resource policies that strengthen aspects like work-life balance and family friendly environments, etc.

A different way to see this problem is through the vertical segregation that occurs across sectors for women, regardless of the numbers of women at entry level. This is established by the imbalance between women and men in leadership categories (occupational hierarchies) where men dominate leadership categories while women are concentrated in non-management roles[21,22].

---

[20] Adapted from http://www.ciencia.gob.es (Spanish female scientists report 2015)
[21] Gender segregation in the workplace and its impact on women's economic equality, Commonwealth of Australia 2017 ISBN 978-1-76010-568-6
[22] Women in the Workplace, McKinsey & Co 2018
[23] Reports of EFFORTI (www.efforti.eu) http://uis.unesco.org/sites/default/files/documents/fs51-women-in-science-2018-en.pdf https://ec.europa.eu/eurostat/web/products-eurostat-news/-/EDN-20190211-1

"We need additional actions targeting the quantum technologies community, where the statistical numbers collected so far indicate a larger gender inequality."

Approach to gender equality in the Quantum Flagship

The current CSA (QFlag) underlying the Quantum Flagship does not have the budget to create and implement a full strategy to help solve the gender inequality that the quantum technologies field faces. However, it has created a working group dedicated to this matter; the gender equality working group (GE-WG) aims to provide structure and support to the members of the quantum technologies community. This WG has identified the following working areas:

Statistics around gender distribution in the community and at events

There are several reports[23] available that describe gender distribution in research and innovation or science and technology in different geographical areas. There is though, little information centred specifically on the quantum technologies arena. While many people perceive that the number of women in this field is low, the community lacks numbers based on facts. This information is key to present the challenge of gender inequality in an unbiased way so that measures can be put in place to correct the situation and to be able to measure the impact of the actions that are set in place to correct the gender imbalance.

Identification and organisation of activities/actions to improve gender equality

Many countries, institutions and national research initiatives have programmes to help support women in STEM. However, we need additional actions targeting the quantum technologies community, where the statistical numbers collected so far indicate a larger gender inequality. These actions include unconscious bias training, support programmes and events to involve the community at large in acknowledging and tackling gender inequality, ensuring that the approach has cross-gender, cross-generational reach and involves internal and external experts in science, gender and technology policies. This will bring content and perspective to the challenge and will especially become a useful tool and insight provider for the quantum community as well as the European Commission in order to work towards gender balance and inclusivity.

Raise awareness and especially raise visibility of female scientists

The visibility of women scientists is important for two reasons: because it is only fair that professionals with the same accomplishments get the same recognition and visibility, and because it is often the case that women are able to attract more female talent to their teams than their male colleagues. One reason for the low number of women in leadership positions, as speakers in scientific meetings, as experts on boards or interviewed by the media, is that women are less visible than men. Studies have shown that articles with women in dominant author positions receive fewer citations than those with men in the same positions[24], decreasing the visibility of women as equally qualified scientist in comparison to their male colleagues. Senior researchers have to be encouraged to highlight and evaluate merit equally. Transparency is a key element here and goes hand in hand with visibility; there needs to be transparent and objective criteria for choosing candidates and speakers.

The quantum community needs to make an effort to increase the participation of women in visible and/or prestigious positions in a transparent and objective way with clear criteria for choosing candidates and speakers that leads to a broader representation in public positions beyond the traditional core group. Part of the community is already

[24] Global gender disparities in science, V. Larivière et al, Nature, Vol. 504, 12 December 2013; https://www.nature.com/news/bibliometrics-global-gender-disparities-in-science-1.14321

aware of the importance of including women in their structures and events. Unfortunately, given the low visibility of the female community overall, only a few women are being constantly requested. This leads to a saturation of the agendas of these few women. It is thus important to have a database that includes female scientists and to make it widely available, so that organisers of events, boards or media requests, are aware of this pool of talent. At the same time, having women of the community more visible will help to influence young and early-career female students in the process of deciding their career paths and to pursue a career in quantum technologies.

Create a networking and mentoring structure

It is important to create a networking structure for the community to get together on gender issues and to serve as a safe protected channel to communicate any issues related to discrimination that its members might be facing or witnessing, as well as provide each member of the quantum community another tool to contribute to the creation of a fair ecosystem. It is necessary to have this structure open and reachable especially to the early-career members of the community with the involvement of the members in more senior positions. Mentors and role models play an important role in career path options, and as mentioned before, women often attract other women to the field, so that systems in which we can bring together and encourage mentoring schemes can be effective tools for the career advancement of women. We would also note that men are mentoring women very effectively. This is mainly due to two reasons; men typically have better networks, and the eye-opening effect that mentoring has on the male mentors in terms of the barriers that their female mentees face. Of importance here is to determine the right mentoring and networking schemes that are best suited for the quantum community, as different models have different impacts and benefits[25].

Conclusion

Gender equality, as with all diversity issues, are key to the quantum community not only for social fairness but because it has been proven that it has a positive impact on productivity and innovation. The community perception is that in quantum technologies the gender imbalance is particularly large. However, we need to acquire suitable statistics to have a clear picture of the landscape in the field, as well as a suite of actions to address the gender imbalance. Actions have to be carried forward and structures put in place, to create an ecosystem that enables the number and visibility of female scientists to increase across all levels of the value chain of quantum technologies, from the Quantum Flagship itself to the related industries, and to the future workforce of the field. For that, we need funding in the form of dedicated CSAs in addition to emphasising the importance of a dedicated "gender concept" section in all research and innovation calls.

[25] Women and leadership: the role of mentoring and networking, Schipani at el. 2008 ALSB National Proceedings

roadmap

3 year vision

Gender Equality

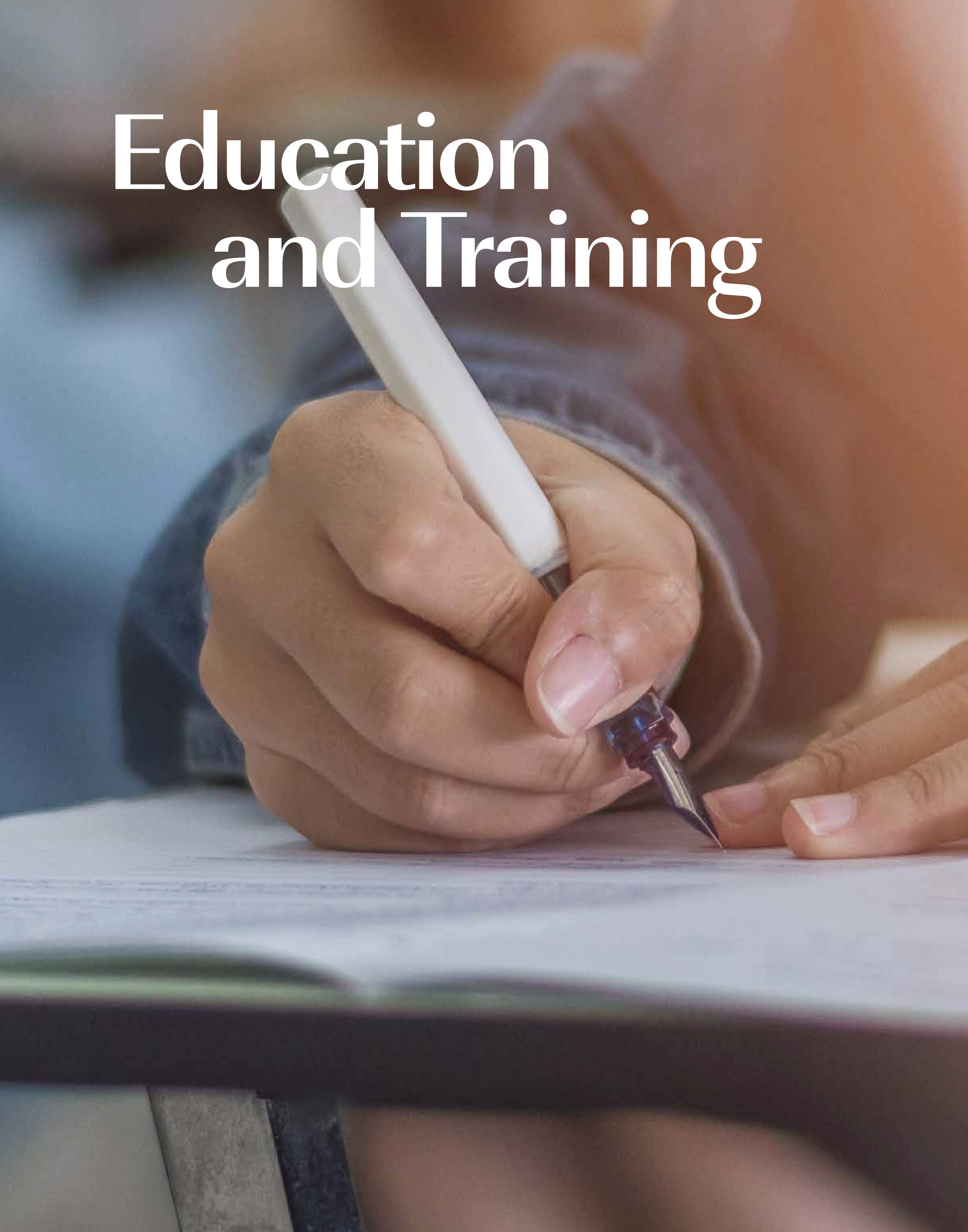
- **Statistics and key performance indicator (KPI) methodologies in place:** A procedure to collect and monitor gender-related information including quantitative data and qualitative aspects that will allow us to understand the actual situation in terms of gender equity and existing ecosystem as well as measure the impact of the measures that the Quantum Flagship is taking.
- **Charter for gender equality at conferences created:** The Quantum Flagship will create a charter for gender equality at conferences that event and conference organisers will have to follow for the Quantum Flagship to endorse them by helping with their dissemination and even participating in them.
- **Special dissemination channels and materials:** to increase the presence of female quantum technology researchers at conferences as attendees as well as engage the female scientific community in quantum technologies. The Quantum Flagship should collaborate with forums, networks and associations directed to women scientists and engineers, in academia and the industry to better leverage these efforts.
- **Unconscious bias training program for the quantum community:** biases affect everyone, regardless of their own personal beliefs and opinions; signs of these behaviours in science are everywhere, starting in schools and continuing through all levels of the career ladder. This translates into women in science earning less, being less likely to be promoted or receive letters of recommendation, and more likely to quit altogether[26]. Training is an essential part of the professional development of scientists and engineers in academia and industry,and to correct the unconscious bias, specialised training is needed. Training material and events will be collected, publicised, and made available to the community. The training must be carried out by professionals with expertise in gender diversity that must engage with the quantum community at all levels of seniority. This is important to help women progress in their careers and move to leadership positions, and to create the right ecosystem that promotes everyone's careers.
- **Creation of outreach programs:** it is key to increase the number of potential professionals in quantum technologies, and for that, we need to increase the number of female students in STEM careers, especially those that show a more direct link to quantum technologies (e.g. physics, engineering, mathematics and computer science). For that, we need outreach programs directed to female high school students and STEM undergraduates, to promote and increase visibility of professional opportunities that quantum technologies provide to them.

[26] K Dutt et al, Nat. Geosci., 2016, 9, 805 (DOI: 10.1038/ngeo2819)
[27] http://www.jamaissanselles.fr/

6–10 year vision

- **Gender equity in conferences:** through the implementation of the conference charter and the promotion of the visibility of women in quantum, Quantum Flagship related conferences will reach full gender equality in their speaker, moderators and panels (similar number of male and female participants, about 50-50%).
- **A mentoring system in place:** The Quantum Flagship needs to have mentoring structures and systems in place specifically targeted and adapted to the quantum technologies community. Working together with experts from organisations such as WISE (Women in Science and Engineering), and learning from initiatives such as #JamaisSansElles[27], the Quantum Flagship needs to set up a mentoring system that provides support to the community, especially to the career promotion of women.
- **Unconscious bias training:** The aim is to have all members of Quantum Flagship projects undergo unconscious bias training at the beginning of the project as a project condition, and the PI and Co-PI having demonstrated that they have undergone the training as a condition for the project proposal, as well as having a gender concept section in each project, to be considered for funding.
- **Monitor the KPIs of the gender equality actions:** follow the gender equality situation of the quantum community monitoring the KPIs and underlying methodologies.
- **Gender equality in the Quantum Flagship:** to reach full gender equality in leading roles in the Quantum Flagship structures as well as in its membership
- **Increase the number of women in Quantum Flagship projects:** Women in WP leadership positions should be at least 30% of the total positions in projects within the Quantum Flagship
- **Increase the number of female PhD students in quantum technologies:** an increase of at least 50% in the number of PhD students in quantum technologies-related programs to be women.
- **Expansion of outreach programs directed to female STEM undergraduates:** ensure that outreach programs directed at female STEM students are being rolled out across Europe.
- **Impact assessment of the gender equality actions** in terms of the increased presence of women in the quantum technologies community and of the changes in the ecosystem and its impact in the research and innovation of the Quantum Flagship.

Education and Training



© Chinnapong / iStockphoto.com

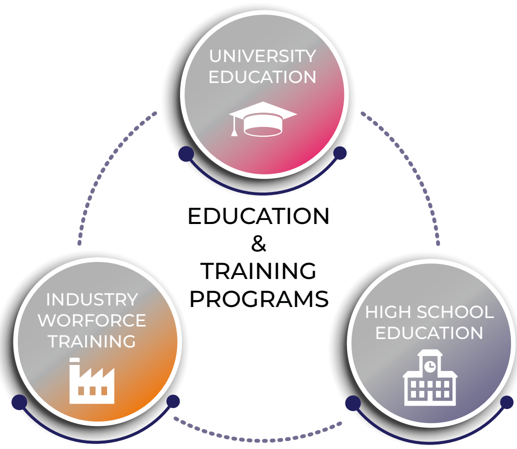
The creation of a learning ecosystem embracing the concepts of quantum physics at all levels ranging from school up to the working environment is required, not just for a quantum-ready workforce to emerge, but for a well-informed society with knowledge and attitudes towards the acceptance of quantum technologies.

Education and Training

If Europe strives to be a leading force in the field of quantum technologies, the need for a quantum workforce and a well-informed society with knowledge and attitudes towards the acceptance of quantum technologies is evident. In order to provide a solid long-term, sustainable implementation and progress of quantum technologies, a strong support of European quantum education is necessary. The challenge of an immense scaling-up in training and education while increasing interdisciplinarity and drawing acute attention to current and future corporate and societal needs can only be achieved with a comprehensive and coordinated effort. This endeavour has to establish an ecosystem bringing together all involved stakeholders**.**

Current status

While quantum physics today is included in all university physics curricula and touched upon in high school curricula in some, but not all European countries[28], this does not satisfy the needs for a workforce ready to bring quantum technologies into engineering applications. In order to move the emerging field of quantum technologies closer to the needs of industry and general society, a modern and dedicated quantum education programme is needed throughout Europe, leading to quantum awareness and literacy for a broader range for schools, university students and the workforce. Furthermore, it is necessary to teach quantum topics also in other curricula, e.g. computer science or quantitative business. This will foster the range of future applications of quantum technologies.



To address the challenge, the Quantum Community Network (QCN) has joined forces with leading physics education experts. As a result, a new community gathering educators, academics, communicators and industry representatives engaged in quantum education at all levels is emerging. This summary presents the first outcomes; envisioned pillars of the strategic education agenda within the flagship build upon the community needs[29] as well as first recommendations for the short- and long-term actions.

Advances in quantum education and educational research needed to meet future challenges

The most urgent challenge consists in developing and evaluating effective training and educational modules for a variety of learners in the areas that traditionally do not get in touch with quantum physics (e.g. engineering, computer science, mathematics). The conventional formal introduction to quantum physics, based on the concepts of 20th-century physics, will not meet the needs of these audiences. An educational approach conveying “quantum awareness” and motivation is needed, shifting the emphasis to more conceptual and intuitive understanding. This is particularly pertinent in view of the paradigm shift from quantum theory as a theory of microscopic matter to quantum theory as a framework for technological applications and

[28] Stadermann, H.K.E., van den Berg, E., Goedhart, M.J., Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic. Phys. Rev. Phys. Educ. Res. 15, 010130 (2019).
[29] Education / Training and networking section from Supporting QT beyond H2020 summarizing the Quantum Flag-ship community meeting in Oberkochen (Germany) on 19. 04. 2018, https://qt.eu/engage/resources/

information processing. This paradigmatic change in teaching and learning of quantum physics merges decades of physics education research[30] and recently developed ICT-based approaches incorporating visualisations, simulations, education experiments, visitors' labs, science festivals and games. Research in physics education shows that a conceptual and intuitive approach will also enhance the education of physics students.

A conceptual approach to teaching quantum also ensures a low barrier of entry to the core concepts of quantum physics as well as the motivation for engaging with the more mathematical aspects of the topics. The emphasis on the conceptual and intuitionbased aspects of quantum physics will also foster large-scale quantum awareness through implementation into the secondary (and eventually primary) school system and public engagement initiatives. Such a new approach would also be interdisciplinary and different segments of society could cross-reference with their own field of expertise. Such a familiarisation with quantum concepts is key for a mindful and non-prejudicial interaction with quantum devices on a large scale. Thus, a conceptual approach based on educational research will provide a valuable addition to the existing expert training in physics.

A corresponding education and training program can be based on three interconnected pillars addressing different audiences:

1. **University education.** In this pillar the main target is a modern quantum curriculum for future quantum technology workforce. By joining forces across Europe for building quality-controlled teaching resources and methods based on empirical educational research, quantum education at the university level can be greatly enhanced. Target groups in this pillar are students at the Associate Degree and Bachelor, Masters and PhD levels in Quantum Science and Technology, related topics such as Physics, Mathematics, Engineering, Computer Science and Chemistry, pre-service teachers in these topics, as well as academic staff and decision makers (ministries, university and faculty boards).
2. **Training of industry workforce.** The main issue for industry is to develop concepts for raising the awareness of the workforce to current quantum technologies and their potential. This involves decision makers in industry (CEOs, CTOs, SME organisations), as well as the members of the current workforce themselves, who need special training courses to keep up with the progress of the second quantum revolution.
3. **High school education.** In high school education, two targets need to be addressed, building general quantum awareness for all citizens and quantum literacy for the future quantum scientist and engineers. This pillar will address *in-service teachers* and *high school students* through new quantum curricula recommendations and teaching strategies, based on educational research, as well as *decision makers* in this sector (ministries of education, school organisations, e.g. for building a quantum curriculum).

Conclusion

In summary, the creation of a learning ecosystem embracing the concepts of quantum physics at all levels ranging from school up to the working environment is required for the quantum-ready workforce to emerge. The envisioned strategy is an educational approach based on a combination of conceptual understanding and formal training that starts with the societal and company needs and builds up into a quality controlled educational concept.

> "A new community gathering educators, academics, communicators and industry representatives engaged in quantum education at all levels is emerging."

[30] Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A. & van Joolingen, W. R. Insights into teaching quantum mechanics in secondary and lower undergraduate education. Physical Review Physics Education Research 13, (2017).

roadmap

Education and Training

For the coordination of the efforts there is an immediate need for an Education Coordination and Support Action to: **(1)** perform an extensive mapping of current and future requirements for education and training, **(2)** define standards for implementing appropriate educational strategies, **(3)** host existing and newly developed teaching materials and resources within a repository, **(4)** develop strategies for scaling up advanced quantum technology training programs (e.g. QuTech Academy), and **(5)** establish a network between science and industry to exchange ideas, needs,

3 year vision

- Consolidate the needs and challenges of Quantum Education at the (i) university and (ii) high school education level and of (iii) the quantum industry and formulate measures for how these needs can be met.
- Build a repository of scientific literature and education studies, material and resources, documenting and classifying learning activities and methods as well as listing key partners for quantum technologies education in Europe.
- Research the needs and feasibility of a quantum technologies curriculum for all levels, resulting in a proposed quantum technologies curriculum description and example teaching material, teaching methods and evaluation concepts.
- Formulate standards for quantum technologies competencies at different competence levels. Since quantum engineering is an emerging discipline, there is no generally accepted definition of the competencies to be acquired. The Quantum Competence Framework (QCF) will be modelled after the example of the European Digital Competence Framework (DigComp). It will be empirically assessed and serve as a guideline for newly developed education programs.
- Build a network platform and establish regular national and international meetings between the quantum technologies research community, education research community, quantum technologies industry, educational authorities and further key partners.
- Develop pilot programs for a Masters degree in quantum technologies and quantum engineering for scientists and engineers, with student training in companies in each EU country, coming from different backgrounds (physicists, engineers, computer scientists).
- Develop pilot programs for summer schools at the PhD/early postdoc level for scientists in quantum science and related fields, including theoretical lectures as well as practicals.
- Specifically address the needs of member states and associated countries in Europe, which don't yet have a strong quantum technologies research community and industry, to:
  - Develop and evaluate formal and informal quality learning resources made accessible online at no cost (e.g. MOOCs, Jupyter Notebooks/Labs, Virtual Quantum Lab, gamification, quantum technology demonstrators, apps...) using the most up-to-date online and virtual training technologies.
  - Provide hands-on learning experiences that are reproducible and scalable at low cost by developing laboratory experiments based on the most recent results of research in quantum technologies and physics education.
  - Develop exchange programmes (e.g. COST action, Erasmus Mundus+, mobility grants...) to foster local expertise and support regional education clusters in university and high school education (teachers and students) and job rotation programs and secondments to academia for existing work-force to access unique quantum technologies infrastructures and expand their knowledge base.
  - Set-up joint summer schools for High School students involving quantum-physics laboratories in different European universities.
  - Develop and implement intense training programs for Quantum Education (e.g. summer/winter schools) for university students, PhD students and industry workforce.
- Raise quantum awareness across all member states in Europe through short-term, immediate actions to demonstrate societal benefits of quantum technologies (e.g. via public experiments on quantum technologies or the presence in traditional and social media).

and human resources (e. g. in the form of student internships). Moreover, there is a need to establish a European Quantum Education Community Network, with a structure similar to the Quantum Community Network (QCN) that comprises representatives of the member states, to help coordinating the education activities and strategies between the Education Coordination and Support Action and the national initiatives.

6–10 year vision

- A pilot program to implement a reformed approach of both formal and informal quantum technologies learning in selected member states for the (i) university and (ii) high school education level and (iii) the quantum industry, including:
  - A certificate system in Quantum Technology based on the empirically evaluated QCF standards.
  - Pan-European launch of interdisciplinary quantum technologies Masters courses in Quantum Engineering containing a component of leadership, industry and entrepreneurial skills training, based on the evaluation results of the pilot program.
- Establish self-sustained pan-European education programmes in quantum technology.
- Implement innovative research-based curricula for the (i) university and (ii) high school education level and (iii) the quantum industry that will:
  - Include frontier science and real-life scientific challenges.
  - Build on a combination of formal, rigorous education in quantum science and technology and conceptual, intuition-based learning approaches, including gamification and approaches based on virtual reality methods.
  - Integrate school activities and extracurricular activities embedded in national initiatives (e.g. exhibitions, science festivals, student laboratories...).
  - Test and evaluate in real teaching situations in teachers' education.
- An educational approach for secondary schools and teacher education based on conceptual and intuitive understanding, including research-based quantum curricula recommendations and empirically evaluated teaching strategies for secondary schools and teacher education.
- Joint international graduate schools for learners from different areas with opportunity for students to gather international experience (Marie Skłodowska Curie ITN/ETN).
- University activities for high school students (Quantum Masters Classes) Involvement of decision makers through e.g. educational advisory boards, job-shadowing, grey literature/ briefings/ recommendations.
- Network platform and regular international meetings systematically extended to SMEs.
- Transcending support across all measures to address inclusiveness in terms of diversity in internal (e.g. gender, ethnicity), external (e.g. parental status, work experience) and organisational dimension (e.g. work location, seniority).
- Recommendations for education at primary level in preparation for quantum technologies education at secondary level.
- A satisfactory level of awareness on the benefits quantum technologies bring to society.

Appendix

Evolution of the Strategic Research Agenda

The Quantum Flagship Strategic Research Agenda (SRA) was based on the high-level steering committees' (HLSC) final report[31] and has undergone revision after community consultation discussions at meetings in Oberkochen in Germany, Vienna in Austria, Grenoble in France, and Helsinki in Finland during the period 2018–19. These meetings were moderated by the Strategic Research Agenda and Innovation work groups, and after its formation, discussed and developed with the Strategic Advisory Board (SAB).

Following these meetings, the first draft of the SRA was compiled and a wide-ranging consultation has taken place. This was firstly done through the Science and Engineering Board of the Flagship, the QuantERA project coordinators, leaders from the quantum COST programmes, and EURAMET. A revised draft was then opened up to a public consultation through the web portal for the quantum flagship (qt.eu) during August of 2019.

This SRA was complimented with sections on Innovation, International cooperation, Gender Equality as well as Education and Training, that go beyond the original scope of the original HLSC SRA. This is due to the natural evolution and expansion during this "ramp-up" phase of the Quantum Flagship. Work groups have been formed in Innovation and Gender Equality during this time, while small teams, managed by the QSA and QFlag Coordination and Support Actions, have been working towards funding calls for Education and Training as well as International Cooperation.

The members of the SAB and work groups are listed below and on page 93.

Strategic Advisory Board

Chair: Jürgen Mlynek
Vice-Chair: Jaya Baloo

Anna Sanpera	Daniel Esteve
Elisabeth Giacobino	Marek Kus
Maria Luisa Rastello	Peter Loosen
Radu Ionicioiu	Vladimír Bužek
Wim van Saarloos	Fabio Cavaliere
Ulises Arranz	Grzegorz Kasprowicz
Christoph Sandner	Thierry Botter

[31] https://qt.eu//app/uploads/2018/04/170922_HLSC_Final_Report_online.pdf

Strategic Research Agenda Work Group

Chair: Rob Thew

Communication	Computing	Simulation	Quantum Sensing & Metrology	Basic Science
Andrew Shields	Thomas Monz	Jens Eisert	Fedor Jelezko	Toni Acin
Stephanie Wehner	Walter Riess	Francesca Ferlaino	Piet Schmidt	Philippe Grangier
Nicolas Gisin	Lieven Vandersypen	Pol Forn Diaz	Ivo Degiovanni	Ana Predojevic
Eleni Diamanti	Andreas Wallraff	Michael Marthaler	Stefan Kröll	Andris Ambainis
Tracy Northup	Fabio Sciarrino	Françoise Remacle	Eugene Polzik	Sabrina Maniscalco
Hugues de Ried-matten	Daniel Esteve	Jacqueline Bloch	Mathieu Munsch	Albert Schleisser
Rupert Ursin	John Morton	Andreas Ruschhaupt	Thierry Debuisschert	Ivette Fuentes
Grégoire Ribordy	Iuliana Radu	Maciej Lewenstein	Martin Plenio	
Helmut Griesser	Frank Wilhelm-Mauch	Christian Gross	Christiane Koch	
Renato Renner	Harry Buhrman		Steffen Glaser	
	Iordanis Kerenidis		Philippe Bouyer	
	Cyril Allouche			

Innovation Work Group

Chair: Thierry Debuisschert – Rogier Verberk

Anke Lohmann	Grégoire Ribordy
Cristina Andersson	Matthieu Munsch
Peter Soldan	Garrelt Alberts
David Kolman	Paul Ullmann
Mario Agio	Maud Vinet
Cathal Mahon	Mika Prunnila
Jurczak Christophe	Emanuele Pelucchi
Walter Riess	Iuliana Radu
George Tudosie	Yves Samson
Thomas Strohm	Johan Ulander
Cyril Allouche	Max Riedel
Andrew Shields	Michael Marthaler

Gender Equality Work Group

Chair: Lydia Sanmartí-Vila

Chiara Macchiavello	Roberta Zambrini
Géraldine Haack	Rob Thew
Christiane Koch	Irene D'Amico
Oxana Mishina	Araceli Venegas-Gomez
Ruth Oulton	Laure Le Bars
Iuliana Radu	John van de Wetering
Paola Verrucchi	Guido Pupillo
Stephanie Wehner	

Glossary

BoF	Board of funders
CSA	Coordination and support action
EC	European commission
ETSI	European Telecommunication Standards Institute
EURAMET	European Association of National Metrology Institutes
EuroQCI	European quantum communication infrastructure
EuroQSC	European quantum computing and simulation infrastructure
EuroQSM	European quantum sensing and metrology infrastructure
HLSC	High level steering committee
KPI	Key performance indicator
NISQ	Noisy intermediate scale quantum computer
NMR	Nuclear magnetic resonance
QCN	Quantum community network
QFlag	Quantum Flagship Coordination and Support Action
QKD	Quantum key distribution
QRNG	Quantum random number generator
QSA	Quantum coordination and support action
QuantERA	QuantERA ERA-NET cofund in Quantum Technologies
RTO	Research and technology organisations
SAB	Strategic advisory board
SEB	Science and engineering board
SME	Small and medium enterprises
SQL	Standard quantum limit
SRA	Strategic research agenda
STEM	Science technology engineering mathematics
TRL	Technology readiness level

QUANTUM FLAGSHIP