

# Annual Report 2017



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**Front Cover** Award-winning image of an optical fibre preform illuminated by the light of a hydrogen discharge tube. This will be used to create quantum memories to help in the development of large-scale quantum networks / *Rob Francis-Jones*

**This Page** Vacuum chamber for a cavity-based light-matter quantum interface / *David Fisher / NQIT*



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NQIT's key objectives are to develop the expertise, the partnerships, and the practical components required to build and demonstrate the core of a universal quantum computer.

# Foreword

**The Networked Quantum Information Technologies Hub (NQIT) is the largest of the four Hubs in the UK National Quantum Technologies Programme, a £270 million investment by the UK government to establish a quantum technology industry in the UK.**

NQIT's key objectives are to develop the expertise, the partnerships, and the practical components required to build and demonstrate the core of a universal quantum computer. The resulting machine, called the Q20:20 engine, will bring together the most advanced quantum technological platforms and combine them into a device containing hundreds of qubits that will be at the heart of the first generation of scalable quantum information processors.

The release of our second Annual Report marks the halfway point through NQIT's five-year programme, and we cover the progress made in our second year of the project, up to the beginning of 2017.

The halfway point was marked by a mid-term evaluation by our funding body, the Engineering and Physical Sciences Research Council (EPSRC), as well as a review of the overall UK Quantum Technology Programme by the Strategic Advisory Board. NQIT passed the review with flying colours, supported by very positive comments from the reviewers on our progress towards our objectives. As a consequence, EPSRC confirmed that our funding would continue without change.

The first two years have seen the consortium focus its efforts towards refining the overall system architecture and design to deliver the Q20:20 quantum computer demonstrator. We have made significant advances in both system and engineering design, and identified the most effective components for assembling the system.

We have achieved significant benchmarks in the underpinning core technologies, reaching new performance levels in trapped ion logic gates and quantum photonic networks, as well as delivering new quantum science in diamond defects and superconducting circuits.

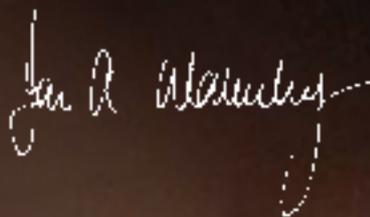
As part of our preparation for the review we evaluated all elements of our programme. As a result, we realigned the applications theme, introducing emulation as a key element of the project.

The applications theme now covers all aspects of programming of a quantum computer, from hardware-specific "machine code" to high-level languages that will inform future compilers. The emulation work is supported by software engineering through Partnership funding that will enable us to work with new users, to explore the use of quantum computing in specific applications of interest to individual users.

One of the review outcomes was a mandate for the Quantum Technology Hubs to work more closely together. In response to this, NQIT has taken on the task of leading the work on Responsible Research and Innovation for the National Quantum Technology Hub network, in partnership with the EPSRC. This is an important part of the programme which involves developing external perception of quantum technologies, and has engaged research and development staff across the consortium.

Industrial engagement has expanded significantly through the work of the User Engagement Team, which we have built up over the past year. The User Engagement programme has implemented a robust process for the allocation of our £3.4m Partnership Resource; we have supported 14 industrial partnership projects with these funds, four of which are now complete and more are in the pipeline. Eleven new companies and one new academic partner are now part of the NQIT programme.

Overall, we are confident that the Hub is now well established, has made excellent progress towards its strategic objectives, achieved key early milestones and built an effective team focused on the critical technologies for the Q20:20 quantum computer demonstrator.





An important outcome of our activity will be a skilled, connected ecosystem which will underpin a new technology sector

# Introduction

## Vision

**This century will see the realisation of a practical quantum computer.**

NQIT will contribute to this ambitious agenda by designing the architecture and building the core components to create a universal quantum computer based on a hybrid light-matter network, as well as developing the skills needed to seed this new technology sector.

The NQIT strategy builds on our existing world-leading performance in two cutting-edge quantum information-processing platforms: trapped ions and photonics, creating the hybrid light-matter network. NQIT's technology development programme is necessarily high risk and long term; but we have identified the potential uses of the Q20:20 device for applications such as quantum simulation and secure communications.

NQIT contributes to the establishment of a new technology sector by contributing ideas, technology, and skills that will grow UK capability and capacity in the emerging quantum information industry.

## Plan

Our technology goals for the NQIT programme are:

- To develop new concepts and devices for quantum information processing;
- To engineer these to prove their operation;
- To build demonstrations of sufficient scale to create a compelling case for their exploitation.

This is being undertaken with our academic and industrial partners, bringing together the necessary capabilities and capacities that will enable these goals to be realised. Associated with these technology goals are training, advocacy, and responsible innovation targets.

An important outcome of our activity will be a skilled, connected ecosystem which will underpin a new technology sector, emerging in the best environment nationally and globally for quantum technologies.

The critical path to the Q20:20 quantum computer demonstrator has naturally been refined as new ideas have arisen. Following consultation with our Technical Advisory Board and industry partners, we have identified new areas in which technology could be applied or for which new capabilities are required, such as the need for emulation software oriented to new users.

## Global context

The disruptive potential of quantum computing is attracting growing interest and substantial investment from industry and governments globally

The realisation of a practical quantum computer will be one of the greatest scientific and engineering achievements in history. It will profoundly transform the global IT industry by radically changing the power of computers to solve new kinds of problems.

The disruptive potential of quantum computing is attracting growing interest and substantial investment from industry and governments globally. This is happening even with the understanding that the time until a universal quantum computer becomes commercially available is still uncertain.

Despite its infancy, confidence in the future of quantum computing is growing. Research company Market Research Media have projected the quantum computing market to exceed US\$5 billion by 2020. The companies with commercial interests specifically in the development of quantum computing range from start-ups to established technology multinationals. These companies are largely based in Australia, Canada, China, Europe and the USA. Commercial investment has been accelerating year by year since 1999, when the first investment was made into quantum computing with the founding of Canadian firm D-Wave Systems, Inc.

Having the broad and deep technical capabilities to deliver our focused engineering ambition places NQIT in the leading group among centres of excellence in quantum technologies globally



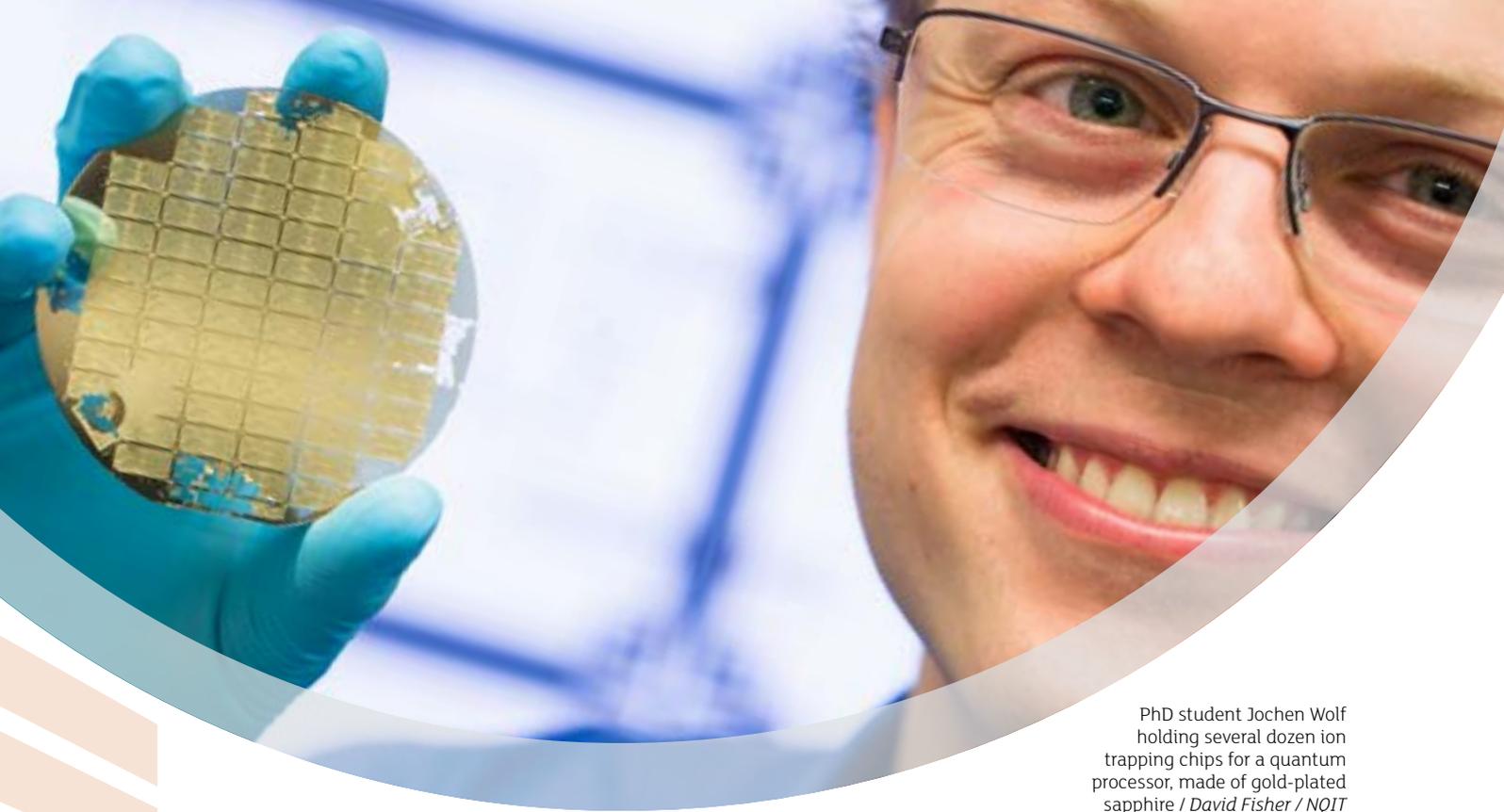
## Commercial Innovations

In 2016, IBM announced free public access to their experimental five-qubit quantum computing platform, the “IBM Quantum Experience”, allowing researchers and students to run experiments on the quantum processor through the cloud. On the commercial front, the only quantum computer that can be purchased today is produced by D-Wave Systems, Inc. Their latest generation quantum annealing machine, the D-Wave 2000Q™, became commercially available in 2017, has 2000 qubits, and costs in the region of US\$15 million. Although this quantum computer is far from a universal computer, it nonetheless allows early experimentation in the field.

Research in quantum computing by universities and companies is generating revenue for suppliers on a local, national and global basis, through the purchase of specialist equipment and components. One such supplier is M Squared Lasers, a Scottish company founded in 2006, who provide lasers for the scientific, medical and defence sectors and for whom quantum computing is a growth area.

Although the market is at an early stage of development, there have been encouraging signs of growth through a wide range of start-ups providing consultancy, software and devices of various kinds. The presence of established firms in this space, such as Hewlett Packard and Lockheed Martin, helps build confidence, and strategic partnerships and initiatives to stimulate the market have begun.

As an academic research field, quantum computing has gained substantial research momentum over the last decade. Many countries including Australia, Austria, Canada, China, France, Germany, Netherlands, Japan, Switzerland, Singapore, Spain, USA and the UK have research programmes on quantum computing with substantial funding.



PhD student Jochen Wolf holding several dozen ion trapping chips for a quantum processor, made of gold-plated sapphire / David Fisher / NQIT

## Building Networks

As a project, and through our consortium members, we are continually making links with organisations locally, nationally and internationally. We are engaging with businesses who are already interested in the potential of quantum computing as well as bringing in new sectors who will benefit from quantum computing in the long term.

Having the broad and deep technical capabilities to deliver our focused engineering ambition places NQIT in the leading group among centres of excellence in quantum technologies globally. Because of its focus, NQIT has already emerged as a prominent international centre for the development of quantum technologies. We have instigated collaborations with other leading centres of quantum technology research at universities around the world, as well as industry and government agencies in the UK, the USA and Europe.

NQIT has played a leading role in championing EU quantum programmes. We contributed to the Quantum Manifesto for Quantum Technologies and our Director, Professor Ian Walmsley, is a member of the Commission Expert Group on Quantum Technologies for the EU Quantum Flagship initiative.

Our Co-Director for Systems Integration, Professor Dominic O'Brien, was on the expert panel contributing to the recent Blackett Review of Quantum Technologies by the Government Office for Science. This report concludes with 11 important recommendations, the first of which states, *"There is a strong case for continuing the UK National Quantum Technologies Programme to maintain our world-leading position in a promising and now globally emerging area of technology."*

## Science and Innovation Audit (SIA)

NQIT is a proud contributor to the Science and Innovation Audit (SIA) for Oxfordshire, whose purpose is to catalyse a new approach to regional economic development. The SIA is an alliance of 4 transformative technologies being developed in the region: 'Autonomous Vehicles', 'Digital Health', 'Space-led Data Applications' and 'Technologies underpinning Quantum Computing'.

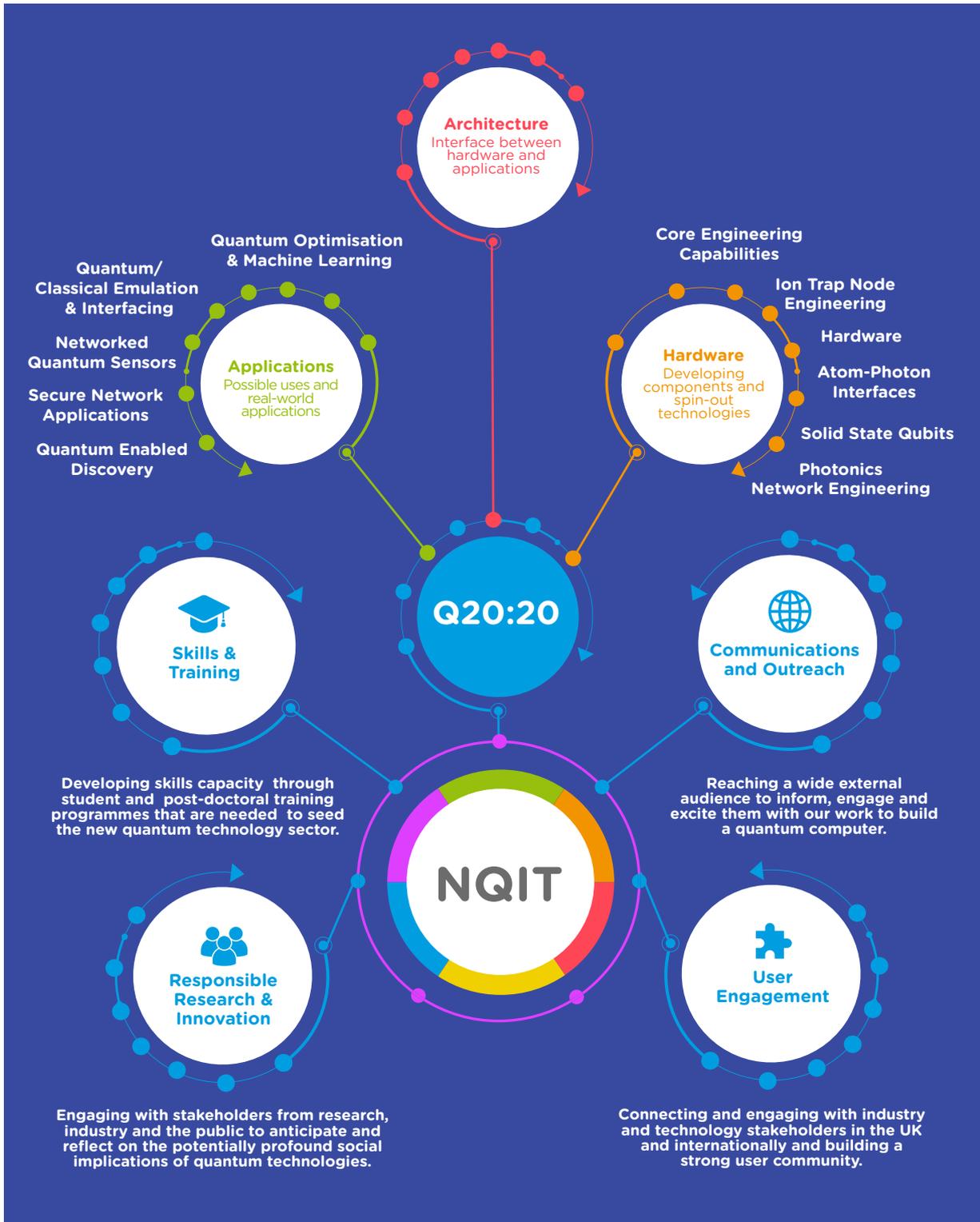
The hypothesis that we tested for 'Technologies underpinning Quantum Computing' was the feasibility of establishing a 'Quantum Valley' that will benefit the whole of the UK and beyond by 2030, creating 10,000 jobs across the supply chain.

The SIA process has shown NQIT's deep connections on a regional, national and international basis, and how its world-leading research and innovation is driving growth, creating new supply chains and business opportunities for the emerging quantum technology sector, its applications and the formidable business advantage from the use of quantum computing.

We have identified cross-opportunities with our SIA partners that involve big data and machine learning, and we are exploring new industrial challenges that have subsequently emerged.

The UK, and Oxford in particular, is demonstrating global leadership in this transformative technology and NQIT is a nucleation point for potential clusters. We are working hard to meet our mission goals and to establish a long-term vision for the UK.

# Programme Structure



## Our plan for the NQIT Hub covers technology delivery and commercialisation, with primary applications in computing, communications and sensing.

We are continuing to work with our consortium partners to develop and deploy a general-purpose quantum technology platform, substantially increasing the readiness levels of the core technologies required.

Our research programme is divided into three streams: **hardware, applications and architecture**, each of which is further split into multiple work packages.

- The **hardware** stream is focused on developing the components of the Q20:20 engine and producing spin-out technologies.
- The **applications** stream looks at the possible uses of the Q20:20 engine and how it might be used for real-world applications such as quantum optimisation and machine learning.
- The **architecture** stream builds the interface between our hardware and applications research by developing performance requirements for the components, coordinating the engineering design and road-mapping of the Q20:20 engine.

Our technically and commercially literate User Engagement team is engaging with businesses and technology stakeholders in the UK and internationally, through face-to-face meetings and visits, symposia, and online, to build a strong user community of those interested in quantum information technology. The team draws on expertise in finance, commercialisation and manufacturing from users and investors to collaborate with other Quantum Technology Hubs, funders and policy makers to generate wealth for the UK economy.

## The NQIT Consortium

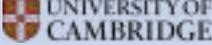
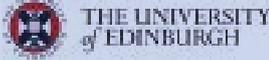
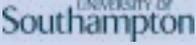
The NQIT Consortium is an Oxford-led alliance of ten universities, organisations and leading experts across a range of backgrounds from academia, industry and government agencies, working together to achieve the ambitious goal of building a universal quantum computing demonstrator. The university partners are Bath, Cambridge, Edinburgh, Leeds, Southampton, Strathclyde, Sussex and Warwick, and we have also connected with others including Heriot-Watt and Bristol. In addition, we have assembled a network of more than 25 companies including Lockheed Martin, Raytheon BBN, Google and Toshiba; government laboratories, such as NPL, DSTL and NIST; and a number of small and medium sized enterprises, including Rohde & Schwarz and Oxford Instruments, who are investing resources and manpower.

# NQIT Partners

## UKNQT Partners

- 1 EPSRC
- 4 NPL
- 6 DSTL
- 2 Innovate UK
- 5 GCHQ
- 7 KTN
- 3 BEIS

## NQIT Academic Partners

- 1  UNIVERSITY OF BATH
- 2  UNIVERSITY OF CAMBRIDGE
- 3  THE UNIVERSITY OF EDINBURGH
- 4  UNIVERSITY OF LEEDS
- 5  HERIOT WATT UNIVERSITY **\*NEW PARTNER**
- 6  UNIVERSITY OF OXFORD
- 7  UNIVERSITY OF Southampton
- 8  UNIVERSITY OF SUSSEX
- 9  UNIVERSITY OF SUSSEX
- 10  WARWICK

## Other Quantum Technology Hubs

- 1 UK National Quantum Technology Hub Sensors and Metrology
- 2 QuantIC (Quantum Technology Hub in Quantum Enhanced Imaging)
- 3 Quantum Communications Hub

## Centres for Doctoral Training (CDTs) and Skills and Training Hubs

- 1 EPSRC Centre for Doctoral Training in Quantum Engineering & The Quantum Enterprise
- 2 EPSRC Centre for Doctoral Training in Quantum Dynamics & Imperial Centre for Quantum Engineering and Science
- 3 EPSRC Centre for Doctoral Training in Delivering Quantum Technologies & Innovation in Quantum Business – Applications, Technology and Engineering (InQuBATE)



# Industrial Partners



# People

## Directors

### ***Professor Ian Walmsley, Director***

Ian Walmsley has an extensive record of leadership in quantum technologies spanning more than a decade. He has been driving the agenda for quantum technology in the UK and EU. Ian's vision and drive unifies the consortium and motivates their delivery of the ambitious objectives of the Hub. His research group in ultrafast quantum optics and optical metrology sustains research efforts in three areas: quantum optics, coherent control of atoms and molecules, and nonlinear optics. Ian actively engages with decision-making bodies about the latest developments in quantum computing, for example through his membership of the Commission Expert Group on Quantum Technologies - High Level Steering Committee for the EU Quantum Technology Flagship.

### ***Professor Dominic O'Brien, Co-Director for Systems Integration***

Dominic O'Brien has two decades of experience in photonic systems integration, including system design, integration process development and control system development, resulting in world-leading optical wireless system performance. He has worked extensively with international academic and industrial partners and has 200 publications in this area and eight patents granted or in progress. Recent collaborations include work with Samsung on wireless beyond 100Gbit/s and with Airbus on unmanned aerial vehicles.

### ***Dr Tim Cook, Co-Director for User Engagement***

Before joining NQIT, Tim Cook was formerly the Managing Director of Isis Innovation (now Oxford University Innovation), Oxford's technology transfer company, for ten years and later non-executive Director. Tim has an outstanding record of managing technology companies and was Visiting Professor of Science Entrepreneurship at the Saïd Business School. He also advises universities in the UK and abroad on technology transfer and innovation. Tim led the industrial engagement mission of the Hub until his retirement in December 2016, and is now replaced by **Evert Geurtsen**.

### ***Evert Geurtsen, Co-Director for User Engagement***

Evert Geurtsen joins NQIT from his role as Head of Licensing and Ventures for the Physical Sciences at Oxford University Innovation (OUI). At OUI, where Evert worked since 2009, he and his team helped founders to start more than 50 new ventures, created the Oxford Startup Incubator and secured licence agreements for many Oxford inventions, software and other research outcomes, latterly also from the Humanities and Social Sciences Divisions.

Prior to Oxford, Evert's career has included new product development roles and directorships at large and medium-sized companies in the automotive industry including General Motors and Lotus Engineering. He has also founded his own ventures and raised investment pioneering the introduction of affordable electric cars.



## Associate Directors

- Professor Simon Benjamin, Associate Director for Partnerships, University of Oxford



- Professor Jason Smith, Associate Director for Skills and Training, University of Oxford



- Professor David Lucas, Associate Director for Hardware, University of Oxford



- Professor Peter Smith, Associate Director for Fabrication, University of Southampton



- Professor Elham Kashefi, Associate Director for Applications, University of Edinburgh



## Co-Investigators

### Architectures, Standards and System Integration

Professor Simon Benjamin (University of Oxford)  
*Work Package Leader*

### Ion Trap Node Engineering

Professor Winfried Hensinger (University of Sussex)

Professor David Lucas (University of Oxford)  
*Work Package Leader*

Professor Andrew Steane (University of Oxford)

### Atom-Photon Interfaces

Dr Almut Beige (University of Leeds)

Professor Peter Horak (University of Southampton)

Professor Alexey Kavokin  
(University of Southampton)

Dr Matthias Keller (University of Sussex)

Professor Axel Kuhn (University of Oxford)  
*Work Package Leader*

Professor Pavlos Lagoudakis  
(University of Southampton)

### Photonic Network Engineering

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Professor Martin Dawson (University of Strathclyde)

Dr Corin Gawith (University of Southampton)

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Dr Joshua Nunn (University of Bath) *Work Package Leader*

Professor Peter Smith (University of Southampton)

Dr Michael Strain (University of Strathclyde)

Professor William Wadsworth (University of Bath)

Dr Ian Watson (University of Strathclyde)

### Solid State Node Engineering

Dr Erdan Gu (University of Strathclyde)

Dr Peter Leek (University of Oxford)

Dr Gavin Morley (University of Warwick)

Professor Mark Newton (University of Warwick)

Professor Jason Smith (University of Oxford)  
*Work Package Leader*

### **Secure Network Applications**

Professor Jonathan Barrett (University of Oxford)  
*Work Package Leader*

Professor Elham Kashefi (University of Edinburgh)

### **Networked Quantum Sensors**

Professor Justin Coon (University of Oxford)

Dr Animesh Datta (University of Warwick)  
*Work Package Leader*

Professor Jacob Dunningham (University of Sussex)

### **Quantum Enabled Discovery**

Professor Dieter Jaksch (University of Oxford)  
*Work Package Leader*

### **Quantum/Classical Emulation and Interfacing**

Professor Samson Abramsky (University of Oxford)  
*Work Package Leader*

### **Core Engineering Capabilities**

Professor Martin Booth (University of Oxford)

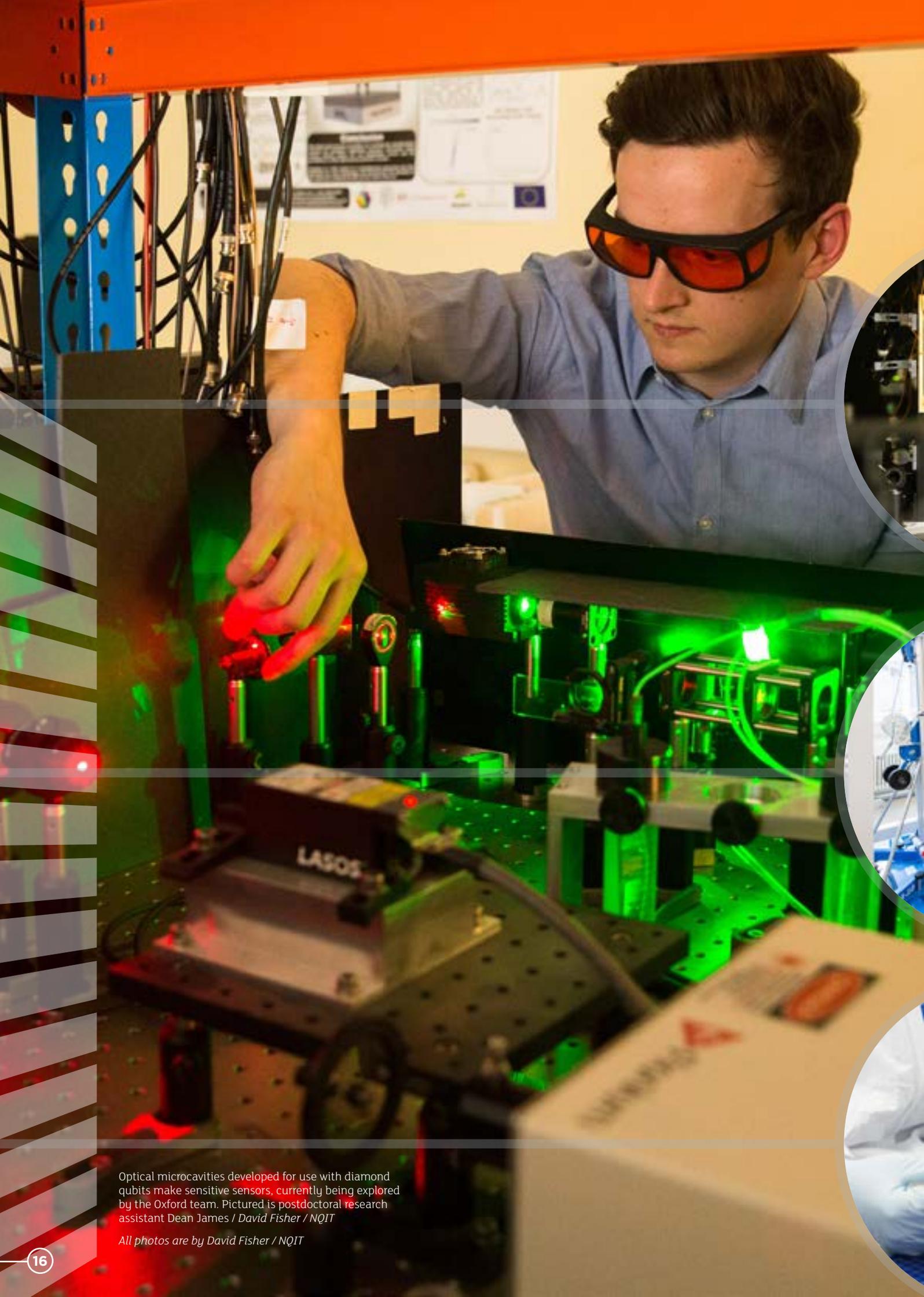
Professor Steve Collins (University of Oxford)

Professor Dominic O'Brien (University of Oxford)  
*Work Package Leader*

Professor Christopher Stevens (University of Oxford)

### **Responsible Research and Innovation**

Professor Marina Jirotko (University of Oxford)  
*Work Package Leader*



Optical microcavities developed for use with diamond qubits make sensitive sensors, currently being explored by the Oxford team. Pictured is postdoctoral research assistant Dean James / David Fisher / NQIT

All photos are by David Fisher / NQIT

# Objectives



**The NQIT Hub is designed around a programme of research and development that will deliver all of the elements needed to realise the Q20:20 quantum computer demonstrator.**

The network architecture ensures that larger machines can be constructed once we have developed the nodes and the channels of the quantum network to a sufficient level of performance. The critical technology path is based on a network of trapped ion microprocessors interconnected using light, configured so that the whole is fault-tolerant. We will also deliver spin-off technologies from the work, including technologies that may be useful to the work of other Quantum Technology Hubs.

Our approach is to use matter – atoms – as elementary processors for quantum information, and light – photons – as the means to transport the information between the atoms.

The architecture is thus a hybrid light-matter quantum network, which will leverage all of the important features of classical networks that make them indispensable for classical communications and computation.

The NQIT programme also encompasses technology development for applications in some of the most promising of the competing technologies, particularly colour centres in diamond and superconducting circuits. These can be utilised in the same architecture as the Q20:20 engine and will provide some early spin-off technologies. This approach enables NQIT both to deliver applications in these important technologies and to grow expertise so that NQIT can make use of developments elsewhere in the world if they positively impact the Hub's goals.



## Building the Quantum Technology Industry

We are putting considerable effort into establishing connections with industry, government agencies and investors, both to engage their expertise in delivering the Q20:20 engine, and to explore with them ways in which quantum technology may impact established businesses and to develop opportunities for new businesses. We have set up a number of new projects in these areas, utilising our Partnership Resource, and we are now considering new approaches to building a quantum technology industry by exploiting know-how developed in the Hub. We are also addressing the need for skilled scientists and engineers in this quantum technology and have set up a skills programme and a process for funding postgraduate research students undertaking their thesis research on NQIT projects.

Additionally, we are seeking ways to work with the recently-announced Quantum Technology Skills Hubs to bring together the training and personnel they oversee to the Quantum Technology Hubs themselves.

Further, NQIT is working with the other three Quantum Technology Hubs on joint programmes, including the annual Quantum UK Conference, responsible research and innovation, and jointly coordinating publicity and public engagement.



# Year Two Achievements and Progress

**The National Quantum Technology Programme aims to advance quantum technologies and demonstrate real applications, kick-start a quantum industry, and create the skills-base required to sustain it.**

**In the second year of NQIT we have made significant progress in all these areas.**

**We have advanced the key technologies with NQIT, and:**

- Developed an architecture that promises the same performance as the Q20:20 quantum computer with a simplified node structure.
- Demonstrated key concepts in ion-traps and quantum logic gates at the levels of performance required for the Q20:20 engine.
- Developed blueprints for engineering the Q20:20 quantum computer.
- Obtained world leading performance in future ion trap architectures that promise simpler systems.

**We have interacted with a wide range of industries and organisations, and:**

- Funded 14 partnership projects across a broad range of different technologies.
- Hosted visits from centres of research worldwide: Quantum Technology research (for example CQI (Canada), CQT (Singapore), EQUS (Australia), NIST (USA)), from industry (including Lockheed-Martin, Raytheon, Nokia, Airbus), from government agencies (DoE and DoD (US), MEXT (Japan) and the European Commission) and academies (such as National Research Council (US)).
- Filed ten patents with more in the pipeline to follow.
- Developed plans for start-up companies with five in progress.
- Contributed to the Blackett Review of Quantum Technologies.
- Published a Technical Roadmap for Fault-tolerant Quantum Computing.
- Published the Commercial Prospects for Quantum Computing.

**To ensure the skills required to sustain these developments, we have:**

- Developed a network of interactions with the Quantum Skills Hubs.
- Recruited a cohort of graduate students across the Hub.
- Developed a broad training programme accessible to all, through highly successful skills days.

We have engaged with over **80**

organisations, ranging from quantum technology start-ups and SMEs (small and medium enterprises) through to multinationals, government bodies and other institutions

### Online engagement:

- 700**  followers on Twitter
- 500**  new followers on Twitter
- 13,000**  visitors to the website

From over 100 countries

### Academic engagement:

- 43**  peer-reviewed publications
- 10**  talks given
- 16**  new graduate studentships

### Industry engagement:

- 22**  industry events attended
- 5**  spin-out companies
- 10**  patents
- 14**  partnership projects between industry and academia
- 4**  complete projects
- 80**  organisations engaged with
- 3**  key reports
- 140**  copies of market report requested

We have so far used around one-third of our **3.4m** Partnership Fund along with 70% matched funding, to establish 14 partnership projects, 4 of which are complete, 3 new ones are in the works

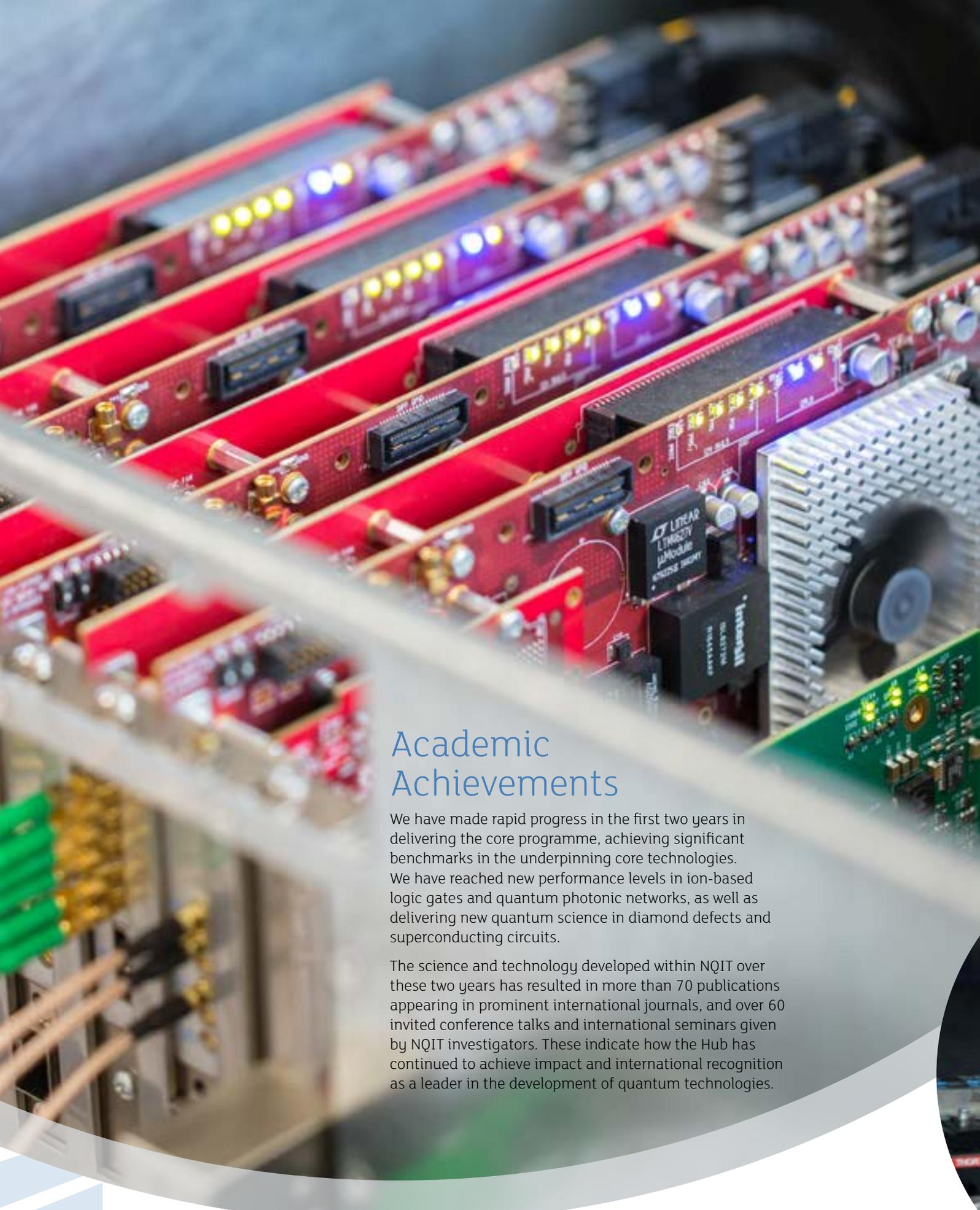
This network is rapidly expanding



We have added **11** new industry partners to the original 25 that were founding members of the consortium

**3 major reports published**





## Academic Achievements

We have made rapid progress in the first two years in delivering the core programme, achieving significant benchmarks in the underpinning core technologies. We have reached new performance levels in ion-based logic gates and quantum photonic networks, as well as delivering new quantum science in diamond defects and superconducting circuits.

The science and technology developed within NQIT over these two years has resulted in more than 70 publications appearing in prominent international journals, and over 60 invited conference talks and international seminars given by NQIT investigators. These indicate how the Hub has continued to achieve impact and international recognition as a leader in the development of quantum technologies.

**This page** Multi-channel microwave control electronics for superconducting quantum circuits / *David Fisher / NQIT*

**Page opposite**

**Top** PhD student Joelle Boutari checking the fibre-couplings in the Oxford Photonics Lab / *David Fisher / NQIT*

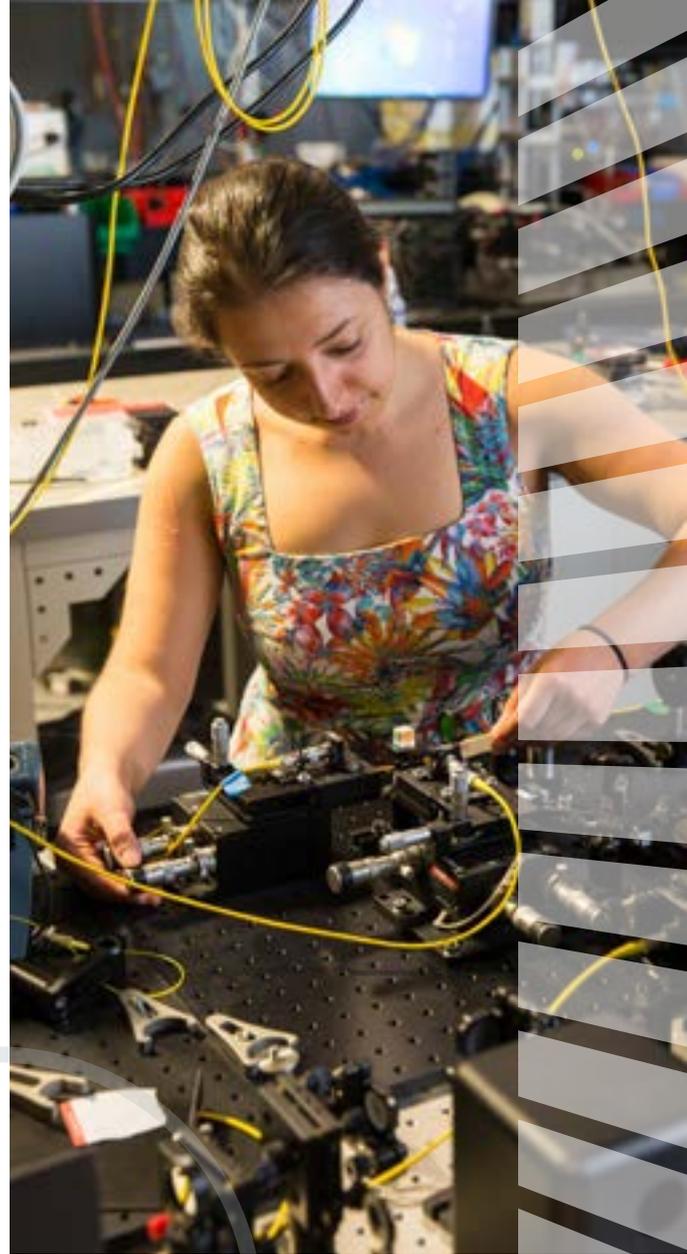
**Bottom** Non-linear wavelength conversion for long distance communications; output from collaboration with Covision Ltd, with Dr James Gates (University of Southampton) caught in reflection / *Dan Tsantilis / EPSRC*

## Industry Achievements

Our industrial engagement and commercial programmes have advanced substantially in the past year. We have five spin-out companies in progress, with ten patents related to quantum technologies. We have allocated around one-third of our £3.4m Partnership Resource fund to support 14 new industry-academia projects, all of which either have immediate applications or a longer technology maturity timeline but substantial industrial interest. Four of these are now complete and we have three more in the pipeline to launch later in 2017.

We have also engaged with more than 80 organisations, ranging from quantum technology start-ups and SMEs (small and medium enterprises) through to multinationals and government bodies. These cover a wide range of sectors, including aerospace, finance, health, software and telecommunications. We are actively working on establishing a new quantum technology industry in the UK by supporting and working with many UK-based companies.

In addition, we have produced two key reports that are being distributed globally, which have helped to strengthen our position as a trusted source of quantum computing information. The first, “Commercial prospects for Quantum Computing”, is a market report that covers global investment in quantum computing in the past decade; so far over 140 organisations from around the world have requested a copy. The second is a “Technical Roadmap for Fault-tolerant Quantum Computing” and sets out the concepts and potential applications of a small quantum computer.



## Engineering Progress

We have focused on demonstrating key functions that are required for the Q20:20 quantum computer demonstrator and defining its functional architecture, as well as defining and refining the engineering architecture. Excellent progress has been made in all these areas including, for example, the world's first demonstration of a mixed-species quantum logic gate, and the world's highest-fidelity two-qubit logic gate.

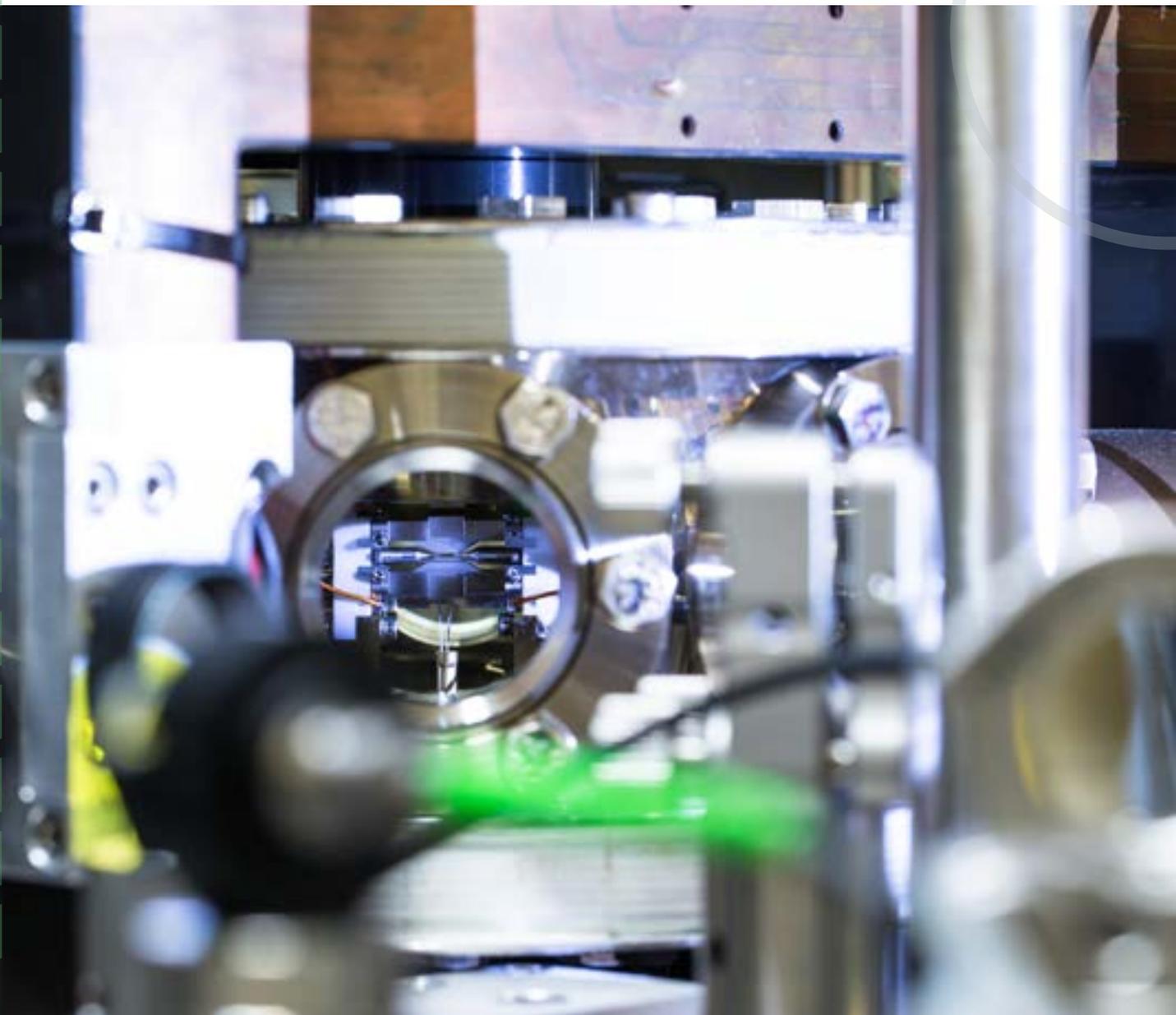
We have developed a reduced complexity ion trap design with good scaling properties. This is a significant breakthrough, as it allows us to reduce the engineering complexity required in an individual node, but shows similar performance (for the same total number of ions) as the Q20:20 configuration originally envisaged. This design has been partitioned into four engineering subsystems: optical power supply, control and electronics, entangler, and quantum module, and we have developed draft requirements, specifications and timelines for the delivery of each of these. Implementation of all these subsystems is underway, using partners across the project, and new collaborations. We are also collaborating internationally with leading research facilities and standards laboratories to develop our control hardware and software standards, as well as using Partnership resource for technology development, with more to follow.

# Towards the Q20:20 Vision

**Our vision is an optically networked system of small ion trap processors, that can be scaled by adding more processor modules. We have simplified the design of individual modules so that five, rather than 20, ions can be used within a single processor.**

To keep the same overall performance the number of modules needs to be increased, and this has led to a blueprint for a Q5:50, rather than a Q20:20 concept. This shifts the challenge from creating complex modules to one of production of a number of simpler modules, which we believe will be significantly more straightforward, and will yield results faster. Just as microprocessors have become more complex as technology evolves, this will also be the case for ion trap based processors, and NQIT partners are working on more sophisticated modules and concepts that will fit into such 'next generation' systems.

*Ion trap set inside a vacuum system in the Oxford Physics Lab / David Fisher / NQIT*



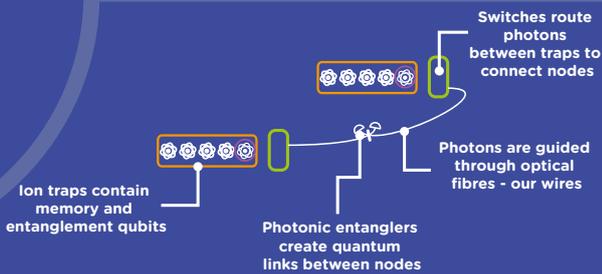
# Hardware

**Quantum computing requires new hardware, with many demanding performance requirements, and we have five hardware work packages and substantial effort addressing this challenge.**

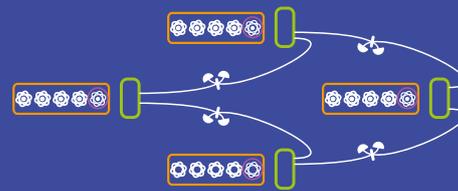
Much of this effort is dedicated to delivering the Q5:50 blueprint, and for this we are developing world-leading capabilities in ion traps, photonics, electronics and integration. In addition, we are advancing the field of superconducting quantum computing devices, and the use of diamond in quantum computing.

Work in the first year focused on refining architectures and demonstrating key functions required for the NQIT quantum computer demonstrators. Whilst this work continues our key goals now focus on the engineering required to deliver the NQIT vision.

## Networked Quantum Sensors

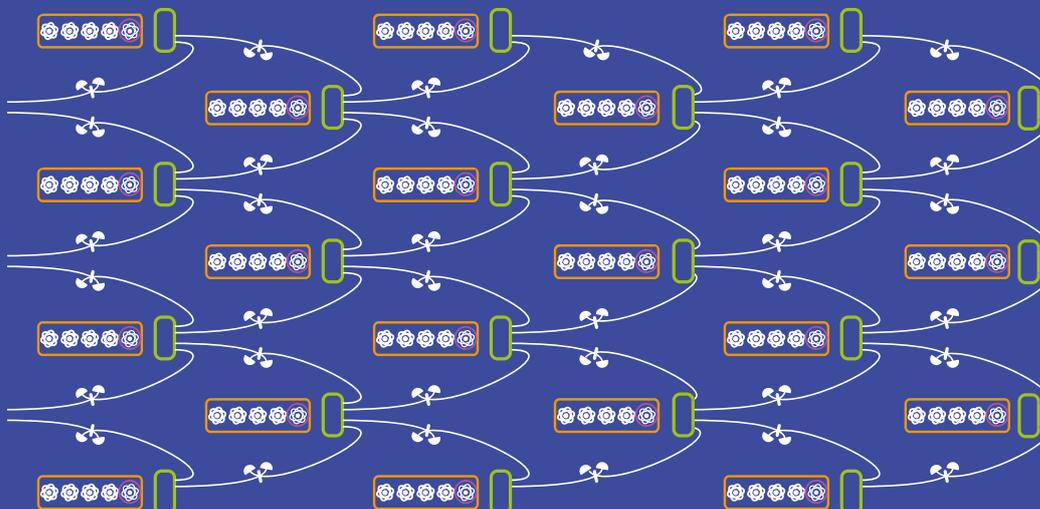


## Quantum Communications and Simulation



**We can increase the level of complexity with our scalable hardware**

## Large-scale network computing



## Hardware Progress

The broad range of capabilities we are developing allows us to address the challenges of engineering the hardware we need, and creates a rich range of spin-out technologies and interactions with industry. Highlights of the year include:

- Continued world-leading ion trap results from NQIT partners
- New photonics results in the area of cavity development, a key enabling technology for future demonstrations
- Engineering designs for the entangler, and first implementations of modular optical power supplies for ion trap modules
- New patented architectures for superconducting quantum processors
- New methods for engineering qubits within diamond
- Working with global partners to develop the necessary control electronics, and test-equipment manufacturers to develop the testing facilities required to verify their operation

Progress in each of these key areas is set out below.

## Ion Trap Node Engineering

NQIT will deliver two distinct trapped ion quantum computer demonstrator devices, in order to fully develop relevant quantum computing technologies towards industrial exploitation. These are being developed at Oxford and Sussex universities.

The Q20:20 machine will use positively charged atoms, or ions, as quantum versions of the traditional computer bit. Two energy levels of each ion are selected to represent the '0' and '1' qubit (quantum bit) states. Microwave or laser radiation can be used to excite the transition between the two qubit states and to perform logic gates between qubits. The Oxford Ion Trap group has recently demonstrated the world's highest-fidelity (lowest error) quantum logic gates between two ions in both microwave-driven and, concurrently with NIST in the USA, laser-driven systems.

The Q20:20 machine will be built from modules consisting of several ions suspended in electric potentials generated by devices called ion traps. Calcium ions in the modules will act as 'memory ions', storing quantum information. Strontium ions will serve as 'interface ions'; photons emitted by these ions will be used to transfer quantum information between modules of the computer.

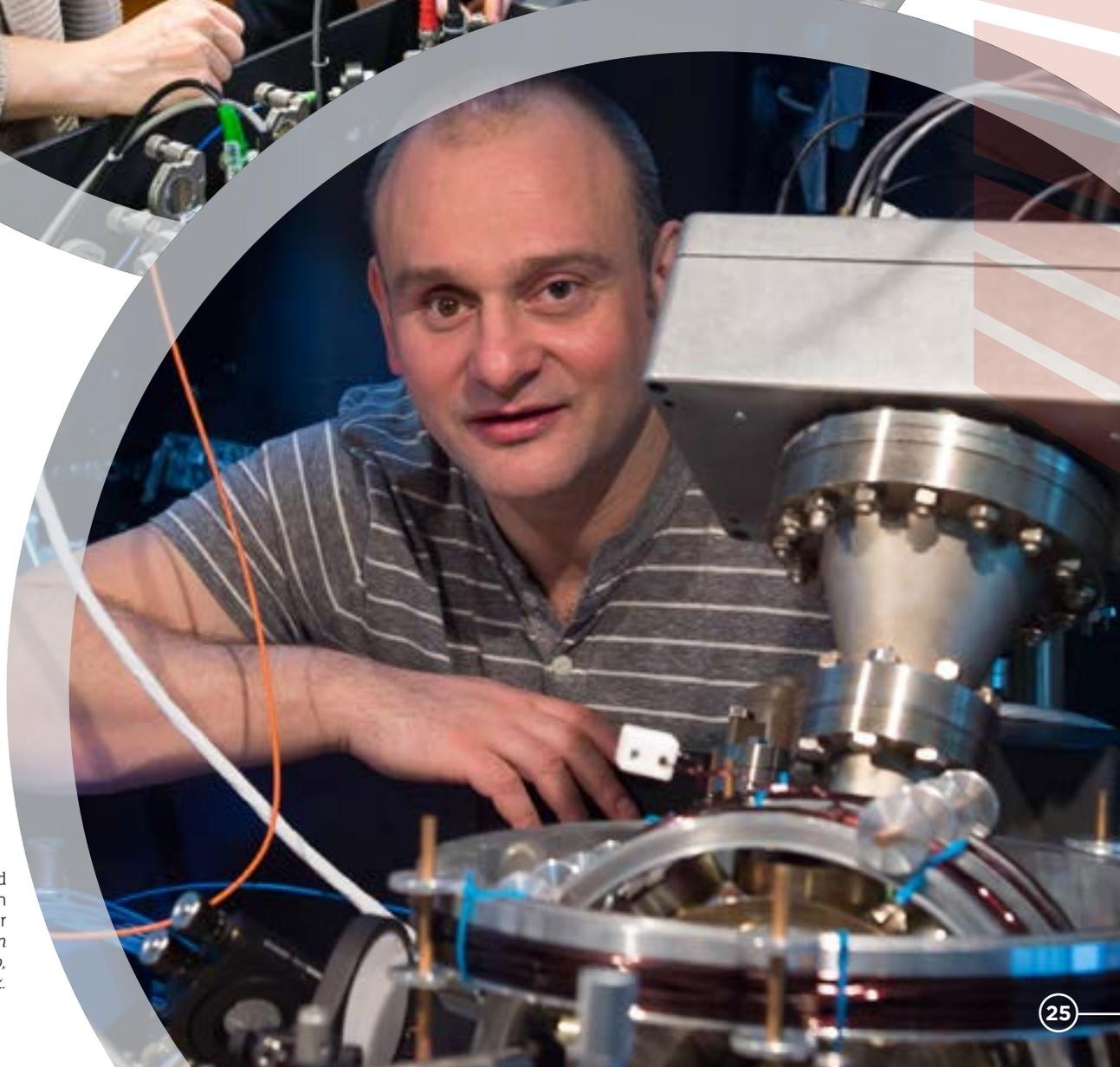
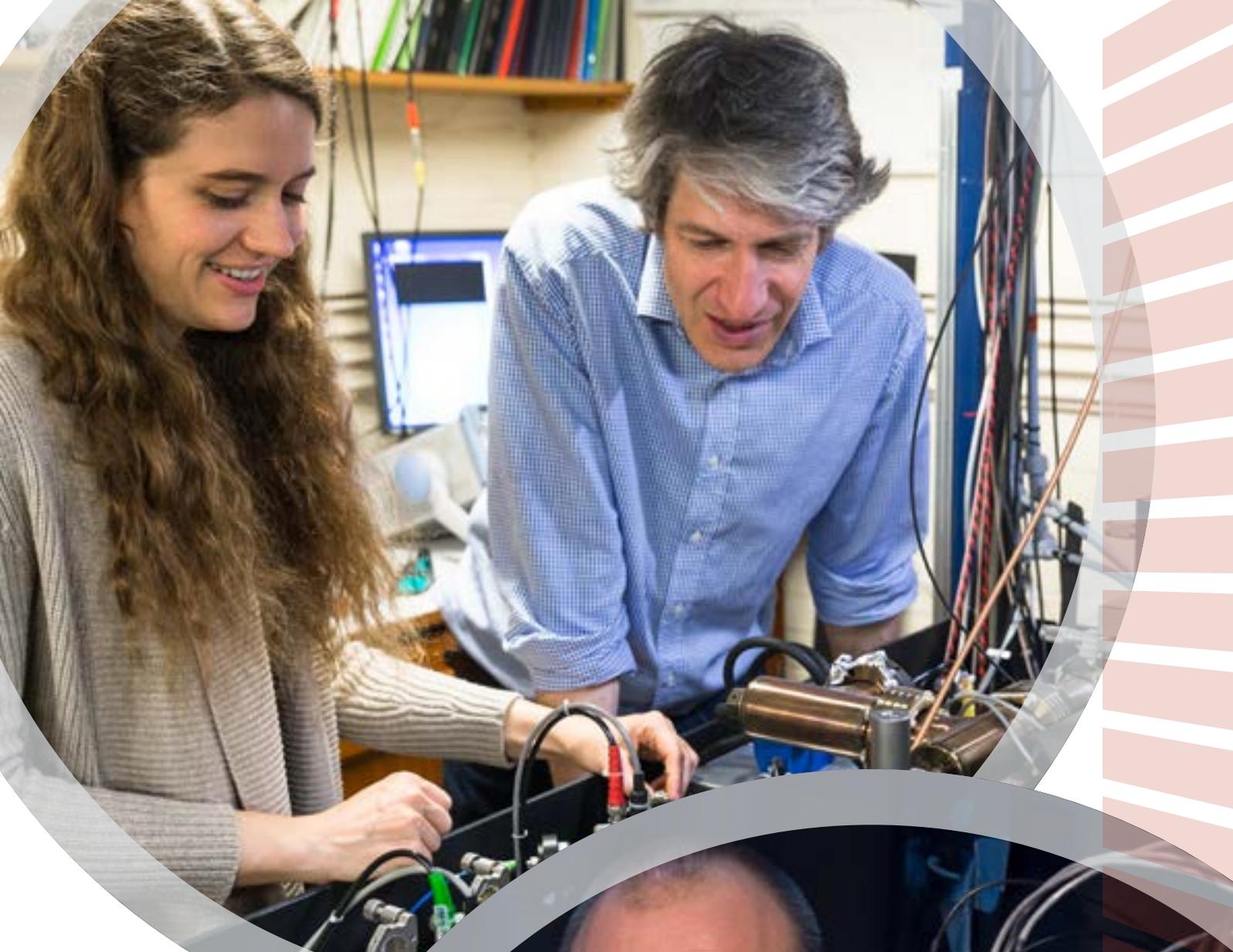
This year, the Oxford team demonstrated two key ingredients required to implement this photonic interface: the generation of quantum entanglement

between an ion and a single photon, and a quantum logic gate between a calcium 'memory ion' and a strontium 'interface ion'.

The team at Sussex are working on more complex ion trap designs that will allow individual 'processors' to perform more complex operations in the future, and methods to connect these up to create large-scale computers. Early in 2017 they published a blueprint for such an architecture that features two recent inventions by the Sussex team, both having the potential to greatly simplify the construction of large-scale quantum computers.

The Sussex team invented a simple method whereby voltages applied to a quantum computer microchip are used to execute quantum gates, potentially replacing many laser beams or individual microwave fields that would otherwise be required to build large-scale quantum computers.

The second invention consists of a new method to connect individual quantum computing modules. Instead of using photonic interfaces, this innovation introduces connections created by electric fields that enable actual ions to be transported from one module to another. This has the potential to create large processor 'arrays' without the need for optical interconnects between them, simplifying the path to large scale quantum computers.



Professor Winfried Hensinger working on a quantum computer prototype / *Ion Quantum Technology Group, University of Sussex.*

(From left to right) PhD student Tom Barrett, Professor Axel Kuhn and postdoctoral research assistant Dustin Stuart and their cavity-based single-photon source used for linear optics quantum processing  
/ David Fisher / NQIT



## Atom-photon Interfaces

Central to NQIT's goal is the ability to interconnect multiple small-scale quantum processors, which requires a reliable interface between atoms and photons. The challenge here is to engineer interactions between atoms and photons, as the quantum information is usually lost before it can be transferred from the moving qubit (the photon) to the stationary qubit (the atom). This prevents us from building an efficient network of quantum processors without using further tricks. We use devices called *optical cavities* (or simply *cavities*) to enhance the interaction between atoms and photons.

The NQIT team at Sussex University has successfully integrated an ion trap with an optical cavity. With this system, the information from the ion trap can be directly channelled to another quantum processor via an optical fibre.

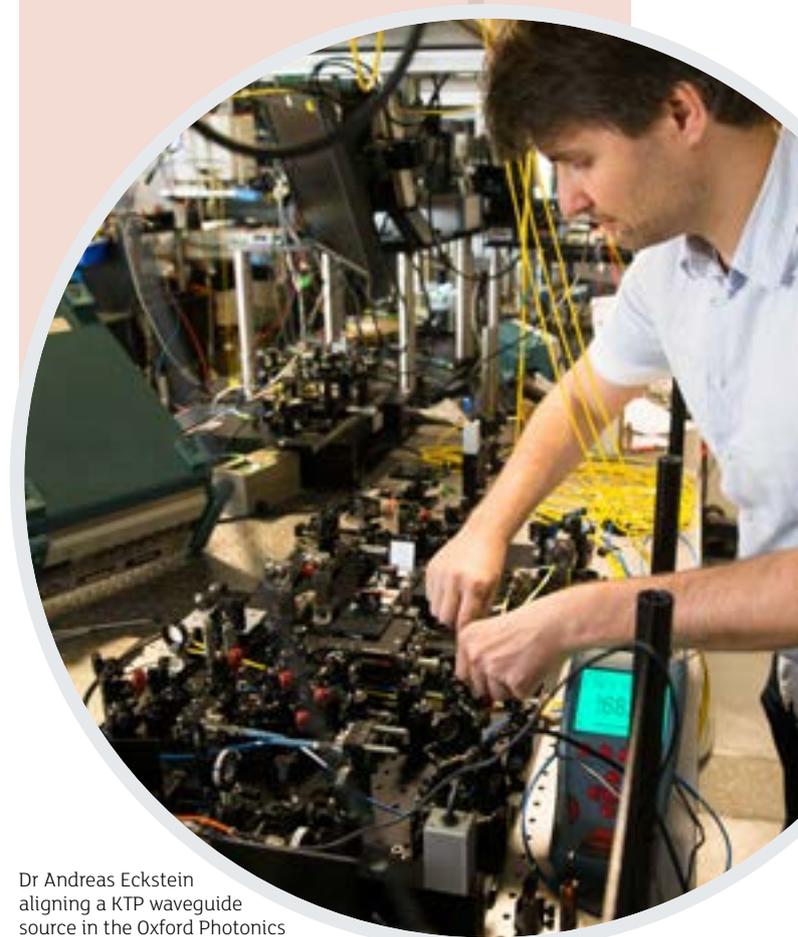
Furthermore, the team at Sussex, together with collaborators at Southampton, have designed and created a novel cavity which substantially improves the efficiency of information transfer to 90%, from previously realised systems which have efficiencies of less than 30%.

## Photonic Network Engineering

Photonics is another way of saying optical-wiring, and is about creating, manipulating and detecting single photons – elementary particles of light. Photons will serve as messengers between the components of the Q20:20 machine, distributing information between nodes and thus facilitating communication between the building blocks of the device. They form the 'wires' of the Q20:20 machine, and as such require flexible routing through integrated circuits. One highlight of our photonics research is the development of enhanced versions of these circuits that are smaller in size and more resilient compared to established techniques.

In addition, we have improved on the technology for storing photons, an essential component of photonic networks. By tailoring the storage operation, we managed to reduce thermal noise, which renders current devices unsuitable for operating with single photons, by a factor of three.

Some of the anticipated spin-out technologies as a direct result of photonics research include quantum random number generation, quantum simulation, and the development of single-photon sources.



Dr Andreas Eckstein aligning a KTP waveguide source in the Oxford Photonics Lab / David Fisher / NQIT

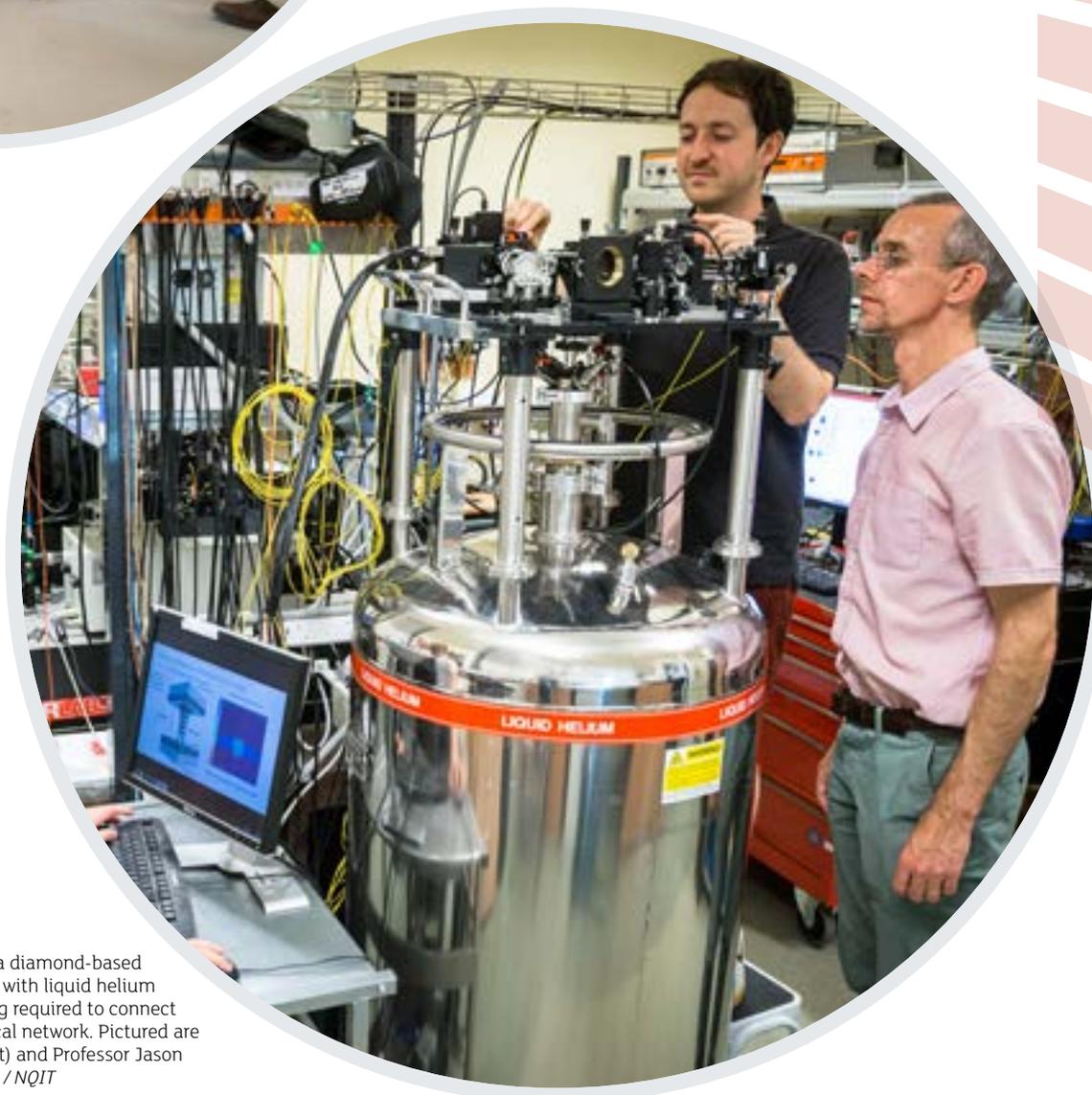
Customised dilution refrigerator for operation of quantum microwave circuits at less than a degree above absolute zero, with PhD student Andrew Patterson and Dr Peter Leek / *David Fisher / NQIT*



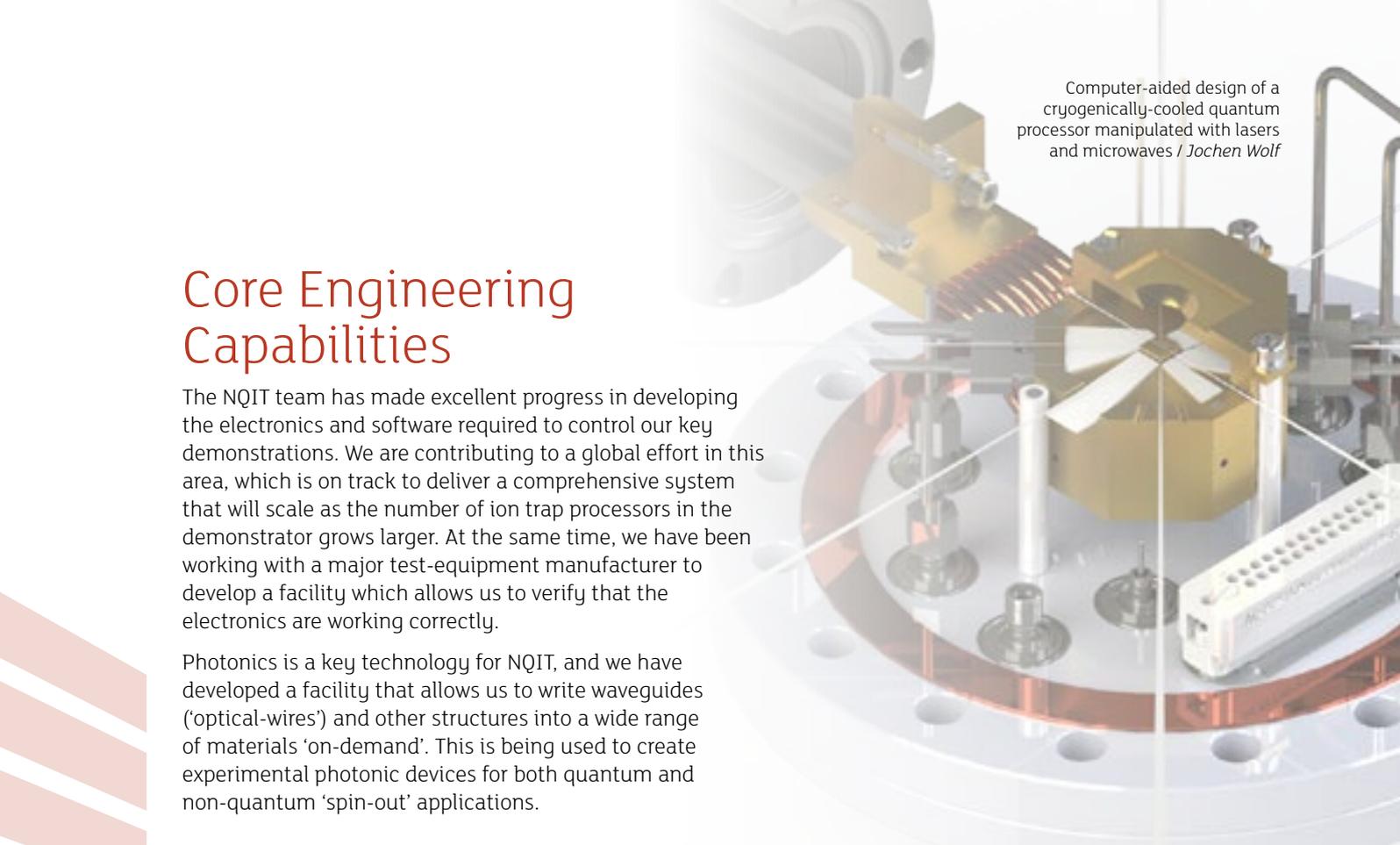
## Solid state Qubit Node Engineering

Solid state devices are based on bulk solid materials (the ubiquitous silicon chip is an example) rather than gases or discrete atoms. We are investigating solid state alternatives to the current ion trap node technology, with potential advantages including less exacting optical requirements and faster operations.

This year we have demonstrated deterministic placement of high-quality qubits in diamond using a world-first technique of “writing” them into a diamond surface using a high-power laser. This allows us to optically address an array of identical solid state qubits. Additionally, we have performed coherent laser control of another diamond-based qubit type, and for the first time demonstrated an increase in useful qubit lifetimes by a factor of 100. Finally, we are employing novel optical cavity designs to efficiently extract useful photons from our solid state qubits, for launching into a scalable photonics-based networked processor.



Building a node for a diamond-based quantum computer, with liquid helium providing the cooling required to connect the qubit to an optical network. Pictured are Dr Sam Johnson (left) and Professor Jason Smith / *David Fisher / NQIT*



Computer-aided design of a cryogenically-cooled quantum processor manipulated with lasers and microwaves / Jochen Wolf

## Core Engineering Capabilities

The NQIT team has made excellent progress in developing the electronics and software required to control our key demonstrations. We are contributing to a global effort in this area, which is on track to deliver a comprehensive system that will scale as the number of ion trap processors in the demonstrator grows larger. At the same time, we have been working with a major test-equipment manufacturer to develop a facility which allows us to verify that the electronics are working correctly.

Photonics is a key technology for NQIT, and we have developed a facility that allows us to write waveguides ('optical-wires') and other structures into a wide range of materials 'on-demand'. This is being used to create experimental photonic devices for both quantum and non-quantum 'spin-out' applications.



### RESEARCH CASE STUDY

#### Photonic Interconnects

We have developed a novel strategy for interconnecting an arbitrary number of optical channels in a complex, reconfigurable photonic network. These networks will form the backbone of light-based quantum simulators – a first step towards fully-fledged quantum computers. One highly anticipated result of this research is the demonstration of quantum advantage. In other words, this means proving without doubt that quantum machines can outperform classical machines.

The interconnect works like a marshalling yard for light: at one end, light comes in along a series of tracks (waveguides) and there is a series of points (couplers) where some of the light in one track can be diverted to an adjacent track. Such interconnects are usually implemented on a chip, for example by writing waveguides into a photosensitive material using light.

Our researchers have developed a novel scheme for the layout of such circuits. Our method is more robust to loss and occupies a smaller footprint on-chip than previous methods, meaning an increased integration density and thus a larger number of individual components in the same box. This invention will not only find applications in quantum technologies, but also in classical optical systems and IP protection is currently under way.

Photonic chip developed at University of Oxford / David Fisher / NQIT

Dr Chris Ballance adjusting the lasers on an ion trap system in the Oxford Physics lab  
/ David Fisher / NQIT



## RESEARCH CASE STUDY

### Oxford ion traps

Entangling two ions means creating a correlation between them, such that the energy state of one depends on that of the other. This type of correlation is what allows us to perform logic gates between quantum bits (qubits) and – when created between distant ions via a photon – to transfer information between sectors of the quantum computer.

The Q20:20 machine will use two different ions to perform computations: one type to store information and act as a ‘memory qubit’ and the other to act as an ‘interface qubit’, interfacing with photons to link different parts of the computer.

Last year, the Oxford Ion Trap group demonstrated a laser-driven quantum logic gate between two different isotopes of calcium ions. The work, published in *Nature*, was chosen as one of *Physics World*’s top ten physics breakthroughs of the year, alongside a similar experiment performed concurrently at NIST in the USA.

This year, we have performed this gate between two ions of different elements: calcium and strontium, the two elements we plan to use as ‘memory’ and ‘interface’ qubits in the Q20:20 machine. We have now also demonstrated entanglement between a strontium ion and a single photon – an essential step towards networking memory modules of the Q20:20 quantum computer demonstrator.

# Applications

**Our applications programme is aimed at providing the tools to make the Q20:20 engine available to users, and developing ways that it can be used to solve real-world problems.**

The research is split into work packages on various themes, including: secure network applications, quantum sensing, quantum-enhanced discovery, optimisation and machine learning, and the development of the interface of the Q20:20 engine with classical computing.

We aim to answer three key questions for emerging quantum devices such as the Q20:20 engine, to make the translation from theory to practice possible:

- 1 What will the Q20:20 quantum computer demonstrator be good for?
- 2 How will we tell whether it is functioning properly?
- 3 How do we program the Q20:20 engine?

Over the next decade, quantum technologies will become part of the high-performance computing landscape. The first few generations of these machines will have high variability in terms of architectures and capacities. They will not be universal in terms of having a simple programming model, nor will they be easily applicable to all problems. Our work on the applications of these early quantum devices will help address these issues.

Future information and communication networks will certainly consist of both classical and quantum devices, with various degrees of functionality, ranging from simple routers to servers executing quantum algorithms. NQIT's applications programme is providing the building blocks for these future powerful quantum servers.

## Applications Progress

The last year was hugely productive in understanding how NQIT can best approach answering the above questions about applications on the Q20:20 engine. Following the mid-term review, and motivated both by developments in our research and by the advice of the Technical Advisory Board, the applications work packages have been restructured to simplify the organisation of the applications programme:

- The work package on Secure communications and verification has been extended to include secure computation which was formerly part of the work package on hybrid quantum/classical computing. The resulting work package is now entitled **Secure Network Applications**.
- The work package on **Networked Quantum Sensors** continues to make significant progress in developing new and enhanced classical sensor systems with quantum sensor technology embedded within, demonstrating improvements and new features not previously possible.
- The work package on Quantum digital simulation is now called **Quantum Enabled Discovery** and continues its work on investigating how scalable quantum devices can be developed to help solve physics and materials problems.





- The work package on Hybrid quantum/classical computing has been revised to focus more on the deliverables concerning software tools for quantum software development, including a new objective: development of a quantum computer software emulator. It is now called **Quantum/Classical Emulation and Interfacing**.
- A new work package has been created on the theme of **Quantum Optimisation and Machine Learning**, in which NQIT can expand its expertise into ways that optimisation problems in general, and machine learning in particular, may benefit from the application of quantum technologies.

## Secure Network Applications

This work package is concerned with secure communications and computation over networks, and protecting against potentially malicious parties. Tasks of this flavour include quantum key distribution for communication that is secure against any eavesdropper; blind quantum computing, where a client contracts a server to perform some quantum computation for them, without allowing them to learn the desired computation, or the input; other functions useful for cryptography, such as efficient and certifiable quantum random number generation, numbers that by their very nature can never be predicted.

We have also developed a series of new protocols covering randomness certification (even with untrusted devices), a fast quantum key distribution using the colour and arrival time of light, and distributed quantum computing. In particular, we have developed new protocols for secure multi-party computation and verifiable blind quantum computing where not all of the devices can be trusted. We are currently pursuing new ways to make these applications for networked quantum computing more practical for the flagship NQIT machine.

## Networked Quantum Sensors

Classical networks abound in the present age, and a sustainable future for quantum sensors will lie in our ability to embed them in classical sensor networks. NQIT is amalgamating expertise in classical network theory and multi-parameter quantum sensing from Warwick, Sussex and Oxford to establish formalisms to make this possible. Recent work has quantified the level of centralization or decentralization associated with quantum sensor networks, and will inform engineers on how to structure them to improve information flow across the network. It will now be combined with our earlier work that designed quantum sensors with capabilities impossible classically, such as estimating multiple parameters simultaneously or covertly. Thus, we are working towards improving classical networks with new features previously considered impossible, with limited impact on existing networks and infrastructure costs.

## Quantum Enabled Discovery

We have been studying how next generation scalable quantum devices could be used to perform computations that solve specific physics and materials problems. Our work concentrates on augmenting highly successful “Dynamical Mean Field Theory” (DMFT) methods which are widely used for investigating strongly correlated electron systems, and designing quantum materials with novel functionalities. Over the past year, we have developed a minimal version of a hybrid quantum-classical DMFT scheme that requires only a five-qubit quantum co-processor. The scheme uses a classical feedback loop and is designed to allow seamless integration between classical and quantum parts of the algorithm. It could be implemented in current generation small quantum devices and scales straightforwardly with the size of the quantum device it is running on.

## Quantum/Classical Emulation and Interfacing

This research area focuses on mathematical and software tools to allow end users to effectively determine and predict the capabilities of the NQIT architecture, and eventually form a programming interface for the NQIT machine.

Both the development of hardware and the development of compilers have historically evolved in tandem. Researchers at the Computer Science department in Oxford are collaborating with their counterparts in our Architecture work package, to identify how best to use the limited resources within the individual modules. This will ultimately determine the “machine code” of the computational platform. By matching the compiler tools closely to the machine language, we can attempt to get the greatest benefit from the quantum computing resources available.

In the near term, the available quantum computing technology will be limited. To better engage with the eventual users of quantum computing technology, we also plan to develop a software emulator, which can act as an alternative back-end for the compiler. This will facilitate bridge-building with industrial partners, who can begin to explore the possibilities quantum computation may have for them.

## Quantum Optimisation and Machine Learning

Optimisation problems occur frequently in real-world settings, for example in logistics where the most efficient route between locations needs to be found, and these are a likely application of quantum computing technology. NQIT is expanding to incorporate the solution of optimisation problems, to better position us as a source of information for practical applications of quantum information technology, and a trusted authority on quantum technologies in general.

Machine learning is one example of an approach to solving optimisation problems, which recent developments suggest can benefit from the use of quantum technology. To better investigate quantum applications to machine learning, we are recruiting an expert in classical machine learning. This expert will lead a new work package on Quantum Optimisation and Machine Learning, providing the background and expertise necessary to clarify the objectives that quantum technologies should target in machine learning, with others providing the required expertise in quantum technologies.

### RESEARCH CASE STUDY

#### Secure Multi-Party Computation

Imagine you have two distrusting billionaires and they want to find out who is wealthier, but without revealing their individual worth. In computer science terms, they want to compute some function (the wealthiest person) based on their personal data, without revealing this data. This is an example of secure multi-party computation, and has multiple applications, from e-voting, bitcoin, sharing of confidential information (such as medical records), and gambling.

The networked approach to quantum computing pioneered by NQIT makes an excellent platform for protocols such as secure multi-party computation. For example, two parties each may be in possession of a small quantum device, such as an ion trap, and wish to share resources to perform a quantum computation, but do not trust each other. We can then involve a third party that can receive information from the other two, say in the form of photons, and then link the two parties together. If the other two trust this third party then certain secure computational tasks could become possible that were previously impossible. We will explore further how protocols of this flavour, using networks with limited mutual trust, can be implemented within the NQIT architecture.

# Architecture

The NQIT Hub's hardware development effort is guided by a plan for the system architecture, which itself is the subject of ongoing development. The designs being considered by NQIT consist of a network of many small, reliable quantum systems, which cooperate to provide a coherent information processing platform. This modular approach places scalability at the forefront of the design requirements, and so promises to yield significant computing power sooner than a monolithic approach. At the same time, this approach will provide the versatility associated with computer networks.

To succeed, the plan for the architecture must determine performance requirements for each of the modular components, so that they perform optimally in the computational network. These requirements range from how well entanglement can be generated and purified by the devices, to the efficiency of photonic switches and photodetectors and the reliability of photonic memories. The components can then be used to provide the entanglement links necessary to link together the modules, allowing them to act in concert. With enough modules, we can then realise operations which no conventional computer could perform.

## Architecture Progress

The decision taken by NQIT to pursue networks of “small” quantum devices (each containing fewer than 50 qubits) allows us to attempt to perfect the design of a low-cost and easily-produced device. This raises the question of just how small the individual modules can be, and how interconnected they must be, to provide a scalable computing platform.

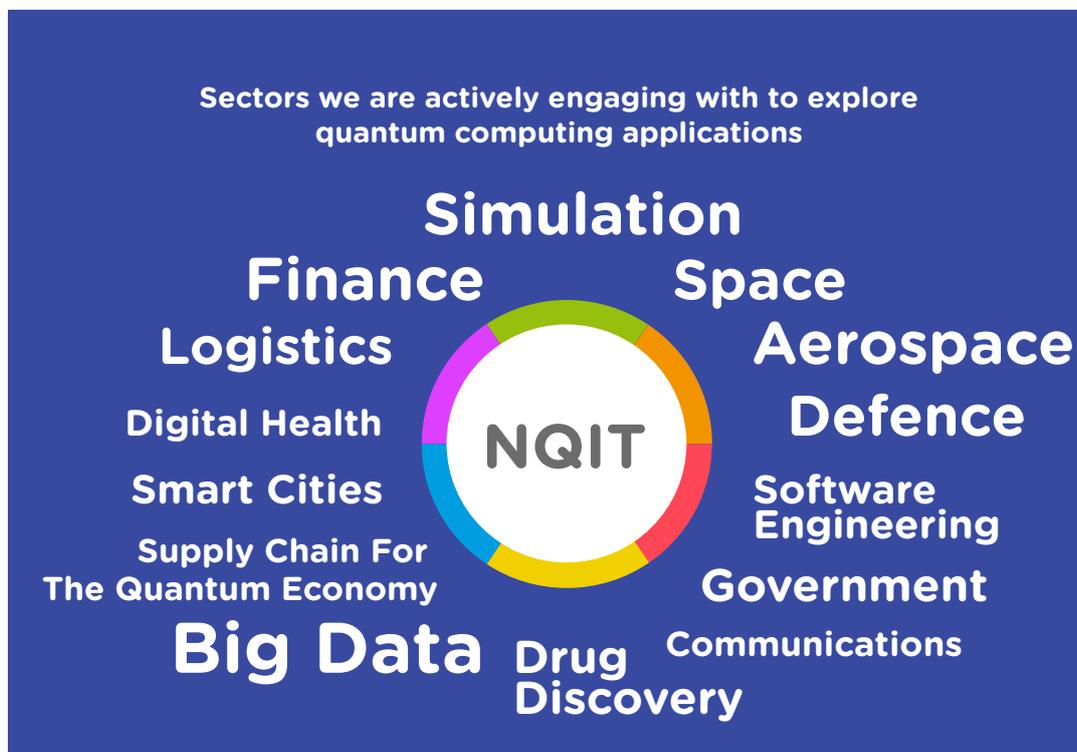
A requirement for a networked quantum architecture is the availability of high-quality entanglement links, to allow modules to collaboratively protect and compute with quantum data. For linear ion traps, we have compiled down the protocol to produce high-quality entanglement, into device-level operations including shuttling and cooling events. We found that only a small number of helper ions would suffice to achieve the quality of entanglement required for scalable computational networks, given the operational quality seen in recent experiments. This development motivated us to re-examine the architecture of the Q20:20 platform: rather than 20 ion traps each containing 20 ions, we are considering a larger number of smaller and easier-to-build modules, such as 50 ion traps each containing five ions.

The latter “Q5:50” blueprint is currently the most promising direction for the NQIT architecture, and opens up the possibility of more rapid production of modules for the computational platform. However, with advancing experimental techniques, it may still prove practical to make medium-scale ion traps containing as many as 20 ions, but with fewer demands made on their connectivity. Recent work has shown that if this should be the case, scalable quantum computation is also achievable on a linear network of “medium-sized” ion traps (containing 15 to 35 ions). This provides us with the flexibility to react to progress in the hardware work packages.

Microwave ion trap chip for quantum computation / Diana Prado Lopes  
Aude Craik & Norbert Linke

# Industry Engagement

**NQIT is a technology development project with the strong objective of commercialising quantum information technologies at its centre. Our User Engagement team is working to build a network of businesses, universities and government agencies focused on developing the new quantum technology sector.**



We have engaged with over 80 organisations, ranging from quantum technology start-ups and SMEs (small and medium enterprises) through to multinationals, government bodies and other institutions. This network is expanding rapidly: we have added 11 new industry partners to the original 25 that were founding members of the consortium.

We have so far used around one-third of our £3.4m Partnership Fund, along with 70% matched funding, to establish 14 partnership projects between industry and academia that are directed towards either developing the essential relationships that will be needed in the manufacture of a quantum computer, or technologies that will have a more immediate

commercial impact. These projects have brought in world-leading industries; their enthusiasm to invest and commit to quantum technology research indicates the importance which industry places upon this emerging sector.

Projects that are now complete have looked at quantum simulators to improve the design of wing structures with BAE Systems, quantum algorithms for optimisation of transport routing with Route Monkey, medical sensors using quantum properties of diamond with Bruker, and high performance optical switches with Gooch & Housego. The rest are still underway and we have three more in the pipeline.

The User Engagement team are working with NQIT scientists to bring new quantum technologies to market. Ten patents have been filed and we are developing five new spin-out companies.

We continue to host a six-monthly Industry User Forum, where people from industry worldwide are invited to discuss their commercial requirements with NQIT scientists.

We demonstrated our technology at several national events including the annual Quantum Technology

Showcase, the DSTL Quantum Technology Day, several Knowledge Transfer Network (KTN) events, the British Standards Institute Industry Day and a British Telecom Industry Day, organised by the Quantum Communications Hub.

We have been successful in securing additional investments from industries and Innovate UK, for example Innovate UK, Nokia and SME Bay Photonics have invested £250k in total on a Quantum Wireless Systems project.

## INDUSTRY PARTNERSHIP CASE STUDY

### Quantum Algorithms for Transport with Route Monkey

This project saw NQIT partnering with Route Monkey, a Scottish optimisation business, and quantum physicists at Heriot-Watt University in Edinburgh to develop, test and commercialise quantum algorithms for optimising transport and mobility.

Route Monkey is an award-winning leader in the development and provision of complex, multi-criterion algorithms. Their optimisation solutions eliminate unnecessary mileage and improve vehicle utilisation, typically helping to reduce fleet costs by up to 20 per cent and substantially cut carbon emissions. The algorithms are capable of making millions of calculations in a relatively short space of time, vastly improving on manual transport planning. They provide a competitive edge to businesses and also help cities deal with growing urban challenges like congestion.

For these sorts of algorithm-based solutions, a quantum computer has the advantage that it only has to run one set of calculations to analyse various scenarios. It can also deal with much larger, more complex data sets and crunch the numbers much faster.

*"With Heriot-Watt University and the NQIT Hub, we can address the increasingly complex challenges of moving people and goods around our cities, while simultaneously cutting wasted miles and reducing emissions from road transport." Route Monkey*



## INDUSTRY PARTNERSHIP CASE STUDY

### Diamonds for Medical Applications with Bruker

Artificial diamonds created with deliberate “colour centre” defects called Nitrogen Vacancy (NV) centres can be used as qubits for quantum computation and also as magnetic field sensors for medical applications, such as detecting the tiny magnetic field emitted by the heart (magnetocardiography (MCG)) or the brain (magnetoencephalography (MEG)).

This industry partnership project teamed up diamond researchers from NQIT with Bruker GmbH, a manufacturer of scientific instruments, to design and develop a prototype magnetometer and to assess its commercial competitiveness over existing MCG technologies, such as superconducting quantum interference devices (SQUIDS) and alkali metal atomic vapour cell magnetometers.

Bruker saw the project as an opportunity to start to develop sensors with applications in medicine, including brain imaging. We were fortunate to have Bruker as our project partner, as they have the infrastructure and resources to carry out subsequent product development and a route to market for commercial exploitation.

This project has allowed Bruker to evaluate the commercial potential of this approach, and decide on the next steps in its commercialisation strategy.

We concluded that if an MCG system were available with the same functionality as the existing SQUID systems, but at a tenth of the cost, the estimated market worth would be over US\$10 billion.

Diamond magnetometers offer the benefits of robustness, significantly lower costs and can be placed in close proximity to the patient. However, the sensitivity of diamond magnetometers cannot currently compete with that of the more mature SQUID and atomic vapour cell magnetometers. Nevertheless, the future for diamond sensors holds great promise, and orders of magnitude of improvement will be achieved over the next few years through optimisation of the diamond material, sensor configuration and detection technology.



PhD student Diana Prado Lopes Aude Craik, in front of her award-winning photo of an ion trap microchip, explaining her research at the Quantum Technology Showcase / Dan Tsantilis / EPSRC

## Industry News Highlight: Quantum Technology Showcase 2016

We helped organise, and were a major exhibitor at, the second Quantum Technology Showcase, held in November 2016 at the Queen Elizabeth II Conference Centre in Westminster. This one-day event was an opportunity for us to showcase our innovative research and technology development work to more than 400 delegates from industry, business and government, and to network with current and potential collaborators from around the world.

NQIT's exhibits included a diamond magnetometer, the result of our industry partnership project with Bruker GmbH, and a demonstration of wavelength conversion, which we have developed in partnership with Covesion Ltd.

We also exhibited our cutting-edge ion trap technology, with demonstrations explaining the underlying physics and a live, interactive exhibit that allowed you to remotely take control of a single ion in the Ion Quantum Technology laboratory at Sussex, perform a "quantum coin" experiment and see the results in real time.

The next Quantum Technology Showcase will take place in London in November 2017.

"We all agreed that it is one of the most comprehensive descriptions of the quantum computing environment and you have captured the timelines very well." D-Wave Systems, Inc

"I found your roadmap extremely useful. It provided both a comprehensive, up-to-date survey of the field, and an apples-to-apples comparison of different leading quantum computing technologies in metrics that are easy to understand."

## Outputs

As part of our aim to be a trusted source of information about quantum computing, we have produced two key reports that are being distributed globally. The reports are both authoritative and accessible to a non-research readership and feedback has been very positive. The first, "Commercial prospects for Quantum Computing", is a market report that covers global investment in quantum computing in the past decade. Over 140 organisations from around the world have so far requested a copy, and we have received comments that it is being actively used to help inform company strategy, shape strategic investment, and assist with market research and industry mapping. It is also enabling the discovery of new opportunities in quantum computing as well as helping assess risks, and is contributing to the planning decisions for future company products and market growth.

The second key report is a "Technical Roadmap for Fault-tolerant Quantum Computing" and sets out the concepts and potential applications of a small quantum computer. This too has been extremely well received, and is being used by organisations to help gain a deeper understanding of the quantum technology landscape and current research direction, the potential for future applications, and is helping to facilitate strategy discussions within technical departments and at board level.



# Wider Engagement

## Responsible Research and Innovation

Responsible Research and Innovation (RRI) engages with stakeholders from research, industry and the public to anticipate and reflect on the potentially profound social implications of quantum technologies.

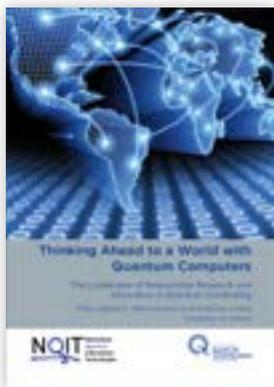
We have completed the Landscape study of RRI in Quantum Computing and from this we have produced a report entitled “Thinking Ahead to a World with Quantum Computers” with an associated Policy Brief.

We are now investigating the issues outlined in the Landscape report in a series of case studies. Towards the end of 2016, a high-level workshop on the RRI implications of Quantum Technology for Defence and National Security was held at the Oxford Martin School. Further workshops and studies are in progress for 2017/18.

We have worked to increase capacity and awareness of RRI more widely, with a series of “Roadshow” events at the UK National Quantum Technologies Hubs. We have also held training workshops at NQIT Skills Forums.

The mid-term review recommended that RRI activities should extend across each of the four Quantum Hubs, with each one taking the lead on a particular area of expertise. We have produced a revised RRI strategy to put this into effect, and maximise the reach of RRI-led public engagement activities in each Hub.

The separate Public Dialogue process being conducted by EPSRC should provide valuable insights for the understanding of public attitudes to quantum technologies.



*“This excellent policy brief builds on the EPSRC framework for responsible innovation to develop a set of principles that, if enacted, will be of value not only for the quantum technology hubs but more generally in other areas of potentially disruptive and transformational technology. The key thing is for the hubs to adopt this and put the principles into practice.”* Professor Richard Owen, University of Exeter

## Public Engagement

In the first year of the programme, we established the core communications channels for NQIT: a new website, a strong presence on Twitter (we now have more than 700 followers and counting) and a programme of recurring annual events.

Since then, we have been engaging with a wide range of audiences.

We took NQIT to two science festivals – the Cheltenham Science Festival and the Oxfordshire Science Festival – to engage with young people and families. This was a great opportunity for graduate students and early career researchers to talk with members of the public about their research and how quantum computers will affect people in their everyday lives. We plan to attend more science festivals, including the Oxfordshire Science Festival, in 2017.

We commissioned an **animated film about quantum computing from world-leading visual communications company, Scriberia, to demystify quantum computing in an engaging and fun way.** The film touched on aspects of responsible research and innovation by showing how we are thinking about the wider implications of quantum computing.

We have also been engaging with a local business audience. We won an Oxford University Knowledge Exchange Seed Fund Award to stage an event to explain “How will Quantum Technologies change how you do business?” attended by 40 people from local businesses in the Oxfordshire area.

**“The NQIT project is ahead of the curve in thinking about the implications of quantum computing and how researchers and society as a whole can prepare for them.”** Professor Jim Al-Khalili, University of Surrey



## Inter-Hub Collaboration

We have been working closely with the other partners in the UK National Quantum Technologies Programme, in particular the other Quantum Technology Hubs. We have collaborated on several national events, including the Quantum UK Conference, the Quantum Technology Showcase and public engagement events such as the Cheltenham Science Festival.

We are taking the lead on Responsible Research and Innovation, working with EPSRC to deliver a series of workshops across the National Programme and have welcomed visitors from across the Programme to events such as our twice-yearly Skills Forum.

Three new projects have been set up across three Quantum Technology Hubs to explore technologies where we have mutual interests. We are working with the UK Quantum Technology Hub for Sensors and Metrology and DSTL, to develop a high-flux source of laser-cooled atoms for quantum sensing applications. We are also working with the Quantum Communications Hub in developing a flexible platform for short-range wireless quantum communication, and the third project involves studying the impact of quantum-enhanced encryption systems. These collaborations will increase as the planned deliverables are achieved in the next few years, leading to new subsystems and devices being available across the Hubs.

## Skills and Training

NQIT is working with the other Quantum Technology Hubs to develop skills capacity through student and post-doctoral training programmes. We are partnering with the Quantum Technology Skills Hubs and Centres for Doctoral Training to set up an internal programme of funded studentships across the Hub partners, 16 of which have now been externally advertised, with a new cohort of graduate students beginning in October 2017.

We organise a Skills Forum twice a year, open to researchers, students and industry partners across the UK National Quantum Technology Programme, to provide the technical, engineering, entrepreneurship and communications training needed to seed the new quantum technology sector.

Discussions at the NQIT Project Forum,  
University of Oxford / Department of  
Engineering Science, Media Unit



## Skills & Training News Highlight: Skills Forum

As part of our Skills and Training Programme, we are holding a Skills Forum every six months. This is a free day of training sessions attended by around 80 researchers from within NQIT and across the UK National Quantum Technologies Programme, as well as industry partners and graduate students from the Quantum Centres for Doctoral Training.

Sessions are in four streams: developing a technology, business and entrepreneurship, applications of quantum technologies, and engineering skills. They have ranged from highly technical – **“COMSOL multiphysics modelling**, a unique opportunity to advance your skills in **“multiphysics simulation”** – to business-focused – **“The Elevator Pitch**: one-minute chat-up lines for entrepreneurs” to practical communications skills – **“Podcasting your research”**. Delegates are able to attend sessions across the streams throughout the day, and feedback has been extremely positive, with one describing the experience as personalised “tailor-made training”, and another industry partner stating the importance to their company, saying that “workshops and exchanges with scientists are very important to keep our research updated with latest trends.”



## Policy News Highlight: Nicola Blackwood MP visit

Nicola Blackwood MP visited the Physics Department in December 2016. She was Parliamentary Under Secretary of State for Public Health and Innovation in the Department of Health and, until July 2016, was also the Chair of the Science & Technology Select Committee.

The visit was a part of the Royal Society Pairing Scheme, in which MPs welcome a scientist for a few days in Westminster, and then spend a week with them to learn more about their work. Nicola Blackwood was partnered with Dr Matthew Levy, a Royal Society Newton International Fellow based at Wolfson College, Oxford University, who organised a Symposium in the Physics Department for Nicola Blackwood entitled 'Science & Innovation Sessions'. During this, she spoke with our NQIT researchers and User Engagement team about our innovative quantum computing work.

Nicola said: "It has been inspiring to learn about Matthew's work and the exciting research going on in and around Oxford. Today has been brilliant in highlighting just how innovative we are and how we can encourage younger generations to continue the trend."

Nicola Blackwood MP meets researchers and NQIT's User Engagement team during her visit to University of Oxford, Department of Physics / Valeria Crowder



The new Beecroft  
Building, with Keble  
College in reflection  
*/ David Fisher / NQIT*

# Looking Ahead

## Short-term Plans

**Our new laboratories in the Beecroft building will be complete at the end of 2017, allowing us to house key members of our team and the Q20:20 quantum computer demonstrator in a state-of-the-art facility. These facilities will also be made available to academic, governmental and commercial organisations by secondments and exchanges, particularly as the experience of our post-doctoral cohort grows. Meanwhile work progresses in recently renovated laboratory space.**

We will build on progress made in architecture and engineering systems to focus on hardware development for the Q20:20 demonstrator, and review the state of each of the candidate technologies as the programme evolves to ensure we adapt to the rapid pace of developments.

In addition, our extensive industry engagement and consultancy activity has identified the need for an emulator to allow users to try small-scale quantum applications, on laptop-scale platforms. Activities by IBM and Microsoft have shown the success that such systems can have. At the same time, an emulator to model the Q20:20 hardware specifically would allow applications of the small-scale networked quantum system to be trialled, with the aim of transitioning to real hardware once possible. We therefore plan to create two distinct emulators:

- 1** A Q20:20 emulator using NQIT supercomputing resources, to strengthen the links between the application and hardware teams and allow rapid transitioning to real hardware once it becomes available.
- 2** A freely available emulator for generic quantum computation, to allow a base of users to develop new domain problems and techniques for quantum computing.

We will continue to work with the National Institute of Standards and Technology (NIST) in the USA on open standards for control systems, and with the National Physical Laboratory (NPL) in the UK to understand the standards landscape. Verification is a key part of this, and we will use the results of our research in this area to influence any future standards.

Our highly successful industry engagement activities will continue, and we will carry on pursuing spin-out technologies, such as the open-wall cavity sensor and Quantum Random Number Generator. We are also developing a plan for a quantum engineering spin-out company, to transfer and exploit the growing engineering know-how across the Hub.

University of Oxford Vice-Chancellor Professor Louise Richardson at the Beecroft Building Topping Out Ceremony with (from left to right) Mr Adrian Beecroft (Oxford Physics Alumnus and benefactor), Mr Liam Cummings and Mr Rob Cooper (from construction company Laing O'Rourke) / Stuart Bebb / Department of Physics



## Investment News Highlight: Beecroft Building

Last summer we were looking down at a huge 17m-deep pit outside our offices in the Department of Physics, Oxford. Now we are looking up at the six-storey skeleton of a new building. This ambitious building project is costing £47m, of which £3.6m has been contributed by the EPSRC directly for the benefit of the NQIT Hub.

The two basement levels of the Beecroft Building will house state-of-the-art laboratory space to allow interaction between industry and academia and the use of technology demonstrators. The new labs will have a highly-controlled environment that maintains very low vibration levels and temperature control to within 0.1°C.

In February 2017, we celebrated the “Topping Out” ceremony, attended by the Vice Chancellor of Oxford University, Professor Louise Richardson, and benefactors including Adrian Beecroft.

The Beecroft Building is due to be finished at the end of 2017 and will open for research at the beginning of 2018.

## Long-term Vision

Our plans for the six-to-ten year NQIT programme are to continue engineering the processing nodes themselves, focusing on reducing complexity and size, and improving reliability. Developments from the first five years, such as the order of magnitude improvement in microwave gate performance achieved in the first two years of the programme, will doubtless impact the technologies chosen.

A critical goal will be the integration of optical cavities with ion traps to increase the speed of quantum logic operations. This work will be undertaken in partnership with companies and industry wherever possible, and use the wide range of facilities that the UK National Quantum Technology Programme has created.

We will be working on a second generation, larger-scale quantum computing demonstrator, with faster operation and a higher degree of systems integration, again in partnership with industry. In addition, we are planning to develop first generation computing co-processors and smaller-scale devices, using the photonic and NV technologies currently under development in the NQIT programme.

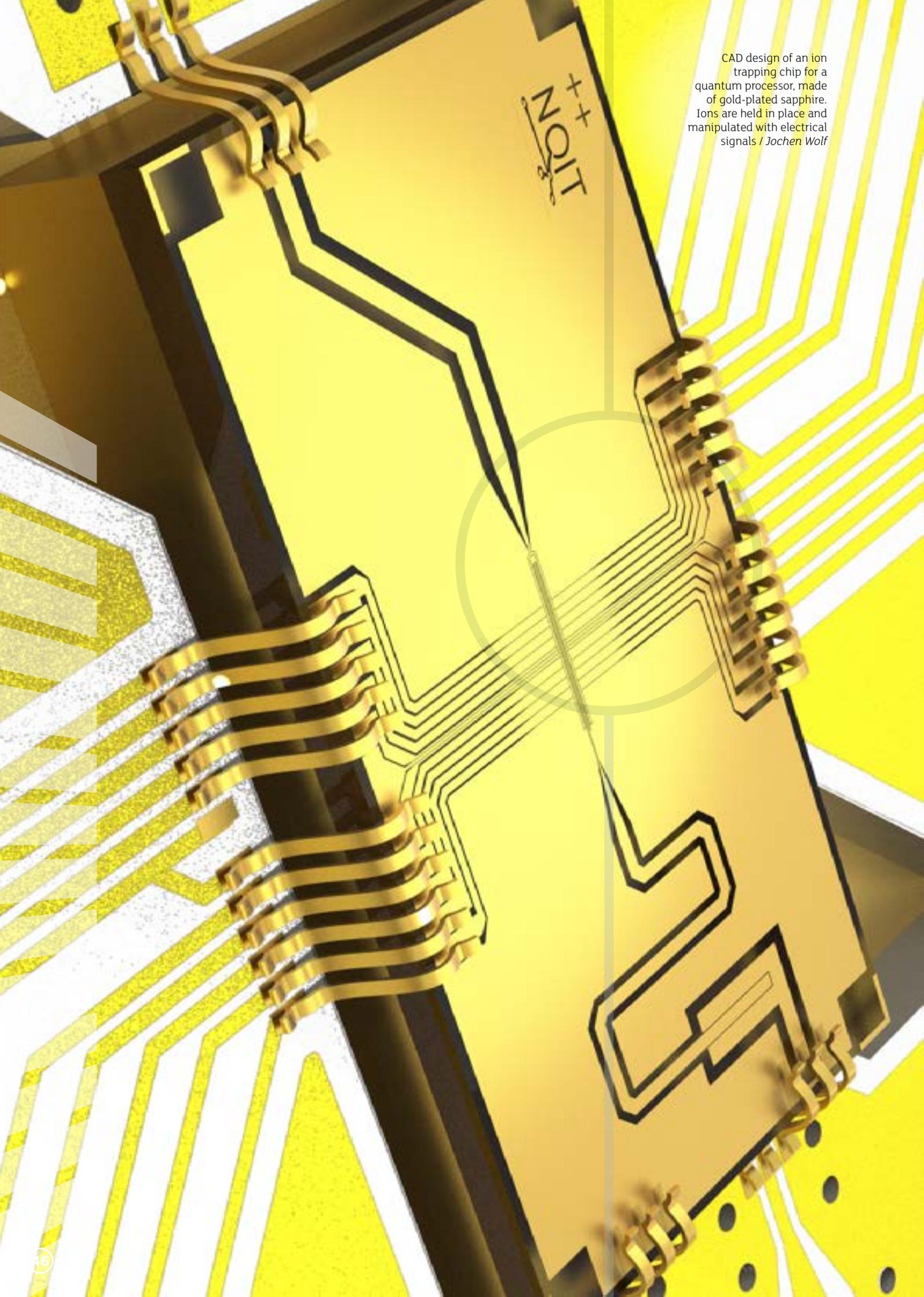
We will pursue smaller-scale processor nodes, memories and wavelength conversion that will enable the vision of a secure quantum internet, by combining information processing and secure transmission. Similarly, technological developments will enable us to implement a demonstration application of quantum sensing.

A key software goal is to continue investigating new applications and algorithms that can exploit the benefit of quantum computing, particularly for the small-scale devices that will emerge from first generation programmes. We will also design robust tools that allow quantum co-processors to additionally work in combination with conventional computation, and develop software for the larger-scale demonstrators we envisage.

The culmination of these efforts will be to enable technology transfer to the ecosystem of companies and industries that the UK National Quantum Technologies Programme is nurturing.



CAD design of an ion trapping chip for a quantum processor, made of gold-plated sapphire. Ions are held in place and manipulated with electrical signals / Jochen Wolf



# Programme Outputs

## Publications

- Allcock, D. T. C., et al. (2016). "Dark-resonance Doppler cooling and high fluorescence in trapped Ca-43 ions at intermediate magnetic field." *New Journal of Physics* 18(2): 023043 (023010 pp.)-023043 (023010 pp.).
- Ballance, C. J., et al. (2016). "High-Fidelity Quantum Logic Gates Using Trapped-Ion Hyperfine Qubits." *Physical Review Letters* 117(6): 060504.
- Baumgratz, T. and A. Datta (2016). "Quantum Enhanced Estimation of a Multidimensional Field." *Physical Review Letters* 116(3): 030801.
- Begley, S., et al. (2016). "Optimized Multi-Ion Cavity Coupling." *Physical Review Letters* 116(22): 223001.
- Beige, A. (2016). "Quantum optics: A new take on the slit experiment." *Nat Photon* 10(5): 290-291.
- Bennett, R., et al. (2016). "A physically motivated quantization of the electromagnetic field." *European Journal of Physics* 37(1): 11.
- Blandino, R., et al. (2016). "Channel purification via continuous-variable quantum teleportation with Gaussian post-selection." *Physical Review A* 93(1): 11.
- Chen, Y.-C., et al. (2016). "Laser writing of coherent colour centres in diamond." *Nat Photon* advance online publication.
- Clark, L. A., et al. (2016). "Quantum-enhanced metrology with the single-mode coherent states of an optical cavity inside a quantum feedback loop." *Physical Review A* 94(2): 023840.
- De Motte, D., et al. (2016). "Experimental system design for the integration of trapped-ion and superconducting qubit systems." *Quantum Information Processing* 15(12): 5385-5414.
- Francis-Jones, R. J. A., et al. (2016). "All-fibre multiplexed source of high-purity single photons." *Optica* 3(11): 1270-1273.
- Francis-Jones, R. J. A. and P. J. Mosley (2016). "Characterisation of longitudinal variation in photonic crystal fibre." *Optics Express* 24(22): 24836-24845.
- Gagatsos, C. N., et al. (2016). "Gaussian systems for quantum-enhanced multiple phase estimation." *Physical Review A* 94(4): 042342.
- Harty, T. P., et al. (2016). "High-Fidelity Trapped-Ion Quantum Logic Using Near-Field Microwaves." *Physical Review Letters* 117(14): 140501.
- Heshami, K., et al. (2016). "Quantum memories: emerging applications and recent advances." *Journal of Modern Optics*: 1-24.
- Holleccek, A., et al. (2016). "Quantum Logic with Cavity Photons From Single Atoms." *Physical Review Letters* 117(2): 023602.
- Jizba, P., et al. (2016). "One-parameter class of uncertainty relations based on entropy power." *Physical Review E* 93(6): 060104.
- Knott, P. A. (2016). "A search algorithm for quantum state engineering and metrology." *New Journal of Physics* 18(7): 073033.
- Knott, P. A., et al. (2016). "Correspondence: Enhancing a phase measurement by sequentially probing a solid-state system." *Nature Communications* 7: 11520.
- Knott, P. A., et al. (2016). "Practical quantum metrology with large precision gains in the low-photon-number regime." *Physical Review A* 93(3): 033859.
- Knott, P. A., et al. (2016). "Local versus global strategies in multiparameter estimation." *Physical Review A* 94(6): 062312.
- Kok, P., et al. (2017). "Role of entanglement in calibrating optical quantum gyroscopes." *Physical Review A* 95(1): 012326.
- Kreula, J. M., et al. (2016). "Non-linear quantum-classical scheme to simulate non-equilibrium strongly correlated fermionic many-body dynamics." *Scientific Reports* 6: 32940.
- Lee, C. M. and M. J. Hoban (2016). "Bounds on the power of proofs and advice in general physical theories." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science* 472(2190).
- Lekitsch, B., et al. (2017). "Blueprint for a microwave trapped ion quantum computer." *Science Advances* 3(2).
- Li, Y. and S. C. Benjamin (2016). "Hierarchical surface code for network quantum computing with modules of arbitrary size." *Physical Review A* 94(4): 042303.
- Liu, H., et al. (2016). "Large radius of curvature micro-lenses on single crystal diamond for application in monolithic diamond Raman lasers." *Diamond and Related Materials* 65: 37-41.
- Main, P., et al. (2016). "Hybrid microfiber-lithium-niobate nanowaveguide structures as high-purity heralded single-photon sources." *Physical Review A* 94(6): 063844.
- Márquez Seco, A., et al. (2016). "Novel Ion Trap Design for Strong Ion-Cavity Coupling." *Atoms* 4(2): 15.

- Nigmatullin, R., et al. (2016). "Formation of helical ion chains." *Physical Review B* 93(1): 014106.
- Nikoghosyan, G., et al. (2016). "Universality in the Dynamics of Second-Order Phase Transitions." *Physical Review Letters* 116(8): 080601.
- Ohadi, H., et al. (2016). "Tunable Magnetic Alignment between Trapped Exciton-Polariton Condensates." *Physical Review Letters* 116(10): 106403.
- Podoliak, N., et al. (2016). "Comparative Numerical Studies of Ion Traps with Integrated Optical Cavities." *Physical Review Applied* 6(4): 044008.
- Ramil, N., et al. (2016). "Minimally complex ion traps as modules for quantum communication and computing." *New Journal of Physics* 18(10): 103028.
- Saunders, D. J., et al. (2016). "Cavity-Enhanced Room-Temperature Broadband Raman Memory." *Physical Review Letters* 116(9): 501-501.
- Sperling, J., et al. (2016). "Quantum Correlations from the Conditional Statistics of Incomplete Data." *Physical Review Letters* 117(8): 083601.
- Szczykulska, M., et al. (2016). "Multi-parameter quantum metrology." *Advances in Physics: X* 1(4): 621-639.
- Trichet, A. A. P., et al. (2016). "Nanoparticle Trapping and Characterization Using Open Microcavities." *Nano Letters* 16(10): 6172-6177.
- Walk, N., et al. (2016). "Experimental demonstration of Gaussian protocols for one-sided device-independent quantum key distribution." *Optica* 3(6): 634-642.
- Walmsley, I. A. and J. Nunn (2016). "Editorial: Building Quantum Networks." *Physical Review Applied* 6(4): 040001.
- Wan, C., et al. (2016). "Tolerance in the Ramsey interference of a trapped nanodiamond." *Physical Review A* 93(4): 043852.
- Wan, C., et al. (2016). "Free Nano-Object Ramsey Interferometry for Large Quantum Superpositions." *Physical Review Letters* 117(14): 143003.
- Weidt, S., et al. (2016). "Trapped-Ion Quantum Logic with Global Radiation Fields." *Physical Review Letters* 117(22): 220501.

## Talks

- January 2016, "A New Generation of Computers: Towards Quantum 2.0 Technologies", Professor Ian Walmsley, UK Alumni Seminar, hosted by the British Embassy Seoul, Korea.
- January 2016, "Seminar on Quantum Computing", Professor Ian Walmsley, Korea Institution of Science and Technology, Korea.
- January 2016, "Multiphoton quantum interference in multiphoton integrated optical circuits: from

teleportation to Boson Sampling", Professor Ian Walmsley, Optical Society of Korea (OSK) Winter Annual Meeting 2016, Korea.

February 2016, "Diamond for Quantum Technology", Professor Ian Walmsley, SU2P Workshop on Diamond for Quantum Technologies and Sensing, Strathclyde, UK.

March 2016, QuProCS Annual Meeting 2016, Ian Walmsley.

March 2016, "Quantum Photonic Networks", Professor Ian Walmsley, Quantum Probes for Complex Systems Annual Meeting 2016, Italy.

March 2016, "Computing with Encrypted Data", Professor Elham Kashefi, Oxford Cryptography Seminar 2016, Oxford, UK.

June 2016, "Quantum Logic and Feedback with Cavity Photons from Single Atoms", Professor Axel Kuhn, "Constructing a Long-Wavelength Radiation Trapped-Ion Quantum Computer", Professor Winfried Hensinger and "Interfacing Ions and Photons", Professor Matthias Keller, Control of Quantum Dynamics of Atoms, Molecules and Ensembles by Light Workshop 2016, Bulgaria.

June 2016, "Constructing a Trapped-Ion Quantum Computer", Professor Winfried Hensinger, Seoul Conference on Frontiers in Quantum Information Science, ICAP 2016, Korea.

August 2016, "Quantum Computing: The World's Most Incredible Machines", Professor Winfried Hensinger, US Department of Energy's Cyber Distinguished Speaker Series lecture, USA.

## Public Engagement Activities

"The Dawn of Quantum Technology": public lecture by Professor Simon Benjamin, part of the Oxford Martin School's series on Technology for Tomorrow – the Research Shaping our Future, Oxford, UK. This talk was streamed live on YouTube and has had nearly 5,000 views.

"A New Generation of Computers: Towards Quantum 2.0 Technologies": talk by Professor Ian Walmsley to a group of UK alumni at the British Embassy in Seoul, Korea.

Oxfordshire Science Festival 2016: NQIT had a stand in the Science Fair in Oxford Town Hall for the duration of the weekend event.

"How will Quantum Technologies change how you do business?": We were awarded an Oxford University Knowledge Exchange Seed Fund Award to host an event attended by around 50 local business people and members of the public.

Cheltenham Science Festival 2016: NQIT had a stand for three days at the Discover Zone at the Cheltenham Science Festival, visited by hundreds of school children, families and members of the public.

## Other Events Attended

March 2016, Innovate UK and the support available for academic/industrial collaborations, Oxford, UK

May 2016, Nature / Entrepreneur First Innovation Forum in Quantum Technologies, London, UK

May 2016, Quantum Technology for the 21st century, Royal Society, London, UK

May 2016, Quantum Manifesto Launch at Quantum Europe Conference, Amsterdam, The Netherlands

June 2016, NQIT Responsible Research and Innovation Roadshow, Oxford, UK

June 2016, Venturefest, Oxford, UK

September 2016, Funding competition: commercialisation of quantum technologies, Innovate UK webinar

September 2016, Quantum UK 2016 Conference, Birmingham, UK

September 2016, Oxford Physics Industry Day, Oxford, UK

October 2016, Workshop on Responsible Research and Innovation in Quantum Technologies for Defence, Oxford, UK

November 2016, National Quantum Technologies Showcase, London, UK

November 2016, EU Quantum Flagship event at the EU Parliament, Brussels, Belgium

December 2016, Nicola Blackwood MP visits Physics Department, Oxford, UK

January 2017, Industrial Strategy Challenge Fund Engagement Workshop, London, UK

January 2017, Industrial Strategy Challenge Fund Engagement Workshop, Birmingham, UK

February 2017, Science Innovation Audit - Digital Health Workshop (AHSN), Oxford, UK

February 2017, Science Innovation Audit - Satellite Catapult Workshop, Oxford, UK

March 2017, "Hacking nature's computers: exploring quantum computation with organic molecules", Professor Vlatko Vedral, Oxford, UK

March 2017, Quantum Technology Enterprise Centre talk, Oxford, UK

March 2017, Quantum technologies public dialogue stakeholder workshop, London, UK

March 2017, Quantum Innovation Lab, Bristol, UK

March 2017, Challenges for Quantum Computer Science & Simulation, Bristol, UK

## Further Funding

Established Career Fellowship, Dr Elham Kashefi: Verification of Quantum Technology

▣ Dates of award: October 2015 to September 2020

▣ Amount: £1,237,804

▣ Funder: Engineering and Physical Sciences Research Council EPSRC

▣ Grant reference: EP/N003829/1

Strategic Equipment - a Dual Beam FIB/SEM with large area patterning, EBSD and nanoprobe capabilities, Dr Jason Smith and Oxford Instruments

▣ Dates: January 2016 to June 2017

▣ Amount: £12,825

▣ Funder: Engineering and Physical Sciences Research Council EPSRC

▣ Grant reference: EP/N010868/1

Feasibility study of handheld Quantum Key Distribution, Nokia Ltd, Bay Photonics and University of Oxford

▣ Dates: May 2015 to April 2016

▣ Amount: £87,398

▣ Funder: Innovate UK

▣ Grant reference: 131882

Collaborative Research & Development: FEMTO - Femtosecond Measurement Technology Options, Chronos Technology Limited, TMD Technologies Ltd and University of Bath

▣ Dates: June 2015 to September 2016

▣ Amount: £192,003

▣ Funder: Innovate UK

▣ Grant reference: 102247

## Selected Media Coverage

Record-breaking logic gate “another important milestone” on road to quantum computers

- ❑ Oxford University website: “Record-breaking logic gate ‘another important milestone’ on road to quantum computers”

<http://www.ox.ac.uk/news/2016-08-08-record-breaking-logic-gate-another-important-milestone-road-quantum-computers>

- ❑ Phys.org: “Record-breaking logic gate ‘another important milestone’ on road to quantum computers”

<http://phys.org/news/2016-08-record-breaking-logic-gate-important-milestone.html>

Construction of practical quantum computers radically simplified

- ❑ Phys.org: “Construction of practical quantum computers radically simplified”

<http://phys.org/news/2016-11-quantum-radically.html>

- ❑ Tech Times: “A Quantum Computing Breakthrough? Scientists Invent Groundbreaking Method To Simplify Construction Of Quantum Computers”

<http://www.techtimes.com/articles/187006/20161126/a-quantum-computing-breakthrough-scientists-invent-groundbreaking-method-to-simplify-construction-of-quantum-computers.htm>

- ❑ Electronics Weekly: “Quantum computing without millions of lasers”

<http://www.electronicweekly.com/news/research-news/quantum-computing-without-millions-lasers-2016-11/>

- ❑ International Business Times: “Quantum computing breakthrough: UK scientists develop technique to greatly simplify trapped ions”

<http://www.ibtimes.co.uk/quantum-computing-breakthrough-uk-scientists-develop-technique-greatly-simplify-trapped-ions-1593317>

- ❑ BBC News: “The supercomputer of the future?” <http://www.bbc.co.uk/news/science-environment-38106482>

Top Technology Breakthroughs of 2016

- ❑ Physics World: “LIGO’s gravitational-wave discovery is Physics World 2016 Breakthrough of the Year”

<http://physicsworld.com/cws/article/news/2016/dec/12/ligo-gravitational-wave-discovery-is-physics-world-2016-breakthrough-of-the-year>

- ❑ Physics World: “Physicists take entanglement beyond identical ions”

<http://physicsworld.com/cws/article/news/2016/jan/12/physicists-take-entanglement-beyond-identical-ions>

- ❑ International Business Time: “The best technology breakthroughs in 2016 from quantum computing to AI” <http://www.ibtimes.co.uk/best-technology-breakthroughs-2016-quantum-computing-ai-1598710>

Route Monkey Takes Quantum Leap for Fleet Optimisation

- ❑ Transport Engineer: “Route Monkey announces quantum leap for fleet optimisation”

<http://www.transportengineer.org.uk/transport-engineer-news/route-monkey-announces-quantum-leap-for-fleet-optimisation/150492/>

- ❑ Green Car Congress: “Route Monkey working with NQIT to develop transport & mobility algorithms for quantum computers”

<http://www.greencarcongress.com/2017/01/20170119-routemonkey.html>

- ❑ Scotland B2B: “Livingston tech firm takes Quantum Leap into future of travel”

<http://scotlandb2b.co.uk/2017/01/20/livingston-based-route-monkey-takes-quantum-leap-into-the-future/>

New Blueprint for Large-Scale Quantum Computing

- ❑ Nature: “Physicists propose football-pitch-sized quantum computer”

<http://www.nature.com/news/physicists-propose-football-pitch-sized-quantum-computer-1.21423>

- ❑ Phys.org: “First ever blueprint unveiled to construct a large scale quantum computer”

<https://phys.org/news/2017-02-blueprint-unveiled-large-scale-quantum.html>

- ❑ BBC News: “Quantum computer ‘construction plan’ drawn up”

<http://www.bbc.co.uk/news/science-environment-38811255>

- ❑ The Independent: “Quantum computing breakthrough could help ‘change life completely’, say scientists”

<http://www.independent.co.uk/news/science/quantum-computers-quantum-physics-sussex-university-holy-grail-a7558036.html>

- ❑ Sky News: “UK scientists come up with blueprint for Deep Thought supercomputer”

<http://news.sky.com/story/uk-scientists-come-up-with-blueprint-for-deep-thought-supercomputer-10752680>

- ❑ Scientific American: “Physicists Call for a Soccer-Field-Sized Quantum Computer”

<https://www.scientificamerican.com/article/physicists-call-for-a-soccer-field-sized-quantum-computer/>

- ❑ International Business times: “Quantum Computing Update: Researchers Unveil ‘Construction Plan’ For An Actual Large-Scale Device”

<http://www.ibtimes.com/quantum-computing-update-researchers-unveil-construction-plan-actual-large-scale-2485009>

New quantum device could make contactless payment transactions more secure

- ❑ Oxford University website: "New quantum device could make contactless payment transactions more secure"  
<http://www.ox.ac.uk/news/2017-03-28-new-quantum-device-could-make-contactless-payment-transactions-more-secure>
- ❑ Phys.org: "Quantum key system could make mobile transactions far more secure"  
<https://phys.org/news/2017-03-quantum-key-mobile-transactions.html>

The Quantum Team at the Oxfordshire Science Festival. From left to right: PhD student James Tarlton, Dr Ben Keitch, and PhD students Gil Triginer Garces and Mihai Dorian Vidrighin / Hannah Rowlands / NQIT



# Glossary

**Diamond colour centres** A solid state alternative to using ion-traps as qubits in the Q20:20 engine and involve making use of colour defects present at an atomic scale in diamonds

**Fault-tolerant** In computation, something that is fault tolerant can continue operations after it encounters a problem, allowing the issue to be worked around and recovered from.

**Ion** An electrically-charged atom - an atom where an outer electron has been stripped away, leaving the whole atom with an electric charge.

**Ion Trap** A device which holds individual atoms, electrically-charged and levitating stably within an electric field, where they can be controlled with lasers and used for information processing.

**Isotopes of Calcium** Isotopes are elements that vary in the number of neutrons they have in the nucleus whilst the number of protons remains constant. Calcium-40 and calcium-43 are used in our quantum logic gates to allow quantum information to be transferred from one qubit to another: one isotope acts as the memory qubit, the other as the interface qubit.

**Photon** An elementary particle of light and electromagnetic radiation

**Photonics** This is essentially 'optical wiring' and means controlling photons, particles of light, to use in detection and manipulation.

**Quantum** In physics, a quantum is a discrete quantity of energy proportional in magnitude to the frequency of the radiation it represents, and refers to the smallest unit of a physical quantity - for example a photon is a "quantum of light". It also refers to the field of quantum physics, which describes the fundamental interactions of particles in nature.

**Quantum 2.0** This is a term used to describe the newest wave of quantum technologies that make use of the fundamental quantum nature of particles, such as superposition and quantum entanglement. These technologies use equipment such as highly stabilised laser systems, cryogenically-cooled solid state devices and ion traps to create, manipulate and then use quantum effects for applications such as information processing, computing, simulation, secure communications, sensing and imaging.

Quantum 2.0 is distinguished from early quantum technologies, such as lasers and semi-conductors, which rely on the effects of quantum mechanics, by the way they create and manipulate quantum states.

**Quantum entanglement** This counter-intuitive phenomenon can occur when two or more particles interact with one another, either directly or by using light as a mediator. When an action is performed on one of the entangled particles, it affects their mutual state, even when they are separated by great distances.

**Quantum network** A system composed of nodes and channels used to transfer quantum information. In the case of NQIT, our quantum network will be a hybrid light-matter network.

**Quantum states** A state of a quantised system which is described by a set of quantum numbers. Unlike a classical binary system, quantum numbers can exist in multiple states at once.

**Quantum technology** Technologies that make use of the fundamental quantum nature of particles, such as superposition and quantum entanglement.

**Qubit** A qubit, or quantum bit, is a unit of quantum information, similar to a 'bit' in classical computing. However, unlike a bit, which can either be 0 or 1, a qubit can be 0 and 1 at the same time - a quantum superposition of both states. When multiple qubits are combined, they can store vastly complex data.

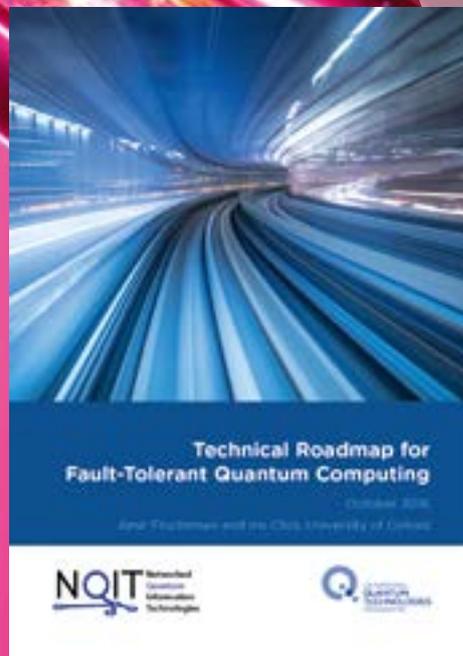
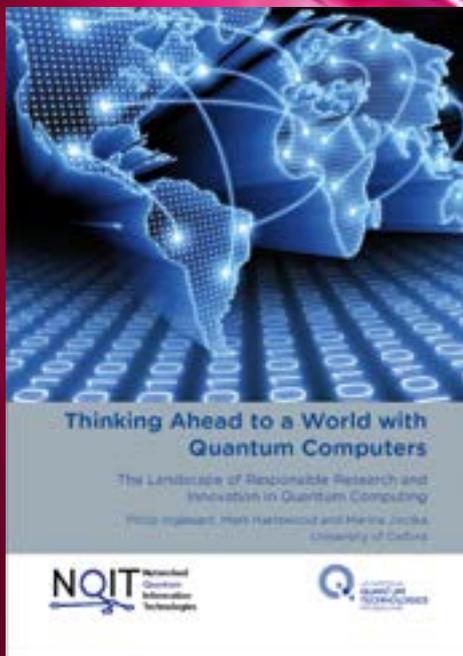
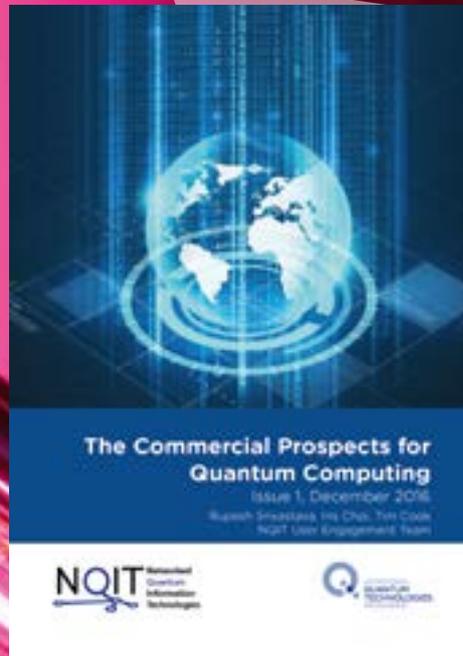
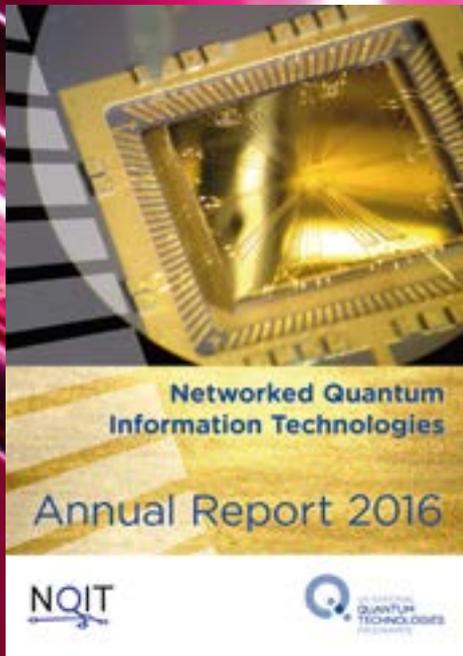
**Superconducting qubit** This is a cavity-based system that can be used as an alternative to ion traps as qubits in the Q20:20 engine. They offer increased network scalability which means larger, more powerful quantum computers.

A photograph of a magneto-optical trap (MOT) setup. The image shows a complex arrangement of metal components, lenses, and fiber optic cables. A bright, glowing orange-red spot is visible in the center, representing the trapped rubidium atoms. The background is dark, with various colored lights (red, purple, blue) illuminating the scene. A vertical line and a circle are overlaid on the image, highlighting a specific area. On the right side, there is a vertical strip with horizontal lines, possibly a scale or a decorative element.

## Getting Involved

If you have an idea for a quantum technology project that aligns with the aims of the NQIT Hub, please get in touch with our User Engagement Team.

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For more information about NQIT, please visit our website:  
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