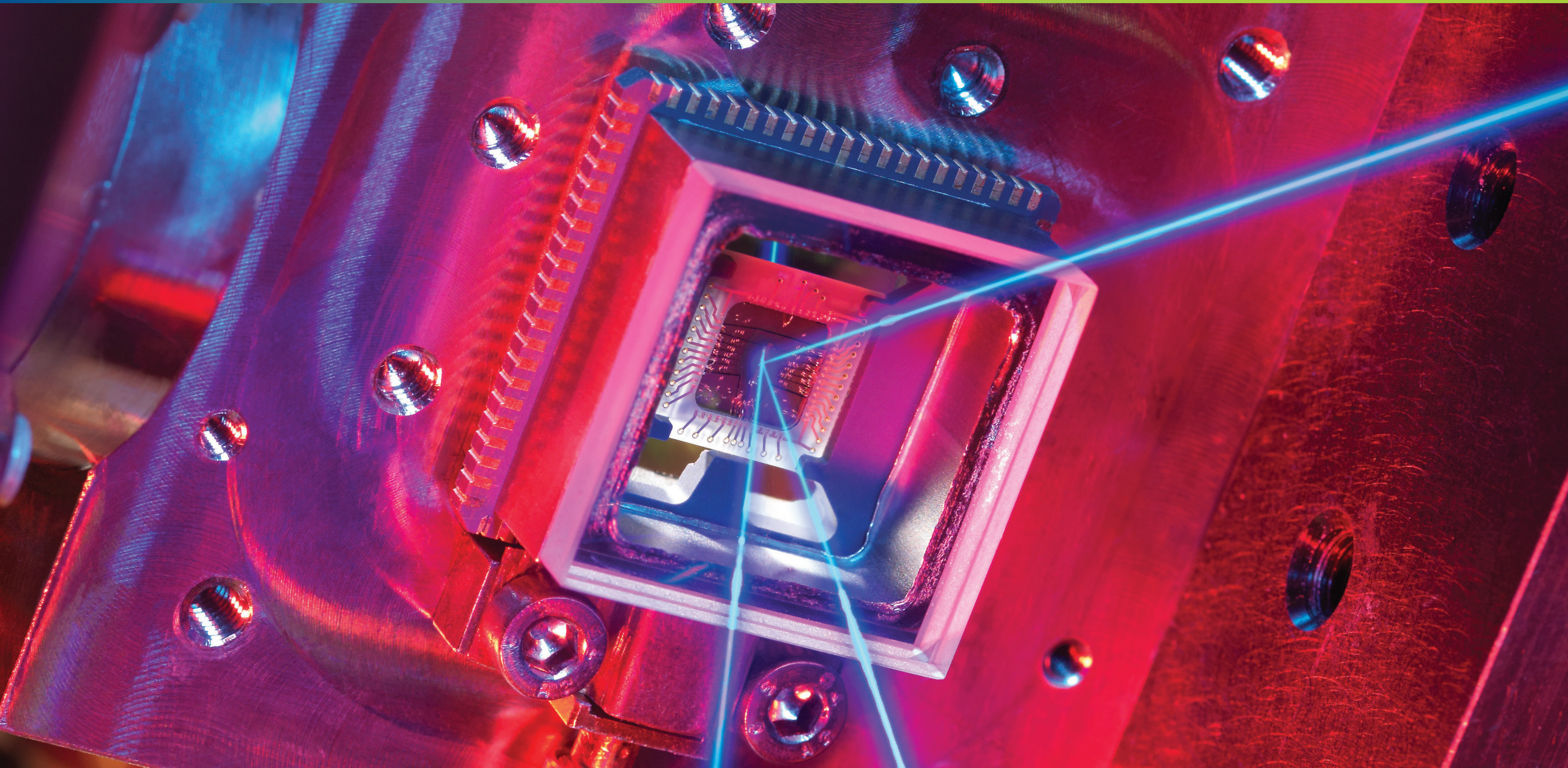
Strategic Intent

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME



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Department for Business, Energy & Industrial Strategy

Ministry of Defence

[dstl]

UKRI Engineering and Physical Sciences Research Council

GCHQ

NPL National Physical Laboratory | QMI Quantum Metrology Institute

UKRI Innovate UK

UKRI Science and Technology Facilities Council

Executive Summary

This new era of quantum technologies will transform economies in our maturing digital age and help to address society's challenges; advancing health care and environmental protection, achieving net zero targets and better land use, supporting financial services and communications, providing defence and security capabilities and computing power. These technologies will create new global market opportunities and competitive advantage for those able to develop and exploit them, unlocking innovation by integrating them into complex systems[1]. For this reason, significant efforts are being put into developing quantum technologies globally. The UK is poised to be part of the creation, as well as the application, of quantum technologies and this Strategic Intent document sets out objectives to realise that opportunity and develop a quantum-enabled economy.

The National Quantum Technologies Programme (NQTP) was established in 2014 by the partners (EPSRC, STFC, IUK, Dstl, MoD, NPL, BEIS, GCHQ, NCSC[2]) to make the UK a global leader in the development and commercialisation of these technologies. World class research and dynamic innovation, as the Government's R&D Roadmap stresses, are part of an interconnected system. The NQTP's achievements to-date have been enabled by the coherent approach which brings this interconnected system together. This focus sets the UK apart from the international competition.

In the past five years remarkable progress has been made towards both producing integrated systems, many of which are now nearing the market, and creating a UK quantum technologies industry. Our thriving and unique interconnected ecosystem is comprised of world-leading research institutes, innovative quantum technology spin-outs, systems integrators and components suppliers from existing industries, as well as major multinationals, all interacting to generate real successes and drive the development of products and services. This has laid the foundations, putting the UK in a prime position to take advantage of the opportunities, increase productivity and realise Government's ambition to be a Science Superpower. But the UK needs to progress quickly as the next technological revolution, driven by a fusion of technologies, data and advanced computational abilities, gathers pace.

A new strategic vision for the next 10 years

An evolved vision to create a 'quantum enabled economy', in which quantum technologies:

- are an integral part of the UK's digital backbone and advanced manufacturing base;
- unlock innovation across sectors to drive growth and help build a thriving and resilient economy and society and;
- contribute significant value to the UK's prosperity and security.

To achieve this, we aim to make the UK:

- a global centre of excellence in quantum science and technology development;
- the 'go-to' place for quantum companies or for global companies to locate their quantum activities, and;
- a preferred location for investors and global talent.

This document lays out a series of objectives for the next phase of the programme to unleash a new wave of innovation across the economy and ensure the UK is the go-to place for quantum technologies, talent and investment. It seeks to harness the sector's long-term goals and growth aspirations to deliver economic prosperity, national security and societal needs. The document sets out a new ambitious 10-year forward vision for the UK to become a quantum-enabled economy; one where quantum technologies are an integral part of the UK's digital backbone and the manufacturing base, unlocking innovation across sectors to drive growth and help build a resilient, prosperous and secure nation.

With an expanded focus on industrial scale up, stimulating private funding and investment and rapid commercialisation, alongside a re-invigorated focus on world leading research and efforts to attract and retain exceptional people, this document sets out our ambition to ensure that quantum technologies in the UK deliver the maximum benefit for the nation. We will use this to engage with the community to identify actions and owners to achieve objectives in the coming months.

[1] Systems integration refers to the process of bringing together component sub-systems into one system that provides the desired functionality.

[2] The Engineering and Physical Sciences Research Council, Science and Technology Facilities Council, Innovate UK, Defence and Science and Technology Laboratory, Ministry of Defence, National Physical Laboratory, Department for Business, Energy and Industrial Strategy, Government Communications Headquarters, National Cyber Security Centre.

Stimulate market growth, unleash innovation, and grow a thriving ecosystem

Maintain the UK's excellence in research and technology

Build a resilient network of national assets and mutually beneficial international relationships

Grow, attract and retain talent

Stimulate market growth, unleash innovation and create a thriving ecosystem

Transformative technologies come from excellent research and from companies who employ skilled people, produce and export innovative products and play their parts in the global supply chain. The continuation of industry and societal challenge-led activities will enable interaction and growth within the innovation ecosystem, and build supply chains, products and services. For those technologies near market we need to expand the focus on industrialisation and technology adoption, understand sector needs and undertake demonstrator work to enable scale-up.

Stimulating investment will be a key component of the programme and ensuring spin-outs have access to advice about how to scale and protect their assets. We will help industry navigate current and future regulatory requirements and will facilitate engagement in the development of international standards and benchmarking, We will develop testing and evaluation capabilities to support sustainable UK market growth and work with industry to showcase capabilities and open-up markets and investments.

Maintain and build the UK's excellence in research and technology

Through the Quantum Technology Hub networks and wider community the UK has established itself as a major global player in quantum technology founded on its scientific excellence and its focus on applications and industry needs. We will continue to build on existing excellence to strengthen our global position in research, build the skills pipeline and open-up new opportunities for technological convergence, enabling work across disciplines to unlock innovation. As an enabling technology we will develop new quantum tools and opportunities for wider science applications. Given the need to mitigate potential threats associated with the misuse of these technologies and the risk to loss of IP we will continue to champion responsible and trusted research activities.

Quantum computing represents a unique challenge and opportunity due to the scale and complexity of activity required, the size of the opportunity, the time to market, and the challenges that quantum computing presents to modern encryption. This requires a different approach to bring the community together and realise opportunities for growth. Being quantum-ready requires companies and government to engage now to upskill and explore applications that could have a significant impact on industry and wider society. Through the newly established National Quantum Computing Centre we will undertake a programme of hardware building and software development, developing a UK capability, skills and knowhow and enabling the UK economy to explore useful applications.

Build a resilient network of national assets and mutually beneficial international relationships

The NQCC and the Quantum Technology Hubs are part of a wider network of infrastructure and capabilities that underpin the ability of the programme to deliver on its vision and objectives. This includes NPL's testing and evaluation capabilities, Dstl laboratories, STFC facilities and wider regional laboratory and fabrication facilities. We will continue to build a resilient network of facilities and UK capabilities to ensure they meet the needs of the growing sector and society. But scientific discovery cannot be undertaken in isolation and we will continue to work to identify and develop mutually beneficial global partnerships to advance the field and achieve wider Programme objectives.

Grow, attract and retain talent

Talented people and knowhow drive scientific discovery, innovation and growth. The UK is recognised globally for its excellent workforce in academia and industry and the Programme seeks to grow these capabilities to meet the sector's growing needs. We will ensure that doctoral training for quantum technologies meets the skills demand within industry, while producing highly qualified people to pursue research careers. Fellowships programmes will help to retain our current leaders, develop our future leaders and attract the best talent from around the world. We will continue to engage with the growing sector to better understand its wider skills needs for the future at all levels; and seek to raise the profile of quantum technologies amongst the public and within education syllabuses to build the future pipeline and facilitate discussions about the role of these technologies in society.

Objectives to achieve this vision

Stimulate market growth, unleash innovation, and grow a thriving ecosystem

- Map out how technologies will be applied to unlock innovation across sectors; undertake demonstrator activities with industry
- Continue challenge-led activities to create products and services
- Stimulate investment and help companies to start and scale
- Strengthen engagement in international standards and benchmarking; develop testing and evaluation capabilities to support market growth
- Showcase UK capabilities, identify opportunities to open-up markets and investments

Maintain the UK's excellence in research and technology

- Ensure that the scale of research programmes protects the pipeline of excellence in quantum science research
- Ensure growing programmes in engineering and physical sciences continue to be guided by market opportunities and business needs
- Undertake an accelerated quantum computing programme of activities led by the NQCC
- Develop new quantum tools for wider science applications and facilitate the exploration of novel applications
- Continue to champion responsible and trusted research within the Programme

Build a resilient network of national assets and mutually beneficial international relationships

- Continue to manage and build the network of facilities and capabilities to meet the needs of the sector and society
- Continue to develop mutually beneficial global partnerships to achieve the Programme's objectives

Grow, attract and retain talent

- Ensure doctoral training meets the skills demands within industry, while producing highly qualified researchers
- Ensure fellowships programmes attract and retain science leaders and future leaders
- Raise the profile of quantum amongst the public and in syllabuses
- Continue to engage the sector on skills needs for the future
- Support a diverse and inclusive research environment within quantum technologies

Foreword

On behalf of the National Quantum Technologies Programme Board, I am pleased to outline the NQTP's Strategic Intent for the coming years. We publish this document at an unprecedented time, recognising now more than ever the importance of science and innovation for societal gain and economic recovery. This document sets out the NQTP partners (EPSRC, STFC, IUK, Dstl, MoD, NPL, BEIS, GCHQ, NCSC) and wider community's ambitions and shared vision to create a quantum-enabled economy; one in which these remarkable technologies are an integral part of the UK's future digital backbone and its manufacturing base that the nation requires, unlocking innovation across sectors to drive growth and help build a resilient, prosperous and secure nation.

This focused vision and intent sets out our ambitions to cement the UK's position as a global leader in both the underpinning science and its commercialisation; a place where global companies choose to locate their quantum activities, and a preferred destination for investors and international talent. To secure global leadership in quantum technologies and deliver on our vision requires measures to assure the long-term competitiveness and integrity of the UK sector. The NQTP Partners are committed to working to develop a holistic approach to protect and grow the sector. We will be agile in creating the best environment for UK quantum technology businesses to innovate and grow with confidence.

Much has been achieved in the first five years of this pioneering Programme due to excellent science, extraordinary collaboration, and the dedicated UK community. But we must not lose sight of the fact that the science is far from done and significant engineering challenges remain.

We must continue to build on our efforts rather than lose momentum to provide continuity in these challenging times and help the sector to reach its full potential. We will continue to develop the pipeline of applied quantum technologies by backing the best people and ideas to deliver on their commercial potential; opening up opportunities for the UK to benefit from the transformative potential of quantum technologies.

Dame Lynn Gladden,
Chair of the NQTP Programme Board

1. Introduction

The UK in the quantum era

1.1 What is quantum

Quantum technologies are the result of our ever-deepening understanding of the physical world, a place where the normal laws of classical physics do not apply, but in whose nature dwell extraordinary possibilities to advance our lives.

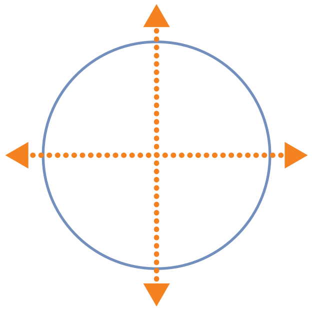
Technology has repeatedly transformed human society through step changes. We are on the cusp of another as the advance into quantum technologies accelerates. In the last 50 years the digital revolution has enabled technologies that were the preserve of science fiction only a generation ago. Many of the devices on which this revolution was built rely on the physics of quantum mechanics.

The advancing understanding and control of what are known as 'quantum effects' such as superposition and entanglement will lead to a new wave of advances that will underpin our economy and society: sensing, data transmission and encryption, timing and computing. The programme seeks to develop and exploit these quantum effects, to best unleash their potential as agents for change for the UK.

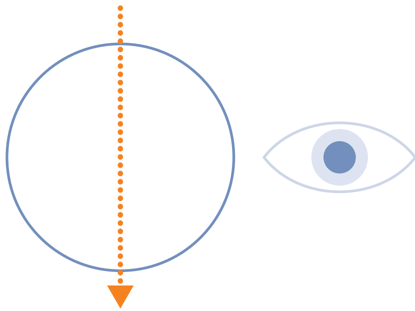
Superposition and Entanglement are two examples of quantum phenomena upon which the discovery and development of quantum technologies is based:

Superposition

A particle can be in two or more states at once

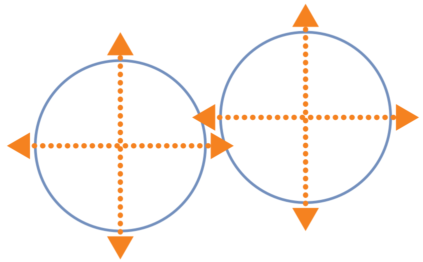


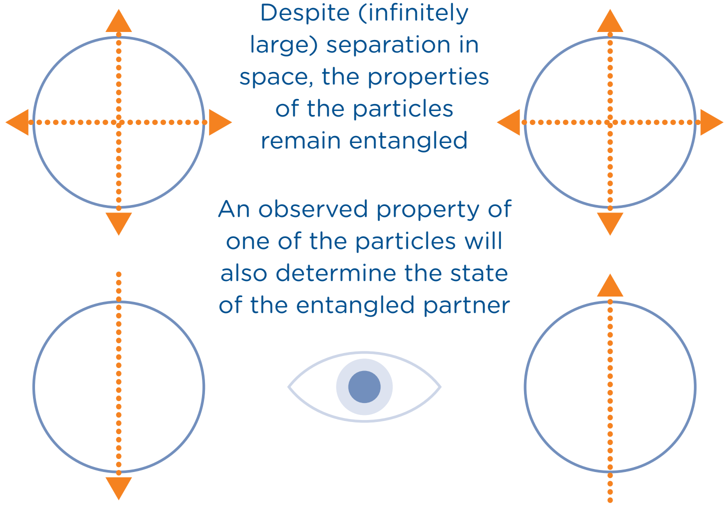
When the particle is observed it settles into one of its possible states



Entanglement

Two paired particles are created; the state of the two cannot be described as the sum of their individual states





1.2 What can quantum do for society?

A quantum enabled economy

Quantum technologies are central to building a healthier, wealthier and more resilient UK. Similar assessments have been made by most developed economies, leading to widespread government-supported initiatives to develop quantum-enabled products and services.

By taking advantage of the physical properties of photons, electrons, atoms, and condensed matter to achieve technological advances we can apply these new capabilities to a range of sectors. For example: a more precise clock for time stamping to gain advantage in financial systems; a more accurate and portable sensor for cheaper, non-invasive brain imaging and diagnosis; an exponentially more powerful computer to help solve some of society's complex problems; or new communications techniques to help to transmit data securely and enable wider innovations across the nation's digital backbone.

> **The UK is leading a global race in Quantum Technology, thanks to the National Quantum Technologies Programme (NQTP), a coordinated alliance of academia, industry and government to transform our research strengths into commercial advantage. This strategic intent sets out our ambitions for this exciting venture at a time when the fruits of our investment are there to be harvested.**

Sir Peter Knight,
Chair, NQTP Strategic Advisory Board

The ten-year vision is to realise a world in which quantum technologies produce innovations that impact multiple sectors, contributing significant value to our economy, security and international profile as a dynamic trading nation. A quantum-enabled economy is one in which these technologies are not passive, but part of what underwrites the UK's digital backbone and advanced manufacturing base.

Example quantum technology applications for different sectors[1]

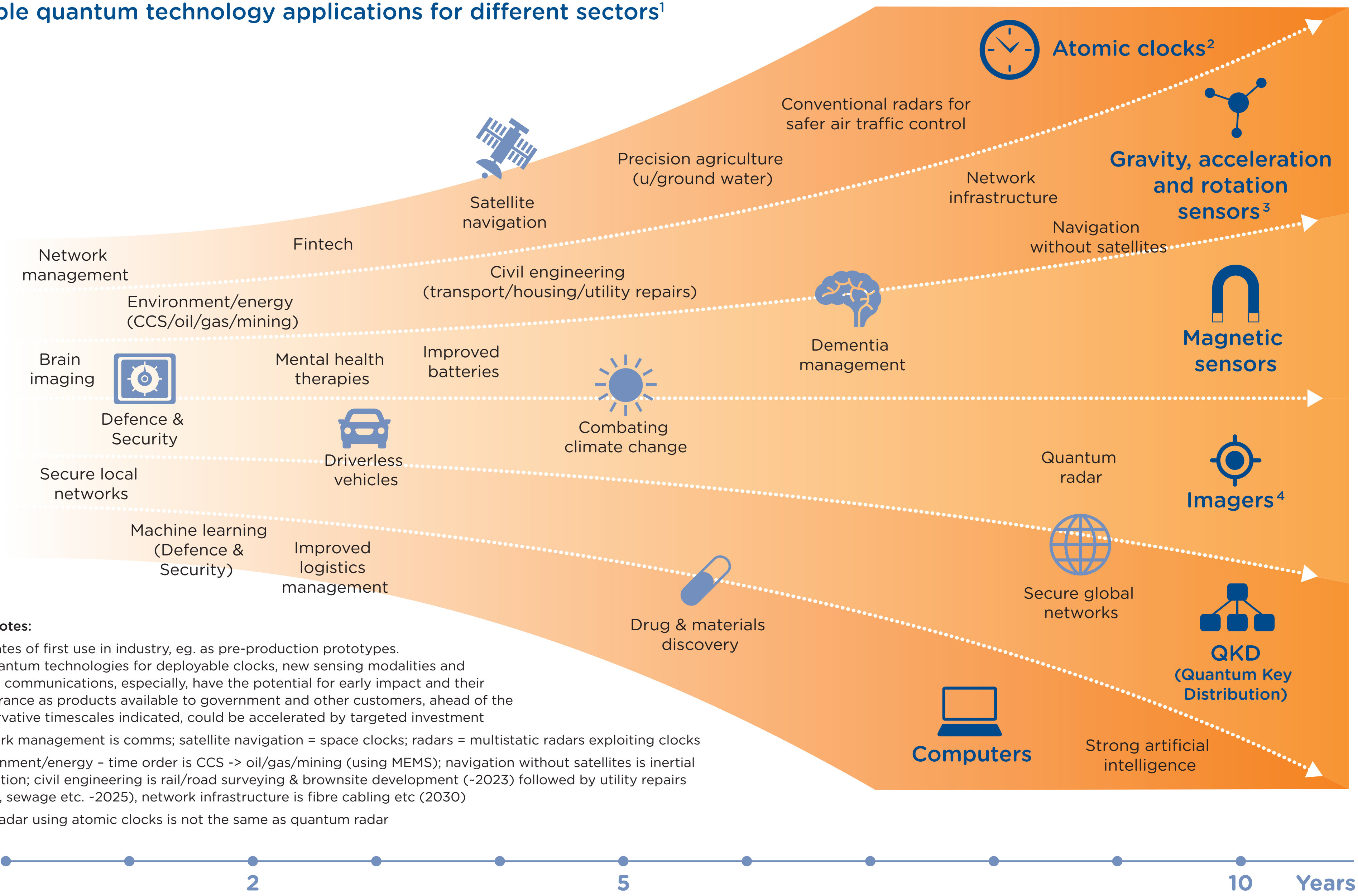


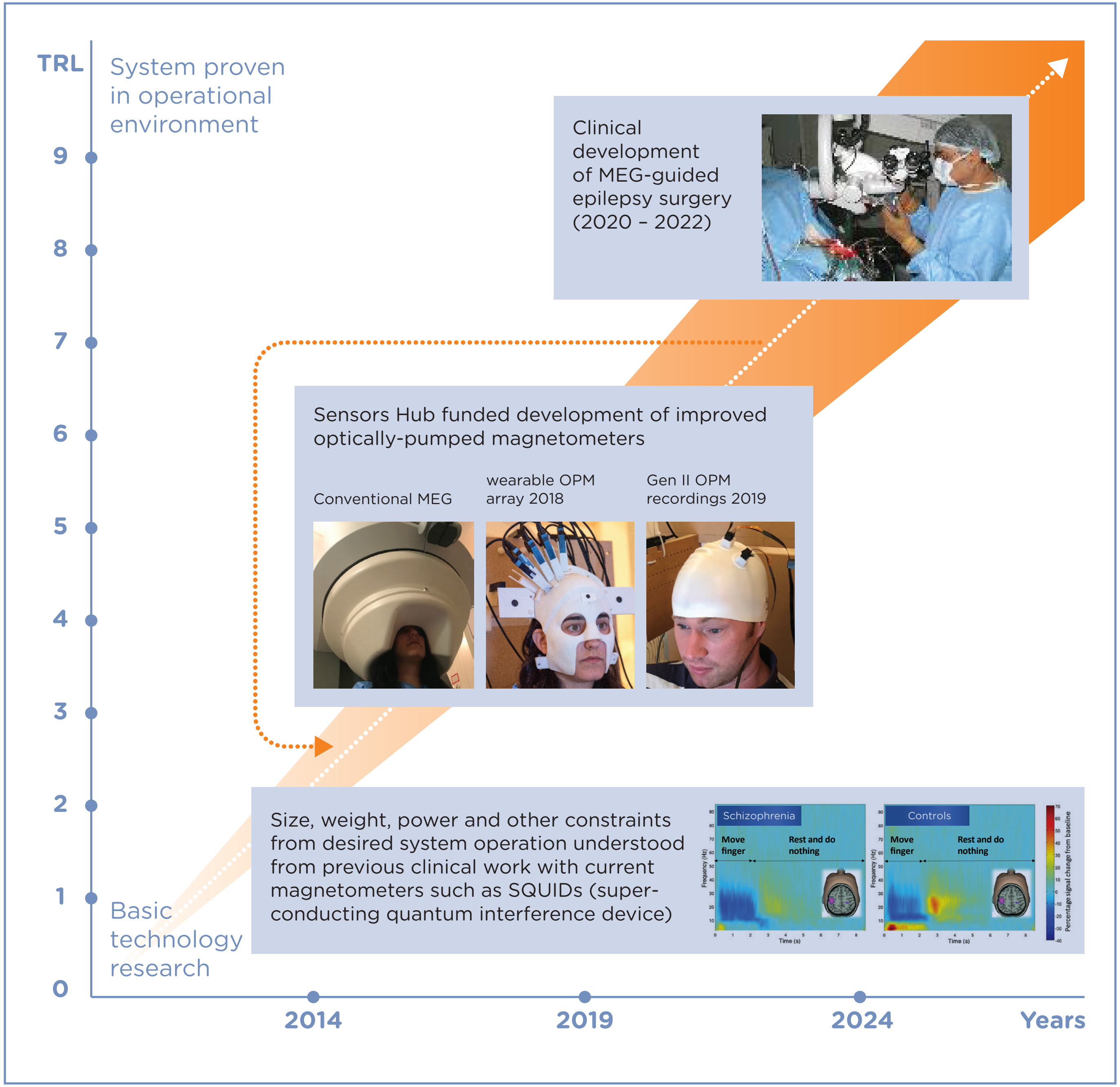
Diagram notes:

1. Estimates of first use in industry, eg. as pre-production prototypes. UK quantum technologies for deployable clocks, new sensing modalities and secure communications, especially, have the potential for early impact and their appearance as products available to government and other customers, ahead of the conservative timescales indicated, could be accelerated by targeted investment
2. Network management is comms; satellite navigation = space clocks; radars = multistatic radars exploiting clocks
3. Environment/energy – time order is CCS -> oil/gas/mining (using MEMS); navigation without satellites is inertial navigation; civil engineering is rail/road surveying & brownsite development (~2023) followed by utility repairs (water, sewage etc. ~2025), network infrastructure is fibre cabling etc (2030)
4. Note radar using atomic clocks is not the same as quantum radar

Case study:
Wearable technologies for brain imaging

The UK Quantum Technology Hub in Sensors and Timing has been leading work to create world leading capability in medical imaging using high-sensitivity, wearable technologies for magneto-electrical medical imaging, known as quantum magnetometers.

Led by the University of Nottingham, a wearable skull cap for magneto-encephalography (MEG: a technique for mapping brain activity by recording magnetic fields), developed in phase 1 of the national programme, is now being used in clinical trials to guide epilepsy surgery, especially in children. Other medical applications are envisaged for the future, for example in diagnosis of traumatic brain injuries.

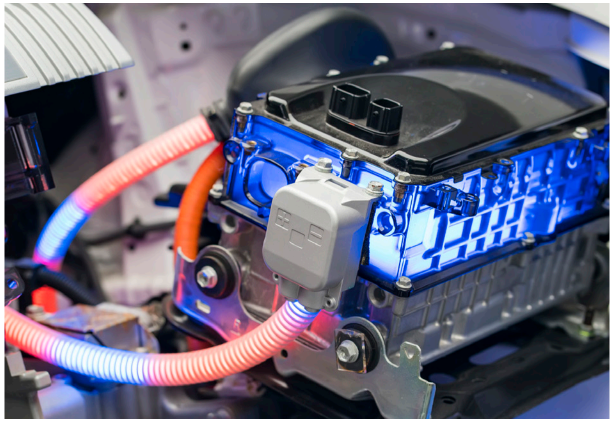


TRL – Technology Readiness Level

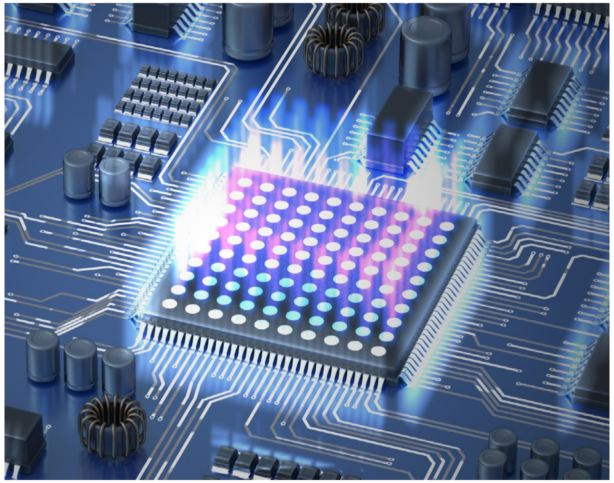
Case study:
Clean growth challenge

Quantum technologies can help to address the challenge of generating and storing reliable, clean and sustainable energy. For example the following projects are already underway as part of the ISCF Commercialising Quantum Technologies Challenge:

A project led by **AMTE Power**, with 9 other businesses, universities and research centres, to use quantum sensing technology to diagnose flows in the ageing process of lithium batteries. This will make the manufacture of lithium batteries for electrical vehicles quicker, cheaper and greener as their demand increases.



The Gravity Delve project led by **Nemein Ltd** and the UK Quantum Technology Hub for Sensors and Timing. This will explore the use of quantum gravity sensors to optimise renewable energy harvesting and carbon storage for the oil and gas industry. It will enable the quantum sensor developed by the Hub to be tested in harsh underground borehole environments.



A project led by **Rahko** to explore how quantum computing can be used to design and optimise new and efficient catalysts, with applications in developing cleaner fuel technologies and reducing environmentally harmful emissions in industry.

The SPLICE project led by start-up **QLM** in collaboration with 10 other partners, including oil and gas firm BP and the National Grid, to develop quantum enabled gas sensors for detecting and visualising industrial gas leaks, helping to prevent greenhouse gas emissions.

1.3 The economic opportunity

The economic impact of quantum technologies is expected to be wide-ranging and transformative; it has the potential to create new markets and disrupt existing ones, across a wide range of sectors. The ways in which quantum computing could impact on society are so profound it is hard to ignore. In addition to improved efficiency, productivity and competitiveness, there are likely to be entirely new products and services as unprecedented computing power is unleashed, and quantum software is developed to unlock new opportunities.

The potential economic value associated with quantum technologies is difficult to estimate given the wide-ranging applications, but market estimates highlight the significant scale of the anticipated opportunity. In 2020 CSIRO the Australia's National Science Research Agency estimated the global quantum sector could grow to be worth $86bn[3] by 2040. Global productivity gains across all sectors derived from quantum computing are predicted to be £3bn in 5 years, growing to £20–35bn in the next 10 years, and then in excess of £350bn over the following decades[4].

Many of the companies that could benefit from quantum computing already have a strong presence in the UK economy, including those involved in new materials, pharmaceuticals, chemicals, energy, aerospace, defence and financial services. But most potential end users are just beginning to consider the technology and the impact it will have on their operations.

1.4 Global context

Many governments are investing in quantum technologies as are large technology multinationals. Recent years have seen a move from a primary focus on scientific research toward product development.

The UK is a serious global challenger in the race to realise the biggest quantum innovations based on the successes of the first phase of the programme. It has achieved success by focusing on quantum technologies and not just quantum science from the outset, and because it builds on excellent research and the existing industrial base. The NQTP's coherent programme sets the UK apart from international competitors. Whilst many countries can claim strong science and robust industries, few can claim to have the coherent innovation ecosystem that exists in the UK. This point is demonstrated by the decision of global companies such as Teledyne, Toshiba and Hitachi, and more recently Rigetti to base quantum R&D activities in the UK. This success will draw more major corporations, venture capitalists and scientists to locate here.

We must maintain this lead and outpace challengers as they emerge, collaborating where appropriate and offering protections in recognition that some technologies and capabilities are becoming critical to our security and prosperity.

[3] Australian dollars. Commercial figures do not reflect the total value creation potential of quantum technologies. This would include broader benefits such as gains in productivity, improved national security and indirect industry growth and job creation.

[4] https://www.bcg.com/en-gb/publications/2019/quantum-computers-create-value-when

2. Building on Strong Foundations

2.1 The NQTP

£400m of public funding was invested during the first phase of the NQTP. This investment into the UK research base and infrastructure included the establishment of four research Quantum Technology Hubs, focusing on technology development and working with industry. The first phase of collaborative innovation programmes and wave 2 of the Industrial Strategy Challenge Fund (ISCF) involved over 100 companies and moved technologies toward exploitation.

This document updates the NQTP strategy and the programme's activities, presenting progress to date and setting new objectives in response to the changing global and national landscape. It seeks to stretch ambitions to create a quantum-enabled economy with long-lasting economic, national security and societal benefits for our country.

Successes of phase 1 in numbers

Training a diverse workforce

150 students trained through Quantum Centres for Doctoral Training

14 Fellowships to support the most innovative individuals in quantum technology research and development

46 PhD projects funded through the Defence Science and Technology Laboratory

76 PhD students received funding from or hosted at the National Physical Laboratory

Supporting new businesses

Over 25 spin-outs

emerged from, or supported by the Programme

Connecting with businesses across the UK

Over 150 businesses partnered

with the UK Quantum Research Hub network

170 businesses

applied for ISCF funding, demonstrating huge appetite for collaboration

£20m of government funding

went to 25 businesses and 12 research organisations for ISCF wave 2 collaborative technology R&D projects in 2018

Creating new knowledge

214 grants

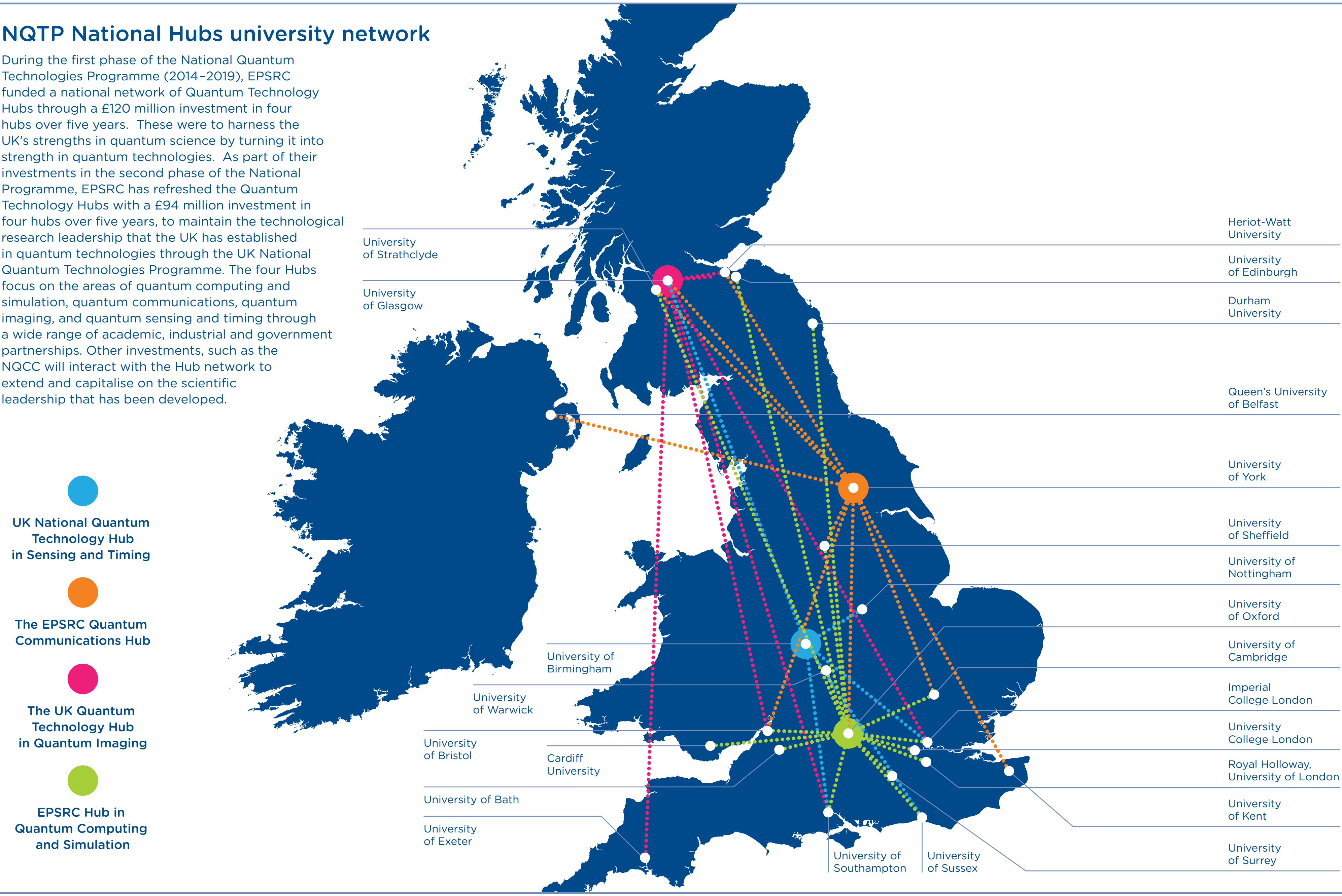
provided by EPSRC to support research in its quantum technology portfolio, totaling over £350 million

397 peer reviewed papers published

by the UK research community

NQTP National Hubs university network

During the first phase of the National Quantum Technologies Programme (2014–2019), EPSRC funded a national network of Quantum Technology Hubs through a £120 million investment in four hubs over five years. These were to harness the UK's strengths in quantum science by turning it into strength in quantum technologies. As part of their investments in the second phase of the National Programme, EPSRC has refreshed the Quantum Technology Hubs with a £94 million investment in four hubs over five years, to maintain the technological research leadership that the UK has established in quantum technologies through the UK National Quantum Technologies Programme. The four Hubs focus on the areas of quantum computing and simulation, quantum communications, quantum imaging, and quantum sensing and timing through a wide range of academic, industrial and government partnerships. Other investments, such as the NQCC will interact with the Hub network to extend and capitalise on the scientific leadership that has been developed.



Hub achievements in phase 1

Headline consolidated figures across all hubs:

Over 150
companies partnered

Over £35m
in industry contribution to Hub projects

Over 10
spinout companies supported

Over £13m
awarded to PhD studentships associated with the hubs

Achieved UK firsts
The Hub in Sensors and Timing, in collaboration with M Squared, carried out the first industrial demonstrations of a quantum gravimeter, capable of highly sensitive gravity measurements, and the first transportable, standalone quantum accelerometer for navigation.

Made commercial breakthroughs
The Quantum Communications Hub built and launched the UK's first quantum network extending over 410km, demonstrated the world's first chip-to-chip QKD encrypted transmission, and demonstrated free space QKD between a handheld device and a wall mounted terminal, paving the way towards secure QKD technology for consumer markets.

Brought products to market
4 products were brought to the market through the Quantum Enhanced Imaging Hub, including a correlated photon pair source and a photon counting camera for use in research activities globally, fluorescence imaging technology of molecular processes with impact on medical research, and a gas sensing LIDAR for fast and accurate leak detection.

Delivered world-leading performance
The Quantum Computing and Simulation Hub achieved 4 world records in ion trap quantum computing, leading performance of quantum logic gates in any hardware platform, a quantum network with a leading combination of speed and fidelity, and the world's faster emulator, QuEST, for quantum algorithm development.

Successes of phase 2 to date

Expanded activity with businesses across the UK

£75m in ISCF support in 2020

for project consortiums to deliver ground-breaking quantum technology products and services to market

At least £12m

of grant and equity funding

to be provided to companies operating in quantum technologies through an investment accelerator partnership between the IP group and Innovate UK

80 businesses + **30** research organisations

partnered through project consortia for ISCF wave 3

£30m

of private investment

secured to-date through ISCF wave 3 funding

For ISCF wave 3 overall:

£153m

of government funding

To generate an additional £205m from industry match and catalyse private investment

Growing the network of innovative facilities and programmes

An enhanced quantum test and evaluation programme at NPL to support projects across the NQTP

£93m

in Government funding

for the National Quantum Computing Centre, launched in September 2020 to help deliver quantum computing capabilities for the UK and support the growth of the industry.

Successes of phase 2 to date

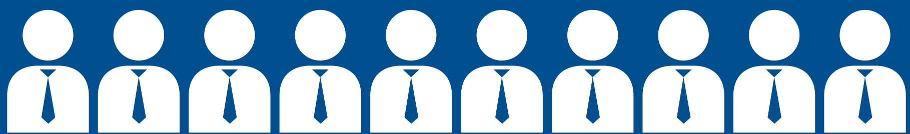
Maintaining technological research leadership

£94m to be invested

in the four National Quantum Technology Hubs over five years

£11.6m committed

to Centres for Doctoral Training to take in new cohorts of students



"The National Quantum Technologies Programme (NQTP) is an exemplar of how UKRI in partnership with Government can galvanise UK academia and industry. It has enabled the UK to turn its world-class science into pioneering quantum technology products and services. BT was involved in the formation of the Quantum Communications Hub in 2015, leading to the creation of the first commercial-grade quantum test network in 2019 and the installation of the UK's first quantum-secure industrial network in October 2020."

Jonathan Legh-Smith,
Head of Scientific Affairs, BT

2.2 Moving closer towards commercialisation

Since 2014 when the first phase of the Programme began, great strides have been made. The UK is now a globally-recognised centre of excellence for quantum science and technology development. The UK quantum sector has grown considerably, becoming a byword for profitable co-operation between Government, academia and industry. In phase two more than half the funding for innovation programmes is now expected to come from the private sector. Altogether, the National Quantum Technologies Programme is currently expected to represent a £1bn public and private investment over its planned 10-year term (2014–2024). Innovation funding and the Hubs have been the engine providing mechanisms for industry to access research excellence and facilities through collaborative projects.

The Hubs have become a touchpoint for industry and academia, supporting the development of early demonstrators. These have in turn developed into ISCF projects for the next crucial stage of their journey to commercial viability. In a further sign of the energy, innovation and demand now being generated, wave 3 ISCF competitions have so far received applications from over 140 companies, 80 which of are involved in projects.

Strengths in Places

The UK Quantum Technology Hubs have considerable regional strengths, acting as centres for innovation and creating clusters of high value activities across the UK. This has helped to attract significant additional regional investment, contributing to growth and wealth creation across the nation. Critically, the NQTP has ensured a harmonised approach across different parts of UK government, industry and academia. Co-ordination through programme partner work aligns activities, enabling the community to work to a common goal and achieve outcomes that are greater than the sum of its parts.

2.3 Building on our momentum

The UK is in a strong position to benefit from the growth opportunities promised by quantum technologies but the global landscape is competitive. To realise the benefits of our world leading position we need to strengthen what has underpinned our success to date: research excellence, the coherent commercially-focused approach, a favourable business and regulatory environment, and existing advanced manufacturing capabilities.

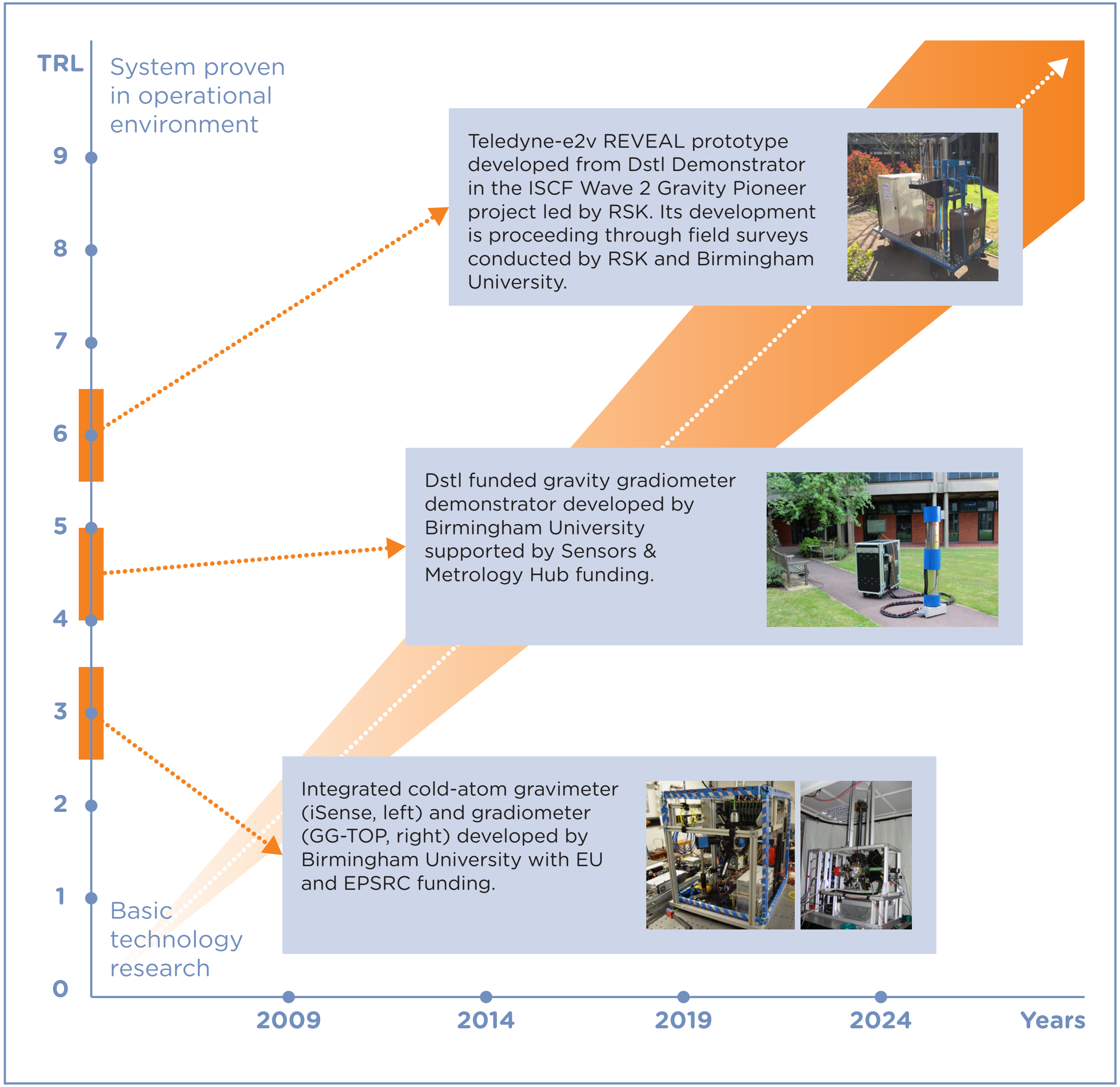
This document sets out the NQTP's approach to nurture, protect and sustain these capabilities, retaining benefits in the UK and putting quantum products and services in the hands of users.

Case study:
Field-deployable cold-atom gravity sensing

The National Programme has sought to deliver rapid quantum technology development through coordinated investment by government and industry.

In this case, sustained funding through the UK Quantum Technology Hub in Sensors and Timing, and the ISCF Wave 2 Gravity Pioneer project, as well as other industry and government partners, has led to the development of a prototype quantum cold-atom sensor to detect and monitor objects beneath the ground.

Quantum gravity sensors could have wide-ranging uses in earth and climate sciences, agriculture and water management, surveying (infrastructure, oil, gas and minerals), and in navigation.



TRL – Technology Readiness Level

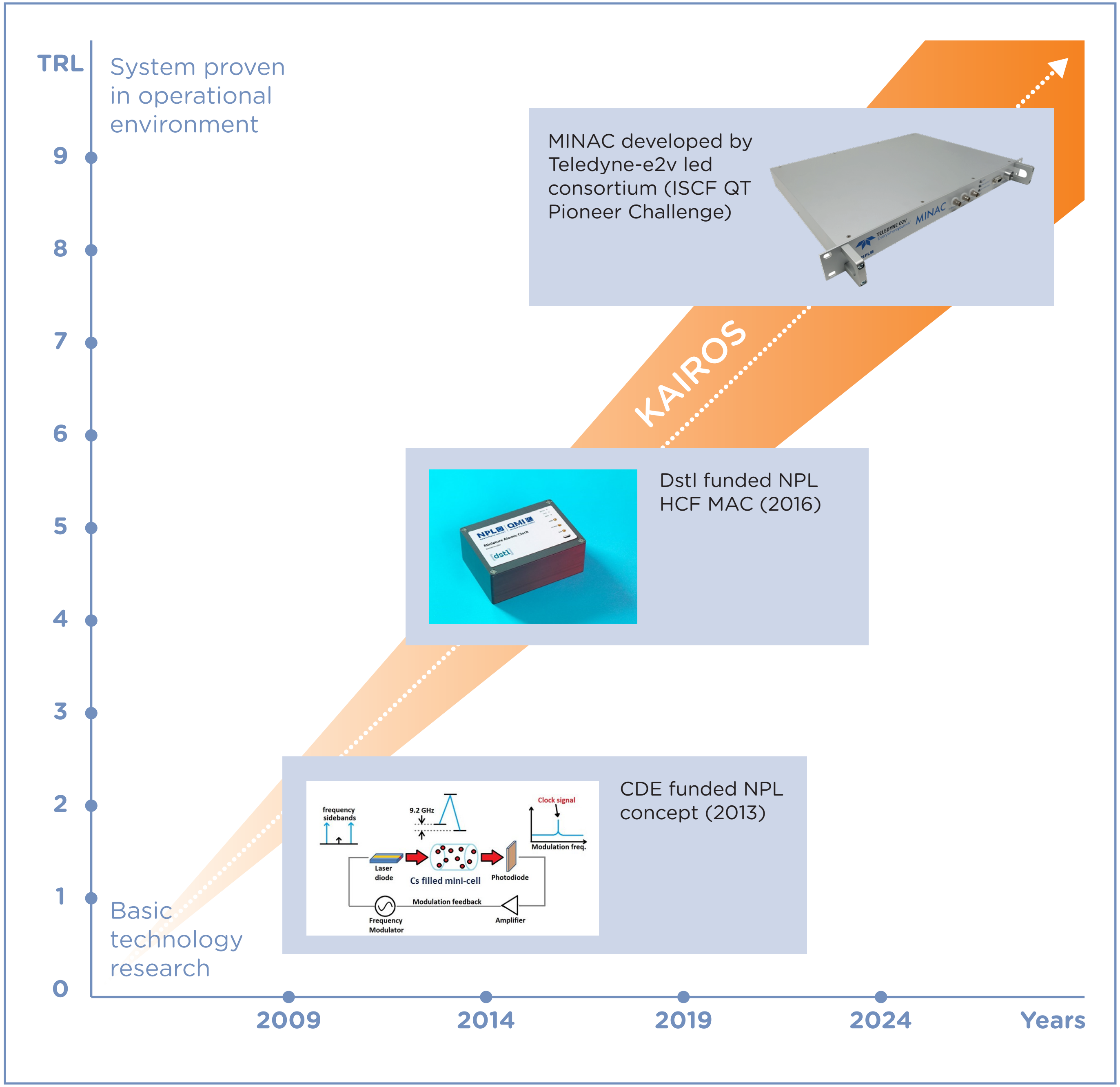
Case study:
Miniature atomic clocks for precision timing across the globe

Atomic clocks use the quantum nature of atomic particles to provide highly accurate timing for quantum technologies, with applications across a wide variety of technology sectors, including defence and security, space and aerospace, telecoms, and infrastructure. For example, atomic clocks can be used to time stamp high-frequency trading transactions in financial markets, ensuring that an accurate record is kept that is impervious to hacking or other disruptions.

Work has been underway since 2013 to develop a UK supply chain of miniature, eventually chip scale, atomic clocks.

After a 2013 Centre for Defence Enterprise call to develop a miniature atomic clock, Dstl funded NPL to develop the Hollow-Core Fibre Miniature Atomic Clock (HCF MAC) concept with better performance than Microsemi's chip-scale atomic clock (CSAC).

The output from this project at TRL ~4 is being commercialised by the ISCF Wave 2 Pioneer atomic clock project KAIROS, led by Teledyne-e2v with 9 other project partners. This miniature atomic clock (MINAC) aims to exceed CSAC's claimed stability at 1000 seconds by at least one order of magnitude.



TRL – Technology Readiness Level

Case study:
M-squared lasers

M Squared is a global photonics and quantum technology company and systems integrator. Since 2006, M Squared's light-based technologies have been helping to move novel science from the laboratory into the real world.

The Glasgow and London-based company is a major exporter of lasers and related systems for the global quantum community, achieving an export rate of ~90 per cent and active in over 30 countries, representing all major research economies. Currently, M Squared's hardware is used in the majority of active efforts in cold matter-based quantum computing programmes.

"We are responsible for achieving what we believe to be several UK quantum firsts, such as the first commercial quantum gravimeter and the first commercial quantum accelerometer. The team has established core capabilities in cold atom technologies through several Innovate UK-funded collaborations. The National Programme's support for cold atom gravimeters and optical lattice clocks has yielded several UK firsts in the commercialisation of integrated quantum systems and established several new and emerging product lines.

We are now leading the UK's largest industry-led consortium to commercialise quantum computing. DISCOVERY is an Innovate UK-funded, £10m project designed to address technology barriers to commercial quantum computing, it will both build on our national capabilities and drive significant advancements in making phonotics-enabled quantum computing a reality."

Dr Graeme Malcolm OBE, CEO and Founder, M Squared

MSquared's quantum accelerometer developed with Imperial College London with support from Dstl funding, pictured at MSquared's Quantum Innovation Centre in London.

3. Driving Commercialisation and Industrialisation

Quantum as an enabling technology

3.1 Stimulating market pull and investment

As the sector matures, the programme intends to shift the balance between public and private funding over the next decade; making a significant contribution to the Government's 2.4% R&D target. The partnerships initiated by ISCF projects need to continue to grow and demonstrate value to encourage investment into the UK. The programme will work with the UK's major sectors to map out time to impact. The NQTP will need to evolve, continuing to encourage demonstration but also increasing the focus on stimulating VC and corporate investment. The programme will continue to work to cement the UK's position as the top destination in Europe for VC[5], with inward investors attracted by our talented and diverse workforce, our innovation ecosystem as well as our cutting-edge technologies and services.

Government will need to explore how it can act as a customer for quantum-enabled products and services which could impact significantly on society. New mechanisms may also be needed to further encourage the exploration of potential applications by key markets.

Standards play an important part in enabling integration of quantum devices into wider complex systems. We will look to develop a more proactive approach to shaping standards with international partners and relevant Government standards bodies.

For quantum computing we will work through the newly established NQCC, the relevant Hub and industrial partners to explore applications for this emerging capability. We will establish collaborations with scientists and industrial partners across a diverse set of interests to learn how their research and operational challenges can transfer from traditional high-performance computing environments to that of quantum computing.

3.2 Unleashing innovation and the emergence of a sustainable quantum ecosystem

The programme will focus on translating quantum technologies from academic research into prototype devices. This is critical for demonstrating usefulness to commercial applications. A thriving innovation culture is key to capturing the benefits of any emerging technology, and quantum is no different.

The ISCF for quantum technologies has ensured access to funding so that innovative ideas can be developed, helping fledgling ventures to collaborate with industry and academic partners and overcome commercial and technical challenges. The NQTP has served as a crucial landing platform for spin-outs emerging from academia. It also serves as an entry point for interested end-users to explore commercial opportunities and develop prototype devices and products.

Demonstration and proof of concept work is vital, but the programme also recognises that it is the mass production of quantum devices that will be the true test, closing the loop from research through to industrialisation. The opportunity for commercial exploitation is now imminent for some quantum enabled technologies and the UK will build on the experience of its successful photonics and wider advanced manufacturing industries to enable scale-up of the production of new devices and systems.

The programme will continue to fund collaborative R&D and feasibility projects designed to grow the supply chain and push quantum technologies up the maturity levels, reducing costs and facilitating mass production for global markets.

[5] https://blog.dealroom.co/wp-content/uploads/2020/01/2019-A-record-year-for-VC-investment-in-the-UK.pdf

Case study:
SPLICE: gas plume visualisation technology

- Uses time correlated single photon counting and exploits previous NQTP funded R&D in QuantIC and Bristol University
- £2.46m grant funding from IUK to commercialise world-leading technology for gas imaging
- 11 organisations, led by QLM, evaluated by NPL, and including end users National Grid Plc, Ametek Land and BP
- Addresses a multi-£100m business opportunity to help the global oil & gas industry combat climate change

Single photon lidar imaging of carbon emissions

- Accurate, repeatable, eyesafe measurements at standoff distances of 150m
- Uses mature telecoms technology for affordable and versatile emissions monitoring systems
- Portable and simple to use and export data
  — Heat maps overlaid on visual scene and, with known wind velocities, gives dynamic leak rate data in near-real time
  — Pre-programmable, autonomous measurements for a range of emissions

www.thespliceproject.com

Case study:
NISQ.OS

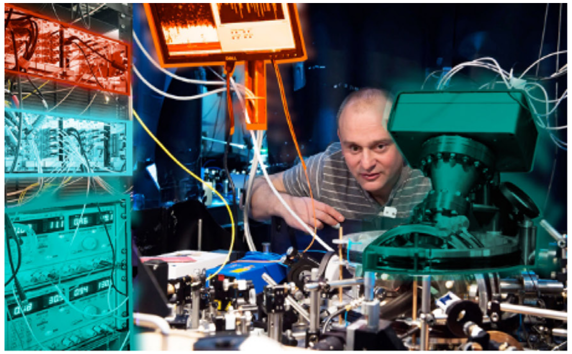
NISQ.OS is a an ISCF wave 3 challenge consortium, which has been awarded a £7.6m grant to develop one of the world's first quantum computing operating systems – Deltaflow.OS – which will be deployed across all major hardware platforms.

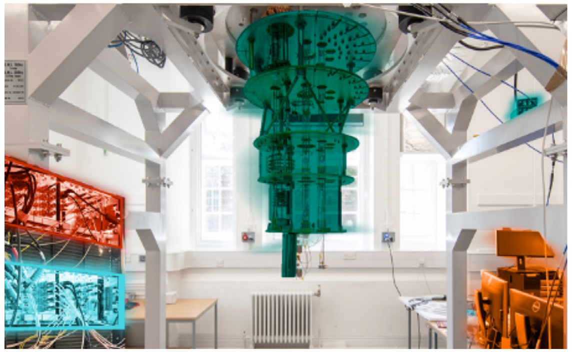
The project is being led by Riverlane, based in Cambridge, working alongside innovative hardware companies SeeQC, Hitachi Europe, Universal Quantum, Duality Quantum Photonics, Oxford Ionics, and Oxford Quantum Circuits, as well as chip designer Arm and the National Physical Laboratory.

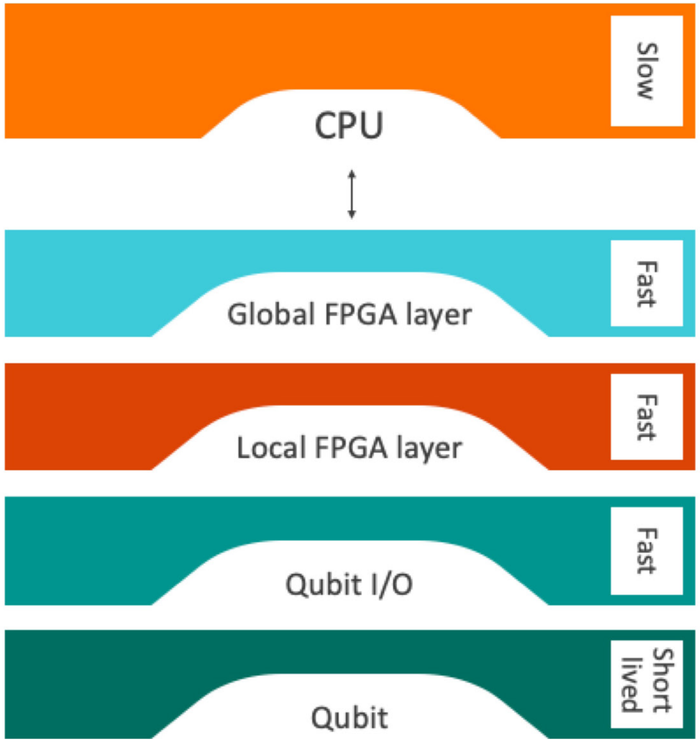
In September 2020, Deltaflow.OS was successfully trialled on a quantum computer at the University of Oxford in partnership with quantum hardware company Oxford Ionics. The software successfully completed a key technical task through its interface, referred to as the 'hardware abstraction layer'.

Deltaflow.OS will be installed on all working quantum computers in the UK which includes all four quantum hardware technologies: trapped-ion qubits, superconducting qubits, silicon qubits and photonic qubits.

Deltaflow.OS exposes the different elements of the full quantum computing stack, helping to improve the performance of quantum computers by orders of magnitude and make applications portable to all qubit technologies.







Case study: QKD-based communications systems

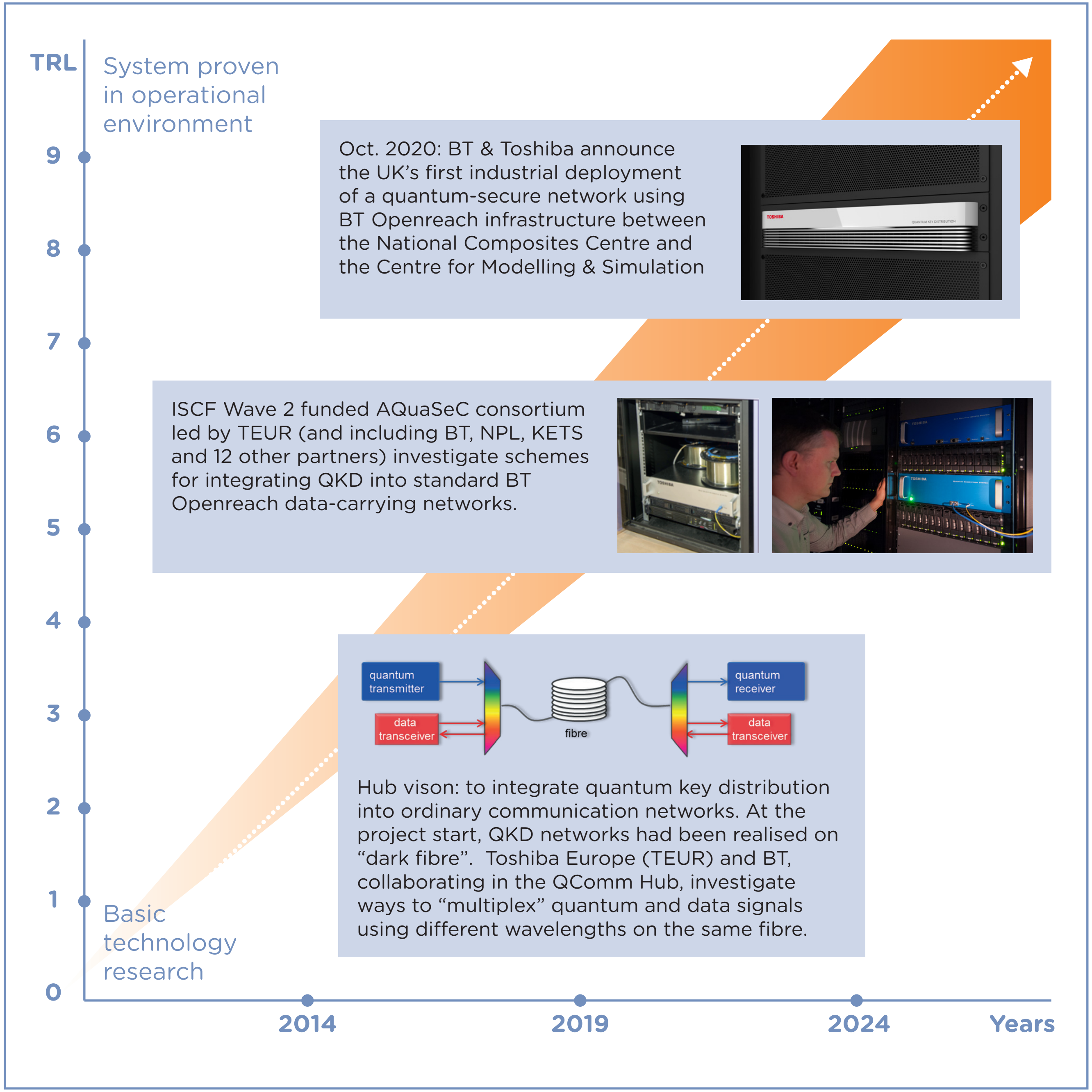
Over the first five years, programme partners led by the UK Quantum Communications Hub have advanced proven concepts for secure communications, such as quantum key distribution (QKD), towards commercialisation. This has included building the UK's first quantum network and work on international standards.

Improvement in secure transmission of information is an important requirement for government, businesses and individuals. Public (shared) key cryptographic systems, based on current cryptographic algorithms using one-way functions, may become vulnerable to attack by future quantum processors.

Quantum key distribution is a provably secure (provided certain system vulnerabilities are protected), mature quantum technology for the secure transmission of encryption keys. The Quantum Communications Hub is developing a number of approaches to this technology, including chip scale, portable QKD-based devices which are robust, cost-effective and, through mass manufacture and integration into conventional technologies, commercially viable.

QKD-based communications systems are expected to find widespread use in the world's future secure communications infrastructure, from financial transactions and the handling of personal information, to managing smart grids.

An evolved Hub vision for 2019 onwards includes QKD in space, hybrid QKD/PQC (quantum-resistant conventional cryptography) systems and entanglement distribution towards a future quantum internet. Breakthroughs in entanglement networking have already been achieved.



TRL – Technology Readiness Level

Building on regional strengths

Case study: Compound semiconductor cluster

Since 2015, a regional cluster in advanced semiconductor (CS) materials and manufacturing has emerged in South Wales.

Leading-edge university researchers have been brought together with high-tech companies focused on delivering market-ready products with critical application in quantum technologies.

This activity has been underpinned by the UKRI Strength in Places Fund through the establishment of centres of excellence, such as the Institute for Compound Semiconductors and a Future CS Manufacturing Hub, both located at Cardiff University, and the new Centre for Integrated Semiconductor Materials at Swansea University. IQE, a global leader in the design and manufacture of semiconductor epiwafer products, has been the driving force of much of the industrial activity.

The NQTP seeks to build on this regional excellence, and to date the cluster has been a UK manufacturing source for novel quantum components. In the first phase of the Programme it participated in multiple collaborative research projects to deliver prototype components, such as lasers for atomic clocks and magnetometers, single photon sources for QKD in terrestrial and satellite applications, and single photon detectors for quantum imaging and sensing systems.

In September 2020, the cluster initiated the UKRI funded £4M project QFoundry. This project will deliver a national open-access quantum semiconductor device foundry and create the foundations for robust, scalable component manufacture in the UK to enable the scaling of a quantum technology system industry.

‘Compound semiconductor’ materials, composed of chemical elements of at least two different species, are a key enabling supply chain technology for fields such as quantum technologies because they offer a hundred-fold improvement in processing speeds over traditional ‘silicon-only’ semiconductors. They offer huge advantages not just in storing and transmitting data but also in emitting light, very high temperature operation, and saving energy.

Building on regional strengths

Case study:
Photonics cluster

Scotland has a vibrant and long established sector in the field of photonic technologies, with an annual industrial turn-over of £1.2bn in 2018 (Photonics Leadership Group), which in turn has led it to be an important region for quantum technology development in the UK.

The region is marked by the emergence and growth of innovative start-ups, leading manufacturers (such as Coherent Scotland and M Squared), and large defence systems integrators with strong laser and radar divisions. This is combined with a world-class research base, with several universities having extensive legacies in lasers and photonics as well as in quantum optics and cold atom work.

The cluster is also supported by other leading research & development and innovation centres such as the James Watt Nanofabrication Centre based at the University of Glasgow, and the Li-Fi Centre at the University of Strathclyde.

Helping to tie the ecosystem together is the Fraunhofer Centre for Applied Photonics UK, a world-leading centre in applied laser research and development.

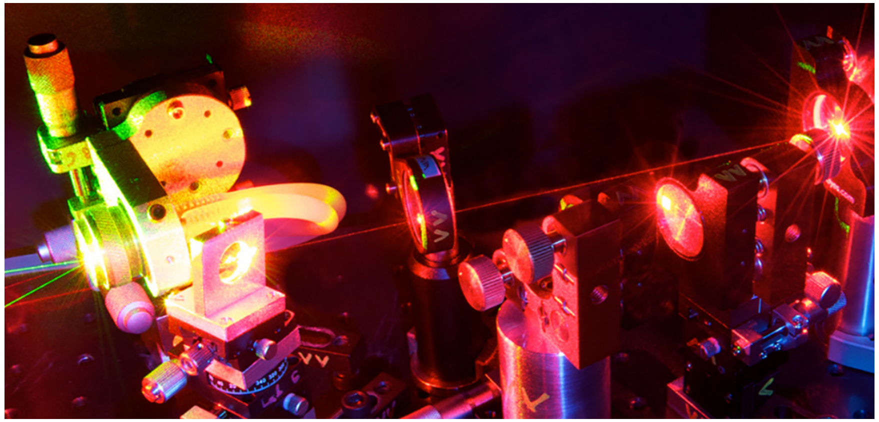
The network of institutions in the Central Belt is closely tied to the NQTP, notably through the Quantum Imaging Hub (QuantIC) led by the University of Glasgow (partnered in Scotland with the Universities of Edinburgh, Heriot-Watt and Strathclyde), but with the other three of the UK's quantum technology hubs also having a strong presence in university physics departments in Scotland.

To date, Scottish organisations have been involved in 90 of the Innovate UK funded NQTP projects. In ISCF-supported quantum technology projects roughly a third of project partner (or leader) roles are filled by Scottish organisations, with Fraunhofer CAP and MSquared Lasers leading the way.

Photonics is the science and technology of the creation, manipulation and detection of light to deliver advances in areas as varied as materials processing, displays, healthcare imaging, robotics, and the UK's communications infrastructure. Photonics plays a central role in the enhanced power and performance of quantum technologies.

The photonics industry is worth over £13bn annually to the UK economy, with regionally distributed GVA/employee of £70k–£90k (£89.5k in Scotland in 2018).

Photonics Scotland
THE SCOTTISH OPTOELECTRONICS ASSOCIATION



3.3 Making the UK the go-to place for companies to start and grow, and for multinationals to base their quantum activities

The UK is a global hub for science and innovation, ranked fourth on the Global Innovation Index[6]. The NQTP and its associated world-leading academic centres, its industrial strengths, talented people, and the UK's business-friendly environment have made the UK attractive to set-up, scale-up or relocate quantum businesses and activities. This is evidenced by the significant number of new spin-outs and the number of key multinationals who have recently located research activities to the UK.

The UK is particularly well placed to draw in more investment and talent with an innovative and transparent regulatory environment, world-class IP and competitive tax regimes, as well as a highly skilled workforce and dedicated visa schemes for innovative companies. The UK's high value manufacturing capabilities, the existing presence of key systems integrators capable of creating and integrating complex systems and end use sectors for quantum has increased the draw for many companies looking to successfully incubate ideas and take advantage of the interconnected innovation ecosystem and supply chains.

Innovation funding through the ISCF is a significant draw for companies due to the collaborations it creates, but also the private investment it attracts into the sector. Alongside innovation funding, the Government's 10-year action plan to unlock over £20 billion to finance growth in innovative firms sets out a series of measures to encourage investment into the sector. This includes the establishment of the British Patient Capital Programme[7] and the National Security Strategic Investment Fund (NSSIF), which are supporting businesses to grow and draw in long-term equity investment.

"The UK National Quantum Technologies Programme has been critical in supporting our development of a range of reduced SWAP-C Laser products and photonic components to enable the transition of Quantum instruments, such as Clocks, Gravimeters and Magnetometers, from the research lab to real-world applications. The funding from the NQTP has allowed significant multi-million pound co-investment from our Parent Company, TUV NORD, and has ensured that our UK site is recognised within our Group as our Global Centre of Excellence for Quantum and Photonics, which in turn is driving significant job creation and future investment in new applications across our Group. The national programme has also given us the opportunity to work with some of the best academics and researchers in the UK and indeed in the world. Such collaboration has been critical as we made a difficult transition from a mostly manufacturing services company to one offering products as well."

Stephen Duffy, CEO, Alter Technology UK

[6] https://www.wipo.int/global_innovation_index/en/2020/

[7] The £2.5 billion British Patient Capital Programme is aimed at leveraging an additional £5bn of patient capital from the private sector and the £135mn NSSIF is supporting businesses to grow and draw in long-term equity investment into technologies that could contribute to the UK Government's national security mission.

4. Research

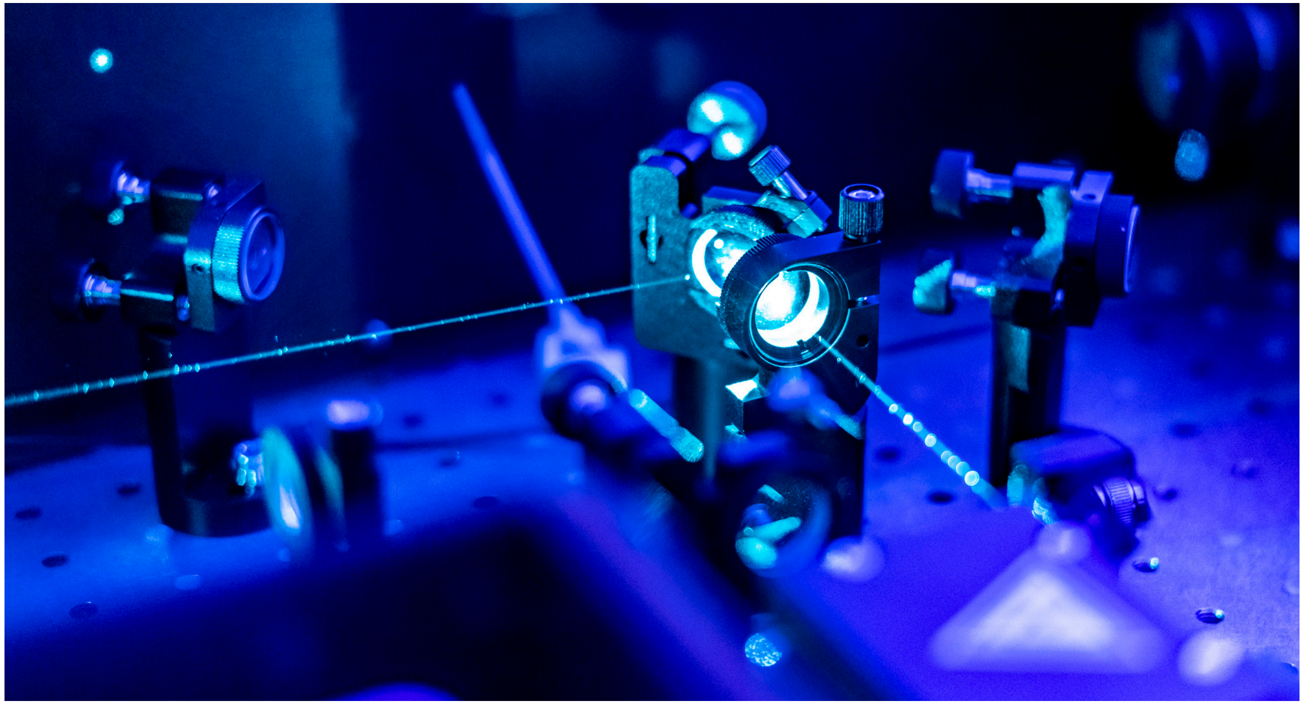
Generating new ideas

Through the four Quantum Technology Hubs and the wider community, the UK has established itself as a major player in the field of quantum research. The UK has flourished by producing world leading research and forming lasting partnerships between industry, Research and Technology Organisations (RTOs), academia and government. This is supporting the rapid exploitation of quantum technologies on the road from academia to business and towards industrial maturity.

It is imperative to build on previous success and knowledge to grow the UK portfolio of quantum science and technologies research. Funding for the continuation and evolution of the four Quantum Technology Hubs, the recent investment in the National Quantum Computing Centre[8], and the recently funded UKRI Quantum Technologies for Fundamental Physics Programme[9], demonstrates a continuing ambition to grow and evolve research and technology development activities within the programme. However, we need to continue to ensure that the UK has a balanced portfolio, is flexible and open, so that promising quantum technologies continue to emerge.

We are increasingly seeing convergence as technologies are used in combination to unlock innovation through the creation of integrated systems. As a result, there is a growing need for interdisciplinary collaboration, bringing together the physical sciences with engineering, mathematics and computing disciplines to enable products to be developed that will meet the needs of industry. The programme will encourage this interaction to take place through an enhanced programme of research activities, overcoming technical challenges, creating a skilled workforce, and strengthening our global position in research.

Because protection of intellectual property and ensuring adherence to regulatory frameworks are critical issues for research integrity and the quantum technology community in the UK, the Programme will continue to champion responsible and trusted research activities.



[8] Jointly delivered by EPSRC and STFC.

[9] A £40 million joint initiative between STFC and EPSRC to explore how quantum technologies can be applied to the fundamental mysteries of physics.

5. Building National Capabilities

Building a resilient network of national capabilities and mutually beneficial international partnerships for the benefit of society and the economy

Combined activities and facilities across the programme will create a network of national and international capabilities for academia, industry and government. This will ensure the UK has assured capabilities across the technologies to meet societal, economic and national security objectives, and will build resilience into the sector and the wider economy.

The global quantum landscape is rapidly evolving. To support and grow our capabilities the NQTP will continue to engage international programmes and link with government agencies where our security and prosperity objectives align to ensure that programmes, such as those resulting from global expert missions[10], continue to grow mutually beneficial relationships with other nations and act as a leading voice for technology development on the global stage. As investment accelerates globally and quantum expertise flows to where it is most encouraged our capacity to collaborate will need to increase.

The UK quantum sector will need some protections against the potential loss of intellectual property and capabilities critical to its future sustainability and integrity. Measures may be necessary to assure the long-term leadership, research integrity, and commercial competitiveness of the sector and to enable companies to work effectively across borders. The NQTP is committed to working with its partners and collaborators to align security, defence and prosperity objectives with the sector's long-term goals. We will consider the full spectrum of levers available to create the best environment for UK quantum technology businesses to innovate and grow with confidence.

The programme will be forward looking in its consideration of future national and international regulatory issues that may impact on the sector or its ability to stimulate growth and realise societal benefits.

The National Quantum Computing Centre, launched in September 2020, to help deliver quantum computing capabilities for the UK and support the growth of the industry.

The vision is to be a world class centre, where government, academia and industry work collaboratively to develop quantum computing, securing this strategically important technology for the benefit of the UK.

The centre will support the development of a quantum ready economy; one that can take advantage of the opportunities presented by quantum computing to generate and retain value across the economy, achieve societal benefits and maintain national security.

The centre's strategic intent is to:

- Establish a UK trusted authority
- Create a UK capability
- Promote and drive quantum computing within the UK economy
- Catalyse the UK supply chain delivery into the emerging quantum computing sector
- Establish a focus for the rapid development of quantum computing in the UK
- Create a landmark facility on the Harwell campus

As part of its Strategic Intent document, the centre has developed a technical roadmap for quantum computing.

Above: An artist's impression of the new NQCC facility, due to be built at the Harwell Campus in Oxfordshire.

[10] The Global Expert Missions (GEM) programme is funded by Innovate UK to support the Industrial Strategy's ambition for the UK to be the international partner of choice for science and innovation. To-date the programme has run GEM's on quantum technologies to Canada and the US.

The Quantum Metrology Institute at the National Physical Laboratory, launched in 2015, is focussed on building and delivering an enduring capability to support the UK's objectives in quantum technologies.

The NPL quantum programme includes:

- Designing, building and commissioning quantum test and evaluation infrastructure to accelerate the commercialisation of new products based on quantum technologies.
- Delivering technology development projects as part of the quantum technology hub programme.
- Partnering in quantum product development projects led by industry as part of the ISCF programme.
- Researching alongside universities in academic-led Quantum Technology for Fundamental Physics projects.
- Supporting skills and training at all levels in quantum science and engineering.
- Delivering National Metrology Institute work on new scientific developments, international metrology and quantum standards.

The QMI consists of more than 80 staff scientists, hosting over 30 PhD students from UK universities across the country. In 2021 the Advanced Quantum Metrology Laboratory (AQML) will open, expanding NPL's capacity to build new infrastructure and to host industry and academic partners.

6. Skills

Creating the next generation of researchers, quantum entrepreneurs and business leaders in the UK

People and know-how are the most important elements of the emerging ecosystem. The UK needs a creative, agile and adaptable, diverse and networked workforce with the right balance of skills to ensure it benefits from opportunities in quantum technologies.

The transition of quantum technologies into commercial products requires a new generation of quantum physicists, engineers and mathematicians who are fluent in multi-disciplinary and systems-based approaches, possess the right entrepreneurial and business skills, and can adapt to new roles in the industry. The continued growth of manufacturing capabilities relies on a ready supply of skilled engineers and machine operators.

Skills providers must offer a balance of training to satisfy the demands of industry and research organisations. Higher education activities aligning to the work of NQTP have started, but more is needed to diversify the quantum technologies workforce. Industry must engage with providers throughout the skills pipeline – from vocational training routes through to PhD opportunities – to ensure that needs are met.

Co-working between people from different backgrounds and specialisms is key to creating this diverse and well-rounded skillset. This means bringing together people from relevant industries to work alongside quantum researchers.

The sector faces a challenge in growing the diversity of its people. To address inequalities at every level it will be necessary to work with thought leaders in the social sciences and the third sector to better understand the challenge we face and ensure that we build an inclusive culture where anybody can succeed and they are encouraged to do so.

The NQTP partners will work with skills providers and industry to encourage rapid learning and a positive flow of skilled people into the UK. We will explore approaches that enable students, researchers and those in the private and public sectors to develop familiarity with quantum technologies and commercial awareness, knowledge of intellectual assets and entrepreneurial skills.

Given the scale of global competition, there is a risk that the flow of people skilled in quantum technologies out of the UK will outweigh those coming in, harming the UK quantum technologies ecosystem should the UK not have sufficient measures to attract and retain these individuals. The scale and depth of Programme activities alongside Fellowships will continue to play a key role going forwards but further thought needs to be given to ways of proactively backing people and great ideas.

Postdoctoral demand continues to be strong across academia and industry. The programme activities provide a pipeline of highly skilled postdoctoral researchers in quantum technologies to maintain the health of the discipline and future leaders.

In the early stages of business growth, doctoral skills requirements are likely to continue to dominate, but as the sector grows, and within existing industrial components of the emerging ecosystem, there will be a need to ensure that wider skillsets exist. Early indications suggest that further efforts are required to grow technical and fabrication capabilities and there is a need to attract and provide opportunities for the UK's advanced manufacturing workforce to move into the sector. For quantum computing specifically, there will be a need for a significant number of engineers, technicians, mathematicians and software engineers as machines start to scale, as well as commercial staff with a sufficient understanding of quantum computing. The programme partners will work with industry and professional bodies to better understand the growing sector's skills needs and design vocational training programmes and conversion courses to meet demand.

PhD training routes
Support for doctoral students in quantum technologies is met through the Doctoral Training Partnership and Centres for Doctoral Training through EPSRC (representing £50m of investment to-date) and Dstl's PhD sponsorship. They produce high quality graduates to meet the skills demands of the sector. The centres have strong links with over 20 industrial partners enabling students to be exposed to, and undertake projects relating to, real world problems. There is demand for individuals with doctorates in quantum science and technologies as demonstrated by high employability rates of graduated students within quantum.

“It is the combination of the fundamentals of quantum physics and mathematics with engineering that makes this a truly successful approach to training.”

BAE Systems on the Quantum Technologies CDT approach

Person profile: Anthony Laing

My 5 year, £1.2M EPSRC fellowship was awarded at the end of 2015, when I was a postdoc. A month later I was appointed as a lecturer at Bristol.

The broad aims of my fellowship were to use integrated quantum photonics to simulate the dynamics of molecules. The work led to a number of papers, in particular for Nature in 2018 which experimentally demonstrated new quantum algorithms for simulating molecular processes (e.g. breaking apart of ammonia) and a Nature Physics paper in 2017 which pinpointed the boundary for quantum advantage in photonics (i.e. showed how big and complex our experiments need to be before they outperform supercomputers).

Based on these successes, I then became the Photonics WP leader in the National Programme phase 2 QCS Hub. I co-founded Duality Quantum Photonics to take the next steps in building the quantum simulators that were conceptualised for my fellowship. We have secured £1M funding, including an Innovate UK project.

I am now an Associate Professor at Bristol with a research group of 15 extremely talented young scientists.

This journey would not have been possible without my EPSRC fellowship, and the wider support from the EPSRC team, who have been brilliant. To give a bit more context here, in 2001 as a 25 year old mature student from the North East with no A Levels, I joined Bristol's undergraduate course 'Physics with a Preliminary Year'. Winning my fellowship in 2015 was a dream come true and I made the absolute most of its flexibility – it has really transformed both my international profile and my personal development.

Person profile: Michael R. Vanner

I am a UKRI Future Leaders Fellow and lead the Quantum Measurement Lab (qmeas.net) at Imperial College London. We pursue a combination of experiment and theory to deepen our understanding of the very foundations of quantum physics and to develop powerful new quantum technologies. To follow this research programme, we combine the exquisite precision of quantum optics with the versatility of micro and nanofabrication to create and study quantum states of motion of mechanical oscillators. This opens a rich new avenue for quantum science and technology including testing quantum superpositions at an unprecedented scale, performing quantum sensing of very weak forces, and sidestepping current roadblocks in the development of quantum memories and transducers for quantum information processing.

My team is supported by a UKRI Future Leaders Fellowship (£1.6M), an EPSRC Strategic Equipment Grant (£1.6M), the Royal Society, DSTL, and STFC. This level of support enables our team to compete at the forefront of quantum science, internationally, and a real strength of the UK system is the excellent opportunities available for early-career researchers.

Person profile: Ilana Wisby

I gained my PhD in quantum physics from Royal Holloway, University of London, where I spent most of my PhD as a student in industry at the National Physical Laboratory, Teddington. After my PhD I entered the world of start-ups with a number of different companies before merging my quantum and start-up experience in early 2018 when I joined Oxford Quantum Circuits (OQC) as the CEO. Since then I have ensured that the company remains at the forefront of the quantum revolution. Having built what we believe to be the UK's most advanced quantum computer, and the only one commercially available, we are creating the core of the quantum revolution.

Recently OQC, along with our partners from the academic and commercial spheres, have been awarded grants totalling just under £10m across two ISCF wave 3 quantum challenge projects, helping to accelerate the development of our technologies and grow our commercial presence. These projects aim to address the technological challenges in the manufacture and measurement of coherent superconducting devices and will build a hugely innovative quantum operating system. These projects began in the summer of 2020 and are making excellent progress, enabling companies and academics to interact and speed up development feedback loops.

Person profile: Steve Brierley

I spent 10 years as a leading academic at Cambridge and Bristol universities on algorithms and architectures for quantum computers. This was followed by 8 years at the Heilbronn Institute (part of GCHQ) and time within industry. In 2017 I founded Riverlane which is developing an operating system for quantum computers (think windows for quantum). In 2019 we secured funding from Amadeus, Cambridge Innovation capital and Cambridge University. Over the next year our operating system will be installed on 20% of the world's quantum computers and we are expanding in to the US, EU and Asian markets.

Using ISCF wave 3 challenge funding, Riverlane built the perfect customer reference program for our operating system with 6 hardware manufactures, every major technology platform for quantum and expertise in standardisation and digital computing (NPL and ARM). This could only happen in the UK. The UK has the highest concentration of quantum hardware companies of any country in the world, world beating hardware technology and leading experts in quantum applications. This is a direct result of the prior investment into quantum technologies by the UK over the past 10 years.

The quantum computing industry is at an inflection point: moving from physics to engineering. The long track record of Cambridge as a centre for computer innovation means that we are able to recruit the world's best engineers and the UK's position in quantum means we can build a world leading product. The UK missed out on creating a global category leader in the first digital revolution – we don't intend to make the same mistake again.

Person profile: Richard Walker

I have a background in physics and microelectronics. After eight years of PhD and postdoctoral research experience leading on the design and development of 3D imaging equipment and scientific image sensors with both academic and scientific partners, I was awarded an RSE Enterprise Fellowship allowing me to co-found Photon Force as a spin-out from the University of Edinburgh in 2015.

This led to us winning first prize in the Converge Challenge – Scotland's premier company formation competition – and receiving a Scottish Edge Award. It's been a real pleasure to bring a fantastic, highly-skilled team and collaborators together to design and supply innovative time-resolved, single photon sensitive cameras. Our customers use our products to push boundaries in fields such as quantum optics and biomedical imaging.

For me, one key strength of the NQTP and the UK quantum community is the support of not only quantum systems but also the key component technologies. We have collaborated with the QuantIC Hub and received multiple grants through the ISCF Commercialising Quantum Technologies Challenge. Inclusion of the component supply chain is crucial, as this helps bring new products to market in the short, medium and long term, resulting in a quick but sustained return on investment. As an example, the UK leads the world in the commercial supply of ultra-high speed, time-resolved SPAD sensors, and it's a privilege to have personally been part of that journey from early stage academic research, through to technology transfer, product R&D and commercialisation; with the early support being crucial to our later commercial success.

The UK is very well placed to continue the development of new quantum devices and systems, thanks to a robust research sector and resourceful entrepreneurial community, with the backing and funding supplied through the Quantum Technologies Programme and Quantum Hubs. The security that this type of funding brings enables higher risk developments to be undertaken, with the results providing ground-breaking technology that solidifies the UK as a world-leader in the supply chain.

Person profile: Carmen Palacios-Berraquero

I carried out my PhD and postdoctoral at the Cavendish Lab, studying single-photon sources in novel 2-dimensional materials via experimental quantum optics. During those years we discovered how to reliably create quantum emitters in these materials and patented the invention. In 2019, I co-founded Nu Quantum with Matthew Applegate, another researcher at the Cavendish who had also filed several patents on detection and information theory.

Nu Quantum has been fantastically supported by the Quantum ISCF. We have been awarded 4 grants totaling £3.6m, with the aim of developing our technology, testing it, and piloting its compatibility with different commercial systems including quantum communication, in collaboration with over 30 partners, including the likes of BT and NPL. These projects began in the summer of 2020 and they have already been incredibly fruitful. The opportunity given to Nu Quantum by this initiative has been and will continue to be instrumental to our development.

In my opinion, the strength of the UK quantum community is its collaborative approach, the large base of excellent research institutions who lead in quantum, and the quantum programme's capacity – via the right amount of funds and a clever structure – to direct the whole of the quantum community towards commercially-oriented goals. The tech and entrepreneurship ecosystem in Cambridge is, in my opinion, unrivalled in the UK and perhaps in Europe. UK investors have large funds and they are knowledgeable about deep tech, which is instrumental – especially for quantum.

Annexes

Annex 1: Programme Objectives

1. Stimulate market growth, unleash innovation, and create a thriving ecosystem.

The NQTP will:

1.1. Work with sector leads to map out how and when quantum technologies will be applied to unlock innovation across the economy and undertake demonstrator activities in collaboration with industry, building on regional excellence generated by the Hubs.

1.2. Continue challenge-led activities to encourage collaborative innovation between industry, academia government users and integrators to establish suppliers, engage end users and create products and services.

1.3. Stimulate investment through co-investment, investor showcases and wider activities, ensuring companies have access to training and advice about how to start and scale, as well as how to protect their assets and navigate regulatory requirements; identifying applications that may require a regulatory response in the future.

1.4. Strengthen our engagement in the development of international standards and benchmarking and develop testing and evaluation capabilities to support UK market growth and protect national assets.

1.5. Work with industry to understand the UK landscape in the global context, showcase our capabilities and identify opportunities to open-up markets and investments nationally and internationally.

2. Maintain the UK's excellence in research and technology

The NQTP will:

2.1. Ensure that the scale of the quantum research programme protects the pipeline of excellence in quantum science research and that our activities continue to be characterised by interdisciplinary working.

2.2 Ensure that growing quantum research programmes in engineering and physical sciences continue to be guided by market opportunities and the needs of businesses.

2.3. Undertake an accelerated programme of activities on quantum computing led by the NQCC to enable the UK to stimulate the growth of a sustainable market and remain at the forefront of use case exploration.

2.4. Develop new quantum tools for wider science applications and facilitate the exploration of novel applications.

2.5 Continue to champion responsible and trusted research within the programme to help retain research integrity.

3. Grow, attract and retain talent

The NQTP will:

3.1. Ensure doctoral training for quantum technologies meets the skills demands within industry, while producing highly qualified people to pursue research careers.

3.2. Ensure fellowships programmes attract and retain science leaders and future leaders.

3.3. Raise the profile of quantum technologies amongst the public and within education syllabuses at every level to build the future pipeline and ensure the programme is addressing societal needs.

3.4. Continue to engage with the growing sector to better understand its skills needs for the future.

3.5 Support a diverse and inclusive research environment within quantum technologies to encourage the best talent into research and innovation careers.

4. Build a resilient network of national assets and mutually beneficial international relationships

The NQTP will:

4.1. Continue to manage and build the network of facilities and UK capabilities to ensure it meets the needs of the sector and society.

4.2. Continue to work to identify and develop mutually beneficial global partnerships to achieve this programme's objectives.

Annexes

Annex 2: Programme and governance

The National Quantum Technologies Programme (NQTP)

The NQTP is a ten-year programme (2014–2024) representing £1bn of public and private investment to bring together academia, industry and government to accelerate the translation of quantum technologies into the marketplace, open new opportunities to British businesses, and unlock new capabilities that can make a difference to our everyday lives.

The programme supports investment in research, innovation, skills, technology demonstration, and also funds grants to UK companies to help them identify and develop uses and applications for quantum technologies.

A national network of Quantum Technology Research Hubs has led the development and demonstration of these new technologies in partnership with universities, businesses, and Government departments. Additionally, the Quantum Metrology Institute at the National Physical Laboratory (NPL) provides the measurement expertise and facilities needed to underpin this technology development.

The programme has also been enhanced by aligning with the UK's Defence Science and Technology Laboratory (of the Ministry of Defence) programme to develop demonstrators in quantum timing, navigation and gravity imaging devices, and embedding Dstl PhD students in Hub universities.

Centres for Doctoral Training hosted at UK universities provide training for the next generation of leading researchers in this field.

Launched in September 2020, the National Quantum Computing Centre is the newest addition to the programme. It will bring together the UK quantum computing community to address key challenges, such as scaling-up this technology and making it commercially viable. Working closely with industry and the research community, the Centre will provide businesses and research institutions with access to quantum computers as they are developed around the world and grow the UK's thriving quantum computing industry.

Programme Governance

The NQTP is delivered through the following departments and agencies.

The Programme Board, chaired by Dame Lynn Gladden, provides coordination and strategic direction for the programme, and has representation from each of the partner agencies.

The Strategic Advisory Board, chaired by Sir Peter Knight, provides advice to help steer the strategic direction of the programme, and is made up of eminent figures from across industry, academia, and Government.

The Delivery Group coordinates activities of the partner organisations to ensure that they align with the vision of the NQTP.

Department for Business, Energy & Industrial Strategy

Ministry of Defence

dstl

GCHQ

NPL National Physical Laboratory | QMI Quantum Metrology Institute

UKRI Engineering and Physical Sciences Research Council

UKRI Innovate UK

UKRI Science and Technology Facilities Council

Image credits

Front cover 3D "microtrap" ion trap within a vacuum chamber being addressed by lasers. *Courtesy of NPL*.

Page 6 Dame Lynn Gladden, Chair of the NQTP Programme Board. *Courtesy of Lynn Gladden*.

Page 10 Wearable technologies for brain imaging (top to bottom)

A. Epilepsy surgery in progress at Jaslok Hospital, Mumbai, 2010. Shared under the Attribution-ShareAlike 4.0 International license. *Credit: Mansiagrawal, Wikimedia Commons*.

B. Gen II optically pumped magnetometer (OPM), 2019. *Courtesy of Prof. Matt Brookes*.

C. Wearable optically pumped magnetometer (OPM), 2018. *Courtesy of Prof. Matt Brookes*.

D. Conventional magnetoencephalography (MEG). *Courtesy of Prof. Matt Brookes*.

E. MEG measurements of neural oscillations in schizophrenia. *Courtesy of Prof. Matt Brookes, The University of Nottingham*.

Page 11 Clean growth (top to bottom)

A. AMTE – Electric car lithium battery pack and power connections. *Courtesy of kynny, Getty images*

B. Nemein – Aerial photo of oil rig in a calm, blue ocean. *Courtesy of HeliRy, Getty images*

C. Rahko – Quantum computing concept. Processor of quantum computer. *Courtesy of vchal, Getty images*

D. QLM – Chimneys and cooling tower of a coal fired power station at sunset. *Courtesy of Schroptschop, Getty images*

Page 19 Gravity sensing (top to bottom)

A. Teledyne e2v REVEAL, a prototype quantum gravimeter for subterranean surveying. *Courtesy of Teledyne-e2v*.

B. Gravity gradiometer demonstrator, The University of Birmingham. *Courtesy of Dr Michael Holynski*.

C. GG-TOP, a cold-atom graviometer, The University of Birmingham. *Courtesy of Dr Michael Holynski*.

D. iSense, an integrated cold-atom gravimeter, The University of Birmingham. *Courtesy of Dr Michael Holynski*.

Page 20 Miniature microwave atomic clocks (top to bottom)

A. Teledyne e2v MINAC, a pre-production prototype of a miniature atomic clock. *Courtesy of Teledyne e2v*.

B. NPL miniature atomic clock demonstrator funded by DSTL, 2016. *Courtesy of NPL*.

C. NPL concept diagram of a miniature atomic clock, 2013. *Courtesy of NPL*.

Page 21 A quantum accelerometer developed by M Squared Lasers with Imperial College London, pictured at M Squared's Quantum Innovation Centre in London. *Courtesy of M Squared Lasers*.

Page 23 SPLICE (top to bottom)

A. QLM gas sensing camera concept. *Courtesy of QLM*.

B. QLM example user interface. *Courtesy of QLM*.

Page 24 NISQ.OS: the full quantum computing control stack, pictured alongside quantum computing hardware technologies developed by Universal Quantum and Oxford Quantum Circuits. *Courtesy of Riverlane. Image source top left: Universal Quantum. Image source bottom left: Oxford Quantum Circuits*.

Page 25 QKD-based communications systems (top to bottom)

A. Toshiba's commercial QKD system developed in Cambridge. *Courtesy Toshiba Europe Ltd*.

B. Installation of a prototype QKD system. *Courtesy Toshiba Europe Ltd*.

C. Toshiba QKD system installed at the BT Customer Showcase. *Courtesy Toshiba Europe Ltd*.

D. Quantum and conventional data signals carried on different optical wavelengths can be combined on a single optical fibre. *Courtesy Toshiba Europe Ltd*.

Page 26 Map of compound semiconductor cluster facilities. *Courtesy of Dr. Wyn Meredith*.

Page 27 Photonics Scotland logo. *Courtesy of Simon Andrews*.

Page 29 Laser reflected on optic table in quantum laboratory. *Courtesy of* Михаил Руденко, *Getty images*

Page 30 An artist's impression of the new NQCC facility, due to be built at the Harwell Campus in Oxfordshire. *Courtesy of Dr. Michael Cuthbert*.

Page 31 The new AQML facility at NPL Teddington, due to be opened in 2021. *Courtesy of NPL*.

Page 33 (left to right)

A. Anthony Laing headshot. *Courtesy of Anthony Laing*.

B. Michael R. Vanner headshot. *Courtesy of Michael R. Vanner*.

Page 34 (left to right)

A. Ilana Wisby headshot. *Courtesy of Ilana Wisby*.

B. Steve Brierley headshot. *Courtesy of Steve Brierley*.

Page 35 (left to right)

A. Richard Walker headshot. *Courtesy of Richard Walker*.

B. Carmen Palacios-Berraquero headshot. *Courtesy of Carmen Palacios-Berraquero*.