UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

A roadmap for quantum technologies in the UK

UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

More information

Innovate UK

For more information about this roadmap
and about Innovate UK funding programmes
email: support@innovateuk.gov.uk

EPSRC
Engineering and Physical Sciences
Research Council

For more information about the UK National
Quantum Technologies Programme
and the quantum hub network email:
quantumtechnologies@epsrc.ac.uk

Contents

Foreword by Trevor Cross

Dr Trevor Cross

Chair of Quantum Technologies Special Interest Group

Member of Quantum Technologies Strategic Advisory Board

The university laboratories of the United Kingdom have seen some ground-breaking work in quantum physics over the last 20 years. Across the globe, there are more than 7000 active researchers and an annual investment of €1.5bn. Now is the time to turn that work into new products and services that could change our lives and drive significant economic growth in the UK.

The UK punches above its weight in this area and, in 2013, our government recognised this opportunity when it announced a £270 million investment in the National Quantum Technologies Programme. We in the Quantum Technologies Strategic Advisory Board have been asked to champion this effort and work with our partners at the Department for Business Innovation and Skills, the Engineering and Physical Sciences Research Council, Innovate UK, the National Physical Laboratory, the Defence Science and Technology Laboratory and CESG (the national technical authority for information assurance) to drive the programme forward.

We published a national strategy earlier this year to guide public and private work and investment in quantum technologies. The publication of this roadmap is part of that strategy. It was drawn up following a series of workshops that involved representatives of business, academia and public funders.

This roadmap is for anyone with an interest in this emerging sector, particularly business. It shows companies where new opportunities in quantum technologies overlap with their interests and helps them to understand how these new applications could drive their growth. It also highlights the challenges and barriers that must be overcome if we are to make UK businesses world-leading in new quantum technologies.

If you are not already involved, find out more about the quantum technologies programme by reading this roadmap and the national strategy. Join us at the Quantum Technologies Special Interest Group and help to shape the future of this emerging industry. And get involved with EPSRC's quantum hubs and the publicly-funded activities of Innovate UK.

Quantum science promises to have a major impact on the finance, defence, aerospace, energy and telecommunications sectors. I look forward to seeing that happen and the part we will all play in maximizing the benefits in and for the UK.

Executive summary

Quantum physics is at the heart of the modern world. It has given us the electronics that underpin telecommunications and media, computing and the control systems that govern our infrastructure and transport.

A second generation of quantum technologies based on new and previously unexploited quantum effects has begun to emerge over the last two decades. These technologies promise to change our lives profoundly. They will affect some of the world's biggest markets, including the semiconductor industry, the oil and gas industry, mobile communications, construction and computing.

They are expected to lead to more secure digital communication, more efficient ways of delivering construction projects and new and more powerful computers able to solve complex problems.

The UK government recognised the potential of new quantum technologies when it announced in the 2013 Autumn Statement £270 million to set up the National Quantum Technologies Programme. 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 national technical authority for information assurance CESG.

The national programme is championed by the Quantum Technologies Strategic Advisory Board (QT SAB), which published a national strategy for quantum technologies in 2015. That strategy is now followed by this roadmap.

A roadmap for quantum technologies in the UK

Roadmapping workshops were organised by Innovate UK and attended by representatives of industry, academia and public funders. Five core themes for the roadmap emerged from these workshops. They were:

- stimulating application and market opportunities
- enabling a strong foundation of capability in the UK
- growing a skilled UK workforce in quantum technologies
- creating the right social and regulatory context
- maximising UK benefit through international engagement

Developing technologies and market opportunities

The roadmapping workshops identified groups of technologies with near-term (0-5 years) or mid-term (5-10 years) potential for commercial application – components for quantum systems; quantum clocks; non-medical-imaging technologies; quantum secure communications; medical imaging technologies; navigation; second generation components. A further three longer-term technologies were identified – quantum secure communications; quantum technologies in consumer applications; quantum computing. These technologies have been brought together in seven technology roadmaps for: component technologies; atomic clocks; quantum sensors; quantum inertial sensors; quantum communications; quantum enhanced imaging; and quantum computers.

The UK Ministry of Defence and the space industry are expected to be early adopters of quantum technologies for such things as quantum-enabled clocks, quantum navigators, and quantum gravity imaging devices.

Enabling a strong foundation of capability in the UK.

The UK is ideally placed to be a world leader in new quantum technologies. The national programme is supported by a number of public bodies and £120 million has already been invested in a series of quantum technology hubs. We must support a solid foundation of science that is flexible enough to respond to new opportunities and that is focused on the challenges faced by those seeking to exploit quantum technologies commercially. The UK quantum technologies programme should seek to protect intellectual property and ensure that all those in the field work together to create an effective supply chain.

Growing a skilled UK workforce in quantum technologies

The UK needs a workforce that can develop demonstrators and prototype devices into products that can be manufactured and maintain the businesses needed to make those devices possible. Both academia and industry need to play their part in developing a wide skills base not only in the physics but also in engineering, systems engineering, production engineering, business and entrepreneurship. Training should be provided both to young researchers and qualified people looking to adapt to new jobs and roles in quantum technology.

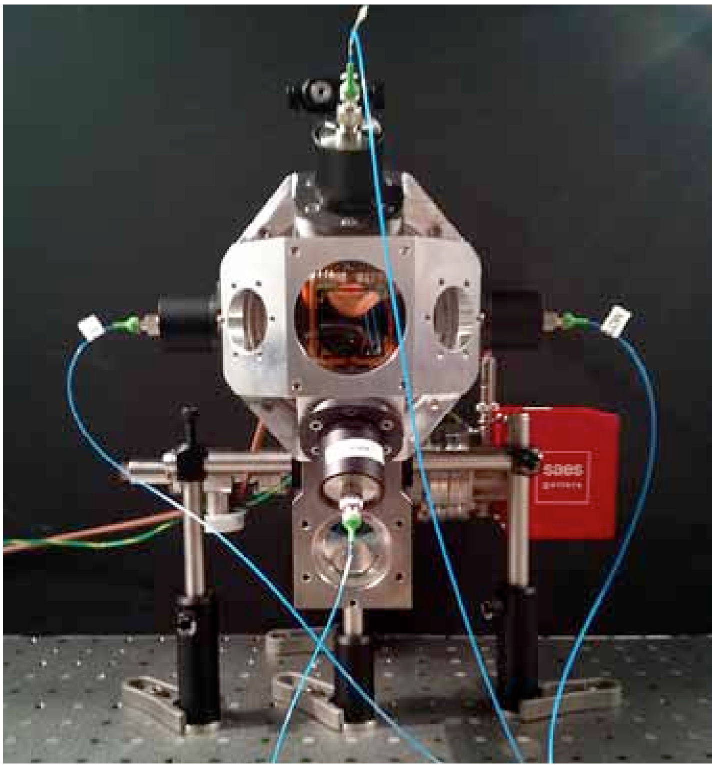
Creating the right social and regulatory context

Development of quantum technologies should not cause a negative reaction among the public. We must promote responsible research and innovation (RRI) that is socially desirable, undertaken in the public interest and widely and openly discussed.

Development of standards and regulations can play a part in opening up markets to businesses and are crucial to delivering market uptake, reliability and interoperability.

Maximising UK benefit through international engagement

The UK must work on the international stage to gain access to the best talent, new markets and opportunities, skills or capabilities, and inward investment. We also have an opportunity to shape new global standards and regulations. We must strike a balance between harnessing the benefits of international collaboration and protecting the UK advantage. The UK must take care to ensure that export controls at home and abroad do not have an impact on the success of the quantum technologies programme.



Quantum gravity sensors being developed at the University of Birmingham under the iSense project could have a big impact on many industries

Introduction

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.

The demand for quantum technologies is being driven by large and significant societal challenges, including the need to build in more inhospitable places, for greater security around information and transactions, for better medicines and therapies, and to counter cyber terrorism.

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 [1] and the £1.6 trillion [2] world oil and gas industry. Quantum timing devices are expected to be necessary in future 5G base stations to coordinate the timing of data packets, without over-reliance on GPS timing signals, while quantum communications will enable ultra-secure data transmission. Quantum gravity sensors will also allow for significantly improved sub-surface imaging, which could significantly impact the construction sector. They will help builders to identify pipelines and underground obstructions before starting work. Significantly, a number of spin-off applications for the components used in quantum technologies are also expected, such as narrow line-width lasers for use in spectroscopy. These devices are expected to create significant commercial opportunities in their own right.

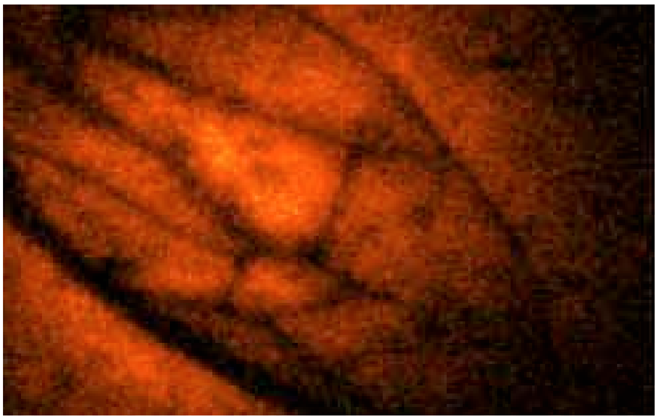
There is a common belief that the strength of research underpinning quantum technologies is more promising than ever before. Most of the fundamental research that needed to be understood has been understood. The timing is right to begin the transition of research and lab-based demonstrators into commercial products.

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. Quantum theory introduced two effects that cannot be explained by conventional 'classical' physics. These are known as superposition and entanglement.

Superposition is commonly thought of as being 'in two states at once'; it is useful because once an object is in a superposition state, it becomes very sensitive to changes in its local environment – to time, and to electric, magnetic and gravitational fields. Entanglement was described by Einstein as being 'spooky action at a distance'. It is a quantum effect that links pairs of particles in a way that cannot be explained by classical physics. Entangled states are useful as they are unique and sensitive to interference, for example caused by eavesdropping of a secure data channel.

Technological advances in lasers and electronics have allowed scientists to reproduce these quantum effects in many laboratories around the world. They are now driving and enabling a new generation of commercially important devices and systems in many diverse applications, from breathtakingly powerful medical imaging devices to entirely new methods of computing to solve currently intractable problems.



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.

A national vision, strategy, and roadmap

The UK government responded to this opportunity by announcing a 5-year £270 million investment to establish the UK National Quantum Technologies Programme – championed by the Quantum Technologies Strategic Advisory Board (QT SAB).

This programme links excellent research in UK universities with business to grow a profitable and sustainable quantum industry deeply rooted in the UK. This requires sustained and continuous government investment to help companies to explore new opportunities arising in this sector and to support the UK's strong foundation of research, skills and facilities.

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, such as £30 million from the Ministry of Defence chief scientific adviser's research programme.

A national strategy was published in March 2015 [3] and is followed by this roadmap for quantum technologies in the UK. This roadmap will evolve into several specific live and detailed roadmaps as our understanding develops. Together, the strategy and roadmap will guide work and investments over the next 20 years.

The UK national strategy for quantum technologies

The National strategy for quantum technologies was drawn up by the Quantum Technologies Strategic Advisory Board (QT SAB). Its recommendations are designed to build the early framework for a quantum technologies industry that would be worth £1 billion to the UK in the future. The recommendations said 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 is working with partners in the national programme to develop action plans to implement this strategy.

The UK National Roadmap for Quantum Technologies

The purpose of this roadmap is to realise the strategy by:

- producing a snapshot of the current quantum technologies landscape
- identifying the application areas where businesses can use their strengths and capabilities to generate revenue
- producing a broader set of actions for business, academia and the public sector designed to overcome future barriers to the development of a UK quantum technologies industry

Evidence to support this roadmap came from two specially structured workshops that brought together representatives of the academic, regulatory and industrial parties most active in exploiting quantum technologies.

Five core themes for the roadmap emerged from these workshops, and are listed as the areas for further action in the UK national strategy. They are:

- stimulating application and market opportunities
- enabling a strong foundation of capability in the UK
- growing a skilled UK workforce in quantum technologies
- creating the right social and regulatory context
- maximising UK benefit through international engagement

This publication contains several visual representations of the roadmap. It designed to be either read from start to finish or as a reference, using the index to identify the impact on a particular individual area or sector.

Developing technologies and market opportunities

"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."

The National Strategy for Quantum Technologies

Quantum technologies are expected to underpin future multi-billion-pound industries across many markets and sectors. Companies must be able to unlock private investment with a convincing business case that offsets the scale of the opportunity against the expected risk. Many quantum technologies have been proven in experimental laboratory demonstrators. However, technology advances must be made so that these systems can be made reliable, durable and operable without PhD-level training. Viable market opportunities must also be identified. This chapter will help companies to identify where their core strengths overlap with specific opportunities in quantum technologies and help them to build a convincing case to invest.

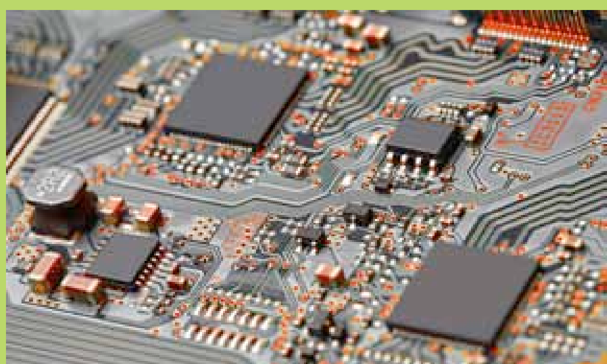
The example of the semiconductor industry

There are many parallels between the potential impact of quantum technologies and the emergence of semiconductor-based electronics which replaced the large vacuum tubes or valves.

Transistor devices started life in 1947 as discrete components which replaced valves, but these were expensive and bulky. Computers built with these devices were so large and specific that they led IBM's president, Thomas J Watson, to say: "There is a world market for about five computers."

These early computing systems were huge machines which operated for only minutes before failing and had a calculation capacity that would be dwarfed by a modern pocket calculator. Through successive iterations and the successful identification of applications, we moved from discrete transistors to the incredibly complex yet cheap and reliable integrated circuit. A single chip computer now costs much the same as a single transistor did in 1960.

The 50-year transition was driven by a succession of very large-scale investments fuelled by escalating product demand. This development was underpinned by a very comprehensive roadmap agreed by all the leading companies, with actions for individual companies and shared end goals and objectives, and is still being used today to guide the developments of the industry [www.itrs.net].



Unlocking private investment in quantum technologies

Interest and investment from private sector companies is fundamental to developing products and services with commercial potential. However, such early-stage investment is difficult to justify on payback timescales that are potentially longer than 3 years. The quantum technologies programme will help companies to identify a case for this investment. We will do this through three streams of activity:

- public funding for demonstrators – these activities encourage better understanding of the potential properties of quantum devices and highlight and overcome the remaining technical challenges in the way of potential market applications
- encouraging effective communication and co-working, networking, roadmapping, 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 facilitate the rapid build-up of industrial supply chains for quantum devices (such as in defence)

The outline roadmaps

The quantum technology roadmapping workshops identified 7 groups of technologies believed to have near (0-5 years), mid (5-10 years) or long-term (10-plus years) potential for commercial exploitation.

Short term (0-5 years):

- components for quantum systems
- quantum clocks
- non-medical imaging technologies (electro-magnetic, gravity imagers, single photon imaging)
- quantum secure communications (point-to-point secure communications)

Mid term (5-10 years):

- medical imaging technologies
- navigation (precision inertial navigation)
- second generation components (solid-state, miniaturised, self-contained quantum devices, for example accelerometers)

Long term (10 years+)

- quantum secure communications (complex network communication)
- quantum technologies in consumer applications
- quantum computing

The opportunities in these 10 groups have been brought together in 7 individual roadmaps for: component technologies; atomic clocks; quantum sensors; quantum inertial sensors; quantum communications; quantum enhanced imaging; and quantum computers.

Roadmap for component technologies

Components are themselves a significant opportunity for many UK companies. They offer opportunities for immediate sales to research organisations, have numerous early spin-off applications, and will remain central to a future quantum industry as it grows.

There is an estimated immediate national and international market of over £1 billion [4] for quantum technology components among researchers. Components for this market are currently high-value, state-of-the-art and bespoke items, used exclusively for quantum technology applications. For example, the market for components and modules using photonic crystal devices is estimated to be worth $100 million a year globally, with the value growing 33% a year between 2012 and 2017 [5]. In the UK alone, demand for components for QT research is growing by around £100 million a year.

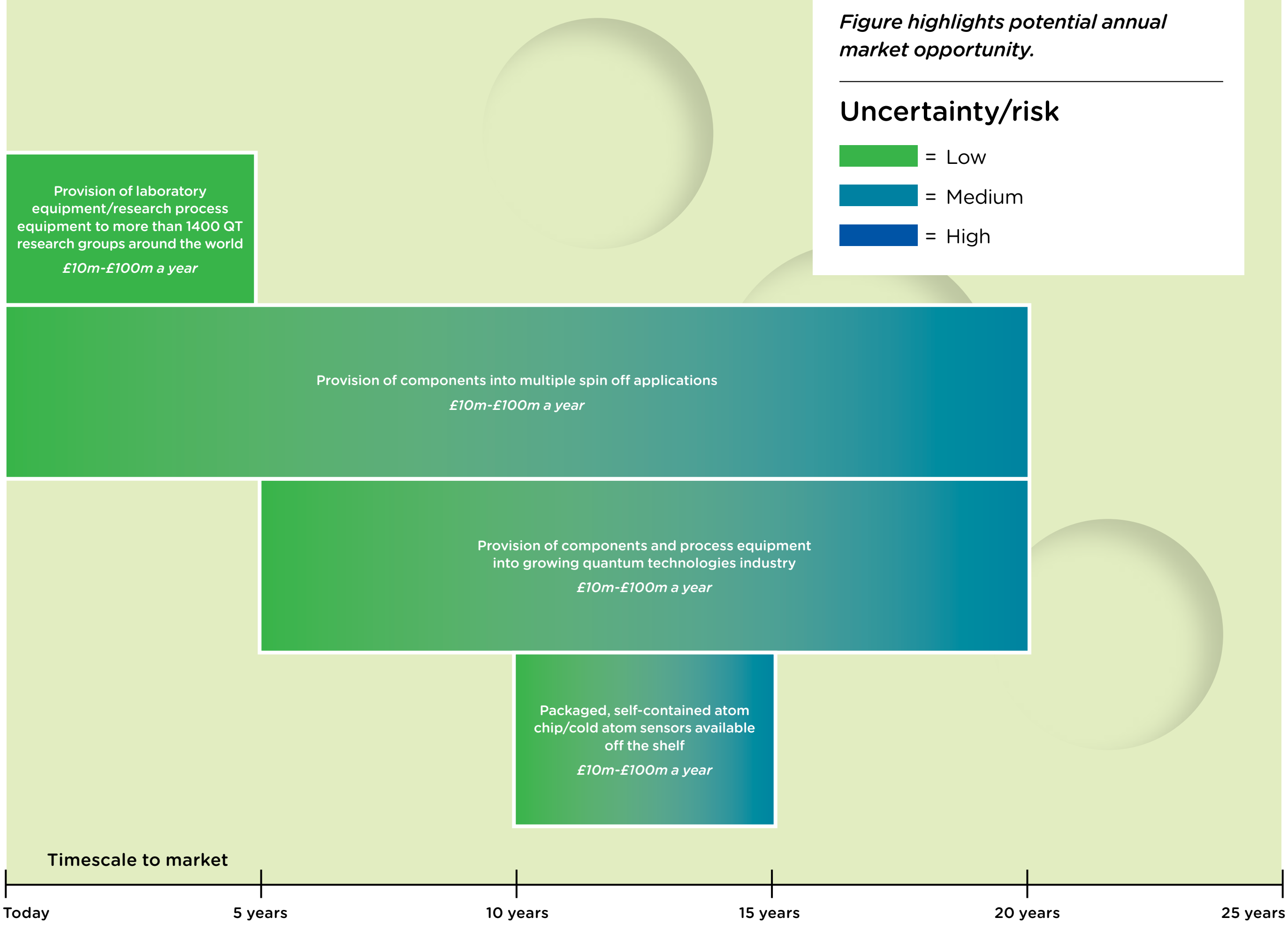
As demand for quantum systems increases and extends to commercial applications in 3 years from now, the market for the components that make up these systems will grow alongside it. Components will have to evolve from one-off bespoke pieces of equipment into devices with 'good enough' performance for use across multiple applications. This change will drive larger scale manufacturing, lead to higher quality components and reduce costs. It will unlock more low-cost, and potentially consumer-led, applications. These complex assemblies will develop into small, self-contained modules as the technology matures. They could be produced at higher volumes and with greater profit margins and will be made using highly controlled and well-known processes, such as electron beam lithography and surface mounting, and using other processes that may currently be unknown.

Potential commercial components include:

- miniature oscillators (clocks)
- precision accelerometers/gravimeters (beyond any performance that can be purchased at present)
- quantum random number generators
- precision gyros (beyond any performance that can be purchased at present)
- quantum-communication-related modules, for example, modulators and repeaters
- component subsystems:
  - o highly stable, highly coherent and high-power specialist lasers
  - o miniature optical frequency combs
  - o miniature magneto optic traps
  - o ion traps
  - o entangled photon sources
  - o optoelectronic waveguides and circuits, including optical switches
  - o superconducting devices
  - o single photon detectors and arrays
  - o diamond with accurately positioned nitrogen-vacancy (NV) sites
  - o electronic controllers, for example based on field-programmable gate arrays (FPGA)
  - o pure materials in special form, for example caesium vapour held in a short fibre with optical couplings
  - o high vacuum systems, such as ion pumps

These components may have a large impact across many applications such as miniaturised spectroscopy, estimated to be worth $5.9 billion by 2018 [6], and novel control algorithms. These spin-off applications are expected to lead to many early revenue opportunities for component manufacturers. They will help to finance a toolkit of components and create a market for components that can be used by companies developing quantum systems.

Figure 1: Roadmap for component technologies



Roadmap for UK atomic clocks

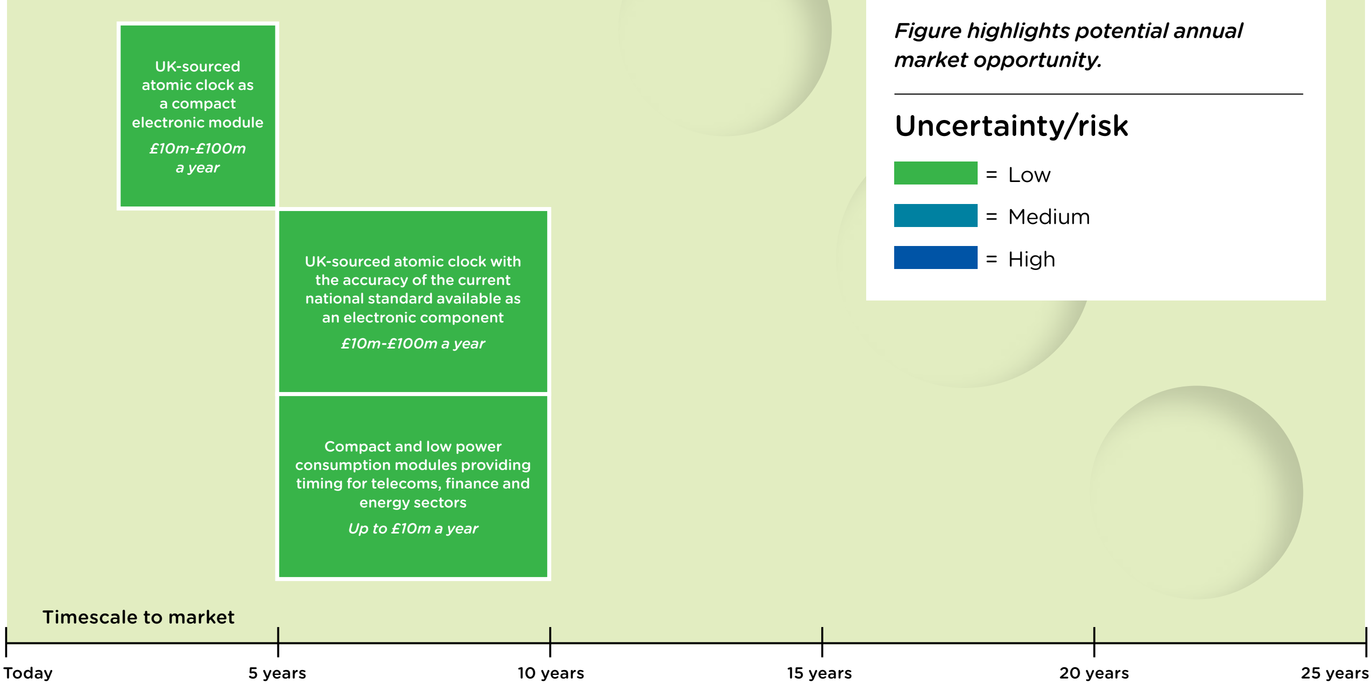
Next-generation atomic clocks and secure quantum communication systems are expected to emerge in the next 5 years and will enable accurate timing and navigation devices for defence, telecommunications, and finance industries [7]. In many of these cases, timing currently comes from global positioning satellite (GPS) signals. A study by the Royal Academy of Engineering [8] exposed substantial UK vulnerabilities to intercepted or blocked GPS signals, which, unless mitigated, could have a significant impact on the 7% of the UK economy that is currently dependent on GPS.

The UK atomic clocks roadmap foresees devices that are globally competitive in 3 years. Second-generation clocks, such as cold-atom or lattice clocks with equivalent accuracy to current national primary standard clocks, can be realised in 5-10 years.

The short-term market for these technologies will be in more durable navigation devices for defence and aerospace (impacting the $26 billion market for GPS navigation devices [9]), resilient telecommunication infrastructure with increased data capacity, research and for time-stamping of financial transactions.

For example, it is widely reported that next-generation 5G telecommunications networks, which are expected to be rolled out in 2020 will require coordination between base stations [10]. Localised timing devices accurate to within 500ns of UTC will be needed to provide hold-over for up to 2 days if they lose connection to a GPS fix. Currently, only expensive Caesium clocks achieve the required specifications. Quantum devices offer cost reductions that will allow them to be made for less than £500 – the benchmark for initial uptake by telecommunications suppliers. Based on these assumptions, the market for quantum timing devices is expected to become a £100 million in 5-10 years, growing to a multi-hundred-million-pound market in 10-20 years.

Figure 2: Roadmap for UK atomic clocks



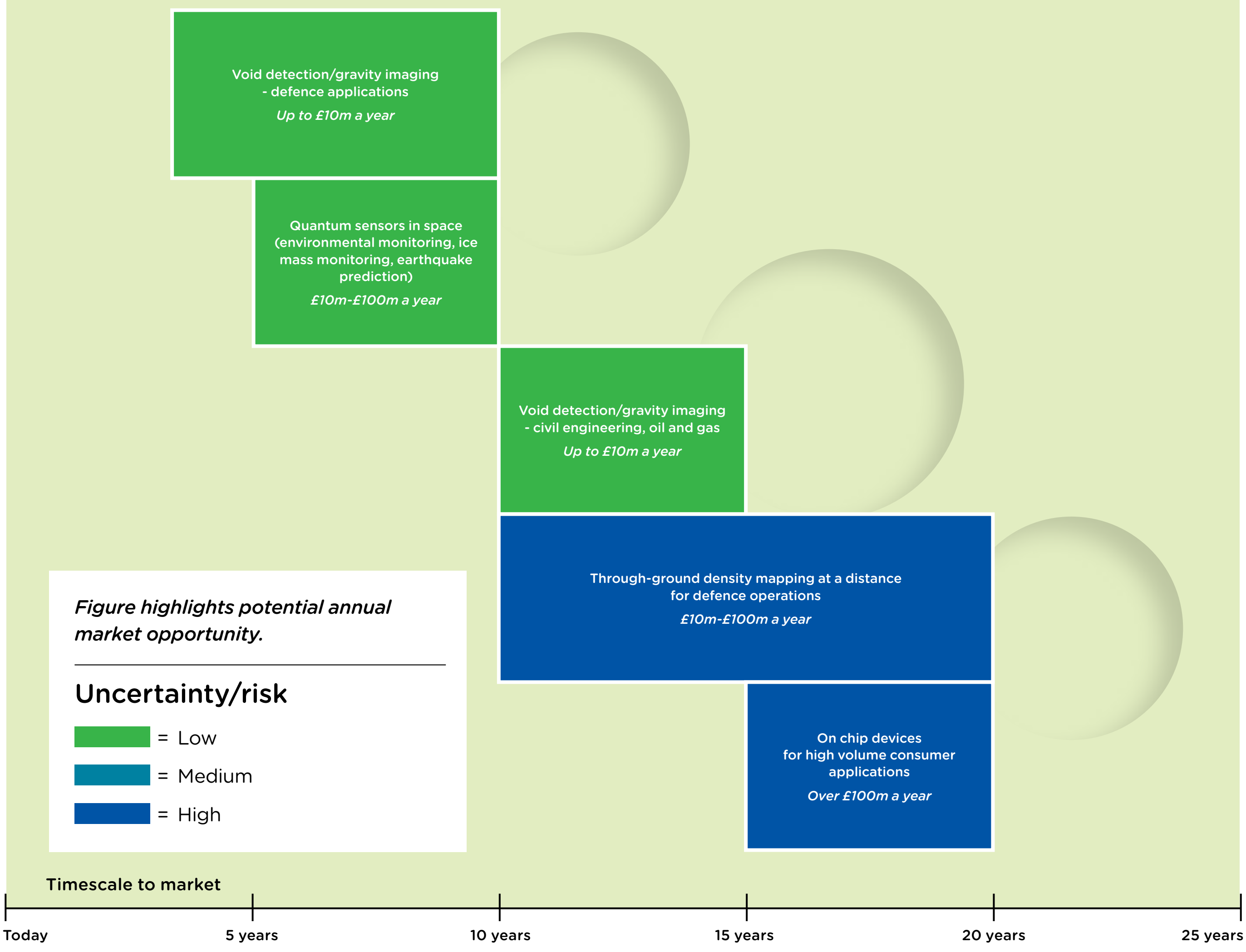
Roadmap for quantum sensors – through-ground imagers, gravity mapping and electromagnetic sensors

Over the next 10 years, quantum gravity field and gradient sensors will be developed. They can be used to build a 3D map of the density of material around them and will have a significant impact on the world's construction and oil and gas sectors.

The trend towards urban dwelling means more building on brownfield sites or in areas of existing infrastructure. Legacy infrastructure hidden below the ground and forgotten imposes a substantial cost: 60% of holes dug to access existing infrastructure are in the wrong place. Gravity sensors will also significantly impact the £318 million market for remote sensing technologies for oil, gas and mineral exploration [11] for the discovery of new reserves, and for the efficient extraction from existing reserves [12]. For example, quantum technologies may allow companies to monitor the movement of oil and water underground during extraction. This may make it easier to use novel techniques to more efficiently extract oil from difficult environments. There is already competition in this field and evidence that testing of quantum gravity mapping devices is already underway in the US [13].

In the long term, quantum sensors may be used for neuroscience and the interpretation of electrical signals from the brain. Although still a long way from a complete understanding of brain function, researchers are starting to map some electromagnetic signatures into movement [14]. Much of this research has been conducted using electromagnetic implants into the brain, which have a finite lifetime. Quantum electromagnetic sensors may allow these signals to be measured outside the body and offer a high level of precision. Their compact size would allow for multiple sensors around the head, and they could offer improved noise rejection and signal interpretation. An early market for quantum magnetic sensors may be for gesture recognition in computer gaming, a market that is estimated to grow to $23.5 billion by 2020 [15].

Figure 3: Roadmap for quantum sensors

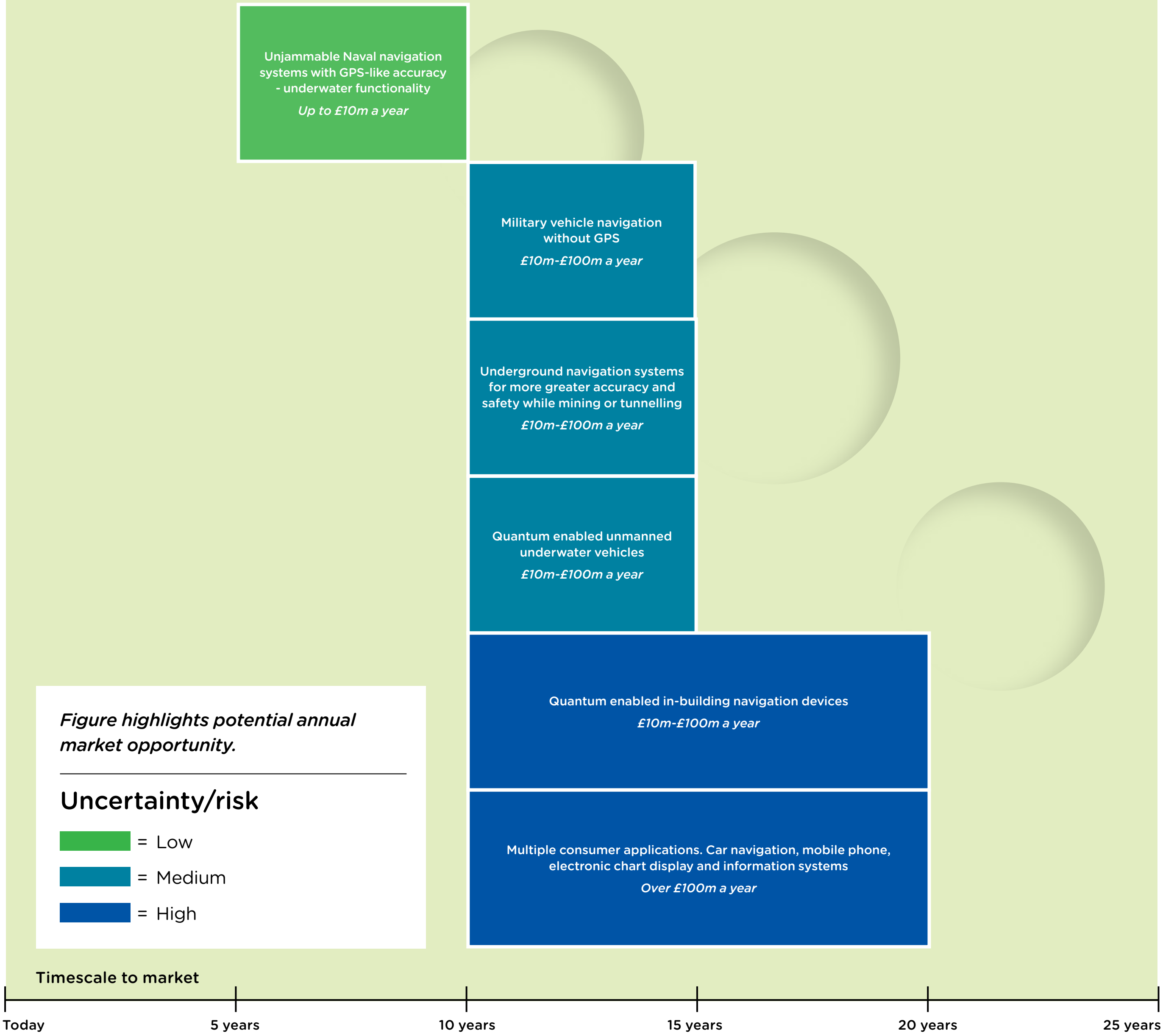


Roadmap for quantum inertial sensors

Quantum inertial measurement units (IMU) are expected to arise between 5 and 10 years from now and to offer a thousand-fold improvement on existing IMUs. They will allow a more versatile and more durable alternative to navigation by GPS.

Between 2018 and 2030, the defence and aerospace industry is expected to provide an initial market for new quantum navigation systems for use where satellite navigation systems are impractical. They could be used in submersibles, for precision navigation for robotics in buildings, underground or in other situations where artificial denial of GPS may be an issue. The market for accelerometers, gyros and IMU sensors was $5 billion in 2012 [16] and is an area where quantum technologies are expected to have a major impact.

Figure 4: Roadmap for quantum inertial sensors



Roadmap for quantum communications

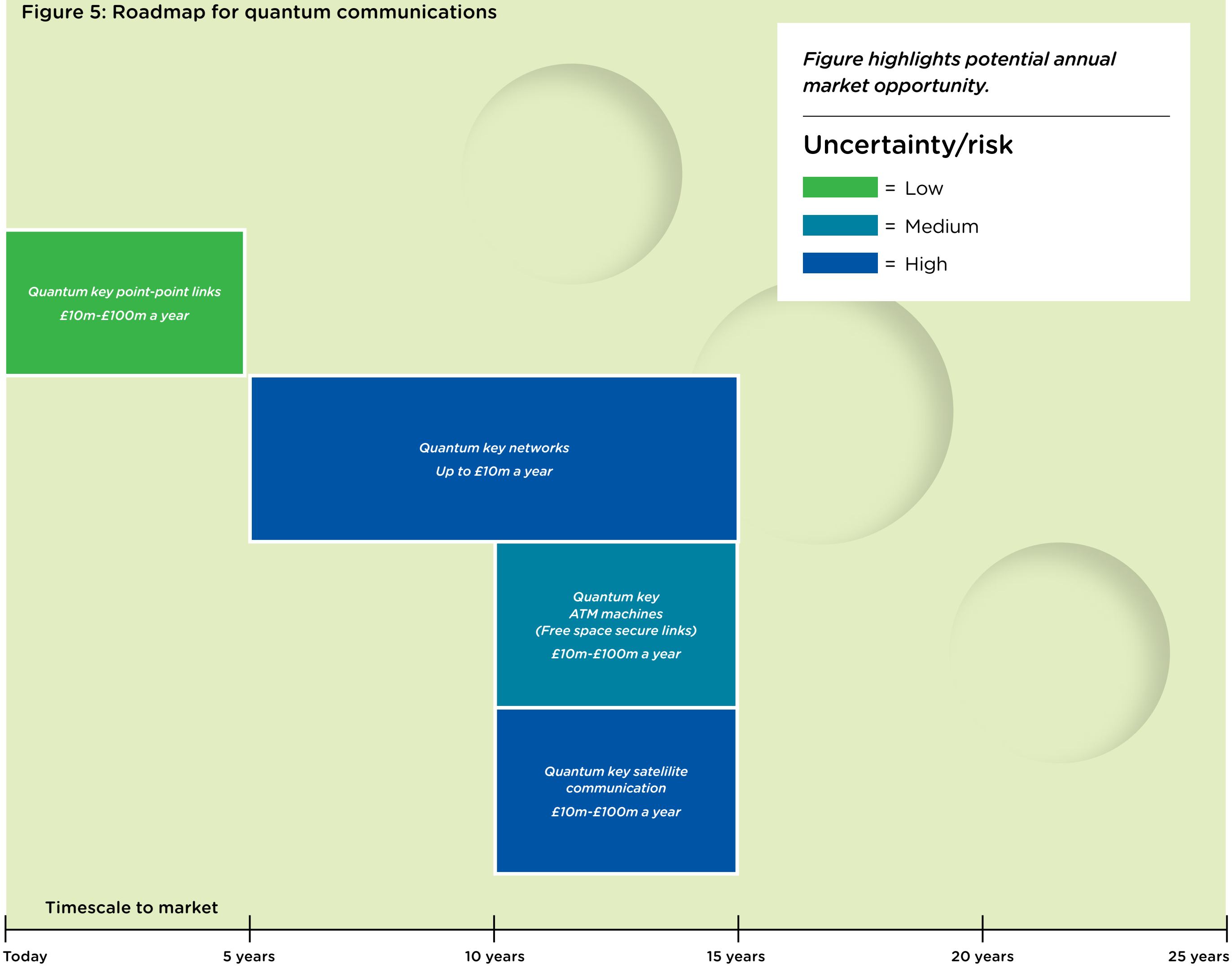
Public key cryptographic systems are based on the assumed difficulty of certain mathematical operations. Currently deployed systems rely on the hardness of mathematical operations, such as factorising large numbers, that will be vulnerable to quantum computing. As crypto systems can take many years to roll out, it is important that we start to implement "quantum-safe" cryptography as soon as possible. The options for replacement include quantum-safe public key cryptography (QSPKC), which relies on mathematical assumptions, and/or quantum-technology-enabled key distribution (QKD), which is secured by the fundamental laws of quantum physics. An appropriate blend of these two distinct kinds of cryptography is expected to make it possible to ensure the safety of communications now, and in the future, for the ongoing protection of sensitive transmissions of data.

Prototypes of point-to-point quantum encryption equipment are already available, and commercial uptake is expected to occur over the next 0-5 years.

Passing quantum signals through existing optical fibre networks is still a challenge, however, due to the extreme intensity contrast between quantum and conventional signals and the high loss of optical switches used in networks. The first generation of devices is therefore likely to operate over point-to-point links of up to 200-300km in length, and be applied to mission critical links in the defence, government, healthcare, financial or corporate sectors. Secure networks, linking offices or telecommunications switching stations over a larger geographical area, will be possible in the medium term. In the long term, global quantum communications may be enabled by fibre optic quantum repeaters or by using satellites.

Standardisation and regulation is expected to play an important role in delivering confidence in quantum encryption for customers.

Figure 5: Roadmap for quantum communications

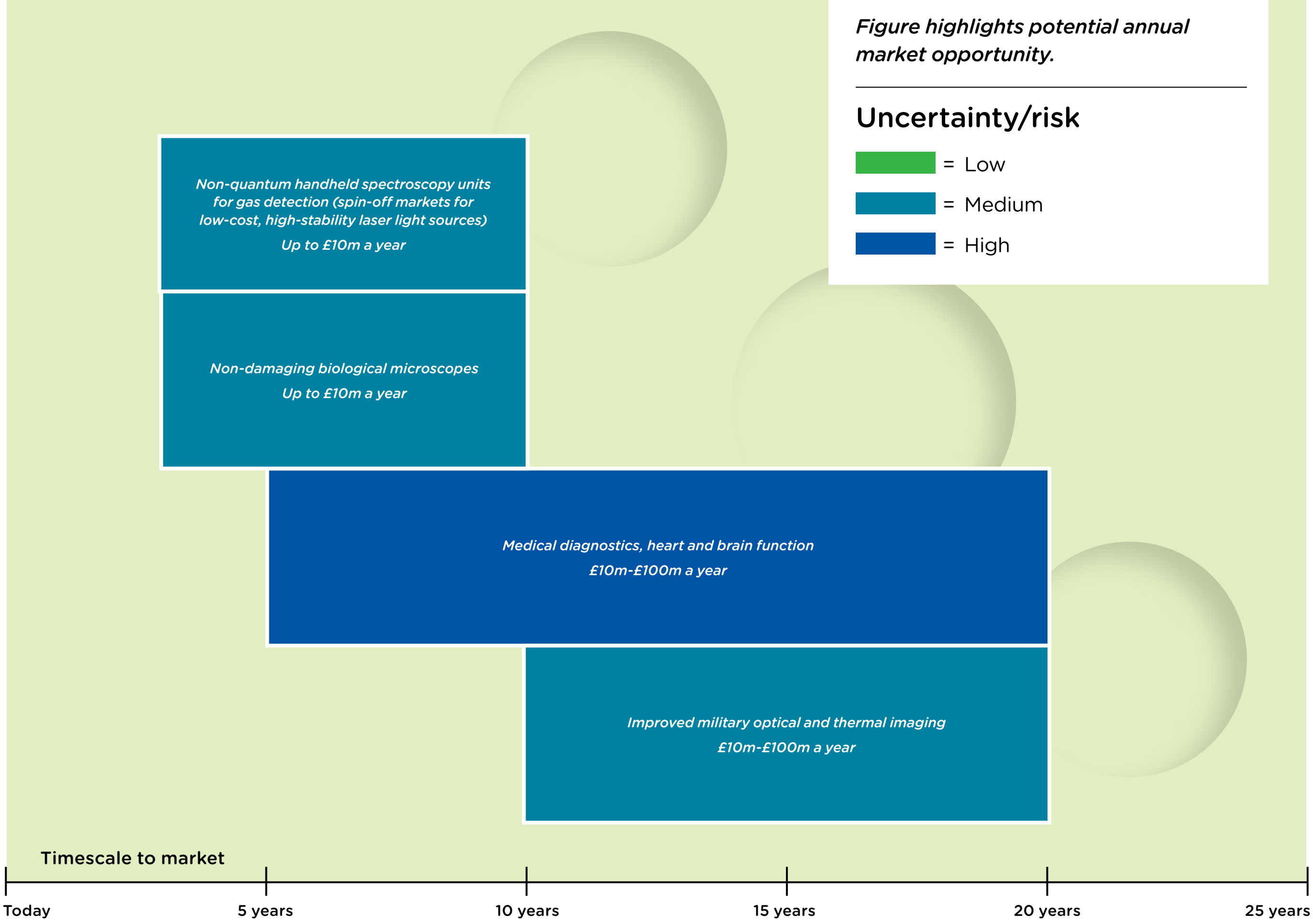


Roadmap for quantum enhanced imaging

Quantum enhanced imaging systems are expected to provide new opportunities in areas such as imaging and range finding in low light, or low-cost multi-spectral imaging technologies.

Applications are expected within 5 years for scientific devices such as microscopes and telescopes, in defence, and in environmental monitoring. Quantum enhanced imaging could have applications for medical imaging devices within 5-10 years once the regulatory approval is acquired.

Figure 6: Roadmap for quantum enhanced imaging

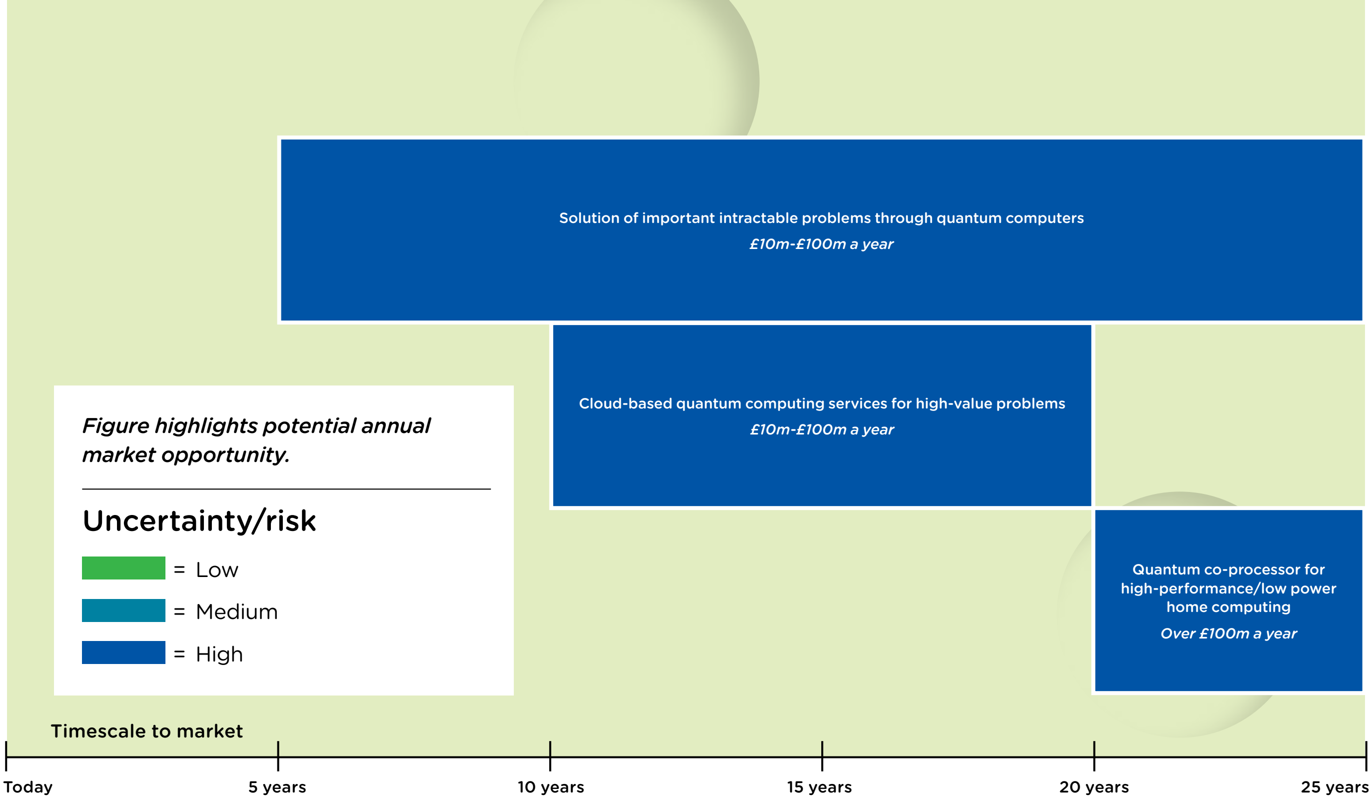


Roadmap for quantum computers

Quantum computers could have a very high impact, but outside a few small, very niche applications or the possibility of an unexpected technology breakthrough, it is expected to be 10-20 years before commercial solutions are widely available. These computers store information using quantum bits, or qubits, which have been theoretically proven to process certain types of problems and information more effectively than a digital computer. This offers a new and powerful method of solving problems or tackling large-scale challenges that conventional computers struggle with. Examples include machine learning algorithms, including image recognition, optimisation such as for maximising the return from a financial portfolio or for the movement of goods in a network, number factorisation and mathematical problem solving such as large simultaneous equations.

Some degree of standardisation is needed to enable more focused research into quantum computers and to aid uptake and understanding by companies. This should recognise and allow comparison between the different types of qubit, and the parameters that describe them, such as number of qubits, correlation, and coherence time.

Figure 7: Roadmap for quantum computers



Potential markets for quantum devices

Quantum technologies for defence

The UK Defence, Science and Technology Laboratories (Dstl) published a UK Quantum Technology Landscape document in February 2014. It outlined the key application areas they saw as potentially important to defence in the next 3-10 years. The review suggested four applications for further study: quantum clocks, quantum communications, quantum sensors, and quantum simulation. It also mentioned computing and a further suite of underpinning and enabling technologies such as molecular and solid state advances with potential economic or societal significance.

Dstl's Knowledge, Innovation and Futures Enterprise group (KnIFE) are currently funding projects to produce demonstrators for:

- quantum-enabled clocks
- quantum navigators
- quantum gravity imaging device

The market for these devices has been assessed at £10 million a year to the UK in 2020, growing to £100 million a year worldwide.

Quantum technologies for space

Both optical atomic clocks and atom interferometers are cross-cutting technologies with applications in many areas of the space industry. These include earth observation of ocean circulation; earthquake monitoring; earth and extra-terrestrial measurement of gravitational and magnetic fields; navigation (particularly in deep space); secure and high-throughput telecommunications; and fundamental physics, such as tests of general relativity.

Current missions driving the development of atomic clocks within Europe are the ACES mission (Atomic Clock Ensemble in Space) planned for launch to the International Space Station in 2016, and the navigation payloads for the Galileo satellite constellation. European Space Agency (ESA) is currently planning a future gravity mission using cold atom interferometry to achieve a gravity field recovery; this is expected to deliver a tenfold improvement in performance compared to its previous Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite (2009 – 2013).

Galileo satellites will drive the development of 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."

The National Strategy for Quantum Technologies

The existing foundation

The UK has an extraordinary foundation of quantum science. The national quantum technologies programme will use UK strengths in companies, universities and the public sector as a foundation for growth. This will create an anchor of skilled and technical people, facilities and investment that are difficult to re-locate, ensuring that the benefits to the UK are long-lived.

In order to begin the transition from science to technology and to build clusters of activity with industry, EPSRC has invested £120 million in a national network of quantum technology hubs. These are led by the universities of Birmingham, Glasgow, York and Oxford.

UK Quantum Technology Hub for Sensors and Metrology

UK National Quantum Technology Hub in Sensors and Metrology

This hub is led by the University of Birmingham and focuses on sensors and metrology. It will use cold atoms to develop quantum gravity sensors, magnetic sensors, precision rotation sensors and imaging systems. Fundamentally, this hub will seek to develop a full supply chain for these new technologies, and will work closely with industry partners to develop components such as advanced optical components, cold-atom systems, and packaging and enclosures. The hub is expected to produce demonstrator gravity sensors that it will test at dedicated facilities in Birmingham.

Quantum Hub in Quantum Enhanced Imaging (QuantIC)

QUANTIC

This hub is led by the University of Glasgow and specialises in quantum-enhanced imaging. It will use quantum correlations, entanglement and timing to create images using novel methods. This will include imaging using very low light levels to allow imaging of objects "hidden" out of line of sight, improved resolution imaging using quantum correlations, imaging using only a small number of photons and "stealth" imaging. Quantum effects will also be used to extract images from noisy signals. The hub will look to develop the supply chain for these devices, and will work on the development of underpinning technologies such as single photon sources and detector arrays, micro-electro-mechanical systems (MEMS) and nano-electro-mechanical systems (NEMS) technologies.

Quantum Hub for Networked Quantum Information Technologies (NQIT)

This hub is led by the University of Oxford and specialises in networked quantum information technologies, including quantum computing. It will look to develop an architecture known as '20:20', a modular network of 20 by 20 ion traps, connected by photonic links. These modular devices can be configured individually, so that the individual node acts as a sensor, or with multiple nodes, to form a re-configurable quantum computer system. It will also look to use early generations of the 20:20 architecture to develop devices such as a chemical nose, random number generators, and quantum cryptography range extenders.

Quantum Hub for Quantum Communications

This hub is led by the University of York and will deliver a range of practical, real-world quantum-protected communications systems for a range of applications, from high-value financial transactions to everyday consumer applications. The core capability will be a range of quantum key distribution (QKD) technologies, including those operating over optical fibre and free space links systems. It will build a large-scale quantum network in the UK, connecting quantum metro networks in Cambridge and Bristol with a long-distance quantum secure link. It will also develop next-generation quantum communication technology, such as measurement-device-independent QKD and systems for quantum digital signatures.

Other foundations in the UK

The UK 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 optics, electronics, nano-fabrication and vacuum systems.

The national programme has support from a number of public bodies: Innovate UK and EPSRC, which are able to provide funding for innovation work within companies and academia; the UK MOD, which has identified a need for quantum devices, and has demonstrator projects underway; the NPL with its new centre for quantum standardisation and metrology; and GCHQ. This group has agreed to work together to achieve the stated objectives of the quantum technologies programme. In time, it will look to bring in other public sector bodies, such as the UK Space Agency, the European Space Agency, the NHS and the Home Office to help with identification of new opportunities and to act as a first adopter through schemes such as SBRI (Small Business Research Initiative).

Encouraging exploitation of existing 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."

The National Strategy for Quantum Technologies

Developing an ecosystem for innovation

The creation, and continued support, of a solid foundation of science is essential to allow for a full pipeline of new and future technologies to feed commercial exploitation in later years. This fundamental research should be strongly linked to exploitation efforts, looking to present solutions to exploitation and implementation. Academia must look to provide the same level of support to entrepreneurial individuals trying to exploit technology as it does to individuals involved in exploratory, fundamental research.

Companies also need support in adapting to new market opportunities, re-directing efforts, and employing people with new skills. Each of the quantum hubs is investing in incubator spaces for new businesses, and public funding will be available to develop the facilities – such as in nano-fabrication and high-value electronic production – that companies can use to develop these new devices. It is vital these companies are given the necessary support and advice to produce compelling business cases and strategies for investment in quantum. The national programme will look to support researchers and other individuals with commercially important intellectual property, to help them to form spin-out companies.

Protecting intellectual property

The UK quantum technologies programme will help UK companies and academics to develop intellectual property through patenting, trade secrets and know-how. It will support collaborative work between researchers and individuals who are looking to develop intellectual property and exploit technology, and will work with quantum hubs and other academic and research organisations to support the validation of ideas and, where necessary, production of patents.

Connecting people

The complexity of early quantum technology devices means that most companies will be unlikely to possess all of the knowledge, expertise or facilities needed to deliver a whole quantum system. The quantum programme will support collaborations between companies, academics and facilities providers that develop the chain that supplies components into higher level systems integration companies. The programme will look to draw in potential customers and companies supplying devices or services to ensure an efficient and responsive development process. Those researching or commercialising future technology should be flexible and able to adapt to new ideas and new directions in order to produce research and devices well suited to the needs of an identified end user.

The Knowledge Transfer Network and the Quantum Technologies Special Interest Group.

The Knowledge Transfer Network's (KTN) Quantum Technologies Special Interest Group (QT SIG) and quantum technologies steering group will play a key role as a connector and mediator. The QT SIG was set up by the KTN to further exploit quantum technologies by increasing awareness among potential users and by connecting markets to suppliers.

It will provide relevant information and publicise forthcoming events (**https://connect.innovateuk.org/web/quantum-technology**).

The QT SIG allows industry and academics to share their views through an advisory group of 10 people. It will advise on and coordinate early commercial activities for quantum technologies, both within and outside the national quantum technologies programme.

Growing a skilled UK workforce in quantum technologies

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

National Strategy for Quantum Technologies

The UK must have access to skilled people who can develop one-off demonstrators and prototype devices into ones that can be manufactured. The quantum technology programme will support initiatives that create the maintenance, support and business models needed to make those devices profitable.

An expert quantum resource

Ensuring industry is familiar with the possibilities of quantum research will be increasingly important as technologies develop. The national programme will look to fund programmes that ensure a workforce with the right skills is available to companies as they seek to exploit these opportunities.

Both industry and academia must play a role in training. Industry should be encouraged to work with the public sector and universities to define the skills and knowledge required, offer secondments and take part in knowledge transfer. Academia must be responsive and accommodating to the needs of industry when developing the relevant courses.

The skills needed will be wider than can be provided solely through university physics departments. They will include engineering, systems and production engineering, business and entrepreneurship. A focus on building demonstrator systems using the existing industrial supply chains will help to develop the skills needed for successful engineering and later scale-up of manufacture.

Our training programmes will not be limited to students and early stage researchers, but will extend to qualified people who are looking to adapt to new jobs and roles in quantum. This could be achieved, for example, by providing short courses for industrialists, and non-technical introductory training that can inform and excite director-level decision-makers about the opportunities and risks of quantum technologies.

Multidisciplinary training

There are many existing providers already responding to the requests for skills training. These include centres of doctoral training (CDTs), the Dstl PhD training scheme, universities and the EPSRC training and skills hubs.

Recruitment of other disciplines alongside physics is a common aim across all the centres for doctoral training. They have already started to train individuals in this multidisciplinary and flexible way.

Centres of doctoral training

Three centres of doctoral training directly relevant to quantum technologies (many more are indirectly relevant) have been set up:

- controlled quantum dynamics, Imperial College London
- quantum engineering, University of Bristol
- delivering quantum technologies, University College London

These centres are pivotal in the training and development of the people who will deliver the future quantum technologies industry. They will be well integrated into the exploitation work of the quantum hub network and into the work of industry partners to ensure relevant, hands-on experience for new trainees.

Publicity and media coverage

The quantum technologies community must pursue a consistent and inspiring message with media organisations to ensure public awareness and understanding develops in parallel with the technology. The quantum technologies programme and the quantum hubs will work with the media to grow awareness of the programme worldwide.

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"

National Strategy for Quantum Technologies

Regulatory and standards development

Standards are a useful enabler of future technology development, giving confidence and commonality in an emerging market that can be recognised internationally by all parts of the supply chain. The national quantum technologies programme will work to ensure that standards are developed at an appropriate pace and used appropriately to facilitate uptake of new technologies.

The experience and connections of the NPL will be pivotal to delivering standards. A new quantum centre for metrology and standardisation will be developed as a go-to place for industry and academia to test, compare, and standardise new quantum technologies.

Introducing standards for many applications of quantum technologies will be crucial to delivering significant market uptake, helping to develop markers for proof of quality (such as reliability and consistency) and interoperability with existing infrastructure, systems and components. This will allow non-technical people to use devices with trusted performance or operation.

It is important to correctly judge the timing for the introduction of new standards. A large and prescriptive standard applied too early can stifle competition and innovation. Standardisation applied at the right time, however, can create a world-leading environment to develop new, innovative devices that will draw businesses to the UK.

The first wave of quantum products expected to require standardisation are precision timekeeping and secure communications [17]. Here, standardisation will be of particular and immediate importance to assure performance against other incumbent products and existing protocols.

The key steps in the uptake of standardisation are:

- identification of existing standards to understand the current regulations that may apply to a new technology or application
- early collaboration to ensure product developers construct devices compatible with one another, and they agree and share similar or comparable performance metrics
- consultation with relevant stakeholders to better understand whether there is a need for a standard, when it should be introduced and what the scope of the standard should be, including how the standard will be measured and tested
- development of and access to the technical capabilities and facilities required to validate and verify performance, safety, quality and lifetime
- dissemination to ensure standards can be used effectively by UK stakeholders, including training, secondments, best-practice guides and protocols
- fast-tracking UK standards into international standards to gain market position and competitive advantage for the UK and establishing UK standards bodies as the leaders

Responsible research and innovation

It has been well reported that the general public are largely unaware of the developments in quantum technology [18]. However, there is anecdotal evidence to suggest the public are excited about the meaning and the concept of the new technology. The quantum technologies programme will work to guide the development of the technology so that it does not cause a negative reaction amongst the public.

Responsible research and innovation (RRI) is key to shaping public understanding of quantum technologies by promoting 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.

An open and transparent framework will be developed that allows the political and social impacts to be widely discussed. These discussions can address potential points of conflict and ambivalence before they become major issues [19]. The UK will produce the first comprehensive public perspective on quantum technology and develop a bespoke framework and effective governance structure to guide the development of public attitudes to new technologies. This framework will incorporate the EPSRC guidelines for responsible innovation, which ask researchers to anticipate, reflect, engage and act [20].

Maximising UK benefit through international engagement

"The UK is not alone in recognising the potential value of quantum technologies. However, there is an opportunity for the UK to be the global leader and a 'go-to' place for quantum technologies."

National Strategy for Quantum Technologies

The UK is not alone in having identified quantum technologies as a future global growth area. Other countries, such as the USA, China and the Netherlands (figure 8) have launched similar investment programmes. Working on the international stage will help to reinforce the UK lead in quantum technologies. It will give the UK access to:

- the best talent from around the world
- new markets and opportunities
- missing skills or capabilities
- the opportunity to set standards and regulations for the world
- opportunities for inward investment, or other sources of funding

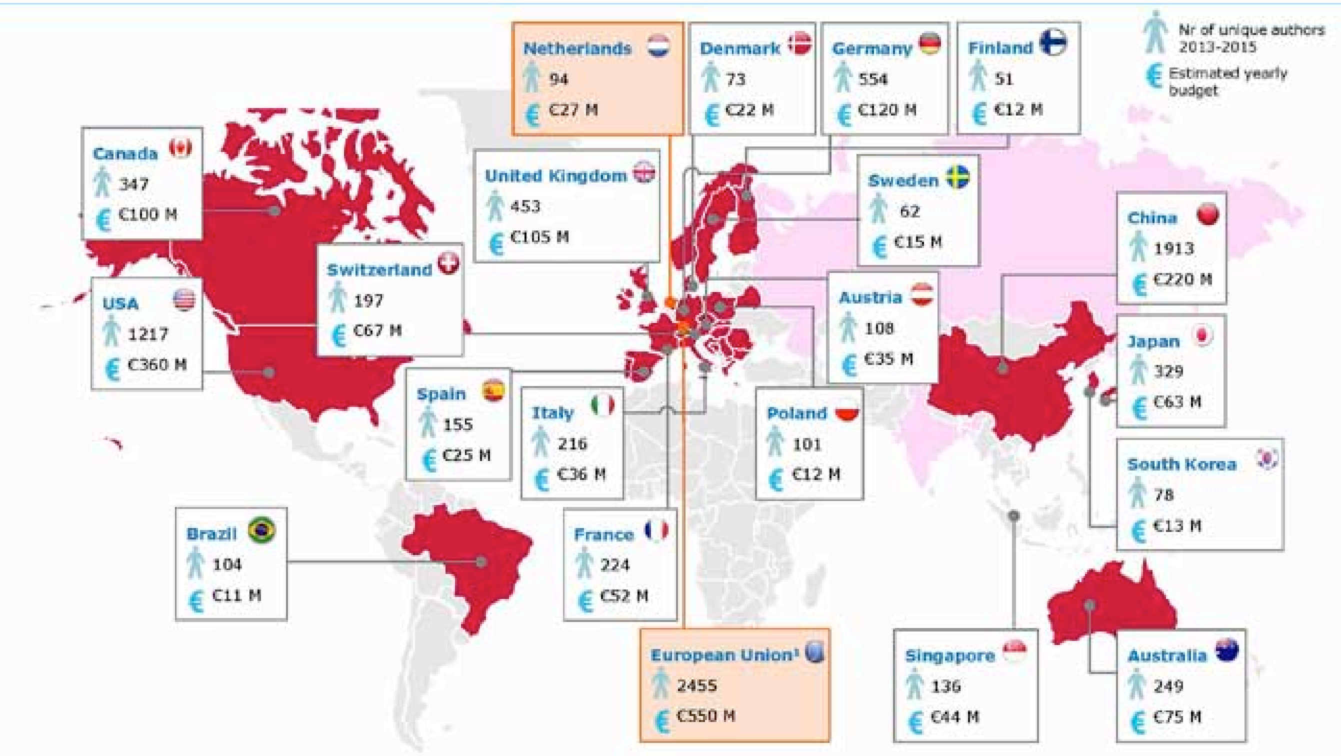


Figure 8: World map of quantum technologies activities showing spend on research and estimated number of researchers. Image courtesy of the Ministry of Economic Affairs, Netherlands 2015.

Preserving the UK advantage

It is widely acknowledged that the UK approach of supporting close co-working between industry and academia to develop devices for multiple sectors is unique. The national programme will take advantage of this head start and work to create an environment that draws companies and innovative people to the UK to do business, while looking to achieve a lead in this large and promising future global industry.

We will:

- use our investment to create an environment that motivates UK and international companies to do business in the UK, including creating incubation spaces and offering public funding to de-risk developments
- ensure that our intellectual property is protected through patents, trade secrets or non-disclosure agreements
- grow a global industry for quantum technologies while also preserving our own advantage through a full understanding of the opportunities and risks in each collaboration, before we proceed

Export controls

We must take care that export controls do not have an impact on the success of the UK quantum technologies programme. The US is already a well-established player in quantum research and atomic clock manufacture, and is expected to apply extra-territorial export restrictions, such as International Traffic in Arms regulations (ITAR), to systems and components that incorporate its intellectual property.

Similarly, the UK may impose export controls [21] on new devices. A list of items that may be subject to restrictions is available from the Department for Business, Innovation and Skills [22].

References

1 Semiconductor Industry Association (SIA) 2014. *The U.S. Semiconductor Industry – 2014 Factbook.*

2 OPEC 2014. *OPEC Annual Statistical Bulletin 2014.*

3 UK National Quantum Technologies Programme 2015. *National strategy for quantum technologies* [www.gov.uk/government/publications/national-strategy-for-quantum-technologies]

4 Dutch Ministry for Economic Affairs

5 BCC Research 2013 *Global Markets and Technologies for Photonic Crystals.*

6 MarketsandMarkets [www.marketsandmarkets.com/PressReleases/molecular-spectroscopy.asp]

7 Symmetricom Inc, *2012 Annual Report.*

8 Royal Academy of Engineering 2011, *Global Navigation Space Systems: reliance and vulnerabilities.*

9 MarketsandMarkets [www.marketsandmarkets.com/PressReleases/gps.asp]

10 *Ericsson Business Review,* Issue 2, 2013 [www.ericsson.com/res/thecompany/docs/publications/business-review/2013/5g-signals.pdf]

11 BCC Research 2013, *Remote Sensing Technologies and Global Markets.*

12 Halliburton, *Enhanced Oil Recovery to Maximize Economic Value,* [www.halliburton.com/en-US/ps/consulting/enhanced-oil-recovery.page?node-id=hkv12s6e]

13 [www.navy.mil/navydata/cno/n87/usw/winter99/waterfront.htm]

14 MIT Technology Review [www.technologyreview.com/featuredstory/528141/the-thought-experiment/]

15 MarketsandMarkets [www.marketsandmarkets.com/PressReleases/touchless-sensing-gesturing.asp]

16 Frost and Sullivan 2013, *Global Accelerometers, Gyroscopes and IMU Sensor Markets.*

17 European Telecommunications Standards Institute 2014, *ETSI Work Programme 2014-2015.*

18 J. Stilgoe, R. Owen and P. Macnaghten 2013, *Developing a framework for responsible innovation,* Research Policy, vol. 42 [1568-1580].

19 G. Eden, M. Jirotka and B. Stahl 2013, *Responsible Research and Innovation: Critical reflection into the potential social consequences of ICT,* Research Challenges in Information Science (RCIS) 7th International Conference, 2013.

20 EPSRC Framework for Responsible Innovation [www.epsrc.ac.uk/index.cfm/research/framework/]

21 [www.gov.uk/beginners-guide-to-export-controls]

22 Department for Business, Innovation and Skills 2015, *UK strategic export control lists: consolidated list of strategic military and dual-use items that require export authorisation,* [www.gov.uk/government/uploads/system/uploads/attachment_data/file/422364/controllist20150417.pdf]

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

September 2015 CO004