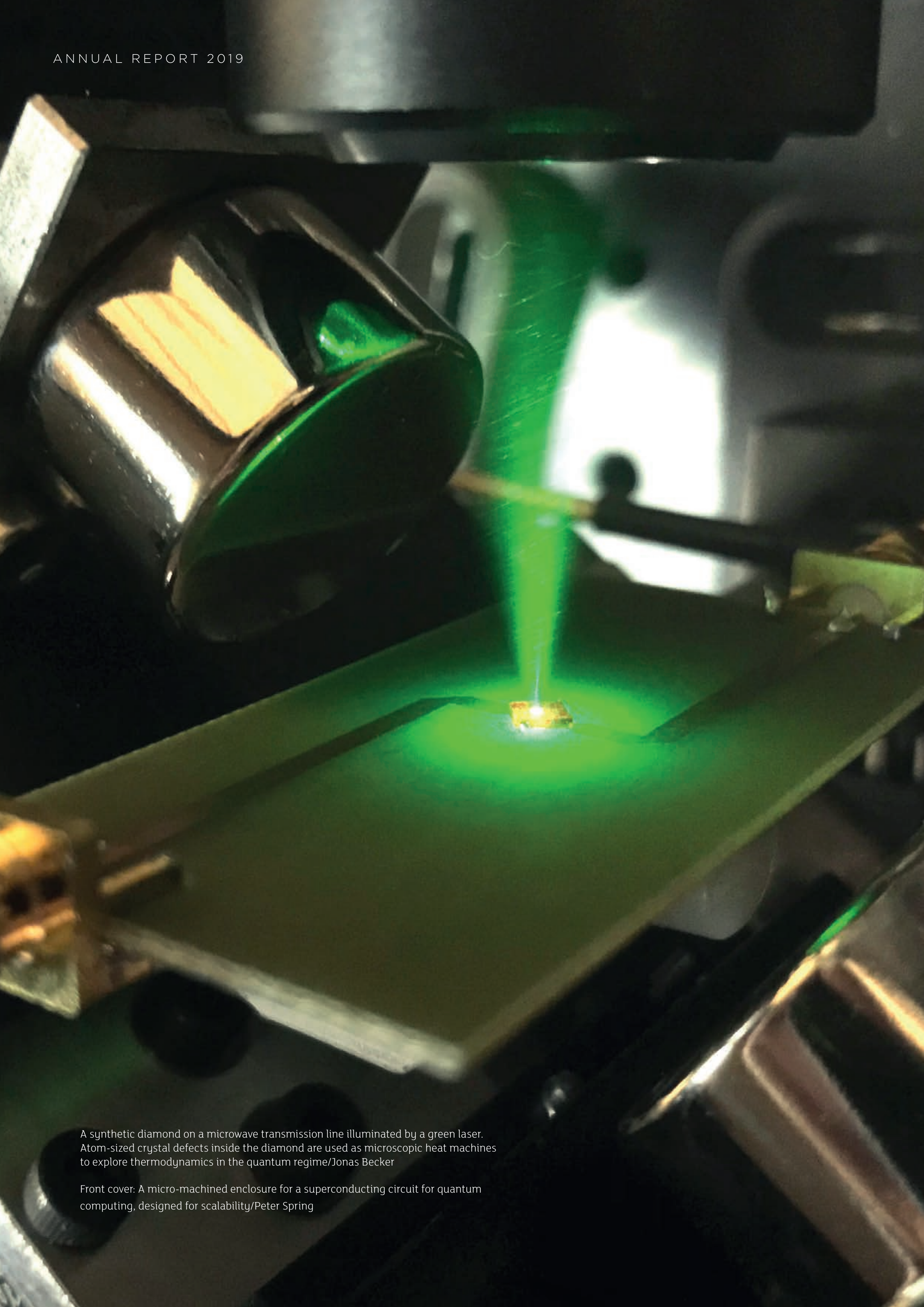
Annual Report 2019

NQIT Networked Quantum Information Technologies

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME



A synthetic diamond on a microwave transmission line illuminated by a green laser. Atom-sized crystal defects inside the diamond are used as microscopic heat machines to explore thermodynamics in the quantum regime/Jonas Becker

Front cover: A micro-machined enclosure for a superconducting circuit for quantum computing, designed for scalability/Peter Spring

Contents

Photo credit: Imperial College London

Foreword

In its fourth year, NQIT continues to lead the UK's efforts in quantum computing, having made significant progress in its hardware programme of developing quantum networks for computing and simulation, in its software and application programme developing algorithms and protocols for using such machines and in building a larger user community for current and future quantum computing devices. We have achieved some key milestones in device design, performance and fabrication that put the UK at the forefront of several platforms internationally.

Our work takes in all aspects of the emerging quantum information technology economy in the UK – from collaborations with the supply chain to engaging with the emerging software sector through to growing a base of skills and awareness. Responsible research and innovation initiatives and continued engagement through broader community and public outreach activities are designed to ensure the widest positive impact of quantum computing so that the UK becomes a fully quantum-literate nation.

Significant benchmarks have been achieved in the underpinning hardware and core technologies necessary for a quantum network, reaching world-beating performance levels in trapped ion logic gates, developing new approaches to superconducting circuits and photonic network components, as well as delivering new science arising from the precise control and manipulation of quantum systems. On the software and applications side, the emulator project is already expanding the range of possible users by enabling them to assess whether their core business applications can be enhanced by running on a quantum computer. The emulation work is supported by software engineering that provides a "front door" for new users.

R&D collaborations in industry-led projects have contributed to understanding more about market forces and the potential use for quantum computing technology by established and new ventures. We have seen growth in the number of collaborations via our user projects, which continue to rise. We have also seen a sharp increase in the number of events, meetings and presentations to industry about future applications and the potential impact of quantum computing. A successful engagement with the space sector, has explored the potential for quantum computing in addressing emerging challenges. We have defined key areas for further exploration at a quantum computing hackathon that will be a first for NQIT.

The recently announced UK government commitment to continuing the UK Quantum Technologies Programme for a further 5-year programme – together with a new world-first National Quantum Computing Centre (NQCC) – will accelerate the progress towards a quantum computer, and will keep the UK at the forefront of this global race. Increased leadership from the emerging industry sector, harnessing the Industrial Strategy Challenge Fund, has enabled new and stronger partnerships between universities and businesses, helping to establish the sector and supply chain.

The results of the first phase of the UK Programme were also considered in detail in 2018 by the House of Commons Science & Technology Committee's Quantum Technologies enquiry, to which we provided written and oral evidence. The Committee's report, endorsed by the Government, urges that quantum technologies offer the potential for significant economic growth and improved capabilities across multiple industry sectors.

More than three quarters of the way through NQIT's five-year programme, it is heartening to see NQIT's vision becoming a reality, positioning the UK to be a leader in delivering the next information revolution.

Professor Ian Walmsley FRS

Director of NQIT

Provost & Chair in Experimental Physics, Imperial College London

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 over four years (2014 – 2019) by the UK government to establish a quantum technology industry in the UK.

Aim

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

Objectives

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, and through training, collaboration and knowledge transfer
- Engage with the wider public.

Our programme at a glance

Industry Engagement

This key part of our strategy involves different strands of activity. We work with industry partners, both in research collaboration and through industry events, such as our annual Industry Day and National Quantum Technologies Showcase, in order to gain insights into business challenges and how quantum computing might transform ideas and businesses. NQIT has also stimulated innovation through technology spin-outs and start-ups.

Technology overview

Since the commencement of NQIT in 2014 we have significantly progressed our ion trap engineering. We have connected 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. 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.

Wider Engagement

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

Skills and training

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

Future plans

We are beginning to plan for the second phase of the UK National Quantum Technologies Programme and quantum computing and simulation in particular. 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.

Programme Structure

NQIT

Industry Engagement

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

Hardware & Engineering

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

Applications & Software

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

Wider Engagement

- Outreach events: science festivals, museum exhibitions, online and social media presence
- Responsible Research and Innovation: workshops, case studies, reports, dialogue
- Reports and publications
- News, TV, podcasts
- Inter-hub collaboration

Skills & Training

- Skills Forum
- Graduate Studentships
- Careers in Quantum

NQIT, the UK's quantum computing technologies hub

Positioning the UK to be a leader in delivering quantum computing and the next technology revolution

Achievements to date

Key milestones in device design and performance

4
world records in ion trap quantum computing

2
new patents granted

61
research papers produced

69
invitations to speak at international scientific events

1,500+
unique visitors to QuEST, the open source quantum simulator/toolkit

Greater collaboration and engagement with industry

140+
companies, national and international

100%
increase in attendance at Industry Day

34
industry-partnered Projects

5
spinout companies, one in the pipeline

50
companies identified for quantum readiness

Increased reach to wider society

25
public events (lectures, exhibitions, festivals)

2,000+
Twitter followers

#
#QuantumCity launched

10,000+
visitors/school visits at science festivals

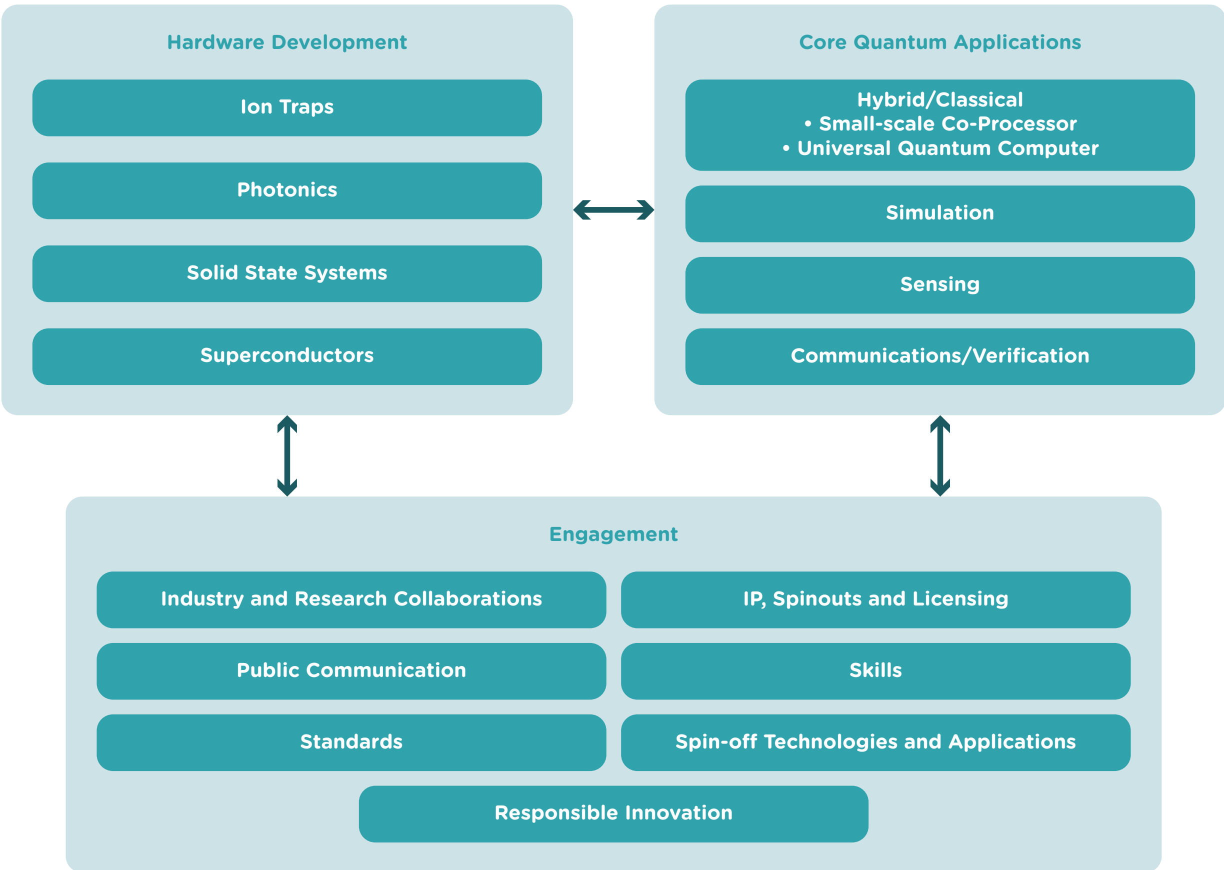
15%
growth in website visitors

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, Imperial College London and Sheffield.

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.

Programme Organisation



UK Partners

UKNQT Partners

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

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

New Academic Collaborators

1. University of Bristol
2. Durham University
3. Heriot Watt University
4. Imperial College London
5. The University Of Sheffield.

Other Quantum Technology Hubs

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

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

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

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

Cognizant

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®

pureLiFi

Raytheon

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 two decades and he has helped drive 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. 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 recent role as President of the Optical Society (OSA). His research group in ultrafast quantum optics and optical metrology contributes directly to the work of both NQIT and QuanTIC, through the development of new methods and platforms for quantum simulation, quantum networking and quantum imaging using light.

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, with more than 200 publications in this area and eight patents granted or in progress.

Evert Geurtsen, Co-Director for User Engagement

Evert Geurtsen joined NQIT in 2017 and is based at the Technology and Innovation Centre of Strathclyde University in Glasgow. His previous role was Head of Licensing and Ventures for the Physical Sciences at Oxford University Innovation (OUI) where he and his team helped founders to start more than 50 new ventures, created the Oxford Startup Incubator, secured licence agreements for many Oxford inventions and software programmes and initiated a greater engagement with the Humanities and Social Sciences.

Prior to joining the university sector Evert worked in industry, where he led complex engineering projects and held directorships in the automotive industry at large and medium-sized companies 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)

Professor Ian Walmsley
(University of Oxford/Imperial College London)

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)

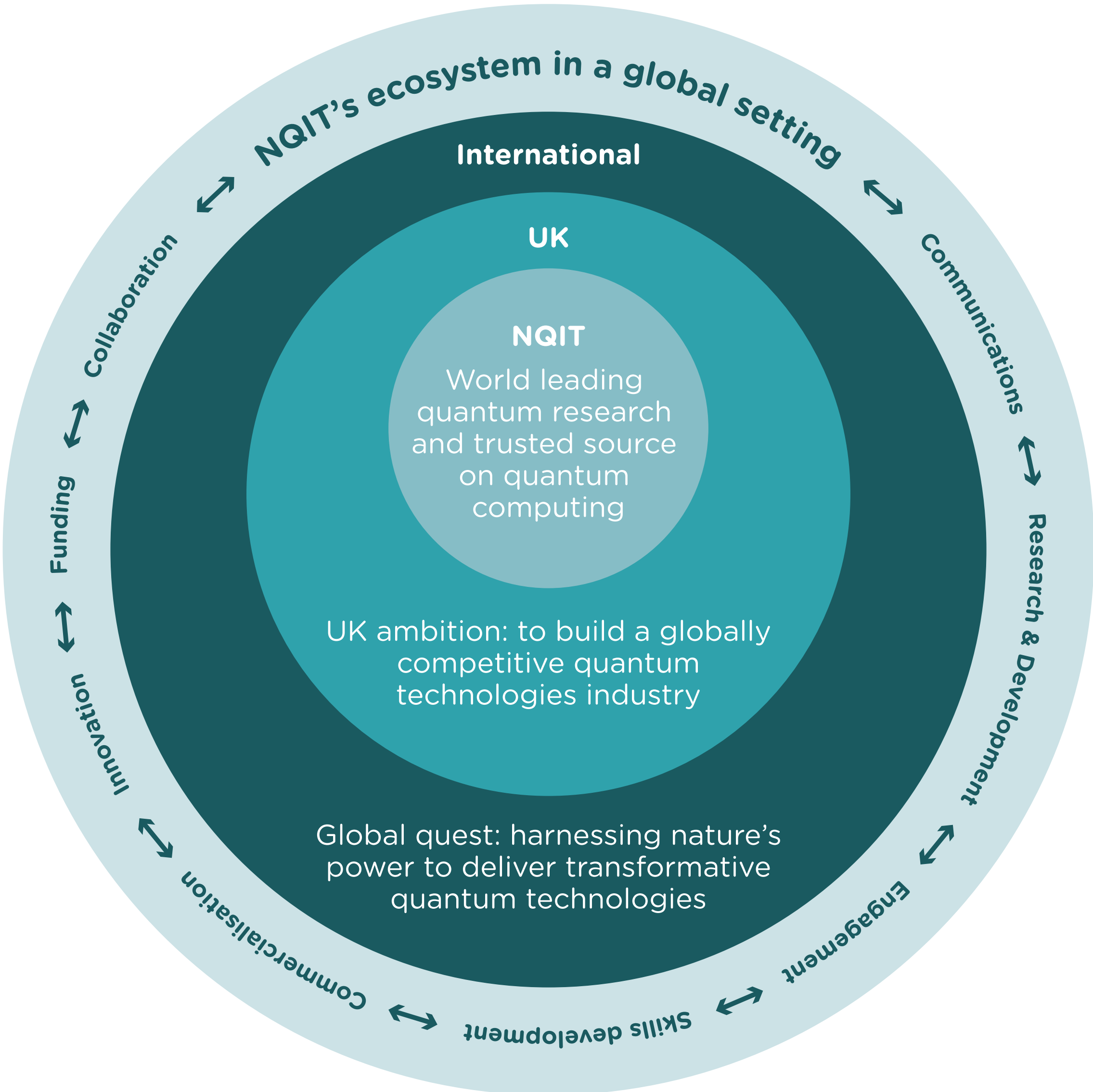
Professor Dominic O'Brien (University of Oxford)
Work Package Leader

Professor Christopher Stevens (University of Oxford)

Responsible Research and Innovation

Professor Marina Jirotka (University of Oxford)
Work Package Leader

NQIT's ecosystem in a global setting



International

Multinational companies, other national programmes

- European Flagship on Quantum Technologies
- U.S. National Quantum Initiative Act
- Expanded IBM Q Network
- Google's first major international academic collaboration in the UK
- Growth in global investment

UK

UK National Quantum Technologies Programme

- Industrial Strategy Challenge Fund
- UK RI EPSRC
- Spinout and startup companies

NQIT

NQIT Hub

- World leading quantum research
- Hardware, Software, Applications
- Engagement and partnership with Industry

Quantum computing in a global context

Quantum computing scientists and technologists around the world are making good progress on all fronts. The leading qubit technologies are on a steady path to reduce error rates – a problem to date. They are also learning how to scale machines, i.e. build more qubits and connect them together, the latter presenting another technical challenge. Although few will commit to a timeline, the developments provide ample confidence that fault-tolerant quantum computers are technically possible and will become an important part of the IT landscape.

It is exciting to see that interest in quantum computing is increasing, with significant developments in national programmes, commercial activities and investment. The list below is not exhaustive but provides a snapshot of some of the major developments worldwide:

- The UK has announced that its pioneering National Quantum Technologies Programme will be extended for a further five years, and the UK will also establish a National Quantum Computing Centre to support and augment the UK's quantum computing industry.
- In the EU, the Quantum Flagship has launched 20 projects across quantum technologies with OpenSuperQ (€10.3 million) and AQTION (€9.58 million) relevant to quantum computing (UK-based NQIT researchers participate in both these projects).
- In December 2018, the USA passed the National Quantum Initiative Act to co-ordinate efforts and accelerate the development of quantum computing with $1.2 billion funding over five years.
- IBM has continued to expand its Q Network, with Oxford University being selected as a Hub partner. The IBM Q Oxford Hub was launched in June with a series of industry and skills events. Later in the year IBM also unveiled further developments in its quantum computing platform: the IBM System One.
- Google has launched their first major international academic collaboration in the UK with a £5.5 million prosperity partnership over five years with Bristol University and University College London, to study and develop quantum software for modelling and simulation.
- D Wave announced Pegasus, a new quantum annealing platform, with support for 5,000 qubits, that will come to market in 2020. With the much higher number of qubits combined with the much higher connectivity this should enable quantum programmers to tackle more complex challenges.
- There has been a growth in start-up companies with investors from around the world establishing quantum portfolios. Several UK spinouts have raised investment and are proving internationally competitive.
- We are also seeing new hardware startups, including multi-million investments in Oxford Quantum Computing and Quantum Motion Technologies in the UK.
- The number of reports on the global value of quantum computing is increasing, with market research firms forecasting the value of quantum computing and providing trends in regional growth and new market opportunities.

The quantum workforce is global and globally mobile, which presents challenges and opportunities and must continue to be addressed. Prizes such as Rigetti's $1million Quantum Advantage Prize and Airbus' Quantum Computing Challenge offer enticements, for both companies and individuals.

Ian Walmsley, Director of NQIT, addresses Industry Day participants at Saïd Business School/David Fisher

IBM Q exhibition comes to the foyer of Beecroft Building/John Cairns

Industry Day 2018 was our second such event, held in June in Oxford. It was a day dedicated to quantum computing and the opportunities for business to engage with the NQIT team/David Fisher

Industry Engagement

NQIT's User Engagement activities work on all aspects of the emerging quantum information technology economy – from collaborations with the supply chain to supporting and engaging with the emerging software sector to growing a base of skills and awareness. Since the start of the programme NQIT has engaged with more than 140 companies, both national and international.

Collaboration

NQIT has set aside substantial funding to support promising quantum technology projects that have early commercialisation potential. User Projects are the collaborations between researchers in NQIT and companies or other academics outside the NQIT network. They have been a very productive tool to encourage access to industry's expertise and capabilities, facilitate industrial participation and embrace new research that was not part of the original 2014 plan but has become relevant to the NQIT mission. To the end of 2018, 34 User Projects have been approved, with four more applications to be considered.

The nature of the User Projects is as follows:

- Research to develop enabling technologies (22 out of the 34 projects approved)
- Theory, software tools and algorithms (four out of the 34 projects approved)
- Application development or impact reports (eight out of the 34 approved)

In software and applications they include established international system vendors, new UK quantum ventures and future users in the aerospace and logistics sectors, amongst others.

Academic institutions not in the NQIT network but engaged through Partnership Resources are Sheffield, Durham and Heriot-Watt.

We have noted a growing interest and willingness by companies to engage on applications, as is evident in their attendance at meetings and events. As yet, however, these often do not progress to research collaborations because the platforms on which they can experiment are at an early stage. The contribution by the collaborators to the total costs of User Projects has remained at around two thirds of total project costs – a very encouraging sign of industry's willingness to invest in collaborative R&D in this field.

Impact and Industry Achievements

Intellectual Property – in the form of new know-how, discoveries and disclosures – is expected from developments in the NQIT universities: of Warwick, Sussex and Bath, amongst others. They will join an existing list of inventions for which the University of Oxford has applied for patent protection. There are a growing number of startups and spinout companies and we expect these new ventures will be the most likely licensees of the majority of IP-registered products and inventions.

The User Project involving IBM, Sheffield and Oxford plans to release its results as Open Source Software to encourage more future users. The same is planned for the QuEST Emulator software being developed under the dedicated Partnership Project, which aims to make it available as an efficient and comprehensive development tool for companies and researchers who wish to experiment in quantum programming.

Last year, NQIT teams reported three completed spinouts (Oxford Quantum Circuits, Quantum Motion Technologies and Oxford HighQ), a completed startup (Verivin) and one spinout in the pipeline (Oxford Quantum Engineering). The completed spinouts and startup are all operational, have raised funding and are employing staff. Also formed last year in France and independent of NQIT is VeriQloud, whose co-founders, Elham Kashefi, Josh Nunn and Marc Kaplan, are exploring a research collaboration as a User Project as part of growing their business activity in the UK.

The current pipeline of spinouts includes a quantum computing engineering spinout from Oxford University, Universal Quantum; a quantum computing spinout from Sussex University; a quantum photonics spinout from University of Bath and Imperial University; and a quantum sensing spinout from Warwick University.

The hub and its partners continue to work closely with UK startups, including Cambridge Quantum Computing (Cambridge), Riverlane Quantum Computing (Cambridge), Phasecraft (UCL), KETS Quantum Security (Bristol), Q&I (UCL, Oxford, Edinburgh and Bristol) and Rahko (UCL).

The Bristol Quantum Technology Enterprise Centre (QTEC) is stimulating and supporting further quantum entrepreneurship, including Nu Quantum, a spinout from Cambridge University. QTEC was a partner in the most recent NQIT Skills Forum.

Industrial Engagement

The NQIT Industry Day 2018 was held at the Saïd Business School, Oxford. This was the second such event and attendance was nearly double what it was in 2017, with a higher level of seniority in attendees and more international participation. We used the event to showcase the UK quantum computing ecosystem, for example the innovation and entrepreneurship activities in Bristol, the solid-state technology developments in UCL and the software activities in Sheffield. More than half the day's presentation content was provided by companies including Cambridge Quantum Computing, QxBranch, IBM, D-Wave and others. The audience included investors and one of the presenters spoke for IP Group, a leading intellectual property commercialisation company. Will Hutton was one of the keynote speakers, providing a socio-economic perspective on disruptive technologies such as quantum computing.

NQIT supported the UK Quantum Technologies Showcase event in London in November, attended by over 700 delegates. NQIT had a Hub stand, with a further nine individual stands from our investigators across many of the exhibition sectors.

As well as the NQIT Industry Day, a number of other events have been organised or attended by NQIT to increase awareness and stimulate participation in industry:

- Alan Turing Gateway, Quantum Applications event, Cambridge (KTN)
- Oil & Gas Industry and Quantum Technologies, Sunbury (BP), InnovateUK
- Space Industry Quantum Workshop, Oxford, NQIT
- BAE Systems Quantum Workshop, London, BAE Systems
- Quantum Computing for Planning and Scheduling, London, QCAPS and Plantagenet
- Bristol Quantum Information Technologies Workshop, Bristol, BTEQ
- AFME Annual Conference Quantum Technology Panel, AFME/IBM

The NQIT presence at these events and others has resulted in contacts with more than 140 companies, helping to stimulate awareness of and interest in quantum computing and its potential impact.

Alongside raising industrial interest, we also organised a workshop for scientists in the fields of chemistry, structural biology, materials, mathematics and bio-informatics. This is an area of interest that merits further workshops and encouragement.

In October 2018 Riverlane, Dividiti and NQIT co-organised a Quantum Hackathon in Shoreditch, London. We intend to hold a similar event in early 2019.

Two new public reports have been published:

- NQIT 2018 Annual Report (June 2018)
- Responsible Innovation in Quantum Technologies applied to Defence and National Security (RRI, November 2018)

Towards the end of 2019 we will publish our final annual report and write a final report setting out our achievements over the five years, summarising the state of the project and the technical and impact achievements.

Quantum Readiness and IBM Q Partnership

In 2018 Oxford University entered into an agreement with IBM Q to work jointly on the concept of Quantum Readiness. The agreement provides the scientists at Oxford with access to IBM quantum computing equipment and software; Oxford and NQIT will support IBM's users with advice and access to researchers.

Alongside the IBM Q Project in Oxford, a collaboration with CQC on Quantum Readiness is further intended to raise awareness in industry and science of the possibilities and challenges of future quantum computing. The elements we wish to develop are awareness and education, early access for experimentation and skills development, and the discovery and definition of applications, especially for the intermediate-scale devices that are now on the horizon.

Other Engagements

NQIT provided written and oral evidence to the House of Commons Science & Technology Committee in 2018, together with the other Hubs. It also took part in the industry consultation organised by the Department for Business, Energy & Industrial Strategy (BEIS) and the Quantum Technologies Advisory Panel organised by the Department for Digital, Culture, Media & Sport (DCMS) and BEIS.

NQIT continues to play a strong part in the UK National Quantum Technologies Programme, including supporting the Industrial Strategy Challenge Fund, Centres for Doctoral Training, Fellowships and other funding initiatives.

Roger McKinley, Challenge Director: Quantum Technologies, at UKRI, addresses the Quantum Technologies Showcase held in central London/Dan Tsantilis

Amy Hughes, D Phil student in the Oxford ion trap laboratory, adjusting rack-mounted optics. /Rupesh Srivastava

Hardware & Engineering

The NQIT research and development programme is divided into Work Packages – five of them related to Architecture, Hardware and Engineering covering multiple approaches to qubit development, the interconnections between qubits and engineering systems integration.

Highlights of the year include:

- performance of our core architecture by means of the "quantum volume" metric gives good reason to continue with the ion-photon network approach.
- achievement of remote entanglement of two ions by the network, with world-leading performance in fidelity and the potential to achieve this at higher bit rates.
- significant benchmarks in the underpinning core technologies, reaching new performance levels in trapped-ion logic gates, superconducting circuits and photonic network components, as well as delivering new science.
- further progress with the Sussex modular design prototype, as well as techniques to improve gate robustness
- single-step quantum conversion of blue light (at ion emission wavelengths) to wavelengths used for transmission of signals in fibre over longs distances (c-band light);
- a new method for deterministic writing of colour-centre defects in diamond, with applications in quantum networks
- quantum random number generators are a key early application for quantum technologies and results implementing a patented design for authenticated all-optical entropy generation are being prepared for publication

Progress in each of these key areas is set out on the following pages.

Ion Trap Node Engineering

Charged atoms or ions are one of the most promising physical systems to build practical quantum computers. Within NQIT, we are working on two complementary quantum computing demonstrators. The Oxford 20:20 engine consists of quantum computing modules which are connected using optical fibres (photonic interconnects) with logical quantum gates being executed making use of laser beams. The second demonstrator, the Sussex Modular Microwave Engine consists of quantum computing modules connected via electric fields with quantum gates being executed by the application of a voltages on a microchip making use of microwave technology.

It has been an exciting year for the Oxford group. Going into the final year of NQIT, we obtained key results from the UK's first elementary quantum network – a system of two ion traps linked by a quantum-optical fibre interface. We were able to prove that we had entangled two trapped-ion qubits, one at each end of the link. Initially the rate at which we could generate entanglement was fairly low, but within a matter of weeks we had exceeded the fastest rate ever achieved for this type of experiment. Another key ingredient is the ability to perform quantum logic between two different species of trapped-ion qubit, in this case calcium and strontium ions. Although we performed an initial demonstration of this back in 2016, the precision of the operation was poor; we have now improved this until it is now at least as high as any previous demonstration worldwide. In the final year of NQIT we will be combining these techniques to attempt *entanglement distillation* across the network – this is an essential algorithm necessary for our vision of networked modular quantum computation. We will also use these techniques in a partnership project with quantum startup VeriQloud, to demonstrate the key ideas behind "blind" quantum computing, a network protocol that allows users to access a quantum computer without the need to divulge the program code itself.

Sussex University has made a major breakthrough concerning one of the biggest problems facing quantum computing. In the real world, technological solutions need to operate in imperfect conditions; what can be successfully tested in a highly controlled laboratory may fail when presented with realistic environmental factors, such as the fluctuations in voltages from electronic components or stray electromagnetic fields emitted by everyday electronic equipment. Making use of radio-frequency signals capable of manipulating the quantum effects in individual charged atoms (ions), the Sussex team managed to reduce substantially the effect of such environmental effects on the operation of a trapped-ion quantum computer. This is particularly important for constructing quantum computers that can host millions of qubits and will pave the way towards construction of practical devices. The Sussex team was also successful in manufacturing a new generation of ion microchips that enable ion transport from one quantum computing module to another quantum computing module making use of electric field connections. These microchips are at the core of the quantum computer prototype at Sussex – now nearly complete – which also features a fully functional cooling system to dissipate the heat generated by the quantum computing microchips.

Photonic Network Engineering

Photonics is a critical platform technology for quantum information processing because light, made up of streams of photons, can carry quantum information along optical fibres. A key goal of NQIT is to develop quantum computers in which atoms are connected by optical fibre links, and we are developing these links alongside techniques to convert the wavelength of the light from blue – matching our trapped strontium atoms – to infra-red c-band wavelengths – best for fibre transmission.

An interesting feature of light is the way its constituent photons distribute themselves when a light beam is split. We have used the photon statistics downstream from a single beam splitter to generate certified random numbers, and we have shown how the statistics produced by many beam splitters reveals signatures of quantum computational complexity. These techniques could have applications in secure communications and quantum simulation of molecular chemistry. We have also demonstrated how such simple linear optical primitives can be used to simulate molecular spectra, and to estimate efficiently some of the parameters that describe the molecules. The impact of imperfections in the input quantum states, as well as the losses inherent in any integrated circuits, has been shown to be critical to maintaining asymptotic scaling advantages. This is important for the next generation of NISQ processors.

Over the past year our researchers also established that silicon atoms in diamond interact very strongly with light, which could make it possible to amplify or buffer optical signals in diamond, and we have used a green laser to drive magnetic oscillations of nitrogen atoms in diamond, showing how quantum coherence boosts the efficiency of a nano-scale quantum heat engine beyond the classical limits.

Methods for multiplexing photonic signals by storing them or shifting their frequencies remain an important research direction, and we have continued to develop technologies for generating, manipulating and detecting photons in waveguides.

In the remaining months of NQIT we hope to deploy a fibre link to connect the quantum states of two trapped atoms – something that has already been achieved with a free-space link in Oxford. We are working on intermediate wavelength conversion (Bath), quantum interferometry (Oxford), cavity-enhanced photon sources (Imperial) and switching based on Kerr and Brillouin non-linearities (Bath). The work will provide crucial underpinning capabilities for future developments.

Alternative Qubits

Diamond Qubits

In what could prove to be a significant breakthrough in the engineering of solid state quantum devices, NQIT researchers have developed a method for writing individual colour centre defects in diamond using laser processing with near-unity yield. Building on their previous work to write nitrogen-vacancy (NV) centres using a tightly focused laser pulse to create vacancies followed by thermal annealing, the new method utilises an extended sequence of laser pulses – first to create and then to mobilise the vacancies until binding to a nitrogen impurity occurs and an NV centre is formed. A sensitive fluorescence monitor is employed to detect light emitted from the region being processed, such that the process can be actively controlled in response to the observed signal.

By combining local control and feedback, the new method facilitates the production of arrays of single NV centres with exactly one colour centre at each site – a key capability in building scalable technologies. Two or more NV centres can be created per site as desired, and a degree of control can be exercised over the defect orientation in the crystal lattice and the local environment. The rapid single-step process is easily automated with each NV centre taking only seconds to create. This was demonstrated at the 2018 Quantum Technology Showcase, where visitors controlled the laser in the Oxford lab via an internet link from the QEII centre in London to write their own qubits!

Having demonstrated the basic process, the team is now investigating its optimisation for use in producing arrays of high-quality qubits. Their ultimate goal is to use the method to fabricate centimetre-scale diamond chips containing ~100,000 qubits as a route towards universal fault-tolerant quantum computing. In the nearer term the technique will allow the engineering of advanced diamond materials for quantum sensors, contributing to emerging commercial activity in this area. At the time of writing the work has been accepted for publication in the journal *Optica*.

Superconducting Qubits

Superconducting qubits – built from electrical circuits fabricated from superconductors and operated at microwave frequencies at very low temperatures – are a popular quantum computing technology being pursued worldwide and are the first to be commercialised. In Oxford, we are continuing the development of a novel and patented superconducting circuit architecture that combines high-coherence qubits and 3D connectivity to build scalable systems. We have already proven our architecture in 2-qubit prototypes. Building upon this success we now have developed first prototype 4-qubit circuits, with average measured single-qubit gate fidelities of 99.5%, and average two-qubit gate fidelities of 90%. We have also developed and filed a patent on a key new technical improvement to our architecture to eliminate problems associated with scaling up microwave circuits. This involves micro-machining special enclosures for our circuits with features that penetrate the chips and connect to the other side, effectively 'shorting' out microwave modes of the enclosure that can interact undesirably with the qubits. We are continuing to work hard towards improving the metrics of our small-scale circuits and building a larger-scale quantum computing demonstrator, with support from our spinout company, Oxford Quantum Circuits (OCQ), and the state-of-the-art laboratories in the new Oxford Physics Beecroft Building.

Atom-photon Interfaces

NQIT's approaches to building the core components of a quantum computer is based on a distributed architecture of small processors interconnected by optical links. Building one large system which allows full control of its constituent physical qubits 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 it becomes to minimise losses. To resolve this, reliable and efficient interfaces between atoms and photons are required. We have defined a roadmap to quantum networking by light-matter interactions, mapping a path to integrated quantum interfaces and building on the successes of this work package. The University of Oxford team has successfully demonstrated over 60% of the milestones of this roadmap with neutral atoms.

To harvest photons efficiently from highly localised emitters requires smaller cavities than currently exist. Together we are pushing the boundaries of micro-cavity engineering with micro-cavity arrays for multiple emitters and fibre assemblies to improve the interface efficiency. We have fabricated large arrays of hundreds of cavity mirror substrates with high repeatability, and have tested 125 μm fibre micro-cavity in an operational environment. Working at small scales – with highly curved mirrors – leads to a pronounced cavity birefringence. Exploring the light-matter interaction in this uncharted regime, we have highlighted how non-linearities and birefringence can be employed to beat most standard limits of photon emission. Further demonstrations with these cavities for quantum networks rely on our ability to deterministically place single emitters in cavities with microscopic precision.

Having demonstrated many core principles encompassed by the roadmap, we are embarking on a journey of integrating these technologies for practical quantum networking. Looking ahead, a key capability will be the Oxford team's ability to produce large arrays of micro-cavities reliably and at a competitive cost. The Sussex team plans to create a fibre-fibre-linked interface between two ion traps this year. Ultimately, we will develop our capabilities to implement a quantum network of a useful scale and dimension.

Core Engineering Capabilities

The NQIT team has made excellent progress in developing and implementing the electronics, optics and software required to control our key demonstrations. The engineering work package continues to contribute to a global collaboration on quantum control system development for delivering electronic hardware and firmware.

Effort has also been made on generating more precise and modularised timing control signals to support future networking of the processors. A real-time verification instrument has been developed and is being finalised with a major test-equipment manufacturer. The instrument enables easy debugging and rapid diagnostics for scaled-up control systems.

The first prototype of a beam delivery system, which has been manufactured and assembled, combines up to five incoming laser wavelengths delivered from optical fibres and directs them into the vacuum chamber, which contains the ions in the Q5:50 module. The system significantly simplifies laser beam alignment tasks when preparing quantum computing experiments. The assembly and alignment procedure for the system is being optimised, and stability testing is being prepared.

A waveguide writing facility forms part of NQIT core engineering capabilities. This facility is fully operational, with automatic depth adaptability and writing laser power regulation and was used to demonstrate a photonic Majorana bound state – a significant breakthrough in realistic photonic topological quantum simulation. In addition to waveguide and photonic integrated circuits (PIC) fabrication, diagnostic and testing techniques, including the in-situ testing of individual elements, is being developed.

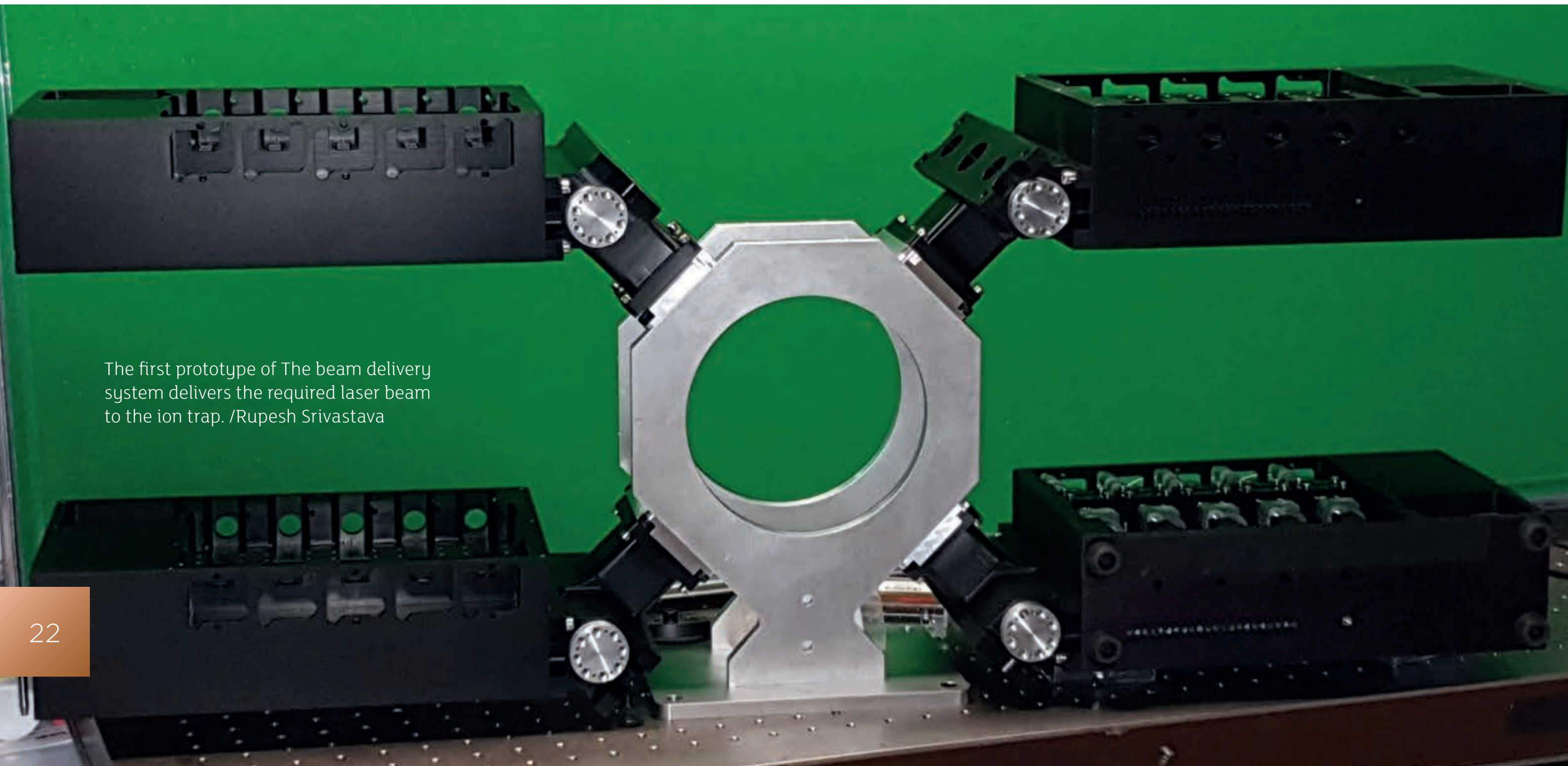
Architecture Progress

Machine learning, optimisation, and quantum computing are dynamic research fields that have undergone tremendous developments in the past few decades. As interdisciplinary fields, both quantum optimisation and quantum machine learning have strong impact on quantum computing for solving classically intractable problems. Targeting quantum simulation of many-body systems, including chemistry, biology, and condensed matters, we aim to apply techniques in optimisation and machine learning for advancing existing quantum algorithms.

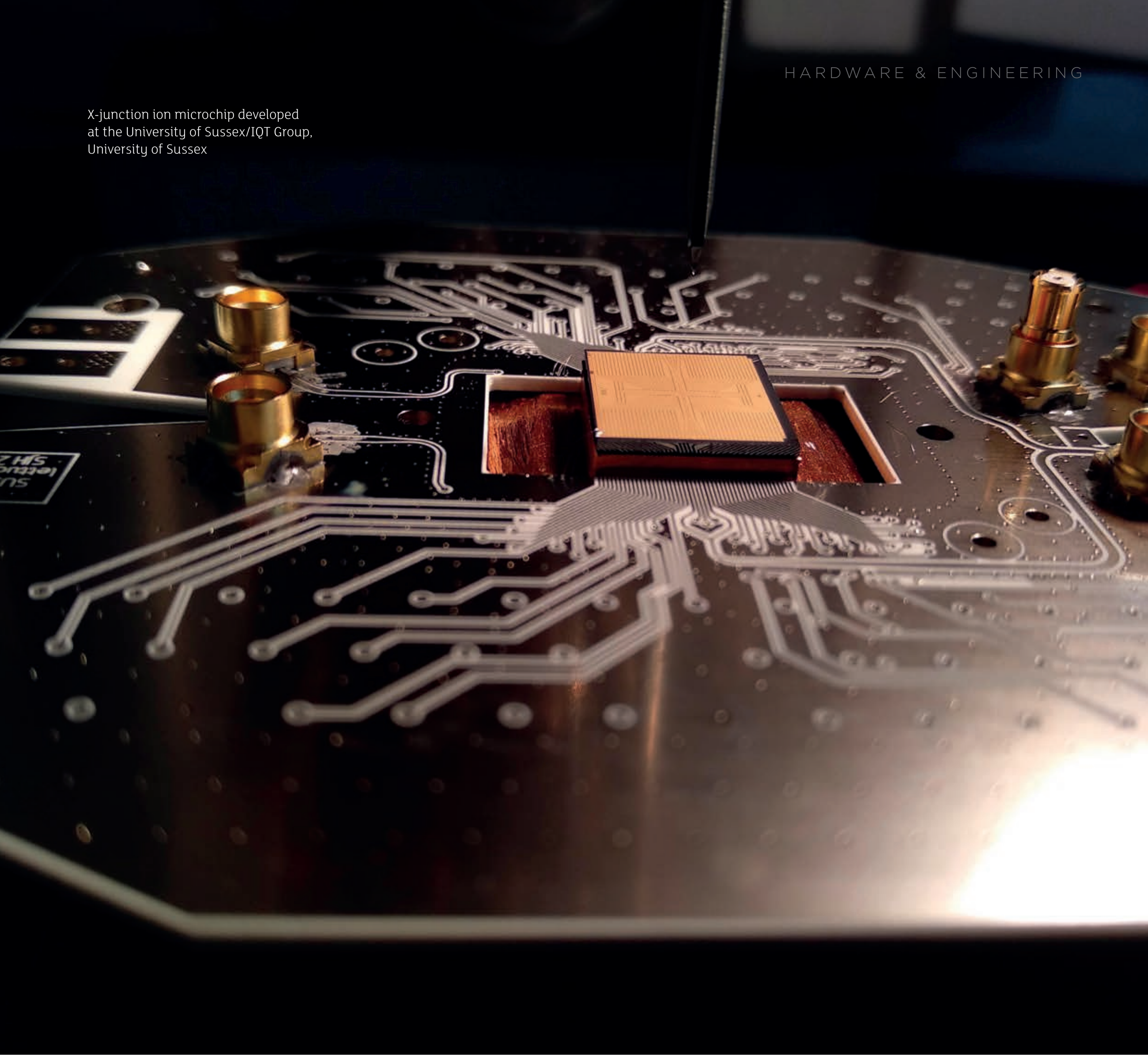
Our work in the area of Quantum Optimisation and Machine Learning overlaps strongly with our efforts on Architectures, Standards and Systems integration. For example, the question of selecting the appropriate circuit layout (in hybrid quantum-classical computing, often called the ansatz) depends on the efficiency with which different layouts can be realised. Moreover, the question of overcoming noise in a quantum computer lies at the heart of both architectural design and the design of practical near-term algorithms.

Focusing on near-term quantum hardware, we studied a novel measurement-driven model for optimisation. This, and other work, was enabled by our fast emulator which allows conventional computers to mimic small quantum computers. More broadly, we developed a suite of variational algorithms for problems including electronic structures, molecular vibrations, combinatory optimization, linear algebra, and general open quantum systems. We show how quantum optimisation and machine learning methods can be applied to solve these problems. On the crucial topic of noise, we studied quantum simulation with noisy intermediate-scale quantum (NISQ) devices and showed how errors can be suppressed with error mitigation methods. With these results, we have appreciably increased the prospects for real-world benefits from NISQ hardware with potential applications in chemistry, biology, and materials science.

Meanwhile, collaborating with Professor Alán Aspuru-Guzik from the University of Toronto, we finished a review article for the field of computational quantum chemistry. We reviewed the latest developments with a discussion of potential applications and challenges with NISQ hardware and a universal quantum computer.

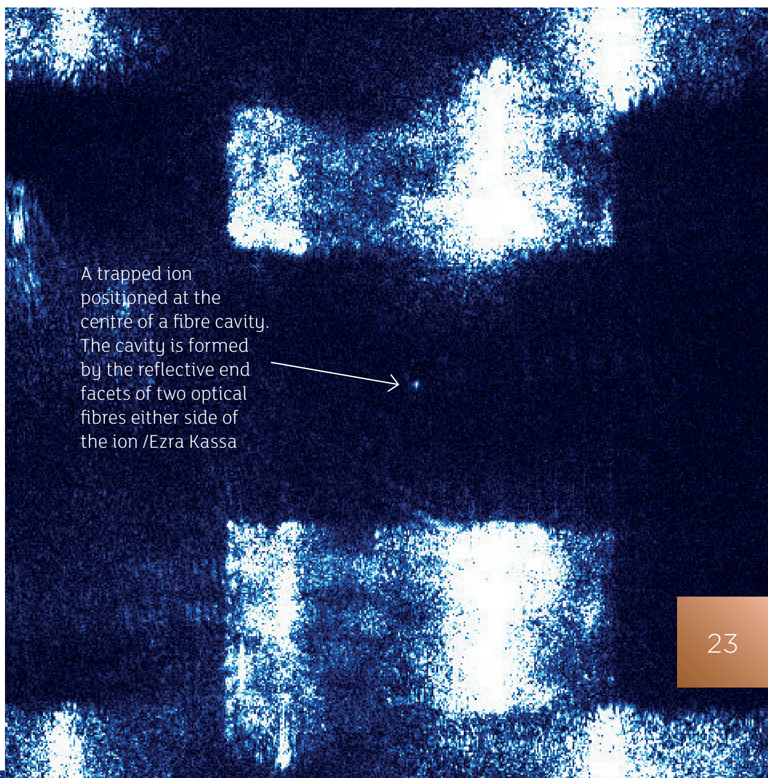


The first prototype of The beam delivery system delivers the required laser beam to the ion trap. /Rupesh Srivastava

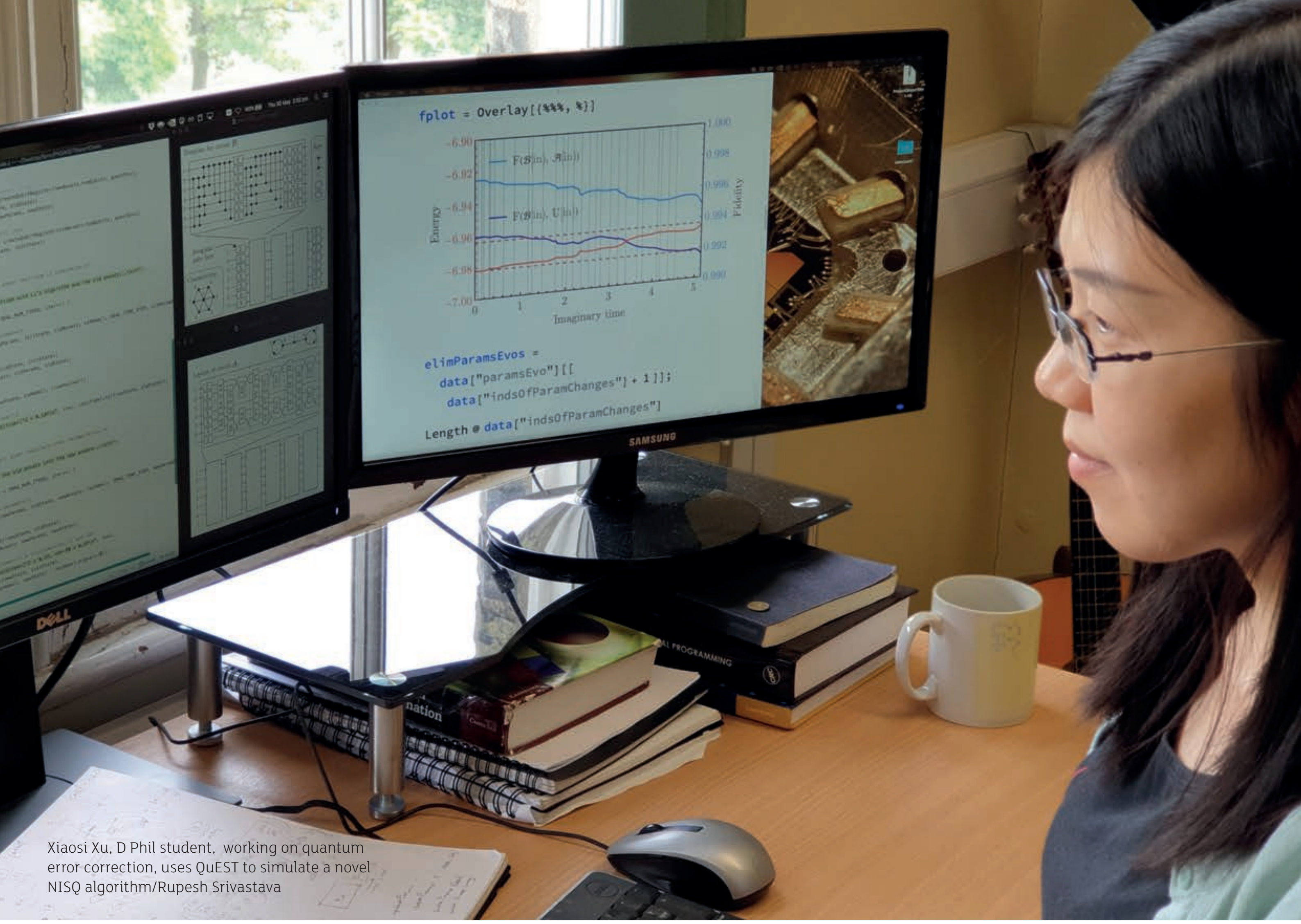


X-junction ion microchip developed at the University of Sussex/IQT Group, University of Sussex

The beam combiner can combine five different wavelengths to deliver to an ion trap /Rupesh Srivastava

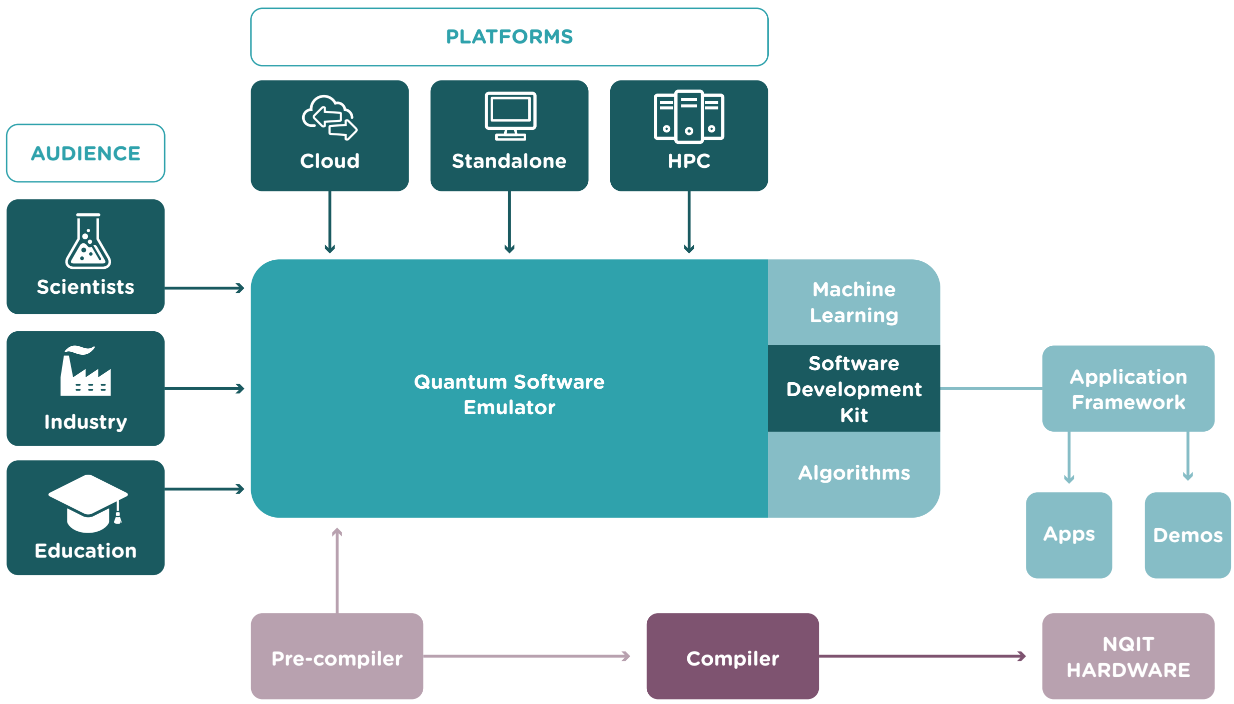


A trapped ion positioned at the centre of a fibre cavity. The cavity is formed by the reflective end facets of two optical fibres either side of the ion /Ezra Kassa



Xiaosi Xu, D Phil student, working on quantum error correction, uses QuEST to simulate a novel NISQ algorithm/Rupesh Srivastava

Application development ecosystem



Applications & Software

Our applications programme is aimed at providing the tools to make the Q20:20 engine available to users, in order to develop ways that it can be used to solve real-world problems. With access to near-term platforms for experimentation and NQIT's emulator programme we are encouraging scientists, engineers and industrial researchers to learn about the potential future range of applications, from simulating new molecules to enhancing artificial intelligence.

Secure Network Applications

This work package is designed as a part of NQIT to enable the users to perform secure communication and computation across various networks. This includes cryptographic instances such as quantum key distribution, where the end-to-end users perform secure communication in the presence of an eavesdropper; quantum money where the bank distributes the notes among untrusted users and has robust verification against a note counterfeiter; secure quantum e-voting where the process of casting the vote by eligible voters is private and ensures no voter casts a double vote; and various other applications. We also include blind quantum computation where a weak client (typically classical or with limited quantum resource) delegates a quantum computation to a powerful quantum server while maintaining the privacy of his input and the computation he intends to perform; and secure multi-party computation where multiple users perform a joint computation on their private input without revealing much about them. This work package also covers the verification of devices, either those that are trusted but noisy, or those that claim to be a universal quantum computer but in reality might just be a strong classical computer pretending to be a quantum computer.

Despite the rapid growth of the technologies involved, we do not yet have what can be seen as a fully functional universal quantum computer. In the near future we will have devices that are in the regime known as NISQ: noisy intermediate scale quantum. These typically have 50-100 qubits as well as providing noisy and imperfect gate operations. With this limitation in mind, we have developed a number of protocols and demonstrators. These include robust verification and validation of a NISQ device using formal approaches like benchmarking and hypothesis testing, a testing scheme to differentiate between a device with quantum and classical capabilities.

We have developed QFactory, a tool to enable a classical user to perform secure computation on a quantum device that can overhaul the necessity of a quantum communication channel. We have developed novel physical cryptographic tools for secret key generation and device authentication and are developing architecture for quantum random access memory, the backbone of various quantum machine learning tasks. We have also ventured into the domain of post-quantum cryptography to develop secure classical communication across networks which are believed to be robust against adversaries with quantum computers.

Quantum Enabled Discovery

Our work has focused on developing hybrid quantum-classical approaches to solve partial differential equations (PDEs) that have numerous scientific and industry applications, and on improving Dynamical Mean Field Theory (DMFT). We have designed algorithms with the potential to outperform existing classical routines and we have implemented them on the latest IBM quantum computers.

Running the algorithms on IBM's commercial quantum hardware allows us to demonstrate how they may assist in potential applications in quantum technologies. Interestingly, our quest for a new quantum algorithm – using techniques from both quantum many-body and information theory – has led to a new classical algorithm for solving PDEs, which in some cases can be exponentially faster than certain standard PDE solvers. We are now investigating the performance of this classical algorithm in the context of turbulence and fluid dynamics – a phenomenon that is considered to be genuinely hard for standard PDE solvers. This work is being done in collaboration with BAE Systems.

We have also completed a study on specific experimental architectures that might become useful for quantum simulation in the future (time-bin quantum optics in fibre loop experiments), and looking at practical quantum simulation approaches and tools that help in understanding and engineering the quantum setup. During the last year of NQIT, we will continue our theoretical analysis of PDE algorithms and their experimental realisation on an IBM quantum computer.

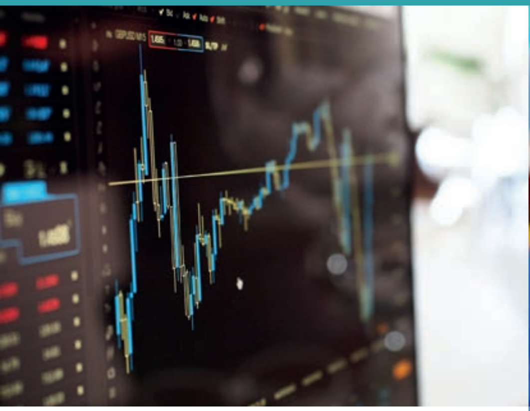
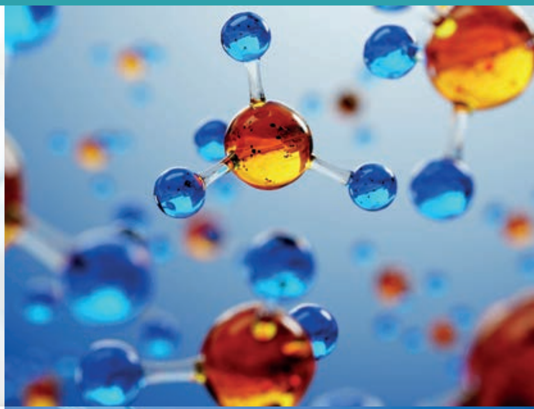
Quantum/Classical Emulation and Interfacing

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.

To make the best use of the resources of a networked quantum computer for error correction, we have determined how best to describe the individual operations which would form the 'machine language' of a fault-tolerant quantum computer. Together with international research collaborators, we have formalised a set of operations on error-corrected memories, in a way which connects to leading work in formal logic for 'tensor networks' – the mathematics of computing global behaviour from smaller pieces. This will help us to develop optimising compilers for computers such as the Q20:20 engine. We are expanding on existing standards in parallel processing, to define the 'microcode' for the Q20:20 machine. This would be used to co-ordinate quantum error correction at a fine-grained level, and also to carry out quantum computations on smaller, near-term networked systems.

We have also begun the development of a stand-alone quantum emulator, building on the alpha emulator libraries which we developed last year. We are exploring techniques which would make it possible, in some cases, for users to emulate computations which use more qubits, and to do it more quickly, than would be possible otherwise. By developing this and other software tools for emulation, we are promoting the development of quantum technologies – making it easier to predict how a quantum computer should act and also making it easier for students and the public to learn how quantum computers will work.

We look forward to the work we have planned in the next and final year of the NQIT project. We will publish specifications for quantum programming languages, designed to interoperate with existing ones. These will be usable as the input format for the stand-alone emulator which we are developing, which will help to contribute to the development of skills and technology. We will also describe ways to manage resources on a fine-grained level to make the most of the Q20:20 engine. These will all contribute towards the development of the software and expertise required to make the most use of networked quantum computers, once we make them a reality.



Practical areas NQIT is exploring with industry

Machine learning and AI
Quantum computing algorithms will allow us to enhance what's already possible with machine learning, from leveraging big data for industry to making predictions from data, such as in a medical context.

Simulation
Quantum simulators and computers will be used to aid the design of quantum materials through computational modelling, such as enabling corrosion prediction and detection and material development for extreme environments or in bio-informatics that can aid the development of new diagnosis and therapeutics.

Engineering processes
Quantum computing will be able to speed up engineering processes such as material modelling and inform the design and development of software tools.

Optimisation and scheduling
Modelling and scheduling form the basis in many sectors such as finance, meteorology or network management. Quantum computing approaches can potentially produce higher efficiencies and productivity or more reliable complex systems.

Computation and communication speed
A quantum computer can harness quantum states to offer exponential growth in computation speed and power, an important aspect in many business settings from global financial trading systems to onboard planning and control systems.

Validation and verification
Applications in verification and validation using quantum computers may benefit complex or critical systems, including healthcare, aerospace and automotive industries.

NQIT Technical Advisory Board members Professor Andrew White and Dr Peter Langsford at the Quantum Technologies Showcase/Dan Tsantilis

Professor Marina Jirotka attended the launch of the All-Party Parliamentary Group on Data Analytics enquiry into data and technology ethics/APGDA

Researchers from the University of Sussex revealed the secrets of quantum computers to the UK public at the Science Museum in London/IQT Group, University of Sussex

Wider Engagement

We have continued to reach out to reach out to the general public, to the general public through science festivals and our online activities whilst also engaging with stakeholders from an early stage on responsible innovation and the societal implications of quantum computing.

Public Engagement

A new cross-Hub initiative called Quantum City is our main vehicle for communicating with the public and with school children. Supported by the communication teams of all seven Hubs (Technologies and Skills) this has created a dedicated website with its own hashtag and a set of marketing materials to convey the main goals of the UK National Quantum Technologies Programme. Quantum City, with exhibits from all the hubs, attends major science festivals with information materials developed jointly. In 2018 public engagement activities took place around the UK, from the York Festival of Ideas in June, the New Scientist Live event in London in September, the IF Oxford Science and Ideas Festival in October, to the Festival of Physics held in Edinburgh in November. The public's response to Quantum City has been overwhelmingly positive.

On a local level, there have been many opportunities, such as engaging with Oxfordshire Local Enterprise Partnership (OxLEP), as quantum computing is one of the four transformative technologies highlighted in the Oxfordshire 2017 Science and Innovation Audit. NQIT will contribute to OxLEP's House of Commons economic briefing on quantum computing planned in the near future.

Responsible Research and Innovation

This is an exciting time for quantum computing as it starts to produce demonstrable outputs. Whilst not being able to predict the course of events, Responsible Innovation can anticipate plausible scenarios, engage with stakeholders, and act as a resource for creative thinking so that society as a whole shares the benefits of quantum technologies.

We continue to explore Responsible Innovation through case studies. Our study in Responsible Innovation in Quantum Machine Learning began in 2017, and continues to evolve as a research field in our case study. In addition, we are studying the implications of pathways to innovation from quantum computing. NQIT offers a unique opportunity to observe innovation in action in this crucial period, as industry explores ways for quantum computing to transform ways of working.

It is important to consider societal implications of quantum computing from an early stage, as it will be difficult to make changes once the technology has become embedded. However, these implications are unlikely to be simply "more of the same" as classical computing: the special nature of quantum means that applications and their implications will be felt in quite specific areas.

Quantum computing is changing. We might not see full-scale error-corrected universal devices for some years, but increasing interest in Noisy, Intermediate-Scale Quantum Computing and Quantum Simulation means that quantum computing, in these forms, may arrive soon.

We continue to promote Responsible Innovation through multiple channels and through conferences and events. Reports from our work are available on the NQIT website. In November 2018 we published a briefing from the results of a case study in the applications of quantum technologies for defence and national security, drawing on a workshop held in October 2016. We distributed this briefing and displayed our work in Responsible Innovation at the UK National Quantum Technologies Showcase.

We also participate in the Steering Committee of the All-Party Parliamentary Group on Data Analytics. We maintain links with policy-makers in BEIS and DCMS and have participated in policy workshops including the Centre for Science and Policy in Cambridge and a seminar on quantum computing, to be hosted by Lord Stewart Wood, at the Houses of Parliament in March 2019.

In the final months of NQIT, we will draw together the findings from four case studies – the overall landscape, defence and national security, quantum machine learning, and pathways to innovation – and present these in a final discussion event.

The House of Commons Science and Technology Committee report on quantum technologies said that Responsible Innovation should continue, with each Hub to produce an annual update on the societal impacts of its quantum technologies sector.

Inter-Hub Collaboration

As part of the UK National Quantum Technology Programme we work closely with the other partners, in particular the other hubs. We have continued to collaborate on the annual Quantum Technologies Showcase. The communications group from across the hubs meets regularly with ESPRC staff to facilitate the Showcase and communicate publicly about the event.

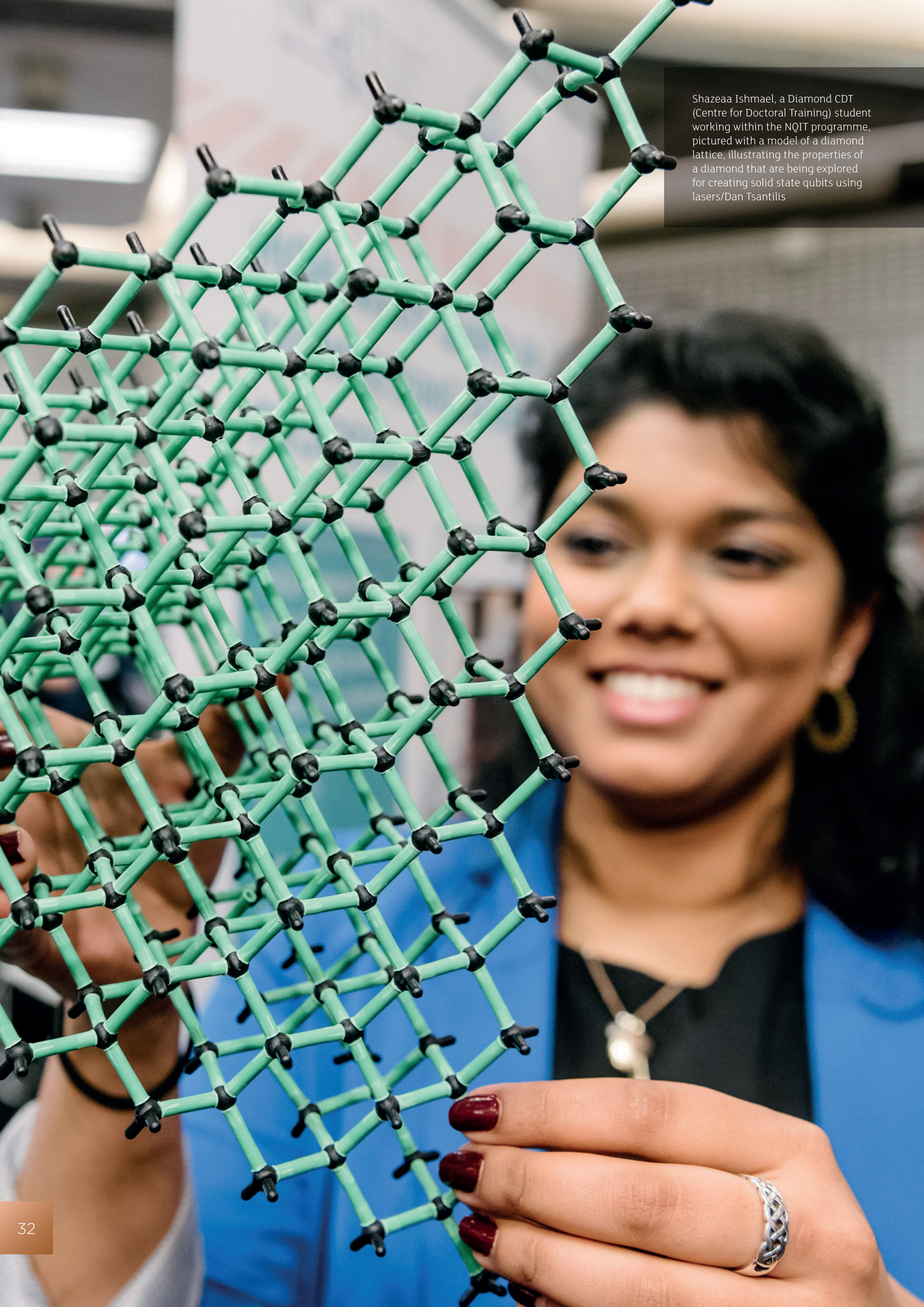
We are very pleased with the public response to our jointly funded and supported initiative 'Quantum City', which we take to science festivals and other community events. As well as inspiring visitors about the changes quantum technologies could make to everyday life, we also encourage young visitors to think of a career in quantum technologies, not just in the academic sphere but also at the technician and apprenticeship levels.

The recent briefing paper: *Responsible Innovation in Quantum Technologies applied to Defence and National Security* is a joint publication with the other hubs. The briefing paper is the outcome of a workshop and also draws upon interviews and a review of literature, to present issues for considerations by policy-makers and innovators responsible for applying quantum technologies to defence and national security. It addresses the challenges of adopting these technologies in a responsible way in a complex market economy and changing international operating environment.

The UK House of Common's Science and Technology Committee held an inquiry into the opportunities and challenges for quantum technologies, with the hubs providing written evidence. Professor Kai Bongs, Director of the Quantum Technology Hub for Sensors and Metrology, Professor Ian Walmsley, Director of the Networked Quantum Information Technologies Hub, and Professor Winfried Hensinger, Professor of Quantum Technologies at the University of Sussex also gave oral evidence to the committee. The Committee's report (6 December 2018) outlined how the National Quantum Technologies Programme should turn the UK's world-leading quantum research into a world-leading industry with opportunities for significant economic growth and improved capabilities across most industry sectors.

Quantum City, the joint public engagement initiative by partners of the UK National Quantum Technologies Programme, attracted over 10,000 visitors at Science Festivals around the UK, including Tim Peake who visited our stand at New Scientist Live/New Scientist Live

The NQIT team at the Cheltenham Science Festival/Quantum City



Shazeaa Ishmael, a Diamond CDT (Centre for Doctoral Training) student working within the NQIT programme, pictured with a model of a diamond lattice, illustrating the properties of a diamond that are being explored for creating solid state qubits using lasers/Dan Tsantilis

Skills & Training

NQIT recognises the importance of developing skills and training and the strong demand for quantum physicists, computer scientists and engineers for industry. We are continuing to invest in training and further development through centres for doctoral training to enable early-career scientists to explore quantum computing technologies.

The 2018 NQIT Skills Forum took place at Oxford's Department of Engineering Science on 21 June. The Forum began with a session of excellent talks from PhD students supported by EPSRC Doctoral Training Partnership studentships and working on NQIT-related topics. Titles included "Coaxial circuits for superconducting quantum computing", "Readout of trapped ion qubits", "Verification of quantum computations in early-days devices", "High-fidelity remote entanglement generation between two ion trap nodes", and "Gaussian boson sampling: certification and applications". After coffee NQIT's Winni Hensinger gave a talk on "Engineering challenges to construct a large scale ion trap quantum computer" which was followed by an introduction to the IBM Quantum Experience by a team from IBM. The session after lunch focused on Careers in Quantum Technologies, with presentations from IBM, Teledyne e2v and the QTEC Hub.

The second event of the year was a Quantum Computing Hackathon for the Space Sector at the Saïd Business School in Oxford in March 2019. NQIT teamed up with the UK Satellite Applications Catapult to coordinate this event, while UK startup companies Riverlane and Dividiti jointly ran the Hackathon itself. It was a huge success, with over 80 attendees from a range of backgrounds tackling problems related to the Space Sector using quantum coding. Participants used Qiskit, IBM's quantum computing framework, along with its emulator of a quantum computer to tackle the challenges presented to the hackathon teams. Video footage of the event and interviews with attendees were broadcast live on Facebook.

Postdoctoral researchers, in the Oxford superconducting devices group, Brian Vlastakis and Martina Esposito, closing up a dilution refrigerator for a test run in the new superconducting quantum device lab in the Beecroft Building /Jack Hobhouse

Future Plans

NQIT will continue to deliver on its key technical, policy and training and engagement goals. Each work package has identified key enabling milestones which will provide a foundation for the second phase of the National Programme, and we will use the final period of Phase I to ensure that these are delivered.

The goal of optically networked ion traps has now been achieved, with record performance, and work to demonstrate operation of a five ion-node continues, forming a key enabling element for work in the second phase of the programme. Enabling engineering for this work is reaching completion, with control systems and beam delivery at an advanced stage. Superconducting circuit development is also progressing at pace with competitive gate performance across arrays of four transmon qubits demonstrated by means of the novel NQIT device control design. The promising work on NV centre writing, to deliver spins systems with optical and magnetic properties compatible with the best, will continue, refining the unique capabilities for scaling potential that we have in this area. Photonics for quantum simulators will build on the capabilities and know-how developed in NQIT to prepare for the work package in Phase II. In all our hardware work packages, both core and spinout technologies that will contribute to the UK quantum economy continue to be developed. Applications work on emulation, architectures, and verification continues. Emulation and work on IBM Q will allow us to understand the near-term applications of quantum computers.

The User Engagement activities will continue to support the emerging quantum economy in the UK with the encouragement of entrepreneurship, through engaging investors and connecting quantum software developers and users in industry, science and government. These activities include an intensification of the Quantum Readiness Programme and participation in industry events in the UK and internationally until the end of 2019, ready for a continued growth in user engagement in the next Hub and the National Quantum Computing Centre.

NQIT will be completed at the end of 2019, and a detailed programme of work that builds on the results of NQIT in the forthcoming computing Hub – the EPSRC Hub in Quantum Computing and Simulation – is in the final stages of approval. Together with the 2018 announcement that the UK will build a National Quantum Computing Centre – the first such announcement globally – we are confident that the UK will continue to build on the successes of NQIT and the wider UK strengths in quantum technologies.

Outputs

Publications

Ballance, T. G., Goodwin, J. F., Nichol, B., Stephenson, L. J., Ballance, C. J., & Lucas, D. M. (2018). A short response time atomic source for trapped ion experiments. Review of Scientific Instruments, 89(5), 053102. doi:10.1063/1.5025713

Barbone, M., Montblanch, A. R. P., Kara, D. M., Palacios-Berraquero, C., Cadore, A. R., De Fazio, D., . . . Atatüre, M. (2018). Charge-tuneable biexciton complexes in monolayer WSe2. Nature Communications, 9(1), 3721. doi:10.1038/s41467-018-05632-4

Barrett, T. D., Rubenok, A., Stuart, D., Barter, O., Holleczek, A., Dilley, J., . . . Kuhn, A. (2019). Multimode interferometry for entangling atoms in quantum networks. Quantum Science and Technology, 4(2), 025008. doi:10.1088/2058-9565/aafaba

Barrett, T. D., Stuart, D., Barter, O., & Kuhn, A. (2018). Nonlinear Zeeman effects in the cavity-enhanced emission of polarised photons. New Journal of Physics, 20(7), 073030. doi:10.1088/1367-2630/aad14e

Betzold, S., Herbst, S., Trichet, A. A. P., Smith, J. M., Würthner, F., Höfling, S., & Dietrich, C. P. (2018). Tunable Light–Matter Hybridization in Open Organic Microcavities. ACS Photonics, 5(1), 90-94. doi:10.1021/acsphotonics.7b00552

Blackmore, J. A., Caldwell, L., Gregory, P. D., Bridge, E. M., Sawant, R., Aldegunde, J., . . . Cornish, S. L. (2018). Ultracold molecules for quantum simulation: rotational coherences in CaF and RbCs. Quantum Science and Technology, 4(1), 014010. doi:10.1088/2058-9565/aaee35

Branford, D., Miao, H., & Datta, A. (2018). Fundamental Quantum Limits of Multicarrier Optomechanical Sensors. Physical Review Letters, 121(11), 110505. doi:10.1103/PhysRevLett.121.110505

Chabaud, U., Diamanti, E., Markham, D., Kashefi, E., & Joux, A. (2018). Optimal quantum-programmable projective measurement with linear optics. Physical Review A, 98(6), 062318. doi:10.1103/PhysRevA.98.062318

Clements, W. R., Renema, J. J., Eckstein, A., Valido, A. A., Lita, A., Gerrits, T., . . . Walmsley, I. A. (2018). Approximating vibronic spectroscopy with imperfect quantum optics. Journal of Physics B: Atomic, Molecular and Optical Physics, 51(24), 245503. doi:10.1088/1361-6455/aaf031

Cosco, F., Borrelli, M., Mendoza-Arenas, J. J., Plastina, F., Jaksch, D., & Maniscalco, S. (2018). Bose-Hubbard lattice as a controllable environment for open quantum systems. Physical Review A, 97(4), 040101. doi:10.1103/PhysRevA.97.040101

Coulthard, J. R., Clark, S. R., & Jaksch, D. (2018). Ground-state phase diagram of the one-dimensional *t–J* model with pair hopping terms. Physical Review B, 98(3), 035116. doi:10.1103/PhysRevB.98.035116

Coyle, B., Hoban, M. J., & Kashefi, E. (2018). One-Sided Device-Independent Certification of Unbounded Random Numbers (Vol. 273, pp. 14-26), Electronic Proceedings in Theoretical Computer Science

Dietrich, A. S. D., Kiffner, M., & Jaksch, D. (2018). Probing microscopic models for system-bath interactions via parametric driving. Physical Review A, 98(1), 012122. doi:10.1103/PhysRevA.98.012122

Dustin, S., & Axel, K. (2018). Single-atom trapping and transport in DMD-controlled optical tweezers. New Journal of Physics, 20(2), 023013. doi:10.1088/1367-2630/aaa634

Ferracin, S., Kapourniotis, T., & Datta, A. (2018). Reducing resources for verification of quantum computations. Physical Review A, 98(2), 022323. doi:10.1103/PhysRevA.98.022323

Field, J. W., Posner, M. T., Berry, S. A., Bannerman, R. H. S., Gates, J. C., & Smith, P. G. R. (2018, 2018/07/02). Fabricating a Prototype Spectrometer Using a Large-Angle Direct UV-Written Chirped Tilted Grating. Paper presented at the Advanced Photonics 2018 (BGPP, IPR, NP, NOMA, Sensors, Networks, SPPCom, SOF), Zurich.

Furtak-Wells, N., Clark, L. A., Purdy, R., & Beige, A. (2018). Quantizing the electromagnetic field near two-sided semitransparent mirrors. Physical Review A, 97(4), 043827. doi:10.1103/PhysRevA.97.043827

Gheorghiu, A., Hoban, M. J., & Kashefi, E. (2018). A simple protocol for fault tolerant verification of quantum computation. Quantum Science and Technology, 4(1), 015009. doi:10.1088/2058-9565/aaeeb3

Gheorghiu, A., Kapourniotis, T., & Kashefi, E. (2019). Verification of Quantum Computation: An Overview of Existing Approaches. Theory of Computing Systems, 63(4), 715-808. doi:10.1007/s00224-018-9872-3

Gow, P. C., Gates, J. C., Bannerman, R. H. S., Nunn, J., Posner, M. T., Mennea, P. L., & Smith, P. G. R. (2018). Taking quantum entanglement out of the lab. Proceedings Volume 10741, Optics Education and Outreach V; 107410M (2018). doi:10.1117/12.2321079

Gow, P. C., Jantzen, A., Boyd, K., Simakov, N., Daniel, J., Gray, A. C., . . . Holmes, C. (2018). Consolidation of flame hydrolysis deposited silica with a 9.3 µm wavelength CO_2 laser. Electronics Letters, 54(15), 945-947. doi:10.1049/el.2018.0039

Guan, J., Liu, X., & Booth, M. J. (2018). Ultrafast laser writing quill effect in low loss waveguide fabrication regime. Optics Express, 26(23), 30716-30723. doi:10.1364/OE.26.030716

Guan, J., Liu, X., & Booth, M. J. (2019). Investigation of structural mechanisms of laser-written waveguide formation through third-harmonic microscopy. Optics Letters, 44(4), 1039-1042. doi:10.1364/OL.44.001039

Han, J., Vogt, T., Gross, C., Jaksch, D., Kiffner, M., & Li, W. (2018). Coherent Microwave-to-Optical Conversion via Six-Wave Mixing in Rydberg Atoms. Physical Review Letters, 120(9), 093201. doi:10.1103/PhysRevLett.120.093201

Hill, P., Gu, E., Dawson, M. D., & Strain, M. J. (2018). Thin film diamond membranes bonded on-demand with SOI ring resonators. Diamond and Related Materials, 88, 215-221. doi:10.1016/j.diamond.2018.07.020

Hoban, M. J., & Sainz, A. B. (2018). A channel-based framework for steering, non-locality and beyond. New Journal of Physics, 20(5), 053048. doi:10.1088/1367-2630/aabea8

Holland, N., Stuart, D., Barter, O., & Kuhn, A. (2018). Benchmarking modern algorithms to holographically create optical tweezers for laser-cooled atoms. Journal of Modern Optics, 65(18), 2133-2141. doi:10.1080/09500340.2018.1499978

Holmes, C., Jantzen, A., Gray, A. C., Lynch, S. G., Carpenter, L. G., Gow, P. C., . . . Smith, P. G. (2018). Integrated Optical Fiber: A Fresh Approach to Planar Photonics. Paper presented at the 2018 IEEE 7th International Conference on Photonics (ICP).

Janacek, H., Steane, A. M., Lucas, D. M., & Stacey, D. N. (2018). The effect of atomic response time in the theory of Doppler cooling of trapped ions. Journal of Modern Optics, 1-8. doi:10.1080/09500340.2018.1428771

Jesús, R., Paul, K., & Jacob, D. (2018). Non-asymptotic analysis of quantum metrology protocols beyond the Cramér–Rao bound. Journal of Physics Communications, 2(1), 015027. doi:10.1088/2399-6528/aaa234

Kaczmarek, K. T., Ledingham, P. M., Brecht, B., Thomas, S. E., Thekkadath, G. S., Lazo-Arjona, O., . . . Walmsley, I. A. (2018). High-speed noise-free optical quantum memory. Physical Review A, 97(4), 042316. doi:10.1103/PhysRevA.97.042316

Kiffner, M., Coulthard, J. R., Schlawin, F., Ardavan, A., & Jaksch, D. (2019). Manipulating quantum materials with quantum light. Physical Review B, 99(8), 085116. doi:10.1103/PhysRevB.99.085116

Kiffner, M., Jaksch, D., & Ceresoli, D. (2018). A polynomial Ansatz for norm-conserving pseudopotentials. Journal of Physics: Condensed Matter, 30(27), 275501. doi:10.1088/1361-648x/aac85d

Lee, C. M., & Hoban, M. J. (2018). Towards Device-Independent Information Processing on General Quantum Networks. Physical Review Letters, 120(2), 020504. doi:10.1103/PhysRevLett.120.020504

Li, Y., & Benjamin, S. C. (2018). One-dimensional quantum computing with a 'segmented chain' is feasible with today's gate fidelities. npj Quantum Information, 4(1), 25. doi:10.1038/s41534-018-0074-2

Lubasch, M., Moinier, P., & Jaksch, D. (2018). Multigrid renormalization. Journal of Computational Physics, 372, 587-602. doi:10.1016/j.jcp.2018.06.065

Lubasch, M., Valido, A. A., Renema, J. J., Kolthammer, W. S., Jaksch, D., Kim, M. S., . . . García-Patrón, R. (2018). Tensor network states in time-bin quantum optics. Physical Review A, 97(6), 062304. doi:10.1103/PhysRevA.97.062304

Mansfield, S., & Kashefi, E. (2018). Quantum Advantage from Sequential-Transformation Contextuality. Physical Review Letters, 121(23), 230401. doi:10.1103/PhysRevLett.121.230401

Meesala, S., Sohn, Y.-I., Pingault, B., Shao, L., Atikian, H. A., Holzgrafe, J., . . . Lončar, M. (2018). Strain engineering of the silicon-vacancy center in diamond. Physical Review B, 97(20), 205444. doi:10.1103/PhysRevB.97.205444

Mennea, P. L., Clements, W. R., Smith, D. H., Gates, J. C., Metcalf, B. J., Bannerman, R. H. S., . . . Smith, P. G. R. (2018). Modular linear optical circuits. Optica, 5(9), 1087-1090. doi:10.1364/OPTICA.5.001087

Michelberger, P. S., Karpiński, M., Walmsley, I. A., & Nunn, J. (2018). Engineering the spectral and temporal properties of a GHz-bandwidth heralded single-photon source interfaced with an on-demand, broadband quantum memory. Journal of Modern Optics, 65(14), 1668-1679. doi:10.1080/09500340.2018.1444801

Mills, D., Pappa, A., Kapourniotis, T., & Kashefi, E. (2018). Information Theoretically Secure Hypothesis Test for Temporally Unstructured Quantum Computation (pp. 209-221): Open Publishing Association.

Mur-Petit, J., Relaño, A., Molina, R. A., & Jaksch, D. (2018). Revealing missing charges with generalised quantum fluctuation relations. Nature Communications, 9(1), 2006. doi:10.1038/s41467-018-04407-1

Naveh, Y., Kashefi, E., Wootton, J. R., & Bertels, K. (2018). Theoretical and practical aspects of verification of quantum computers (pp. 721-730), Design, Automation And Test in Europe (DATE 2018). Institute of Electrical and Electronics Engineers (IEEE). 10.23919/DATE.2018.8342103

Posner, M. T., Hiemstra, T., Mennea, P. L., Bannerman, R. H. S., Hoff, U. B., Eckstein, A., . . . Smith, P. G. R. (2018). High-birefringence direct UV-written waveguides for use as heralded single-photon sources at telecommunication wavelengths. Optics Express, 26(19), 24678-24686. doi:10.1364/OE.26.024678

Posner, M. T., Mennea, P. L., Gow, P. C., Bannerman, R. H. S., Berry, S., Smith, D. H., . . . Smith, P. G. R. (2018). Taking large optical quantum states out of the lab: engaging pupils and the public on quantum photonics sciences. Vol. 10741, Optics Education and Outreach V. doi:10.1117/12.2319391

Proctor, T. J., Knott, P. A., & Dunningham, J. A. (2018). Multiparameter Estimation in Networked Quantum Sensors. Physical Review Letters, 120(8), 080501. doi:10.1103/PhysRevLett.120.080501

Randall, J., Lawrence, A. M., Webster, S. C., Weidt, S., Vitanov, N. V., & Hensinger, W. K. (2018). Generation of high-fidelity quantum control methods for multilevel systems. Physical Review A, 98(4), 043414. doi:10.1103/PhysRevA.98.043414

Renema, J. J., Menssen, A., Clements, W. R., Triginer, G., Kolthammer, W. S., & Walmsley, I. A. (2018). Efficient Classical Algorithm for Boson Sampling with Partially Distinguishable Photons. Physical Review Letters, 120(22), 220502. doi:10.1103/PhysRevLett.120.220502

Sainz, A. B., Aolita, L., Piani, M., Hoban, M. J., & Skrzypczyk, P. (2018). A formalism for steering with local quantum measurements. New Journal of Physics, 20(8), 083040. doi:10.1088/1367-2630/aad8df

Salek, S., Cadamuro, D., Kammerlander, P., & Wiesner, K. (2018). Quantum Rate-Distortion Coding of Relevant Information. IEEE Transactions on Information Theory 65(4), 2603-2613.

Sandstrom, R., Ke, L., Martin, A., Wang, Z., Kianinia, M., Green, B., . . . Aharonovich, I. (2018). Optical properties of implanted Xe color centers in diamond. Optics Communications, 411, 182-186. doi:10.1016/j.optcom.2017.11.064

Schäfer, V. M., Ballance, C. J., Thirumalai, K., Stephenson, L. J., Ballance, T. G., Steane, A. M., & Lucas, D. M. (2018). Fast quantum logic gates with trapped-ion qubits. Nature, 555, 75. doi:10.1038/nature25737

Scholl, S. L., Jantzen, A., Bannerman, R. H. S., Field, J., Gates, J. C., Boyd, L. J., . . . Holmes, C. (2018, 2018/07/02). Classification of Small-Spot Direct UV Written Fiber Bragg Gratings Through Extreme Thermal Treatment. Paper presented at the Advanced Photonics 2018 (BGPP, IPR, NP, NOMA, Sensors, Networks, SPPCom, SOF), Zurich.

Scholl, S. L., Jantzen, A., Bannerman, R. H. S., Gow, P. C., Smith, D. H., Gates, J. C., . . . Holmes, C. (2019). Thermal approach to classifying sequentially written fiber Bragg gratings. Optics Letters, 44(3), 703-706. doi:10.1364/OL.44.000703

Simmons, D. E., Coon, J. P., & Datta, A. (2018). The von Neumann Theil index: characterizing graph centralization using the von Neumann index. Journal of Complex Networks, cnx061-cnx061. doi:10.1093/comnet/cnx061

Trichet, A. A. P., Dolan, P. R., & Smith, J. M. (2018). Strong coupling between 0D and 2D modes in optical open microcavities. Journal of Optics, 20(3), 035402. doi:10.1088/2040-8986/aaaa3b

Webb, A. E., Webster, S. C., Collingbourne, S., Bretaud, D., Lawrence, A. M., Weidt, S., . . . Hensinger, W. K. (2018). Resilient Entangling Gates for Trapped Ions. Physical Review Letters, 121(18), 180501. doi:10.1103/PhysRevLett.121.180501

Weinzetl, C., Görlitz, J., Becker, J. N., Walmsley, I. A., Poem, E., Nunn, J., & Becher, C. (2019). Coherent Control and Wave Mixing in an Ensemble of Silicon-Vacancy Centers in Diamond. Physical Review Letters, 122(6), 063601. doi:10.1103/PhysRevLett.122.063601

Wright, T. A., Francis-Jones, R. J. A., Gawith, C. B. E., Becker, J. N., Ledingham, P. M., Smith, P. G. R., . . . Walmsley, I. A. (2018). Two-Way Photonic Interface for Linking the Sr^+ Transition at 422 nm to the Telecommunication *C* Band. Physical Review Applied, 10(4), 044012. doi:10.1103/PhysRevApplied.10.044012

Xu, X., Beaudrap, N. d., O'Gorman, J., & Benjamin, S. C. (2018). An integrity measure to benchmark quantum error correcting memories. New Journal of Physics, 20(2), 023009. doi:10.1088/1367-2630/aaa372

Talks

March 2018, Dr Animesh Datta, 'Quantum limits of sensing and imaging', UCL CDT Spring School, Windsor, UK.

March 2018, Professor Winfried Hensinger, 'Constructing a multi-module trapped-ion quantum computer prototype', CAMEL 14, Control of Quantum Dynamics of Atoms, Molecules and Ensembles by Light Workshop, Bansko, Bulgaria.

March 2018, Dr Petros Wallden, 'Verification of quantum computing', Date 18 Design, Automation and Test in Europe Conference, Dresden, Germany.

March 2018, Professor Axel Kuhn, 'Elements of a cavity-based atom-atom entangler', CAMEL 14, Control of Quantum Dynamics of Atoms, Molecules and Ensembles by Light Workshop, Bansko, Bulgaria.

March, 2018, Dr Gavin Morley, 'Quantum science and technology with nitrogen vacancy centres in diamond', Hasselt Diamond Workshop 2018 - SBDD XXIII, Hasselt, Belgium.

April 2018, Professor Martin Booth, '3D Dynamic laser processing for functional devices in diamond', rank prize funds diamond photonics: sources and senses symposium, Grasmere, UK.

April 2018, Dr James Gates, 'UV written integrated waveguides for quantum photonics', SPIE Photonics Europe Conference, Strasbourg, France.

April 2018, Professor Winfried Hensinger, 'The ION quantum computer', nextM Future Conference, Vienna, Austria.

April 2018, Professor Marina Jirotka, 'Responsible innovation in quantum information science', International Conference on Challenges in Quantum Information Science, Tokyo, Japan.

April 2018, Professor Axel Kuhn, 'Quantum networking with cavity photons', NUDT-Oxford workshop on quantum technologies, Oxford, UK.

April 2018, Dr Gavin Morley, 'Pure nanodiamonds for levitated optomechanics in vacuum', MAQRO workshop, Vienna, Austria.

April 2018, Professor Ian Walmsley, 'Quantum enhancement in optical microscopy', University of Warwick workshop, Coventry, UK.

April 2018, Professor Ian Walmsley, 'Building quantum machines out of light', SPIE Photonics Europe Conference, Strasbourg, France.

April 2018, Professor Ian Walmsley, 'Arachnophilia: Measuring ultrashort optical pulses using spectral shearing interferometry', Frontiers of Ultrafast Science UK Workshop, Rutherford Appleton Laboratory, Harwell Campus, Harwell Oxford, Didcot, UK.

May 2018, Professor Winfried Hensinger, 'Constructing a multi-module trapped-ion quantum computer prototype', APS Division of Atomic, Molecular and Optical Physics APS Annual Meeting, Ft. Lauderdale, USA.

May 2018, Naomi Holland, Student Award, 'Optical tweezers for Neutral Atoms: The Key to a Reliable Atom-Photon Quantum Interface', PicoQuant 2018 Single-Photon Conference, Berlin, Germany.

May 2018, Professor Ian Walmsley, 'Photonic quantum networks: a ubiquitous platform for quantum technologies', PicoQuant 2018 Single-Photon Conference, Berlin, Germany.

May 2018, Professor Ian Walmsley, 'Building quantum machines out of light', SPIE Photonics Europe Conference, Glasgow, UK.

May 2018, Professor Axel Kuhn, 'Quantum logic and photon steering with single cavity photons in integrated photonic circuits', picoquant 2018 single-photon conference, Berlin, Germany.

June 2018, Professor Martin Booth, '3D Dynamic laser processing for functional devices in diamond', Progress in Ultrafast Laser Modifications of Materials Workshop, Telluride Science Research Centre, Telluride, USA.

June 2018, Professor Martin Booth, 'Dynamic optics for ultrafast laser machining and high-resolution microscopy', Microsoft Research Seminar, Cambridge, UK.

June 2018, Professor Winfried Hensinger, 'Constructing a trapped ion quantum computer', AI Summit, London, UK.

June 2018, Professor Elham Kashefi, 'Verification of quantum computation', Formal methods and verification Colloquium, Brussels, Belgium.

June 2018, Professor Elham Kashefi, 'Quantum Internet Alliance', The Quantum Internet; Charting the Critical Path, Toronto, Canada,

July 2018, Professor David Lucas, 'Fast entangling gates with trapped ions', NIST (National Institute of Standards and Technology), Boulder, USA

October 2018, Professor Elham Kashefi, 'Many-body dynamics and open quantum systems', DOQS2018, Glasgow, UK.

July 2018, Dr Christopher Holmes, 'High temperature operation of integrated optical fiber', Conference on Lasers and Electro-Optics/Pacific Rim, Hong Kong.

July 2018, Professor Elham Kashefi, 'On the possibility of classical client blind quantum computing', Seefeld workshop on Quantum Information, Seefeld, Austria.

July 2018, Professor Elham Kashefi, 'Quantum computing and the future of smart contracts', Interdisciplinary Workshop on Blockchains, ENS, Paris, France.

July 2018, Professor Elham Kashefi, Logical Aspects of Quantum Information Workshop, Lorentz Center, Leiden, The Netherlands.

July 2018, Dr Peter Leek, 'Coaxial multilayer superconducting circuits for quantum computing', International Conference on Superconducting Quantum Technology, Moscow, Russia.

July 2018, Dr Gavin Morley, 'Levitating nanodiamonds containing NVcenters', CECAM Qubits Workshop, Bremen, Germany.

July 2018, Professor Ian Walmsley, 'Building quantum machines out of light', Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

July 2018, Professor Ian Walmsley, 'Building quantum machines out of light', Pacific Rim Conference on Lasers and Electro-Optics (CLEO-Pacific Rim), Hong Kong.

August 2018, Dr Animesh Datta, 'Verification of quantum computation and simulation', International Workshop on Quantum Tomography, 2018, Shanghai, China.

August 2018, Dr Animesh Datta, 'Verification of quantum computation and simulation', IBM Q Hub, Keio University, Tokyo, Japan.

August 2018, Dr Animesh Datta, 'Fault tolerant quantum metrology', Asian Quantum Information Science Conference 2018, Nagoya, Japan.

August 2018, Dr Gavin Morley, 'High-sensitivity detectors II', SPIE Optics and Photonics, San Diego, USA.

August 2018, Professor Ian Walmsley, 'Introducing the Q20:20: Towards a scalable quantum computer', Alumni Talk, University of Oxford China Office, Hong Kong.

September, 2018, Dr Niel de Beaudrap, 'Building up from atoms to algorithms', Quantum Interaction Conference, Nice, France.

September 2018, Professor Elham Kashefi, 'Quantum programming languages', Dagstuhl Seminar, Leibniz Center for Informatics, Saarbrücken, Germany.

September 2018, Professor Axel Kuhn, 'Cavity photons for integrated quantum logic and cluster-state preparation', Quantum Technology International Conference 2018, Paris, France.

September 2018, Professor David Lucas, 'Faster and better quantum logic with trapped ions', Quantum Technology International Conference 2018, Paris, France.

September 2018, Dr Gavin Morley, 'Magnetometry with nitrogen vacancy centres in diamond: towards magnetocardiograph, European Workshop on Magnetocardiography, London, UK.

September 2018, Professor Ian Walmsley, 'Photonic quantum networks', OSA Frontiers in Optics Conference, Washington DC, USA.

September 2018, Benjamin Yuen, 'Polarised single-photons from a cavity-enhanced atom-light interface in photonic quantum networks', 'Quantum logic and photon steering with single cavity photons in integrated photonic circuits', Photon 2018, Birmingham, UK.

September 2018, Naomi Holland, 'Optical tweezers for neutral atoms: The key to a reliable atom-photon quantum interface', Photon 2018, Birmingham, UK.

October 2018, Professor Elham Kashefi, 'Certifiable quantum simulation', DOQS 2018, Glasgow, UK

October 2018, Dr Joshua Nunn, 'Taking quantum entanglement out of the lab', SPIE Optical Engineering + Applications 2018, San Diego, USA.

October 2018, Professor Ian Walmsley, 'Quantum photonic networks for computing and simulation', IEEE Photonics Conference, San Antonio, USA.

October 2018, Professor Ian Walmsley, 'Building quantum machines out of light', Asia Communications and Photonics Conference, Hangzhou, China.

October 2018, Professor Ian Walmsley, 'Photonic quantum networks', Optics & Photonics Japan, Tokyo, Japan.

November 2018, Professor Winfried Hensinger, 'Developing a modular microwave trapped ion quantum computer', Fifth European Conference on Trapped Ions (ECTI), Rehovot, Israel.

November 2018, Professor Elham Kashefi, 'Quantum cloud computing', Linnaeus Colloquium, Gothenburg, Sweden.

November 2018, Professor Elham Kashefi, 'Quantum internet applications', ESA-ESRIN Quantum AI workshop, Rome, Italy.

November 2018, Dr Peter Leek, 'Coaxial multilayer superconducting circuits for quantum computing', Zurich Instruments Quantum User Meeting, London, UK.

November 2018, Dr Peter Leek, 'Coaxial multilayer superconducting circuits for quantum computing', KIAS 2018 Workshop on Superconducting Quantum Information, Seoul, Korea.

November 2018, Professor David Lucas, 'Trapped-ion entanglement: faster and further', European Conference on Trapped Ions, Tel Aviv, Israel.

December 2018, Dr Animesh Datta, 'Fault tolerant quantum metrology' , Quantum Information Processing and Applications 2018, Allahabad, India.

December 2018, Professor Elham Kashefi, ' Quantum protocol zoo', Fondation Sciences Mathématiques de Paris, Huawei Paris, France.

December 2018, Professor Ian Walmsley, 'Photonic quantum networks', Australian Institute of Physics Congress, Perth, Australia.

January 2019, Philip Inglesant, 'Quantum computing and simulation: a responsible perspective', Institute for Science, Innovation and Society, University of Oxford, Oxford, UK.

February 2019, Professor Winfried Hensinger, 'Developing a modular microwave trapped ion quantum computer', Asia-Pacific Workshop on Trapped Quantum Systems, Daejeon, South Korea.

February 2019, Professor Axel Kuhn, 'Cavity - QED and applications', LIMQUET Winter School, Brighton, UK.

February 2019, Professor David Lucas, 'Quantum logic with trapped ions: precise, fast, networked', Cavendish Quantum Colloquium, University of Cambridge, Cambridge, UK.

March 2019, Dr Animesh Datta, 'Verifying quantum supremacy with no overheads ', American Physical Society, Boston, USA.

March 2019, Professor Ian Walmsley, 'Photonic quantum networks', American Physical Society, Boston, USA.

March 2019, Dr Philip Inglesant, 'Responsible Innovation in quantum computing', Computing Frontiers seminar, Oxford Brookes University, Oxford, UK.

March 2019, Dr Peter Leek, 'Multilayer coaxial superconducting circuits with integrated 3D wiring', APS March Meeting, Boston, USA.

Engagement activities

March 2018, ATOM Festival of Science, in Abingdon-on-Thames. The festival, in its fifth year, celebrated Abingdon as the centre of science in Oxford and the Science Vale, including the Harwell Campus and Culham Science Centre. Demonstrations included the Oxford Optics and Photonics Student Society (OxOPS) stall and NQIT's work on Quantum Computing.

May 2018, Y Combinator, Architectures for Quantum Computing. Professor Simon Benjamin is interviewed by Y Combinator, a seed accelerator company that provides seed funding for startups. Their YouTube channel has over 150,000 subscribers. https://www.youtube.com/watch?v=LHZKDTJJknE

May 2018, Pint of Science Festival, Coventry. Dr Gavin Morley and NQIT PhD student, Yashna Lekhai, gave a talk entitled "Can a diamond be in two places at once?" https://pintofscience.co.uk/event/diamonds-cats-and-rollercoasters

May 2018, London Quantum Computing Meetup. Dr Joshua Nunn gave a talk entitled 'Platforms for quantum computing'. https://www.meetup.com/London-Quantum-Computing-Meetup/events/250042948/

June 2018, York Festival of Ideas. Professor Winfried Hensinger participated in an expert panel: The shape of things to come? Life in the quantum age. http://yorkfestivalofideas.com/2018/talks/life-in-the-quantum-age/

June 2018, Cheltenham Science Festival. NQIT researchers participated at the Quantum City stall, the joint public engagement initiative by partners of the UK National Quantum Technologies Programme, featuring interactive activities to illustrate the work of NQIT. https://nqit.ox.ac.uk/index.php/event/cheltenham-science-festival-2018

June 2018, NQIT Industry Day. This was our second such event, dedicated to quantum computing, the status of NQIT and the opportunities for business to engage with this transformative technology. https://nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2018-07/NQIT%20Industry%20Day%20Report%202018.pdf

June 2018, Saturday Mornings of Theoretical Physics, Oxford. NQIT researchers gave talks on the challenges of implementing quantum computation and cryptography practically, also about using ion traps and photonics to build a quantum computer. http://saturdaytheory.physics.ox.ac.uk/events/quantum-amplitudes-classical-ignorance-quantum-information-processing

September 2018, Venturefest. NQIT held two panel sessions at Venturefest Oxford: Building a Quantum Computer!, Quantum Applications. https://venturefestoxford.com/wp-content/uploads/2019/04/VFest-Programme-2018.pdf

September 2018, New Scientist Live. NQIT participated at the Quantum City stall, the joint public engagement initiative by partners of the UK National Quantum Technologies Programme, featuring interactive activities and demonstrations. https://live.newscientist.com/2018-pictures

September 2018, Oxford Space Industry Day. NQIT introduced the audience to the NQIT programme, as well as the overall objectives and scope of NQIT's programme. https://www2.physics.ox.ac.uk/enterprise/research-and-collaboration/space-industry-day

October 2018, London Quantum Computing Meetup. Dr Rupesh Srivastava gave a talk on NQIT, as part of the Quantum Computing Hack Day. https://www.meetup.com/en-AU/London-Quantum-Computing-Meetup/events/254156028/

October 2018, If Oxford Science + Ideas Festival. NQIT researchers led the Quantum City stall, featuring interactive activities and demonstrations to illustrate the work of NQIT, together with the general background to the UK National Quantum Technologies Programme.
https://if-oxford.com/wp-content/uploads/2018/08/IF-2018-programme_A4-for-web.pdf

October 2018, Physics: form the lab into your life, Oxford. NQIT researchers provided interactive activities and demonstrations and undertook laboratory visits, showcasing their research work within NQIT's programme.
https://www2.physics.ox.ac.uk/events/2018/10/16/physics-from-the-lab-into-your-life

October 2018, University of Worcester (Combined IOP/IET/BCS). Professor Winfried Hensinger gave a talk 'The emergence of quantum computers: technology and societal implications'.
https://herefordandworcester.bcs.org/?page_id=540

November 2018, Cambridge University Physics Society, Harnessing the Quantum World. Professor Simon Benjamin gave a talk at the Cambridge University Physics Society, open to both the University's physics community and the wider public.
https://www.youtube.com/watch?v=3QbHynuqeKg

November 2018, University of Ulm. Professor Winfried Hensinger gave a guest lecture.

November 2018, National Quantum Technologies Showcase. NQIT had 10 exhibits at this fourth annual showcase event, attended by an industry and government audience.
https://nqit.ox.ac.uk/index.php/event/national-quantum-technologies-showcase-2018

November 2018, Quantum Computing for the Space Sector. This event, co-hosted with the Satellite Applications Catapult, brought together the quantum computing industry, academia and space industry. The goals of the workshop were to understand the developments and the state of the art of quantum computing in the UK and explore the realms of possibility and opportunities for quantum computing in the space sector.
https://nqit.ox.ac.uk/event/quantum-computing-space-sector

December 2018, Government Digital Services Academy. Professor Winfried Hensinger gave a talk 'Quantum computers – the world's most incredible machines'.
https://www.gov.uk/guidance/gds-academy-masterclasses

December 2018, Centre for Science and Policy, University of Cambridge. Evert Geurtsen presented and Philip Inglesant took part in an invited policy workshop on 'Future threats and challenges of quantum technologies'.

January 2019, London Quantum Computing Meetup. Phillip Inglesant, from the Responsible Research and Innovation team gave a talk on responsible innovation in quantum computing at London Quantum Computing Meetup.
https://www.meetup.com/London-Quantum-Computing-Meetup/events/257318810/

January 2019, Spin-NANO Think-Ahead Workshop 3. Dr Philip Inglesant led a participatory session on Responsible Innovation in quantum technologies.
http://spin-nano.sites.sheffield.ac.uk/think-ahead-workshop-3---jan-2019-cambridge

January 2019, Quantum Startup Lightning Talks & Networking Event. Dr Joshus Nunn gave an introduction to the UK Quantum Technology Programme and how it has stimulated commercialisation of quantum technologies.

February 2019, Schools Challenge Final at the London Science Museum. Final event for Year 9 students that have taken on a challenge to solve some of London's most pressing environmental issues. Dr Steve Kolthammer and his student Mengbo Long exhibited their quantum random number generator in the STEM marketplace, introducing the students to examples of state-of-the-art technology and innovation.
https://www.imperial.ac.uk/news/190274/london-school-students-science-solve-city/

NQIT in the News

16 March 2018, 'The legacy of Professor Stephen Hawkins'

- University of Warwick: https://warwick.ac.uk/newsandevents/expertcomment/prof_stephen_hawkings/
- TRT World Now: https://www.youtube.com/watch?v=Tikheu8tawk

23 May 2018, 'Now's the time to invest in quantum computing skills

- Digital Journal: http://www.digitaljournal.com/business/now-s-the-time-to-invest-in-quantum-computing-skills/article/522985

15 June 2018, Professor Winfried Hensinger on BBC Radio 4's Today Programme

- University of Sussex Twitter https://twitter.com/sussexunipress/status/1007583484234301440

1 November 2018, 'Sussex breakthrough prepares quantum computers to leave the lab'

- University of Sussex: https://www.sussex.ac.uk/news/all?id=46639
- NewScientist: A zap from a laser could make bigger quantum computers possible https://institutions.newscientist.com/article/2184236-a-zap-from-a-laser-could-make-bigger-quantum-computers-possible/
- MailOnline: A super-fat 'quantum internet' for everyone is one step closer to reality as British researchers make a major breakthrough' https://www.dailymail.co.uk/sciencetech/article-6338899/A-super-fast-quantum-internet-one-step-closer-reality.html
- Daily Telegraph: Scientists plans to build new quantum computing facility in Brighton https://www.telegraph.co.uk/technology/2018/11/05/scientists-plan-build-new-quantum-computing-facility-brighton/

7 November 2018, 'Quantum computers proven to be better than classical computers'

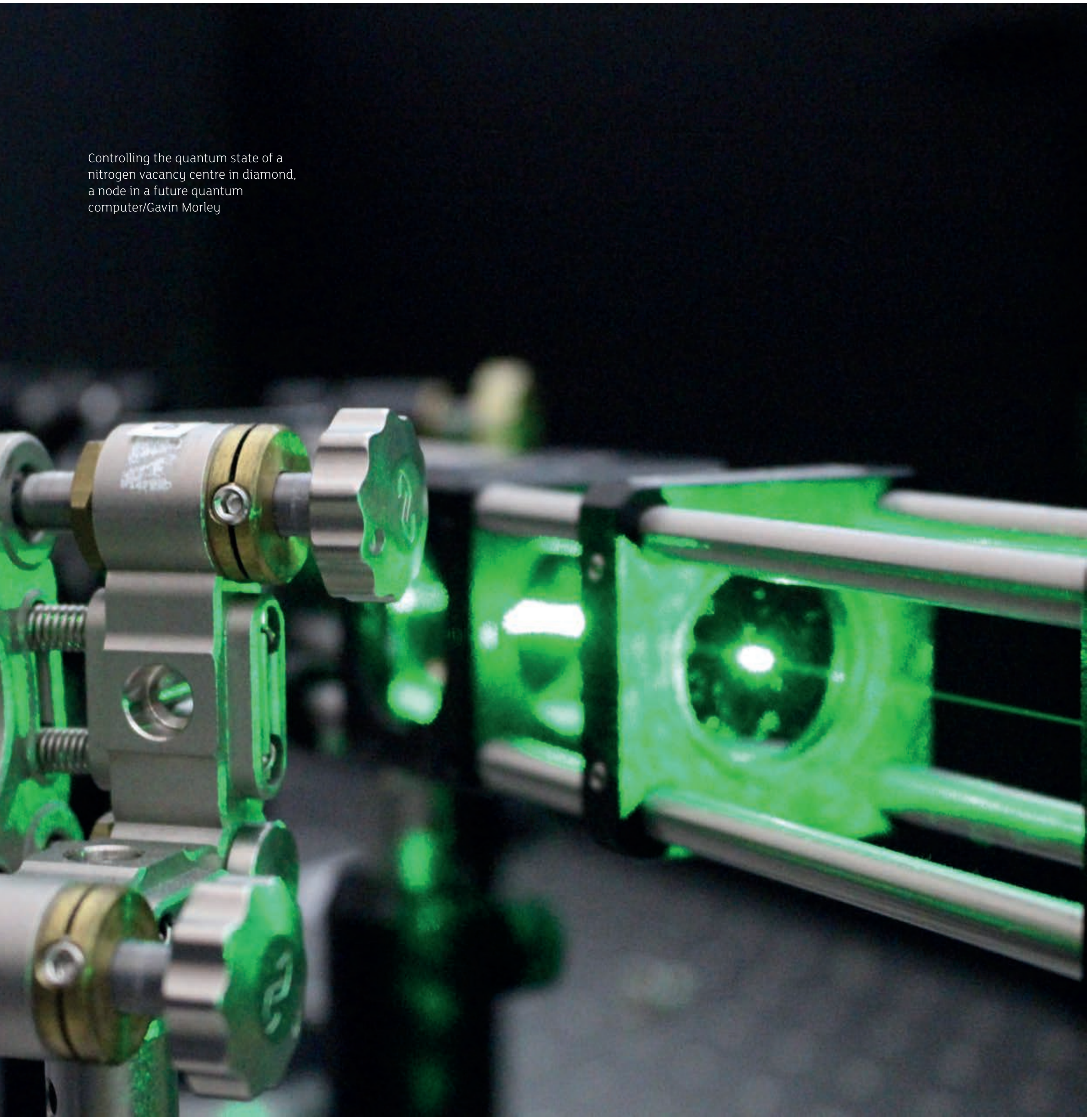
- The Oxford Student: https://www.oxfordstudent.com/2018/11/07/quantum-computers-proven-to-be-better-than-classical-computers/

12 November 2018, 'Tech company launches to develop quantum-era sensors'

- Cleanroom Technology: https://www.cleanroomtechnology.com/news/article_page/Tech_company launches_to_develop_quantumera_sensors/148926
- Zenopa.com https://www.zenopa.com/news/784/2m-investment-for-startup-company-oxford-highq

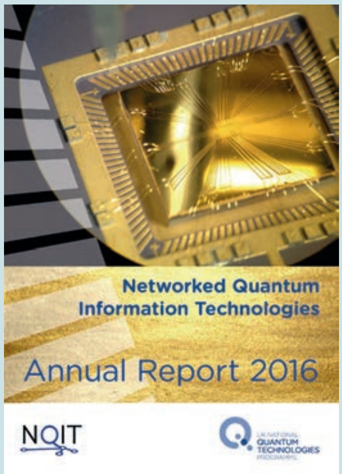
UK House of Commons Science and Technology Committee inquiry into quantum technologies, announced February 2018, takes evidence and publishes report in December 2018

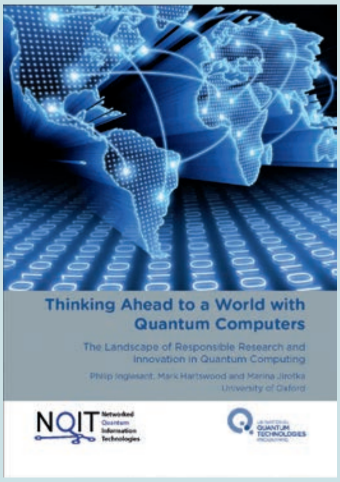
- UKTN.news: The quantum revolution is underway and the opportunity if Britain's for the taking https://www.uktech.news/news/industry-analysis/quantum-revolution-underway-opportunity-britains-taking-20180503
- Optics .org: UK Quantum chiefs urge MPs to back funding commitment for industry phase http://optics.org/news/9/6/6
- The Register: Boffins ask for £338 to fund quantum research. UK gov: Here's £80 m https://www.theregister.co.uk/2018/09/17/quantum_underfunding/
- Computer Weekly: UK can do more to explore potential of quantum tech https://www.computerweekly.com/news/252453897/UK-can-do-more-to-explore-potential-of-quantum-tech

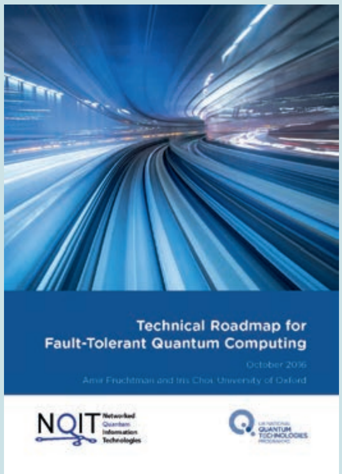


Controlling the quantum state of a nitrogen vacancy centre in diamond, a node in a future quantum computer/Gavin Morley

Resources

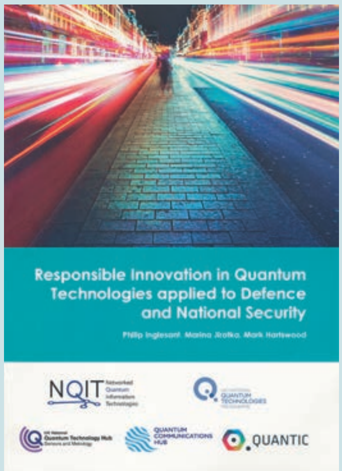


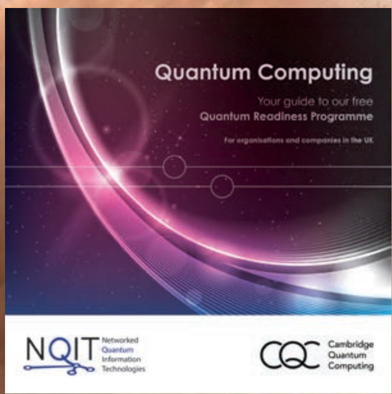




Please visit our website to learn more about our research and technology development

www.nqit.ox.ac.uk





Creating a quantum computing sector in the UK

NQIT is the Quantum Computing Technology Hub of the UK National Quantum Technologies Programme

Get involved with NQIT

www.nqit.ox.ac.uk engage@nqit.ox.ac.uk @NQIT_QTHub