Towards a UK co-operative for the advancement of quantum technology

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Towards A UK Co-Operative For the Advancement of Quantum Technology (CoFAQT)


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Summary
The meeting was the fourth in DSTL’s series of community meetings and had a Systems Engineering theme – recognising the increasing importance of this topic for many in the Quantum Technology (QT) community. There is a growing recognition that, although there are significant research challenges associated with realising the commercial and societal benefits anticipated from quantum technologies, there are also other challenges which concern the physical, commercial, societal and regulatory environments into which these new technologies will be integrated.

Similar difficulties have been faced and overcome by the information and communications industry. One of the striking characteristics of this sector over the past 20 years has been the speed at which advances in semiconductor technology have been exploited by industry. Each new generation of semiconductor devices has led to new system designs and to new user capabilities which represented a major advance upon the systems and capabilities that came before them. However, to achieve this required a large number of different components and tools to become available at the right time, and at an affordable price. The routine achievement of this is evidence of how companies and institutions within the sector have been able to communicate effectively and establish a high level of collaboration, whilst still maintaining intense competition at the product level.

QT is very different to the semiconductor industry. While a number of target applications exist the discipline is very much in its infancy. At one end of the spectrum, there are some applications in communications and sensors that are relatively close to market, and, at the other end, there are some applications in computing and simulation that are still far from market. Many choices of enabling technologies and materials have yet to be fixed, and there is, as yet, very little first-hand experience of the problems that will arise when companies seek to establish repeatable manufacture of quantum components and systems.

What can we learn from the International Technology Roadmap for Semiconductors (ITRS) that might benefit the Quantum Technology community? Generating an additional quantum roadmap would merely duplicate previous work – but establishing a small number of cross-community working groups might be a way to assist UK industry to gain a competitive edge in the application of quantum technologies, without duplicating the existing activities by other bodies such as InnovateUK, British Standards Institution (BSI), European Telecommunications Standards Institute (ETSI), Defence Science and Technology Laboratory (Dstl) etc. This document reports on discussions held at the meeting around this question and, leveraging this input, seeks to provide clear and appropriate recommendations to the UK QT community.
Recommendations

**Recommendation 1:** The community must now identify and agree a small number of platforms and enabling technologies, and develop, and share, detailed roadmaps for each of these. A systems integration view needs to be established from the outset.

**Recommendation 2:** The community must now identify the key subsystems, components, tools and services that are realistic for the UK to seek to become a leading supplier. This should involve the UK Quantum Technologies Strategic Advisory Board (QT SAB), Innovate UK, industry and academia. The list should be made available to the community, funding and policy making bodies.

**Recommendation 3:** The quantum technologies programme needs further and challenging demonstrator programmes focussed around specific application areas to reduce risk, build skills and know-how within industry, and to provide hard evidence of performance that can be used to engage a broader range of systems companies and end users. Building commercial activity at an early stage is important in securing and sustaining support from companies and funding agencies.

**Recommendation 4:** The community must now take advantage of the existing market that is comprised of the 1400 or so research groups around the world to (i) discover and understand user requirements, (ii) develop skills and know-how within industry to develop a UK advantage and (iii) build meaningful and sustainable relationships between suppliers and users.

**Recommendation 5:** The quantum community must now engage end-users and systems companies, working across organisational and technology boundaries, to develop a shared vision of the benefits for end-users who become early adopters of quantum technologies, and a shared understanding of the real world challenges that systems companies will face as early adopters and suppliers of quantum technologies.
Discussion
This section expands on the recommendations setting them within the context of the meeting itself and the discussions held by the discussion groups on the day. The recommendations have been distilled from notes taken at the meeting by breakout session chairs and rapporteurs.

Recommendation 1: The community must now identify and agree a small number of platforms and enabling technologies, and develop, and share, detailed roadmaps for each of these. A systems integration view needs to be established from the outset.

Possible platforms and enabling technologies\(^1\) include\(^2\):

- **System modules/platforms**
  - atomic clock modules – a small suite of complementary devices will be needed for a range of applications.
  - Precision lasers (Ultra-stable, ultra-low noise lasers) - these are required for many applications - sensing, metrology, imaging and computing.
  - Optical frequency combs – these are required for many applications where a digital system (operating at MHz or GHz) is locked to the optical output of a quantum system.

- **Enabling technologies/platforms**
  - Integrated optics - required for many applications: sensing, metrology, imaging and computing.
  - Solid state spintronic platforms - silicon, GaAs quantum dots and diamond based platforms.
  - Precision compact cold atom vacuum enclosures – required for many instrumentation and wider applications.
  - Control electronics – required in similar ways for a range of applications.

A systems integration view needs to be established from the outset:

- To facilitate component level integration of QT elements into existing systems, quantum components should be developed that are interchangeable in Size, Weight, Power and Cooling with classical components (trade-off of scale vs performance needs).
- To facilitate the development of new systems\(^3\) a Reference Architecture or similar should be developed to break down the system into platforms and components and thereby aid in identifying boundaries/interfaces of QT components.
- To relate QT element performance to Measures of Effectiveness for the 'Integrated System'.

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\(^1\) In this context, and for clarity, by platform technology is meant here a general set of underpinning systems and components on which multiple systems using a range of technologies can be built (such as integrated optics) while enabling technologies are specific developments necessary to allow particular technologies to have multiple uses (such as cold atom vacuums).

\(^2\) The list of examples shown here is for illustration only. Dstl is currently in the process of compiling lists of applications to identify component markets that will greatly expand on the examples listed here.

\(^3\) Truly innovative devices are difficult to set requirements, as there is lots of work still to do to identify the benefits.
• To understand the limiting factors of the technologies; the performance benefit vs size, risk and cost of components; the design space for future systems; and the cost of owning and operating QT systems.
• To reduce the cost of QT components⁴ and modules and assist industry to develop repeatable manufacturing processes:
  o Reusable standardised components/"platforms" should be identified which are likely to have multiple system applications.
  o The community should explore ways to engineer devices which are less sensitive to specifications and thereby reduce the need to use very high-specification ‘selected’ components.
• Appropriate system models and documentation to identify and specify the individual devices/modules and their interfaces need to be developed⁵.

The community needs to take positive action to accelerate the development of applications for quantum technologies by:

• Promoting a platform approach to make the technologies more accessible and hence engage a wider range of potential users – this then becomes a way to accelerate the discovery of unexpected markets and applications
• Agreeing upon which ‘platforms’ the UK will invest in and then ensuring that a complete ecosystem is developed for each platform [Standardised processes, well defined interfaces and appropriate standards, reference designs, design tools, user toolkits, awareness and training activities etc.]
• Developing specification sheets for platforms and selected technologies and using these to start conversations between members of the community, and between the community and end-users⁶.
• Identifying the full range of performance parameters that are of importance to systems designers and ensuring that all of these are explored in the research programme.
• Exploring ways to provide early estimates for component reliability so that companies can assess more accurately the cost and risk of adopting QT in the systems they manufacture.
• Encouraging broader entrepreneurship. A focus on in quantum technologies has been the spin-out, most often from academic institutions. Spin-ins are just as relevant, and facilities must be made available to allow the spin-in to the quantum technology space by organisations of all sizes.
• Encouraging parties that are not currently involved to enter into the QT space. This is partially accomplished by detailed road-mapping and the formation of transparent working groups (with a lifespan short enough to prevent the formation of inaccessible

⁴ Existing devices are often expensive as they are purposefully tested and calibrated, and selected for higher-than-average specification.
⁵ Interface Control Document by layer (eg physical, data, semantics); Detailed behaviour under various stimuli/ICD settings; Error modes and restoring normal operation; Resistance to external effects (magnetic field, heat, humidity, dust etc); Actual (reproducible) performance and envelope. Also need to use standardised interfaces which are as open and widely applicable as possible. The definition of these interfaces is controlled by the componentisation solution/ref architecture.
⁶ Dstl has already begun developing specification sheets for inertial sensors and clocks.
clubs). However, this will need to be supplemented by the direct engagement of end-users and systems companies (Recommendation 5).

- Establishing open testbeds that make it simpler for a wider community to test ideas, gain first-hand experience of integrating their products into larger systems, and similarly gain experience of integrating other products into their system.
- Exploring additional ways to facilitate collaboration between researchers, industry and end-users. Centres for innovation might provide a valuable way to accelerate the exploitation of quantum technologies. Centres for innovation provide variously: company space, shared equipment, and academic, financial and business expertise. The French structure for nuclear technologies may be worth investigating as a reference.

**Recommendation 2:** The community must now identify the key subsystems, components, tools and services that is realistic for the UK to seek to become a leading supplier. This should involve the UK QT SAB, Innovate UK, industry and academia. The list should be made available to the community, funding and policy making bodies.

- A balance between platform technologies and specific catapult technologies must be achieved: if we are to gain a national advantage the answer is to pursue both in a sensible balance.

**Recommendation 3:** The quantum technologies programme needs further and challenging demonstrator programmes focussed around specific application areas to reduce risk, build skills and know-how within industry, and to provide hard evidence of performance that can be used to engage a broader range of systems companies and end users. Building commercial activity at an early stage is important in securing and sustaining support from companies and funding agencies.

*Academic groups and industrial partners must deliver the demonstrator milestones within the existing Hub Programmes to provide essential signposts to reaching future markets & applications.*

*The demonstrator programme needs to bridge the gap between lab science and user needs*\(^7\)* with specific emphasis on end-user and system company engagement to:*

- Inform the potential user community of what is available or possible.
- Understand what the user really wants.
- Assist the user to develop a Concept of Operations/Concept of Use of a system or System of Systems incorporating Quantum Technology.
- Assist the user to articulate the Expected Business Benefit of a system or System of Systems incorporating Quantum Technology.
- Develop quantitative end user requirements and understand the units of merit they consider relevant.

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\(^7\) The bridge across the ‘valley of death’ is normally built from the low TRL side; the burden then falls on the QT community to understand the units of merit considered relevant by users, along with their prioritisation and future outlooks. Once this is achieved, we can, in the language of the industries and user communities that the QT community is bridging towards, ‘engage in consultations’.
• Identify specific gaps between user expectation and the quantum community’s ability to fulfil that expectation.
• Increase visibility of new ideas and build relationships with systems companies that will form the higher levels of the various supply chains.
• Identify specific gaps between system company needs and the quantum community’s ability to fulfil that expectation.
• To assist the UK QT community to discover ‘unknown unknowns’.

The demonstrator programme needs to be structured to seek both near term ‘early wins’ and longer term ‘big wins’.

• In other programmes this issue has been addressed through a portfolio approach comprising a mix of lower risk ‘Core Projects’ and higher risk ‘Threshold Projects’.

The demonstrator programme needs to draw upon skills and experience across the community to avoid pitfalls that others have already discovered ‘the hard way’

The demonstrator programme needs to enable UK industry to:

• Gain experience in designing the overall system architecture, the sub-systems, the components and the tools.
• Make maximum use of common components, common services such as foundries.
• Make maximum use of all emerging UK manufacturing capabilities.
• Solve the design and manufacturing challenges that UK industry will face as it scales up manufacture in the ‘chicken and egg’ process by which new technology and new applications lead to growth in demand.
• ‘Use the research market’ to develop a deeper understanding of user needs.
• Explore integration issues.
• Demonstrate the capability of quantum systems in a realistic environment.
• Gain a deeper understanding of the failure modes and reliability statistics for components and systems in realistic environments.

Industry must work appropriately with MOD/DSTL, UKSA/ESA and the EU to expand the demonstrator programme

Recommendation 4: The community must now take advantage of the existing market that comprises the 1400 or so research groups around the world to (i) discover and understand user requirements, (ii) develop Intellectual Property, skills and know-how within industry and (iii) build meaningful and sustainable relationships between suppliers and users.

The community needs to ‘Use the research market’ to:

• Develop a deeper understanding of user needs and to assist users to understand how to use the technology most effectively.
• Explore integration issues.
• Develop the ‘in-house know-how’ that underpins the development and manufacturing processes in any successful organisation.
• Create Intellectual Property that can generate licence revenue when a large market develops for a component and the manufacture moves offshore.
  [In the semiconductor industry there are numerous examples of this - mobile phones are one]
• Gain experience in designing quantum sub-systems, key components and the tools to design and use these items.
• Make maximum use of common components and common services such as foundries.
• Make maximum use of all emerging UK manufacturing capabilities.
• Start solving the design and manufacturing challenges that UK industry will face as it scales up manufacture in the ‘chicken and egg’ process by which new technology and new applications lead to growth in demand.
• Gain experience of the performance and the reliability of quantum systems in a realistic environment.
• Provide the design knowledge and the understanding of user requirements that enables the community to begin developing standards for QT components.8

**Recommendation 5:** The quantum community must now engage end-users and systems companies, working across organisational and technology boundaries, to develop a shared vision of the benefits for end-users who become early adopters of quantum technologies, and a shared understanding of the real world challenges that systems companies will face as early adopters and suppliers of quantum technologies.

To this end, the UK QT Strategic Advisory Board (‘SAB’) have published a Strategy document, and Innovate UK has published a roadmap document. The roadmap document outlines generic technology, the application space and potential market applications.

**A key activity, that underpins the exploitation of all QT Community activities, is to extend the existing roadmaps to provide:**

• Further detail of expected requirements in each application area.
• Further detail of specific platforms and technologies.
• A mapping of expected requirements against specific platforms/technologies.
• An indication of the potential performance and volume capabilities that will be required throughout the supply chain.
• An indication of the challenges to be overcome throughout the supply chain.

A discussion is needed on how the roadmaps are evolved and maintained; successful roadmaps in other sectors have been the results of persistent development over sufficient time to have covered full development cycles (from lab to industrial delivery), it is by this process that they gain both credibility and perspective over a field.

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8 There is a timeline for the development of platforms and the evolution of standards. Whilst components and systems are still being designed- the design and the way the component or system will be used are still changing - they should not be locked down. It is not helpful to try to standardise a device before there is a demand.
A roadmap development of this sort should spawn suitable working groups\(^9\). Two forms of working groups are likely to emerge: one form to **undertake the development and maintenance of a roadmap**, and a second form to **find solutions to particular technological challenges**\(^{10}\) – especially those solvable in the near term.

Working groups\(^{11}\) involve a delicate balance between cooperation to achieve the best outcome for the UK and the need for individual organisations to maintain a competitive position in the marketplace. Where the issues are exclusively pre-competitive there is rarely a serious problem. Where the issues to be resolved are focussed around a particular product-level technology there will be a more difficult conflict with competitive advantage.

**Immediate actions**

Many of the activities to enable all the above could be undertaken by a small number of Working Groups which could be set up under the Special Interest Group(s).

**A first Working Group focused upon engagement and with the user community could provide an effective and efficient means to:**

- Inform the potential user community of what is available or possible.
- Understand what the user really wants in each specific application area – or alternatively why a user is reluctant to engage with the QT community.
- Assist the user to develop a Concept of Operations/Concept of Use of a system or System of Systems incorporating Quantum Technology.
- Assist the user to articulate the Expected Business Benefit of a system or System of Systems incorporating Quantum Technology.
- Develop quantitative end user requirements and understand the units of merit they consider relevant.
- Identify the specific gaps between user expectation and the quantum community’s ability to fulfil that expectation.
- To assist the UK QT community to discover ‘unknown unknowns’.
- Co-ordinate the delivery of QT education and training across the QT and user communities.
- Provide a forum for the QT community to engage with the external organisations that shape policy, develop strategy and fund programmes.

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\(^9\) Working Groups provide a valuable forum for industrial negotiations: the role of a working group is as much problem solving as design negotiation

\(^{10}\) We need to consider how to discover the unknown unknowns, working groups are typically focussed on known unknowns.

\(^{11}\) An initial round table discussion suggested possible working groups including: Modelling /simulation of QT devices, Microfabrication, Vacuum systems, Electronics, Standards and interfaces
A second Working Group focused upon defining platforms and exploiting opportunities in existing systems and markets would be able to:

• Identify key commonalities between QT sub-systems, platforms and other components.
• Agree the most appropriate way to define platforms.
• Map the output of the User Engagement Working Group onto the platforms and components.
• Engage academia and industry.

A third Working Group seeking to maximise the opportunity for the QT community to supply the existing market of 1400 or so research groups around the world

• Identify markets at the component and system levels - e.g. lasers, electronics. simulation models and clock modules.
• Build meaningful and sustainable relationships between suppliers and users.

To make most efficient use of people's time, Requests for Information (RFIs) can be used to collect information and identify the need for improved capabilities. An RFI can establish:

• What is already available off the ‘international shelf and the ‘UK shelf’.
• What is currently planned within the QT and user communities.
• What will the specifications be like in 5-10 years?

Small working parties could explore specific issues on behalf of the Working Groups

Conclusions & Implementation Plan

The discussion arising from the Event has resulted in a community driven set of recommendations that, if followed, could result in developing significant advantage for the UK within the QT space. It is too early to put in place a detailed implementation plan but in the short term two actions can be implemented.

• Firstly, it is necessary for the community to populate the three recommended working groups (see preceding section). Membership should follow good practice elsewhere and comprise a core team that do most of the hard work supported by a wider interest group. This could be facilitated through the Dstl QT Community forum, the KTN SIG in QT and/or the Hubs (Dstl and Loughborough would be willing to facilitate the administration of this process).

• Secondly, we need to convene meetings of these groups. Dstl, Loughborough and NPL have expressed willingness to host a number of meetings until long term support can be secured.
Annex A – Additional Programme Background

The UK National QT Hubs programme has provided underpinning investment (~£150m) in the academic community for research and development. DSTL have invested (~£30m) in ambitious demonstrator programmes in timing, navigation and gravity imaging. This investment has stimulated a great deal of leveraged investment from industry.

There is clear evidence that some systems thinking has begun to be developed, and applied, within the community especially with regard to system integration testing and end-user requirements.

Defence is likely to be one of the early adopters of Quantum Technologies.

In order to establish the UK as a leading supplier of quantum technology, and overcome the “valley of death”, planning needs to acknowledge that:

- The cost to establish and sustain a viable manufacturing capability for a new technology can be very high.
- When planning defence capabilities the UK has to consider both the cost of acquiring a system and the cost of maintaining/upgrading that system throughout the planned operational lifetime of the system.
- If UK Defence exploits a new technology for which there are no major civil applications then the full cost of establishing and sustaining a technology manufacturing capability would fall to the defence sector – this can make the cost to maintain defence systems very high, or even ‘unaffordable’.
- An obvious way for MOD and the defence industries to avoid the ‘cost problem’ is to use only existing technologies; or to introduce only ‘very small tweaks’ to existing technologies – and this may be the most appropriate approach when one is seeking to provide the greatest capability within the constraints of the UK defence budget [An analogy might be using one’s budget to buy a fleet of BMW cars rather than a single F1 car].
- However, when a major new technology like Quantum is emerging, the UK defence industries are likely to find themselves at a serious disadvantage against offshore competition if they are unable to exploit such new technologies until after a supply chain for civil applications has been established. The challenge companies face is that the cost, and the risk, of being the first to establish such a capability can be very high. [There a numerous examples in the history of the semiconductor industry where the companies that were ‘later to market’ were able to save a great deal of time and money in setting up their manufacturing facility because they were able to use knowledge that the ‘first companies’ had ‘learned the hard way’.]
- The high risk of seeking to be one of the first companies to market with the new generation of quantum products is likely to constrain the early involvement of UK industry – UK government funding for demonstration projects can make a big difference and can make it possible for UK companies to bring products to market much earlier.

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11 Additional background that was provided in presentations and in the scene setting discussions within Breakout Groups.