Annual Report 2018

NQIT Networked Quantum Information Technologies

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

The NQIT Entangler, developed by the University of Southampton / Paul Gow & Paolo Mennea

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Foreword

The third year of NQIT has been an important transition year, embedding new applications programmes as well as a software emulator, and working with the other UK Quantum Technology Hubs to deliver improved public and industry engagement. NQIT continues to lead the UK's efforts in quantum computing and simulation, achieving key milestones in the development of hardware and software that will deliver core capabilities in these disruptive technologies by harnessing expertise across the UK and partnerships across the world.

There have been some important changes in NQIT in the past year. The reconfiguration of the software and applications programmes following the mid-term review has opened opportunities for bringing in new academic partners. For example, in machine learning and our NQIT emulator project, we are enabling external partners in government and industry to begin to develop applications that can run on quantum machines.

The hardware programme continues to deliver world-leading developments on the way to a scalable quantum computing machine. We have demonstrated the first stage of the photonic network that can entangle ion traps and we expect to have completed a full entanglement distribution protocol by the end of NQIT. Extending the network will be possible by means of the single-step quantum conversion of blue light to telecoms C-band light, which was recently demonstrated. Our work on using diamond as an alternative qubit node has progressed and new laser writing techniques that enable near deterministic generation of defect colour centres have opened up the possibility of scaling this technology to a large array of spins.

The development of a vibrant and broad user community is a critical factor for success in developing the first generation of truly scalable quantum computers. Over the past year, NQIT has successfully continued to develop a wide range of new partnerships. A particularly significant event was the launch of the IBM Q Network, of which we are a founding partner, the only University in Europe. This new partnership provides NQIT researchers, through the University of Oxford, access to IBM's latest quantum devices. These are quantum circuits containing tens of qubits that can perform elementary computing operations and allow small-scale quantum software programmes to be run.

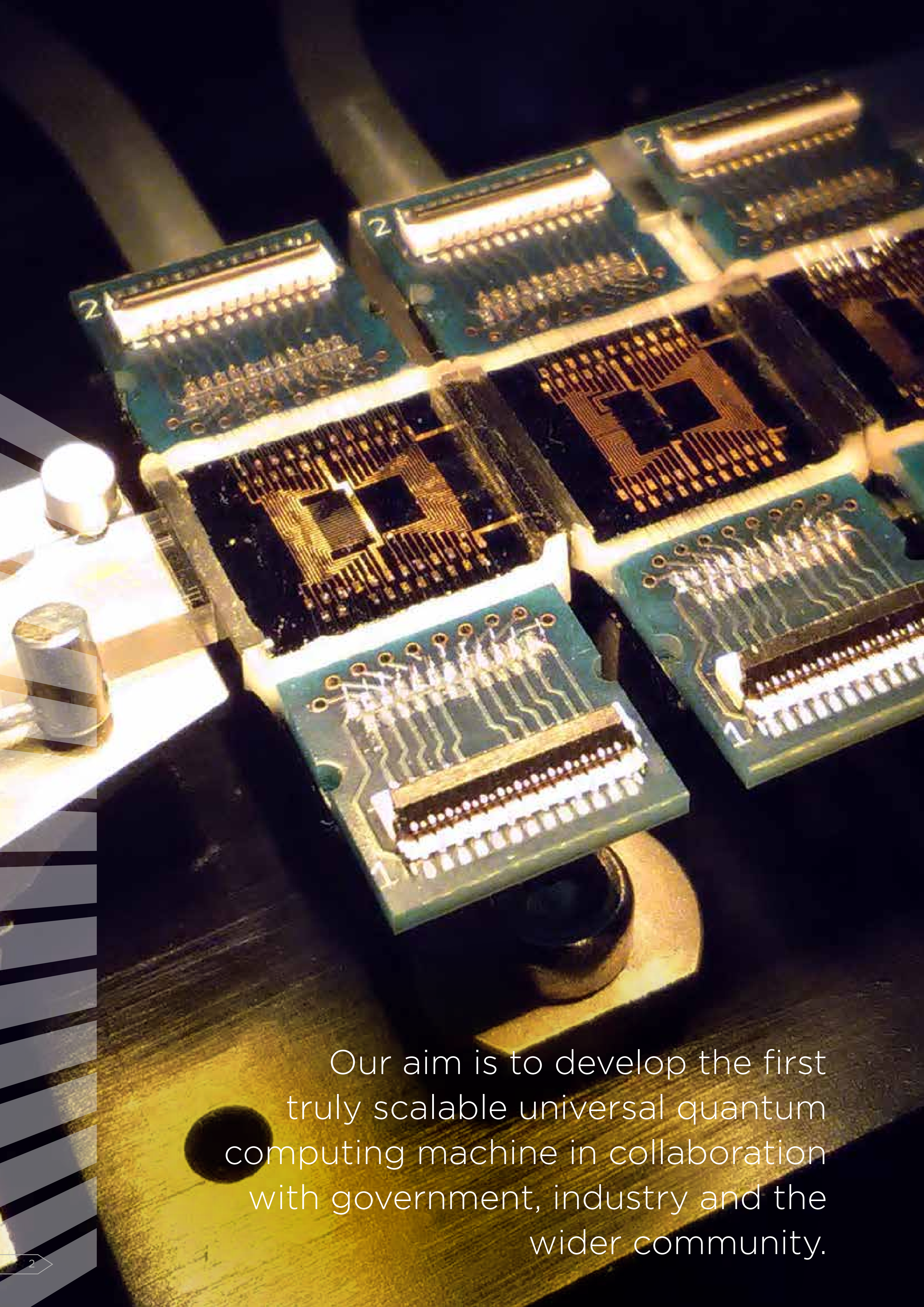
This opportunity will help NQIT to develop software suited to applications identified by our academic and industry partners across a wide range of applications from new research in quantum chemistry to optimisation of logistics networks for commerce.

We have also been successful in attracting new UK government funding to partner with the best programmes around the world in quantum information science. The Rutherford International Partnership programme provides funding to support visiting researchers from Canada and Australia to join NQIT projects for up to 12 months, helping to build new and strengthen existing partnerships with the world-leading efforts in these countries.

Planning for Phase II of the UK National Quantum Technology Programme is now underway and NQIT is working with government to help structure the community and shape the landscape for this next phase. Phase II will focus on scaling our core ion trap technology to operational machines, broadening the development of applications and supporting the development of promising alternative qubit technologies.

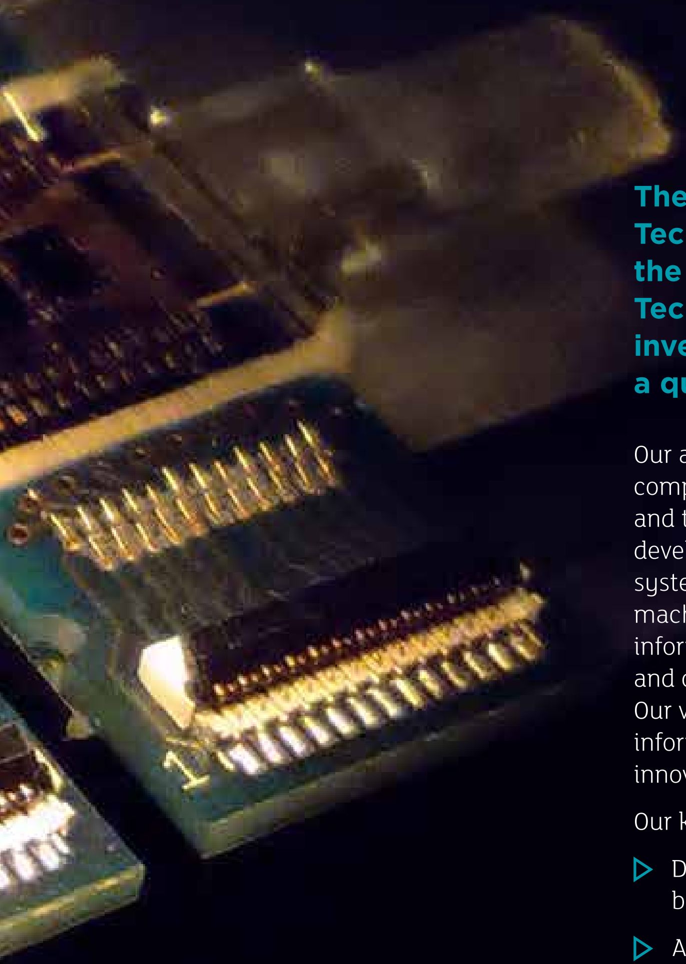
Overall, we are confident that the Hub is making excellent progress towards its strategic objectives and is achieving key milestones. We are building an effective community of researchers and industry partners focused on building the critical technologies for the Q20:20 quantum computer demonstrator and creating a new UK quantum computing economy.

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



Our aim is to develop the first truly scalable universal quantum computing machine in collaboration with government, industry and the wider community.

Introduction



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

Our aim is to develop the first truly scalable universal quantum computing machine in collaboration with government, industry and the wider community. The architectures that NQIT is developing have the highest performance of any current qubit system, and we are advancing on the path to create such a machine. We are building a new industry sector around quantum information technology, from the supply chain, through the build and operation, to programming and use of quantum computers. Our vision is for the UK to become the centre of a global quantum information processing industry, with a rich mixture of research, innovation and commercialisation in all parts of the UK.

Our key objectives are to:

- Demonstrate a scalable quantum computing architecture based on ion qubits and photonic networks
- Advance promising emerging and enabling quantum information processing technologies
- Seed and develop the commercialisation of these technologies through engagement with industry and investors through training, collaboration and knowledge transfer
- Engage with the wider public and community

Since the commencement of NQIT in 2014 we have progressed our ion trap engineering significantly. We are close to connecting our ion trap 'processors', and the engineering required to control these systems is well-advanced. Significant progress has been made in emerging qubit technologies, including new approaches for controlling superconducting qubits and new methods for preparing qubits in diamonds, where a new process to write qubits is yielding promising results. We have also demonstrated enabling technologies such as wavelength conversion, and these technologies may become future products and components in the supply chain for quantum and other industries.

An integrated photonics chips used to manipulate photons to perform quantum computation tasks / William Clements & Paolo Mennea

We are developing the software systems to program and operate our quantum computing machine and are working on our own quantum computing emulator platform for high performance computers, which will enable scientists in research and industry to develop algorithms and applications for the emerging hardware.

Industry engagement is a key part of our strategy with different strands of activity:

- Partnership Projects - we work with our industry partners on research projects across hardware and applications that will further NQIT's mission to advance technology transfer
- Industry Day - we hold an annual event for companies to meet with leading scientists and discover the latest developments and future direction. We also participate in national and global industry events, such as the National Quantum Technologies Showcase
- Industrial Strategy Challenge Fund - we are working with companies and Innovate UK to grow the quantum economy through innovative projects with large companies as well as startups
- Commercialisation - we support commercial activities resulting from research, such as patenting inventions and creating spinout companies. There are now three NQIT spinout companies, which have raised multi-million pound investments, with development of a fourth underway
- Users - we are building cross-disciplinary collaborations and a broad user base to identify problems that may benefit from the new possibilities in quantum computing

NQIT recognises the importance of developing skills and training and the strong demand for quantum physicists, computer scientists and engineers for industry. We hold a bi-annual Skills Forum and work with the Training and Skills Hubs in Quantum Systems Engineering to address this important issue.

The NQIT Hub operations team has grown over the past year in pace with the expansion of public engagement, industry partnerships and momentum on research delivery. The team now contains seven members, including a full time Project Resources Manager, Communications Manager and two User Engagement Technology Associates as well as three part time team members. The whole team ensures efficient delivery of financial and administrative processes across a wide range of responsibilities including staffing, procurement, events management and research collaborations with industry.

We have expanded our programme of public engagement activities and continue to work closely with the other Quantum Technology Hubs to deliver on Responsible Research and Innovation, public engagement and industry collaboration for the benefit of the UK and the UK National Quantum Technologies Programme.

We remain focused on key technical, training and engagement goals, and are beginning to plan for the second phase of the UK National Quantum Technologies Programme. Our vision is a combined ecosystem of industry and new startups, an innovation centre that will operate a national quantum computing and simulation facility for developers and users, and continued research within an information processing Hub.

Year Three Achievements

6 inventions available for licensing

130+ organisations engaged with LARGE and small from diverse sectors regional, national and global

Spinout companies:
3 have raised multi-million pound investment
1 more raising investment

Partnership Projects:
7 finished
9 in progress
10 in the pipeline

£5,090,644 funding from Innovate UK grants

Industry partners:
25 founding members of the consortium
11 added in 2016
12 new industry partners in 2017

59 new peer-reviewed publications

14 graduate students undertaking NQIT-funded PhDs
12 new graduate studentships being advertised this year

46 presentations as a keynote or named speaker at a conference

30 events for the general public including lectures, exhibitions and festivals

1500 average visitors per month

1436 followers on Twitter
Number of followers more than doubled during 2017

Number of website visitors up 59% compared to 2016

Programme Structure

NQIT

Industry Engagement

- Partnership Projects
- Supply chain for quantum computing
- End user sectors
- Applications of quantum computing
- Spin-out companies
- Patents
- Gateway to access other quantum computers

Engineering & Hardware Development

- Ion trap node engineering
- Atom-photon interfaces
- Photonic network engineering
- Alternative qubits
- Core Engineering Capabilities

Applications & Algorithms Development

- Architecture
- Secure Network Applications
- Networked quantum sensors
- Quantum Enabled Discovery
- Quantum/classical emulation and interfacing
- Quantum optimisation and machine learning

Responsible Research and Innovation

- RRI Workshops
- Public Dialogue
- Quantum Technology Case Studies

Skills & Training

- Skills Forum
- Graduate Studentships
- Careers in Quantum

Communications & Outreach

- NQIT website
- Twitter
- Science Festivals & museum exhibitions
- Outreach events
- Reports & publications
- News, TV, podcasts

The NQIT Consortium

The NQIT Consortium is an alliance of nine universities led by Oxford University, plus more than 30 commercial and government organisations comprising leading experts across a range of backgrounds from academia, industry and government agencies, working together to achieve the ambitious goal of developing a universal quantum computer. The university partners are Bath, Cambridge, Edinburgh, Leeds, Southampton, Strathclyde, Sussex and Warwick, and we have connections with others including Heriot-Watt, Bristol, Durham and Imperial College London.

Beyond academia, we have assembled a comprehensive network of companies including IBM, Lockheed Martin, Raytheon BBN, Google and Toshiba; government laboratories, such as the National Physics Laboratory (NPL), the Defence Science and Technology Laboratory (Dstl) and the National Institute of Standards and Technology (NIST); and a number of small and medium sized enterprises, including Rohde & Schwarz, Covesion and Oxford Instruments, who are investing resources in the form of both finances and expertise.

Networking in the garden of Rhodes House at the NQIT Industry Day / David Fisher

UK Partners

UKNQT Partners

1. EPSRC
2. Innovate UK
3. BEIS
4. NPL
5. NCSC
6. DSTL
7. KTN

NQIT Academic Partners

1. University of Bath
2. University of Cambridge
3. The University of Edinburgh
4. University of Leeds
5. University of Oxford
6. University of Southampton
7. University of Strathclyde Glasgow
8. University of Sussex
9. Warwick – The University of Warwick

Other Quantum Technology Hubs

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

New Academic Collaborators

1. University of Bristol
2. Durham University
3. Heriot Watt University
4. Imperial College London

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

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

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Industry and Strategic Partners

ASPEN ELECTRONICS INCORPORATING ADMIRAL MICROWAVES

BAE SYSTEMS
INSPIRED WORK

BRUKER

CQC
Cambridge Quantum Computing

CATAPULT
Satellite Applications

covesion

CQT Centre for Quantum Technologies
National University of Singapore

[dstl]

elementsix™
a De Beers Group Company

ETSI
World Class Standards

EPSRC
Engineering and Physical Sciences Research Council

Fraunhofer
UK

Gooch & Housego

Google

IBM®

LOCKHEED MARTIN

M SQUARED

NPL
National Physical Laboratory

OXFORD CAPITAL

OXFORD INSTRUMENTS
The Business of Science®

ROHDE & SCHWARZ

ROUTEMONKEY®

TMD

TOSHIBA
Leading Innovation >>>

People

Directors

Professor Ian Walmsley, NQIT 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, EU and worldwide. Ian's vision and drive unifies the consortium and motivates their delivery of the ambitious objectives of the Hub. His research group in ultrafast quantum optics and optical metrology sustains research efforts in three areas: quantum optics, coherent control of atoms and molecules, and nonlinear optics. Ian has a presence at a national level liaising with Research Councils and Government, including as a member of the EPSRC Council and actively engaging with decision-making bodies about the latest developments in quantum computing. Ian is recognised worldwide for his expertise and knowledge of quantum technology, reflected through his membership of the Commission Expert Group on Quantum Technology - High Level Steering Committee for the European Quantum Technologies Flagship and his current role as President of the Optical Society of America.

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

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

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

Associate Directors

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

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

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

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

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

Co-Investigators

Architectures, Standards and System Integration

Professor Simon Benjamin (University of Oxford)
Work Package Leader

Ion Trap Node Engineering

Professor Winfried Hensinger (University of Sussex)

Professor David Lucas (University of Oxford)
Work Package Leader

Professor Andrew Steane (University of Oxford)

Atom-Photon Interfaces

Dr Almut Beige (University of Leeds)

Professor Peter Horak (University of Southampton)

Professor Alexey Kavokin (University of Southampton)

Professor Matthias Keller (University of Sussex)

Professor Axel Kuhn (University of Oxford)
Work Package Leader

Professor Pavlos Lagoudakis (University of Southampton)

Photonic Network Engineering

Professor Martin Dawson (University of Strathclyde)

Dr Corin Gawith (University of Southampton)

Dr Peter Mosley (University of Bath)

Dr Joshua Nunn (University of Bath)
Work Package Leader

Professor Peter Smith (University of Southampton)

Dr Michael Strain (University of Strathclyde)

Professor William Wadsworth (University of Bath)

Dr Ian Watson (University of Strathclyde)

Solid State Node Engineering

Professor Mete Atature (University of Cambridge)

Dr Erdan Gu (University of Strathclyde)

Dr Peter Leek (University of Oxford)

Dr Gavin Morley (University of Warwick)

Professor Mark Newton (University of Warwick)

Professor Jason Smith (University of Oxford)
Work Package Leader

Secure Network Applications

Professor Jonathan Barrett (University of Oxford)
Work Package Leader

Professor Elham Kashefi (University of Edinburgh)

Networked Quantum Sensors

Professor Justin Coon (University of Oxford)

Dr Animesh Datta (University of Warwick)
Work Package Leader

Professor Jacob Dunningham (University of Sussex)

Quantum Enabled Discovery

Professor Dieter Jaksch (University of Oxford)
Work Package Leader

Quantum/Classical Emulation and Interfacing

Professor Samson Abramsky (University of Oxford)
Work Package Leader

Quantum Optimisation and Machine Learning

Dr Michael Gutmann (University of Edinburgh)
Work Package Leader

Core Engineering Capabilities

Professor Martin Booth (University of Oxford)

Professor Steve Collins (University of Oxford)

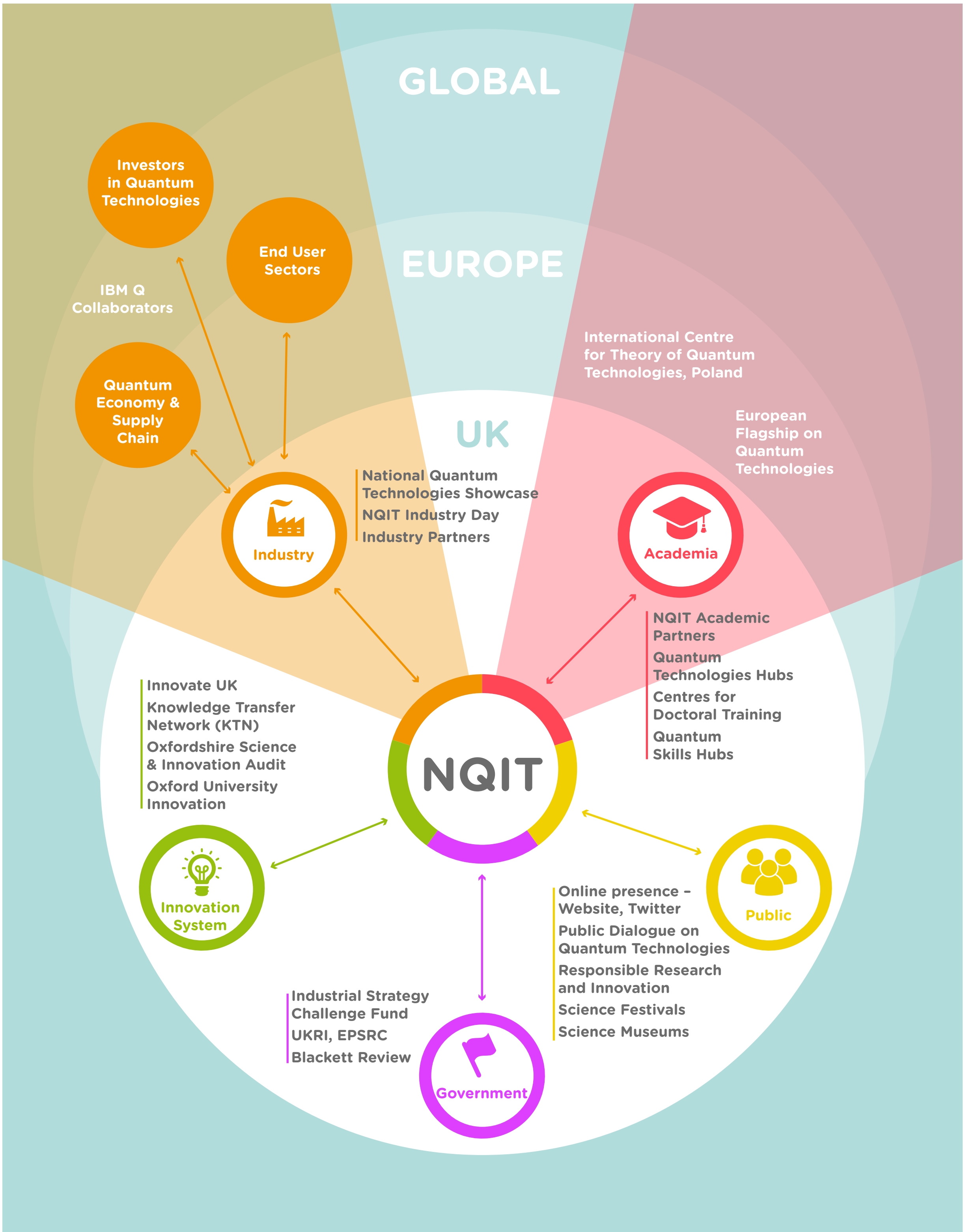
Professor Dominic O'Brien (University of Oxford)
Work Package Leader

Professor Christopher Stevens (University of Oxford)

Responsible Research and Innovation

Professor Marina Jirotka (University of Oxford)
Work Package Leader

NQIT Ecosystem



Quantum Computing in a Global Context

Developments in quantum computing are edging closer to the watershed moment where a quantum processor will perform calculations beyond the scope of current computing technologies.

Early quantum machines have arrived with IBM's announcement of a 20 and 50 qubit quantum processor [1], and Google unveiling their 72 qubit 'Bristlecone' processor [2]. These systems will enable research into system error rates and scalability, as well as exploring potential application areas across a variety of scientific and industrial sectors.

The European Flagship on Quantum Technologies, an investment of €1bn over 10 years in quantum research was announced in 2016. The European Commission is now presenting a 'mission' or challenge-based approach to fuel innovation in science [3]. An example of a challenge, suggested by the Commission's Director of Policy Development and Coordination in DG Research, Kurt Vandenberghe, is building a quantum computer by 2030 [4]. The UK already has a challenge-based approach through the Industrial Strategy Challenge Fund [5], where quantum computing has applications across the challenge areas.

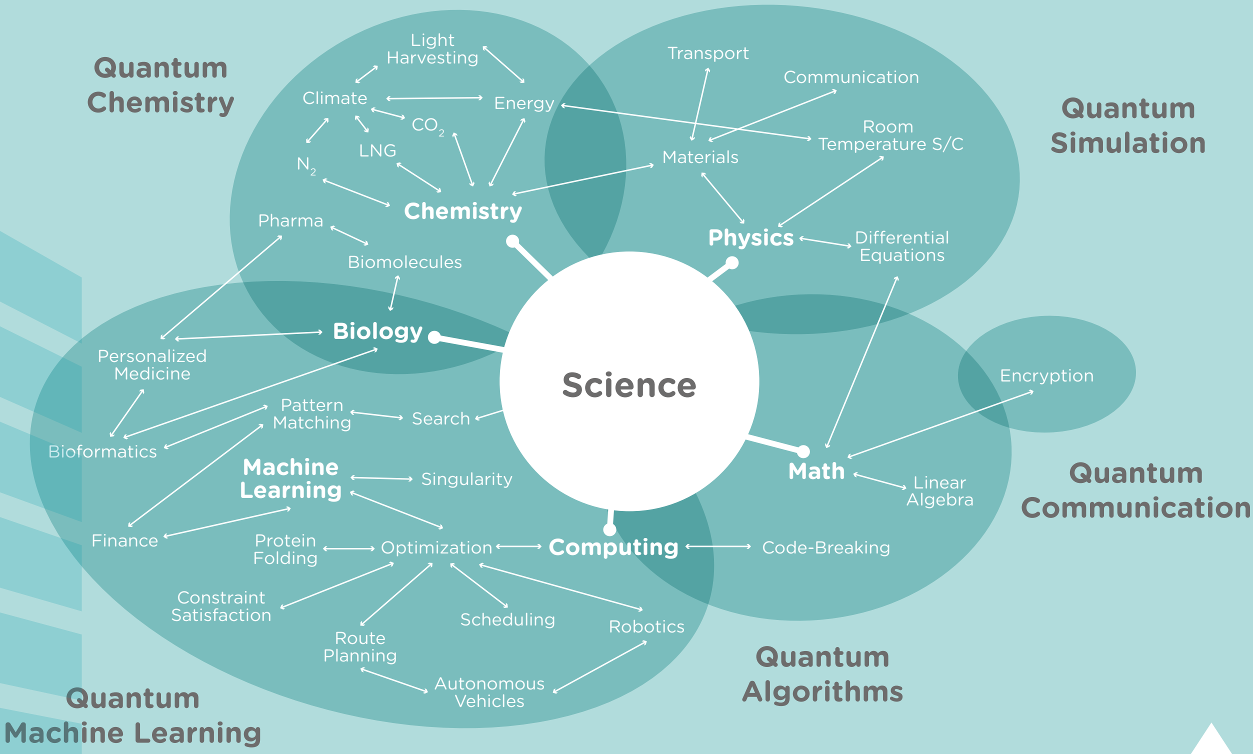
New national initiatives in quantum computing and technologies research have been announced. In Europe, recent examples are the Wallenberg Centre for Quantum Technology (WACQT) in Sweden, which has attracted SEK 1 billion in funding [6], and two centres for quantum technologies research in Poland, each receiving PNL 35 million over 5 years. [7]

In the USA, the National Science Foundation has awarded a $10 million grant to five universities to study new algorithms, software and hardware designs for quantum technologies capable of 100 to 1,000 quantum bits [8].

Established companies are making strategic investments in quantum computing. These include the Chinese Internet giants: Baidu, Alibaba and Tencent. Baidu have launched their own quantum institute to focus on research and applications [9], and Alibaba Cloud and Tencent each have a quantum computing cloud platform [10].

The car manufacturer, Daimler, is seeking to gain early experience of quantum computing and is working with Google and IBM on the future of mobility and providing innovative new services [11][12].

New companies have formed with ambitions to develop quantum computers and have obtained multi-million dollar investments. As examples, in Austria, Alpine Quantum Technologies, a spinout from the University of Innsbruck, has received €10m to build a commercial quantum computer based on trapped ions [13]; Silicon Quantum Computing Pty Ltd, an Australian venture, has received AU $83m to produce a working quantum computer prototype and commercialise research [14]; and in the UK, Oxford Quantum Circuits (OQC) will develop superconducting circuit architectures for quantum computing, and Quantum Motion Technologies (QMT) will develop silicon-based quantum computing.



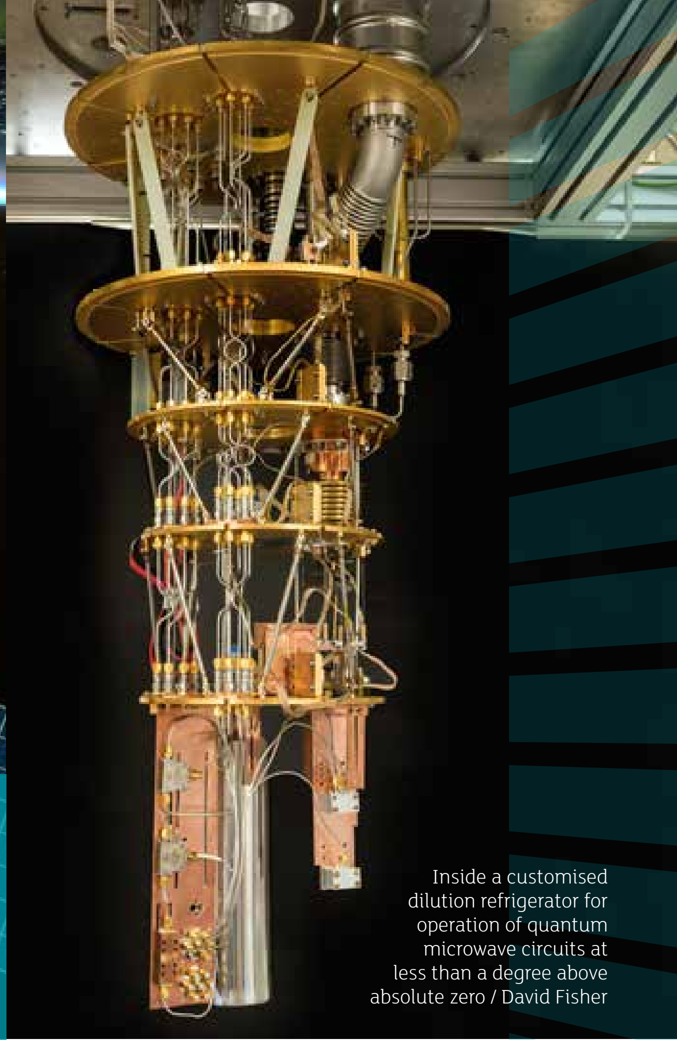
Adapted from Pete Shadbolt and Jeremy O'Brien

These are exciting developments and the global picture is changing rapidly. The UK is continuing to champion quantum computing and leads the world in qubit quality, precision [15] and fast quantum logic gates for ion trap based technologies [16].

1. https://spectrum.ieee.org/tech-talk/computing/hardware/ibm-edges-closer-to-quantum-supremacy-with-50qubit-processor
2. https://research.googleblog.com/2018/03/a-preview-of-bristlecone-googles-new.html
3. https://ec.europa.eu/info/news/bold-science-meet-big-challenges-independent-report-calls-mission-oriented-eu-research-and-innovation-2018-feb-22_en
4. https://sciencebusiness.net/framework-programmes/news/eu-pitches-lofty-achievable-science-missions
5. https://www.gov.uk/government/collections/industrial-strategy-challenge-fund-joint-research-and-innovation
6. http://www.chalmers.se/en/news/Pages/Engineering-of-a-Swedish-quantum-computer-set-to-start.aspx
7. https://www.fnp.org.pl/en/trzeci-otwarty-konkurs-w-programie-mab-rozstrzygniety/
8. https://quantumcomputingreport.com/news/nsf-awards-10-million-for-research-on-enabling-practical-scale-quantum-computing/
9. https://www.chinamoneynetwork.com/2018/03/08/baidu-launches-quantum-computing-institute-focus-research-application-potential
10. https://www.alibabacloud.com/press-room/alibaba-cloud-and-cas-launch-one-of-the-worlds-most
11. http://media.daimler.com/marsMediaSite/en/instance/ko/Daimler-joins-forces-with-Google-to-research-the-application-of-quantum-computers.xhtml
12. https://www.zdnet.com/article/ibms-20-qubit-system-jpmorgan-daimler-samsung-test-quantum-computer/
13. http://www.globaluniversityventuring.com/article.php/6513/innsbruck-processes-alpine-quantum
14. http://www.afr.com/technology/unsw-joins-with-government-and-business-to-keep-quantum-computing-technology-in-australia-20170821-gy0tki
15. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.060504
16. https://www.nature.com/articles/nature25737

SCIENCE AND INNOVATION AUDIT FOR OXFORDSHIRE

The Science and Innovation Audit (SIA) for Oxfordshire is a major report to inform the UK Government on its strategy and investment for science and innovation to 2030, and capture evidence for transformational economic growth, social benefit, and industrial impact.



Inside a customised dilution refrigerator for operation of quantum microwave circuits at less than a degree above absolute zero / David Fisher

The ambition for the Oxfordshire SIA was to show how innovation in the region leads to benefits nationally and beyond. Four transformative technologies were chosen from a wider list of technology themes and are: 'Technologies underpinning quantum computing', 'Autonomous Vehicles', 'Digital Health' and 'Space-led Data Applications'. The report was published in September 2017 and is available from the Oxfordshire Local Enterprise Partnership (OxLEP) website: https://www.oxfordshirelep.com/publications

Oxbotica's Geni driverless car / Oxbotica

Oxfordshire is part of a national capability in quantum technologies as evidenced by SIAs from Innovation South, Glasgow Enterprise Leadership and South Wales. This clearly demonstrates the UK's strengths in a globally competitive market.

We were delighted to be selected to demonstrate our leadership role in creating and shaping a future quantum computing industry for the UK. We have shown our deep connections to industry and institutions in the region, across the UK and internationally and our world-leading research is driving innovation and growth, creating new supply chains and business opportunities, resulting in new investments and jobs.

Access to a quantum computer will give businesses a formidable advantage. Through the SIA we have presented our vision for an Innovation Centre to host the UK's networked quantum computing infrastructure, and to work with businesses on new applications and services to grow the quantum economy.

With our SIA technology partners, we have also identified cross-opportunities for machine learning and data analytics, and are exploring new industrial challenges that have emerged.

NQIT is a nucleation point for potential clusters and attracts investors, businesses, researchers and Government representatives from all over the world, demonstrating the UK's global leadership in this transformative technology.

We are committed to meeting our mission goals and to ensure that the UK remains a globally trusted source of quantum computing.

Professor Simon Benjamin's presentation, questions and networking at the NQIT Industry Day / David Fisher

Industry Engagement

The User Engagement activities of NQIT are driven by a clear vision: NQIT takes a national approach to quantum technology innovation and capitalising on these to ensure a centre of technological, manufacturing and economic gravity has been created in the UK that matches the international prominence of the UK's scientific strengths.

To achieve that vision, we are working on all aspects of the emerging Quantum Information Technology economy:

1. Collaborations with the supply chain which benefit from the UK's world leadership in photonics and high precision engineering
2. Building a new sector of quantum computing technology, with designers and developers emerging through new spinout companies backed by the UK and international investment community and in partnerships with established technology companies
3. Expanding the UK's creative software sector in collaboration with existing companies and with new companies emerging in this sector
4. Encouraging and supporting the practical application of quantum computing technology in business and science so that users can make new discoveries and build competitive advantages

In practice this means that we work through collaborative User Projects with technology companies to develop new enabling technologies. Intellectual Property in the form of new know-how and inventions are captured and commercialised to feed innovation that is already helping to create new or improved products.

Several spinouts with a focus on new quantum computing technologies have been created already and more are in the pipeline with considerable interest from the investment community.

This year has also seen the emergence globally of early available quantum computers whilst emulators and platforms are advancing. For the first time developers and users can begin to experience quantum computing. To encourage users, we are working with other technology providers to offer access to these earliest platforms. NQIT is taking a number of initiatives to encourage and support future users from science and industry to get access to early platforms, be informed on their use and participate in initiatives that will help the discovery and development of applications for quantum computing.

NQIT INDUSTRY DAY 2017

We held our first NQIT Industry Day in July 2017 in the beautiful surroundings of Rhodes House, Oxford. It was a unique forum bringing together the national and global investment and business community with key quantum computing scientists and engineers from our UK-wide research consortium.

Together we explored the commercial opportunities of quantum computing and shared important developments within the UK and elsewhere - such as the €1 billion European Flagship for Quantum Technologies and NQIT's progress towards our quantum computer demonstrator, the Q20:20 engine.

Thirty-two organisations attended, including multi-nationals, SMEs and start-ups from a variety of sectors including manufacturing, aerospace, finance, hi-tech, digital, telecoms, oil and gas, and IT.

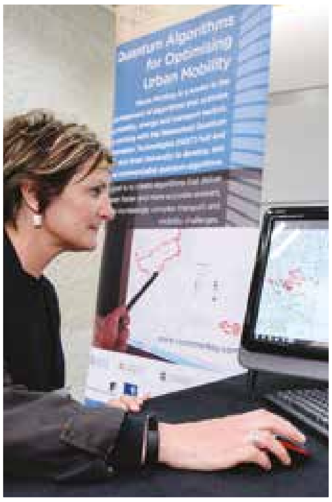
The day began with an overview of quantum computing from Professor Simon Benjamin, explaining the difference between adiabatic machines and universal fault-tolerant quantum computers. This was followed by presentations about NQIT's industry-academia partnership projects, such as the collaboration between the University of Warwick and Bruker Gmbh to develop a new, high precision magnetometer, based on diamond colour centres, to detect the tiny magnetic fields emitted by the heart.

The session after lunch presented exciting opportunities for quantum computing, such as the launch of the Atos Quantum Learning Machine, simulating up to 40 qubits. Attendees also heard about the Science and Innovation Audit for Oxfordshire and the latest funding opportunities from the UK Government via Innovate UK.

The programme concluded with an industrial panel Q&A session on the topic: 'What is the commercial future for quantum technologies?' On the panel were Jeremy Ward from Qinetiq, Paolo Bianco from Airbus, Chris Doran from ARM and Charles Radclyffe from Deutsche Bank.

"May I just take this opportunity to congratulate you on a splendid event, which I found hugely enjoyable. Thank you again for the invitation to participate." – feedback from attendee from Deutsche Bank

Exhibits at the National Quantum Technologies Showcase / Dan Tsantilis, EPSRC



NATIONAL QUANTUM TECHNOLOGIES SHOWCASE 2017

We had our largest presence yet at the third National Quantum Technologies Showcase in November 2017 at the QEII Centre in London, with 12 of the 60 exhibits in the Exhibition Hall.

This one-day event highlighted the latest technology developments from the UK National Quantum Technologies Programme, with exhibits from academia and industry and collaborations between the two.

Our exhibits covered application sectors such as Healthcare Technology, Communications, Transport and Finance. NQIT's exhibits were:

- Competitive advantages with Quantum Computing for Route Monkey, an SME providing optimisation software for transport and energy sectors
- Diamonds for your Heart
- Catching the Flu - Virus trapping and analysis using optical microcavities
- Precision manufacturing for the Quantum economy: photonics, lasers and systems
- Wireless power transfer through the wall of a vacuum chamber for driving miniaturised ion trap quantum computers
- Live tune-up of a quantum logic gate
- ORCA - a practical and noiseless quantum memory
- Coherent Optical Interconnects
- Highly Efficient Ion-Light Interfaces for Quantum Computing and Quantum Communication
- Quantum Random Number generation
- Sussex microwave trapped ion quantum computer prototype
- Responsible Innovation in Quantum Technologies

There were also several breakout sessions where NQIT academics and industry partners spoke about the benefits of collaboration and their vision of the future of quantum technologies. We heard from exciting new quantum startup companies from each of the UK Quantum Technology Hubs, including Oxford Quantum Circuits, a new spinout led by Dr Peter Leek.

The Showcase was a great opportunity to demonstrate our technology development and to meet new industry and government partners.

IBM Q COLLABORATION

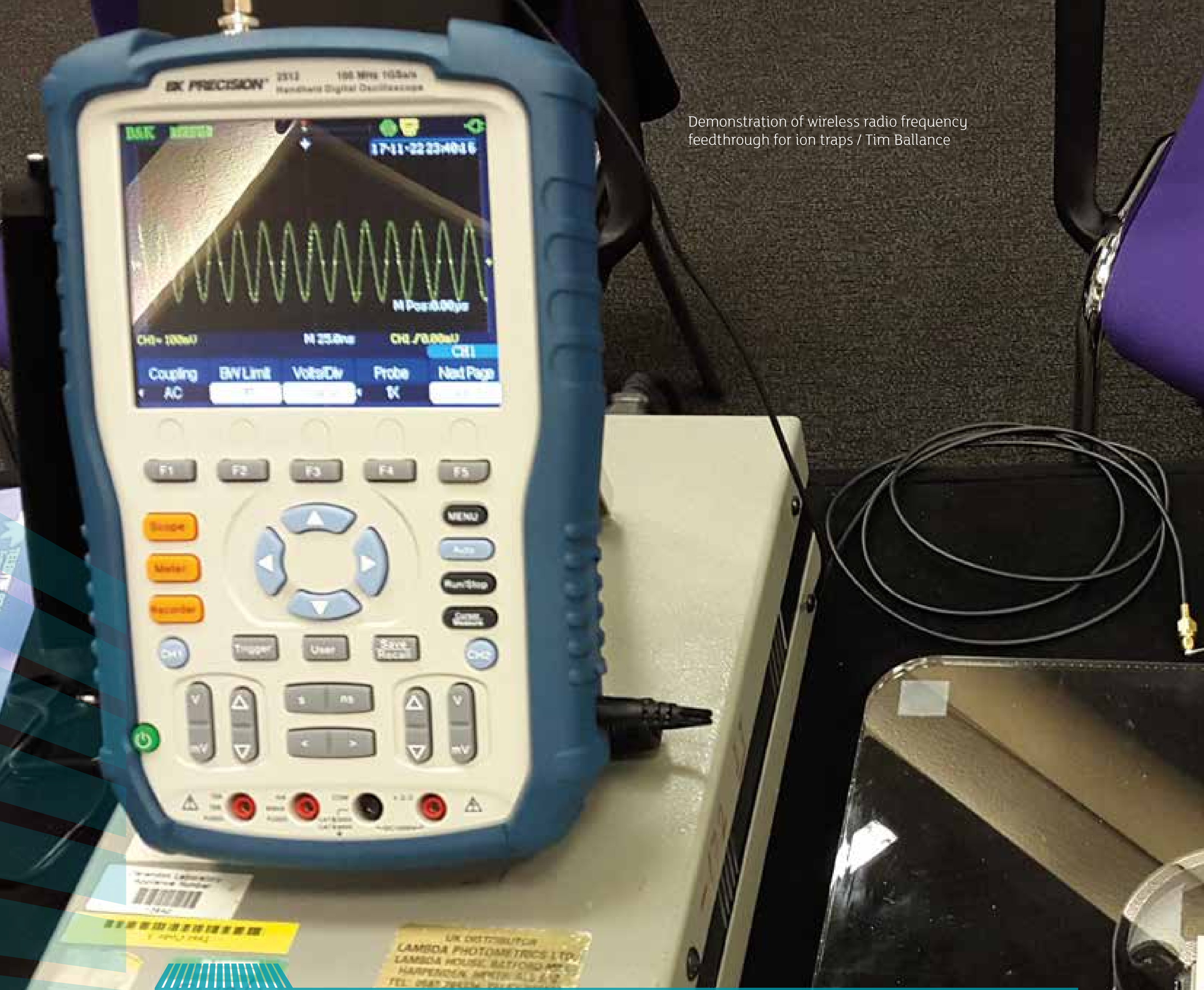
In December 2017, we announced that the University of Oxford, representing NQIT, would be an initial member of the newly formed IBM Q Network, a collaboration of leading Fortune 500 companies, academic institutions and national research labs working directly with IBM to explore potential practical applications using IBM's quantum computing systems. With NQIT leading this collaboration in Oxford, we will be able to tap into the IBM Q early-access commercial quantum computing systems, an industry-first initiative to build commercial universal quantum computing systems for business and science applications.

Oxford University and IBM are both dedicating considerable resources to this exciting new field of quantum information technologies - both hardware and software - for research and commercial applications.

As a result of the collaboration, Oxford will serve as the IBM Q Hub in the UK, supporting others in using the IBM Q systems and will be able to collaborate with companies and other universities, adding to existing NQIT and Oxford research and quantum computing developments. This places NQIT and Oxford at the centre of the burgeoning quantum technology industry in the UK.

NQIT Director Professor Ian Walmsley said
"I am delighted with this new collaboration with IBM. Working with one of the world's leading information technology companies to develop new applications for a quantum computer will enhance Oxford's and the UK's capability in quantum technology, by providing a unique resource for the Oxford-led Networked Quantum Information Technologies (NQIT) Hub. NQIT's emulator programme will work with IBM to convene scientists, engineers and industrial researchers and developers across a wider range of fields, from simulating new molecules to enhancing artificial intelligence to show how quantum computers can dramatically transform their ideas and businesses."

The IBM Q quantum computing facility at the Thomas J Watson Research Center / Connie Zhou & Andy Aaron, IBM



Demonstration of wireless radio frequency feedthrough for ion traps / Tim Ballance

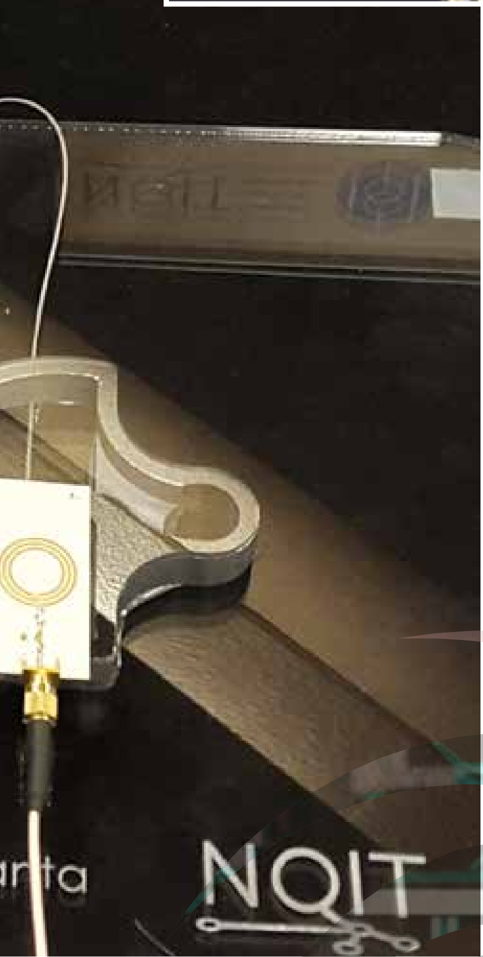
WIRELESS RADIO FREQUENCY FEEDTHROUGH FOR ION TRAPS WITH COLDQUANTA

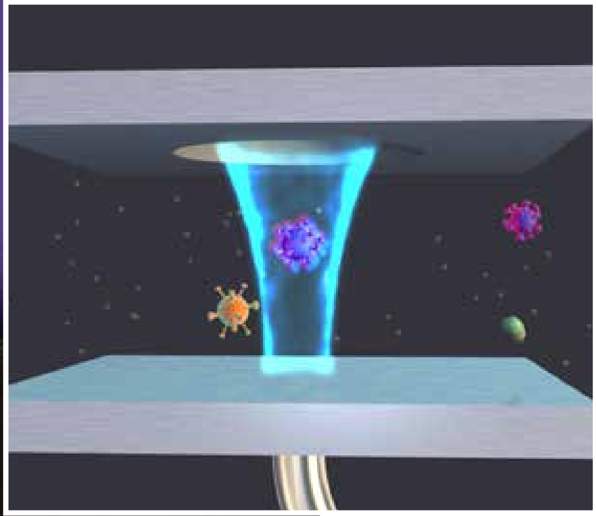
Conventional ion trapping systems require large, bulky stainless-steel vacuum systems complete with several pumps needed to reach the ultra-high vacuum (UHV) pressures needed to trap an ion and isolate it from collisions with background atoms that would destroy the quantum state of the qubit.

The wiring in ion traps can be cumbersome due to the mechanical complexity of vacuum-to-air feedthroughs. To produce the required radio frequency voltage across trap electrodes, a radio frequency source must be fed from the air side into the vacuum system and attached to the trap.

This project partnered NQIT ion trap researchers with ColdQuanta, a company based in Boulder, Colorado, which develops and designs instruments and systems for quantum technology applications. The work focused on producing a compact and simple electrical feedthrough using wireless power transfer in order to drive an ion trap inside a miniaturised vacuum chamber which would be suitable for production at scale.

The partnership is part of a move by ColdQuanta to grow ties within the burgeoning UK quantum technology sector. Currently, the UK is seen as the epicentre of development with quantum technologies experiencing not only growth of demand for quantum systems, but also the establishment of a highly trained world-class quantum workforce. An additional part of this move was the founding of a subsidiary company, ColdQuanta UK Ltd, in 2015 with a mission to develop cold and ultracold atom components, systems and expertise, in the UK. The company established new office and lab space at the Oxford Centre for Innovation and hired its first full-time employees, recent post-doctoral researchers from the Universities of Oxford and St. Andrews. ColdQuanta UK Ltd has partnered with UK companies and universities in several Innovate UK projects, including one with the University of Oxford to develop a Miniaturised Ion Trap Atomic Source (MITAS) and one with M Squared Lasers to develop a Photonically Integrated Cold Atom Source (PICAS).





Schematic showing a microcavity being used as a sensor for biological pathogens, being developed by Oxford HighQ Ltd / Photonic Nanomaterials Group, University of Oxford

Spinout Companies

NQIT is spearheading a nationwide academia-driven effort to create the world's first true universal quantum computer with the launch of three quantum computing spinout companies based on university research.

The companies are:

- Oxford Quantum Circuits (OQC): headed by Dr Peter Leek, at the Department of Physics, OQC will develop superconducting circuit architectures for quantum computing.
- Oxford HighQ (OHQ): a spinout from Oxford University's Departments of Materials and Chemistry, OHQ will produce next generation chemical and nanoparticle sensors that offer a step change in fluid-based sensing across a wide range of applications and markets.
- Quantum Motion Technologies (QMT): a collaboration between Oxford's Department of Materials and University College London (UCL), OQM will develop silicon-based quantum computing.

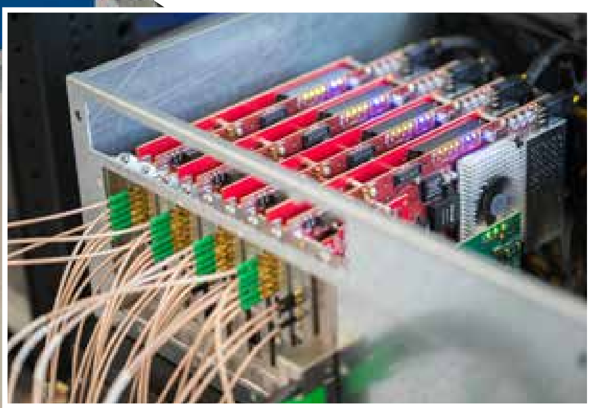
These companies form the vanguard of NQIT's efforts to commercialise its quantum computing research which has been ongoing since 2014. We plan to create at least one other new company during 2018 whose objective is to make commercially available quantum computers based on the NQIT ion-trap architecture.

Academics behind the three new spinouts worked with Oxford University Innovation (OUI), the University's research commercialisation office, to develop the companies, with additional assistance from UCL Business for QMT. The companies have raised a collective multi-million pound seed investment, received government grants through Innovate UK, and brought in strong talent from industry to lead and scale the companies. With investment coming from prominent British-based investors, this has the potential to boost the UK economy in the long-term and bring quantum technologies to market.

OXFORD QUANTUM CIRCUITS

Oxford Quantum Circuits (OQC) is a recently formed spin-out company from the University of Oxford, established in June 2017. They are developing superconducting electric circuits for quantum computing, based on intellectual property and know-how from Dr Peter Leek's research group in the Department of Physics at the University of Oxford. OQC has attracted substantial start-up venture capital, with which it is working towards demonstrating within two years a prototype quantum computer processor that is scalable for commercial applications.

Dr Peter Leek in the lab with a customised dilution refrigerator for operation of superconducting electric circuits / David Fisher



Innovate UK: Commercialisation of Quantum Technologies

Researchers from NQIT and our industry partners were particularly successful in winning awards from Innovate UK in their Commercialisation of Quantum Technologies funding rounds 3 and 4, held during 2017. This competition, co-funded by Innovate UK and the Engineering and Physical Sciences Research Council (EPSRC), provides £14 million to UK businesses and researchers for ground-breaking quantum technologies that are emerging from science.

In all, we are involved in nine funded projects, for a total consortium funding of £5,090,644. Two of these projects involve the new NQIT spinout companies - Oxford Quantum Circuits Ltd and Oxford HighQ Ltd - whilst others are collaborations with established industry players, such as Airbus, and key businesses within the emerging quantum technology sector, such as M-Squared Lasers Ltd.

- Q-DOS light: quantum key distribution for drones with optimal size, weight and power: £987,871
  Universities of Oxford and Bristol, Airbus, KETS Quantum Security Limited, ID Quantique Ltd
- Nanoparticle and chemical sensors using optical microcavities: £884,931
  University of Oxford, HighQ Instruments Ltd and Malvern Instruments Ltd
- ESCHER: Establishing Supply Chains for Emergent Quantum Computers: £1,232,888
  Universities of Oxford, Southampton and Sussex, M-Squared Lasers Ltd and Covesion Ltd
- Quantum Enhanced Sensing of Trace Compounds in Sealed Containers: £240,124
  University of Oxford, VeriVin Ltd
- Compilation & Circuit Layout Optimisation For Superconducting Quantum Processor: £382,540
  University of Oxford, Cambridge Quantum Computing Ltd and Oxford Quantum Circuits Ltd
- IOTA: Compact Ion Clock for Precision Timing Applications: £399,533
  University of Sussex, M-Squared Lasers Ltd
- Quantum Fibre Clock (QFC): £381,612
  University of Bath, Chronos Technology Ltd and TMD Technologies Ltd
- MITAS: Miniaturised Ion Trap Atomic Source: £235,151
  University of Oxford, ColdQuanta UK Ltd
- Handheld Quantum Wireless for Secure Financial Transactions and Sensitive Information: £345,994
  Universities of Bristol and Oxford, Cognizant Business Services UK Ltd

Hardware & Engineering

Building the foundations of a quantum computer requires new, specialised hardware with many demanding performance requirements. We are addressing this challenge with five hardware work packages covering multiple approaches to qubit development, the interconnections between qubits and engineering systems integration.

Strong collaborations and a broad range of expertise across hub partners have allowed us to progress work in hardware in the area of ion traps, photonics and alternative nodes, with a major effort towards the development of networked nodes for quantum computing.

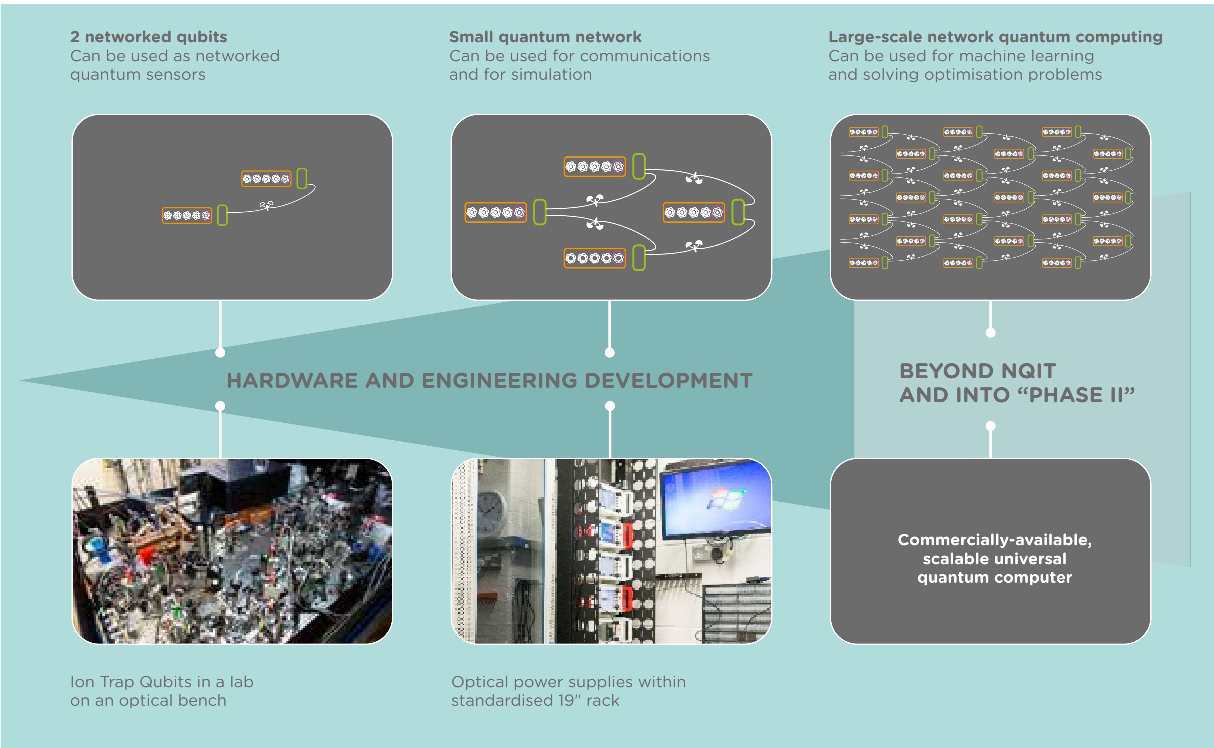
Several hundred ions, arranged in 20 optically connected traps with the performance that is available now for simple traps, along with realistic estimates of the connection performance, would lead to a machine with performance far beyond current quantum processors. This is the ambitious goal that led to the Q20:20 concept, the flagship goal of the hub. Last year, the original Q20:20 concept underwent substantial simplification, with joint work across architecture and hardware leading to a simpler Q5:50 architecture, offering similar performance, but substantially simpler nodes. This concept has now been adopted and effort is focused on developing nodes and networks for this new design.

A key recent achievement at the University of Oxford was the improvement of the speed of our two-qubit gate, demonstrating sub-microsecond entanglement generation, the fastest ever with trapped ion qubits, whilst parallel work at the University of Sussex has led to a modular architecture for a microwave gate based system.

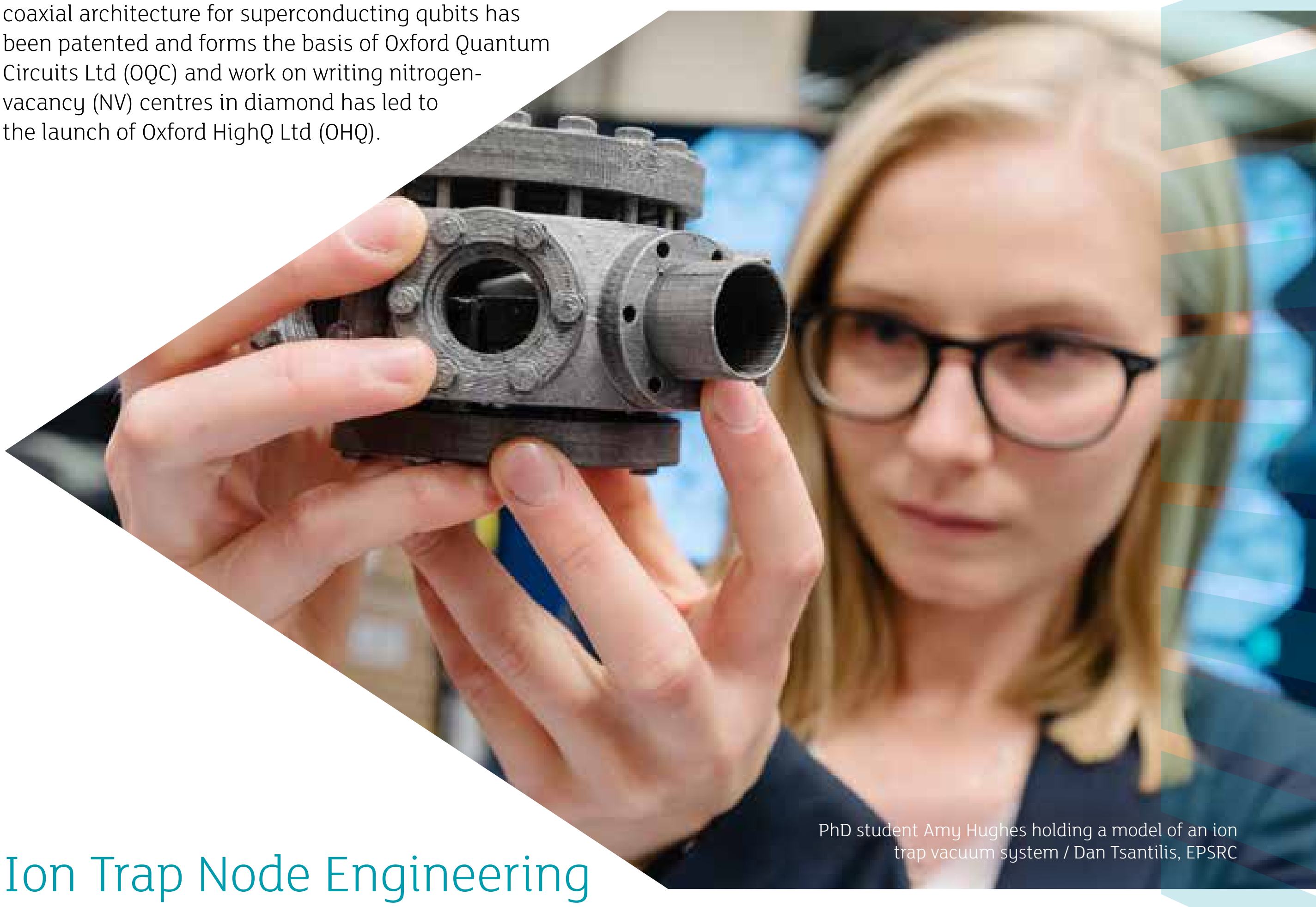
Cavities are a key enabling technology required to increase the ultimate 'processor speed' for the Q5:50 demonstrator. Recent work has involved refining our initial results for ion-cavity coupling to achieve strong coupling between ions and a cavity.

Work on simple, robust photonic memories for quantum repeaters has delivered a noise-free room-temperature quantum memory and significant progress has been made toward deterministic single photon sources. Photonic simulations require multiphoton interference, and we have made advances in this area including new designs for efficient on-chip interferometers.

Hardware



Two new spinout companies have been set up as a result of our work on alternative qubit technologies. A new coaxial architecture for superconducting qubits has been patented and forms the basis of Oxford Quantum Circuits Ltd (OQC) and work on writing nitrogen-vacancy (NV) centres in diamond has led to the launch of Oxford HighQ Ltd (OHQ).



PhD student Amy Hughes holding a model of an ion trap vacuum system / Dan Tsantilis, EPSRC

Ion Trap Node Engineering

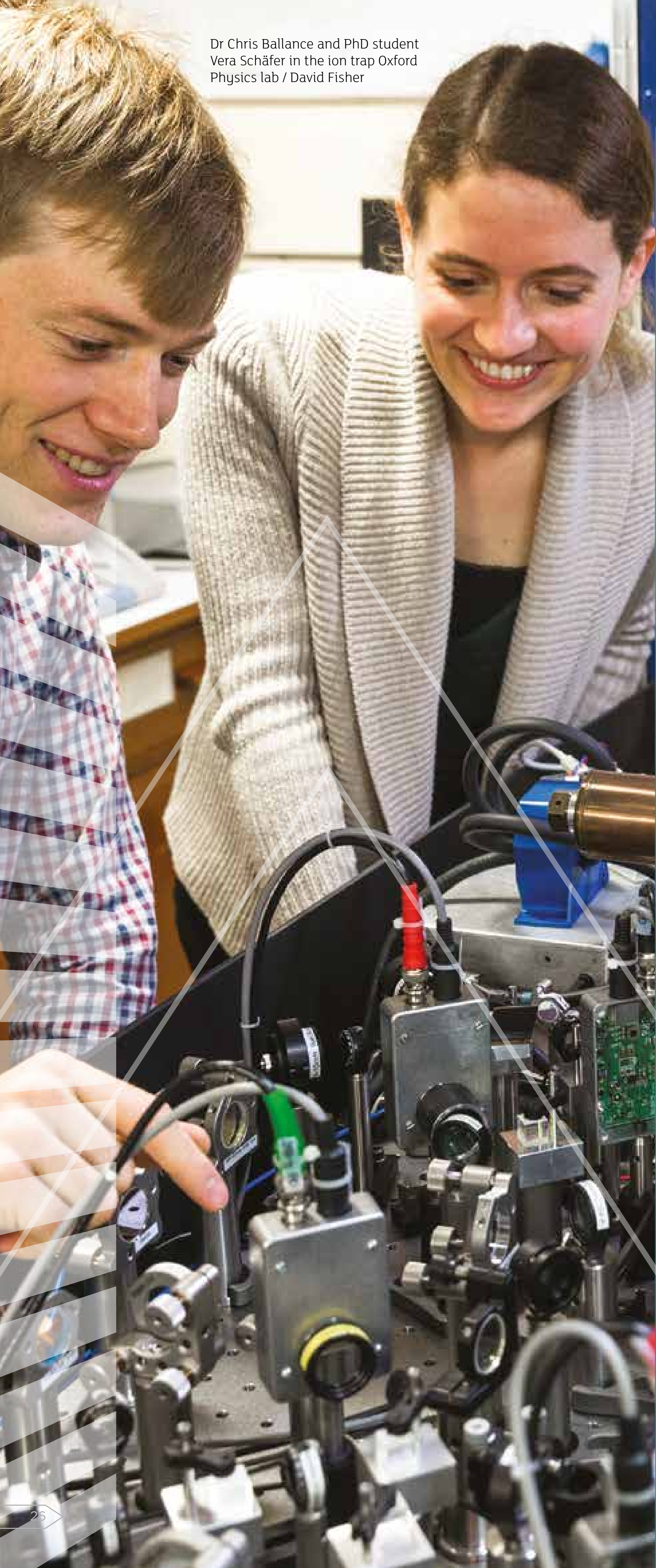
In ion traps, positively charged atoms are suspended in vacuum using electrical fields. Two energy levels of each atom are chosen to represent ‘0’ and ‘1’, making a ‘qubit’, a quantum analogue of a digital computer bit. Laser or microwave radiation can be used to implement single- and multi-qubit logic gates with what are currently the lowest error rates among all qubit technologies. We are working at Oxford and Sussex Universities to deliver two distinct trapped ion quantum computer demonstrator devices.

In the Q20:20 machine, information will be processed on calcium ‘memory’ ions. Strontium ions will serve as ‘interface’ qubits, emitting photons used to transfer quantum information between the modules. Network node #1 has been completed and tested with both ion species in Oxford. It is being integrated with next-generation electronics for flexible real-time control and radio-frequency synthesis. Node #2 is under construction; we expect to show entanglement between the modules in the next six months.

Using an ion trap chip manufactured by the University of Southampton, the Oxford University team have also completed the test assembly of a cryogenic experiment which aims to improve microwave logic gate performance. We demonstrated a technique for fast laser-driven logic gates that greatly improves operation speed, and characterised the memory qubit error rate at an unprecedented level of sensitivity relevant to fault-tolerant operation. We are also investigating a qubit readout method using fewer laser beams to reduce device complexity.

At Sussex University, we have been working on constructing a prototype based on the blueprint for a large-scale ion trap quantum computer we published last year. This device features a new invention where individual modules are connected by electric fields enabling ion transport between modules. Quantum gates are executed by the application of voltages to individual modules. The two-module quantum computer includes a Helium gas cooling system for efficient cooling of the electronics contained within each module. We will complete construction within 12 months.

The Sussex team also completed a cryogenic testing setup for ion chips demonstrating chip testing with one day turnaround time and highly suppressed motional heating rates at 4K operation. We implemented a new technique for protecting quantum gates from noise and demonstrated a way to convert qubits to a different qubit type that is well-suited for transporting ions, with fidelity well above the fault-tolerant threshold.



Dr Chris Ballance and PhD student Vera Schäfer in the ion trap Oxford Physics lab / David Fisher

FAST ION TRAP QUANTUM LOGIC GATES

NQIT researchers in the Ion Trap Quantum Computing group at Oxford University, led by Professor David Lucas and Professor Andrew Steane, have set a new speed record for the trapped ion 'logic gates' that form the building blocks of quantum computing.

The study was reported in the journal Nature and builds on previous work in which the team achieved a world record for the precision of the logic gate, reaching the demanding accuracy set by theoretical models of quantum computing.

We asked lead author, Oxford doctoral student Vera Schäfer, to explain the significance of this result:

What is the background to this piece of research?

"Previous work in our group produced quantum logic gates with record-breaking precision. We then began work on increasing the speed of those gates without compromising their accuracy, which is tricky. Trapped ions move like a pendulum during the gate operation, but when this process is sped up they become sensitive to a number of factors that cause errors."

So how does this work solve those error problems?

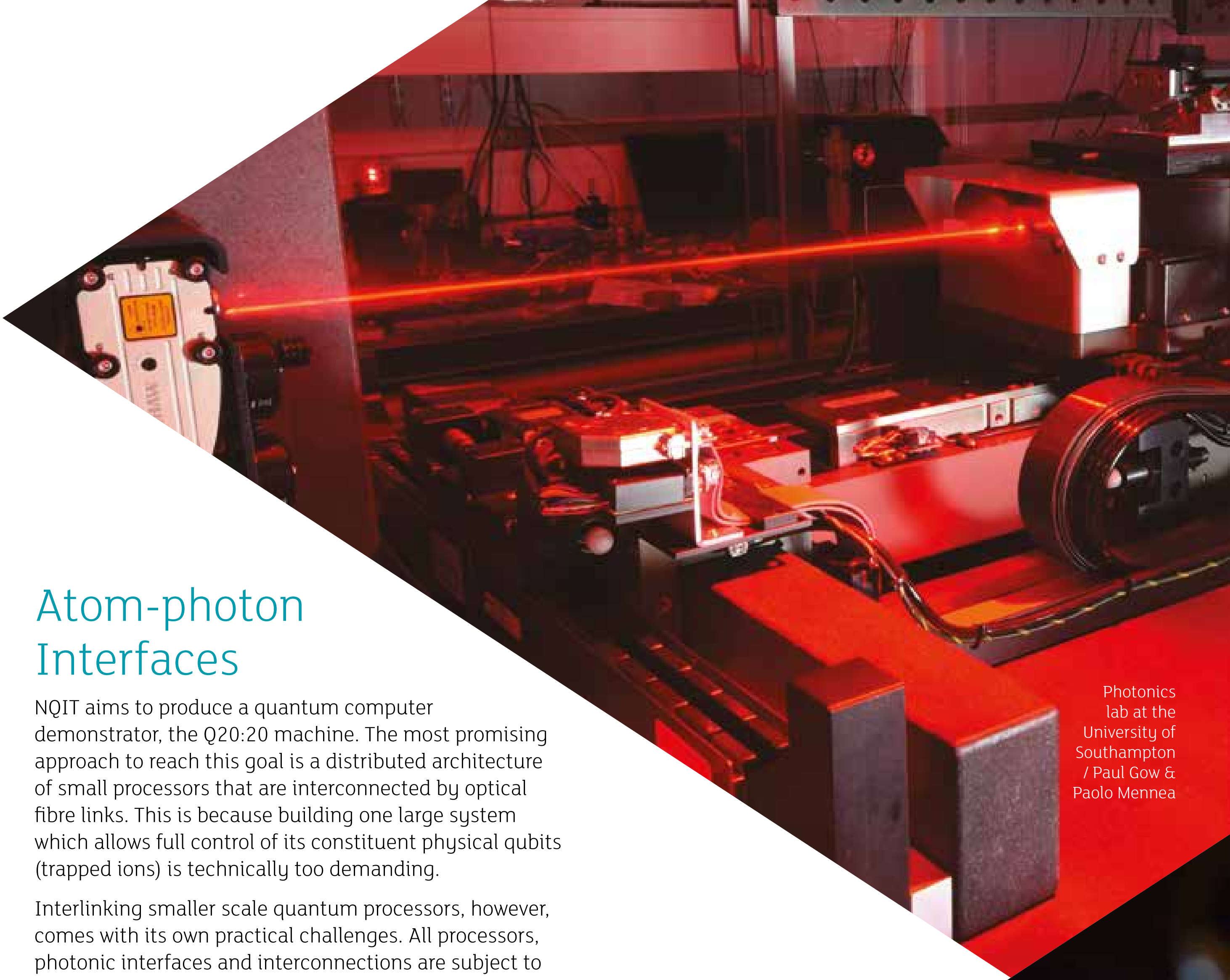
"By making use of a technique that precisely shapes the force on the ions such that the gate performance becomes robust to these factors, we were able to increase the speed by a factor of 20 to 60 compared with the previous best gates - 1.6 microseconds long, with 99.8% precision."

What does this mean for your ion traps?

"We have now produced the highest fidelity and the fastest gate, reaching a point where our gates are in principle good enough for quantum computing."

What is the next step?

"We will think about it in practical terms and work towards scaling up our system to create a viable quantum computer, which will be ideally suited for tasks such as factorising large numbers or simulating complex reactions between molecules to help with drug development."



Photonics lab at the University of Southampton / Paul Gow & Paolo Mennea

Atom-photon Interfaces

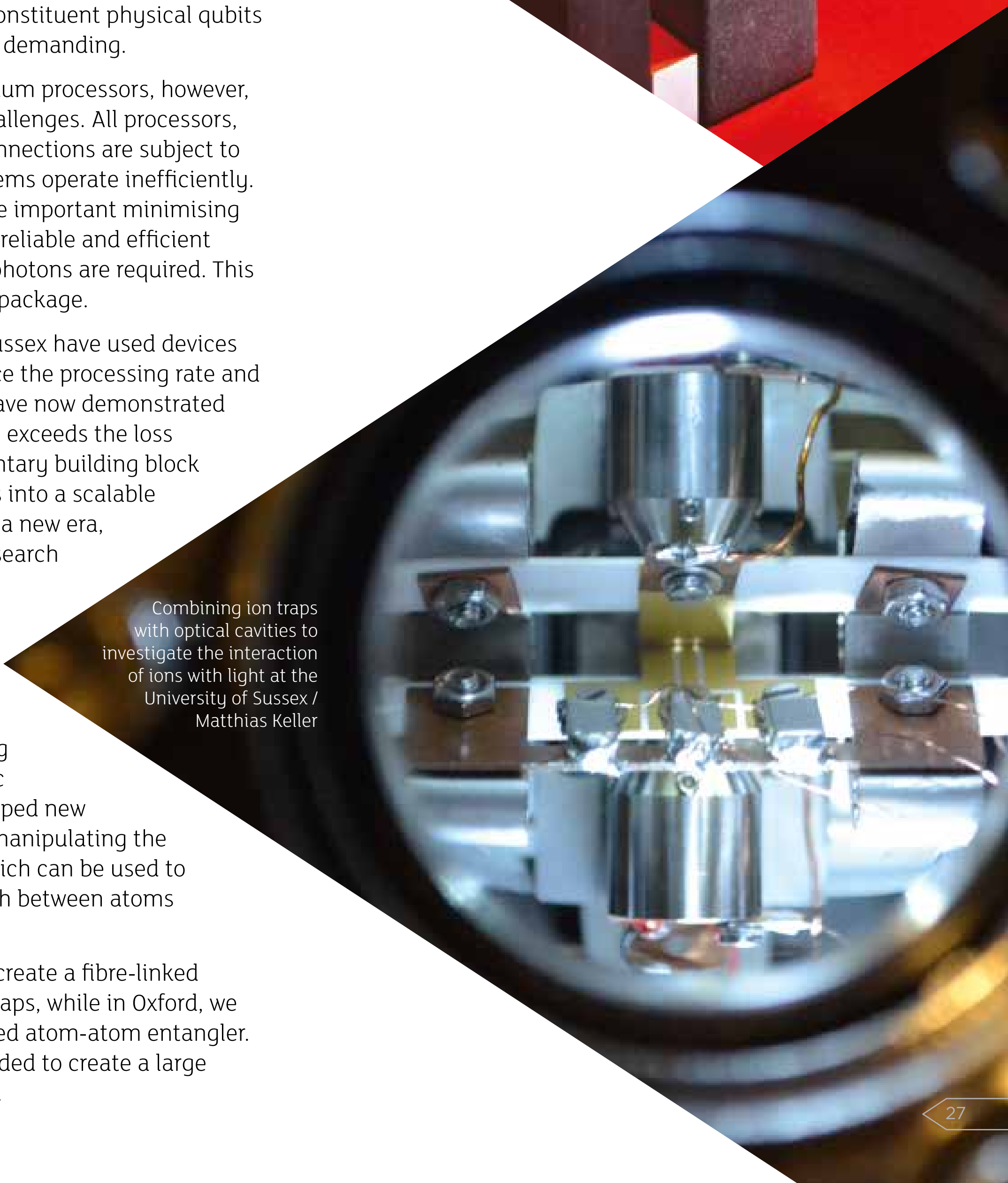
NQIT aims to produce a quantum computer demonstrator, the Q20:20 machine. The most promising approach to reach this goal is a distributed architecture of small processors that are interconnected by optical fibre links. This is because building one large system which allows full control of its constituent physical qubits (trapped ions) is technically too demanding.

Interlinking smaller scale quantum processors, however, comes with its own practical challenges. All processors, photonic interfaces and interconnections are subject to losses which tend to make systems operate inefficiently. The larger the network, the more important minimising losses becomes. To resolve this, reliable and efficient interfaces between atoms and photons are required. This has been the focus of this work package.

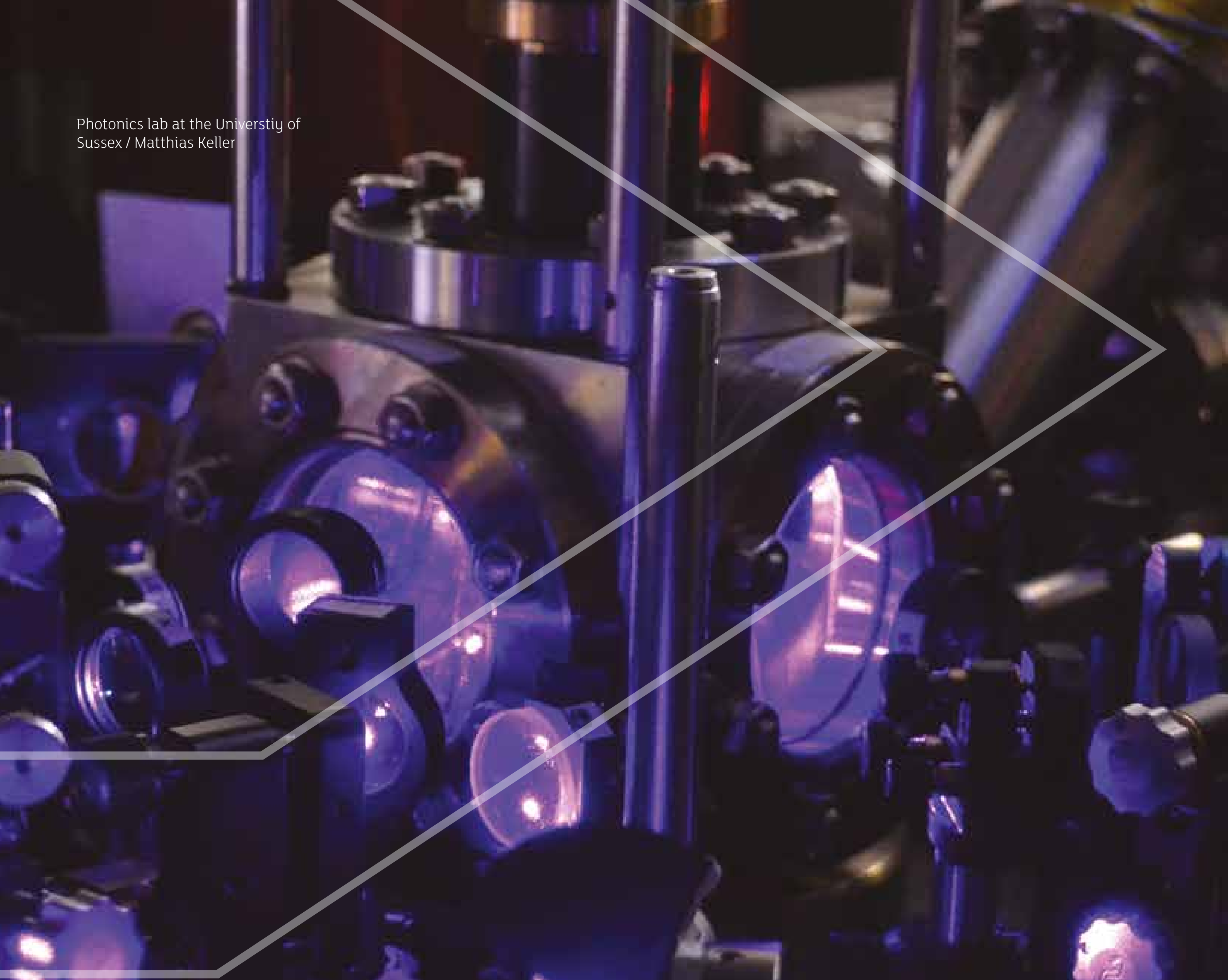
The team at the University of Sussex have used devices called optical cavities to enhance the processing rate and surpass the rate of losses. We have now demonstrated a system whose interaction rate exceeds the loss rate which represents an elementary building block for interlinking small processors into a scalable quantum computer. This marks a new era, solving a decade-long global research challenge.

In parallel, the team at the University of Oxford has proven the feasibility of entangling multiple cavity-emitters in one single step using integrated multi-mode photonic interferometry, and have developed new techniques for controlling and manipulating the position of atoms in a cavity which can be used to enhance the interaction strength between atoms and photons.

This year, in Sussex, we plan to create a fibre-linked interface between the two ion traps, while in Oxford, we plan to implement a cavity-based atom-atom entangler. These are the key elements needed to create a large network of quantum processors.



Combining ion traps with optical cavities to investigate the interaction of ions with light at the University of Sussex / Matthias Keller



Photonics lab at the Universtiy of Sussex / Matthias Keller

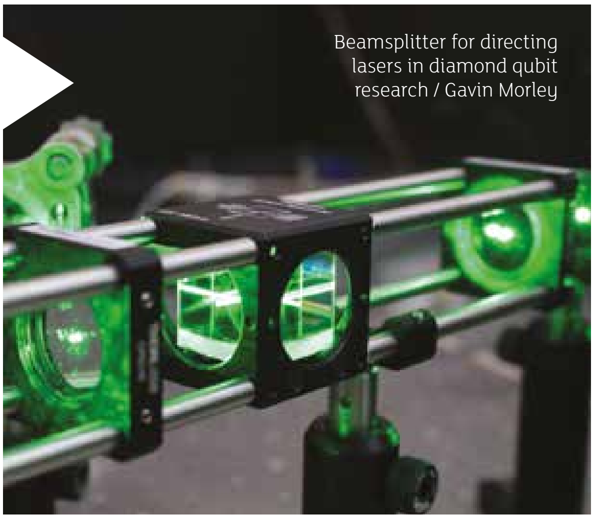
Photonic Network Engineering

The goal of photonics is to find ways to create, guide, manipulate and detect single particles of light, so-called photons. When combined, these abilities enable an important range of technologies: some, such as random number generation, that have direct application, and others that support the central NQIT goal to exchange information between individual nodes of the Q20:20 quantum computer demonstrator.

As examples, we have assembled an entangler capable of creating a quantum state distributed across several local nodes of the Q20:20 machine and we have demonstrated conversion of blue photons, such as those emitted by the ions in the nodes of the Q20:20 machine, to the infrared regime. This conversion is necessary to bridge larger distances, as it minimises absorption in optical fibres. In the next year, we will further optimise the efficiency of the entangler and we will attempt to use the wavelength conversion to link different node technologies operating at different wavelengths. Additionally, we will investigate new crystal defects in diamond with the goal of making them available to store quantum information encoded in photons, another crucial component for long-range quantum networks.

Component of the NQIT entangler that couples the light emitted from ion traps into an optical fibre for testing the loss and extinction of fibre components / Paul Gow & Paola Mennea

Alternative Qubits


Beamsplitter for directing lasers in diamond qubit research / Gavin Morley


Superconducting qubits lab / David Fisher


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


Superconducting qubits lab / David Fisher

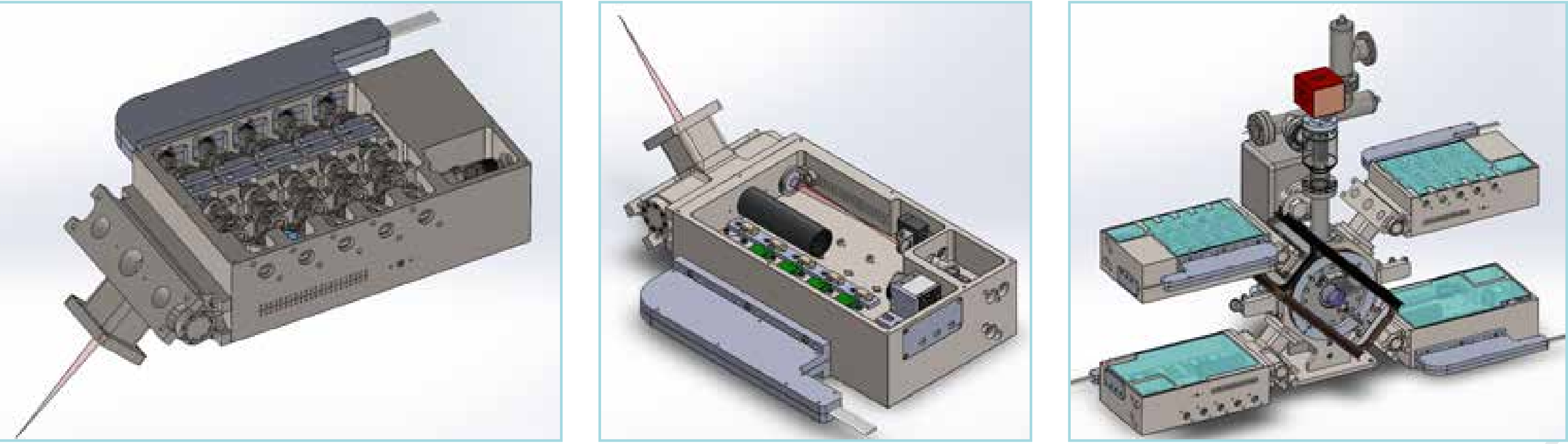
Diamond Qubits

In the past year, researchers at the Universities of Cambridge, Oxford, Strathclyde and Warwick have been making steady progress in the development of colour centres in diamond as solid state qubits that can be connected to optical networks. We have been advancing our work on efficient optical coupling to negatively charged nitrogen-vacancy (NV) centres in diamond, with effort focused on the fabrication of high quality diamond membranes with a thickness of around one micrometre to allow insertion into an optical microcavity. As a result of this effort we reached the important milestone of measuring enhanced photon emission from an NV centre in a membrane.

We have also been developing the laser writing of colour centres in diamond as a means of controlled fabrication of arrays of high quality qubits on a chip. This is advancing our capabilities for the coherent control of colour centre spins using magnetic resonance techniques, and continuing to advance our understanding of the potential of negatively charged silicon vacancy (SiV) colour centres as high speed, high efficiency networked spin qubits.

Superconducting Qubits

Superconducting circuits are a potentially disruptive quantum computing technology that is hotly pursued around the world. In Oxford, we are developing a novel superconducting circuit architecture that combines high coherence qubit designs with 3D connectivity to address the challenge of maintaining high fidelity circuit operation as we move to increasingly larger circuit scale and complexity. In the last year we have proven our architecture in 2-qubit prototypes, already demonstrating quantum logic gate fidelities of 99.8% for single-qubit and 97% for two-qubit operations. We have also developed prototype quantum-limited superconducting amplifiers with support from the Oxford Centre for Applied Superconductivity, to be used in high fidelity qubit readout, and scalable microwave control electronics for running quantum algorithms. We are now working hard to combine these components into a larger scale quantum computing demonstration, with support from our recently formed spinout company Oxford Quantum Circuits (OQC), and state-of-the-art laboratories in the new Oxford Physics Beecroft Building.



3D models of the beam delivery systems / Rushikesh Deshmukh

Core Engineering Capabilities

We have made good progress in developing and implementing the electronics, optics, and software required to control our key demonstrations. The global collaboration on quantum control system development which we are contributing to, has been delivering prototypes of electronic hardware and firmware. These will be manufactured in volume in the coming year, and are a key part of being able to scale the number of ion trap processors.

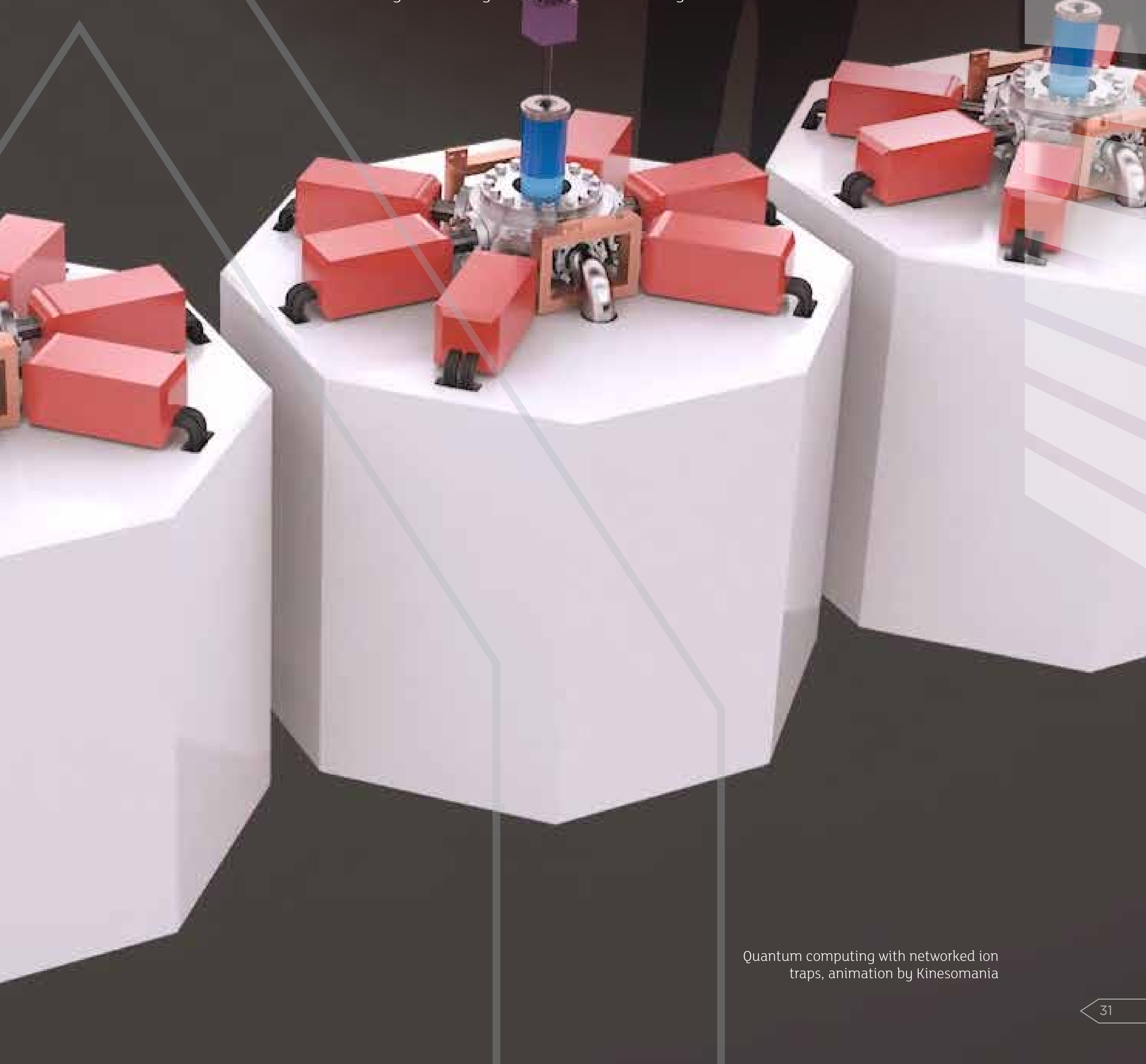
We have also been focusing on generating more precise control signals to improve their performance and have been working with a major test-equipment manufacturer to achieve control system "on-line" verification. We have delivered prototype equipment which will allow us to verify the basic control system functionality and, for the Q20:20 demonstrator, we have designed a compact Beam Delivery System that delivers the required optical signals to the ion trap processor. This system is currently in the process of being manufactured.

Ion trap optics engineered into a standard rack-mounted system / David Fisher

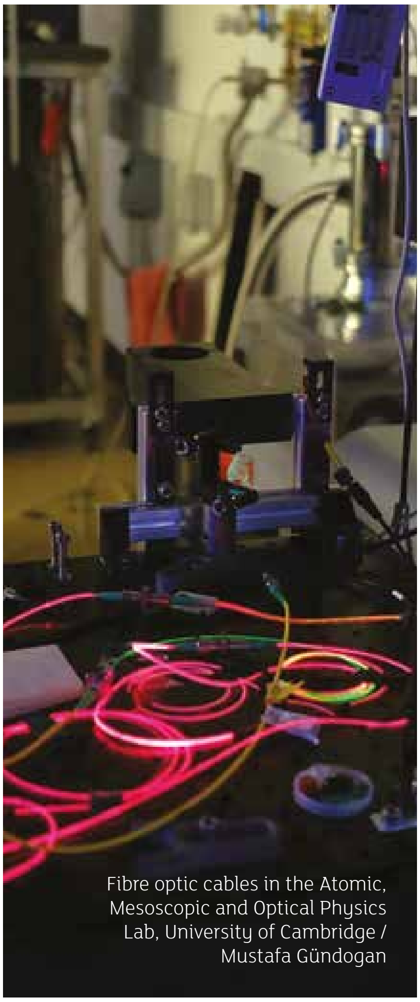
Architecture Progress

Recent work by the NQIT architectures team has focused on ways to use software for error correction caused by imperfections in hardware.

The team developed an approach called a Variational Quantum Simulator. The purpose of the algorithm is to be a discovery tool for chemists, pharmacologists or materials scientists, by predicting the behaviour of as-yet non-existent systems such as a new molecule (perhaps, some novel drug) or a new material (say, a high temperature superconductor). It works like this: the classical computer is capable of solving a certain set of equations, but first it must obtain some key coefficients for those equations which are very hard for it to compute. So the classical computer offloads the task of finding those coefficients to the quantum coprocessor - a task that the quantum device can handle easily. Once the classical computer receives the information back then it can indeed solve the equations, which actually leads to a new set of equations, and the process begins again. Eventually, after many cycles, the algorithm is complete and we discover how the system of interest (the molecule, say) would behave. If it's what we were hoping for, then the scientist will try to replicate that success in the lab. If not, we can try something else, all without wasting lab time and resources.

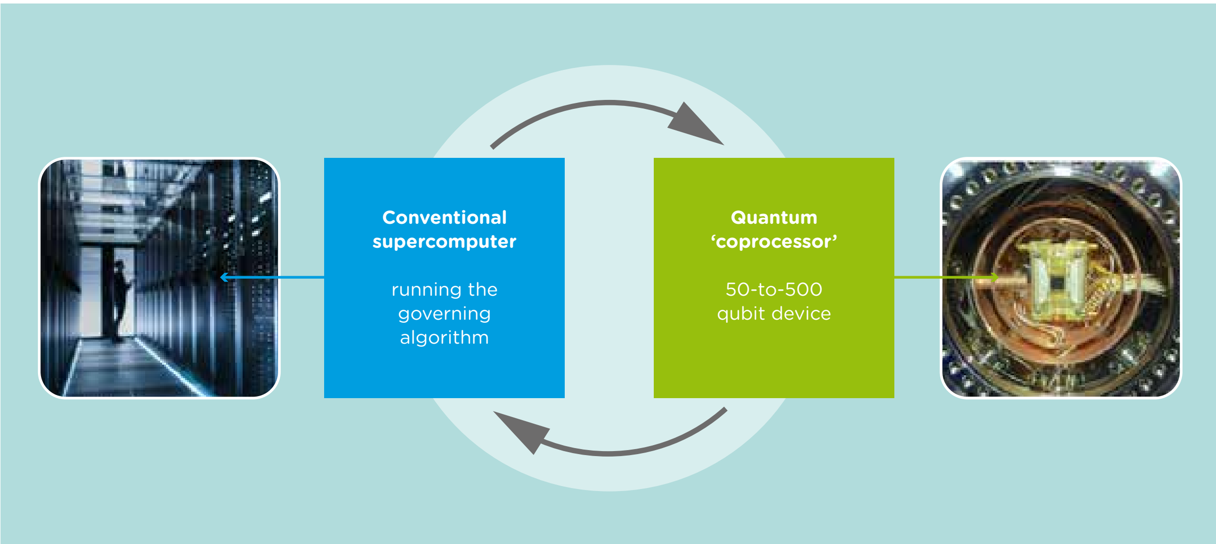


Quantum computing with networked ion traps, animation by Kinesomania



Fibre optic cables in the Atomic, Mesoscopic and Optical Physics Lab, University of Cambridge / Mustafa Gündogan

Clean room for manufacture of ion trap chips at the University of Oxford / David Fisher



In creating this new algorithm, the NQIT researchers actually stumbled upon something interesting that may have still wider applicability. They asked whether the Variational Quantum Simulator would still work even if the quantum coprocessor was imperfect - if its operations were noisy. They found while small amounts of noise would not be catastrophic, it was detrimental. But then lead researcher Ying Li hit upon an interesting idea: what if the quantum computer is used twice, once with the noise levels set as low as they can be made, and then a second time with the noise deliberately increased. The second calculation would be less reliable, but by comparing the two results it would be possible to estimate what effect noise was having, and thus to guess what the output of the perfect noise-free machine would be. This simple idea works wonderfully, and allows the Variational Quantum Simulator to become very robust against noise. Since then, NQIT researchers have developed the idea further, and incorporated ideas from other groups (notably, one from IBM) so that they now have a general prescription for using these so-called error mitigation techniques as a general tool for many different algorithms.

QUBITS: QUALITY VS. QUANTITY

How can we benchmark the various quantum computers coming online at the moment? If a new machine becomes available to users, how can they measure its power? Or to turn the question around, how can builders of quantum computers design them to be as powerful as possible?

Perhaps the simplest thing that we could do is to count the number of qubits in the device. The behaviour of any quantum computer with fewer than around 45 qubits can be predicted by feeding the laws of quantum physics into one of today's supercomputers. So, any such device is likely to be useful only as a demo system. However, the amount of RAM needed by a supercomputer to predict the behaviour of a quantum computer with, say, 90 qubits would become astronomical. We can say that a quantum computer might have unique 'postclassical' capabilities once it is large enough that no conventional computer can predict it. This milestone, which has been given the dramatic title of "quantum supremacy", will mark the beginning of the era where quantum computers could be useful beyond physics.

Our qubit count is only half the story. Another crucial aspect is the accuracy with which manipulations of the qubits can be performed. This is termed 'fidelity', which can be thought of as the chances that the quantum computer will do what it is told to when it is given a basic instruction, versus doing something random. The concept relates to decoherence - the way a quantum system degrades. It's crucial to understand that adding more qubits will not help make your quantum computer more powerful if it doesn't have sufficient fidelity - basically because errors will overwhelm any calculation before it is complete. The error rate of an operation is just the difference between the fidelity and a 100% perfect operation.

The trickiest operation, in ion traps and pretty much all other hardware approaches, is the task of getting one qubit to change depending on another - the so called two-qubit gate. This is crucial to having a computer rather than just a memory system and is where fidelity is the most difficult to achieve. The world record is jointly held by NQIT ion trap researchers in Professor David Lucas and Professor Andrew Steane's group at the University of Oxford and in Boulder, Colorado, under Nobel laureate David Wineland, and the number is about 99.91%. So, we can say that about one time in a thousand, a two-qubit gate will 'go wrong'.

Given that we want as many qubits as possible, but we also need them to behave as accurately as possible, is there a single number that can combine both factors? Well there are several ways we might come up with such a number, but a practical suggestion was made by a team of IBM researchers who coined the term 'quantum volume'. The idea is that you work out which is your worst problem: the restricted number of qubits you have or the error rate. Which of these is actually holding you back? And then you report the worst one as the metric for your machine.

There is one further consideration to do with connectivity - the question of how well interlinked the qubits of our computer are. Imagine that they are all laid out in a square grid, and that each qubit can only directly 'talk' to its nearest neighbours. Sometimes, fortuitously, the algorithm you are running may call for an operation between neighbouring qubits - then, this can simply happen directly. But more likely, a given operation will call for operations between non-neighbouring qubits. Then, you will need to perform some swap operations to get the two qubits, initially non-neighbouring, to come close to one another and this hopping process will create errors.

The way around this is to build a computer with higher connectivity. The NQIT goal of a networked system embraces this philosophy. For small or medium-scale installations we could support all-to-all connectivity between our modules. Even for networks with thousands or millions of modules, we can design the network so that there are only a few 'degrees of separation' between any two nodes, so the number of hops needed to bring two qubits within reach of one another is small.

So, given all the above considerations, what kind of quantum volume might we see for machines that may emerge in the next few years? Let's take two technologies: a grid of superconducting qubits with nearest-neighbour links, and a network of ion traps with all-to-all linkage (like NQIT's Q20:20 or Q5:50 architectures).

Using the best reported fidelities to date, the superior error rate and connectivity of the ion trap leads to nearly seven times the quantum volume of the equivalent superconducting grid. The "future" ion trap system is actually the only one that really benefits from increasing the qubit count beyond 50 - its low error rate and high connectivity yields a quantum volume over ten times higher than alternative systems.

Ion trap chip mounted in a vacuum system / Ion Quantum Computing Group, University of Sussex

Applications & Software

Applications Introduction

Our applications programme, encompassing half of our work packages, is engaged in developing the tools to make the Q20:20 engine available to users, and investigating how it can be used to solve real-world problems.

The next decade will see the introduction of quantum technologies into the high-performance computing landscape. The first few generations of these machines will vary substantially in architecture and computational capacity: they will not be easily applicable to all problems, and so they may not have a simple, unified programming model. Our work on applications will help address these issues, in a way which will naturally develop to accommodate the longer-term prospect of mature quantum technology, developed in the UK and worldwide.

Our work is driven by three key questions for emerging quantum devices, such as the Q20:20 engine, to allow quantum technology to be used to its fullest:

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

NQIT's applications programme is split into work packages on four themes: secure network applications, quantum-enhanced materials discovery, optimisation and machine learning, and developing the classical network and programming interface of the Q20:20 engine.

Future supercomputers and communication networks will certainly consist of both classical and quantum devices, with degrees of functionality ranging from simple routers to servers executing quantum algorithms. Our work in this area focuses on designing the building blocks for these future powerful quantum servers.

Secure Network Applications

This work package addresses the challenge of secure and private communication and computation across networks. This includes improved quantum random number generators for applications in simulation and as a resource for other cryptographic protocols; quantum key distribution where end-point users perform communication secure against any third party; blind quantum computing where a client delegates to a server a quantum computation maintaining the privacy of her input and output; secure multiparty (quantum) computation (SMPC), where multiple parties perform a joint, possibly quantum, computation on their private inputs. These tools can also be applied to the critical problem of verifying the correctness of trusted but noisy devices.

Concretely, we have developed a number of protocols and demonstrators: a prototype device for generating high-speed, certified quantum randomness from an untrusted photonic source (in collaboration with the hardware work package on photonics); a protocol for boosting the performance of classical SMPC, for parties with limited computational power, using quantum resources that were then implemented on a photonic platform; protocols for quantum secure multiparty computation where we require the simplest quantum abilities and communication from the parties involved; and various improvements in blind quantum computation protocols including reduction of the cost for verification, reduction of the (quantum) interaction and reduction of the trust on the workings of the devices needed.

Networked Quantum Sensors

NQIT is establishing formalisms to embed quantum sensors in classical networks. We are achieving this by unifying the quantum principles of estimating multiple parameters simultaneously with the practical classical sensor networks. Oxford and Warwick Universities have identified classical coding strategies for maintaining quantum estimator performance in classically networked systems of quantum sensors. Professor Justin Coon at the University of Oxford, who is leading this work, presented it at IEEE GLOBECOM 2017 in Singapore, demonstrating how NQIT's work is being accepted in the wider communications community outside of the quantum information sphere.

At the University of Sussex, we recently led a study to obtain the requirements for estimating multiple parameters on networked quantum sensors and at the University of Warwick, we have been developing the notion of fault tolerant quantum sensing. This development could overcome 'noisy' circumstances and enable universal quantum-enhanced sensing, which will be valuable in networked as well as stand-alone quantum sensors.

Quantum Enabled Discovery

We have been working on how to use the concept of a hybrid quantum-classical approach to solve the difficult problem of simulating how electrons interact in materials. These methods could eventually be used to aid the design of quantum materials through computational modelling. We have been looking for ways to take quantum advantages in hybrid algorithms, particularly to utilise two-electron properties to describe a many-electron system, which can substantially reduce the computational complexity.

We are currently developing the protocol of a new hybrid algorithm in quantum circuits for finding the ground-state energy of quantum materials. In the next year we will focus on the demonstration of simulating few-electron systems in ion trap or superconducting circuit systems to show the potential of practical quantum simulation under realistic defects using hybrid algorithms.

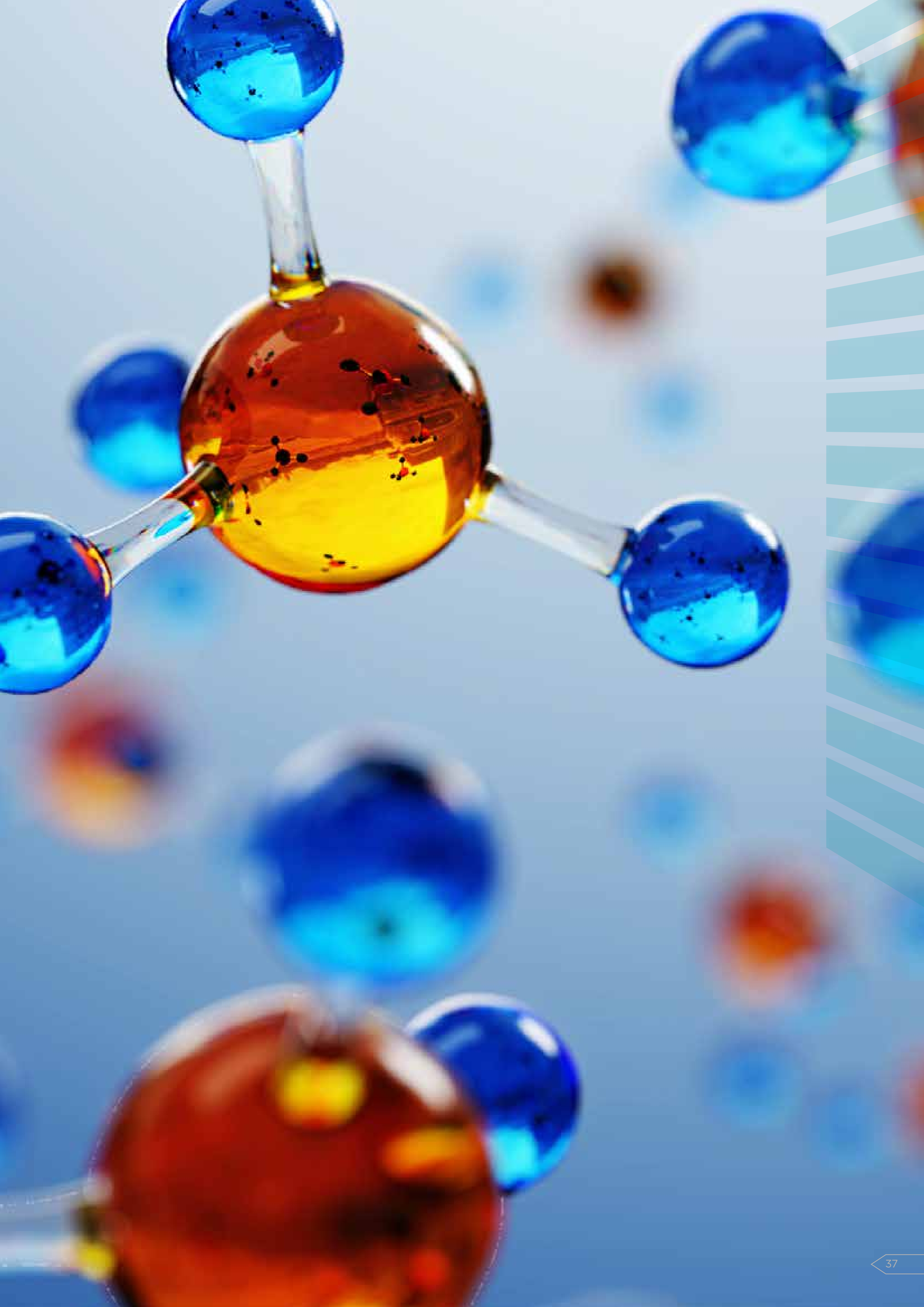
Quantum/Classical Emulation and Interfacing

This research area focuses on software tools to allow users to access quantum technology, and mathematical tools to make the best use of the available resources, once hardware such as the Q20:20 machine becomes available.

At the beginning of 2017, we decided to develop a “software quantum emulator”, which may be used by researchers and end-users to prototype and test the capabilities of the Q20:20 engine. We have now completed a publicly usable “alpha” version of a unitary-circuit emulator. We are also in advanced dialogue with a global IT provider to develop this emulator further for public use, incorporating advanced simulation techniques for special cases of unitary circuits to achieve the best possible performance.

We are now in the process of defining the machine-code level instructions which will govern how the components of the Q20:20 engine will co-ordinate to perform computation. This, and the software interface of the software emulator, represent two distinct back-ends for an NQIT compiler system, to be provided for users of the Q20:20 device. Using a common interface for both quantum technologies and for software emulators will allow us to make the transition to available quantum technology as seamless as possible.

In the past year, we have also found novel ways of describing computation on error-corrected memories which may allow us to use fault-tolerant resources in a more versatile way.



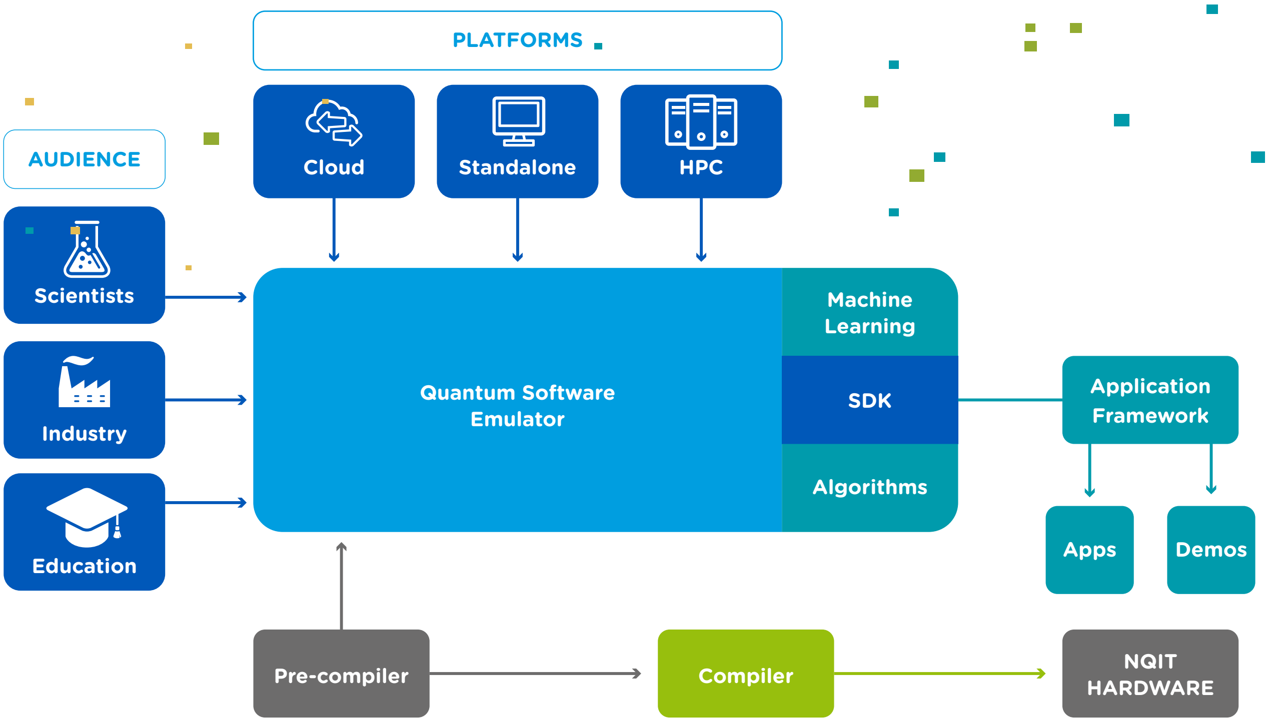
DEVELOPMENT OF QUANTUM APPLICATIONS

This year several companies are claiming to have achieved so-called "quantum supremacy" after presenting devices with a qubit count of 49 or greater, generally accepted to be above the limit of what can be emulated in classic computing. But, as NQIT's Professor Simon Benjamin points out, "quantum supremacy" is only the point at which we can't predict what the quantum machine will do using regular supercomputers; it is not the point at which we can build useful applications. That will require not only a certain number of qubits but also the highest precision in both qubits and their connection.

Nevertheless, with the availability of the early generation of 'noisy' devices with qubit counts never seen before, attention now focuses on the development of applications. That requires devices or capable emulators, users, software tools and algorithms that exploit the unique possibilities of quantum computing. With nearly half of NQIT's work packages dedicated to the theory and software of quantum computing, NQIT is progressing all these aspects of application development. The diagram below shows this application development eco-system.

NQIT has also added a new work package for Quantum Optimisation and Machine Learning led by Dr Michael Gutmann in Edinburgh University.

With the availability of an advanced emulator, application and software development and the new partnership with IBM Q Network, NQIT is also launching an Algorithm and Application Syndicate to bring together future quantum information technology users from industry and science to learn about quantum computing and develop new applications in a new open environment.



Quantum Optimisation and Machine Learning

Our new work package on Quantum Optimisation and Machine Learning is now well underway, with the recruitment of Dr Michael Gutmann, Senior Lecturer in Machine Learning at the University of Edinburgh, who is an expert in classical machine learning. Michael provides the background and expertise necessary to clarify the objectives that quantum technologies should target in machine learning, with others within NQIT providing the required expertise in quantum science and technology.

Machine learning, optimisation, and quantum information are dynamic research fields that have undergone tremendous developments in the past few decades. As two interdisciplinary fields, both quantum optimisation and quantum machine learning exploit quantum information processing to design new quantum algorithms to speed-up existing classical ones. Although the quantum algorithms may have improvements in solving certain problems, such as solving linear equations, the performance of quantum optimisation algorithms with real quantum machines is as yet unknown and the generalisation of quantum machine learning algorithms to other problems is yet to be discovered.

For quantum optimisation, we will test a quantum optimisation algorithm with the state-of-the-art D-Wave quantum computer. In real world optimisation, it is important that solutions are not only highly optimal, but also robust. This was identified as a concern and a motivation for exploring quantum approaches, which can potentially produce quite optimal and also robust solutions.

The inference problem lies at the heart of many machine learning tasks, such as autonomous driving and image recognition. It requires one to construct a correlation model and optimise the model such that it best represents the observed data. Due to the limited representation or computation power of classical computers, classical machine learning cannot efficiently solve a general inference problem. However, quantum computers can more efficiently represent and calculate general multiple variable probability distributions. This enables the possibility of designing quantum inference algorithms and applying them to general machine learning tasks. Ultimately, by considering a few other machine learning tasks, we will show several quantum machine learning algorithms that provide advantages in a variety of different tasks.

HOW DOES QUANTUM COMPUTING INTERSECT WITH MACHINE LEARNING?

We asked Dr Michael Gutmann to explain what machine learning is and how it links in with quantum computing and optimisation problems.

What is machine learning?

A recent report by the Royal Society defines machine learning as "a technology that allows computers to learn directly from examples and experience in the form of data." The report lists a number of "classical" applications of machine learning, such as machine translation, recommendation systems, or fraud detection.

https://royalsociety.org/~/media/policy/projects/machine-learning/publications/machine-learning-report.pdf

Machine learning is about extracting valuable or actionable information from data. The data may come from commercial, scientific, or many other kinds of sources, which makes machine learning widely applicable.

It spans a range of activities: some people may work on developing new principles to efficiently "learn from data", while others are more concerned with implementing existing principles.

How will quantum computing intersect with machine learning?

Machine learning is often subject to a cost-quality or time-quality trade-off. Certain learning principles yield provably accurate results but are computationally infeasible. Even on modern computer clusters, you have to wait too long for a result, so that you settle for an approximate but computationally feasible solution. We hope that quantum computers may allow us to strike a better trade-off than conventional computers.

An example where current machine learning faces limits is uncertainty quantification: we can use machine learning to make predictions from data, but these predictions are never clear-cut. A variety of different predictions may be in line with the data, and often, such as in a medical context, it is important to have an idea about how probable they are.

Wider Engagement

Professor Winfried Hensinger explains quantum entanglement using the flip of a coin at the NQIT public lecture / David Fisher

Responsible Research and Innovation

Following an overview of RRI issues in our report "Thinking Ahead to a World with Quantum Computers", we are deepening RRI through case studies. Firstly, a White Paper on the RRI implications of the use of quantum technologies for defence and national security will be launched in the second quarter of 2018. The next topic will be a study on the implications of quantum methods for machine learning, which has strong overlaps with the new NQIT work package in this area.

Under the leadership of EPSRC, a Public Dialogue process, conducted by Kantar Public, has sought views on quantum technologies from a wide cross-section of the public. Professor Marina Jirotka was on the Advisory Board for this process and we participated in a preparatory stakeholder workshop and in three dialogue workshops. When finalised, the report will greatly expand our knowledge of public attitudes and awareness of quantum technologies.

In keeping with the recommendations of the mid-term review of the UK National Quantum Technology Programme, we have prepared a revised RRI strategy to extend the RRI work in NQIT to the other Quantum Technology Hubs and to link with Public Engagement. This strategy will complete the RRI requirements across the Hubs and address the findings of the Public Dialogue process.

Raising awareness of RRI across the quantum research community, we have held training workshops at the regular NQIT Skills Forum and at the QuantERA RRI workshop in October 2017 and we presented an RRI exhibit at the UK National Quantum Technologies Showcase. Marina Jirotka has given invited talks on RRI at IEEE e-Science 2017, e-Research Australasia, and is an invited speaker at the International Conference on Challenges in Quantum Information Sciences in Japan. We are actively involved with the recently launched ORBIT (Observatory for Responsible Research and Innovation in ICT) online resource, extending its remit from ICT to encompass quantum computing.

As the Quantum Technology Hubs move towards completion of their first phase, moving technologies from the laboratory to the market, this is a unique opportunity to embed RRI in industry innovation as well as in research. We are very excited to follow this process and to prepare to carry RRI forward into any successor projects. We will present our results and activities in RRI in NQIT in a public event towards the end of 2019.

Public engagement

2017 was an exciting year for public engagement as we developed and expanded our NQIT Public Engagement Strategy. We continued our annual presence at the Oxfordshire Science Festival and held another packed-out public lecture - "Quantum Computers: the World's Most Incredible Machines" by Professor Winfried Hensinger. We organised "An Evening of Quantum Discovery", a major event for the general public in the Physics Department in Oxford, involving talks by researchers, lab tours and a hands-on science fair, all on the theme of quantum physics. Visitors could also vote on their favourite image in our Quantum Photography Competition.

Several NQIT researchers took part in Oxford University's Curiosity Carnival - part of European Researchers' Night - including a Quantum Story Corner, baking an "Ion Trap Quantum Computing" cake for the Great Research Bake Off and a quantum-inspired ballet performance.

NQIT Researchers from Professor Winfried Hensinger's group at the University of Sussex exhibited their pop-up "walk-in quantum computer" installation at the British Science Festival and again at Spitalfields Market, allowing the public to step into a virtual quantum computer prototype. They have also curated an exhibition at the London Science Museum entitled "Could quantum computers change the world?" which will be displayed in the Tomorrow's World gallery space until September 2018.

We took part in the Public Dialogue on Quantum Technologies, commissioned by EPSRC, where several NQIT researchers acted as expert advisors to the members of the public taking part in the dialogue workshops and to facilitators from Kantar Public, who ran the public dialogue exercise.

NQIT research was featured heavily in a piece on quantum computing in BBC Click, the BBC's flagship technology show, including coverage of the National Quantum Technologies Showcase and the Ion Trap lab in Oxford.

Online, our Twitter followers have more than doubled since last year and the number of website visitors is up by 59% compared to 2016, with an average 1,500 visitors per month.

NQIT at the Curiosity Carnival: PhD student Amy Hughes with her Trap Ion Quantum Computing Cake; PhD student Merritt Moore performing a quantum-inspired ballet in the Ashmolean Museum and Helen Chrzanowski and Kanta Dihal explaining quantum entanglement in the Quantum Story Corner / Ian Wallman, University of Oxford

Playing the Pirate Treasure Map game to understand the Travelling Salesman problem at the Oxfordshire Science Festival / Hannah Rowlands

AN EVENING OF QUANTUM DISCOVERY

"An Evening of Quantum Discovery" was a public engagement event we held in the Physics Department in Oxford in October 2017. The event was divided into a family-friendly set of activities from 5pm followed by activities for a general 12+ audience from 6.30pm.

The quantum theme included a wide range of physics topics such as quantum computing, photonics, quantum materials, and superconductivity.

Activities included:

- 20-minute talks by members of the Physics Department
- Guided lab tours in 6 labs
- A hands-on science fair with 7 stalls
- A "Quantum Story Corner" for children
- Voting for your favourite image in a Quantum Photography Competition

More than 150 people attended on the night and we had some great feedback from visitors:

"We thoroughly enjoyed the evening and thank everyone for all the work they put into making it such an interesting and stimulating event."

"Interactive, amazing, not one bit was boring and completely captivated my children's minds and my own, wish it was that interesting at school"

36 students and researchers from the department volunteered to help with lab tours, talks and the science fair - thanks to all of you for helping!

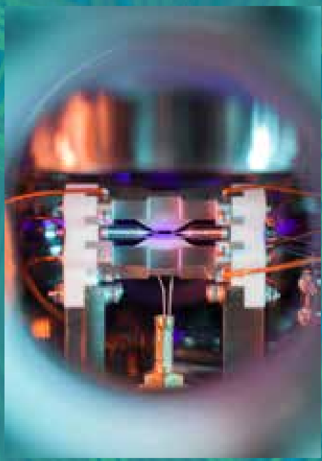
Talks and hands-on demos at an Evening of Quantum Discovery / Olga Brecht

QUANTUM PHOTOGRAPHY COMPETITION

In the lead up to our "Evening of Quantum Discovery", we launched a Quantum Photography Competition. We invited students and researchers working in quantum from around the world to submit a photo of their research that best captures the innovation and beauty of their work. Photo submissions were related to research or technology development in quantum physics, but we defined this broadly and encouraged researchers to be use their imagination to show the world what they are working on.

We received nine fantastic entries, all of which were displayed at the "Evening of Quantum Discovery", where visitors could vote for their favourite image. 75 people voted and there was a clear winner: David Nadlinger's beautiful image of a single atom in an ion trap.

This photo went on to win the EPSRC Science Photography Competition early in 2018 and is on the front cover of this report.



Entries to the Quantum Photography Competition:

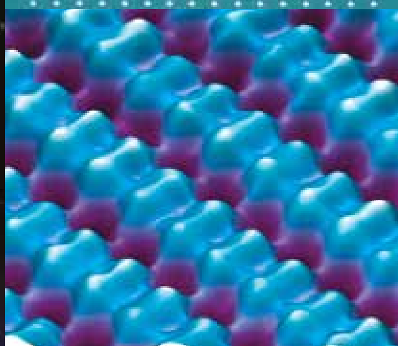
Top - Optical fibres by Chris Wade

Bottom left - The Single Pixel Camera from QuantIC in Glasgow, Scotland by Kevin Mitchell

Top middle - Atomic scale qubits and single electron transistors in a universal quantum computer surface code architecture by Joris Keizer

Bottom middle - Silicon Atoms for Quantum Computing by Ludwik Kranz

Bottom right - Control Electronics for Superconducting Nanowire Single Photon Detectors by Chris Wade



WALK-IN QUANTUM COMPUTER INSTALLATION

NQIT researchers from the University of Sussex, led by Prof Winfried Hensinger, created a walk-in quantum computer installation. This is the first time a UK university has taken quantum technology to the streets and invited the public along to see the ground-breaking work being carried out to develop quantum computers. The designed structure housed an authentic quantum computing experience incorporating four amazing exhibits that helped develop a greater understanding of quantum computing for anyone entering the space.

Visitors to the quantum computer installation were able to quiz the team on how their discoveries may shape the future, watch immersive video projections of experiments being carried out in the lab and see exhibits including real chips used in a quantum computer as well as a model of the quantum computer prototype currently being constructed at the University of Sussex.

The installation was taken to the centre of London’s financial district, Spitalfields Market, in order to interact with the general public. The audience was diverse with visitors including London business executives, school students and their parents, artists, corporate lawyers, bankers and even some England Cricketers. The team explained what it is like to work at the cutting edge of scientific research, how this might help solve some of life’s most complex problems and how this technology can impact everybody’s life.

Sussex researchers also exhibited the walk-in quantum computer installation at the British Science Festival allowing hundreds of visitors to interact with state-of-the-art quantum computing technology. The editors of The Conversation showcased quantum computing as the highlight of the British Science Festival in their festival podcast.

Walk-in quantum computer installation at Spitalfields Market / Ion Quantum Technology Group, University of Sussex

Inter-Hub Collaboration

We work closely with the other partners in the UK National Quantum Technologies Programme, in particular the other Quantum Technology Hubs. We have continued to collaborate on national events such as the National Quantum Technologies Showcase and Quantum Technology for the Oil and Gas Industry led by the Quantum Technology Hub for Sensors and Metrology - a similar event is being planned for later in 2018 for the Space industry, led by the Quantum Communications Hub and NQIT. We also organised a cross-hub workshop on “Quantum Information Technologies: Challenges and Applications” held at Edinburgh University in October 2017.

We are developing a joint Public Engagement Strategy with other partners within the National Programme including a brand new exhibit entitled “Welcome to Quantum City”, which we will take to several national science festivals around the UK in 2018, and an associated website where members of the public can learn about the impact of quantum technologies in their lives.

We are taking the lead on Responsible Research and Innovation, working with EPSRC to deliver a series of workshops and case studies across the National Programme, have welcomed visitors from across the Programme to events such as our twice-yearly Skills Forum and work with the other Quantum Technology Hubs to promote the careers and enterprising initiatives from QTEC, an initiative borne out of the Training and Skills Hubs in Quantum Systems Engineering in Bristol.

We are working on several projects with the other Quantum Technology Hubs to explore technologies where we have mutual interests. One such project with the Quantum Communications Hub is developing a flexible platform for short-range wireless quantum communication. Work has focused on developing a short-range Quantum Key Distribution (QKD) link between a handheld terminal and a ‘quantum ATM’. Excellent progress has been made, with the demonstration of a prototype at the National Quantum Technology Showcase in 2017, and a recently filed patent application. In addition we have won additional funding from Innovate UK to demonstrate its use for financial transactions in a project led by Cognizant, involving Oxford and Bristol Universities.

A new project with QuantIC, the UK Quantum Technology Hub in Quantum Enhanced Imaging, involves developing a photon sensor for high-precision estimation of phase shifts induced by nonlinear responses in materials, with possible applications in switching and imaging. The quantum light sources developed in the two Hubs are also part of an Innovate UK project led by M-Squared Lasers.

Skills and Training

NQIT is developing skills capacity in quantum technologies by interfacing with student training programmes and providing skills training on focused areas for members of the consortium.

Student engagement activities focus on providing opportunities for doctoral students to carry out research projects of relevance to the NQIT programme. We do this by two methods: through joint supervision relationships in partnership with national Centres for Doctoral Training, and through the selection of projects to be funded by Doctoral Training Partnership (DTP) studentships at NQIT partner universities. These activities have so far led to 14 doctoral students carrying out NQIT-related projects, with a further 12 projects allocated for 2018 enrolment. These students benefit from training and supervision by NQIT project leaders, access to equipment used within the NQIT programme, and interactions with our industrial partners. For the DTP-funded projects a call for proposals is issued in October each year, with any research group at an NQIT partner university eligible to apply.

The NQIT Skills Forum provides regular one-day meetings for the provision of focused interdisciplinary training sessions for NQIT staff, industrial partners, and the wider quantum technologies community. The Forum covers topics related to business and entrepreneurship, responsible research and innovation and intellectual property, alongside market-oriented topics related to applications of quantum computing and simulation and useful technical topics such as finite element modelling and systems engineering. For the June 2018 Forum we are planning to include for the first time a "careers in quantum" session in which students and postdocs working in the field can find out about job opportunities in the field directly from our industrial partners.

We are building links with the Quantum Technology Enterprise Centre (QTEC) programme to foster entrepreneurship within NQIT. This programme, part of the UK National Quantum Technologies Programme, is a joint initiative between the University of Bristol and Cranfield University which aims to connect quantum-minded engineers to quantum technology. It is a generously funded year-long programme which brings together companies, investors, and the facilities and skills essential for the incubation of early-stage businesses in the emerging quantum technology industry.

We are looking forward to welcoming new Research Fellows in Quantum Physics from Canada and Australia thanks to an award from the Rutherford Fund Strategic Partner Grants, which provides funding for eligible UK higher education institutions that will build on and enhance their global strategic partnerships. These fellowships are funded by the UK Department for Business, Energy and Industrial Strategy (BEIS) through the Rutherford Fund, with the aim of attracting global talent and strengthening the UK's research base.

Future Plans

NQIT continues to grow well with a wide range of achievements in both industry engagement and technology development.

All of our work packages have identified the key goals for the end of the project. These were chosen as the major enabling milestones to advance our vision into the planned second phase of the UK National Quantum Technologies Programme.

In our core hardware these are focused on engineering the ion trap nodes and their connections, in preparation for the scaling to operational systems that is the focus of our vision for Phase II. In our work on diamond qubits, the goals remain the creation of magnetometers for sensing and efficient interfaces that enable Nitrogen Vacancy centres as qubits. For superconductors, we are targeting small circuit modules. We believe that these research advancements will lead to a technology that can be applied within the quantum computing economy in the mid-term.

In applications we are focused on development of secure applications, quantum simulations, potentially using access to third party quantum computers such as those from IBM Q, and to the development of an emulator that models the performance of the Q5:50 architecture. Our detailed discussions with industry to understand the needs of end users will allow us to continue to grow knowledge and expertise in this area.

Ion traps remain the highest quality qubit technology, by a substantial margin, and networked ion traps offer a rapid route to a scalable machine. Our initial demonstrations involve prototypes which, although functionally scalable, will require substantial reductions in cost and complexity before mass application. Developing compact, miniature traps, with optical cavities to enable a high-performance network connection to adjacent nodes, together with miniaturisation and simplification of control electronics is a key goal in the longer term. At the same time, core science that improves performance of the individual nodes, which will yield substantial gains in the capability of future machines, must remain a focus.

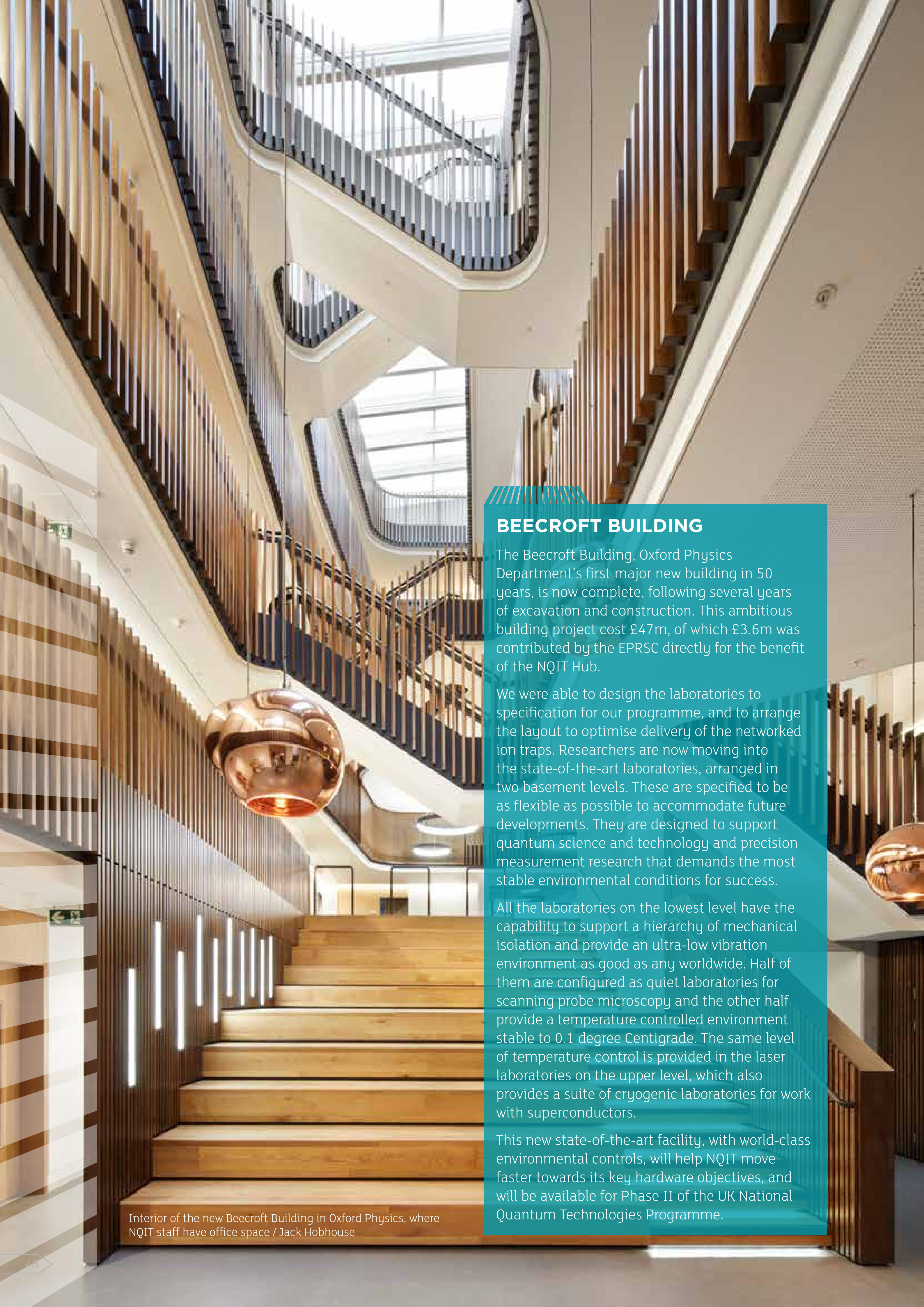
NQIT has focused on the development of a core ion trap based processor as well as the improvement of promising alternative node technologies. At the same time new applications and algorithms have resulted from this first phase of work, and there have been a wide range of spinout technologies.

Planning for Phase II of the UK National Quantum Technology Programme is now underway. The new programme will be under the auspices of the new UK Research and Innovation Council (UKRI), which brings together both discovery and application elements of public funding for research and development, across all disciplines. This offers new opportunities for the UK National Quantum Technology Programme to deliver impact by driving the formation of a new industry sector, in which the skills, ideas, science and technology delivered by the Technology and Skills Hubs will be key enabling factors for this emerging new engineering segment.

NQIT is helping to structure the community and shape the landscape for the next phase of the programme. We hosted a national workshop in partnership with EPSRC to scope the opportunities arising from outstanding research activity across the UK, in the context of leading developments across the world in quantum computing platforms and applications. We expect that the next phase of the Hub will continue to push forward with the leading computing technologies, based on ion traps and photonic networks, as well as help to speed up the development of other promising platforms and architectures for quantum computers and simulators, including superconducting quantum circuits, photonics, silicon, diamond, and ultra-cold atoms.

The next phase of NQIT will continue to push the boundaries of concepts and performance of the leading platforms for quantum computing, with particular focus on the networking architectures that have considerable promise for a scalable machine. The consortium will also engage a user base that can apply it to a wide variety of problems and to develop the skills and expertise necessary to drive the emerging quantum technologies industry.

Exterior of the new Beecroft Building in Oxford Physics, housing state-of-the-art laboratories / Jack Hobhouse



Interior of the new Beecroft Building in Oxford Physics, where NQIT staff have office space / Jack Hobhouse

BEECROFT BUILDING

The Beecroft Building, Oxford Physics Department's first major new building in 50 years, is now complete, following several years of excavation and construction. This ambitious building project cost £47m, of which £3.6m was contributed by the EPRSC directly for the benefit of the NQIT Hub.

We were able to design the laboratories to specification for our programme, and to arrange the layout to optimise delivery of the networked ion traps. Researchers are now moving into the state-of-the-art laboratories, arranged in two basement levels. These are specified to be as flexible as possible to accommodate future developments. They are designed to support quantum science and technology and precision measurement research that demands the most stable environmental conditions for success.

All the laboratories on the lowest level have the capability to support a hierarchy of mechanical isolation and provide an ultra-low vibration environment as good as any worldwide. Half of them are configured as quiet laboratories for scanning probe microscopy and the other half provide a temperature controlled environment stable to 0.1 degree Centigrade. The same level of temperature control is provided in the laser laboratories on the upper level, which also provides a suite of cryogenic laboratories for work with superconductors.

This new state-of-the-art facility, with world-class environmental controls, will help NQIT move faster towards its key hardware objectives, and will be available for Phase II of the UK National Quantum Technologies Programme.

Outputs

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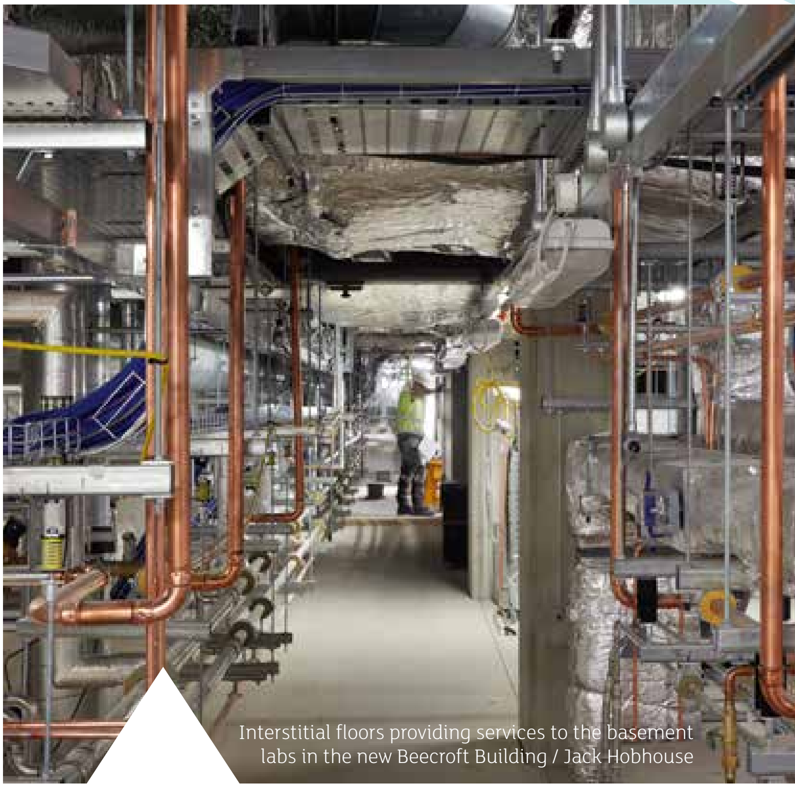


Interstitial floors providing services to the basement labs in the new Beecroft Building / Jack Hobhouse

Talks

February 2017, Professor Dieter Jaksch, "Optically driven strongly correlated quantum systems", Scientific Meeting on Future directions in non-ergodic dynamics in quantum systems, Chicheley Hall, Milton Keynes, UK

April 2017, Dr Peter Horak, "Integration of Fiber-Tip Cavities in Single-Ion Traps for Quantum Sensing", Optical Fiber Sensors (OFS-25), Jeju, Korea

April 2017, Dr Gavin Morley, "Optical Levitation of Nanodiamonds in Vacuum without Heating", Materials Research Society (MRS) Spring Meeting & Exhibit, Phoenix, Arizona

April 2017, Professor Dieter Jaksch, "Early Applications of First Generation Quantum Information Devices", SU2P 8th Annual Symposium, Heriot-Watt University, Edinburgh, UK

April 2017, Dr Iris Choi, "Quantum Technology Landscape in UK and Handheld Quantum Encryption", American Physical Society Conference on Actualization of the Internet of Things, California, USA

April 2017, Bristol Quantum Information Technologies Workshop BQIT, Bristol, UK:

- Dr Joshua Nunn, "Finally: a noise-free quantum memory"
- Professor Winfried Hensinger, "Constructing a microwave trapped ion quantum computer"
- Dr Almut Beige, "From optical cavities to cavity-fibre networks"
- Professor Jason Smith, "Optical microcavities for quantum technologies"

June 2017, Control of Quantum Dynamics of Atoms, Molecules and Ensembles by Light Workshop 2017, Nessebar, Bulgaria:

- Professor Axel Kuhn, "Boson or Fermion? Quantum Confusion with Cavity Photons"
- Dr Matthias Keller, "Interfacing ions and photons"
- Professor Winfried Hensinger, "Constructing a microwave trapped ion quantum computer"

June 2017, Professor Ian Walmsley, "Photonic Quantum Networks", CLEO/Europe-EQEC 2017, Munich, Germany

June 2017, Professor Elham Kashefi, "Verification of Quantum Computation and the Price of Trust", 12th International Computer Science Symposium, Kazan, Russia

June 2017, Professor Elham Kashefi, "Garbled Quantum Computation", Cryptography and Information stream of the Computability in Europe 2017 Conference, Turku, Finland

July 2017, Professor Ian Walmsley, "Why three Interfering photons are different than two and when more are not", Quantum Optics to Quantum Technology Workshop, Imperial College London, UK

July 2017, Professor Ian Walmsley, "Quantum Photonic Networks", 9th International Conference on Information Optics and Photonics (CIOP 2017), Harbin, China

August 2017, Dr Almut Beige, "Quantising the electromagnetic field near semi-transparent mirrors", Conference on Quantum Information and Quantum Control VII, Toronto, Canada

August 2017, Dr Matthias Keller, "Interfacing ions and photons", 24th Congress of the International Commission for Optics (ICO), Tokyo, Japan

August 2017, Professor Winfried Hensinger, Focused Research Group on Quantum Supremacy Workshop, Bristol, UK

August 2017, Dr Almut Beige, "Quantising the electromagnetic field near semi-transparent mirrors", Conference on Quantum Information and Quantum Control VII (CQIQC-VII) at the Fields Institute, Toronto, Canada

September 2017, Dr Peter Leek, "Dispersive coupling of a superconducting qubit to a SAW resonator", Foundations and Applications of Nanomechanics, Trieste, Italy

September 2017, Professor Dieter Jaksch, "Quantum Fluctuation Relations in the Presence of Conserved Quantities", Advanced School and Workshop on Quantum Science and Quantum Technologies, Trieste, Italy

September 2017, Professor Ian Walmsley, "The Future of Optics", Optics Centenary Event, Imperial College London, UK

September 2017, Professor Ian Walmsley, "Photonic quantum networks: a ubiquitous platform for quantum technologies", 10th Italian Conference on Quantum Information Science (IQIS 2017), Florence, Italy

September 2017, Professor Ian Walmsley, "Hybrid Quantum Networks", Conference on Quantum Cryptography (QCrypt 2017), Cambridge, UK

September 2017, Professor Elham Kashefi, "Verification of quantum technology", International Conference on Integrated Quantum Photonics, Rome, Italy

September 2017, Dr Almut Beige, "Quantising the electromagnetic field near semi-transparent mirrors", Biennial International Conference on Quantum, Atomic, Molecular and Plasma Physics (QuAMP) 2017, Glasgow, UK

October 2017, Professor Ian Walmsley, "SPIDER, 20 years of arachnophilia", Ultrafast Optics XI (UFO XI), Jackson, Wyoming

Professor Winfried Hensinger delivering the NQIT public lecture 'Quantum Computers: the World's Most Incredible Machines' / David Fisher

October 2017, Professor Elham Kashefi, "Entrapping Nature", 13th European Computer Science Summit, Lisbon, Portugal

October 2017, Professor Marina Jirotka, "I don't think I've come across an unethical scientist", 13th IEEE eScience Conference, Auckland, New Zealand

October 2017, Professor Marina Jirotka, "The best science for the world – not only the best science in the world", e-Research Australasia 2017, Brisbane, Australia

November 2017, Professor Axel Kuhn, "Boson or Fermion? Quantum Confusion with cavity photons", ICQOQI (XV International Conference on Quantum Optics and Quantum Information), Minsk, Belarus

February 2018, Professor Ian Walmsley, "Network-based quantum computing", Bilateral International Meeting organised by the Royal Society and the Royal Netherlands Academy of Arts and Sciences (KNAW), Chicheley Hall, Newport Pagnell, UK

February 2018, Dr Peter Leek, "Coupling superconducting qubits to surface acoustic wave resonators", Frontiers of Circuit QED and Optomechanics FCQO18, Institute of Science and Technology Austria (IST Austria)

February 2018, Professor Dieter Jaksch, "Cavity mediated topological superconductivity", Finite Temperature Non-equilibrium Superfluid Systems (FINESS) 2018, Wanaka, New Zealand

February 2018, Dr Almut Beige, "Scattering photons for quantum information processing", Workshop on Higher Gauge Theory: Where should we look for higher gauge matter? (From emerging physics and topological quantum computing to string and M-theory), Leeds, UK

March 2018, Dr Gavin Morley, "Levitating nanodiamonds containing spins to test the limits of quantum mechanics", Hasselt Diamond Workshop 2018 - SBDD XXIII cultuurcentrum Hasselt, Hasselt, Belgium

March 2018, Dr Peter Leek, "Circuit Quantum Acoustodynamics with Surface Acoustic Waves", GRC Mechanical Systems in the Quantum Regime, Ventura CA, USA

March 2018, Professor Ian Walmsley, "Some experimental contributions to the study of thermodynamics in quantum systems", DPG Frühjahrstagung (Spring Meeting) of the Atomic, Molecular, Plasma Physics and Quantum Optics Section (SAMOP), Erlangen, Germany

Additional funding

Innovate UK Commercialisation of Quantum Technologies, Collaborative Research & Development, Round 3:

Q-DOS light: quantum key distribution for drones with optimal size, weight and power

- Academic Partner: Universities of Oxford and Bristol
- Industrial Partners: Airbus, KETS Quantum Security Limited, ID Quantique Ltd
- Consortium Funding Amount: £987,871
- Reference: 103874
- Dates: December 2017 – March 2019

Nanoparticle and chemical sensors using optical microcavities

- Academic Partner: University of Oxford
- Industrial Partners: HighQ Instruments Ltd and Malvern Instruments Ltd
- Consortium Funding Amount: £884,931
- Reference: 103879
- Dates: January 2018 – March 2019

ESCHER: Establishing Supply Chains for Emergent Quantum Computers

- Academic Partners: Universities of Oxford, Southampton and Sussex
- Industrial Partners: M-Squared Lasers Ltd and Covesion Ltd
- Consortium Funding Amount: £1,232,888
- Reference: 104000
- Dates: January 2018 – June 2019

Innovate UK Commercialisation of Quantum Technologies, Feasibility Studies, Round 3:

Quantum Enhanced Sensing of Trace Compounds in Sealed Containers

- Academic Partner: University of Oxford
- Industrial Partner: VeriVin Ltd
- Consortium Funding Amount: £240,124
- Reference: 133092
- Dates: December 2017 – November 2018

Innovate UK Commercialisation of Quantum Technologies, Collaborative Research & Development, Round 4:

Compilation & Circuit Layout Optimisation for Superconducting Quantum Processor

- Academic Partner: University of Oxford
- Industrial Partners: Cambridge Quantum Computing Ltd and Oxford Quantum Circuits Ltd
- Consortium Funding Amount: £382,540
- Reference: 104153
- Dates: March 2018 – February 2019

IOTA: Compact Ion Clock for Precision Timing Applications

- Academic Partner: University of Sussex
- Industrial Partner: M-Squared Lasers Ltd
- Consortium Funding Amount: £399,533
- Reference: 104158

Quantum Fibre Clock (QFC)

- Academic Partner: University of Bath
- Industrial Partners: Chronos Technology Ltd and TMD Technologies Ltd
- Consortium Funding Amount: £381,612
- Reference: 104165
- Dates: March 2018 – February 2019

MITAS: Miniaturised Ion Trap Atomic Source

- Academic Partner: University of Oxford
- Industrial Partner: ColdQuanta UK Ltd
- Consortium Funding Amount: £235,151
- Reference: 104159
- Dates: March 2018 – February 2019

Handheld Quantum Wireless for Secure Financial Transactions and Sensitive Information

- Academic Partners: Universities of Bristol and Oxford
- Industrial Partner: Cognizant Business Services UK Ltd
- Consortium Funding Amount: £345,994
- Reference: 104161
- Dates: April 2018 – March 2019

Research Fellowships

Royal Society for University Research Fellowship, Dr Gavin Morley “Quantum technology and fundamental physics experiments with electron spins”

- Funder: The Royal Society
- Amount: £334,173
- Dates: October 2017 – October 2020

Junior Research Fellowship at Christ Church College, University of Oxford, Vera Schäfer

- Funder: The University of Oxford
- Amount: £32,494 annually
- Dates: October 2018 – September 2021

Rutherford Fund Strategic Partner Grants

- Funder: Department for Business, Energy & Industrial Strategy
- Amount: £150,000
- Funding awarded to the University of Oxford for five Research Fellows in Quantum Physics from Canada and Australia

Engagement Activities

February 2017, IOP Northern Ireland John Bell lecture. Professor Winfried Hensinger was invited to deliver the IOP Northern Ireland John Bell lecture at a special public event and concert in Belfast.
http://www.iop.org/news/18/february/page_71083.html

March 2017, Oxford Martin School "Hacking nature's computers: exploring quantum computation with organic molecules". Dr Philip Inglesant was invited to give a presentation about Responsible Research and Innovation in Quantum Computing as part of the Oxford Martin School's event "Hacking nature's computers: exploring quantum computation with organic molecules" with Prof Vlatko Vedral. Philip's presentation formed the basis of a panel discussion about the future implications of quantum computing.
https://www.youtube.com/watch?v=5puYxdmCM6k

May 2017, Pint of Science 2017. Professor Winfried Hensinger was invited to give a public lecture entitled "Quantum Computing: The world's most incredible machines" in London as part of the Pint of Science festival.
https://pintofscience.co.uk/event/small-is-beautiful

May 2017, Studentship opportunities with the UK National Quantum Technology Hubs. This webinar was arranged by the four Quantum Technologies Hubs and hosted by the Institute of Physics to allow current graduate students to find out about studentship opportunities available across the UK Quantum Technology Hubs. The webinar was presented by the Hub Directors.
http://www.nqit.ox.ac.uk/event/webinar-studentship-opportunities-uk-national-quantum-technology-hubs

May 2017, DEVOXX UK. Professor Winfried Hensinger was invited to give the opening keynote address at a highly prestigious software developers conference (DEVOXX UK).
https://www.youtube.com/watch?v=uHw6ikgknXQ&t=0s&list=PLRsbF2sD7JVq8QYW0vlbOS2JuXUWaWMnT&index=2

June 2017, Oxfordshire Science Festival. NQIT attended the science fair for the second year running, with a stand addressing the questions "Will a quantum computer change your life?", "What are we doing to make quantum computers a reality?", and "How do you build a quantum computer?"
http://www.nqit.ox.ac.uk/news/nqit-oxfordshire-science-festival

June 2017, Question and Answer session: How UK partners can participate in the EU Quantum Technologies Flagship Programme. NQIT organised an event where Professor Dr Jürgen Mlynek, Chair of the EU Expert group on Quantum Technology, gave an "open-house" talk/Q&A session on the EU Quantum Technology Flagship for the benefit of stakeholders in the UK.
http://www.nqit.ox.ac.uk/event/eu-quantum-flagship-talk

July 2017, NQIT Public Lecture. Professor Winfried Hensinger gave the first NQIT Public Lecture at Rhodes House in Oxford in July 2017. The talk was entitled "Quantum Computers - the World's Most Incredible Machines".
http://www.nqit.ox.ac.uk/event/quantum-computers-p ublic-lecture-2017

July 2017, NQIT Industry Day. We held our first NQIT Industry Day in July, bringing together the national and global investment and business community with key quantum computing scientists and engineers from the UK-wide research consortium.
http://www.nqit.ox.ac.uk/news/nqit-industry-day

July 2017, Oxford China Lecture 2017. Professor Ian Walmsley was invited to present the prestigious, annual Oxford China Lecture in Beijing in July 2017. His talk was entitled "Quantum technology: A new era in computing".
http://www.nqit.ox.ac.uk/event/oxford-china-lecture-2017-quantum-technology-new-era-computing

August 2017, "Walk-in quantum computer" installation, Spitalfields Market, London. Professor Winfried Hensinger and his group created a walk in quantum computer installation which was taken into the centre of London's financial district in order to interact with the general public.
https://www.youtube.com/watch?v=7xEoZdFkn1E

August 2017, London Sessions - Next Gen Tech - Advanced Computing. Dr Iris Choi, NQIT Technology Associate, was part of a panel discussing the rapidly changing landscape of Advanced Computing, cryptography and cybersecurity, building meaningful applications on the blockchain and the disruptive force of quantum technologies.
http://www.nqit.ox.ac.uk/event/london-sessions-next-gen-tech-advanced-computing

September 2017, New Scientist Live. Professor Simon Benjamin gave a talk at New Scientist Live! 2017 at ExCel London entitled "Quantum Leaps: the Next Industrial Revolution"
http://www.nqit.ox.ac.uk/event/new-scientist-live-quantum-leaps-next-industrial-revolution

September 2017, NQIT at the Curiosity Carnival. Oxford's Curiosity Carnival 2017 was part of the 2017 European Researchers' Night, celebrated by universities across Europe. Researchers from NQIT took part in several activities on the day.
http://www.nqit.ox.ac.uk/news/nqit-curiosity-carnival

September 2017, "Future of the Workplace" Brighton Chamber of Commerce. Invited talk and panel discussion given by Dr Seb Weidt, organised by the Brighton Chamber of Commerce

September 2017, British Science Festival 2017. Professor Winfried Hensinger was invited by the Physics Section of the British Science Association to deliver a public lecture at the British Science Festival.

September 2017, "Walk-in quantum computer" installation, British Science Festival. Professor Winfried Hensinger and his group at the University of Sussex exhibited a walk-in quantum computer installation at the British Science Festival in Brighton. They created a walk in quantum computer installation in order to provide an authentic quantum computing experience.
https://www.britishsciencefestival.org/event/discover-quantum-an-immersive-laboratory-experience-4/

October 2017, An Evening of Quantum Discovery. An event held for the general public in the Physics Department in Oxford, attended by more than 150 people. Activities included 20-minute talks by members of the Physics Department, guided lab tours in 6 labs, a hands-on science fair with 7 stalls, a "Quantum Story Corner" for children and voting for your favourite image in a Quantum Photography Competition.
http://www.nqit.ox.ac.uk/news/evening-quantum-discovery

October 2017, New Scientist presents... Instant Expert: The Quantum Revolution. This was a one-day masterclass where six leading experts, including Professor Winfried Hensinger, guided the audience through one of today's most exciting fields of science.

October 2017, Brighton Nerd Night. Professor Winfried Hensinger gave a lecture about quantum computing at Brighton Nerd Night
https://brighton.nerdnite.com/2017/10/10/nerd-nite-brighton-45-waves-vision-quantum/

March, September & October 2017, Participation in Kantar Public dialogue on Quantum Technologies. Several researchers within NQIT took part in the public dialogue exercise carried out by Kantar Public on behalf of EPSRC. This included attending an initial stakeholder workshop in London and attending several all-day workshops involving members of the public.

November 2017, National Quantum Technologies Showcase. NQIT had 12 exhibits at this third annual showcase event, attended by an industry and government audience.
http://www.nqit.ox.ac.uk/news/nqit-national-quantum-technologies-showcase-2017

November 2017, British Computer Society (Oxfordshire). Dr Seb Weidt gave a talk entitled "Quantum Computers and their potential to revolutionise our lives" at the AGM of the Oxfordshire branch of the British Computing Society.
http://www.oxon.bcs.org/programme/quantum-computers-and-their-potential-to-revolutionise-our-lives-and-agm/

February 2018, Quantum Computer Exhibition, London Science Museum. Researchers from the University of Sussex reveal the secrets of quantum computers to the UK public at the Science Museum in London in an exhibition called "Could quantum computers change the world?"
https://blog.sciencemuseum.org.uk/how-do-you-solve-a-problem-like-quantum/

February 2018, Sussex Universe Lecture Series. Jacob Dunningham gave a talk entitled "Made to measure: using quantum to see more" as part of the Sussex Universe Lecture Series. These talks are organised by Sussex University undergraduate students, and are aimed at a level suitable for undergraduates and A-level students.
https://sussexuniverselectureseries.wordpress.com/page/

February 2018, Festival of Imagined Worlds at Cheney School. Dr Nathan Walk took the Quantum Story Corner to the Festival of Imagined Worlds at Cheney School. This was a presentation to school children about quantum entanglement and randomness.
http://eoccc.org.uk/iris-festival-of-imagined-worlds

February 2018, Wheatestone Lecture, Department of Physics, Kings College London. Professor Ian Walmsley was invited to give this annual lecture with a talk entitled "Building quantum machines out of light".
https://www.kcl.ac.uk/nms/depts/physics/newsevents/eventrecords/Wheatstone-Lecture-Building-quantum-machines-out-of-light.aspx

Royal Society Parent-Carer-Scientist. Dr Gavin Morley featured in an online booklet from the Royal Society entitled "Parent Carer Scientist". This booklet celebrates the diversity of work life patterns of 150 scientists across the UK with the aim of increasing the visibility of people combining a career in science with a family life.
https://royalsociety.org/topics-policy/diversity-in-science/parent-carer-scientist/

NQIT Photography Competition. NQIT held a Quantum Photography Competition, where we invited students and researchers from around the world working in quantum to submit a photo of their research that best captures the innovation and beauty of their work.
http://www.nqit.ox.ac.uk/content/nqit-quantum-photography-competition-round-one

Quantum computing exhibition at the London Science Museum / Ion Quantum Computing Group, University of Sussex

Selected Media Coverage

January 2017, "Route Monkey Takes Quantum Leap for Fleet Optimisation"

- NQIT website: http://www.nqit.ox.ac.uk/news/route-monkey-takes-quantum-leap-fleet-optimisation
- Transport Engineer: Route Monkey announces quantum leap for fleet optimisation http://www.transportengineer.org.uk/transport-engineer-news/route-monkey-announces-quantum-leap-for-fleet-optimisation/150492/
- Green Car Congress: Route Monkey working with NQIT to develop transport & mobility algorithms for quantum computers http://www.greencarcongress.com/2017/01/20170119-routemonkey.html
- Scotland B2B: Livingston tech firm takes Quantum Leap into future of travel http://scotlandb2b.co.uk/2017/01/20/livingston-based-route-monkey-takes-quantum-leap-into-the-future/

February 2017, "New Blueprint for Large-Scale Quantum Computing"

- NQIT website: http://www.nqit.ox.ac.uk/news/new-blueprint-large-scale-quantum-computing
- Nature: Physicists propose football-pitch-sized quantum computer http://www.nature.com/news/physicists-propose-football-pitch-sized-quantum-computer-1.21423
- Phys.org: First ever blueprint unveiled to construct a large scale quantum computer https://phys.org/news/2017-02-blueprint-unveiled-large-scale-quantum.html
- BBC Website: Quantum computer 'construction plan' drawn up http://www.bbc.co.uk/news/science-environment-38811255
- The Independent: Quantum computing breakthrough could help 'change life completely', say scientists http://www.independent.co.uk/news/science/quantum-computers-quantum-physics-sussex-university-holy-grail-a7558036.html
- Sky News: UK scientists come up with blueprint for Deep Thought supercomputer http://news.sky.com/story/uk-scientists-come-up-with-blueprint-for-deep-thought-supercomputer-10752680
- Scientific American: Physicists Call for a Soccer-Field-Sized Quantum Computer https://www.scientificamerican.com/article/physicists-call-for-a-soccer-field-sized-quantum-computer/
- International Business times: Quantum Computing Update: Researchers Unveil 'Construction Plan' For An Actual Large-Scale Device http://www.ibtimes.com/quantum-computing-update-researchers-unveil-construction-plan-actual-large-scale-2485009

March 2017, Gadget Show – interview with Professor Winfried Hensinger

- https://www.my5.tv/the-gadget-show/season-25/episode-3

July 2017, Naked Scientist Podcast – interview with Professor Winfried Hensinger

- https://www.thenakedscientists.com/articles/interviews/quantum-computer-plans-unveiled

December 2017, BBC Click: "Quantum at Solstice"

- https://www.bbc.co.uk/iplayer/episode/b09jlw4y/click-quantum-at-solstice

December 2017, "University of Oxford Becomes UK Collaborator in IBM's Quantum Computing Network"

- NQIT website: http://www.nqit.ox.ac.uk/news/university-oxford-becomes-uk-collaborator-ibms-quantum-computing-network
- Oxford University News: Oxford Becomes UK Partner in IBM's Quantum Computing Network http://www.ox.ac.uk/news/2017-12-14-oxford-becomes-uk-partner-ibm%E2%80%99s-quantum-computing-network
- Bloomberg Technology: IBM Taps Samsung, JPMorgan, Daimler in Quantum Computing Push https://www.bloomberg.com/news/articles/2017-12-14/ibm-taps-samsung-jpmorgan-daimler-in-quantum-computing-push
- ZDNet: IBM's big quantum push: Samsung, Daimler sign up for 20-qubit test drive https://news.google.com/news/story/d5m27ynu-IPQGbMueYH7h90O1uapM?hl=en&ned=us

January 2018, "Developing a secure, un-hackable quantum network"

- NQIT website: http://www.nqit.ox.ac.uk/news/developing-secure-un-hackable-quantum-network
- New Scientist: Clever maths will stop hackers spying on the quantum internet https://www.newscientist.com/article/2158510-clever-maths-will-stop-hackers-spying-on-the-quantum-internet/

February 2018, "Single Trapped Atom Captures Science Photography Competition's top prize"

- NQIT website: http://www.nqit.ox.ac.uk/news/single-trapped-atom-captures-science-photography-competitions-top-prize
- EPSRC: Single Trapped Atom Captures Science Photography Competition's top prize https://www.epsrc.ac.uk/newsevents/news/single-trapped-atom-captures-science-photography-competitions-top-prize/
- University of Oxford: Image of strontium atom wins national science photography prize http://www.ox.ac.uk/news/science-blog/image-strontium-atom-wins-national-science-photography-prize
- The Independent: Picture of single atom suspended in electric fields wins top science photography prize https://www.independent.co.uk/news/science/atom-photograph-top-prize-strontium-david-nadlinger-oxford-university-engineering-physical-sciences-a8206196.html
- Newsweek: Student pictures single trapped atom, wins national science photography prize http://www.newsweek.com/atoms-photography-prize-806419
- Science Alert: This Photo of a Single Trapped Atom Is Absolutely Breathtaking https://www.sciencealert.com/photo-of-a-single-trapped-atom-wins-uk-science-photo-prize
- PetaPixel: Picture of a Single Atom Wins Science Photo Contest https://petapixel.com/2018/02/12/picture-single-atom-wins-science-photo-contest/

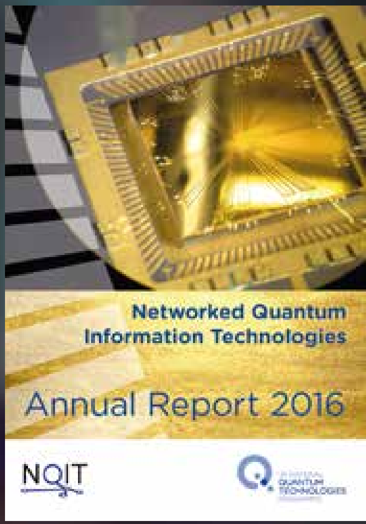
March 2018, "New speed record for trapped-ion 'building blocks' of quantum computers"

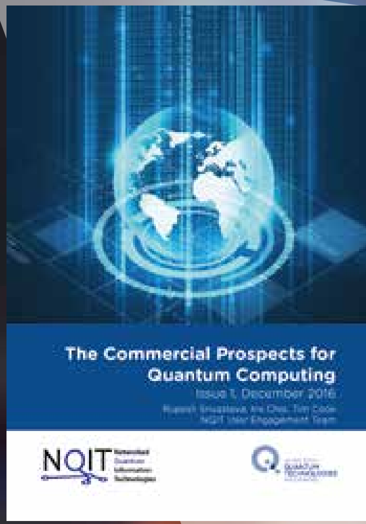
- NQIT website: http://www.nqit.ox.ac.uk/news/new-speed-record-trapped-ion-building-blocks-quantum-computers
- Nature: Fast quantum logic gates with trapped-ion qubits https://www.nature.com/articles/nature25737
- Nature News & Views: Qubits break the sounds barrier https://www.nature.com/articles/d41586-018-02402-6
- Oxford University: New speed record for trapped-ion 'building blocks' of quantum computers http://www.ox.ac.uk/news/2018-03-01-new-speed-record-trapped-ion-building-blocks-quantum-computers
- The Independent: Quantum Breakthrough Massively Speeds Up The Speed of the "Building Blocks" of Computers of the Future https://www.independent.co.uk/life-style/gadgets-and-tech/news/quantum-computing-logic-gates-oxford-university-breakthrough-latest-discovery-a8235281.html

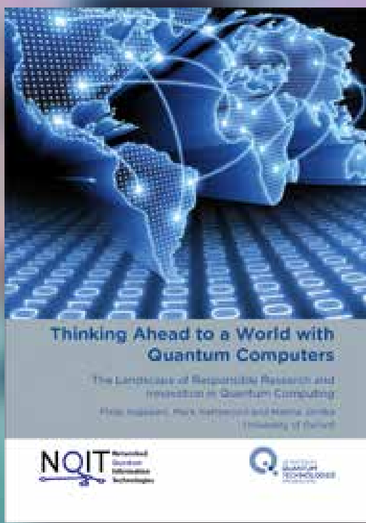
Getting Involved

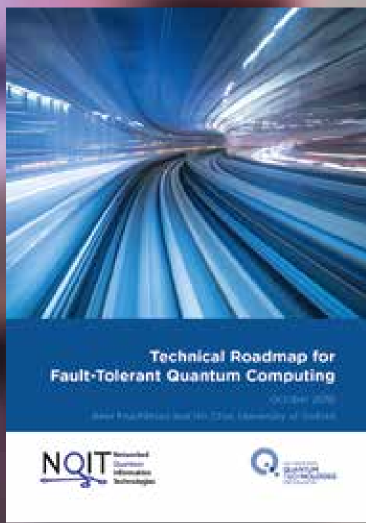
If you have an idea for a quantum technology project that aligns with the aims of the NQIT Hub, please get in touch with our User Engagement Team: engage@nqit.ox.ac.uk

Dr Tom Harty and PhD student Clemens Loschnauer setting up the ion trap optics systems in a standard rack-mounted system / David Fisher









For more information about NQIT, please visit our website:

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NQIT Networked Quantum Information Technologies

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