資料4－1
科学技術・学術審議会 研究計画・評価分科会
量子科学技術委員会（第10回）
平成29年4月10日

国際政策動向

量子研究推進室

・http://qurope.eu/system/files/u7/93056_Quantum%20Manifesto_WEB.pdf
・https://www.epsrc.ac.uk/newsevents/pubs/quantumtechstrategy/
・https://www.aip.org/fyi/2016/national-science-board-and-nsf-big-ideas-hand-intend-%E2%80%9Cplay-offense%E2%80%9D
・https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf

※黄色マーカーや赤線の強調は、説明のため事務局で付したもの。

Quantum Manifesto

A New Era of Technology

May 2016

This manifesto is a call to launch an ambitious European initiative in quantum technologies, needed to ensure Europe’s leading role in a technological revolution now under way.

Manifesto for an initiative

This Manifesto calls upon Member States and the European Commission to launch a €1 billion flagship-scale initiative in Quantum Technology, preparing for a start in 2018 within the European H2020 research and innovation framework programme. It is endorsed by a broad community of industries, research institutes and scientists in Europe.

This initiative aims to place Europe at the forefront of the second quantum revolution now unfolding worldwide, bringing transformative advances to science, industry and society. It will create new commercial opportunities addressing global challenges, provide strategic capabilities for security and seed as yet unimagined capabilities for the future. As is now happening around the world, developing Europe's capabilities in quantum technologies will create a lucrative knowledge-based industry, leading to long-term economic, scientific and societal benefits. It will result in a more sustainable, more productive, more entrepreneurial and more secure European Union.

Goals of this initiative

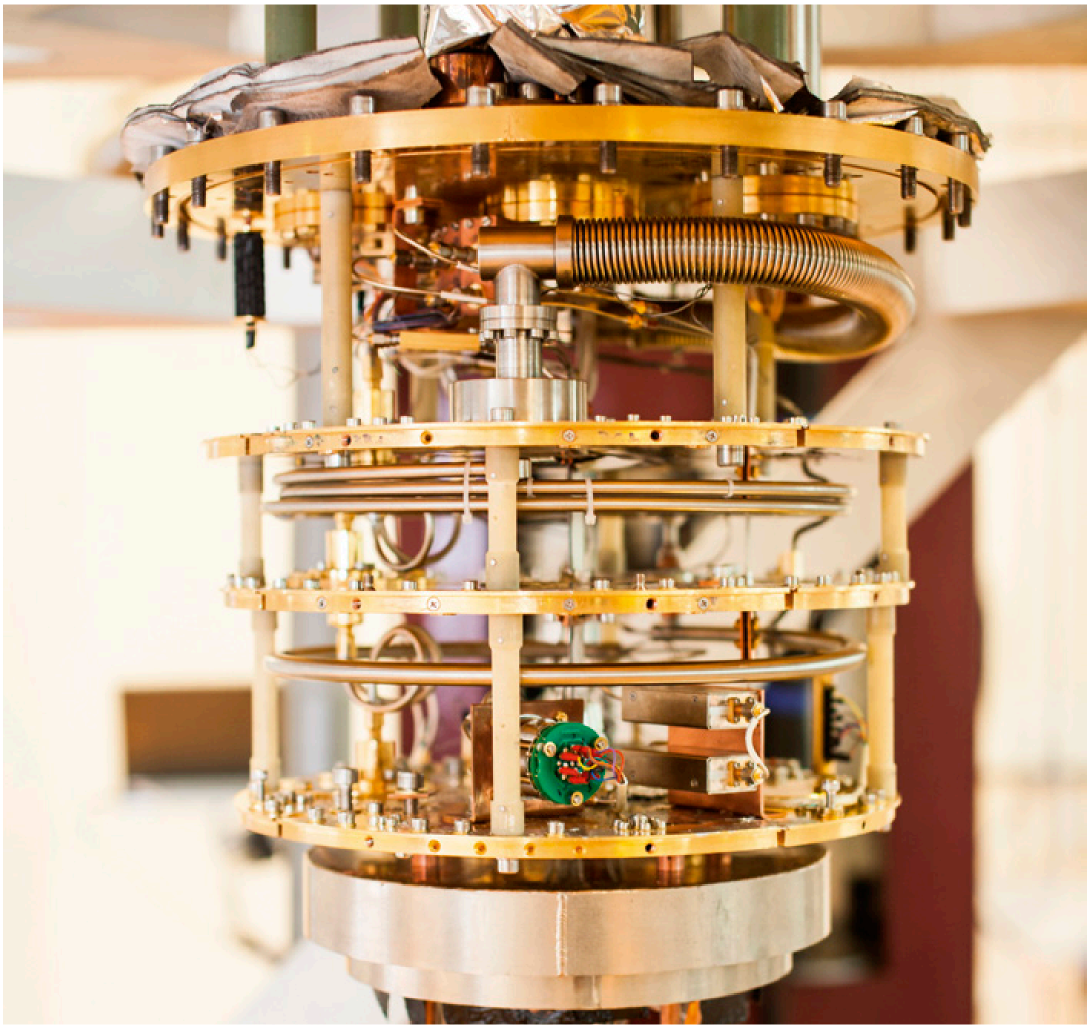
- Kick-start a competitive European quantum industry to position Europe as a leader in the future global industrial landscape.
- Expand European scientific leadership and excellence in quantum research.
- Make Europe a dynamic and attractive region for innovative business and investments in quantum technologies.
- Benefit from advances in quantum technologies to provide better solutions to grand challenges in such fields as energy, health, security and the environment.

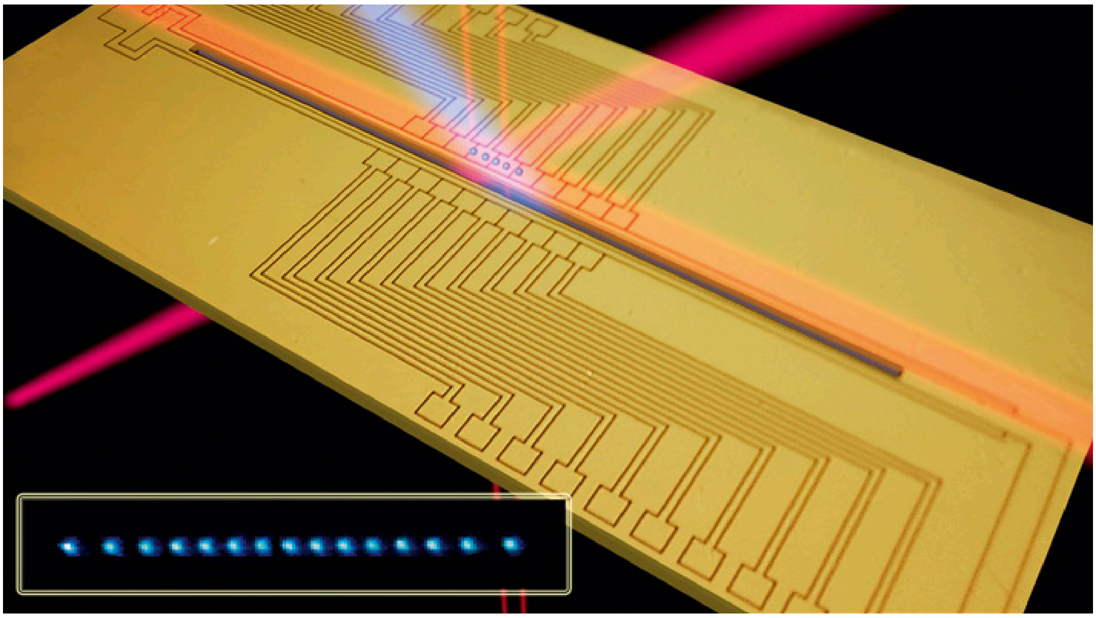
Key activities suggested by this Manifesto

1. Support growth in scientific activities linked to quantum technologies.
2. Create a favourable ecosystem of innovation and business creation for quantum technologies.
3. Facilitate a new level of coordination between academia and industry to move advances in quantum technologies from the laboratory to industry.
4. Create a new generation of quantum technology professionals in Europe through focused education at the intersection of science, engineering and business, and by strengthening public awareness of key ideas and capabilities.
5. Coordinate public investments and strategies in quantum technologies at the European level.
6. Promote the involvement of member regions that do not currently have a strong quantum technologies research programme.

The supporting parties of this Manifesto, as listed in the Appendix, call upon Member States and the European Commission to implement the proposed actions progressively and to offer their support to help establish the European flagship-scale initiative.
The European Commission has recognised in its Communication from 19th of April 2016 on a European Cloud Initiative[1] the importance of Quantum Technologies and the need to launch an ambitious European flagship initiative to ensure that Europe stays at the forefront of this technology and takes a leadership role in its future industrial exploitation.

[1] Communication on a European Cloud Initiative-Building a competitive data and knowledge economy in Europe





Top: Low temperature dilution refrigerator (<5mK) with experiments for superconducting qubits as the basis for quantum computers. L. DiCarlo, QuTech, Delft.

Bottom: A segmented chip trap for ion quantum computing and simulation. R.Blatt, IQOQI Innsbruck.

Table of **content**

Europe needs strategic investment now in order to lead the second quantum revolution. Building upon its scientific excellence, Europe has the opportunity to create a competitive industry for long-term prosperity and security.

SECTION 1: Why Europe needs to act now

Europe needs strategic investment …

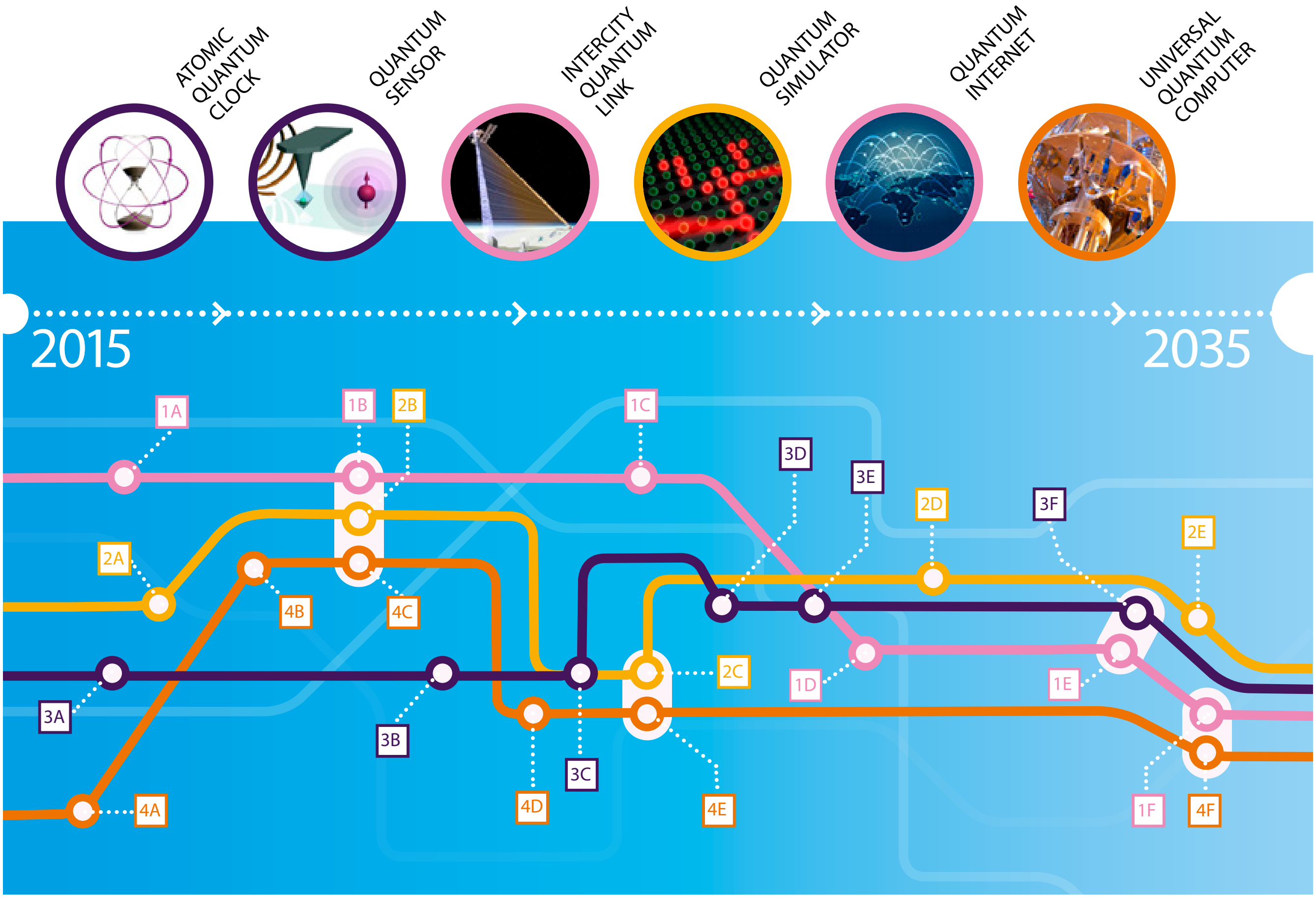
Technologies based on the laws of quantum mechanics, which govern physics on an atomic scale, will lead to a wave of new technologies that will create many new businesses and help solve many of today's global challenges. Over the last century, humankind has mastered the underlying quantum physics. Now, previously untapped aspects of quantum theory are ready to be used as a resource in technologies with far-reaching applications, including secure communication networks, sensitive sensors for biomedical imaging and fundamentally new paradigms of computation. In each of these applications, quantum technologies could result in revolutionary improvements in terms of capacity, sensitivity and speed, and will be the decisive factor for success in many industries and markets. Applications are of strategic importance to Europe's independence and safety – in the field of secure information storage and transmission, for instance, and in creating new materials for energy solutions and medicine. Governments and companies worldwide, including Google, Microsoft, Intel, Toshiba and IBM, are investing substantially to unleash this potential. For Europe to remain at the forefront of this emerging technology and to participate in a global quantum industry, it needs to scale up investments and make the best use of its excellence in science and engineering.

… in order to lead the second quantum revolution …

The first quantum revolution – understanding and applying physical laws in the microscopic realm – resulted in groundbreaking technologies such as the transistor, solid-state lighting and lasers, and GPS. Today, our ability to use previously untapped quantum effects in customised systems and materials is paving the way for a second revolution. With quantum theory now fully established, we are required to look at the world in a fundamentally new way: objects can be in different states at the same time (superposition) and can be deeply connected without any direct physical interaction (entanglement). There are many transformative applications, varying from products with a relatively short time to market to revolutionary new technologies that may require more than a decade of research and development. Quantum computers are expected to be able to solve, in a few minutes, problems that are unsolvable by the supercomputers of today and tomorrow. This, in turn, will seed breakthroughs in the design of chemical processes, new materials, such as higher temperature superconductors, and new paradigms in machine learning and artificial intelligence. Based on quantum coherence, data can be protected in a completely secure way that makes eavesdropping impossible. Given the explosive growth of cybercrime and espionage, this is a highly strategic capability. Quantum technologies will also give rise to simulation techniques well beyond current capabilities for material and chemical synthesis, and to clocks and sensors with unprecedented sensitivity and accuracy, with potential impact in navigation, the synchronisation of future smart networks and medical diagnostics.

The developments in the leading areas of quantum technologies – illustrated in the figure – can be expected to produce transformative applications with real practical impact on ordinary people. Each of these areas has its own timeline. New quantum sensors are expected to emerge in commercial markets in the near future, for instance, whereas quantum computers are more than a decade away. The technology tracks showing the underlying scientific and engineering milestones paving the way for disruptive applications are based on predictions from leading scientists in Europe. This timeline should be seen as illustrative and incomplete. History has proven that it is very difficult to predict the key applications of a disruptive technology; such technologies invariably create their own applications. Section 3 provides a more detailed description of the milestones on the technology tracks.

Quantum Technologies Timeline



1. Communication

2. Simulators

3. Sensors

4. Computers

0 – 5 years

1. Communication

- A Core technology of quantum repeaters
- B Secure point-to-point quantum links

2. Simulators

- A Simulator of motion of electrons in materials
- B New algorithms for quantum simulators and networks

3. Sensors

- A Quantum sensors for niche applications (incl. gravity and magnetic sensors for health care, geosurvey and security)
- B More precise atomic clocks for synchronisation of future smart networks, incl. energy grids

4. Computers

- A Operation of a logical qubit protected by error correction or topologically
- B New algorithms for quantum computers
- C Small quantum processor executing technologically relevant algorithms

5 – 10 years

1. Communication

- C Quantum networks between distant cities
- D Quantum credit cards

2. Simulators

- C Development and design of new complex materials
- D Versatile simulator of quantum magnetism and electricity

3. Sensors

- C Quantum sensors for larger volume applications including automotive, construction
- D Handheld quantum navigation devices

4. Computers

- D Solving chemistry and materials science problems with special purpose quantum computer > 100 physical qubit

> 10 years

1. Communication

- E Quantum repeaters with cryptography and eavesdropping detection
- F Secure Europe-wide internet merging quantum and classical communication

2. Simulators

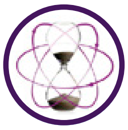
- E Simulators of quantum dynamics and chemical reaction mechanisms to support drug design

3. Sensors

- E Gravity imaging devices based on gravity sensors
- F Integrate quantum sensors with consumer applications including mobile devices

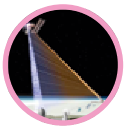
4. Computers

- E Integration of quantum circuit and cryogenic classical control hardware
- F General purpose quantum computers exceed computational power of classical computers

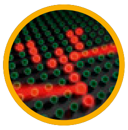


Atomic quantum clocks can be synchronised with GPS to provide very high levels of timing stability and traceability, even in hostile environments where GPS is unavailable or denied. These timing solutions can be useful within future smart networks, for instance for the synchronization of energy grids, as well as in telecoms, broadcasting, energy and security.

Quantum sensors that exploit quantum superposition and/or entanglement to achieve a higher sensitivity and resolution will be purchased and used by companies and public institutions for demanding construction projects; for instance, to measure voids under the ground and to detect mineral deposits or legacy infrastructure. They will also be used to provide non-invasive point-of-care diagnosis.



A secure **intercity quantum link** between a number of European capitals will allow transmission of highly sensitive data without any risk of interception. It may contain ground or satellite-based protected nodes derived from the development of trusted nodes and quantum repeaters.



Quantum simulators can be constructed for the special purpose of simulating materials or chemical reactions. Simulation allows new processes or properties to be explored before the material exists, as a tool to design new materials that are needed in multiple sectors, such as energy or transport.

A global **quantum-safe communication network** – a quantum internet combining quantum with classical information and encryption – offers security for internet transactions against the threat of a quantum computer breaking purely classical encryption schemes.

Universal quantum computers will be available with computational power at a level of performance that will exceed even the most powerful classical computers of the future. They will be reprogrammable machines used to solve demanding computational problems, such as optimisation tasks, database searches, machine learning and image recognition. They will contribute to Europe's smart industry, helping to make European manufacturing industries more efficient.

Building on Europe's scientific excellence ...

Quantum physics was created in Europe in the first decades of the twentieth century by a generation of young physicists who are now familiar names: Bohr, Planck, Einstein, Heisenberg, Schrödinger, Pauli, Dirac, Curie, De Broglie and others. One hundred years on, Europe still plays a leading role in quantum research. Compared to the rest of the world, Europe has more researchers and a broader research scope, linking fundamental and applied science and engineering. Top institutions can be found across Europe, covering all aspects of quantum technologies from basic physics to electronics and computer science. At the European level, €0.5 billion have been invested over the last 20 years to support pioneering research in this domain. Early-stage support from the EU Future and Emerging Technology (FET) programme has been instrumental in fostering a well-organised and truly European scientific community with widely acknowledged world-class scientific and technical expertise in quantum technologies. Financial support for quantum technologies is increasing in several Member States, most notably the UK (£270 million for a five-year programme) and the Netherlands (€146 million for a ten-year programme) as well as through a €30 million ERANet programme (QuantERA) for quantum science and technologies.

… and established and growing interest from industry.

Interest from industry in Europe, including companies like Airbus Defence and Space, Alcatel Lucent, ASML, Bosch, IBM, Nokia, IMEC, Safran, Siemens and Thales, is growing. High-tech SMEs, like e2v, Gooch & Housego, ID Quantique, M Squared Lasers, Muquans, Single Quantum and Toptica, occupy leading positions in their specific markets. Europe's key position in global value chains for the semiconductor, electronics and optical industries makes further industry take-up likely. It is vital that the interests of companies be recognised in a future programme, if quantum technologies are to have an economic impact. It is companies that will deliver devices engineered for use and manufactured within a commercial environment. They will drive higher-volume production, reduce costs and stimulate the growth of new applications and markets. Other parts of the world, including the US, China and Japan, are also showing increased interest in harnessing the potential of quantum technologies. Governments are raising their strategic and economic ambitions and many non-European industries are already investing significant amounts, both inside and outside Europe.

About Quantum Communication

Communication security is of strategic importance to consumers, enterprises and governments alike. At present, it is provided by encryption via classical computers, which could be broken by a quantum computer. This motivates the development of post-quantum cryptography, i.e. encryption methods that quantum computers could not break. Secure solutions based on quantum encryption are also immune to attacks by quantum computers, and are commercially available today, as is quantum random number generation – a key primitive in most cryptographic protocols. But they can only function over distances up to 300 km: quantum information is secure because it cannot be cloned, but for the same reason it cannot be relayed through conventional repeaters. Instead, repeaters based on trusted nodes or fully quantum devices, possibly involving satellites, are needed to reach global distances. The advantage of trusted-node schemes is that they provide access for lawful intercept, as required by many nation states, and they are already being installed. The advantage of quantum repeaters, exploiting multimode quantum memories, lies in extending the distances between trusted nodes.

The building blocks for fully quantum repeater schemes are twofold: a small quantum processor and a quantum interface to convert the information into photons similar to the optoelectronics devices used in today's internet, but with quantum functionality. These building blocks have already been demonstrated in the lab, but years of R&D are still needed for them to reach the market. As soon as this happens, true internet-wide quantum-safe security could become a reality.

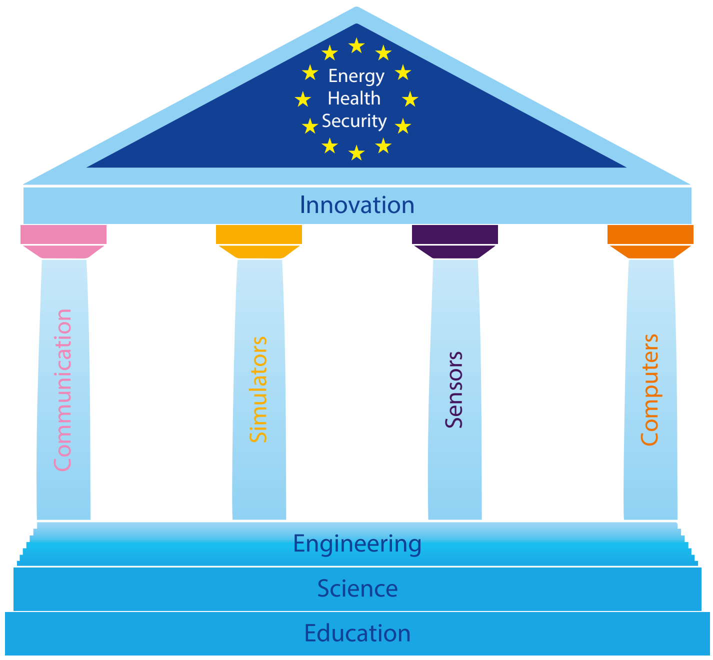
While long-distance qubit transmission can only take place via photons, various platforms exist to realise quantum memories for storage and processing at repeater nodes. Trapped ions, atoms in optical resonators, solid-state rare earth ions, colour centres in diamond and quantum dots are the main options currently being investigated in programmes funded at both the European and the Member State level. As well as world-leading SMEs like the Swiss firm ID Quantique, big companies like Toshiba are strongly active in this field in Europe, and national telecommunication companies, such as British Telecom, are increasingly involved, while standardisation is well under way thanks to the European Telecommunications Standards Institute (ETSI).

SECTION 2:
Launch of an ambitious European programme

... to create a competitive industry for long-term prosperity and security.

To make sure Europe reaps a large share of the benefits of the second quantum revolution and secures its independence and prosperity, we need to act now to scale up and coordinate European efforts. A world-wide race for technology and talent has started, as the strategic and economic stakes are high. Other parts of the world are speeding up and Europe cannot afford to lag behind and so risk a brain and knowledge drain. It is important to recognise that, as yet, there is no coherent, large-scale Europe-wide quantum technologies programme to compare with those already in existence in the US and other countries. European quantum technologies research and development risk fragmentation and replication of efforts. Continued investment by Member States and the Commission over the past two decades has given Europe a strong position that should enable it to capitalise on the emerging opportunities. Targeted investment in developing technologies would leverage past investment in the underpinning science, potentially to great advantage. In addition to the main applications, spin-off technologies with economic and societal impact in other sectors usually result from game-changing technologies.

An ambitious, long-term, flagship-scale initiative combining education, science, engineering and innovation across Europe is needed in order to unlock the full potential of quantum technologies, to accelerate their development and to bring commercial products to public and private markets. An inclusive European programme will see excellent research teams and relevant industry actors collaborating on an ambitious roadmap towards a common set of goals, while balancing long-term quantum technology research with complementary investment in shorter-term programmes. Public support for innovation must be made available for companies to kick-start the supply chain for these new technologies and to translate laboratory demonstrators into commercial products. Elements of a European programme are shown in the diagram below.



Elements of a European programme in quantum technologies.

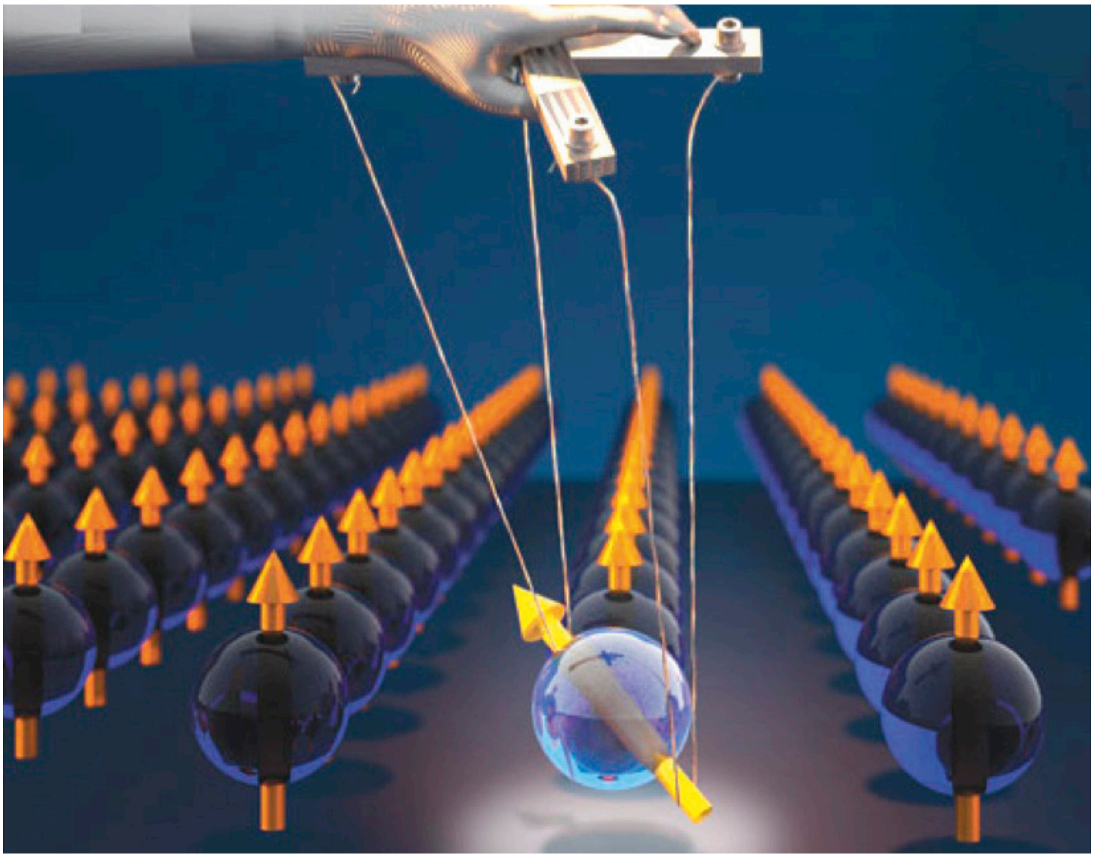
About Quantum Simulators

The design of aircraft, buildings, cars and many other complex objects makes use of supercomputers. By contrast, we cannot yet predict if a material composed of few hundred atoms will conduct electricity or behave as a magnet, or if a chemical reaction will take place. Quantum simulators based on the laws of quantum physics will allow us to overcome the shortcomings of supercomputers and to simulate materials or chemical compounds, as well as to solve equations in other areas, like high-energy physics.

Quantum simulators can be viewed as analogue versions of quantum computers, specially dedicated to reproducing the behaviour of materials at very low temperatures, where quantum phenomena arise and give rise to extraordinary properties. Their main advantage over all-purpose quantum computers is that quantum simulators do not require complete control of each individual component, and thus are simpler to build.

Several platforms for quantum simulators are under development, including ultracold atoms in optical lattices, trapped ions, arrays of superconducting qubits or of quantum dots and photons. In fact, the first prototypes have already been able to perform simulations beyond what is possible with current supercomputers, although only for some particular problems.

This field of research is progressing very fast. Quantum simulators will aim to resolve some of the outstanding puzzles in material science and allow us to perform calculations that would otherwise be impossible. One such puzzle is the origin of high-Tc superconductivity, a phenomenon discovered about thirty years ago, but still a mystery in terms of its origin. The resolution of this mystery will open up the possibility of creating materials able to conduct electricity without losses at high temperatures, with applications in energy storage and distribution and in transportation.



Manipulating electron spins to create and process quantum states. D.D. Awschalom, IME Chicago.

The quantum technologies programme structure builds on a strong foundation of education and science. It uses mission-driven engineering projects working on focused goals to transition this foundation into innovation that strongly attracts the interest of companies.

This programme combines the strength and flexibility of a broad, de-centralised programme with the clustering and coordination of focused initiatives. While a broad programme can harness many different capabilities and ideas from multiple academic and industry partners across Europe, it simultaneously provides the resources needed to accelerate those concepts agreed as having the largest potential.

The engineering referred to in this programme is understanding the design, construction and use of new technologies. Generally speaking, it is the transition from concepts, theories and one-off experiments to devices suitable for use in an application.

Each element of this structure will address a vital component of a future knowledge-driven industry for Europe, which will bring it prosperity, cleaner energy, better health and security. For this to achieve the maximum impact, it is essential that no part of the structure be left out. It is estimated that the total amount of funding needed for this programme is approximately €1 billion over the ten years required to develop this technology and bring it into use.

1. Education

- Run educational programmes for a new generation of technicians, engineers, scientists and application developers in quantum technologies.
- Run a campaign to inform European citizens about quantum technologies and engage widely with the public to identify issues that may affect society.

About Quantum Sensors

Superposition states are naturally very sensitive to the environment, and can therefore be used to make very accurate sensors. As a result of steady progress in material quality and control, cost reduction and the miniaturisation of components such as lasers, these devices are now ready to be carried over into numerous commercial applications.

Solid-state quantum sensors, such as NV centres in diamond, have been shown to be useful for measuring very small magnetic fields. This in turn may help with multiple applications, ranging from biosensors to magnetic resonance imaging and the detection of defects in metals. Superconducting quantum interference devices are one example of an early quantum technology now in widespread use, in fields as diverse as brain imaging and particle detection.

Quantum imaging devices use entangled light to extract more information from light during imaging. This can greatly improve imaging technologies by, for example, allowing higher resolution images through the use of squeezed light or creating the ability to produce an image by measuring one single photon which is entangled with a second, differently coloured and entangled photon that is being used to probe a sample.

Atomic and molecular interferometer devices use superposition to measure acceleration and rotation very precisely. These acceleration and rotation signals can be processed to enable inertial navigation devices to navigate below ground or within buildings. Such devices can also be used to measure very small changes in gravitational fields, magnetic fields, time or fundamental physical constants.

2. Science

- Invest in excellent scientific projects across Europe, from basic science to proof-of-principle experiments. Sustained investment is needed to attract new researchers into the field and to Europe.
- Support European research calls where excellence in the field of quantum science and technologies is the leading criterion.
- Encourage international collaboration, and cooperation between university and government laboratories, through new international funding mechanisms.

3. Engineering

- Establish a focused programme to foster ecosystems of scientists, engineers and companies to work on shared mission-driven technology roadmaps and to develop and standardise tools and software.
- Support engineering hubs that enable open consortia of main partners to work together in geographical ecosystems with open ties to other partners in Europe and the world.
- Recognise and support the need for engineering approaches before marketable technology is ready. In this highly technical field, expanded engineering activity is also needed for basic scientific advances.

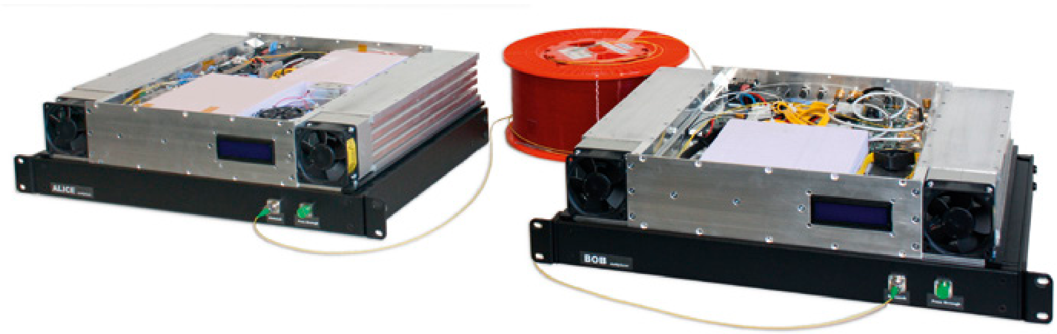
4. Innovation

- Develop an EU-wide quantum innovation fund to finance companies of all types and sizes that are working to turn quantum technologies into products. This funding must make the maximum use of the skills and expertise that reside within companies; they should be used for projects that are led by companies, performed within companies and conducted in collaboration with research and technology organisations (RTOs) and academia. These projects should support companies working on all parts of a future supply chain for quantum technologies.
- Promote market-finding activities to explore realistic and profitable applications and sectors for quantum technologies, both public and private.
- Create incubators and support technology transfer for small, high-potential quantum technology companies. Provide these companies with facilities, skills, public and private funding and the contacts with larger organisations that will allow them to grow.

Coherence in the programme-related activities throughout Europe is a key factor for success. To enhance cooperation and coordination, the programme will:

- Coordinate national strategies and activities through strategic platforms, since national programmes already exist, and any EU programme should build on these in a coherent way.
- Promote international collaboration, exchange and networking of people and information between different centres, and across academia and industry, thus promoting mobility and knowledge exchange.
- Integrate national metrological institutes in developing quantum-based standards for the most mature quantum technologies (e.g. quantum key distribution).
- Form an industry leadership group to steer and guide actions that will generate and sustain a greater level of interest from industry.
- Instil a strong sense of purpose and direction through an advisory body, comprising individuals drawn from academia, business and government, that will oversee this programme and make recommendations to ensure that it is working as effectively as possible.
- Identify those governmental needs that are best served by quantum technologies.
- Promote the integration of and collaboration between education, science, engineering and innovation.
- Assist nascent quantum technologies programmes to ensure that the whole of the EU contributes to and reaps the benefits of the second quantum revolution.

It should be noted that Figure 1 has been produced to show the structure for a future programme only. Details such as the themes associated with each pillar, the number and respective size of the pillars and the split in funding between the four components (education, science, engineering and innovation) will be reviewed in a process following this report. In this design phase of the programme, a suitable governance model will be chosen.



Quantum key distribution system: autonomous GHz-rate prototype, H. Zbinden, University of Geneva.

About Quantum Computers

Quantum computation is among the most far-reaching and challenging of quantum technologies. Based on quantum bits that can be zero and one at the same time and instantaneous correlations across the device, a quantum computer acts as a massive parallel device with an exponentially large number of computations taking place at the same time. There already exist many algorithms that take advantage of this power and that will allow us to address problems that even the most powerful classical supercomputers would never solve.

Quantum computers using different platforms have been demonstrated over the last two decades. The most advanced are based on trapped ions and superconducting circuits, where small prototypes for up to 10-15 quantum bits have already run basic algorithms and protocols. Many platforms and architectures have demonstrated the basic principles of quantum computing based on solid-state systems (electron spins in semiconductors, nuclear spins in solids, Majorana zero modes) and on atomic and optical systems (nuclear spins in molecules, hyperfine and Rydberg states in atoms and photons, to name but a few).

Due to technological interest and the evident limitations of existing approaches, referred to as the "end of Moore's Law" of computational scaling, global IT companies have been taking an increased interest in quantum computing in the last decade. Advances in quantum computer design, fault-tolerant algorithms and new fabrication technologies are now transforming this "holy-grail" technology into a realistic programme poised to surpass classical computation by ten to twenty years in some applications. With these new developments, the question companies are asking is not whether there will be a quantum computer, but who will build and profit from it. Intel, HRL Laboratories and NTT, for example, are supporting spin qubits in semiconductors; Google, IBM and Intel are investing in superconducting qubits; D-Wave is producing a superconducting quantum annealer; Microsoft is betting on topological quantum bits; and Lockheed Martin and INFINEON are supporting research with trapped ions and their interface with photons. With world-leading research in quantum computing located in Europe, many IT companies have chosen academic partners in Europe for their R&D efforts.

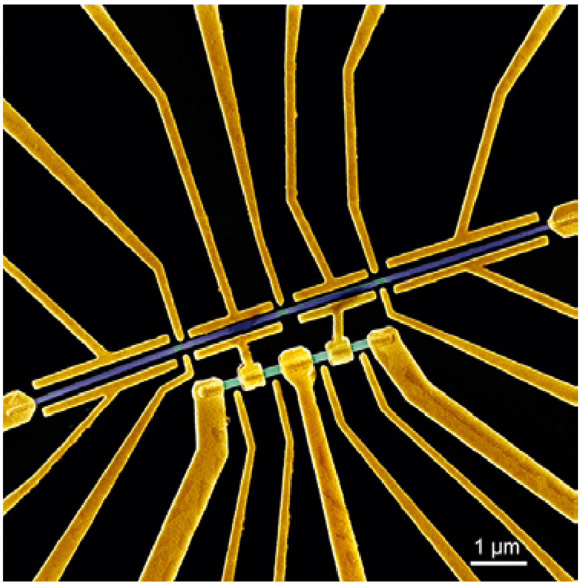
Realising quantum computing capability in Europe on a decade-long timescale will require synergy between industrial and academic partners, as well as involvement of engineers from institutes like Fraunhofer, IMEC, VTT and LETI in multidisciplinary consortia. The hardware efforts have to be complemented by the development of quantum software to obtain optimised quantum algorithms able to solve application problems of interest. Europe is a leader in the development of software for classical high-performance computing applications and so is well placed to establish the emerging field of quantum software engineering, with a number of leading quantum software groups already active and interacting with hardware teams.

Conclusion

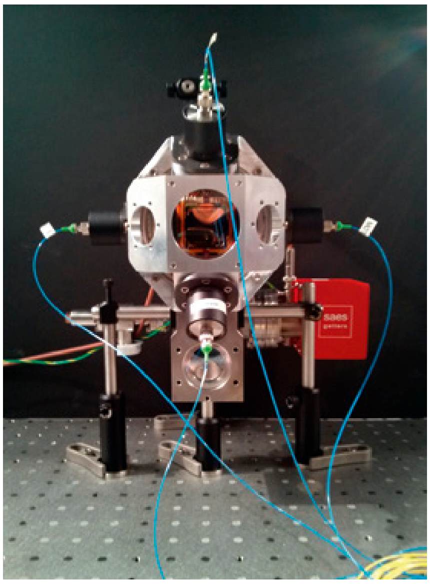
Europe needs bold strategic investment now in order to lead the second quantum revolution. Building on its scientific excellence, Europe has a window of opportunity to foster the competitive quantum technology industry essential for the delivery of long-term prosperity and security.

To that end, this Manifesto calls upon Member States and the European Commission to launch an ambitious, long-term, flagship-scale initiative combining education, science, engineering and entrepreneurship across Europe.

To succeed, this initiative should aim, on the one hand, at consolidating Europe's excellent position in research, keeping a broad scope and allowing the time it takes to achieve the basic results. On the other hand, it should engage with industry to unlock the full innovation potential of quantum technologies, thus accelerating their development and take-up by the market in order to deliver fully on their promising economic and societal benefits.



A micron-scale nanowire device for demonstrating concepts of topological quantum computing. D. Razmadze, Center for Quantum Devices, University of Copenhagen.



Integrated quantum sensors (iSense) project funded in the FP7 FET Open programme.

16

SECTION 3:
R&D goals in quantum technologies

Short-term goals (0-5 years)

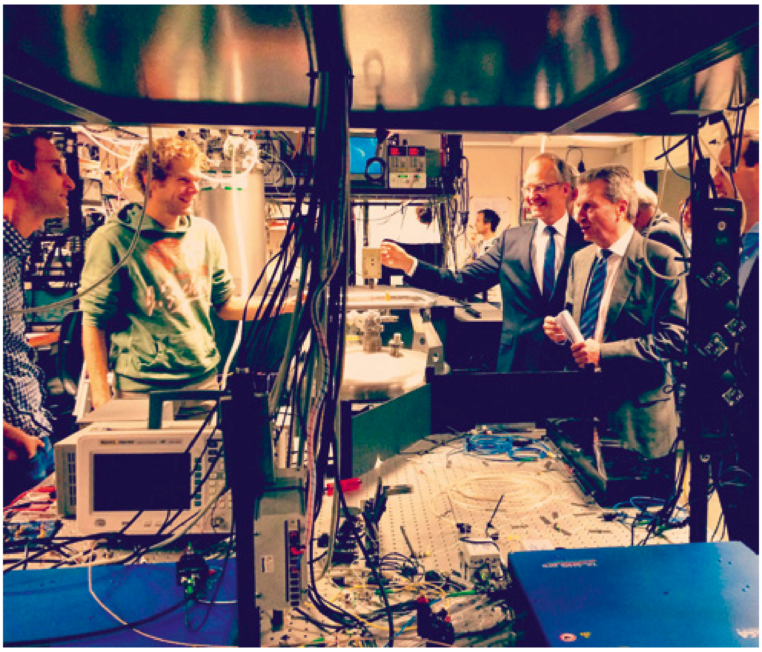
- Develop the core technology of quantum signal repeaters that work with cryptography capability and eavesdropping detection, enabling long-distance point-to-point quantum-secure links.
- Realise a quantum simulator to address problems relevant to chemical processes and the design of materials.
- Develop more precise atomic clocks that can be used for synchronisation of future smart networks, such as for energy and telecommunications.
- Demonstrate exponential protection and control of a topological qubit.
- Integrate a functional quantum circuit with high-speed cryogenic classical control hardware.
- Develop quantum sensors for special-purpose applications, such as gravity sensors for defence, oil and gas and space, quantum clocks for timing applications and magnetic sensors for medical use and imaging.
- Discover new algorithms, protocols and fields of application for quantum simulators, computers and communication networks. For instance, to analyse and design useful chemical processes.
- Demonstrate a small quantum processor executing quantum algorithms and the operation of a logical qubit protected by quantum error correction in an atomic or solid-state platform.
- Develop the supply chain of components like cryogenic or electronic amplifiers and components, or laser sources. These are fundamental to building quantum devices, as well as to numerous spin-off applications.

Medium-term goals (5-10 years)

- Realise versatile simulators of material magnetism and of such electronic properties as superconductivity, supporting the development and design of new materials with exotic properties.
- Simplify quantum sensors so that they can be produced at lower cost for larger-volume applications such as manufacturing, automotive, construction and geosurveying.
- Enable secure communication between distant cities via quantum networks, which enhance information security and make eavesdropping impossible.
- Solve problems in chemistry and materials science with special-purpose quantum computers operating at high speeds beyond one hundred physical qubits.
- Develop handheld quantum navigation devices precise to 1 mm/day and able to function indoors.
- Engineer quantum devices to improve their manufacturability and reliability, reduce their cost and make them available for more mainstream markets.
- Demonstrate ground-to-satellite quantum cryptography.

Long-term goals (>10 years)

- Create a secure and fast quantum internet connecting the major cities in Europe using quantum repeaters running quantum communication protocols.
- Design new materials with tailored properties (e.g. electric conductivity or magnetism) using special-purpose quantum hardware.
- Build a universal quantum computer able to demonstrate the resolution of a problem that, with current techniques on a supercomputer, would take longer than the age of the universe.
- Develop quantum computers to model physical and chemical problems and to solve chemical reaction problems faster and more accurately than is possible with the fastest supercomputer. For instance, for the development of novel catalysts and for drug design.
- Develop on-chip quantum sensor devices that can integrate within mobile phones, etc., to allow quantum information and sensing applications within multiple consumer applications.
- Correlate measurements from an array of gravity sensors to create gravity images.
- Integrate quantum sensors with consumer applications, such as integrated photonic or solid-state devices for mobile devices.
- Develop other applications like quantum credit cards and quantum keys, as well as unanticipated discoveries and applications.

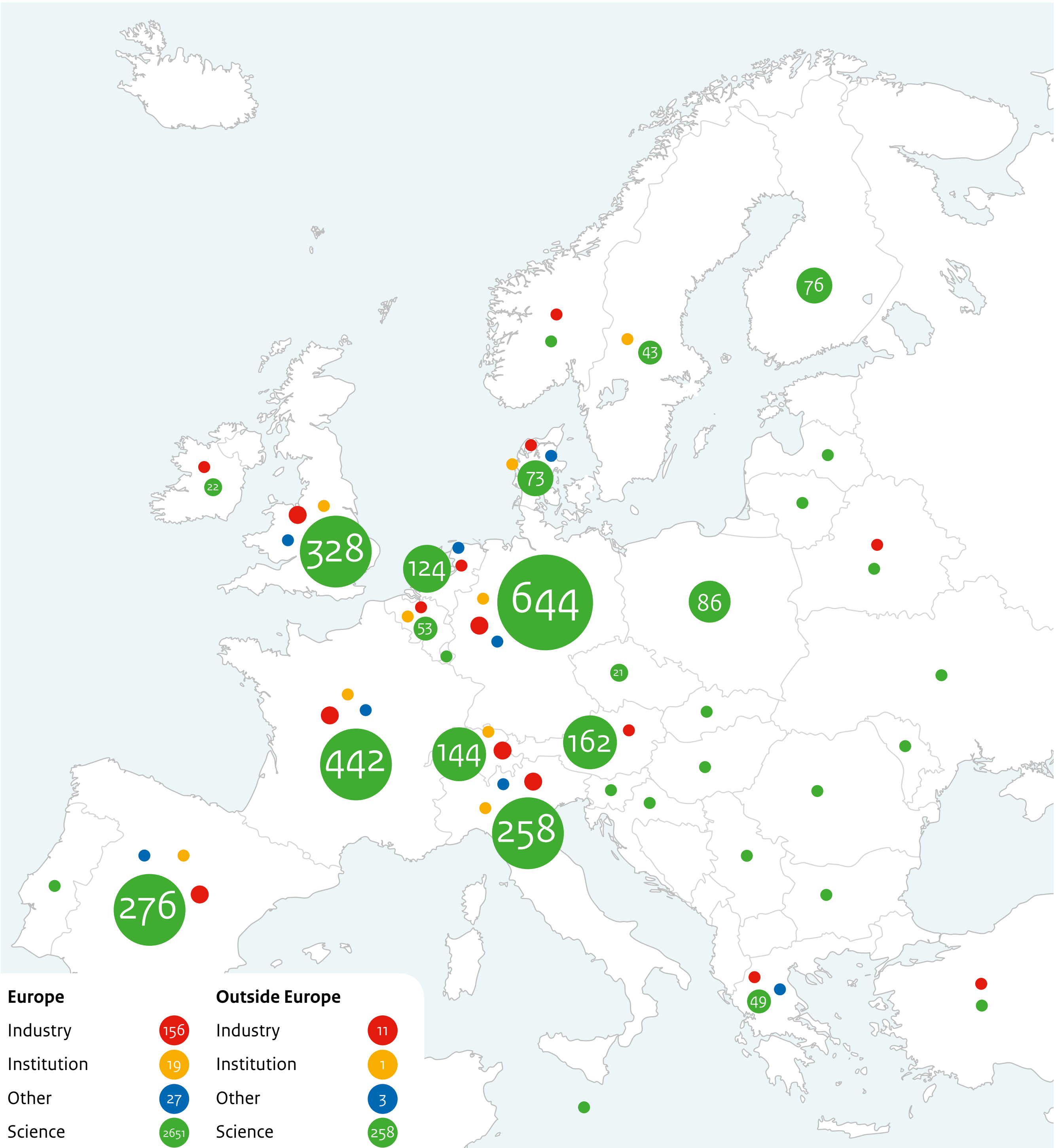


Top: Commissioner Gunther Oettinger and Minister Henk Kamp visit QuTech lab in Delft.
Bottom: Commissioner Oettinger visits IQST lab in Ulm.

18

Appendix:
Map of Europe with a list of all endorsing parties

The Quantum Manifesto was endorsed by more than 3400 individuals from academia and industry. This shows the broad support for an ambitious flagship-scale initiative in the field of Quantum Technologies across Europe. The complete list of endorsers is found at http://qurope.eu/manifesto/endorsers.



UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

National strategy for quantum technologies

A NEW ERA FOR THE UK

The Quantum Technologies Strategic Advisory Board (QT SAB) was set up to provide a visible focus for quantum technologies in the UK and to act as a co-ordinating body for UK interests. It has an oversight of the UK National Quantum Technologies Programme and has drawn up a strategy for quantum technologies in the UK.

QT SAB has 12 members – an independent chair, currently Professor David Delpy; leading representatives of industry and academia; representatives from EPSRC, Innovate UK and BIS; and representatives from the quantum hubs.

The 'National strategy for quantum technologies' was drawn up by QT SAB on behalf of the UK quantum community.

The vision is to create a coherent government, industry and academic quantum technology community that gives the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets, and to substantially enhance the value of some of the biggest UK-based industries.

Professor David Delpy
Chair, Quantum Technologies Strategic Advisory Board

Contact: quantumtechnologies@epsrc.ac.uk

Quantum technologies: a new era for the UK

Quantum physics has given us the electronics that control the fabric of our world, including telecommunications and media, computing, and the control systems that underpin our infrastructure and transport systems.

New emerging quantum technologies now promise the next generation of products with exciting and astounding properties that will affect our lives profoundly. They will have a major impact on the finance, defence, aerospace, energy and telecommunications sectors and have the potential to improve imaging and computing in ways that cannot be predicted.

The UK is one of the world's major investors in quantum research and, over the last two decades, has grown a vibrant academic community. Recent advances in the science, together with novel engineering and manufacturing capability, make this the right time for the UK to bring this next generation of quantum technologies out of the physics laboratory and into the marketplace.

New quantum technologies are expected to have a profound impact on many of the world's biggest markets – for example, significantly enhancing the £305.6 billion global semiconductor industry and the $2.5 trillion world oil and gas industry. In daily life they could enable faster 5G or 6G communications for mobile devices. They could also lead to faster and more efficient construction projects, with reduced delays for all as workers will be using quantum sensor technology to identify pipelines and underground obstructions before starting work.

A national vision and strategy

The UK government responded to this transformative opportunity by announcing in its 2013 Autumn Statement a £270 million investment to establish the UK National Quantum Technologies Programme – championed by the Quantum Technologies Strategic Advisory Board (QT SAB).

The programme is a coordinated effort between the Department for Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK and the National Physical Laboratory (NPL), in partnership with the Defence Science and Technology Laboratory (Dstl) and the Government Communications Headquarters (GCHQ). These partners will also enhance the programme by aligning other investments, a key example being £30 million from the Ministry of Defence chief scientific adviser's research programme.

To realise the benefit of quantum technologies, the UK must succeed in converting its world-leading research into innovative and marketable products. This requires a national strategy, sustained over time, to which all parties remain committed. This strategy has been drawn up by the Quantum Technologies Strategic Advisory Board on behalf of the UK quantum community. Its purpose is to guide new quantum work and investments over the next 20 years to help deliver a profitable, growing and sustainable quantum industry deeply rooted in the UK.

The vision is to create a coherent government, industry and academic quantum technology community that gives the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets, and to substantially enhance the value of some of the biggest UK-based industries.

The vision is not only to grow and develop a quantum technologies industry, but to ensure it remains strongly rooted in the UK and delivers long-term benefits to society as a whole.

"New quantum technologies are expected to have a profound impact on many of the world's biggest markets"

The National Quantum Technologies Programme has already brought about some dramatic changes in the UK, including investment by EPSRC to set up a national network of quantum technology hubs; investment by the UK MOD to build demonstrators for quantum navigation and gravity imagers; and activities by Innovate UK to enable businesses to explore the commercial opportunities that quantum technologies may bring to the UK. EPSRC has also invested in centres for doctoral training to provide high-level skills for a future workforce.

An energetic and integrated academic and industrial community approach is needed, and public investment must be sustained at scale for the next 10 years and beyond.

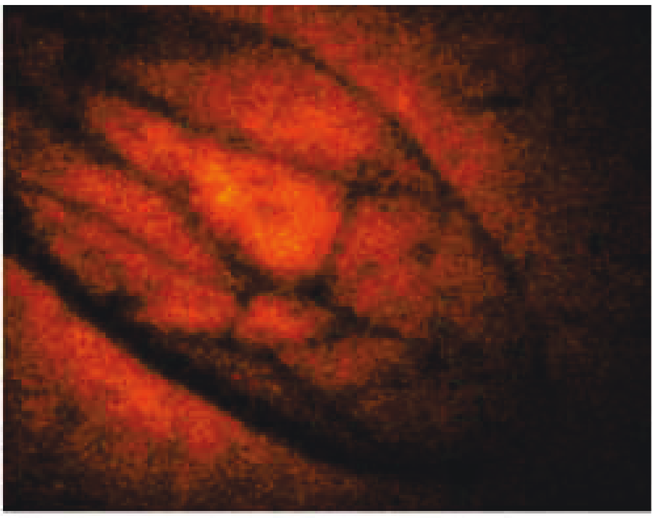
The current investment is the first step towards rooting a quantum technologies industry in the UK, creating environments and skills for early innovation and product development. Subsequent investment will secure this foothold and stimulate growth of the emerging industry, ensuring a pipeline of new ideas. Failure to invest would mean failing to capitalise on the UK's strengths, leaving it trailing other countries.

Our strategy for quantum technologies

What are quantum technologies?

Quantum theory arose in the first quarter of the 20th century to explain how light and matter behave on a fundamental level. It is one of the most successful theories ever devised. Understanding it gave us the worldwide semiconductor industry. We now travel in vehicles controlled by quantum devices, we watch screens and talk into phones made possible by them and we take pictures using them.

A new generation of quantum technologies has moved beyond simply exploiting naturally occurring quantum effects. They are now driving and enabling a new generation of hitherto impossible devices and systems, from breathtakingly powerful medical imaging devices to entirely new methods of computing to solve currently intractable problems – all made possible by the engineering of quantum effects into next-generation technologies.



Scientists at the University of Glasgow used quantum mechanics to take this image of a wasp's wing using an extremely small amount of light. The technique has potential applications in areas where light can damage or fade fragile materials and in biological imaging and defence.

Our strategy for quantum technologies identifies five areas for further action by the UK:

- enabling a strong foundation of capability in the UK
- stimulating applications and market opportunity in the UK
- growing a skilled UK workforce
- creating the right social and regulatory context
- maximising benefit to the UK through international engagement

It also proposes a number of recommendations aimed at the wider quantum technologies community.

RECOMMENDATIONS

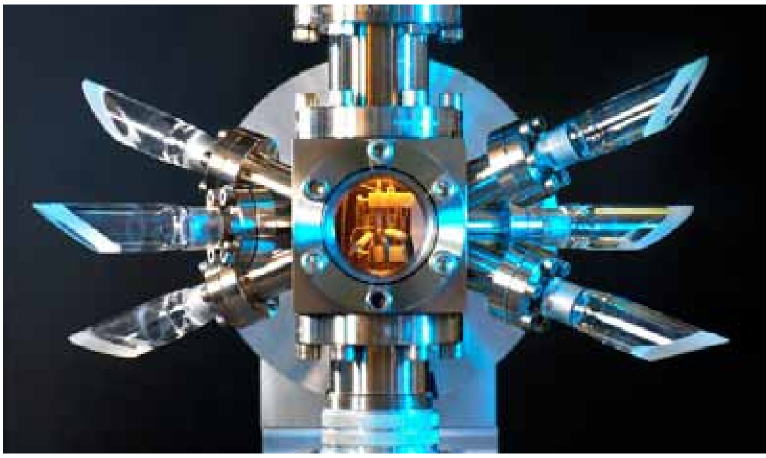
The UK must:

- invest in a 10-year programme of support for academia, industry and other partners to jointly accelerate the growth of the UK quantum technologies ecosystem
- sustain investment in the vibrant UK quantum research base and facilities
- incentivise private investment, including through roadmapping and demonstration, and support early adopters of these new technologies as they emerge over differing timescales
- enable industry to use state-of-the art UK university facilities
- invest in the development of a dynamic workforce that meets the needs of future industry
- support the free flow of people, innovation and ideas between academic, industrial and government organisations
- drive effective regulation and standards and champion responsible innovation
- preserve its competitive advantage as a global supplier of quantum devices, components, systems and expertise while continuing to play a leading role in engaging globally in the development of quantum technologies

The QT SAB will work with partners in the national programme to develop action plans to implement this strategy.

Quantum-enabled clocks for 5G, finance and navigation

Quantum-enabled 'atomic fountain' clocks, such as the one at the National Physical Laboratory in Teddington, provide the world standard for time. Within 10 years, miniaturisation of quantum technologies is expected to bring this precision timing to more portable and compact timing devices. The applications of this technology have far-reaching market potential – enhancing precision in 5G data communications, high-frequency financial transactions, and navigation systems.



The National Physical Laboratory is developing clocks in the form of ion traps that could offer 100 times the accuracy of current atomic clocks.

Enabling a strong foundation of capability in the UK

The UK is ideally placed to be a world leader in the new quantum technologies industry and to command a significant proportion of a large and promising future market. Our vision is for a profitable, growing and sustainable quantum industry deeply rooted in the UK.

This requires sustained and continuous government investment to support the UK's strong foundation of research, skills and facilities. It also demands even stronger relationships between industry, academia and the public sector as the basis for an innovative and high-value ecosystem that provides skills, employment and national wealth.

The existing foundation

The UK has a high-performing and highly productive research base compared with other major international research nations. Between 2008 and 2012, the UK was ranked second internationally for the quality of research across both engineering and physical sciences.

We must continue to support our internationally excellent research in quantum physics and engineering, and capitalise on it by ensuring that our research base is embedded in the rest of the new National Quantum Technologies Programme.

The programme is investing, as a major first step, £120 million in a national network of quantum technology hubs, involving 17 universities, and with more than 50 partner organisations collectively contributing a further £60 million support.

The hubs are led by the universities of Birmingham (sensors and metrology), Glasgow (quantum-enhanced imaging), York (quantum secure communications) and Oxford (networked quantum information systems). These hubs will deliver UK excellence in research and innovation and help to drive the pace of development in quantum technology by building clusters of activity with industry.

The UK also has a strong foundation of highly innovative businesses that can provide the multidisciplinary skills and capabilities to bring quantum technologies to market. These companies supply products and services into many of the world's biggest innovation-driven markets, such as in many areas of optics, electronics, nanofabrication and vacuum systems. It is vital these companies are given the support and advice needed to draw up compelling business cases, and strategies, for investment in quantum technologies and opening up new applications.

"UK is ideally placed to be a world leader in the new quantum technologies industry"

The UK construction industry could benefit greatly from quantum technologies

Helping the construction industry

It is estimated that up to four million holes are cut into the UK road network each year to install or repair buried infrastructure. In London alone, 36 per cent of traffic delays are caused by roadworks. The total cost to London business is not far short of £1 billion. Quantum technology sensors will enable the mapping of pipework and cabling under the road surface before digging takes place, avoiding unnecessary disruption.

Further potential applications for 'gravity sensing' technology include monitoring water levels in aquifers in drought-prone areas, locating and identifying mine shafts and sinkholes, and locating oil, gas and mineral deposits in challenging conditions where traditional geophysical sensors would not work.

Encouraging exploitation of existing investment

Exploitation will happen most effectively with the right combination of people, business acumen and government support and investment.

The National Quantum Technologies Programme is creating an open quantum technologies community – one that has good inter-connections, is attractive to new members, and has a shared vision and principles for the quantum programme. Maintaining this momentum is crucial. Participants from a full range of disciplines and potential market sectors must be involved to realise the broadest range of applicability for each technology. They should include system integrators, whose expertise includes reliability engineering, interoperability, modularity and standardisation. The newly formed Quantum Technologies Special Interest Group will have a key role here.

The community needs to be responsive to new knowledge, discoveries and opportunities, and operate flexibly so that these developments can be incorporated into current and future technologies.

New quantum technologies will continue to emerge from research. Strong investment in the UK's vibrant science base must be maintained and, if possible, grown to ensure a pipeline of new technologies and skilled people to exploit them. Government and industry must continue to generate the technical and commercial knowledge to bring new products to market – stimulating and encouraging university teaching and early career development to reflect the needs of industrial employers and enable entrepreneurship.

Those engaged in research and exploitation activities should recognise the value that may be generated and seek to identify and protect key intellectual assets.

We must focus our research efforts on supporting the most promising application areas for quantum technologies.

Developing and maintaining an open infrastructure

Quantum technologies require a good network of supporting infrastructure, such as fabrication and testing facilities. These are prohibitively expensive for all but the largest companies. Nonetheless, the UK's existing infrastructure allows it the opportunity to provide all players, especially businesses, with convenient and commercially viable access. For example, the quantum technology hubs will build on the existing success of facilities, such as Kelvin Nanotechnology at the James Watt Nanofabrication Centre in Glasgow, that understand commercial needs – competitive costing, quality and turnaround time.

RECOMMENDATIONS

The UK must:

- invest in a 10-year programme of support for academia, industry and other partners to jointly accelerate the growth of the UK quantum technologies ecosystem
- sustain investment in the vibrant UK quantum research base and facilities
- enable industry to use state-of-the art UK university facilities

Stimulating application and market opportunities

"Public investment must be sustained at scale for the next ten years and beyond."

Quantum technologies will lead to major advances in precision timing, sensors and computation, destined to have a major impact on the finance, defence, aerospace, energy, infrastructure and telecommunications sectors.

While it is difficult to predict which sector will benefit most, parallels can be drawn between the potential impact of quantum technologies and the emergence of semiconductor-based electronics.

Next-generation atomic clocks and secure quantum communication systems – enabling accurate timing and navigation devices for defence, telecommunications, and finance industries – are expected to arise in the next 5 years. Quantum sensor and imaging technologies for subsurface imaging for better flood prediction or construction surveys are expected to arise between 5 and 10 years from now. And quantum computing – enabling solutions to problems that are prohibitively complex for current computer systems, such as large search and optimisation or the discovery and creation of new highly effective medicines and materials – is potentially 10-to-25 years away.

Early commercial opportunities will exist for component and device manufacturers, and then for second-tier exploiters building and using systems. For example, those developing and manufacturing 5G communications may be among the first to benefit from the new generation of quantum clocks.

Despite huge promise, substantial investments are unlikely as the potential cost and risks involved are too great at the present time for all but the largest companies. We must incentivise private investment by:

- funding demonstrators to better understand technical challenges and the value of potential market applications
- encouraging effective communication, networking, road-mapping, undertaking market analysis and investigating standards to build greater confidence and understanding
- identifying early adopters for new technology, and, where appropriate, using government procurement to solidify some of the early market opportunities (such as in defence)

An energetic and integrated academic and industrial community approach is needed, and public investment must be sustained at scale for the next ten years and beyond. Failure to invest would mean failing to capitalise on these strengths and leave the UK trailing other countries.

RECOMMENDATION

The UK must:

- incentivise private investment, including through road-mapping and demonstration, and support early adopters of these new technologies as they emerge over differing timescales

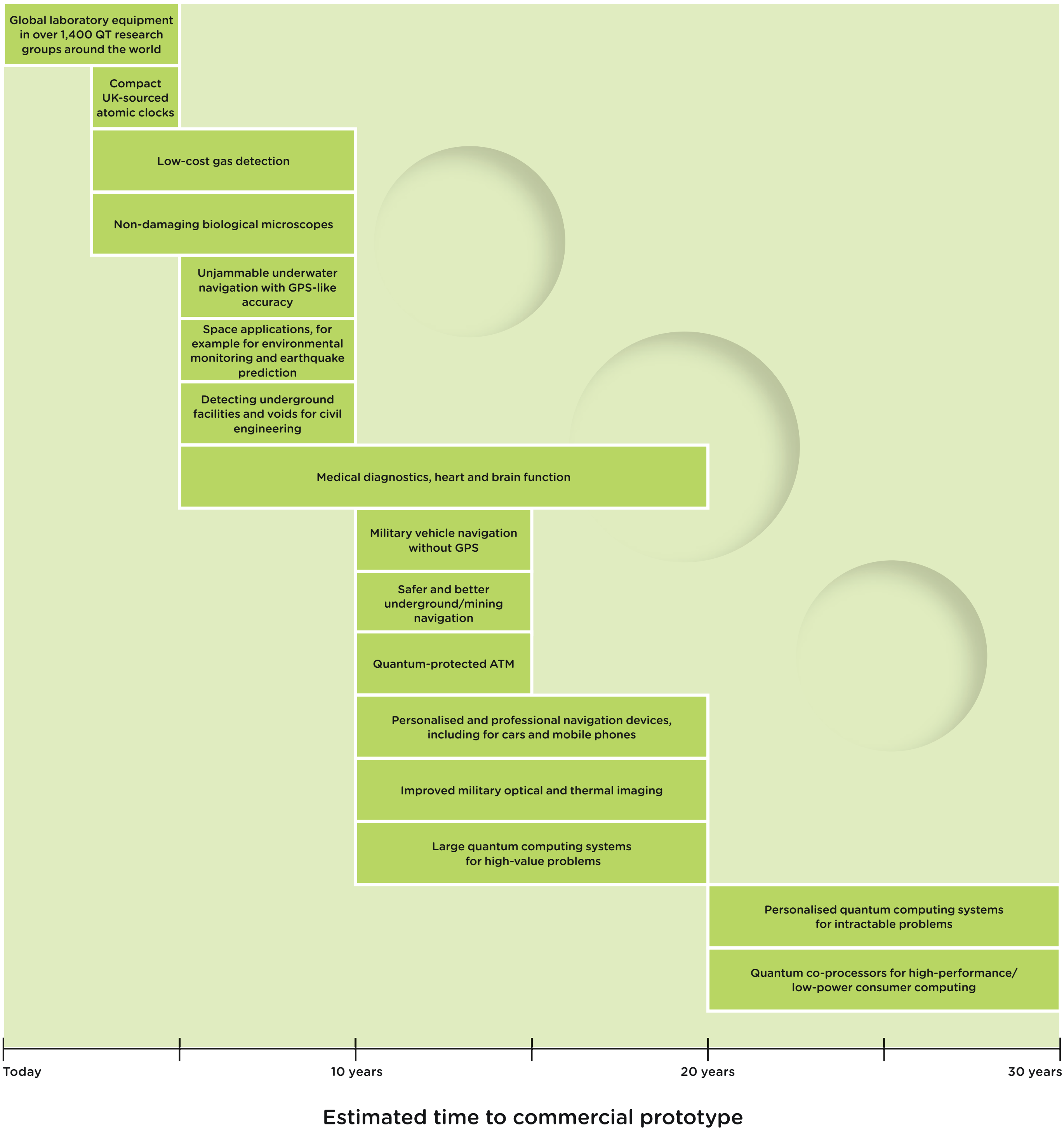
In order to have practical application, the new quantum technology devices will have to be integrated into systems. An immediate challenge for the new quantum industry is to move to a point where use of quantum devices does not require specialist knowledge or training and where the inherent quantum 'strangeness' will be hidden from both systems designers and day-to-day users.

These components are themselves a significant wealth-creation opportunity for the UK. Highly specialised, yet packaged and self-contained components such as single photon sources and detectors, silicon waveguides, synthetic diamond, superconductors, lasers, ultra-low vacuum cells, optical fibres and ultra-low temperature (cryogenic) refrigerators, are very real and potentially very lucrative opportunities for early quantum sales and other far-reaching spin-off applications.

Quantum navigation has great potential

Scientists at Imperial College London have developed quantum navigation technology that could work where GPS cannot. The technology could allow submersibles to navigate to unprecedented accuracy without surfacing for a GPS fix. For robots inside buildings, accuracy could be better than millimetric. It has the long-term potential to be applied to planes, cars, mobile phones and even construction. It might also be used for indoor navigation such as in multi-storey car parks, shopping malls, airports and tunnels. The current global market for GPS systems is US$27 billion (£17.5 billion).

Future commercial uses for quantum technologies



Growing a skilled UK workforce in quantum technologies

"The wider UK workforce must grow and adapt alongside the emerging industry."

The UK needs a creative, adaptable, diverse and networked workforce with the right balance of skills to ensure it benefits from new opportunities in quantum technologies.

The transition of quantum technologies into commercial products will require a new generation of quantum engineers – specialists in physics, engineering, photonics, electronics or computer science who are conversant in multi-disciplinary and systems-based approaches, possess the right entrepreneurial and business skills, and are able to adapt to new jobs and roles in the emerging industry.

Skills providers in academia, industry and government must offer the right number of skilled people the right balance of training. Higher education is already responding – for example through EPSRC's cohort-based centres for doctoral training, and the Dstl PhD studentship programme – but we must go further.

Co-working is key to our success

Co-working between people from different backgrounds and specialisms is key to creating this diverse and well-rounded skill set. This means bringing together people in relevant application areas from industry to work alongside quantum researchers.

The National Quantum Technologies Programme partners will work with skills providers to encourage rapid learning and movement of skilled people and promote opportunities for co-working and knowledge exchange. We will also explore with them approaches that enable students, researchers and those in the private and public sectors to develop familiarity with quantum technologies and the commercial awareness, knowledge of intellectual assets and entrepreneurial skills that are required to capitalise on emerging opportunities.

The wider UK workforce must grow and adapt alongside the emerging industry so that it is equipped to support the development and adoption of quantum technologies. Multi-disciplinary and systems-based approaches must be encouraged at all levels of our education system. The quantum technologies community must also pursue a consistent and inspiring message with media organisations to ensure public awareness develops in parallel with the technology, and interest in quantum-related career opportunities is stimulated at all skills levels. The UK must also ensure that skills are retained in the UK by providing clear opportunities for the quantum technologies workforce.

RECOMMENDATIONS

The UK must:

- invest in the development of a dynamic workforce that meets the needs of future industry
- support the free flow of people, innovation and ideas between academic, industrial and government organisations

Quantum technologies could transform computing

Quantum computers will be able to perform tasks too hard for even the most powerful conventional supercomputer and have a host of specific applications, from code-breaking and cyber security to medical diagnostics, big data analysis and logistics.

Quantum computers could accelerate the discovery of new materials, chemicals and drugs. They could dramatically reduce the current high costs and long lead times involved in developing new drugs.

Creating the right social and regulatory context

The UK must put in place the necessary practices and environments to be recognised as a leading nation for developing quantum technologies.

Realising the societal and economic opportunities requires early and broad engagement with UK society. Proactively engaging with a wide range of stakeholders at an early stage will not only enable innovation to be driven responsibly, but will ensure the commercial viability of quantum technologies and facilitate the creation of an effective regulatory and standards regime.

Responsible research and innovation

Responsible research and innovation promotes science and innovation that is socially desirable and undertaken in the public interest. It involves a two-way discussion between a wide range of stakeholders at an early stage of the innovation process. It potentially enriches the process and improves the chance of commercial success by stimulating creativity; informing standards, regulation and governance; and ultimately allowing products to be developed that are more likely to be embraced by the public.

The UK has an opportunity to produce the first comprehensive public perspective on quantum technology and to develop a bespoke framework and effective governance structure to guide its development.

Regulatory and standards development

Standards are a useful enabler to future technology development, giving confidence and commonality in an emerging market that can be recognised internationally by all parts of the supply chain. Our goal is to ensure that they are developed at an appropriate pace and used appropriately to facilitate the planned development of quantum technologies.

Similarly, the review of regulations can often be used to open opportunity in an emerging market. The development of effective regulation that embraces innovation in quantum technologies will drive forward the overall vision.

RECOMMENDATION

The UK must:

- drive effective regulation and standards and champion responsible innovation

Tackling internet fraud

e-crime is estimated to cost the UK retail sector £205 million every year. Physicists at the University of Strathclyde and Heriot-Watt University are using quantum physics to crack down on internet fraud.

The systems that underpin the security of internet transactions, known as digital signatures, are founded on complex mathematical formulae. These can be cracked and are therefore vulnerable to e-crime. The team have used quantum technology to develop what is effectively an unbreakable digital signature.

Quantum technology could make buying over the internet much safer

Maximising UK benefit through international engagement

"There is an opportunity for the UK to be the global leader and a 'go-to' place for quantum technologies."

The UK is not alone in recognising the potential value of quantum technologies. Others such as USA, Australia, China, Canada, Singapore and several European countries are establishing or have already established centres of excellence in quantum technologies. However, there is an opportunity for the UK to be the global leader and a 'go-to' place for quantum technologies.

We must work on the international stage to achieve this and be efficient and agile in how we do it. A balance must be struck, however, between harnessing the benefits of international collaboration and protecting and guiding UK academics and industry on how to deliver the maximum value from technology to the UK. The UK quantum technologies community should be astutely aware of legislation with extra-territorial effect that could restrict the movement and sale of quantum products and services.

Taking into account this risk, it is important that the UK continues to support international collaboration as a means to attract the best talent, to access a wider range of customers and markets, and to encourage inward investment. The UK must strengthen its international connections, for example, by continuing our dialogue with the European Commission in order to identify suitable opportunities for Horizon 2020 funding.

The National Quantum Technologies Programme will ensure that the UK's quantum technology research and technology base is promoted as a key partner in international networks and foster effective collaboration with identified international centres of excellence.

RECOMMENDATION

The UK must:

- preserve its competitive advantage as a global supplier of quantum devices, components, systems and expertise while continuing to play a leading role in engaging globally in the development of quantum technologies

UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

Published by Innovate UK and the Engineering and
Physical Sciences Research Council on behalf of
the Quantum Technologies Strategic Advisory Board

March 2015 T15/080

Looking Ahead: Ten Big Ideas

全米科学財団（NSF）
2016年8月
コルドバ長官発表資料

Navigating the New Arctic

Harnessing Data for 21st Century Science and Engineering

Work at the Human-Technology Frontier: Shaping the Future

RESEARCH IDEAS

Understanding the Rules of Life: Predicting Phenotype

The Quantum Leap: Leading the Next Quantum Revolution

Windows on the Universe: The Era of Multi-messenger Astrophysics

PROCESS IDEAS

Growing Convergent Research at NSF

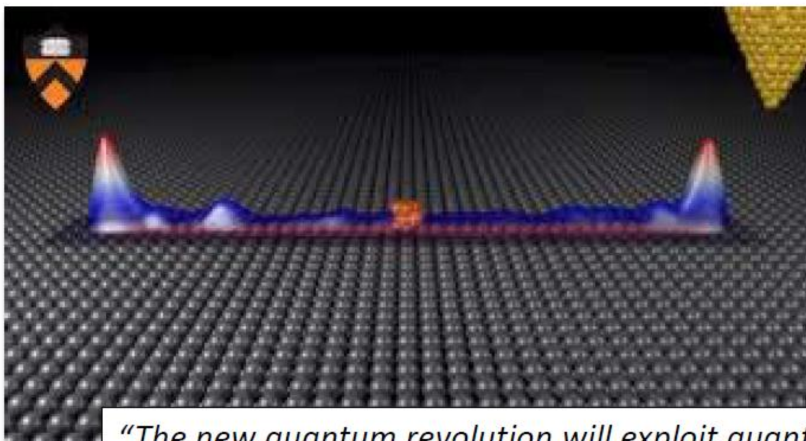
NSF-Includes: Enhancing Science and Engineering through Diversity

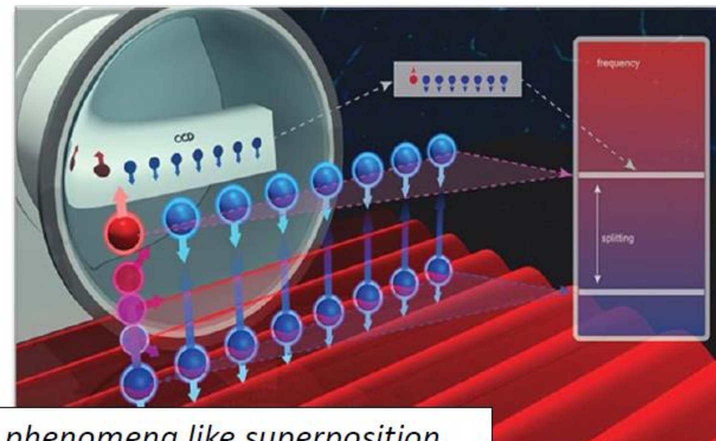
Mid-scale Research Infrastructure

NSF 2050: Seeding Innovation

The Quantum Leap

Leading the Next Quantum Revolution

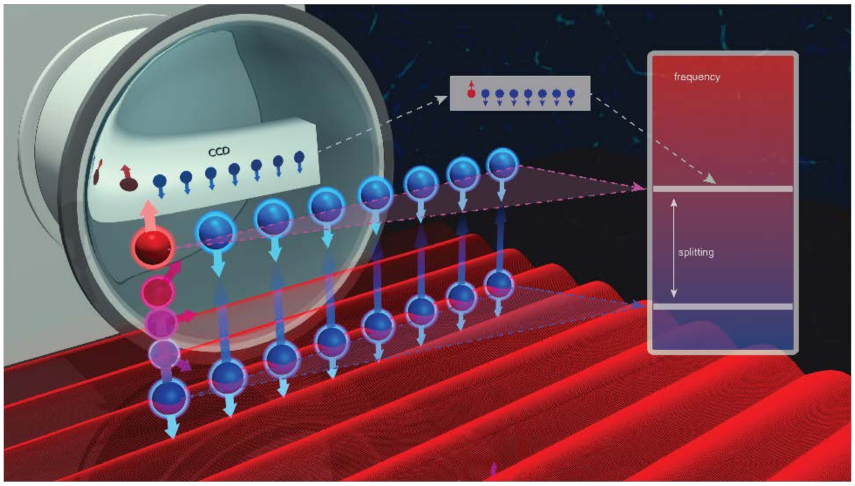




"The new quantum revolution will exploit quantum phenomena like superposition, entanglement, and squeezing to enable the next wave of precision sensors, and more efficient computation, simulation, and communication. NSF would invest in research that addresses the manipulation of quantum states, and the control of material-light interactions, involving physicists, mathematicians and engineers."

Dr. Córdova

The Quantum Leap: Leading the Next Quantum Revolution



In the first half of the 20th century, physics was revolutionized when scientists began to examine and understand the behavior of matter and energy at very small -- atomic and subatomic -- scales, creating the branch called quantum physics. The world is on the threshold of the next quantum revolution and the National Science Foundation (NSF) has a leading role to play. Many of today's technologies -- lasers, computers and LEDs among them -- rely on the interaction of matter and energy at extremely small and discrete dimensions. By exploiting interactions of these quantum systems, next-generation technologies for sensing, computing, modeling and communicating will be more accurate and efficient. To reach these capabilities, researchers need understanding of quantum mechanics to observe, manipulate and control the behavior of particles and energy at dimensions at least a million times smaller than the width of a human hair.

The Quantum Leap: Leading the Next Quantum Revolution is NSF's approach to identifying and supporting this research. It will address fundamental questions about quantum behavior and the manipulation of quantum systems.

NSF can drive this compelling basic research and its potentially significant applications across a broad swath of S&E. NSF has invested in fundamental research related to quantum systems for decades and possesses the firm foundation needed to make this initiative a success.

Research into quantum materials is essential for preparing future scientists to implement the discoveries of the next quantum revolution into technologies that will benefit the average consumer. There will be strong connections to industry, federal agencies and international partners.

Image credit: S. Kelley/Joint Quantum Institute (JQI), University of Maryland

10 Big Ideas for Future NSF Investments

In the nearly seven decades since it was founded, the National Science Foundation (NSF) has played a critical role in establishing U.S. leadership in science and engineering (S&E), creating innovations that drive the nation's economy and educating the next generation of scientists and engineers.

As we look ahead to the coming decades, we must envision bold questions that will drive NSF's long-term research agenda -- questions that will ensure future generations continue to reap the benefits of fundamental S&E research.

This is the reason behind these 10 "big ideas." They capitalize on what NSF does best: catalyze interest and investment in fundamental research, which is the basis for discovery, invention and innovation. They are meant to define a set of cutting-edge research agendas and processes that are uniquely suited for NSF’s broad portfolio of investments, and will require collaborations with industry, private foundations, other agencies, science academies and societies, and universities.

Funding these ideas will push forward the frontiers of U.S. research and provide innovative approaches to solve some of the most pressing problems the world faces, as well as lead to discoveries not yet known.