Europe’s Quantum Flagship initiative

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Abstract
As the first applications leap out of research laboratories toward commercialization, the global race for dominance in the maturing field of quantum technologies is becoming ever fiercer. To retain its historical lead and kick-start a continent-wide quantum-driven industry and accelerate market take-up, Europe has launched the Quantum Flagship, an ambitious €1 billion, 10 year endeavor. This article provides an overview of the underlying considerations and the current state of the initiative. Furthermore, it briefly presents the 20 projects selected to be at the core of the ramp-up phase of the initiative, which will address core applications of quantum technologies such as communications, computing, simulation, as well as sensing and metrology, all of which are supported by basic science. Finally, we present the broader ecosystem of European funding instruments and institutions which aim to create the next generation of disruptive technologies within quantum sciences, placing Europe as a worldwide knowledge-based industrial and technological leader in this innovative field.

Europe and the second quantum revolution

What seemed impossible to the founding theorists of quantum physics a century ago is routinely done in labs around the world today: we can prepare single quantum objects and control their ‘strange’ quantum properties both in superposition states and via entanglement. Over the last 20 years, the reliability and degree of automation of our experimental setups and the fidelity of our control has increased dramatically. In many cases, it has now reached a level that allows the use of quantum systems for real-world applications in sensing, secure communication, computing, and simulation.

The second quantum revolution is currently unfolding worldwide. Recent advances in quantum computing and simulation, combined with the promise of unprecedented disruption in and beyond the IT sector, have raised attention from media, policy-makers, and the industry alike. Although today’s quantum computers are not yet able to provide benefits to real-world applications, American and Chinese global IT companies are investing heavily to bring commercially successful quantum computers to the market. They push engineering to a level that is beyond what is commonly done in physics laboratories, leveraging their experience and facilities from classical chip fabrication. They also invest large amounts in research at their own R&D departments and in collaboration with the global academic research community. Similar progress is happening in quantum communication, with a particularly strong engagement of the Chinese government.

Europe is not only the birthplace of a field that has grown into a global enterprise. About a hundred years after the publication of revolutionary ideas from Einstein, Schrödinger, and others, the continent still retains the largest share in academic output. Furthermore, it is home to a very diverse quantum technology (QT) research landscape with many groups being considered pioneers and leaders in their respective fields. Some world-leading companies have spun-off from European labs, fostering the QT supply chain with innovations in the research equipment market, as well as advancing quantum communication and sensing. However, QT devices
are still relatively complex, often bulky, fragile, expensive, and advantageous only in specific applications. QT is thus perceived as relevant mainly for defense/security and niche markets, for which its limitations are less critical than for mass-market products. Correspondingly, take up by European industrial end-users has been slow. This is not all too surprising, considering that there are no IT behemoths in Europe like those in the US and China pushing the development of quantum computer hardware or the software ecosystem.

The European Quantum Flagship: the initiative to retain scientific leadership, kick-start the European QT industry and accelerate market take-up

The progress in quantum computing illustrates the three factors that are necessary to bring QT out of the lab: relevant use-cases with significant market potential, professional engineering on a large scale, and significant research to overcome current scientific and technological limitations.

Many EU member states have recognized this situation and have been investing strongly in national QT programs or centers in the past. The European commission (EC) has funded QT research over the last two decades with more than €500 million [1], mostly through the Future and Emerging Technologies programme (FET) for collaborative efforts, the European research council (ERC) for individual researchers, and the Marie Skłodowska-Curie actions for researcher mobility and training. The European QT Roadmap [2, 3] is a result of these activities, which has ultimately led to the Quantum Flagship. It did so by coordinating the research community’s efforts, objectives, and application needs in the framework of a 150-page document, which outlines the status quo, the short-, medium-, and long-term goals, as well as the current and future research and development challenges for a variety of QT fields.

As the next milestone towards the QT flagship, the European community published the Quantum Manifesto [4]. This strategic document, endorsed by over 3500 representatives from academia and industry, called on the EC to exponentially invest in QT as a core future technology. The community did not have to wait long for a response: shortly thereafter, the EC decided to launch the Quantum Flagship initiative, a 10 year scheme with €1 billion funding to further stimulate Europe’s strengths and overcome its weaknesses. The flagship, however, is not a mere funding instrument, but an overarching concept. The goal is to create a federated effort from the EC and the EU member states by bundling resources and thus creating a critical mass, with the following three key objectives:

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

Implementation of the Quantum Flagship

After announcing the Quantum Flagship the EC appointed the high-level steering committee, an independent expert group tasked with proposing a strategic research agenda (SRA), the implementation and the governance model for the initiative [5].

The initial SRA from July 2017 includes technological milestones for the next 3, 6, and 10 years, based on the aforementioned QT Roadmap. In the future, the SRA will be regularly updated to include recent research results and technology developments from both of the Quantum Flagship and the global QT community. As an example for the previously discussed quantum computing domain, the document currently foresees that:

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

Regarding implementation and governance, the Quantum Flagship utilizes experiences from the Graphene Flagship and the Human Brain Project, the first two flagships started by the EC in 2013. It consciously and
continuously maintains core values such as inclusivity, transparency, excellence and impact-orientation. However, in contrast to the two previous flagships, the Quantum Flagship will not be run as a single, closed consortium. It will function as an all-encompassing initiative, held together through a clear SRA and the close coordination between its funded projects and the national QT programs.

The Quantum Flagship will fund research and innovation actions in four application domains (Communication, Computation, Simulation, Sensing/Metrology) and the cross-cutting domain of basic science over a 10 year period (see figure 1). They should always address education/training as well as at least one of the two enabling aspects, engineering/control and software/theory. The projects in the application domains are also expected to have significant industrial participation in the consortia.

The first Quantum Flagship call was published in Fall 2017, with a total budget of €130 million: €110 million was dedicated to research and innovation actions in the application domains; €20 million to basic science; and €2 million to the coordination and support action (CSA). The success of the tender is shown by the overwhelming interest: 141 proposals were submitted, bidding for more than €600 million. Following a peer-reviewed evaluation, 20 projects were selected to start on 1 October 2018 (for the composition overview, see figure 2).

The quantum communication domain includes four projects: developing cheap, compact, faster and more secure random number generators; two projects developing components and systems for continuous variable quantum communication; creating a blueprint for the pan-European quantum internet by developing all essential subsystems and giving the first experimental demonstration.

Two projects aim to develop quantum computers that are competitive with state-of-the-art machines available commercially and at research institutes. One project will realize a fully automated ion-trap quantum computer while the other will build a computer with up to 100 superconducting qubits, which will be accessible for the community.

In the quantum simulation domain, one project aims at push the already well-advanced neutral atom and ion-based quantum simulation platforms far beyond the state-of-the-art reach of classical computation, addressing quantum annealing or optimization problems through full programmability. The other selected project will create a quantum simulator platform made of ultracold atoms, thus engineering a new generation of quantum cascade laser frequency combs characterized by non-classical emission and entanglement among the comb nodes.

In the quantum sensing domain, two projects exploit atom-like defects in diamond to develop a variety of sensors and in magnetic resonance imaging to improve the detection of cardiovascular diseases. A third project will develop novel and compact atomic clocks. The fourth project will combine state-of-the-art quantum sensor physics with MEMS atomic vapor cells, allowing for high-volume, high-reliability, low-cost deployment.

Finally, within the domain of basic science, seven projects will investigate a variety of topics and technologies, with a focus on microfabricated devices and photonic systems.
To focus the efforts on the most promising technologies and applications outlined in the SRA, the number of projects may be reduced or bundled in joint consortia in the following years. Beyond the application domains, though, there will be constant funding for basic research to generate new ideas, tackle fundamental problems, and eventually enable 'quantum leaps' in the technology development over the entire duration of the initiative. The flagship thus recognizes the importance of fundamental science to enable elementary breakthroughs, which can bring QT to a new level.

Just as in the SRA and the implementation, the Quantum Flagship strives for an agile yet coordinated efforts in its governance. The Strategic Advisory Board (SAB) monitors the flagship progress and recommends appropriate measures to the EC. The Science and Engineering Board (SEB) consisting of representatives from all funded projects, ensures a steady flow of information among the projects and fosters synergies, such as the joint use of fabrication facilities and the cross-domain utilization of project results. The quantum community network (QCN) [7], assembled from representatives from each European member state, ensures a close connection of the flagship initiative with the respective national programs. The CSA coordinates the interaction between the projects and the governance bodies, gathers input from the QT community to refine the SRA, and drives standardization. It will also reach out to the general public and potential non-quantum-aware end-users as well as coordinate education and training of a future quantum workforce.

**Beyond the flagship: a quantum fleet**

The €1 billion Quantum Flagship is only one element in the interconnected network of European institutions and undertakings that foster the wider ecosystem around quantum sciences and play into all areas of science and innovation, also known as framework program (FP). While the next FP, called horizon Europe, is still in the making, it is already clear [8] that flagships will continue to play an important role in the future. The Quantum Flagship itself will be accompanied by several other funding instruments, forming a whole 'quantum fleet'.

**QKD testbed**

The EC calls for proposals to build an experimental platform to test and validate the concept of end-to-end security, providing quantum key distribution as (economically justified) service. Proposals may ask for up to €15 million in funding and will have to develop an open, robust, reliable and fully monitored metropolitan area (>40 km) testbed network and demonstrate different applications and use cases. The call closed on 14 November 2018.
Missions
An important yet fairly new concept in horizon Europe are so-called missions [9]. They aim to simultaneously highlight the value of investments in research and innovation to European citizens and maximize the impact of these investments at the same time. Missions should therefore be bold and inspirational, spark activities across disciplines, sectors, and actors, and hence have wide societal or economic relevance. Missions could include QT-specific calls (e.g. build a quantum-secure communication network) or more general calls in which QT could play a significant role as a key enabling technology.

European research council (ERC)
The ERC was set up in 2007 to provide substantial grants to researchers working throughout Europe, independent of their origins, with the aim of realizing ground-breaking ideas. Over the course of the current FP, an estimated €100 million was awarded to individual grants addressing various aspects of quantum computing, sensing and communication.

European innovation council (EIC)
Horizon Europe will launch the EIC as a new funding instrument. Its main objective will be to support innovators transforming disruptive science and technology ideas into market-pushing innovations and products. Due to the disruptive nature of QT and its level of maturity, we expect it to be selected as an EIC focus area.

Digital Europe
In parallel to horizon Europe, the EC will launch the first digital Europe program and invest over €9 billion to increase EU’s international competitiveness as well as develop and reinforce Europe’s strategic digital capacities. These key capacities concern high-performance computing, artificial intelligence, cybersecurity and advanced digital skills, and ensuring their wide use and accessibility across the economy and society by businesses and the public sector alike.

QuantERA
A network [10] of 32 funding organizations from 26 countries, QuantERA supports international research projects through the coordination of national and regional research funding programs in the field of quantum sciences. Its first call ended in 2017, awarding a total funding of €32 million to 26 projects. The second call, worth €20 million, ended in February 2019.

Quantum in space
The European space agency (ESA) has long recognized the potential of quantum technologies. For secure communication, there have been feasibility studies under the ARTES [11] program and open calls for the development of a demonstrator for In-Orbit-Test (Scylight). The European community has proposed space QUEST [12] with an entangled source and a single photon detector on the ISS. An industrial phase A/B study is currently being performed under an ESA SciSpace contract. Furthermore, the ESA and the French agency CNES were the first agencies worldwide that recognized the potential of next-generation time and frequency transfer by developing the atomic clock ensemble in space [13] mission.

Metrology
The European metrology research program joint undertaking supported research on metrology from 2009 to 2013. Some of this work used devices based on quantum effects which received €10 million EU funding from 2009 to 2013. This program has been followed by the European metrology program for innovation and research (EMPIR) [14] initiative in H2020. The follow-up program to EMPIR is currently being planned by the European Association of National Metrology Institutes (EURAMET) and a close collaboration with the flagship has already been initiated through a series of joint workshops.

National quantum initiatives
QT has a high priority in the research and innovation budget of many EU member states and associated countries. However, the structures of these programs are quite heterogeneous, thus it is difficult to create an all-encompassing overview of their funding. Even by the most conservative estimates (only factoring QuantERA, dedicated national programs, and the funding of large-scale research centers), at least €200 million per year will be invested in QT by European countries in the coming years. The largest national programs are those of the UK and the recently announced German program (€650 million in 2018–2022) [15].
Conclusion

The Quantum Flagship has sent a strong signal to researchers, industry and policy-makers: quantum technologies are ready to take a step out of the labs and into the market. The three-year ramp-up phase of the initiative has just started, in which partnerships will be formed, a variety of technologies will be developed further and evaluated, and various actions to foster market up-take, outreach, and education will be launched. In short, the European QT ecosystem is being expanded and strengthened. In the seven-year steady-state phase after 2021, the Quantum Flagship will focus the research and development activities on the most promising technologies, and simultaneously foster a constant stream of new ideas and concepts that could be disruptive. This federated, long-term effort will create new breakthroughs in the field of QT which will enable the development of applications from which not only Europeans, but the entire global community, will benefit.

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