



UK NATIONAL  
QUANTUM  
TECHNOLOGIES  
PROGRAMME

# Delivering the National Strategy for Quantum Technologies

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Since the announcement of the UK National Quantum Technologies Programme in December 2013 the government's £270 million investment in this ambitious initiative is already bearing fruit on many levels, including the development of products on the cusp of commercial launch.

The key partners in the programme – EPSRC, Innovate UK, BEIS, National Physical Laboratory, GCHQ, the Defence Science and Technology Laboratory (Dstl) and the Knowledge Transfer Network – enjoy a strong and supportive working partnership that has fostered a growing interdependent network of research and innovation between UK universities, leading international companies and the country's dynamic and growing industrial base in quantum technologies, including SMEs and large established primes.

Driven by the challenges set out in the National Strategy for Quantum Technologies, the outputs from the programme are steadily increasing, and they are being realised through a multi-faceted combination of research and technology, innovation, knowledge transfer, skills and capital equipment.

Civil engineers are working with physicists to create quantum sensors that can map our underground utilities and infrastructure; PhD students are driving commercial R&D collaborations with UK and international partners; state-of-the-art laboratories are being created to enable frontier research in this field; and UK scientists, engineers and industrialists are taking the lead in translating our strong science base and developing the vital standards and regulatory framework the world needs for quantum technologies and their applications.

The four Quantum Technology Hubs, which involves at least 17 UK universities as well as leading UK and international companies and SMEs, are now well established as part of an integrated national programme, and are taking a global lead in the development of technologies for quantum communications, quantum computing, quantum enhanced imaging, and quantum sensing and metrology.

Perhaps the most significant progress, however, comes from our investment in people, and in the next generation of scientists and engineers, and it is pleasing that many of the world's most talented young individuals are working here in the UK, and making major contributions to the UK National Quantum Technologies Programme.

Under the programme, a £49 million investment in training and skills has already seen the creation of three EPSRC Centres for Doctoral Training in Quantum Technologies; three Training and Skills Hubs in Quantum Systems Engineering and 14 Quantum Technologies Fellowships awarded to international research leaders whose work will complement the investments connected to the National Programme.

Dstl has also contributed a further £30 million which currently supports 46 studentships and a series of major quantum demonstrator programmes.

Pushing the boundaries of knowledge and pioneering ways to exploit it provide the bedrock for research and innovation; and this has been complemented by a range of calls and investments by Innovate UK, which, together with industrial partners, is helping to drive research out of the lab and into the marketplace.

Through the UK National Strategy for Quantum Technologies we are making excellent progress because we know where we are going and know how we will get there. Our success to date is demonstrable, as you can see from the case studies and profiles in this brochure. We will continue to build on this success to strengthen the UK's position as a leading nation in quantum technologies.

**Professor David Delpy, Chair,  
Quantum Technologies Strategic Advisory Board**

## Delivering the National Strategy for Quantum Technologies

The UK National Quantum Technologies Programme is championed by the Quantum Technologies Strategic Advisory Board, (QT SAB), set up to provide a visible focus for quantum technologies in the UK and to act as a coordinating body for UK interests.

On behalf of the UK quantum community, the QT SAB published a National Strategy for Quantum Technologies in March 2015 to guide new quantum work and investments over the next 20 years, and to help deliver a profitable, growing and sustainable quantum industry deeply rooted in the UK.

The strategy identifies five areas for further action by the UK:

- Enabling a strong foundation of capability in the UK
- Stimulating applications and market opportunities in the UK
- Growing a skilled UK workforce
- Creating the right social and regulatory context
- Maximising UK benefit through international engagement.

## Enabling a strong foundation of capability in the UK

Building an innovative and high-value UK quantum technologies ecosystem, including a strong capital infrastructure that provides skills, employment and national wealth, requires sustained and continuous government investment, and deeper long-lasting relationships between industry, academia and the public sector. The UK National Quantum Technologies Programme is addressing these challenges through an integrated investment programme:

### Research

- EPSRC has invested £120 million in four university-led quantum technology hubs across 17 universities which, in partnership with industry, are tackling the key technological challenges that need to be overcome to realise the promise of quantum technologies.

### Capital

- NPL has established the Quantum Metrology Institute which provides the measurement expertise and facilities needed to underpin the development of quantum technologies.
- EPSRC's £120 million hub investment includes £50 million of capital infrastructure across the hubs. In addition it has invested £25 million in strategic capital infrastructure at seven universities to enable further development of quantum technologies in the UK.

### Skills

- EPSRC has invested in Centres for Doctoral Training; Training and Skills hubs and Fellowships; and Dstl has invested in 46 studentships at 16 universities (see Growing a skilled workforce).

### Digging Deep

The UK National Quantum Technology Hub in Sensors and Metrology brings together physicists and civil engineers to develop quantum gravity sensors to locate utilities buried underground such as pipelines and cabling without having to excavate.

By exploiting the extreme sensitivity of quantum gravity sensors, engineers will be able to make much more precise maps of sub-ground conditions, and could be a game changer, speeding up the location process one hundred fold and potentially leading to annual savings to the UK economy of several hundreds of millions of pounds. The sensors also have numerous potential applications, such as monitoring water levels in aquifers.

The work builds on two major EPSRC-funded projects led by civil engineers at the University of Birmingham, which made huge strides in the development of a shared multi-sensor platform through the application of technologies such as vibro-acoustics, passive magnetic fields and ground penetrating radar.

Trevor Cross, Chief Technology Officer at project partner e2v, says: "The crucial partnerships formed through the UK National Quantum Technologies Programme will enable us to jointly translate state-of-the-art laboratory technology into commercially viable deployable practical devices."

## Stimulating Application 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.

In order to stimulate application and market opportunities an energetic and integrated academic and industrial community approach is needed. The UK National Quantum Technologies Programme is facilitating this integrated approach through:

### Innovation

- Innovate UK, EPSRC and Dstl supported 20 industry-led feasibility studies and collaborative UK R&D projects in 2015. Innovate UK has also funded extension projects to a number of these and has launched further feasibility and collaborative R&D calls.
- A Quantum Technologies Special Interest Group with over 300 members from a range of sectors has been created by the Knowledge Transfer Network to explore market opportunities and help build vital supply chains to promote a thriving UK industry.
- Dstl has invested in demonstrator programmes in areas such as: gravity imaging and quantum navigation.
- NPL has created NPL Time®, which offers the financial sector a certified precise time signal, directly traceable to Coordinated Universal Time. This allows for transactions to be accurately time-stamped without any reliance on GPS.

### Research

- Flexible partnership resource funding available to the Quantum Technology Hubs has enabled new academic collaborations with industry. Leading companies such as M Squared Lasers have benefited from these collaborations with the hubs (see case study), used to facilitate partnering with industry in line with the development of the technologies.

## Growing a Skilled UK Workforce

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 UK National Quantum Technologies Programme is working with skills providers to help deliver this workforce:

- Dstl has funded 46 studentships at 16 universities.
- EPSRC has three Training and Skills Hubs in Quantum Systems Engineering and three Centres for Doctoral Training with direct relevance to quantum technologies.
- NPL's Quantum Metrology Institute is hosting 37 PhD studentships linked with 14 university partners to add specialist metrology skills to the UK knowledge base.

### The Single Pixel Camera

Researchers at the UK Quantum Technology Hub in Quantum Enhanced Imaging (QuantIC) are developing a camera capable of seeing clearly through smoke, visualising gas leaks and looking for tumours under the skin.

Conventional infrared cameras have millions of pixels; this camera can outperform them with just one. The camera is highly sensitive to single photons, and can be tuned to wavelengths from infrared to X-ray, giving it the potential to provide a low-cost alternative to imaging outside the visible spectrum.

The partnership resource funding available to academics through the hub enabled QuantIC to build on an already successful collaboration with specialist laser company M Squared Lasers. This project is investigating the gas detection performance capabilities of the prototype camera in an industrial setting and has resulted in technology based around the imaging of gas leaks which has important applications in areas such as gas sensing, construction, healthcare and water treatment.

Dr Graeme Malcolm, CEO of M Squared Lasers, says: "QuantIC's approach to industrial collaboration is focused on supporting companies by adding value to their existing products and services. The input from their researchers has been invaluable."

### On Course for Success

Andrew Lamb, a doctoral student at the University of Birmingham, is developing a quantum gravity sensor which one day could be employed in anything from a fighter pilot to an autonomous car.

The Dstl-funded project aims to create a robust and portable quantum sensor capable of measuring two axes of rotation and absolute pointing, and the measurement of gravity, all in a single device. This offers applications in navigation, improving on the performance of current devices and increasing resilience against loss of GPS.

In developing a core system for the sensor, Andrew, with fellow researchers at the UK National Quantum Technologies Hub for Sensors and Metrology, has already drastically improved the portability of cold atom systems, allowing the team to move the technology out of the laboratory.

Andrew says: "Making something with this level of portability has meant developing skills which are not just those of a physicist – but also a strong mix of engineering skills and systems-level thinking – creating a unique skill set required for translating fundamental science into technology. It also creates excellent opportunities for jobs within industry."

## 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 societal and economic opportunities requires early and broad engagement with UK society.

Proactive engagement at an early stage with a wide range of stakeholders will not only enable innovation to be driven responsibly, it will ensure the commercial viability of quantum technologies and facilitate the creation of an effective regulatory and standards regime.

The UK National Quantum Technologies Programme is taking the necessary steps to ensure that research and innovation are carried out responsibly:

- The newly-created Quantum Metrology Institute brings together all of NPL's leading-edge quantum science and metrology research. It provides the expertise and facilities needed for academia and industry to test, validate, and ultimately commercialise new quantum research and technologies.
- The four Quantum Technology Hubs all have responsible research and innovation activities underway and are providing input into a Quantum Technologies Public Dialogue commissioned by EPSRC.

### Vital Standards

ETSI, the European Telecommunications Standards Institute, produces globally-applicable standards for Information and Communications Technologies, including fixed, mobile, broadcast and Internet technologies.

Industry Specification Groups (ISGs) operate alongside their traditional standards-making committees in specific technology areas. ETSI currently has 13 ISGs of which two directly relate to quantum technologies in the areas of Quantum Key Distribution and Quantum-Safe Cryptography.

Andrew Shields (see page six), from Toshiba, a key partner in the UK National Quantum Technologies Programme, chairs the ISG for Quantum Key Distribution, which is leading the way in developing standards for quantum communications. The group is addressing a number of issues integral to the commercialisation of quantum cryptography, such as interoperability with other equipment used in the network and ensuring that the technology is implemented securely.

Andrew says: "The markets for most quantum technologies will be international, so it's important that the UK is at the forefront of developing industrial standards to gain maximum benefit for its citizens and the economy."

## Maximising UK Benefit through International Engagement

The UK Quantum Technology Hubs are linked strongly with international organisations including recent expansion of activities with Airbus, Thales and Nokia. They continue to work with attaches in the Science and Innovation Network and specialists at the Department for International Trade to build new connections and explore export opportunities, with strategic links made in Japan, South Korea and Singapore.

The UK are key players in European quantum programmes, including ERA-NET 'Quant-ERA' and the Future Emerging Technologies (FET) flagship programme on Quantum Technologies. The UK provides expertise to the Commission's High Level Steering Committee for the QUTE flagship.

The programme delivery partners monitor and review domestic capability and fund schemes such as Quantum Technologies Innovation Chairs to promote international collaboration. The overall international engagement strategy is coordinated through the Quantum International Working Group, a sub group of the Strategic Advisory Board.

### Infinite Variety

The microprocessor inside a computer is a single multipurpose chip that has revolutionised people's lives, allowing them to use one machine to surf the web, check e-mails and keep track of finances. Now, researchers from the University of Bristol and Nippon Telegraph and Telephone (NTT) in Japan, one of the world's leading telecommunications companies, have pulled off the same feat for light in the quantum world by developing an optical chip that can process photons in an infinite number of ways.

The fully reprogrammable chip, developed through the UK National Quantum Technologies Programme, marks a major step forward in creating a quantum computer that can tackle challenges such as designing new drugs, conducting superfast database searches, and performing mathematics beyond the reach of supercomputers.

The project was carried out in Dr Anthony Laing's group at Bristol. Dr Laing says: "A whole field of research has essentially been put onto an easily controlled single optical chip. The implications go beyond the huge resource savings. Now anybody can run their own experiments with photons, much like they operate software on a computer. They no longer need to convince a physicist to painstakingly build and conduct a new experiment."

# The People behind the Technology...



## Andrew Shields

Assistant Managing Director at Toshiba Research Europe Ltd

Toshiba is a front-runner in the development of quantum technologies, and is a key partner in the UK Quantum Technologies Programme. Andrew Shields wears two hats – as a scientist and innovator and also as chair of the Industry Specification Group for Quantum Key Distribution (see page five).

Andrew says: “We are interested in using quantum technologies to develop new services and products, often with a capability that is not possible today. One example is in cryptography, where quantum effects allow us to test the secrecy of a communication for the first time. This could be useful for distributing secret digital keys and digital signatures on communication networks. Another example is quantum computing, which one day might allow us to solve machine learning problems that are very difficult today.

I lead a work package in the Quantum Communications Hub, which is developing large-scale networks for quantum communications. In particular, we are interested in integrating quantum communications into the ordinary fibre optic telecom network. That would allow us to bring the techniques into far more widespread use than is possible today. We partner also with the NQIT Hub which is using quantum communications to link small-scale quantum processors.

At Toshiba we have successfully demonstrated a state-of-the-art Quantum Key Distribution (QKD) system, capable of counting up to one billion single photons per second, that is breaking new ground in encrypted communications. We have made several field trials of the technology over data-carrying fibre with organisations such as BT, NPL and ADVA Optical Network.

In the near term our technology can be used to secure high bandwidth data communications links carrying sensitive data. Other applications include encryption of valuable financial, government or corporate information or securing critical infrastructure.

As the technology becomes cheaper, we envisage that QKD can be widely used in communication networks, to individual offices and eventually to residential customers.”

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The research brings together two complementary skill sets

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## Dr Nicole Metje

Reader in Infrastructure Monitoring, University of Birmingham

**Nicole leads the Gravity in Civil Engineering work package within the UK National Quantum Technology Hub in Sensors and Metrology. She also leads the Assessing the Underworld project.**

Nicole says: “Knowing where gas and water pipelines, electricity cables and sewage outlets are located is not always easy. Using quantum gravity sensors to locate and monitor them (see page three) could lead to massive time and cost savings. It is estimated that our technology, which is close to commercial launch, will reduce current gravity survey times from weeks to just hours.

Several different technologies exist to see through the ground, but many rely on transmitting an electromagnetic wave, which is then reflected off a buried pipe or cable back to the surface. However, the ground, especially wet clay, can make it really difficult to see anything deeper than a few centimetres. Conventional sensors are also easily affected by surrounding buildings, vibration from traffic, and wind and ocean tides to name but a few, making it impossible to detect smaller objects.

The quantum sensors developed in collaboration with physicists at the Quantum Sensors and Metrology Hub use a technique called atom interferometry which suppresses several noise sources and creates a sensor useful in everyday applications.

The research brings together two complementary skill sets. While the physicists work on creating an advanced QT sensor, the civil engineering team provides guidance on how it needs to be used and what problems need to be addressed. This is a diverse activity, including close collaboration with end-users, such as geophysical surveying companies, to understand what the applications and limitations of existing technologies are. More importantly, it provides a reality check as the developing QT technology has to survive the harsh environment on site. At the same time, we are the early adopters of the QT sensor and trial early prototypes, helping to create a roadmap for potential applications.”



## Richard Middlemiss

Doctoral Student, UK Quantum Technologies Hub in Quantum Enhanced Imaging (QuantIC)

**Together with his supervisor, Dr Giles Hammond, Richard has adapted accelerometer technology found in most smartphones to make a small but powerful quantum gravimeter able to measure tiny changes in the Earth's gravity.**

Richard says: “There are many different applications for gravimeters. They allow one to see things of different density underground. Perhaps the most ubiquitous use at present is in the oil and gas exploration industry. Although this industry is a target market for our work, the application that I'm most excited about personally is volcanology. If you can see intrusion of magma you can aid volcanic eruption predictions.

Since our devices have the potential to be so cheap, we could create networks of them around volcanoes to help predict eruptions and to negate the need for volcanologists to complete dangerous surveys with gravimeters that can't be left in situ due to their enormous expense.

During my research I have benefited from contact with many different industrial partners, particularly Bridgeport Geophysics, a specialist geosciences company. Bridgeport is testing the device in the field and will undertake comparative testing against a standard commercial gravimeter. The results of the project will be used to inform the design for a full demonstrator.

As QuantIC's focus is on translating research into technology applications, I have had the reward of seeing a vague idea of three years ago metamorphose into a computer model, then into broken trials, and finally into a fully functioning device with which I've been able to take incredibly exciting data.

I have been able to apply for a patent and write papers; I have been able to travel the world to communicate my work to academics and the public; I have made a documentary, been interviewed on the news, and appeared on a chat show; I have done something different each day of my PhD, and I've not been bored yet...”

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Despite my scientific achievements, I'm even more proud of having assembled a world leading group

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## Professor Winfried Hensinger

UK Quantum Technology Hub on Networked Quantum Information Technologies and UK Quantum Technology Hub on Sensors and Metrology

Winfried says: “I lead the Ion Quantum Technology Group at the University of Sussex. We are developing different quantum technologies, in particular, quantum computing, quantum simulation and quantum sensing. I have very ambitious plans, such as constructing a large-scale quantum computer and quantum simulator. Building a practical quantum computer is a very worthy goal which will likely transform all our lives in areas such as code breaking, cyber security, medical diagnostics, big data analysis and logistics. In addition, it will provide an extremely powerful tool for all the sciences.

I also work on the development of portable quantum sensors and clocks. I am fascinated by the opportunity of turning the perceived spookiness of quantum physics into tangible disruptive technologies.

We have made some significant recent breakthroughs which make it seem realistic to build an actual quantum computer. For example, we invented a powerful new microchip capable of holding the voltage equivalent to a micronscale bolt of lightning that could be the key for developing next-generation, super-fast quantum computers.

The first generation of quantum computers will be R&D tools used to accelerate the discovery of new materials, chemicals and drugs. Drug discovery can involve the mapping of trillions of combinations of amino acids in search of new cures, and it typically costs hundreds of millions of pounds to bring new drugs to market. Quantum computers could dramatically reduce costs and speed-up lead times.

Despite my scientific achievements, I'm even more proud of having assembled a world-leading group, thanks to an EPSRC Leadership Fellowship, who are ready and capable of realising the most challenging quantum technologies.

Collaborating with other outstanding groups in the UK and elsewhere will provide the critical mass to make the UK the best place for quantum technology research and commercialisation in the world.”

**“Over the last two decades, EPSRC-supported researchers have made pioneering contributions to quantum technologies, and helped to develop a thriving UK quantum community. The UK Quantum Technologies Programme is building on this work. It’s rewarding to see gifted scientists and engineers from academia and industry collaborating to accelerate the development of the next generation of quantum devices, systems and standards that will lead to substantial benefits for the UK economy and society.”**

Liam Blackwell, Head of Quantum Technologies, EPSRC

**“The UK Quantum Technologies Programme is a joint action with a collective vision. Separately we would struggle to deliver this, but together, through the collaborative strategy we have developed, we can realise a wealth of quantum research – and other countries are sitting up and paying attention.**

**“At Innovate UK, our purpose is to build a ladder that leads from where we are now in rapid steps to some of the bigger and more ambitious applications. If our international partners are a little shocked and awed by our progress, then great. They should be.”**

Simon Bennett, Director of Knowledge Exchange, Innovate UK

**“The National Physical Laboratory is the UK’s National Measurement Institute. Working with the UK Quantum Technologies Programme Hubs, industry, and with national measurement institutes around the world NPL is taking a leading role in the development of international standards for quantum technologies.”**

Rhys Lewis, Director of the Quantum Metrology Institute, National Physical Laboratory

**“Our collaboration with the Quantum Community brings together world-class research, Dstl’s ambitious technology demonstrator programme and proven industrial expertise to deliver a collective vision. This will enable us together with our partners to translate state-of-the-art laboratory technology into deployable practical devices. These crucial partnerships support the development of smaller, lighter and cheaper components to make quantum devices a commercially viable reality that will ultimately improve, save and protect people’s lives.”**

Trevor Cross, Chief Technology Officer at e2v

**For more information on the UK National Quantum Technologies Programme please visit [www.uknqt.epsrc.ac.uk](http://www.uknqt.epsrc.ac.uk)**