

# Quantum Manifesto

A New Era of Technology

Draft - March 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.

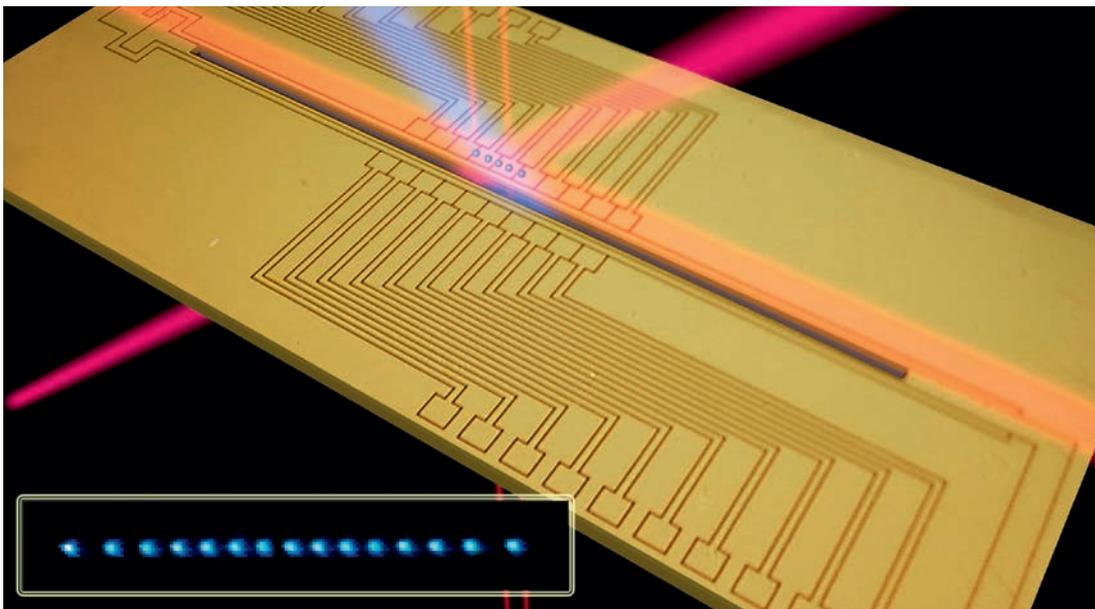
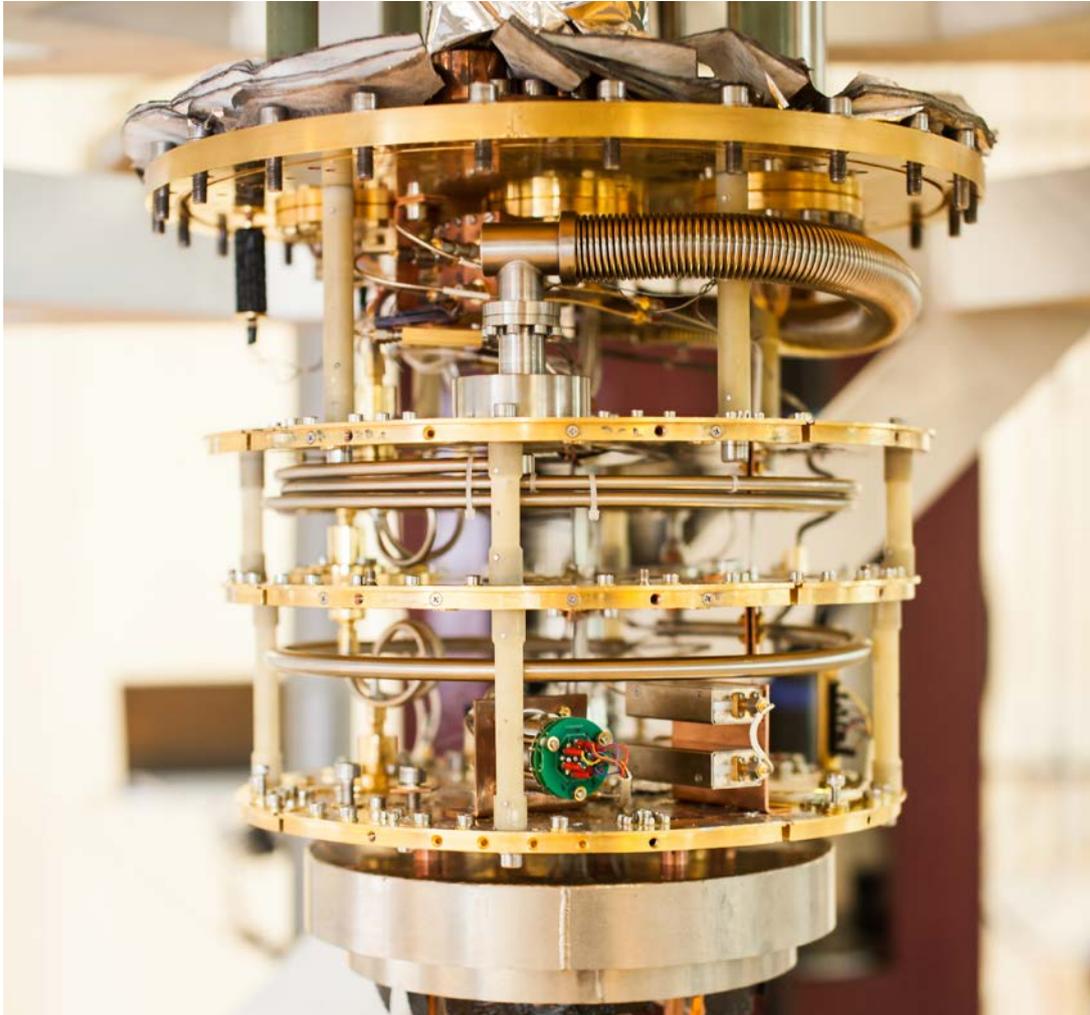
## Goals of this initiative

- 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.**



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

<b>SECTION 1:</b>	Why Europe needs to act now	7
<b>SECTION 2:</b>	Launch of an ambitious European programme	11
<b>SECTION 3:</b>	R&D goals for quantum technologies	17
<b>APPENDIX:</b>	Map of Europe with a list of all endorsing parties (to be added)	19

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 ...

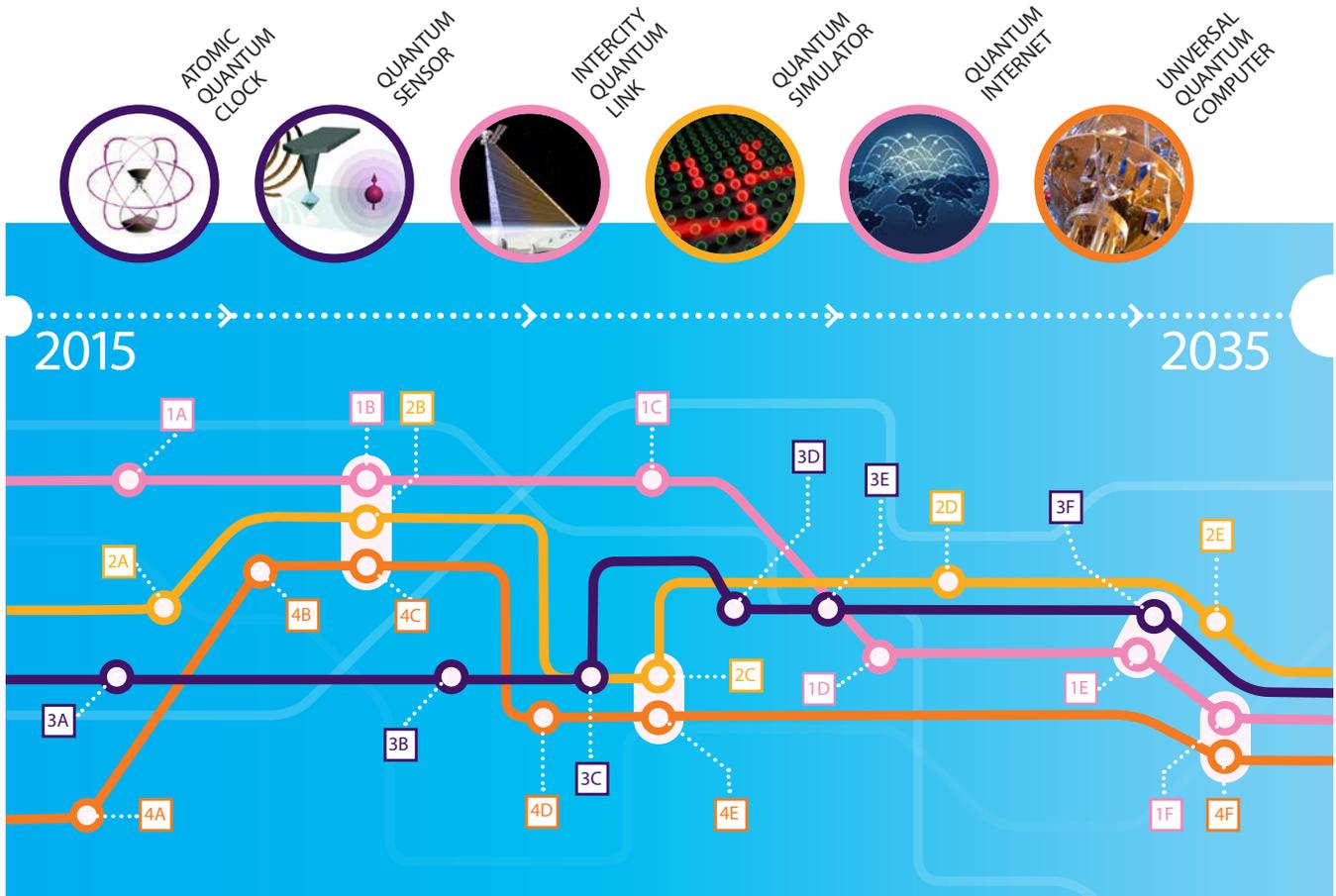
Technologies based on the laws of quantum mechanics, which govern physics on an atomic scale, will lead to a wave of new technologies that will create many new businesses and help solve many of today's global challenges. Over the last century, humankind has mastered the underlying quantum physics. Now, 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 tracking of financial transactions 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	<p><b>A</b> Core technology of quantum repeaters</p> <p><b>B</b> Secure point-to-point quantum links</p>	<p><b>A</b> Simulator of motion of electrons in materials</p> <p><b>B</b> New algorithms for quantum simulators and networks</p>	<p><b>A</b> Quantum sensors for niche applications (incl. gravity and magnetic sensors for health care, geosurvey and security)</p> <p><b>B</b> More precise atomic clocks for time stamping of high-frequency financial transactions</p>	<p><b>A</b> Operation of a logical qubit protected by error correction or topologically</p> <p><b>B</b> New algorithms for quantum computers</p> <p><b>C</b> Small quantum processor executing technologically relevant algorithms</p>
5 – 10 years	<p><b>C</b> Quantum networks between distant cities</p> <p><b>D</b> Quantum credit cards</p>	<p><b>C</b> Development and design of new complex materials</p> <p><b>D</b> Versatile simulator of quantum magnetism and electricity</p>	<p><b>C</b> Quantum sensors for larger volume applications including automotive, construction</p> <p><b>D</b> Handheld quantum navigation devices</p>	<p><b>D</b> Solving chemistry and materials science problems with special purpose quantum computer &gt; 100 physical qubit</p>
> 10 years	<p><b>E</b> Quantum repeaters with cryptography and eavesdropping detection</p> <p><b>F</b> Secure Europe-wide internet merging quantum and classical communication</p>	<p><b>E</b> Simulators of quantum dynamics and chemical reaction mechanisms to support drug design</p>	<p><b>E</b> Gravity imaging devices based on gravity sensors</p> <p><b>F</b> Integrate quantum sensors with consumer applications including mobile devices</p>	<p><b>E</b> Integration of quantum circuit and cryogenic classical control hardware</p> <p><b>F</b> General purpose quantum computers exceed computational power of classical computers</p>



**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 financial institutions – to regulate the timing of high-frequency trades, allowing greater regulation and increasing the stability of financial markets – 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. Secure solutions based on quantum encryption are immune to this risk, 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.

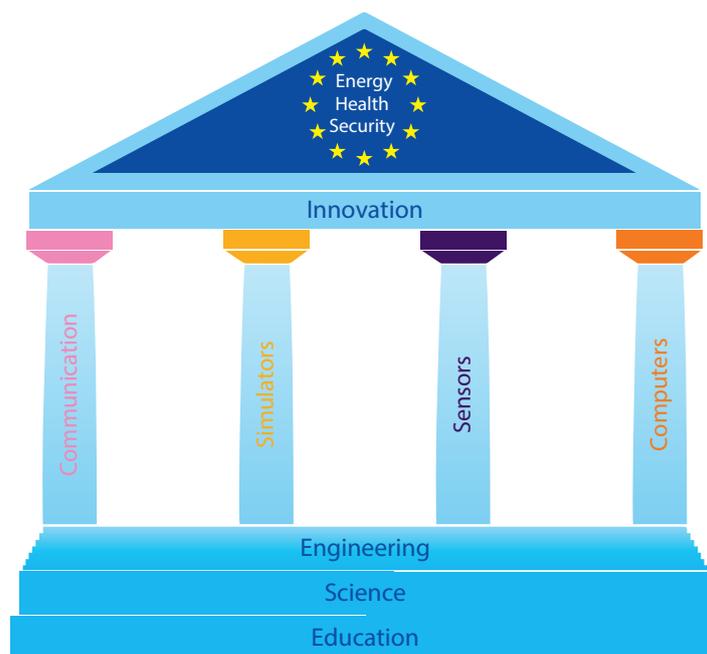
While long-distance qubit transmission can only take place via photons, various platforms exist to realise quantum memories for storage and processing at repeater nodes. Trapped ions, atoms in optical resonators, colour centres in diamond and quantum dots are the main options currently being investigated 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.*

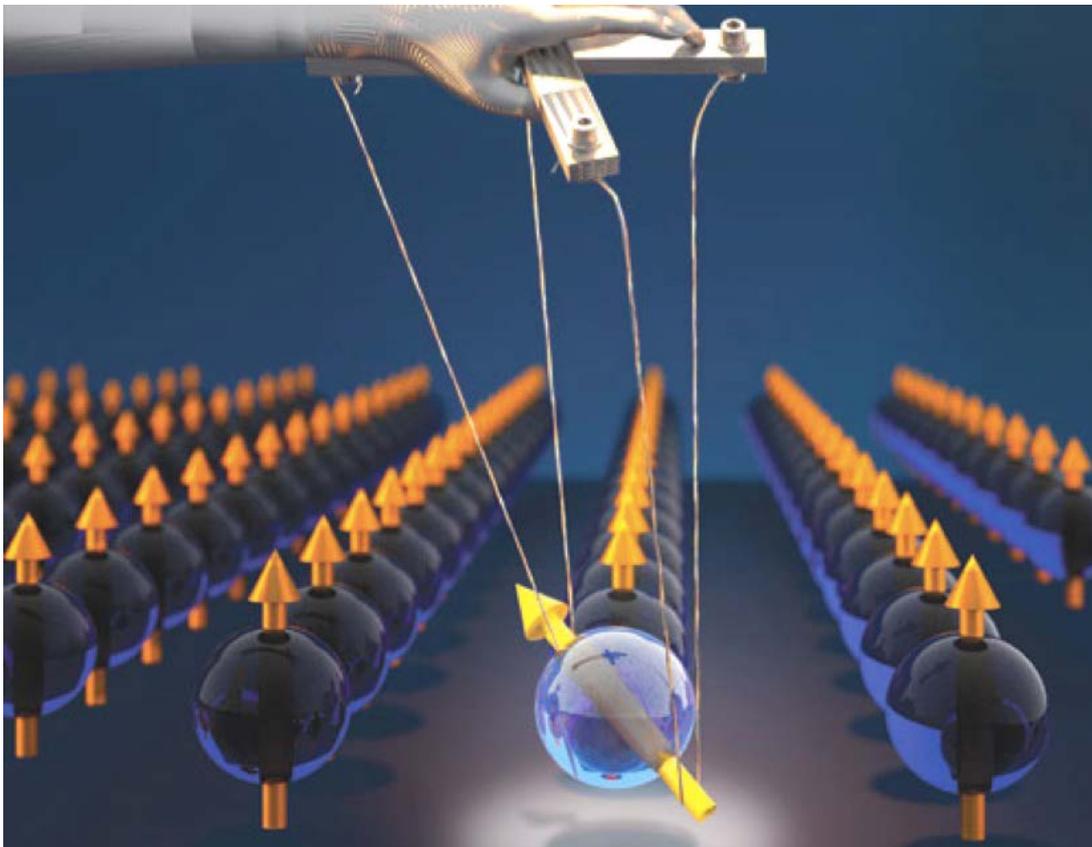
## About Quantum Simulators

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- $T_c$  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.

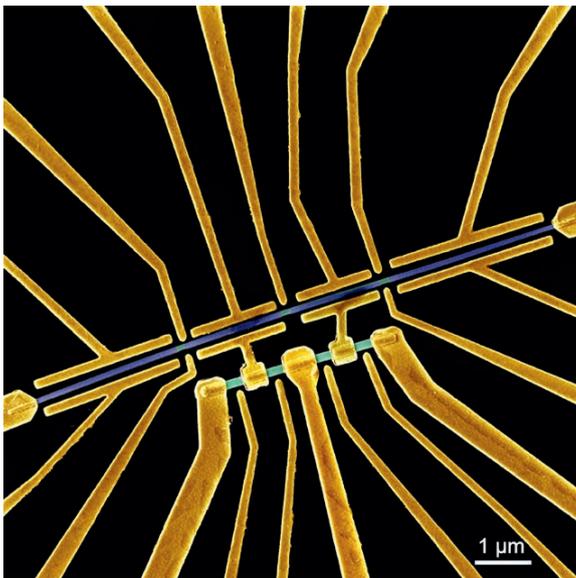
Realising quantum computing capability in Europe on a decade-long timescale will require synergy between industrial and academic partners, as well as involvement of engineers from institutes like Fraunhofer, IMEC, VTT and LETI in multidisciplinary consortia. The hardware efforts have to be complemented 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

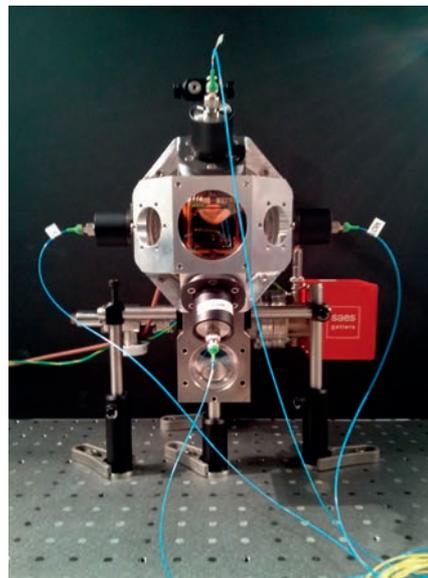
Europe needs bold strategic investment now in order to lead the second quantum revolution. Building on its scientific excellence, Europe has a window of opportunity to foster the competitive quantum technology industry essential for the delivery of long-term prosperity and security.

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.*

## SECTION 3:

# R&D goals in quantum technologies

### Short-term goals (0-5 years)

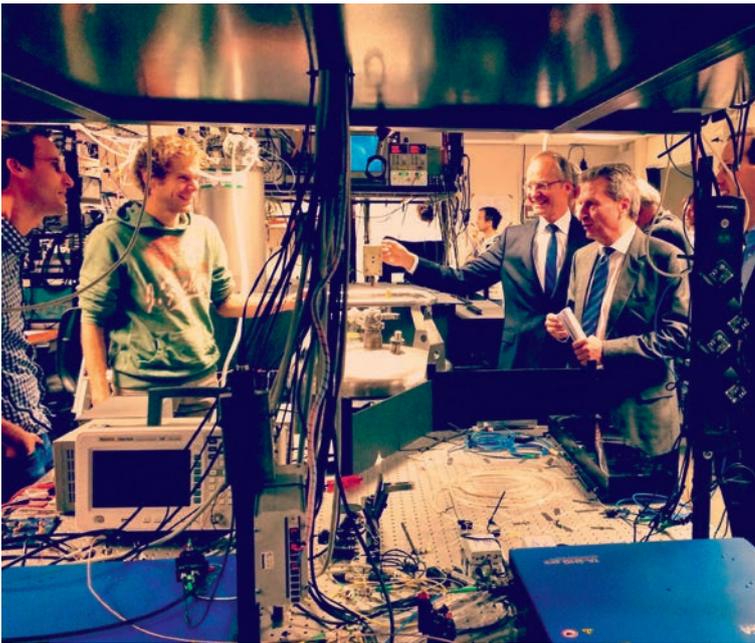
- Develop the core technology of quantum signal repeaters that work with cryptography capability and eavesdropping detection, enabling long-distance point-to-point quantum-secure links.
- Realise a quantum simulator to address problems relevant to chemical processes and the design of materials.
- Develop more precise atomic clocks that can be used for time stamping of high-frequency financial transactions, allowing better regulation and security of global markets.
- 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.

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

to be added in May 2016