Appendix 4: Overview of the UK quantum landscape

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1. The UK research activity in quantum technologies

1.1 Research groups, hubs and national centres

Following the mapping exercise undertaken by Innovate UK KTN during the summer of 2020, we currently count around 160 research groups in the UK, which are investigating quantum sciences and applications. The research groups are well distributed across UK universities with some having multiple research groups around quantum theory and information, solid state and condensed matter physics. Apart from fundamental science and quantum mechanics, several research groups are also looking into engineering disciplines such as nanofabrication, materials and systems engineering and from other annex disciplines such as optics and photonics, semiconductors, computer science, telecommunications, machine learning and computational methods and many more branches listed in the research section of the UK quantum landscape map openly available on Innovate on the Innovate UK KTN website (Figure 1).

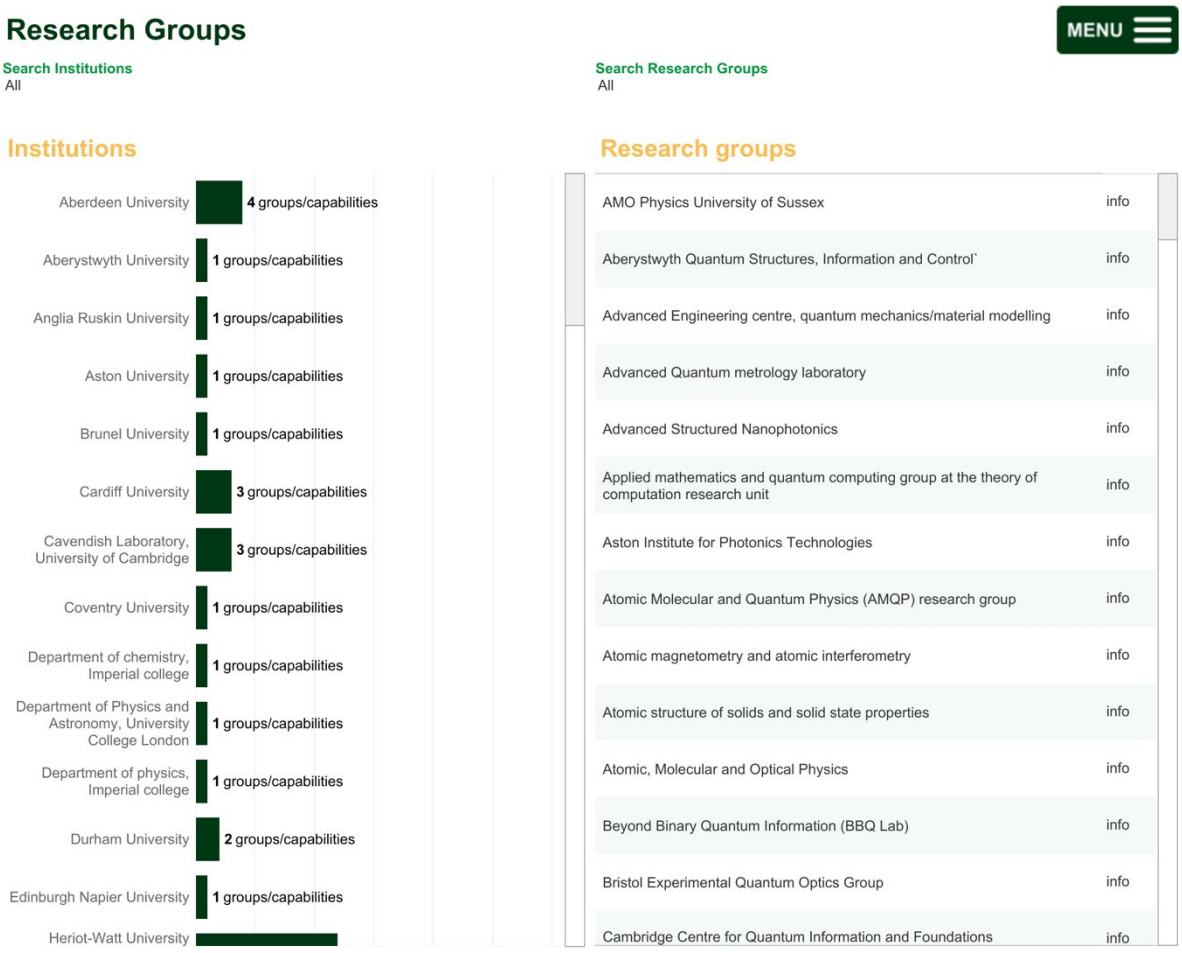

Figure 1: Snapshot of the list of UK research groups in quantum technology. Extract from the Innovate UK KTN quantum landscape map.

The full list of research groups, their affiliations and contact information are available under the research groups section of the UK quantum landscape map hosted at: https://ktn-uk.org/programme/quantum-landscape/

The main research focus and activities in quantum technologies are carried by the UK national quantum programme through the four quantum hubs namely: The Quantum Computing and Simulation (QCS) hub led by the University of Oxford, the Quantum Communication hub led by the University of York,

the UK national Quantum technology hub in sensing and timing led by the University of Birmingham and the UK Quantum Technology hub in Quantum Enhanced imaging (QuantIC) led by the University of Glasgow. The quantum hubs conduct their research work with a focus on sciences and applications in communication, computing and simulation, imaging and sensing (Figure 2). The hubs' research work also involves several academic and industrial partners and has developed several applications.

Besides the national quantum hubs network, the UK benefits from the know-how and capabilities of the Quantum Metrology Institute of the National Physical Laboratory. The Quantum Metrology Institute capability is wide and covers a considerable area of quantum research including quantum sensing, materials, superconducting electronics and information systems, photonics and electrical standards.

The UK will also set up through UKRI funding its first national quantum computing centre (NQCC), due to be in place by February 2023. The NQCC aims to place the United Kingdom at the forefront of quantum computing, where government, academia and industry work collaboratively to develop quantum computing, securing this strategically important technology for the benefit of the United Kingdom.

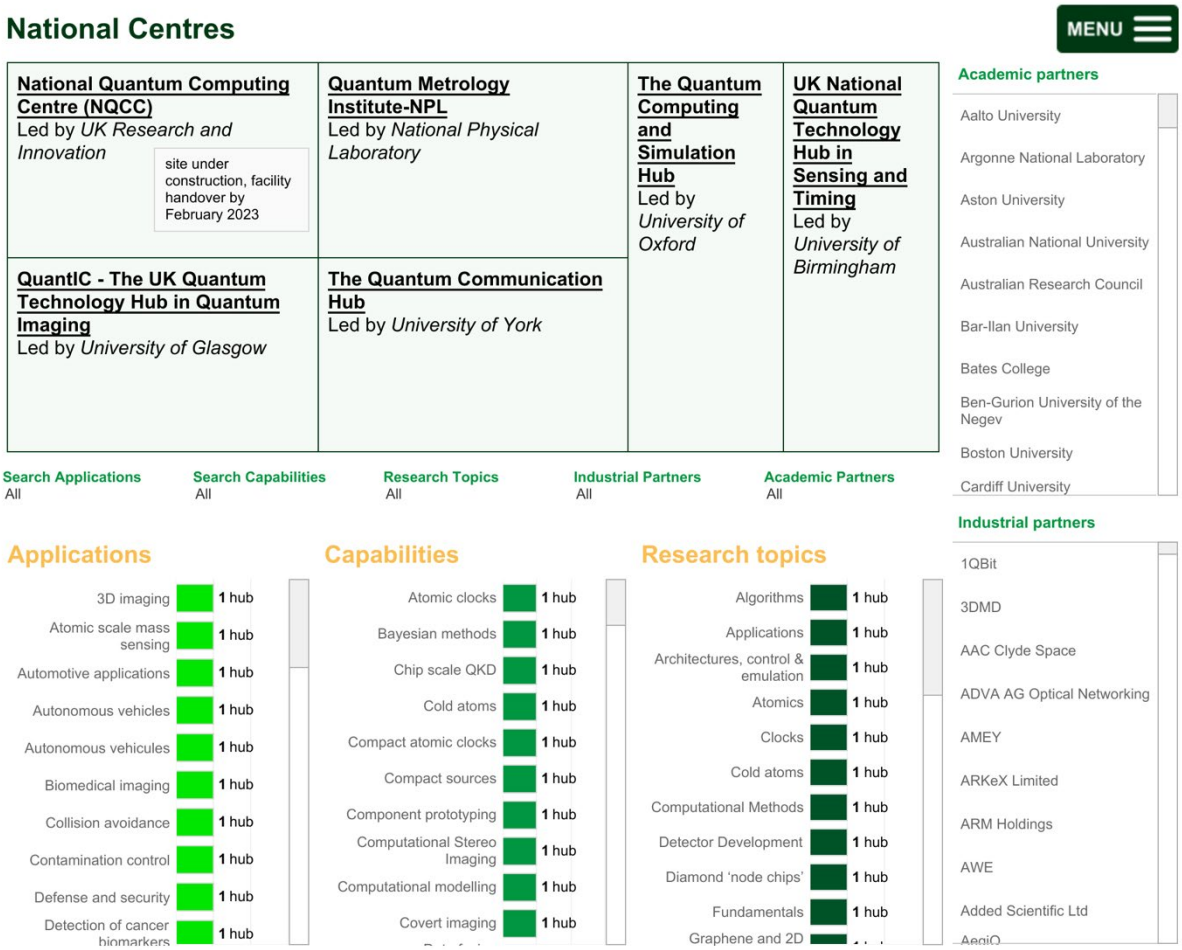

Figure 2: UK quantum technology hubs and national centres for quantum technology. Extract from the Innovate UK KTN quantum landscape map.

1.2 Main research projects

According to the UKRI gateway to research website, there are over 1,300 active projects involving quantum sciences and applications involving several UK universities but also thousands of UK and international businesses. The projects are mainly funded by the Engineering and Physical Sciences Research Council and other delivery partners of the UK national quantum technologies programme.

Other research projects are funded under EU initiatives or private funding are detailed in Section 2.3.

1.3 Key technologies and applications

Quantum technologies are expected to have applications across multiple future multi-billion-pound industries in many markets and sectors such as pharmaceutical, environmental sensing and civil engineering, healthcare, finance, telecommunications, space, energy and defence.

The main devices to be developed include quantum timing devices, quantum gravity sensing devices, quantum positioning systems, quantum secure communications, quantum enhanced imaging, single photon detection and quantum computers.

2. Industry engagement mechanisms for quantum sciences and technologies

2.1 Capabilities and research priorities

Priority research areas in quantum technology in the UK include sensing and metrology, computing and simulation, communication and imaging. The first phase of the UK National Quantum Programme has given birth to tremendous advances in quantum technologies and other adjacent technologies including laser sources, precise positioning, material processing and cryogenics. Some of the main highlights of the first phase of the national quantum programme include the launch of the UK's first quantum networks: the UKQN, a research-focused network connecting the multi-node quantum 'metro' networks in the cities of Bristol and Cambridge over the National Dark Fibre Infrastructure Service and the UKQNtel, a quantum-secure connection between the Cambridge node of the UKQN and Adastral Park, home to BT's Research & Innovation Labs and Innovation. Both based on a Quantum Key Distribution (QKD) protocol, the networks extend over 410km in the South of England and will be deployed to increase the density of users in specific locations. Other important achievements include advanced 3D-imaging technologies based on single photon detection, gravity sensors, ultra-precise atomic clocks, etc.

2.2 Collaboration mechanisms between industry and academia

Since its launch in 2015, the UK national quantum programme has set an excellent example of industry engagement by involving industry in funding competitions and supporting its engagement with research and academia to drive innovation in quantum technologies.

The UK national quantum programme has attracted several local and international businesses working in partnership with research groups and the four main UK quantum hubs to address current challenges in communication, computing, imaging, sensing and metrology in several sectors including healthcare, transport, telecommunications, space, energy, finance, etc. The quantum hubs are also provided with a partnership resource funding as part of the commercialisation strategy of the UK national quantum technology programme. This funding is dedicated to early-stage projects where academics and businesses work together on early applications of quantum research.

The quantum technologies team at Innovate UK KTN has recently completed the mapping of industry and research capabilities in the UK as well as the current public funding landscape. This mapping exercise showed the involvement of over 200 UK businesses from start-ups, SMEs and larger international corporations. Another strong way of engaging industry was achieved through the industrial partnership in many of the UK skills building and training programmes for quantum engineers and scientists.

2.3 Public funding schemes

Quantum technologies in the UK are mainly funded through the UK Research and Innovation UKRI funding agency. With the great potential of quantum technologies in addressing important matters like secure communication, fast computing and precise sensing, the UK launched its national quantum programme in 2015.

The UK National quantum technologies programme is delivered by the following funding partners: Engineering and Physical Sciences Research Council (EPSRC), Science and Technology Facilities Council (STFC), Innovate UK (IUK), Department for Business, Energy and Industrial Strategy (BEIS), National Physical Laboratory (NPL), Government Communications Headquarters (GCHQ), the Defence Science and Technology Laboratory (DSTL), National Cyber Security Centre (NCSC2) and the Ministry of Defence (MoD).

The total funding in quantum technologies in the UK has reached £1bn and is awarded through multiple schemes and councils as detailed in the following.

2.3.1 The Engineering and Physical Sciences Research Council EPSRC

During the first phase of the national quantum technologies programme (2014 – 2019), EPSRC funded a national network of quantum technology hubs through a £120M investment in four hubs over five years. These were to harness the UK's strengths in quantum science by turning this into strength in quantum technologies. As part of their investments in the second phase of the national programme, EPSRC has refreshed the quantum technology hubs at the end of 2019, with a £94M investment over five years, to maintain the technological research leadership that the UK has established in quantum technologies through its national programme.

2.3.2 The Industrial Strategy Challenge Fund ISCF

Besides the UK's national programme efforts to support the industrialisation of quantum technologies and the advancing of fundamental quantum science, the Industrial Strategy Challenge Fund or ISCF has also launched the commercialising quantum technologies challenge by investing around £173M in quantum technologies supported by a further £205M fund from industry helping turn quantum science into quantum engineering and to provide essential support to businesses developing quantum-enabled products by removing barriers to productivity and competitiveness.

In March 2021 and following the success of previous ISCF calls, Innovate UK has invested a further £47M for collaborative research and development (CRD) or technology projects for second generation quantum technologies or Quantum 2.0. The aim of the competition was to advance the commercialisation of quantum technologies in the UK increase private sector investment by identifying clear market opportunities for a quantum product or service and innovative project which exploits it or by describing a technological barrier to the commercial or industrial exploitation of quantum technologies in the UK and providing a solution to it.

In October 2021, the UK Quantum Challenge team unveiled the full list of projects and businesses funded under the ISCF in 2020/2021 as well as the distribution of the awards by UK region. According to the report, about £100M was awarded to 49 business led projects involving 91 UK companies.

On 17 January 2022, Innovate UK will open a new round for feasibilities studies and invest up to £6M to exploit the second generation of quantum technologies and advance their commercialisation in the UK by addressing technical challenges in areas such as connectivity, seeing the invisible, positioning, navigation and timing and in the area of computing.

2.3.3 The Science and Technology Facilities Council STFC

Through the UK national quantum programme and in collaboration with EPSRC, STFC is currently supporting seven projects with a £31M investment to demonstrate how quantum technologies could solve some fundamental questions in our universe. Some of the research projects aim to develop quantum-enhanced interferometry, sensors, atomic clocks and quantum simulators to address topics in cosmology, dark matter, black holes and fundamental constants.

In collaboration with EPSRC and through UKRI, The STFC is also leading a programme to establish the National Quantum Computing Centre (NQCC). The new computing centre represents a £93M investment over 5 years and will establish 4 key technology work streams including a 100+ qubit NISQ demonstrator hardware platform(s), quantum software, algorithm and applications development, high performance, scalable qubit technology development and a roadmap and architecture towards fault-tolerant general purpose quantum computing.

In June 2021, science Minister Amanda Solloway has unveiled a five-year, £210M partnership between STFC and IBM. Its mission is to support UK businesses and the public sector by reducing the risk of exploring and adopting innovative new digital technologies, such as artificial intelligence (AI) and quantum computing, by breaking down practical barriers to innovation such as access to infrastructure or digital skills gaps within their organisation. The new programme called, the Hartree National Centre for Digital Innovation (HNCDI), will apply AI, high performance computing and data analytics, quantum computing and cloud technologies to accelerate discovery and develop innovative solutions to industry challenges including materials development, life sciences, environmental sustainability and manufacturing. This programme will also recruit 60 additional scientists, interns and students to join the Hartree Centre and IBM Research within STFC.

2.3.4 EU initiatives and Horizon Europe

For several years, The UK has been a key partner in several EU funding initiatives in quantum technologies such as the EU Quantum Flagship (€1bn over 10 years), QuantERA (€60M over 10 years) and several more Horizon 2020 EU initiatives which are driving excellence in quantum research and promoting collaboration across several EU countries members and partners. Within the 'Horizon Europe - Digital and Emerging Technologies and Fit for the Green Deal' funding call, the European Commissions proposes several streams to support building Europe's workforce in quantum sciences and technologies.

Following H2020 legacy, the European Commission launched, in early 2021, Horizon Europe, an EU research and innovation programme with a total budget of €95.5 billion and running until 2027. Within the digital and emerging technologies for competitiveness and 'fit for the green deal' funding call of the Horizon Europe work programme, the European Commission proposes several streams to support research in quantum including basic science, quantum sensing and strengthening the quantum software ecosystem for quantum computing platforms. In the funding calls 'Strategic autonomy in developing, deploying and using global space-based infrastructures, services, applications and data' in 2021 and 2022, applications are called for innovative space capabilities such as space quantum gravimetry.

The EU is still in the process of formalising the UK's association. But UK-based applicants can begin applying straight away. In December 2021, the UK government has confirmed, if the delay to UK association continues, successful Horizon Europe applicants will receive funding from UKRI regardless of the outcome of the UK's efforts to associate to Horizon Europe. This applies to the first wave of calls where the delay to UK association to the programme may prevent them from signing grant agreements.

2.3.5 International collaboration calls

At an international level, Innovate UK and the Natural Sciences and Engineering Research Council of Canada (NSERC) have partnered at the end of 2020 to launch a call for research proposals on quantum technologies following the 2018 global expert mission led by the UK (Innovate UK KTN and UKRI) to Canada. This call will allow for collaboration between leading-edge scientists and potential innovative users, from industry and/or government sectors to accelerate the development of quantum technologies. About 15 UK universities and businesses have benefited from this call including research areas such as diamond sensing and magnetometry, quantum communication for satellite-based networks, photonic and silicon platforms for quantum devices and low noise quantum computing.

2.4 Private investment and funding

The UK accounts for nearly half of quantum start-ups in Europe. Figure 3 enumerates the top funders. In this list, all top investors are UK funders except for Quantonation, a French investor created only in 2018 and investing in deep physics techs with a focus on quantum technologies. In the top 5 on the list, we find Parkwalk Opportunities EIS fund, Amadeus Capital partners, BGF Growth Capital, Oxford Sciences Innovation and Ahren Innovation Capital. The list notably comprises big corporations such as IBM and some start-up and university funds (Start Up and Early Stage Capital, The University of Cambridge Enterprise fund, UCL Technology Fund).

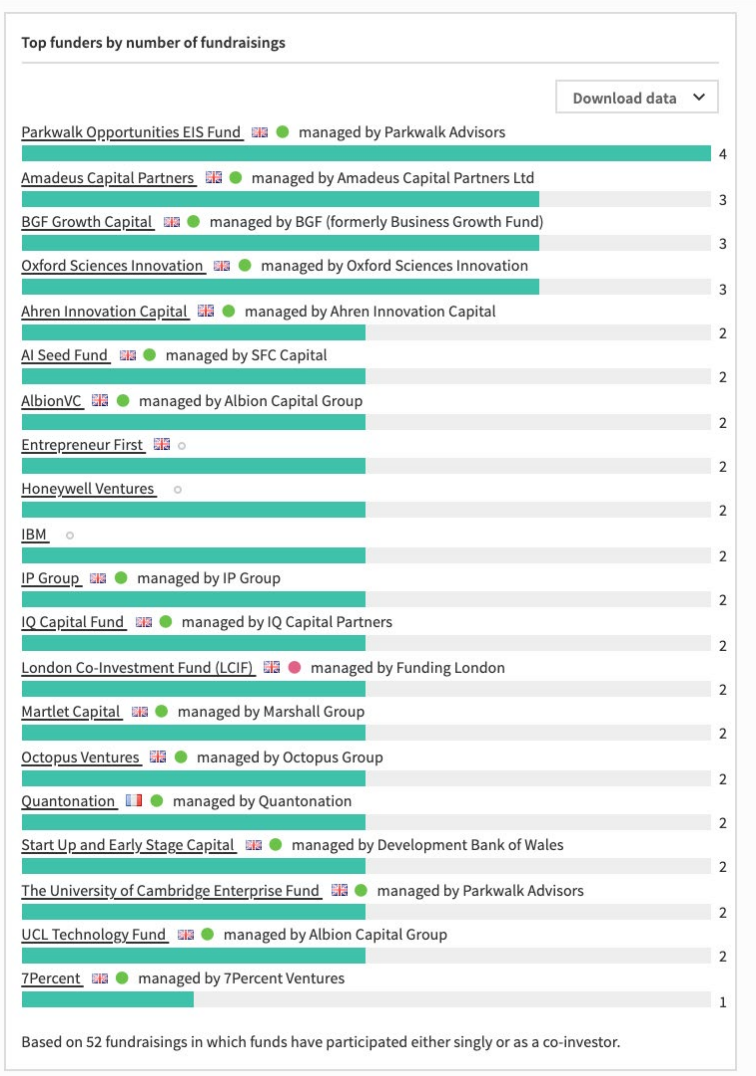

Figure 3: Top investors in quantum technologies between 2011 and 2020 (courtesy of Beauhurst).

Parkwalk Opportunities EIS fund sitting at the top of the list is a leading investor in 'hard science' companies and aiming to commercialise the scientific discoveries made at the UK's globally-ranked research universities. Parkwalk is also the UK's most active investor in the university spinout sector, and currently has over £300M of assets under management. Quantum companies in Parkwalk's portfolio include Nu Quantum, Phasecraft, Quantum Motion Technologies and Oxford Quantum Circuits. Other technologies in Parkwalk's portfolio include deep healthtechs and neurotechs, photonics and silicon, AI and machine learning and battery technology, just to name few. Amadeus Capital comes second on the list of the top investors in quantum in the UK. Amadeus Capital companies' portfolio's is made of AI and machine learning, cyber security, digital media, healthcare and digital health, FinTech, InsurTech and Regtech, semiconductors, telecoms and enterprise software companies. Quantum companies in Amadeus Portfolio include Riverlane and Nu Quantum.

Third on the top investors list, BGF capital presents a broader portfolio than Parkwalk's and Amadeus including other sectors like media, food and drink, education, oil and gas and E-commerce. BGF has invested £6.4M across three rounds of funding to support M Squared's pioneering work in quantum innovation and technologies to help tackle climate change. The business has grown 10-fold since the first investment in 2012.

Oxford Sciences Innovation coming fourth in the top investors list was created in 2015 and focuses on the creation of fundamental technology companies built on science, in partnership with the University of Oxford. OSI mainly invests in life sciences, deep tech, healthtech, AI and software. Some of the quantum companies in its portfolio include Oxford Quantum Circuits, Quantum Motion Technologies, Oxford HighQ, Orca Computing, Oxford Ionics and PQShield.

Ahren Innovation Capital being in the top 5 of investors in quantum businesses in the UK has four broad domains of interest including brain & AI, genetics & platform technologies, space & robotics and efficient energy. Some of the quantum companies in its portfolio include Nu Quantum and Zapata Computing.

Other investors in the list have a long history of partnering with UK universities and academics to support businesses from creation and early stages to maturity such IP Group Capital. In summer 2020, IP Group launched a £12M investment partnership in quantum technologies with Innovate UK where early stage UK businesses, academics and entrepreneurs can seek up to £1M matched funding for their projects. IP Group has previously invested in hardware businesses such as Quantum Motion Technologies and Oxford Quantum Circuits. IP Group is now looking to expand the portfolio, capturing opportunities across the board, from a full stack software solution to hardware and computing to encryption.

3. Education and training

3.1 Graduate and postgraduate studies

Training in quantum technologies and sciences in the UK is mostly delivered through postgraduate research studies or doctoral studies. The studentships are mostly funded through EPSRC and other delivery partners of the UK national quantum technologies programme and through other EU initiatives such as the MSCA H2020 calls.

Despite the training in quantum being mostly gained and delivered through doctoral studies, some universities have already set programmes for graduate students. In the summer of 2020, the University of Bristol launched a master's degree in optoelectronic and quantum technologies. This one-year programme aims to provide graduate students with a deep understanding of the design, fabrication and use of the next generation of integrated circuits, sub-systems and systems that combine optics, electronics and quantum engineering for applications in communications, computing, sensing, and healthcare. As part of the course, students complete a research project, either based at the university or with one of the industrial partners.

3.2 Doctoral training programmes and centres for doctoral training

There are currently about 32 active training programmes in the UK including centres for doctoral training (CDTs), doctoral training partnerships (DTPs) and training and skills hubs involving international and UK businesses. These training programmes involve large international organisations such as Google, Microsoft Research, Toshiba, Hitachi, BAE Systems, IBM, Nokia Research, Agilent Technologies, Boeing and Thales group, just to name a few (Figure 4). The main research and training topics include quantum information and quantum computing, quantum communication and cryptography and other areas such as quantum chemistry and biology.

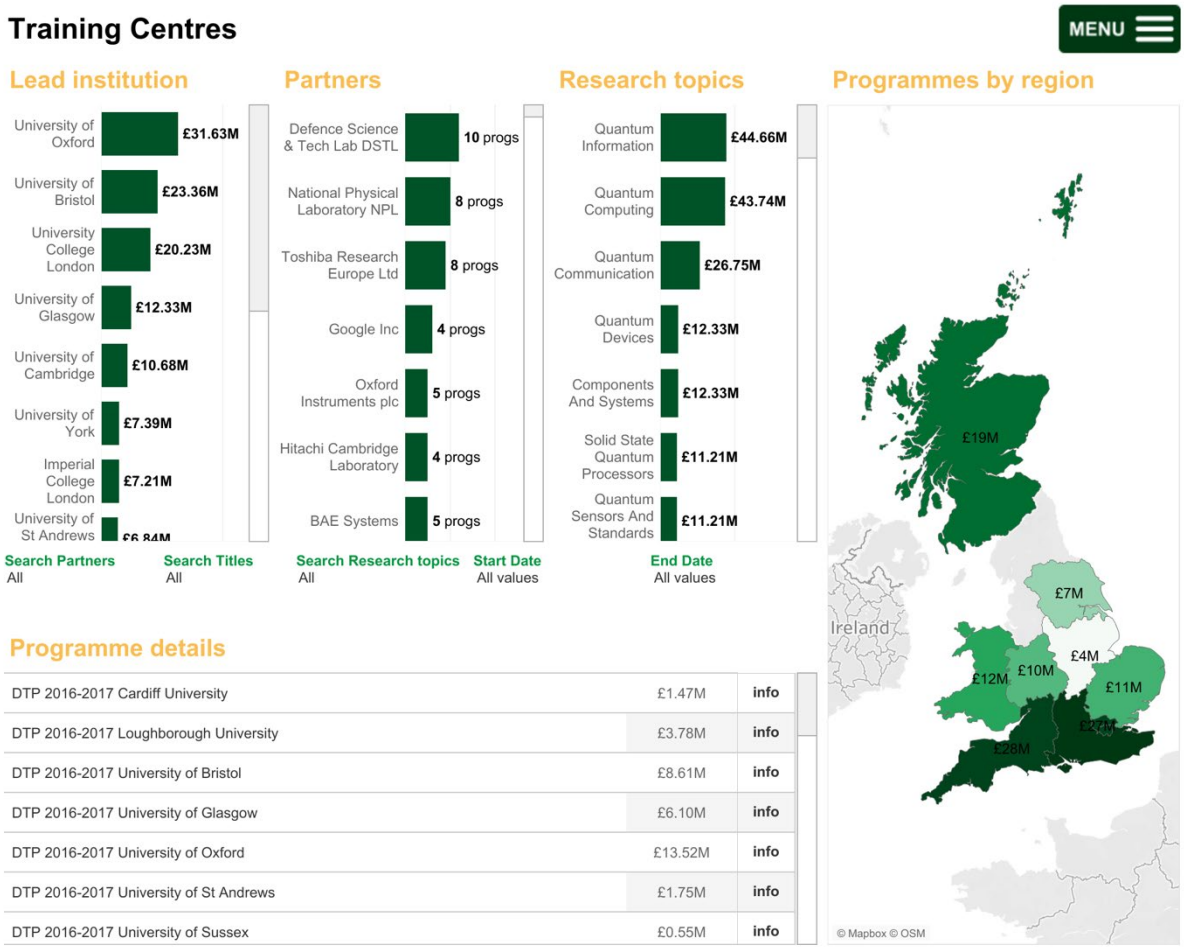

Figure 4: Training centres, partners and research topics in quantum technologies. Extract from the Innovate UK KTN quantum landscape map.

3.3 Entrepreneurship and business training

One big step to moving quantum technologies from the lab to the market involve providing a suitable environment for quantum engineers and scientists to evolve as future leaders of the quantum industry. In 2016, the Engineering and Physical Sciences Research Council EPSRC allocated a funding of £4.4M to the University of Bristol to create QTEC, the Quantum Technology Enterprise Centre to accelerate the industrialisation of quantum technologies and capabilities developed in the UK. Being well anchored in the UK national quantum programme, QTEC has been working with quantum researchers to successfully bring new quantum technologies to the market, by developing their entrepreneurial skills and providing tailored mentoring and coaching from experts and visiting entrepreneurs. QTEC offers a twelve-month fellowship to provide academics with the skills they need to set up a successful technology start-up which will underpin the UK's quantum technology industry. Now in its fourth and final cohort, QTEC has supported the creation of 17 new companies based on technologies which underpin the quantum industry. Successful start-ups within the fellowship include Kets Quantum Security, FluoretiQ, Nu Quantum, Qureca, SeeQC, Universal Quantum, Raycal, Quantum Dice just to state few.

3.4 Privately funded education and training initiatives

Quantum is a big hype area that attracts interest of professionals and students from different backgrounds and career levels. This explains the abundancy of free and open-source training and education materials especially in the area of quantum computing.

One of the biggest education and training platform is IBM Qiskit. Launched by IBM Quantum, Qiskit contains a large set of freely open courses introducing quantum hardware, algorithms and protocols and quantum machine learning. Qiskit is also globally known for its summer schools that takes students from beginner level to solving advanced quantum problems on a quantum computer. These two-week courses are designed to empower the next generation of quantum developers with the knowledge to explore quantum applications on their own.

In 2021, UK quantum start-up Qureca based in Glasgow launched several courses including Quantum for everyone. This non-technical course teaches students and professionals how to navigate the rise of quantum technologies and its applications across industries. Qureca also proposes tailored courses around specific areas of applications such as quantum for finance in collaboration with French start-up QuantFi and business training for quantum scientists. Qureca delivers its courses quantum experts with a broad range of academic and industry experience and counts several high-profile partners such as MIT, Stanford University, Airbus, SANOFI, the European Space Agency ESA and French rail company SNCF.

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