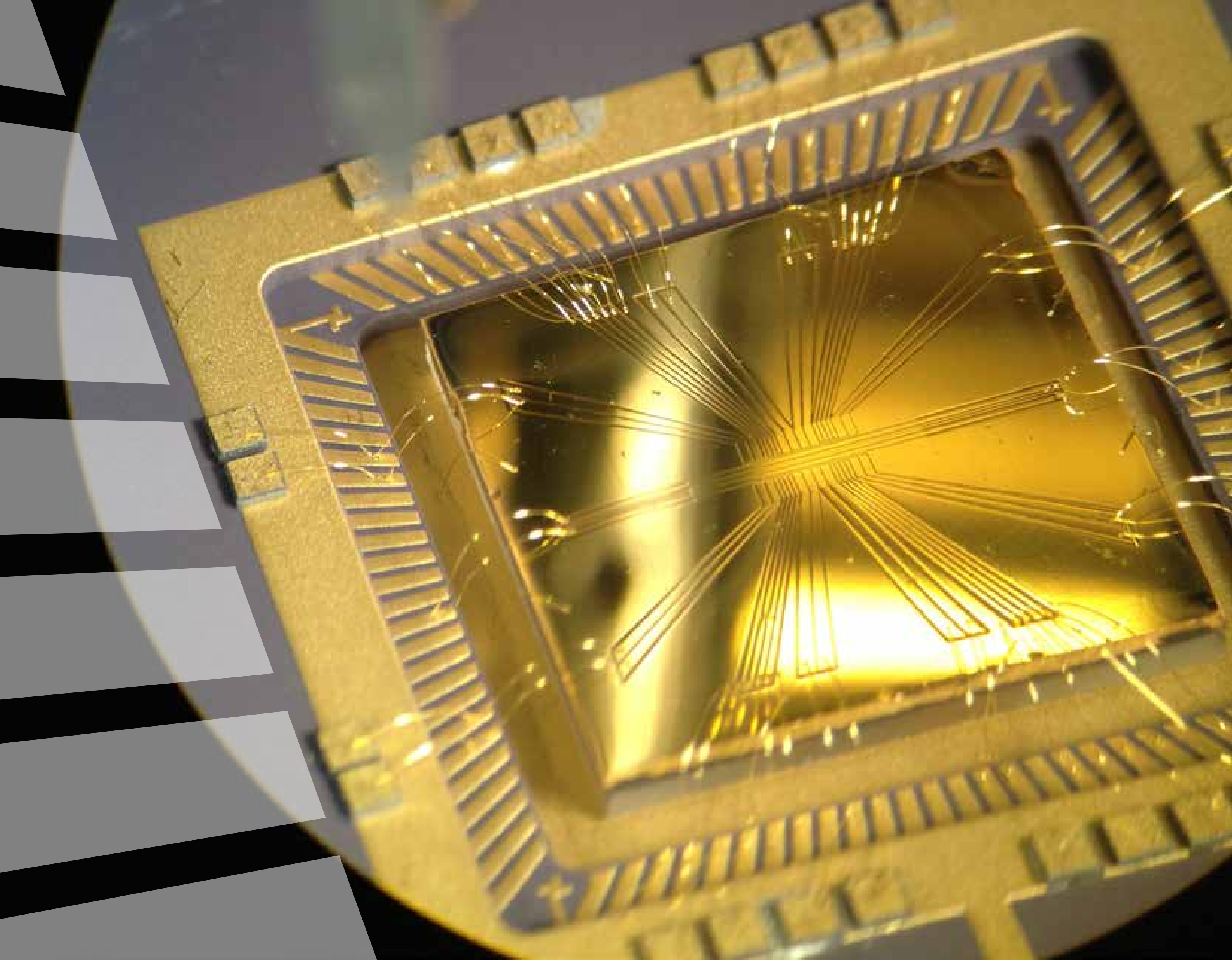


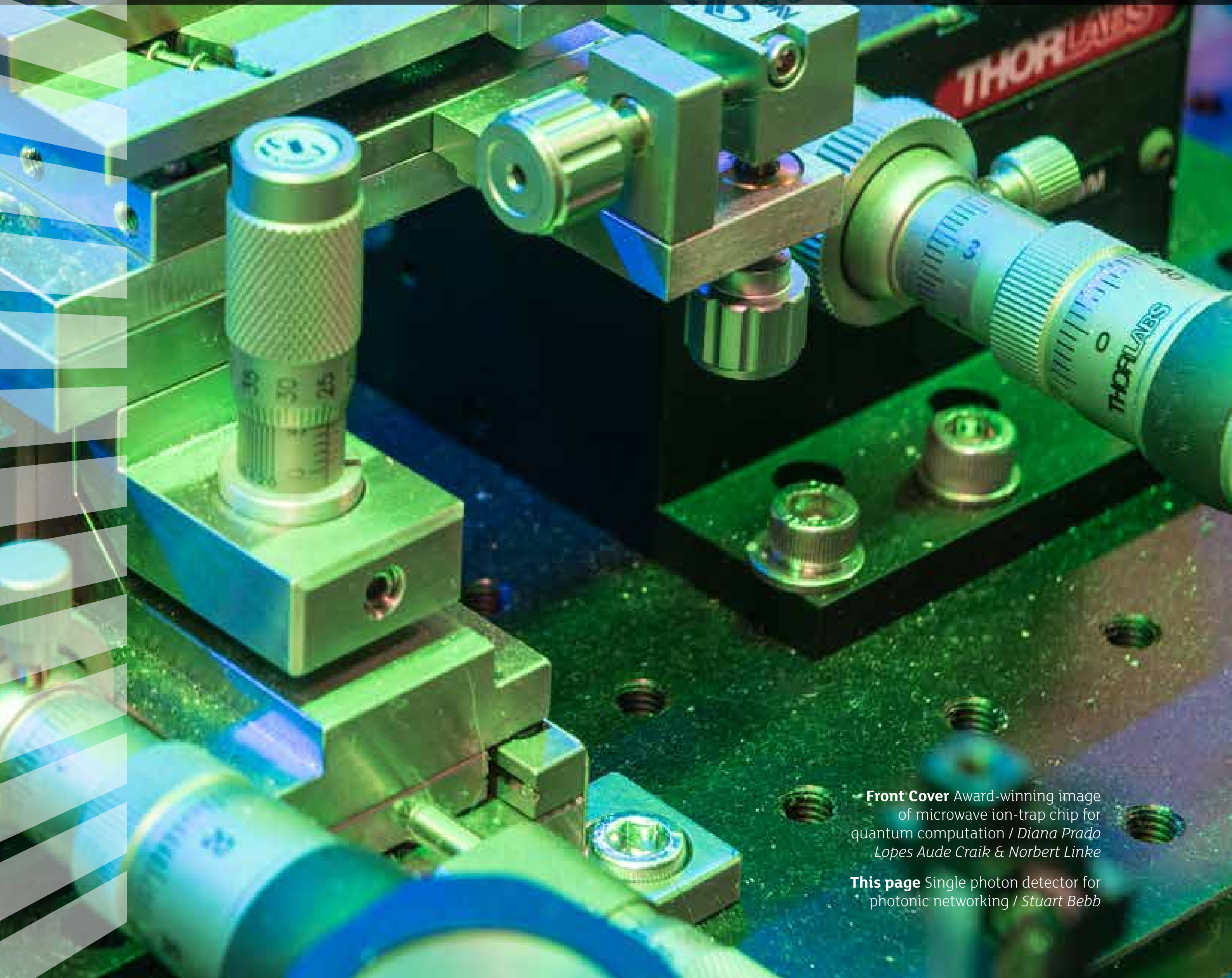
Networked Quantum Information Technologies

Annual Report 2016

NQIT

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

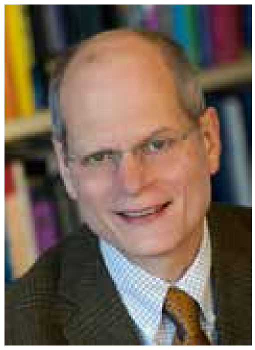
Contents



Front Cover Award-winning image of microwave ion-trap chip for quantum computation / *Diana Prado Lopes Aude Craik & Norbert Linke*

This page Single photon detector for photonic networking / *Stuart Bebb*

Foreword



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

The realisation of a practical quantum computer will be one of the biggest scientific and engineering achievements in this century. NQIT has the objective of building the core component of such a universal quantum computer. This machine, the Q20:20 engine, will bring together the most advanced quantum technological platforms and combine them into a 400-qubit device that will be at the heart of the first generation of a scalable quantum computer.

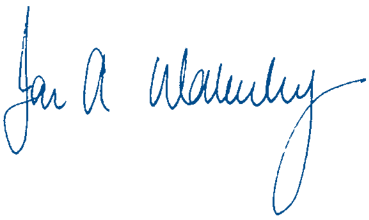
The programme is necessarily high risk and long term. Quantum computing remains a formidably difficult task, since it requires the construction of machines in macroscopic quantum states, which are exceptionally sensitive to their environment. NQIT is developing the significant engineering required to achieve the dual, conflicting goals of full control and near perfect isolation of the elementary units of the Q20:20 engine, both at a component and systems level.

The NQIT strategy builds on our existing world-leading performance in two promising quantum information processing platforms: trapped ions and photonics, creating a hybrid light-matter network. We are also looking at the potential uses of the Q20:20 device for applications such as quantum simulation and secure communications.

We have made rapid progress in the first year in delivering the core programme. 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.

In order to achieve this, we have drawn together a wide array of expertise from many different partners, each of whom were chosen because of the skill and know-how they brought to the project. Their specialist fields range from analysis of quantum coherent networks and design of fault-tolerant architectures to control of individual trapped ions and the manipulation of individual photons, as well as system engineering and integration of components. This collaboration represented a new paradigm for the research partners, and they have coalesced over the past year into a coherent and focused team for delivering the Q20:20 engine.

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



Professor Ian Walmsley, Director of NQIT, Hooke Professor of Experimental Physics and Pro-Vice-Chancellor (Research and Innovation), University of Oxford

Introduction

Ion trap chip mounted in a vacuum can / *Jeff Sherman*

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.

The Networked Quantum Information Technologies Hub has brought together a world-leading consortium of academic, commercial and government expertise in order to accelerate progress towards building real-world quantum technologies.

Our primary objective is to undertake the engineering necessary to deliver the central components of a universal quantum computer, and thus to realise the promise of **Quantum 2.0**. This revolutionary computing platform will harness quantum effects to achieve tasks that are currently impossible, by engineering small, high precision quantum systems and linking them into a network to create the world's first truly scalable quantum computing engine.

Our ambitious flagship deliverable is the Q20:20 quantum computer demonstrator: a network of 20 quantum modules each consisting of ion traps capable of storing 20 **qubits**. This 400-qubit system will primarily demonstrate the components and performance needed to realise a scalable architecture that can ultimately lead to a full quantum computer. It will also be useful for a variety of medium-term applications, such as protecting a single qubit of information for a long time and performing specialist small-scale simulations.

We have developed detailed computational models that identify the performance targets needed to surpass the **fault-tolerant** threshold for universal quantum computing. Crucially these targets have already been exceeded in our labs. Building the Q20:20 device therefore involves refining these components and integrating them into a single system.

Along the way, we envisage that the technologies we develop will have impact in other applications, from sensing to communications, and we work closely with the three other UK Quantum Technology Hubs to understand how mutual benefit can arise from our respective development activities.

Quantum 2.0 This is a term used to describe quantum technologies – that is, 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.

Fault-tolerant This is about reliability. 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.

Dilution refrigerator for photon detection at less than a degree above absolute zero / *Stuart Bebb*

Ion trap experiment / *Ion Quantum Technology Group, University of Sussex*

This revolutionary computing platform will harness quantum effects to achieve tasks that are currently impossible

The Global Race to Build a Quantum Computer

Quantum information science has held the attention of researchers around the world for more than two decades. More recently, advances in materials, photonics, systems engineering and design have driven the idea that a range of quantum technologies, in which advanced functionality for sensing, metrology, imaging, communications and simulation can be enhanced by the application of quantum engineering principles. Leading groups in the USA, Canada, Australia, China, Singapore, Japan and Europe are all pushing the technology needed to realise these applications.

Now there is a global race to build a quantum computer. There are several different approaches. One leading technology is **ion traps,** which is the primary platform for NQIT and which is also being pursued by groups in Austria, the USA and elsewhere. A competing platform, led by researchers in the USA, Netherlands, France and Japan, is that of superconducting circuits. Approaches using solid state impurities, trapped cold atoms or **photons** are also being pursued in the UK, USA, Europe, China, Singapore, Australia and Japan. NQIT maintains development efforts in several of these alternative approaches which, while less advanced than the leading platforms, can nevertheless provide advantages for some specific applications.

Ion trap This is 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.

Photon A photon is the elementary particle of light and electromagnetic radiation.

NQIT has links to, and in some cases active collaborations with, all of the leading groups in these areas. Our Investigators participate in joint EU projects with the major European groups, we are part of US consortia and we partner with Australian, Canadian and Singaporean groups. Links to Chinese research are less formal, but nonetheless strong, with frequent visitor exchanges and joint conferences or workshops.

How is NQIT different?

Our approach, and its context in the UK Quantum Technology Programme, give the programme its unique strength. We are part of a Hub network that has the task of seeding a new technology sector based on quantum engineering. The breadth and scope of activities in this Hub network will enable early “wins” from quantum-inspired imaging and sensing, as well as longer-term fully realised quantum technologies.

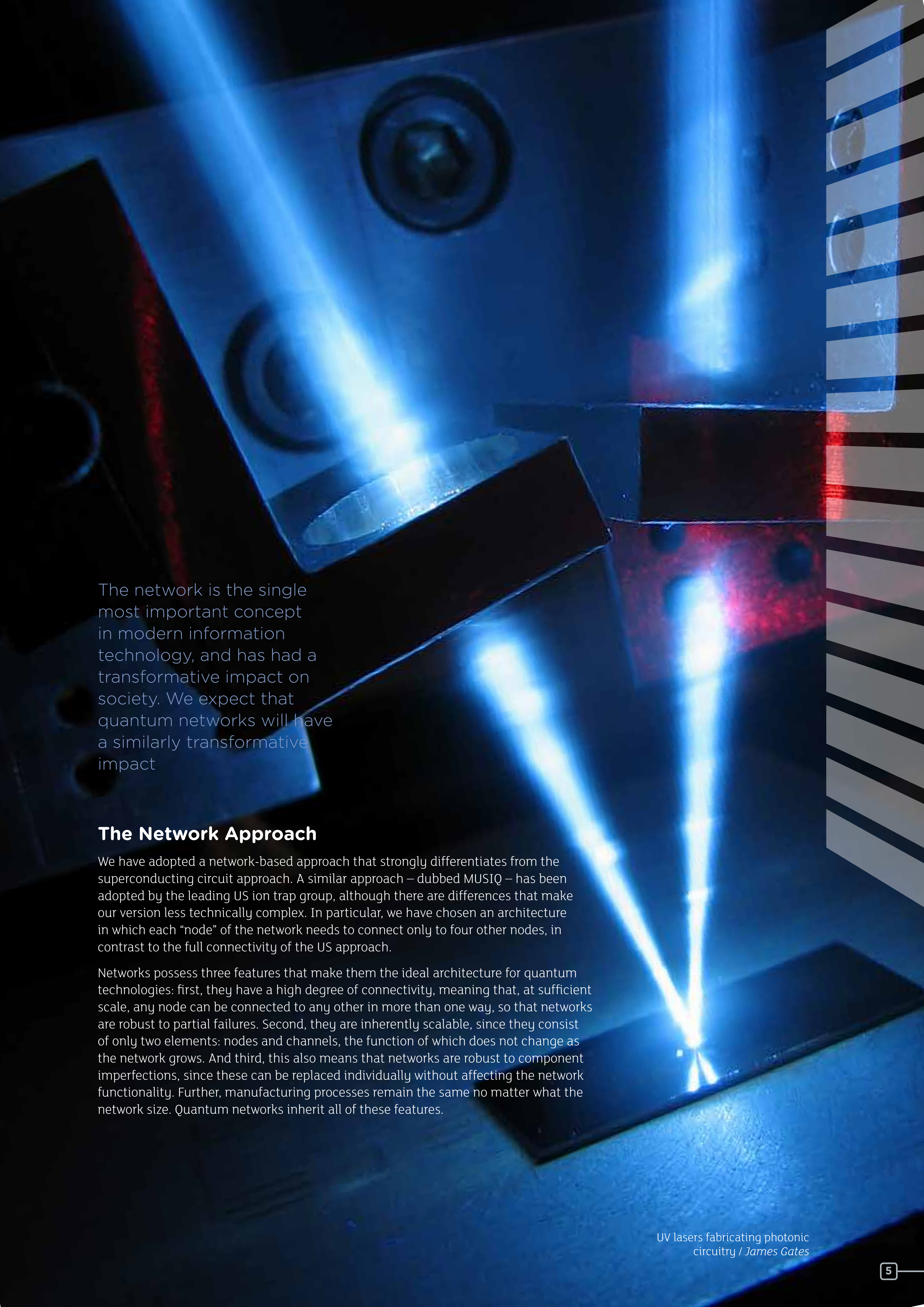
We are part of a Hub network that has the task of seeding a new technology sector based on quantum engineering.

Equally important, NQIT and the other Quantum Technology Hubs are training a cohort of new quantum engineers who are technology-focused and industry-engaged, who will make the UK the go-to place for investing in this new technology that will be very difficult to replicate or to purchase.

NQIT has links to all of the major international competitors and our members are active in visiting overseas research laboratories and attending international conferences. We are well-informed about the status of research across the world, and rapidly bring the best ideas to the Hub.

The main NQIT platforms are in world-leading positions in terms of the fidelity of operations in single-ion and two-ion quantum logic as well as in the operation of integrated quantum **photonic** networks. Nonetheless, new ideas and technologies are emerging continually, and we have to continue to work hard to remain at the forefront of the field. This leading position makes it feasible for us to embark upon such an ambitious programme because we have already demonstrated the underlying elements.

Photonics this is essentially ‘optical wiring’ and means controlling photons, the particles of light, to use in detection and manipulation.



The network is the single most important concept in modern information technology, and has had a transformative impact on society. We expect that quantum networks will have a similarly transformative impact

The Network Approach

We have adopted a network-based approach that strongly differentiates from the superconducting circuit approach. A similar approach – dubbed MUSIQ – has been adopted by the leading US ion trap group, although there are differences that make our version less technically complex. In particular, we have chosen an architecture in which each "node" of the network needs to connect only to four other nodes, in contrast to the full connectivity of the US approach.

Networks possess three features that make them the ideal architecture for quantum technologies: first, they have a high degree of connectivity, meaning that, at sufficient scale, any node can be connected to any other in more than one way, so that networks are robust to partial failures. Second, they are inherently scalable, since they consist of only two elements: nodes and channels, the function of which does not change as the network grows. And third, this also means that networks are robust to component imperfections, since these can be replaced individually without affecting the network functionality. Further, manufacturing processes remain the same no matter what the network size. Quantum networks inherit all of these features.

UV lasers fabricating photonic circuitry / *James Gates*

Programme Structure

Our plan for the NQIT Hub covers technology delivery and commercialisation, with primary applications in computing, communications and sensing. We will deliver more than 20 spin-off technologies, several of which will be at the commercialisation stage within the lifetime of the five-year Hub.

We are working 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 involving up to four 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 secure communications and digital simulation. 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.

We have also established a technically and commercially literate User Engagement team to engage locally with businesses and technology stakeholders through face-to-face meetings, and globally through symposia, visits, and online to build a strong user community of those interested in quantum information technology. They are drawing 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

In order to achieve this ambitious goal of building a universal quantum computing demonstrator, we identified the expertise and knowledge needed to deliver the hardware and software, as well as the applications that would result. We then invited leading experts across a range of backgrounds from academia, industry and government agencies to join the consortium. The resulting Hub is an Oxford-led alliance of nine universities with complementary expertise in quantum technologies Bath, Cambridge, Edinburgh, Leeds, Strathclyde, Southampton, Sussex and Warwick. We have assembled a network of more than 25 companies including LockheedMartin, Raytheon BBN, Google and Toshiba; government laboratories, such as NPL, DSTL and NIST; and a number of small and medium-sized enterprises, including PureLiFi, Rohde & Schwarz, Aspen and Oxford Instruments, who are investing resources and manpower.

Industrial Partners

People

Directors

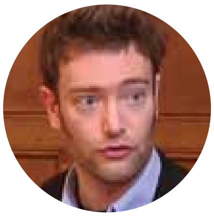
Professor Ian Walmsley, Director
Ian Walmsley has an extensive record of leadership in quantum technologies spanning more than a decade. He has been driving the agenda for quantum technology in the UK and EU. Ian's vision and drive unifies the consortium and motivates their delivery of the ambitious 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.

Dr Tim Cook, Co-Director for User Engagement
Before joining NQIT, Tim Cook was formerly the Managing Director of Isis Innovation, Oxford's technology transfer company, for ten years and later non-executive Director. He is leading the technology development mission of the Hub. Tim has an outstanding record of managing technology companies and was Visiting Professor of Science Entrepreneurship at the Saïd Business School. He now advises universities in the UK and abroad on technology transfer and innovation.

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 8 patents granted or in progress. Recent collaborations include work with Samsung on wireless beyond 100Gbit/s and with Airbus on unmanned aerial vehicles.

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

University of Bath:
- Dr Peter Mosley
- Dr William Wadsworth

University of Cambridge:
- Professor Mete Atature

University of Edinburgh:
- Professor Elham Kashefi

University of Leeds:
- Dr Almut Beige

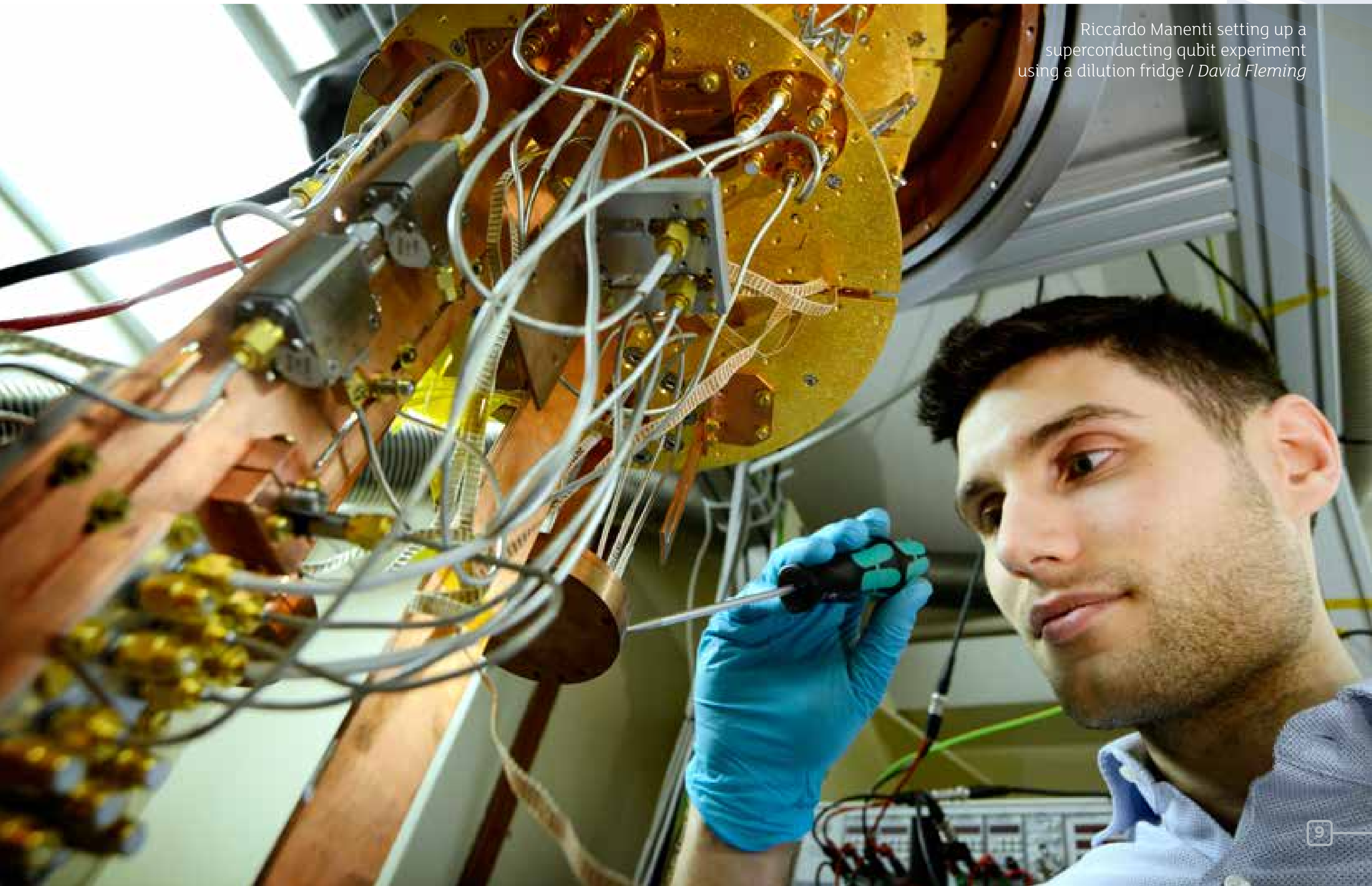
University of Oxford:
- Professor Samson Abramsky
- Dr Jonathan Barrett
- Professor Simon Benjamin
- Dr Martin Booth
- Dr Steve Collins
- Professor Justin Coon
- Dr Animesh Datta
- Professor Dieter Jaksch
- Professor Marina Jirotka
- Professor Jong Min Kim
- Professor Axel Kuhn
- Dr Peter Leek
- Professor David Lucas
- Dr Joshua Nunn
- Professor Dominic O'Brien
- Dr Stephanie Simmons
- Dr Brian Smith
- Professor Jason Smith
- Professor Andrew Steane
- Dr Christopher Stevens
- Dr William Kolthammer

University of Southampton:
- Dr Peter Horak
- Professor Alexey Kavokin
- Professor Peter Smith
- Professor Pavlos Lagoudakis
- Dr Corin Gawith

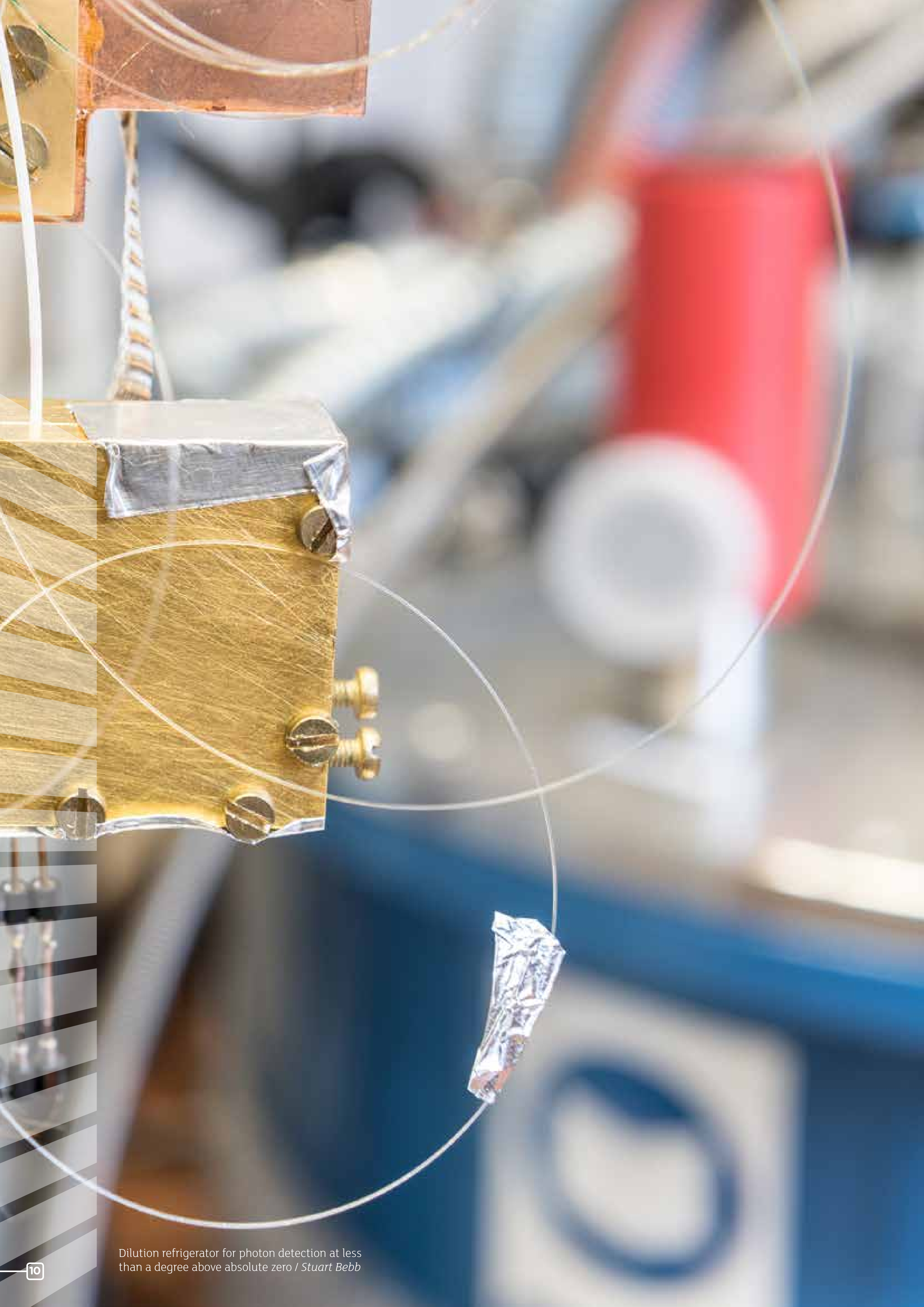
University of Strathclyde:
- Professor Martin David Dawson
- Dr Erdan Gu
- Dr Michael Strain
- Dr Ian Michael Watson

University of Sussex:
- Dr Jacob Dunningham
- Professor Winfried Hensinger
- Dr Matthias Keller

University of Warwick:
- Professor Mark Newton
- Dr Gavin Morley



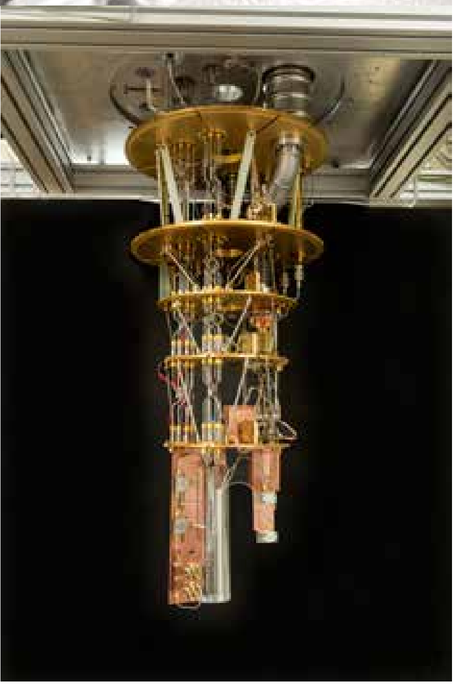
Riccardo Manenti setting up a superconducting qubit experiment using a dilution fridge / *David Fleming*



Dilution refrigerator for photon detection at less than a degree above absolute zero / *Stuart Bebb*

Objectives

A microwave cavity acting as a superconducting qubit / *Stuart Bebb*



Customised dilution refrigerator for operation of quantum microwave circuits at less than a degree above absolute zero / *Stuart Bebb*

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.

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.

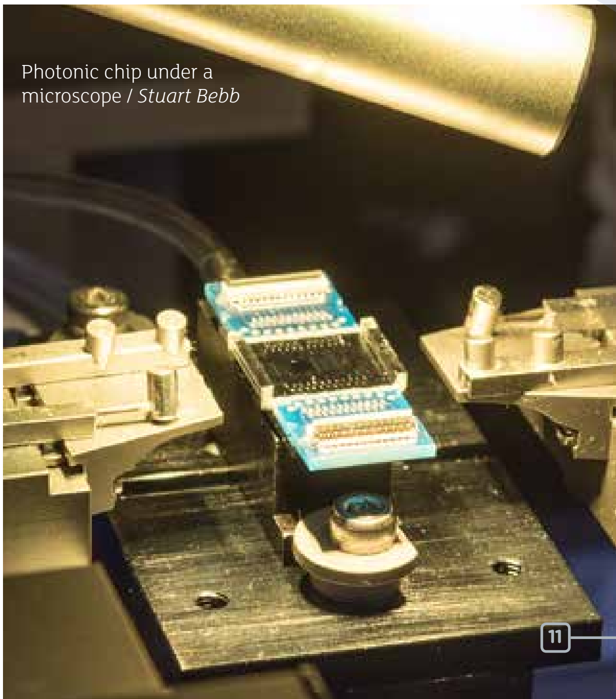
Further, NQIT is working with the other three Quantum Technology Hubs on joint programmes, including the annual Quantum UK Conference, responsible research and innovation, and coordinating publicity and public engagement with them.

Diamond colour centres

these are 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.

Superconducting qubit

this is a cavity-based system that can be used as an alternative to ion traps in the Q20:20 engine. It offers increased network scalability which means larger, more powerful quantum computers."



Photonic chip under a microscope / *Stuart Bebb*

Year One Achievements and Progress

The Hub began work on 1 December 2014 and in the first year has concentrated on setting up and refining the detailed programme of activity as well as producing significant scientific output.

In the first year we have:

- Revised the work programme and funding allocations following discussions with our funders, the Engineering and Physical Sciences Research Council (EPSRC)
- Developed a detailed blueprint for the Q20:20 quantum computer demonstrator, and ensured that all work packages are delivering toward this system plan
- Set up the management structure and hired key staff, including the Project Resources Manager (Kirsty Allen), Communications Manager (Hannah Rowlands), Administrative and Events Assistant (Karen Green) and a Technology Associate (Dr Iris Choi)
- Developed a communications strategy to improve the visibility of the Hub across all of our stakeholders
- Engaged with our founding partners and brought in many new external partners and begun to explore how quantum technologies may help them
- Set up the process for allocating Partnership Resource and used it to advance the Hub agenda, including joint funding of industry projects with other Quantum Technology Hubs
- Engaged with other Quantum Technology Hubs and the UK National Quantum Technology Programme, taking early initiative in publicising the Hub network internationally and contributing to strategy for the national programme
- Delivered significant science and technology progress in the underpinning quantum platforms for network nodes and interconnects, as well as in new applications
- Developed a framework for Responsible Research and Innovation (RRI) for the Quantum Technology Hub network
- Built a training programme for Quantum ICT to develop the skills required for the next generation of researchers and innovators in this field, including students (funded by the Oxford University Doctoral Training Partnership for all NQIT Hub partners), researchers and industry partners
- Planned interactive workshops that provide training in cross-disciplinary skills, covering entrepreneurship and business skills, applications of quantum technologies, technology building and engineering skills
- Submitted 3 patents on near-term spin-out technologies

Achieving a high level of operational momentum has been made possible by regular weekly meetings of the Directors and the Co-Investigators, along with quarterly meetings of the Management Board and a twice-yearly Project Forum involving all researchers in NQIT. We have engaged with our Technical Advisory Board, and sought their advice and guidance on a number of issues, including skills, partnerships, and collaborations.

First Year Summary

ENGAGEMENT

6 additional industrial partnerships

13 new academic partnerships

20 new business engagement interactions

EVENTS

56 seminars around the UK

16 engagement events introducing NQIT

45 keynote talks at conferences by NQIT academics

7 Public lectures

1000 More than 1000 members of the public engaged

ADDITIONAL FUNDING

EPSRC
Engineering and Physical Sciences Research Council

£2.5m additional grants from EPSRC for equipment

£887k for 3 Innovate UK grants

Innovate UK
Technology Strategy Board

OUTPUTS

30 peer-reviewed publications

3 patents submitted

35 new higher education jobs created

30 academic visits

ONLINE

200 followers on Twitter

WWW

More than 6000 visitors to the website

From over 40 countries

The Q20:20 Quantum Computer Demonstrator

The Hub's flagship goal is to realise the Q20:20 engine: a hybrid light-matter quantum computer involving twenty nodes, optically interlinked, where each node is a small quantum processor of twenty qubits.

Realising this ambitious target requires rapid development in multiple hardware efforts: these include engineering the nodal processors themselves, each of which requires integrated laser and microwave subsystems, as well as the optical links formed from fibres, photonic switches, splitters and detectors.

Each processing node will be an ion trap, a device within which a small number of charged atoms – ions – are held suspended in a vacuum and manipulated by laser and microwave systems. Each trap will be segmented, meaning that it can shuttle ions back and forth like beads on an abacus, and will be capable of holding two different atomic species simultaneously – we will be using calcium and strontium. A single unit of quantum information, one qubit, is embodied within the internal hyperfine states of each ion, and control of the qubits is achieved optically via integrated lasers and through microwave manipulation.

Each trap will be segmented, meaning that it can shuttle ions back and forth like beads on an abacus

Interlinking between the traps will be realised by single photon emissions, which are combined and measured by fibres, splitters, switches and detectors. The protocols for achieving information processing with this structure have been modelled in detail theoretically, and these models undergo continual evolution in tandem with the hardware development. The design achieves robustness versus hardware imperfections through a process called "**entanglement** purification" which involves upgrading the fidelity of the connective link by using it several times and filtering.

During the programme we will build a series of demonstrations that show the key steps in creating the Q20:20 engine. Initially we will connect two ion traps, then four using a switch. This will allow us to prove the concepts that we need to show work. Whilst we are doing this we will also be developing the miniature components that will allow us to shrink the system size to our target. We will use all of these components to build the final Q20:20 quantum computer demonstrator.

quantum entanglement

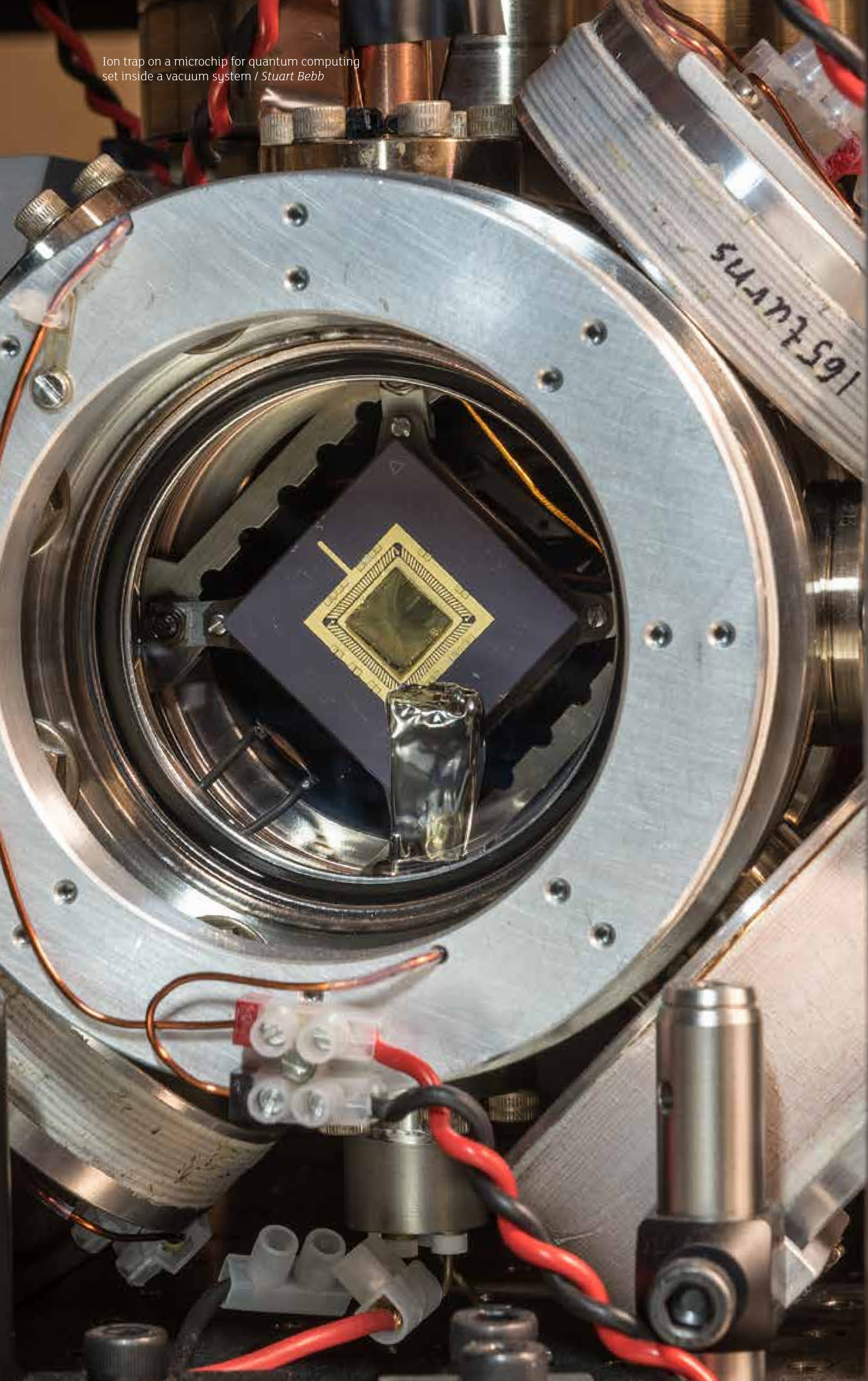
This counter-intuitive phenomenon can occur when two or more particles interact with one another, either directly or by using light as a mediator. When an action is performed on one of the entangled particles, it affects their mutual state, even when they are separated by great distances.

Prior Achievements

The Q20:20 engine will be vastly more powerful than anything that has been achieved to date. It is an ambitious objective but progress made by NQIT Hub members in three areas prior to the start of the project makes it a feasible goal.

First, Oxford researchers designed a way to build a quantum computer from precisely-controlled qubits linked together by photons. Importantly, these links can be far from perfect without seriously compromising the performance of the device. Second, Oxford's ion trap researchers recently achieved new world records for precision control of two-qubit and single-qubit gates, attaining 99.91% and 99.9999% accuracy, respectively. Third, we pioneered the control photonic interference inside small silica chips, together with advanced photodetectors that enable the remote generation of entanglement.

We are harnessing the exciting opportunity to combine these advances to create a hybrid light-matter network computer that gets the best of both worlds and overcomes long-standing impracticalities like technological complexity of matter-only systems, or the immense resource requirements of purely photonic approaches.



Ion trap on a microchip for quantum computing set inside a vacuum system / *Stuart Bebb*

Complementary Hardware Threads

Beyond the core hardware themes, which are essential to the success of the Q20:20 engine, we are also working on a number of complementary hardware threads. These would dramatically increase the Q20:20 engine's utility if they can be brought online. For example, NQIT researchers are working towards ion traps with integrated photonic cavities. Achieving this in a mature form for manufacture may lie beyond the five-year time horizon of the Hub, but it will greatly increase the efficiency of the light-matter interface.

We are also working on photon frequency conversion, which is important if the Q20:20 device is going to be useful for secure communications. Long-range telecoms require infrared light, whereas the ions in the Q20:20 nodes emit visible light, so the ability to convert this output to a frequency which is useful for real-world application is crucial.

Finally, there are development efforts in alternative types of processors including superconducting systems and diamond-based platforms. These systems are at an earlier stage, but they offer potential advantages in certain applications, such as field sensing with diamond systems.

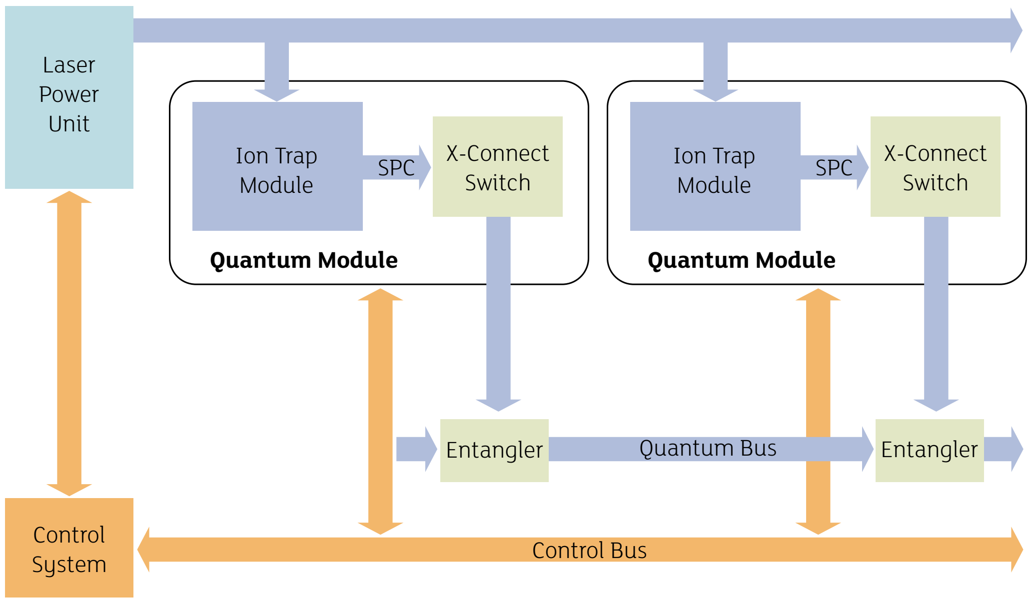
Engineering Plan

We have broken down the Q20:20 engine into four different subsystems:

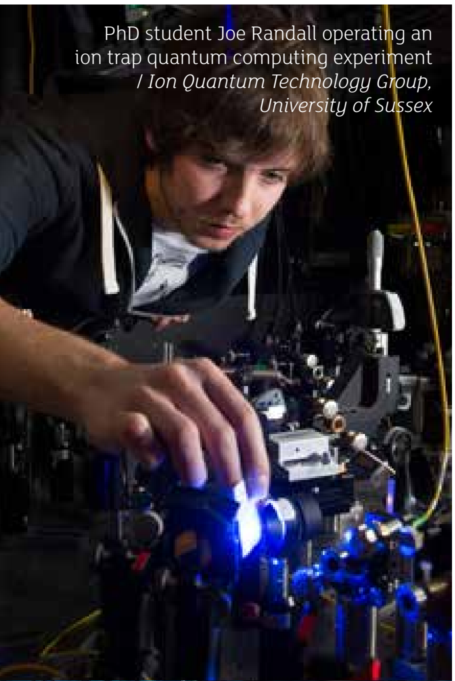
- The Optical Power Supply and Laser Power Bus create the laser light that is required to control the ions and distribute it to each of the 20 Quantum Modules.
- The Control System takes the 'program' that will run the Q20:20 demonstration and translates this into the electrical signals needed to control the ions and the laser beams. It ensures that the Quantum Modules are synchronised, and that the optical switches that connect the traps are properly configured.
- The Quantum Module is the most complex part of the Q20:20 system. At its centre is the ion trap, under vacuum to isolate the ion from the outside world. Around the trap are magnets that set the magnetic field around the ion. Electrical signals are fed from the control system onto the trap, where electrodes create the fields that the ion sits in. Light from the Optical Power Supply is fed into the trap using lenses that take light from the supply and focus it onto the ion.
- The Entangler makes the quantum connection between the modules. Photons from the ions are collected and sent to the entangler, where they meet photons from another module, making the quantum connection. Different connections can be made using an optical switch.

Isotopes of Calcium

Isotopes are elements that vary in the number of neutrons they have in the nucleus while 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



We have the capabilities to create the integrated system that we need



PhD student Joe Randall operating an ion trap quantum computing experiment
/ Ion Quantum Technology Group, University of Sussex

Ion trap quantum computing setup
University of Sussex

Errors have been successfully minimised by a factor of 30 beyond what had been expected

Engineering Challenges

The Q20:20 demonstrator requires the extremely precise control of the atomic state of individual ions. This is achieved by magnetic and electric fields that are applied to the ion, as well as laser beams which cool and manipulate it. Each ion trap might require 20 separate electrical signals, as well as more than ten individual laser beams. All of these must be controlled to within very demanding limits. At the moment the traps and these systems systems require large optical tables and manual adjustment. The challenge for NQIT is to shrink these systems, and make them reliable, so that one module might be the size of a small fridge.

We will fabricate miniature ion traps based on techniques used to make silicon chips, and create compact systems around these using techniques borrowed from space technology and electronics.

Within the Hub we have skills in electrical and electronic engineering, optical engineering and system design, and together with our industrial partners, we have the capabilities to create the integrated system that we need.

Progress on the Q20:20 Engine in the First Year

For NQIT's ion trap development teams, a key goal in year one was to establish whether microwave control could substitute for the more established laser manipulation in ion-ion gate operations. This is highly desirable as it can dramatically reduce the system integration challenges and costs. The year one milestone was to achieve 90% fidelity using microwaves. In fact, the Oxford and Sussex groups have exceeded that target and achieved fidelities up to 99.7%. This means that errors have been successfully minimised by a factor of 30 beyond what had been expected. Together with related encouraging results on minimising microwave crosstalk, this may permit dramatic reductions in processor node complexity.

Meanwhile NQIT theorists studying purification protocols have established that while the '20-qubits per processor' goal of the Q20:20 engine is desirable, as few as 'five-qubits per processor' may suffice for the majority of purposes, even when arranged in a purely linear geometry. Trap designs are being re-evaluated to optimally exploit these encouraging new factors. The goal of ion-photon entanglement has been postponed until trap optimisation is complete.

NQIT researchers were among the first in the world to realise "dual species" quantum gates using two isotopes of calcium, **calcium-40 and calcium-43**, a vital enabler for the Q20:20 engine's protocols (see "Research Case Study: 'Hybrid' Quantum Logic Gate").

A desirable long term goal is to optimise the light-matter coupling inside the Q20:20 engine by emitting photons from ions into waveguide chips via a cavity. As a vital precursor, the year one goal was to do this with neutral atoms rather than **electrically-charged ions**. This has been achieved with the coupling of near infra-red (~780nm) wavelength photons emitted from the atom-cavity system into waveguide chips.

Ion An ion is an electrically-charged atom.

Work is progressing towards establishing that diamond colour centres make a viable solid state network node, as an alternative to using ion traps. Here it is vital to enhance the optical coupling efficiency, we are starting the first experiments that use diamond membranes, implanted with nitrogen-vacancies and aligned within microcavities. Meanwhile, our exploration of the younger silicon-vacancy system has been encouraging, as it showed full optical control of silicon vacancy spin and an optical coupling enhancement by a factor of ten.

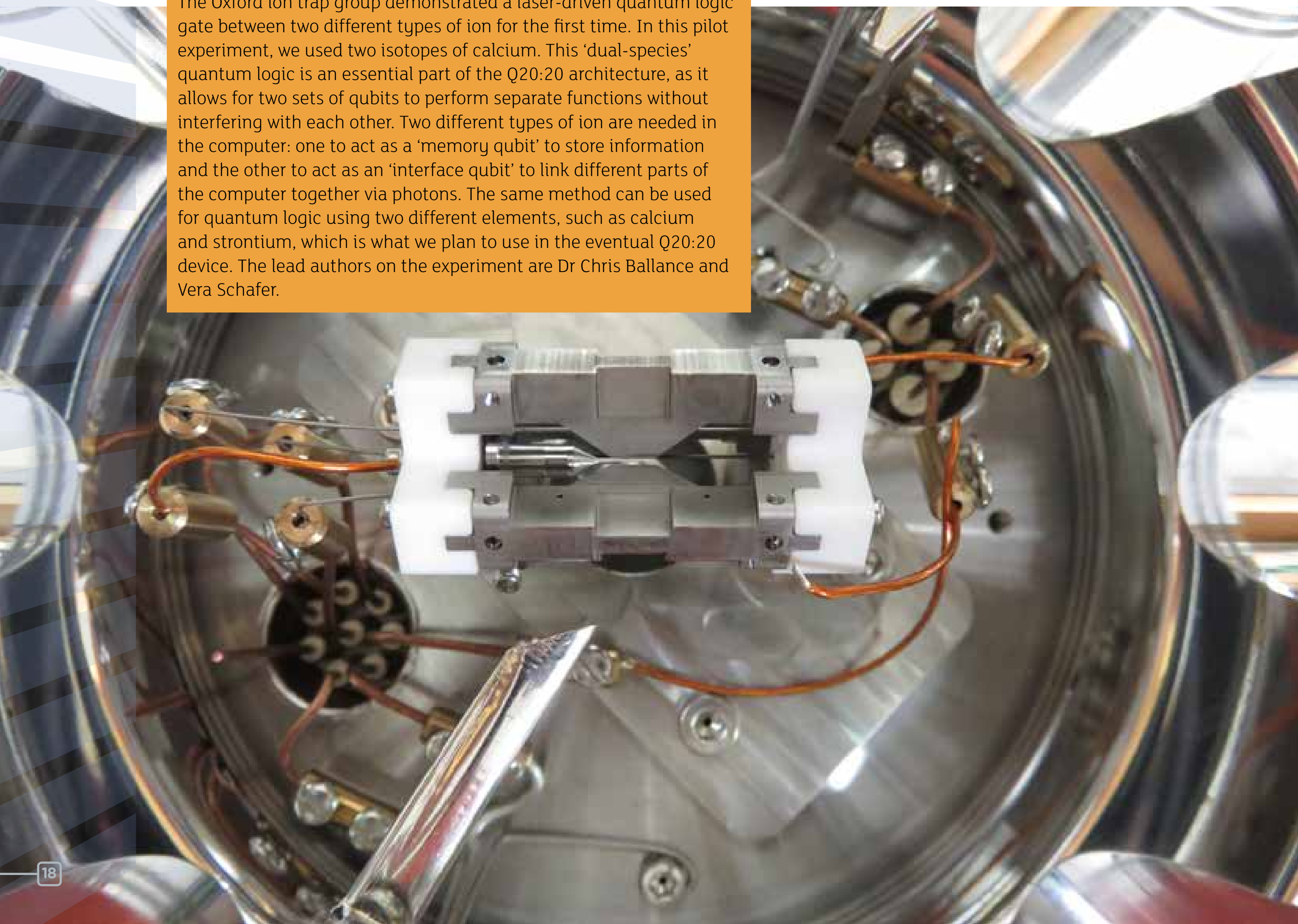
Furthermore, we have improved the overall architecture of the Q20:20 device. We determined the optimal approach for the particular components we are using and have studied new algorithms, including novel approaches to machine learning and to simulation using quantum co-processors. These link the Hub to real-world applications, and many of these activities are undertaken jointly with our industrial partners.

We have also refined the Q20:20 machine definition into a detailed system engineering plan from which component specifications, both in performance and interoperability, have been derived. Our approach has been to identify the shortest path to a network of restricted scale, both physically and in connectivity, in order to get to grips as soon as possible with the challenges of handling and using multi-qubit machines.

RESEARCH CASE STUDY
‘Hybrid’ Quantum Logic Gate

The Oxford ion trap group demonstrated a laser-driven quantum logic gate between two different types of ion for the first time. In this pilot experiment, we used two isotopes of calcium. This ‘dual-species’ quantum logic is an essential part of the Q20:20 architecture, as it allows for two sets of qubits to perform separate functions without interfering with each other. Two different types of ion are needed in the computer: one to act as a ‘memory qubit’ to store information and the other to act as an ‘interface qubit’ to link different parts of the computer together via photons. The same method can be used for quantum logic using two different elements, such as calcium and strontium, which is what we plan to use in the eventual Q20:20 device. The lead authors on the experiment are Dr Chris Ballance and Vera Schafer.

Microfabricated ion trap ‘chip’ used to trap calcium ion qubits, designed and fabricated by David Allcock in the Oxford physics clean room / *Jeff Sherman*



Hardware

The Hub's hardware development takes place in four parallel work packages covering photonics, ion traps, atom-photon interfaces and solid state qubit nodes.

In 2014 our ion traps were already in a world-leading position, having the record for highest levels of control of any qubit

The ion traps form the qubit quantum information storage in the Q20:20 quantum computer demonstrator and the photonics link these qubits together in an optical network. The solid state qubit nodes research is looking at colour centres in diamond and superconducting microwave cavities as alternatives to ion traps for the matter processing system within the quantum computing device.

Our four work packages will merge to deliver a variety of hybrid light-matter devices on various time scales over the course of NQIT's five-year programme.

On the photonics side, the early goals are low-loss switches, photonic memories, and frequency shifters. Developing an all-photonic quantum random number generator is also a priority (See "Spin-out Technology Case Study: Quantum Random Number Generator")

In 2014 our ion traps were already in a world-leading position, having the record for highest levels of control of any qubit. The early development goals are oriented towards realising a cost-effective, reproducible system for manufacture.

The superconducting qubits and diamond colour centre qubits start from a less advanced position, and have more exploratory targets including 3D cavity systems and diamond membranes-in-microcavities. The microcavities required for the diamond systems are also being developed as sensor devices in their own right (See "Spin-Out Technology Case Study: Quantum Sensors").

Hardware Progress

A design for a fast quantum random number generator has been developed and patented

The first year has seen dramatic progress towards the hardware goals for the Q20:20 system, but we have achieved a number of advances in parallel areas as well.

It was a year one goal to build a fibre-coupled magnetic field sensor as a spin-off technology. We achieved this and we achieved this and featured it in the Quantum Technology Showcase event at the Royal Society in November 2015. The limit of detection of this sensor is currently an order of magnitude superior to the original, targeted value (see "Spin-Out Technology Case Study: Quantum Sensors" on page 20).

In a second spin-off, a design for a fast quantum random number generator has been developed and patented, and further development is now proceeding with input from Fraunhofer UK (see "Spin-out Technology Case Study: Quantum Random Number Generator"). Additionally, we are working on a multiplexed heralded single photon source, a light source that emits precisely one photon on-demand.

We carried out detailed modelling work on a quantum optical imaging interferometer and this revealed that it is unlikely to be commercially realisable with foreseeable technology and have therefore ceased development towards this goal. However, the models and expertise are being taken forward in a new collaboration with the QuantIC Hub in a project on quantum-enhanced fluorophore detection.

In an unforeseen and exciting development, NQIT researchers conceived a novel method for quantum-coherent microwave-to-optical frequency conversion, and have filed a patent. While not part of NQIT's goals, this promises to have a high impact, for example enabling superconducting qubits, which have no optical transitions, to be connected in the same modular way as ions traps.

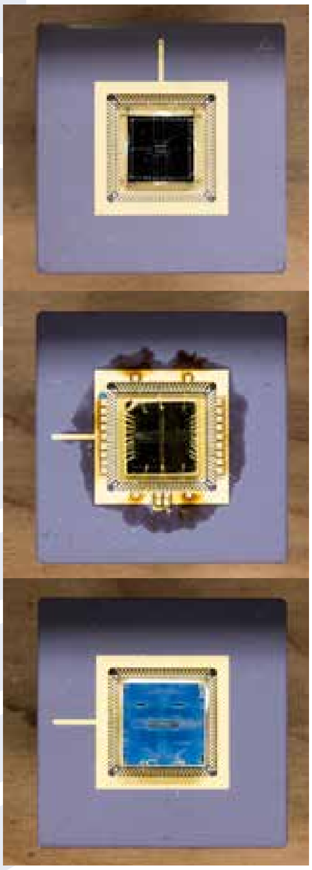
Diamond containing nitrogen vacancies fluorescing due to illumination with green light / *Jon Newland*

SPIN-OUT CASE STUDY
Quantum Sensors

We are working on two types of sensors: magnetic field sensors using defects in diamond and chemical and particle sensors using optical microcavities.

Diamond defect sensors offer high sensitivity to magnetic fields due to the action of the field on the quantum spin state of the defect, which is itself a miniature magnet that can be measured with high precision. One of the applications we are working towards with these sensors is medical imaging of the brain – "magnetoencephalography" – and the heart – "magnetocardiography". Diamond defects offer the possibility of enormous reductions in cost of these procedures compared with existing approaches.

Optical microcavity sensors are spin-off technologies that arise from our efforts to create a light-matter interface for quantum networks. The exquisite sensitivity of such devices can be employed to probe chemical or biological entities in minute quantities of gas or liquid and can be tuned to the absorption/emission frequencies of specific molecules, or nanoscale pathogens. The device offers potential for wide ranging applications in security, healthcare and environmental science, for example point of care diagnostics of early stage viral infection or cancer. So far we have demonstrated some basic functionality of the sensor with selected passive targets, and are investigating both the limits of their sensitivity and the most promising routes towards commercialisation for specific applications.



Ion traps on a microchip for quantum computing / *Stuart Bebb*

Ion Trap Node Engineering

Led by Professor David Lucas
We designed and constructed a new ion trap with high optical access which will be used for initial experiments in interfacing trapped-ion 'memory' qubits using photonic 'communication' qubits. This is the basic element of the Q20:20 network architecture. Two key achievements from our first year are:

1. The demonstration of a laser-driven, quantum logic gate between two different species of trapped-ion qubit (see "Research Case Study: 'Hybrid' Quantum Logic Gate" on page 18).
2. The achievement of Two-qubit quantum logic gates driven by electronic (microwave) signals with world-leading precision.

Atom-photon Interfaces

Led by Professor Axel Kuhn
The major aim of NQIT is to create a powerful quantum computing device by interconnecting many simple quantum processors that we have already demonstrated in our laboratories. To do this we need reliable interfaces at the single-quantum level to establish such a connected network.

We harness the emission of light from non-moving quantum bits stored in single atoms. We have designed special laser pulses that trigger an atom to emit single photons into optical resonators and into a network of optical transmission lines. With an unprecedented level of single-photon emission control we can apply these laser pulses at the push of a button. Together with our collaborators in Bristol, the Oxford team has recently shown that we can now control the coherence properties of these photons so faithfully that we can reliably operate a complex quantum-optical network.

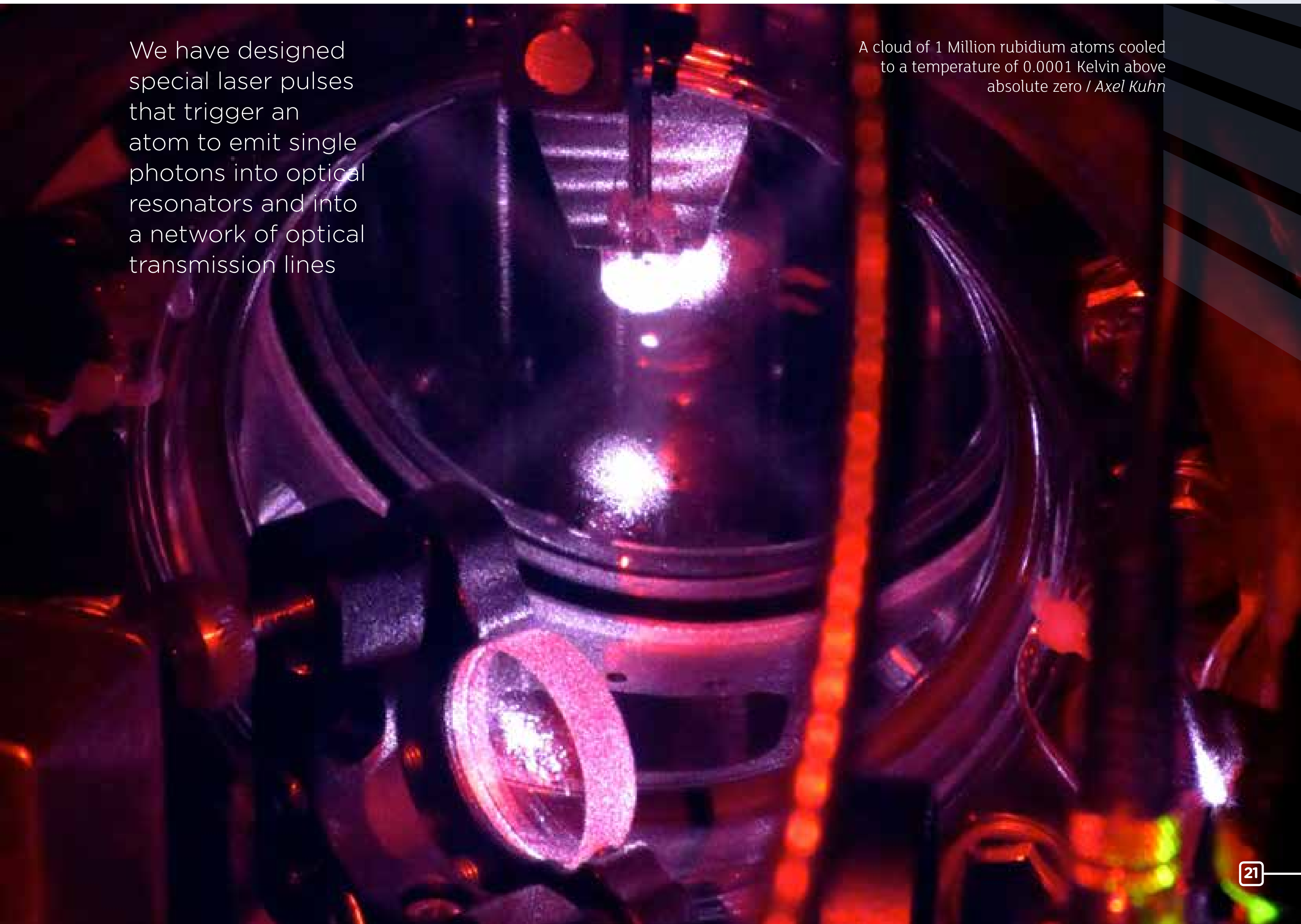
Photonics is another way of saying “optical wiring”

In parallel to this, NQIT researchers in Sussex and in Southampton have been modelling and exploring novel optical resonator designs that significantly improve the photon emission from trapped ions into optical fibres. Meanwhile, our theoreticians in Leeds invented a promising new method for the transfer of quantum states between remote atoms which we are now going to explore in the laboratory.

Photonic Network Engineering

Led by Dr Joshua Nunn

Photonics is another way of saying “optical wiring” and in NQIT we are developing the optics to wire-up individual atoms, by collecting photons, particles of light, which they emit and using measurements to build a quantum connection between the atoms, known as entanglement. In parallel, we are also developing devices to enable quantum technologies based on light: for example, a quantum random number generator (see “Spin-out Technology Case Study: Quantum Random Number Generator” on page 22), and a light source that emits precisely one photon on-demand. We also recently demonstrated a new kind of quantum memory, which can store the quantum information carried by photons as a magnetic wave in a gas of atoms. The next generation of this device will make it possible to synchronise the signals in very large quantum networks, enabling a quantum internet for secure communications and new kinds of sensors.



We have designed special laser pulses that trigger an atom to emit single photons into optical resonators and into a network of optical transmission lines

A cloud of 1 Million rubidium atoms cooled to a temperature of 0.0001 Kelvin above absolute zero / *Axel Kuhn*

Single photon source for photonic networking / *Stuart Bebb*

SPIN-OUT CASE STUDY
Quantum Random Number Generator

Random numbers might sound like they are useless. After all, a calculator that spits out random numbers would not be helpful. But in fact, randomness is very valuable. Why is this? Because it cannot be predicted ahead of time and that is extremely useful. The first random numbers were generated for lotteries, where millions of pounds needed to be allocated fairly. Then, they were used for encryption, to scramble messages sent by the government or the military. Nowadays they are used to simulate noise in computations that rely on statistical fluctuations, and they underpin a large and lucrative gaming industry.

However, before quantum physics, randomness was just an approximation: if you really knew exactly how a coin was flipped, or a roulette ball was thrown, you could in principle predict the outcome. But this is no longer possible with single atoms or single particles of light. These systems obey quantum mechanics, where as far as anyone knows, it seems that randomness is a fundamental property. The results of certain measurements simply cannot be predicted, even if you had perfect knowledge of the entire universe and its history.

We have developed a quantum random number generator that will provide billions of truly random numbers every second by making measurements on light. Furthermore, the device works even if the light source is controlled by an adversary who wants to compromise or influence the randomness.

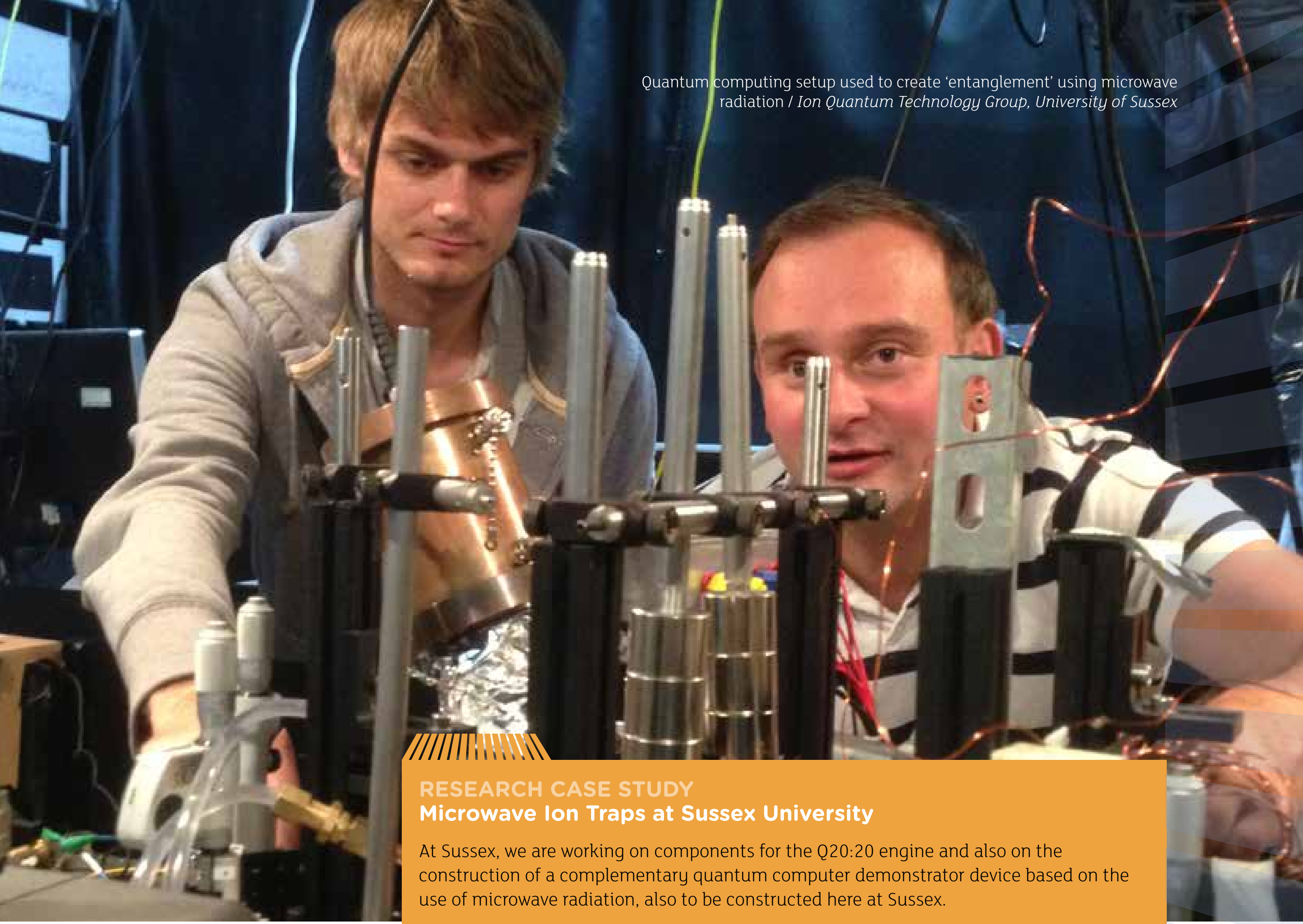
A proof-of-principle experiment is currently underway and we are in discussions with industrial partners to produce a prototype device.

Solid State Qubit Node Engineering

Led by Professor Jason Smith
This work package covers solid state alternatives to the ion trap nodes at the core of the NQIT approach, which may offer different functionality in a quantum network and possibly alternative routes to a scalable processor.

In the first year we addressed some key aspects of the performance of defects in diamond and superconducting circuits as solid state quantum information nodes. With defects in diamond our focus is on the optical interface with spin qubits: being able to control qubits using lasers and being able to extract light efficiently for the purposes of building networks.

With superconducting qubits we are exploring a new design of qubit/cavity system that offers a high degree of networking scalability.



Quantum computing setup used to create 'entanglement' using microwave radiation / *Ion Quantum Technology Group, University of Sussex*

RESEARCH CASE STUDY

Microwave Ion Traps at Sussex University

At Sussex, we are working on components for the Q20:20 engine and also on the construction of a complementary quantum computer demonstrator device based on the use of microwave radiation, also to be constructed here at Sussex.

In conventional trapped-ion quantum computers, laser beams are used to implement quantum gate operations. A large scale quantum computer may require millions of such laser beams for successful operation. In the microwave quantum computing engine, however, global microwave fields originating from a single emitter can replace all these laser beams, tremendously simplifying the engineering required to build large-scale quantum computers.

While the Q20:20 engine connects individual quantum computer modules via photonic links, the microwave quantum engine instead uses transport of ions to link modules. This technology is not yet as developed as the laser-based method, but the opportunities provided by this new approach, such as faster operations, may offer a significant advantage for quantum information processing. Last year we were able to demonstrate two-qubit gates with error rates small enough to illustrate that this technology is fit for real-world devices. With NQIT developing this technology towards practical application, the UK is assured to maintain and extend the comprehensive range of technologies required to build a practical quantum computer.

Core Engineering Capabilities

Led by Professor Dominic O'Brien

We have been working on waveguides, which are similar to optical fibres, and allow small quantum information processing systems to be fabricated on a chip. We have built a facility that allows us to make 'circuits' from such waveguides. This facility is now up-and-running, and we are beginning to make test devices which will be tested as part of NQIT's photonics work.

We have also been working on the design of the control system for the Q20:20 system, which involves close collaboration with the ion trap and photonics hardware groups within NQIT. Additionally, we are talking to industrial partners and companies who can make the electronics and software we need.

Standards are important and we are helping to write a standard that will allow different groups worldwide to use the same control hardware and software, and share resources. Standards (such as Wi-Fi) ultimately allow the cost of systems to be reduced, and ensure that components are available from multiple suppliers, and our work will help to obtain these advantages.

Applications

Our applications programme is looking at how we might use the Q20:20 quantum computer demonstrator to solve real-world problems.

The research is split into four work packages looking at secure communications, quantum sensors, quantum digital simulation and hybrid quantum/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 is the Q20:20 quantum computer demonstrator good for?
2. Is it functioning properly?
3. How do we program the Q20:20 machine?

Black box device A black box device is a system where you reliably feed information in and receive useful output without needing to know the precise details of what happens inside.

Over the next five to ten years we will see a state of flux as quantum technologies become part of the mainstream computing landscape. These emerging machines will have high variability in terms of architectures and capacities and 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.

In a device-independent protocol, the users will still be secure

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 application programme is providing the building blocks for these future powerful quantum servers.

Device independence Device independence increases the utility of a device as it allows it to be used wherever it is need without needing to be reconfigured or otherwise altered.

Applications Progress

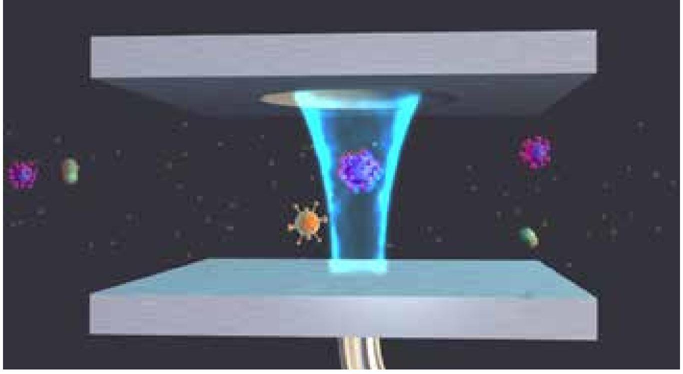
Led by Professor Elham Kashefi
On the one hand, we are exploiting the Q20:20 machine as a **black box device** for optimisation and simulation functionality, boosting the performance of any previously known classical algorithm. On the other hand, the modular architecture of NQIT provides the blueprint for the future quantum web.

We are studying how quantum encryption might work since some users of this future quantum web are expected to behave maliciously. In order to tackle this, an entanglement link between potential clients provides new cryptographic functionality ranging from general secure multi-party computing all the way to day-to-day enhanced network sensing and metrology.

We are tailoring verification and validation techniques for the quantum device as a whole and for elements of communication networks in order to foresee and handle the intricacies of real-life implementation.

Secure Communications and Verification

Led by Dr Jonathan Barrett
Over the past year, we have developed a new kind of protocol for quantum communication, which we call "**device-independent**". The idea is that in a device-independent protocol, the users will still be secure, even if the quantum devices they are using are compromised by errors in manufacture or a deliberate backdoor. We have developed device-independent quantum protocols for the transmission of secret messages, and also for a slightly different problem where a user needs to verify that an untrusted quantum device is behaving as it should. We are working with NQIT researchers in Oxford, who are building the hardware that will be able to implement these new protocols.



Schematic showing a microcavity being used as a sensor for biological pathogens / *Photonic Nanomaterials Group, University of Oxford*

Networked Quantum Sensors

Led by Dr Animesh Datta

Quantum metrology is a growing area of quantum technology that uses quantum effects such as entanglement to enable an increase in precision when estimating a parameter of a system, such as a particular characteristic of a particle, compared to making a classical measurement of the same thing. This could have wide ranging applications in fields such as microscopy and optical, electromagnetic, or gravitational field imaging.

In our recent work we looked at the problem of estimating the magnetic field in three dimensions of a fixed number of particles, which is something you might want to do for trapped ions or nitrogen-vacancy centres in diamond defects, both of which are part of NQIT's core hardware.

We compared two scenarios for this estimation:

1. A classical strategy where the probes are uncorrelated and each measurement is made separately.
2. A quantum strategy where the probes are correlated and measurements of all three directions of the magnetic field are made simultaneously.

We found that the quantum strategy results in a precision that is better than is possible using multiple classical sensors. This theoretical result, where we have shown how to estimate all the components of a multi-dimensional field simultaneously, is our key achievement in the last year. It can now be tested experimentally by hardware researchers within NQIT and could guide the next generation of gyroscopes and magnetic field sensors.

We found that the quantum strategy results in a precision that is better than is possible using multiple classical sensors

Current NQIT efforts to develop scalable quantum computing technologies have the potential to outperform classical DMFT simulations in the near future

Quantum Digital Simulation

Led by Professor Dieter Jaksch

We have been studying how next generation scalable quantum devices could be used to perform computations that solve specific physics and materials problems. In particular, we are investigating a possible early use of quantum devices in predicting the behaviour of quantum materials. Our simulation scheme aims to enhance an existing, successful method for investigating strongly correlated quantum materials called "non-equilibrium Dynamical Mean Field Theory". This scheme proposes a hybrid quantum-classical simulator, made up of a quantum co-processor, with only a few tens of qubits, and a classical simulator component. So far, we have shown that it should be possible to outperform purely classical simulations with quantum co-processors. In a recent paper, we concluded that current NQIT efforts to develop scalable quantum computing technologies have the potential to outperform classical DMFT simulations in the near future.

Hybrid Quantum/Classical Computing

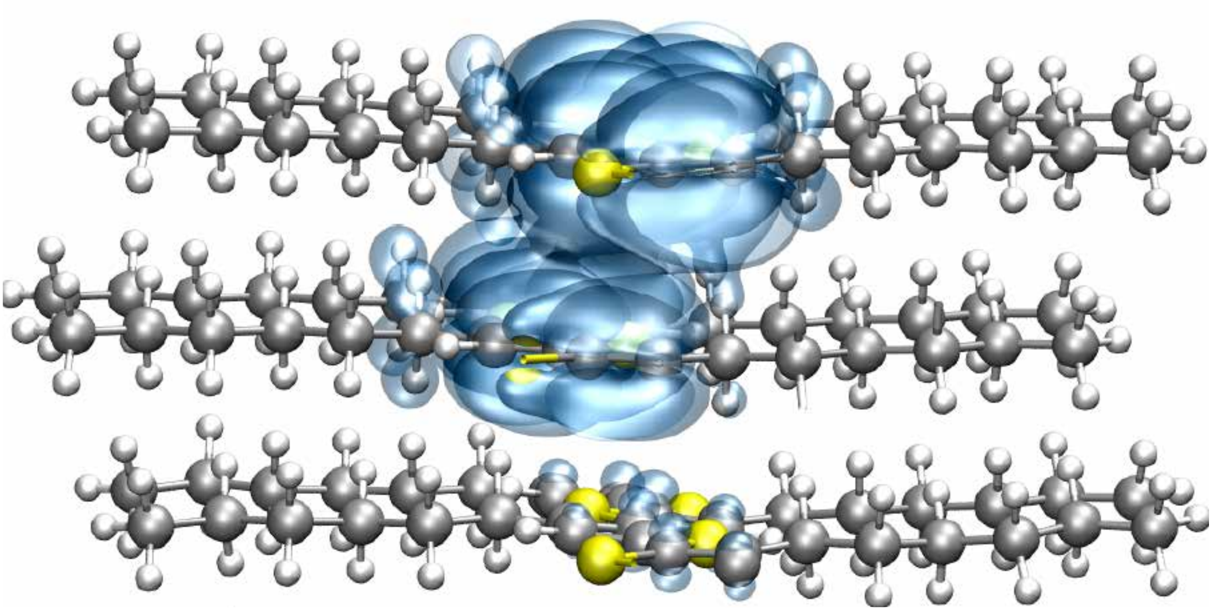
Led by Professor Samson Abramsky

This research area aims to develop computation models for the NQIT architecture and to develop applications which leverage limited quantum resources in hybrid quantum/classical systems to serve as demonstrators for the NQIT architecture.

At Oxford, we have developed an abstract architecture model for NQIT which will act as a translation platform between the hardware groups and application developers, with detailed noise models and error-correction schemes. We are developing high-level diagrammatic notations for this architecture, based on "bialgebra mathematics", which is both intuitive and allows for rigorous analysis.

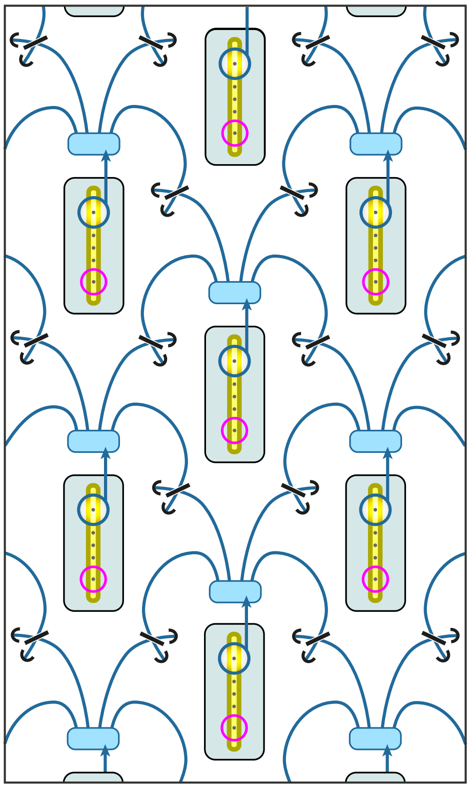
Researchers at Edinburgh have been working on security and have made a preliminary result on secure multi-party computing with a passive adversary. We are now working on the full security proof as well as the effect that the NQIT architecture and imperfections might have on security. We are exploring the extension of a recent photonic implementation of a simple client-server protocol for classical computing to a multi-party setting with further functionality.

The Q20:20 device could be used to simulate quantum materials / *Keian Noori*



Architecture

The NQIT Hub's hardware development effort is guided by detailed and continually updated plans for the system's architecture. The Hub's core proposition is that networking together quantum systems makes for a powerful and flexible information processing platform. Architectural theory and modelling must specify the performance requirements for the nodal devices, and should determine how best they can perform core operations such as entanglement purification, where we upgrade the fidelity of a connective link by using it several times and filtering. Similarly it is essential to identify the requirements for the network's connective fabric, such as tolerable photon loss rates, switching requirements, detector efficiency and dark count rates, as well as assessing the benefits of introducing advanced components such as photonic memories.



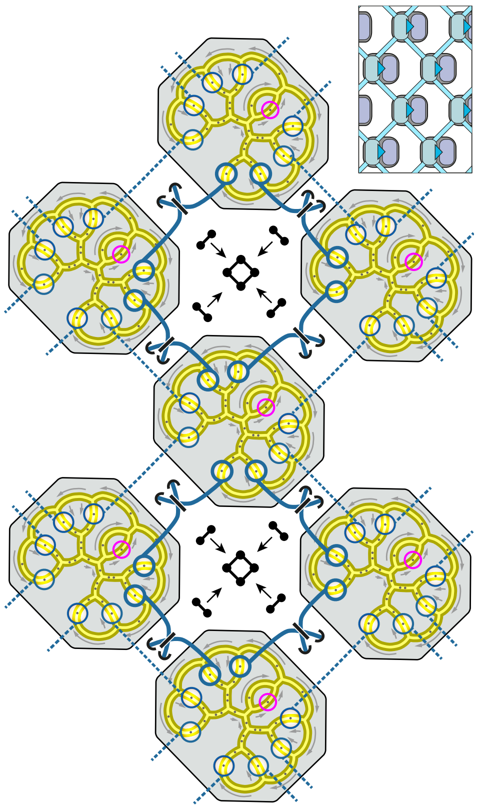
Schematic showing how simple ion trap chips, devices with a few trapped atoms within, can be networked to form a computer / *Simon Benjamin*

Architecture Progress

Led by Professor Simon Benjamin

Because NQIT is focused on networks of small quantum devices a very fundamental architectural question is "just how small can these individual devices be?" In a theoretical study, We researchers have compared a fine-grained network involving devices with around five to ten qubits versus a coarse network whose nodes have hundreds of qubits. The study found that the processing capacity of the two systems was the same to within about a factor of two, for a fixed total number of qubits. The analysis required the creation of a novel approach to fault tolerance in modular systems: "the hierarchical surface code". This encouraging result indicates that the nodes can be whatever size is most convenient for experimental reasons, without loss of performance or costly overheads.

Another related question is, "how can we best use the limited resources within each node to perform **purification** to remove noise on the interlinks?" We researchers have answered this in case of a linear ion trap. We compiled down the protocol from the abstract language of quantum gates into device-level operations including shutting and cooling events. An unexpected and encouraging observation was that within each trap 'zone' it is never necessary to target a given ion while avoiding another of the same species. A consequence is that laser control systems do not need to have a narrow 'waist' and instead 'fat' beams that target entire zones may suffice. This should result in considerable reductions in the complexity and cost of the individual units.



Schematic showing advanced ion trap chips, each a 2D grid of pathways along which atoms travel, networked together to form a computer / *Simon Benjamin*

Purification a method to upgrade the quality of a quantum link by using it several times, each time creating a 'noisy' entangled pair of qubits, and then combining these qubits to create a smaller number of more perfectly entangled pairs.

Industry and Public Engagement

Industrial Engagement

Led by Dr Tim Cook

Engagement with industry is a major aim of the UK National Quantum Technology Programme as a whole and for the NQIT Hub within the national programme.

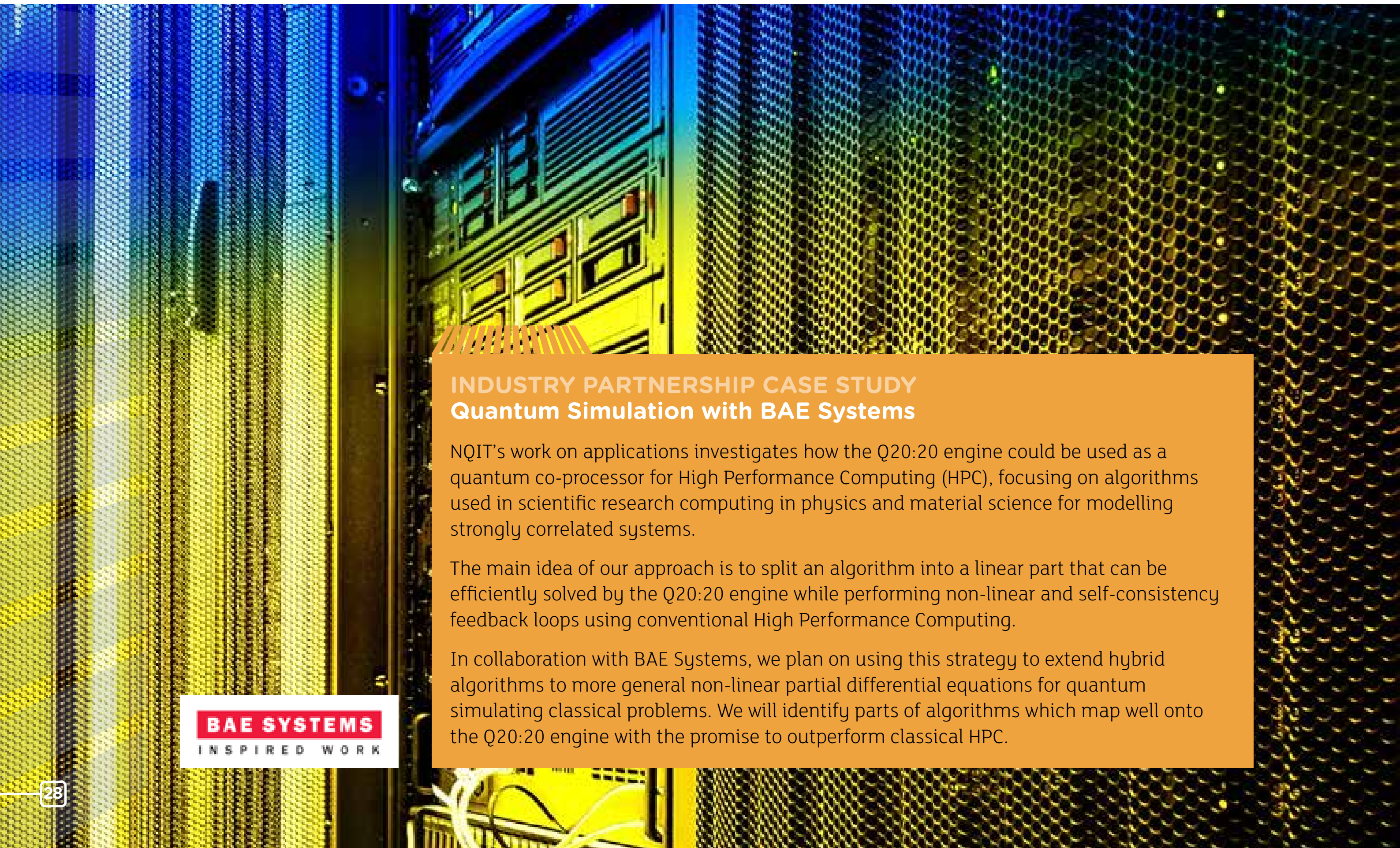
We have started ongoing activities with an additional 20 companies, more than half of which are UK-based

The three primary objectives of the User Engagement team are to:

1. Raise awareness of quantum technologies and build long term relationships with companies that will contribute to, and benefit from, their development.
2. Link industrial partners, as rapidly as possible, to the commercial opportunities created during the development of the Q20:20 engine.
3. Create new opportunities from the Hub's internal resources and external partners using our £3.4m Partnership Resource.

Since the start of the project, in addition to the 23 organisations on our project proposal, we have started ongoing activities with an additional 20 companies, more than half of which are UK-based.

These partners are providing services such as technology and market information and contributing to the design of bespoke components. We are also working with partners to develop test facilities for new technologies and commissioning them to specify flexible hardware development.



INDUSTRY PARTNERSHIP CASE STUDY
Quantum Simulation with BAE Systems

NQIT's work on applications investigates how the Q20:20 engine could be used as a quantum co-processor for High Performance Computing (HPC), focusing on algorithms used in scientific research computing in physics and material science for modelling strongly correlated systems.

The main idea of our approach is to split an algorithm into a linear part that can be efficiently solved by the Q20:20 engine while performing non-linear and self-consistency feedback loops using conventional High Performance Computing.

In collaboration with BAE Systems, we plan on using this strategy to extend hybrid algorithms to more general non-linear partial differential equations for quantum simulating classical problems. We will identify parts of algorithms which map well onto the Q20:20 engine with the promise to outperform classical HPC.

BAE SYSTEMS
INSPIRED WORK

INDUSTRY PARTNERSHIP CASE STUDY

Building Magnetometers with Element Six

We are building sensitive magnetometers that make use of the quantum spin of nitrogen vacancy centres in diamond. This is a collaboration between NQIT researchers in Warwick and Oxford Universities and Element Six, one of our UK-based industrial partners.

In the first year of NQIT, we built a portable nitrogen vacancy magnetometer from scratch and took it to the Quantum Technology Showcase at the Royal Society in November 2015. The sensitivity of this device beat our milestone goal ahead of schedule. In the coming year, we will reduce the size of our magnetometer by using dedicated, cheaper components, rather than the multi-purpose instrumentation we have used so far. We will also increase the sensitivity by using microwaves to flip the spins of the nitrogen vacancy centres.

elementsix a De Beers Group Company

Magnetometer being developed by the University of Warwick, using nitrogen-vacancy centres in diamond / Gavin Morley

Work in 2015 focused on raising awareness and building relationships, expanding the network of NQIT partners, developing emerging opportunities and creating new ones. We have been exploring links with a wide range of end user sectors, including data security, finance, telecommunication, instrumentation and biomedical applications.

We have produced and distributed publicity material aimed at an industry audience, including relevant pages on the NQIT website and booklets on user engagement, consultancy and quantum computing.

The User Engagement team has presented at a wide range of networking events and organised a large number of visits and meetings for interested companies. We also hold regular User Forums (See "Industry Engagement Case Study: User Forums") where we engage directly with existing and potential industrial partners.

With our £3.4m Partnership Resource we can co-fund new projects involving activities which either expedite the achievement of the Q20:20 engine – by acceleration or risk reduction – or develop specific commercial opportunities. To date we have considered 18 such projects and three are close to approval.

With our £3.4m Partnership Resource we can co-fund new projects involving activities which expedite the achievement of the Q20:20 engine

Dr Tim Cook explaining NQIT's industrial engagement activities / *University of Oxford Department Engineering Science Media Unit*

INDUSTRY ENGAGEMENT CASE STUDY
User Forums

We hold a regular User Forum every six months to facilitate dialogue between researchers and industrial and commercial end users of NQIT technology. This provides an opportunity for these end users to find out about our latest research and development. It also ensures that the researchers are fully aware of our users' requirements, specifications and technology expectations, and can align their research with industrial and commercial demands.

These events have led to a number of requests to work further with NQIT, either through Partnership Projects or other funding routes, such as supporting doctoral students.

INDUSTRY PARTNERSHIP CASE STUDY
Optical Switching with Gooch & Housego

The transistor is known as the ubiquitous switching element in electronic circuits. It is desirable to have an analogous device for switching optical signals. The telecommunications industry has developed several technologies over the last few decades, but these have been optimised to work in the red wavelengths. For coherent quantum control, often short-wavelength blue light is needed. However, current switch technology consists of expensive, bulky crystals that have to be installed and aligned by hand.

With Gooch & Housego, a UK-based photonics technology business, we are developing a fiberized switch that leverages telecommunications technology to reduce costs and dramatically improve reliability for quantum technology applications.

These devices will also be useful in the biotech world, which increasingly uses shorter wavelengths to reach further realms of science.

20 new companies being brought into the consortium in the first year

£3.4m Partnership Resource to fund new projects

COLLABORATIONS WITH INDUSTRY PARTNERS:

- Building sensitive magnetometers with Element Six
- Manufacturing waveguide chips with Covesion
- Quantum simulatio with BAE Systems
- Wavelength conversion with Gooch & Housego
- Developing cryogenic platforms for quantum computing with Oxford Instruments

NQIT DIALOGUE WITH INDUSTRY PARTNERS HAS COVERED:

- NQIT dialogue with industry partners has covered:
- Potential financial technology applications with QxBranch
- Biomedical applications of quantum technologies with Bruker Corporation
- Quantum potential for defence and security with BAE Systems
- New directions for manufacturing instruments in the UK with Gooch & Housego and M Squared Lasers

INDUSTRY ENGAGEMENT

23 founding industrial and government partners

4 major partnerships have been approved

NETWORKING EVENTS IN 2015:

- Hosted twice-yearly NQIT User Forum (Oxford)
- Leading participant at the Quantum Technology Showcase (Royal Society, London)
- 'Meet the Hubs' Knowledge Transfer Network day
- Quantum Information Processing and Communication Conference 2015 (Leeds)
- Industry Day (British Telecom plc, Ipswich)
- UK Photonics Network meeting (Oclaro Inc, Towcester)
- DSTL Quantum Technology Day (Loughborough)
- Oxford Physics Day (Oxford)
- Quantum Metrology Institute launch (London)
- British Standards Institute Industry Day (London)

END USER SECTORS INCLUDE:

- Data security
- Finance
- Telecommunications
- Instrumentation
- Biomedical

Top left 'Quantum of Spin' at the Royal Society Summer Science Exhibition / *Quantum Nanotechnology Group, University of Oxford*

Top right Dr Tim Cook, Co-Director for User Engagement, at the NQIT Hub Launch / *Stuart Bebb*

Bottom Explaining our new technology development at the Quantum Showcase at the Royal Society / *Dan Tsantilis, EPSRC*

Responsible Research and Innovation

Led by Professor Marina Jirotka

NQIT has responded to the risks and uncertainties of quantum computing by committing to a programme of Responsible Research and Innovation (RRI).

The quantum technologies developed through NQIT will have the potential to change our world profoundly. These changes may be hard to predict, as emerging technologies combine with existing technologies and markets in unexpected ways to lead to new possibilities in economics, society and culture.

RRI draws in a wide range of stakeholders throughout the research and innovation process, to promote science and innovation that is socially desirable and in the public interest. A key task will be to explore how this relates to quantum computing and related technologies.

The strategy for RRI in NQIT is based around a three-year programme, moving from a broad-ranging Landscape study based on a review of literature and qualitative interviews, through focused case studies on key issue areas, to produce a framework which will embed RRI in the future of NQIT and beyond. The Landscape study includes interviews with researchers across the project, and has produced new insights and analysis of the nature of quantum computing and likely impacts as well as considering how RRI can address the emergent outcomes.

Work in RRI across the Quantum Technology Hubs and within other areas of government is also underway, and this will be taken into account as it develops.

Public Engagement and Communications

Communications activities in the first year focused on building awareness of the NQIT Hub and its activities across a range of audiences including the general public, industry, academia and government.

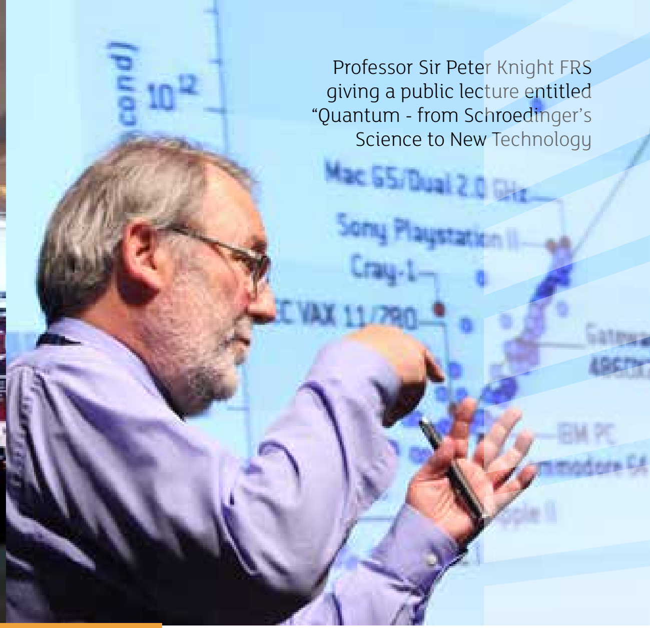
We attended several Science Festivals to explain to the general public what quantum computing is and to discuss what its potential impact might be. Three NQIT academics led a panel at the Cheltenham Science Festival entitled "Can we build a quantum computer?" where they discussed with an audience of around two hundred how theoretical quantum computing will become reality.

NQIT has cultivated a strong online presence and engages actively with the quantum community through our website and on Twitter (@NQIT_QTHub). We have been active in organising a number of events, including the NQIT Hub Launch in Oxford, a User Forum for our industrial partners and the Quantum UK 2015 Conference and Exhibition, a major new annual academic event highlighting quantum technology research in the UK (see "Academic Engagement Case Study: Quantum UK 2015 Conference").

One recent highlight was that we were a leading participant at the Quantum Technology Showcase held at the Royal Society in November 2015, where we demonstrated our cutting-edge research to current and potential industrial partners. We also commissioned a video promoting the UK National Quantum Technology Programme, which is available to view on our website.

Responsible research and innovation promotes science and innovation that is socially desirable and in the public interest

Networking at the Quantum UK Conference



Professor Sir Peter Knight FRS giving a public lecture entitled "Quantum - from Schroedinger's Science to New Technology

ACADEMIC ENGAGEMENT CASE STUDY
Quantum UK 2015 Conference

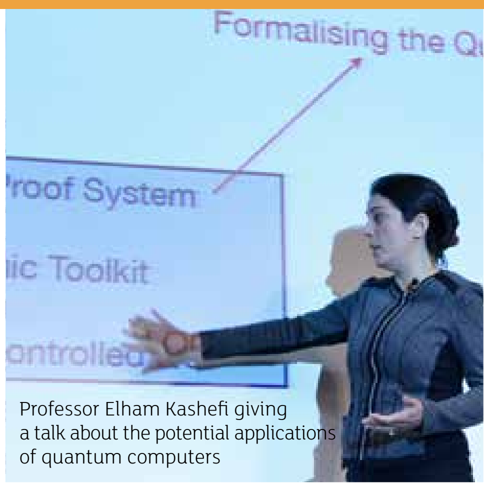
We hosted a major new national quantum technologies conference, Quantum UK 2015, in September, which is the major annual academic event of the UK National Quantum Technology Programme.

The conference was a forum to discuss scientific progress, innovations and technical challenges across all these sectors.

It was an opportunity to bring together industrial stakeholders and academic and government researchers, to exchange ideas, stimulate new projects and form new collaborations.

Nearly two hundred people attended the conference. Overall the event served the dual purpose of bringing together scientists and industrial partners from within the UK Quantum Technology Hub Network, and raising the international visibility of the UK programme.

Networking during the coffee break



Professor Elham Kashefi giving a talk about the potential applications of quantum computers

Dr Vivien Kendon giving a talk about qubit gates

Industry exhibitors demonstrating their new technologies

Dr James Gates explaining wavelength conversion at the Quantum Technology Showcase / *Dan Tsantilis, EPSRC*

INDUSTRY ENGAGEMENT CASE STUDY
Quantum Technology Showcase, Royal Society

This one-day event, held at the Royal Society in London, showcased the innovative research and technology carried out by the four Quantum Technology Hubs within the UK National Quantum Technology Programme. It was attended by three hundred delegates from industry, business and government.

The NQIT Director presented the NQIT Hub's work at the event, and there were demonstrations of NQIT research, such as the functionality of ion traps, from both early career and more established researchers.

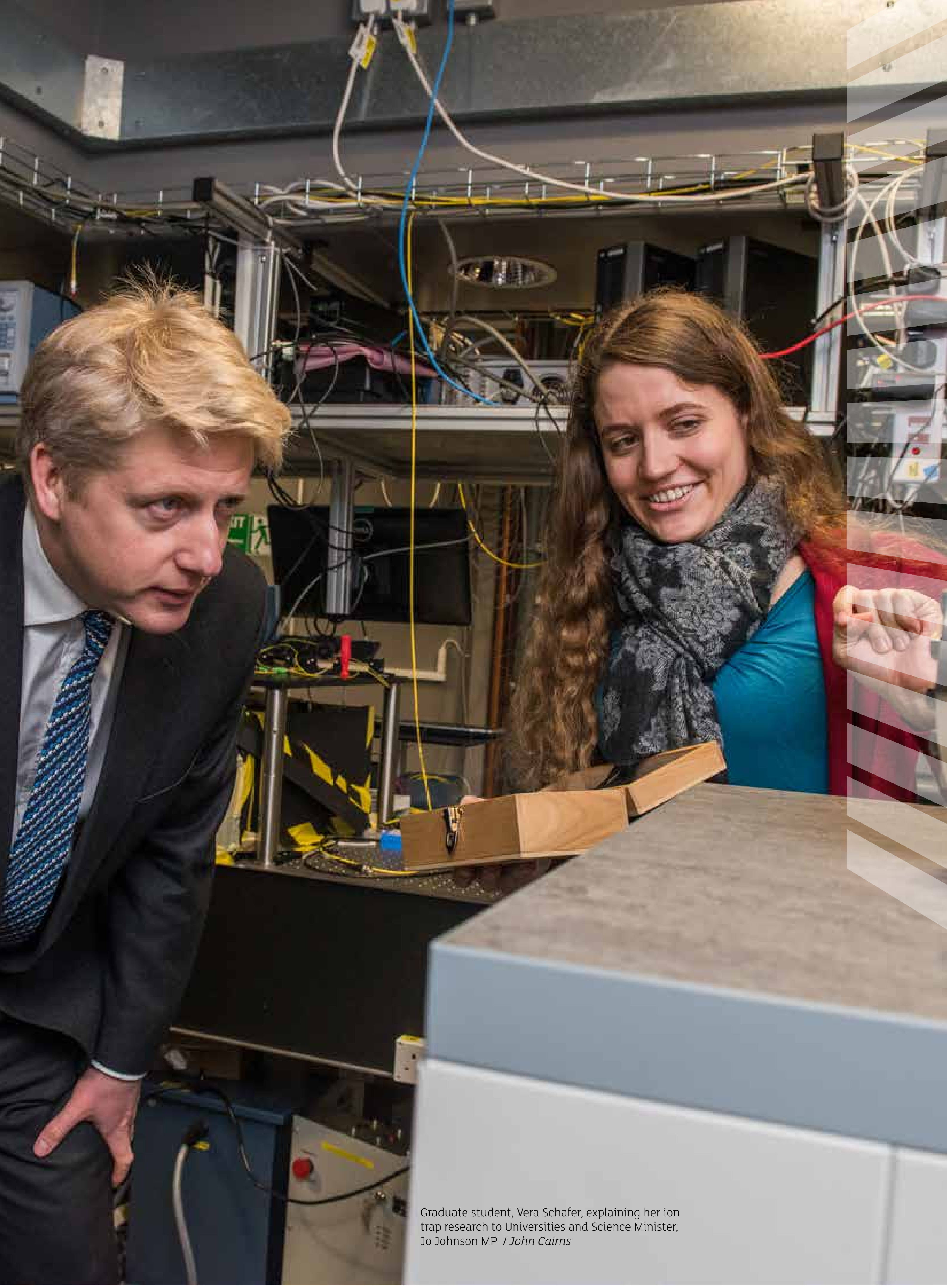
The feedback we collated after the event showed that the demonstrations of technology, as well as the time spent networking with researchers, were very much appreciated by attendees.

POLICY ENGAGEMENT CASE STUDY
Visit from Jo Johnson MP, UK Minister for Universities and Science

Jo Johnson MP visited the NQIT labs in Oxford where he was shown laboratory and workshop facilities and met with our doctoral students. The NQIT Directors discussed with Mr Johnson the UK National Quantum Technology Programme and why quantum technology is such an exciting area for research and technology development. He was given a tour of our NQIT lab in the Physics Department where Vera Schafer, a doctoral student, and Dr Ben Metcalf, a post-doctoral researcher, explained how their research into ion traps and photonics provide the core hardware for NQIT's Q20:20 quantum computer.

During his visit to Oxford, Mr Johnson announced new Government funding to support graduate students in engineering and physical sciences, as well as significant funding geared towards boosting the UK's research into quantum technologies.

Mr Johnson said in the press: "We are committed to securing the UK's position as a world leader in science and innovation. The Government is ensuring major new discoveries happen here, such as the creation of super-powerful quantum computers which scientists are working on in Oxford. This new funding builds on our protection for science spending by supporting research in our world-leading universities and helping to train the science leaders of tomorrow."



Graduate student, Vera Schafer, explaining her ion trap research to Universities and Science Minister, Jo Johnson MP / *John Cairns*

Looking ahead

NQIT is a five-year programme of research and technology development, with the Q20:20 quantum computer demonstrator as its ultimate goal. This is part of a longer, ten-year 'roadmap' which will guide the introduction of quantum computers into diverse commercial environments.

Progress towards the Q20:20 engine is broken down into a series of key technical achievements involving increasingly complex network operations, building on increasingly advanced ion traps. Initially we will target two linked ion traps, two linked multi-ion traps and a star network of multi-ion traps. These units will then be engineered into a compact and efficient format and integrated into the Q20:20 device. Lastly, they will be optimised for secure universal communications node networking at room temperature.

As well as the critical path to the Q20:20 engine, we are working on a number of spin-out technologies that will be developed over the course of the project.Change this to In the second year of the project, we expect to produce the first of these, which will be a heralded single photon source. Following this will be adaptive optics 3D waveguide fabrication, a time-frequency quantum key distribution and a GHz quantum random number generator, a quantum random number generator, time-frequency Quantum Key Distribution system, advanced microwave control system and adaptive optics 3D waveguide fabrication.

As the project progresses, we are constantly interacting with our industrial partners, user projects and other external leveraged funding to assess and evolve the technical specifications required for the integrated Q20:20 demonstrator components and sub-systems. We have also initiated collaborative work on the necessary standards that will allow different groups worldwide to use the same quantum computer control hardware and software.

On the industrial engagement side, we plan to launch a consultancy service to promote the uptake of quantum technology and to develop intellectual property and exploitation paths. We will also develop links with investors to put in place financing for the engineering resources required for the accelerated development and scale-up of the Q20:20 system.

The Beecroft Building, a state of the art working space for theorists and high-tech laboratories for experimentalists, is currently being built to house new NQIT laboratory facilities / Hawkins/Brown

Time Line

YEAR 1 · YEAR 2 · YEAR 3 · YEAR 4 · YEAR 5

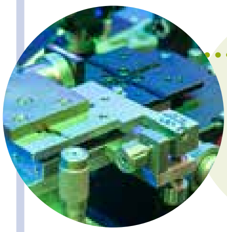
Early Project Deliverables

These deliverables are associated with non-core NQIT activities, and are spin-outs from the main programme that have commercial application or are of interest to users in non-quantum areas:

Heralded single photon source

Adaptive optics 3D waveguide fabrication

Time-frequency quantum key distribution system



GHz quantum random number generator

Q20:20 Milestones

The Q20:20 milestones are a series of increasingly complex demonstrators, as set out in this figure:

Entanglement between two ions

Entanglement between two multi-ion traps

Switched entanglement between ion traps

Engineered ion trap

Q20:20 node

Q20:20 demonstrator

INVESTMENT CASE STUDY
New Beecroft Building for Oxford Physics Department

The Beecroft Building, the Physics Department's first major new building in 50 years, is currently under development adjacent to the existing Clarendon laboratory. It will contain state-of-the-art laboratories and will enable new science to take place.

The basement laboratories will provide a high quality environment with very low vibration levels and excellent temperature control.

The total cost of this building project is £47m. The EPSRC has contributed £3.6m so that NQIT will have world-class technology development facilities.

NQIT will have bespoke, vibration-proof laboratories in the basement of the new Beecroft Building / *Hawkins/Brown*

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. (2015). "Hybrid quantum logic and a test of Bell's inequality using two different atomic isotopes." Nature 528(7582): 384.

Barlow, T. M., et al. (2015). "A master equation for a two-sided optical cavity." Journal of Modern Optics 62: S11-S20.

Baumgratz, T. and A. Datta (2016). "Quantum Enhanced Estimation of a Multidimensional Field." Physical Review Letters 116(3): 030801.

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 postselection." Physical Review A 93(1): 11.

Cohen, I., et al. (2015). "Multi-qubit gate with trapped ions for microwave and laser-based implementation." New Journal of Physics 17: 12.

Denny, S. J., et al. (2015). "Proposed Parametric Cooling of Bilayer Cuprate Superconductors by Terahertz Excitation." Physical Review Letters 114(13): 5.

Forst, M., et al. (2015). "Spatially resolved ultrafast magnetic dynamics initiated at a complex oxide heterointerface." Nature Materials 14(9): 883-+.

Gheorghiu, A., et al. (2015). "Robustness and device independence of verifiable blind quantum computing." New Journal of Physics 17: 22.

Giscard, P. L., et al. (2015). "An exact formulation of the time-ordered exponential using path-sums." Journal of Mathematical Physics 56(5): 18.

Hangleiter, D., et al. (2015). "Nondestructive selective probing of phononic excitations in a cold Bose gas using impurities." Physical Review A 91(1): 13.

Heshami, K., et al. (2016). "Quantum memories: emerging applications and recent advances." Journal of Modern Optics: 1-24.

Hoban, M. J. (2015). "Causality gets entangled." New Journal of Physics 17: 2.

Holleczek, A., et al. (2015). "Qubits, qutrits, and ququads stored in single photons from an atom-cavity system." Advances in Photonics of Quantum Computing, Memory, and Communication Viii. Z. U. Hasan, P. R. Hemmer, H. Lee and A. L. Migdall. Bellingham, Spie-Int Soc Optical Engineering. 9377.

Johnson, S., et al. (2015). "Tunable cavity coupling of the zero phonon line of a nitrogen-vacancy defect in diamond." New Journal of Physics 17: 9.

Johnson, T. H., et al. (2015). "Capturing Exponential Variance Using Polynomial Resources: Applying Tensor Networks to Nonequilibrium Stochastic Processes." Physical Review Letters 114(9): 5.

Li, Y., et al. (2015). "Resource Costs for Fault-Tolerant Linear Optical Quantum Computing." Physical Review X 5(4): 15.

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.

Mendoza-Arenas, J. J., et al. (2015). "Coexistence of energy diffusion and local thermalization in nonequilibrium XXZ spin chains with integrability breaking." Physical Review E 91(4): 13.

Michelberger, P. S., et al. (2015). "Interfacing GHz-bandwidth heralded single photons with a warm vapour Raman memory." New Journal of Physics 17: 10.

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.

Poem, E., et al. (2015). "Broadband noise-free optical quantum memory with neutral nitrogen-vacancy centers in diamond." Physical Review B 91(20): 10.

Saunders, D. J., et al. (2016). "Cavity-Enhanced Room-Temperature Broadband Raman Memory." Physical Review Letters 116(9): 501-501.

Schafer, V. M., et al. (2015). "Optical injection and spectral filtering of high-power ultraviolet laser diodes." Optics Letters 40(18): 4265-4268.

Singla, R., et al. (2015). "THz-Frequency Modulation of the Hubbard U in an Organic Mott Insulator." Physical Review Letters 115(18): 6.

Smith, P. G. R., et al. (2015). "Fabrication of silica integrated waveguide circuits for quantum enhanced sensing, quantum information processing and number resolving detection." Quantum Sensing and Nanophotonic Devices Xii. M. Razeghi, E. Tournie and G. J. Brown. Bellingham, Spie-Int Soc Optical Engineering. 9370.

Stokes, A. and R. Bennett (2015). "The Casimir effect for fields with arbitrary spin." Annals of Physics 360: 246-267.

Weidt, S., et al. (2015). "Ground-State Cooling of a Trapped Ion Using Long-Wavelength Radiation." Physical Review Letters 115(1): 5.

Talks

January 2015, "Multiphoton quantum interference in multiport integrated optical circuits: from teleportation to Boson sampling", Professor Ian Walmsley, Optical Society of Korea Winter Annual Meeting

March 2015, "Networked Quantum Information Technologies", Professor Ian Walmsley, UK-Singapore Quantum Symposium 2015, Singapore

April 2015, "Computing on Encrypted Data", Professor Elham Kashefi and "Quantum memories for scalable photonics", Dr Joshua Nunn, Bristol Quantum Information Technologies Workshop 2015, UK

April 2015, US National Academy of Science's Committee on Atomic, Molecular and Optical Sciences annual meeting 2015, Professor Ian Walmsley, USA

April 2015, "Storing photons: quantum memories for the real world", Professor Ian Walmsley, Advanced Materials for Quantum Technology Workshop, Manchester, UK

May 2015, "Machine learning as the killer app for quantum technology", Professor Simon Benjamin, Royal Society Workshop on Machine Learning, London, UK

May 2015, "Dipole-dipole bound Rydberg molecules", Professor Dieter Jaksch, New Trends in Complex Quantum Systems Dynamics 2015, Spain

May 2015, "A la recherche du clair perdu: quantum memories for the real world", Professor Ian Walmsley, Quantum Physics of Nature 2015, Switzerland

June 2015, "On optimising quantum communications in verifiable quantum computing", Professor Elham Kashefi, Trustworthy Quantum Information, USA

June 2015, 46th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Professor David Lucas, USA

June 2015, "Quantum tomography: beginning, middle and end" and "Quantum Memories for Light", Professor Ian Walmsley, DTU Summer School on Quantum and Nonlinear Optics 2015, Denmark

June 2015, “Multiphoton quantum interference in multiport integrated optical circuits: from teleportation to Boson Sampling”, Professor Ian Walmsley and “Dynamic Optics for 3D Laser Material Processing”, Professor Martin Booth, CLEO 2015 Joint Symposium on Integrated Quantum Optics, Germany

July 2015, “Towards classical-quantum hybrid cloud”, Professor Elham Kashefi, Keynote Address, 7th Conference on Reversible Computation, France

July 2015, “Parametric cooling of Josephson junction arrays”, Professor Dieter Jaksch, JQC mini-conference on non-equilibrium quantum dynamics in low dimensions, Durham, UK

July 2015, “Bad Cavities for Good Memories: Storing Broadband Photons with Low Noise”, Dr Joshua Nunn, Central European Workshop on Quantum Optics 2015, Poland

July 2015, “Nitrogen-vacancy Defects in Diamond Coupled to Open Microcavities: Towards an Efficient Spin-Photon Interface”, Professor Jason Smith, PIERS 2015, Czech Republic

August 2015, “First generation controlled quantum hardware: What’s it good for, and when can we have it?”, Professor Simon Benjamin, 2015 CCPQ Workshop, Windsor, UK

September 2015, “Verification of Quantum Computing”, Professor Elham Kashefi, EACSL Annual Conference on Computer Science Logic (CSL), Germany

September 2015, “Quantum correlations in photonic networks”, Professor Ian Walmsley and “First generation controlled quantum hardware: What’s it good for, and when can we have it?”, Professor Simon Benjamin, IOP International Conference on Quantum, Atomic, Molecular and Plasma Physics 2015, London, UK

September 2015, “Quantum Correlations in Photonic Networks”, Professor Ian Walmsley, 3rd International Conference on Correlation Effects in Radiation Fields 2015, Germany

October 2015, “Hybrid Quantum-Classical DMFT Simulation”, Professor Dieter Jaksch, Quantum Simulations: Theory Meets Experiment Workshop, Oxford, UK

October 2015, “Building large quantum states out of light”, Professor Ian Walmsley, Keynote Speech, Aston University Year of Light Workshop 2015, UK

October 2015, “UK Quantum Initiative”, Professor Ian Walmsley, Quantum Information on a Chip Workshop 2015, Italy

October 2015, “Integrated photonic systems for quantum technologies”, Professor Ian Walmsley, Optical Society of America Frontiers in Optics 2015, USA

October 2015, “How Light Shaped Science: From Fleas to Qubits”, Professor Ian Walmsley, Laser Science XXXI, USA

October 2015, “Quantum Coin Flipping”, Dr Anna Pappa, CryptoForma, Strathclyde, UK

November 2015, “Quantum enhanced technologies using light”, Professor Ian Walmsley, Unifying Physics and Technology in Light of Maxwell’s Equations, Royal Society, London, UK

December 2015, “Experimental verification of multipartite entanglement in the presence of dishonest parties”, Dr Anna Pappa, QUISCO, Glasgow, UK

February 2016, Professor Simon Benjamin and Dr Iris Choi, Bordeaux Quantum Forum, France

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

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, UK

Additional talks given by NQIT's Director, Professor Ian Walmsley:

- "Networked Quantum Information Technologies", ARC Centre of Excellence for Engineered Quantum Systems, Australia
- IARPA Multi-Qubit Coherent Operations Program Technical Exchange Meeting on Algorithms and Next Generation Designs, New York, USA
- "Towards scalable quantum memories", Lecture at Institute for Molecular Science, Tokyo, Japan
- "Building quantum machines out of light", Colloquium at Nanjing University, China
- "Building quantum machines out of light", Lecture at Shanghai Jiao Tong University, China
- "Building quantum machines out of light", Professor Ian Walmsley, Keynote Address, Max-Planck Institute for the Science of Light Workshop 2015, Germany

Additional Funding

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

- Dates : 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: Quantum Waveguides for Indistinguishable Single-Photon Sources (QWISPS), Covesion Ltd and the University of Southampton

- Dates: April 15 to March 2016
- Amount: £110,436
- Funder: Innovate UK
- Grant reference: 131877

Foundational Questions Institute (FQXi) Large Grant: Quantum Bayesian networks: the physics of nonlocal events, Rafael Chaves, Freiburg University and Matty Hoban and Raymond Lal, Oxford University

- Dates: July 2015
- Amount: $76,296
- Funder: Foundational Questions Institute (FQXi) Physics of What Happens program

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

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 over 1,000 views.

"Quantum - from Schroedinger's Science to New Technology": public lecture by Professor Sir Peter Knight FRS, Oxford, UK. This talk was filmed and is available to view on the NQIT website.

"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

"Can We Build A Quantum Computer?": panel discussion at the Cheltenham Science Festival 2015 with Dr Gavin Morley, Professor Winfried Hensinger and Professor Elham Kashefi

Oxford Physics Alumni Day, June 2015: Dr Joshua Nunn's research group contributed to a stall promoting the activities of NQIT to a group of Oxford Physics Alumni.

"Superconducting Quantum Circuits": talk by Dr Peter Leek during a visit organised by Institute of Physics for retired physicists, April 2015

Pint of Science talk "Nonlinear light: from missile defence to quantum computers": talk by Professor Peter Smith to members of the public in Southampton

University of Southampton Science and Engineering Day 2015: Professor Peter Smith and Dr James Gates organised tours of their NQIT lab for members of the public

Cheltenham Science Festival Variety Night: An Evening of Unnecessary Detail: Dr Gavin Morley did 8 minutes of stand-up comedy on "Quantum Weirdness" to an audience of over 600 members of the general public.

Salisbury Sixth Form Cleanroom Tours: Dr James Gates and Matthew Posner organised a cleanroom tour to a group of Women Sixth Form students.

Quantum 'wow': researchers at Southampton University hosted a group of sixth form students for a tour of the integrated photonics laboratory.

Graduate student, Anna Webb, demonstrating the technology behind ion traps with an analogous 'dust trap' at the Quantum Technology Showcase at the Royal Society / Dan Tsantilis, EPSRC

Selected Media Coverage

Announcement of Quantum Hub funding:

- Physics World: "UK unveils £120m quantum-technology hubs"

  http://physicsworld.com/cws/article/news/2014/nov/26/uk-unveils-GBP120m-quantum-technology-hubs

- Optics.org: "UK selects quantum development hubs"

  http://optics.org/news/5/11/42

Quantum Technology Showcase, Royal Society, November 2015:

- Phys.org: "UK's Quantum Hubs show future technology"

  http://phys.org/wire-news/208870113/uks-quantum-hubs-show-future-technology.html

- New Electronics: "Future technology on show at Quantum Technology Showcase"

  http://www.newelectronics.co.uk/electronics-news/future-technology-on-show-at-quantum-technology-showcase/109917/

- 11th of November 2015, Today Programme, BBC Radio 4, 8.55 am, interview with Miles Padgett

'Hybrid' logic gate publication in Nature:

- EurekAlert: "Oxford team demonstrates 'hybrid' logic gate as work towards quantum computer continues"

  http://www.eurekalert.org/pub_releases/2015-12/uoo-otd121515.php

- Phys.org: "Rese demonstrates 'hybrid' logic gate as work towards quantum computer continues"

  http://phys.org/news/2015-12-rese-hybrid-logic-gate-quantum.html

- Science Daily: "Team demonstrates 'hybrid' logic gate as work towards quantum computer continues"

  https://www.sciencedaily.com/releases/2015/12/151216134325.htm

Jo Johnson visit to Oxford and announcement of further funding for quantum technology:

- Oxford Mail: "Oxford could be at the forefront of British science thanks to huge boost in funding from the government"

  http://www.oxfordmail.co.uk/news/14310379.Huge_boost_in_funding_will_provide_Oxford_University_with_futuristic_science_and_engineering/

- Oxford Student: "Jo Johnson visits quantum laboratories following announcement of £204m science fund"

  http://oxfordstudent.com/2016/03/06/70747/

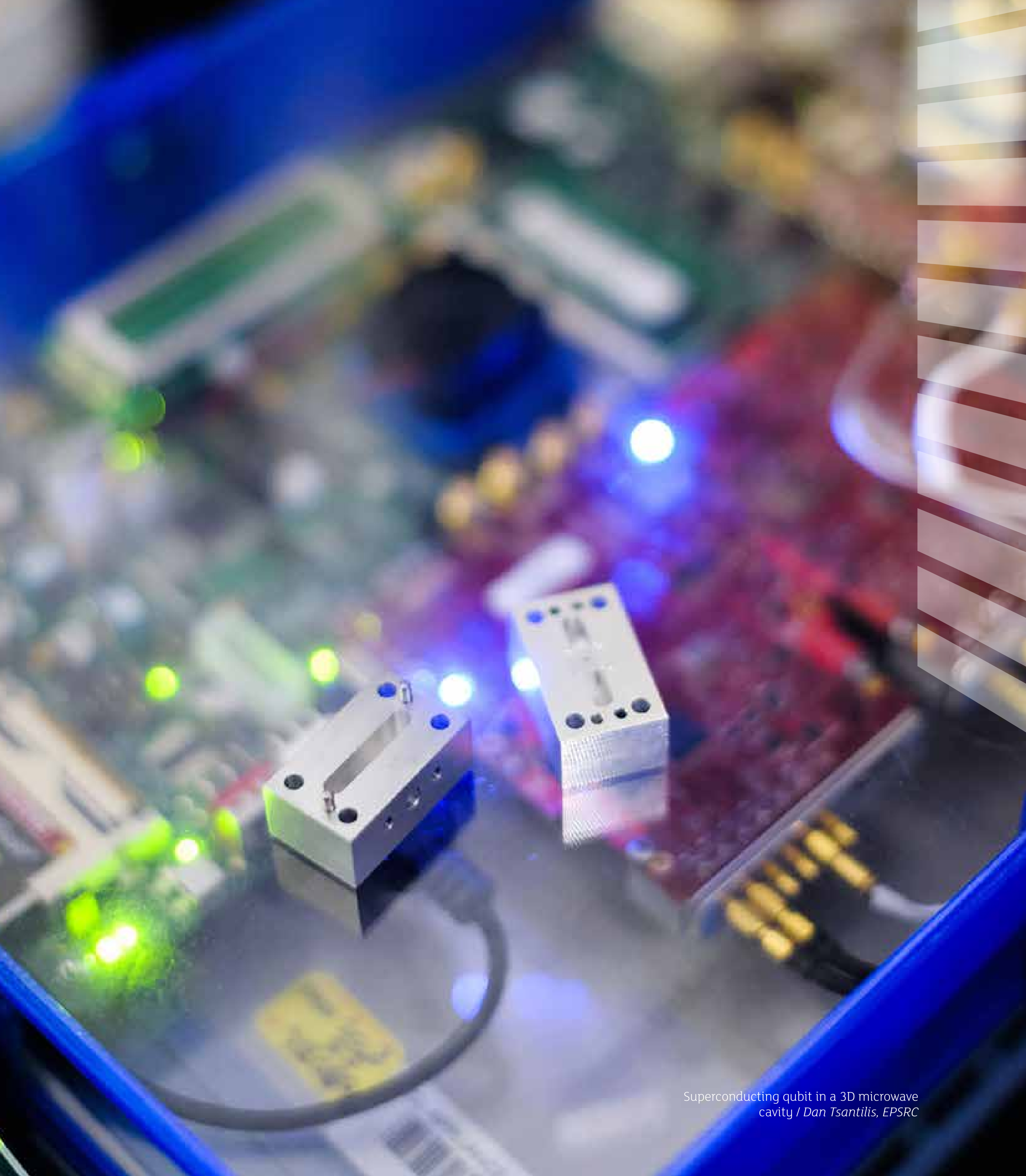
- ZD Net: "Quantum research gets funding boost"

  http://www.zdnet.com/article/quantum-research-gets-funding-boost/

Getting Involved

NQIT has set aside substantial funding to support promising quantum technology projects that have early commercialisation potential. These are divided into User Projects, which have immediate applications, and Partnership Projects, which have a longer technology maturity timeline but substantial industrial interest.

If you have an idea for a project that aligns with the aims of the NQIT Hub, would help speed up NQIT deliverables and uses NQIT scientists with commercial partners to advance quantum technology, please do get in touch with our User Engagement team.



Superconducting qubit in a 3D microwave cavity / *Dan Tsantilis, EPSRC*

For more information about NQIT, please visit our website:

http://www.nqit.ox.ac.uk

Or send us an email:

Or get in touch

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NQIT

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME