NPL

Quantum

How measurement is driving innovation in the emerging quantum industry

A summary of achievements in the first years of NPL's Quantum Metrology Institute and a vision for the future

npl.co.uk/qmi

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FOREWORD

Rhys Lewis, QMI DIRECTOR

Quantum technologies are based on the properties of single atoms, electrons and photons, and how they interact. The behaviour of quantum systems gives rise to extraordinary properties, and many companies hope to create new products based on developments being made at universities and at NPL.

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The UK National Quantum Technologies Programme is a significant government investment in the commercialisation of quantum technologies in order to grow the UK economy and to use these new developments to make the UK more secure and resilient.

The national programme consists of activities in universities, companies and government. In the quantum metrology institute at NPL we are concerned with the creation of new prototypes for commercialisation, the establishment of new testing and assurance methods to build confidence in these novel devices, and the development of skilled people to power the emerging quantum economy. We are also engaged in work to raise the awareness of and involvement in the national programme among businesses and sectors not yet engaged. An activity we carried out in early 2018, at the request of Sir Mark Walport, has made recommendations on how best to encourage major companies to invest in Quantum Technologies and so deliver economic benefit to the UK.

One of the most talked of applications is quantum computing. This takes advantage of quantum superposition – whereby particles can exist in two states simultaneously. This allows the creation of 'qubits' – quantum equivalents of 'bits' which represent the 1s and 0s in standard computing and digital communications. Their quantum nature allows qubits to store and process orders of magnitude more information than ordinary computers.

Producing quantum computers requires research and innovation that expands the understanding and application of fundamental physics. We must understand how single particles behave and how their environment changes their state. We must develop technologies to emit, control, and detect them, as well as to isolate these sensitive particles from noisy environments. All of this requires the application of highly advanced measurement, and much progress is still needed before we can realise a quantum computer.

For all the hype, quantum computing is far from the only technology that takes advantage of quantum phenomena. Quantum communication can create new means of secure information transfer and storage. This involves developing techniques to measure the quantum properties of light passed along fibre optic cables. NPL has been instrumental in developing testing techniques and written standards for Quantum Key Distribution (QKD), a theoretically ultra-secure communication method and one of the closest to market quantum technologies.

Atomic clocks have long used the quantum nature of atomic particles to provide accurate timing, since their invention at NPL in the 1950s. Improvements in atomic clocks – both their accuracy and the development of more compact versions for industrial use - are underpinning a wide range of important applications, from developing new communications tools, to navigating in space, to detecting changes in gravitational fields.

Quantum interactions also create new sensing applications. For example, QMI scientists are using atomic systems to measure very small magnetic fields to detect phenomena as varied as brain activity, explosives, and corrosion.

Measurement bridges the gap between research and commercial exploitation. For companies to innovate in quantum technology, they need to understand and define the properties of the systems they are developing. To develop saleable products, they need to provide verified evidence that the technology is built on sound scientific and engineering principles, and that it will perform as described.

At the heart of all measurement sits the SI units – the base units of measurement on which all other measurements are based. In 2019 these are expected to be redefined based on new quantum definitions – the result of decades of work by NPL and the global measurement community. The maintenance of these units, the establishment of testing capability, and the development of technology to transfer these measurement techniques to industry will be critical to innovation and the development of confidence, trust and common standards in emerging quantum technologies.

The Quantum Metrology Institute, established at NPL in 2015, has a central role to play for the emerging quantum industries. We are developing the quantum measurement infrastructure to independently test, measure and validate new innovations as they progress through technology readiness levels. We are engaging directly with industry to develop new quantum technologies and products, as well as nurturing quantum skills through training and apprenticeships. The soon-to-be-completed Advanced Quantum Metrology Laboratory will take this further still, providing access to the world's most sophisticated measurement technology and highly controlled environments for physical and electronic measurements.

The QMI will be a partner to the many innovators that will emerge in the quantum industry, both in the UK and around the world. We will conduct research and development that underpins the UK's quantum innovations, we will train and support industry, and we will develop our capabilities and facilities as required to address the key test and measurement issues. We are helping UK industry develop quantum technologies which drive UK economic growth by solving measurement challenges and unblocking routes to commercialisation.

The following report provides insights into the cutting-edge research, technology development and industry support that has been provided by the QMI in its first years, and a snapshot of its future potential to support the UK's quantum industry.

HIGHLIGHTS

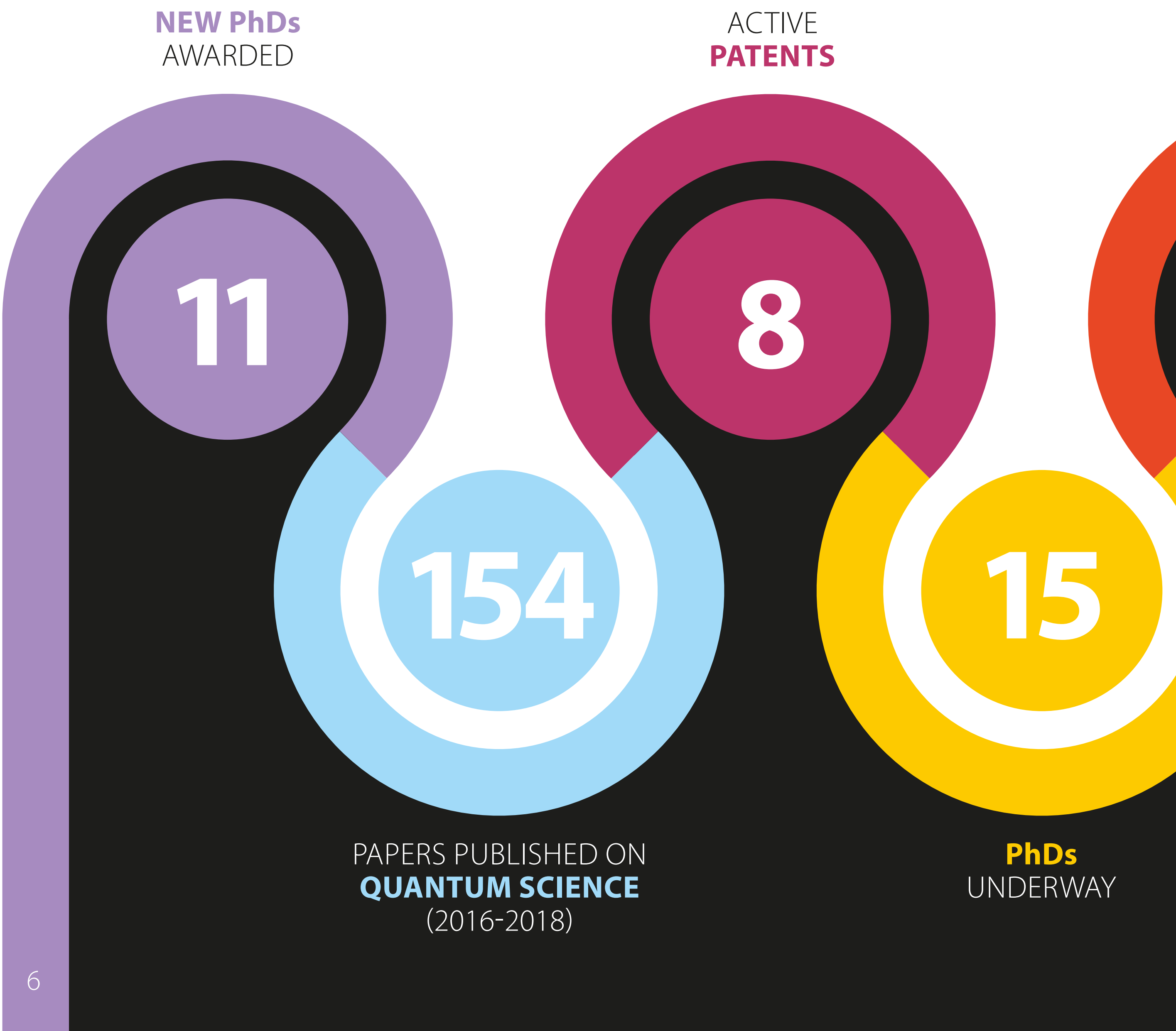
We have supported the commercialisation of **Quantum Key Distribution**, a theoretically ultra-secure method of communications, by developing and validating methods for counting photons and measuring their quantum states.

We have developed **cold-ion microtraps**, a scalable on-chip technology for encoding quantum information, and a strong candidate for use in quantum computers.

We have produced the **MINAC Miniature Atomic Clock**, a portable reference that brings atomic timing to many new applications.

We have developed **atomic magnetometers**, which could be used as quantum sensors able to detect brain waves, heart arrhythmia, explosive residue, and corrosion under insulation of pipework.

We have developed ways to use atomic clocks as **sensors of gravity potential**.



A FEW OF OUR INDUSTRIAL AND ACADEMIC PARTNERS

NUMBER OF **STAFF**

70

PhD STUDENTS AND VISITING **GUEST** WORKERS

50

1

ACTIVE **TRADEMARK** (NPL*Time*®)

20

COUNTRIES REPRESENTED BY STAFF AND STUDENTS

ABOUT THE QMI?

The Quantum Metrology Institute brings together NPL's leading-edge quantum science and metrology research and provides the expertise and facilities needed for academia and industry to test, validate, and ultimately commercialise new quantum research and technologies.

The Institute provides the measurement expertise and facilities needed to underpin the UK government's National Quantum Technologies Programme and the investment to date of over £400M and about to enter a second phase.

By bringing together scientists, engineers and academic researchers in a highly collaborative environment, the QMI plays a key role in the creation of a UK industry based on quantum technologies.

THE QMI SENIOR TEAM

Sir Peter Knight FRS:
QMI CHAIR

As well as chairing the QMI and being a leading figure in the UK quantum programme, Peter is Senior Research Investigator in Physics at Imperial College London and principal of the Kavli Royal Society International Centre.

He is a Fellow of the Institute of Physics, the Optical Society of America and the Royal Society and a Government Scientific Adviser. He has held a number of prestigious roles including President of the Institute of Physics, Chief Scientific Advisor at NPL, and chair of the Defence Scientific Advisory Council at the UK Ministry of Defence.

Rhys Lewis:
QMI DIRECTOR

Rhys is Director of the Quantum Metrology Institute, responsible for NPL's strategic direction in quantum and for the involvement of NPL in the UK National Quantum Technologies Programme.

Rhys joined NPL in 2007 following a career in industry developing optical and analytical instrumentation, including roles as an independent consultant working with SME and start-up companies. He has held leadership roles across several NPL groups.

Patrick Gill MBE FRS:
QMI SCIENTIFIC CO-DIRECTOR

Patrick is Senior NPL Fellow in the NPL Time & Frequency team which conducts state-of-the-art research into quantum frequency standards and atomic clocks. He has represented NPL and the UK on a variety of international committees for Time & Frequency, and for Length.

Patrick joined NPL in 1975 after completing his DPhil at the University of Oxford. He has published more than 200 scientific papers and has been a Fellow of Institute of Physics since 1998. He was elected to be a Fellow of the Royal Society in 2016.

Jan-Theodoor (JT) Janssen:
QMI SCIENTIFIC CO-DIRECTOR

JT is NPL's Director of Research, NPL Head of Science and Engineering Profession for the Government Science and Engineering (GSE), and Head of the National Graphene Metrology Centre.

His research is focused on quantum electrical effects and he has co-authored over 100 publications, including on single electron transport, the quantum Hall effect and the Josephson effect, and the properties of graphene. His work is instrumental in the development of a quantum standard for electrical current.

He is a Chartered Physicist and a Fellow of NPL, the Institute of Physics, and the Institute of Engineering and Technology

The National Quantum Technologies Programme

The National Quantum Technologies Programme is a government investment designed to make the UK the go-to place to develop and commercialise quantum technologies, and a leader in the supply chain that services them.

It is divided into four hubs: Networked Quantum Information Technologies (Quantum computing), Quantum Sensors, Quantum Communications Technologies, and Quantum Enhanced Imaging. These are centred on Oxford, Birmingham, York and Glasgow respectively, and include input from over 30 universities.

The QMI supports all of these hubs, in particular through its world-leading work in timing, sensors and communications. We are specifically developing tools which can be used in assessing the quality of quantum information processing techniques, and harnessing measurements of quantum effects to develop novel sensors. Our work on timing and measuring quantum effects at the single photon level is underpinning a new generation of communications technologies.

Sue Witheridge:
HEAD OF THE QUANTUM SCIENCE DEPARTMENT

Sue is the Head of the Quantum Science Department at NPL, responsible for leading the quantum science team and for the delivery of all the projects across quantum.

Sue joined NPL in 2016 after a career at BP which covered a wide range of scientific, commercial and business roles.

Helen Margolis:
NPL FELLOW AND SCIENCE AREA LEADER; TIME AND FREQUENCY

Helen Margolis leads NPL's research activities in optical frequency metrology, part of a programme to develop a new generation of high accuracy optical atomic clocks based on laser-cooled trapped ions and atoms.

Helen joined NPL in 1998 from the University of Oxford, where she was involved in research to test the theory of quantum electrodynamics by spectroscopy of highly charged ions. She is an NPL Fellow in Optical Frequency Standards and Metrology and represents NPL and the UK on a range of international committees for time and frequency.

Alexander Tzalenchuk:
NPL FELLOW AND SCIENCE AREA LEADER; SOLID STATE QUANTUM TECHNOLOGIES

Alexander (Sasha) is involved in research on superconducting and magnetic quantum systems, scanning probe microscopy, single particle detection and counting, and the properties of graphene.

He has over 30 years' experience in solid-state physics, nanotechnology and quantum metrology, which has including developing submicron technology for the high-temperature superconductors. Alexander is also a Professor of Physics at Royal Holloway, University of London, where he teaches 'Frontiers of Metrology' and supervises PhD students. Alexander is an NPL Fellow in Solid State Quantum Technologies.

Alastair Sinclair:
PRINCIPAL RESEARCH SCIENTIST; QUANTUM INFORMATION PROCESSING

Alastair is involved in researching the quantum nature of trapped ions and single photons, with applications in quantum information processing and quantum-based communications.

Alastair leads the programme to develop a scalable three-dimensional ion trap for applications in quantum information processing, and our work in the characterisation of quantum communications systems.

INDUSTRY, ACADEMIA AND GOVERNMENT COLLABORATION

Measurement is a rigorous scientific discipline, but its impact exists in the real world. Through collaborations with industry and academia, we ensure UK innovators can develop quantum technologies with confidence, and industry needs are fed back to help shape government policy.

Ytterbium ion microwave trap

Secure communications: Testing Quantum Key Distribution

PARTNERS: BT AND TOSHIBA

Quantum key distribution (QKD) is a secure communication method and one of the most commercially-advanced quantum technologies. It enables a party sending encrypted information to produce a random secret key – transmitted in a quantum state – which can decrypt the message. York University leads the quantum communications hub in the national programme, researching into techniques and applications of these technologies.

QKD takes advantage of a fundamental aspect of quantum mechanics, that observing a system changes its quantum state. Therefore, any third party trying to intercept the key, will introduce changes which can be detected when it is received. The encrypted message will only be sent if the key has arrived unchanged – making transmission of information potentially 100% secure.

One of NPL's most significant and long-standing quantum industry collaborations is on commercialising QKD. We are working with BT Research and Toshiba, amongst others, who hope to create useable methods for sending encrypted messages, allowing customers

NPL LEADS QUANTUM INDUSTRY ENGAGEMENT ACTIVITY

In February 2018, Sir Mark Walport, Chief Executive of the newly formed UK Research and Innovation (UKRI), asked Dr Pete Thompson, CEO of NPL, to explore how to incentivise major companies to invest in Quantum Technologies.

NPL conducted an intensive cross sector analysis through industry events, presentations and extensive 1-2-1 interviews. The resulting report made specific recommendations across three broad themes needed to drive investment

- Industries must be supported to appreciate the game changing potential of Quantum Technologies to their business
- Industries will invest in driving new product development when they identify "Proof of Value" rather than "Proof of Concept"
- The UK must lead the world in creating a vibrant environment for commercialisation for quantum technologies

As the national quantum programme develops, NPL will continue this work, ensuring that industry engages with the growing opportunities presented by quantum technologies, and that their requirements are fed back into the programme.

The full report is available on the NPL website.

to communicate with certainty that no one is listening in. They have set up a fibre link between their sites to test quantum communications, where they have carried out a series of demonstrations with increasing data rates and complexity.

The QMI provided critical input by characterising the fibre link and providing measurement test and validation, including methods for counting photons and measuring their quantum states. In December 2017, Joseph Pearse, a York PhD student based at BT Research labs, spent two days with NPL's quantum photonics team, learning how to calibrate free-running single-photon avalanche photodiodes, the detector used with the fibre link.

State-of-the-art atomic clocks

PARTNER: TELEDYNE-E2V

The QMI is carrying out research which will underpin a broad range of advances in atomic clocks.

One major advance comes from the new MINAC Miniature Atomic Clock, created at NPL with support from Dstl, and now being developed towards commercialisation with Teledyne-e2v. The prototype caesium atomic clock is a discrete and portable timing reference, making it suitable for providing precise timing to a variety of essential services such as for reliable energy supply, transport, mobile communications, data networks and electronic financial transactions. Today, these services rely on GPS for a timing signal which is easily disrupted. In the event of prolonged GPS unavailability, these services would stop functioning.

On a slightly larger scale, an ytterbium ion microwave clock prototype has also been developed which holds a cloud of electrically charged atoms that can be used as a frequency standard. This system offers greater accuracy than the MINAC, but is still compact enough to be suitable for many industrial timing applications.

At the higher accuracy end, NPL continues to develop state-of-the-art Optical atomic clocks, including in the use of strontium and ytterbium ions and Strontium atoms as optical frequency standards.

Through these clocks, NPL is creating a product line which offers different combinations of accuracy balanced with size, weight and power to cover a spectrum of potential timing applications.

Government: A trusted advisor

Two of the QMI senior team, Sir Peter Knight and Helen Margolis, contributed to a publication from the Parliamentary Office of Science and Technology (POST) on the opportunities and challenges offered by quantum technologies.

Following extensive research and consultation, POST concluded:

- Quantum technologies could become comparable in size to the consumer electronics sector (worth an estimated £240 billion a year globally)
- Quantum technologies have many potential uses including in navigation, health, telecommunications, and oil and gas exploration
- A new generation of quantum technologies are already becoming commercially available, whilst others may take over a decade to develop

Academia: Supporting the UK quantum hubs

As part of the UK National Quantum Technologies Programme, the government made a £120 million investment in four Quantum Technology Hubs. The QMI is actively involved in supporting all four to deliver their mission to support the UK's growing quantum industries. In Phase two of the national programme there will be many more opportunities to use the capabilities of the QMI to work alongside the hubs in technology development and test.

- **Sensors Hub** (led by Birmingham): The QMI is supporting the development of new atomic clocks and stable lasers for a wide range of industrial timing and sensing applications.
- **Networked Quantum Information Technologies** (led by Oxford): The QMI is developing scalable, manufacturable, ion microtraps, which could play a key part in processing information in future quantum computers.
- **Quantum Communications Hub** (led by York): The QMI is supporting the development of new technologies for quantum communications, including QKD, including characterising photon detectors and emitters.
- **Quantum Imaging** (led by Glasgow): The QMI has collaborated on work including the development single photon detectors used for imaging applications.

TECHNOLOGICAL ADVANCES

For industry to innovate successfully in the complex world of quantum, they need precise measurement capabilities in house and in their supply chains. The QMI is developing the cutting-edge measurement technology which will allow R&D departments to reliably detect and exploit quantum effects, as well as the test and measurement tools that will provide the quality assurance for new products as production is scaled up.

The QMI is a measurement partner to industry and academia. We provide the expertise and facilities to research, test and validate new technologies which take advantage of quantum phenomena.

Quantum hall resistance standard

Computing and electronics

Next-generation ion microtrap – a potential quantum processor

Quantum computers will store information in qubits. The development of such systems requires devices to create these qubits by confining individual particles, so that information can be encoded into them with a laser.

Cold-ion microtraps are one of several possibilities for confining particles for creating qubits. They are at an earlier stage than some other approaches, but they have the particular advantage among ion trap technologies that they can be scaled up to build tens of ion trap chips on a standard size silicon wafer. This makes them a strong candidate for use in quantum computers. NPL has considerable expertise in ion trapping as a result of its work on quantum information processing and atomic clocks.

The demonstration of a new-generation of ion microtrap devices shows excellent ion storage times and ion motional heating rate. The motional heating rate is of paramount importance for applications reliant on high-fidelity entanglement. The promising results are down to exceptional control of the microtrap fabrication process and surface treatment of the electrodes along with fine control of the associated laser performance.

NanoSQUIDs: Spotting disturbances in quantum circuits

Quantum technologies, which harness the properties of individual particles, need tools to detect and measure these single particles.

Superconducting Quantum Interference Devices (SQUIDs) detect changes in magnetic fields by measuring changes they induce in superconducting loops. NanoSQUIDs represent a new manifestation of this technology. By minimising component size, NanoSQUIDs overcome sensitivity limitations caused by thermal noise. This allows much greater sensitivity of measurement, down to single particle spin detection.

The QMI has developed a particularly straightforward method for fabricating nanoSQUIDs using a focussed ion beam. These are expected to impact widely on spin-based quantum sensing, by bringing greater insight into the behaviour of materials at a quantum level, including those used in quantum electronics and computers. They also hold the potential to be used in quantum technologies to measure and manipulate qubits.

The quantum Hall effect in graphene: A game changer for routine resistance measurements

Precise measurement of electrical resistance is of enormous practical importance, with end users in a wide range of industries from aerospace, to microelectronics, to power generation.

At NPL the primary resistance standard is based on the quantum Hall effect, an exotic manifestation of quantum mechanics. Measuring the effect requires low temperatures, high magnetic fields, and electrons confined to two dimensions.

Until now, routine resistance measurements were made using specially engineered semiconductors, cooled to 0.3Kelvin with a monster 14 Tesla superconducting magnet – phenomenal accuracy is obtained, but only with complex and expensive infrastructure.

Graphene is a game changer. It is intrinsically two-dimensional so manifests the quantum Hall effect without processing. Research, much of it carried out the QMI, shows that graphene manifests the effect under considerably more relaxed temperature and magnetic fields than traditional semiconductors such as gallium arsenide. Inspired by these findings, QMI scientists is partnering with UK Company Oxford Instruments to develop a "table top" quantum Hall system, to bring a quantum resistance standard to a wide customer base.

Following extensive development, the graphene system has proved itself to be exceptionally straightforward and easy to operate and delivers the same part-per-billion accuracy as existing systems, but without the complexity and liquid helium cost. The graphene system could be operated by a commercial calibration lab, bringing a quantum-based standard closer to the end user.

Quantum sensors

QMI scientists develop new technique to detect underwater earthquakes

New research, kick-started by the accidental detection at NPL of a distant earthquake, is offering a solution to a problem that has long frustrated seismologists: the measurement of underwater earthquakes on a global scale. Today, most underwater events go undetected, as the large majority of seismic stations are on land. It is prohibitively expensive to install them in large numbers at the bottom of seas and oceans, with cost estimated between $700 million and $1 billion for a network large enough to systematically cover the Earth's waters. This substantially limits our understanding of the interior of our planet and its dynamic behaviour.

In recent experiments, QMI scientists, in collaboration with INRiM, the British Geological Survey, Politecnico di Torino (Italy) and the University of Malta, detected earthquakes using land-based and underwater fibre optic links of lengths up to 535 km and ranging from 25 to 18,500 km from the earthquake's epicentre. Optical fibre has been previously used to transmit data between earthquake-detecting devices, but in the new method the fibre itself is used as the sensing element. The researchers used the land-based and undersea cables to measure the earthquake-induced vibrations along the length of the cable.

By using this new technique on the existing undersea telecommunications network, a global network for underwater earthquake monitoring could be implemented, without the need to install additional devices on the seafloor. Over 1 million km of optical fibre already spans the Atlantic and Pacific oceans and is rapidly expanding in line with the exponential rise in mobile services and the Internet. With water accounting for 70% of the Earth's surface, seismic data from such global network could unlock new discoveries in geophysics and beyond.

In the future, the technique could also be used to provide life-saving warning time in the event of tsunamis, or even changes in volcanic structure. Although the innovation has not been tested in this area, the ability to detect underwater earthquakes close to the epicentre, rather than after they are picked up by on-land seismometers, presents an exciting and crucial future opportunity.

The work was published in *Science* on 14th June.

Graphene's unique properties let it sniff out danger

Much of our work on graphene falls within the QMI because of its impact on quantum measurements. Graphene makes a great sensor because its 2D structure allows for very well understood electrical characteristics. Anything which induces a change in conductivity can therefore be measured with very high degree of sensitivity.

This has been applied to gas sensing. A recent NPL and Imperial paper in Nanotechnology "Graphene gas sensing using a non-contact microwave method", reports a technique to measure trace gases on graphene using a dielectric microwave resonator.

Another project used graphene-based biosensors to detect allergens, specifically milk protein in food products. This was achieved by functionalisation of graphene with antibodies. When the target protein is introduced, antibodies bind to it, transferring electrons to the graphene, increasing its resistance, which can be measured.

These sensors can detect binding events down to parts per million accuracy and can practically be used for real-time detection of allergens in production plants. It could also be expanded to a wide range of biosensing applications.

EXPORTING OUR CLOCKS AROUND THE WORLD

NPL successfully built and delivered three caesium fountain systems – the most accurate primary frequency standards – to customers in Canada and Poland. Two systems were delivered to the Polish Academy of Sciences for their satellite ranging station (which maintains its own timescale), and one to the National Research Council, the Canadian NMI.

Atomic sensors can detect heart disease, explosives and defects in materials

The QMI is developing atomic magnetometers, which could lead to a new class of quantum sensors able to detect effects as diverse as brain magnetic field, heart arrhythmia, explosive residue, and corrosion.

The sensors are atomic vapour inside glass cells. By probing the atoms with lasers it is possible to detect the influence that very weak magnetic fields have upon the atoms – creating a very sensitive magnetic field detector.

This has a wide range of applications, such as detecting the magnetic 'fingerprint' of explosives, and measuring magnetic fields produced by the heart and brain to look for anomalies that may indicate neurodegenerative pathologies or heart disease. This could replace the SQUID systems used in hospitals for Magnetoencephalography (a type of brain scan) which are large, expensive and require cryogenic liquids to operate.

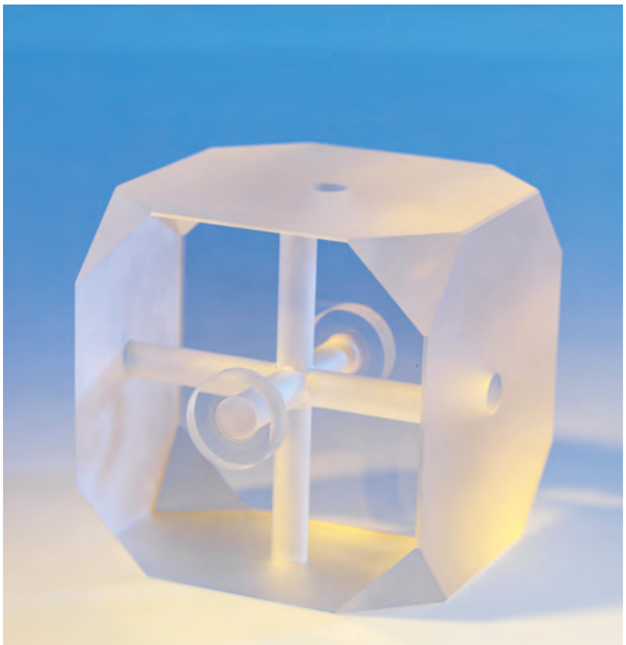
The most advanced application so far is for detecting corrosion in metals, with applications in oil & gas and engineering. This involves inducing a magnetic field in the metal to create a magnetisation, and using the magnetometers to measure changes in that magnetisation, which can reveal levels of corrosion.

Timing and communications

New tools to advance QKD – the ultra-secure communications platform

The QMI is working with the University of Bristol to produce a suite of tests to determine the characteristics of chip-scale quantum devices designed for transmitting and receiving quantum keys.

These include methods for characterising single photon sources and detectors, including for measuring the number of photons and the various ways of encoding information into photons. Results obtained from initial measurements were presented at Photonics Europe 2018, with the aim of informing further development of the system.



Ultra-stable optical cavity in space for future GNSS and next generation gravity missions (NGGM)

Ultra-stable optical cavity ensures ESA doesn't get lost in space

The QMI is developing an 'optical stabilising reference cavity' for the European Space Agency (ESA). This will be used to provide low-drift, ultra-narrow linewidth laser light for e.g. NGGM missions and as a vibration-insensitive laser local oscillator for locking to future optical atomic space clocks.

The QMI is drawing on our expertise in stable laser systems – developed through our atomic clock research.

The optical reference cavity comprises a pair of super-polished mirrors kept a precise distance apart, which enables the laser spectral linewidth to be very significantly reduced, with low drift and vibration insensitivity suitable for space deployment. QMI scientists designed the cavity and a mount, which is tested under simulated operational conditions, ensuring it remains stable as it is accelerated into space.

Such highly stable lasers will serve at the heart of next-generation 'optical atomic clocks', used for timing and navigation, as well as enabling ultrasensitive gravity detectors. We are further developing the cavity for full space use.

Timing for high frequency trading

NPL's timekeeping expertise is helping the financial sector meet new regulations.

Every financial transaction needs to have a time and date stamped on it. This is required by the recently implemented MIFID II regulations to ensure a consolidated view of a company's financial transactions, though it is also important for the functioning of the communications systems that conduct such trades. The accuracy required depends on the transaction, with high frequency trading needing to be recorded down to one microsecond. This stamp also needs to be traceable to the global timekeeping system: UTC (universal coordinated time).

NPL*Time*® offers the financial sector a certified precise time signal traceable to UTC and fully compliant with the MiFID II RTS 25 timing traceability requirement. The service eliminates reliance on GPS and removes susceptibility to jamming, spoofing, urban canyon effects and solar storms.

The signal is maintained using NPL's atomic clock ensemble including our caesium fountain, a primary frequency standard accurate to the equivalent of one second in 150 million years (2 x 10-16), which are also used to maintain the UK's National Timescale, UTC(NPL).

Optical clocks test special relativity

The QMI took part in an international collaboration using optical atomic clocks to perform the most accurate test yet of time dilation predicted by special relativity.

Optical clocks at NPL, SYRTE (France) and PTB (Germany) were compared using state-of-the-art optical fibre links. If violations of special relativity were observed, these could provide vital clues to physicists looking to link Einstein's theory of general relativity with quantum mechanics.

Optical clocks, based on the probing of atoms or ions with lasers, are the most precise measurement devices in the world and their unparalleled performance makes them ideal for tests of fundamental physics. This work is the first of a new generation of tests of fundamental physics using optical clocks and fibre links. As clocks and fibre links improve, researchers expect that these tests will improve by orders of magnitude in the near future.

SCIENTIFIC ADVANCES

Tomorrow's quantum measurement capabilities, which will be necessary to achieve the many breakthroughs the UK National Quantum Technologies Programme aspires to, will spring from today's cutting-edge research. The QMI is at the forefront of this research, helping understand the nature of quantum phenomena and how to measure them. The understanding this produces will inform a new generation of innovations.

Computing and electronics

Cleaning up quantum circuits

One of the biggest challenges in building quantum circuits comes from the noise intrinsic to these devices, which can interfere with qubits and is detrimental to the circuit's performance.

The origin of this noise has puzzled scientists for decades. Quantum devices are inherently extremely sensitive to their environment and existing tools simply do not have the sensitivity to fully characterise the materials used to fabricate qubits.

But two NPL papers now pave the way for identifying and eliminating noise in quantum circuits.

Quantum devices such as qubits and sensors are plagued by performance-degrading material defects. Typically, these defects can be divided into two types: surface spins that cause magnetic flux noise and local variations in the magnetic field; and surface charges that cause charge (or dielectric) noise.

The first paper showed that signatures of atomic hydrogen – previously used by astronomers to study the violent birth of stars – reveal themselves in very small quantities in tiny ultracold quantum circuits.

It describes a technique for detecting these spins using micro-ESR, an on-chip version of the well-established electron spin resonance (ESR) spectroscopy technique, many orders of magnitude more sensitive. The identification of these elusive yet detrimental spins sheds new light on the origin of magnetic noise in quantum circuits, showing great promise for its mitigation.

In 2018, the team took this research further, demonstrating that removing surface spin defects dramatically reduces charge noise of quantum devices.

Traditionally, the two types of defects and the noise they produce have been studied separately. The breakthrough result of this second paper is in identifying the sources of charge noise by their spin signature. In doing so, the researchers showed that removing surface spin defects dramatically reduces charge noise.

This experiment shows that micro-ESR is a very powerful tool that can be used to identify the 'chemical fingerprint' of both sources of flux noise and sources of charge noise in quantum devices. This makes it invaluable for developing high-coherence materials and scaling-up quantum computing circuits.

The findings were the result of two European collaboration between the National Physical Laboratory (NPL) and European partners including Chalmers University in Sweden, the University of Latvia, Microtechnology and Nanoscience, Sweden, and the Laboratoire de Physique Théorique et Hautes Energies (LPTHE), France. The papers were published in the journal *Physical Review Letters* and *Nature Communications* respectively.

Quantum coherence device supports quantum standard for electrical current

Important advances have been made in a new device which could pave the way for a quantum standard for electric current, and could be capable of disseminating the new definition of the ampere.

The device is the Charge Quantum Interference Device (CQUID). It acts in the opposite way to the better-known superconducting quantum interference device (SQUID). Instead of sensing a magnetic field via its influence on the current flow, the CQUID senses charge as a result of quantum interference due to the flow of magnetic flux.

This could allow precise measurements of flows of electricity at a single electron level, which could play an important part in the establishment of the new quantum definition of the ampere. It could also have important role in the development of nanoscale electronics and sensors.

The device was born out of an international collaboration, involving researchers from the QMI, which demonstrated a quantum coherent effect in a device made out of continuous superconducting wire. Results were published in *Nature Physics*.

Sensors

Microresonators for practical optical measurements

The QMI is at the leading edge of research into microresonators: optical devices that circulate light around a tiny ring, allowing very high levels of optical power density to be created in tiny micron-scale volumes.

One key application of microresonators is optical frequency combs. Larger versions of these combs are common tools for spectroscopy and optical clocks. They can be locked onto the frequency of a stable electromagnetic wave – eg that of a laser – and use that to create other equally stable frequencies.

The QMI has shown microresonators to be promising candidates for shrinking optical frequency comb generators into chip-based devices for out of-the-lab use (microcombs). These have a wide range of applications including in transportable optical clocks, novel sensor systems, calibration of astrophysical spectrometers, channel generation for telecom signals, and rapidly updated position measurements for global positioning systems.

Another interesting effect of microresonators is spontaneous symmetry breaking. When light is shone in both directions through a microring resonator at the same power levels, apparently at random one direction of circulation becomes blocked and only the other direction is allowed. This curious effect was discovered recently at the QMI, and new Horizon-2020 funding has been received to study applications, which could include a novel gyroscope for sensing acceleration and rotation.

Timing and communications

Atomic clocks double up as gravity sensors

An experiment showed that optical atomic clocks can measure differences in the earth's gravity potential. A transportable optical clock developed at German measurement institute PTB was taken out of the lab into a tunnel high up inside a mountain. There, with the help of a transportable frequency comb from NPL, it was compared with a second clock at INRIM (the Italian measurement institute), 90 km away in Turin at a height difference of about 1000 m. By detecting the gravitational redshift of the clock operating frequency, scientists were able to measure the gravity potential difference between the two locations.

This method could allow scientists to monitor continental height changes related to sea levels and the dynamics of ocean currents with unprecedented accuracy. It will also lead to more consistent national height systems, helping to prevent potentially costly mistakes in engineering and construction projects. The work was published in *Nature Physics*.

STANDARDS

As any industry evolves, it must develop a shared set of national and international technical standards to provide assurances of quality and to make collaboration and integration of different parts easier. The QMI is supporting the development of many new standards for quantum technologies and represents the UK on many international standards organisations.

New standard to support QKD technology

New single-photon detectors and QKD technologies are emerging, and these new devices will require metrology to support them in the near future. NPL led the drafting of a Group Report ETSI GR QKD 003 v2.1.1 (2018-03), which summarises the main QKD protocols, and the properties of the sources and detectors used in implementing such protocols. It is a preparatory action to the drafting of new measurement standards for characterising such devices, which will augment the previous standard, also led by NPL.

Electron pumps provide quantum ampere standards

Two recent papers show progress in electron pumps, which work by rapid manipulation of single electrons. The new SI definition of the quantum ampere defines charge as the number of electrons passing a point in a second. In the future re-defined SI system, electron pumps will directly realise the SI ampere.

The first paper in *Metrologia* showed a gallium-arsenide electron pump operating with 1 part-per-million accuracy at a temperature of 1.3 K. The accurate operation of electron pumps at this temperature is a promising step towards adoption of quantised charge pumps as practical current standards.

The second paper, published in *Scientific Reports*, describes high-speed pumping using an electron pump based on a single atomic trap site in silicon, without loss of accuracy, generating a current of more than 1nA. This represents a benchmark result for high-speed electron pumping and the starting point for promising future work.

THE SI, FUNDAMENTAL CONSTANTS, AND QUANTUM TECHNOLOGIES

The SI system defines seven base units on which all other measurements are based. Ensuring our definitions of these units is accurate is important as technology relies on ever smaller and complex physical processes, and increasingly those in the quantum realm.

As science advances, ever more accurate measurements are both required and achievable. The standard and definition for each unit must reflect this increasing accuracy.

From May 2019, all the base units are expected to be defined in terms of fundamental natural constants – the most stable things we have ever encountered – creating a Quantum SI.

The Quantum ampere in particular is key to delivering a leading capability for the UK in electrical standards for voltage, resistance and current which will be essential for quantum electronic devices. The second – already defined by quantum phenomena, will be essential in developing faster communications. The new definition of the kilogram will be implemented using what is essentially an electrical experiment, known as the Kibble balance. The realisation of the kilogram is therefore also reliant on the accuracy with which we can realise the electrical units.

The research required for these redefinitions is also creating the technology to deliver accurate measurements to industry, traceable back to the new SI. New portable primary quantum standards which will support the development of quantum technology are already in development, such as a metrology grade resistance standard based on the quantum properties of graphene, which can be installed on a factory floor.

QMI representing the UK in the redefinition

The QMI is playing a leading role int the international collabrations driving the Quantum SI redefinitions.

On 4th September 2017, Helen Margolis attended a meeting of the CODATA task group on fundamental constants to discuss special adjustment of the fundamental constants to determine the recommended values of the Planck constant (h), the elementary charge (e), the Boltzmann constant (k) and the Avogadro constant (NA). These are to be used in the anticipated redefinitions of the kilogram, ampere, kelvin and mole.

At the subsequent October meeting of the International Committee for Weights and Measures (CIPM) a resolution was passed recommending the redefinition of these four SI base units.

This recommendation will go before the General Conerence on Weights and Measures (CGPM) for final international agreement in November 2018. If passed, the change will come into force on 20th May 2019 (World Metrology Day), after which the four units will be based on exact values of the four fundamental constants.

The final values for these four fundamental constants have been calculated under the auspices of the CODATA Task Group on Fundamental Constants, and a summary paper describing the results of this calculation, of which NPL's Helen Margolis is a co-author, is now available on the Metrologia website.

OUTREACH AND ENGAGEMENT

For all the excitement surrounding it, quantum science is a complex branch of physics, and many find it challenging to see how it can have such a major impact on real world innovation. To help raise awareness and understanding of the possibilities, both amongst the industries innovating in quantum and society at large, the QMI is actively involved in a wide range of outreach and education activities to spread the word.

Events

Since its inception, the QMI has hosted many events bringing together global expertise in quantum, and its members have represented the UK around the world, ensuring our expertise is transferred into research and industry. Examples include:

National Quantum Showcase: The QMI showcased the importance of measurement in quantum at the National Quantum Showcase event in November 2017. We joined university hubs and the companies developing quantum devices in displaying and promoting the potential of quantum.

The QMI had four stands displaying an array of devices and capability, including specific stands on time, space, and microtraps. We also had a presence on a Bristol University stand covering quantum communications. The event and associated talks showed attendees that the QMI is committed to supporting industry to create the necessary infrastructure to support development of a trusted quantum industry.

TIME FROM NPL APP LAUNCH

In 2018, NPL launched a new app "Time from NPL" which connects smartphones to the NPL atomic clocks that realise the UK's time scale, and helps increase understanding of the role of atomic clocks and NPL's work in this area. The app displays the difference between the time on your phone and NPL time and contains information about the science of timekeeping. The app is available now on the iOS app store (Android coming soon) or by scanning the QR code.

NPL showcases measurement advances to tech giants: The QMI was represented at a Quantum Technologies Initiative Workshop at Chalmers University of Technology in Sweden, on superconducting quantum computing. NPL presented posters on the source of noise in quantum circuits and on the CQUID. All three posters showcased the role of measurement in quantum technologies to the 200+ attendees which included companies at the forefront of quantum computing such as Google, IBM, Microsoft and Intel.

The 6th Defence and Security Quantum Technologies showcase event hosted at NPL: Around 50 external visitors attended to see talks on quantum technologies from e2v, M2 lasers, Birmingham University, and civil engineering consultancy RSK who are interested in gravity sensors for site mapping.

Summer Science: At this year's Royal Society Summer Science Exhibition in July, NPL's stand "The Measure of All Things" explained the upcoming SI redefinition.

The QMI is also actively involved in sharing expertise at conferences and workshops around the world, including:

- Presented at the Single Photon Workshop 2017 in Boulder, Colorado, on characterisation of single-photon detectors and emitters.
- Attended the 28th international conference on low temperature physics in Gothenburg, Sweden, describing the most recent work on reduction of noise and decoherence in superconducting quantum devices carried out at the QMI.
- Presented an invited talk on 'NanoSQUIDs: new limit and new materials' at the 16th International Superconductive Electronics Conference in Italy
- Hosted the 2nd biennial symposia in April 2017, as part of the strategic quantum technologies partnership between NPL and NIM in China, including sessions on secure quantum communications and redefining the SI second.
- Hosted or attended events on precise timing for the financial sector, including: The Alliance for Telecommunications Industry Solutions workshop at the New York Stock Exchange; and an NPL and International Timing and Sync Forum MiFID II workshop at the Gibson Hall, Threadneedle Street, which brought together timing and synchronisation equipment vendors and the end users in the financial sector

Nurturing skills for the quantum workforce

As quantum industries grow, there will be a growing demand for new technical skills in business and research. NPL is helping ensure that today's students – tomorrow quantum workforce – have the measurement skills they need. For example, the QMI has an established partnership with Royal Holloway University London (RHUL) to educate a new generation of scientists and engineers about metrology.

- An undergraduate course has been developed "Frontiers of metrology" taught by the QMI's Alexander Tzalenchuk, which covers the physical phenomena that form the foundation of quantum metrology. A number of leading UK universities including Imperial, Glasgow and UCL are looking at introducing similar courses.
- NPL's Jonathan Williams also teaches an undergraduate course at RHUL, "Signal handling and recovery" centred on electrical measurement techniques. Jonathan drew on his extensive experience of quantum electrical metrology to devise the course material.
- The QMI offer regular summer placements to RHUL students to work on joint projects, some of whom go on to carry out final year projects with NPL. Three jointly funded NPL-RHUL PhD positions are filled each year.

SELECTED PUBLISHED PAPERS

Suppression of low-frequency charge noise in superconducting resonators by surface spin desorption

(2018) de Graaf, SE; Faoro, L; Burnett, J; Adamyan, AA; Tzalenchuk, AY; Kubatkin, SE; Lindstrom, T; Danilov, AV:

NATURE COMMUNICATIONS Volume: 9, Article Number: 1143

DOI: https://dx.doi.org/10.1038/s41467-018-03577-2

Charge quantum interference device

By: de Graaf, S. E.; Skacel, S. T.; Honigl-Decrinis, T.; Shaikhaidarov, R.; Rotzinger, H.; Linzen, S.; Ziegler, M.; Huebner, U.; Meyer, H-G; Antonov, V; Il'ichev, E.; Ustinov, A., V; Tzalenchuk, A. Ya; Astafiev, O., V

Source: NATURE PHYSICS Volume: 14, Issue: 6

DOI: https://dx.doi.org/10.1038/s41567-018-0097-9

Intensity stabilisation of optical pulse sequences for coherent control of laser-driven qubits

By: LiThom, J; Yuen, B; Wilpers, G; Riis, E; Sinclair, AG

Source: APPLIED PHYSICS B-LASERS AND OPTICS Volume: 124, Issue: 90, Article Number: 90

DOI: https://dx.doi.org/10.1007/s00340-018-6955-4

Superconducting coincidence photon detector with short timing jitter

By: Miki, S; Miyajima, S; Yabuno, M; Yamashita, T; Yamamoto, T; Imoto, N; Ikuta, R; Kirkwood, RA; Hadfield, RH; Terai, H

Source: APPLIED PHYSICS LETTERS Volume: 112, Issue: 26

DOI: https://dx.doi.org/10.1063/1.5037254

Investigation of Dayem Bridge NanoSQUIDs Made by Xe Focused Ion Beam

By: Godfrey, T; Gallop, JC; Cox, DC; Romans, EJ; Chen, J; Hao, L

Source: IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY Volume: 28, Issue: 7, Article Number: 1100605

DOI: https://dx.doi.org/10.1109/TASC.2018.2854624

Micro-combs: A novel generation of optical sources

By: Pasquazi, A; Peccianti, M; Razzari, L; Moss, DJ; Coen, S; Erkintalo, M; Chembo, YK; Hansson, T; Wabnitz, S; Del'Haye, P; Xue, XX; Weiner, AM; Morandotti, R

Source: PHYSICS REPORTS-REVIEW SECTION OF PHYSICS LETTERS Volume: 729, Pages: 1-81

DOI: https://doi.org/10.1016/j.physrep.2017.08.004

Geodetic methods to determine the relativistic redshift at the level of 10^{-18} in the context of international timescales: a review and practical results

By: Denker, H; Timmen, L; Voigt, C; Weyers, S; Peik, E; Margolis, HS; Delva, P; Wolf, P; Petit, G

Source: JOURNAL OF GEODESY Volume: 92, Issue: 5, Pages: 487-516

DOI: https://doi.org/10.1007/s00190-017-1075-1

Geodesy and metrology with a transportable optical clock

By: Grotti, J; Koller, S; Vogt, S; Hafner, S; Sterr, U; Lisdat, C; Denker, H; Voigt, C; Timmen, L; Rolland, A; Baynes, FN; Margolis, HS; Zampaolo, M; Thoumany, P; Pizzocaro, M; Rauf, B; Bregolin, F; Tampellini, A; Barbieri, P; Zucco, M; Costanzo, GA; Clivati, C; Levi, F; Calonico, D

Source: NATURE PHYSICS Volume: 14, Pages: 437-441

DOI: https://doi.org/10.1038/s41567-017-0042-3

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

By: Giuseppe Marra; Cecilia Clivati; Richard Luckett; Anna Tampellini; Jochen Kronjäger; Louise Wright, Alberto Mura; Filippo Levi; Stephen Robinson; André Xuereb; Brian Baptie; Davide Calonico

Source: SCEINCE ADVANCES Volume: 361, Issue: 6401, Pages: 486-490

DOI: https://doi.org/10.11.26/science.aat4458

Non-destructive structural imaging of steelwork with atomic magnetometers

By: Bevington, P; Gartman, R; Chalupczak, W; Deans, C; Marmugi, L; Renzoni, F

Source: APPLIED PHYSICS LETTERS Volume: 113, Issue: 6

DOI: https://doi.org/10.1063/1.5042033

Optical frequency transfer over submarine fiber links

By: Clivati, C; Tampellini, A; Mura, A; Levi, F; Marra, G; Galea, P; Xuereb, A; Calonico, D

Source: OPTICA Volume: 5, Issue: 8, Pages: 893-901

DOI: https://doi.org/10.1364/OPTICA.5.000893

Absolute frequency measurement of the S-2(1/2) -> F-2(7/2) optical clock transition in Yb-171(+) with an uncertainty of 4 x 10(-16) using a frequency link to international atomic time

By: Baynham, CFA; Godun, RM; Jones, JM; King, SA; Nisbet-Jones, PBR; Baynes, F; Rolland, A; Baird, PEG; Bongs, K; Patrick, Gill; Margolis, HS

Source: JOURNAL OF MODERN OPTICS Volume: 65, Issue: 5-6, Pages: 585-591

DOI: https://doi.org/10.1080/09500340.2017.1384514

Water on graphene: review of recent progress

By: Melios, C.; Giusca, C. E.; Panchal, V.; Kazakova, O

Source: 2D MATERIALS Volume: 5, Issue: 2, Article Number: 022001

DOI: http://dx.doi.org/10.1088/2053-1583/aa9ea9

2017

Direct Identification of Dilute Surface Spins on Al2O3: Origin of Flux Noise in Quantum Circuits

By: de Graaf, S. E.; Adamyan, A. A.; Lindstrom, T.; Erts, D.; Kubatkin, S.E.; Tzalenchuk, A. Ya.; Danilov, A. V.

PHYSICAL REVIEW LETTERS Volume: 118, Issue: 5

DOI: http://dx.doi.org/10.1103/PhysRevLett.118.057703

Ultrafast voltage sampling using single-electron wavepackets

By: Johnson, N; Fletcher, JD; Humphreys, DA; See, P; Griffiths, JP; Jones, GAC; Farrer, I; Ritchie, DA; Pepper, M; Janssen, TJBM; Kataoka, M

APPLIED PHYSICS LETTERS Volume: 110, Issue: 10, Article Number: 102105

DOI: http://dx.doi.org/10.1063/1.4978388

High-accuracy current generation in the nanoampere regime from a silicon single-trap electron pump

By: Yamahata, G; Giblin, SP; Kataoka, M; Karasawa, T; Fujiwara, A

SCIENTIFIC REPORTS Volume: 7, Article Number: 45137

DOI: http://dx.doi.org/10.1038/srep45137

Time-resolved single-electron wave-packet detection

By: Kataoka, M; Fletcher, JD; Johnson, N

PHYSICA STATUS SOLIDI B-BASIC SOLID STATE PHYSICS Volume: 254, Issue: 3, Special Issue: SI, Article Number: UNSP 1600547

DOI: http://dx.doi.org/10.1002/pssb.201600547

Thermal-Error Regime in High-Accuracy Gigahertz Single-Electron Pumping
By: Zhao, R; Rossi, A; Giblin, SP; Fletcher, JD; Hudson, FE; Mottonen, M; Kataoka, M; Dzurak, AS
PHYSICAL REVIEW APPLIED Volume: 8, Issue: 4
DOI: http://dx.doi.org/10.1103/PhysRevApplied.8.044021

Recent trends and perspectives of nanoSQUIDs: introduction to 'Focus on nanoSQUIDs and their applications'
By: Hao, L; Granata, C
SUPERCONDUCTOR SCIENCE & TECHNOLOGY Volume: 30, Issue: 5, Article Number: 050301
DOI: http://dx.doi.org/10.1088/1361-6668/aa68d6

Controlling Single Microwave Photons: A New Frontier in Microwave Engineering
By: Lindstrom, T; Lake, R; Pashkin, YA; Manninen, A
MICROWAVE JOURNAL Volume: 60, Issue: 5, Pages: 118-130

Toward the Use of NanoSQUIDs to Measure the Displacement of an NEMS Resonator
By: Patel, T; Li, B; Li, TY; Wang, R; Gallop, JC; Cox, DC; Chen, J; Romans, EJ; Hao, L
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY Volume: 27, Issue: 4, Article Number: 1602005
DOI: http://dx.doi.org/10.1109/TASC.2017.2667404

Robust operation of a GaAs tunable barrier electron pump
By: Giblin, SP; Bae, MH; Kim, N; Ahn, YH; Kataoka, M
METROLOGIA Volume: 54, Issue: 3
DOI: http://dx.doi.org/10.1088/1681-7575/aa634c

Weak link nanobridges as single flux quantum elements
By: Shelly, CD; See, P; Ireland, J; Romans, EJ; Williams, JM
SUPERCONDUCTOR SCIENCE & TECHNOLOGY Volume: 30, Issue: 9
DOI: http://dx.doi.org/10.1088/1361-6668/aa80cd

Multiplexing Superconducting Qubit Circuit for Single Microwave Photon Generation
By: George, RE; Senior, J; Saira, OP; Pekola, JP; de Graaf, SE; Lindstrom, T; Pashkin, YA
JOURNAL OF LOW TEMPERATURE PHYSICS, Volume: 189, Issue: 1-2, Pages: 60-75
DOI: http://dx.doi.org/10.1007/s10909-017-1787-x

Quantum Engineering of InAs/GaAs Quantum Dot Based Intermediate Band Solar Cells
By: Beattie, NS; See, P; Zoppi, G; Ushasree, PM; Duchamp, M; Farrer, I; Ritchie, DA; Tomic, S
ACS PHOTONICS Volume: 4, Issue: 1, Pages: 2745-2750
DOI: http://dx.doi.org/10.1021/acsphotonics.7b00673

Silicon microfabricated linear segmented ion traps for quantum technologies
By: Choonee, K; Wilpers, G; Sinclair, AG
IEEE 2017 19TH INTERNATIONAL CONFERENCE ON SOLID-STATE SENSORS, ACTUATORS AND MICROSYSTEMS (TRANSDUCER)
Pages: 615-618
DOI: 10.1109/TRANSDUCERS.2017.7994124

Note: A high-performance, low-cost laser shutter using a piezoelectric cantilever actuator
By: Bowden, W.; Hill, I. R.; Baird, P. E. G.; Gill, P.
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DOI: http://dx.doi.org/10.1063/1.4973774

Symmetry Breaking of Counter-Propagating Light in a Nonlinear Resonator
By: Del Bino, L; Silver, JM; Stebbings, SL; Del'Haye, P
SCIENTIFIC REPORTS Volume: 7, Issue: 5, Article Number: 43142
DOI: http://dx.doi.org/10.1038/srep43142

Kerr superoscillator model for microresonator frequency combs
By: Silver, JM; Guo, CL; Del Bino, L; Del'Haye, P
PHYSICAL REVIEW A Volume: 95, Issue: 3, Article Number: 033835
DOI: http://dx.doi.org/10.1103/PhysRevA.95.033835

Ultra-high-finesse NICE-OHMS spectroscopy at 1532 nm for calibrated online ammonia detection
By: Curtis, EA; Barwood, GP; Huang, G; Edwards, CS; Gieseking, B; Brewer, PJ
JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B-OPTICAL PHYSICS Volume: 34, Issue: 5, Pages: 950-958
DOI: http://dx.doi.org/10.1364/JOSAB.34.000950

Frequency comb-based time transfer over a 159km long installed fiber network
By: Lessing, M; Margolis, HS; Brown, CTA; Marra, G
APPLIED PHYSICS LETTERS Volume: 110, Issue: 22, Article Number: 221101
DOI: http://dx.doi.org/10.1063/1.4984144

Test of Special Relativity Using a Fiber Network of Optical Clocks
By: Delva, P; Lodewyck, J; Bilicki, S; Bookjans, E; Vallet, G; Le Targat, R; Pottie, PE; Guerlin, C; Meynadier, F; Le Poncin-Lafitte, C; Lopez, O; Amy-Klein, A; Lee, WK; Quintin, N; Lisdat, C; Al-Masoudi, A; Dorscher, S; Grebing, C; Grosche, G; Kuhl, A; Raupach, S; Sterr, U; Hill, IR; Hobson, R; Bowden, W; Kronjager, J; Marra, G; Rolland, A; Baynes, FN; Margolis, HS; Gill, P
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DOI: http://dx.doi.org/10.1103/PhysRevLett.118.221102

Distributed quasi-Bragg beam splitter in crossed atomic waveguides
By: Guarrera, V; Moore, R; Bunting, A; Vanderbruggen, T; Ovchinnikov, YB
SCIENTIFIC REPORTS Volume: 7, Article Number: 4749
DOI: http://dx.doi.org/10.1038/s41598-017-04710-9

Rydberg electrometry for optical lattice clocks
By: Bowden, W; Hobson, R; Huillery, P; Gill, P; Jones, MPA; Hill, IR Neu, V; Kazakova, O
PHYSICAL REVIEW Volume: 96, Issue: 2
DOI: http://dx.doi.org/10.1103/PhysRevA.96.023419

Towards practical autonomous deep-space navigation using X-Ray pulsar timing
By: Shemar, S; Fraser, G; Heil, L; Hindley, D; Martindale, A; Molyneux, P; Pye, J; Warwick, R; Lamb, A
EXPERIMENTAL ASTRONOMY Volume: 44, Issue: 2, Pages: 259-260
DOI: http://dx.doi.org/10.1007/s10686-017-9552-3

A matter of time
By: Margolis, H
NATURE PHYSICS
DOI: http://dx.doi.org/10.1038/nphys4327

Update on the NPLTime (R) Service and Future Developments with White Rabbit
By English, EL; Whibberley, P; Langham, C; Hicks, D; Lobo, L
PROCEEDINGS OF THE 48TH ANNUAL PRECISE TIME AND TIME INTERVAL SYSTEMS AND APPLICATIONS MEETING

QMI IN THE MEDIA

Since its launch, the QMI and its work has attracted considerable media attention. Measurement often happens behind the scenes, underpinning scientific breakthroughs and technological innovations. But sometimes measurement itself hits the headlines, and the QMI has shown quantum measurement is interesting and relevant, not just to industry, but to the general public.

Quantum at Solstice

Click, the BBC's flagship technology programme spoke to the QMI at the UK Quantum Technology Showcase for a feature on quantum in December 2017. The BBC interviewed our quantum team, highlighting the role measurement plays in quantum technologies and showcasing innovations such as the Quantum Detection ion microtrap and a Time & Frequency compact reference laser for CO_2 detection.

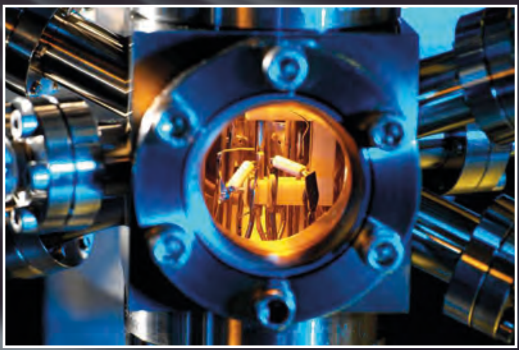
http://www.bbc.co.uk/iplayer/episode/b09jlw4y

Earthquake detection coverage is off the (Richter) scale

Our work on earthquake detection received widespread attention around the world, with the story picked up by *The Economist*, *El Mundo*, *Physics World*, *BBC's Science in Action* and a range of industry titles.

Relatively important measurements

Our work on accurate measurements of relativity with atomic clocks was featured in *New Scientist* in March 2017.



AWARDS

Patrick Gill received the 2017 Time Lord Award from the International Timing & Synchronisation Forum (ITSF) for a lifetime contribution to the timing community.

Pascal Del'Haye received the 2017 Young Scientist Award from the European Frequency and Time Forum.

Sean Mulholland won the EFTF 2018 student best paper competition in the area of Microwave Frequency Standards.

Tianyi Li, a Quantum Detection Group PhD student, was awarded the best poster prize at an Institute of Physics international conference *'Advances in Quantum Transport in Low Dimensional Systems'*.

Patrick Gill

Pascal Del'Haye

Sean Mulholland

Tianyi Li

PhDs awarded

A number of PhDs have been awarded for work carried out wholly or partly at the QMI.

Héctor Corte-León was awarded a PhD in Domain wall spintronics in novel magnetic nanostructures from at Royal Holloway, University of London.

Christos Melios was awarded an Engineering Doctorate in Micro- and NanoMaterials and Technologies at the University of Surrey. Christos' work is on Graphene Metrology.

Trupti Patel was awarded a PhD in superconducting devices coupled to nanoelectromechanical systems, completed jointly at NPL and UCL.

Jonathan Jones was awarded a PhD by The University of Birmingham for research carried out with the Yb+ optical clock team at NPL.

Bo Li was awarded a PhD in nanodosimetry using superconducting detector, completed jointly at NPL and University of Surrey.

Soliman Edris was awarded a PhD from University College London which explored the ratchet effect with cold caesium atoms in a two-dimensional driven optical lattice, focussing specifically on the emergence of quasi-periodic behaviour.

Héctor Corte-León

Christos Melios

Trupti Patel

Jonathan Jones

Bo Li

Soliman Edris

FUTURE PLANS

Advanced Quantum Metrology Laboratory

To develop the QMI capabilities further, the government department for Business, Energy and Industrial Strategy has commissioned a new Advanced Quantum Metrology Laboratory (AQML). This will house state-of-the-art facilities to advance research and support collaborations in developing quantum technologies.

The Advanced Quantum Metrology Laboratory (AQML) is currently under construction; it includes the refurbishment of an existing building to provide laboratories, office and meeting accommodation, and a completely new build of high spec labs.

The AQML facility is designed to achieve a high grade of research environment in terms of freedom from vibration, acoustic and radio frequency interference, magnetic stability and tightly controlled temperature and humidity parameters.

The new labs in the AQML will provide state of the art facilities to push forward new developments in optical atomic clocks and their associated technologies. The new facility will also provide an environment for collaboration between NPL, industries and universities including the delivery of test and evaluation of new technologies.

Our timing laboratory is expected to include high performance, continuously operated optical atomic clocks. These will serve as the top-level frequency reference for our test and evaluation capability for characterisation of the new quantum clocks and other timing products being developed within the UK Quantum Technologies programme. Other labs will include a suite of frequency combs and the hub of an optical fibre network which will enable dissemination of highly stable and accurate time and frequency signals to key users across the UK. Additional space will be dedicated, versatile workspace for the development, demonstration and test of new quantum clocks and sensors progressing towards commercialisation by UK industry.

The refurbished building will provide new laboratories to advance our work on low temperature and solid-state quantum technologies.

The areas of work planned to be delivered from this facility include superconducting nano-devices, in particular 'nanobridges' with potential application in the design and fabrication of superconducting circuits for on-chip signal processing, nanoSQUIDs for sensing applications, nano-electromechanical systems and high frequency mechanical resonators with applications to accelerometers and microwave-to-optical direct conversion; single-electron devices and other solid-state quantum systems; in particular addressing barriers to the performance of superconducting technologies as building blocks of quantum computers.

The vision for the AQML is to deliver a measurement infrastructure to support UK innovation and help accelerate the development and commercialisation of quantum technologies.

Advanced Quantum Metrology Lab, to open for business in 2019

National Physical Laboratory

NPL is a world-leading centre for the development and exploitation of measurement science, technology, related standards, and best practice in a diverse range of technical areas and market sectors. As the UK's National Measurement Institute, our capabilities underpin the UK National Measurement System (NMS), ensuring consistency and traceability of measurements in support of UK and overseas customer interests. We aim to provide world-class science and engineering with economic, social and environmental benefits to the UK.

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