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PERSPECTIVE

The European quantum technologies flagship programme

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Abstract

Quantum technologies, such as quantum communication, computation, simulation as well as sensors and metrology, address and manipulate individual quantum states and make use of superposition and entanglement. Both companies and governments have realised the high disruptive potential of this technology. Consequently, the European Commission has announced an ambitious flagship programme to start in 2018. Here, we sum up the history leading to the quantum technologies flagship programme and outline its envisioned goals and structure. We also give an overview of the strategic research agenda for quantum communication, which the flagship will pursue during its 10-year runtime.

Why a flagship and why now?

We are currently experiencing a 'second quantum revolution'. In the first quantum revolution, the fundamental laws of the microscopic realm were discovered and quantum science was formulated. In the following years, ground-breaking technologies such as the transistor and the laser were developed. These inventions can only be understood and developed with the help of quantum mechanics (e.g. to understand the band structure of a semiconductor or the nature of a coherent state), but they are based on bulk effects, where many quantum degrees of freedom are manipulated at once.

In the second quantum revolution, which is unfolding now, technologies are being developed that explicitly address individual quantum states and make use of the 'strange' quantum properties, such as superposition and entanglement, commonly referred to as quantum technologies (QT). Why do we believe that this revolution is happening now? On the one hand, a number of start-up companies were founded over the last decade which offer QT to very specialised markets. Quantum cryptography is among the most advanced QT with highly specialised small and medium-sized enterprises[4] already selling their products to governments, banks and other customers with highest security requirements. On the other hand, and even more importantly, large global companies, including Google [1], IBM[5], Intel [2], Microsoft [3] and Toshiba[6] have recently started to invest heavily in QT. They are attracting top talents that just a couple of years ago would have only had the choice between pursuing an academic career and leaving the field altogether. Governments are also picking up on the trend and starting large funding programmes in the field[7]. Besides quantum computation, quantum communication is particularly high on the agenda of many countries, especially in China, who plans to invest massively, at a scale larger than the European flagship, and has recently launched a satellite with quantum communication devices [4].

4 Examples: IDQuantique www.idquantique.com; Quintessence Labs www.quintessencelabs.com; MagiQ Technologies http://www.magiqtech.com.
5 http://research.ibm.com/quantum/.
6 http://www.toshiba.eu/eu/Cambridge-Research-Laboratory/Quantum-Information-Group/.
7 UK: http://uknqt.epsrc.ac.uk/; Netherlands: www.qutech.nl; Germany: www.qutega.de

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Europe has a well acknowledged world-class expertise, world leading in many areas of quantum science and technology. In the period of 2013–2015, 2455 authors of quantum physics papers came from the EU, compared with 1913 from China and 1564 from North America [5]. Over 50% of academic papers in the field come from European scholars. The European Commission has also supported quantum science heavily over the last 20 years, with a cumulative investment reaching around €550 M [6]. Within Horizon 2020, the EU Framework Programme for Research and Innovation, the European Commission is already actively supporting QT[8]. However, both commercialisation of research results and the interest of large industrial players is less developed in Europe than it is, for example, in North America. In the past, Europe has famously failed to capitalise on major technology trends (e.g. digital platforms) and we should not miss the opportunity this time. A strong urgency for Europe to start fast with real focused and consolidated efforts to keep up with QT global developments is felt by many experts and decision makers.

This urge was expressed in the Quantum Manifesto[9], endorsed by over 3500 stakeholders from a broad community of industries, research institutes and scientists in Europe and published in April 2016. As a reaction to the Manifesto, the European Commission proposed the launch of an ambitious, long-term and large-scale flagship initiative to ensure that Europe stays at the forefront of developments in QT and has a leading role in their future exploitation [7].

Overview of the programme

The QT flagship programme will be a large-scale initiative, comparable in size (~1 billion EUR) and time scale (10 years) to the two ongoing FET flagship projects, the graphene flagship[10], and the Human Brain Project[11]. A fundamental difference to the existing flagships is, however, that there will be no single core project. The QT flagship will rather be a coherent and well-aligned programme consisting of research and innovation projects, which will be selected through peer-reviewed calls for proposals based on the flagship's strategic research agenda. The calls will be part of the EU H2020 and FP9 funding programmes; financing is expected also through national funding programmes and investment by industrial partners. The projects will be further complemented by a number of centrally managed activities, e.g. for outreach, community-building or market analysis.

The goals of the QT flagship are to:

- Consolidate and expand European scientific leadership and excellence in quantum research, including training the relevant skills;
- Kick-start a competitive European industry in QT 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.

An independent high-level steering committee (HLSC) [8] made up of 13 renowned academic members was appointed by the European Commission and later joined by 12 industrial members [9]. The HLSC, chaired by Prof. Jürgen Mlynek, has a mandate of one year to propose a strategic research agenda with clear and ambitious goals, as well as an efficient approach to its implementation and governance. To achieve this goal, it should work in an open and transparent way, together with the wider community of stakeholders from academia and industry and in close collaboration with member states. For the strategic research agenda, the HLSC can build on the QT strategic report[12], a 'living document' developed over the last decade [10] by leading European experts in the field as part of several coordination initiatives [11]. The implementation and governance details are still being discussed right now, with broad inclusion of the quantum science and technology community. One example for this community consultation was a workshop held in November 2016 in Berlin as part of the Falling Walls Conference with more than 300 attendees.

The final recommendation will be submitted to the EC in summer 2017, the first calls for research and innovation projects funded by the flagship are expected in winter 2017 and the projects are planned to start in the beginning of 2019. Although still in the preparation phase, a number of important corner stones of the flagship programme are already clear today, which we will outline in the following.

[8] For further information, context and announcements, see https://ec.europa.eu/digital-single-market/en/quantum-technologies.
[9] http://qurope.eu/manifesto.
[10] http://graphene-flagship.eu.
[11] https://humanbrainproject.eu.
[12] http://qurope.eu/content/qipc-roadmap.

Four application domains plus basic science

The long-term vision of the flagship programme is clear: quantum computers, simulators, sensors and metrology devices are interconnected via quantum networks and distribute information and quantum resources such as coherence and entanglement. On the corresponding time scale—which is in fact longer than the flagship's expected duration of 10 years—the performance enhancements resulting from QT 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.

Following the vision above, the flagship will be structured along four mission-driven application domains:

- Communication, to guarantee secure data transmission and long-term security for the information society by using quantum resources for communication protocols;
- Computation, to solve problems beyond the reach of current or conceivable classical processors by using programmable quantum machines;
- Simulation, to understand and solve important problems, e.g. chemical processes, the development of new materials, as well as fundamental physical theories, by mapping them onto controlled quantum systems in an analogue or digital way[13];
- Sensing and metrology, to achieve unprecedented sensitivity, accuracy and resolution in measurement and diagnostics by coherently manipulating quantum objects.

The projects in these domains will have strong perspectives for application, an engineering focus and aim at societal impact and commercial exploitation; many of them already in the ramp-up phase (the first three years) include proof-of-principle and/or demonstrators among their objectives. Proposals will have to include demanding but achievable goals, measurable key performance indicators (KPIs) and intermediate milestones. Most importantly, in the application domains, only projects will be funded that envision a clear, long-term path to productization, even if this goal lies beyond the funding period of the respective call.

Although the flagship has the goal of bringing technologies to the market, we should not forget that significant, non-incremental progress often requires the development and testing of completely new ideas. For this reason, the flagship will also fund basic science projects to develop new concepts, tools, components, materials, methods and processes that could eventually help advancing the four application domains significantly.

As mentioned before, QT opens up new career paths in industry for quantum scientists. On the other hand, a basic knowledge of quantum theory and technology should become a critical component of every engineer's education. A central objective of the QT flagship is therefore also the training of successful 'quantum engineers' and more in general a quantum-aware workforce. This goal will have to be addressed by all projects of the flagship but also by additional overarching measures.

To ensure that these well-educated young talents stay in Europe and to even reverse the current brain-drain, we need to ensure that they find attractive jobs in Europe. We therefore need not only to strongly involve European industry in the innovation projects, we also need to take additional measures to make Europe an attractive region for 'quantum entrepreneurs' and investment in QT.

Quantum communication research agenda

The flagship denotes one of its four application domains to the subject of this focus issue of QST: quantum cryptography and quantum networking. In flagship terms, this domain is simply called quantum communication. Its main applications are in provably secure communication, long-term secure storage, cloud computing and other cryptography-related tasks, as well as, in the future, secure quantum communication networks distributing quantum resources like entanglement and connecting remote devices and systems.

In the first three years, the flagship aims at the development and certification of QRNG and QKD devices and systems, addressing high-speed, high technology readiness level (TRL) [12] and low deployment costs. It will explore novel protocols and applications for network operation and develop systems and protocols for quantum repeaters and long-distance communication. In six years, cost-effective and scalable devices and systems for

[13] Compared with computing, where the aim is to have a fully fault-tolerant and universal quantum computer, simulations are more specialised and require neither fault-tolerance nor universality, hence allowing earlier and more efficient scaling through quantum software specialised and optimised for these simulators.

inter-city and intra-city networks will demonstrate end-user-inspired applications. Another objective is the development of scalable solutions for quantum networks connecting devices and systems, e.g. quantum sensors or processors. Finally, in 10 years, at the end of the flagship, autonomous metro-area, long-distance (>1000 km) and entanglement-based networks (sometimes referred to as the 'quantum internet' or 'quantum web') should be in reach.

To achieve these goals, several software and theory challenges need to be addressed. Protocols and applications that build on or go beyond the standard QRNG- and QKD-based primitives, as well as novel approaches for their certification, including methods to test and assess the performance of quantum networks need to be developed. Also, more efficient algorithms and security proofs targeting practical systems will be in focus, including the combination of classical and quantum encryption techniques for holistic security solutions and expanding the potential application market. On the other hand, engineering and control solutions need to be further improved to enable scaling and volume manufacturing. Examples include high-speed electronics, like FPGAs/ASICs, integrated photonics, packaging and compact cryo-systems.

Conclusions

The QT flagship is Europe's bold commitment to stay at the forefront of quantum research and innovation. Over the next years, QT will start to play a role in many application areas, from healthcare to mobility and security. Quantum communication is already used today for niche applications, but as the technology develops, its use will spread and it has the potential to become an integrated, standard component of our world-spanning communication networks. To reach this goal, besides tackling various theoretical challenges, a significant amount of software and hardware engineering as well as system integration still needs to be conducted in close co-operation between academia and industry.

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