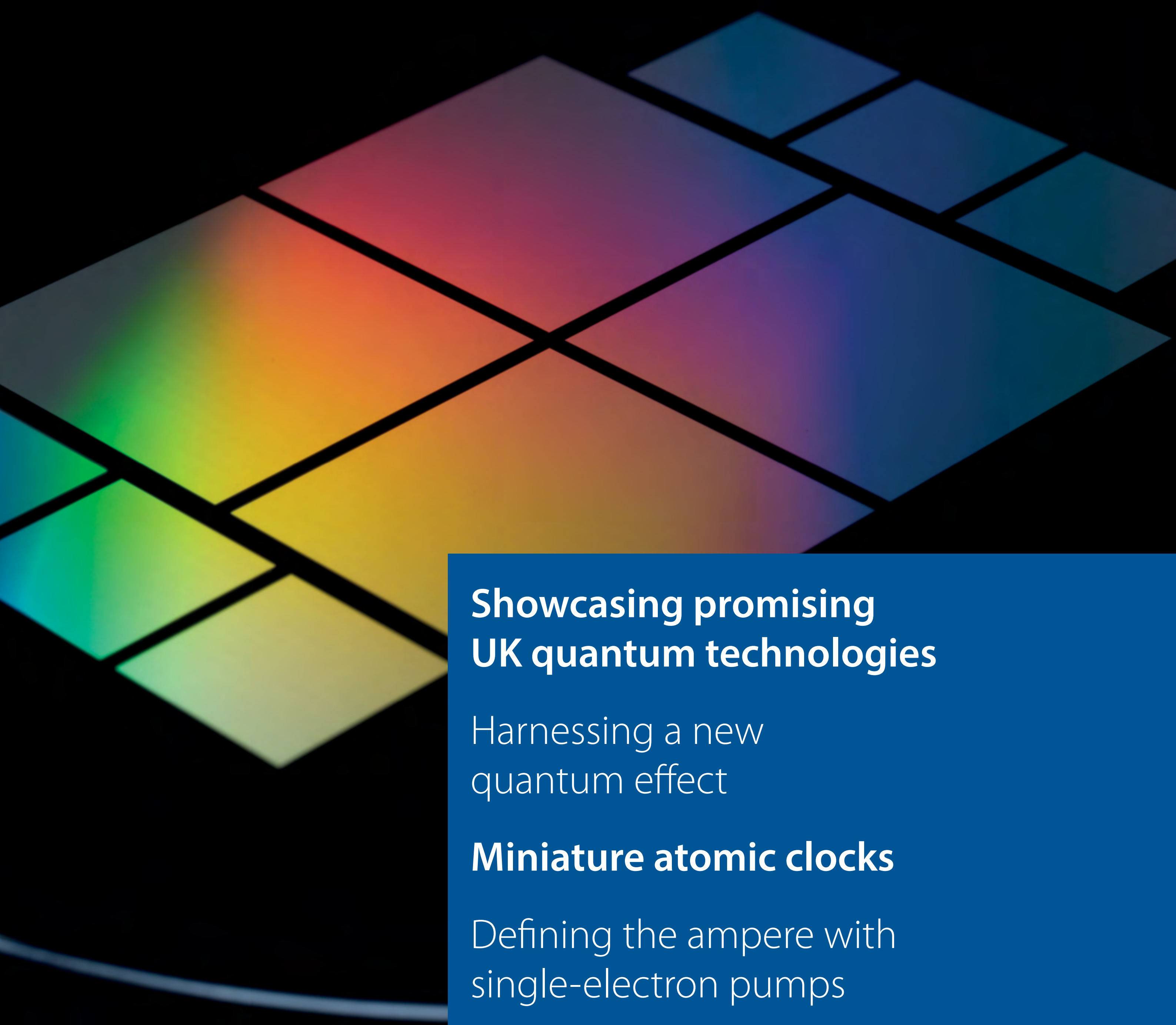
NPL
National Physical Laboratory

Insights

Beyond measurement



Showcasing promising UK quantum technologies

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Welcome to the Quantum edition of Insights – Beyond Measurement

Insights – Beyond Measurement explores how the science and technology community in the UK can come together to deliver world-class science that can change the way we live our lives and do business, influence government funding and policies, and continue to deliver value for money.

This edition of Insights looks at quantum technology, which recently received backing from the UK government in what has been described as the UK's biggest ever single investment in a disruptive technology. Better understanding of, and control over, the quantum world of photons, atoms, ions and electrons has promising implications for communications, navigation, timing and information security. We examine how government funding and strategic partnerships are helping to translate quantum research from the laboratory into successful commercial technologies, which will help maintain the UK's leading position in the field.

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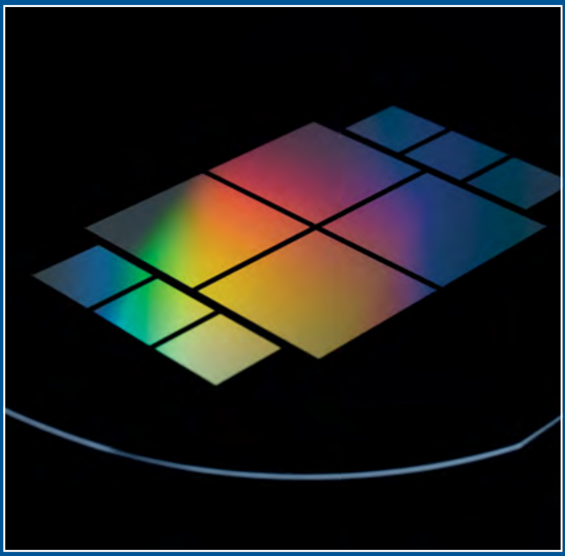


Front cover: NPL's semiconductor chip with microfabricated surface grating that transforms a single incoming laser beam into a light field, specially tailored for trapping and cooling atoms for quantum research and technology.

The National Physical Laboratory (NPL) is one of the UK's leading science and research facilities. It is a world-leading centre of excellence in developing and applying the most accurate standards, science and technology available. NPL occupies a unique position as the UK's National Measurement Institute and sits at the intersection between scientific discovery and real world application. Its expertise and original research have underpinned quality of life, innovation and competitiveness for UK citizens and business for more than a century.

Foreword

David Delpy, Chairman of the Strategic Advisory Board for UK National Quantum Technology Programme

On 4 November 2013, the Chancellor allocated £270 million (see p. 06) in his autumn budget towards the development of a wide range of quantum technologies. This is the biggest single investment in a disruptive technology of the modern era, indicating the government's belief in the economic potential of the UK's excellent research base.

The UK has long been recognised as a world leader in quantum research, and we now have a real chance to build a solid and successful industrial base around that excellence in fundamental science and engineering. A concerted effort could open the doors to a tremendously exciting and disruptive area of innovation, allowing us to build a fully-functioning quantum ecosystem with UK manufacturing based around the science. In effect to create an industry that will deliver clear benefits back to the UK.

Five quantum areas have been specifically identified for development in the call for proposals though others may well emerge. These are: Secure Communications, Metrology, Sensing, Simulation and Quantum Computing. All will be needed if we are to develop a flourishing industry, and converting innovation in any one area into a product will require engineering and manufacturing techniques that can only emerge from the others.

NPL will have a critical role to play across the lifetime of this programme, both within the field of metrology and beyond. Many of the new techniques will require very specialist manufacturing tools, and NPL's new metrology centre will provide crucial resources to help support the whole network. This work is already happening through its role in quantum atomic time and its support to the Dstl, both of which are discussed in more detail in this publication.

The programme is specifically designed to foster collaboration between national laboratories, universities and industrial partners. We intend to build an integrated, national programme that can be managed in a flexible way to react speedily to change and reward progress.

The current vision for quantum technology can be described as a flexible landscape rather than a predetermined roadmap. The possibility of unexpected advances means that all potential areas of relevance need to be examined. We cannot afford to be restrictive at this early stage.

The UK's willingness to invest early in such a speculative area of research will also strengthen our relationship with scientific partners abroad. International collaborators will be important throughout the process, and significant international talent will be attracted to the UK to work in this field.

Let's be clear, we have the indicators to prove that we produce excellent science in the UK. To date we have often not developed this into new industries, populated by truly global companies. The National Quantum Technology Programme will give us every opportunity to now achieve this.

UK field trial of quantum encryption on lit fibres

Dr Andrew Shields from the Cambridge Research Laboratory of Toshiba Research Europe Ltd (TREL) describes the first successful field trial integrating quantum key distribution (QKD) with commercial high-bandwidth data transmission, heralding a breakthrough in the viability of quantum encryption.

Quantum Technologies, exploiting the peculiar concepts of quantum superposition and entanglement, are the focus of a current UK funding initiative. Of these, Quantum Communications, sending information encoded on single photons (particles of light), is widely regarded as one of the most technologically advanced and a realistic prospect for commercial exploitation.

A recent field trial of the technology conducted by TREL and NPL, in collaboration with BT and ADVA Optical Networking, has demonstrated the viability of operating Quantum Communication in ordinary data networks.

Quantum messages have the remarkable feature that their secrecy can be measured directly. In fact quantum theory dictates that anything an eavesdropper can do to gain information about the encoding of the single photons will inevitably leave a detectable trace. This allows eavesdropping on an optical network to be monitored. The technique is most useful for distributing the secret digital keys important for protecting our personal data, such as bank statements, health records and digital identity.

In the past, implementing a secure communication link based on QKD has required at least two fibres – one for the encrypted data and a second to distribute quantum keys. This has meant that installing QKD in a communication system has required additional 'dark' fibre. However, unused fibres are not available in many real-world application scenarios and, even when they are, can be prohibitively expensive. Now, new developments may allow more cost-effective implementation of quantum encryption by integrating QKD onto ordinary data carrying networks.

Modern data communication systems use a technique called wavelength divisional multiplexing, to combine typically 40 – 160 different data channels, each operating at a different wavelength of light, onto a single fibre. The most appealing implementation of QKD would encode the quantum signals on a single wavelength on the fibre, rather than requiring an extra dedicated fibre. This would allow a much more cost-effective implementation of QKD and enable use in a wide range of telecom applications.

However, combining QKD with conventional data is not straight-forward, as the data signals are typically much, much stronger than quantum ones, scattered light from the data lasers can easily contaminate and overwhelm the quantum photons, rendering QKD impossible. These problems have meant that previous single fibre demonstrations of combined QKD and data transmission have been limited to the lab and relatively low data bandwidths.

TREL have recently developed several techniques to extract the delicate quantum signals out of noisy, data-carrying fibres. This includes placing a narrow filter in front of the detector that allows only light at the wavelength of the quantum signals to pass. Furthermore, the detector is biased in such a way that it is operational only for a very brief time (approximately 1/10,000th of a microsecond) at the expected arrival time of the single photons. These techniques reduce the scattered light on the quantum channel by a factor of about 10,000, to a level at which it is weaker than the quantum signals. Thanks to this deployment, quantum encryption on installed fibre is now possible.

On 24 April 2014, TREL along with collaborators at BT, ADVA Optical Networking and NPL successfully demonstrated the integration of QKD with high-bandwidth data transmission on a single fibre, installed in the BT network at Martlesham, Suffolk. The transmission equipment, supplied by ADVA Optical Networking, was configured to supply four 10 Gb/s data channels. The data was encrypted using the standard AES encryption algorithm and QKD was used to regularly refresh the encryption key. Two different geometries were tested: the first with the four data channels co-propagating with the quantum signals and a second with two co-propagating and two counter-propagating channels.

The field trial demonstrated the combination of QKD with four 10 Gb/s channels of encrypted data, i.e. an aggregate bandwidth of 40 Gb/s – the highest that has been possible to date. Although the experiments in April were limited by the number of data channels available, the tests suggest much higher bandwidths will be possible in the future. The level of scattered light indicates it is feasible to combine QKD with over 100 data channels - an aggregate bandwidth over 1 Tb/s - enough to transmit 50,000 HDTV channels simultaneously.

This work originates from a project funded by the UK innovation agency, the Technology Strategy Board, and conducted by TREL and NPL, to develop the metrology for QKD. Metrology is very important for the secure operation of QKD. As the technique is based upon measuring attributes of the communication system, such as photon detection and error rates, it is important that parameters, such as the source intensity and detection efficiency, are known with precision. The project has developed methods for accurate measurement of component values and has been important for the development of industrial standards.

Quantum Technologies tend to be multi-disciplinary in their character. Taking this nascent field from fundamental science to the level of a useful technology, requires the development of complete solutions encompassing a diverse range of R&D challenges in metrology, engineering, telecommunications, cryptography and device physics. The project partners look forward to continuing their fruitful collaboration in the future.

"The level of scattered light indicates it is feasible to combine QKD with over 100 data channels – an aggregate bandwidth over 1 Tb/s – enough to transmit 50,000 HDTV channels simultaneously."

The UK's biggest single investment in a disruptive technology

New facilities soon to be built at the NPL will form part of a quantum innovation centre – this is just one manifestation of the UK government's commitment to quantum technology. In the 2013 autumn budget, Chancellor George Osborne guaranteed £270 million over the next five years to "support translation of the UK's world-leading quantum research into application and new industries".

This sum, 70% of which represents new funding allocated by the Treasury, will go towards generating a national network of quantum technology centres focused on five key areas of research: Quantum Secure Communications, Quantum Metrology, Quantum Sensors, Quantum Simulators and Quantum Computation.

The funding will be divided across three national bodies, with £234M earmarked for the Engineering and Physical Sciences Research Council (EPSRC), £32M for the Technology Strategy Board, and the remaining £4M for NPL.

EPSRC will use the funding to develop a national network of quantum technology Research hubs, with strong industrial engagement, high level skills provision via Doctoral Training and Fellowships, and a programme of activities to support innovation.

"This investment builds on the recognised strength of UK quantum science internationally," says Rachel Bishop, the team leader for Quantum Technology at EPSRC. "A key feature of the quantum science community in the UK is that it is incredibly well networked, both within itself and internationally, which means it is very well positioned to move forward and develop a national activity in this area."

The aim is to ensure the successful transition of quantum technologies from laboratory to industry, where they can make a real difference to the UK's wealth creation ability. Exciting projects such as the Toshiba quantum secure communications test are already putting research into practice, and the possibilities of what might come next are truly breathtaking.

"Identifying the low hanging fruit is very important at this stage," according to Simon Bennett, Director of Knowledge Exchange at the Technology Strategy Board. "That will create an infrastructure from which other more ambitious, longer term opportunities will arise.

"There is a lot of focus on quantum computing, for instance, and while there is no doubting its importance, quantum clocks and quantum secure communications systems are already on the market. Our purpose is to build a ladder that leads from where we are now in rapid steps to some of the bigger and more ambitious applications."

One partner especially keen to see progress is the Defence Science and Technology Laboratory (Dstl), as the defence community has traditionally been an early adopter of new technology. It is hoping to make use of quantum technology to build a high-accuracy navigation system that will function even if conventional GPS systems are not available, as well as an imager that can see structures hidden beneath the surface of the Earth.

Five years is a long time in such a fast-moving field, and it is difficult to say with certainty where the first successes will be. This underscores the need for flexibility and collaboration, so that early breakthroughs in one field can be harnessed elsewhere.

The importance of such cooperation has been highlighted by Sir Peter Knight, Professor of Quantum Optics and Senior Research Investigator at Imperial College London, and Principal of the Kavli Royal Society International Centre. As one of the UK's most prominent scientists, he played a central role in securing this statement of support from the Treasury.

"The £270M programme has been developed with the wider research community," he stressed. "It has not been imposed on anyone but has been born from a series of community meetings. Everyone is in harmony and there is a lot of goodwill out there to make sure this works. At a time of increased competition for resources, that is exceptional."

"This is a joint action with a collective vision, and that united approach is something the Chancellor noted. Separately we will struggle to deliver this, but together we can realise a wealth of quantum research."

The scale of the investment in a disruptive technology is unprecedented in the UK, and has made a bold statement to potential rivals abroad. "Other countries are sitting up and paying attention," says Simon Bennett. "This is going to have a global impact and naturally our purpose is to make sure some of the benefit to the UK is sticky. Hence our enthusiasm to get up and running really quickly. If our international partners are a little shocked and awed by our determination to get on with this then great, let's go for it!"

Lesley Thompson, Director of Science and Engineering at EPSRC, believes that this investment will make the UK an attractive destination for researchers currently based abroad. "We are looked at quite jealously from researchers in other countries," she says.

"Globally the sector has been initially taken aback by our approach, but is now quite excited. It certainly will not mean that we lose quantum physicists to other research labs around the world. As a scientist you want to work somewhere exciting where you can explore your ideas in a well funded research environment and that's exactly what the government is doing in quantum."

Central to the success of the project over the next five years will be the metrology work undertaken at NPL. £4 million out of the total quantum budget has been allocated directly to build new quantum facilities at NPL, in recognition of the importance of standardisation in the development of new technologies.

One example of quantum research being carried out at NPL is an innovative attempt to realise a quantum definition of the ampere, the fundamental unit of electrical current. The project is led by Professor Oleg Astafiev of Royal Holloway, University of London and involves the exploitation of a fundamental effect known as Coherent Quantum Phase Slip (CQPS). According to Astafiev, a better understanding of this effect might also pave the way to technological advances.

"By providing alternatives to existing systems, superconducting quantum systems which display CQPS could lead to improvements in the design of quantum computers."

Establishing a fully-fledged quantum industry will not be without its challenges.

"Obviously this is still an emerging technology," says Rachel Bishop. Recent years in the labs have seen a lot of promising developments that have led people to believe there is an opportunity here that the UK can capitalise on."

Sir Peter Knight agrees, and where some refer to Quantum as the 'ninth' great technology, a reference to the 'eight great technologies' name-checked by David Willetts in 2013, he cautiously prefers to call it the eighth and a half. "The science the government is now trying to exploit is the next generation of quantum research," he adds. "The new initiative is to build an exploitation strategy to pull all this out of the laboratories and into practical realisations in the real world."

As promising as the immediate future is, Simon Bennett of the Technology Strategy Board is keen to stress that we may have to wait beyond the five years of the current plan before seeing results. "I think it is fair to say that although this is a very significant investment in the translation of technology into application, this £270M is only a start. Personally I don't believe that this injection of funds and the five year period will be enough to launch a fully fledged quantum technology industry and market infrastructure. It is clear that something needs to follow on from this initial funding."

Cautious scepticism aside, all parties are convinced that the potential impact of this funding boost could be truly transformative for the British economy. "I think this is a fantastic opportunity for the UK to build on the strength of our science and to really make a difference out there," says Lesley Thompson. "It is a once in a lifetime opportunity."

EPSRC: **www.epsrc.ac.uk**
TSB: **www.innovateuk.org**
Imperial: **www3.imperial.ac.uk**
Kavli Royal Society International Centre
www.royalsociety.org/about-us/history/kavli

Harnessing a new quantum effect

Oleg Astafiev, Chair of Experimental Physics at Royal Holloway, University of London and Project Leader at NPL

This is an exciting time to be working at NPL. At the start of 2014 we began building a centre of excellence for the validation of quantum enabled technologies, partnering with experts from academia and industry to create a hub for quantum research and undertake valuable projects in the field over the next five years.

My team and I are working on the first project supported by the centre, an attempt to demonstrate that a quantum phenomenon known as Coherent Quantum Phase Slip (CQPS) is truly universal, which is to say that it can be observed in a variety of superconducting materials. If this proves to be the case, CQPS could lead to a redefinition of the ampere and have far-reaching implications for quantum computing.

CQPS is a fundamental prediction of superconductivity theory, which describes the behaviour of materials that have zero electrical resistance when cooled below a certain threshold. Although superconductivity was discovered over a century ago, CQPS itself was not directly proposed until 2006 by Hans Mooij and Yuli Nazarov (although NPL's John Gallop had suggested it in a different form as early as 1985), and only observed in the laboratory two years ago.

CQPS takes place when lines of magnetic flux pass between two areas of free space through a thin layer of superconducting material. What makes this remarkable is that superconductors should behave like magnetic insulators, expelling all magnetic field lines from their interior. The magnetic flux overcomes this restriction by exploiting a quantum phenomenon known as tunnelling, which allows it to pass straight through energy barriers that classical physics forbids it from climbing over.

A similar phenomenon known as the Josephson Effect describes the tunnelling of electrons between conductors across a thin layer of insulating material and has been known about for over 50 years. The applications of Josephson physics have proved extremely valuable, not least in the field of precision metrology. A new standard definition of the volt has been proposed relating it to the frequency of electron tunnelling in a Josephson circuit, which can be accurately measured. CQPS would allow for a solution to one of the most vexed questions in the field (see p. 12-13), by providing a similar standard for the fundamental unit of electrical current, the ampere.

Superconducting quantum systems which display CQPS could also be useful in the development of quantum computers, by providing alternatives to existing systems based on the Josephson Effect.

Over the first three years of the project, we aim to produce CQPS devices ourselves and conduct high-precision measurements of the effect here at NPL.

Showcasing promising UK quantum technologies

On 15 May 2014, the Defence Science and Technology Laboratory (Dstl), part of the UK Ministry of Defence (MOD), held an event at the National Physical Laboratory (NPL) to showcase the latest developments in quantum technologies for precision navigation and timing (PNT). Here, Stephen Till and Jonathan Pritchard from Dstl discuss the implications of quantum technologies, whose development Dstl is funding.

New advances in quantum science have the potential to generate disruptive capability on a similar level to the exploitation of quantum mechanics in the 20th Century.

Then, quantum mechanics heralded a new era of technology. This 'first quantum revolution' brought about semiconductors, microprocessors, lasers, nuclear energy, thermal imagers and digital cameras, all of which provide countless benefits for society as well as for the military. The new technologies that are being developed will precipitate a 'second quantum revolution'.

Now, we are on the cusp of that new era. The understanding of quantum science has changed significantly over the past 30 years. Enabling technological developments, such as nano manufacturing and laser cooling of atom clouds, have opened up new possibilities. These are driving the miniaturisation of a broad range of quantum technologies to make them useful and practical for a wide range of novel applications.

The May 2014 showcase included a demonstration of some of the UK's most promising quantum technologies for PNT that are being funded by Dstl. The Dstl work is led by its Knowledge Innovation and Futures Enterprise, a centre of excellence for technology innovation, which focuses on understanding emerging and disruptive technologies for defence and national security. Initial investigation of quantum technology identified highly miniaturised atomic clocks as one of the first quantum technologies with potential for exploitation. Collaborators for the PNT programme were selected using Dstl's Centre for Defence Enterprise which was established to encourage MOD's non-traditional suppliers to engage with Dstl for the early stage development of promising technologies.

The technologies closest to implementation (within about five years) are miniaturised atomic clocks of increasing accuracy and stability. Full scale atomic clocks are increasing in precision every year and our understanding of them is well established. However, they are typically very large, power hungry pieces of equipment often dominating an entire laboratory. Two of Dstl's projects are concerned with developing miniature precise clocks, one the size of a match box and a more accurate version that could be held in the hand. Another has a target specification that will rival national standards and is designed to fit in a low power, light package the size of two small shoe boxes. There are also a number of longer term projects, such as the development of extremely sensitive matter wave interferometers that will result in ultra-precise accelerometers and gyroscopes.

Compact atomic clocks will have applications across a wide variety of sectors including high frequency financial trading and network synchronisation for energy supply systems and telecoms. The clocks, accelerometers and gyroscopes will be used to develop an inertial guidance system of sufficient accuracy that could eventually rival, and possibly even replace, global navigation satellite systems (GNSS). They will allow accurate navigation in GNSS-denied environments such as underground, underwater or inside buildings. Civilian markets have the potential to be worth hundreds of millions of pounds per year to the UK economy.

Dstl's investigative work in 2013 culminated in a Quantum Technology Landscape document which identified even more areas of quantum science for accelerated translation into technologies. This was developed in collaboration with leading academics and colleagues from industry, as well as the Research Councils and the Technology Strategy Board.

Defence often acts as a pioneer in the development of new technologies. In the past, the MOD has invested in magnetrons for airborne radar, thermal imagers for 'seeing in the dark', and liquid crystal display devices. All of these technologies are now readily available and in ubiquitous use by consumers. In the last ten years Dstl has set up its own company, Ploughshare Innovations Ltd, to enable the exploitation of technologies originally developed for defence needs into wider commercial markets. A recent example is P2i, a company which uses technology originally developed for protection against chemical warfare agents, to provide a unique waterproofing capability for consumer goods.

In order to replicate such successes with new quantum technologies, there is a need to commercialise the fruits of the UK's world class academic community. Dstl aims to facilitate building a supply chain from academic research to end users. It believes that the UK can translate quantum science into military and security innovation, then onward to large scale industrialisation. That way the UK will become a major player on the world stage. The quantum technologies that Dstl has identified in the quantum landscape document have the potential to contribute to UK wealth creation as well as yielding disruptive defence and security capabilities. For example, the unprecedented levels of precision available from quantum sensing will enable the development of some of the more advanced concepts, such as the 'gravity telescope'. By measuring gravity fields using highly sensitive quantum enabled devices it is possible to infer the mass distribution that is creating the local field and hence form an image. Such telescope-like devices could allow us to use gravity measurements to identify and image large masses such as hidden, dense metallic objects, or voids such as tunnels or sinkholes underneath the ground, and even generate detailed maps of underground water resources. More detailed detection of oil and gas reserves could permit more efficient extraction with a potentially huge impact on the economy; just 1% increase in oil extraction could lead to billions of pounds of added value. Civil engineering and maintenance of services underneath conurbations could represent larger scale markets as the unit price decreases.

The UK has many research groups with world leading expertise in quantum science. The key now is to translate the fruits of the UK's strong academic base into technologies, products and services. These will have the potential to revolutionise the defence capability, bolster national security and in the process generate economic growth. Much of the technology is sufficiently advanced for the first quantum systems to be ready for market in less than five years.

The event in May 2014 was an important opportunity to bring together NPL, key government departments, academia, industry and commerce to celebrate the progress in exploiting this important technology.

Defining the ampere with single-electron pumps

Masaya Kataoka, Principal Research Scientist in the Quantum Detection Group at NPL

The world around us would be unrecognisable without electricity. And yet even now, nearly 200 years after it was first harnessed for technological ends, it remains an extremely difficult phenomenon to measure accurately.

The most important quantity to define has long been electrical current, the term given to the motion of electric charge, such as the flow of negatively-charged electrons along a wire in household circuits. The fundamental unit of current is the ampere, one of the seven base units of the SI system and also one of the hardest to accurately measure.

In many cases, our ability to track important variables such as radiation dosage or gas concentration is through their dependence on electrical quantities. Improved accuracy in measurements of electrical quantities is therefore of vital importance.

Current attempts to provide a reliable definition revolve around a complicated piece of equipment known as the Watt Balance, of which there are only a few worldwide. There is therefore a pressing need to establish a simpler definition for the ampere in terms of universal physical constants, allowing for more laboratories to make use of it in their research.

Our work with single-electron pumps offers a much more intuitive definition of current by passing electrons across a barrier one-by-one so that they can be accurately counted. So long as the rate at which electrons pass across the barrier is known, the current can be measured with a very high degree of accuracy.

The attempt to use single-electron pumps in metrology is nothing new, but over the last 20 years experiments have all too often been plagued by inaccuracies or pumping frequencies too low to be useful. What my colleagues at NPL and I have done is gain a deeper understanding of the underlying physics in order to develop a particular type of pump that can work accurately at high frequencies.

At the heart of the pump is a cavity less than 0.0002 mm wide called a 'quantum dot', whose shape is controlled by the voltages applied on either side. By modifying these voltages with a high level of precision, we are able to trap individual electrons in the quantum dot before letting them flow through to the other side – much like water passing through locks in a canal.

The electron pump itself can be compared to a water pump in that it produces a flow by a repetitive action. The tricky part is making sure that exactly the same amount of electronic charge is transported in each cycle. In the classical world, you may think of electrons as solid particles with well-defined positions, but quantum mechanics says that electrons have wave-like properties. This

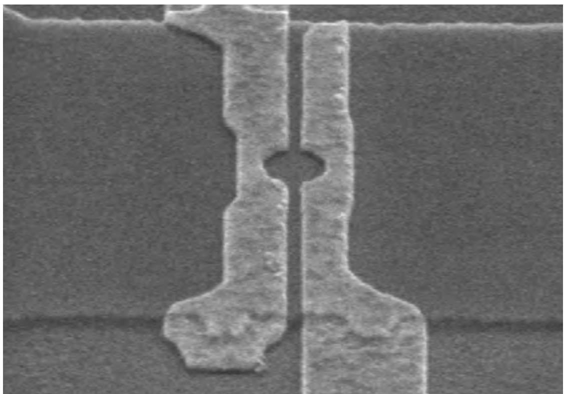
An artist's impression of the electron pump: the white walls represent electrostatic potential of the pump, the liquid surface is the Fermi sea of electrons and the 'flying' spheres are individual electrons.

means they can behave like water, and part of an electron can be 'spilled'.

The way that the electrons in our device behave is quite similar to water; if you try and scoop up a fixed volume of water, say in a cup or spoon, you have to move slowly otherwise you'll spill some. This is similar to what used to happen to our electrons if we went too fast.

In order to keep a tighter control over the electron flow, we modified the timings of the pump so that the electron trapping took place more quickly, giving us more time to devote to their precise release.

These modifications allowed us to produce a steady current in excess of 150 picoamperes (one ten billionth of what you'd need to boil a kettle)



Electron pump SEM image.

with an accuracy of one part in a million. For an experiment to be good enough to serve as a definition for the ampere, however, it needs to be 100 times more accurate still, while consistently producing a current 10 times as strong. We are currently improving our experiment to meet these goals, and are hopeful of making good progress in the next few years.

In the meantime, the increased ability to measure low currents accurately will prove extremely valuable. The Ionising Radiation experiments at NPL, for instance, which test for the presence of radioactivity by searching for tiny electrical currents produced by radiation, have already made use of our technique. Closer to home, many devices that claim to be energy-saving reduce their energy output by operating on a lower current. Our system could allow for the improved calibration of such devices, potentially leading to substantial energy savings.

If we succeed in our grander aim of defining the ampere in relation to the fundamental quantum constants of nature as we propose, the implications will be very exciting. Single-electron pumps operate on semiconductor chips that are only millimetres wide, making them simple to produce and transport, and allowing NPL to bring an accurate current metrology system within reach of laboratories across the world.

Miniature atomic clocks

Patrick Gill, Senior Fellow in the Time & Frequency Group at NPL

NPL is focused on translating its long-standing experience in atomic clock research to provide a class of miniature atomic clocks suitable for applications across a wide variety of technology sectors, including defence, space and aerospace, that can benefit from improved clock and timing performance for navigation and mobile communications.

Since the demonstration of the first caesium atomic clock at NPL in 1955, there have been major improvements in their capabilities and performance by several orders of magnitude.

These improvements have been felt both in primary standard clocks developed and operated at the national measurement institutes such as NPL, and the commercial clock systems employed in widespread precision navigation, timing and synchronisation applications that the global society has come to rely on.

Precision navigation & timing in GPS-denied situations

Atomic micro-clock capability offers faster re-acquisition of high-accuracy satellite navigation signals for accurate positioning in transport and field operations in the event of reduced access to base clock and satellite location signals. It also allows for longer periods of self-autonomous timing synchronisation between network clocks within mobile systems. This synchronisation is essential for error-free data transfer, and integration of relatively low-cost atomic micro-clocks into mobile communications equipment offers this over and above standard quartz oscillator performance by some orders of magnitude. This is critical in respect of loss of access to master clock synchronisation signals (e.g. from GPS) due to operation within high-rise urban environments, inside buildings or in the presence intentional jamming.

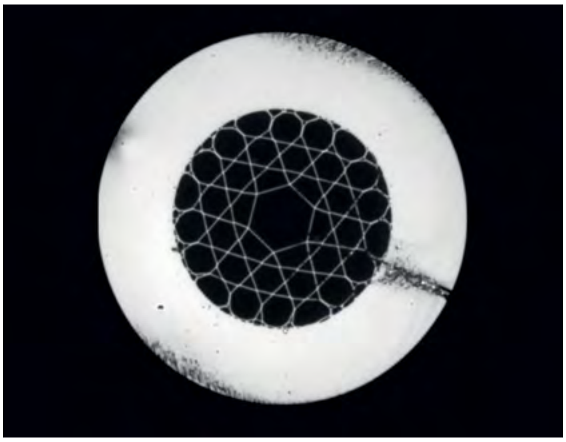
Fountain clocks

The caesium fountain primary clocks used to define the SI unit of time (the second) make use of caesium atoms laser-cooled to microkelvin temperatures above absolute zero which are launched one metre upwards in vacuum and allowed to fall back under gravity. The clock signal is derived by microwave probing of the atoms in flight at a frequency of close to 9.2 GHz, which corresponds to the interval between two low-lying energy states of the caesium atom. Recent fountain developments at NPL now provide timing accuracies of 20 picoseconds per day, or 1 second in 158 million years. The size of these clocks, however, (three metres high and one metre wide excluding optics and electronics) makes them unsuitable for mobile situations.

Micro-clocks

There are many thousands of commercial versions of the caesium microwave clock in use today, all of which use uncooled caesium atoms. These systems offer lower performance but are normally housed within standard 0.5 m wide electronics racks. More recently, we have seen the emergence of the chip-scale atomic clock (CSAC), which employs a tiny (sub-mm size) caesium absorption cell, and has a total package including electronics of about the size of a matchbox.

At NPL we are currently researching an alternative micro-clock based on a short length of hollow core fibre, where the 0.08 mm core diameter is filled with caesium vapour, which should give us high-contrast narrow-spectral-width caesium clock signals when probed with laser light modulated at the 9.2 GHz microwave frequency.

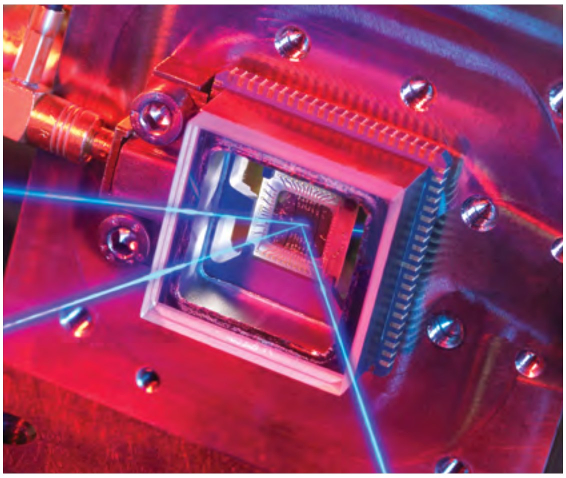


Cross section of hollow core fibre, showing 80 micro-metre diameter core and surrounding microstructure holes.

Miniature ion clocks & microtraps

Using electrode structures driven at RF frequencies (e.g. 20 MHz), we have confined small numbers of ions, or even a single one, within an ion trap under high vacuum conditions. The ions are laser-cooled to millikelvin temperatures, which reduces the 'Doppler' spectral broadening due to the ions' thermal motion. They can then be probed in-situ by microwave-modulated laser light, or unmodulated laser light, to provide microwave or optical clock signals, respectively. In the former case, the ytterbium ion has a microwave clock absorption at 12.6 GHz which offers better frequency stability over the thermal caesium micro-clock case by some 2 to 3 orders of magnitude. However, the added complexity of laser cooling and ultra-high- vacuum production result in a larger 'shoe-box' size physics package. The ytterbium optical clock based on a highly-stable laser probe at a blue wavelength offers even higher stability and accuracy by further orders of magnitude, and is already capable of demonstrating clock performance exceeding that of the primary caesium fountain.

One significant contribution to further down-sizing the ion clock footprint is the micro-trap. Here, NPL has achieved trapping of cold ion strings within apertures etched into 0.3 mm thick doped silicon wafers with segmented electrode structures patterned into the wafer surfaces. Such an 'ion-chip' has been integrated into an industry-standard 29 mm x 29 mm semi-conductor chip carrier held within a simple high-vacuum package with direct laser access for cooling and probing of the ions via a vacuum window covering the wafer. This points the way to both microwave and optical micro-clocks that challenge or exceed caesium fountain performance.



NPL micro-trap showing the 29 mm x 29 mm chip carrier behind the laser access window.

The micro-trap offers even further capability by virtue of its architecture. Techniques such as entanglement and quantum logic, which have been primarily developed for experiments in quantum computing, also have direct application to enhanced clock performance. The segmented electrode structure of the micro-trap is an ideal vehicle for shuttling and entanglement of the ions without suffering environmental decoherence of the ions' quantum states, offering a host of novel techniques for improved clocks and sensors.

Commercially available atomic clocks until recently in no way matched the small size, weight and power (SWaP) requirements for fast, accurate and easy access to navigation and timing synchronisation in rapidly-deployed mobile ground-based and aerospace situations across the defence, security and civil sectors. Particularly problematical is operation in difficult terrain, high-rise city environments and in intentional signal jamming situations. The advent of micro-clocks with improved time and frequency performance goes some way to providing local timing holdover and communications synchronisation in such scenarios.

National Physical Laboratory

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