

Business Case – Quantum Technologies

Version History v 2.0

Project SRO:					
Version	Submission Date	Policy	Group Analysis	Group Finance	SPT
1 st Investment Gateway	23/08/2013 rev. version 02/09/2013				
2 nd Investment Gateway	19/09/2013				

Strategic Case

Quantum technologies possess two properties of strategic importance to the UK: orders of magnitude improvement upon conventional computing power; and the harnessing of quantum physics to deliver unique capabilities and significant benefits to industry and wider society.

Quantum technologies represent a major opportunity for the UK given the UK's competitive global position and the willingness for key partners across the UK to work together. Although the disruptive nature of quantum technologies means that existing businesses would not necessarily be able to adopt these technologies into their current businesses, a number of global companies have established R&D collaborations in UK universities.

If the UK is to capitalise on its two year global lead then it must act now through significant government intervention to ensure that a centre of economic, scientific, technological and manufacturing gravity will remain anchored within the UK, securing long term growth.

The proposal

£269m capital and resource funding over 5 years for EPSRC to support the development of quantum technologies in the UK, through building a National Network of Research Centres with high levels of engagement from global businesses, creating high level skills to help build new sectors of the economy in areas demonstrating strong promise, and an innovation programme to support translation of research into application and new industries.

An additional £4m capital funding is requested over 3 years for National Physical Laboratory (NPL) to kit out its new Advanced Metrology Laboratory (AML). The additional investment will complement EPSRC's network of centres and help develop an integrated programme of fundamental and applied Quantum Technologies across academia, government labs and industry.

Background and Rationale for Intervention

Quantum Technologies involve the control and manipulation of quantum states, such as the energy, spin or momentum of a particle to achieve results not possible with classical matter. They are in a sense the next step on from nanotechnology – not only transforming the scale of the system but exploiting the laws of physics in radically new ways. They promise future dramatic changes in the technological capabilities in several key areas, including secure communications and metrology (see Annex B for full list of areas).

Many of the pioneering ideas for Quantum Technologies were developed in the UK, including; the first proposal for a quantum Turing machine, the first algorithm for quantum speed up, the first proposal for quantum key distribution, and the first algorithm for quantum error correction. Thanks to the efforts of the UK research community and significant (primarily EPSRC) financial support over the last decade, we are leading in several

experimental areas; such that the UK is well positioned to exploit this capability and take it through to technology.

We already see many hi-tech companies exploiting this capability, including Toshiba, Nokia and Hitachi that have placed their main research labs in Quantum Technologies in the UK, and UK universities have become key partners for other global companies such as Google, Lockheed-Martin, NEC and D-Wave. NPL also has a significant activity in the rapidly developing application of quantum techniques to measurement and standards, which this intervention will need to be coordinated with (most likely through the new Advanced Metrology Laboratory). Furthermore, other UK companies have significant links with research in Quantum Technologies through their world-leading technological capabilities. For example, Element Six (diamond fabrication) and Oxford Instruments (cryogenic apparatus).

To develop these technologies requires multiple disciplines: physics, mathematics, materials, electronics, photonics, engineering and computer science, in an interdisciplinary research and development activity. There is an opportunity to build on the research base that has been developed and draw in researchers from outside of physics, particularly engineers, in order that the science can be taken through to technology in a manner that will benefit UK society and the economy.

The UK should build on the capabilities it has developed over the last decade and take advantage of its strengths to establish itself as a leading player in a developing Quantum Technologies industry. Given the UK's world-class research base in this area we should make every possible effort to ensure that as a Quantum Technologies industry emerges, it happens here. We should start building the UK "Quantum Technologies cluster" now, with a target that within 5-10 years, it is perceived to be the most dynamic place in the world to develop in Quantum Technologies. Which would be through connections with industry based on demonstrable real-world technology opportunities that will make us the preferred choice for all things concerning quantum technologies. Ranging from the provision of credible and effective advice, the ability to translate research into products and services, and presence of skilled and expert people.

How this fits in to the policy strategy

The UK is in an excellent position to exploit its strong research capabilities in this area and provide a first-mover advantage from the clustering effect created by the national network of centres in the UK. It is important to capitalise on our gains now to stand a chance of competing with other countries who are increasing their efforts to exploit these groundbreaking technologies.

Capabilities in Quantum Technologies offer potentially transformative impacts across a range of sectors and this intervention could cement the UK's position as a leader in this emerging technology and deliver a vibrant cutting edge industrial sector. Intervention to establish the UK as leader in Quantum Technologies will be an investment to deliver one of the next generation of Great Technologies.

BIS, through its agency the National Measurement Office is working to establish a new operating model for the NPL, through a long-term strategic partnership, ideally based on equity between it and high quality UK or international academic institutions and/or applied research organisations. This new operating model aims to meet the Minister's aspiration for better use of facilities through a further strengthening of the Laboratory's links with academic partners. This builds on and strengthens the capacity for NPL to work more closely with the research base.

A new £25m Advanced Metrology Laboratory (AML) funded by BIS will house the new capabilities at NPL. The AML will provide an extremely stable environment ideally suited to quantum metrology and quantum sensing.. The £4m capital will ensure the AML is equipped to take forward research in this area to fully support the broader investment in quantum technologies. Investment in this equipment will help ensure that other QT centres have available the measurement methods and where applicable equipment required to take their research forward. It will also mean that the UK will be better able to commercialise the scientific discoveries arising from this investment. International standards for many aspects of quantum technologies have not yet been developed and agreed and NPL will have a critical role in helping to keep the UK at the forefront because of their role in standards development.

GCHQ are closely following the development of quantum technologies using its network of academic and industry contacts and are conducting internal research into new non-quantum algorithms that will protect UK networks from a future "quantum attack" as well as sponsoring academic research into the same. They are also researching potential improvements to quantum attacks on existing cryptography that might affect our estimates on when the threat to current systems could be realised. GCHQ support BIS's investment in quantum technologies and the strategy of growing UK capacity through a network of expertise and approaches rather than consolidating now. It is anticipated that any Centre based on quantum secure communications would have GCHQ as a partner.

What the intervention is, what the money will be spent on and the objectives it aims to achieve

This intervention would comprise of investment in postgraduate skills, research programmes, capital for new equipment (rather than buildings) and innovation (a Special Interest Group, feasibility studies and demonstrators) to ensure the Quantum Technologies capability within the UK is strengthened, keeps pace with international investments and ensures the UK remains at the forefront of this rapidly expanding and developing domain.

This would be through the establishment of network of national centres in Quantum Technologies which focus on taking the science through to technology, combined with complementary high level skills provision and an innovation programme. These centres would each have their own foci and work together to give breadth and depth across the five areas described above. Capital funding in the centres would be for clean-room and fabrication systems, high stability radiation sources, ultrafast lasers, high stability lasers, superconducting detectors and electronics, high speed and high sensitivity electronics and associated cryogenic cooling equipment, low-noise and low-temperature environments, and ultra-sensitive instrumentation.

The objective of this additional investment is to enable the UK to capitalise on and exploit its research strengths by creating capability in Quantum Technologies that is broad and deep enough to pull them through to application, and deliver economic and societal benefit.

The £4m capital investment at NPL within the AML will enhance UK's quantum metrology capability and help attract collaborators as part of David Willetts overall aspiration for the Laboratory and the AML, as well as cementing links to the other QT centres. A summary of the planned investment at AML is summarised at Annex A and described in the economic and management cases.

How the intervention is different to existing policy, projects and programmes

EPSRC currently invests approximately £30M into research, training and fellowships of direct relevance to Quantum Technologies¹; this value exceeds £150M when complementary research areas which are vital to the successful development of Quantum Technologies are included, such as photonics, electronics, communications, functional materials, sensors, instrumentation, and computer science².

This intervention would deliver a focus on resolving the key technological challenges that need to be overcome to enable Quantum Technologies to be delivered across the five areas identified (Annex B), draw on the existing research strength in complementary areas, train people with skills to exploit the science and take this through to application, and facilitate the development of a UK Quantum Technologies industry. It would be an increase in the level of funding the UK directs towards the development of this emerging technology; drawing on strengths from across the UK research landscape, in a manner where there is coordination with other relevant agencies and partnership with industry.

This intervention will also exploit several advantages the UK holds over its competitors. The geographical nature, institutional landscape and strong reputation of the UK allows a cohesive network involving world leading research groups to be formed. This synergy would be very difficult for our main competitors to achieve

¹ Research, training and fellowship grants in the *Quantum Optics and Information* research area.

² Research, training and fellowship grants in the *Photonic Materials and Metamaterials, Optoelectronic, Devices and Circuits, Optical Devices and Subsystems, Non-CMOS Device Technology, RF and Microwave Devices, Optical Communications, Sensors and Instrumentation, Programming Languages and Compilers*, research areas.

because they lack either the geographical concentration or the personal contact and history of collaboration found among researchers in the UK.

The request is separate to the £25m investment in an Advanced Metrology Lab at NPL, expected to reach completion in 2017, and the existing budget will cover the building costs and renewal of assets but not new equipment needed to establish it as a flagship facility for cutting edge QT research and capability. The additional £4m capital is needed to purchase new characterisation and fabrication facilities to accelerate the application of quantum-enabled technologies in the UK.

The need for intervention and why current policy is not working

At present the bulk of research in the UK in this domain can be described as fundamental research, where the focus is on the study and control of quantum superposition and quantum entanglement that underpin technological and scientific applications and the outputs are primarily high quality research publications. Intervention is needed to build the critical mass needed to support development of quantum technologies. Currently, engineers, in the main, do not fully recognise the opportunity advances in our understanding of quantum superposition and entanglement present. There is an opportunity to build on the research base that has been developed and draw in researchers from outside of physics in a constructive manner, in order that the science can be taken through to technology in a manner that will benefit UK society and the economy.

This intervention would address this issue by shifting the focus of investment and effort towards tackling key technological challenges without losing the flow of new science into this area, and exploit the strength which exists across the UK research landscape. These are important requirements for holding a leadership position in Quantum Technologies.

The intervention would also be comparable to those being made by competitor countries³, which are detailed below:

- Canada: The Institute for Quantum Computing at Waterloo. Total QT investment £190M since 2001. *"...establishing Waterloo and Canada as the world's Quantum Valley."* - IQC 2012 Report.
- Singapore: The Centre for Quantum Computation. £75M in committed in 2007, with more now coming on-stream, *"For actual systems and solutions that can be exported to the rest of the world"* - Dr Tan Keng Yam, President of Singapore 2012.
- China: The Centre for Quantum Information at Tsinghua. Undisclosed total investment, but quantum technology identified as one of four priorities: *"China will make farsighted arrangements for research in cutting-edge technologies in the fields of biology, nanoscience, quantum control and information networks."* - Premier Wen Jiabao 2010.

Large national centres in quantum technology are also being established in Russia and in Korea, with increasing investment taking place in multiple centres across Australia and the US.

The proposal is based on advice sought from key industry partners e.g. Toshiba, Nokia, and its partnerships with engineers and technologists across universities such as Bristol and UCL, as well the NPL and their efforts in linking industry and academic training in this area. We (BIS and EPSRC) have successfully mobilised the community and gained their support for the proposal - and key partners such as NPL are already investing in complementary activities. The momentum and rate of progress of research in this area make it the best time to intervene - any further delay would mean the UK loses out to competition overseas.

How the policy fits in to the departments overall delivery plan

This intervention in Quantum Technologies would constitute a significant step in the development of an emerging technology and contribute to the next generation of Great Technologies. It will lead to significant new UK research and industrial capability, particularly in national defence and security, as evidence from

³ quantum:UK, John Morton (UCL) and Simon Benjamin (Oxford), 1 July 2013.

involvement of GCHQ and Dstl in recent ministerial level discussions and expression of interest in engaging on a quantum technology strategy.

The policy also fits into EPSRC's overall Delivery Plan. Quantum physics for new quantum technologies was identified by EPSRC as a Grand Challenge for Physics, which recognises that the next generation quantum technologies relies on our understanding of coherence and entanglement. It forms one of the strategic priority themes for EPSRC's current Centres for Doctoral Training competition. The related capital bid for new equipment in the CDTs will not duplicate the request in the capital element of the Quantum bid, as any Quantum technology CDTs (assuming they are funded following decisions from peer review panels in October) will be for state of the art equipment for training purposes, as opposed to special equipment and hi-tech facilities in the network of quantum technology centres to conduct cutting edge research.

Main benefits, associated risks, constraints and dependencies of the proposal, and how they will be managed

The main benefit of this intervention is that it will establish a coordinated UK capability in Quantum Technologies which focuses on taking the science through to technology and consequently application.

EPSRC has no institutes and deliver all its research and training programmes through the universities. Previous similar investments by EPSRC, which have led to significant economic and societal impact, include Interdisciplinary Research Centres⁴, Innovative Manufacturing Research Centres⁵, Centres for Innovative Manufacturing⁶, and Centres for Doctoral Training⁷. Management of the network of quantum technologies centres will be through a coordinating group involving the Directors of all the Centres, overseen by the EPSRC. Each Centre will be led by a university (or in some cases pair of universities) where it is likely to be based, and will collaborate with the groups in other institutions and also form wider partnerships with industry and other relevant users of the research (e.g. GCHQ, Dstl). The centres would need to have the critical mass across the range of research areas relevant to tackle the specific quantum technology as well as the basic suite of experimental and fabrication facilities.

To be successful this investment depends on the continued support of underpinning capabilities from across the wider research base, and constructive engagement between scientists, technologists and engineers. There are existing relationships between a small number of companies and end users with the academics whose specialism relates closely to their business interests: from research collaborations between universities and other institutes (Glasgow/Fraunhofer, Oxford/Harwell, UCL/IC/NPL) to business links Toshiba/Cambridge; Bristol/Nokia; London Centre for Nanotechnology/Lockheed Martin). Generally however the partnership with industry needs strengthening, some of which is currently unaware of the potential offered by Quantum Technologies or lacks capabilities or trained people in this area.

Finally, these investments would be dependent on EPSRC's competitive process and peer review of bids, but would build on current centres of academic strength and reinforce emerging business collaborations as described above. Given the distribution of quantum technologies intellectual leadership, this is not an area suitable for investment into a single centre unlike the Crick Centre or Graphene at Manchester. This was confirmed at the quantum technologies roundtable with David Willetts on 4 July (Annex C).

Economic Case

A number of market failures are likely to impact the development of a quantum technology sector in the UK and as such require government intervention:

Spillovers: Private sector companies are generally unable to appropriate entirely the benefits from their research, which consequently has significant spillovers in the wider economy. As such, social benefits are

⁴ <http://www.epsrc.ac.uk/funding/routes/capacity/Pages/ircs.aspx>

⁵ <http://www.epsrc.ac.uk/research/centres/imrcs/Pages/currentimrcs.aspx>

⁶ <http://www.epsrc.ac.uk/research/centres/innovativemanufacturing/Pages/centres.aspx>

⁷ <http://www.epsrc.ac.uk/skills/students/centres/Pages/centres.aspx>

higher than private benefits and the private sectors does not have sufficient incentives to invest at a socially optimal level. Government funding is necessary to bring R&D expenditure to an optimal level, in particular in groundbreaking areas such as Quantum Technologies.

Risk and uncertainty: Science and research activities are highly uncertain, in particular for groundbreaking areas, which means that individual companies may be reluctant to invest in such areas. The State, by providing funding to the entire research area, can hedge the risk associated with individual research projects and promote an entire sector which will have clear benefits to the economy.

Timescale: Such uncertainty is exacerbated by timeframes for eventual benefits which can exceed what is feasible for a private company – this, again, will lead to underinvestment by the private sector. The State can sustain a much longer timescale for benefits and must provide funding for research where benefits are unlikely to be in an acceptable timeframe for the private sector.

Coordination failure: Large projects which would benefit all private actors (as well as public services possibly) may be impossible to be set up privately as the costs involved outweigh the benefits to any single individual actor, even though the sector or society as whole may benefit from them. This is the case at present since such large research centers would benefit a range of businesses and research projects which would otherwise struggle to coordinate in order to set them up.

Industrial strategy: Quantum Technologies are a groundbreaking field in which early development of capabilities could provide a first-mover advantage as it could lead to a clustering effect in the UK. In the context of strategic efforts by other countries to develop research capabilities in this area (as described previously), if the UK did not secure sufficient research capacity it could affect its ability to compete in the area and its potential industrial developments in the future. In short, groundbreaking technologies can have path-dependency effects which could lead to large benefits if supported at an early stage, and lost economic opportunities if neglected.

It has long been considered in the economic growth literature that technological change is the key driver of long-term economic growth. More recently, Aghion and Hewitt (2007) found that Total Factor Productivity accounted for 70% of UK economic growth between 1960 and 2000. Reviewing the academic literature, Salter *et al.* (2000) and Salter *et al.* (2001) found that most studies put the social rate of return to publicly funded R&D at between 20% and 50%. Griffith *et al.* (2003) estimated a social rate of return to R&D-based innovation of 40% to 60%.

The BIS approach to modelling R&D benefits has in the past taken the cautious but realistic approach of assuming, for the periods of highest benefits from science and research, social rates of return between 30% and 50%, with NPV/DEL ratios ranging between 10.2 and 18.9. Given the highly specific nature of the project and the high uncertainty surrounding its outcomes, calculating a specific NPV would be extremely hazardous. The NPV/DEL ratios quoted above can give an idea of the typical returns to science and research as a whole.

Some of the potential benefits from Quantum Technologies can already be foreseen, but it is likely, as with much groundbreaking research, that many benefits cannot be yet predicted (for example, the Global Positioning System (GPS) could not have been developed without breakthroughs such as the Theory of General Relativity (1919) or Atomic Clocks (1950s)⁸, and yet the GPS had not been foreseen as a potential application back then). The exploitation of quantum superposition and quantum entanglement offer the prospect of significant impact and the ultimate improvements in precision, sensitivity, accuracy and speed that the laws of physics allow⁹, in a range of areas which collectively can be described as Quantum Technologies (Annex B).

Advances in Quantum Technologies are therefore potentially very disruptive and consequently present the prospect of current technologies being surpassed by alternative approaches which exploit quantum superposition and quantum entanglement. UK industries in relevant areas will therefore need to adopt and exploit Quantum Technologies or risk their products being out performed, with implications for the skills and

⁸ <http://www.stfc.ac.uk/resources/PDF/OE%20Satellite%20Navigation%20Case%20Study.pdf>

⁹ The Age of the Qubit, Institute of Physics, http://www.iop.org/publications/iop/2011/file_52078.pdf

capabilities that they possess. Furthermore, there is the potential that establishing a lead in these Quantum Technologies will be lasting.

A key point here is that there will be a Quantum Technologies industry¹⁰. The question is how significant an industry it will be and how the UK (with its academic research strengths in the field) can be at the centre of it. Quantum technology systems are being demonstrated and some niche products are available on the market today, such as the 512-qubit “D-Wave Two” quantum computing device (Lockheed Martin sponsored some quantum computing studentships at UCL to allow access to the device). Examples of how the research activities are now maturing and progressing up the technology readiness level scale:

- The Centre for Quantum Photonics (CQP) at the University of Bristol demonstrated a photonic quantum computational device – a 2 qubit machine – using a single silicon chip. The University has engaged with Nokia, Toshiba, MoD, XMOS and NTT in the development of quantum ICTs – the first commercial communication devices is expected to be on the market in 2-3 years. CQP also launched as part of the British Science Festival in August 2013, the first on-line free access quantum processor and simulator for schools and researchers.
- The simulation of molecules at the quantum level is expected to produce more accurate modelling tools with possible applications in healthcare (e.g. shortening lead times to drug discovery and development). The prestigious Korber European Science Prize, which recognises groundbreaking research projects (Andre Geim was the Korber Prizewinner in 2009) was this year awarded to a German physicist, Immanuel Block, for his groundbreaking work in the field of quantum simulation for ultracold atoms by trapping quantum gas in a laser cage. The UK also is strong in this area, with NPL working closely with Dstl in next, Imperial College, Glasgow and Strathclyde collaborating to develop a portable way to produce ultracold atoms for quantum technology for miniaturised sensors and processors which could be developed to be used in navigation, telecoms, geological exploration and medical imaging.
- Quantum cryptography which uses the laws of quantum mechanics to detect secure transmission of information in the smallest of units of light energy (photons) - will be the basis of a security system that can't be beaten without knowledge of those sending and receiving data.
 - [REDACTED] demonstrated Toshiba Research Europe's quantum cryptography prototype system for detecting the tapping of fibre communications of information shared over networks at the Royal Society summer exhibition.
 - Early stage quantum cryptography products aren't currently supported by standards or certification from national measurement institutes such as NPL. However NPL have funding through the National Measurement Strategy to work on these technologies to underpin the security of online shopping and international financial transactions. This includes a 3-year research project (Entangled Photons in Quantum Metrology) for the UK's National Measurement System, in collaboration with Cambridge University and Imperial College London.

The Technology Strategy Board's Emerging Technologies and Industries programme has looked at the available market research reports, and these suggest that the potential global market in quantum technologies could be in the order of £10bn in around 10 years time. This figure relates to the potential worldwide market – more work could be done to demonstrate the capability and appetite of UK business to capture a part of this, the barriers that they face on the route to market, and therefore the precise shape of a national innovation programme. For this reason, the larger innovation investments in this proposal are scheduled later in the programme, whilst the science investments are more evenly spread.

Other government departments are interested in translating the technology into industry applications. GCHQ, NPL and Dstl are working together with their academic counterparts and companies such as BAE Systems in assessing the potential of quantum computing and cryptography for security and defence applications. These

¹⁰ As shown by the purchase of a D-Wave Two processor by NASA, <http://www.bbc.co.uk/news/science-environment-22554494>

companies and agencies have described quantum technology retypes for detecting tapping of optical fibre communications, and applications of quantum technologies in computing moving to the cloud and the internet of things in energy efficient ways, for wider societal benefit. They have further highlighted how quantum technologies can be game changing and disruptive¹¹. However, there are a broader range of sectors which would be impacted on by developments in Quantum Technologies, but don't yet understand the UK's capability. There is growing interest internationally, as a small number of multinational companies who have the capacity and capability to explore new technological opportunities, such as Nokia and Toshiba, begin to spin out companies from universities operating in this space.

As stated earlier companies such as Toshiba, Nokia and Hitachi have already placed their main research labs into Quantum Technologies in the UK, and UK universities have become key partners for others which don't have a UK presence (such as Google, Lockheed-Martin, NEC and D-Wave). The UK has a strong position with regards to patents in areas such as quantum computing and quantum cryptography. We have requested patent data and trends for quantum technologies which the Intellectual Property Office has promised. We were advised that there are small but significant and sustained levels of patenting activity in quantum computing and quantum cryptography (worldwide), with the UK comparatively well represented. [REDACTED] (IPO technologist) noted that (worldwide) patent application data shows that a large portion of the inventors named on patent applications in these areas are resident in Europe, and within these, half are resident in the UK.

A number of options were considered when developing this proposed intervention.

- **Current approach:** This would not harness the strength that exists across the UK research landscape effectively or focus the efforts of researchers on taking the science through to technology. Nor would establish Quantum Technologies as a priority for the UK or provide the critical mass required to make progress.
- **One or two national centres:** It would be extremely difficult for one or two single centres to cover deliver the breadth and depth of strength to achieve progress in taking the science through to technology. However, it would not enable sufficient focus on a specialism within Quantum Technologies or effective partnering with industry. Nor would it harness the strength that exists across the UK research landscape effectively. Particularly as there are not one or two centres which stand out as choices for such a centre or two.
- **Several centres:** This would deliver the breadth and depth across Quantum Technologies, harnessing the strengths across the UK research landscape. However, centres should focus on a particular theme within Quantum Technologies both to differentiate them, concentrate their efforts and foster partnerships with industry in specific areas. There would need to be some coordination of the centres to ensure they work as a national network and have an international visibility.
- **National hub with additional nodes:** While this would go some way to harnessing the strength that exists across the UK research landscape, the hub would lack the breadth and depth required, have insufficient focus, and nodes would be sub-critical.

In addition, it was considered that this intervention would need to include the provision of high level skills to ensure there are researchers and practitioners in Quantum Technologies to ensure the UK has strength and capabilities in this emerging technology. Plus an innovation programme to ensure the research is taken through to application and industrial capabilities and capacity are delivered in Quantum Technologies.

This thinking, based on advice from leading academic researchers and industrialists, has led to package that is described in the next section being proposed.

NPL research investment returns

NPL is the UK's National Measurement Institute, and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available. NPL maintains a wide

¹¹ Note of Quantum Technology Roundtable – 4 July 2013-long version- Final 20130723 (see Annex B)

portfolio of internationally visible research programmes that advances measurement science, underpins the SI system and supports various cross-disciplinary technologies.

There is strong evidence regarding the impact NPL has in its delivery of the National Measurement System:

- A study by PA Consulting estimated that measurement delivers a significant impact into the economy of 0.8% of GDP, or £11B today.¹²
- A study by economists at BIS estimated an additional Government investment of £6M in the National Measurement System (NMS) would produce a return between £300M and £400M for the UK economy.¹³
- An independent survey of 1,000 companies accessing knowledge from the NMS quantified the benefit delivered to product and process innovation by UK businesses as £700M in additional profitability for a single year.¹⁴

The NPL is working closely with Dstl colleagues on quantum technologies such as, next generation microtrap technologies (see article: <http://www.npl.co.uk/news/scalable-device-for-quantum-information-processing>) for quantum metrology devices, compact atomic clocks based on hollow core fibres, and new types of waveguide atom interferometers based on ultraslow atoms. NPL has already delivered a number of technology reviews in this space. Dstl has identified NPL as a key partner for its PNT (Precision, Navigation and Time) activities, as a leading centre in quantum time devices.

Leverage against public investment in Quantum Technologies:

Currently industrial and other users of research collaborating on research grants in the £30m EPSRC portfolio of direct relevance to Quantum Technologies provide nearly £1.5m¹⁵ in contributions. While this might seem low, it will be in addition to any broader more dynamic leverage effects that occur alongside cutting-edge public R&D investments and reflects the fact that currently this research is basic in nature. Furthermore leverage rates are higher in the complementary areas that are vital the successful development of Quantum Technologies, such as photonics, electronics, communications, functional materials, sensors, instrumentation, and computer science; where around 40% of projects have a project partners from industry or other user organisations.

It is reasonable to predict that as the science is taken through to technology this leverage rate will steadily increase. As connections with industry currently not aware of what Quantum Technologies offer are made, confidence in their potential increases, and the research focuses increasingly on overcoming technological challenges. This is borne out by the higher leverage rate seen on bids for Centre for Doctoral Training which are focused on our *Towards Quantum Technologies* priority in this call, which is nearly 30%, and shows the strong interest from beyond academia in the provision of skilled people in this area¹⁶. It is also bolstered by the placement of hi-tech companies of their research labs in Quantum Technologies in the UK, and the partnerships being formed by global companies with UK universities.

Financial Case

This case is for a complete package which spans the whole range of what EPSRC consider to be required to take the science through to deliver quantum technologies. There are three main elements to this intervention, a national network of research centres, provision of high level skills training, and an innovation programme. This intervention would therefore comprise of a suite of awards and actions, which are described in more detail below.

¹² www.bis.gov.uk/assets/bispartners/nmo/docs/nms/economic-reviews-august-2010-updates/pa-review-of-the-nms1999.pdf

¹³ www.bis.gov.uk/assets/bispartners/nmo/docs/nms/nms-consultation-doc-support-docs-may-09/sept-economic-impact.pdf

¹⁴ http://www.bipm.org/utis/common/pdf/KPMG_report.pdf

¹⁵ Cash and in-kind contributions from non academic institutions or research institutes to research and research training grants in the Quantum Optics and Information portfolio.

¹⁶ Cash and in-kind contributions from academic institutions or research institutes to proposals considered to have strong alignment to the *Towards Quantum Technologies* priority in the 2013 Centres for Doctoral Training Call.

- **National network of research centres (£80M Recurrent/£75M Capital)**

There are five thematic research areas where investment should initially be focussed to build on the UK's current international lead in the area of Quantum Technologies. The expertise and momentum that exists within these foci are most likely to lead to the key breakthroughs that will ensure the UK has the best opportunity for harnessing the technology.

- **Quantum Secure Communications:** particularly quantum photonic device technology, quantum key distribution and quantum cryptography which exploits the laws of physics to ensure that no information was intercepted. Capital investment should be directed to fabrication technologies for devices which have the capability of making a step change in performance and/or cost.
- **Quantum Metrology:** ultra-fine and accurate measurements at the quantum level to deliver new standards for time, frequency, length, charge and other fundamental measures. Capital investment should be directed to metrology specific pico second lasers, superconducting detectors and electronics, high speed and high sensitivity electronics and associated cryogenic cooling equipment.
- **Quantum Sensors:** precision for environmental monitoring, healthcare and security, enhanced capabilities (e.g. imaging individual biomolecules and structures) and near perfect inertial navigation (e.g. electromagnetics and 'jam-proof GPS positioning systems). Capital investment should be directed to sensing specific ultra short pulse lasers, superconducting detectors and electronics, high speed and high sensitivity electronics and associated cryogenic cooling equipment, and fabrication technologies for the development of demonstrator devices.
- **Quantum Simulators:** tool for more accurate modelling and simulation of real molecules and their behaviour and interactions with other systems, as well as investigating new types of materials (e.g. room temperature superconductors) or drug development. Currently the research relies on classical computing to process information, but coupled with progress in quantum computing could lead to more powerful modelling tools (e.g. for climate forecasting). Capital investment should be directed to dedicated clean-room processing, low-noise and low-temperature environments and high-stability lasers.
- **Quantum Computation:** a universal quantum computer for significant step change in the power of computing. Capital investment should be directed to microwave integration for control of atomic, ionic and solid-state qubit registers; cryogenics for superconducting devices; laser systems; control instrumentation and computational facilities for simulation and design.

This element of this intervention would comprise of a network of five or six centres, each with its own particular focus, which would work together, to tackle the key technological challenges relating to Quantum Technologies. This would harness and exploit the research strengths that exist across the UK academic landscape and facilitate partnering with industry and with complementary research areas.

- **High Level Skills provision (£60M Recurrent)**

The provision of skilled researchers in quantum technologies who can go into the academic and industrial UK research base is critical to making the UK the most dynamic place in the world to develop in Quantum Technologies.

EPSRC has a Centre for Doctoral Training call in progress which aims to provide skills to the next generation of researchers with a particular focus on working at the interfaces between maths, physics, ICT and engineering. EPSRC currently has 17 quantum relevant high quality bids under consideration (with over 20 industrial partners) - four with a significant focus on Quantum Technologies, and the others supporting complementary training which is closely related to this challenge. Support and mobility of people is at the heart of successful research, discovery and translation. It is thus important to continue supporting fellowships around this grand challenge. Fellowships allow our current and

future leaders the time and space to push the quantum agenda forward, to make new collaborations both to source wider research expertise to overcome technical barriers, and to engage with the industry partners who will potentially utilise these technologies. Subsequent inward attractor packages may be required as the landscape evolves, and partnership with the Funding Councils and the Royal Society/Royal Academy of Engineering will be key.

- **Innovation programme (£50M Recurrent)**

The EPSRC and Technology Strategy Board (TSB) will encourage and support networking and engagement with researchers in complementary areas and with industry. Linking this to existing networks and forums such as the Electronics Sensors and Photonics Knowledge Transfer Network and existing academic research networks is a priority. The TSB will focus on supporting the innovation phase once the technologies are shown to be within sight of commercial exploitation.

Capturing the benefits for the UK revolves around creating bridges between academic research and tangible commercial propositions, ensuring that there is an indigenous eco system of supporting engineering (and other) skills to enable exploitation. The cross fertilisation of ideas and skills through a Special Interest Group (a Quantum Technologies SIG) looks like a good candidate to bring together industry and academic partners from a range of disciplines will facilitate the rapid development of end user applications. Identifying SBRI opportunities would be a sensible step beyond that, as and when the technology is sufficiently mature to support the delivery of real products. TSB anticipate that the early formation of a Special Interest Group. Funding of the SIG in subsequent years would be covered by the Business Innovation programme as described below.

To keep the scope broad to investigate various avenues aligned with the UK strengths, an element of this intervention would be an innovation programme to drive translation of research into application. This first phase of this would take the form of demonstrator challenges to ensure a focus on taking the science through to technology, and identify the technological solutions with the most potential. This would be followed as the technology develops by actions in partnership with the Technology Strategy Board to develop capacity, such as feasibility studies, and we would look to develop an Innovation and Knowledge Centre to provide research space with commercialisation expertise where academic and industrial partners can work alongside each other, with TSBs contribution focussing on business development – recurrent funding to enable companies and academics to work together at the centre. This would provide a platform for subsequent larger innovation investments depending on the direction of the technology and speed of adoption.

The early development of Quantum Technologies demonstrators will enhance business appetite for the potential and push forward the applications. Early discussion with respect to partnering has already taken place between DSTL and NPL on GPS and atomic clocks. Other interested parties will include GCHQ, Nokia, Toshiba, BAE Systems, IBM, Google Inc and D-Wave Systems Inc.

This investment is focused on areas of UK strength where the UK can hold a leadership position. Other areas, where the UK is less strong, will continue to be supported through normal competitive peer review so that the UK can understand technological capabilities that arise and continue to be an intelligent customer.

- **Research capital for AML (£4M Capital) - complementary to EPSRC investment in centres**

The National Physical Laboratory will include a new Advanced Metrology Laboratory (AML) opening in 2017. The AML is designed to have a uniquely stable environment, suitable for frontier quantum metrology research. We are seeking capital funding to ensure the NPL is able to fully utilise the AML to drive forward the measurement science needed for the UK to capitalise on its strengths in quantum technologies.

Establishing the capabilities within the AML on the timescale needed to realise the benefits of quantum technologies will require an additional capital investment of £4m across 3 years from 15-16 to 17-18. This investment will fund:

- **Nanoprobe Manipulation Facility** - unique in the UK, allowing quick and efficient characterization and performance assessment of quantum scale devices without the need for full-scale connections to an external electrical circuit. This has the potential to vastly increase the number of quantum devices suitable for experimentation.
- **Development of a Revolutionary 3D Chemical Microscope.** This instrument uses a focused ion beam with 20 nm resolution to probe surfaces, combined with analysis by mass spectrometry. This novel instrument will enable the surface chemistry of graphene to be imaged including dopants, functionalisation and barrier layers as well as 3D images of the near surface chemistry where substrate impurities are known to degrade quantum device performance.
- **Fabrication and Cryogenic Characterisation for Quantum Devices.** This includes lithography, printing equipment, evaporators, sputtering, deposition and etching equipment for device fabrication. A cryogen free dilution refrigerator will achieve conditions to within fractions of a degree of the absolute zero of temperature and house the delicate experiments required for quantum devices. These experiments will include work on new electronic quantum devices manufactured from graphene, and on devices able to produce electrons or photons on demand for applications in precision metrology and quantum information processing (QIP).

Some equipment is suitable to be built, commissioned and tested prior to relocation in the new AML. The Quantum Technology Infrastructure for the AML will be established most effectively if some of the capital investment is made prior to the completion of the AML building. This is particularly important for the Quantum metrology work where delays in establishing the underpinning capabilities could impact support for the other centres. The profile of investment for NPL line has been amended to spread the capital costs at AML. This has been done to take into account lead time required to build and install the necessary equipment.

Profile of investment

(spend £Ms)	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	Total
High level skills (recurrent RDEL)	12	12	12	12	12	60
Research recurrent	16	16	16	16	16	80
Research capital (EPSRC)	25	20	15	10	5	75
NPL capital	0	1.5	1.5	1	0	4
Science Innovation (EPSRC recurrent)	0	3	5	5*	5*	18
Business Innovation* (TSB recurrent)	0	2	5	10*	15*	32
Total ~	53	54.5	54.5	54	53	269

~ Total for new funding required in Quantum technologies. Does not include figures e.g. capital for Centres for Doctoral Training (see CDT business case), existing £30m EPSRC quantum tech grants and £25m for NPL's Advanced Metrology Laboratory.

+ 15/16 and 16/17 RDEL then depending on technology developments and commercial viability, potential CDEL for 17/18 and 18/19

* Depending upon the success of earlier, smaller, investments

Commercial Case

Some of the technologies emerging in the quantum space are likely to find application in areas highly relevant to the Government interests, for example, in the area of sensors, secure communications, threats to data security from the potentially high computational power of quantum computation (factorising prime numbers) etc. There is the potential for Government to act as a lead adopter to help pull through demand for such technologies, and potentially to help finance their development. It is proposed to explore, within the programme, the contribution that the SBRI programme could make to this agenda.

NPL is extending its quantum metrology capabilities which will be taken forward in the AML as part of its role in delivering the underpinning capability; however this additional £4M capital injection will enhance this and allow alignment with the requirements for supporting the QT centres. As such the QT centres will also benefit from alignment with the existing programme investments BIS makes in NPLs quantum metrology (£4-5M per annum), and supporting capital investment.

Management Case

This intervention involves the establishment of a network of national quantum technology centres and complementary high level skills provision and an innovation programme. These centres would have their own specific foci and need to work together in a coordinated manner. The EPSRC will be managing and delivering the grants, since it has considerable experience ensuring that multiple centres do work together in an integrated way for the benefit of the UK as a whole¹⁷, and would ensure through the terms of our funding that this was the also case for this intervention in Quantum Technologies.

EPSRC will be the majority recipient of the capital and resource funding (£233 million) in this bid, which they would allocate to UK HEIs through a competitive process. They would run a managed call with appropriate criteria to meet the needs of the business case and based on the published principles of peer review (<https://epsrc.ukri.org/funding/guidance/basics/Pages/prprinciples.aspx>). Peer review of bids would be carried out by independent assessors based on standard criteria of quality and excellence, national importance (within a 10-50 year timescale and impact to UK economy and emerging industries) and impact.

We would have more details of the criteria for selection once the overall investment is known and EPSRC has completed its current stakeholder workshops on quantum technology. The call(s) for capital and research programme could be run together or in a series of competitions, published by EPSRC to select the very best centres. Past examples where EPSRC have applied specific conditions to ensure the applications are strategic in nature, for example necessary links and collaboration, requirement for size of existing portfolio (their previous 8 technologies capital call only accepted applications from universities holding grants exceeding £10m in value). This will enable the funding to be allocated to centres of excellence with the existing strength, and build and reinforce this capability and emerging business collaborations.

A new EPSRC centre for quantum metrology is likely to involve partnering with NPL (through a university). EPSRC will interact closely with NPL in order to align their investment with the current plans for the Advanced Metrology Laboratory to extend NPL's quantum metrology capabilities. The new BIS funded Advanced Metrology Laboratory will house the new capabilities at NPL to address measurement problems so critical to successful application of quantum technologies. The plans for this facility mean up to 50% of the researchers will not be NPL staff, but embedded or visiting collaborating researchers not only from the other QT centres but from the research base more widely. This approach is a key consideration in its design and configuration. The National Measurement Office will manage the funding and contracts for AML.

NPL has a track record of delivering this impact from the development of capabilities (with the research base), integration through knowledge transfer, and then support into the economy through calibrations and a realised measurement infrastructure. This infrastructure must be developed for Quantum Technologies and NPL will use the capital investment made here to ensure BIS strategy (through the NMS) to build and support this is realised for the UK so that similar levels of impact are achieved.

¹⁷ Examples include Centres for Innovative Manufacturing and Centres for Doctoral Training.

The TSB will continue to monitor the emerging quantum technologies landscape and would work closely with EPSRC to decide the most appropriate mechanism of support to businesses to ensure that the innovation programme pulls through the most promising technologies. It will establish a new Quantum Technologies Special Interest Group (consisting of existing academic research networks and other KTNs) to steer and facilitate the technology transfer. The innovation programme is expected to be scaled up gradually; from initial demonstrator challenges to feasibility studies as the technology develops.

Annex A – NMO case for additional £4m capital investment in Advanced Metrology Lab at NPL

NPL is the focus of the UK's infrastructure in measurement, a field which is becoming increasingly reliant on quantum technologies. The Advanced Metrology Laboratory (AML) is designed to have a uniquely stable environment allowing frontier quantum metrology research. Construction has already begun on the £25 million lab at NPL. It is expected to reach completion in 2017. When complete, NPL will be uniquely suited to the exploitation and development of quantum technologies. NPL's commercial and legal structure also naturally encourages commercialisation of new technologies and is actively encouraged to participate in knowledge transfer activities with universities and industry across the UK.

There is a need for the equipping of the AML which cannot be met from existing allocations. Establishing the capabilities within the AML on the timescale needed to realise the benefits of quantum technologies will require additional capital investment to supplement NPL's current capital spend. NPL manages its own capital budget, for which the majority is required to ensure the National Measurement Infrastructure is robust and can be consistently delivered (i.e. most capital is spent on the renewal of assets).

The impact of quantum technologies is critically linked to measurement science. Many of the immediate applications of quantum technologies are measurement problems – notably precision navigation/timing and quantum sensing. To enable disruptive quantum-enabled products to reach the market and achieve consumer/regulator acceptance there is a need for an agreed means of:

- Verification;
- Validation; and
- Certification.

NPL's work is a critical part of any infrastructure for quantum technologies: its involvement will support commercialisation through validation and by demonstrating confidence in the performance of these technologies. The AML would be a flagship facility for such cutting-edge science.

The funding of the construction of the AML was met by government with an expectation that NPL would share access with academic and industrial communities. Furthermore, it is essential to the integrity of NPL that facilities such as the AML are collaboratively accessible and populated by academic and industrial researchers and NPL researchers. NPL's ongoing interactions with academia and industry will ensure that this investment will benefit the research base more widely.

The impact of the AML in the field of quantum technologies can be accelerated with investment in some key pieces of capital infrastructure:

Nanoprobe Manipulation Facility. This will be a unique in the UK, allowing quick and efficient characterization and performance assessment of quantum scale devices without the need for full-scale connections to an external electrical circuit. This has the potential to vastly increase the number of quantum devices suitable for experimentation.

Development of a Revolutionary 3D Chemical Microscope. This instrument uses a focused ion beam with 20 nm resolution to probe surfaces, combined with analysis by mass spectrometry. This novel instrument will enable the surface chemistry of graphene to be imaged including dopants, functionalisation and barrier layers as well as 3D images of the near surface chemistry where substrate impurities are known to degrade quantum device performance.

Fabrication and Cryogenic Characterisation for Quantum Devices. This includes lithography, printing equipment, evaporators, sputtering, deposition and etching equipment for device fabrication. A cryogen free dilution refrigerator will achieve conditions to within fractions of a degree of the absolute zero of temperature and house the delicate experiments required for quantum devices. These experiments will include work on new electronic quantum devices manufactured from graphene, and on devices able to produce electrons or photons on demand for applications in precision metrology and quantum information processing (QIP).

Annex B – Categories of quantum technologies and proposed areas of coverage in National Network of Research Centres

- **Quantum Secure Communications:** As the secrecy of quantum communications can be measured directly, it is very useful for distributing secure digital keys on networks. Quantum key distribution is widely regarded as one of the first quantum information technologies with commercial applications. Working systems already exist and are applied to niche applications. The opportunity now is to realise the breakthrough in affordability and network integration that will enable widespread use of the technology. Next generation quantum communication technologies will be based on distributed quantum entanglement. This can be used to create quantum networks that implement more advanced protocols, such as quantum-secure database query or distributed quantum information processing. Here the emphasis should be on the realization of scalable network architectures, low-cost solid-state sources of quantum entanglement and devising new protocols and applications.
- **Quantum Metrology:** Measurement underpins commerce; the definition of standards for trade and industry is the basis for a thriving economy. Next generation metrology capabilities will be based on quantum phenomena, and will deliver new standards for time, frequency, length, charge and other key fundamental measures. These will have immediate important applications, such as miniaturized, robust, atomic clocks that can act as "fly-wheels" for GPS. These will enable better standards for rapid electronic stock trading, for instance, as well as new navigation opportunities. Further, new measurement methods and devices derived from quantum metrology approaches and new methods for certification of such techniques and instruments, will enable validation of other Quantum Technologies, such as detectors for quantum sensors and register readout measurements for quantum computers.
- **Quantum Sensors:** Sensors are now ubiquitous, but are often limited by their precision, size and efficiency. Quantum sensing technologies harnesses the advantage given by quantum systems to provide measurement precision beyond conventional methods. This approach will enable sensors to be deployed that can detect at the single molecule level; that can sense ultra-weak electromagnetic and gravitational fields with unprecedented precision. These sensors will provide new paradigms for healthcare and medical imaging technologies; security and environmental monitoring; and manufacturing of high value materials.
- **Quantum Simulators:** The modelling of real molecules or materials at the atomic scale is key to technological problems ranging from the interaction of drug molecules with their targets, to the nature of high-temperature superconductivity. This modelling relies on quantum phenomena at the chemical scale and is very difficult using purely classical computers, because the effort required to achieve a reliably accurate result scales very rapidly (in fact exponentially) with the size of the system. In the long term a full quantum computer could perform this simulation exponentially more quickly on any target quantum system. However in the shorter term significant gains could be made by engineering well-controlled quantum systems whose behaviour mimics the specific system under study, either in an analogue fashion or through a digital simulation. Promising quantum systems to use as the 'mimic' include trapped atoms, ions or molecules, multiple photons interacting via linear optics, superconducting circuits, or electron spins in solids.
- **Quantum Computation:** Quantum physics offers the possibility of a computing engine capable of solving problems that are completely intractable on current and future generation conventional hardware. The hardware required to build such a computer would also deliver revolutionary capabilities for other Quantum Technologies. Quantum computation encompasses all elements of the field, from foundational studies of the generation, manipulation and utilization of entanglement and other quantum correlations, to development of hardware and components with the properties needed for fabricating a true quantum computer.

Annex C - Note of the Quantum Technologies Roundtable, 4th July 2013

Why act now?

This meeting between industry, researchers and government organisations highlighted the UK's competitive position and the willingness to work together in a national endeavour to translate scientific leadership into economic benefit. The disruptive nature of quantum technology means that existing businesses would not necessarily be able to adopt these technologies into their current business.

Recent rapid developments in quantum technologies, including the sales of the D-Wave Two quantum computer¹⁸ and commercial quantum cryptography systems, have brought to the fore the potential disruption that harnessing quantum technologies could offer across a broad spectrum of applications and potential commercial growth as highlighted by the investments our competitors are making in this area – Switzerland, Canada and Singapore are making significant investments.

Quantum technologies offer the prospect of very disruptive impact and the ultimate improvements in precision, sensitivity, accuracy, speed and security that the laws of physics allow, in a range of areas, from secure communications, metrology, sensors, simulation, to information processing and computing. The UK has a strong position with regards to patents in areas such as quantum computing and quantum cryptography.

Why the UK?

The UK has played an international role leading the research base in quantum physics – now is the time to move beyond physics to seize the potential of quantum technologies for the UK. We have some unique and complementary centres of excellence each of which enjoys strong links to potential industrial or user organisations. The UK also has a strong position with regards to patents in this area.

At the meeting, [REDACTED] summarised the UK's strengths which can contribute to quantum information science and technology being turned into applications and industries. He laid out the reasons why the UK environment is highly conducive to this, stressing the strengths throughout the UK academic research landscape across the range of potential quantum technologies i.e. quantum computing, cryptography, sensing, metrology, imaging and quantum information processing. He also highlighted the areas which can contribute to advances in science being transformed into advances in technology and engineering, such as photonics, semiconductor optoelectronics, high frequency electronics, computer science and communications.

Representatives from NPL, DSTL Nokia, Toshiba Research Europe and BAE Systems were all able to explain the threat or opportunity that their business saw from the rapid advances in quantum technology, an area that was progressing much faster than any of them had anticipated; the recent product launch of D-Wave Two system being one such example. Importantly, there was an immense breadth to potential impact of quantum technologies, ranging in their maturity levels.

Future workforce

Critical to the exploitation of quantum technologies, will be the supply of highly skilled people. This is an area that is really exciting young people with the demand from undergraduates of the highest quality to undertake PhDs far in excess of available opportunities. Increasingly business, if adopting quantum technologies will need quantum engineers who can simplify and enhance the robustness of quantum devices and systems. This is being recognised in Europe with this area being a priority for Horizon 2020. The UK can deliver these highly trained individuals through its world leading institutions in tertiary education.

¹⁸ D-Wave sells second quantum computer – this time to NASA (Physics World, July 2013)

Requirements to realise the promise

- expand this group and collaborate further to promote the opportunities for quantum technology;
- effort to build on and take advantage of the strengths in quantum science and technology that are distributed across the UK;
- focus on agreeing and addressing the key technological research challenges that need to be overcome to enable the development of effective quantum technologies, to ensure that the science is taken through to technology and engineering;
- exploit common ground with other research areas, which can support progress in the development of quantum technologies, and which the UK has strength;
- foster links with industry and other partners in order to build an understanding of the potential and of the capability needed, to deliver a platform of opportunities for the UK;
- the provision of state of the art equipment and facilities is essential to maintain and further develop UK research strengths in quantum technologies;
- exploit the high level of interest in quantum technologies, particularly through the supply and training of highly skilled individuals into this area;
- connect UK efforts in quantum technologies through information sharing and community building activities, in order to make this a national network.

Next Steps

By the end of September 2013 we will have explored the formation of a network of quantum technology centres which take account of the key points described above and will send the Minister a forward plan of action. The participants of this round table discussion all agreed to be involved in these deliberations and to share quantum technology roadmaps where they are developing these.

Appendix 1: Discussion

The discussion prior to the arrival of David Willets, Minister for Science and Universities, started with a focus on the UK's strengths in quantum technologies, the barriers that need to be overcome, and efforts of competitor countries.

In answer to the question on UK strengths in quantum technologies, these were described by participants as being in quantum theory, and according to patent information, in quantum computing and quantum cryptography. With the UK strengths in semiconductors and photonics research stressed as being important for taking the science through to technology. In addition, UK capabilities and expertise in precision timing and metrology were highlighted as being important to UK industry. It was also stressed that the UK has a broad platform of expertise academically and strong training environment which is attractive to high quality students.

In response to the question on barriers preventing the development of quantum technologies the underutilisation of sophisticated industrial and university facilities in micro and nano-fabrication were noted. An important barrier noted was as the requirement to get engineers to understand the potential of quantum technologies and what is needed to deliver them. The need to bring a range of academic research communities and industry to develop and exploit key capability was described. A strong interest in this happening was noted from the Dstl and NPL.

In answer to the question on what our competitor countries are doing, significant investments by Switzerland, the US, France, and China were noted. The US government support of the company D-Wave, who have made a quantum computational system was described in particular. In the case of France, the production of atom interferometers which exploit quantum superposition, after 15 years or research was noted, while in China, the integration at a government and commercial level was highlighted.

The discussion then focused on what the UK can do, and a range of points were raised.

Firstly, the need to find niche, specialist markets and applications, to get the products developed and platforms which can built on was described. Which it was stressed required up skilling to develop technologies and a down skilling of the technology itself to make it accessible to users. These initial technologies should be used to develop supply chains.

Developments in areas such as the Internet of Things, big data, smart energy networks etc. where there will be deluge of data from multiple, connected devices, should be used to drive applications in security. In addition, the need to make sense from large amounts of data in an energy efficient manner can be used to drive progress on quantum information processing. The importance of approaching such sectors as finance to assess their needs was pointed out.

The large market in the UK for precision location and timing services, particularly for precision navigation was highlighted as an important application area. It was reported that Dstl and NPL are running a study on what is possible in this application area, which brings together academia, industry and end-users.

BAE Systems described the overlap of their interests with Dstl, and that they now see quantum technologies as much closer to market than they did only a few years ago. Noting that the purchase by Lockheed Martin and Boeing in D-Wave's system is an indicator that the technology has real prospects. The need for the UK to have a capability was stressed, as we cannot rely on technology being shared by the US, and competitive advantage will otherwise be lost.

A timing window was described, which won't last long. In connection with this it was noted that currently there is a high level of interest from students to study this area in the UK. This was described as an opportunity that shouldn't be missed to develop highly skilled people for this area.

In response to the question on what the potential is for the UK, the intellectual property landscape was described as being well populated in the areas of cryptography, communications, sensors and computing, with the first spin-offs being in the area of metrology. It was stressed that potential is there, but more opportunities will arise. More communication with end users was noted as a key requirement for this to happen, with there being the potential to use demonstrators to draw people together.

A key message that was given was the need to maintain breadth and depth of expertise. It was noted that picking the correct approach is extremely difficult, as shown by the approaches which have failed and those that have been successful. It was stressed that linking the science to engineering was one of the first things to address. The efforts by NPL to link to industry and training in this area were noted as a part of this. The need to use the networks that exist in the UK and maintain a research base that can deliver progress on quantum technologies was highlighted.

Following the arrival of David Willets, Minister for Science and Universities, [REDACTED] summarised the discussion so far as:

- that the UK has an academic research lead in several areas;
- industry investment in other countries is being made now;
- there is a need to be able to build a community between academia, industry and government;
- quantum technologies are very attractive to young people.

[REDACTED] then summarised the current UK position in quantum technologies. He described why the UK environment is highly conducive to this, and stressed the strengths across the UK academic research landscape in quantum computing, cryptography, sensing, metrology, imaging and quantum information processing. He highlighted the areas which can contribute to advances in science being transformed into advances in technology and engineering, such as photonics, semiconductor optoelectronics, high frequency electronics, computer science and communications.

Following on from this, the capability of NPL in atomic clocks, was described, which led onto its projects on precision metrology for precision navigation and timing on a 5-10 year timescale, with civilian and defence applications. The advantage of these instruments will be through quantum technologies giving them a much smaller physical footprint.

[REDACTED] explained Nokia's perspective that quantum technologies can have application in computation moving to the cloud, multiple connected devices that want to access data anywhere, and multiple the sensors everywhere, the so called internet of things. He noted deluge of data, keeping it secure, and interpreting it a meaningful way. He stressed that classical computing can tackle these but would consume large amounts of energy and money in doing so.

[REDACTED] from the Intellectual Property Office explained that there are small but significant and sustained levels of patenting activity in quantum computing and quantum cryptography (worldwide), with the UK comparatively well represented. He noted that (worldwide) patent application data shows that a large portion of the inventors named on patent applications in these areas are resident in Europe, and within these, half are resident in the UK.

The connections between prospective quantum technologies were described as now pointing towards a whole new industry, with new technology platforms. In addition the connections to companies in the UK which can contribute to the development of this industry and form and support a supply chain were clarified.

[REDACTED] from Toshiba Research Europe, reported that they now have a quantum technology prototype system for detecting the tapping of fibre communications. The motivation behind this was explained that most information is now shared over networks. He noted that the system is being demonstrated at Royal Society Summer exhibition where the minister would be able to see it.

[REDACTED] from BAE Systems explained that major competitors and customers are now buying and investing in quantum technologies, which they see as a game changing development. The view of Dstl and BAE Systems was that quantum technologies are now much closer than originally thought. [REDACTED] from Dstl expanded on this, by commenting they are looking at how they can drive forward timing, sensing and cryptography. They are conducting collaborative work with NPL on timing for niche benefits in the defence and wider market.

The Minister summed up the discussion, stating that he accepted that the advice of the participants at this round table discussion will be key for taking quantum technologies forward in the UK. He acknowledged that EPSRC has nurtured the area with funding and asked how can we create a more cohesive community.

██████████ explained that everyone present was committed to taking this forward. The Minister asked if is this an opportunity for the TSB and does this area require capital kit and facilities.

The roundtable participants explained that there is a need to ensure underpinning infrastructure at universities and industry and that state of the art fabrication facilities are used, together with the new £25M measurement laboratory at NPL. The potential for precision timing to be an initial focus, with the inclusion of training, was raised.

The Minister asked what quantum technologies adds with respect to precision timing over current atomic clocks, and it was explained that it would give additional precision and some devices would have a much smaller footprint and be so more portable and more widely used. It was explained that currently there are devices that could be carried on a submarine to extend the time between it confirming its position using GPS, but that these could not be carried in a soldier's backpack. Such a development was described as giving advantages in resilience if GPS infrastructure is lost, which is a credible threat due to the availability of low cost GPS jamming technology. The existence of a range of non-defence applications was also noted for this potential technology.

The minister asked what interested the TSB with respect to quantum technologies, which ██████████ was not yet, but that there is potential to take through some niche applications and then expand from these, by taking advantage of the skills and capability that will have developed.

The Minister also asked if there is other capital investment needed besides that at NPL. In response the need to bring together research and user communities to map out the capital requirements for next 5 to 15 years was explained. The importance of maintaining breadth and depth in the research bases was stressed, because of the complementary areas needed to take the science through to technology and applications.

The geographical co-location of academic research and industry strength in this area was described as being very good in UK. With the opportunities to make local and national connections stressed. Further to this it was explained that the UK should build on its strengths and focus on a number of areas with potential, but not restrict itself to only one approach to quantum technologies.

It was explained that industry and academia working together was essential and facilities were needed where that can happen. For instance labs alongside each other where different types of expertise can be brought together in a complementary fashion. It was further clarified that these would require a range of types of capital items to support the range of the research into quantum technologies. It was noted that these often take the form of electronic diagnostics equipment and are on the order of £100,000 and can be purchased from existing suppliers.

The Minister clarified that it was expensive labs but not expensive unique labs that need to be built. In response it was explained the need was to keep instrumentation state of the art, and the need for fabrication facilities, characterisation, and measurement.

The role of Europe and Horizon 2020 was discussed, and it was stressed that quantum technologies is now in programme, together with microelectronics.

The participants also explained that the investment in skills and training was very important for the development of a quantum technologies industry in the UK, together with the involvement of industry in this training. Alongside this it was noted that Royal Society Fellowships are oversubscribed in the area of quantum technology, demonstrating the potential for the UK to attract high quality individuals into this area.

The Minister finished by expressing that he liked the argument that this is disruptive technology and big advances mean that the scale is reset and incumbents in current technologies do not enjoy a clear advantage.

At this point the Minister left the meeting and the discussion turned to next steps. The Minister's interest in galvanising efforts in this area was noted, as was the need for the landscape to be mapped out.

Dstl offered to share the roadmap they have started building from security perspective on quantum technologies. BAE Systems explained they are currently drawing up the plan going forward and aligning quite closely with Dstl. [REDACTED] explained that Nokia do not have a roadmap but that they can share some of their non-confidential thinking on this area. Building on this, it was agreed that it is important to take this area beyond the physics department.

With respect to capital it was noted that:

- We need scoping exercise
- In 2013/2014 there was £500m to invest in scientific capital and this is going up to £1.1billion
- The Minister needs to get announcement out – we need leverage
- There needs to be a case in quantum technologies on what capital is needed in science base to keep UK competitive
- The approach should be to secure the funding and distribute based on more detailed proposals submitted from academia.

There was discussion on the geographical distribution needed. It was agreed that this couldn't be placed in a single centre as this would not give satisfactory access to academic researchers and industry across the UK. It was also stressed that one centre is not sufficient to nurture the range of ideas in quantum technology, but that there needs to be some facility for students to meet to train on equipment.

Building on this point, it was noted that capital bids should be made alongside the Centres for Doctoral training bids that are being considered at the moment so that there can be the effective delivery of skilled people. As a consequence it was acknowledged that the outcome of this completion will influence the funding landscape.

With regards to timeframe it was agreed that by the end of September 2013 we should have a proposal to submit with a view to this area being announced as the 9th great technology. It was stressed that main ask is to keep science stable and to fit this with capital and other funding. It was stressed that in the meantime researchers should still apply for funding from EPSRC in this area. It was noted that there is some anxiety amongst applicants about making submissions in this area which take the science through to technology, which can be addressed to some extent by the participants being protagonists for this.

It was acknowledged that the key technological challenges need to be thought out and put to both the scientists and the engineers. With an effort made to draw researchers from the different communities together, by exploiting areas where there is a co-location of interest.

It was also recognised that some work between EPSRC and TSB to explore how to generate interest from industry was needed.

Appendix 2: Attendance List

David Willetts, Minister for Universities and Science

[REDACTED], Director EPSRC (chair)
 [REDACTED], University of Bristol
 [REDACTED], Oxford University
 [REDACTED], Heriot Watt University
 [REDACTED], University College London
 [REDACTED], Imperial College
 [REDACTED], Nokia Research Centre
 [REDACTED], Toshiba Research Europe
 [REDACTED], BAE Systems
 [REDACTED], Dstl
 [REDACTED], NPL
 [REDACTED], IPO
 [REDACTED], TSB

Officials present

[REDACTED], BIS
 [REDACTED], BIS
 [REDACTED], EPSRC
 [REDACTED], EPSRC
 [REDACTED], EPSRC

