Quantum technology

A billion pound opportunity for Scotland

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Foreword

Quantum technologies are poised to transform the world in which we live over the coming decades.

They are opening the door to innovation 'leaps' that will revolutionise areas such as computing, sensing, imaging, and communications. In doing so, they will unlock previously unattainable efficiency and productivity benefits with the potential to revolutionise our industries, from healthcare and transport to manufacturing and financial services. In addition, the power available through these technologies will support the development of products and services crucial to our ability to tackle the key global challenges of today – climate change, sustainability, public health and security.

Given this potential, it is perhaps not surprising that these technologies have been the focus of global interest and investment for over a decade. While many technical challenges remain, and there persists some uncertainty over the scale and direction of future commercial markets, the enormous potential of quantum technologies has proved irresistible to government and private industry alike. Indeed, the UK Government has recently committed £2.5bn of investment over 10 years as part of its National Quantum Strategy[1].

At this exciting time for quantum technologies, Scotland finds itself at a crucial juncture.

Our internationally recognised photonics sector has created the perfect platform to exploit the future quantum opportunity. With an estimated 80% of quantum developments currently dependent on lasers and advanced optics, our photonics capability represents a national advantage in an increasingly competitive global market. Couple this with Scotland's adjacent strengths in key first-adopter markets such as healthcare, space, renewables and financial services and Scotland has all the ingredients to maximise the significant global opportunity quantum represents.

This leading position has already been recognised by the Scottish Government within the National Strategy for Economic Transformation which highlights '…enabling and emerging technologies such as photonics and quantum technologies…can contribute to improved productivity of traditional industries and underpin the industries of the future…'[2] However, now must be the time to press home this position. As commercial markets for quantum technologies crystalise and grow, we must make sure Scotland is positioned to grow too. This will require a collaborative effort between industry and academic partners supported by government and its agencies.

This paper sets out a series of recommendations that will support a vision to develop Scotland's quantum sector into a billion pound industry by the end of this decade. It is a vision built on skills, investment, and internationalisation, building a globally competitive cluster that will ensure Scotland benefits from the job growth, productivity improvements and accelerated innovation that these revolutionary technologies will bring.

Executive summary

The global market for quantum technologies is set to grow rapidly over the next decade, accelerated by significant global investment and an improved understanding of their commercial use.

With global quantum markets set to top $62bn by 2030[3], the opportunity for Scotland is considerable, and with traditional strength in the adjacent area of photonics, the industry in Scotland is well positioned to secure future success.

This paper sets out the opportunity for Scotland and makes the case for future investment and strategic intervention that could develop our quantum sector into a billion pound industry by 2030. Industry, academia, and government will all have a role to play, and the recommendations outlined in this paper assume a collaborative response from across the quantum technologies community.

Supporting a vision to create a billion pound quantum industry in Scotland by 2030.

The nine recommendations outlined in this paper have been developed in consultation with Technology Scotland members and the wider quantum technologies community. They are designed to provide a framework for future decision making and a focal point for Scotland's quantum ambitions over the coming years.

Recommendations are categorised into four pillars and given the clear connection to Scotland's photonics sector, have been designed to align with those pillars outlined in our 2019 Paper – Photonics in Scotland – A Vision for 2030[4]:

Developing a workforce for the future	Supporting business growth	Growing Scotland's position	Developing Scotland's cluster

Summary of recommendations

Developing a workforce for the future

- Build the multi-level engineering skills base required to develop and commercialise quantum technologies in Scotland.
    - ◊ This should include efforts to improve feedback channels between industry, higher and further education providers, and skills agencies via the creation of a formal quantum skills group.

- Attract and retain local talent to the Scottish quantum cluster by inspiring the next generation of quantum professionals.
    - ◊ Highlight the role of quantum technologies in our global future and raise awareness of the diverse and rewarding career opportunities within the sector in Scotland.
    - ◊ Encourage greater diversity within Scotland's quantum sector workforce through initiatives such as Opening up Photonics.

- Develop a coordinated approach to attracting international talent to Scotland, including efforts to establish Scotland as a global lead in quantum technologies.

Supporting business growth

- Identify targeted, strategic funding of established translational assets supporting quantum technology development in Scotland.

- Identify early-stage markets and potential early commercial adopters of quantum technologies.
    - ◊ Government should consider its role as 'first customer', stimulating the market via 'grand challenge' or demonstrator funding.
    - ◊ Develop a coordinated programme of activities to accelerate the adoption of quantum technologies in key sectors for the Scottish economy.

- Consider targeted, strategic incentives and co-investment programmes to cultivate an attractive private investment landscape, including foreign direct investment.
    - ◊ These should be linked to a wider effort to develop the entrepreneurial and commercial skills required to realise the potential of our quantum capabilities.

Growing Scotland's position

- Build Scotland's international profile for quantum technologies through the recently established 'Glentanglement®' brand.
    - ◊ Leverage the growing profile of Glentanglement® to attract international talent, foreign direct investment and global customers and collaborators.

- Develop a coordinated, multi-channel approach to the international promotion of Scotland's quantum technologies capability.
    - ◊ This will include, but is not limited to, support funding for key trade shows and international conferences, SDI led trade missions, increased in-market support, and the development of shared collateral under the Glentanglement® brand.

Developing Scotland's cluster

- Formalise Scotland's quantum cluster and seek accreditation for cluster activities in line with recognised standards.
    - ◊ This aggregated body should provide a first point of contact for all stakeholders and engage with UK and international bodies to coordinate Scottish input to worldwide standards development and policy.

1. Quantum technologies

Quantum technologies, and the principles of quantum mechanics that underpin them, remain relatively impenetrable to many of us. Yet these technologies are positioned to transform the world in which we live over the coming decades.

In fact, some concepts of quantum physics already underpin a plethora of everyday devices with major implications to our daily lives. These include the semiconductors found in our phones and other electrical goods, MRI systems for medical diagnostics, lasers and GPS navigation systems. These have been developed under what is often termed the 'first wave' of quantum development, or Quantum 1.0.

International attention has now turned to the second wave of quantum development, or Quantum 2.0. These technologies promise a further giant leap in performance, revolutionising industries from computing and communications to healthcare and transport. For that reason, they are generating global attention, attracting significant investment as governments and private organisations alike vie to exploit this potentially enormous opportunity.

These developments are based on two underpinning principles of quantum mechanics – entanglement and superposition. This paper will not attempt to provide detailed theoretical explanations for these principles; however, it is useful to provide a very basic overview to help understand their potential over the coming decades.

Entanglement – Quantum entanglement is a state by which two particles are connected (entangled) despite being separated. Theoretically there is no limit to the distance between particles and if the properties of one are changed then the other would also change. This could have huge implications in areas such as data communications and cyber security.

Superposition – Quantum superposition states that sub-atomic particles exist in multiple states at the same time. While this is a difficult concept for many of us to grapple with, it has significant consequences for computing, offering an opportunity to carry out complex calculations at incredible speeds.

Our ability to exploit these concepts has accelerated rapidly over the last decade, proliferating an equally rapid development of technologies and devices based on them. Increasingly, quantum technologies are moving from science fiction into 'real world' applications, catalysing further global investment and efforts to understand their implications across all areas of our economy.

The speed of development, and extent of disruption, relating to these technologies remains difficult to predict, and there are many conflicting forecasts as to when such technologies will become commonplace. However, early applications are already here and, with global interest and investment so high, it is inevitable that these technologies will have a huge impact over the coming decades.

2. Applications

As the second quantum wave evolves from the laboratory and into the commercial world, the breadth of application will expand dramatically, offering extraordinary opportunity across a multitude of market sectors.

While quantum computing provides most of the headlines, it represents only a sub-section of the quantum opportunity. Future applications are broadly split into three sub-areas – quantum sensing and imaging, quantum communications and quantum computing. The following section describes just some of the potential applications in these sub-areas.

Quantum imaging and sensing
Quantum technologies, specifically the exploitation of entanglement and quantum correlation, offer a breakthrough change in imaging and sensing performance, overcoming limitations in sensitivity and resolution available through conventional optical methods.

- **Object detection** – quantum sensors provide improved sensitivity, accuracy, and stability offering an opportunity to 'see' where we are currently unable. This includes the detection of underground features (e.g. pipes and voids) and imaging in extreme conditions. The application of these 'quantum eyes' includes civil engineering (underground surveying), autonomous vehicles (poor weather navigation) and defence (hazardous, low light conditions).

- **Medical imaging diagnostics** – quantum technologies offer the possibility of imaging through human tissue, providing an opportunity for non-invasive diagnostics and a cheaper, more portable alternative to MRI and X-ray equipment.

- **Positioning, navigation, and timing (PNT)** – Accurate PNT methods are critical to the functioning of much of our key infrastructure. The development of quantum clocks offers an opportunity to improve timing accuracy by an order of magnitude over current standards. This has implications for applications in which high timing accuracy is important such as financial transactions, defence applications and navigation systems for autonomous vehicles.

Quantum computing

Quantum computing is arguably the highest profile of the quantum technology sub areas. It harnesses the laws of quantum mechanics to solve complex problems beyond the capabilities of classical computers. To date, developments have largely been focussed on the building blocks of quantum computers – the hardware. However, as quantum computing approaches commercial application, the opportunity to perform rapid calculations on complex data sets will transform the way we approach some of the key challenges of today. A recent analysis by McKinsey indicates that, over the longer term, the highest value quantum computing use cases will likely be in the life sciences and financial services sectors[5].

- **Life sciences** – drug development requires a thorough understanding of molecular interaction, often trying to mimic the complex processes found in nature. This understanding is beyond the capability of conventional computers. Quantum computers will allow rapid modelling of such systems, greatly accelerating the development times of new, lifesaving medicines.

- **Financial services** – from risk analysis and fraud protection to trading optimisation and prediction, the financial services industry relies on a vast framework of complex mathematical and actuarial calculations. Quantum computing offers the opportunity to perform these tasks at speeds unattainable via conventional calculation methods, providing significant efficiency savings and generating competitive advantage for our financial institutions.

Quantum communications

Advances in quantum computing represent a real threat to current cyber security measures. Current encryption techniques are simply not built to withstand the computational power available through such systems. This has dangerous implications for information security, everything from personal finance and health details to national infrastructure and security programmes. It is therefore vital that we develop quantum resilient encryption techniques before these systems are readily available.

Fortunately, quantum technologies will also provide the solution to this security risk. Quantum communication networks encode transmitted data into quantum states – usually in the form of photons. Crucially these quantum states cannot be observed without fundamentally altering their fragile quantum properties. In other words, they cannot be hacked without leaving an obvious trace. Using a process called Quantum Key Distribution (QKD), in which the sender and receiver agree on a secure 'key' to encrypt and decrypt information, data can be sent via quantum networks without interference from a third party. This has huge implications for our future cyber resilience with applications across all aspects of our life, including national security and resilience.

3. Scotland's strength

The fact that Scotland is well positioned to exploit the emerging quantum market owes much to its strength in an adjacent but well-established market – photonics.

While quantum is rightly generating huge interest and profile, it is important to acknowledge that the development of these technologies relies heavily on photonics, with some estimates suggesting that around 60-80% of all quantum technology is dependent on lasers and advanced optics. This has been particularly true through the first wave of quantum development, but will continue to be an important consideration, and national advantage, as the second wave progresses.

Scotland's vibrant £1.2bn photonics cluster has been the foundation of Scotland's quantum accomplishments to date. This cluster, containing around 60 companies supported by a world leading academic base, has been responsible for around 40% of the UK's collaborative research in quantum technologies over the last 10 years. Like much of the quantum market to date, this has been largely focussed on hardware, through component and device development and manufacturing.

This ecosystem has been nicely illustrated through recent work by Fraunhofer CAP, a leading research technology organisation in photonics and quantum and an important asset in Scotland's quantum ambitions. Their mapping exercise as part of the creation of Glentanglement®, provides an overview of the current quantum ecosystem in Scotland.

The map shows a strong academic base, including the University of Strathclyde (the only UK university to be involved in all four Quantum Hubs funded through the UK National Quantum Technologies Programme), QuantIC (the UK Quantum Technology Hub in Quantum Enhanced Imaging hosted by the University of Glasgow), and the Quantum Computing Applications Cluster (see case study in appendix). As well as providing vital research capability, this base also provides a conveyor belt of talent that supports a vibrant industrial cluster that includes component and device development through to full system integration.

With quantum developments still largely focussed on hardware, this will create further immediate opportunity for Scotland. As a key application area for Scotland's photonics sector, it will also support this sector's ambitions to treble in size by 2030[4]. However, as the application and commercialisation of quantum technologies accelerates – in areas like computing, imaging, sensing and communication – it will be important for Scotland to look beyond the boundaries of its photonics cluster and towards those key market areas and first adopters that will drive the wider proliferation of quantum applications.

Here, Scotland also has significant opportunity, with traditional strengths in areas like defence, renewable energy, and life sciences, all of which will be key early markets for quantum technologies. Add to this Scotland's more recent cluster of excellence in FinTech, our accelerating ambitions in the space sector, and our globally recognised capability in informatics through the University of Edinburgh, and Scotland can quickly build a strong quantum foundation, not just on component development but in wider exploitation and application through a strong domestic market.

4. Measuring the opportunity

The global quantum technologies market remains relatively immature, with future roadmaps and forecasts regularly impacted by the latest technological developments or applicational success.

Several research reports over the last few years have attempted to measure the global opportunity by the end of this decade with estimates varying widely up to higher end forecast of $62bn[3], reflecting the problematic nature of predicting a nascent market.

However, what these reports can agree on is that the market is set to grow substantially, with all reports predicting annual double-digit growth until at least 2030 (between 17% and 34% CAGR[3,5,6]). This growth is forecast across all the major quantum market themes - computing, sensing and communication - accelerated by high levels of government and private investment and an expanding portfolio of applications across multiple vertical sectors.

Scotland's opportunity

Predicting the direct economic opportunity for Scotland is not straightforward for some of the reasons outlined above. However, comparisons between previous and future government investment, alongside current market share, can provide useful metrics on which to base predictions.

Two recent reports comparing government investment in quantum technologies, agreed that the UK has contributed around $1.3bn in a total global investment of approximately $30bn to date (4.3%)[5,6] . This does not include the recent commitment from UK Government to a further £2.5bn over the next 10 years. This investment has supported the UK in securing an estimated 9% of the global market share in quantum technologies in 2021/22. Furthermore, the UK Government has an aim to build this market share to 15% by 2033[1]. Working at the higher end of global forecasts, this could convert to a total opportunity for the UK of around $5-9bn (£4-7.5bn).

Further approximation of the potential opportunity for Scotland can then be made by comparing the proportion of UK collaborative funding received by Scottish based organisations. Over the last 5 years, this has been approximately 40% (based on published Innovate UK figures). Applying this figure to the UK opportunity, **generates a total potential opportunity for Scotland of between £1.6bn and £3bn**. While it is acknowledged that this represents a relatively crude calculation, it does at least give an indicative prediction of the scale of the opportunity for Scotland. Furthermore, an ambition to convert our success in securing collaborative funding to genuine commercial opportunity, must be a primary goal of the quantum cluster in Scotland.

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While these headline figures illustrate the ambition of the sector in Scotland, we must also acknowledge the further benefits of positioning Scotland as a global lead in such a high-tech, innovative sector, particularly in relation to high value job creation and exports. To do this we can make comparisons with our adjacent photonics sector, already a £1.2bn sector in Scotland. Photonics supports over 6,000 high value jobs at a GVA per employee of nearly £100,000[7]. It is also a high export sector with recent analysis showing that 97% of goods manufactured are exported outside of Scotland[8]. Given the alignment between our photonics and quantum ambitions it is a credible assumption that similar numbers will underpin our growing quantum cluster.

5. Building the talent pipeline

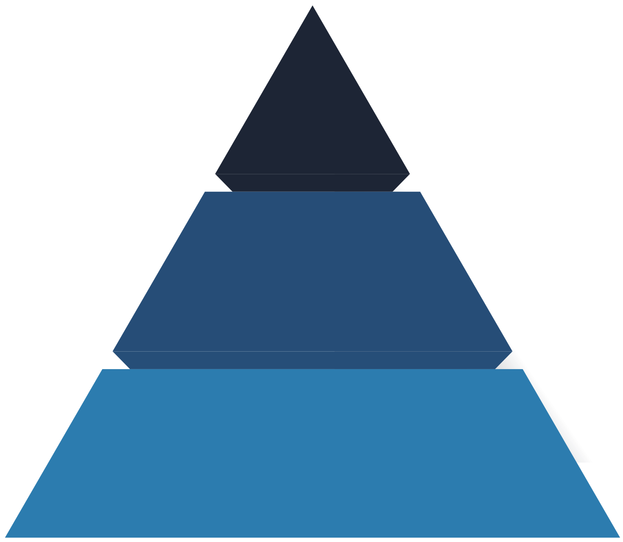
Access to high calibre talent has been a key component of Scotland's quantum success to date.

However, it is well established that perhaps the biggest single challenge facing Scotland's technology sub-sectors is access to skills. Indeed, access to, and retention of, skills has been highlighted as the biggest impediment to growth in each of the last three Photonics Scotland Annual Surveys. Scotland's quantum ambitions will not be immune to this challenge and building the right talent pool with the right skills profile will be critical in meeting the opportunities that will emerge over the coming decades.

The quantum skills profile is a broad and diverse one, reflecting the multi-disciplinary approach required and the market reach of these technologies. While many people will perhaps have a particular perception of what a quantum professional may look like, the truth is a wide range of skill sets, backgrounds and experiences will be needed to realise the quantum opportunity in Scotland.

The skills pyramid

A recent study of the US quantum industry[9] highlighted this diversity. While demand for specific quantum related skill sets was high, for example, quantum algorithm developer or error correction scientist, the study also showed that most of the job types required within the sector did not require specific quantum skills, instead requiring expertise in areas such as test engineering, optics, maintenance engineering and assembly. As the quantum market matures, and greater emphasis is placed on production and commercialisation, it is expected that this diversity will expand further to include a greater focus on manufacturing roles and commercial functions. Indeed, it is estimated that for every one quantum scientist employed, a further seven employees will be needed in supporting and adjacent functions. This creates a **quantum 'skills pyramid'**, with highly technical, upper-level degree roles at the top and an increasing demand for wider skill sets below this.



Specific quantum skills
e.g., quantum algorithm developer, error correction scientist, theoretical/experimental physicist

General technical and engineering skills
e.g., device/component engineer, test/measurement engineer, data scientist, photonics/optics scientist

Supporting skill sets
e.g., maintenance technician, test/measurement engineer, system assembly, technical sales/marketing

Alternative further education routes

Developing such a diverse talent pool requires a diverse approach to skills development, from university education to alternative higher education routes, apprenticeships, and upskilling/reskilling programmes. The UK Quantum Technologies Strategy recognises that there is an immediate, short-term demand for higher degree level education and is committed to funding 1,000 postgraduate research students by 2033. However, there will be an increasing demand for alternative education backgrounds as the market matures.

Aligning industry demand with higher and further education programmes will be critical. In an area of rapid technological change, this must be a continuous process and efforts must be made to ensure a robust feedback loop between industry, higher education providers and skills agencies. Establishing a **formal quantum skills** group will support these efforts, providing a focal point to identify skills gaps and inform programme content and delivery.

Attracting and retaining talent

The viability of any skills programme requires demand, both from industry and from the future talent pool. Feeding the skills pipeline is vital and a concerted effort must be made to **raise the profile of quantum technologies** and their applications at all stages of education. This will require a coordinated effort between industry, academia, and skills providers to position Scotland's quantum industry as a viable and rewarding career. Coordinated engagement with schools, students and parents should be a primary focus of the sector, leveraging initiatives such as the Quantum City (supported through the UK National Quantum Technologies Programme), to highlight the diversity of skills required and career paths available.

While building a domestic quantum skills pipeline should be a primary focus, there will also need to be an increased effort made to **attract international talent** to Scotland. In line with many other technical sectors, it is acknowledged that even with the best local skills development programmes, there will always be a need to attract specific expertise to augment the skills pool in Scotland. Efforts must be made to position Scotland as a global lead in quantum, sending a message around the globe that Scotland is serious about quantum technologies and has the university base and industry opportunity to support a long and rewarding career. These communication channels should be delivered in parallel to efforts to reduce known barriers to attracting international talent, for example, giving greater consideration to opportunities to fast-track current visa procedures.

Recommendations

- Build the multi-level engineering skills base required to develop and commercialise quantum technologies in Scotland.
    - ◊ This should include efforts to improve feedback channels between industry, higher and further education providers, and skills agencies via the creation of a formal quantum skills group.

- Attract and retain local talent to the Scottish quantum cluster by inspiring the next generation of quantum professionals.
    - ◊ Highlight the role of quantum technologies in our global future and raise awareness of the diverse and rewarding career opportunities within the sector in Scotland.
    - ◊ Encourage greater diversity within Scotland's quantum sector workforce through initiatives such as Opening up Photonics.

- Develop a coordinated approach to attracting international talent to Scotland, including efforts to establish Scotland as a global lead in quantum technologies.

6. Supporting business growth

Despite significant progress in the last decade, the quantum industry remains relatively immature, with current commercial opportunities still found primarily on the hardware side, through component and device manufacturing. However, this market should not be underestimated, with such devices sold into a huge variety of systems.

This provides an immediate opportunity for Scotland, and we must leverage our existing strength in this area to de-risk further expansion of our quantum efforts in future.

While the longer-term opportunity for quantum applications is huge it comes with significant risk, not least the levels of investment required, for the most part beyond all but the largest companies. Scotland must look to incentivise private investment, identify early adopters of new technologies, and, where necessary, consider government procurement routes to de-risk early market opportunities.

Continued infrastructure investment

Scotland already benefits from world leading infrastructure in quantum hardware development, including the James Watt Nanofabrication Centre at the University of Glasgow. Facilities such as this are an important focal point for Scotland's quantum ambitions, providing industry with commercially viable access to capital equipment and crucial research capability. Together with world leading research assets such as Fraunhofer CAP in Glasgow, these facilities also represent an important conduit for collaborative funding, an area of huge success for Scotland over the last decade.

Scotland must continue to invest in infrastructure, identifying targeted, strategic support for established assets that will accelerate the goal to translate our leadership position in quantum research to commercial opportunity. The National Institute for Quantum Integration (NiQi), led by the University of Glasgow, provides an excellent example of this. Currently at the proposal stage, this initiative, which has received wide support from industry, brings together six leading UK academic nanofabrication facilities and the National Physical Laboratory with a newly created National Integration Hub in Glasgow. The key aim of NiQi is to provide access to expensive infrastructure for start-ups and SMEs and resource to de-risk early prototyping activities (see case study in appendix).

Market stimulation

Unlocking private sector investment will be crucial over the next decade but, in the face of significant risk, this is likely to require **appropriate incentivisation measures.** To date, this has been channelled primarily through UK Government collaborative funding, providing support to understand technical challenges and measure market opportunities. While significant progress has been made, major technical challenges still exist (with more to be uncovered) and further support of this kind will be required in the longer term.

As with any immature market, clarity on direction of travel can greatly reduce associated risk. It is vital that stakeholders in Scotland and the wider UK come together to create and inform future technology road maps, policy interventions, and relevant standards. The role of the cluster is important here (discussed in more detail in Section 8), with the cluster manager providing the focal point and facilitation to coordinate cluster responses in key areas.

In some cases, it will be appropriate to leverage Government procurement to accelerate early market opportunities and build local supply chains, acting as 'first customer' in key areas such as defence, security, and national infrastructure. This could include approaches such as demonstrator funding or grand challenges and, in this regard, it is important to note that the UK Government's Quantum Strategy includes a priority action to "Establish stronger mechanisms and catalyst funding through a quantum catalyst fund to accelerate government procurement and enable government to act as an intelligent, early customer of quantum technologies…"

Finally, the success of Scotland's quantum industry will hinge on the identification of early commercial adopters. This will be no mean task given the potential breadth of quantum applications and the likelihood that some of these adopters will be based outside of Scotland (and the UK). The approach must therefore be two-fold.

Firstly, we must develop our domestic market through a coordinated educational programme to accelerate the adoption of quantum technologies in key sectors to Scotland's economy, infrastructure, and security. This should include focussed programmes on the role of quantum technologies in supporting our manufacturing, life science, defence, and financial services sectors.

Secondly, we must identify international partners and customers, leveraging research and intelligence capabilities within our international trade agencies (e.g. Scottish Development International and the Department of Business and Trade) and developing Scotland's global quantum profile as part of wider internationalisation efforts (see Section 7).

Business growth through scale up and start up

Given Scotland's enviable success in securing UK collaborative funding (securing around 40% of all UK funding in quantum in the last 10 years), it is perhaps surprising that there has been relatively few new enterprises created as a result. This is largely a consequence of collaborative funding being secured by established hardware and component developers within Scotland's photonics sector. This brings advantage of course, allowing Scotland's early quantum industry to thrive on the back of a core of stable, internationally competitive organisations.

However, as the quantum opportunity expands beyond the competencies of these core companies, growth will increasingly be fuelled by start-up and scale up enterprises. While future government investment will remain critical, fostering an **attractive private investment landscape**, including foreign investment, will be important to catalyse this growth. Targeted, strategic incentives/co-investment programmes will help to cultivate this landscape and Scottish Government should consider its role in developing Scotland's quantum supply chain. This will necessitate further strategic intervention from government to back a sector already highlighted as a future key industry within its National Strategy for Economic Transformation.

These investment efforts should be linked to a wider effort to develop the entrepreneurial and commercial skills required to realise the potential of our quantum capabilities. The importance of this approach has recently been highlighted within the National Strategy for Economic Transformation. While there is already excellent support available in this area, there is evidence to suggest that perhaps this is being underutilised and it will be important to link academic groups, spin outs and start-ups to the support mechanisms available.

Recommendations

- Identify targeted, strategic funding of established translational assets supporting quantum technology development in Scotland.

- Identify early-stage markets and potential early commercial adopters of quantum technologies.
    - ◊ Government should consider its role as 'first customer', stimulating the market via 'grand challenge' or demonstrator funding.
    - ◊ Develop a coordinated programme of activities to accelerate the adoption of quantum technologies in key sectors for the Scottish economy.

- Consider targeted, strategic incentives and co-investment programmes to cultivate an attractive private investment landscape, including foreign direct investment.
    - ◊ These should be linked to a wider effort to develop the entrepreneurial and commercial skills required to realise the potential of our quantum capabilities.

7. Internationalisation

Scotland already enjoys a preeminent position for quantum technologies within the UK. This is particularly true for quantum hardware and components and is reflected in a disproportionate share of UK collaborative funding.

However, for Scotland to fulfil its potential in this increasingly competitive global market, it will be vital to build Scotland's reputation globally, particularly across key markets in Asia, Europe and North America. These efforts should focus on three important areas:

- **Building the global customer base** – Quantum technologies and their applications represent a global opportunity and success will require organisations – large and small – to negotiate complex international markets and supply chains. Visibility will be hugely important to this and the collective marketing of Scotland as global lead in quantum development and applications will create opportunities, not just direct sales opportunities but also important collaboration and supply chain relationships.

- **Building the talent pool** – The skills requirement has already been addressed elsewhere in this report, but it is worth emphasising that the current skills gap is unlikely to be solved through domestic talent alone. Attracting international employees will be vital and Scotland must leverage the strength of its quantum cluster as a magnet for overseas talent.

- **Attracting foreign direct investment** – Quantum technologies also represent a significant opportunity for attracting investment. Those regions/nations able to coordinate their marketing efforts, backed by incentives/co-investment programmes, will secure greatest success in this area (see Section 6). Fortunately, Scotland has a strong history in attracting such investment through its internationally recognised photonics sector. There is every reason to believe that similar success could be found in the quantum arena.

Whether it is identifying customers, building talent or securing investment, it is clear that a coordinated communications programme is required, built around a credible international reputation and a recognisable brand. Efforts in this area have already started, spearheaded by Fraunhofer CAP and the creation of Glentanglement®.

Glentanglement® should provide the foundation on which to build Scotland's international profile for quantum technologies, providing a focal point for a coordinated, multi-channel marketing programme. This programme should be developed with industry partners and include support from organisations including Scottish Development International, Scotland's International Directorate for Trade and Investment, Global Scots and the Department of Business and Trade.

Specific internationalisation activities should be directed through the Scottish Government's Technology Sector Export Plan (Technology Scotland sits as a member of the delivery group for this plan) which already recognises quantum technologies as an opportunity area. These activities must include at least 5 years commitment of support and should include:

- Identification of, and support for, key international trade shows and conferences.
- Expansion of in-market technical support in key geographies.
- SDI led trade missions, preferably with Ministerial support where possible.
- Modern, data led approaches to target early adopter companies/geographies.

Recommendations

- Build Scotland's international profile for quantum technologies through the recently established Glentanglement® brand.
    - ◊ Leverage the growing profile of Glentanglement® to attract international talent, foreign direct investment and global customers and collaborators.

- Develop a coordinated, multi-channel approach to the international promotion of Scotland's quantum technologies capability.
    - ◊ This will include, but is not limited to, support funding for key trade shows and international conferences, SDI led trade missions, increased in-market support, and the development of shared collateral under the Glentanglement® brand.

8. Building Scotland’s cluster

Many of the organisations leading Scotland’s quantum journey already benefit from being part of a long standing, vibrant cluster – photonics. This will work strongly in Scotland’s favour, providing a ‘head start’ when it comes to developing a formal quantum cluster in Scotland.

Cluster development

Developing such a cluster is important. It is now well established that active clusters increase the productivity of companies operating within them, supporting above average job growth, stimulating new business and promoting collaboration. Indeed, the National Strategy for Economic Transformation recognises the vital role clusters will play in Scotland’s future, as will Scotland’s soon to be published Innovation Strategy.

Management of these clusters is crucial if those operating within them are to realise the full benefits. Clusters without management, or those poorly managed, can remain fragmented and their visibility and influence reduced. Again, Scotland can benefit from an accelerated start in developing the managed cluster model for quantum in Scotland. For nearly 30 years Scotland’s adjacent photonics sector has benefited from a cluster manager, most recently through Photonics Scotland managed by Technology Scotland, the industry body for Scotland’s enabling technologies sector.

With the influence of photonics so prevalent in the early stages of quantum cluster development, this existing cluster management model should be leveraged and expanded to formally support quantum activity. This should include recognised accreditation for cluster activities in line with international standards.

As well as providing a platform for local activity – events, networking, knowledge exchange – the cluster manager’s primary role should be to provide a first point of contact for all stakeholders across the UK and internationally, presenting a neutral, unified voice for the sector. This should include the coordination of Scottish input to UK and international policy and standards development.

Capability Directory

An important aspect of any cluster is visibility. Clusters operate most successfully when participants have a full knowledge of others operating within it. To this end, it would be valuable to develop and maintain a capability directory for Scotland's quantum cluster, to include industry and academia alongside testing and manufacturing capability. As well as providing a useful domestic tool for those wanting to engage with relevant participants in the cluster, such a directory would also represent an important 'shop front' for international engagement and should provide a vital piece of collateral as part of the coordinated internationalisation approach discussed in Section 7.

Recommendations

- Formalise Scotland's quantum cluster and seek accreditation for cluster activities in line with recognised standards.
    - ◊ This aggregated body should provide a first point of contact for all stakeholders and engage with UK and international bodies to coordinate Scottish input to worldwide standards development and policy.

Appendix: case studies

Alter Technology UK

Alter UK provides contract package design and precision assembly services for photonic, microelectronic, MEMS and PIC devices, from fast-turn prototyping to production manufacturing. Our turn-key packaging services enable customers to reduce development and manufacturing costs, accelerate time to market and reduce new product introduction risk. Alter works in sectors for which quality and reliability are paramount.

In 2003, Scottish Enterprise set up Alter UK (then Optocap) in Livingston to address a gap in packaging and assembly services in the optoelectronics and microelectronics supply chain. Optocap became part of the Aerospace division of Alter TÜV Nord in 2016. Alter is the leading provider of micro and electronics services in space and harsh environment markets and by acquiring Optocap was able to strengthen its market position and provide a broader suite of services and solutions to its customers.

In 2021, Alter established a Photonics Design Centre in Glasgow, ~ €6M to the Livingston site and to the Design Centre. The Design Centre leverages the success of the manufacturing site in Livingston to develop Alter's own line of highly integrated, miniaturised and robust photonic products to be used for quantum enabled PNT systems and optical satellite communications. The key factors in selecting the location were the photonics and quantum eco-system, access to skills and proximity to key partners in the area.

Fraunhofer Centre for Applied Photonics

Fraunhofer Centre for Applied Photonics, Fh-CAP, has core technical strengths in quantum technologies including sources, atom sensors, clocks, quantum key distribution, imaging, and precision devices for quantum computing. Our Quantum Technology (QT) business unit business unit designs, develops and tests high-performance components for industrial customers. Fh-CAP has, for example, the ability to manipulate and readout states of trapped atoms and generate and detect single photons.

Fraunhofer CAP work with industry to support the commercialisation of quantum technologies, participating in the Industrial Strategy Challenge Fund (ISCF) more widely than any other UK organisation. Fraunhofer CAP has been key in in the development of collaborative partnerships across Glentanglement and across the UK in quantum technologies, helping build the supply chain.

The QT Assemble project addresses the challenges of size, weight, power and reliability through the use of innovative assembly processes such as waveguide writing, nanoscale alignment and monolithic integration. Fraunhofer CAP leads in partnership with 13 organisations from across the UK: the University of Strathclyde, INEX Microtechnology, the University of Southampton, PowerPhotonic Ltd, Gooch & Housego (Torquay) Ltd, Photon Force Ltd, ColdQuanta UK Ltd, UniKLasers Ltd, Covesion Ltd, RedWave Labs Ltd, Caledonian Photonics Ltd, Alter Technology Tuv Nord UK Ltd and AegiQ Ltd. The project will enable the wider adoption of QT by producing miniature, integrated devices such as lasers and photon sources, detectors and sources of cold atoms. The project is analogous to the challenge that electronics faced in moving from large discrete components, such as valves, to thumbnail units with ubiquitous applications. As well as widening opportunities in existing markets, such as navigation and situational awareness, communications and computing, the project will open up new markets.

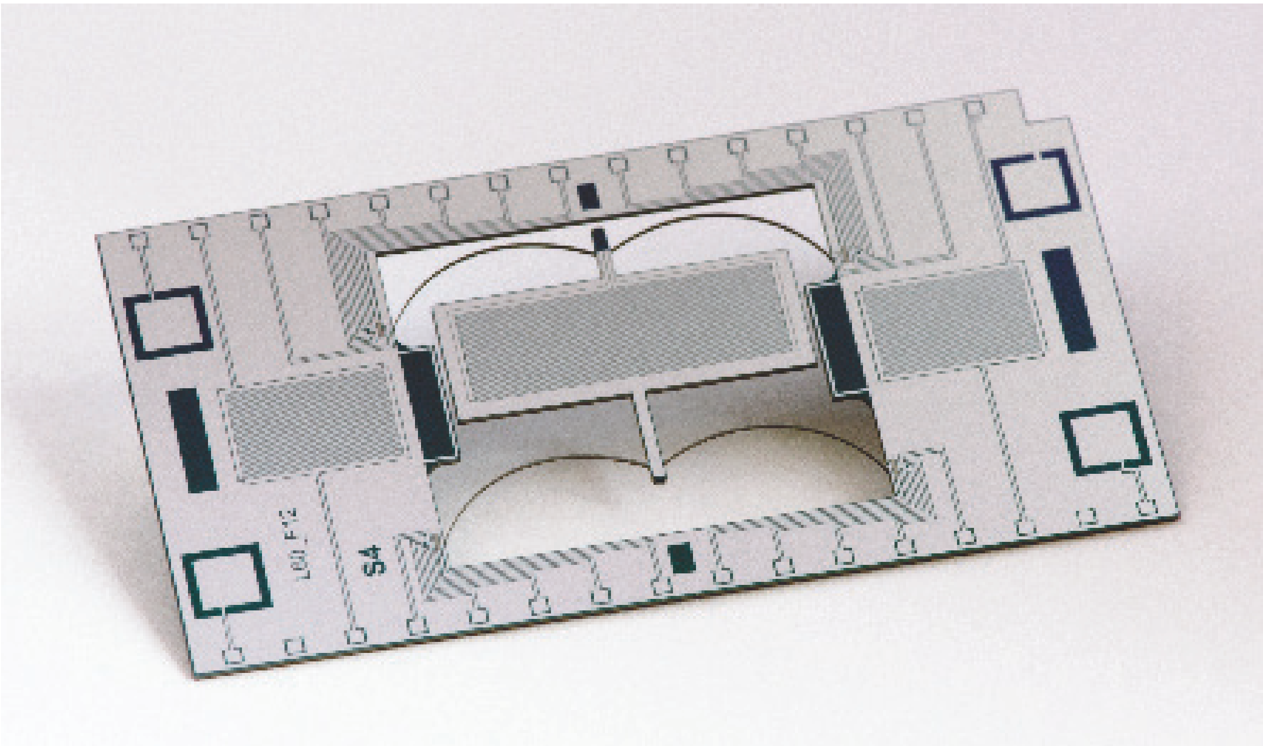
[FLAME: Frequency Stabilised Laser]

Kelvin Nanotechnology

Based at the University of Glasgow, quantum technology and photonics company Kelvin Nanotechnology (KNT) has been in operation for over twenty years. KNT was set up in 1997 to provide nanotechnology services and solutions to industry, government and academia using the world-class facilities of the James Watt Nanofabrication Centre at Glasgow University. Since then, KNT has built up an extensive global blue-chip customer base and has provided micro- and nanofabrication R&D, prototyping, and manufacturing services to over 170 clients in 23 countries in the last three years. KNT is now an established comprehensive photonic fabrication service provider for diverse market sectors and a qualified supply chain partner for multiple global product lines in the telecoms and datacoms markets. The company is proud to be one of the first suppliers to bring miniaturised quantum components to the market. KNT is successfully driving forward innovation in the fabrication of quantum components that enable systems for information processing and computing, chip-scale cold atom sources, sensors, and high precision timing and navigation.

As a Scottish company supplying international customers, KNT's challenge is to match their understanding of the business opportunities quantum technology can provide with potential buyers of their emerging technology.

KNT works very closely with the exceptional university base and strong photonics supply chain network within Scotland; applying its inter-disciplinary expertise to develop novel miniaturised quantum devices. As the sector matures, KNT will continue to identify appropriate business models for the profitable deployment of this exciting and revolutionary technology.



[Wee-G, portable gravimeter]

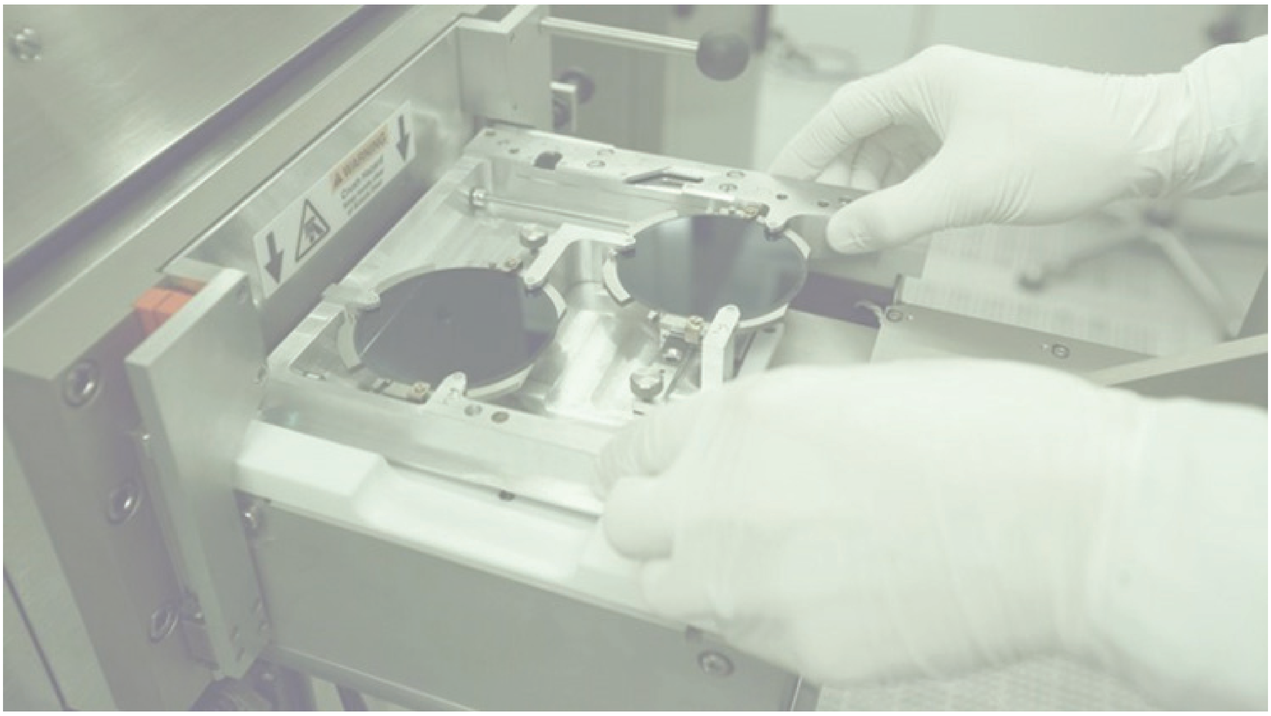
National Institute of Quantum Integration (NiQi) Pilot Accelerator

The NiQi Pilot Accelerator led by University of Glasgow's the James Watt Nanofabrication Centre (JWNC) aims to build an engineering capability that will aid the growth of the Scottish photonics and quantum cluster. It creates an engineering centre including design, test and manufacturing engineers who will work alongside senior University of Glasgow researchers and use the world class facilities of the JWNC to deliver industry defined nanofabrication component and component integration projects. This provides a critical mass of resource and expertise to take on projects that are too risky for one company to invest in alone, accelerating industry product development timelines and opening up volume market opportunities.

Working with 10 industrial partners, the initial cross supply chain projects have been defined as:

- Lasers for alternative navigation, quantum computing and quantum communications
- The development of superconducting quantum circuits for QT foundry services
- Integrated laser-based systems for applications including 3D printing
- Low loss, low power photonic integrated circuit (PIC) based systems for quantum communications and free space optics

This Pilot acts as a model for the University's proposed cross-UK National Institute of Quantum Integration (NiQi), an ambitious proposal to enable the UK to deliver the next generation of integrated, miniaturised quantum components. NiQi will have the staff, nanofabrication equipment and engineering infrastructure to drive advances in the reliability and integration of semiconductor and superconducting quantum devices. The proposed NiQi Hub at the University of Glasgow will act as a front door for global industry to engage with UK quantum nanofabrication expertise and position Glasgow and Central Scotland as a world leader in quantum technology, serving as a beacon for further inward investment into the region.



[Wafer processing]

Photon Force

Founded and based in Edinburgh, Photon Force is an award-winning SME providing innovative single-photon avalanche diode (SPAD) detector technologies. We are the leading commercial developer of CMOS time-resolved SPAD array cameras and sensors, offering the world's highest throughput devices. Our products accelerate industrial and research applications in areas including biomedical research, advanced LiDAR, and diffuse correlation spectroscopy for brain-computer interfacing.

The benefit of using CMOS technology for single-photon detection is not solely the ability to tile many 1000s of SPADs in a 2D array, but also the circuitry that can be integrated within each pixel. Our main product, the PF32, has 1024 pixels, each with its own counting and timing circuitry, capable of time-stamping a photon's arrival to an accuracy of 55ps.

Alongside the application areas mentioned above, our current sensors have been used for free-space quantum communications, quantum-enhanced imaging, and fundamental quantum optics. The quantum sector can often be perceived as quantum computing and communications; however, the technologies developed for this sector are wider reaching, benefiting many current technologies and facilitating step-changes in performance.

Photon Force continues its innovative product development programme for next generation SPAD-based devices with a focus on underwater depth imaging, gas sensing, and SWIR single-photon detection, while facilitating their inclusion in quantum applications in the future.

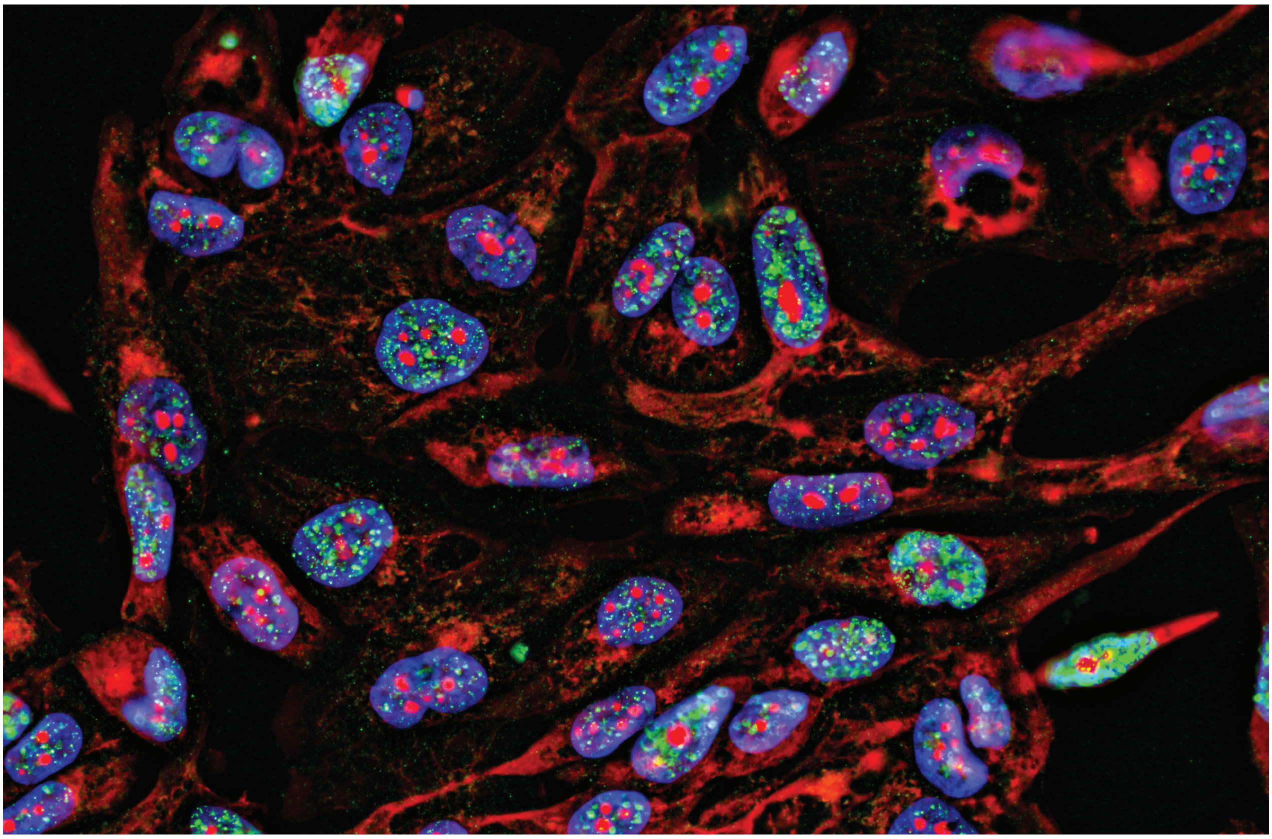
[PF32 time-resolved single-photon counting camera]

QuantIC

QuantIC is the only UK National Quantum Technology Hub to be located within Scotland, lead through the University of Glasgow, and connects many of the primary Scottish universities. Its goal, of furthering the research and commercialisation of UK quantum imaging achieved through partnerships with local industries and talent.

This scheme is providing merit improvements to technologies of all sectors, alongside economic impact that is present today. We can directly evidence this through in the product and job creation seen in Scottish enterprises.

An example of this is the development of quantum detectors, utilised for the next generation of cameras in healthcare and life sciences. These detectors can image the smallest quants of light, single photons. Such devices have enabled companies such as Photon Force (a new Scottish quantum start-up) and Horiba (a major multi-national company) to produce equipment that far exceeds conventional capabilities. The high sensitives of these quantum detectors enable widely adapted bio-medical fluorescence imaging (FLIM) to be conducted, wide-field, in a matter of seconds instead of hours or minutes. This drives mission-level change to diagnose times, drug discovery, and biological advancements. Major barriers to understanding state-of-the-art biological processes, limited by photobleaching and short timescales are being eroded via these quantum imaging technologies. Today, FLIMera the novel quantum detector, is developed and sold in Scotland to an international market.

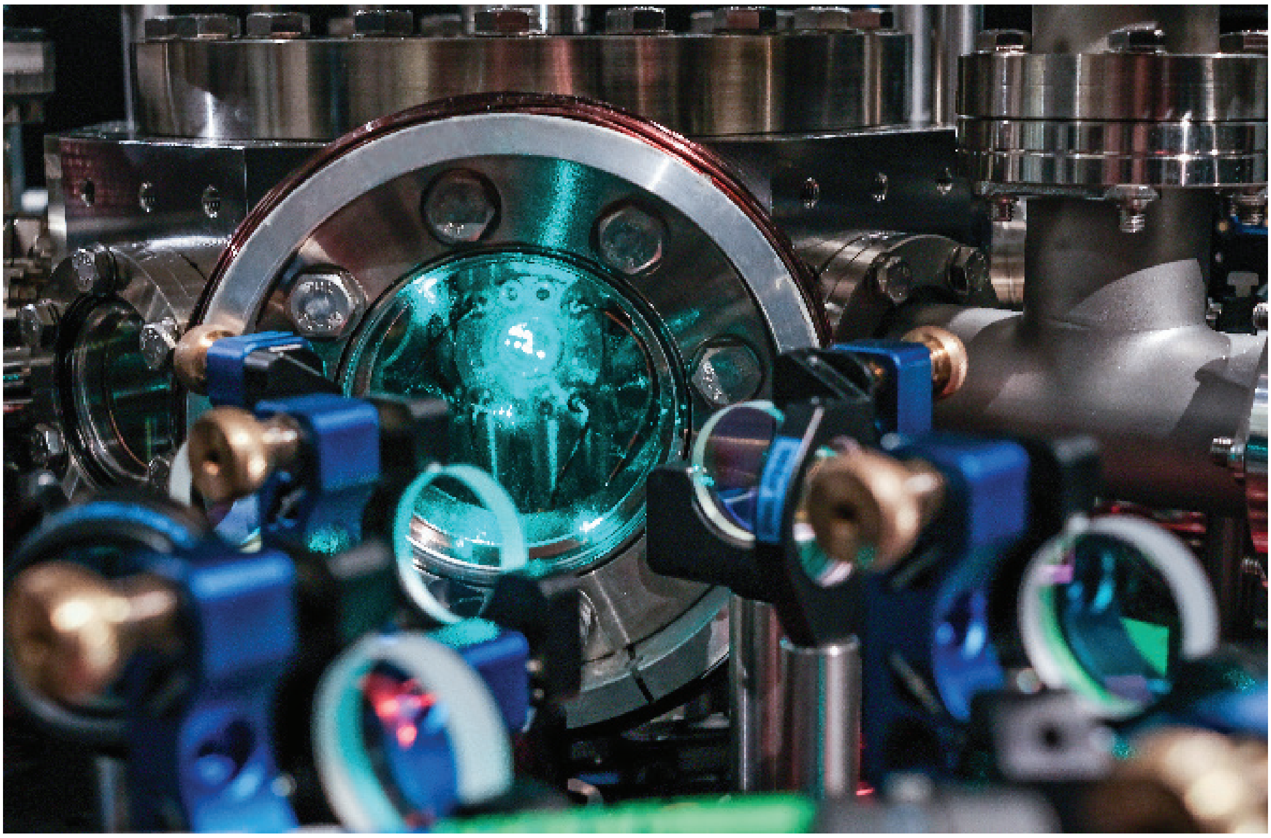


[Fluorescent Imaging immunofluorescence of cancer cells growing in 2D]

Quantum Computing Applications Cluster

The Quantum Computing Application (QCA) Cluster was established in 2019, and joins up academic capabilities to help expand and further develop the ecosystem for quantum computing and simulation across the Scottish Central Belt. Formed by researchers from the University of Edinburgh, University of Glasgow, University of Strathclyde, and EPCC (High-Performance Computing Centre) the cluster combines expertise in quantum hardware and software as well as classical HPC. All of the groups are strongly embedded within the UK National Quantum Technologies Programme (NQTP), with strong links to the National Quantum Computing Centre (NQCC), including the newly established Quantum Software Lab at the University of Edinburgh.

The central goal of the cluster is to join up strengths across the ecosystem to identify end-user computational challenges that can be addressed with quantum computing, developing software solutions and understanding the timescales for impact on each sector. The cluster is engaging closely with Scottish Government and Scottish Development International to explore inward investment opportunities for quantum computing in Scotland. Scientists from the cluster are working together to develop next generations of hardware and software for quantum computing, and to bring added value to the training of PhD students and researchers at all levels across the traditional academic boundaries of physics, engineering, computer science, and high-performance computing.



[Neutral atom setup, University of Strathclyde (Image credit: Hao Yang)]

About us

About Photonics Scotland

This paper has been prepared by Photonics Scotland in consultation with its members and we would like to thank them for their continued support.

Photonics Scotland is a community for all photonics and photonics-enabled organisations in Scotland. We are the focal point for the sector and a trusted partner to our members allowing us to represent their views to a number of key stakeholders. We also facilitate a cohesive sector, providing a range of events, working groups and networking opportunities that help to drive collaboration between industrial and academic partners.

Ultimately, our goals are simple: to raise the profile of the sector, help grow this thriving cluster, and drive innovation in photonics in Scotland.

Founded as the Scottish Optoelectronics Association in 1994, it is one of the oldest national photonics organisations in the world and remains one of the largest technology communities in Scotland.
Photonics Scotland is a network managed by Technology Scotland.

About Technology Scotland

Technology Scotland is the representative body for the Enabling Technology Sector in Scotland.

We support a vibrant community of industrial and academic organisations who are developing technologies to deliver product advancements in markets from healthcare and communications to manufacturing and mobility.

Technology Scotland delivers clear business value to members, providing a catalyst for growth and supporting the community through networking, collaboration, lobbying and thought leadership.

- Representing industry interests to government
- Promoting Scottish technology capabilities within the UK and internationally
- Influencing policy at both Scottish and UK government level
- Supporting the community through events, workshops and forums
- Interfacing to key national and international stakeholder

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