Strategic Intent

UKRI
National Quantum Computing Centre

Acknowledgements
Grateful thanks to Prof Peter Leek, Hawkins/Brown, Roz Hayward, Katherine Keenan, Clem Hitchings & Jo Enderby

About
NQCC is a £93m investment by UKRI through EPSRC and STFC to establish UK sovereign capability in the field of Quantum Computing.

Find out more at www.nqcc.ac.uk

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Foreword

In recent years, scientists and engineers have developed unprecedented capabilities to isolate, control and sense quantized phenomena. This capability underpins the development of a range of transformational quantum technologies; imaging, sensors & timing, cryptography & secure communication and computing & simulation. Since 2014 the UK has committed £1bn of private and public investment in a 10 year programme to leverage well established academic and research excellence in order to drive the successful commercialisation of these technologies.

Quantum computing operates in a fundamentally different way to conventional or classical computers. It has the potential to unlock unprecedented parallel processing and consequently create a step change in computing power. Given this potential to accelerate resolution of complex problems and enable previously intractable computations, QC will impact across a wide range of sectors. Early examples are to be found in molecular and materials modelling, drug discovery, machine learning, active routing and complex scheduling.

The potential is exciting, but the technology is still at an early stage, with many technological and engineering challenges to be overcome, thus necessitating a comprehensive programme of research, innovation, and training activities.

As part of a long-term endeavour UKRI are investing in a new national facility to spearhead this effort for the UK . The strategic goal of the NQCC is to ensure the UK has access to this emerging transformational technology, to develop and provide access to prototype machines and support an emerging QC industry in the UK. Finally, by ensuring the UK is quantum ready, the NQCC will support the long term strategic goal of employing quantum computing to deliver prosperity and security for societal good.

On behalf of the NQCC Programme Advisory Committee I welcome the progress being made on strategy and technology road mapping and look forward to the NQCC playing a major role in the UK quantum landscape in the coming years.

Prof. Sheila Rowan
MBE FRS FRSE FInstP

University of Glasgow
Chair NQCC Programme Advisory Committee
Chief Science Advisor for Scotland

2nd September, 2020

Executive Summary

Quantum computing has the potential to unlock unprecedented parallel processing creating a step change in computing power. By harnessing and exploiting this capability the UK has an ambition to become the worlds first quantum ready nation. To achieve this a renewed effort is required leveraging the £1bn, 10 year investment already committed into quantum technologies since 2014.

Our effort is part of a global race with significant international investment in hardware, software and skills. Recruiting and retaining top talent is of key importance. The long term impact on society and the economy is potentially huge with a projected global market of $450-850bn annually over the next 15-30 years.

Building on the investments made in enabling science a new National Quantum Computing Centre (NQCC) is established on the Harwell Campus with an initial investment of £93m over 5 years by UKRI. The primary purpose of the NQCC is to fill a key gap in the research and innovation landscape addressing the challenge of scaling quantum computing.

The NQCC's initial 5 years will focus on developing a Noisy Intermediate Scale Quantum (NISQ) machine to demonstrate the technology with superconducting and trapped ion hardware prototype projects being commissioned from 2021 onwards.

The NQCC will give assured and direct access to developers and promote the formation of a strong UK-based quantum computing supply chain, whilst driving efforts towards universal fault tolerant quantum computer.

$10bn Global quantum tech investments announced since January 2020	**£93m** UKRI investment in NQCC	**19** Number of UK quantum computing related start-ups	**£20-35bn** Projected market impact of quantum computing applications by 2027
£1bn Projected quantum computing product & services market by 2027	**300** Partners collaborating as part of the UK quantum hub network	**£1bn** UK 10 year investment commitment to quantum technologies since 2014	**>£135m** UK start-up investment capital raised

UK Vision

Through the development and exploitation of quantum computing the UK will harness this new technology delivering societal benefits, prosperity and security.

The UK vision aims to:

- Ensure UK leadership in this pioneering area of computing, backing ideas and great people at scale, and helping to make the UK a science superpower.
- Maintain sovereign or assured capabilities in the UK, and enable the Government to be an intelligent customer of future QC services.
- Create a sustainable UK quantum industry
- Establish the UK as the worlds' first quantum ready nation.

Such a vision requires the UK to be leading in the development, application and commercialisation of quantum computing to meet prosperity and security objectives. In addition to security-focused activities, the vision will require additional activities to accelerate the growth of UK business and the wider manufacturing base within the UK.

It is likely that early (so-called NISQ) prototypes would provide benefit to a number of application areas. Supporting the development of QC, an underpinning capability impacting the whole economy can be provided through quantum readiness, and quantum computers can offer further capabilities in areas such as:

- Optimising logistics
- Simulation and modelling of molecules in the pharmaceutical and chemical industry
- Supporting challenges relying on data and AI
- Accelerating scientific advances in developing more efficient batteries

The primary purpose is to establish a dedicated national Centre that will lay the foundations to enable the UK to remain at the forefront of quantum computing, helping to deliver future prosperity and a resilient economy by building on UK strengths in research built through decades of investment and the national programme. Such a Centre will secure this strategically important technology for the benefit of the UK, with advantages gained by addressing economic and security challenges together. This Centre will build capabilities to meet economic, security and societal needs, and to understand and mitigate against potential threats by enabling the creation of the first generation of quantum computers in the UK. The National Quantum Computing Centre will focus and accelerate the UK's efforts in quantum computing and give the UK the benefits that this revolutionary technology promises, helping the UK to forge a path as a science superpower.

A Quantum Ready Economy

A quantum ready economy is one that can take advantage of the opportunities presented by quantum computing to generate and retain value across the economy and achieve societal benefits as well as maintain national security and sovereign capabilities.

Enabling Pillars

Skills

Training and career development are critical to delivery of the quantum technologies mission.

Quantum computing has the potential to energise a future generation of tech entrepreneurs, scientists and engineers alike through inspirational impact in solving some of the biggest problems facing society around healthcare, energy, climate change and materials science.

Enabling Science

The UK has leading research groups across quantum hardware, software and algorithm development.

The Quantum Computing and Simulation Research (QCS) Hub, is a collaboration of leading research teams across 17 universities working in partnership with over 25 national and international commercial, governmental and academic organisations. UK based enabling science in quantum computing has been funded in excess of £62m since 2014. [1]

Innovation

The UK is targeting 2.4% of GDP spend on R&D across the public and private sectors by 2027.

Through Innovate UK ISCF wave 3 funding, 10 quantum computing projects have been funded involving 21 industrial partners for projects between 18 and 36 months committing £27m of public funding and £11m of private sector match funding. [2]

300

Partners collaborating as part of the UK quantum hub network

£1bn

UK 10 year investment commitment to quantum technologies since 2014

19

Number of quantum computing related UK start-ups

Supply Chain

The UK has a thriving supply chain of well established global businesses as well as start-ups and SME's.

Of the key underpinning technologies needed to develop quantum computing products and services the UK has a strong representation in cryogenics, vacuum, lasers, photonics, microwave technology and nanofabrication – both in components and systems.

>40

UK based quantum computing supply chain companies

User Community

The UK has well established materials, pharma, chemicals, energy, aerospace, defence and financial services sectors.

Early users will draw from industry, academic research and government. This thriving eco-system will enable the UK to be *the* place for start-ups to form and businesses to scale successfully making the most of the UK's talent and entrepreneurial ethos.

300

Partners collaborating as part of the UK quantum hub network

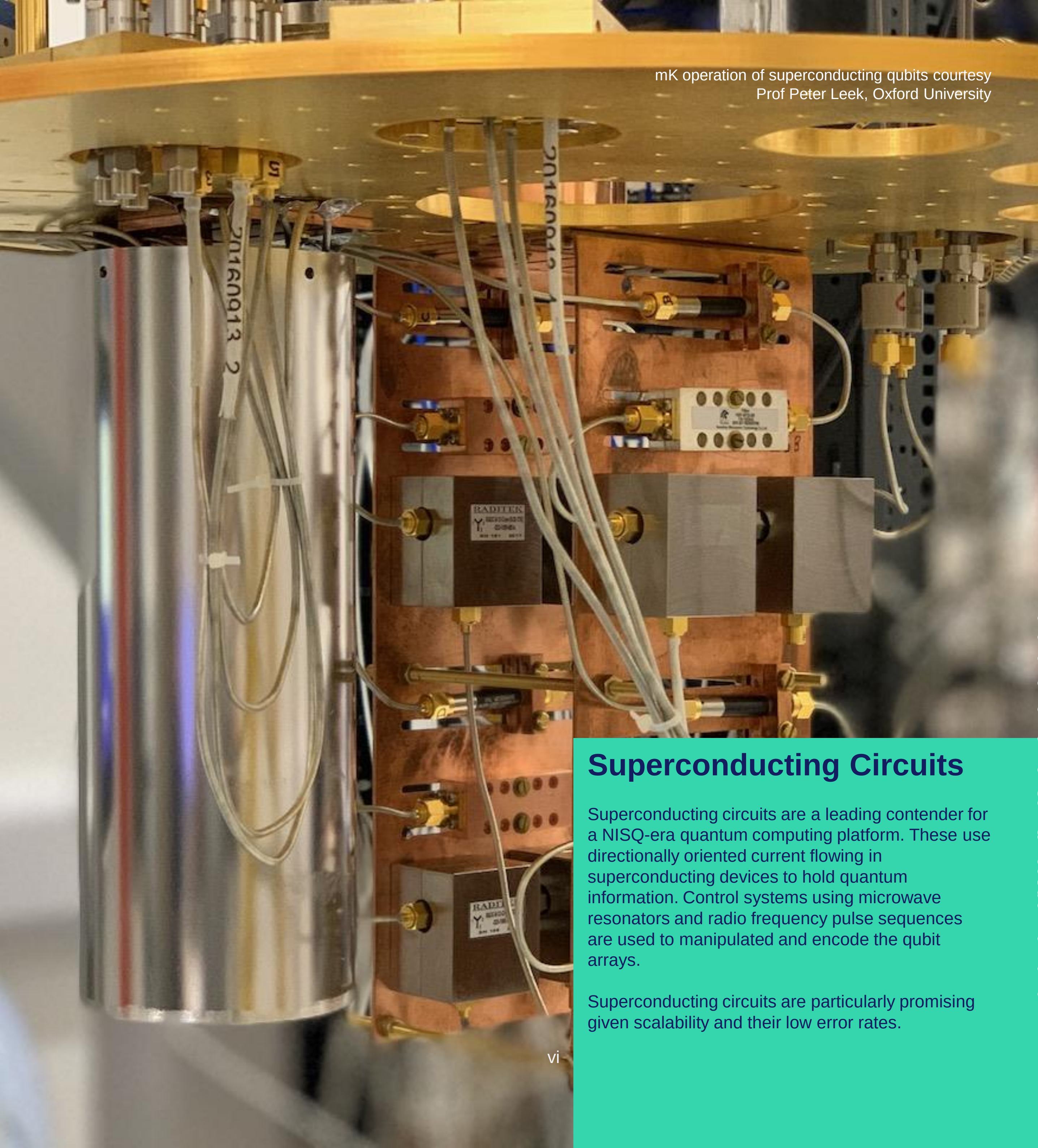
Readiness

The UK has a strategic ambition to be the worlds first quantum ready economy.

By engaging user groups through outreach, education and user access the UK can take quantum computing from laboratory research programmes to operational pivot points driving economic benefits.

£20-35bn

Projected market impact of quantum computing applications by 2027



mK operation of superconducting qubits courtesy
Prof Peter Leek, Oxford University

Superconducting Circuits

Superconducting circuits are a leading contender for a NISQ-era quantum computing platform. These use directionally oriented current flowing in superconducting devices to hold quantum information. Control systems using microwave resonators and radio frequency pulse sequences are used to manipulated and encode the qubit arrays.

Superconducting circuits are particularly promising given scalability and their low error rates.

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The Opportunity

	In 2017	By 2027
Quantum Computing Supply Chain	£200m	£500m
Quantum Computing Products & Services	£25m	£1bn
Quantum Computing Applications Impact	pre-revenue	£20-35bn

Boston Consulting Group: May 2019 [3]

Quantifying the future market opportunity for quantum computing is challenging whilst the technology remains immature. However, its economic impact is expected to be wide-ranging and transformative; it has the potential to create new markets and disrupt existing ones.

The BCG Henderson Institute predicts three phases of quantum computing identified as ‘early prototypes, (also termed NISQ-era) ‘intermediate QC’ (also termed Quantum Advantage) and ‘general purpose QC’ (also termed Universal Fault-Tolerant). The availability of quantum computing during these phases will impact many sectors, enabling improvements in efficiency, productivity and competitiveness as well as the creation of new products and services.

In particular in the UK, there are many companies with a strong presence that could potentially benefit, including those in new materials, pharma, chemicals, energy, aerospace, defence and financial services. The potential end-users are only just beginning to consider the technology and the impact it will have on their operations.

Of the key quantum computing end-user target sectors, financial services, chemicals, pharmaceuticals and energy contributed over £260bn to the UK economy. Consequently, the UK QC market is anticipated to grow rapidly. Secondary positive societal impacts on healthcare, renewable energy, clean air and reduced power consumption offer additional long term promise.

Early adopters stand to gain expertise, market visibility, intellectual property and structural preparedness ahead of widespread adoption but this is a long-term endeavour.

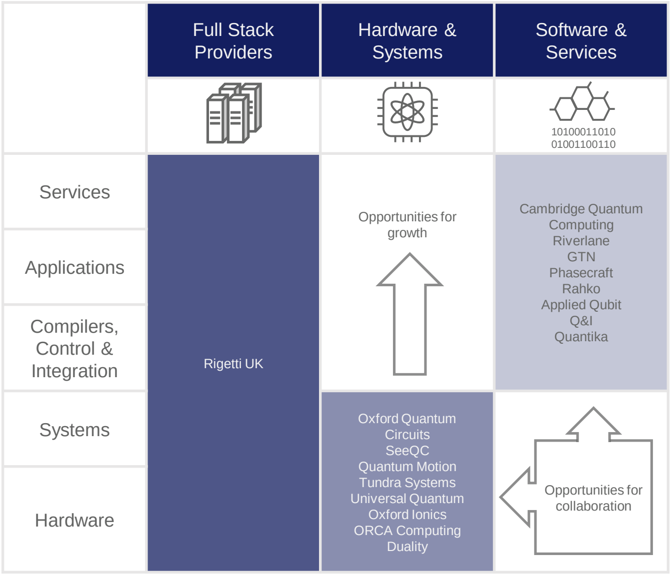
The UK Eco-System

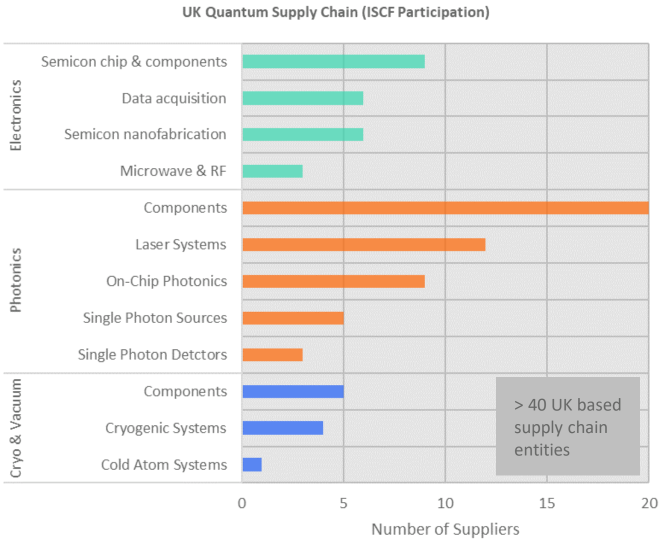
The UK lacks a large industrial systems integrator developing QC hardware at this point in time. By contrast the international landscape is dominated by tier 1 systems integrators developing hardware and QC services delivered via cloud access or field deployment.

Nonetheless, the UK has a growing start-up community actively seeking opportunities as end-users, hardware and software component providers and experts in applications and algorithms. At present, the number of companies is modest with many of these early life cycle. Given the capability and expertise in the UK the NQCC seeks to support this emerging sector and act as a catalyzing force enabling a QC industry to grow and for the UK to be seen as *the* place to establish a quantum business. [4]

Furthermore, the UK has a thriving quantum supply chain. Of the key underpinning technologies needed to develop QC products and services the UK has a strong representation in cryogenics, vacuum, lasers, photonics, microwave and nanofabrication – both in components and systems. [5]

The market impact and productivity gains promised through quantum computing also come with a direct quantum computing hardware and services market, both set to grow significantly in the coming years. In the intervening period the component supply chain opportunity is well identified and promises near term growth.





Strategic Intent

A quantum ready economy is one that can take advantage of the opportunities presented by quantum computing to generate and retain value across the economy and achieve societal benefits as well as maintain national security and sovereign capabilities.

The National Programme

The National Quantum Technologies Programme (NQTP) phase 2 investment included £93m to establish a National Quantum Computing Centre (NQCC) on the Harwell campus. The intent is that the NQCC will position the UK as a key player in the quantum computing (QC) sector. Investing in the NQCC will help build a Britain that is fit for the future.

Quantum Landscape

The NQCC will be an integral part of the NQTP and is designed to extend and capitalise on the scientific leadership the UK has established in this emerging technology. It will leverage other investments in this area, including the Quantum Computing and Simulation Research (QCS) Hub, the Industrial Strategy Challenge Fund (ISCF) commercialising quantum technologies and interact with the Centres for Doctoral Training (CDT) and other National Laboratories. It will be a key capability for the UK, helping the nation to achieve a leadership position in quantum computing over the longer-term.

Strong investments by other governments and IT majors highlight the importance to national security and economic advantage that can be gained, as well as the pace of developments.

The primary purpose of the NQCC is to fill a key gap in the landscape by providing a capability focused on addressing the challenge of scaling quantum computing. It will convene all the necessary players in the landscape to achieve this, and secure a national capability in this technology, with its expected prosperity and security advantages, for the UK.

Working with partners across industry, government and the research community, the NQCC will create the necessary R&D capabilities through co-ordination and delivery of a technical programme, alongside the commissioning and operation of new facilities, to deliver assured quantum computing capability, enabling the UK to remain internationally competitive.

Quantum Ready

This will attract industry investment, raise awareness and build skills to make the UK economy quantum ready, supporting growth in the existing supply chain to help build a sustainable industrial capability in the UK. It will contribute to the government's Industrial Strategy, support UK research and contribute towards the grand challenges facing society by developing next generation computing innovation in a strategically important emerging technology and fostering the growth of new industrial sector. The NQCC's initial 5 years will focus on developing early stage quantum computing platforms to demonstrate the technology, give assured and direct access to developers, and promote the formation of a strong UK based QC supply chain, whilst driving efforts towards a fully scalable, fault tolerant, general purpose quantum computing capability for the UK.

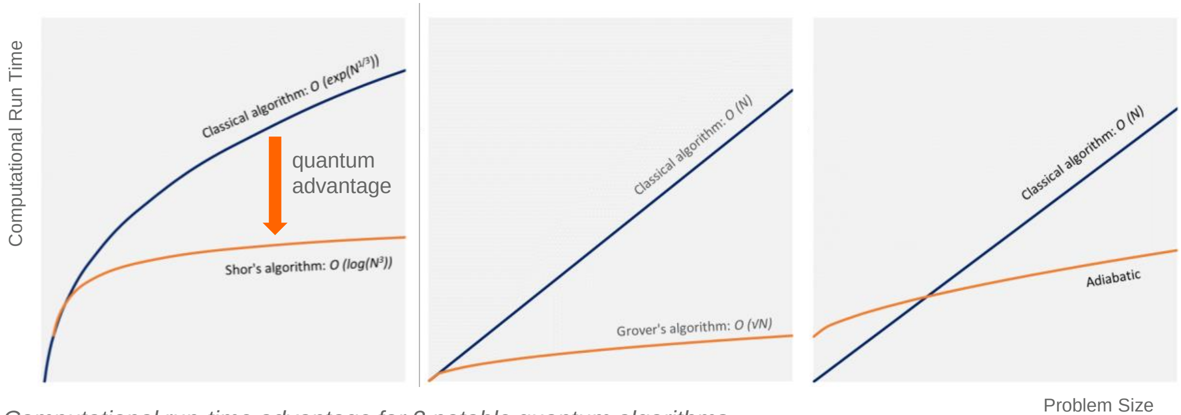
Applications

Through the encoding of entangled states with quantum information, QC has the potential to unlock unprecedented parallel processing. This so-called quantum advantage is evident in the well known algorithm examples of Shor (factorization) and Grover (unstructured search). However, quantum advantage is also a function of the number of available qubits and their susceptibility to noise.

Given this potential to accelerate resolution of complex problems and enable previously intractable computations, it is desirable to identify early use cases not reliant on fault tolerance and error correction. Such early examples are to be found in quantum chemistry, fluid dynamics, machine learning, small molecule simulation and optimization. Annealing processes have shown promise in machine learning and optimization with qubit arrays of a few thousand.

A core element of the NQCC will be to work across industry sectors to develop use cases and value propositions through applications.

Candidate early use-case and applications for NISQ-era qubits & computing



Computational run-time advantage for 3 notable quantum algorithms

A Global Effort

There are a growing number of international programmes, research groups, start-ups and industrial players across the quantum technologies landscape. Given the potential impact, quantum computing is attracting significant investment.

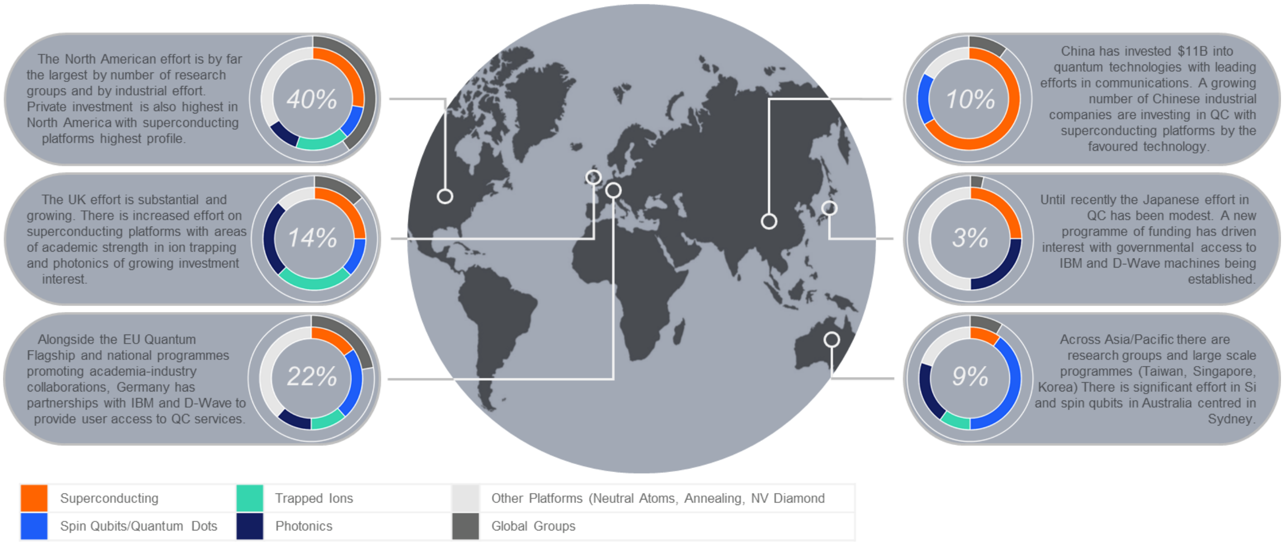
High profile progress has been made among industrial players in North America. However, around the world the pace of development and the investment is growing.

The leading architectures for qubit development across public and private sector investment are trapped ions, superconducting, spin-qubits and photonics. Many of the leading industrial efforts have developed from academic research groups with corporate venturing a growing feature of the QC landscape with direct investment into academic groups and start-ups.

Over $10bn of new public investment has been announced since Jan 2020 with over $1bn awarded through public competitions and a similar amount raised in private capital in the same time period. [6]

Over 550 patents have been filed in QC technology with over half in the US, predominantly on QC platform hardware. IP protection in software, algorithms and error correction is growing.

Selected National Quantum Technologies Investments	
£1-2bn	US, CN, EU, DE, FR, IN, **UK**
£0.5-1bn	RU, CA
<£0.5bn	AU, JP, TW, KR, NL, DK, SE, FL, ES, IT, CH



National Quantum Computing Centre

UKRI, through EPSRC and STFC, is leading a programme to establish the National Quantum Computing Centre (NQCC) as part of phase 2 of the National Quantum Technologies Programme (NQTP). The NQCC represents a £93m investment over 5 years and will establish 4 key work streams.

- NISQ demonstrator hardware platforms
- Quantum software, algorithm & applications
- High performance, scalable qubit technology
- Roadmap and architecture towards fault-tolerant general purpose quantum computing

NQCC Design Intent

Purpose

The primary purpose of the NQCC is to fill a key gap in the research and innovation landscape by providing a capability to address the challenge of scaling quantum computing. It will convene all necessary stakeholders across academia, business and government to achieve this.

The NQCC's initial five years will focus on developing a Noisy Intermediate Scale Quantum (NISQ) machine to demonstrate the technology, give assured and direct access to developers and promote the formation of a strong UK-based quantum computing supply chain, whilst driving efforts towards a fully scalable, fault tolerant, general purpose quantum computer over the longer term, enabling the creation of increasingly powerful quantum computers.

Strategic Intent

- To establish a UK trusted authority
- To create UK sovereign capability
- To promote and drive quantum computing within the UK economy
- To catalyze the UK supply chain delivery into the emerging quantum computing sector
- To establish a focus for the rapid development of quantum computing in the UK
- To create a facility on the Harwell campus

Images: ©Hawkins\Brown

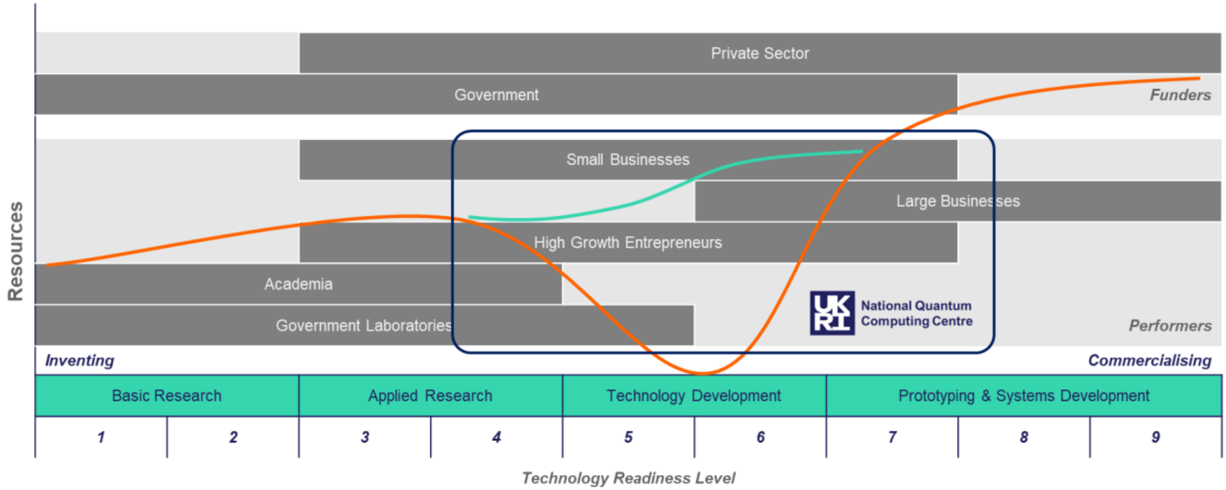
National Quantum Computing Centre

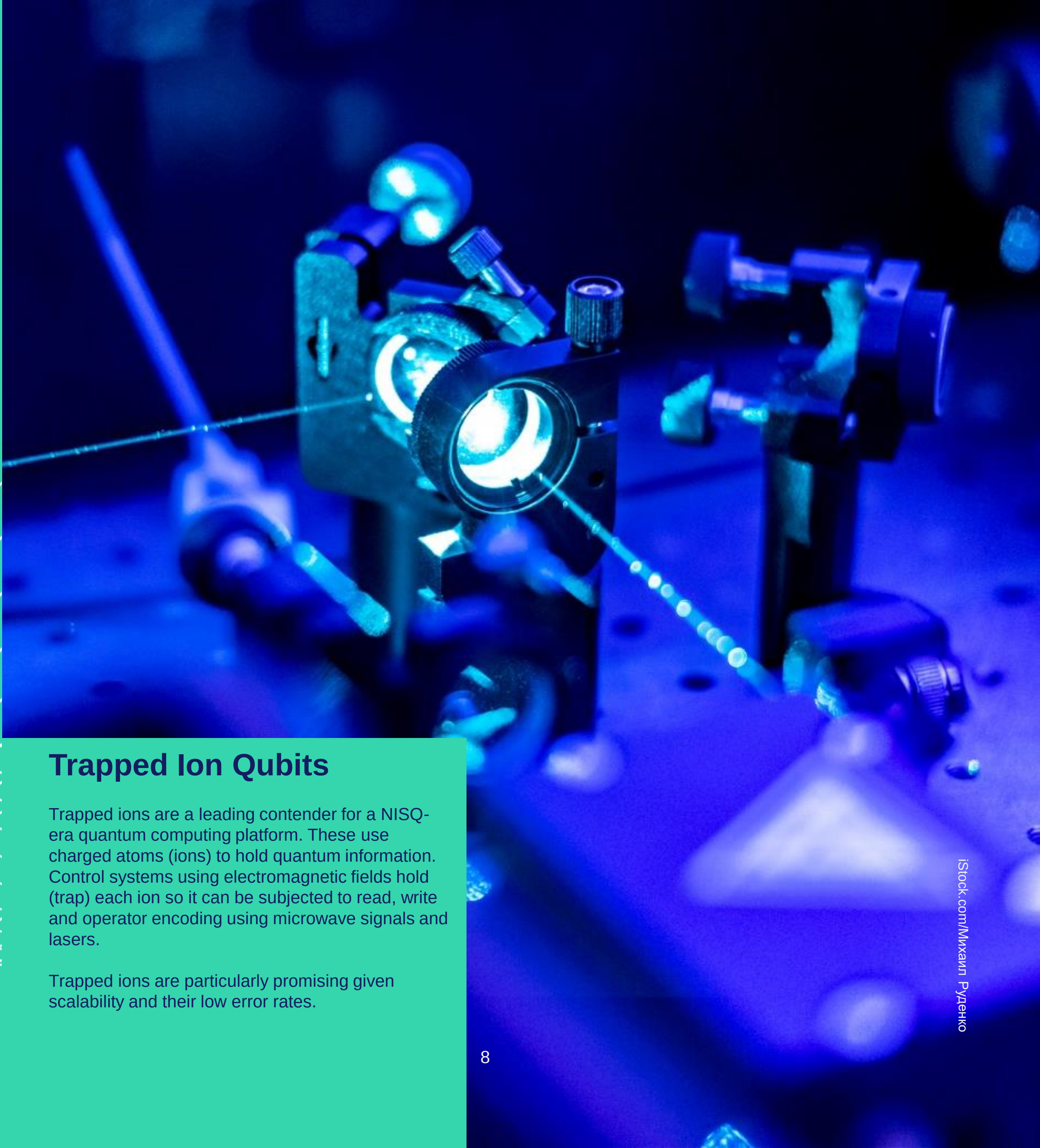
It is often observed that as technologies are advanced from the innovators and inventors to commercial products and services there can be a gap in resources transitioning out of research lead activities through technology development stages and into commercial exploitation.

Building a quantum computer requires a number of significant technological challenges to be overcome and requires expertise and capabilities in a broad range of areas across science and engineering. The NQCC seeks to help the emerging UK quantum industry bridge that resource gap. Furthermore, by focusing on technology platforms as they mature enabling scaling the NQCC fulfills a clear remit within the UK landscape collaborating with academic groups, other national laboratories, start-ups and industrial partners. The NQCC will also identify long term underpinning technologies required for scaling towards universal fault tolerant machines of the future and commission early work to ensure these building blocks are in place as they are called for on the roadmap. This will include items such as cryo-electronics, nanofabrication, bench marking, verification and error correction.

Governance

The commissioning of projects within the eco-system will be administered through existing commercial processes within STFC. The NQCC is managed through a Programme Board that delegates the day to day management to the leadership team via the Director. Oversight is maintained through our Programme Advisory Committee and Technical Advisory Group providing advice, support and challenge on the activities of the NQCC to the leadership team. Governance is assured through monitoring and evaluation through to EPSRC and STFC. The NQCC Director sits on the Operations Board of STFC and on the NQTP Strategic Advisory Board.





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Trapped Ion Qubits

Trapped ions are a leading contender for a NISQ-era quantum computing platform. These use charged atoms (ions) to hold quantum information. Control systems using electromagnetic fields hold (trap) each ion so it can be subjected to read, write and operator encoding using microwave signals and lasers.

Trapped ions are particularly promising given scalability and their low error rates.

Qubit Platforms

PHYSICAL QUBITS

In conventional computing, information is encoded as binary digits or ‘bits’, a basic unit of information, that can be represented as either ‘0’ or ‘1’. In quantum computing the equivalent unit is a quantum bit or ‘qubit’, which can exist either in a state uniquely as ‘0’ or ‘1’ or as a simultaneous combination of both ‘0’ and ‘1’ - **superposition**.

A register can be constructed from multiple qubits, which can then become correlated with each other in a powerful way that cannot exist in the, classical world - **entanglement**. The combination of superposition and entanglement means that a quantum register can encode information in a large number of states simultaneously. The information encapsulated in the quantum register doubles with every additional qubit. This feature is crucial in enabling a quantum computer’s power, allowing it to perform computations for tasks that are intractable for even the largest current supercomputers.

LOGICAL QUBITS

There are several candidate hardware architectures on which to base quantum computers, each with their own merits and at various stages of technology maturity. The common feature is that physical qubits are inherently fragile, requiring precise control and protection from the external environment. The states need to be as long-lived as possible and the operations on them high-fidelity, otherwise errors accumulate, and more computational resource is required for error correction. Architectures that require limited or even no error correction are being investigated. Technical hurdles have continually been overcome as the field has advanced, but there are significant engineering challenges that lie ahead in scaling to ever greater numbers of qubits with low noise.

Scaling qubit numbers without scaling noise is a critical challenge. Architectures enabling error mitigation and error correction leading ultimately to logical qubits that can operate impervious to noise are a key element of the NQCC technology roadmap. Such logical qubits may require ensembles of 000’s of physical qubits to support the error correction control overhead. For universal fault tolerant quantum computing with 000’s of logical qubits architecture scaling is of critical importance.

Superconducting Circuits

Chip compatible device architecture enabling scaling. The only technology to have demonstrated quantum advantage globally to date. A mature and demonstrated technology with improving error rates.

Noise scaling is unproven, The chip architecture is a 2D topology, cryogenic temperatures are required, control apparatus scaling is complex and costly.

The UK is internationally recognized in the superconducting circuit area.

A key evaluation criterion for proposed development will be a technical comparison with the known details of efforts in major groups/companies worldwide. Benchmarking of qubit performance and scaling will gate ongoing activity. Intellectual Property and freedom to operate will be important elements of the technical delivery given the active global landscape.

HIGH PRIORITY

	Trapped Ions	Spin States	Photonics
STRENGTHS	A mature and demonstrated technology with the lowest error rates. High connectivity between qubits	Diamond and other crystals can act like solid state ion traps, and can be optically accessed, good for communications. Si devices can access $tr fabrication industry;High density, low cost per qubits for scaling	On chip operation via waveguides, while fibre networks leverage mature technology. Room temperature operation possible
CHALLENGES	Unproven outside the lab, potentially bulky, scaling beyond NISQ-era challenging with potentially high power overheads.	Limited fidelity demonstrated. High cost commercial chip fabrication 2 qubit gate performance remains low in Si	Cryogenics for detector cooling and noise suppression likely. Photons have very weak interactions so operations are non-deterministic
NQCC POSITION	The UK is internationally leading in scientific research involving ion traps. UK-based teams to date have focused on high performance qubit operation over scaling. As as with other groups worldwide no compact ion trap devices are yet suitable for 'leaving the laboratory‘ and field deployment. A key evaluation criterion for proposed actions will be to consider how UK scientifically outstanding results can be scaled to deliver more qubits and packaged into compact devices for deployment.	The UK is internationally recognized in scientific research involving aspects of colour centre based QIP, especially in nano-fabrication. The UK is recognized for Si based QC research particularly on control and readout. The international lead over the UK in demonstrating qubit operations is significant, and the lack of comprehensive roadmap is limiting; any NQCC-supported initiatives should show full awareness of these challenges and argue for some unique selling point or advantage.	The UK is internationally leading in scientific research involving aspects of photonic QIP. However the commercial lead from US-based companies is significant; targeting complementary themes may be necessary. A criterion for evaluating proposed NQCC support will be to determine how the UK can exploit its extensive world leading photonics industry into QC applications and how the UK should grow its photonic QC effort in a landscape where relatively large commercial entities are already established.
	HIGH PRIORITY	**MEDIUM PRIORITY**	**MEDIUM PRIORITY**

The maturity of alternate qubit technology platforms remains under constant review by the NQCC, such as neutral atoms and optical lattices. Important research continues supported through other aspects of the NQTP. As progress towards the NISQ or universal fault tolerant goals of the NQCC is made, these technologies will be incorporated into the NQCC roadmap.

Technology Roadmap

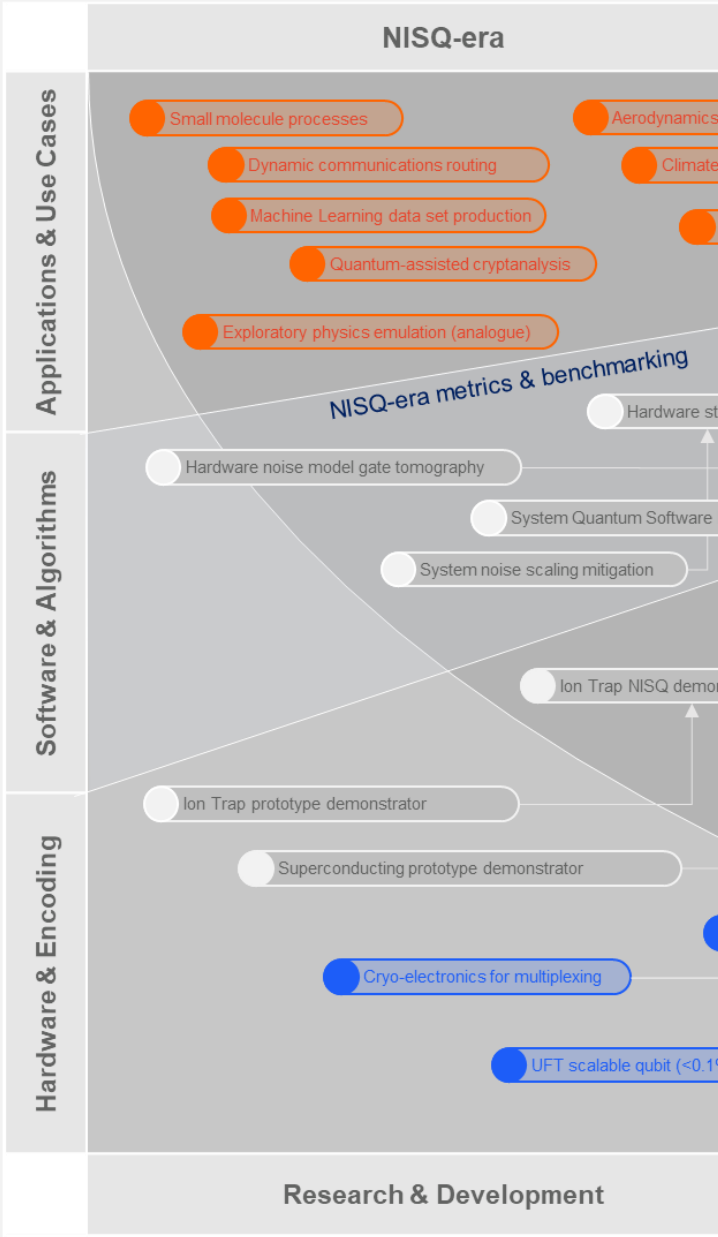
Through extensive consultation across academia and industry experts the NQCC has developed a technology roadmap identifying detailed initial steps towards the goal of a 100+ qubit NISQ-era machine by 2025. These first steps will be realised through a series of project commissions across the UK eco-system, ahead of the NQCC facility completion in early 2023. Work streams addressing hardware, software, algorithms and applications will be established. Within these work streams the topics of underpinning technologies, scaling, error and noise mitigation, bench marking and verification as well as solution packaging and user accessibility will be tackled.

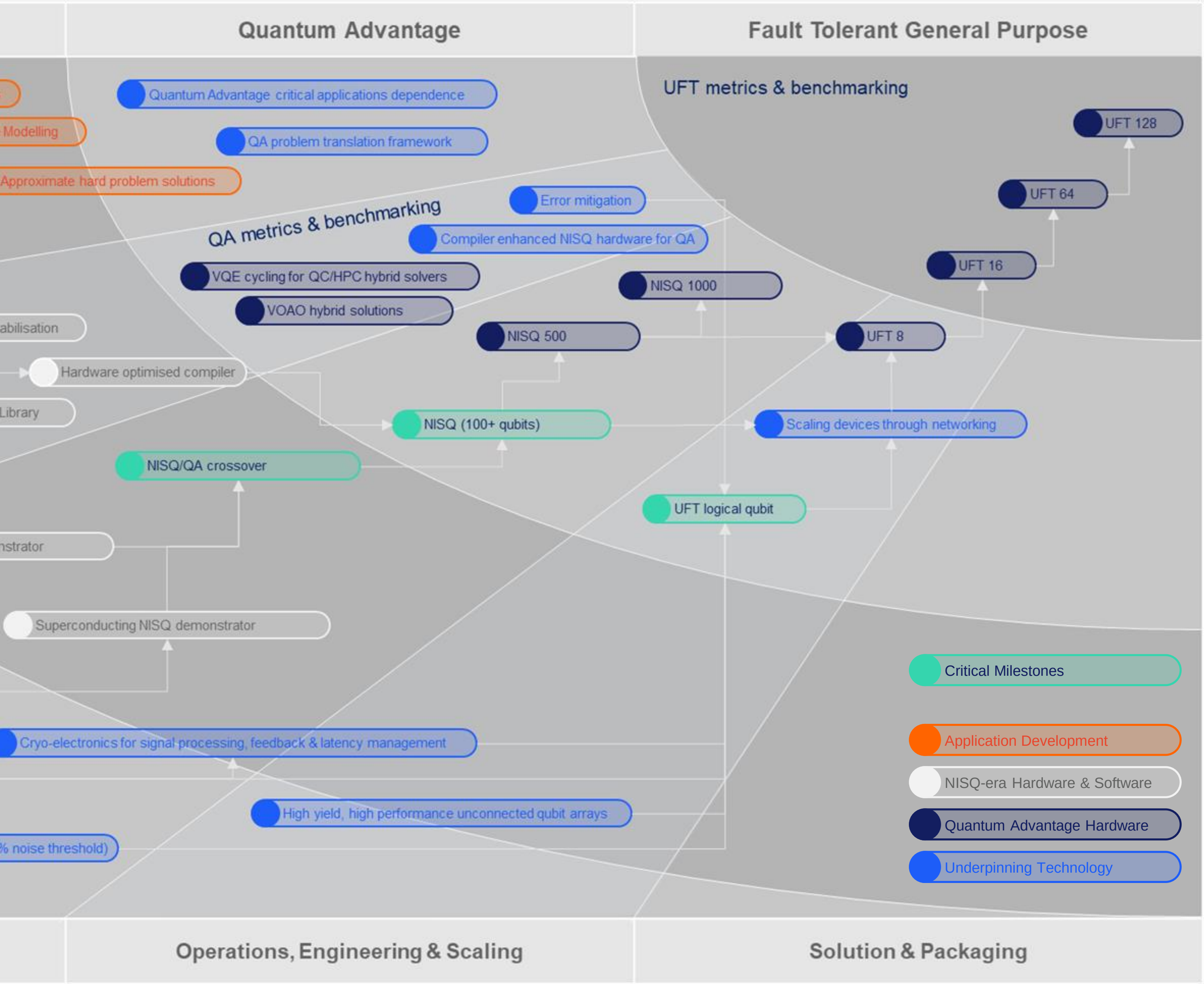
The initial focus will be on superconducting and trapped ion qubit platforms as these are currently the most mature. However, the roadmap will be driven over time as a gated process, enabling promising new platforms and technologies to be adopted and hard decisions made regarding platforms unable to scale to the performance levels needed to deliver universal fault tolerance.

Three critical milestones have been identified as the Centre established its technical delivery.

- A NISQ/Quantum Advantage crossing point
- A NISQ-era 100+ qubit machine
- A scalable logical qubit architecture

Through verification and benchmarking as well as international participation on identification of QC standards and metrics, progress towards compiler enhanced NISQ hardware is anticipated to be a key aspect of software enhanced hardware performance.





Quantum Advantage
Fault Tolerant General Purpose
Quantum Advantage critical applications dependence
QA problem translation framework
Modelling
Approximate hard problem solutions
QA metrics & benchmarking
Error mitigation
Compiler enhanced NISQ hardware for QA
VQE cycling for QC/HPC hybrid solvers
VOAO hybrid solutions
abilisation
Hardware optimised compiler
Library
NISQ (100+ qubits)
NISQ/QA crossover
NISQ 500
NISQ 1000
UFT metrics & benchmarking
UFT 128
UFT 64
UFT 16
UFT 8
Scaling devices through networking
UFT logical qubit
nstrator
Superconducting NISQ demonstrator
Cryo-electronics for signal processing, feedback & latency management
High yield, high performance unconnected qubit arrays
% noise threshold)
Critical Milestones
Application Development
NISQ-era Hardware & Software
Quantum Advantage Hardware
Underpinning Technology
Operations, Engineering & Scaling
Solution & Packaging

Quantum Readiness

Quantum computing has a formidable ramp up challenge. Programming the quantum stack represents a significant shift from conventional computing therefore existing computing resources, skills and teams will not make the transition on their own. Early adopters stand to gain expertise, market visibility, intellectual property and structural preparedness ahead of widespread adoption but this is a long-term endeavor with the timing of technology breakthroughs uncertain. Therefore traditional technology adoption models are unlikely to be observed. The innovators to laggards stages are more likely to be skewed to the later stages as awareness and capability develops.

For some industrial sectors, already users of high performance computing, QC represents a clear opportunity with internal development teams and technology advocates already in place. For them the critical pivot point comes when they transition from a research focus to operational delivery. By integrating QC into their existing business model with enhanced capabilities they will seek to create market differentiation. For other sectors QC offers the opportunity to develop new business models.

Finally for some sectors QC may appear to offer no competitive advantage, however, the threat that QC may impose on their organisations should also be considered particularly with regard to data integrity and security.

To aide this process the NQCC seeks to support industry through training and outreach and by engaging in use case development and help build advocacy within organisations through articulating the benefits of QC. Further support through provision of access to early prototypes and application specialists is also needed.

As the technology develops from the NISQ-era through Quantum Advantage towards universal fault tolerant quantum computing engagement with the wider economy will be necessary to act as a source of assurance and to provide impartial support on the requirements to participate, the impact of participation and the likely most suitable operational insertion point.

Prepare for the future now

McKinsey report three steps businesses should be taking today to prepare for quantum computing at scale in the future: [7]

Watch for developments	Monitor the market, Identify talent within your organisation, Stay informed
Secure your data	Flag sensitivities, Identify legacy weaknesses, Centralize sensitive data
Prepare for change	Identify use cases, Create disruptive innovation teams, Understand operational pivot points

Skills and Workforce Capability

Without access to skilled individuals across all levels of the ecosystem, the UK will be unable to realize its ambitions in quantum computing. Sustained action is needed to ensure a pipeline of talent and skills into research and industry to allow the UK sector to reach critical mass and avoid losing ground to global competitors.

There is already high demand between academia and businesses for quantum computing skills. This demand is expected to increase rapidly as QC technology matures in the coming 5 years.

The NQCC seeks to support the increasing need for skilled talent in the UK and to not only bolster the training and career trajectories of skilled individuals, but also increase the UK's ability to seek out and attract highly qualified persons from overseas.

Skills Development

Skills development is being pursued through 4 priority activities:

- Increasing numbers trained to a post-graduate level through additional doctoral studentships
- Delivering career opportunities in QC for the most promising individuals through QC fellowships.
- Attracting and retaining talent in the UK
- Increasing access to appropriately skilled technicians and individuals to fill roles below PhD level by expanding apprenticeships for technical-level roles, providing placements and whole career CPD programmes.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An increased skills provision will open up further opportunity for students and professionals in adjacent industries to retrain and secure good quality, well-paid work in a sector with huge market opportunity.

A highly talented workforce will promote and facilitate the UK as a destination for investors, entrepreneurs and technology managers, researchers, engineers and development partners. Increased private investment for UK quantum companies will allow them to scale at pace and bring products to market more rapidly.

Attraction and retention of world-leading experts will enable the strong research base in the UK to continue to deliver cutting-edge research and accelerate the delivery of quantum computing to market.

Glossary

Quantum information science (QIS) exploits quantum principles to describe how information is acquired, encoded, manipulated, and applied.

A **quantum state** is a mathematical representation of a physical system, such as an atom, and provides the basis for processing quantum information.

Quantum computers, which use qubits and quantum operations, will solve certain complex computational problems more efficiently than classical computers.

Quantum-inspired technology uses the learning, principles and methods developed in quantum computing to enhance conventional or classical computing techniques.

Noisy Intermediate Scale Quantum (NISQ), a description of early prototype quantum computers likely to operate with a small number of qubits susceptible to noise and prone to errors.

Quantum advantage, describes how a quantum computer may be able to out perform a classical computer on specific tasks. The word 'advantage' is often used to describe both the threshold point and machines capable of demonstrating significant speedup over classical computers – especially when practically useful.

Universal Fault Tolerant, is the term used to describe a general purpose quantum computer unencumbered by noise or errors.

Quantum Annealer, a specific branch of computing used to find minimum energy states by mapping real world problems onto energy distributions. Optimisation problems are well suited to this approach. They are different from a quantum computer in the way the qubits are addressed and the tasks they can perform. An annealer cannot practically perform Shor's algorithm, used in integer factorisation.

Simulator, using an array of qubits; molecules, chemical reactions and other physical phenomena can be simulated as a quantum system rather than calculated as a mathematical model.

Emulator, using classical compute power a quantum system or quantum computer with small numbers of qubits can be emulated for the purpose of benchmarking, test and validation.

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£93m investment by UKRI

4 key technology work streams

- NISQ demonstrator hardware platforms
- Quantum software, algorithm & applications
- High performance, scalable qubit technology
- Roadmap and architecture towards fault-tolerant general purpose quantum computing

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