UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

National strategy for quantum technologies

A NEW ERA FOR THE UK

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

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

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

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

Professor David Delpy
Chair, Quantum Technologies Strategic Advisory Board

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Quantum technologies: a new era for the UK

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

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

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

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

A national vision and strategy

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

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

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

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

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

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

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

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

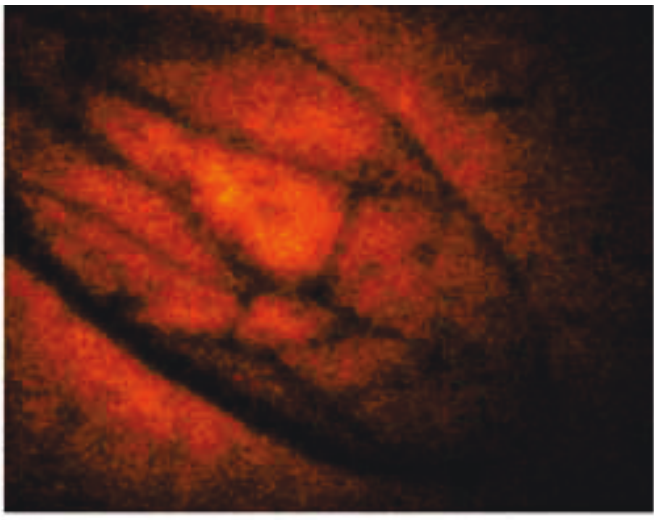
The current investment is the first step towards rooting a quantum technologies industry in the UK, creating environments and skills for early innovation and product development. Subsequent investment will secure this foothold and stimulate growth of the emerging industry, ensuring a pipeline of new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

Our strategy for quantum technologies

What are quantum technologies?

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

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



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

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

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

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

RECOMMENDATIONS

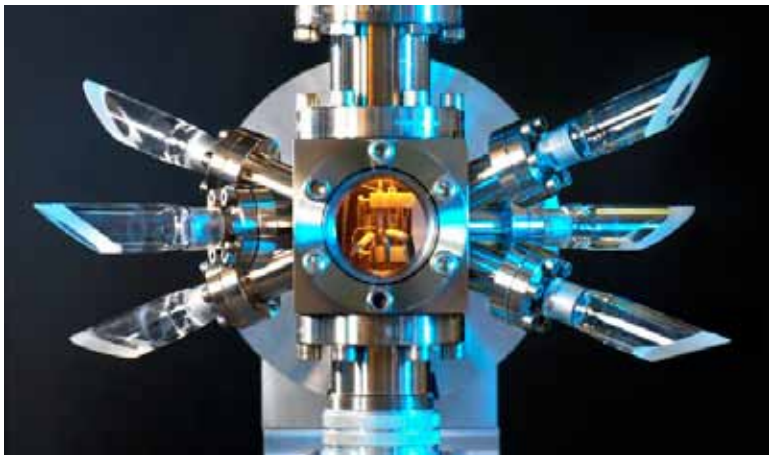
The UK must:

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

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

Quantum-enabled clocks for 5G, finance and navigation

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



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

Enabling a strong foundation of capability in the UK

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

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

The existing foundation

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

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

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

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

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

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

The UK construction industry could benefit greatly from quantum technologies

Encouraging exploitation of existing investment

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

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

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

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

Helping the construction industry

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

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

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

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

Developing and maintaining an open infrastructure

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

RECOMMENDATIONS

The UK must:

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

Stimulating application and market opportunities

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

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

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

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

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

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

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

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

RECOMMENDATION

The UK must:

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

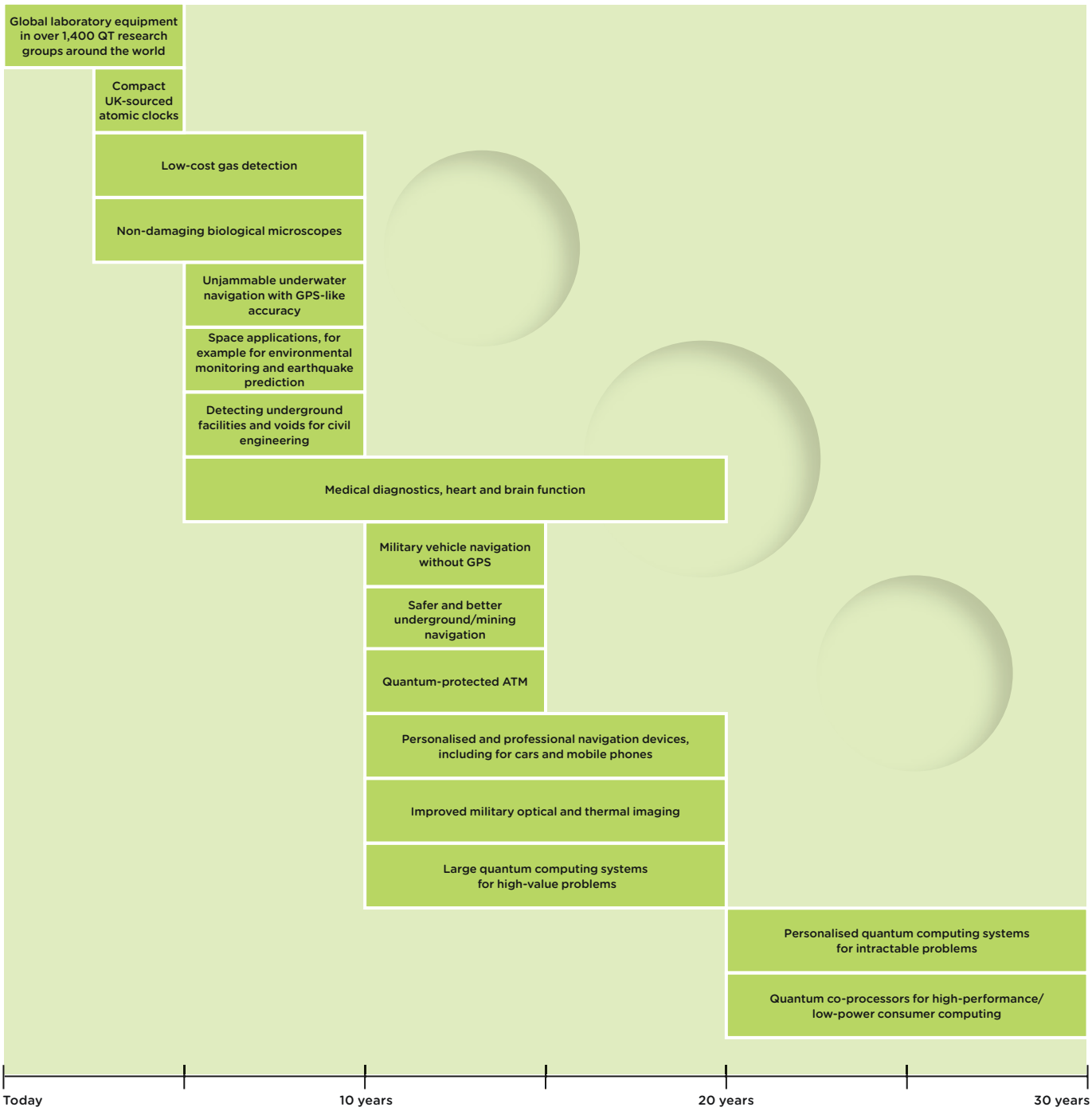
In order to have practical application, the new quantum technology devices will have to be integrated into systems. An immediate challenge for the new quantum industry is to move to a point where use of quantum devices does not require specialist knowledge or training and where the inherent quantum 'strangeness'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

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

Quantum navigation has great potential

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

Future commercial uses for quantum technologies



Estimated time to commercial prototype

Growing a skilled UK workforce in quantum technologies

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

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

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

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

Co-working is key to our success

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

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

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

RECOMMENDATIONS

The UK must:

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

Quantum technologies could transform computing

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

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

Creating the right social and regulatory context

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

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

Responsible research and innovation

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

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

Regulatory and standards development

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

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

RECOMMENDATION

The UK must:

- drive effective regulation and standards and champion responsible innovation

Tackling internet fraud

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

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

Quantum technology could make buying over the internet much safer

Maximising UK benefit through international engagement

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

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

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

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

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

RECOMMENDATION

The UK must:

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

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