Annual report

Year 3 | April 2022 – March 2023

npl.co.uk/qmi

NPL National Physical Laboratory

Department for Science, Innovation, & Technology

Contents

This picture shows the laser beams coming from the cavity-stabilised laser being divided in different branches and coupled into optical fibres so that stable light can be sent to multiple users at NPL, such as optical clocks, frequency combs and optical links teams.

Introduction

The NPL Quantum Technologies Programme

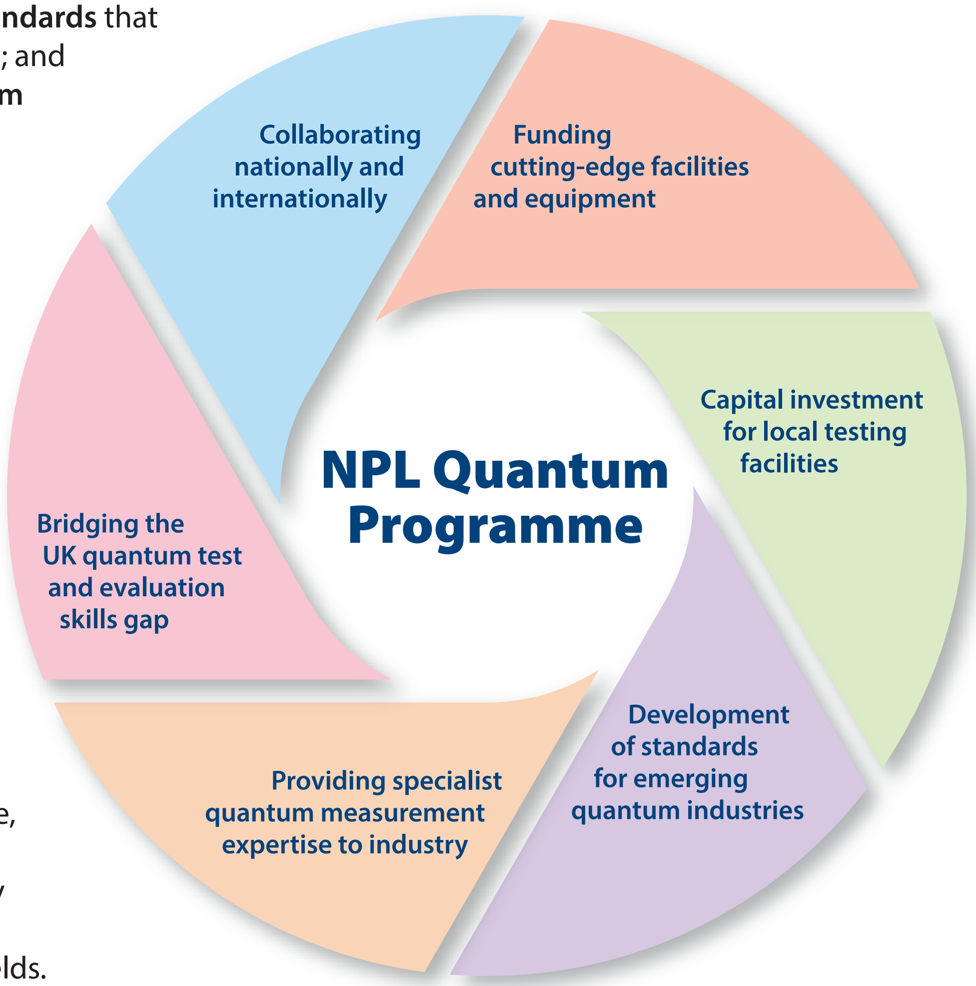
Each year – thanks to the hard work of world-leading scientists and engineers around the UK, quantum research advances and quantum technologies move closer to commercialisation. But this remains a long journey, and there is much still to do to turn quantum communications, timing, computers, sensors, and materials into a mainstream commercial reality.

To this end, the National Physical Laboratory (NPL) continues to play a major role across the whole of the UK National Quantum Technologies Programme (NQTP) – a one billion pound collaboration between industry, academia, and government, to support the development of quantum technologies.

This is a programme that aims to maximise the UK benefit from significant economic growth from quantum technologies, and that the UK becomes significantly more secure and resilient through the exploitation of quantum technologies.

NPL is well placed to support these objectives, in particular through three areas: supply chain, standards, and skills. In other words, **providing industry access to our technical measurement capabilities and expertise** to develop and secure the supply chain from SMEs to large corporations; **supporting the development of standards** that will underpin the emerging industry; and **developing the short- and long-term skills pipeline** that will be needed as the industry grows.

Through this programme, our wide range of measurement capabilities, delivered with the discipline of a National Metrology Institute, are making a vital contribution to the development, validation and commercialisation of the full range of these exciting emerging technologies. We have helped to accelerate quantum product development, and built infrastructure and facilities to test and evaluate new components and systems, enabling UK quantum innovators to develop products with confidence, proving value to investors and eventually customers. This capability builds on decades of underpinning expertise in quantum and related fields.



We have taken a lead role in the development of emerging quantum standards, which will ultimately underpin confidence in buying and selling quantum technologies.

We are developing skills, from training courses, to apprenticeships, to PhDs, to ensure that the UK has the highly skilled scientists and engineers it needs as our industry base grows.

In support of all of this, we are **proactively engaging with industry and academia, standards organisations, and the public, through events, workshops, and collaborations**. Through this outreach, we ensure industry understands our capabilities, and can access them effectively, but more importantly this continuous dialogue ensures that NPL understands industry, so that we shape new capabilities, standards development and training to respond to their evolving commercial needs.

Ultimately all of this will come together to enable the commercialisation of these products, contributing to UK economic growth, high-skilled jobs, and a more secure and resilient UK. These are the goals of the NQTP and NPL will continue to support those goals in future years by playing a leading role in implementing the recently announced National Quantum Strategy.

Structure of NPL programme & report

This report summarises the substantial progress made to date across the programme's objectives, with particular focus on progress over Year 3 (2022-2023), showcasing outputs and impacts that directly contribute to "significant economic growth" and the UK becoming "more secure and more resilient". In sections 1-3 we discuss progress in advancing capabilities, progressing standards and developing quantum skills. In section 4 we discuss the outreach, engagement and collaboration we are pursuing in support of the above. We end on an optimistic note on the new quantum strategy and the promising direction for UK quantum technologies and the emerging industry.

Dr Rhys Lewis
Head of NPL Quantum Programme

Quantum technology has huge potential across sectors

The worldwide market for quantum technologies could be worth more than $86bn by 2040.

Quantum technology applications across various sectors:

Life sciences

- Medical imaging devices (brain imaging)
- Drug & materials discovery

Space

- Telescopes
- Satellite navigation
- Navigation without satellites (inertial navigation)
- Secure satellite communications

Finance

- Random number generation for trading predictions
- Accurate time stamping
- Quantum key distribution (QKD) and post-quantum cryptography (PQC) to secure financial data

Security & defence

- Navigation and positioning tools for GPS-denied environments
- More precise radar systems
- Low light and 3D surveillance

Information & communication technology

- QKD and PQC for secure networks
- Real physical systems simulation
- Improved conventional electronics
- Quantum internet (quantum repeaters and routers)

Environment

- Environmental monitoring
- Highly sensitive and selective chemical sensing
- Emissions monitoring
- True random number generation for forecasting

Sources: Statista, 'Quantum Computing' 2019; University of Waterloo, 'Transformative Quantum Technologies', accessed Apr 2021; Government Office for Science, 'The Quantum Age: technological opportunities'.

1. Technical capabilities

Advancing the UK's technical capabilities in quantum measurement

Underpinning all of our work supporting the UK quantum industry, are our technical capabilities: the combination of expertise and facilities that allow us to make the measurements that help quantum innovators characterise and validate their technologies, and which underpin emerging standards.

These capabilities draw on decades of world-class experience making traceable measurements of light, electricity, time and many other things. These are being deployed, advanced and reinvented to meet the specific needs of the quantum industry.

Measurement can be particularly challenging for quantum systems. As an emerging technology without mature standards, new methods and protocols need to be invented. NPL's expertise and impartiality has a crucial role to play in ensuring the successful exploitation of innovations that are right at the cutting edge.

> "The UK is ideally placed to be a world leader in the new quantum technologies industry and to command a significant proportion of a large and promising future market. Our vision is for a profitable, growing, and sustainable quantum industry deep rooted in the UK.
>
> **The National Strategy for Quantum Technologies**

In this section we will discuss specific capabilities, and highlights of recent advances in:

- **Quantum communications**
- **Quantum timing**
- **Quantum computing**
- **Quantum sensors & imaging**
- **Quantum materials**

Why measurement matters for quantum communications

Quantum technologies will play a critical part in securing UK and global communications. Today's system of information transfer – from fibre, to mobile data, to satellites – which forms the backbone of global communications, relies on encrypting information in transit using maths-based algorithms. But such encryption may not be resilient to the future processing power of quantum computers.

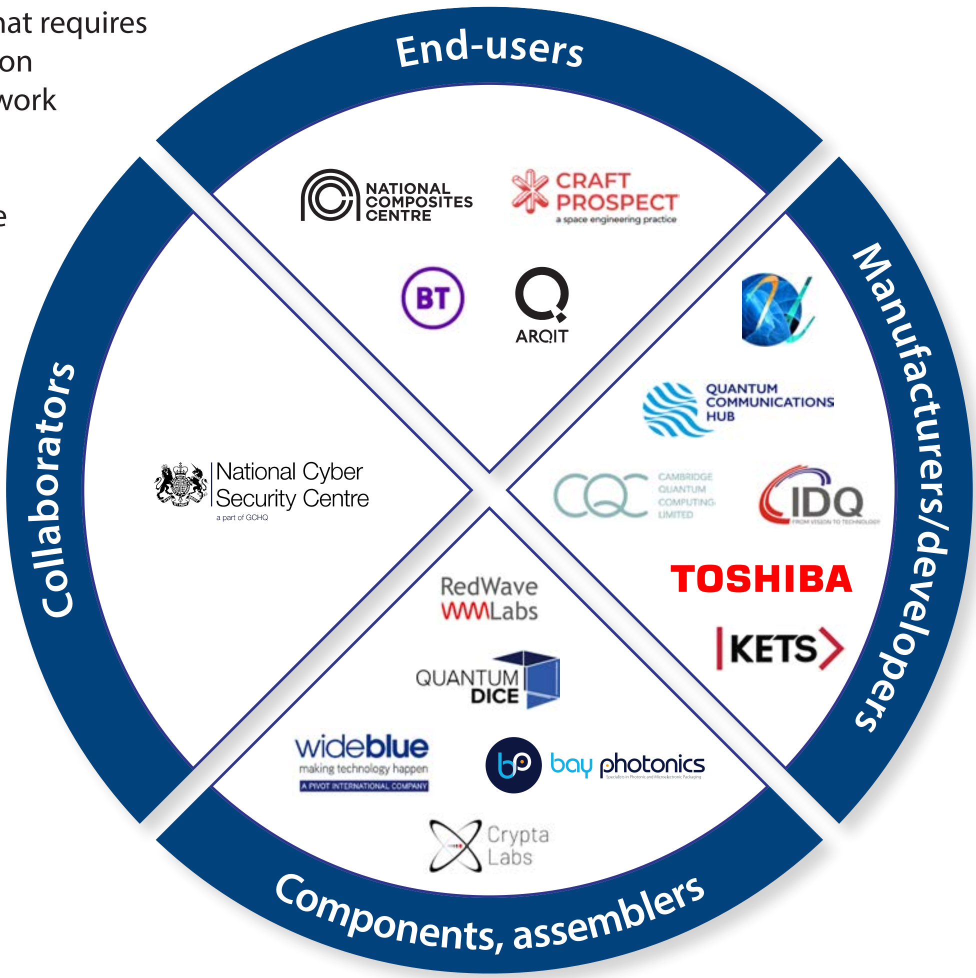
To address this, future secure communications aims to take advantage of quantum techniques, to encode encryption keys into strings of individual packets of light (photons). These are secure since any attempt to read the key will change the photons' properties in detectable ways ("knowing an eavesdropper is on the line"), at which point the information transfer can be stopped and key reissued.

Quantum communications – in particular quantum key distribution (QKD) – is one of the most mature quantum technologies, but challenges of scale remain. To make this a reality, there is a need to transfer stable quantum-encoded photons over fibre links, over short air gaps (e.g. between a router and a computer) and between satellites and ground stations.

Security rests on: the ability to generate single photons, to ensure they are truly single, to change their state, to hold that state over a distance, and to accurately detect them at the other end in various environments. That requires technological advances in photon sources and detectors, and network infrastructure for a wide range of environments, from stable electonics racks in highly secure labs, through chips on phones and satellites, to long distance fibre and repeater stations. These all present significant measurement challenges.

The EPSRC Quantum Communications Hub is delivering a range of real-world quantum-protected communications systems. NPL has supported the hub and industry to test various quantum communications protocols, validate quantum communications technologies, identify and solve problems, and advise on optimal designs.

The UK quantum communications ecosystem



New capabilities for characterising single-photon detectors

Single-photon detectors are key components in QKD, delivering the means of reading the photon states that form the quantum keys. Over the past year, NPL developed the capability to characterise fibre-coupled single-photon detectors in the visible/near-infrared (vis/NIR) spectral region. NPL had previously developed capability to characterise vis/NIR free-space SPDs. Some free-space (from short-range to satellite distance) QKD receivers employ fibre-coupled single-photon detectors, since engineering them into a QKD receiver is easier. We have already deployed this new capability in two IUK ISCF projects to characterise fibre-coupled SPDs for application in satellite QKD, and QRNG, hardware.

New test methods for continuous-variable QKD

Methods have been developed and implemented to test the transmitters and receivers of continuous-variable QKD (CV-QKD) systems. CV-QKD encodes information into light pulses, utilising both their amplitude and phase, and thus requires continuous modulation and measurement of electromagnetic field properties. It could offer a higher rate of key transfer compared to discrete-variable single-photon QKD systems that NPL has worked on previously.

This capability will be used in future years to test devices being developed by the University of York and its spin-outs, as part of QTRAX – the Quantum Communications Hub's York-Leeds-Huddersfield-Manchester pilot field-deployment of CV-QKD over track-side fibre.

Fibre link connects NPL to UK quantum network

A fibre link has been contracted to connect NPL to Telehouse North, and so directly into the UK quantum network (UKQN). The UKQN comprises metro-scale fibre networks in Bristol and Cambridge and leverages the UK National Dark Fibre Facility to connect the two. This will be used to test QKD technology and develop the test & evaluation required for distributing and processing single- and entangled-photon states over a communication network.

Why measurement matters for quantum timing

The world's first atomic clock was developed at NPL. Atomic clocks offer the world's most precise timing. A quantum technology in their own right, their accuracy makes them hugely valuable for quantum research and high accuracy position, navigation and timing applications.

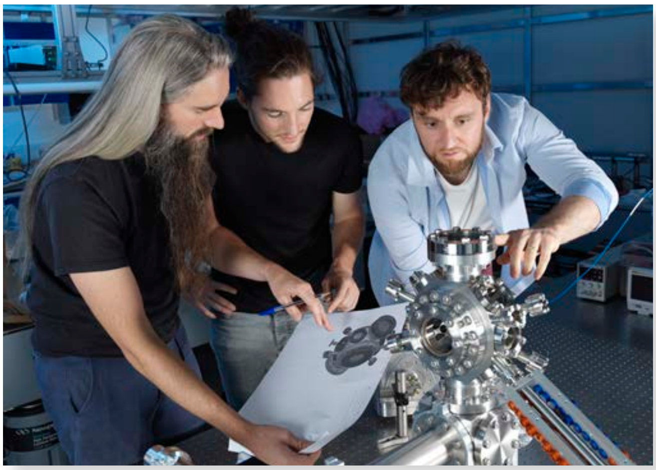
NPL has long been at the forefront of time and frequency metrology. Through the Quantum Programme – and our wider work – we are developing ever more accurate atomic clocks to provide robust time signals to support companies, academia, and metrology end users of quantum technologies. We are also supporting companies to develop practical high accuracy clocks which provide precise timing capabilities in challenging environments such as at sea or in space.

How NPL is supporting the quantum timing industry | Year three highlights

Significant milestones towards a clock Test & Evaluation facility

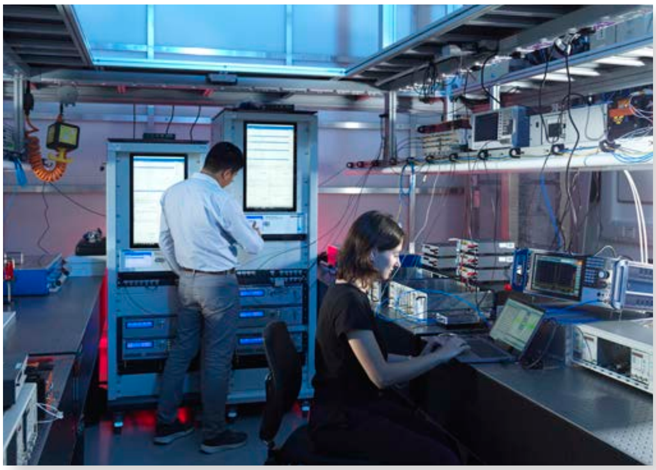
In 2022 we moved into our new laboratories for test and evaluation of quantum clocks and their sub-components. Many instruments – including the new ytterbium optical lattice clock, an ultrastable laser, and optical frequency combs – are now being set up and the first characterisation of RF clocks has been demonstrated with traceability back to the UK time scale UTC(NPL).

The facility, housed in our advanced quantum metrology laboratories (AQML), is a major element of the NPL quantum programme, where we will produce stable and accurate reference signals at relevant frequencies – from optical through to microwave and radiofrequencies – allowing new timing technologies developed in the UK to be easily compared to NPL's on-site primary frequency standards. It will become a one-stop-shop for testing and calibrating timing equipment and their components, supporting quantum innovation, and enabling quantum timing innovators to sell their products with confidence.



Yb+ lattice clock

Scientists discussing details of the Yb optical lattice clock science chamber, a critical component of the optical atomic clock which will provide the underpinning frequency reference for the quantum test and evaluation facility.



Frequency combs

Scientists operating the optical frequency combs at the AQML.

Ultrastable laser

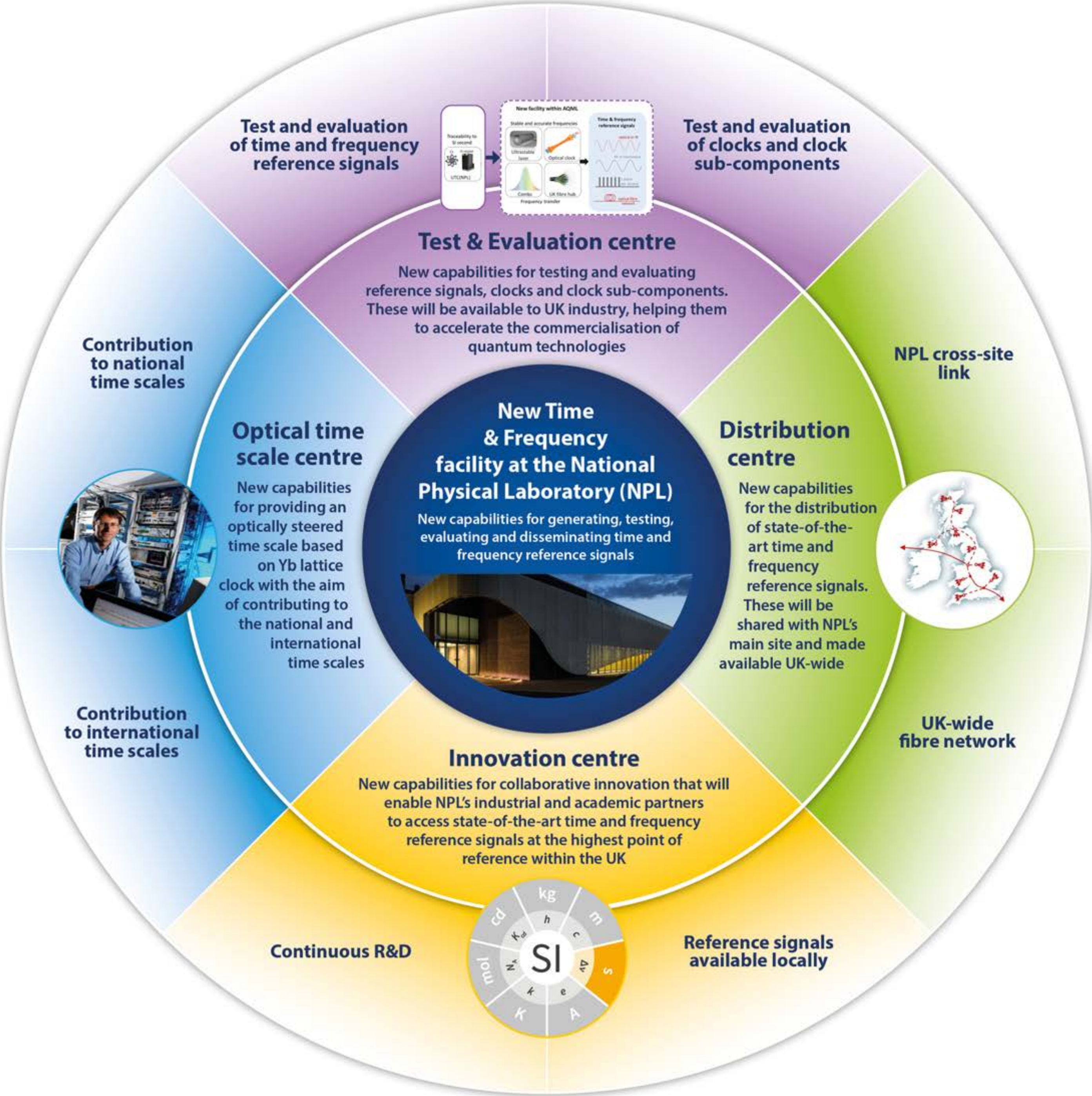
The scientist is optimising the alignment of a mirror sending light to a photodetector used to frequency stabilise the laser to the cavity resonance.*

Fibre links

Fibre links team with a cavity stabilised laser used for the dissemination of frequency signals across the labs.

* NPL's optical reference cavity displayed in this picture will be used to realise the most stable lasers ever made in the UK and worldwide. It is made in ultralow expansion glass and it is one of the manufactured artefacts with the most stable length ever realised, aiming to achieve a residual length fluctuation over 100 times smaller than the diameter of a proton over a macroscopic length of 68 cm! In a shorter cavity, NPL has already demonstrated fractional stability only three times larger than this, equivalent to a wobble of the distance between the Earth and the Sun of under 10 microns!

New Time & Frequency facility at NPL



Fibre link to University of Birmingham

A major goal of the time & frequency facility is to distribute traceable timing signals across the UK via a network of optical fibres. To this end, this last year has seen an optical fibre link set up between NPL and Birmingham University, home of the Sensors and Timing Hub.

NPL can now send a highly accurate timing signal through the fibre, which will enable testing and calibration at labs in Birmingham. One of the first uses will be in Birmingham's radar testbed facility, which requires an accurate frequency reference for synchronising a network of radar systems. The link will also be used to help develop a future network of quantum clocks to act as a sensitive detection system for exploring fundamental physics.

The link to Birmingham will provide a demonstrator for expanding time and frequency dissemination by fibre to the wider UK research community and exploiting distributed references to support photonic and quantum technology manufacturers and users.

NPL helps Aquark develop cold atom trap demonstrator

To support the next generation of quantum sensing and computing, Aquark, a quantum technology start-up, is developing a compact cold atom trap; a device capable of operating at low power, and robust enough to leave the confines of the laboratory environment. To prove the concept to the market, Aquark wanted to develop an atomic clock demonstrator to showcase their cold atom system.

Aquark's expertise was around the miniaturisation of the cold atom trap, but they had limited knowledge of timing. As Aquark's technology is based on different physics parameters to regular cold atom systems, it posed integration questions around building an atomic clock.

Through an M4Q project, NPL's experts reviewed the schematic for Aquark's prototype and provided recommendations to accelerate development. These included advice on what architecture and rubidium isotope would be best for the clock, along with information about specific components the system required. We advised on how to deal with operating challenges, such as unwanted magnetic field effects.

The clock demonstrator allows Aquark to show the practical potential of its technology to partners, customers and investors. Aquark anticipates it will help them to find collaborators and establish how their cold-atom technology can be used in different ways. The demonstrator is a major first step towards the commercialisation of Aquark's technology and could form the basis of its first product, since atomic clocks now represent the primary target market. Aquark believes working with NPL saved it at least six months of full-time research.

MINAC® portable clock deployed for naval navigation

Accurate time signals are crucial for operational success at sea. Atomic clocks give a more precise set of 'ticks' for the vessel's onboard navigation and sensing systems to synchronise with – far more stable than the GPS systems normally used for time signals. As well as greater stability, portable quantum timing also offers timing when satellite navigation systems break or are unavailable, which can be the case close to the North and South Poles.

In early 2022, the UK aircraft carrier HMS Prince of Wales was fitted with the MINAC® miniature atomic clock, ahead of setting off on naval exercises in the Arctic. The laptop-sized clock, the first of its kind, was used to provide a reference frequency standard to the vessel during the exercise.

The atomic clock on board HMS Prince of Wales (Picture: Royal Navy).

The MINAC® Miniature Atomic Clock was one of the "first five", quantum products highlighted by UKRI as ready for real-world use. The MINAC® started its journey at NPL as a TRL 4 demonstrator in 2016, and has since been developed towards commercialisation through the £7M ISCF project KAIROS, led by Teledyne-e2v. NPL inputted expertise into the clock design, evaluating clock performance and characterising the Vertical Cavity Surface Emitting Lasers (VCSELs), on which these portable clocks rely. We have recently been working with Teledyne-e2v to establish manufacturing capabilities to produce the clocks at their site in Essex.

Technical capabilities | **Quantum computing**

Why measurement matters for quantum computing

Quantum computing uses qubits, quantum equivalents of 'bits' in classical computing. By using different quantum states to replace the binary 1s and 0s of bits, qubits can store and process orders of magnitude more information than classical computing, and do so in a way that can best model real atomic and molecular systems. But creating and scaling stable qubits is challenging.

NPL is supporting the quantum computing industry by developing and deploying testing capability for a range of relevant areas. We are developing capability to characterise the various devices and components that make up quantum computers – those involved in encoding and processing quantum information in qubits.

Characterising qubits is a new measurement capability, but one that is advancing rapidly. As quantum technologies advance, a particular challenge will be scaling up from measuring individual devices to measuring systems. As quantum processors grow in size there will be a need to understand not just how devices work, but how they work in different environments, how different elements interact, and how to shield those that interfere. This will be a complex task, but one we are embracing through, for example, our collaboration with Royal Holloway University of London allowing us to characterise quantum devices as they are produced at the SuperFab facility providing the rapid quality assessment necessary to progress large-scale processor technology.

How NPL is supporting the quantum computing industry | Year three highlights

New cryogenic probe for superconducting quantum processors up and running

SuperFab at Royal Holloway University of London, operated in partnership with NPL, is a world-class cleanroom for fabrication of Superconducting Quantum Systems. In year 3, a new cryogenic probe station for automated on-wafer testing of superconducting circuits – which was installed last year – has begun to be used for testing. This will open new possibilities for studying and characterizing superconducting quantum processors.

NPL scientist preparing the cryogenic probe station at the SuperFab for automated electrical characterisation of devices at 4 K.

Quantum noise model improves qubit characterisation

Quantum noise is detrimental to quantum systems, though its analysis and control can be challenging.

Quantum noise models are critical for error mitigation and correction in quantum computing. We have developed a model which is able to successfully describe noise observed in experimental data obtained from a qubit in an IBM superconducting quantum computer.

One challenge in developing noise models is how to choose appropriate sources of noise to include in the model. By using techniques from uncertainty quantification and trustworthy AI, we were able to arrive at a minimal noise model that can accurately model the experimental results providing also their uncertainty. The work was presented at the American Physical Society March 2023 Meeting in Las Vegas where it was very well received.

Being able to characterise the single-qubit noise accurately has led to the improvement of multi-qubit noise characterisation at NPL. In an ISCF project with Cambridge Quantum (now Quantinuum) and the University of Edinburgh, NPL is developing a noise model scalable to large quantum computers. The project has shown the importance of including all sources of noise in the modeling of multiple qubits in order to best evaluate the performance of the quantum computers available today.

Micro-machining an atom shield

As part of the development of an ion microtrap quantum processor we micro-machined an atom shield prototype device, in collaboration with University of Southampton. This shield protects the electrodes of the ion microtrap from excessive atomic flux while loading the trap. Such deposits of elemental material can cause additional electronic noise in the device, which in turn causes the trapped ions to lose quantum coherence.

Characterising superconducting quantum processors

Seeqc UK quantum engineers have used NPL facilities and expertise to characterise superconducting quantum processors. Seeqc is an international quantum computing company that is developing a platform based on superconducting qubits. A significant portion of their R&D is done by their UK subsidiary Seeqc UK. NPL has been hosting Seeqc's quantum engineers who have used a combination of Seeqc-own instrumentation and NPL's state-of-the art facilities to characterise several generations of successively more advanced quantum processors. This project is an excellent example of how NPL can work closely with UK's emerging quantum computing sector and is providing UK SMEs with T&E capabilities.

First parametric amplifier system installed

To advance our capability to characterise superconducting quantum processors, we have installed a commercial Josephson parametric amplifier in our main dilution refrigerator. This device amplifies qubit state information – conveyed in low power microwave signals – making them easier to measure. We characterised the device down to 300 mK, and confirmed its performance.

Technical capabilities | **Quantum sensors & imaging**

Why measurement matters for quantum sensors & imaging

NPL is working on projects exploring advanced highly sensitive sensors, including those based on quantum materials, magnetic sensors, optical memories, single-photon detectors in applications ranging from non-destructive evaluation to data storage, and in tests of fundamental physics. Testing fundamental physics is complicated and requires expertise in these sensors alongside experience in fundamental metrology.

How NPL is supporting the quantum sensors & imaging industry | Year three highlights

Detecting dark matter with quantum sensors

The QSNET project (funded by ISCF and UKRI via the Quantum Technologies for Fundamental Physics programme) aims to build a network of atomic and molecular clocks that will achieve unprecedented sensitivity in testing variations of the fine structure constant, α, and the electron-to-proton mass ratio, μ.

These measurements will help refine a wide range of fundamental physics theories. Over time, this can be used to inform particle physics theories, to achieve a better understanding of the nature of matter in our universe, and answer big questions in modern physics, such as reconciling differences in the theories of gravitation and quantum physics.

To support this work, NPL is deploying three of its clocks, based on Sr, Yb+ and Cs. Initial results of the project, submitted for publication in 2023 with The University of Sussex have already placed new limits on time variations of fundamental constants, leading to new constraints on the strength of possible couplings between dark matter and ordinary matter.

The search relied on the fact that if dark matter couples to ordinary matter (such as atoms), then the energy levels in the atoms will be disturbed, and that will change the rate at which the clocks 'tick'. Whilst we haven't yet found direct evidence for dark matter coupling to atoms, we were able to look in more detail than has ever been done before, which allowed us to place new constraints on the scale of the couplings to certain types of dark matter.

RF atomic magnetometry sensor advances

Atomic magnetometers are sensors that measure magnetic fields, which can provide highly accurate information, for example about the structure of materials. They have a wide variety of uses, including medical imaging, subsurface mapping, detecting metals and landmines, as well as for studying fundamental physics.

Radiofrequency (RF) magnetometers detect the strength of a magnetic field by measuring the amplitude of atomic oscillations which the field creates. Over the past year, we made improvements to our RF Magnetometry Sensors, improving beam power and stabilisation, and control of RF field distribution, enabling the development of baseline measurement for sensor calibration. The experimental setup is now significantly more efficient, with better control and suppression of experimental noise.

We evaluated the sensor's performance in industrially relevant problems, such as material defects in high value manufacturing, through comparisons with other trusted techniques such as thermal imaging and commercial eddy current detection.

Technical capabilities | **Quantum materials**

Why measurement matters for quantum materials

The success of commercially viable scalable quantum technologies to a large extent rests on disruptive developments in materials research. Quantum materials are designed by exploiting the quantum nature of the constituent components, employing combinations of atomically defined building blocks, for example one-atom-thick crystalline layers of many different compounds, interfaces between different materials with perfect atomic termination, or individual atoms placed at will in a crystalline matrix. Their optical, electronic, magnetic, thermal, and mechanical properties can be precisely engineered to fulfil specific quantum applications as exemplified by nanoscale sensors, photon emitters and detectors already demonstrated. More conventional materials, such as conductors, insulators, or optical media, also need to be carefully characterised and adapted to ensure they are fit for such demanding applications.

NPL supports the development of such materials through advanced measurement of material and electrical properties, with traceability to quantum standards.

University of Manchester-NPL joint symposium on materials for quantum technologies

In May 2022, more than 20 delegates from NPL and the University of Manchester attended a joint Quantum Material symposium at the National Graphene Institute, to discuss collaboration and strategic partnership on research and innovation for materials for quantum technologies. An overview of NPL's Quantum Programme was presented, followed by research talks covering materials fabrication, engineering, characterisation and device applications.

The symposium held a round-table discussion on the development of materials for quantum technologies, highlighting the importance of a closer partnership between NPL and the forthcoming UK Materials for Quantum Network (M4QN) led by UoM and Imperial College, with pathways to joint research projects, studentships, appointments, and facilities.

2. Quantum standards

Developing quantum standards

Standards represent an agreement on how to do something, and to be able to repeat it with the same result time and again. They are proven to facilitate trade, ensuring a user knows they are buying something that will meet their expectations, and holding the seller to at least a minimum level of quality. Good standards also encourage efficient innovation by involving stakeholders in their development, and providing long-term market certainty for innovators.

In short, standards create trust and confidence.

Trust is particularly important for new technologies, where there is lots of disparate innovation, and lots of uncertainty amongst users. Quantum is perhaps the most complex set of commercial technologies ever to emerge, and few users have the knowledge to properly assess them.

Trusted standards will, therefore, be absolutely critical as quantum technologies move out of the lab and into the market.

Standards bodies curate input from industry and other experts to establish what 'good' looks like. To date, few quantum standards exist, but it is critical that they are developed by the time these technologies reach the mass market.

NPL, with its detailed understanding of such technologies is in an ideal position to provide valuable input across the board. Furthermore, technology standards will usually include characterisation – i.e. how well a product meets certain criteria, such as rate of single photons emitted, which must be assessed by precision measurement. NMIs like NPL – who have the capability to make such rigorous measurements, combined with independence – are amongst the only organisations in the world who can reliably define such test methods.

Quantum standards: The story so far

In recent years, various quantum standards have begun to be developed by organisations such as ISO and IEC.

The most advanced are the ETSI (the European Telecommunications Standards Institute) and ITU-T standards on QKD and QKD networks, to which NPL contributed expertise based on our experience assessing QKD equipment.

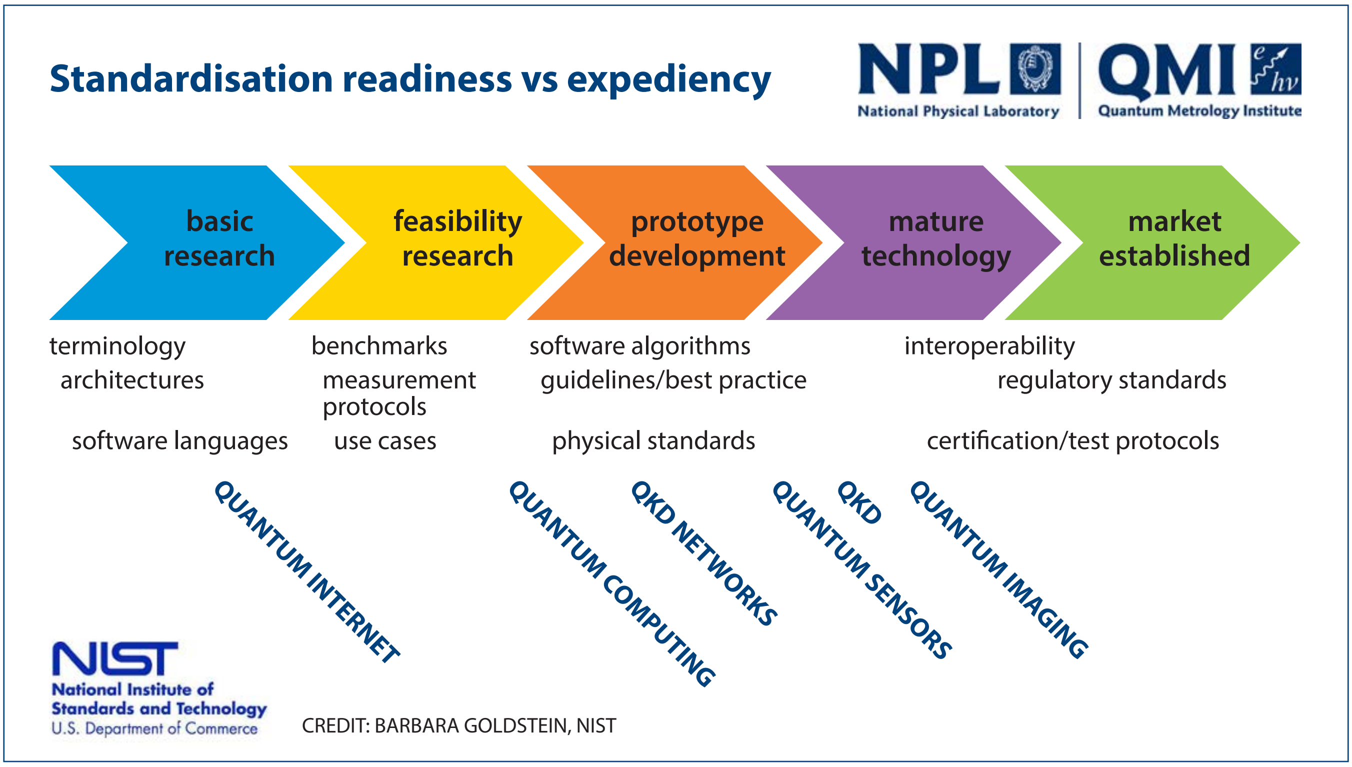
The ISO/IEC joint technical committee on ICT has a working group on quantum computing that has developed a vocabulary on the subject, with contribution from NPL experts. NPL is participating in discussions to agree the committee structure and priorities. Standards will be developed in subjects such as quantum computing fundamentals (qubit characterisation), software, and supporting technologies.

Quantum standards | Year three highlights

During this year, NPL has:

- Appointed a dedicated quantum standards manager to lead the delivery of standards within the NPL Quantum Programme
- Hosted two industry workshops to identify and discuss standards required for quantum computing and quantum communications
- Contributed to quantum standards development in standards development organisations at European and Worldwide levels
- Contributed to the recently published CEN-CENELEC roadmap for quantum technology
- Proposed – alongside BSI – a new ISO/IEC joint technical committee to co-ordinate and deliver standards for quantum technology – now under consideration
- Coordinated an NMI 'mini summit' on standards for quantum technologies – with participants from UK, US, Germany, Japan, Canada and Australia – ahead of a worldwide summit planned for early 2024
- Presented on standards at a wide variety of industry events, including Quantum Technology Europe
- Through the recently formed IMEKO TC25 – a forum led by NIST, PTB, and NPL to discuss quantum-based measurement – organised two sessions at the Precision Electromagnetic Measurements conference, one on Quantum Sensing, and one on national and international perspective on wider quantum technologies

One of the key areas of the NQTP is to "strengthen engagement in international standards and benchmarking". Through all the above, we have promoted the UK as a driving force for global standardisation in quantum technology



The future of quantum standards

Quantum standards are still evolving. NPL will remain at the heart of UK and global standards development for emerging technologies, and in particular quantum technologies. We will continually engage with industry and academia to review the current state of play across quantum standards development.

We will collaborate with other NMIs to coordinate development of methodologies for complex areas such as the characterisation and assessment of qubits. We are working towards an NMI summit on quantum metrology early in 2024.

We will continue to represent the UK in international and European quantum standards development forums and working groups, and lead UK interests in international agreement of documentary standards to support growth in international trade by UK quantum suppliers.

3. Skills

Building the quantum skills pipeline

As the quantum industry grows, it will need a scale up in skills to support the growing companies and research programmes. These will include highly technical science and engineering capabilities. To play our part in supporting this pipeline, NPL is using its expertise to provide training in quantum test & evaluation for those ready to enter a career in quantum, and inspiration to those who may do so in future.

Building skills & careers

NPL's quantum programme has significantly contributed to quantum skills development in the UK by co-funding, co-supervising and hosting PhD students, joint appointments, apprentices and secondments, providing them with real hands-on experience on live quantum metrology projects. Furthermore, we have started to develop quantum metrology training and resources.

Year 3 | Highlights from the year include:

The quantum area has the largest number of postgraduate students within NPL's Postgraduate Institute for Measurement Science

Developed three bitesize modules, introductory videos covering Microwave metrology for quantum computing, Quantum efficiency of LEDs, and Reflectometry, the first of which launched in March 2023.

Launched an NPL-certified course 'Introduction to clock performance' in March 2023. This is the second in a series from the National Timing Centre (NTC) Programme in partnership with the NPL Quantum Programme, that will help build skills in time and frequency to support services and innovation, which will be required for many sectors to function properly.

2
Apprentices

35
students
in total supporting the Quantum and Time departments

11
PhD students
directly funded by the programme this year

students with
16
universities

3
joint appointments
with UK universities

University of Strathclyde,
Royal Holloway,
University of London

Skills stories

Susan Johny

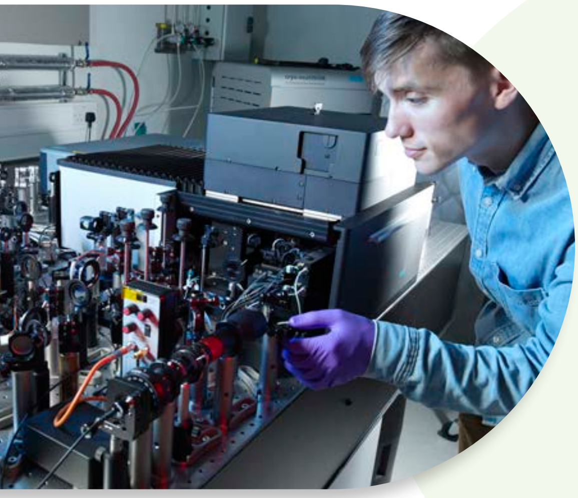
Research Scientist undertaking a PHD

Susan is a Research Scientist who undertook a PhD to further her career with NPL. Through her studentship, she has been trained fully on fabrication and spends her time at Glasgow University to design, fabricate and test devices. Susan enjoys both the research and outreach aspects of her studentship and has participated in several public engagement events, including organising the Single Photon Exhibit which attracted 200+ people.

Hands on work at University of Glasgow's Advanced Research Centre.

Student award:
James Kelly

James Kelly, a joint NPL/University of Glasgow PhD student, was awarded the **ARFTG Roger Pollard Student Fellowship in Microwave Measurement** gold award, worth $7500, for his work in NPL's EET Department relating to the development of high frequency measurement techniques supporting advanced communications and quantum technologies.



Using NPL's scanning near field optical microscopy equipment.

PHD success story:
Tom Vincent

Tom Vincent, a joint NPL-RHUL PhD student, successfully passed his PhD viva in this year. In his thesis entitled **"Nanoscale light-matter interactions in van der Waals materials"**, he employed a broad range of scanning probe and optical microscopy techniques to demonstrate how nanoscale features like bubbles, fractures, grain boundaries and wrinkles can alter the properties of materials as well as how these properties can be optimised by changing the local strain, charge doping or electronic dispersion. His work was of exceptionally high quality, as confirmed by two highly renowned examiners. In June, Tom joined Dr. Jessica Boland's group at University of Manchester, working on topological materials/20 semimetals and ultrafast microscopy.

Measurement Scientist Apprentice:
Henry Bourne

Henry supports the development of the optical clock in the AQML, providing hands-on support for optical local oscillator equipment set-up and characterisations. Through his apprenticeship with NPL, Henry has learnt **"what quantum is from a technical perspective and how to support the practical side of science"**.

EPSRC career development fellowship:
Sebastian De Graaf

NPL Senior Research Scientist Dr de Graaf was awarded an EPSRC quantum technologies career development fellowship. The fellowship aims to deliver the next generation of science leaders in quantum technologies while simultaneously addressing key technology needs for quantum. Dr de Graaf will lead a project which envisages the laying out of the foundations for a new era in materials science relevant for solid-state quantum circuits, including developing a new kind of instrument for understanding the quality of materials used in quantum circuits and quantum computers.

Sebastian De Graaf said:

“ **The fellowship presents a unique opportunity to lay the foundations of a new direction in materials science, develop UK leadership in this important area, and to build a diverse team bringing together skills from other areas of engineering and materials science towards better materials for core quantum technologies.**

Student award:
Marius Hegedus

Marius Hegedus, a PhD student at Royal Holloway University and NPL, and supervised by Dr Sebastian de Graaf, has been awarded a prestigious **SIM Postgraduate Scholarship by the Worshipful Company of Scientific Instrument Makers (WCSIM)**. The WCSIM makes several of these awards each year to research students of exceptional promise in scientific instrumentation; each award is for £2,000.

4. Engagement & outreach

Engaging industry, government, academia and the public to advance quantum together

Quantum is a new set of technologies that will deliver benefits to many business sectors, society and the economy. To go from a community of pioneering innovators to a major global industry, it will need business, government and academia to come together to collaborate, share knowledge and set the direction and standards for the future of the industry.

To deliver all of the above – the capabilities, standards and skills that lay the foundations for a future commercial quantum industry – we need to continuously engage and collaborate with industry, academia, standards bodies and government. That means networking, events and collaborations to bring interested parties together to understand opportunities and challenges and find ways forward.

Across this year, our engagement and outreach work has spanned four key areas:

1. Sharing our work with the broader community, through **events and outreach** to build awareness of quantum, excite potential students, and instil a public readiness for quantum technologies.
2. **Building relationships and collaborations** across national and international centres of excellence, metrology institutes, standards bodies, academia, and industry, to tackle challenges together.
3. Enabling SMEs to access leading quantum test and evaluation knowledge and facilities at no cost, through our **Measurement for Quantum** (M4Q) programme.
4. Forging **cross-UK partnerships** to ensure wider access to measurement expertise and ensure our work meets the needs of the whole country.

Events and outreach

Through events, NPL has reached quantum technology companies to discuss their challenges and inspire the next generation of quantum scientists. The below highlights some of the events we participated in this year, in pursuing this goal. This is not a definitive list and key case studies have been elaborated on below.

April

QNetworks 2022 – discussed latest and forecast quantum communication challenges and solutions with international researchers involved in the Hub programme.

UK's Strength & Weaknesses in QTech Research – contributed to Institute of Physics-led research agenda for future quantum programme, including Hubs.

May

NPL Open Day 2022 – 50 staff demonstrated several quantum exhibits to 2700+ visitors to make our work in the quantum space better understood and to build excitement and trust in the deployment of various quantum technologies.

June

STEM Hub Assembly – NPL engaged with 1000+ secondary school students from across 47 schools who wanted to learn more about STEM career opportunities.

July

The Quantum Advantage Summit – NPL collaborated with government officials, scientists and tech trailblazers to bridge the gap between policy, academia and cutting-edge technology.

Quantum Sensors for Hidden Sector Meeting – First face-to-face collaboration was organised and held at NPL, with 24 people attending talks on progress of project work packages, shared updates and discussions on successes and challenges.

August

NCSLI Conference – Networked with other leading experts in the measurement science industry.

Photon 2022 – NPL scientist was an invited speaker on the application of quantum metrology, imaging and sensing.

29th General Conference of the Condensed Matter Division of the European Physical Society – organised with the Institute of Physics, NPL's work was presented as a poster.

September

The NPL Joint Symposium on Quantum Technologies – This symposium covered the latest advances across all pillars of quantum technologies.
Case study »

Quantum Systems Theory Workshop – NPL led a talk about our work on the axion search in a magnetic field, in addition to chairing a sessions on quantum amplifiers.

QTNM Face-to-Face Consortium Meeting – NPL hosted attendees from UCL, Warwick and Swansea enabled extensive networking opportunities and lab tours. Consortium members were all impressed with NPL facilities and capabilities.

October

International Applied Superconductivity Conference (AS) 2022 – A poster related to the Superconducting Low-inductance Undulatory Galvanometer (SLUG) work was presented.

November

Institute of Physics (IOP) "Quantum on the Clock" Competition – NPL sponsored the competition which challenges students to film creative videos explaining an area of quantum science.
More info can be found here »

NPL & NIST sign Memorandum of Understanding (MoU) – NPL strengthened relationship with the US National Measurement Institute by signing the MoU which solidifies an intent to collaborate further in the quantum space.
More info can be found here »
Case study »

December

SPIE.photonex Conference – 19 NPL scientists presented their research across the quantum ecosystem. At SPIE scientists have the opportunity to present how they can support new product development and enable research & development initiatives.

January

Quantum Technologies for Fundamental Physics (QTFP) Winter School – hosted by University of Cambridge at Robinson College, NPL delivered a lecture and tutorial sessions for students with an interest in pursuing STEM careers with a particular focus on quantum.

NPL and National Quantum Computing Centre (NQCC) sign MoU – A reflection of the commitment of both parties to collaborate further in the field of quantum computing.
More info can be found here »

February

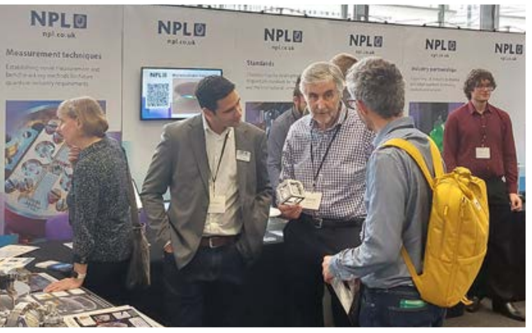
QTFP Engagement Event – NPL was invited to speak in a session focusing on Quantum Metrology for Fundamental Physics

March

New Scientist Manchester – NPL hosted a stand with UKQTP demonstrating our high accuracy clocks.

British Ion Trapping Conference (BrIT-C) – NPL hosted a two-day scientific meeting to showcase the work of the UK's ion-trapping community. The conference was an opportunity to disseminate progress and results, as well as encouraging presentations by early career researchers to aid their professional development.

UK National Quantum Technologies Showcase



NPL had a major presence at the annual UK National Quantum Technologies Showcase event at Queen Elizabeth II Centre London, on 11th November, which attracted over 1,000 attendees from industry and academia. NPL's stand was one of 60 exhibits showcasing the strength of the UK's new quantum industry. We used the showcase to signal to the UK quantum community our expanding capability to support them in solving measurement challenges and accelerating their innovations.

We presented several quantum programme capabilities at the showcase including:

- Quantum Random number generator (QRNG) demonstrator running in real time
- The Quantum Sensors for Hidden Sector project
- NPL's work on cavities and optical clocks, microcombs, the MINAC®, TISOC (Trapped Ion Space Optical Clock), and portable ion clocks
- NPL had a slot in the speaker programme to explain our role supporting UK industry on the path to commercialisation of quantum technologies
- Characterisation of microwave components at cryogenic temperatures and displaying a novel technique for immersion cooling of superconducting quantum processors. Furthermore, we also presented work on the MINAC®, TISOC and portable ion clocks

1st British Conference on Trapped Ions (BrIT-C) hosted at NPL

In March 2023, NPL hosted the first national conference showcasing and discussing the work of the entire UK ion trapping community. The meeting had almost 90 attendees representing 11 research groups from academic institutions and government laboratories, and four companies.

Joint Symposium on Quantum Technologies hosted at NPL

The NPL Joint Symposium on Quantum Technologies attracted over 80 attendees from across industry and academia to present on the latest advances in quantum networks, quantum computing, quantum photonic integrated circuits, quantum metrology and standards.

Secretary of State visits Quantum Labs

On 23rd March, NPL welcomed the Secretary of State for Science, Innovation & Technology, the Rt. Hon. Michelle Donelan MP, to our advanced quantum metrology laboratories. This visit came very soon after the publication of the National Quantum Strategy.

The Secretary of State visited an optical atomic clock lab, where we generate state-of-the-art precision timing reference signals. She met metrology apprentice Henry Bourne who showed her an ultra-stable laser cavity and took part in a demonstration of how to "lock" the laser to the cavity.

She saw where we test and evaluate quantum technologies and ran a test to characterise a miniature atomic clock. She also visited a lab that houses one of NPL's dilution refrigerators where we explained the need to measure quantum properties at temperatures close to absolute zero. We shared an example from the Measurement for Quantum programme, a collaboration with the company Intelliconnect, testing components for use in quantum computers at these low temperatures.

The last part of the tour involved finding out how NPL engages with the public and encourages people into STEM careers, including speaking to NPL scientist Benyam Dejen about his work with the Blackett Lab Family which promotes Black representation in physics.

To conclude the visit, the Secretary of State and NPL CEO Pete Thompson unveiled a plaque that marked the occasion and the opening of new advanced quantum laboratories.

Executive workshop

On Tuesday 24th January 2023, the NPL quantum programme team hosted a workshop at Central Hall, Westminster. The purpose of the day was for NPL to listen to the needs of UK industry. Outputs from the well-attended event will influence the future investment and strategic planning of the NPL Quantum Programme.

We hosted 33 UK industry representatives. In a set of small and candid discussions, participants were able to tell NPL of actions they see would support market adoption of quantum technologies in the UK. A range of people across the value chain, from suppliers to end users, all offered their views.

Four independent rooms were set up to look at Quantum computing and simulation, Quantum communications, Quantum sensors and timing, Quantum enhanced imaging. Each discussion was facilitated and scribed by members of the NPL team.

It provided a terrific opportunity to show the NPL programme to industry and government.

Industry needs assessment

In March 2023, NPL published an assessment of the needs of the UK's quantum industry. The assessment was based on a mix of group discussions, one to one interviewees and other inputs with a total of 377 participants.

The report identified that needs varied widely between companies, who had different priorities and levels of maturity. Nonetheless, through clustering answers, six needs emerged as specifically in demand:

35% identified a need for **Test and Evaluation**, in particular single photon detectors, lasers, and testing quantum products in varying environmental conditions.

23% identified **a need for information to demonstrate the value chain**, including independently produced documents explaining the advantage of quantum over current solutions.

14% specifically mentioned **the need for standards**, with the strongest requests from organisations connected to commercially accelerating technologies such as communications and quantum computing.

12% talked about **a need for support with commercialisation**, with specific requests for more stock-holding of quantum components, and support navigating complicated procurement processes.

8% mention **a need for skilled people and learning**, especially more engineers, and for those in adjacent industries to be cross trained with quantum skills.

5% made comments about challenges of **free international trade** especially the need to make importing and exporting easier.

In response to the challenges identified, this report makes five recommendations.

- NPL to increase efforts to make testing and evaluation available to quantum innovators
- Create good practice guides to support the characterisation of lasers
- Encourage transparent metrology through organisations openly reporting how a measurement was made
- Enhance trade body efforts to champion and strengthen the industry
- Increase funding for skills development, including for practical courses

To access the full report, visit: https://eprintspublications.npl.co.uk/9689/

International and national collaborations

By working with leading organisations, in the UK and internationally, NPL can access state-of-the-art knowledge and capability, and use this to develop the most advanced test and evaluation capability for the UK, giving the UK a competitive advantage.

Year 3 | Collaboration highlights

NIST

NPL and NIST signed an MOU, committing to collaborate in quantum. The quantum programme has been provided with additional investment from DSIT to support these collaborations for the next three years, with the goal to:

1. Be joint leaders in quantum standards and quantum metrology
2. Develop research collaborations, build upon existing research capability, and to enhance collaboration with industry

Dr. Laurie Locascio, Director, NIST stated:

I am pleased that our longstanding relationship with the National Physical Laboratory will be strengthened by this joint commitment to quantum science, International cooperation will be vital to ensure the best research and future standards incorporate the highest technical rigor as the quantum field matures.

Superconducting QMaterials & Systems (SQMS)

On December 15, 2022 the U.S. Department of Energy (DoE) approved a partnership between the US Superconducting Quantum Materials and Systems Centre (SQMS), Royal Holloway University of London, and NPL, in four areas:

- Understanding and mitigation of decoherence in superconducting quantum devices
- Quantum devices and systems for dark matter searches
- Quantum algorithms, benchmarking, certification and verification
- Fundamental limits of quantum devices

The DoE-funded SQMS aims to develop and deploy the world's most powerful quantum computers and sensors. RHUL and NPL operate within a collaboration agreement, which features joint appointments, reciprocal access to infrastructure and joint PhD studentships.

NQCC

NPL and the NQCC are key partners in the National Quantum Technologies Programme. Through an MoU signed this year, we created a commitment to collaborating to accelerate quantum computing for the benefit of the UK.

Over the next five years, the institutes plan to explore collaborations to:

- Enable independent testing, benchmarking, and validation of quantum computing technologies
- Enable coordinated development and delivery of technical roadmaps for quantum computing
- Enable exchange and knowledge of expertise related to the research on quantum computing
- Support development of quantum computing industry standards
- Support UK training to contribute to a skilled and diverse quantum computing workforce

NPL CEO, Dr Pete Thompson said:

Signing this MoU will accelerate the close collaboration between NPL and NQCC. We will ensure that metrology, measurement standards and independent test and validation can enable strategic advantage from quantum computing under the leadership of NQCC, engaging with the many academic and industry organisations contributing to this national effort.

NQCC Director, Dr Michael Cuthbert said:

through this MOU we are bringing our shared expertise in quantum computing hardware, software and applications together to support the development of industry standards. Our early focus is on testing, benchmarking and validation of quantum computing technologies and marks an important step, shaping our collaboration, towards our shared goal of making the UK a quantum-ready economy.

The hubs

The NQTP is based around four hubs – communications, computing & simulation, sensors and timing, and enhanced imaging – each led by a university. Through NPL's quantum programme, we continue to ensure each hub has access to the measurement expertise and equipment it needs to support its industry partners to develop and validate quantum technologies.

UK Quantum tech hubs

Hub title: **Quantum Communications**
Lead: **University of York**

Hub title: **Quantum Imaging**
Lead: **University of Glasgow**

Hub title: **Quantum Sensors and Timing**
Lead: **University of Birmingham**

Hub title: **Quantum Computing**
Lead: **University of Oxford**

In 2022-23, the collaboration between my group at UCL and Dr Rungger's group at NPL has continued and intensified. We have developed an important algorithm which provides a new way to implement quantum materials simulations on a quantum computer. The contribution of the NPL team was critical in providing the background theory in materials simulation which forms the main spine of the quantum algorithm. We have now started joint supervision of a PhD student, Hasan Sayginel, to adapt quantum simulation algorithms, including those developed above at NPL and UCL, to be suitable for fault tolerant quantum computers.

Dan Browne,
Professor of Physics, UCL

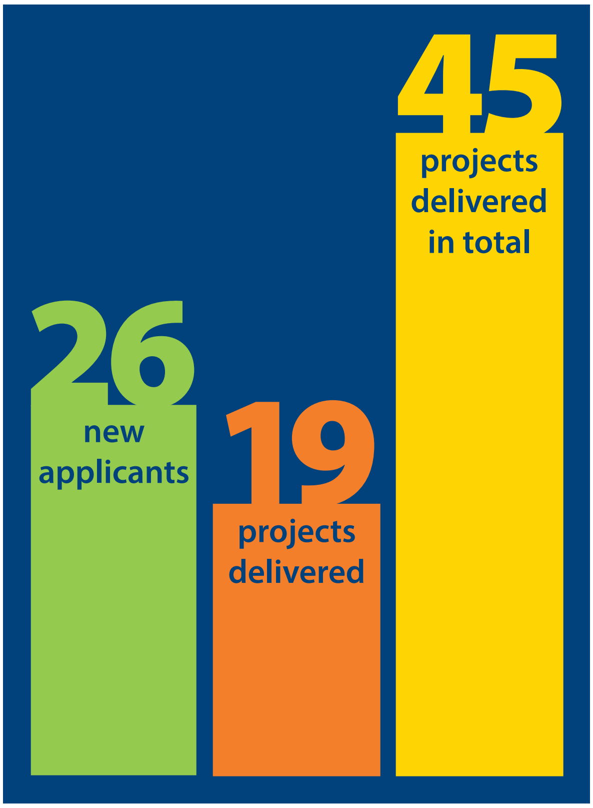
Our partnership between Oxford and NPL has led to the publication of two academic papers. The first presents the characterization of transmon qutrit performance, extending gate-set tomography to qutrit systems. The second highlights the potential advantages of using qutrits over qubits in quantum machine learning (QML). NPL's expertise and experience in qutrits and QML algorithms were instrumental in designing and implementing these methods. Our joint efforts resulted in the successful implementation of the qutrit classifier and demonstrated the potential of qutrits for quantum machine learning.

Peter Leek,
Research Fellow,
University of Oxford

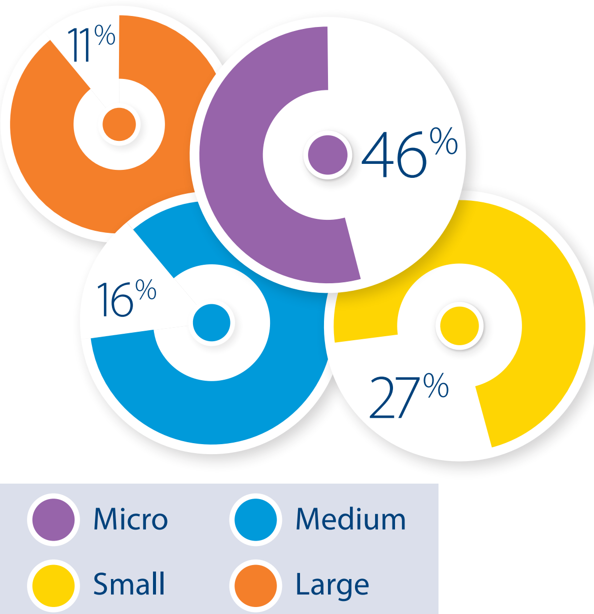
Measurement for Quantum

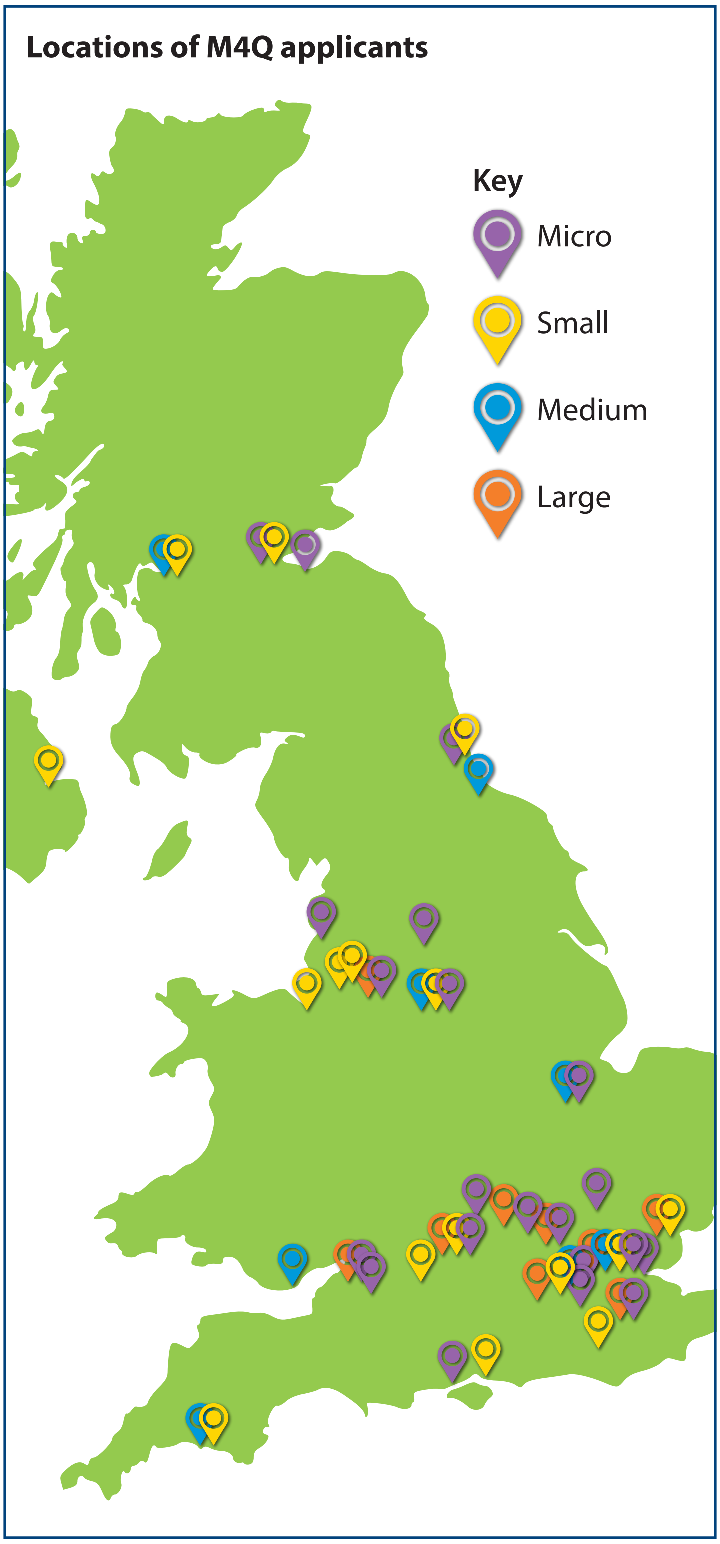
Measurement for Quantum (M4Q) is an NPL programme which brings together world-leading quantum scientists, engineers, and facilities to provide up to 20 days of specialist quantum measurement expertise at no charge to solve a business's measurement challenges. Through M4Q, we help companies to bridge the gap from technology prototype to industry-ready product or service.

2022-23 | This year's M4Q highlights



M4Q applicants company size breakdown





Net promoter score: 93

NPS is a gauge of customer satisfaction using the question **'How likely is it that you would recommend M4Q to a friend or colleague (on a scale of 0-10)?'**.

A score of over 80 is deemed world class.

93

93% of participants expect to **continue working with the team** that delivered their M4Q project.

77

77% of participants say M4Q **supported development** of **new** and **improved products**

58

58% of participants expect to secure **more investment** as a result of the M4Q work

52

52% of participants expect to see **increased sales** as a result of their M4Q project

32

32% of participants expect to see **reduced costs** as a result of the M4Q work

"The research we carried out together has made a direct impact on CQC's products and has helped the company establish itself as one of the leading players in the UK Quantum Technology industry. None of this would have happened without the energy and insight of NPL's scientists, and we hope to continue and deepen this collaboration in the future.

Ross Duncan
CQC Chief Scientist for
Quantum Chemistry Software

"Though most of us are scientists, we didn't have the expertise of building an atomic clock. M4Q accelerated the process… this increased our chances of commercialising this technology… being able to work with NPL definitely increases our chances of success.

Andrei Dragomir,
CEO, Aquark

"Having the NPL data is very useful to our sales and fundraising – it enables us to say that our products have been proven – by the highest measurement authority in the land – to be very stable in a wide range of environmental conditions. That unquestionably inspires confidence in customers and investors.

Marina Starkova,
CEO, Graphene Star Ltd

Cross-UK partnerships

NPL aims to extend access to measurement capabilities to companies and researchers around the UK, through our regional partnerships. We currently have six regional partners actively collaborating, and two more proposed with Newport and Scotland.

6
regional partners we're actively collaborating with

Team based at the Advanced Research Centre (University of Glasgow).

> **Nearfield optical metrology deployed at the Henry Royce Institute in Manchester.**
>
> **The new capability will open up industrial access. We have had several inquiries from industrial partners to conduct s-SNOM in the visible range at both room temperature and cryogenic temperatures. This missing capability was also identified by industry via a road mapping exercise at the 2021 and 2022 UK annual network meeting on THz microscopy and 2D materials. I am excited for this collaboration to continue and strengthen and look forward to the important work that I am certain will result from this partnership.**
>
> Dr Jessica Boland
> Senior Lecturer, UKRI Future Leader Fellow,University of Manchester

Royal Holloway, University of London

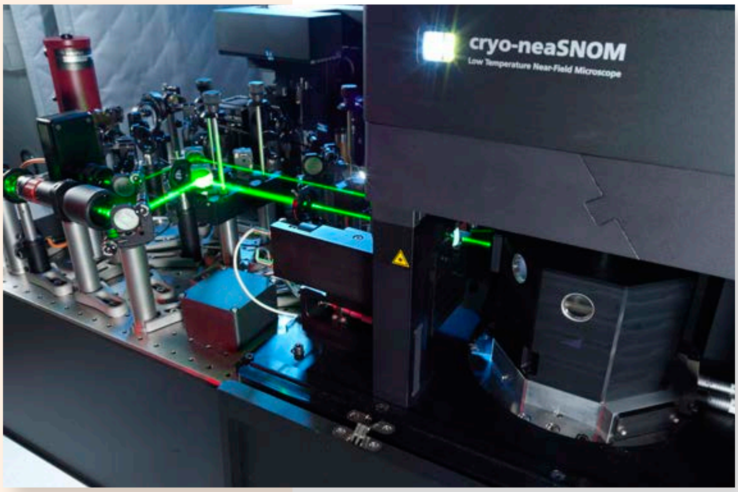
NPL has a strategic collaboration with Royal Holloway, University of London on a number of facilities and projects. These include, the SuperFab metrology suite at Royal Holloway, University of London's world-class cleanroom, and The High Performance Computer Cluster for quantum computing research.

> **SEEQC is developing the first digital quantum computing platform for global businesses. We use the SuperFab cleanroom at Royal Holloway for device fabrication. Access to high quality fabrication facilities is critical to our business and SuperFab is therefore a very important partner.**
>
> Matthew Hutchings,
> CPO, Managing Director,
> Co-founder, Seeqc

> **Oxford Quantum Circuits use the SuperFab cleanroom at Royal Holloway for our Quantum Process Unit (QPU) fabrication. Oxford Quantum Circuits is an SME building quantum computers to provide Quantum Computing as a Service (QCaaS). Access to good fabrication facilities is critical to our business and SuperFab is an important partner to us.**
>
> Dr Connor Shelly,
> Quantum Materials and Devices Lead,
> Oxford Quantum Circuits

SNOM at the Henry Royce Institute in Manchester

NPL's new scattering-type Scanning Near-field Optical Microscopy (s-SNOM) instrument – for analysing the nanostructure of a material's surface – has been located at the Henry Royce Institute to take advantage of expertise and demand. This new system dedicated to visible-infrared operation is the only such systems in the UK that is accessible to industrial users. It is an important addition to the Royce capability to characterise materials for quantum applications. It has already attracted interest from companies including Smartkem, Hitachi, Pilkington, Siemens, Malvern Analytical, and Samsung.



NPL's SNOM equipment at the University of Manchester's custom facility.

This year, we progressed the technical specification of the equipment. On invitation from neaspec, the SNOM manufacturer, NPL-UoM scientists visited their HQ for a technical induction, which included conducting proof-of-concept experiments on samples from NPL and UoM. One result of note was the discovery of high-energy exciton-polaritons in a previously unexplored 2D semiconductor– a result requiring further investigating when the new system arrives, and potentially an important element for future quantum nano-optoelectronics.

Optical Frequency Metrology (OFM) in Scotland

Partnering with The University of Strathclyde, we are developing a characterisation facility that will extend the capabilities of the co-located National Timing Centre Innovation Node. By adding optical frequency metrology capabilities for evaluating emerging quantum technologies, from laser systems to complete clock systems. This will support needs of local companies such as M Squared Lasers, Alter Technologies, BAE Systems, Thales & Leonardo, and the local research community. The major equipment, which includes a frequency comb and an ultrastable laser, has been ordered and more will be done to develop the facility further in year 4.

Optical Table purchased and in lab.

Conclusion & looking to the future

We end Year 3 of the NPL Programme at an exciting time for quantum technologies, especially in the UK. It is nearly ten years since the UK government took the bold decision to get ahead of the game, and invest £250M in a five year National quantum programme. That five years became ten, and the budget grew close to a billion. Through it all, NPL has been at the core of the UK's quantum journey, providing measurement expertise and skills to business, academia and standards bodies and sitting at the heart of many collaborative projects. Thanks to the work delivered under the National Quantum Technologies Programme, the UK is now a world leader in quantum, with others looking to follow our model.

But more important than the prestige is the tangible impact. That nearly-ten years has built strong foundations – facilities, capabilities, standards, and skills – and with them a research base, startups, spinouts, and corporate innovation. We rank second only to the US in number of quantum companies and private investment. To quote the recently published UK quantum strategy 'Our testing and assurance capabilities, through the National Physical Laboratory, are amongst the best in the world and a key enabler for the sector.'

NPL has become home to the biggest cluster of quantum expert staff in the UK. In this report we have highlighted just some of the activities that helped get us to where we are now: from the scientific and technological advances which develop, characterise and validate quantum devices; to the skills development that builds a pipeline for the future quantum workforce; to our work setting the standards that give quantum innovators confidence. In advancing all of these, we have listened to industry and ensured their needs are reflected in our programme.

Those foundations will now power the next stage: taking quantum out of the lab and into commercial applications. The new quantum strategy aims to ensure that the UK is home to world-leading quantum science and engineering, growing skills, supporting businesses, driving adoption, and creating a regulatory framework that supports innovation.

As we move forward, NPL will remain at the heart of business, academia and government as we do more to help deliver this strategy. Our training – from apprenticeships to PhDs – have created highly capable scientists, engineers and technicians, but we could create more. In three years, Measurement for Quantum has helped 45 businesses accelerate quantum technology readiness, assure customers, and secure funding, but many more could benefit from such support. Both programmes provide models that could be scaled as the industry grows, making the UK the go-to place for quantum businesses, investment, and talent. Standards work will need to continue. Standards will be critical to a mature quantum industry, but are currently in their early stages. As an independent NMI we are well placed to lead the field, keeping the UK at the forefront of international quantum standards development whilst ensuring standards are shaped to reflect the needs of our innovators, and to deliver benefits to the UK's economy, society and security.

Although we aim to ensure the UK capitalises on its early advantage in quantum, this will be a global industry. To this end we are working closely with international labs to share knowledge and best practice and to collaboratively build standards and testing infrastructure. This year we signed an important collaboration agreement with NIST in the US, and we hope to make similar agreements around the world in the coming years delivering transformational collaborations with other leading quantum nations.

As we move into the next phase of the national quantum programme, our work to date will provide strong foundations for creating a thriving quantum industry in the UK. But this is all part of a journey and there is work still to be done moving quantum technologies from the lab to the end user. NPL's unique position – with the scientific credibility to work alongside universities, the practical capabilities to support innovation, and the independence of a national lab – means we can play a critical role in making the UK an epicentre for quantum innovation, skills and standards.

Glossary

Acronym	Definition
2D	Two Dimensional
AI	Artificial Intelligence
AQML	Advanced Quantum Metrology Laboratory
ARFTG	Automatic Radio Frequency Techniques Group
BrIT-C	British Ion Trapping Conference
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CEO	Chief Executive Officer
DoE	Department of Energy
EPSRC	Engineering and Physical Sciences Research Council
ETSI	European Telecommunications Standards Institute
GPS	Global Positioning System
HMS	His Majesty's Ship
HQ	Headquarters
IEC	International Electrotechnical Commission
IMEKO	International Measurement Confederation
IOP	Institute of Physics
ISCF	Industrial Strategy Challenge Fund
ISO	International Organisation for Standardisation
LED	Light-Emitting Diode
M4Q	Measurement for Quantum
M4QN	Measurement for Quantum Network
MINAC®	Miniature Atomic Clock
mK	Millikelvin
MoU	Memorandum of Understanding
MP	Member of Parliament
NCSLI	National Conference on Standards Laboratories International
NIST	National Institute of Standards and Timing (US NMI)
NMI	National Measurement Institute
NPL	National Physical Laboratory
NPS	Net Promoter Score
NQCC	National Quantum Computing Centre
NQTP	National Quantum Technologies Programme

Acronym	Definition
NTC	National Timing Centre
PQC	Post-Quantum Cryptography
PTB	Physikalisch-Technische Bundesanstalt (Germany NMI)
QCaaS	Quantum Computing as a Service
QKD	Quantum Key Distribution
QML	Quantum Machine Learning
QRNG	Quantum Random Number Generator
QSHS	Quantum Sensors for Hidden Sector
R&D	Research and Development
RF	Radio Frequency
RHUL	Royal Holloway University of London
SI	Systeme Internationale (or International System)
SLUG	Superconducting Low-inductance Undulatory Galvanometer
SME	Small and Medium Enterprise
SNOM	Scanning Near-field Optical Microscopy
SPD	Single Photon Detector
SPIE	The international society for optics and photonics
SQMS	Superconducting Quantum Materials and Systems
SQUID	Superconducting Quantum Interference Device
s-SNOM	scattering-type Scanning Near-field Optical Microscopy
STEM	Science, Technology, Engineering and Mathematics
T&E	Test and Evaluation
TC	Technical Committee
TISOC	Trapped Ion Space Optical Clock
UCL	University College of London
UK	United Kingdom
UKQN	UK Quantum Network
UKRI	UK Research & Innovation
UoM	University of Manchester
US	United States
UTC	Coordinated Universal Time
VCSEL	Vertical Cavity Surface Emitting Laser

National Physical Laboratory (NPL)

NPL is the UK's National Metrology Institute (NMI), developing and maintaining the national primary measurement standards, as well as collaborating with other National Metrology Institutes to maintain the international system of measurement. As a public sector research establishment, we deliver extraordinary impact by providing the measurement capability that underpins the UK's prosperity and quality of life. We develop the metrology required to ensure the timely and successful deployment of new technologies and work with organisations as they develop and test new products and processes.

Hampton Road, Teddington, Middlesex, United Kingdom TW11 0LW
020 8977 3222 • www.npl.co.uk