Quantum Technologies in H2020

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QUTE-EUROPE White Paper for Sustainability - draft

Introduction

Quantum technologies involve the control and manipulation of quantum systems to achieve results not possible with classical matter. Naively, they can be seen just as the next step on from nanotechnology while still following traditional paradigms. However, quantum technologies give much more than this as they transfer technological applications to a different physical framework where devices are described by quantum laws. All technologies derive their power and their limitations from the laws of physics. Thus, bringing technology to a new and broader physical framework can provide fundamentally new capabilities. And in fact, these quantum technologies offer much more than cramming more and more bits to silicon and multiplying the clock–speed of the ubiquitous microprocessors: they support entirely new modes of computation with qualitatively new and powerful algorithms based on quantum principles, that do not have any classical analogues; they also offer provably secure communications, simulation capabilities unattainable with classical processors and sensors and clocks with unprecedented sensitivity and accuracy.

The present document provides an overview on the main advances in the last years in quantum technologies and identifies game-changing directions for future research. Moreover, it discusses how all this research effort can be incorporated within future proactive initiatives to be included in the next FET work programme for 2016 and 2017.

Since many years, quantum technologies have experienced impressive progress and gained a clear European dimension. There are already several important on-going national efforts, such as the recent UK investment of £270M. Yet, a comprehensive European synergy is essential for the full development of the field. From a scientific point of view, a comparably high level of synergy needs to be maintained between the fundamental and the application-oriented side of quantum technology research, according to the approach that FET has followed in this field since its inception.

The framework for interaction and coordination with the scientific branches of the EU research community in quantum technologies is structured around a set of five Virtual Institutes (VIs): the Virtual Institute of Quantum Communication, the Virtual Institute of Quantum Computation, the Virtual Institute of Quantum Information Sciences, the Virtual Institute of Quantum Simulation and the Virtual Institute of Quantum Metrology, Sensing, and Imaging. Each VI unites some prominent experts in the corresponding field, providing a contact point for consultation and feedback in the relevant areas. The different VIs have partially overlapping research agendas to facilitate close collaborations, complementing rather than duplicating each other. This document is structured around the same five areas and has been prepared in collaboration with the Directors and Executive Secretaries of all the VIs. For each of the areas, it describes the main objectives, the state of the art and the future challenges.

Quantum Communication

Objectives: Quantum communication is the art of transferring a quantum state from one location to another; in this way information, or resources such as entanglement, can be distributed among different locations. From an application point of view, a major interest has been focused on Quantum Key Distribution (QKD), as this offers a provably secure way to establish a confidential key between distributed partners. This has the potential to solve long-standing and central security issues in our information based society as well as emerging problems associated with long term secure storage (e.g. for health records and infrastructure) and will be critical for the secure operation of applications involving the Internet of Things (IoT) and cloud networking.

State of the art: In the last years the field has seen enormous progress, as QKD systems have gone from table-top experiments to compact and autonomous systems and now a growing commercial market. More generally there has been an explosion in the number of groups active in the field working on increasingly diverse physical systems. Quantum memories and interfaces have moved from theory to a wide range of proof-of-principle demonstrations with encouraging results for the future. Conceptually, the idea of device independent quantum information processing made its appearance and has already started to find experimentally feasible applications. While the realisation of basic quantum communication technologies is becoming more routine in the laboratory, non- trivial problems emerge in high-bit-rate systems and long-distance applications as we interface the different technologies and as the network complexity increases.

Future directions: One of the emerging areas of interest for quantum communication schemes is in connecting the nodes within quantum simulators, which can either be all located in the one lab, or more interestingly, in distributed scenarios - the tools from quantum communication playing the role of wiring circuits for these quantum computers. A particular application is a network of entangled clocks providing precise and secure world time reference. While there remain many challenges for proof-of-principle laboratory demonstrations, the transition to deployment in real-world environments defines a new set of challenges in the quantum information domain. The issues of scale, range, reliability, and robustness that are critical in this transition cannot be resolved by incremental improvements, but rather need to be addressed by making them the focal point of the research and technology development agenda as we work towards a quantum internet. To succeed, this needs to target the underlying technologies, ranging from fundamental aspects of engineering quantum systems to integrating quantum and classical, e.g. fast (classical) opto-electrical systems, as well as the end-user applications themselves.

In particular the following need to be addressed:

- Quantum networks, beyond point-to-point, exploring novel protocols, possibly hybrid (continuous-variable and discrete) systems. Quantum repeater concepts will also be critical in the context of computation and simulation, both for short distance scales (local) or large (distributed) processing systems.
- Deterministic and scalable technologies involving on-demand photonic sources, or heralded sources with quantum memories, including quantum memories with multimode capacity.
- Interfaces allowing for the coherent transduction of quantum states between different physical systems.
- The synchronisation and stabilisation of distributed quantum systems and their characterisation – in particular, their quantification with local measurements.
- Device-independent quantum information processing needs to be further investigated and ways to move from purely theoretical concepts to more practical scenarios will be highly relevant. In particular, addressing both QKD and quantum random number generation and providing a new perspective with the potential to also minimise security assumptions and hence simplify the security of real-world quantum communication.

- Systems that exploit increased complexity, e.g. using integrated quantum photonics, which would allow new functionality and protocols in quantum networking.

Quantum Computation

Objectives: A quantum computer is a device that harnesses some of the basic laws of quantum mechanics in order to solve problems in more efficient ways than classical (standard) computers. The main objective in the field of quantum computation is to build such a device. Other objectives include the development of quantum algorithms to solve specific problems, and the creation of interfaces between quantum computers and communication systems. The construction of a quantum computer with thousands of quantum bits would have tremendous consequences on the security in communications (like the internet), by breaking most of everyday used cryptography. It would also allow us to solve certain problems that the most powerful super computers are not able to solve now or in the near future, and possibly never; in particular, those dealing with quantum many-body systems, as they appear in different fields of physics, chemistry, and material science.

State of the art: We already know that the basic principles of quantum computation are correct and there is no fundamental obstacle in constructing such a powerful machine. The basic building blocks of a quantum computer have been demonstrated with many different technologies, including trapped ions, neutral atoms, photons, NV-centers in diamonds, quantum dots, and superconducting devices. Small prototypes have been built using some of those technologies, and some of the quantum algorithms have been demonstrated. The most advanced technologies at the moment are trapped ions and superconducting qubits. With the first one, coherent control has been achieved with up to 15 qubits. Although the control of the latter is still not at the level of the first, it has the potentiality of being scaled up much more easily. With both technologies, proof-of-principle experiments on quantum error correction have been carried out.

Future directions: Despite the strong efforts devoted by many scientists during the last years, the objective of building a quantum computer remains as a central challenge in science. The main obstacle to build a quantum computer is the presence of decoherence, i.e., undesired interactions between the computer’s constituents and the environment. Standard isolation is not a valid solution, since it seems impossible to reach the levels of isolation that are required in large computations. Therefore, the construction of such a device will require the use of quantum error correction techniques. It is not clear, however, which (already or not yet existing) technology will be optimally suited for the implementation of such techniques in a scalable way and/or in distributed settings. On a different note, we only know a limited class of problems where a quantum computer could overcome the limitations of classical ones, and thus theoretical studies for applications of such devices need to be further pursued.

Some specific future directions of research include:

- Further development of all current technologies to understand their limitations and find ways around them.
- Assessment of the capabilities of different technologies for being scaled up.
- Optimization of the performance of error correcting codes, by both increasing the error threshold and decreasing the overhead of required qubits.
- Investigation of new ways of performing quantum computation, in particular based on self-correcting codes (as they appear in topological systems).
- Development of new quantum algorithms and search for problems where quantum computers will be required.
- Development of quantum complexity theory and its application to many body physics.
- Building interfaces between quantum computers and communication systems.
- Development of quantum-proof cryptography to achieve forward-in-time security against possible future decryption (by quantum computers) of encrypted stored data.

Quantum Information Sciences

Objectives: The development of quantum technologies has been driven by theoretical work of scientists working on the boundary between Physics, Computer Science, Mathematics, and Information Theory. In the early stages of this development, theoretical work has often been far ahead of experimental realization of these ideas. At the same time, theory has provided a number of proposals of how to implement basic ideas and concepts from quantum information in specific physical systems. These ideas are now forming the basis for successful experimental work in the laboratory, driving forward the development of tools that will in turn form the basis for all future technologies which employ, control and manipulate matter and radiation at the quantum level.

State of the art: in recent years, novel theoretical ideas have been proposed, extending the range of applicability of quantum information protocols. The novel scenario of device-independent quantum information processing has emerged, where protocols are defined independently of the inner working of the devices used in the implementation. This new approach has led to self-certified schemes for QKD and randomness generation. A strong theoretical effort has opened quantum simulation to quantum field theories and quantum chemistry. From a purely information theory point of view, non-additivity effects of channel capacities with no classical analogue have been proven. Finally, quantum information theory has established strong bridges with other fields, such as condensed matter, quantum thermodynamics, biology or quantum gravity. The study of topological systems for quantum information purposes, the development of novel numerical methods for the classical simulation of many-body quantum systems, the study of Hamiltonian complexity or, more recently, the use of quantum information techniques for a better understanding of the physics of black holes, as well as applications in mathematics and computer science, are examples of these synergies.

Future directions: the impressive experimental progress in controlling quantum particles has brought the field to a regime where experimental setups can hardly be simulated in existing classical computing devices. The design of methods to estimate, control and certify these complex setups is essential for the development of the field. Also, we expect quantum information theory to extend and strengthen its applicability to other fields, providing new insights in quantum thermodynamics, many-body physics or quantum gravity. The recent device-independent scenario, in which protocols are defined independently of the inner working of the devices, also offers promising perspectives, especially for cryptographic applications.

Relevant research directions for the next years include:

- Methods for the reconstruction and estimation of complex quantum states or channels beyond tomography protocols, which are as hard as simulating a quantum system classically.
- Methods for the certification and validation of quantum processes; benchmarking of purely quantum effects with no classical analogue.
- Methods for error correction beyond quantum computation and study of their application to quantum simulation, communication or sensing.
- Methods for the control of complex quantum setups.
- Development of device-independent solutions: novel protocols, general framework for security analysis in this approach or feasible proposals for their experimental realization.
- Novel applications of quantum information concepts in other fields, such as thermodynamics, many-body systems, mathematics, computer science, biology, quantum chemistry, high-energy physics or quantum gravity.
- Development of undecidability theory.

Quantum Simulation

Objectives: Quantum simulation uses controllable quantum systems to investigate the properties of other complex quantum systems, and can tackle problems that are beyond the computational capability of any classical computer. Initial experimental and theoretical work has been mainly directed towards the quantum simulation of condensed matter systems, such as bosonic or fermionic particles in lattices, but more recent work also encompasses such diverse fields as quantum field theory, cosmology and high-energy physics.

State of the art: Experimental platforms for quantum simulation comprise ultracold atomic and molecular quantum gases, ion traps, polariton condensates, circuit-based cavity quantum electrodynamics and arrays of quantum dots or Josephson junctions. All of these platforms aim to explore the potential of quantum simulations for different fields of science. The first demonstrations of quantum simulation were performed on ultra-cold atoms. In this platform, the quantum-gas microscope technique has opened up novel possibilities to probe and manipulate cold-atom quantum simulators at the single-particle level. For trapped ions, the extraordinary level of control of motional and internal quantum states has enabled for example the realization of a digital quantum simulator, and analogue quantum simulation of different spin systems. Recently, also solid-state systems like coupled arrays of cavities or superconducting qubit arrays, or arrays of defect centres, are being explored for quantum simulation purposes.

Future directions: The challenges of the science of quantum simulation can be divided into four categories that need to be addressed:

- Novel manipulation and detection schemes for quantum many-body systems to further improve the controllability of artificial quantum matter realized for quantum simulation purposes. This includes improving fidelities of present preparation schemes, as well a devising novel measurement and control techniques and also include identifying completely novel systems for quantum simulations.
- Extend the reach of quantum simulations into other fields of science, e.g. quantum field theories in high-energy physics, nuclear physics, cosmology (simulation of non-equilibrium dynamics), biology, chemistry and material science.
- Novel strategies toward lower temperatures and entropies of many-body systems. This will allow exploring novel quantum phases of matter that could find important impact in metrology (e.g. atomic clocks), quantum computing or material science.
- Novel strategies for the verification of quantum simulations, studying how finite temperature errors and imperfections in implementations of couplings affect the resulting many-body state.

Quantum Metrology, Sensing, and Imaging

Objectives: Specifically quantum phenomena such as coherence and entanglement can be exploited to develop new modes of measurements, sensing, and imaging that offer unprecedented levels of precision, spatial and temporal resolution, and possibly auto-compensation against certain environmental factors, such as dispersion. These promising applications require development of techniques that will be robust against noise and imperfections to be deployed in real-world scenarios. Quantum technologies will benefit in particular time and frequency standards, light-based calibration, gravitometry, magnetometry, accelerometry, including the prospects of offering new medical diagnostic tools.

State of the art: Reaching quantum-enhanced precision beyond standard quantum limits in metrology relies on generating non-classical collective states of atoms and non-classical multi-photon states of light. Extensive effort has been dedicated to these goals with proof-of-principle demonstrations in the atomic domain and the first squeezed-light-enhanced operation of a gravitational wave detector with practical suppression of vacuum fluctuations. Novel concepts, such as systems with an effective negative mass or negative frequency have been shown to be capable of providing magnetometry with virtually unlimited sensitivity. Possibilities to define new frequency standards have been explored with the readout based on quantum logic techniques borrowed directly from the field of quantum computing and with entangled atoms providing ultimate quantum sensitivity. Enormous progress has been made on single photon sources, both deterministic and heralded, that can be used for optical calibration as well as a building block for photonic quantum communication and computing. Artificial atoms (such as nitrogen vacancy centers) have been investigated as ultraprecise sensors e.g. in magnetometry.

Future directions: Original techniques are needed to make quantum-enhanced metrology and sensing deployable in non-laboratory environments. 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 and room-temperature atomic vapours, artificial systems such as quantum dots and defect centers, as well as all-optical set-ups based e.g. on nonlinear optical interactions. Thorough theoretical analysis of noise mechanisms is needed, leading to feasible proposals that will be subsequently implemented to realize quantum-enhanced strategies. In particular the following need to be addressed:

- Novel sources of non-classical radiation and methods to engineer quantum states of matter are required to attain quantum-enhanced operation.
- Develop detection schemes that are optimized with respect to extracting relevant information from physical systems, with optimization criteria selected for specific applications. These techniques may find applications in other photonic technologies, e.g. increasing transmission rates in optical communication.
- Micro- and nanofabrication of quantum sensors including integration with fiber networks.
- Development of hybrid quantum sensors that use optimal quantum interfaces for transduction of signals across the electro-magnetic radiation spectrum.
- Compact solutions for quantum imaging, allowing for the interconversion of detected frequencies including preservation of coherence, as well as quantum ranging and timing that can suppress the spatial/temporal spread of transmitted signals.
- Implementation of entanglement assisted atom clocks
- Study of the performance of quantum sensing protocols in realistic regimes including noise and losses.
- Extend the reach of quantum sensing and metrology into other fields of science to uncover novel natural phenomena, e.g. biology, fundamental physics, high-energy physics, quantum gravity.

Global perspective and role in the work programme

While the previous presentation has been structured along the different VI’s, the field of quantum technologies has to proceed as a coherent and unified research effort. Indeed, many synergies among the different research directions are expected and essential to attain the previous objectives. To name just a couple of illustrative examples, detection and state-preparation techniques developed in the context of quantum communication will find an application in sensing scenarios, and error-correction techniques developed in the context of quantum computation will be needed for the certification of quantum simulations. In this sense, the role of basic science and theoretical new ideas is essential, as new disruptive theoretical proposals can significantly boost many of the previous promising applications of quantum technologies. Progress in all of these areas is reliant on fundamental research to improve and find new enabling technologies and concepts.

Quantum technologies are already present in the current work programme. Recently, there has been a proactive call on quantum simulation. There are also explicit mentions to quantum concepts in the work programme: in ICT 25 - 2015: Generic micro- and nano-electronic technologies, projects may include activities “related to modelling and simulation: e.g. quantum and atomic scale effects” or study “new computing paradigms like quantum computing”; in ICT 26 - 2014: Photonics KET, new device concepts “based on quantum optics or quantum technologies” are mentioned in the context of disruptive sensing technologies; finally, in ICT 32-2014: Cybersecurity, Trustworthy ICT, postquantum key distribution and several aspects of QKD appear.

In our vision, the framework programme for the next years is a key funding mechanism to support and unite all the previous research activities, from basic theoretical research to industrial applications. In this sense, we expect quantum technologies to gain an even more visible role in future research funding in Europe. A proactive call on quantum technologies, complementary to the recent one on quantum simulations, is timely and can help in bringing the developments described above much closer to applications. As mentioned, theoretical ideas should remain visible in the programme, as we are still far from understanding all that quantum properties can offer for technological purposes. Finally, we also expect quantum aspects to increase their relevance in the photonics, security and nano-technologies programs. For instance, the possibility of self-certified protocols using device-independent techniques brings cryptographic applications to a significantly stronger level of security where a much lower level of trust is needed on the provider. Also, new photonic devices operating at the quantum scale will emerge from the research effort in photonics and nano-technologies. In this sense, calls in these programs parallel to those in FET can be expected to deliver a major synergy effect.

Let us conclude by mentioning that bridging the gap between blue-sky research and applications will take time and several iterations. It should also be understood at this early stage of researching quantum technologies that in all likelihood there will not be one single solution, but many, on the way to developing this key enabling technology of the 21st century and to build a quantum industry.

Endorsement

This memorandum is endorsed by

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