Executive Summary

- The National Physical Laboratory are supportive of a second phase of the National Quantum Technology programme, and see a key goal of this phase to be the further industrialisation and commercialisation of quantum technology.

- Dr Peter Thompson, CEO NPL is leading a national activity on behalf of UKRI to engage major industry across many industrial sectors on the future challenges and opportunities for quantum technologies. Working alongside government and other colleagues, this activity aims to ensure future funding in quantum is focussed on the industry priorities which will generate aligned funding by the private sector and maximise the opportunities for economic growth.

- The UK’s National Physical Laboratory is one of the leading National Measurement Institutes in the world, representing the UK on international bodies creating new standards and regulations, and leading world-class research into measurement science and technology. NPL is based in South West London and has a number of regional hubs across the UK, helping to deliver impact in local economies.

- NPL has a strong history in quantum science, and is continuing to grow its capability in this area to support the UK national programme and to develop new technologies which can feed into a commercialisation process. NPL’s work in quantum science and technologies is delivered by over 100 scientists and engineers.

- NPL is involved in key aspects of responding to the Quantum Technologies Blackett Review recommendations, specifically on reviewing the feasibility of a fully optical fibre network for the purposes of timing and frequency distribution, and the testing of quantum communications systems.

- NPL is working in collaboration with British Standards Institute (BSI) and Intellectual Property Office (IPO) to ensure that measurement, standards and intellectual property considerations are an intrinsic part of all future government-funded challenge programmes. This will ensure that regulations provide the right specifications and support for quantum technologies, while not hindering innovation and development.

Introduction

1. NPL is the UK’s National Measurement Institute, and is a partner organisation within the Department of Business, Energy and Industrial Strategy (BEIS).

2. NPL has a strong history in developing quantum-based technology. Since 1955 when the first practical atomic clock was applied to a timekeeping application at NPL, we have developed our expertise in this area. NPL’s present capability includes a caesium fountain atomic clock, one of the most accurate in the world, providing the basis of UK time. Time is distributed to the public via a number of routes including through radio transmissions and over fibre to the London financial centre.

3. NPL’s work in quantum science and technologies is delivered by over 100 scientists and engineers, including more than 30 PhD students, and extends over a range of technical areas including atomic clocks, optical fibres, quantum sensors, quantum communications and work supporting the development of quantum computing. We also develop new measurement devices based on semiconducting and superconducting circuits.
Written evidence submitted by the National Physical Laboratory (QUT0017)

4. NPL is a key partner in the UK National Quantum Technologies Programme (UK NQTP). The aim of this Programme is to give the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets, and to substantially enhance the value of some of the biggest UK-based industries. The National Programme is delivered by partners from across the research and innovation landscape: EPSRC, Innovate UK, National Physical Laboratory, Dstl, National Cyber Security Centre, and the Knowledge Transfer Network.

5. In order to best formulate the scope and focus of future government investment in quantum technologies, NPL is taking the lead in engaging with UK industry to establish the priority areas and mechanisms for investment from the industry point of view.

6. NPL operates national infrastructure to support quantum technology developments. NPL is developing the capacity to offer test and evaluation for new products based on quantum technologies and to deliver this capability at locations around the country.

7. NPL is an active supporter of the skills agenda through training of graduate students in our scientific and engineering research projects. A Postgraduate Institute for Measurement Science (PGI) has been established at NPL to create the future generation of industry-ready measurement experts crucial if the UK is to lead in creating world-wide industrial impact from science, engineering and technology. The largest single subject area in our PGI is quantum science with over 30 postgraduate students affiliated to a university but working at NPL, being trained as the next generation of quantum engineers.

8. The key element in the PGI’s upskilling approach is its delivery through a three-way partnerships (University/NPL/Industry) and engaging the broad range of multidisciplinary science and engineering at NPL; the whole being a unique, distinctive and enriching experience for postgraduate researchers.

9. NPL has a new set of state-of-the-art laboratories under construction as a world class quantum metrology facility. We will offer industry access to world-class capabilities and equipment to support and drive the development, testing and evaluation of new products based on quantum technologies. The centre is due for completion in early 2019.

Responses to the questions posed in this inquiry

Q1. The progress that has been made on the recommendations in the Government Office for Science’s 2016 report;

Recommendation 1: There is a strong case for continuing the UK National Quantum Technologies Programme to maintain our world-leading position in a promising and now globally emerging area of technology. There should be matched private sector investment in any future phase, to increase the level of industry commitment to the programme, and to accelerate the process of commercialisation.

10. We are very supportive of maintaining the momentum in the UK national programme with continued government funding. The emphasis and goal of the continued programme must be to accelerate the industrialisation and commercialisation of new products and services based on quantum technologies.

11. CEO NPL has been tasked by UKRI with engaging with UK industry to establish the priority areas and applications for investment from their point of view. By exploring industry’s preferred mechanisms for funding, NPL will endeavour to support a programme which could result in industry co-funding. Through a series of events and individual engagements, and in close collaboration with partners in Innovate UK,
EPSRC and others, we will review how industry can best engage in the funding and commercialisation of quantum technologies.

12. The pioneer fund announced in the Industrial Strategy White Paper is a welcome investment to fund a small number of demonstrator projects. A larger and more comprehensive investment is still needed, to allow quantum technologies to reach their full potential.

13. NPL’s new quantum metrology laboratory will also be focussed on supporting commercialisation of quantum technologies. The new laboratory will be a national facility for the benefit of the national programme and will include facilities for testing and validation of quantum technology products and demonstrators, including for quantum clocks. Further investment is needed to allow the lab to provide the full range of testing facilities required.

Recommendation 2: Cabinet Office and the Government Office for Science should review the critical services dependent on GNSS timing signals and mitigate the risks by analysing how long they should be capable of operating with back-up or holdover technology.

14. The recently published Blackett review on the dependence of critical infrastructure on satellite navigation (GNSS) has been undertaken as a direct result of this recommendation. As a national laboratory and the national authority on time, NPL contributed expertise to this government review of critical GNSS dependence.

15. NPL will continue to support and work on recommendations in this GNSS review. Many of the recommendations have a strong NPL focus, and NPL will be looking to use our highly relevant capability to work with other government colleagues to address the issues raised.

16. Specifically, NPL will continue development of improved atomic clocks which can provide the required holdover of precise time, and continue research into the distribution of time and frequency over optical fibre to improve distributed synchronisation across a network.

Recommendation 3: The National Physical Laboratory and the National Cyber Security Centre should support the development of standards for GNSS-resilient timing infrastructure, working with industry, the research community and the relevant standards bodies where appropriate. They should also support the drive for the harmonisation of standards internationally, recognising that in the case of clocks, the applications landscape is complex and involves a number of different standards bodies.

17. It is likely that a consortium of organisations will be bidding into the next wave of Industrial Strategy Challenge Fund with a project based on this recommendation. This project will look to develop infrastructure for GNSS-independent back-up systems across a range of sectors.

18. The financial industry has introduced regulation since this recommendation, defining the accuracy required for financial institutions to be able to time stamp transactions. While sufficiently accurate timing can be provided through GNSS, NPL also provides a service which is independent of GNSS to transmit timing over optical fibre (NPLTime®).

19. In other sectors there is still a large amount of work needed to develop the appropriate standards, and industries such as the telecoms industry need to provide clear requirements for holdover devices to be able to maintain synchronisation and performance independently of GNSS, with standards then being developed based on the requirement.
Recommendation 4: The National Physical Laboratory and the Quantum Communications Hub, working with existing infrastructure organisations, should explore the feasibility of a fully optical fibre network for the purposes of timing and frequency distribution, as well as a test-bed for technology demonstrator experiments. This might start as a city-wide demonstrator project and later expand to key locations around the UK.

20. While NPL’s NPL\textsuperscript{Time} service has provided a unique example of delivering time over fibre, higher accuracy services are possible but as yet less developed and more testing is needed in this area.

21. BEIS has directed NPL to undertake a feasibility project for a fully optical fibre network for time and frequency distribution. This will: explore the interests and requirements in the UK, prioritise links for phased implementation, establish the implementation and running costs, develop the design for supporting infrastructure, and finally assess feasibility of networks to also be used for secure quantum communications.

22. The existing National Dark Fibre Infrastructure Service (NDFIS), currently used for research in telecoms and high speed networks, is suitable for test-bed and demonstrator activity. NPL is working with BT, the York-based Quantum Communications Hub and NDFIS to expand the existing fibre network, to support new activities including the distribution of precision references to key installations. Existing examples of the type of link to develop include the current London to Paris link, NPL (Teddington, SW London) to Harwell, Oxfordshire and London. Further links to universities and end users would also be desirable, such as to Adastral Park, Ipswich - a key telecommunications science park operated by BT, while the network could also benefit other research communities, such as geodesy (e.g. monitoring long-term changes in sea-levels, providing input into models used to forecast the effects of climate change.)

23. Experiments are planned to assess the compatibility of three different types of usage: (1) comparison of optical clocks and high-accuracy services across Europe, (2) NPL\textsuperscript{Time}, (3) quantum key distributions (QKD). This will ensure that any new fibre network developed would be able to service the existing communications infrastructure.

24. NDFIS is not however a suitable infrastructure for long-term time and frequency distribution over optical fibre. Long term plans would aim to set up a dedicated UK-wide dark fibre network. This would require significant and sustained investment from the UK to build the dedicated dark fibre network.

Recommendation 5: Regulation should not present a barrier to the use, deployment and commercialisation of quantum technologies. The National Programme should ensure regulators and standards bodies are aware of the capabilities of the technologies under development, so that regulations are formulated to realise the full potential of these technologies. Test-beds and road-mapping should be considered as a route to development of the regulations by government.

25. NPL is working in collaboration with British Standards Institute (BSI) and Intellectual Property Office (IPO) to ensure that measurement, standards and intellectual property considerations are an intrinsic part of all future government-funded challenge programmes. Through involving these key bodies at the start of new funding, for example in the new ISCF Pioneer fund in quantum, the quantum community can ensure that regulations provide the right specifications and support for quantum technologies, while not hindering innovation and development.

26. The BSI, the IPO and NPL will offer road-mapping and analysis services to projects to ensure that key standards are developed in synchronisation with new technology, and
NPL’s proposed test and evaluation activity will ensure that new technologies can reliably meet required standards.

Recommendation 6: National Quantum Technologies Programme should work with the Alan Turing Institute, the Heilbronn Institute for Mathematical Research and wider academia to identify a set of example challenges which, if solved by a quantum computer or quantum simulator, would have important benefits to government, business and citizens. These challenges would involve algorithm research related to areas such as machine learning, artificial intelligence and the investigation of pharmaceutical drugs and new materials. Government could act as a demonstration client for some of these challenges.

27. This is an ongoing piece of work and would form a part of any future programme in quantum technologies. NPL should be able to contribute to this programme through testing of software and algorithms.

Recommendation 7: The National Quantum Technologies Programme should fund collaborative work between UK quantum communications and cryptography research groups, leading to joint technical developments of both quantum key distribution (QKD) and post-quantum cryptography (PQC), as well as work on digital signatures and other uses of these technologies.

28. NPL has been working in close collaboration with NCSC on the testing and security of quantum communications (QKD). NPL and NCSC are currently putting together a framework for independent testing and validation for systems that are developed in the UK and beyond. Further projects are ongoing with the Quantum Communications Hub on quantum random number generators.

Recommendation 8: The National Cyber Security Centre should support a pilot trial of QKD using realistic data in a realistic environment, with the facilities for the trial being provided by the Quantum Communications Hub. Such a trial should serve to stimulate the supply chain and show UK leadership in secure communications.

29. NPL is part of a group with the Quantum Communications Hub and NCSC exploring how best to test QKD systems in a realistic environment.

Recommendation 9: The National Physical Laboratory, the National Cyber Security Centre and academia should form a partnership to perform conformance tests and issue accreditation certificates. This process would need to involve engagement with other interested parties from industry, such as the communications and financial services sectors, and could lead to the establishment of an independent national facility.

30. NPL is working with the NCSC and the Quantum Communications Hub to define the test and accreditation requirements for commercially available quantum communication systems. NPL is investing in the testing of these products, and this is one of the focus areas NPL will be developing over the next year.

31. NPL has a prominent role in the development of documented standard procedures, for example in testing QKD hardware and components in a quantum communications system. NPL led the drafting of this first measurement standard for a quantum 2.0 technology produced by the European Telecommunications Standards Institute (ETSI) Industry Strategy Group on QKD.

Recommendation 10: The UK, through a competitive process overseen by the National Quantum Technologies Programme, should establish innovation centres. These centres would go beyond the scope of the current Quantum Technology Hubs, involving the co-location of academic and industrial partners with the requirement for matched funding from industry.
32. It is important that the UK should invest in commercialisation of quantum technologies, and it is essential to first find out the key challenges and needs of industry, including how and why they would invest, and to co-develop the portfolio of government investment mechanisms, including innovation centres, which would best accelerate quantum commercialisation. The UK should base its investment on an evidence-led proposal jointly from industry, academia and funding bodies on how to ensure growth in this area, which is tailored to the type of technology being developed.

Recommendation 11: The programme partners in the UK National Quantum Technologies Programme, together with the Quantum Technology Hubs, should establish a body with the funding and sole remit to coordinate activities across the programme more effectively.

33. It is critically important to establish this body for any future programme, which should oversee the wider government investment into quantum technology at a national level, with budgetary control to react in an agile way to changes and opportunities.

34. This body should be led by a senior Director with access to independent scientific advice. The Director would be responsible and accountable to Government, and supported by a secretariat to coordinate and support the activities of the programme and to produce material and metrics covering the overall programme.

Q2. The relative contribution/support from government, researchers and businesses needed to make quantum technologies a success;

35. It is generally recognised within the UK national quantum programme that the involvement of industry at the system integrator and user end of the market needs to be further developed, particularly with the large UK based sector leading businesses who should be the major early investors in quantum technologies.

36. Government investment is needed to support activities which will encourage industry to co-invest. For example, government investment into national facilities for testing new prototypes and products, would generate a larger number of skilled users and appropriate staff, and allow large industry to tap into those skills and test equipment for their own needs.

37. In order to change the proportion of large companies that are involved in quantum technologies, government investment will be needed to increase the technology readiness of quantum products and services up to the point at which businesses are willing to take over. Industry need to see proof of value, not just proof of concept. The later stages of commercialisation and manufacturing will involve significant investment from industry to make quality products, and therefore companies are unwilling to invest in technologies that are too far away from market. CEO NPL is leading on a national activity to engage industry and establish the industry voice in support of a future programme, and ensure that any future programme answers industry challenges.

38. Government should continue to invest in the research base for quantum technologies, both within academia and research organisations, while the principal investment should be focussed on translating science to products, providing prototypes of products to be demonstrated in realistic environment, with reliable testing and evaluation in place.

Q3. The current state of the UK quantum industry and its potential going forward, including particular strengths and challenges;

39. The UK quantum industry is still in its nascent stages though growing rapidly. This is partly because of the wide range of sectors in the UK that quantum technologies can
impact on, such as life sciences, automotive and defence sectors, and is also due to the current state of prototypes and feasibility products in quantum. Existing UK industries, such as the photonics sector (lasers, DVDs, CDs, cameras and screens), will be enhanced by quantum technologies. The photonics industry, with high productivity, added value and employment scale will provide a strong base for quantum industry to build on.

40. Investment in the quantum technology hubs has led to number of spin-out companies, while the four rounds of NQTP funding through Innovate UK calls on quantum have provided support to generally smaller companies and have also encouraged formation of new companies which can benefit from government support in early days. The supply chain side of the quantum technology industry is developing rapidly, and will provide a key asset for future international collaboration and export. Future funding should ensure that this support to small and medium companies continues and is not completely replaced with grand challenge projects.

41. The main challenge is the reluctance of large industry to invest in early stage research projects, even if there is a large, long-term potential benefit. This has been evidenced by CEO NPL’s national activity on industry engagement, where some industries would only invest in technologies that were a maximum of three years from market. In order to better engage large industry, near-market technology solutions need to be practically demonstrated, to provide industry with the confidence to invest in this area.

42. While the UK was an early investor in quantum technologies, and is still seen as a great example of a well-integrated national programme, other countries are now investing much more, and competitors such as China and Germany are also looking to benefit from the commercialisation of quantum technologies. Continuing the programme will help realise the benefits of the world class quantum technology research and to anchor that in the UK, through keeping up momentum of investment, investing in skilled people, involving large industry, and keeping international leadership in the levels of coordination of the programme.

43. It is also worth considering that quantum technology has been put forward as a “silver bullet” for a variety of applications, but it needs to be able to deliver on this to keep both the public and commercial confidence. Early speculation of benefits of quantum technology must now be backed up by demonstrable truth, in order to secure the wider industry engagement on quantum that is needed.

Q4. What oversight or regulation is needed;

44. Implementation of any new system based on quantum technologies would require independent validation and accreditation. This would need to be on a case by case basis, but overarching regulation should ensure that there is a need for accreditation to take place.

45. However, it is also important to consider that quantum technologies often provide alternative technology solutions to existing areas. For example, if quantum technology were to enable navigation, there are already a number of existing regulations that apply to navigation which new technologies would need to take into account.

46. Effective standards for quantum technologies will also be needed, to ensure that products coming to market deliver on the potential. Setting international standards and associated measurements supports emerging technologies, accelerating innovation and commercialisation. Setting the global agenda through NPL and the British Standards Institute will minimise any market barriers, promote the rapid adoption of UK standards and measurement techniques and create a global market platform for UK-
Written evidence submitted by the National Physical Laboratory (QUT0017)

based innovators, which is especially important as we move into a post EU Exit environment.

47. As stated above, NPL, the BSI and the IPO are looking to work with UKRI to ensure that all research projects take due consideration of the standard, measurement and IP needs early on in development.

Q5. Potential barriers for developing quantum technologies, and how these might be overcome;

48. The UK will need to focus on developing large scale integrators within UK industry. Industrial partners in quantum are currently mostly made up of small supply chain companies, where large scale integrators and other end users do not yet have the confidence to invest significantly. This is because there are insufficient demonstrators in quantum technologies to show industry that programmes and products are viable and timescales are realistic.

49. For industry to overcome their reluctance to invest, new technologies will need to be tested and validated. NPL can provide access to unique facilities already in existence, and will develop test and evaluation capability, for example for secure communications and quantum clocks.

50. The key barrier to developing quantum technologies is therefore in keeping up the momentum of funding in the UK. Funding needs to be focussed throughout the product development process, from basic research to test and evaluation centres and large scale demonstrators for industry, similarly to the novel funding model used for the Faraday Challenge.

51. In parallel to funding for commercialisation, a key message coming from the NPL industry engagement is the challenge in the education of industry around quantum science, and demystifying the technology. Education and messaging should focus on the potential outcomes and solutions that quantum technologies can deliver, and what they can help industry do better.

52. A further potential barrier is the availability of suitably qualified and experienced people. Investment must maintain and extend the training of engineers as well as scientists in quantum technologies.

Q6. What research priorities there should be for quantum technologies and their possible uses, and who is best placed to undertake/fund that work;

53. Investment should focus on demonstrators and scale-up of current research work, particularly for technologies that are closer to market, such as quantum clocks and quantum communications. Quantum computing is also an important field to target investment, both in hardware and software, as it will be critical for the UK to retain expertise and sovereign capability in this strategic area, to be able to compete with large investors such as the US and China.

54. Quantum technologies can have impact across many sectors and industries. Some initial applications for quantum technologies have been identified within the programme as follows:

   a. Life Sciences and Health; focussing on novel imaging techniques and early diagnosis through quantum magnetometry, and improving drug design through quantum computing
b. Oil, Gas and Construction; looking at underground mapping, corrosion damage and monitoring of assets, better computing power to process and model data for oil and gas extraction

c. Transport; autonomous navigation and situational awareness, as well as secure data exchange for smart vehicles

d. Security and Defence; looking at secure communications, GNSS-independent navigation, sensing and imaging technologies

e. Finance and Telecommunications; focussing on accurate timing across networks

55. Research work should be undertaken by a combination of universities, research and technology organisations and government laboratories.

Q7. Who should deliver research and innovation;

56. Research activities should be delivered by universities, research and technology organisations and government laboratories. The translation of those technologies into new products should be done by industrial companies. NPL and its partners in the NQTP (EPSRC, IUK, GCHQ, Dstl and the KTN), along with other key academic and industry partners, are well placed to support and coordinate this work. As above, through engaging industry and defining their challenges, research can be focussed on delivering products and technologies that can be used to solve key industry challenges across the UK.

57. Funding schemes covering research and innovation should be designed to enable rapid progress to be made towards commercialisation. Restrictions on what money can be spent on, depending on which scheme has funded the project should be relaxed where possible. Project leadership and accountability should be established and then funding should be best focussed to wherever it is needed to push the project forward at pace.

Q8 The role of international collaboration in quantum technology research and development; and the risks and opportunities of Brexit in this area;

58. NPL has strong links and collaborations with all leading international measurement institutes for quantum technologies focussing on research, such as the comparisons of optical clocks internationally, which is essential to validate the performance of the UK’s best clocks, located at NPL. Another area is joint work to develop metrology for quantum communications. A number of these collaborations involving European organisations are funded by the EMPIR (European Metrology Programme for Innovation and Research) programme – a Horizon2020 metrology funding programme. For example, a recent Nature Physics paper published by NPL on the a proof-of-principle for using atomic clocks to measure gravity potential differences was only made possible through the collaboration between a number of different international NMIs. NPL is also bidding into the EU Quantum Technologies Flagship programme.

59. NPL also works on a number of projects for the European Space Agency (ESA). While ESA work should not be impacted by EU Exit (ESA is separate from the EU), there is a risk that collaborations within the EU would become more difficult, and depending on future models, NPL might not be able to participate in international EMPIR projects, and the development of a European Metrology Network addressing the needs of quantum technologies.
60. On a recent visit to Canada by a UK quantum delegation including NPL, a key output was an agreement to jointly pursue the development of new standards for quantum technologies with other NMI partners.

61. The UK programme is also particularly strong in development of the quantum supply chain, and there is potential to develop new solutions based on components being developed in the UK, such as atom traps, stable lasers, laser cooling solutions, algorithms to manage new quantum devices. These solutions would all be expected to be exportable, and there is therefore scope here for international collaboration, both within and outside of the EU.

62. Looking at quantum technology development and commercialisation, the aim is for this to be based in the UK to ensure that the UK can establish sovereign capability.

63. Finally, a number of leading scientists in the area of quantum science at NPL are European nationals, and EU Exit could impact on NPL’s and the UK’s expertise in quantum technologies.

Q9. Any challenges from potential civil/military ‘dual-use’ applications of the technologies, and how these can be addressed;

64. There are a number of challenges facing certain disruptive applications of quantum technologies, specifically in navigation. Certain aspects of the technology would need not to be disclosed, and might need to be isolated for UK benefit.

65. A number of applications enabled by quantum technologies, particularly for novel sensors, would have particular use in Defence and Security applications. The development of large scale quantum computation has specific implications for some aspects of defence.

66. A tiered approach to performance might be needed to address the challenge, and this model is currently used for technologies that are accessed by the military or accessed by civilians but developed or funded by the military.

Q10. Any potential societal implications—positive and negative—of the development of quantum technologies, including on health, security, privacy or equality.

67. Quantum Technologies will lead to a number of novel and improved applications, as with any new technology, and similarly there are often implications to be considered such as security and privacy. For example, there are already questions on the societal implications of Artificial Intelligence (AI), and advances in quantum computing could impact on AI by making it more intelligent.

68. Benefits include the potential for improved drug development in healthcare through quantum computing, or using magnetometry for brain imaging, while quantum inertial sensors could allow indoor and autonomous navigation independent of satellite systems.

69. Optical clocks could also be used to monitor long-term environmental changes, such as variation in sea levels, and data could be used to input into models forecasting climate change, providing a societal and environmental benefit.

70. The development of quantum computers is considered a threat to public key cryptography which underpins transactions on the internet such as banking. Work is needed to establish alternative cryptographic methods to maintain security when quantum computers become available.
71. A programme of public engagement and education is an important part of any government funded programme.

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