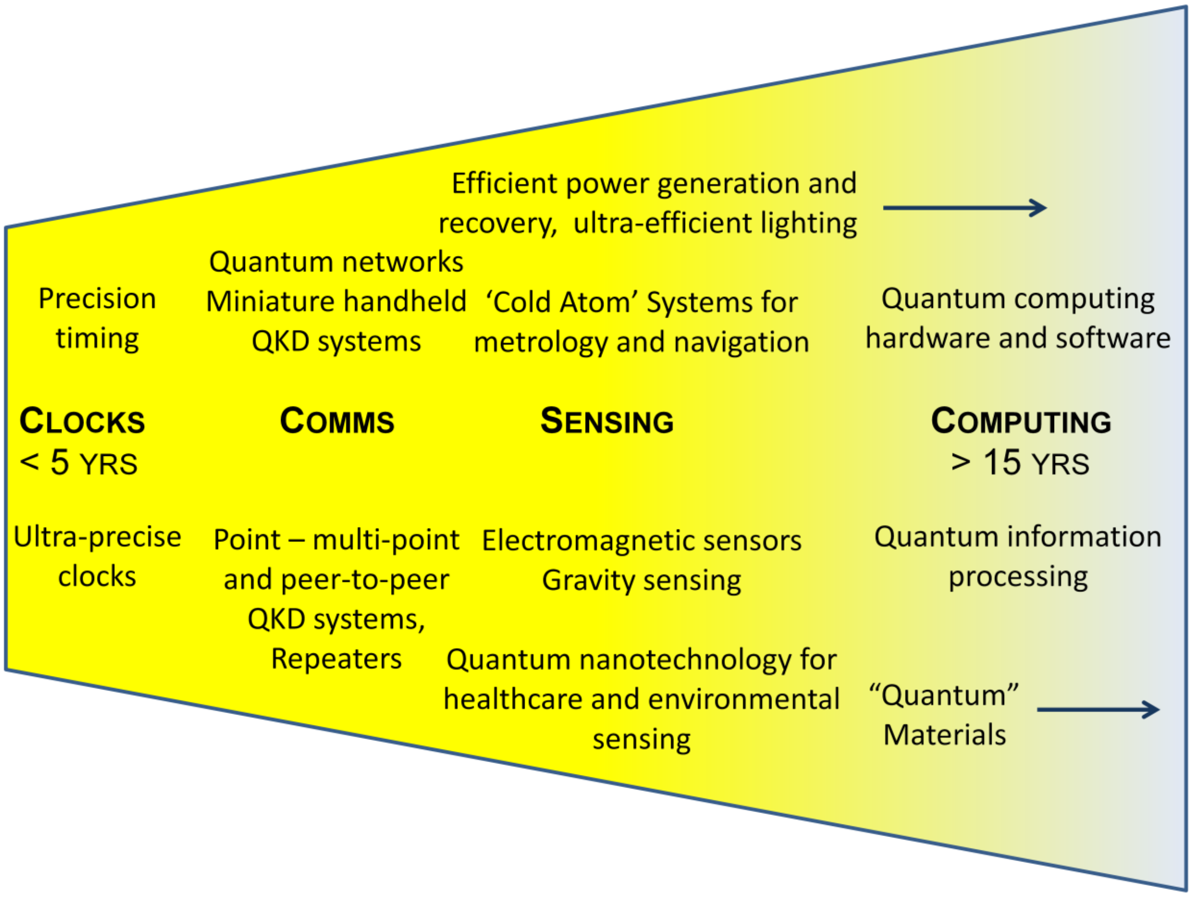
UK Quantum Technology Landscape 2014



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Final Version
14/02/2014
UNCONTROLLED

DSTL/PUB75620

UK Quantum Technology Landscape 2014

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1. Executive summary

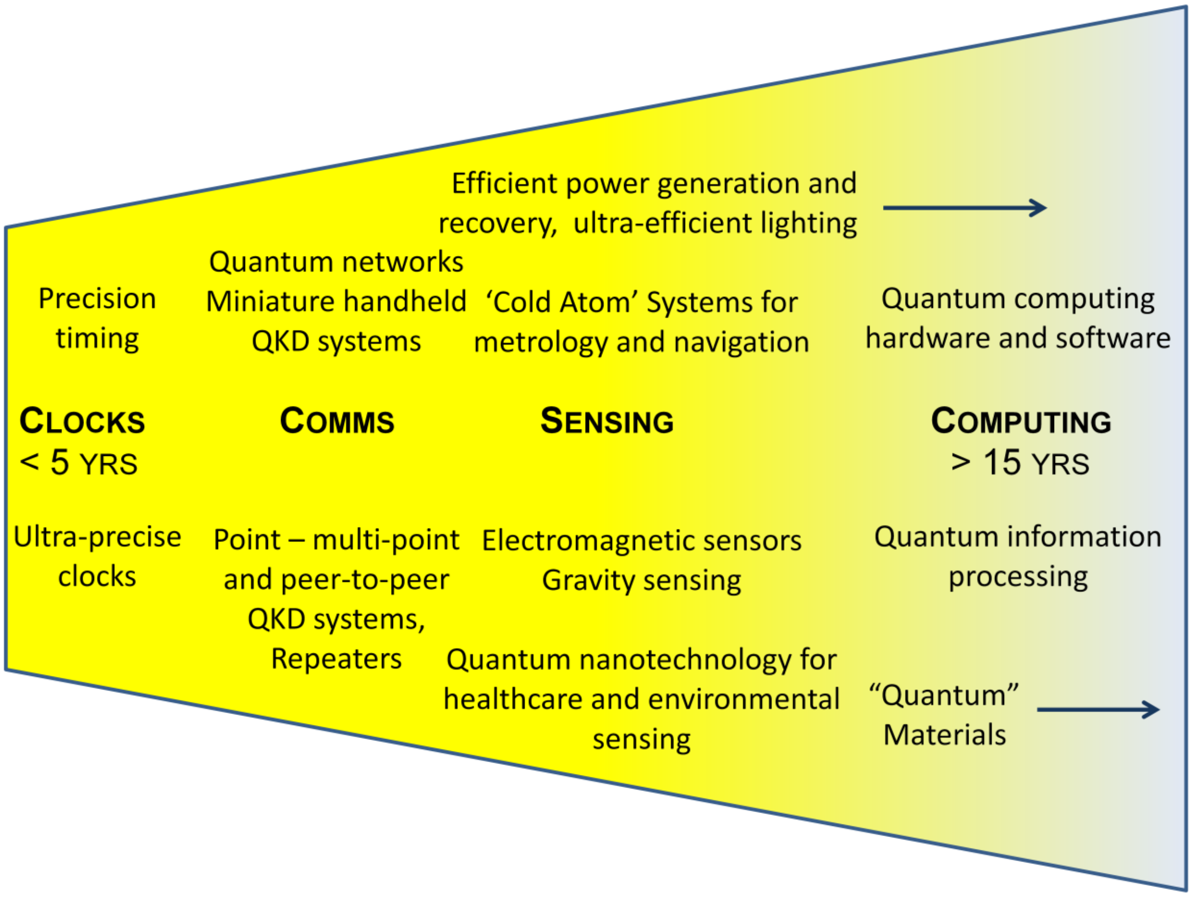

Figure 1 Top level view of quantum technology landscape

This document is a contribution, by DSTL, to the national effort to realise the benefits of quantum technologies as seen through the lens of defence and security.

Quantum technology is technology derived from science that cannot be explained by classical physics, such as Newton's Laws of motion, thermodynamics, and Maxwell's equations for electromagnetism. Many of our existing technologies (such as microprocessors, nuclear power, solid state imaging devices and lasers) are derived from quantum physics and are now quite familiar. We have labelled these as "quantum 1.0". Just as classical physics underpinned the Industrial Revolution, the technologies created by quantum 1.0 have underpinned the Information Age. The emerging quantum technologies that rely on the more subtle, less familiar aspects of quantum mechanics we have labelled as "quantum 2.0". The technologies enabled by Quantum 2.0 have the potential to create a "second quantum revolution".

The MOD Defence Science and Technology Laboratory (DSTL) has undertaken a detailed analysis of the UK quantum technology landscape[1]. We have read and understood the contents of the Witty report[2], which we find informative, and await the response of Government. In partnership with the

[1] DSTL/PUB75620
[2] See "Encouraging a British Invention Revolution: Sir Andrew Witty's Review of Universities and Growth"

Royal Society, DSTL organised a meeting of leading academics, representatives from Industry and relevant government departments at Chicheley Hall from 10-13 November 2013 to develop the evidence base for this analysis . The attendees were selected to enable to the meeting to explore how the UK might exploit emerging quantum technologies for the benefit of defence, security and the wider UK economy. The output from the meeting has been used to refine the quantum landscape document and to develop quantum technology roadmaps and outline development plans.

Our review of quantum technologies and their applications has fallen mainly into the following categories: quantum clocks, quantum communications, quantum sensors, and quantum simulation and computing. We have also considered underpinning and enabling technologies, and some of the most important molecular and solid state advances that have the potential to be economically or sociologically very significant.

In the defence and security domain we conclude that large scale digital quantum computing capability is not likely to become available within a 5-15 year time frame. However, the field is advancing rapidly and our assessment could change. We need to be wary of technology surprise, and recognise that early analogue machines or hybrids could be made to perform valuable functions on a shorter time scale.

In the longer term, research in quantum computing, networks and information processing are expected to become immensely important. That will likely include aspects that we do not yet comprehend; the situation is similar to that of classical computing in the 1950s. in the meantime our world class academic teams will need continued support and encouragement to reach their goals.

Quantum technology offers a new and elegant means to provide secure communication and key distribution but it only addresses a part of the security challenge that modern complex systems face. Therefore, to understand the overall impact that this technology will have upon system security the subject requires further research. However, the quantum technology involved is relatively mature. Many of the components, such as the photon sources and detectors, may also have wider applications in the future quantum programme.

Precision timing and navigation could benefit immensely from quantum technology, and suitable development would have widespread disruptive impact on these domains. Likewise, quantum sensors, especially gravity sensors, if suitably developed, are likely to have significant impact where a step change in sensitivity or additional modalities could be realised. More work needs to be done in this area to define the systems that would deliver the most benefit.

In the commercial domain, we foresee that ubiquitous quantum optics could deliver miniaturised, secure communications systems and sensors into mass markets. There would be specialist applications for chip scale clocks and gravity sensors, extending to mass markets in the financial, civil engineering and geophysics domains as price, size, weight and power is reduced. There will be many scientific applications for most aspects of quantum technology, including a worldwide market in common sub-components as the systems are developed and refined. Advances in healthcare,

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www.gov.uk/government/uploads/system/uploads/attachment_data/file/249720/bis-13-1241-encouraging-a-british-invention-revolution-andrew-witty-review-R1.pdf environmental sensing, and energy technology will be enabled by quantum sensors and quantum nanotechnology. These will have immense impact on the economy and society.

Our conclusion is that we see the most promising threads of development for investment as being:

- Precision timing and clocks
- Gravity sensors (ultimately including gravitational mapping or "imagers")
- Quantum optics, for example to realise miniature, handheld QKD[3] systems for ubiquitous commercial applications or chem/bio sensors. The technology will also be applicable to quantum information processing and quantum networks.
- Metrology and navigation using "cold atom" systems
- Electromagnetic sensors
- Quantum nanotechnology implemented on a large scale for power recovery and generation, environmental sensing and efficient healthcare
- For the longer term, investment quantum simulation and quantum computing should continue

The quantum technology partnership established at the Chicheley meeting is now ready to help MOD prosecute this strategy and engage fully in the activities necessary to realise this vision.

Many of the processes and skills that the UK will need to ensure success are not part of the initial discovery and development activity, but are essential for efficient and effective exploitation. These include:

- Leadership, vision and governance
- An understanding of technology readiness, likely system constraints and user needs
- Skills in transitioning science to technology and system engineering
- Progressive programme and project management
- Dynamic risk management
- Management of intellectual property
- System engineering, interoperability and standardisation
- A suitable collaborative landscape incorporating Government, industry and academia
- Identification and preparation of suitable markets

[3] QKD = Quantum Key Distribution, for cryptography

2. Introduction

Novel quantum technology is at the forefront of scientific and technical development and is derived from the latest advances in physics.

Its realisation holds the promise of game changing advantage in defence and security domains, and the possibility of significant wealth creation in the UK economy.

This document generates a top level, strategic view of quantum technologies in the UK and their potential to deliver operational and economic benefit. We also generate a strategy that will answer specific questions and show the way forward. The questions are:

1. How and where will we obtain advantage from quantum technology in the UK for defence, security and the wider UK economy?
2. Which specific areas should we encourage, and how?
3. Where and how should the available resources be used?

This paper is a precursor to more detailed work in the form of specific roadmaps and outline development plans for key quantum technology threads. These are being generated now that the Chicheley meeting has taken place. The intended audience for the final version of this report and subsequent roadmap studies consists of interested parties in industry, MOD, BIS (especially TSB), and other Government departments, agencies and academics.

Our vision is that quantum technologies will become game changing differentiators for UK defence and security over a 5-30 year time scale, and that their development will become a multi-billion pound industry that will benefit the UK economy over the same period.

We begin by defining what we mean by "quantum physics" and the principal emerging technologies of interest. The technical detail will be kept shallow so that it can be understood by people who may have a light technical background or are perhaps not experts in the field[4]. We will then discuss some applications of those technologies under the headings of "defence and security", and "industrial, personal and scientific".

For the sake of brevity we have avoided any detailed discussion of nanotechnology. Nanotechnology does overlap strongly with quantum, but it is an extensive subject in its own right.

Then, we discuss research in the UK. From this, we derive a technology strategy aiming to deliver value, economically as well as via defence and security capability, by identifying the themes that are most likely to generate the greatest impact and economic benefit on a "reasonable" timescale i.e. 5-15 years.

We also address the non-technical (but crucially important) issues associated with the development and exploitation of these novel technologies. Resolving them is an essential part of delivering the benefits, and is at least as important as the R&D. The result is a framework in which to construct a

[4] The main arguments will not be lost by skipping the detailed reviews in section 4.

meaningful programme with the highest probability of success. Finally, we summarise our conclusions and make recommendations.

3. Overview of quantum technologies

3.1.Quantum physics

Quantum physics can be succinctly described as physics that can't be described by classical laws such as Thermodynamics, Maxwell's equations of electromagnetism and Newton's laws of motion. Most of it derives from the fact that light, matter and energy is quantised, i.e. there is a smallest unit of each, known as a "quantum". For example, the unit (i.e. quantum) of light is a photon, and its energy depends on its wavelength. Objects also exhibit wave-like behaviour, e.g. atoms and molecules can diffract and exhibit interference patterns. We are familiar with the concept of an atom being the smallest unit of everyday matter, however, ensembles of atoms can exist as a continuous "matter wave" at ultra-low temperatures. Generally, these phenomena are referred to as "wave-particle duality".

The fundamentals of "quantum mechanics", i.e. wave (or matrix) mechanics, was developed during the 1920s and led to a deep understanding of such areas as nuclear physics, atomic, molecular and solid state physics, and the detailed interactions between light and matter[5]. The central 60 years or so of the 20th century gave rise to the area of quantum science often referred to as "quantum 1.0". Just as classical physics underpinned the Industrial Revolution, so quantum physics (quantum 1.0) has underpinned the PC, the information revolution, the internet and the World Wide Web.

From the beginning, it was widely recognised that there were paradoxes and effects arising from quantum physics that are counter-intuitive. They could not be explained in any familiar (classical) framework except via the mathematics used to describe quantum behaviour. The implications of these effects have gradually begun to be understood, and they have become the source of quantum science often referred to as "quantum 2.0". Some of these are, for example:

- Quantum superposition, a fundamental form of ambiguity. A micro- or nano- scale object can be in two or more places, or assume more than one value of any internal variable, at once. It is often assumed that the effect fades rapidly with increasing size, as classical laws take over, although this has not been definitively proved. Superposition ceases almost instantly when there has been any interaction with the environment as that represents a "measurement". Superposition seems to be impossible to achieve with macroscopic objects such as chairs, tea cups etc. However, experiments that are demonstrating the effect using objects of increasing size are ongoing, with increasing success - at least up to the ~100µm scale. The exact nature of the "transition" from the quantum to the classical regime, if there is any general mechanism, remains poorly understood and is a subject of great interest[6].

[5] This subject is known as quantum electrodynamics (QED)
[6] See for example http://www.sciencedaily.com/releases/2013/09/130909092835.htm

- Quantum entanglement. Widely separated objects (in time as well as in space) can possess correlations beyond their intrinsic (classical) ability to store information in their internal variables e.g. spin, polarisation etc. A measurement of one will define the state of the other, while it can be proved that no information has been exchanged and that no internal register of "which way round they are" (known as hidden variables) exist prior to the measurement.

- The quantum Zeno effect. Repeated measurement of the state of a quantum object resets its state. It is unlikely to evolve in the manner that it would had the measurements not been made. This is roughly analogous to the notion that "a watched kettle never boils". This can prevent an unstable system from decaying. (There is also an "anti-Zeno effect", which can be observed under certain conditions where the probability of transition is increased.)

- The vacuum is not empty. The contents have been referred to as a sea of activity, consisting of all possible fields and their associated particles at a level below our ability to measure them (i.e. the fundamental "uncertainty limit"). A certain level of experimental proof has been obtained (for example the Casimir effect). The uncertainty limit allows energy to be "borrowed" for extremely small periods of time; this is necessary for many fundamental interactions in particle physics to take place.

3.2. Quantum technology

The insights gained from the original advances in quantum theory ("quantum 1.0") have resulted in many of the technologies that are familiar to us today. Some of these are:

- Nuclear energy;
- Solid state electronics (and hence integrated circuits);
- Lasers;
- Digital cameras and other imaging devices such as some types of thermal imager.

However, although the boundary between quantum 1.0 and 2.0 is not sharp, we will emphasise quantum 2.0 technologies, i.e. those that arise from our understanding of deeper manifestations of the quantum world. Most of these rely on the effects outlined in section 3.1.

4. Technology areas

4.1. Introduction

For convenience, we have divided the major technologies into four groups categorised by value-adding applications that correspond to the paradigms we have for classical systems. However, we should recognise that many of the systems that form these new technologies share common physical principles and are not fundamentally separable. We have chosen (in order of maturity):

- Quantum clocks
- Quantum communications
- Quantum sensors
- Quantum computing, quantum simulation and quantum information processing

We have also considered underpinning and enabling technologies, including fabrication, and solid state and molecular topics where they are of particular economic significance. Unique materials with particular properties, fabricated into hybrid structures on multiple length scales, will result in new devices for research, defence, security and commerce within the next decade. That will pose multiple challenges from materials science through to engineering.

A complete exposition of *all* quantum technologies and their applications, especially the ramifications of nanotechnology, is beyond the scope of this paper and would be unnecessarily long. However, we aim to cover key areas using suitable examples and discuss general issues, challenges and applications. We also indicate UK strengths and weaknesses in each area.

4.2. Quantum timing and clocks

4.2.1. Introduction

The operating principles of atomic clocks lie in atomic physics and (mostly) make use of the electromagnetic radiation that electrons in atoms emit or absorb when they change energy levels[7]. Early atomic clocks are quantum 1.0 devices but the most recent developments are making use of quantum 2.0 effects, however, and we would like to consider significant advances in all species of atomic clocks. Early (microwave) atomic clocks made use of electronic transitions corresponding to frequencies in the microwave region of the electromagnetic spectrum. More recent optical atomic clocks use transitions associated with the optical (visible) part of the spectrum or even the UV (Ultra-Violet).

The central importance of precision timing has been increasingly acknowledged in recent years. The Royal Academy of Engineering (RAE) has warned[8] that many sectors of today's industrialised society are now “dangerously over-reliant” on navigation and timing signals from satellites. The vulnerabilities could arise from active jamming devices or natural phenomena such as solar storms[9]. Global navigation satellite systems (GNSS) are used in many sectors of the civilian economy; examples include emergency services, shipping and air transport, railways, agriculture, data networks and financial systems. The RAE report estimated that around 7% of the UK economy is dependent on GNSS; furthermore, the report anticipates that this proportion will grow rapidly in the coming years. In the report on the potential effect of solar storms, the RAE recommends that “all critical infrastructure and safety-critical systems that require accurate GNSS derived time and or timing should be specified to operate with holdover technology for up to three days.” The Financial Times highlighted the publication of both RAE reports, illustrating the relevance to the UK business community.[10] The availability of precise timing to the military is also of immense importance.

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[7] A good introduction to atomic clocks http://resource.npl.co.uk/docs/networks/time/meeting10/curtis.pdf

[8] [4] “Global Navigation Space Systems: reliance and vulnerabilities”, Royal Academy of Engineering, March 2011. ://www.raeng.org.uk/news/publications/list/reports/RAoE_Global_Navigation_Systems_Report.pdf

[9] “Extreme space weather: impacts on engineered systems and infrastructure”, Royal Academy of Engineering, February 2013.
http://www.raeng.org.uk/news/publications/list/reports/space_weather_full_report_final.pdf

[10] http://www.ft.com/cms/s/2/68d0eb1c-48ee-11e0-af8c-00144feab49a.html#axzz2kXDonY63;
http://www.ft.com/cms/s/0/f30d9e54-7067-11e2-ab31-00144feab49a.html?siteedition=uk#axzz2kXDonY63

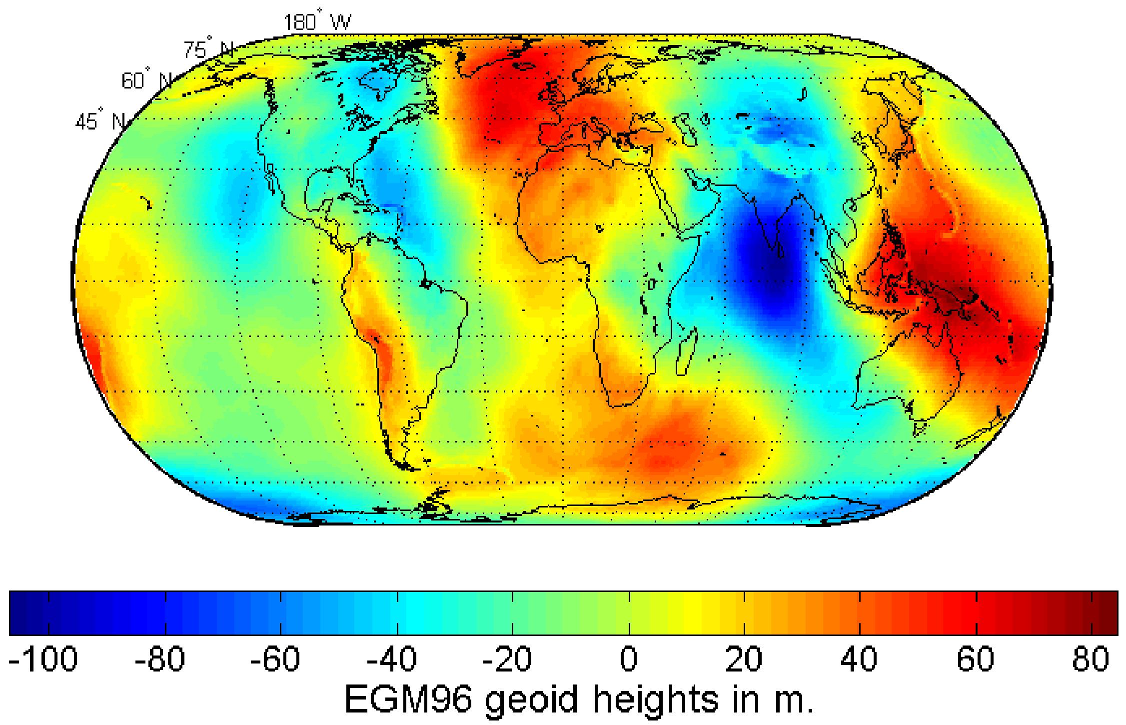

Figure 2 Map of the gravitational potential found at the Earth's surface

Atomic clocks are widely regarded to be precise and accurate. Precision relates to the rate of "ticking" of the clock which is provided by the natural frequency of the electronic transitions in the atoms used. Higher frequencies allow time to be divided into smaller units, thus optical clocks are more precise ("tick" more frequently) than microwave clocks. The accuracy of a clock is related to systematic errors in its operation and the degree to which these errors can be successfully corrected. These errors include factors due to atomic collisions, the Zeeman effect of magnetic fields, interaction with black body radiation and the Doppler effect. All of these change the energies of atomic states in small but quantifiable ways, the biggest effects usually being caused by magnetic fields or black body radiation.

Finally, General Relativity causes a difference in the flow of time (a height reduction of 1 metre at "sea level[11]" is approximately equivalent to a 10^{-16} change in frequency) which must be accounted for at these levels of accuracy. The stability of a clock, its capability to deliver a frequency reference unchanging over the specified time interval, is a measure of the tendency of a clock's rate to vary, perhaps because of a changing environment. The expression of accuracy as "1 in 10^x" is a very loose measure which we will use for the purpose of this report. In practice, there are many factors to be considered, such as jitter, long term accuracy and other measures of stability.

[11] Sea level is a very poor description of the gravitational field strength used to allow an intuitive understanding here. The difference in clock rates depends on the difference in gravitational potential.

4.2.2. Technology development and accuracy of atomic clocks

The idea of using atomic transitions in sodium and hydrogen atoms to measure time was first suggested by William Thompson, later Lord Kelvin, and Peter Guthrie in 1879 before the Bohr model of the atom had been proposed. The basic concepts were later developed during the 1930s and 40s by Rabi resulting in the suggestion of a practical method in 1945. His concept was to use hyperfine[12] atomic transitions in the ^{133}Cs atom at the microwave frequency of 9.1914 GHz. However, the first atomic clock demonstrated was an ammonia maser device built by Lyons and co-workers in 1949 at the U.S. National Bureau of Standards (NBS, now NIST, National Institute of Standards and Technology). It was less accurate than the then extant quartz clocks, but served to demonstrate the concept.

The first Cs atomic clock with greater accuracy than a quartz device was built by Louis Essen in 1955 at the National Physical Laboratory (NPL). NPL has remained world leading ever since.

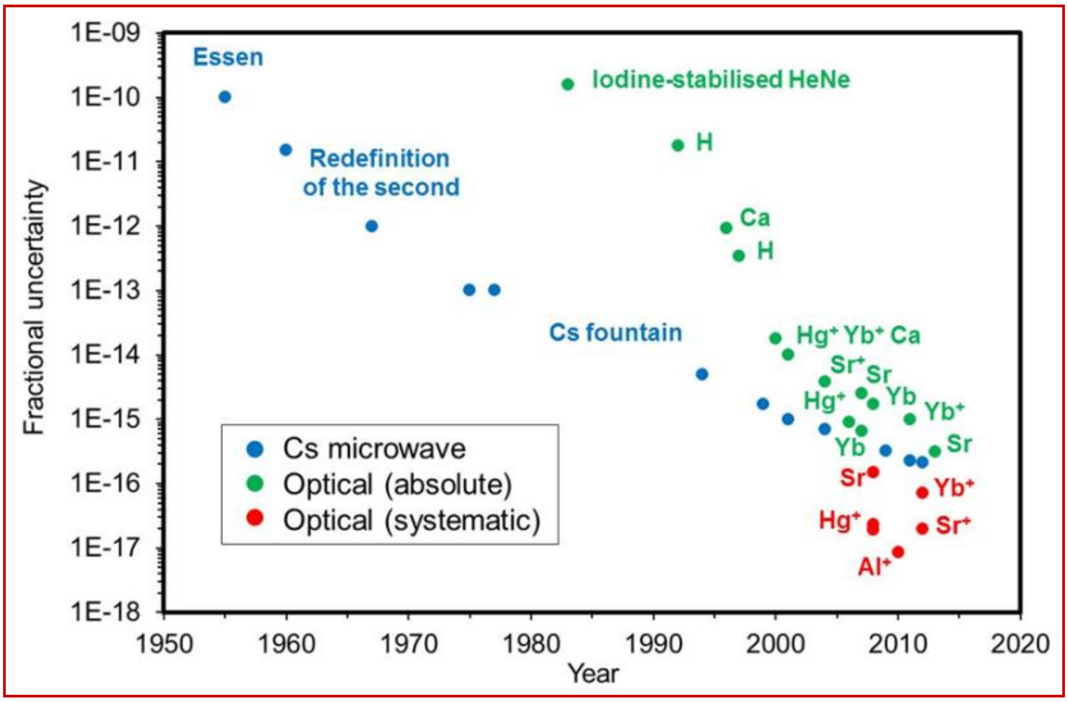

Figure 3 Increase in accuracy of atomic clocks by year. Reproduced by kind permission of Professor Gill of the UK National Physical Laboratory

The first commercial caesium standard clock became available in 1956 but it was the compact Hewlett-Packard model 5060 which became widely adopted and developed into the current Symmetricom Inc. clock. Typically, this has an accuracy of 2 x 10^{-13} although the actual number depends on specific options. Improvements in the accuracy of the caesium standard were subsequently pursued by NBS/NIST in the form of the US NIST F1, although outclassed by the NPL-CsF2[13]. Increasing the Ramsey cavity length, improved vacuum, better state selection of atoms

[12] Hyperfine (very narrow) energy level splitting is caused by the interaction of electrons in atoms and their nuclei.
[13] NPL is the UK National Physical Laboratory and a world leader in accurate time and frequency standards.

(ultimately by lasers rather than permanent magnets) and lower atomic temperatures contributed to these improvements.

The atomic clocks currently used as standards are atomic fountain clocks[14]. When these frequency standards reach accuracies measured by parts in 10^{16}, the limiting factors become fundamental in nature. The accuracy of the US NIST-F2 is near the fundamental limit for such devices, while NPL in the UK are developing a version that will improve stability[15].

Reduction in size of atomic clocks incurs a performance penalty, illustrated semi-quantitatively in Figure 4, however, size, weight and power (SWAP) can be critical factors, especially for some military and aerospace applications. Accordingly there have been a number of programmes to develop low SWAP devices with as high performance as possible.

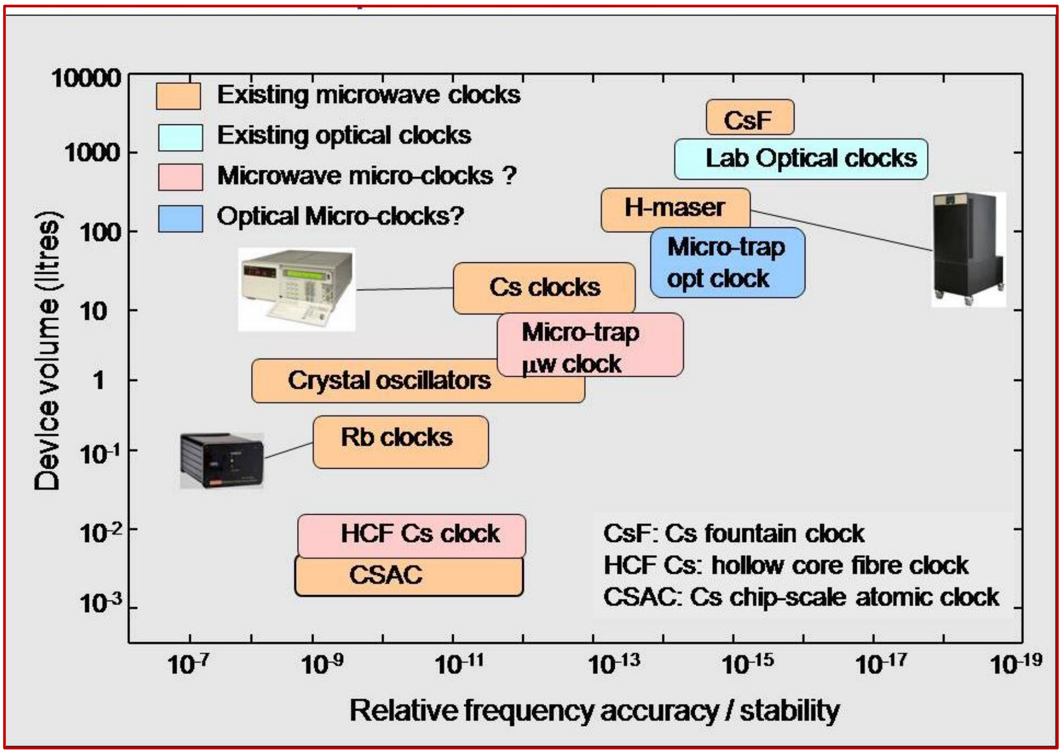

Figure 4 Clock performance as a function of device volume. Reproduced by kind permission of Professor Gill of the UK National Physical Laboratory. NB: Performance of optical clocks increases over microwave systems, but so does clock complexity and hence development time and cost

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14 For a simple explanation of their operation see http://www.npl.co.uk/science-technology/time-frequency/research/microwave-frequency-standards/operation-of-atomic-fountain

15 See http://tf.boulder.nist.gov/general/pdf/2500.pdf and http://www.npl.co.uk/science-technology/time-frequency/research/microwave-frequency-standards/rb-fountain

4.2.3. Coherent population trapping (CPT) clocks

Microwave clocks using passive, vapour-cell frequency references based on coherent population trapping have enabled significant miniaturisation of clocks[16]. Without CPT the minimum size of the clock "physics package" is largely determined by the cavity in which microwave atomic excitation takes place resulting in high power consumption and significant bulk.

In CPT clocks, a diode laser is modulated and the light passed through the atomic vapour, which acts as an extremely sharp notch filter. A change in the transmission of the light through the cell is used to lock the modulation frequency to the atomic resonance.

The technology was originally developed by the US Army (see figure 5) and has been commercialised through a number of stages resulting in the commercially available Chip Scale Atomic Clock (CSAC) manufactured by Symmetricom Inc. The caesium based SA 45s CSAC device uses a custom VCSEL[17] modified from those commonly used in the telecoms industry to pump the upper level of the hyperfine transition. It has an initial accuracy of ~ 5 x 10^{-11} at shipment, weighs 35 g, has a volume of 16 cm^3, and has a power consumption < 120 mW. The device has a warm up time of ~ 2 - 3 minutes and an expected lifetime > 100,000 hours. With careful characterisation and environmental control the accuracy achieved can approach ~1 in 10^{12}.

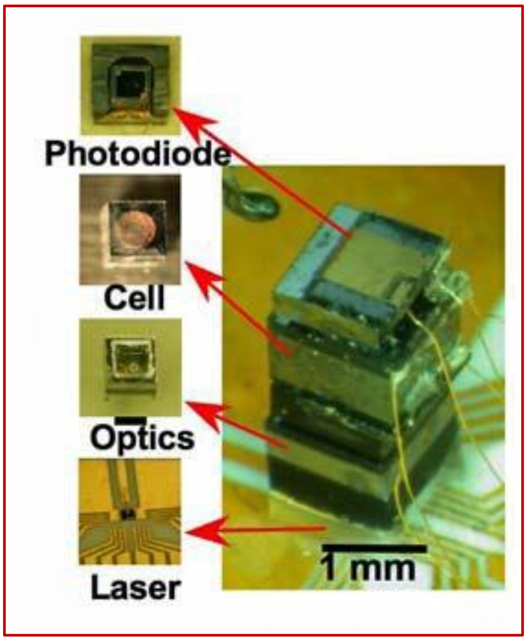

Figure 5 The original CSAC as commissioned by DARPA

The "physics package" for a compact strontium neutral atom optical clock has been developed by AO Sense, Inc (Sunnyvale CA). Full details have not been released but it is known that it comprises a 6 litre package which contains all lasers, a spectrometer and a vacuum system consisting of pumps, strontium oven source, Zeeman slower and magneto-optical trap. The device is probably not a lattice clock, but based on a repeatedly interrogated freely-expanding cold atom cloud following Zeeman slowing and 2D MOT containment. It will therefore most likely have some issues of longer averaging times, as did NIST's original cold calcium atom based on a similar arrangement. Alternatively, it might just be a 3D MOT arrangement, which will give good stability but limited accuracy on account of the large ac Stark shifts (the alternative of trapping the atoms using "magic" laser frequencies[18] via the lattice arrangement avoids this).

More recently, NPL in the UK has started work on an alternative miniaturised physics package. If successful, this could be turned into a superior alternative to CSAC that would achieve greater accuracy and stability due to an improved geometry, yielding a much better signal to noise ratio.

[16] For an explanation of CPT see http://tf.nist.gov/timefreq/ofm/smallclock/CPT_clocks.html
[17] VCSEL = Vertical Cavity Surface Emitting Laser
[18] These are frequencies where undesirable frequencies cancel, see later.

4.2.4. Quantum logic and single ion clocks

An alternative approach to achieving greater accuracy has been the development of quantum logic clocks using spectroscopy and "quantum logic" ions. The term "quantum logic clock" is used as it exploits the same operation as atoms storing data in certain quantum information processing devices. The accuracy obtained is competitive with atomic standards.

The first such clock was developed by the NIST in the US and used closely positioned trapped beryllium (logic) and aluminium (clock) ions to achieve an accuracy of 1 in 10^{17} (cf. a caesium fountain clock which is accurate to ~ 3 in 10^{15}). The "tick" of the clock is measured by precisely tuning the centre frequency of the clock laser using a frequency comb[19]. Subsequently, NIST have developed a new version using a single aluminium ion resonating in the ultra-violet region[20] that achieves an accuracy of about 1 in 10^{17}. This is sufficient to demonstrate gravitational time dilation for differences in height in the Earth's field of about 30 cm (depending on integration time). Also under development is a portable aluminium optical clock. The aim is to accommodate the vacuum and optical assembly on two 1.5 m^2 optical breadboards, and the stabilised lasers (including ultra-stable cavities) and instrumentation in a 19-inch rack mount.

Sandia National Laboratories (Albuquerque NM) is developing a low-power, miniature $^{171}Yb^+$ ion clock under the DARPA Integrated Micro Primary Atomic Clock Technology (IMPACT) project. This aims to deliver a clock of 5 cm^3 volume and 50 mW power consumption, with a stability of 2 x 10^{-14} per month. This is based on the 12.6 GHz microwave clock transition. There is a good opportunity for NPL to develop a very competitive microwave micro-clock capability in the short to medium term, given their extensive experience with the cold Yb^+ ion clocks[21] and using their ion chip trap technology. Prototypes can be tested quickly using the microwave arrangement in the linear blade trap[22], and subsequently transferring to the chip traps as they come on line.

Figure 6 Typical atom chip wafer (courtesy of NPL)

Sussex (Hensinger) is working on a new method to use microwaves instead of lasers for entanglement generation and combining this technology with ion chips. Such integrated microwave ion chip technology may allow the development of portable entanglement based chip clocks.

[19] An optical frequency comb is a series of equally spaced lines of known frequencies used as an optical ruler. Unknown frequencies are determined by using a photo-detector to measure the beating of the unknown frequency with the known comb frequencies. A wide frequency range is needed to ensure a large bandwidth of the frequency comb. See http://www.nist.gov/public_affairs/releases/frequency_combs.cfm
[20] See http://www.nist.gov/pml/div688/logicclock_020410.cfm
[21] S. A. King, R. M. Godun, S. A. Webster, H. S. Margolis, L. A. M. Johnson, K. Szymaniec, P. E. G. Baird and P. Gill, "Absolute frequency measurement of the $^2S_{1/2} - {}^2F_{7/2}$ electric octupole transition in a single ion of $^{171}Yb^+$ with 10^{-15} fractional uncertainty" New Journal of Physics14, 013045 (2012).
[22] Blade traps are described in http://heart-c704.uibk.ac.at/publications/dissertation/brandstaetter_diss.pdf

More broadly the UK are involved in development of similar types of cavity-stabilised lasers and optical clocks for space within ESA contracts (NPL using ions, Birmingham and Strathclyde using atoms). Volumetric footprint reduction and auto-control functionalities that allow the clock systems to run unaided are key objectives of the work.

Qubits and quantum logic gates based on single $^{40}Ca^{+}$ and $^{43}Ca^{+}$ ions are being developed at Oxford (and now represent the state of the art performance in fundamental quantum logic operations). These are directly applicable to the quantum logic spectroscopy used in the most precise optical clocks.

The UK has also developed world-leading component technologies which are highly relevant to these atom- or ion- based devices. Specific examples of microfabricated components for atomic systems include an ion microchip,[23] an atom chip[24] and an array of integrated atom-photon junctions.[25]

4.2.5. Summary of current atomic clock performance

Table 1 lists the frequency stability performance of microwave and optical atomic clock systems for 100-second averaging times, for primary clocks operated in national standards labs, commercial fixed or portable clocks, and micro-clocks. Also included (in red) is information for quantum systems not yet realised as fully-operational clocks, with projected performance figures.

Note that stability over 100 seconds, rather than accuracy, is used to ease the comparison between systems.

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[23] G. Wilpers, P. See, P. Gill and A. G. Sinclair, "A monolithic array of three dimensional ion traps fabricated with conventional semiconductor technology", Nature Nanotechnology, 7, 572 (2012.)http://dx.doi.org/10.1038/nnano.2012.126

[24] C. C. Nshii, M. Vangeleyn, J. P. Cotter, P. F. Griffin, E. A. Hinds, C. N. Ironside, P. See, A. G. Sinclair, E. Riis and A. S. Arnold, "A surface-patterned chip as a strong source of ultracold atoms for quantum technologies", Nature Nanotechnology 8, 321 (2013).http://dx.doi.org/10.1038/nnano.2013.47

[25] M. Kohnen, M. Succo, P. G. Petrov, R. A. Nyman, M. Trupke & E. A. Hinds, "An array of integrated atom–photon junctions", Nature Photonics 5, 35 (2011).http://dx.doi.org/10.1038/nphoton.2010.255

	Microwave clock stability			Optical clock stability			
	Thermal atoms	Cold atoms	Cold ions	Single cold ion clocks	Multiple cold ion clock	Cold atom opt. lattice clock	Entangle-ment based clock
Primary clocks	H-maser 1.4 GHz	Cs fountain 9.2 GHz	Hg^+ 40 GHz 7-ion string	Yb^+ 642 THz Sr^+ 445 THz single ion	Al^+ [Be+] 1121 THz dual ion QLC	Sr 429 THz Yb 518THz lattice	
Stability @ 100s	10^{-14}	2.10^{-15}	3.10^{-14}	3.10^{-16}	3.10^{-16}	3.10^{-17} N ~ 2000	
Fixed / portable clock	Cs & Rb commercial clocks	Rb 6.8 GHz atoms on magchip trap	Yb^+ 12.6 GHz ion cloud Hg^+ 40 GHz Buffer-gas cooled	Ca^+ single ion	Al^+ [Ca+] or In^+ [Yb+] dual ion QLC	Cold Sr 2D MOT 6-litre	
Stability @ 100s	10^{-12}	6.10^{-14}	10^{-14}		3.10^{-16}	10^{-16}	
Micro-clocks	Cs CSAC Cs HCF	Rb 6.8 GHz atoms in opt trap	Yb^+ 12.6 GHz Microtrap string	Micro-trap single ion / dual ion QLC	Micro-trap array (N ~ 100 ions)		Micro-trap 10 ions entangled
Stability @ 100s	3.10^{-11} 10^{-11} projection		3.10^{-13} projection	3.10^{-16} projection	3.10^{-17} projection		3.10^{-17} projection

Table 1 Comparison of current microwave and optical clock performance parameters. (CSAC, chip-scale atomic clock; HCF, hollow core fibre clock; QLC, quantum logic clock; 2D MOT, 2 dimensional magneto-optical trap; N, number of atoms or ions. The 100-second stability data is chosen to facilitate ease of comparison between systems, and to indicate performance in the short term (minutes to hours) window relevant to micro-clock operation. Note these are stability data, not accuracies.) Reproduced by kind permission of Professor Gill of the UK National Physical Laboratory

4.2.6. Atom chip and lattice clocks

The first low temperature (micro Kelvin) atom traps were reported in 1987 when ~ 10^7 sodium atoms were optically trapped for ~ 2 minutes at densities exceeding 10^{11} cm^{-3} and a temperature of 0.4 K, although the set up was large, complex and required significant power.

During the last decade, the technology has advanced quickly through step changes in cooling, trapping and fabrication techniques. Systems can now be realised as miniature devices requiring little power and no infrastructure, since the vapour cells and cooling lasers could be integrated into a chip. The main obstacles to miniaturisation have been the development of effective, integrated, magneto-optical traps (MOTs) and loading atoms into the traps.

"Atom chip" clocks are being investigated by some workers[26] where current carrying wires on the chip are used to create the magnetic fields that trap a cloud of ultra-cold atoms above the surface.

[26] E.g. SYRTE, see http://syrte.obspm.fr/tfc/h_puce_en.php

Optical lattice clocks use the transitions of ultra-cold (~ 100 nK) atoms held in a lattice formed by intersecting laser beams. These are eventually expected to achieve accuracies of 1 in 10^{18} or better, sufficient to measure gravitational potential to the centimetre level at the Earth's surface. In May this year, an optical lattice clock using trapped ytterbium ions was reported[27] with a stability of 1 in 1.6 X 10^{-18}

4.2.7. Quantum clock synchronisation

Synchronisation of two separated clocks is important for many practical applications, such as the global positioning system (GPS) and very large base interferometry (VLBI). Conventionally, the synchronisation is performed by transmitting timing signals between the clocks. If compensation for special and general relativistic effects is implemented properly, and corrections for atmospheric disturbance made, then the accuracy of the synchronisation process is limited by the uncertainty in the timing signal. Ultimately, the best result achievable is limited by the signal to noise ratio (SNR). Given adequate resources, sources of systematic noise can be eliminated so that the fundamental constraint is the shot noise limit (SNL) imposed by the charge on single electrons. In principle, specially prepared quantum states can reduce the effective noise below the SNL but the difficulties of preparing such states are significant.

Care is required when synchronising clocks of extreme accuracy. The effects of general (and special) relativity imply that our attempts to impose a Newtonian lattice on spacetime are no longer valid, e.g. similar clocks at different points on the Earth's surface will run at different rates, and simultaneity will be a function of differing inertial (or Rindler) frames.

4.2.8. Issues and challenges

The key challenge is to realise a progressive development in accuracy, combined with a reduction of size, weight, power and cost. Ideally, there will be a number of "disruptive" advances set against a background of continuous improvement. Concurrently, a number of challenging technical issues will become increasingly important to address. These include susceptibility to stray magnetic or electric fields, vibration, shock and temperature. And it is not only the ultimate precision that counts as improvement, but also the length of time taken to make a measurement.

An important question is where is there a need for more precise clocks than currently available. Space navigation, imaging and communications are likely commercial drivers. In the short term, the strongest driver for clocks of extreme accuracy, due to their bulk and fragility, almost certainly will be demand for increased precision in scientific measurements. Apart from metrology, this will benefit high energy particle physics, astrophysics and extreme tests of relativity, fundamental constants and the behaviour of fields and forces.

The ultimate aim will be not just clocks with unprecedented accuracy. It will be the ability to use atom chip or other micro scale trap technology to produce miniature devices which are cheap and simple to use, integrated into current systems, thereby producing step changes in sensing, data processing and communication capabilities.

[27] See http://arxiv.org/pdf/1305.5869v1.pdf

Timing is a safety critical as well as a commercial issue. We have already mentioned "dangerous" over-reliance of global navigation satellite systems (GNSS). Misleading or missing signals could result in vehicle or shipping accidents, goods stolen from consignments that can no longer be tracked, or misrepresented financial transactions. Small, cheap and highly accurate clocks would mitigate against many of the problems by enabling rapid re-acquisition of signals and the ability to keep time to an accuracy of a microsecond or less for hours or days.

Foreign technology may become export controlled. An indigenous capability is essential; UK has strengths in crucial relevant areas i.e. atomic fountains, trapped ions and neutral atoms. Meanwhile DSTL, with NPL, is supporting investigation of a CSAC alternative, and with Birmingham University exploring the technology required to build a miniature, low power lattice clock with an accuracy comparable with much larger frequency standards.

4.2.9. Synopsis

The field of quantum clocks (and atomic clocks) is advancing rapidly as they are becoming progressively smaller, cheaper, more robust and more power efficient. This is gradually raising the performance and utility of practical devices that can be incorporated into systems. Due to the extensive expertise present in the UK we can expect significant capability and economic benefits given a sufficient level of investment and support.

New generations of clocks are becoming so accurate that they will allow one to measure relativistic effects in a lab environment instead of sending them up on a rocket. Sensitive tests of special and general relativity will become possible.

In the short term the UK is well positioned to develop and commercialize a low-power, low-cost, miniature precise timing device to provide GPS holdover for ~10 days (this would be a leading international solution, and not subject to US export controls). A solution might be based on the NPL hollow-core fibre clock if initial tests are encouraging (in ~1 year timescale and a possible 3-4 year development phase for the technology to reach TRL8). The necessary (subsystem and component) technology capabilities developed as part of such a programme would be relevant across most of the range of quantum technologies and benefit the wider UK community. It is planned that in February 2014 NPL and TSB will be bringing together several likely players as part of Knowledge Transfer Network (KTN) on precision timing, followed on 15th May 2014 by an MoD/NPL showcase to Government/media of some future ideas.

In the longer term, precision timing technologies will enable other applications based on quantum technology such as quantum sensing and quantum information processing. National investment in NPL's Advanced Metrology Laboratory, accessible to industry and academia, will serve as a useful way to accelerate progress, build translational capability and help to equip the UK with skills it needs to lead internationally in quantum 2.0 technologies.

4.3.Quantum communications

4.3.1. Introduction

There are two aspects of quantum communications. The first is the use of quantum technologies to provide secure transmission of classical information ("1"s and "0"s). This is generally seen as one of the possible means to provide cryptography that would be robust to attack by a quantum computer which was able to solve discrete logarithms and thus factorise large bi-primes[28]. The second aspect is the transmission of *quantum* information, typically as part of a distributed quantum information processing system. From a systems point of view the two concepts overlap.

4.3.2. Secure transmission of classical information

Quantum technologies provide an elegant means to exchange information in a secure manner and this has been demonstrated for the exchange of cryptographic keys. The first Quantum Key Distribution (QKD) scheme was described by Bennett and Brassard in 1984 and is known as the BB84 protocol. It was originally described, and later implemented, using photon polarisation states to generate a key to facilitate transmission of classical information over a public "channel", usually fibre or free space. (Parameters other than polarisation could in principle be used).

This was developed over the late 1990s and early 2000s, and now BB84 systems may be bought as commercial products. The principal challenges have been range, bit rate and (in free space) washout from photons in the environment, although performance has steadily been improving. Recently, ranges of hundreds of kilometres have been achieved including key exchange with aircraft. UK expertise is well represented e.g. at Bristol University.

Several companies offer off the shelf QKD systems, including Toshiba, ID Quantique, MagiQ Technologies, Quintessence Labs and SeQureNet. Other large companies have active research programmes.

4.3.3. QKD "2.0"

The E91 protocol was described by Artur Ekert in 1991. This scheme uses entangled pairs of photons. Tests known as "Bell tests" may be performed to be sure that the link is not compromised in any way. This technology is not as well established as the BB84 protocol[29]. However, there are senses in which E91 can be made stronger. This is known as "device independent QKD"[30] which is claimed to be robust against noise or even adversarial preparation.

4.3.4. QKD networks

Several quantum key distribution networks have been trialled in the US (DARPA[31]), Vienna, Tokyo and Geneva. The challenge for this technology is switching or channelling the light through nodes and switches in the system. This must be achieved in such a way that the carriers (photons) on the

[28] Bi-primes are numbers resulting from the multiplication of two (typically large) prime numbers and an important element of the security of many current cryptographic systems.

[29] This is an abbreviated description. A survey of QKD protocols and applications can be found at: http://www.ma.rhul.ac.uk/static/techrep/2011/RHUL-MA-2011-05.pdf

[30] See for example http://arxiv.org/pdf/1210.1810v2.pdf

[31] DARPA = Defense Advanced Research Projects Agency

route are not compromised in the sense that the node has to become secure (i.e. information exchange between the photons and the environment must not take place). This technology is gradually becoming mature.

A quantum repeater (to avoid signal fade in the form of excessive photon loss) is more of a challenge as the photon needs to be absorbed and then re-emitted without its state being measured, or "read". Such a technology would rely on the quantum Zeno effect to "reset" the photon loss probability at each repeater.

Although demanding, some early networks have been demonstrated, e.g. the "no trusted relay" quantum network in Beijing[32].

Such systems could in principle be used to transport *quantum* information. In that case it is essential that the information carriers are kept from interacting with their environment throughout all stages of the link. There are potential applications of such systems across the quantum programme and we expect that many remain to be discovered.

4.3.5. Quantum information transmission and teleportation

The field of quantum networks is developing rapidly with many innovations being produced. For example, as mentioned in 4.5, quantum computers might be realised by connecting many small groups of qubits together using a reliable network. This could help mitigate the problem of scalability, or enable other functions such as secure remote or "cloud" computing.

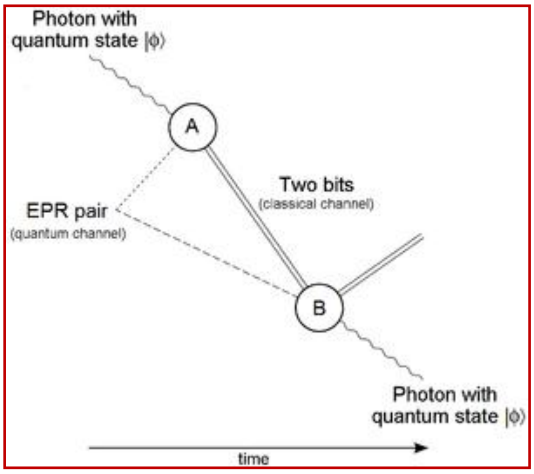

Figure 7 Quantum teleportation flow diagram

There are systems level developments as well, at varying levels of maturity. For example, precise timing could allow quantum and classical communications to coexist on the same carrier. Eventually, quantum relays using solid state systems will be possible.

Quantum teleportation is a method of transporting a *quantum* state from one location to another without it being transmitted through the intervening space (or being copied). To achieve this, one member of an entangled pair plus two classical bits (i.e. standard "1"s or "0"s) need to be transmitted between the two locations. "Entanglement" can be swapped between pairs in an approximately similar manner, and also "gates" may be projected from one location to another, see figure 7.

Teleportation is intuitively a surprising phenomenon, although it is not the same as teleportation described in science fiction. Note that teleportation does *not* apply to the transfer of matter, energy or classical information; only *quantum* information is teleported, and the transmission of classical

[32] See https://sites.google.com/site/quantinfo/research/quantum-cryptography-group for more information.

bits via a conventional communications channel, constrained by the speed of light, is required to make the process work.

It is possible to entangle two separate objects remotely. This could have applications in computing or sensing[33].

A complete understanding of how teleportation may be used in a technological sense has not yet been achieved, although it has been proposed as a basis for teleportation based networking and computing[34].

4.3.6. Quantum random number generators (RNGs)

Truly random and completely unpredictable bit streams need to possess maximum algorithmic entropy[35]; that means that they need to pass *all* tests for randomness. Quantum mechanics allows the generation of truly random numbers using techniques such as (for example) the measurement of entangled particles, or broadband measurements of the vacuum field contained in the RF sidebands of a single-mode laser. The build quality of commercial quantum RNGs is considered to be poor.

A QKD system automatically incorporates random number generation. There are, however, many other commercial uses for truly random numbers. These include:

- Gambling
- Hashing codes
- Simulation
- Stochastic processing

4.3.7. Issues and challenges

The issue of whether quantum key distribution is perfectly secure in practice has been debated extensively. Most potential problems seem to arise from engineering imperfections.

However, quantum key distribution is a 30 year old technology and there are a number of reasons why it has not become commonplace:

- There are practical limitations. To date, the transmission range (although having vastly improved is still limited to ~ 150km. BB84 is fundamentally a point-to-point system and does not integrate well with the internet and its underlying packet based protocols.
- It is a physical technology and requires expensive, special purpose hardware. This makes it unsuitable for cheap commodity mobile and embedded (RFID) devices. Hardware will degrade over time and is relatively complicated to upgrade.

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[33] See http://phys.org/news/2011-05-matter-matter-entanglement-distance.html for example; this has more recently been demonstrated between nitrogen vacancy centres in diamond.

[34] See for example http://www.ncbi.nlm.nih.gov/pubmed/15697787

[35] Algorithmic entropy, or Kolmogorov complexity, is measured by the minimum computer program length required to generate a binary string. When the length of the program has to be as long as the string the algorithmic complexity is at a maximum. Although most possible long strings are maximally random, most of *those* can't be generated classically by conventional computers. It has been proved impossible to write a general program that measures algorithmic entropy.

- QKD only addresses part of the security problem space. For example authentication and integrity are not covered; they would require at least a long term quantum memory preferably at room temperature[36].
- There is nothing fundamentally wrong with current encryption solutions. New algorithms based upon cryptographic primitives that are not efficiently breakable using quantum computers are being developed and these may provide a more cost effective solution than quantum technologies for upgrading current networks and systems. Also, to provide confidence that any proposed quantum solution does not have a major, unrecognised, vulnerability to 'side channel attack' will require a comprehensive investigation of overall security architectures and potential forms of system attack.

However, the UK has delivered world class research addressing some of these practical problems. Toshiba has worked on moving implementation on dedicated dark fibre to commercial leased systems. Bristol has been working on miniaturising QKD for handheld devices. Lancaster has been working on developing practical relays, multiplexing quantum signals with classical (using precise timing) and even further miniaturisation, eventually for embedded RFID devices.

Challenges for QKD networks:

- Faster, smaller, cheaper
  - Better components and hardware
- Improved understanding of vulnerability to side-channel attack
- Implementation of security and standards
- Integration into standard telecom networks
- New quantum protocol development
- Applications engineering
  - Fibre networks
  - Mobile phone
  - Other mobile devices
- Need to identify early adopters in UK

Challenges for quantum internet (based on distributed entanglement):

- Quantum sources - pure single photons. entangled states
- Efficient quantum detectors
- Quantum memory (sufficiently long term)
- Network architectures
- Protocols and applications

[36] The latest reported record is 39 minutes http://www.bbc.co.uk/news/science-environment-24934786

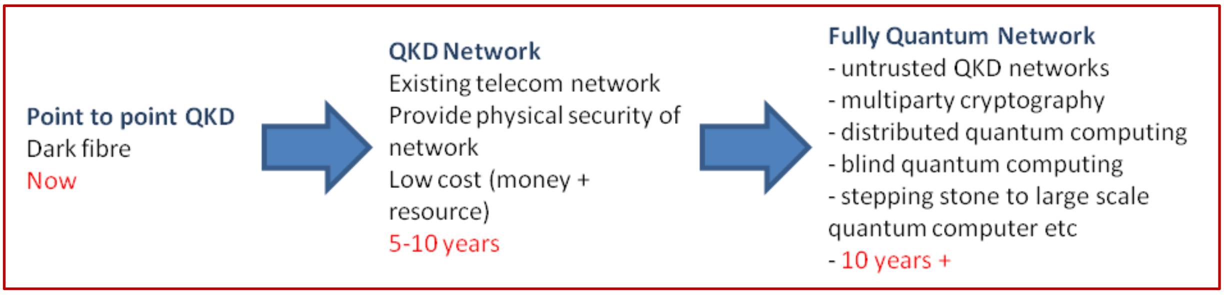

Figure 8 Evolution of quantum communications

As a relatively mature technology there is an issue of interoperability and standardisation. Well written standards would ensure minimum acceptable levels for functionality and build quality, and would stimulate the market and encourage competition.

The establishment of a ubiquitous network for quantum information is a significant challenge. It seems much more likely that such systems might be adopted for bespoke applications for customers such as the financial markets or defence, rather than for any high volume public access networks, see Figure 8.

4.3.8. Synopsis

Secure point to point transfer of quantum keys is now a commercial commodity, although improvements need to be made to enable communications via satellites or complex networks. There are many competitors, both industrial and research, that are working to make the necessary improvements.

However, special purpose hardware is required and the quantum systems only address one aspect of the security issue. The technology could possibly be overtaken by so called post-quantum cryptography which would consist of cryptographic primitives that are not efficiently breakable using quantum computers. To understand better the comparative advantage of quantum technology will require research focussed upon the system issues rather than the fundamental technologies.

There is an opportunity for the UK to contribute to this market, possibly at the component level (e.g. repeaters) or the systems level (insertion of quantum channels into existing carriers) or as miniature integrated photonic devices.

Note that the transmission of *quantum* information will form an essential ingredient of other quantum technologies.

4.4. Quantum sensors

Sensors are of crucial importance for military and security applications. Sensors also represent an important economic activity. By several measures, UK punches above its weight and has 6 - 7% of the world market (estimated at $490 billion in 2013) in sensor components and sensor systems. Growth in the sensors market appears to have been unaffected by the worldwide recession and it is increasing at 8 - 11% per year. The most important markets by sensor type are biosensors, flow sensors, pressure sensors, temperature sensors, imaging sensors, position and displacement sensors, level sensors, accelerometers, motion sensors, magnetic sensors and gas sensors.

Quantum sensors can offer a step change in sensitivity or accuracy, sometimes of many orders of magnitude, or even alternative modalities not accessible to classical devices. A table comparing the demonstrated and potential performance of basic quantum sensors with their classical counterparts is shown below.

Sensor Type	Best classical	Quantum demonstrated	Quantum potential	Comments
Gravity	15 μgal/Hz$^{-1/2}$ (FG5-X falling corner cube) [1]	4.2 μgal/Hz$^{-1/2}$[2] <100 ngal/Hz$^{-1/2}$ (10m fountain, inferred) [3] 1 μgal/Hz$^{-1/2}$ [4]	< 1fgal/Hz$^{-1/2}$	[4] is a commercial device
Rotation	7.8 prad/s /Hz$^{-1/2}$ [5]	600 prad/s /Hz$^{-1/2}$ [6]	5prad/s /Hz$^{-1/2}$ [7]	Best classical being a unpractically large area ring laser gyro
Magnetic Field		200 aT/Hz$^{-1/2}$ [8] 160 aT/Hz$^{-1/2}$ [9]	< 10 aT/Hz$^{-1/2}$	Size is important, see figure 14
MW magnetic field		77 pT/ Hz$^{-1/2}$in 20 μm^{-3} [10]		Size is important Non-invasive
MW electric field sensors	1 m V/cm/Hz$^{-1/2}$ [11]	30 μV/cm/Hz$^{-1/2}$ [11]	100 nV/cm [11] (timescale unclear)	
Phonons	>10^{-12} W/Hz$^{-1/2}$	10^{-15} W/Hz$^{-1/2}$ [12]	10^{-20} W/Hz$^{-1/2}$ [13]	
Short range gravitational acceleration		[14] see graph, Appendix α~10^{10} at 1 μm [15]	α~10^{6} at 1 μm [15]	Mostly fundamental research so far; size is important

Table 2 Comparison of the performance of quantum sensors with their classical counterparts (courtesy of Prof. Kai Bongs Birmingham)

The references in the table are too numerous to list as footnotes so they have been attached to this document as an appendix which also includes additional information.

4.4.1. Inertial and gravitational

There are many varieties (and variations) proposed. Unlike their optical counterparts, many of these sensors are also directly sensitive to electric and magnetic fields. Such characteristics could be useful, or a nuisance, depending on the application. Some of these rely on "atom chip" technology, streams of ultra-low temperature atoms, or coherent condensates[37] (Bose Einstein Condensates (BEC) of such atoms) producing atoms which can be guided along paths on the surface of a "chip". World class research on interferometers using BECs is taking place at Strathclyde, Imperial and Oxford.

We illustrate some examples below:

[37] Loosely speaking, BECs are ensembles of atoms that are so cold that they have coalesced into a single quantum object. They are not essential for interferometry; streams of single atoms may be used provided that their wavelength is sufficiently long.

4.4.1.1. Enhanced Sagnac effect ring gyros

The Sagnac effect[38] is a rotational effect initially discovered in optics. It consists of accumulation of phase shift between two similar counter-propagating light waves around the same closed loop and this forms a rotational reference frame. It is not a relativistic effect.

An increase in precision of (potentially) orders of magnitude may be achieved by replacing the laser by a gas of atoms in the ring to be used as the gain medium. The refractive index of certain species may be controlled externally, and, if this index can be appropriately manipulated, significantly more wavelengths can be enclosed in the ring. This will lead to a greatly enhanced phase shift when the ring is rotated and in turn this will lead to greater sensitivity.

4.4.1.2. Sagnac matter wave interferometer

The Sagnac effect applies equally to matter waves. However, the relative sensitivity to phase of matter waves is of the order of 10^{10} greater than in optical systems. In principle, sensors could be realised that would be able to measure rotational effects down to the level of the effects of general relativity in the local environment, or tidal effects caused by the moon and even (potentially) the planets. A number of variations of the principles involved have been proposed, such as two component BECs and superpositions of rotation states. Durham, Cambridge and Leeds are studying this phenomenon.

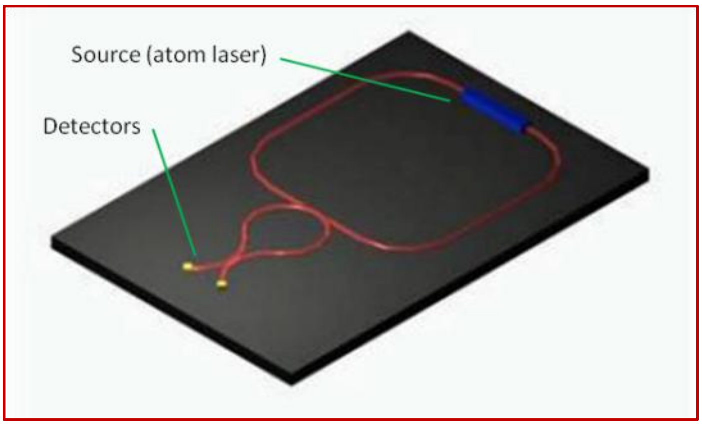

Figure 9 Concept of Sagnac type matter wave interferometer

A specific example is as follows: an atom laser is a device that produces a coherent matter wave, akin to the continuous wave emitted by an optical laser. The principle differences are that the atoms cannot (easily) be created and destroyed; they need to be obtained from a reservoir of Bose Condensate. A population inversion is not required.

An atom laser gain element needs to emit coherent matter waves into two directions of a wave guide formed into a micro-fabricated ring resonator. A directional coupler allows differential detection of the atoms in the two arms using quantum state manipulation via an analogy with a heterodyne detector (see figure 9, the gain mechanism i.e. atom laser is shown in blue)[39]. Estimated sensitivity for this configuration is ~ 10^6 improvement over state of the art (this will be dependent on several parameters such as atomic flux from the atom laser). All of the *components* have been demonstrated in the lab, the requirement is now for the *system* to be realised. Groups at Strathclyde and Nottingham are working on guided wave ring interferometers.

[38] See http://en.wikipedia.org/wiki/Sagnac_effect
[39] A description of such a device may be found in http://www.dtic.mil/dtic/tr/fulltext/u2/a424482.pdf

4.4.1.3. Mach-Zender and Michelson BEC interferometers

Matter wave analogies of optical counterparts to Mach-Zender[40] and Michelson [41] interferometers are beginning to be realised. The key component is the analogy of the half silvered mirror used in optics, this may be implemented as a semi - reflective potential barrier or an appropriately configured micro-grating. NPL are performing some work on this technology.

The basic layout of a Mach-Zender interferometer is shown in figure 10. Changes in the relative path lengths or unequal phase shifts will result in changes in the ratio of outputs from the recombiner.

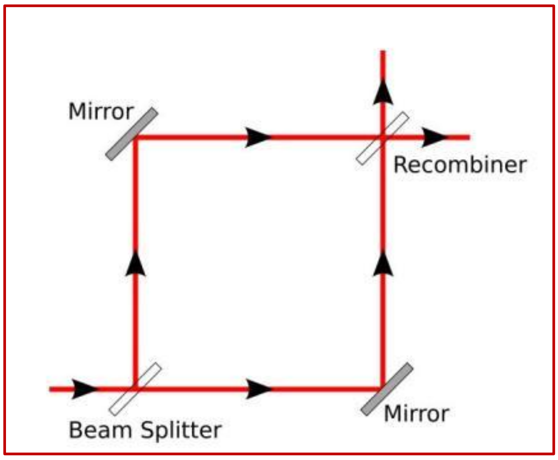

Figure 10 Layout of basic Mach-Zender interferometer

These devices may be used to make a wide variety of precision measurements and have been demonstrated to surpass classical sensors in sensitivity to gravitational and inertial effects. Useful parameters to measure, depending on application, are rotation, gravitational field strength and gravitational field gradient. There is a possibility in the ~ 10 - 15 year timescale of demonstrating a gravitational "imager", sensitive to small variations of the local field with the ability to detect a local "density map" of energy and matter.

These sensors and their applications in gravity imaging and navigation are under investigation in the Midlands Ultracold Atom Research Centre partnership between Birmingham University and Nottingham University

It is also possible to use quantum superpositions of momentum eigenstates to measure projectile body acceleration – a time based rather than space based approach. This method is currently under study at Aberdeen University as part of an MoD funded Anglo-French PhD.

4.4.1.4. Atomic single ion clocks

As clocks become more accurate, they become more useful for sensing gravity, with the long term goal of a comprehensive system forming a gravity "imager". They offer the only sensor technology to measure directly the gravitational potential, i.e. the height above the Earth geoid, complementing the above sensors.

Single ion and optical lattice clocks of sufficient accuracy, and with appropriate integration time, may be used to detect differences in gravitational potential, or, as an ensemble, field strength, gradient or higher order derivatives. The particular mix of sensors that should be used to achieve the best performance will be discovered by future R&D.

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[40] See http://arxiv.org/pdf/1303.1030v3.pdf
[41] See for example: http://arxiv.org/ftp/cond-mat/papers/0407/0407689.pdf

4.4.1.5. Optical lattice

An optical lattice is a lattice of trapped "cold atoms" which can be implemented in 1, 2 or 3 dimensional arrays and held in place by a set of interfering optical beams. There are immense technical challenges involved, not the least being the ideal of placing a single atom in every lattice position to achieve the ideal performance and characteristics. There are many sensing applications of this configuration. For example, a "Wannier-Stark ladder" may be configured to measure gravitational fields and the characteristics of short range effects such as Casimir or Van Der Waals forces. Potentially, these systems could also be used to measure gravitational and inertial parameters used for navigation and orientation, also with unprecedented sensitivity.

4.4.2. Quantum enhanced imagers

4.4.2.1. LIDAR (LADAR) laser "radar" sensors

LIDAR[42]s are well known classical sensors that can image terrain (and smaller scenes) to great accuracy, typically centimetres or millimetres. They work by scanning a beam rapidly over a defined area and measuring the return signal strength and timing. There are many variants of the system implemented classically.

Quantum techniques may be used to improve the performance. The families of such improved sensors fall into the following categories:

- Type 1: All non classical light[43] is propagated to the target.
- Type 2: Classical light is propagated to the target, non classical light is used in the receiver
- Type 3: Some non classical light is propagated to the target and some is retained in the receiver.

Extensive theoretical and proof of principle work has been done on the subject by Harris Corporation

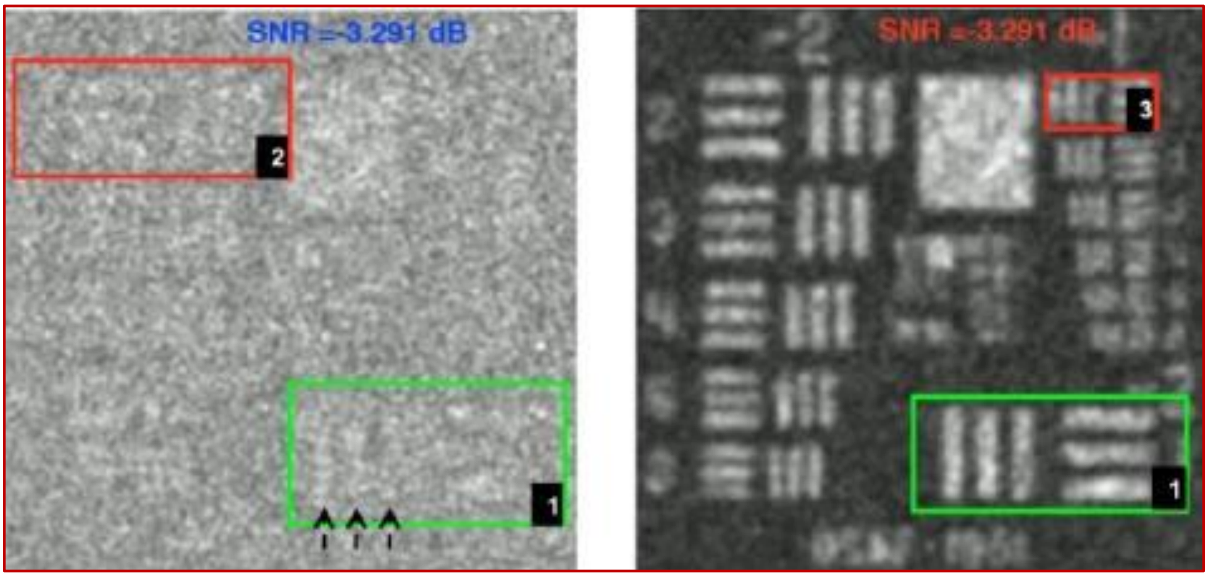

Figure 11 Simulation of LIDAR quantum enhancement (AFRL US) showing theoretical improvement in resolution

[42] From Light and Radar, LADAR from Laser and Radar in the US

[43] Non-classical light in this sense implies that entangled photons are used. It cannot be described by classical electromagnetism.

at the behest of DARPA[44]. The systems are complicated. An angular cell improvement of X 10 could be achieved using a "quantum image enhancer", and by applying yet more sophisticated techniques a 200 fold improvement in voxel (i.e. three dimensional pixel) density might be achieved. Further proof of principle exercises have been demonstrated by MIT. Simulated results are shown in figure 11.

Time Correlated Single Photon Sampling (TCSPC), being investigated at Heriot-Watt University, uses a single photon laser source and very accurate timing to scan objects in air and identify them at distances up to 1km. Currently they are looking at how this might transfer to the underwater environment.

4.4.2.2. Quantum ghost imaging

Ghost imaging (typically) allows a high-resolution camera plus a second photon detector to produce an image of an object that is out of the line of sight of the sensor. The camera records photons from the source and the photon detector records photons scattered by the object. An image is formed computationally from correlations between photons arriving at the two sensors. Ghost imaging was originally demonstrated as a quantum effect involving entangled photons, although later it was shown to be possible using only classical correlations. Subsequently, the use of non-classical light was shown to improve the performance (i.e. resolution enhancement) and extend the scope of such a sensor. More recently, there has been some debate as to whether quantum discord is involved in the formation of a pseudothermal ghost image[45].

Since single pixel detectors may be used, there is potential for using wavebands (via different wavelengths) where no detector arrays are available.

Figure 12 Typical ghost image (USA)

A series of studies have been sponsored by DARPA[46], although as far as we know none of these went forward as a full development programme. Virtual ghost imaging using Bessel beams has been demonstrated by ARL (US Army Research Labs) to show that light can reach a target through obscurants[47]. Generally, the quality of the images to date has mainly been poor, see figure 12 There are a number of variations, such as computational ghost imaging, and compressive ghost imaging.

[44] See **AFRL-RI-RS-TR-2009-208 Final Technical Report "Quantum Sensors Programme" August 2009** for a full exposition.
[45] See http://www.nature.com/srep/2013/130515/srep01849/full/srep01849.html for part of the debate and some useful references.
[46] See DARPA Quantum Sensors Workshop August 27-28 2008 for a series of papers in Session III on "Type 3" quantum sensors.
[47] http://www.arl.army.mil/www/?article=943

Recently work at University of Glasgow has been reported[48] (Miles Padgett and team) with significant increases in image quality.

4.4.2.3. Quantum secured imaging

Techniques similar to QKD have been proposed to secure reflected image data against an attack in which the returned photons have been intercepted and modified in order to present false information[49]. Polarised photons are sent to the target and any attempt to modify the reflection causes a change in the quantum state of the photons, depicted by a change in the false colour of the "spoof" image made up from four linear polarisation states.

4.4.2.4. Quantum Zeno sensors (non interactive sensing)

The quantum Zeno effect is an effect whereby a quantum system, with very high probability, fails to evolve if frequent, repeated measurements of its state are made. That is because a quantum system becomes (is projected on to) an eigenstate[50] when measured. If the measurements are made sufficiently frequently, the probability of the system being measured remaining in the original state can be made arbitrarily close to 1.

In 1996 Scientific American published an article[51] describing how a sensor could be built that would image an object with, in principle, a vanishingly small number of photons impinging on the subject. Theoretically, this would permit "stealth imaging", or non-destructive imaging of a system where the radiation would be damaging to the subject (such as deep UV imaging of a living cell).

We can find little practical work that has been done in this area since[52]. The main problem is that the object to be observed needs to be placed in the arm of an interferometer. The Zeno effect has since been considered as an ingredient for other technologies (e.g. stabilisation of quantum gates or for quantum repeaters). Possibly, non-interactive imaging could be achieved at long range using long (radio or microwave) wavelengths.

4.4.2.5. Optical nano-probes

Advances in nanotechnology to confine light to sub-wavelength spatial distributions, together with efficient quantum based sources and detectors (particularly at 3 - 5 μm), would allow biochemical fingerprints to be obtained at the cellular or sub-cellular level. To achieve such a level of detail using conventional optics would require the use of very short wave (damaging) radiation and would not yield the spectral data needed for analysis of lipids, amides, proteins etc. Ultimately, in the long term (15-20 years), we could expect imaging to be achieved at the sub-cellular level *in vivo*.

Deeper understanding of functions at a cellular level could eventually lead to bio-mimetic sensors (not necessarily quantum) that would deliver high sensitivity detectors for proteins and other

[48] "EPR-based ghost imaging using a single-photon-sensitive camera" Aspden et al, New J Phys **15**, 073032 (2013) preprint http://arxiv.org/pdf/1212.5059v2.pdf
[49] See for example http://arxiv.org/pdf/1212.2605v1.pdf
[50] i.e. a fundamental, measurable state with exactly defined characteristics
[51] "Quantum seeing in the Dark" by Paul Kwiat, Harald Weinfurter and Anton Zeilinger, SciAm November 1996.
[52] For one example see "Quantum Zeno Tomography" Facchi et al, Phys Rev A **66** 012110 (2002)

chemicals. This could lead to new medical treatments. (We also need to be aware that such knowledge could have implications, benign or otherwise, for security.)

4.4.3. Electromagnetic sensors

Most quantum sensors of electric, magnetic and electromagnetic fields have well established classical counterparts. Some of these are very sensitive. There are also established sensors that use "quantum 1.0" phenomena, such as the single photon avalanche detector (SPAD). Those are of interest to us, as they are developing rapidly and we feel they will have potential for defence and security applications.

Rydberg atoms[53] are the best sensors of microwave and terahertz fields. The team at Durham is planning to deliver microwave and THz sensors using cell technology similar to CSAC[54]; this could reach commercial viability within the next 5 years.

4.4.3.1. Electric field sensors

Electric field sensors using quantum effects could be made to be orders of magnitude more sensitive than their classical counterparts. Sensing objects through walls etc. or sensing neural or cardiac activity are potential applications, see figure 13. However, the system as a whole needs to be considered; a highly sensitive sensor will also be more sensitive to noise and interference. The preference would be for sensors operating at room temperature. There are several potential physical configurations for such sensors, these include:

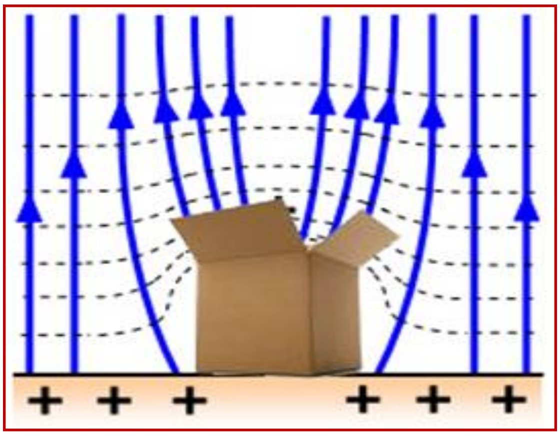

Figure 13 Concept of using a sensor to detect "dents" in the Earth's native electric field. Such dielectric effects can be used to detect a human body at a distance of several meters, often through walls or ceilings

- Diamond impurity: a single NV centre has been used to measure extremely small electric fields less than a micron from the detector. Ability to change between electric and magnetic field sensitivity has been demonstrated.
- A carbon nanotube using a single electron transistor (SET) fabricated as thin epitaxial layers. A steep response to changes in electric field may be achieved by shuttling currents via ions trapped in the nanotube. The trapping leads to a phenomenon known as "quantum confinement" (permitting operation at room temperature) and measurement via double dot tunnelling. Multiple devices could "image" the local electric field to reveal details, or distributions, of objects via their dielectric properties.

Many configurations for measuring electric fields are shared with magnetic field sensors.

[53] Rydberg atoms have at least one electron in a very "high" orbit without being ionised. They have a number of interesting properties including an increased response to electric and magnetic fields.
[54] CSAC = Chip Scale Atomic Clock *op cit*

4.4.3.2. Magnetic field sensors

The conventional (quantum 1.0) magnetic sensor demonstrating the highest sensitivity was for decades the superconducting quantum interference device (SQUID). This requires cryogenic temperatures to operate and the devices can be difficult to set up. There are many alternative realisations of quantum magnetic sensors offering superior performance over a range of length scales; some examples are outlined below:

- Nitrogen Vacancy (NV) centres in diamond[55] (+entangled centres) - nitrogen vacancy (NV) centres are very sensitive to magnetic fields at the smallest scale, i.e. sub-micrometer. These may be remotely entangled to provide greater sensitivity (a naive analogy is the Wheatstone Bridge). NV centres are not the only sensitive impurities that can be embedded in diamond as an impurity, however, they are the most widely studied. There are several centres of activity in the UK.
- Bose-Einstein condensates offer the highest sensitivity at the micrometer scale and allow the simultaneous capture of one-dimensional field maps. Trapped Bose-Einstein condensates uniquely combine single micron resolution with $pT.Hz^{-0.5}$ sensitivity while acquiring large field-of-view (100s of micron) single-shot images in less than a millisecond. This type of sensor is under study at the University of Nottingham.
- Magnetic field sensing beyond the standard quantum limit using NOON[56] States
- Time resolved magnetic sensing with NV centres in diamond
- Magnetic resonance imaging using nanoscale magnetometers
- Hall probes
- Magnetic force microscopes
- Atomic vapour cell magnetometers based on atomic ensembles and operating at room temperature sensors outperform SQUIDs, reaching the best sensitivities of all sensors in the $aT.Hz^{-0.5}$ range and at above mm scale. These devices are studied at NPL, Glasgow nanocentre and Southampton University.
- Trapped ions can be used for the detection of the magnetic fields with nanometre resolution[57] with a measurement sensitivity of 15 $pT\ Hz^{-0.5}$.
- The NIST chip scale magnetometer using a coherent population trapping resonance detects changes in flux density of 50 $pT.Hz^{-0.5}$ at 10 Hz[58].

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[55] An NV centre is a point defect in a diamond lattice which consists of a nearest neighbour pair of a nitrogen atom and a lattice vacancy which together substitute for a carbon atom.

[56] A NOON state is a quantum-mechanical many-body entangled state in which N particles in mode *a* are in a superposition with zero particles in mode *b*, and vice versa. The particles must obey Bose-Einstein statistics and are usually photons.

[57] Reference: Nature 473, 61–65 (05 May 2011)

[58] See http://tf.boulder.nist.gov/general/pdf/2001.pdf

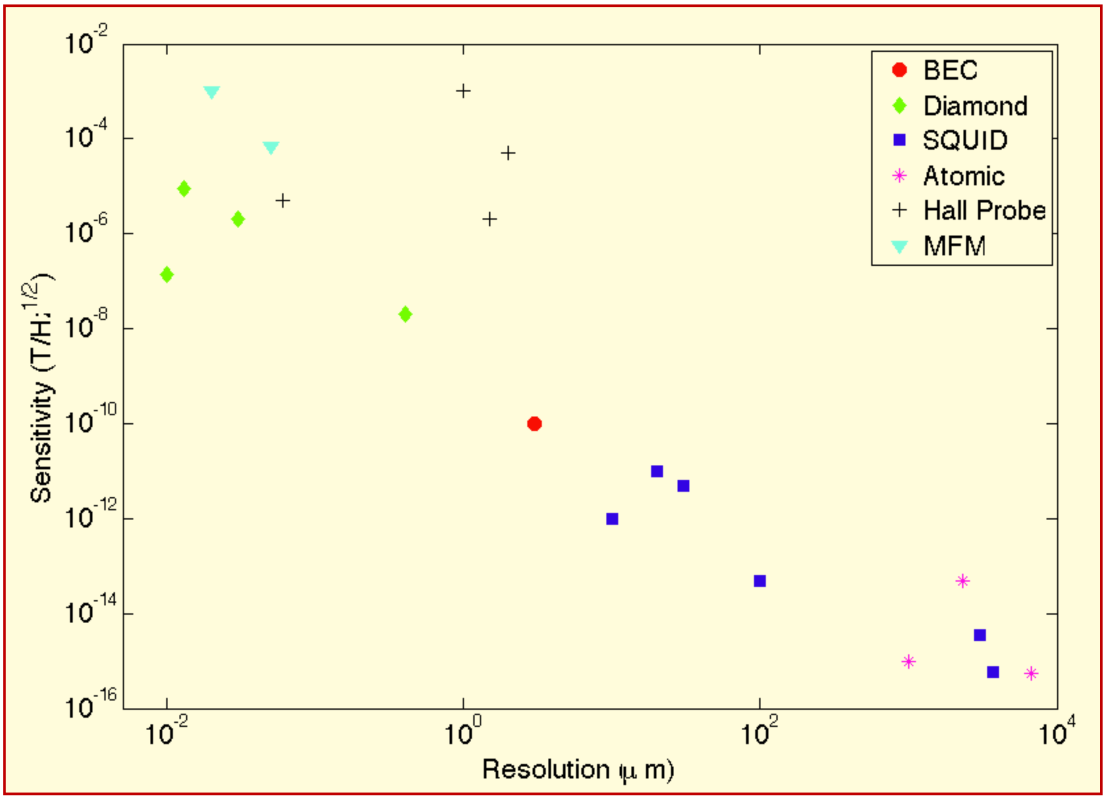

Figure 14 Chart of sensitivity versus resolution for magnetometers (courtesy of Prof. Peter Krüger Nottingham University)

In many experimental contexts, spatial resolution is as important as sensitivity. The literature is extensive and a full exposition of the sensors available is beyond the scope of this report. Figure 14 shows performance vs resolution for the most important families, and references used to construct the graph are contained in the appendix. Meanwhile, "conventional" magnetometers using atomic vapour cells continue to be refined[59].

4.4.3.3. Quantum current standards

NPL is developing quantum current standards to complement and verify the consistency of existing standards such as those quantum Hall effect resistance standard and the Josephson effect voltage standard[60]. Electron pumps are used to allow a single electron to pass through a gate each clock cycle.

4.4.3.4. Imaging sensors for electric and magnetic fields

Imaging sensors for electric or magnetic fields can be made using periodic or non periodic arrays. For example, with further developments, it might be practical to replace the "cap" containing

[59] http://physicsworld.com/cws/article/news/2013/apr/24/atomic-magnetometer-is-most-sensitive-yet
[60] See http://www.npl.co.uk/science-technology/quantum-detection/research/quantum-current-standards/

electrodes, or the more sophisticated SQUID[61] helmet mounted array, with an array of atomic vapour cells operating at room temperature.

Speculatively, one could envisage sprinkling a surface with diamond nanoparticles containing NV centres. A laser could scan these and the florescence recorded using an imaging system. This would result in a number of spatially random data points, however, a clear representation of the underlying field could be obtained via an accurate knowledge of the scan position of each return and the reconstruction technique of compressive sensing.

Bose-Einstein condensates trapped on an atom chip form the basis of a microscopic sensor that acquires high-sensitivity images of magnetic field maps acquired with single micron resolution. Different from conventional scanning probes, the image is obtained in a single shot (< 1 ms) in one dimension, so that a full two-dimensional image can be reconstructed from merely scanning along the remaining direction.

4.4.3.5. Nanoscale thermometry

Nanoscale thermometry may also be achieved in living cells using NV centres For example, a gold nanoparticle together with nanodiamonds may be placed together within a living cell adjacent to a coplanar waveguide. Controlled heat may be applied by laser to the gold nanoparticle. Nanoscale thermometry may then be achieved by using pulsed microwave radiation to perform Ramsay type precision spectroscopy.

To probe temperature fields, an atomic force microscope using point contact thermocouples is also an available technique. This was capable of mapping 10 mK resolution down to < 100 nm spatial resolution in 2010.

4.4.3.6. Electromagnetic radiation sensors and signal detection

These detect "photons" i.e. particles of electromagnetic radiation. They include trapped ions in cavities (QED[62] sensors), nanowires and quantum dots for RF charge sensing. Measurements of the number of photons present in a cavity (down to 1 or 0) may be made without altering their quantum states; such measurements are known as "quantum non demolition" measurements. Experiments to measure single microwave photons have been made using superconducting rings.

Arrays of nano-diamonds containing NV centres (see above) as well as Rydberg atoms may be used for non-invasive electromagnetic field sensing. An example is antennae or receiver characterisation up to millimetre waves or terahertz frequencies. Rydberg atoms have demonstrated record sensitivity to microwave electric fields and one might envision non-invasive laser-interrogated thermal vapour cell systems. These are studied at Durham University.

[61] SQUID = Superconducting Quantum Interference Device (requires cryogenics)
[62] i.e. quantum electrodynamic

4.4.3.7. Single photon detectors

There are many technologies available to detect single photons[63] and these are not necessarily "Quantum 2.0" technologies. However, the field is advancing rapidly and the output is an important enabler for other advances, such as quantum information processing. Apart from old (inefficient) technologies such as photomultiplier tubes, they include superconducting nanowire single photon detectors, quantum dots (Toshiba)[64], superconducting transition edge detectors, visible light photon counters (VLPC) and frequency up-conversion via periodically poled $LiNbO_3$. There is insufficient room here to discuss all of these in detail, however, one of the most promising detectors that can work in a standard lab environment is the silicon based single photon avalanche detector (SPAD). Although single detectors are useful for quantum information processing, arrays are being developed that can be used as imagers with novel characteristics. This example may have significant impact in the military and security domains.

SPAD applications include high end physics, medical imaging (including neurobiology) and astronomy/astrophysics. A recent specification is 350 - 1,000nm wavelength with 70-80% detection success and a repeat sense time of 50-100ps. An example of a commercial (medical) application is Positron Emission Tomography (PET)[65] where a band of SPAD devices surrounding the patient provides multiple detector points, currently 100,000, soon to be increased to 10^6. A new variant has also been described, where a miniature cylindrical probe can be inserted into a body cavity to achieve higher resolution when combined with external detectors. As well as nuclear medicine, these arrays have been used as tools for super-resolution microscopy, molecular imaging and particle physics[66].

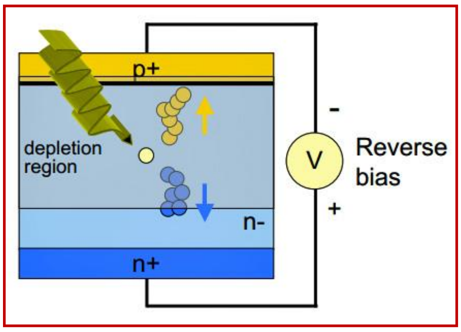

Figure 15 Outline of SPAD device

A planar structure results in a thin device that will run on relatively low voltages, and careful design is used to engineer a device with a "large" zone of constant electric field with very low edge effects. The device is robust against gamma radiation, magnetic fields up to 9.4T and proton radiation. Optimised parameters are dead (recovery) time, after-pulsing[67], dark counts (accidental, random avalanches), photon detection probability and timing resolution.

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[63] A useful review may be found at http://www.mba.ac.uk/pdf/EMBO2011/le_photon_detectors_for_quantum_appl_Hadfield_Nat_Phot_2009%5B1%5D.pdf

[64] See http://www.toshiba-europe.com/research/crl/qig/singlephotondetection.html

[65] This is a technique whereby radioactive material is introduced into the body. It decays to produce positrons (positive electrons) as a by product, these annihilate rapidly and locally by combining with electrons to yield pairs of gamma rays that produce ionisation or fluorescence in detectors. Timing and direction of coincident events may be used to build up a density map of the radioactive marker.

[66] See http://indico.cern.ch/getFile.py/access?resId=0&materialId=slides&confId=121655 for a comprehensive presentation on the subject given to CERN. and for a Philips presentation on a commercial product http://indico.cern.ch/getFile.py/access?contribId=54&sessionId=12&resId=1&materialId=slides&confId=209454

[67] During the avalanche some carriers can be trapped in deep levels. These trapped carriers are decaying (i.e. falling to lower energy levels) and can re-trigger events during subsequent gating occurrences

SPAD imagers can be used to collect photons over a wider area. There are three basic architectures; random access readout, event driven readout and fully parallel processing. These families of imagers each present their own combination of technical challenges:

- Photon counting efficiency and uniformity
- Spatio-temporal uniformity
- Cross talk
- Ultra-high dynamic range
- Spectral range
- Dead time
- Dark count rate
- Timing jitter (between absorption and output signal)
- Resolution of photon number

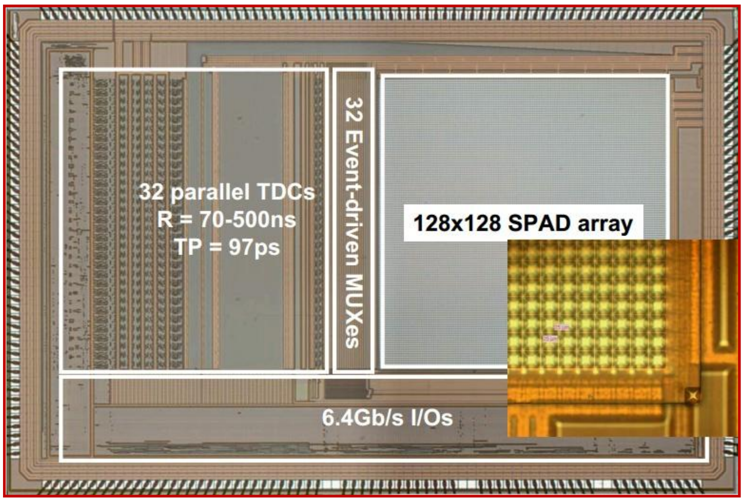

Figure 16 128X128 SPAD array

In 2009 the first fully integrated sensor array was announced. It consisted of a 128X128 SPAD array with 32 parallel time domain counters and a 6.4 Gb.s^{-1} I/O system. This was fast enough to achieve 3-d time of flight imaging. Development has continued following a progression similar to Moore's Law and a megapixel array is expected in 2014/1015. New geometries and materials are forecast to be used, resulting in larger formats and extension of utility into the soft X-ray region. Devices are envisioned which include multi-stage vacuum MEMS to detect harder radiation and InGaAs or InP structures. This will enable imaging as counting, which has a number of military and security applications, for example sophisticated "seeing in the dark".

4.4.4. Mechanical sensors

We do not seek to describe nanotechnology completely in this report, however, quantum enhanced mechanical (and other) sensors naturally overlap. Designers of nanotechnology systems need to be aware of, and take account of, quantum mechanical effects; these become significant at such small scales. A well known example is the presence of Casimir forces at close ranges; these are not yet fully understood. A joined up approach to research in quantum- and nano- is likely to become instrumental in creating novel technologies.

This is a comparatively recent (though extensive) field of research that couples mechanical motion or force to a read-out system, usually electronic in nature. Nano-mechanical oscillators may exhibit quantum behaviour e.g. appear in a superposition of states, and mechanical modes may be used for cooling. Some examples of such sensor systems are:

- The interaction between mechanical spin and vibration allows electron spin flips within molecules to be detected via recoil of a nanostructure or carbon nanotube, which subtly changes its conductance.
- Quantum nanomechanical cantilevers to perform RF / optical conversion on a single photon level
- Optomechanical cantilevers for magnetic field detection, atomic force microscopy ("remarkable" displacement sensitivity up to 20 MHz bandwidth), electrostatic actuators etc.
- Quantum acoustic sensors (e.g. trace gas sensing), mechanical oscillators as quantum coherent interfaces between incompatible systems[68]
- NASA has demonstrated a metal-oxide-polymer sensor based on tunnelling that changes its voltage-current characteristics when a mechanical force is applied. This is expected to become a self-powered or ultra low power sensor of exceptional sensitivity.
- Vibrations in graphene have been measured by using strong quantum vacuum interactions to shift the frequency of a quantum optical emitter.
- "Quantum microphone" single phonon detector i.e. detecting sound waves at the quantum limit (an emerging capability). Also, the possibility of single phonon emission is being researched.

This is a field that is likely to grow significantly over the next decade, with more applications becoming apparent as research progresses.

4.4.5. Some other quantum enhanced systems

4.4.5.1. Quantum fence

A (theoretically) perfect intrusion detection system may be set up by implementing a quantum communications channel around a perimeter[69]. Classical intrusion detectors (such as an infra-red beam transmitted along a path marking the boundary to be monitored) can in principle be defeated. A copy / re-transmit device could hide a break in the fence without its insertion or operation being detected. Because entangled quantum systems cannot be copied/re-transmitted in this way the intrusion can be reliably detected. Experimental work to date appears exclusively to use photons.

4.4.5.2. Telescope baseline extension

Current optical interferometers have limited baseline lengths, and thus limited resolution, because of noise and loss of signal due to the transmission of photons between the telescopes. The technology of quantum repeaters has the potential to eliminate this limit, allowing interferometers with (in principle) arbitrarily long baselines[70].

4.4.5.3. Ranging systems

Quantum mechanics provides various means for improving the resolution and accuracy of measurements made with light. The resolution of optical ranging and timing signals can be enhanced through the use of either frequency entangled states or photon-number-squeezed states (such as

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[68] See for example http://www.physics.utoronto.ca/~colloq/Talk2011_Lehnert/Lehnert.pdf

[69] See for example: **Intrusion Detection with Quantum Mechanics: A Photonic Quantum Fence** Travis S. Humble, Ryan S. Bennink, and Warren P. Grice, Oak Ridge National Laboratory USA

[70] See for example http://arxiv.org/pdf/1107.2939v1.pdf

what are known as N-photon Fock - or number - states). Proposed schemes require not just photon counting but photon-number resolution, i.e. photodetectors able to distinguish between these different Fock states by determining various photon occupation numbers. Such detectors are beginning to become available.

4.4.6. Issues and challenges

The function of a sensor is to give a meaningful output in response to the quantity being measured. Sensor technologies must be fit for purpose and possess appropriate sensitivity, resolution, specificity, response and recovery time, dynamic range and measurement reproducibility. Size, weight, power, stability over time, environmental fragility and cost are also important discriminators that will increase in importance as systems become mature and find wider use.

The issues to consider include:

- The requirement for the additional sensitivity or versatility offered by quantum sensors. Is the benefit over and above their classical counterparts needed for the application?
- Where the sensitivity of a detector is increased by orders of magnitude over its classical counterpart, spurious effects from stray fields or interference could make deployment very difficult. This will be a particular problem with electromagnetic sensors.
- That could cause major system issues that may demand additional complex technology to address. Such problems represent a subject area worthy of investigation in its own right.

4.4.7. Synopsis

There is an immense range of potential quantum sensing technologies and we are not able to describe them all here. There is the potential for orders of magnitude greater sensitivity than classical systems can achieve, especially with respect to position and orientation, and the electromagnetic environment.

Many of these could be made available within a time frame of 5-15 years.

There is a need for strong research activity in parallel to development efforts. While many quantum sensor types have already been proven in the laboratory environment to have better performance than the best classical sensor and thus can immediately be developed into a competitive product, they also have a lot of future potential which still has to be realised by research. The commercial world will thus need a strong link to ongoing/increased research efforts to stay competitive in a very rapidly evolving market. This need is highlighted, for example, by recent developments of large momentum beam splitters for matter waves, which offer the potential of 1000-fold improvement in sensitivity over current quantum gravity sensors.

4.5. Quantum simulation and computing

In this section we review (at a basic level) the principle genres of quantum computing and quantum information processing. We will cover both special and general purpose quantum computers. After an introduction to key concepts, we will discuss first the paradigms and then the technologies used in quantum computing.

4.5.1. Introduction

Richard Feynman first proposed a basic model for a quantum computer in 1982. It would be able to simulate the evolution of a quantum system where, in general, a classical machine of sufficient complexity could not. In 1985 David Deutsch extended the concept to a universal quantum computer, analogous to the universal Turing machine.

This resulted in the circuit model of quantum computing, a quantum analogue of a classical computer, usually used as a paradigm for such machines. Proposals to realise quantum computers have been many and varied, and demonstrations of rudimentary examples have been produced. After the year 2000, several families of quantum computer have been proposed, some are equivalent to the circuit model, some are (arguably) not[71].

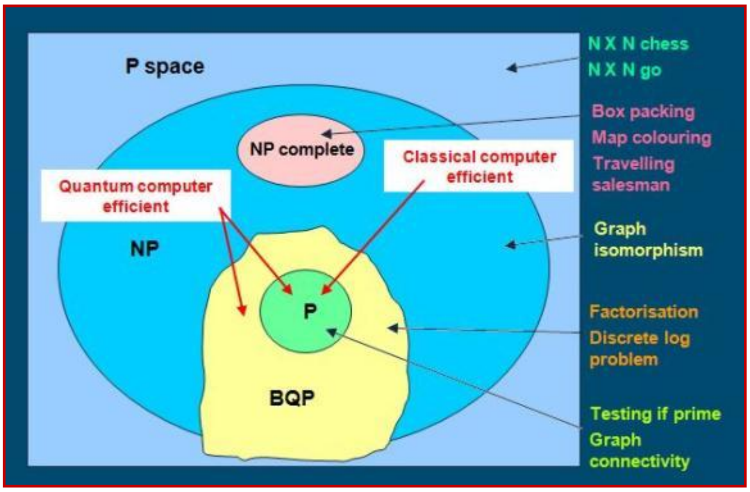

Figure 17 A simplified view of the concept of computational complexity

The types of problem that a quantum computer may be able to solve which a classical machine (realistically) cannot are not yet fully understood. The explanation lies in the field of computational complexity theory. A full description is beyond this paper although we show an indication of the problem complexity hierarchy in figure 17. Some problems (such as playing an optimum game of N X N chess) are too hard for a quantum computer to address - at least on a significant scale. The usual strategy in such cases is to seek approximations to the true optimum which are "good enough".

Below we will discuss and comment on principal families of quantum computer and some general challenges before briefly describing areas where we understand they have a distinct advantage over classical machines.

4.5.2. Classical and quantum information

Classical information is a configuration of a classical system that can be duplicated and stored in many different forms. Essentially, it is a manifestation of symmetry. For example, footprints contain information regarding someone who has previously walked on a surface. The basic (whole) unit of

[71] Simplistically, equivalence implies that they can perform the same type of computation without an impossible increase in the computational resource being required. Some types of quantum computer can only perform a limited range of tasks.

classical information is now widely accepted as a "bit" of information and takes the form either of a "1" or a "0"[72].

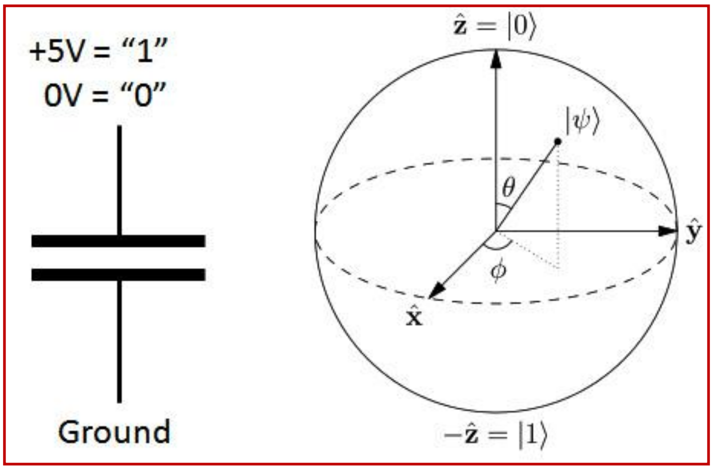

Figure 18 Conceptual representation of a classical bit (left) and a quantum bit (qubit) right

Quantum information is physical information that is inferred to be held in the quantum state of a system. It is never fully accessible to classical interrogation and in theory is infinite in its accuracy. The basic unit of quantum information is the qubit. Conceptually, the qubit is a number that can be represented as any point on a sphere, where the "north pole" is equivalent to a "0" and the south pole is equivalent to a "1". Unlike the classical case, such a system can be in a *superposition* of the two states at once. A qubit cannot be read without its state becoming (definitely) the measured value, either "1" or "0". An arbitrary *quantum* state, however, cannot be copied. The measured value is probabilistic and depends on the latitude (angle) of the point on the sphere. See figure 18.

Quantum operations inside a functioning machine will move the point around the qubit "Bloch sphere" in a pre-defined way, or cause two or more qubits to interact in such a way that the point on one "sphere" causes pre-defined changes in the others. This is similar (simplistically) to logical operations in conventional machines.

It is important to understand that although the "size and power" of a quantum computer is popularly defined as the number of qubits in a machine, that is not the only important factor. The mechanism for operating the qubits, or the connections in the machine that define the interaction between the qubits (depending on the type of computer) are equally important. An analogy is to label the power of a classical machine with the number of switches (or transistors) without regard for the interconnections[73].

4.5.3. Paradigms of quantum computing

The paradigms of quantum computing are not always separable from the technologies. For example, certain technologies may favour one or the other paradigm in terms of ease of implementation.

4.5.3.1. Circuit model quantum computers

Circuit model quantum computers are the most often used to explore quantum computing. Their operating principles may or may not ultimately be seen as the most appropriate paradigm as the

[72] Classical information may be present in fractions of a bit. For example, where one bit of information would definitely choose "A" from the set {A,B}, less than one bit would simply represent a probability intermediate between 1 and 0 of "A" being chosen over "B".

[73] In classical computing and communications, the connectivity and its use of power are rapidly becoming the parameters that will limit future progress. It is interesting in this context to note the exceptionally dense connectivity of the human brain.

ideas are derived from considering the operation of classical digital computers. These in turn are derived from the paradigm of Boolean logic, arithmetic, and switches and relays. Those are familiar, but do not necessarily sit well with the behaviour of quantum objects.

In a classical machine, the information is stored as bits of information that are subject to a sequence of operations that may be reduced (ultimately) to a complicated set of interconnected one and two bit operations. A quantum circuit model takes an array of qubits and subjects them to a series of precisely timed interactions via an arrangement of what are known as "quantum gates". These may be broken down into primitives of one or two qubit operations[74]. The machine needs to be set up with a structure that provides the appropriate interactions and measurements at the right point in the calculation. That arrangement can be very complicated. The operation is typically represented by a diagram such as that in figure 19 where the progress of the qubits |0> and |1> is from left to right and the operations defined by the boxes.

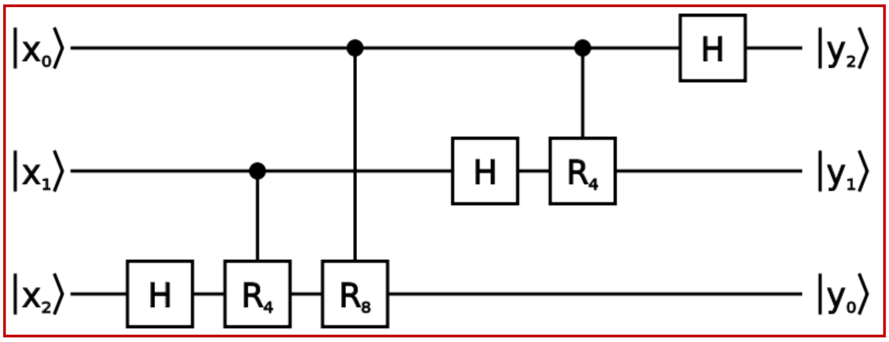

Figure 19 Representation of a typical quantum "circuit" for three qubits

4.5.3.2. Measurement based quantum computing (MBQC)

This genre of quantum computing is also known as the "cluster state model" and has no direct classical paradigm. Clusters of qubits in a highly entangled state are generated and used for computation. Some variants are also known as "one way quantum computing" i.e. the Raussendorf and Briegel variant. This method is seen as an attractive way forward by workers in the field.

The standard circuit model approach assumes the ability to perform any quantum operation from a universal set of gate primitives. This is difficult to achieve practically, particularly in multi-qubit configurations. In an extended computation, in realistic conditions, the quantum state being acted on would be rapidly corrupted and the calculation would fail (see issues and challenges, in 4.5.11 below). Whilst error correction can correct the fault it introduces significant complexity and requires additional computing resources. It is possible to address many of these problems by using the MBQC model instead.

Gottesman and Chuang invented measurement based quantum computing requiring only single qubit gates plus so-called Bell basis measurements or Bell measurement gates. It was shown

[74] It is beyond the scope of this paper to provide a deeper explanation, however there is plenty of material in Wikipedia, for example in http://en.wikipedia.org/wiki/Quantum_computer

subsequently using this approach that universal quantum computation is possible with only linear optical elements and photodetectors. Two Bell measurement gates can move an arbitrary 2-qubit state between two locations using a process known as "teleportation" (see section 4.3.5) and, given the assumed ability to store instances of an entangled state, provide the basis for a more complex machine to perform any feasible quantum operation.

An alternative approach was proposed by Raussendorf and Briegel in 2001, more often known as "one way" quantum computing; only single qubit measurements are required. The system is prepared in an initial, highly entangled, state called a cluster state. A set of measurements is made on single qubits and the order and choice of basis for these measurements defines the computation, the path chosen relying on the results of previous measurements. It is a "one way" scheme because, as the computation is performed, time asymmetry is introduced and the computation can only be run forwards. The approach is attractive because the technical challenge becomes that of preparing the initial cluster states rather than executing the subsequent single qubit measurements: these are assumed to be straightforward. In reality this may not quite be the case, since the single qubit measurements are required not to affect neighbouring qubits and this limits possible architectures.

4.5.3.3. Topological quantum computers

More exotic possibilities arise in the physics of particles confined to move in only two dimensions, particularly at very low temperatures and in the presence of very strong magnetic fields. A topological quantum computer is a theoretical system employing anyons. Anyons are two dimensional quasiparticles (i.e. excitations that usually exist on surfaces) whose world lines (trajectories) form braids in two dimensional space plus time. As time proceeds, the calculation takes place via interactions between these anyons. The system is thought to be comparatively robust due to the stability of these braids (they possess structures similar in concept to knots)[75].

The idea behind Topological Quantum Computing is to encode information into topological degrees of freedom which are intrinsically error free in terms of error avoidance rather than error correction. Topology is a mathematical discipline concerned with geometrical properties which are not affected by continuous deformations including stretching and bending. (Hence, a tea cup is considered to be topologically the same as a doughnut because of its handle)

Such machines would be similar in computing power and capability to circuit models of computation, although certain problems may map more or less easily on to their structure. None of these machines have yet been demonstrated, although work has commenced on some of their building blocks. Experimental evidence for the existence of some types of anyons was observed in 2005. The type of anyons required for topological quantum computing are thought to exist in rotating Bose Einstein condensates, quantum spin systems and superconductors.

4.5.3.4. Adiabatic quantum computers

Adiabatic computation is a well represented field of study. Experimental implementation is mostly at a relatively primitive stage with the exception of D-Wave (see below). D-Wave as developed to date

[75] See for example http://iopscience.iop.org/1367-2630/focus/Focus%20on%20Topological%20Quantum%20Computation

is classed as an adiabatic quantum computer although many argue that its dependence on quantum phenomena may be small or non-existant.

The principle of operation is allied to quantum annealing. A system is prepared in its lowest energy state using a simple energy "surface". The surface is then slowly (adiabatically) distorted into a more complex state and the final configuration of the resulting system provides the "answer".

A useful (if simplistic) analogy is that of a ball on a dimpled surface, not moving because it is in its lowest energy state. The dimpled surface is then slowly distorted into a more complicated landscape and the problem is to discover the lowest point. Normally, the ball will roll downhill but if the surface is very complicated it might get "stuck" in a local minimum i.e. not at the very bottom. In a classical machine, the difficulty of getting stuck is ameliorated by jiggling the ball around using various algorithmic prescriptions, however, this can be a long process and frequently does not yield the best answer. That is known as "simulated annealing".

A quantum adiabatic machine will solve such optimisation problems without getting stuck - provided that the surface is distorted slowly enough. Our metaphor of a ball rolling down hill now allows "quantum tunnelling" through obstacles in the landscape to reach the lowest point. These surfaces can be multidimensional and very complex. Many problems can be converted into such an optimisation problem. This applies not only to obvious candidates such as the travelling salesman problem, but also those such as integer factorisation[76].

4.5.3.5. D-Wave

D-Wave is a machine produced by a private venture Canadian company of that name. It uses a chip containing a cryogenically cooled array of magnetised loops isolated as much as possible from the electromagnetic environment. This array contains a network of connections between the qubits and is designed to settle into a state that represents the solution to an optimisation problem based on preset qubit biases and programmable coupling constants.

Although it is usually referred to as an adiabatic quantum computer, it is not a universal machine[77]. We have chosen to separate out D-Wave as the technology is a technical *tour de force* and well advanced, although, strictly speaking, it does not represent a paradigm in its own right. There is a great deal of controversy in the community as to whether or not it uses quantum effects, although it has recently been shown that evidence for entanglement has been found within, and between (adjacent), unit cells of 8 qubits.

D-Wave claim that the machine works using "co-tunnelling" of the qubits into the lowest energy state, and that the efficacy of this mechanism can be increased by a small amount of noise. Although a programming cycle currently takes 100ms, the machine can perform 10,000 "runs" of a program each second ,and such repeated operation may (in appropriate cases) be used to arrive at a

[76] Integer factorisation using a quantum machine does not necessarily require Shor's algorithm.
[77] A universal machine would be capable of performing a full set of functions offered by a generalised circuit model.

probability distribution that represents the "answer". There is extensive literature available[78]; we do not have the space to review all of it here.

The latest machine has 512 qubits (not all of which can be operated at any one time due to small, residual magnetic fields) and limited connectivity. The link weights and qubit biases effectively have four bits of dynamic range. D-wave claim that the machine is scalable, at least to circa 10,000 qubits. However, if this is achieved, the qubit to qubit connectivity (representing the available problem graphs) is likely to become much sparser, with accompanying intra-chip range problems, although the company say that they can address this problem by tying qubits[79] together. The machine has sparked considerable debate in the community regarding its internal operation (mainly concerning the presence of entanglement), and competitiveness *vis-a-vis* conventional computers.

As currently realised, D-Wave is an optimising machine with many of the characteristics of an adiabatic quantum computer. It will solve certain quadratic binary optimisation ("QUBO") problems. However, D-Wave say that there are many possible design variations and they run ~8 design cycles each year. They are designing a universal adiabatic quantum machine, and variants with increased connectivity. If the machine can be made to be "universal", does continue to scale successfully upwards in size, and works as predicted, it will overtake the available performance of conventional machines within 3-5 years.

4.5.3.6. Boson sampling computers

The principle of the "boson sampling computer" has been known for almost a decade, although it has only recently attracted significant interest and experimentation after detailed analysis by Scott Aaronson[80]. It can be considered to represent a paradigm which is an "odd one out", set apart from the mainstream effort in quantum computing. It is not a universal quantum computer.

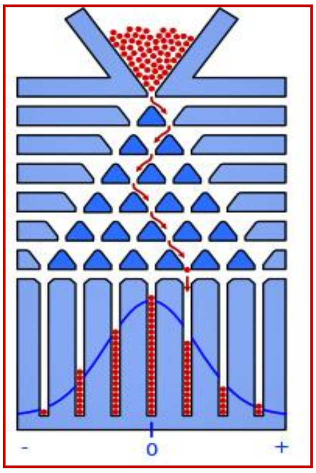

Figure 20 A Galton board

Bosons are elementary particles with integer spins; photons are chosen as being suitable candidates. A number of photons are suitably prepared (i.e. indistinguishable and with precise overlap) and sent into a network of optical couplers. The probability distribution detected at the output ports represents a computation that is (loosely speaking) equivalent to finding the permanent of a matrix[81]. Although this is not a universal quantum computer, the computations represent a higher complexity class[82]. Approximately, the output is the answer to "how many belong to this set" rather than "is there a member of this set present". It is considered to be impossible for a classical machine to emulate a boson

[78] See the D-Wave site http://www.dwavesys.com/en/dw_homepage.html or for an independent view (with useful references) http://physics.aps.org/articles/v6/105

[79] In the current design, for full graph connectivity, the effective number of qubits is √n out of the total

[80] A detailed technical exposition can be found at: http://www.scottaaronson.com/papers/optics.pdf

[81] The permanent of a matrix is like a determinant except that the signs do not alternate between the terms in the formula. This is much harder to calculate than the determinant as short cuts have been discovered for the latter.

[82] The complexity class is P# rather than BQP (bounded quantum polynomial time).

sampling computer if 20 or more photons are used.

A very simple classical analogy to a boson sampling computer is a Galton board. This is a board laid out similarly to a game of bagatelle or pinball. The example in figure 20 shows such a board set up to calculate a normal (Gaussian) distribution.

Recently, a small machine has been demonstrated by Prof Walmsley and Joshua Nunn at Oxford, and Peter Smith at Southampton[83]. They are now engaged in a project with the aim of realising a 24 photon machine. Whether boson sampling computers will be able to solve a wide enough range of problems to make them useful is a matter of debate[84].

4.5.3.7. "Analogue" quantum computers

There are a number of approaches to what might be termed "analogue" quantum computing. This concept is similar to electronic analogue computers, that use continuous values of current and / or voltage to perform a computational task rather than "1"s and "0"s. They would principally be used for simulation (see section 4.6.5). Some examples are:

4.5.3.7.1. Continuous variable quantum computing[85]

In this form of quantum computer, the information is stored as eigenstates[86] of a continuous variable such as position or momentum. It is essentially a theoretical construct with few followers. It could, for example, be used to determine the allowed values of fields at certain points. There is some overlap with the concept of computing with cluster states[87]. It could be argued that CVQC is a separate paradigm in its own right.

4.5.3.7.2. Optical lattices

Optical lattices consist of an interference pattern, i.e. standing waves of photons, generated by intersecting laser beams. These are arranged such that there is a one, two or three dimensional grid of energy minima ("holes") in which trapped ultra-cold atoms can sit, see figure 20. The array needs to be held in an ultra-hard vacuum, although cryogenics are not strictly necessary. Such a set up has been suggested as a method to implement quantum computing, using the individual trapped atoms as qubits. Needless to say there are many practical technical difficulties.

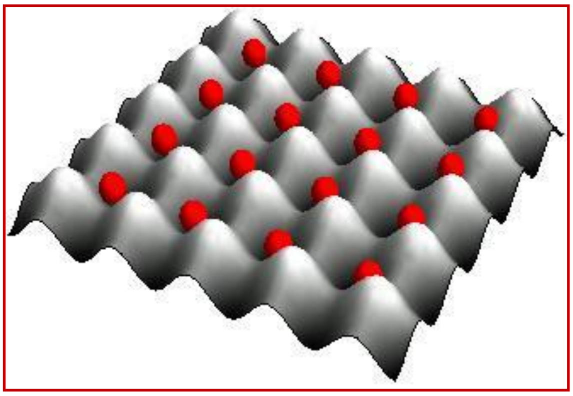

Figure 21 Conceptual representation of 2-D optical lattice

By varying the potentials of the field structures in the lattice, and its contents, the system can in principle be used to emulate fundamental systems by dint of its energy "landscape" (known as the

[83] See http://www.orc.soton.ac.uk/publications/57xx/5716.pdf
[84] One possible application might be the "monomer - dimer problem".
[85] http://www.iqst.ca/events/csqic05/talks/travis.pdf
[86] These are basic allowed states of the system that are the only ones that can be found as a result of a direct measurement.
[87] See for example http://arxiv.org/pdf/1001.2215v1.pdf

Hamiltonian). These energy landscapes can be set up to mimic the behaviour of solid state systems or even some of those that can never be produced on Earth, such as magnetars (stars with exceptionally strong magnetic fields)[88].

4.5.3.7.3. Atomic clocks

Recently, atomic clocks have been proposed as simulators, e.g. for quantum magnetism[89]. NIST and the University of Colorado discovered that a lattice clock (*op cit*) containing approximately 2,000 neutral strontium atoms could, in certain conditions, interact like atoms in magnetic materials. This could be used as a variety of optical lattice computer.

4.5.3.7.4. Bose Einstein Condensate

These have been proposed for communicating quantum information inside a quantum computer[90] and for analogue computation[91]. As yet, these ideas are outside the mainstream of research.

4.5.4. Principal quantum computer technologies and UK strengths

4.5.4.1. Ion traps

Ions, i.e. charged atoms, may be confined in three dimensions using oscillating magnetic fields. Initialisation, manipulation and measurement of their states may be performed by lasers. The qubits may be defined by a pair of hyperfine levels (hyperfine qubits), a ground state and an excited state (optical qubits), or spin states (spin qubits).

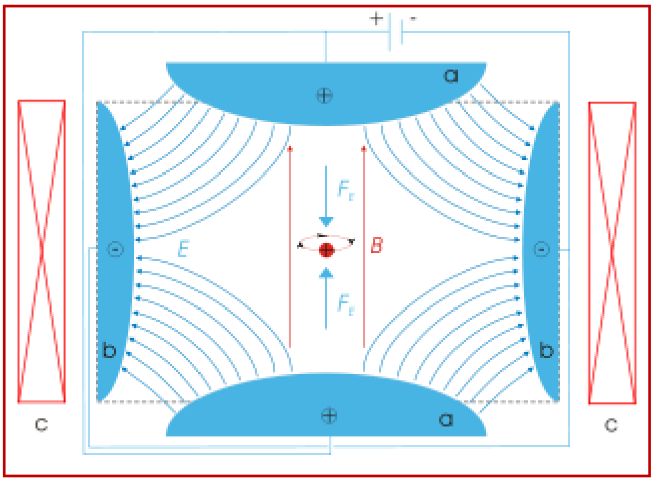

Figure 22 A Penning Trap is an arrangement of electric and magnetic fields designed to trap an ion

UK has good strengths in ion traps. There are some very large worldwide groups (Wineland, Blatt), but UK has strengths in ion traps in general and areas specific to computing e.g. Lucas' group (Oxford) has focused on delivering world-leading levels of precision in control of one- and two-qubit gates. Meanwhile, Sussex (Hensinger) develops novel ion chip technology and a new method for entanglement generation using microwave radiation (rather than lasers) in order to build large scale quantum computers and quantum simulators[92]. This should become a fully scalable technology. Danny Segal at Imperial College is purported to have the best control of ions in a Penning trap in the world.

[88] For a UK leader in the field, see http://mpa.ac.uk/muarc/people/kaibongs.html
[89] See for example http://www.sciencedaily.com/releases/2013/08/130808142132.htm
[90] See for example http://www.sciencedaily.com/releases/2013/04/130411105827.htm
[91] See for example http://phys.org/news145535050.html
[92] see for example: Simple Manipulation of a Microwave Dressed-State Ion Qubit, S. C. Webster, S. Weidt, K. Lake, J. J. McLoughlin and W. K. Hensinger, Phys. Rev. Lett. 111, 140501 (2013) http://link.aps.org/doi/10.1103/PhysRevLett.111.140501

4.5.4.2. Photonic quantum computing

Photonic quantum computers use photons as "flying qubits". Typically, they could consist of a combination of sources, couplers, detectors, switches and gates. There are many possible architectures. A long term vision is to integrate optical quantum information processors with microelectronics.

UK has excellent presence in this area. With the O'Brien group in Bristol and the Walmsley led groups in Oxford, the UK has world-leading strengths both in purely photonic systems and in the approach of phononic qubits+matter memories. Competitors include White (Australia) and Walter group in Vienna.

4.5.4.3. Superconducting qubits

Recently relocated to the UK are some strong researchers previously associated with the NEC effort, including: Pashkin (Lancaster), Leek (Oxford), and Petrashov (Royal Holloway). The UK therefore has a growing strength here, although we should note that there are massive existing strengths in Yale and others

4.5.4.4. Cold atoms and molecules

In this area there is a heavy international presence from e.g. Bloch and Zoller etc. There are, however, strong UK efforts. Implementing operations between elements is the recognised challenge; solutions are either (a) use cold molecules rather than atoms (for example Hinds in Imperial) or Rydberg atoms (e.g. Adams at Durham).

4.5.4.5. Solid state spin systems

- GaAs quantum dots, electrostatically defined, electrically controlled: efforts in UK include, Elzerman (who performed seminal spin-readout experiment on these systems) recently relocated to UK (UCL) and Pepper (UCL). The Cambridge group of Richie is considered a UK leader in this technology. International competitors include Yacoby (Harvard), Marcus (Copenhagen) and Kouwenhoven (Delft).
- Optically active, self-assembled GaAs dots. Good UK strength and activities with Atature (Cambridge), Rarity (Bristol), Skolnick (Sheffield) and Shields (Toshiba). A whole quantum circuit can be fabricated based on this technology, and this is the subject of a programme grant and topic of research at Toshiba. International strength with groups of Vuckovic (Standford), Imamoglu (ETH).
- Impurities in Silicon. Offers the longest measured coherence times of any system (up to 3 hours for the nuclear spin at cryogenic temperatures), and among the highest single-qubit 'quality factors' (decoherence time / single qubit gate time: 10^8 for the electron spin and 10^9 for the nuclear spin). Seamless integration with classical CMOS technology is another important advantage, it is therefore "an approach with a complete solution (memories, processing etc)". UK has world-leading strength in a number of aspects of this platform, including fabrication at the atomic scale (Curson, Schofield, UCL), coherent control of electron and nuclear spins (Morton, UCL), orbital states (UCL, Surrey), electrical measurements of donors and dots in silicon (Cambridge and Hitachi). International leaders include Simmons's new group in Oxford, and Morello and Dzurak, University of New South Wales.

- Diamond NV centres. One of the few systems with realistic prospects for room temperature operation, however there are advantages to operating them at cryogenic temperatures. The relative ease with which single centres can be measured has led to a number of near-term applications, especially with regards to sensing (see above). Specific UK strengths in e.g. cavities (Smith, Oxford), registering NV centre to other technologies (Rarity and O'Brien, Bristol), exploring different kinds of impurity (Atature, Cambridge) etc. However very heavy international competition in the form of Wachtrup (Stuttgart), Jelezko (Ulm), Awschalom (Chicago), Lukin (Harvard), Hanson (Delft).

4.5.4.6. Adiabatic systems

In UK there is a significant effort at UCL (largely funded by industry) toward this class of architecture and its direct applications to learning and optimisation problems in computer science. There also remains a strong collaboration with the University of Chicago on underpinning experiments. Loughborough (Samson) also has an interest, and expertise in superconducting qubits will be needed if the (highly controversial) D-wave machine emerges to be genuinely useful.

4.5.4.7. Hybrid systems

Interfacing different quantum systems to create 'hybrid systems' is important for:

- Addressing the challenges of building a quantum computer by using the relative strengths of different systems (e.g. different systems for memory and processing)
- Building interfaces between 'static' and 'flying' qubits to connect quantum processors, potentially in a secure way
- Specific devices such as quantum memories and quantum repeaters, or quantum transducers (e.g. between optical and microwave ranges)

Generally the coupling of matter systems, whether atomic or solid-state, to photons is a UK strength that may be important in achieving scalability. The UK has, therefore, the opportunity to become a world leader in this field and much can be achieved if we foster collaborative work between groups. For example:

- Trapped ion and superconducting qubits, e.g. ion is memory for the superconducting qubit (Hensinger at Sussex is developing this technology as part of the IQIT consortium[93])
- Trapped ion/atoms and photons (Kuhn (Oxford), Keller (Sussex))
- Rydberg ensemble atoms as interface between optical and superconducting systems
- Spins and superconducting circuits (Morton, UCL; NPL)
- Quantum dots and trapped ions (Atature, Cambridge)

4.5.5. Quantum simulation

Part of our brief has been to identify suitable "stepping stones" on the route to the highest impact quantum technologies. This is particularly difficult for quantum computing and information processing in general, where achieving sufficient scale is an issue.

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[93] See http://www.iqit-research.eu/home/

Hence, full scale, general purpose quantum computing in a commercially viable sense remains a long term goal. However, special purpose computing may be feasible in the medium term, most likely in the form of simulation. This is analogous, at least partially, to the development of classical machines. There are two types of quantum simulator; analogue and digital.

Analogue is possible using a variety of systems and is a particular strength of cold atoms where the exact *number* of atoms is not an issue but having complete system control is. Therefore one can aim to exhibit limited control and mimic the system of interest, usually by means of shaping the Hamiltonian (energy landscape) of the system. An estimate of the time required to develop a working demonstrator is four years (Charles Adams). Examples of applications include:

- Simulation of misaligned layers of graphene to enable a new generation of electronics
- Energy transfer in thermoelectrics (e.g. Lambert's work (Lancaster))
- Energy transfer in synthetic photosynthesis systems
- Semiconductor / organic materials interfaces
- Medical applications, e.g. design of new drugs or simulating cellular functions
- Design of materials e.g. to discover new high temperature superconductors

The development of "digital" simulators is more difficult and the issues align with those of quantum computing in general. However, digital simulation is extremely powerful, since, in principle, it can permit the simulation of *any* system. Thus, for example, there is the possibility of discovering completely new chemistry purely by simulation.

Porras (Sussex) is a world-leading theorist in the field of quantum simulations with trapped ions and collaborates with Hensinger (Sussex) on the practical realisation of large scale ion trap quantum simulators.

O' Brien estimated that a device suitable for specific problems lying outside physics (e.g. chemistry and biology) delivering ~ 100 qubits might be developed in about five years given sufficient funding.

4.5.6. Software and theory

The literature describing software, theory and error correction is extensive but has often followed, in an academic sense, the most interesting or revealing trajectory of research rather than being closely coupled to the immediate needs of the experimentalists. The full potential of quantum computing is not yet understood and will be difficult to discover. For example, the potential role that quantum discord could play is controversial. The mathematics used to explore the subject is not trivial. The general opinion seems to be that software will be lagging behind what the physics could offer when the outstanding challenges have been met.

The scope for quantum computing to outperform classical computing by a very significant factor appears to be limited to comparatively few algorithms, although most are agreed that the scope for simulation (both "digital" and analogue) of quantum systems is significant. However, this situation is a subject of intense study and breakthroughs continue to be made[94]. The latest is concerned with evaluating certain characteristics of systems of simultaneous linear equations, possibly using a hybrid classical / quantum approach.

Applied quantum technology theory is nevertheless a significant UK strength; UK results are quoted and used in groups worldwide. Examples include Imperial (Kim, Rudolph), UCL (Bose, Browne), Leeds (Spiller, Kendon), Oxford (Benjamin, Jaksch, Vedral) who have teams looking at modelling, architectures and thresholds. Our proposed quantum technology partnership would benefit from a thorough survey of UK theory activity, especially *vis-a-vis* UK experimental expertise.

A brief survey finds that many universities host good but small quantum technology theory groups but there are a number of universities that have multiple teams of quantum computing theorists working on applied issues (so not, say, thinking about the deep nature of entanglement and also excluding work on quantum materials not primarily related to computing). These universities comprise Imperial College, UCL, Oxford and Leeds:

- Kim (Imperial) - Atom/optical theory;
- Rudolph (Imperial) - "Blind" QIP, loss tolerant encodings relevant to photonic QIP;
- Bose (UCL) - spin-chains for quantum technology;
- Browne (UCL) - ‘magic state distillation’ for fault tolerant QIP;
- Fisher (UCL) [mainly quantum materials];
- Benjamin (Oxford) - fault tolerant architectures for quantum technology, energy flow calculations;
- Jaksch (Oxford) - simulation of quantum systems;
- Vedral (Oxford) - thermodynamics of quantum systems;
- Pachos (Leeds) - Topologically protected quantum computing;
- Kendon (Leeds) - Ancilla based QIP;
- Beige (Leeds) - Atom/optical theory;
- Spiller (Leeds) - Optical QIP, superconducting and few qubit systems.

Bristol and Cambridge have a number of quantum theory groups whose foci are either quite abstract quantum information or quantum materials.

4.5.7. Issues and challenges

There are a number of issues with quantum computing, most of which need to be resolved before any significant value adding computational activity can take place.

- Decoherence. To exercise its computational power, a quantum system needs to maintain a superposition of its states. Superposition is by nature extremely fragile and is immediately destroyed when tested (=measured) by any interaction with the environment; the qubits in the quantum computer cannot continue to evolve in a coherent manner. Therefore, the elements of the system performing the computation have to be completely separated from

[94] A reasonably comprehensive exposition can be found in the form of the "quantum algorithm zoo" see http://math.nist.gov/quantum/zoo/

the environment and no information exchange can take place. This becomes a rapidly increasing challenge as the scale of the system increases, somewhat akin to attempts to maintain wave-like properties in objects of increasing size.

- Thus: Scalability – difficulty of realisation increases rapidly with size. Large machines (> 10^3 qubits plus suitable interaction schemes) are needed for the most significant applications.
- The exact benefits of QC appear to be poorly defined and more limited than most people realise. The range of applications needs to be defined and more “killer apps” found. There is a great deal of misunderstanding as to which problems could be usefully addressed by a quantum computer. For example, it would not be advantageous to use a quantum computer to perform ordinary arithmetic.
- There is a key engineering conflict between the requirement for complete isolation and the need to interface to inputs and outputs at will.
- Irreducible problem complexity causes trade-off between difficulty of preparing physical states and difficulties in software preparation. This is analogous to the trade-off in classical machines between the complexity of the instruction set and that of the program. It is a "coding" problem in the Shannon sense[95].
- There is a multiplicity of potential approaches, each with (mainly) radically different characteristics and foibles. To explore them all would significantly dilute R&D effort. Therefore, a compromise must be made between "picking a winner" and spreading resources too thinly.
- Lack of classical paradigm makes the area difficult to understand and slows progress.
- Misconceptions – a QC is not fast (in terms of “clock speed”) and will not accelerate every type of computation. There are complexity classes that are (thought to be) too difficult for a QC to address efficiently; they can't solve every problem. The most common misconception is that quantum computers can perform "every possible computation at once, in parallel". It's just not like that!
- Usually, there’s a finite chance of getting the wrong "answer". This usually needs a setup strategy and a verification strategy. Can the answer be verified easily? Are there many similar answers returning the same, or almost the same, measure of success? Note: to measure "how many" rather than "finding" is often in a higher computational complexity class (see notes on boson sampling computers).
- Error correction and its effect on complexity and scale .

The comments above are generalisations and refer to the physics and engineering challenges. Others, general to all quantum technologies will, be discussed later in this document.

Some of the issues (above) could be mitigated by having a distributed quantum computing system. That would consist of a number of small machines connected by a quantum information network.

[95] Computing can be viewed as a communication channel between input and output, where the instruction set defines the symbols that are used to translate the information.

4.5.8. Synopsis

A demonstration of the full technological realisation of quantum computing (in the context of the conventional "circuit model") is probably at least ten years away. Some argue that a realisation of a fully flexible machine tens of thousands of qubits in size or more is impossible; the answer is not yet known.

A solution based on new technology or new physical insight could emerge at any time. The D-Wave machine represents an heroic engineering effort that has had some success and it is capable of addressing certain optimisation problems. However, it is arguable as to whether it can do any better than a well programmed top of the range PC, or be scaled effectively to a size where it can address very important challenges. The boson sampling computer could probably be realised on a significant scale within 5 years, however, it would seem to be limited to addressing a very narrow class of useful problems.

Attempts at developing "software" and associated theory such as error correction is a widespread field, though usually focussed on the circuit model and not always well connected to the work of experimental teams.

Overall, the potential of quantum computing is powerful but may be limited in its applications, although the full range is not yet fully understood.

4.6. Molecular and solid state

In this report we have considered quantum technologies from a defence and security perspective under their main headings. Many quantum applications overlap significantly with nanotechnology and material science. A full treatment of that large subject area is beyond the scope of this report, however, there are some potentially disruptive technologies based on solid state and molecular research that are important enough to consider as part of our process. Some examples are:

4.6.1. Energy generation and recovery

Energy generating and energy saving technologies are crucially important in the commercial sector and could become a source of immense economic benefit. Here, we refer to significant advances in "conventional" quantum technology as well as "quantum 2.0".

Recent research has demonstrated the possibility of assembling, at the molecular level, highly efficient devices that will be able to deliver electrical power from waste heat[96]. This technology will create a new generation of highly efficient thermoelectric materials and devices by exploiting quantum interference at a molecular level. Proof of principle has already been demonstrated in C_{60} junctions. It is likely to become immensely important if it can be realised on a significant scale. To date, conventional systems have been relatively inefficient and mainly used for minor applications. There is a UK gap in experimental capability, which will need multi-discipline collaboration.

Third generation photo-voltaic devices are eventually expected to deliver light with efficiencies of greater than 50%. These are likely to utilise quantum 1.0 or quantum 2.0 effects in semiconductor

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[96] See for example http://arxiv.org/pdf/1305.3229v1.pdf and "Engineering the thermopower of C_{60} molecular junctions" Evangeli *et al*, NanoLetters (2013)

nanostructures, for example via uniform periodic quantum dot arrays, or multiple exciton generation.

Advances in LED technology will allow high efficiency LEDs (> 50%) to be produced in the IR, visible and UV in compact, miniature units which will save significant amounts of energy.

4.7."Black Swans"

"Black swans" are unexpected technologies with significant applications or implications that may come into play rapidly, as defined in the Blackett report[97].

Figure 23 Superconductor levitating above magnets at liquid nitrogen temperatures

It is quite possible that novel quantum technologies that are not contained within our headings can emerge with potential for disruptive defence, security or economic effects. Their emergence could be extremely rapid. One obvious example is a room temperature superconductor with high current carrying capacity and benign mechanical properties. That would have potential for ubiquitous use, and would change almost all aspects of our lives.

Breakthroughs in quantum physics may have effects and applications that haven't occurred to us yet, such as effects at a distance (within the speed of light limit), new propulsion systems, or effects on time and space. It is already known that an object can be entangled with another that has ceased to exist[98]. We do not yet know the extent or potential of the "unknowns".

A successful theory of quantum gravity, such as local supersymmetry (known as ‘Supergravity’), or an unexpected alternative, might also yield completely new perspectives.

4.8.Underpinning and enabling technologies

In this section we define *underpinning* technologies as general capabilities and facilities that are required to realise quantum technology, and *enabling* technologies as specifics.

There are a large number of underpinning technologies required to realise quantum technology. Different combinations of these are required depending on the mix of physical principles used in each case. Important examples are:

- Specialist materials
- A wide range of micro- and nano- fabrication facilities

[97] I.e. high impact low probability risks see http://www.bris.ac.uk/eng-systems-centre/allpdf/blackett-review.pdf

[98] I.e. entanglement in time, see http://phys.org/news/2011-01-physicists-method-timelike-entanglement.html Note that teleportation in this context does not apply to matter, energy or information but to quantum information (see section 4.3.5)

- The ability to produce specialist semiconductors and heterogeneous microstructures
- Cryogenics
- Ultra-high vacuum techniques e.g. small, lightweight UHV cells
- Specialist laser technology, integrated photonics, fine tolerance optical components, possibly including plasmonics and metamaterials
- Electromagnetic shielding
- Theoretical analysis, mathematical modelling and computer simulation
- Inversion algorithms e.g. to enable the operation of sensors correctly within systems
- High power computing, e.g. the ability to simulate quantum states as dynamic entities
- Enabling systems and test beds
- Packaging technology for systems and subsystems

Many enabling technologies are shared with "underpinning" but are more specialised in nature. Some quantum technologies are themselves building blocks that enable more complex *systems* and these may even contribute to *systems of systems*. For example, quantum computing will enable advances in quantum 2.0 technology by emulating quantum systems. Quantum repeaters will enable long range quantum information transmission and quantum networks.

In many areas of science and engineering, advances in materials have enabled technological innovation. The innovations have been of two types, advances in processing known materials (see below) and the development of new materials that may have completely novel properties.

Materials relevant to quantum 2.0 technologies are likely to include semiconductors, metals, alloys, dielectrics, polymers, molecules, low dimensional and spin materials (such as graphene), and may incorporate materials with specific mechanical characteristics.

Quantum materials, and new physical insights derived from them, are likely to make a significant contribution to quantum technology. An example is high temperature superconductors. So called "cold atoms," i.e. Bose Einstein condensates[99], offer the opportunity to explore how electrons display exotic and unusual properties, and self organise, at surfaces of materials and in the bulk. Novel states of "quantum matter" may become possible, leading to properties and applications as yet undiscovered.

Functional materials with carefully designed properties (eg. light-emitting materials, electro- and magneto- optical materials, semiconductors, ferroics, piezo- and pyroelectrics, superconductors, etc.) are also very important to R&D. Devices can also be critical enablers. For example, true photon counters as photon-number resolving detectors based on quantum dot gated field effect transistors, or single photon avalanche detectors, are critical enablers of quantum optical metrology. One of the key blockers for large scale quantum photon technology is the inefficiency of detectors (currently 60-70%) and simple technology to produce photon ensembles with desired properties reliably on demand.

[99] NB cold atom clouds do not have to form Bose-Einstein condensates to be useful

Micro- and nano- fabrication techniques are essential for many instances of quantum technology. For example, single electron transistors, photon emitters and detectors, waveguides, mechanical resonators, quantum dots etc. Some are very sophisticated, e.g. methods of lowering the fundamental quantum "noise floor"[100] locally. Materials with novel properties, and methods of exploiting their characteristics, are reported every week.

The UK has well funded national facilities that are world class and cover an immense range of technologies suitable for realising quantum technologies. These are probably the most important constituents of infrastructure and include Si, SiO_2, III-V semiconductors and integrated photonics, oxynitride, polymer, glass, lasers, resonators, photon detectors etc.

There are at least 28 UK university clean rooms including (for example):

- James Watt Nanotechnology Centre University of Glasgow
- Southampton Nanofabrication Centre and Quantum Technology Centre[101]
- Lancaster Quantum Technology Centre
- Scottish Microfabrication Centre University of Edinburgh
- Cambridge nanoscience centre, CAPE, physics
- EPSRC National Centre for III-V Technologies (III-V epitaxy) University of Sheffield
- Nottingham advanced clean room facility shared with e2v

In addition, there are 22 UK commercial foundries, including Texas Instruments, Semefab, Plessey, RFMD, Oclaro, CSTG, Raytheon, NXP, Huawei etc.

It is important for us to build on our substantial strengths in this area and make sure that there are appropriate facilities to support speculative directions of research. Equally important is the training infrastructure required to remain at the forefront, we estimate this to be 50-100 PhDs in the area.

Ultra-high vacuum techniques have improved and are now miniaturised to the point where "knapsack sized" systems that require small volume evacuated cells with a pressure of less than 10^{-10} Torr are possible. The UK has a leading presence in this area. Small cells for special purposes can even be built using only getters[102] that will function efficiently for a long period of time. The principal problem with this configuration is the gradual penetration of helium atoms through or around the glass envelope or other connectors needed to pass laser beams, however, novel techniques using graphene (which forms a barrier impermeable to helium) are being considered.

Lasers of specific wavelengths, powers and configurations are required for cooling and trapping particular species of atoms or ions. For simplicity and miniaturisation, specialised gratings need to be fabricated to form lattices (i.e. cages) that can trap ions using a single driving laser. Purpose-designed integrated photonics networks are required to miniaturise the large optical bench

[100] See http://www.eurekalert.org/pub_releases/2013-08/ciot-ctp080613.php
[101] Dr Matt Himsworth is already working on the application of planar fabrication and packaging techniques to the miniaturization and integration of cold-atom devices, supported by a fellowship from the Royal Academy of Engineering, see http://phyweb.phys.soton.ac.uk/atomchips/load.php?page=index.xml
[102] Getters are materials that metaphorically act like sponges, mopping up stray atoms in the cell.

configurations used as proof-of-principle, or to construct more sophisticated systems (such as boson sampling computers). A number of detailed techniques will be required, such as directional couplers with adjustable coupling strengths. To increase accuracy and sensitivity beyond state of the art, advances in basic component technology will also be required[103].

By virtue of their inherent sensitivity, many systems are susceptible to stray electromagnetic fields. These need to be eliminated by shielding or compensation applied within the system. For example, the D-Wave machine is extremely sensitive to magnetic fields and requires extensive shielding together with sophisticated setup procedures that can take weeks. Some systems using species of atoms used for clocks and trapped in optical lattices or magneto-optic traps can benefit from laser light of so called "magic wavelengths" where undesired effects cancel out[104].

Quantum technologies are defined by quantum mechanics, a deeply mathematical subject that has evolved into a very sophisticated and specialist skill base over the last few decades. Although elegant descriptions of systems comprising ensembles of atoms and their constituents can be written down and manipulated, to obtain quantitative predictions about the behaviour of systems it is usually necessary to resort to computational simulation. Occasionally a change in perspective, such as the use of symmetry to effect transformations of the problem space can yield significant insights and simplify the calculations needed.

Meanwhile, the theoretical framework necessary to support the development of quantum technology (including practical software development for quantum computers) is a key ingredient of progress, and needs to advance in collaboration with experimental and engineering development. This will be a unique fusion of mathematics, physics and engineering. For this, sufficient computing power (i.e. conventional high performance computer) will need to be available.

Enabling systems and test beds will form essential ingredients of advanced technological development. One example is the proposed UK quantum test bed, which would form a field test for QKD systems. This is potentially a "quick win" for advancing quantum technology if it used existing (dark) fibre infrastructure. It would have the following benefits:

- A test of utility and reliability
- Resolution of security issues and tests of hacking
- Development of standards and tests of interoperability
- Test bed available for developing applications
    - Engagement of system integrators
    - Engagement of higher levels of supply chain
- Integration of other quantum technologies

An early version of a quantum computer i.e. an analogue system (possibly realised using cold atoms in an optical lattice) could be used in the form of a service model to support a number of quantum

[103] See for example http://www.sciencedaily.com/releases/2013/07/130721161723.htm
[104] See for example http://www.nist.gov/pml/div684/grp04/finding-magic-wavelengths.cfm

technology developments by emulating transport effects in various geometries. We have described some of the applications in section 4.6.

Packaging forms an important part of the engineering infrastructure required to industrialise quantum technology. Packing components and subsystems, and suitably ruggedising equipment to meet environmental specifications will be important. That will include thermal management, control of magnetic fields and electromagnetic interference, shock and vibration management, and resistance to moisture, chemicals etc. There are many consideration in this category such as cost engineering, diagnostics, serviceability, user training and interface specification and standardisation.

4.9.UK commercial capacity underpinning quantum 2.0 technology

The UK is already in a strong position in Quantum 2.0 technologies, with a number of companies heavily engaged in supplying technology to world leading groups for the development of Quantum 2.0.

Core technologies where the UK already excels include:

Fibre technology that is integral to transmission of quantum information and is likely to be essential to any choices of implementation. Companies such as Fibercore (based in Southampton) making speciality fibre, used in parametric photon production, for polarization preserving transmission, SPI lasers and Fianium (also Southampton based, producing laser sources), Phoenix Photonics (Birchington, Kent) making fibre based polarisers, etc.

Nonlinear crystals for generating heralded photon pairs, for up-conversion detection, and comb sources, for example, Covesion Limited (Southampton, Hampshire) produces periodically poled devices supplied to many top labs (eg NIST, Stanford, Harvard, NASA, etc.)

Optical waveguide devices – used for linear optical quantum computing, particularly based on silica-on-silicon platform, companies include Huawei / CIP (Ipswich), Kaiam Corp (Livingston – previously Gemfire / Kymata) and Stratophase (Southampton).

Deposition and etching technology for thin film materials (eg quantum wells, superconducting detector layers, etc.), companies such as STSP (Newport, Gwent), Oxford Instruments Plasma Technology (Yatton, Bristol)

Semiconductor wafers and other materials: devices which are core to many semiconductor laser technologies, key company IQE (Cardiff), and diamond materials (Element 6, Harwell and Ascot).

Cryogenic technology essential for superconducting detectors, for low temperature operation in cryostats and magnetic field control, key player is Oxford Instruments (Abingdon)

4.10. Issues and challenges

A key challenge for moving UK quantum technologies forward is the maintenance of the required infrastructure and supply chains. This is a particularly important consideration where export restrictions (from other nations) may appear and we need to maintain a sovereign capability. There are also issues of stability and maintenance of supply sources, materials availability, and potential obsolescence.

5. Applications

5.1. Introduction

This section is designed to answer the question of where quantum technology can provide significant advantage. We will need additional modelling or theory work to predict the utility of certain technologies; for example there are immense engineering challenges to be met in order to implement GNSS free navigation using cold atoms. More generally, much has yet to be discovered about the potential applications of quantum technology.

A full market survey is beyond the scope of this "think piece". However, we will describe some of the most likely near term applications, and make some preliminary (qualitative) assessment of their economic potential. A more comprehensive analysis of markets will be addressed during the development of individual roadmaps, and the formulation of development plans, for individual equipments.

We have divided applications domains into defence and security, and industrial, personal and scientific. We recognise that industrial, and ultimately personal, applications will form the main driver of the economic engine which will make many defence and security embodiments affordable. Scientific applications are also (indirectly) important, since they will drive further discovery and the ability to implement new technologies in the longer term. Scientific research projects and their associated instrumentation are often first adopters.

More broadly, some standardisation of components, facilities and subsystems of quantum technologies could result in profitable businesses supplying enablers for other R & D teams or sub-assemblies for other technologies. The instrumentation market is a good example. This concept significantly augments our opportunity, and standardisation and modularisation will reduce costs.

5.2. Defence and security

The value of quantum technology for security and defence benefit is enhanced by the unavailability of most techniques to asymmetric[105] adversaries. However, the acquisition of such technologies by Government is also important for understanding and appreciating the current state of the art, and how the tools and techniques may be realised as opportunities or threats,.

5.2.1. Quantum timing and clocks

Accurate, stable clocks have game-changing defence and security applications. As the accuracy of the clocks increase, so does the range and impact of potential applications. This also applies to the degree of miniaturisation, power consumption and cost. For example:

[105] Asymmetric adversaries are technologically under-developed factions who do not possess state-scale resources, such as terrorists or extremist groups. Generally, any advantage is ultimately time-limited as technologies are developed commercially.

- Miniature, chip scale atomic clocks can significantly improve the signal acquisition and performance of GNSS based systems.
- Improvements in non-local synchronisation enhances communications reliability and potential for covertness over greater time periods.
- Highly accurate clocks offer the potential for novel communications modalities and hybrid schemes, e.g. the ability to transfer classical and quantum information over common carriers.
- Improved navigation systems become possible. For example "peer to peer" constellations and the use of ultra-accurate clocks in combination with ultra precise accelerometers and rotation sensors.
- Miniaturisation and reduced power consumption allows ubiquitous use with consequential benefits to networked warfare or security systems.
- As the accuracy of available clocks increases, their utility for *sensing* will improve dramatically.

5.2.2. Quantum communications

The application of quantum communications (in the form of secure key distribution) seems to be ideal for defence and secure communications. However, there are some drawbacks *op cit*, for example current technology is only point-to-point and several other security aspects are not addressed, e.g. authentication. Some refinement is required before the technology finds significant use, particularly at long range. However, in the medium term, it is possible that miniaturised, integrated quantum optics could prove useful for local tactical peer-to-peer communications.

The transfer of quantum information (as described in section 4.2) by means of teleportation, gate projection etc. is not likely to find applications in isolation. However, the transport of *quantum* information represents a vital part of a *quantum* information processing system as a whole.

5.2.3. Quantum sensors

Quantum sensors will have significant implications for defence and security.

In the long term, clocks with an available accuracy of greater than about 1 in 10^{16} become progressively more useful to measure gravitational potential, and (in certain configurations) could be useful in pairs or an array to measure acceleration. Cold atom clouds and interferometers would probably be more useful at first measuring gravitational field strength and gradient (and higher derivatives in the form of a "telescope"), delivering information about acceleration and rotation to exquisite precision. There is no known shielding that protects against gravitational sensors, and generally such shielding is thought to be impossible. These sensors would have applications for:

- Sensing through walls and other structures
- Sensing fissile materials in cargo (due to their extreme, localised densities[106])
- Detection and analysis of voids

[106] Plutonium, for example, has a density nearly twice that of lead and about as much as gold. See also "Imaging cargo containers using gravity gradiometry" Kirkendall *et al*, IE^3 Trans. Geosc. and Remote Sensing (2007) http://geophysics.mines.edu/cgem/pdf%20files/KirkendallIEEE.pdf

- Navigation by analysis of the local gravitational environment
- Ultimately, the analysis of a scene (or scenario) using a gravity "imager"
- Detection and analysis of the positioning or movement of local (massive) objects

The applications space of matter waves, including Bose Einstein condensates (BECs) and other quantum interferometer based techniques includes:

- The ability to navigate accurately in a GPS denied environment, potentially to metre accuracy or better on the scale of the size of the Earth[107]
- The ability to orient in space to an unprecedented level of accuracy (rotation)

The above sensors may eventually be combined in systems that provide a holistic view of location, orientation and situational awareness.

Quantum enhanced imagers, if they could be developed to a sufficient level of maturity, could offer advantage in a number of scenarios:

- Quantum enhanced LIDAR (laser version of radar) could allow a significant increase in resolution and noise performance of such systems. These would be realised as "big" military systems in small numbers and would be expensive. They might not be cost effective for the UK.
- Covert ranging systems (e.g. using non classical light) may be more practicable, using single photon probes that cannot be detected by an adversary.
- Quantum ghost imaging could, in principle, be used to "see round corners", with variants able to image or detect through obscurants. Non visible wavelengths, used to interrogate the object of interest, could be used via dual band systems to convert to the optical, e.g. to image THz using a standard camera.
- Non interactive sensing (i.e. where vanishingly few photons interact with the object under scrutiny) might allow "stealth" imaging. This is unlikely to be practical with light, although it might perhaps be feasible with lower frequency radar signals. The equipment required is not likely to be practicable or achieve acceptable cost/benefit within our target timescale.
- A certain level of protection against "spoofing" of return signals is possible by treating the imaging system as a communications channel and applying quantum techniques.

Electric, magnetic and electromagnetic sensors may have significant value-adding potential. However, the challenges are to understand how the increase in the available sensitivity could be protected against noise and unwanted ambient effects. We would also need to ascertain whether such enhanced sensitivity would deliver sufficient added value in specific systems and scenarios over and above their classical counterparts. It is worth noting, however, that naturally evolved organisms (sharks, moths, parasitic wasps, etc.) are able to sense targets using signal strengths much below the background "noise" suggesting that sophisticated signal processing or exquisitely sensitive and specific detection can overcome potential confusion.

[107] The challenges in realising a practical system are formidable and is a topic requiring investigation.

Electric field (and current or magnetic) sensors could, in principle, deliver sensitivities several orders of magnitude greater that existing classical devices. Applications could include:

- Detection and characterisation of objects (including power sources) through certain types of walls or other obstacles
- Detection of dielectrics (objects, possibly buried,) via perturbations in the Earth's native electrostatic field
- Analysis of charge left behind after activities (footprints, handprints, charged materials etc.)
- Analysis of nearby circuitry and characterisation of its activity
- Detection and analysis of nearby neural activity and other bodily functions, such as heartbeats
- The creation of novel sensors capable of operating underwater. For example, the shark projects a sense of "touch" up to a distance of several meters using the local electrostatic environment
- Selection of, or synchronisation with, particular Fourier components (frequencies) or their combinations may allow analysis of nearby, or distant circuits, machinery and generating plants
- MIMO and other antenna characterisation with non invasive EM field detection e.g. using quantum nanoparticles or Rydberg atoms, for RF, radar and THz

Magnetic field detectors' capabilities overlap significantly with these. The SQUID as a quantum sensor, capable of extremely sensitive detection of magnetic flux, has been available for decades, however, it requires a cryogenic infrastructure and its sensitivity is often difficult to manage. Solid state devices with (for example) arrays of diamond based sensors or diamond nanoparticles could be very sensitive and capable of detecting and characterising metallic objects of various sizes at a variety of ranges.

Chemical detectors (e.g. low concentration analysis or quantum enhanced spectroscopy) could be useful for forensics. Detection of illicit or dangerous materials could be significantly enhanced if a sufficient increase in sensitivity and / or range could be delivered. Tracking the unique chemical signatures of individuals could become possible.

5.2.4. Quantum computing and quantum information processing

The full scope of defence applications is not yet known. However, Shor's algorithm, for the factorisation of large numbers, originally formulated in 1994, could be considered a "killer app" for defeating public key cryptography and as such could be considered both an opportunity and a threat.

The realisation of (useful) large scale "digital" quantum computers is (arguably) at least 10 years or more away. However, additional applications in the defence and security domain are gradually beginning to emerge. For example, the emulation of quantum systems could lead to the design of novel or multi-functional materials with desirable physical properties. It is becoming apparent that quantum algorithms could assist conventional computing, for example where there are a large number of simultaneous equations to be analysed or solved[108].

It is possible that "analogue" quantum computers will become available on a shorter time scale. As discussed in section 4.6, these could be used to emulate energy transport and other characteristics of materials and their interfaces.

Quantum computers could have security applications e.g. in discovering and analysing social cliques, e.g. the largest subgroup of a number of people who all know (or otherwise interact with) each other.

Distributed quantum computers (using quantum communications) could yield useful defence applications. It is possible that emulation of defence scenarios might be a useful application of quantum computers where the probability of an outcome would be informative.

5.2.5. Conclusions

In the near and medium term, attractive as they may initially appear, the scope for defence use of quantum computers appears to be limited. This situation may change rapidly, so close monitoring is essential given the (perceived) potential power of quantum techniques. Special purpose quantum computers could be useful for specific security related problems.

We conclude that the technologies most likely to deliver Defence and Security benefit in the short and medium term (~5-15 years depending on impetus) are:

- Highly accurate, low cost, size weight and power (SWAP)
- Precision navigation devices and systems
- Point-to-point or broadcast QKD for exchange of tactical information
- Gravity sensors and "imagers"
- Novel electromagnetic sensors and quantum enhanced spectroscopy

Some more work is required to assess the capabilities and uses of quantum sensors, their potential utility over and above classical systems, and environmental factors that might alter or degrade their ultimate performance. In particular, we should quantify the benefits of quantum enhanced sensing for ISTAR[109].

5.3 Industrial, personal and scientific

5.3.1. Market landscape

Industrial applications will be worth producing if the sales potential or added value is sufficient to justify the investment. Quantum technology could also supply leverage or game changing advantage

[108] This is a field that has only recently been emerging, see for example http://phys.org/news/2013-08-quantum-algorithm-stealth-fighter.html and http://phys.org/news/2013-06-quantum-algorithm-linear-equations.html#inlRlv Note that the full solution of a set of simultaneous equations is not usefully available from a quantum computer alone, rather information that makes certain classical calculations easier to implement.

[109] ISTAR = Intelligence Surveillance Target Acquisition and Reconnaissance

to existing business via technology insertion or replacement. The players are likely to be large corporations for sophisticated systems, and SMEs (small to medium sized enterprises) for specialised areas and niche applications.

Personal applications are likely to benefit from technologies where mass production is feasible. "Quantum 2.0" technologies are generally very sophisticated and often complex, so in the short to medium term it is unlikely that more than a few would be available to the mass market. To achieve economies of scale, large companies are likely to be involved.

The scientific market is likely to contain many early adopters, and as such forms a useful proving ground. This could be useful for reducing non recurring engineering costs (NRE) if managed appropriately. The market is not likely to be large, perhaps dominated by specialist SMEs.

5.3.2. Quantum timing and clocks

Highly accurate clocks could find applications in a number of commercial contexts, particularly where audit of transactions at microsecond level or less is crucial, such as the finance industry. The ability to "flywheel" with great accuracy during GNSS or network outages will become essential.

Ubiquitous, affordable chip scale atomic clocks could find a mass market, possibly as a significant improvement in navigation and positioning accuracy, or novel implementation of communications, broadcast and network systems. Accurate clocks at the nodes of fibre networks have the potential to increase data rates.

In safety critical applications, clocks would be needed to "flywheel" to an accuracy of microseconds for a period of up to a few days. Rapid re-acquisition of GNSS signals and the detection of "spoof" signals by analysis of timing signals would reduce the probability of accidents and eliminate a number of potential criminal mechanisms.

This technology represents an important tool for advancing physics in many areas. Although the research markets are relatively small, the scientific community is likely to be a first adopter for the most accurate and sophisticated applications, e.g. for space systems. Sufficiently accurate clocks could be used as sensors of the gravitational geoid e.g. for determining absolute height[110].

5.3.3. Quantum communications

Quantum key distribution will enable secure communications for many industrial and personal applications. Basic point-to point systems have been commercialised and there are applications for networks in some industrial sectors e.g. finance. There is mass market potential for miniaturised, handheld optical systems to protect peer to peer and customer to vendor transactions, and banking.

However, the technology solves only some of the problems in the security "landscape", and requires special purpose hardware rather than software. We need to assess whether this solution will be any better than others that may become available.

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[110] See for example http://www.sciencedaily.com/releases/2013/10/131002103036.htm

Due to UK capabilities in this area development of, for example, miniature photonic systems is to be encouraged. Such mass market applications, if they take off, may rapidly be adaptable to routine tactical communications for defence and security scenarios.

5.3.4. Quantum sensors

As with computing and clocks, there will be a wide variety of applications in the scientific market, both for terrestrial use and in space, for most families of quantum sensors. Health monitoring applications, already a strong driver of traditional CMOS based technologies, could be an early adopter of quantum enhanced spectroscopy for example.

A key value adding technology will be the ability to sense densities and structures under the Earth's surface. If gravity sensors are able to detect fossil fuel deposits (e.g. "oil bubbles") that have been left unexploited, the value is several trillion dollars per extra percent extracted from all known wells. Typically, less than half of the oil present underneath a well can be extracted using current technology because the pockets remaining after initial pumping cannot be located. There may be an application for supervision of carbon sequestration.

An important application in the context of "sustainable cities" is in the civil engineering field. Survey of locations for foundations of dams, bridges and tunnels etc. will be an early application. With higher resolution, imaging for reduction of roadworks (and avoidance of accidents) is possible by detecting pipe, cables, cellars, sinkholes and mine shafts and other "obstacles". Only 40% of services are accurately mapped in UK cities.

Sufficiently sensitive gravity sensors may also find application for detecting and predicting significant geological events, such as earthquakes and volcano eruptions.

Electromagnetic sensors may be useful for environmental sensing where sensitivity is key, however, consideration needs to be given to noise in the form of ambient fields[111]. They could find use for law enforcement, e.g. tracking individuals by perturbations in the field or residual charge deposited on objects or in the environment[112].

Chemical and spectroscopic sensors relying on quantum effects could be used as part of law enforcement, where packets, substances or the environment need to be sensed with greater sensitivity. They could also be used for prospecting for natural resources (e.g. gases and trace elements), although they would have to deliver sufficient added value over classical or "quantum 1.0" techniques already in use. These could be miniaturised using quantum optics (for example) and eventually find a mass market at the "mobile phone" level of implementation.

Precision navigation is clearly a commercial application, however, until available systems are small enough, accurate enough and cheap enough to usurp GPS they are unlikely to find much traction in

[111] Electric field sensors could also be useful to predict geological activity. The phenomenon of animals becoming agitated before an earthquake is often due to a strong electric field being produced by rocks being compressed before a fault "gives"; it is detected through their fur. Infrasound also probably plays a part in some cases.

[112] Clearly success will depend on the amount of moisture present, although if the environment is dry deposited charge can remain for many hours or even days.

commercial markets. When sufficiently small and cheap, autonomous vehicles (land, air, sea and underwater) could benefit immensely from the technology.

In life sciences, nano- and micro- scale magnetometry, electric field measurement and thermometry will enable a step change in managing chronic diseases such as Alzheimer's and cancers. "Magnetic helmets" that are highly sensitive and not reliant on cryogenics will become available for 3-d dynamic imaging of brain functions. Diamond nanoparticles with NV centres and atomic vapour cells interrogated with lasers are quite likely to be a viable technology.

The ability to analyse cells and their chemical components in detail *in vivo* will make a significant contribution to sustainable healthcare. This is potentially an immense market, as healthcare costs are rising rapidly in the developing world, and ways are being sought to make sophisticated diagnoses and monitoring cheaper and more efficient.

5.3.5. Quantum computing and quantum information processing

Quantum computing has many scientific applications. Some of the most important involve emulation of quantum systems, which will lead to increased understanding and possibly new physics. The study of quantum algorithms is an emerging field that might find industrial applications in a number of areas. The analysis and manipulation of Big Data may eventually become a significant application, as might medical and other image analysis and expert systems, although these are likely to require very large machines which may not out-compete conventional approaches.

D-Wave is a useful indicator of what might happen, although many do not believe it to be a quantum computer in any sense. Few units have been bought, and its utility and capability is still under debate. NASA, Lockheed and Google give some indication of the type of early adopter that could be expected for quantum computing systems. D-Wave are developing new architectures and improvements for their machines, and these will need to be assessed by the community in due course.

5.3.6. Molecular and solid state Quantum 2.0 technologies

Some of these technologies could have immense societal and economic impact and should be explored further as candidates for rapid development. These have been described above. The benefits could include efficient lighting, power generation and power recovery from waste heat (or efficient solid state heat pumps for space heating and refrigeration). Advances in high T_c superconductors may also be possible, perhaps discovered via analogue quantum computers as simulators.

5.3.7. Conclusions

We conclude that the most likely technologies to deliver benefit to the commercial sector in the short to medium term (~ 5 -15 years depending on impetus) are:

- QKD systems (ubiquitous quantum optics) (small ticket / commercial) (Big market)
- Quantum clocks and associated communication networks (big ticket[113])
- Ubiquitous, affordable chip scale clocks (big markets)

[113] I.e. high unit price, high added value, high profit margin.

- Quantum nanotechnology implemented on a large scale for power recovery and generation, environmental sensing and efficient healthcare (massive markets for efficient photovoltaics, thermoelectrics and medical sensing / intervention)
- Novel electromagnetic or chemical (including spectroscopic) sensors
- Gravity sensors and "imagers" (big ticket)

Some more work is required to assess the capabilities and utility of quantum sensors over and above the capabilities of classical systems.

6. Research and development activity

6.1. World view

Quantum technology is being researched vigorously with most developed countries having a practical, or at least theoretical, research programme in place. World class research is conducted in the United States, UK, China, Australia, Germany, Austria, France, Netherlands, Switzerland, Russia, Japan, Italy and Canada. Many others have significant research programmes. The ramifications of quantum technology are immense.

The competitive playing field is fairly level due to the propensity of the academic world to be very open, and to publish detailed results as soon as they can (that aspect of research is competitive). There is also a high volume of interchange of researchers between institutions. Many pre-eminent scientists will travel extensively to attend meetings and conferences, and to give lectures. Hence, the technological capability of a country will depend strongly on having a range of world class institutions characterised by academic freedom and strong academic connections, as well as an appropriate industrial infrastructure including fabrication facilities.

A detailed study of the world picture is not a primary purpose of this report. However, we have analysed the state of UK activity to understand which are our leading institutions in key areas of quantum research.

6.2. UK quantum R&D

It is clear from our analysis and the discussions at Chicheley on November 10-12 2013 that the UK has world leading, or at least world class, academic standing in the majority of quantum technology areas. Details of our pre-eminence in specific areas have been discussed above in section 4. UK R&D in quantum technology received a significant boost (i.e. £270M over 5 years) in the 2013 Autumn Statement. The challenge is now to maximise the benefit of this extra money.

We felt that there was a general need for better connectivity and interaction between universities and teams inside universities.

The groups present at the Chicheley meeting felt that decades ago, there was reasonable alignment between the aim of producing Nature papers and that of producing deliverable technology. However, the two are now seen as divergent. The alignment is not something that is well done in the UK, and the new initiative represents a sea change in intent. Other fields such as engineering and IT were seen by the attendees to align research and technology development with much greater impact.

It must be possible to get appreciation and award "academic currency" to solve engineering type issues and achieve capability and economic impact by productively working with teams outside the prevailing academic model.

Part of our strength lies in the diversity of research present in the community. However, many experimental groups need technology that is essentially similar in nature, such as cells for cold atoms, laser subsystems and magneto-optic traps. Significant gain could be realised if this commonality could be exploited in appropriate areas, saving costs and pooling expertise, rather than duplicating the time, cost and risk to develop special to type components and subsystems each time. It may be beneficial to link such an initiative to others, where progress is already being made in the context of quantum information technology[114], and develop a suitable "toolbox" of devices and techniques.

It would also be useful to explore the physics at the interfaces between the groups that were convened at Chichely. That could form a component of a follow-on event.

There are many interdependencies between groups at different institutions. Some have particular specialisations, e.g. Queen's University Belfast is one of the few centres for research in quantum opto-mechanical effects. We also need to take heed of strong initiatives that have been started relatively recently by universities. Examples are Lancaster (the new Quantum Technology Centre) and Birmingham research into cold matter in partnership with Nottingham. The latter is within the Midlands Ultracold atom Research Centre, which is leading several European collaborations on gravity/inertial quantum sensors and clocks.

We need to focus on:

- Teams and consortia building, or capable of building, demonstrator systems useable in their own right (not necessarily to a high TRL)
- Those developing underpinning technology or components, or delivering essential services (such as fabrication)
- Networks and collaborative projects.

It is important that our research centres interface efficiently and effectively with the industrial organisations that are best placed to exploit the technologies. These may be large national corporations such as BAE systems, Toshiba, Hewlett-Packard, Selex, Nokia etc., or SMEs, or start-ups created for the purpose. Individual roadmaps and development plans will help to define the strategy in each case. Lessons learned from previous examples of commercialisation should be applied.

[114] For example IQIT - the EU collaboration in integrated quantum information technology http://www.iqit-research.eu/home/?lang=de

7. Quantum technology strategy

7.1.Introduction

The key elements of technology strategy are twofold. They concern which technologies should be pursued, and why, and the processes required to develop and exploit them. Particular questions we have been asked to address are:

1. How and where will we obtain advantage from quantum technology in the UK for defence, security and the wider UK economy?
2. Which specific areas should we encourage, and how?
3. Where and how should the available resources be used?

In section 7.2 we outline the technologies that we think are those that should be emphasised, and what needs to be done to expedite development.

From section 7.3 onward we discuss issues that are essential to address to "make it happen".

7.2.Key value adding technologies in the UK context

From Section 5 we can summarise the quantum technologies that are most likely to provide general benefits, although the precise ordering will become apparent from detailed roadmapping exercises some market analysis. Focus areas will be subject to refinement and change because quantum science is evolving rapidly and much remains unknown. To summarise, we propose that the principal value adding technologies will be[115]:

- Precision timing and clocks
- Gravitational sensors (ultimately including "imagers")
- Quantum photonics
- "Cold atom" systems for metrology and navigation
- Electromagnetic sensors, quantum enhanced spectroscopy
- Quantum nanotechnology implemented on a large scale for power recovery and generation, environmental sensing and efficient healthcare
- Quantum simulation and quantum computing

Fortunately, the UK has world-leading expertise in all of these fields. To exploit these areas we need to match the expertise to initiatives designed to bring the technologies to fruition. To achieve that, the following conditions need to be met:

- Effective use of Government investment. This would need to focus on:
  - Infrastructure and enablers for exploitation
  - Skills development for engineering and technology transfer
  - Innovation (in terms of development, demonstrators and reference models or rigs)
  - Applied research.
- A suitable collaborative landscape, i.e. academia, industry and Government.

[115] The order is arguable and depends on interest of potential customers and ongoing advances in each field

- The components and subsystems need to be identified and demonstrated in a form suitable for the target system. For example, an optical bench layout containing a forest of lasers, beam splitters and other items is not likely to be suitable for use as part of a product. It needs to be demonstrated with a suitable form factor, i.e. size, geometry, power consumption etc. with appropriate specifications and packaging. The interfaces need to be carefully considered from the outset, together with issues such as interoperability and standardisation.
- The *system* needs to be demonstrated "in principle" as a working whole.
- A supply chain for component technologies and supporting infrastructure needs to be in place and unit prices calculated.
- Interdependencies need to be identified and managed.
- An intellectual property plan, and its management, needs to be instituted from the outset and maintained. The UK's comparatively poor record for exploiting leading edge technologies needs to be remedied. This will be particularly challenging where the results of applications based research are shared freely amongst all nations. We need a step-change in the pace of realising saleable technology from the science.
- A target customer, or customers, for the research output plus suitable funding needs to be identified. In-house skills pertinent to recipients' needs should be acquired.
- Ideally, the funding should be geared with support from Government, the EU or industry partners and investors.
- A handover needs to be arranged between the research team and the applications developer, together with ongoing support and maintenance of a suitable demonstrator or test bed as a technology baseline reference
- During this process, a suitable market needs to be identified and prepared for the organisation(s) converting the research output into products.

The specifics will depend on the particular technology and its roadmap. We are now developing these, in partnership with academics, government departments and industry, following on from our meeting at Chicheley where key stakeholders were present or represented.

An important characteristic of quantum technology is that many of the theoretical, physical and implementation principles overlap, and many research teams are synergistic. We are therefore proposing that universities and other institutions engaged in key activities are formed into a core team or cluster, and that this cluster is appropriately led and governed.

7.3. Making it happen

7.3.1. Introduction

The challenge of developing quantum technology to the point where it yields benefit to defence and security operations as well as delivering economic benefit is not solely scientific and technical in nature. There are several non technical issues that need to be addressed. Seldom are these all understood in a holistic context by everyone involved in a programme.

To get a technology out of the lab and into everyday use it needs to be fit for purpose, impervious to any detrimental influences of its working environment, easy to use within its defined concept of operation, integrated with surrounding and interconnected systems, easily maintained, reliable and affordable. The process of development and problem solving that needs to be applied to reach the end goal requires as a minimum the ingredients outlined below. They are at least as important as the technology itself and we can't assume that they are "just going to happen".

7.3.2. Leadership and vision

Quantum 2.0 technologies are novel and are evolving rapidly. Many of their characteristics are unexpected, difficult to understand and counter intuitive. They are held to be full of potential, and yet few people understand the details. Misconceptions abound and are commonly propagated.

Strong and inspiring leaders will be needed, together with a recognised structure, to bring the technologies to fruition. Amongst the qualities of leadership required are:

- The ability to create a compelling vision that is communicated to, and adopted by, key parties; i.e. academics, Industry and the relevant Government organisations. The cultures in many such sectors are disjoint and need to be matched or integrated at the boundaries
- To inspire everyone to work enthusiastically towards a common goal, and not to be hidebound by structures and processes - yet they also need to adopt sensible project practices - achieving a balance between the two is a rare skill
- People skills to make the team understand that they are special, and to generate convincing and authoritative arguments for what needs to be done
- An acceptable knowledge of the science and technology, without adopting the "pace setting" style of leadership[116].

[116] This is where the leader attempts to know everything about the science and solve all the problems, with his or her team members as acolytes, in the belief that it is a requirement for authority and leadership. It is a common trap for scientists that become managers.

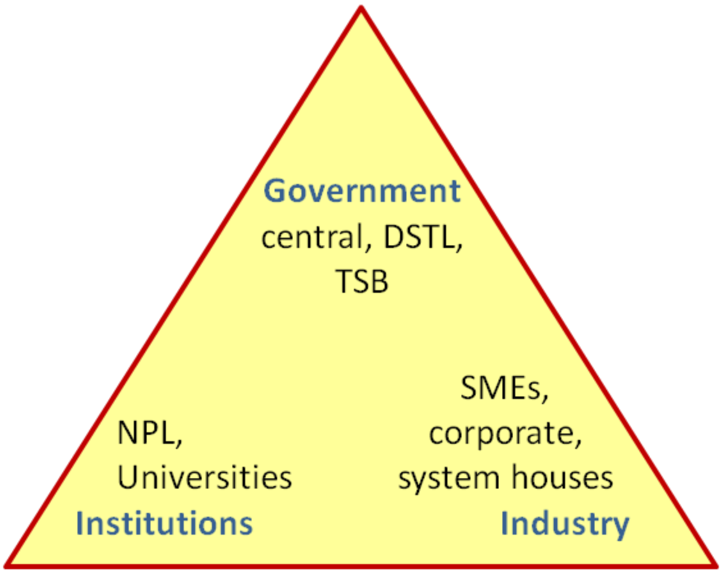


Figure 24 A suitable collaborative landscape is required

7.3.3. Technology readiness

Technology readiness is often expressed in terms of "technology readiness levels" (TRLs). This concept was originally developed by NASA, and although the levels are not used or labelled entirely consistently elsewhere, the basic concept is the same. They are mostly self explanatory (see left hand side of figure 25).

The crucial issue here is that the expense of moving through stages of readiness, and the discipline required to deliver a robust and maximally useful outcome, increases rapidly as a technology progresses up the chart. This is often over simplified and expressed in terms of "out of the lab and into production". The difficulty in applying sufficient funding and the appropriate skills sets is described as "crossing the gap" or "the valley of death". Nevertheless, the application of appropriate skills, rigour and experience can keep the overall programme under control and minimise the cost and risk of failure.

In the US, the "gap" is directly addressed by DARPA[117] in the defence context, IARPA[118] in the security context and commonly by venture capitalists in the industrial context. In the UK large budgets are not so readily available. We will have to invest more in this area to achieve success.

The challenge, in addition to the necessary funding and skills sets, is to join seamlessly the effort of the teams involved in the different stages, and to maintain communication, motivation and cooperation. This could well be driven by a synthesis of RCUK, TSB and MOD in partnership with core institutions and this would form a suitable collaborative landscape. A technology system cannot be considered to be ready for general use until it has reached at least TRL7, preferably TRL8.

[117] Defence Advanced Research Projects Agency
[118] Intelligence Advanced Research Projects Agency

7.3.4. Programme, project and risk management

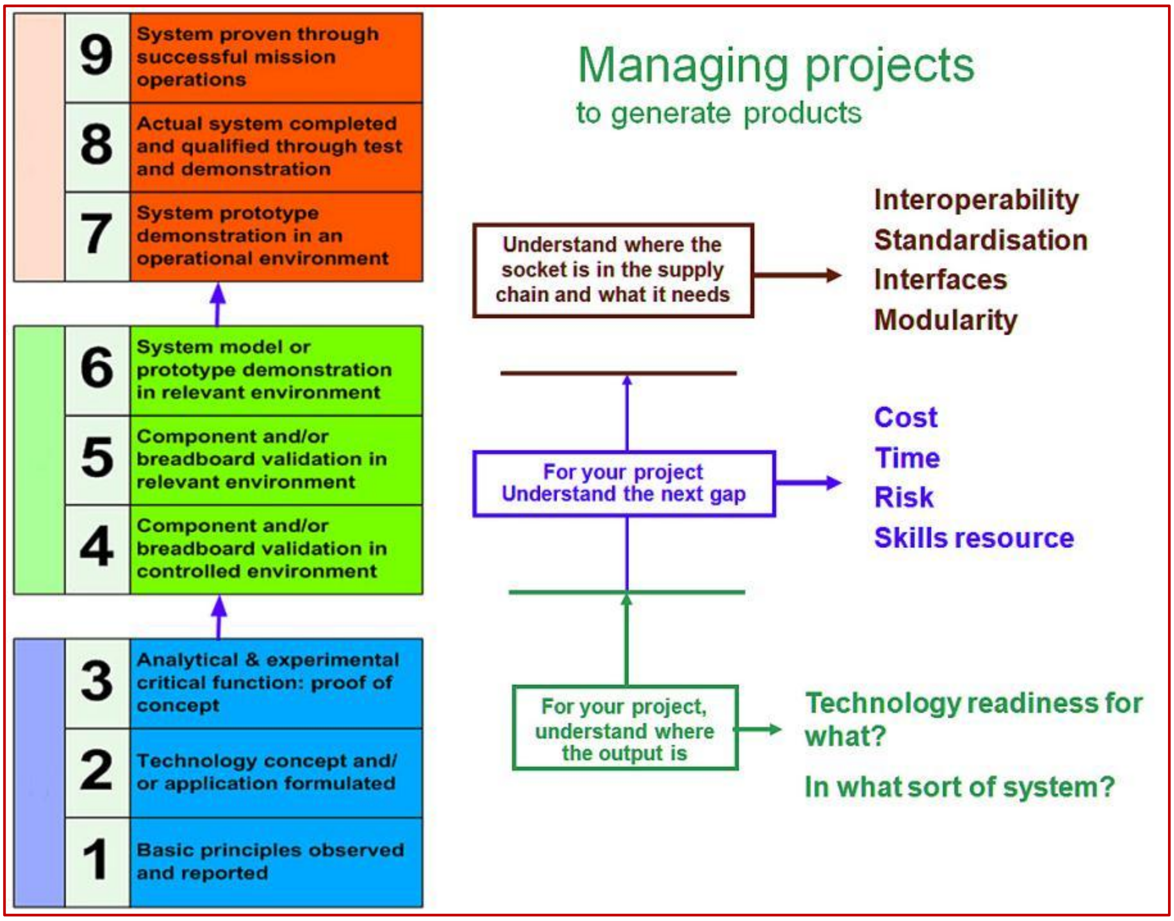


Figure 25 readiness and essential programme management issues

Here, we define a programme as the over-arching set of activities required to deliver a technology, either from a laboratory demonstrator or an ensemble of tested subsystems. We define a project as a separable group of activities focussed on delivering a specific outcome measurable by a well defined criteria or an agreed acceptance test procedure. Both programmes and projects require skilled leadership and technical skills at a number of different levels. Good project management is essential, not as a procedure and accounting function, but as a source of motivation, problem solving, risk management and the application and promulgation of lessons learned.

Some of the specifics required for project management in this context are shown on the right hand side of figure 25.

Over-tight project management discipline when pushing the boundaries of an emerging technology may not be appropriate and some flexibility is essential. Conversely, proceeding by "heroic effort" is a significant risk in itself, and many people do not understand that the risk of failure and increased difficulty increases exponentially (or worse) with complexity and project inter-dependencies. To move up to TRL7+ make-do is not sufficient. That is where project management and *technical* leadership become special skills.

The forecasting, understanding and management of risk are also essential, and represent an important skill set requiring flexibility and dynamic adaptation of the project. Unlike a production environment (such as building an aeroplane), an appropriate risk management structure for development of leading edge technology is not a rigid framework but an interactive (mapped) set of risk management plans. As the project proceeds, opportunities are taken to "buy down" the risk in each plan. Figure 26 shows a fictitious example (for illustration) where the project is an optical lattice gravity sensor and the depicted risk management plan refers to the vacuum subsystem.

Some of this might seem onerous, but if applied properly will ensure success where success is possible.

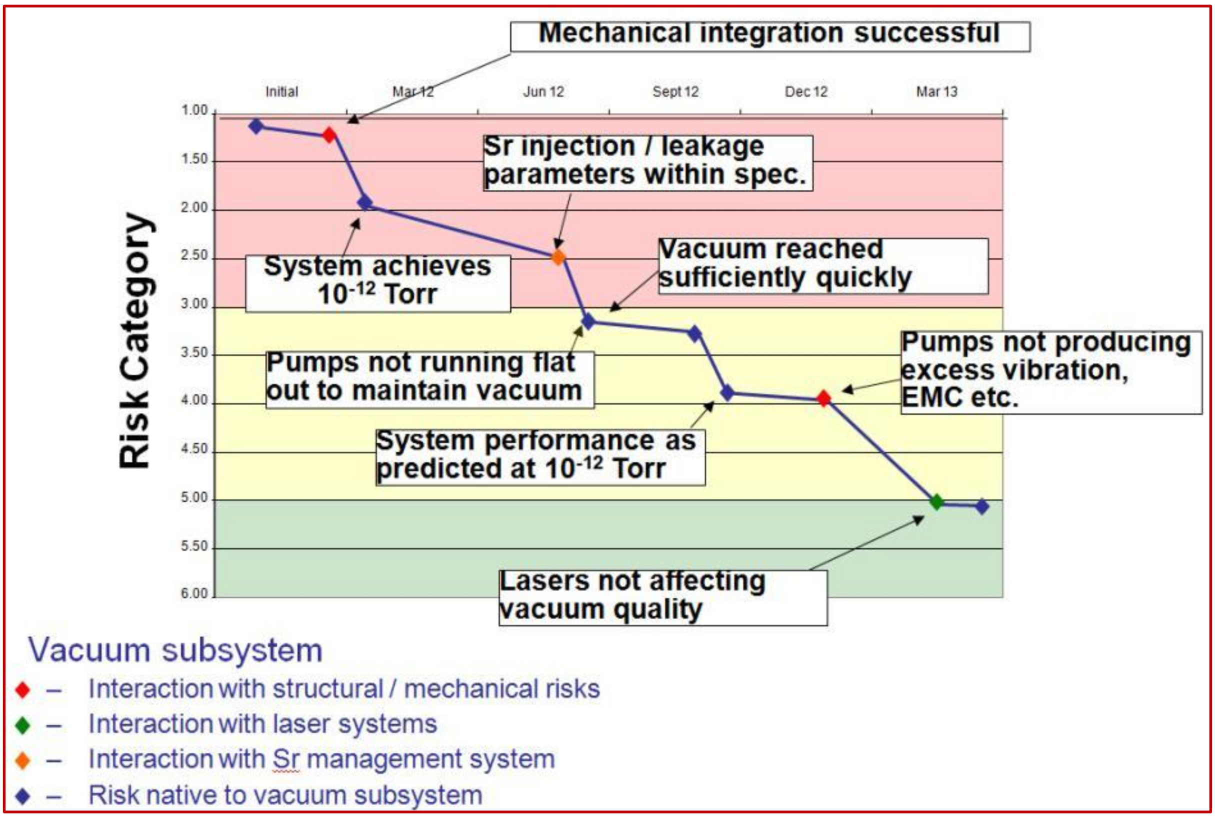


Figure 26 Example of risk buy-down map for vacuum system in a fictitious optical lattice project

7.3.5. System issues

Any project to develop a technology will involve a degree of systems engineering, even if only to facilitate integration and good practice such as modularity, tightly defined interfaces and interoperability. When systems, or systems of systems, are to be considered, new factors need to be taken into account. For example, technical readiness should be seen in the context of "technical readiness for what?" TRL8 for one scenario could be only TRL6 or less in another (e.g. power consumption, noise emission, size, robustness against interference etc.) A system as a whole is only as mature as its least mature component or subsystem. (This defines System Readiness Level (SRL).) System integration is usually a lot more difficult than most people think. Often it is useful to define systems by their interfaces, and take specific views such as Functional, Information, Physical etc, each of which have their own conceptual designs.

The development of a typical system follows a "system engineering V" (see figure 27). However, it is likely that as quantum technology is a difficult and complex area at the forefront of technology, this system will be too rigid. Probably, the statements of user requirement, system requirement, architectural design, system test etc. will need to be modified as risks materialise and behaviour of the system does not turn out as expected.

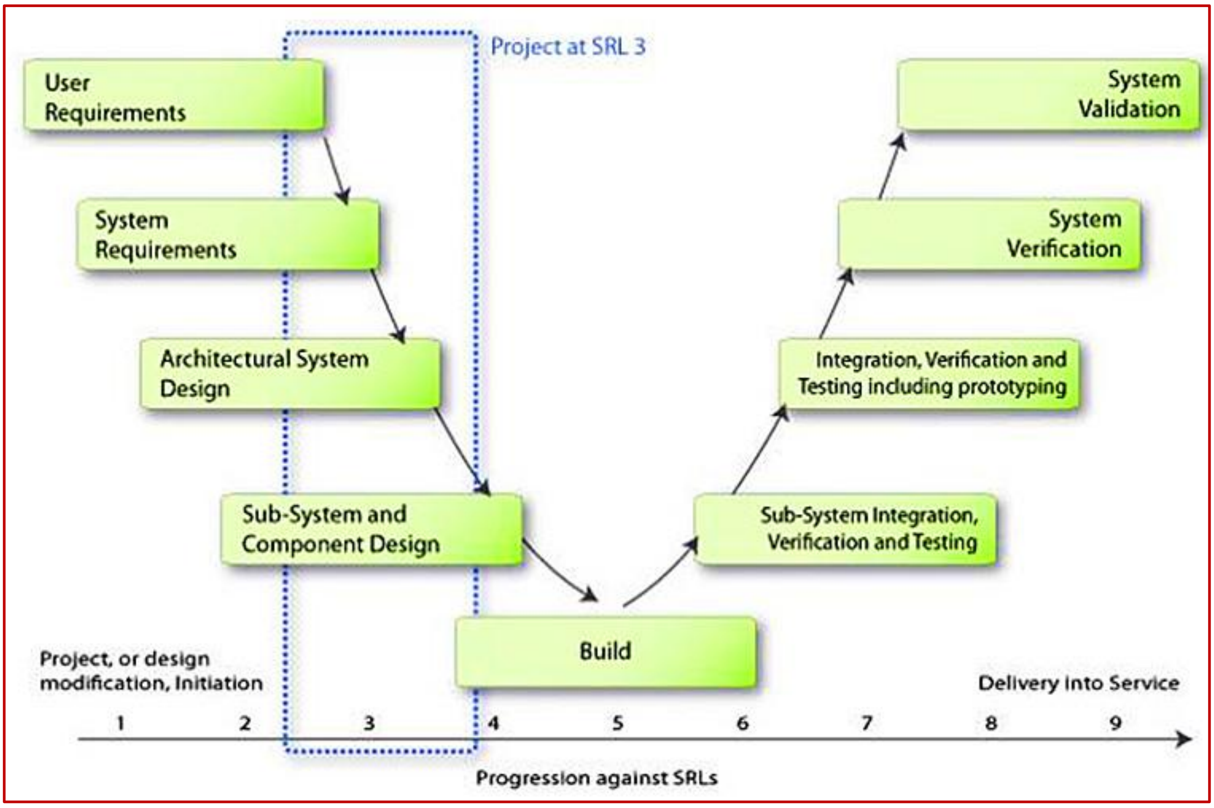


Figure 27 System engineering "V" (MOD view)

This technique is known as "spiral" or "evolutionary" development and it can be envisaged as being several loops through the "V". It is likely to be applicable to many threads of quantum technology development; a full description is beyond the scope of this paper. However, the important point is that the intelligent management of system development in such circumstances is a particular and necessary skill to ensure success and to achieve an acceptable level of time and cost.

7.3.6. The science to engineering interface

Much of our effort in developing practical technologies is focussed on developing demonstrators at TRL 3 or TRL 4. This is, essentially, "technology push" (at least at the beginning) and we will want to be sure that the end product will be fit for purpose and fit for the market that will be served. That requires development; typically costing orders of magnitude more than the original research. Therefore, tighter control of the projects will be required.

Where the investment to transition from TRL 3-4 to TRL 7-8 is significant, Industry will most likely want to adopt more formal methods to control the project. A common approach is to build a test rig at TRL 3-4 which mimics the demonstration equipment developed by academics, and which is suitable for tests, modifications and analysis. A working interface needs to be established between the academics and the engineers without impinging too heavily on the researchers, as these people will be developing seedcorn for further novel technologies.

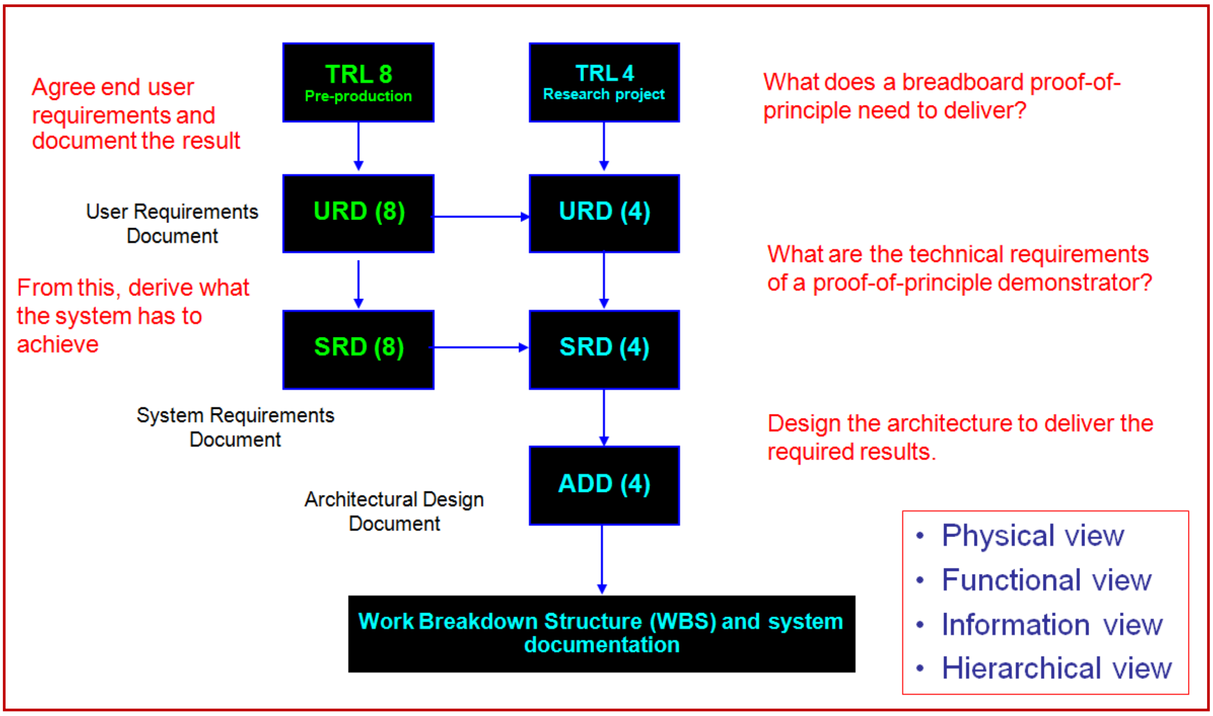


Figure 28 An example of how transition from TRL 4 to TRL8 can be efficiently managed

Generally, user requirements can be captured and these in turn define the system requirements describing the desired behaviour of the TRL8 system. These may be used to generate a parallel set of user and system requirements at TRL 3-4 which will lay out an acceptable envelope of performance for the technical demonstrator. After proving functionality, the architectural design of the TRL 8 production equipment can be satisfactorily achieved. An example of how this more formal process can be made to work is shown in figure 28. This formalism will help to avoid the system design being "backed into a corner" in an early stage of development.

7.3.7. Interoperability and standardisation

We have established that many of the systems used to develop quantum technology share common devices, modules and infrastructure. This presents another opportunity for business and growth, as there is a worldwide market for such items where most research and development groups currently tend to develop their own. There is also an opportunity to supply into other markets (such as instrumentation) as well as reducing costs to our own R&D groups.

The most effective method of ensuring interoperability and standardisation from a systems engineering point of view is to reduce the physical view to a number of distinct modules. This will often form a hierarchy e.g. components such as transistors at the lowest level, circuit boards at the next, and a subsystem further up etc.

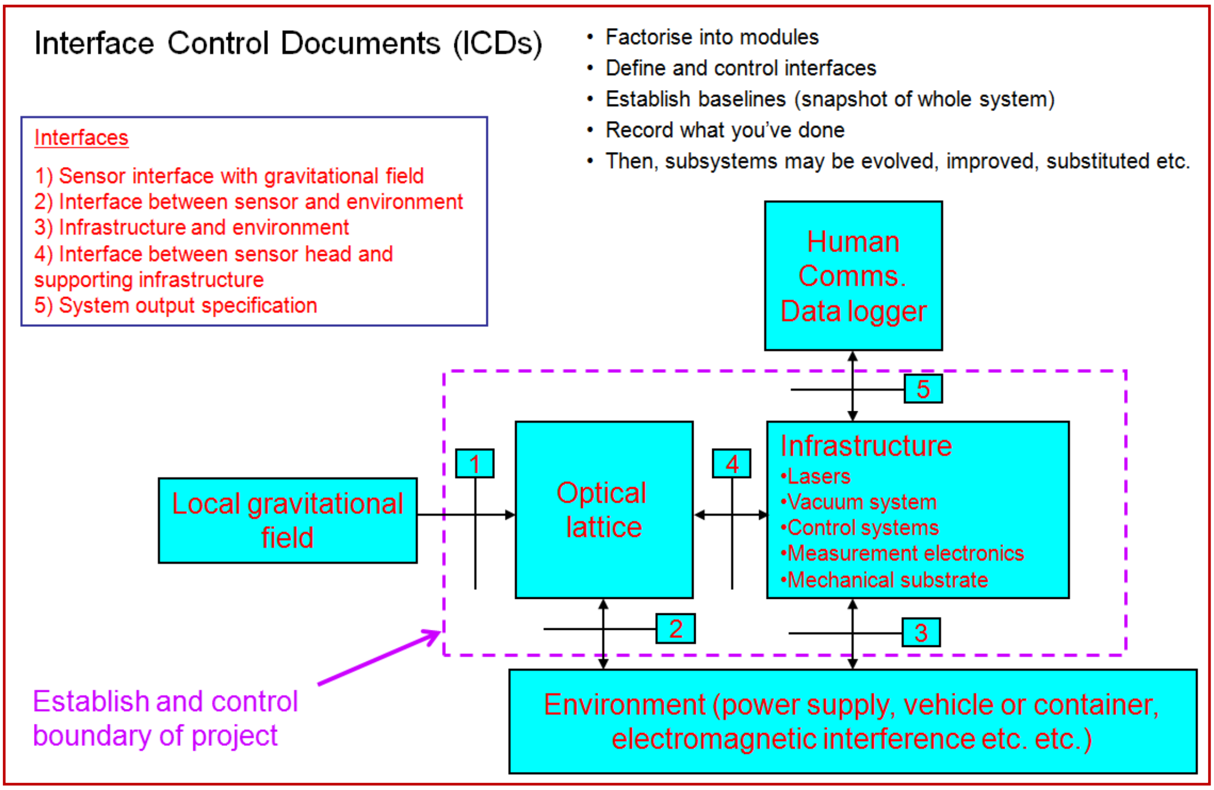


Figure 29 Simplified example of system definition by means of interface specification for a fictitious quantum system

The most important aspect of this approach is to define and control the interfaces, and to make sure that interface specifications, or interface control documents (ICDs), are clear, unambiguous and maintained. In fact, a system can be usefully defined by its interfaces and this makes it easy to facilitate development, technology insertion and upgrade. So called "change races" can be avoided and this becomes more important as equipment increases in complexity. Often, a variety of systems can be constructed from a common set of components or modules, or systems can be easily adapted for different purposes.

A very much simplified example is shown in figure 29 project to demonstrate the principle for our fictitious optical lattice project.

7.4. Timelines

The timelines, i.e. schedule, for taking quantum technologies to market will depend on the following factors:

- Remaining scientific and technical challenges
- Funding, including re-investment from successful industrialisation
- Necessary processes
- Human resources
- Leadership, vision, teamwork
- Project and risk management

These are likely to be specific to the technology to be exploited and we expect that the detailed roadmaps that we generate will contain suitable analyses to be incorporated into the development plans. Much will depend on how seamlessly the technology can be transferred up the TRL ladder and into systems. This will introduce a considerable degree of uncertainty that will need to be managed.

We can, however, offer some rough estimates here. These are based on our opinions and we expect better estimates to be formed as a core activity of developing the roadmaps and outline development plans. The actual timescales achieved in practice will depend on funding, drive, the quality of people engaged in the technology transfer, and materialisation and mitigation of risks.

7.4.1. Quantum timing and clocks:

We expect a rolling, layered level of progress over the next 20 years with gradually improving accuracy, compactness, robustness, power consumption and cost. Although subject to technical and project risk, from the UK standpoint we expect a commercially competitive chip scale atomic clock to become available in a 4-5 year time frame, accuracy about 1 in 10^{13}. A knapsack sized clock with accuracy of ~ 1 in 10^{15} or 10^{16} perhaps on a 5-7 year time frame. A self-contained clock with an accuracy of 1 in 10^{18} may become possible in 8-10 years.

7.4.2. Quantum communications:

Early QKD systems are freely available commercially, although testing and accreditation of specific systems will be necessary before they can be assumed to deliver the highest grade of security.

Ubiquitous, hand held QKD systems, with sufficient investment and encouragement, might reach mass markets in 4-7 years

Quantum networks in various forms and for various purposes have been demonstrated by several countries. We predict that development will continue, and that they will become available commercially, with gradually increasing sophistication, over the 3-10 year time frame. In the region of 10-25 years we might expect highly interconnected, long range quantum networks to become available. In the context of *quantum* information, such networks may form the backbone of distributed quantum computing systems.

7.4.3. Quantum sensors:

The diversity of possible quantum sensors is such that it is impossible to generalise. The numbers will depend very strongly on the funding, impetus and support given to individual R&D programmes. Some key threads are:

Disruptive gravity sensors: 4-7 years, gradually improving to gravity "imagers" of varying sophistication, 8-15 years.

Cutting edge "cold atom" precision navigation and positioning sensors: 10-15 years

Electromagnetic sensors, e.g. using SETs[119] or NV centres in diamond (for example): 4-10 years or even less, depending on degree of sophistication

[119] SET = Single Electron Transistor

Quantum enhanced imaging and spectroscopy: 5-10 years to market depending on technology adopted.

7.4.4. Quantum simulation and computing

Large scale general purpose machines: 2025-2030 with commercial availability ~ +5 years beyond

Specialised, special purpose or niche (e.g. "analogue") machines: Possibly 5-10 years with sufficient investment of effort and funding.

D-Wave is available commercially now, although it remains controversial and there is some doubt that it will develop to the point where it outclasses any available classical machine. Development, however, is continuing at a rapid pace.

Boson sampling computers may become available in perhaps 5-7 years although they represent a backwater in the field and their range of applicability currently seems very limited.

7.4.5. Molecular and solid state

We expect that the development of nanotechnology and its associated quantum effects to take place on a continuous and accelerating basis.

We could see smart imaging for health diagnosis and monitoring and for micro-surgery at a cellular or sub cellular level in 10-20 years, with an increasing level of sophistication and throughput.

On the same time scale we would expect to see sophisticated, widespread availability of environmental monitoring techniques. Highly efficient thermo power devices and photovoltaic systems will also become available, enabling greater efficiency in distributed and micro-power generation. Many are in early stages although there is scope to accelerate development.

Finally, an unexpected breakthrough with immense disruptive impact could occur at any time, with a time scale through to implementation of 5 years or less. An example that might be possible is room temperature (or higher) superconductivity.

7.5. Resources

Sufficient investment funding needs to be applied to:

- Research
- High level skills
- Innovation
- Infrastructure

These resources need to be focussed on the key science and technology threads that were discussed in the November meeting. They will be judged as those that will bring (a) the greatest economic benefit upon exploitation, and (b) the greatest potential for future benefit after further fundamental research. This implies a need for over-arching coordination, responsibility and accountability. Gearing should, as matter of course, be sought via Industry, BIS, venture capital funding and the EU.

Research will provide fundamental, leading edge research, and encourage a network of key centres that will later include early stage business related incubation. Research forms the seedcorn for later phases of development and exploitation.

High level skills will attract, motivate and retain the best minds and ensure that UK becomes the central hub for quantum S&T development and exploitation. Fellowships will encourage mobility and inter-discipline collaboration. Experts in applied science and system engineers will be essential to develop test rigs and demonstrators, and implement technology transfer. They will generally need to have sufficient knowledge of the physics so consideration needs to be given to making technology transfer an exciting career path for PhDs and post docs. Complementary high level skills will need to be developed in industry, and in- and out- secondments of mid to senior level staff between industry and academia will be supported.

Innovation will provide funding to enable rapid transition from research to product or process, and encourage partnering. Technical demonstrators and test rigs may also be developed under this heading and effort should be made to gear efforts with funding from the TSB and EU. Key skills required will include team leadership, and risk and project management.

Infrastructure will focus on ensuring that state of the art labs and processes (and suitable staff) are available throughout the process to develop and implement the target technologies. Specialist test beds should be included and this might include certain quantum technologies being used as a lever for the development of others. Refresh of key fabrication facilities will also be necessary. It will also assure critical supply chains, especially where sovereign capability is important.

In order to maximise the potential for effective and efficient delivery of value, it is important that the funding is focussed on those areas of S&T and institutions most likely to deliver. An attempt to amplify *all* instances of existing research with extra funding is likely to dilute effort and dissipate benefit. It is important to avoid the "fire and forget" investment approach, and a suitable, coordinated portfolio should be constructed.

The science and engineering underpinning the different manifestations of quantum technology overlaps and interacts to a significant degree. Although there are many universities pursuing excellent research in quantum science, it is apparent from our analysis that we need to concentrate resources for rapid technology development in a key subset. Ideally, this initiative might be seen as a modern day "Manhattan project" where vision, a common purpose, teamwork and a will to move output into the commercial world would be paramount.

8. Conclusions and recommendations

8.1.Conclusions

In the Autumn Statement the Rt. Hon. George Osborne announced that an extra £270M will be made available for the development of quantum technologies over the next five years. UK PLC has the resources to grasp and exploit a very significant opportunity for the UK economy, and maintain our outstanding, world class competitive position.

During our analysis, we have found that the scope of quantum science (especially "Quantum 2.0"), and its potential technological spin-off, is vast. Research output grows in scope and volume worldwide by the month. Much is difficult or impossible for the lay person to understand, and misconceptions abound. Much is still not understood by the physicists studying the science. There are also many "unknown unknowns".

However, although the full potential of quantum technologies is unknown, there are a number of distinct areas where sustained investment and effort is likely to yield immense economic benefit as well as a security and defence advantage. We are well placed to deliver that. The potential may even improve drastically as the state of the art of scientific understanding proceeds; it is a rapidly moving field.

We see principal areas of opportunity for the defence and security community in the short and medium term as being timing and clocks, sensors and navigation, and enabling technologies such as quantum optics. There are many commercial applications of these technologies so many of our priorities are shared with the civil sector. Molecular and solid state advances in quantum technology, such as power generation and recovery, and ultra-efficient lighting, could provide immense economic benefit throughout the economy and has the potential to penetrate almost every aspect of our lives in future decades. Quantum computing and quantum information processing is expected to have lesser impact in the short and medium term but immense impact in the longer term, including much that is not yet foreseen. "Black Swans" such as room temperature superconductors or designer materials could produce immense disruption and so technology watch is essential. Key areas for exploitation are outlined in section 5

We emphasise that technical issues represent only part of the challenge. Because of our excellent scientific progress to date, in many areas the challenge is becoming one of maturing the technologies to a suitable technical readiness level. There are many system engineering issues to be addressed. There are a number of structural issues, (such as the need to draw together ingredients e.g. the output of piecemeal research projects), and organisational and process issues (such as the requirement for coordination, leadership, and close connection with Industry and markets) that need to be sufficiently addressed before exploitation can be expected to succeed. These are outlined in section 7 where we discuss what it needed to "make it happen"..

To exploit emerging quantum technology effectively, resources will need to be concentrated in the areas most likely to yield value. This indicates that we need to work with a central team of premier world class UK institutions. We need to form an interface, via teams of engineers, to industry. In some instances new start-ups, SMEs and joint ventures may be needed.

8.2.Recommendations

Our principal recommendations are as follows:

1) That quantum technologies become a key ingredient of the proposed MOD initiative to concentrate and accelerate research in areas that promise disruptive impact on a timescale of 3-10 years. We have received significant encouragement and input from the community, represented by the attendees at Chicheley, and have identified several priority areas (see (4)).
2) An appropriate fraction of investment is made available for the engineering interfaces and to address the challenge of "pull through" to higher TRL demonstrators suitable for industrial uptake.
3) During "pull through" of the science into technology:.
    a. "Academic currency" of some form needs to be awarded to scientists who assist converting their science into technology.
    b. Working interfaces between scientists and engineers, and industry need to be established and maintained. Networks are needed to connect scientists working in the various quantum teams, especially between experimentalists and theoreticians.
    c. We should examine the physics at the boundaries between the different groups and disciplines, to see what more could be added to our endeavour.
4) Priority areas for applied quantum technology development are:
    a. Quantum clocks and associated communication networks (big ticket)
    b. Ubiquitous, affordable chip scale clocks (large markets)
    c. Integrated quantum optics for wide applications e.g. handheld QKD, sensors etc. including plasmonics (small ticket / extensive commercial markets)
    d. Gravity and inertial sensors and "imagers" (big ticket), principally using matter waves
    e. Quantum sensors such as matter wave EM field sensors, chip scale Rydberg sensors for millimetre wave and THz radiation, etc.; molecular scale sensors for medical applications
    f. (Commercial) photovoltaics, thermoelectrics, ultra-efficient lighting etc.
    g. Special purpose quantum computers e.g. for simulation or optimisation (big ticket)
    h. Alongside near term exploitation, continued efforts towards practical and scalable quantum computing technologies
5) Roadmaps to be developed for (but not limited to):
    a. In the short term, a first tranche:
        - Quantum clocks and frequency standards
        - Gravitational telescope

- Navigation without GNSS

b. Later, a second tranche:

- Quantum sensors
- Computation ("quick" wins e.g. analogue, and hybrids)

The directions of technology development that we are pursuing need to be kept under review.

6) We need to investigate how intellectual property can be protected, and implement a suitable plan

7) Interoperability and standardisation is considered as a priority. As this activity is likely to define common modules and subsystems, we need to grasp opportunities for "spin off" businesses e.g. into the scientific research or instrumentation market. This will provide leverage to the development of sophisticated systems by enabling industrial exploitation. This will lead to economies of scale, offset of non-recurring engineering costs (NRE) and refinement of design in terms of size, weight and power requirements.

8) A UK quantum communications test bed is established. As a quick win, this can be initiated on existing infrastructure. It will provide a field test of QKD systems and components as described in section. This can be achieved in collaboration with NPL.

9) Sufficient attention and resources are applied to non-technical issues, e.g.

   a. Leadership, vision and governance
   b. A suitable collaborative landscape incorporating Government, Industry and Academia
   c. Project and risk management
   d. System engineering and transition from science to technology
   e. Interoperability and standardisation
   f. Management of intellectual property
   g. Technology readiness and connection with Industry and other customers
   h. Establishment of suitable engineering - academic interfaces
   i. Identification and preparation of suitable markets (derived from (5))

10) Regular networking within the quantum community, including 4-6 monthly meetings of the community involved in defence and security quantum research..

9. Appendix: additional references used in compiling sensor charts

9.1. Quantum sensor sensitivities

Sensor Type	Best classical	Quantum demonstrated	Quantum potential	Comments
Gravity	15 μgal/$Hz^{-1/2}$ (FG5-X falling corner cube) [1]	4.2 μgal/$Hz^{-1/2}$ [2] <100 ngal/$Hz^{-1/2}$ (10m fountain, inferred) [3] 1 μgal/$Hz^{-1/2}$ [4]	< 1fgal/$Hz^{-1/2}$	[4] is a commercial device
Rotation	7.8 prad/s /$Hz^{-1/2}$ [5]	600 prad/s /$Hz^{-1/2}$ [6]	5prad/s /$Hz^{-1/2}$ [7]	Best classical being a unpractically large area ring laser gyro
Magnetic Field		200 aT/$Hz^{-1/2}$ [8] 160 aT/$Hz^{-1/2}$ [9]	< 10 aT/$Hz^{-1/2}$	Size is important, see figure 15
MW magnetic field		77 pT/ $Hz^{-1/2}$ in 20 μm^{-3} [10]		Size is important Non-invasive
MW electric field sensors	1 m V/cm/$Hz^{-1/2}$ [11]	30 μV/cm/$Hz^{-1/2}$ [11]	100 nV/cm [11] (timescale unclear)	
Phonons	>10^{-12} W/$Hz^{-1/2}$	10^{-15} W/$Hz^{-1/2}$ [12]	10^{-20} W/$Hz^{-1/2}$ [13]	
Short range gravitational acceleration		[14] see graph, Appendix α~10^{10} at 1 μm [15]	α~10^{6} at 1 μm [16]	Mostly fundamental research so far; size is important

[1] http://www.microglacoste.com/absolutemeters.php

[2] Demonstration of an ultrahigh-sensitivity atom-interferometry absolute gravimeter
Zhong-Kun Hu, Bu-Liang Sun, Xiao-Chun Duan, Min-Kang Zhou, Le-Le Chen, Su Zhan, Qiao-Zhen Zhang, and Jun Luo , Phys. Rev. A **88**, 043610 (2013) → 4.2 10–9 g/rt(Hz)

[3] Multiaxis Inertial Sensing with Long-Time Point Source Atom Interferometry
Susannah M. Dickerson et al Physical Review Letters 2013 111 → 10m apparatus, 6.7 10-12 g/shot (inferred, 2.3s + prep time), rotation to 200 nrad/s absolute for ~400 cycles)

[4] http://scpnt.stanford.edu/pnt/PNT12/2012_presentation_files/07-Kasevich_presentation.pdf

[5] K. U. Schreiber and J.-P. R. Wells, Rev. Sci. Instr. 84, 041101 (2013).

041101-9 K. U. Schreiber and J.-P. R. Wells Rev. Sci. Instrum. **84**, 041101 (2013)

TABLE II. Summary of relevant physical properties of a number of rectangular large ring lasers. The table lists the sides a and b, the area enclosed, the perimeter, the finesse F, the quality factor Q, the ringdown time τ, the detection beam power p, the obtained frequency splitting f_{Sagnac}, the corresponding lock-in threshold $f_{lock-in}$ as well as the inferred sensor resolution S.

Ring laser	a (m)	b (m)	Area (m^2)	Perimeter (m)	F	Q	τ (μs)	p (nW)	f_{Sagnac} (Hz)	$f_{lock-in}$ Hz	S (prad/s/$\sqrt{Hz}$)
C-II	1	1	1	4	85 000	5.3×10^{11}	180	20	79.4	0.24	146.2
GEOsensor	1.6	1.6	2.56	6.4	300 000	3×10^{12}	1000	5	102.6	0.014	108.1
G-0	3.5	3.5	12.25	14	113 000	2.5×10^{12}	829	50	288.6	0.013	11.6
G-ring	4	4	16	16	138 000	3.5×10^{12}	1200	20	348.5	0.010	12
UG1	21	17.5	367.5	77	2100	1.2×10^{12}	409	10	1512.8	0.01	17.1
UG2	21	39.7	834.34	121.4	1100	1.5×10^{12}	640	10	2180	0.008	7.8

[6] Rotation sensing with a dual atom-interferometer Sagnac gyroscope
T L Gustavson†, A Landragin‡ and M A Kasevich, Class. Quantum Grav.17 (2000) 2385–2398. → 6 10^{-10} rad/s in 1 s,

[7] Absolute Geodetic Rotation Measurement Using Atom Interferometry
J. K. Stockton, K. Takase, and M. A. Kasevich
Phys. Rev. Lett. 107, 133001 – Published 22 September 2011 → sensor potential for 2 10-12 rad/s /shot (~5 prad/s /$Hz^{-1/2}$)

[8] www.twinleaf.com : commercial SERF thermal atomic vapour sensor

[9] H. B. Dang, A. C. Maloof, and M. V. Romalis, "Ultrahigh sensitivity magnetic field and magnetization measurements with an atomic magnetometer," *Applied Physics Letters*, vol. 97, no. 15, pp. 151110-1–151110-3, 2010 → 160 aT/$Hz^{-1/2}$

[10] Physical Review Letters; Volume 111, Issue 14, 3 October 2013, Article number 143001; Quantum metrology with a scanning probe atom interferometer; Ockeloen, C.F., Schmied, R., Riedel, M.F., Treutlein, P. → 77 pT/√Hz in a probe volume of 20 μm3

[11] Microwave electrometry with Rydberg atoms in a vapour cell using bright atomic resonances
Jonathon A. Sedlacek, Arne Schwettmann, Harald Kübler, Robert Löw, Tilman Pfau & James P. Shaffer; Nature Physics 8, 819–824(2012) doi:10.1038/nphys2423

[12] O O Otelaja, J B Hertzberg, M Aksit, R D Robinson,
Design and operation of a microfabricated phonon spectrometer utilizing superconducting tunnel junctions as phonon transducers,
New J. Phys. 15 043018 (2013)

[13] M. M. Dos Santos, T. Oniga, A. S. Mcleman, M. Caldwell, C. H.-T. Wang,
Toward quantum gravity measurement by cold atoms,
J. Plasma Physics 79, 437 (2013)

[14] Kapner, D.J., et al Phys. Rev. Lett. 98 021101 (2007)

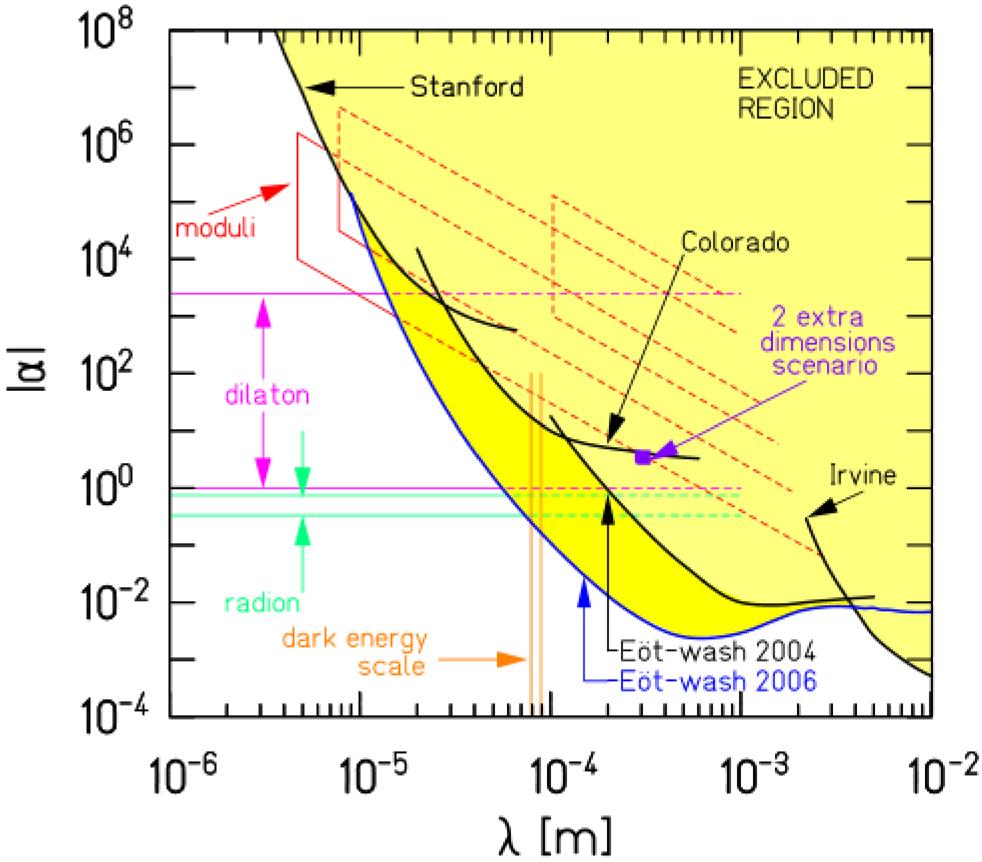
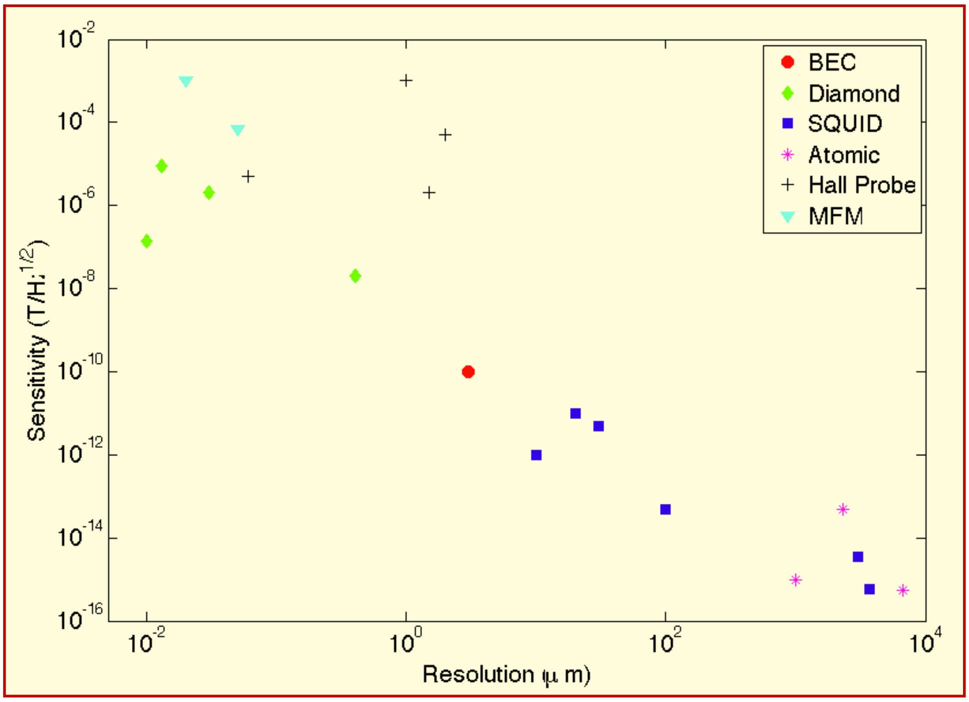


Figure 30: Constraints on Yukawa violations of the gravitational $1/r^2$ law (from [14])

[15] Dimopoulous S., Geraci, A.A. Phys. Rev. D. 68 124021 (2003)

9.2.Magnetic sensors



Nature **422**, 596-599 (10 April 2003) | doi:10.1038/nature01484; Received 24 October 2002; Accepted 4 February 2003, **A sub-femtotesla multichannel atomic magnetometer**, I. K. Kominis[1,2], T. W. Kornack[1], J. C. Allred[3] & M. V. Romalis[1]

→ Here we describe a new spin-exchange relaxation-free (SERF) atomic magnetometer, and demonstrate magnetic field sensitivity of 0.54 fT $Hz^{-1/2}$ with a measurement volume of only 0.3 cm^3. Theoretical analysis shows that fundamental sensitivity limits of this device are below 0.01 fT $Hz^{-1/2}$

Microfabricated Atomic Magnetometers and Applications

John Kitching, Svenja Knappe, Vishal Shah, Peter Schwindt, Clark Griffith, Ricardo Jimenez and Jan Preusser
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→ 50 fT/√Hz to 50 pT/√Hz, and the sensitivity depends on the mechanism by which the field is sensed. Self-contained physics packages with a volume of 12 mm3 and suitable for earth's field-operation have been shown to operate at 6 pT/√Hz.

A Remotely Interrogated All-Optical 87Rb Magnetometer

B. Patton, O. O. Versolato, D. C. Hovde, E. Corsini, J. M. Higbie, and D. Budker
Appl. Phys. Lett. 101, 083502 (2012); http://dx.doi.org/10.1063/1.4747206

→ Operated as a driven oscillator, the
magnetometer measured the geomagnetic field with .3.5 pT precision in a 2 s data acquisition;
The sensor was also operated in self-oscillating mode with a
5.3 pT/pHz noise floor.

Optical Magnetometry
Dmitry Budker and Michael Romalis
arXiv:physics/0611246v1
→ Presently, the most sensitive atomic optical magnetometer is the spin-exchange-relaxation-free (SERF) magnetometer whose demonstrated sensitivity exceeds 10−15 T/√Hz, with projected fundamental limits below 10−17 T/√Hz [12]. SERF magnetometers also offer a
possibility of spatially-resolved measurements with millimeter resolution.
We use a pump-probe measurement scheme to suppress spin-exchange relaxation and two probe pulses to find the spin precession zero crossing times with a resolution of 1 psec. We realize magnetic field sensitivity of 0.54 fT/Hz1/2, which improves by an order of magnitude the best scalar magnetometer sensitivity and surpasses the quantum limit set by spin-exchange collisions for a scalar magnetometer with the same measurement volume operating in a continuous regime. cell size 0.66 cm3

SQUIDs

A scanning superconducting quantum interference device with single electron spin sensitivity
Denis Vasyukov, Yonathan Anahory, Lior Embon, Dorri Halbertal, Jo Cuppens, Lior Neeman, Amit Finkler, Yehonathan Segev, Yuri Myasoedov, Michael L. Rappaport, Martin E. Huber and Eli ZeldovPUBLISHED ONLINE: 1 SEPTEMBER 2013 | DOI: 10.1038/NNANO.2013.169
→ We use the devices to image vortices in a type II superconductor, spaced 120 nm apart, and to record magnetic fields due to alternating currents down to 50 nT.

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007 699
Highly Sensitive and Easy-to-Use SQUID Sensors
D. Drung, C. Aßmann, J. Beyer, A. Kirste, M. Peters, F. Ruede, and Th. Schurig
→ For a 3 mm 3 mm chip size, a noise level of 3.6 fT Hz is obtained at 4.2 K.

Supercond. Sci. Technol. 26 (2013) 035017 (5pp) doi:10.1088/0953-2048/26/3/035017
Noise characterization of highly sensitive SQUID magnetometer systems in unshielded environments
A Chwala, J Kingman, R Stolz, M Schmelz, V Zakosarenko, S Linzen, F Bauer, M Starkloff, M Meyer and H-G Meyer
→ ML7 size 3.7 mm2
The intrinsic white noise of the ML7 type SQUID amounts to 0.6 fT Hz^-1/2, while we achieve 1.5 fT

Hz^-1/2 in magnetic shielding and down to 1.2 fT Hz^-1/2 by estimation via cross-correlation as well as by referencing in the time domain.

Nitrogen vacancy centres

papers with scanning probe -AFM-NVs

Nanoscale magnetic field mapping with a single spin scanning probe magnetometer
L. Rondin, J.-P. Tetienne, P. Spinicelli, C. Dal Savio, K. Karrai, G. Dantelle, A. Thiaville, S. Rohart, J.-F. Roch, and V. Jacques
Applied Physics Letters 100, 153118 (2012); doi: 10.1063/1.3703128
→ sensitivity: 9 $\mu T/sqrt{Hz}$ 110ms sampling time resolution: 13nm (limited by AFM)

NVs in crystals or Nanocrystals (stationary)

PUBLISHED ONLINE: 3 FEBRUARY 2013 | DOI: 10.1038/NPHYS2543
Nanoscale magnetic imaging of a single electron spin under ambient conditions
M. S. Grinolds, S. Hong, P. Maletinsky, L. Luan, M. D. Lukin, R. L.Walsworth and A. Yacoby
→ static fields: 2 $\mu T/sqrt{Hz}$
AC fields: 56 $nT/sqrt{Hz}$ (330 $/mu s $ measurement time)
3 nT magnetic fields at kilohertz frequencies after 100 s

Nanocrystal 30nm

Radio-frequency magnetometry using a single electron spin
M. Loretz, T. Rosskopf, and C. L. Degen
→ In a proof-of-principle experiment we detect a 7.5MHz magnetic probe field of 40 nT amplitude with < 10 kHz spectral resolution. 0.2nT/sqrt(Hz) (at 7MHz)

Arrays of NV, where the NVs are read out individually

Magnetic spin imaging under ambient conditions with sub-cellular resolution
S. Steinert, F. Ziem, L. Hall, A. Zappe, M. Schweikert, A. Aird, G. Balasubramanian,
L. Hollenberg, J.Wrachtrup
→ Array: array of atomic sized NV sensors (~1000 μm^{-2})
microTesla sensitivity proven

Using NV ensembles:

L.M. Pham , D.L. Sage , P.L. Stanwix , T.K. Yeung , D. Glenn , A. Trifonov ,
P. Cappellaro , P.R. Hemmer , M.D. Lukin , H. Park , A. Yacoby , R.L. Walsworth ,
New J. Phys. 13 , 045021 (2011).
→ In the study by Pham et al., 24 the 140 µ m × 140 µ m fi eld of view was divided into 614 nm pixels containing ~ 100 NV centers each, and the diffraction limited resolution was ~ 500 nm. The AC magnetic field sensitivity measured along each NV crystallographic axis was 136 nT Hz –1/2 in each pixel.

L.M. Pham , N. Bar-Gill , C. Belthangady , D. Le Sage , P. Cappellaro , M.D. Lukin ,
A. Yacoby , R.L. Walsworth , in press (**available at http :// arxiv . org / abs / 1201 . 5686**).
→ A factor of 10 improvement in AC magnetic fi eld sensitivity was recently reported, yielding 6.8 nT Hz –1/2 with ~ 10 ^3 NV centers concentrated in a volume of 30 µ m^3 and using a 240-pulse XY sequence.

Hall effect sensors:

High sensitivity and multifunctional micro-Hall sensors fabricated using InAlSb/InAsSb/InAlSb heterostructures
M. Bando, T. Ohashi, M. Dede, R. Akram, A. Oral, S. Y. Park, I. Shibasaki, H. Handa, and A. Sandhu
Citation: Journal of Applied Physics 105, 07E909 (2009); doi: 10.1063/1.3074513

→ 1 mum x1 mu m 0.51 mG/sqrt(Hz)

Sede Amministrativa
UNIVERSITµA DEGLI STUDI DI MODENA E REGGIO EMILIA
Dottorato di Ricerca in Fisica XIX Ciclo

Hall probes magnetometry for the study of molecular nanomagnets
Andrea Candini
Relatore: Prof. M. A®ronte
Tesi presentata per il conseguimento del titolo di Dottore di
Ricerca

→70 x70 nm 30mT (min field)

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Special thanks are due to the following who have provided specific input for later drafts of this document.

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