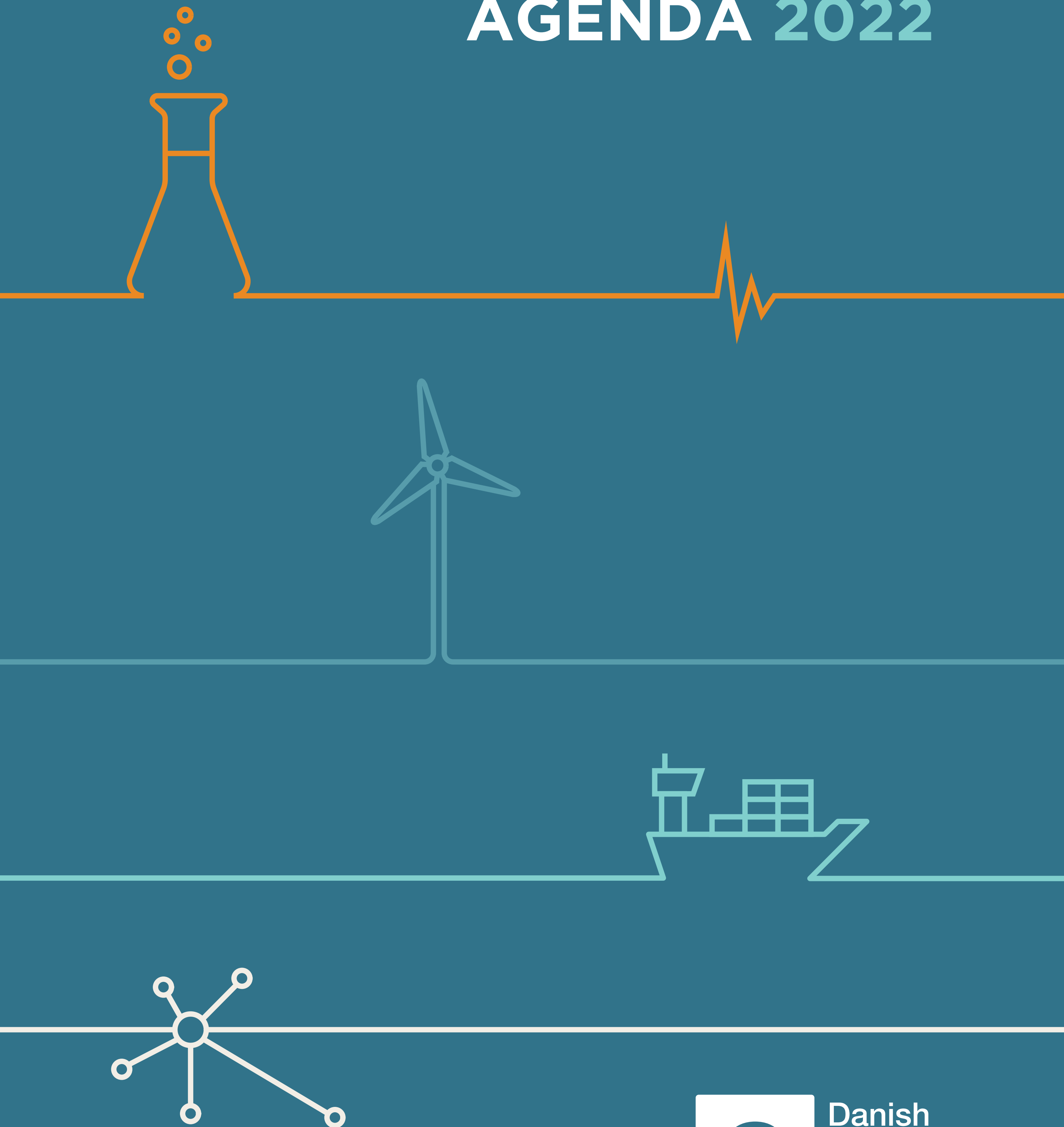
DANISH QUANTUM AGENDA 2022



Danish
Quantum
Community

DANISH QUANTUM AGENDA
By Danish Quantum Community
June 2022

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RESUMÉ

Kvanteteknologi dækker over en bred palet af nye teknologier med anvendelser indenfor sensorer, kommunikation og databehandling. Kvantefysiske processer muliggør et spring i effektiviteten og sikkerheden, hvormed information opsamles, transmitteres og processeres. Teknologierne forventes at finde bred anvendelse i samfundet, f.eks. gennem forbedring af biologisk og medicinsk billeddannelse, løsning af beregningsmæssige udfordringer inden for pharma og kemi samt markant øget cybersikkerhed. Derudover vil kvanteteknologier blive en central del af løsningen på globale udfordringer i forhold til klima og bæredygtighed. Mest modne er anvendelser inden for sensorer og kommunikation, hvor enkelte løsninger allerede er blevet kommercialiserede. En universel "kvantecomputer" til praktiske anvendelser ligger fortsat 10-15 år ude i fremtiden. Imidlertid er kvantecomputeren samtidig den kvanteteknologi, som har det største potentiale for radikal nyskabelse - disruption. Kvantecomputere tilbyder ikke blot forøget regnekraft, men også et nyt informationsteknologisk paradigme. De første demonstrationer af "quantum advantage", dvs. gennemførelse af beregninger, der overgår sædvanlige computeres formåen, er opnået for problemstillinger primært af akademisk interesse. På kort sigt forventes "kvantesimulatorer", designede til at håndtere specifikke opgaver, at muliggøre de første praktisk relevante løsninger til særlige typer af beregningsmæssige problemer. Potentielle eksempler er allerede identificerede inden for finans, logistik og kemi.

På globalt plan er vi vidner til massive investeringer i kvanteteknologi motiveret af teknologiernes strategiske betydning og det betragtelige kommercielle potentiale. Markedsforudsigelser anslår, at de globale markeder for kvantesensorer og kvantekommunikationsteknologier i 2040 vil være på hhv. 1-5 mia. EUR og 1-6 mia. EUR. For kvantecomputere er forudsigelserne mere spredte pga. teknologiernes tidlige stadie, og svinger mellem 8 mia. og hele 80 mia. EUR i 2040. Netop inden for udviklingen af kvantecomputere foregår der et teknologikapløb mellem Kina og USA. Tidlige udviklingsinvesteringer fra tech-giganter som IBM og Google gav USA et forspring. Med afsæt i yderst ambitiøse statslige investeringer i kvanteteknologi, antageligt på 10 mia. USD, er Kina imidlertid ved at indtage en global førerposition. I Europa er udviklingen blevet accelereret af EU kommissionens 1 mia. EUR kvanteflagskib, som blev startet i 2018 og løber over 10 år. Internt i Europa er konkurrencen på det seneste blevet intensiveret af en række nationale strategiske initiativer af størrelsesordenen 1-2 mia. EUR fra hhv. Holland, Frankrig og Tyskland. Kvanteteknologi forventes at skabe værdi for en række erhvervssektorer, herunder danske styrkepositioner som logistik, pharma, grøn energi og ingredienser. Det forventes derfor, at Danmark vil høste stor økonomisk gevinst af den igangværende anden kvanterevolution.

Danmarks forskningsmiljø hører til den absolutte internationale elite takket være meget betragtelige investeringer i grundforskning og forskningsinfrastruktur. I takt med, at fokus hastigt rykkes fra grundforskning til innovation, teknologiudvikling og anvendelser, er der dog behov for en strategisk satsning med en tilsvarende finansiering, hvis vi skal forblive på forkant med udviklingen, sikre en markedsandel der modsvarer potentialet og profitere på vores nuværende forskningsmæssige position. Derfor opfordrer Danish Quantum Community til etableringen af en national strategi med følgende konkrete anbefalinger til nationale tiltag på kvanteteknologiområdet: (i) Styrkelse af samarbejdet mellem industri og universiteter og etablering af en dansk kvanteklynge, (ii) en strategisk investering i tidlig integrering af kvanteteknologi i danske virksomheder gennem en portefølje af demonstratorprojekter, og (iii) igangsættelse af en række ambitiøse langsigtede fyrtårnsprojekter for dansk forskning, som skal udvikle kvanteteknologiske løsninger på problemstillinger relevante for det danske samfund og erhvervsliv. At realisere disse mål fordrer en fælles indsats mellem erhvervslivet, offentlige virksomheder og forskere, støttet af både offentlige og private fonde.

Det seneste år har budt på en række spændende udviklinger med relevans for det danske kvante-økosystem:

- Den politiske aftale om fordelingen af forskningsreserven for 2022 indeholder en beslutning om at gennemføre en kortlægning af kvanteforskningen i Danmark og samspillet mellem universiteter og virksomheder i løbet af 1. halvår af 2022 med henblik på at etablere en national kvanteforskningsstrategi.
- I januar 2022 blev virksomheden Kvantify stiftet - et startup med fokus på quantum computing baseret på forskning fra bl.a. Aarhus Universitet.
- I marts 2022 meddelte kvante-startup virksomheden, QDevil, at virksomheden var blevet købt for et trecifret millionbeløb af den israelske virksomhed Quantum Machines.
- I april 2022 annoncerede NATO, at det var besluttet at placere NATOs accelerator for kvante-startups i Danmark.
- I maj 2022 har Novo Nordisk Fonden løftet sløret for en kommende stor satsning på udviklingen af en dansk kvantecomputer.

Alt i alt gode tegn på, at det danske kvante-økosystem er ved at komme godt igang.

SUMMARY

Quantum technology embraces a broad spectrum of novel enabling sensor, communication, and computing technologies. These all exploit entirely new physical modalities and will disrupt altogether the efficiency and security with which information is acquired, transmitted, and processed. Applications are expected to pervade society e.g., by leaping forward in biological and medical imaging, surpassing computational barriers in pharma and chemistry, and countering cybersecurity threats. Furthermore, quantum technology is considered a key component for solving imminent global challenges relating to climate and sustainability. Quantum sensors and quantum communication technologies are currently the most mature of the emerging technologies and are already on the commercial market. While universal “quantum computers” for real-world applications may still be 10-15 years away, quantum computing carries by far the largest potential to impact and pervade society across all sectors. Quantum computing offers not only an advancement in computing power but also a completely new computational paradigm. ”Quantum advan-tage,” signifying the ability to perform calculations using quantum hardware that cannot be done using conventional computing technology, has been achieved several times for problems so far mainly of academic interest. In the short term “quantum simula-tors”, designed for handling specific tasks, are expected to enable an early practical advantage for certain types of hard computa-tional problems. Potential applications have already been identi-fied within finance, logistics, and chemistry.

Worldwide, we are witnessing massive investments into quantum technology driven by the strategic importance of the technolo-gies and the substantial commercial potential. Market forecasts predict a 1-5 BEUR global market for quantum sensors and 1-6 BEUR for quantum communication technologies by 2040. As quantum computing is still at an early stage, market predictions are subject to larger uncertainties and range from 8 BEUR to as much as 80 BEUR by 2040. A technology arms race is currently taking place between China and the US on quantum computing. While early R&D investments from tech giants like IBM and Google gave the US a head start, China is about to take the lead, thanks to highly ambitious investments, reportedly of 10 BUSD, into quantum technology. In Europe, the development has been accelerated by the European Commission’s 1 BEUR investment into a Quantum Technology Flagship which was initiated in 2018 and will last for 10 years. Within Europe, competition has recently been intensified by strategic national initiatives in the 1-2 BEUR range both from UK, the Netherlands, France, and Germany. Quantum technologies are expected to benefit many business sectors, including Danish positions of strength such as logistics, pharma, green energy, and ingredients. Consequently, Denmark stands to profit significantly from the ongoing second quantum revolution.

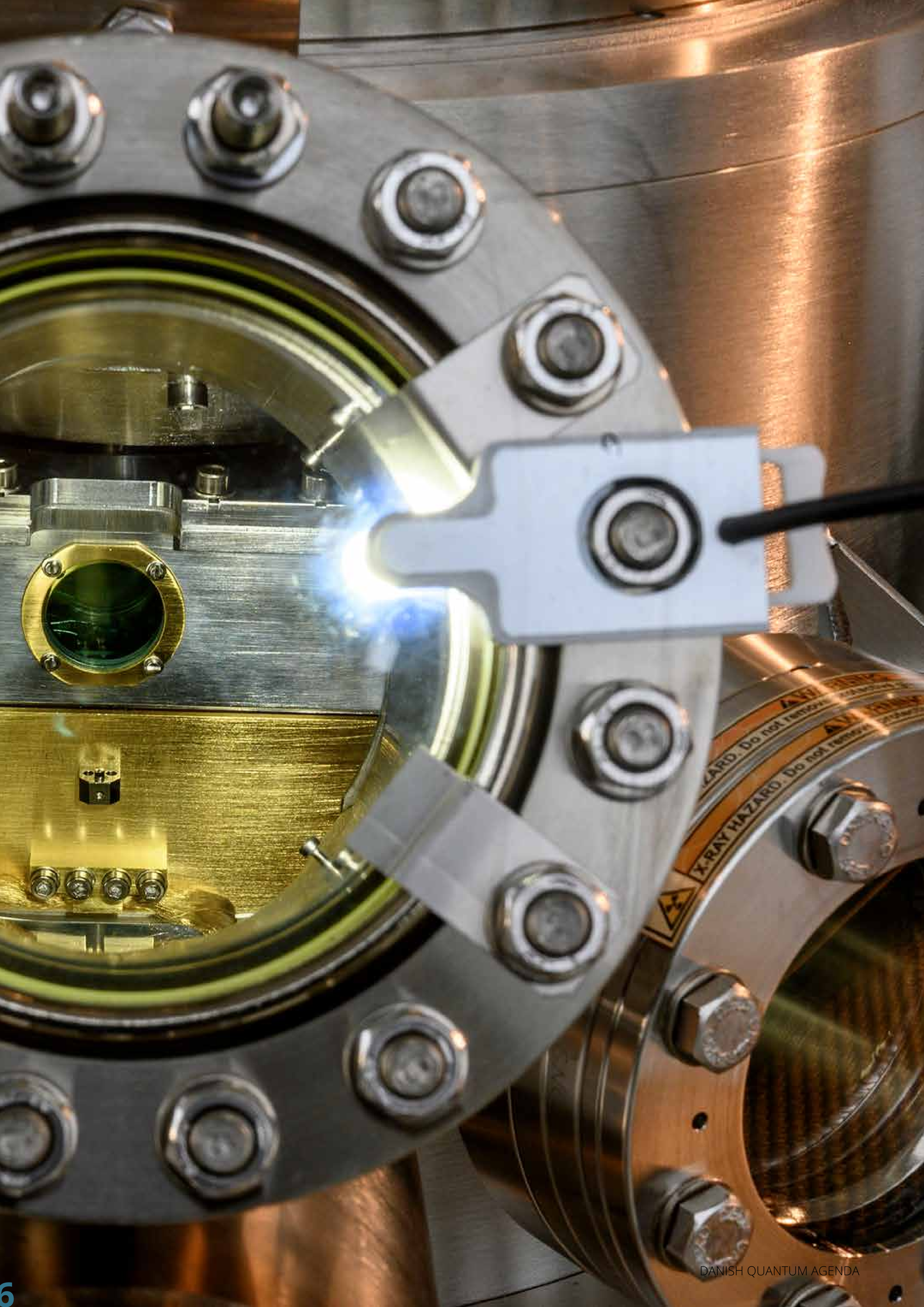
The Danish quantum research community is at the international forefront thanks to years of considerable investments into basic research and research infrastructure. However, as the focus is quickly transitioning from fundamental aspects to innovation, technology development, and applications, a strong strategic push and an entirely different type of funding is required to remain at the cutting edge, gain a proportional market share and capitalize on the hard-earned research position. Therefore, the Danish Quantum Community calls for a national strategy and puts forward the following concrete recommendations for nation-al action on quantum technology: (i) Strengthening of the col-laboration between industry and academia and the formation of a Danish Quantum Cluster, (ii) Strategic investment into early adoption of quantum technologies in Danish businesses through a portfolio of demonstrator projects, and (iii) Initiation of sev-eral ambitious long-term lighthouse research projects developing quantum-based solutions relevant to Danish industry and society. Achieving these goals requires a concerted effort between indus-try, public enterprises, and researchers supported by public and private foundations.

Recently the following events with relevance for the Danish quantum eco-system took place:

- The Danish parliament made an agreement to map the Danish quantum research landscape in the first half of 2022 with the aim to establish a Danish national strategy for quantum research.
- In January 2022, Kvantify was founded, a Danish quantum start-up with focus on quantum computing.
- In March 2022, the Danish quantum start-up, QDevil, announced that the company had been acquired for a significant amount by the Israeli company Quantum Machines.
- In April 2022, NATO announced, that it had decided to place NATO’s accelerator for quantum start-ups in Denmark.
- In May 2022, the Novo Nordisk Foundation stated that it was planning to fund a significant effort to develop a Danish quantum computer.

All in all good signs for the emerging Danish quantum eco-system.

CONTENT


X-RAY HAZARD.

INTRODUCTION

First generation of quantum technologies resulted in several breakthroughs such as MRI scans, nuclear energy, and GPS. In addition, they gave us components enabling the modern information society such as transistors and lasers, the building blocks for powerful computers and long-distance, high-speed communications. Niels Bohr played a central role in the formulation of quantum mechanics around 1920, and for the last 100 years, Denmark has maintained a world-leading position in quantum research.

Second generation quantum technologies will open a completely new world, where single quantum objects such as photons, atoms, or ions may be manipulated and quantum mechanical concepts such as spin, superposition, and entanglement will be brought into practical use. During the 21st century, second generation quantum technologies will unfold and most likely change our society profoundly, not unlike the way information technologies have changed the world during the last 50 years.

In January 2020, Danish quantum researchers took the initiative to form the Danish Quantum Community. In August 2020, the Community was expanded to include industry, trade organisations and other Danish stakeholders. In this report, the Danish Quantum Community presents the opportunities becoming available to Danish society and industry, as second-generation quantum technologies evolve. The evolution may take several decades to unfold completely, yet, several second-generation quantum technologies are ready for commercial use already today, and many more will become available during the coming 5-10 years. Danish researchers hold world-leading positions within several key areas of quantum technology, in particular within quantum hardware, and key research infrastructure is established. To take full advantage of this strong position rooted in basic quantum research, we need to act now to secure Danish opportunities as the emerging second-generation quantum technologies unfold. This report is the Danish Quantum Community's proposal for action.

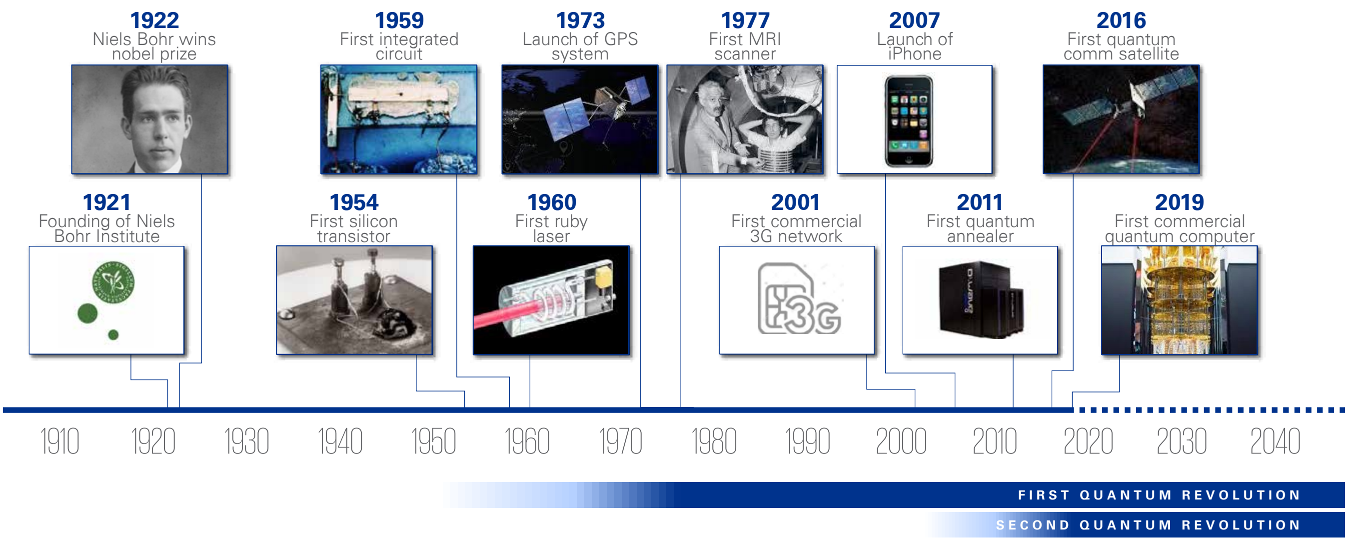


Figure 1: History of quantum technology, courtesy of KPMG and ITB.

1.0 WHY A DANISH QUANTUM AGENDA – AND WHY NOW?

As mentioned, the first quantum revolution brought us the laser and the transistor, both of which have had a significant impact on our everyday life that could not possibly have been foreseen at the time of invention. However, already at an early stage, it was realized that quantum mechanics would have applications reaching far beyond those technologies, as these applications only take advantage of a smaller fraction of the full palette of quantum phenomena surrounding us. The second quantum revolution is now upon us with an insisting push to finally realize the full potential of quantum mechanics for building technologies to the benefit of society, likely to surpass the impact of both the transistor and the laser.

Obvious questions to consider are: 'What generates the current immense global interest in quantum technologies from both governments and commercial enterprises alike?' and 'Why is this particularly important for Denmark?' To answer this, we must look into the tremendous acceleration and maturation the field has experienced in recent years and the leading proficiency present in the Danish research community.

In the early 1980s and through the 1990s, it was realized that classical computers can no longer maintain their exponential performance improvement where the computing power doubles every 18 months, sometimes referred to as Moore's law. Today, the performance of a classical computer has reached a plateau where the only way to increase computing power will be to use more computers in parallel.

In 1982, Richard Feynman suggested using a quantum mechanical platform to simulate nature in its entirety. This marked the inception of the 'quantum simulator', i.e. a controllable quantum system engineered to simulate another quantum system whose properties we would like to know. Another key invention was quantum communications, a method that enables unbreakably secure communication where data integrity is guaranteed by the laws of quantum mechanics. Quantum communications is addressing one of the important cyber security challenges of modern society. The ultimate goal is a 'Quantum Internet' for global secure communication and interconnection of quantum computers.

Through the 1990s, it was explained theoretically how a quantum system may be used to execute 'quantum algorithms', i.e. algorithms that make full use of the intrinsic quantum mechanical features of entanglement and superposition. Famous examples are Shor's factorization algorithm and Grover's search algorithm, both of which have a theoretically proven advantage over classical algorithms. Using these initial algorithmic steps, 'quantum software' for simulating complex quantum systems has emerged in the past decade. These applications have great potential for the industry in

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terms of increasing the precision of chemical simulations such as nitrogen fixation, understanding biological molecules, enabling advanced drug discovery, designing new functional materials, as well as developing new approaches to optimization of industrial and logistical processes. At the end of the last century, the above predictions were theoretical and not verified by experiments, as no quantum simulators or quantum computers had been realized yet.

During the past decade, this situation has fundamentally changed. The first quantum computers and quantum simulators have now been realized, and the ability to execute simple quantum algorithms has been demonstrated.

We are now also witnessing the first practical applications of abstract ideas such as 'quantum teleportation' and 'quantum parallelism'. Starting with small quantum devices with limited functionality, 'roadmaps' for how to scale up these systems towards large-scale operability are now emerging. Furthermore, ground-breaking developments in precision quantum measurements and manipulations have enabled entirely new generation of sensors where an enhanced signal-to-noise ratio is obtained through intrinsic quantum-mechanical behaviour of measurement devices.

The quantum computing platforms that currently attract the most attention are based on superconducting circuits and ion traps. Quantum simulation has also been demonstrated using cold atoms and photonics. Key factors for improving the performance are increase in lifetime of single quantum bits, qubits, and in operation quality. Today we have reached a point, where multi-qubit systems can be implemented, and the field has moved from poor-quality proof-of-principle experiments towards reliable platforms where small algorithms can be tested. The first applications to quantum chemistry have been presented by both IBM and Google. These recent developments have accelerated the push from academia, governments, and from companies around the world to capitalize on the technological developments that will likely follow in coming years. Major nations are now investing heavily in quantum technology, and this is no longer exclusively an academic research effort. Governments are accelerating the transition from research to innovation by investing in collaborations between research labs and end-users in private companies and government entities.

Quantum technologies are so-called enabling technologies, very similar to the transistor, the basis for integrated circuits that enabled the information society. We must take advantage of our knowledge of quantum mechanics to address the immense global challenges such as climate change and sustainability. The power of quantum technology may drive the development of new energy-efficient materials, help us develop new effective chemical processes through advanced catalysis, as well as enable drug discovery and the design of new biomolecular compounds.

Denmark has played a historical role in the development of quantum mechanics, and we are in a unique position to play an important role in the second quantum revolution as well. However, this requires a dedicated effort and an allocation of large-scale resources. To create value for Danish industry and society by means of quantum technologies, Denmark must invest all the way through the value chain, from research to the start-up incubation environment and dedicated private-public collaboration.

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Fortunately, Denmark already has an extremely strong academic landscape in this field. Many research groups around the country conduct cutting-edge research pushing the boundaries of quantum technology, both on the theoretical and the experimental side. Denmark hosts several internationally leading groups, and the Danish research funding system has shown its support for these efforts throughout the last couple of decades. Major centres at the three largest universities working on quantum physics and quantum technologies have been established in the recent past with generous grants from both public and private foundations. This has allowed the academic environment to attract

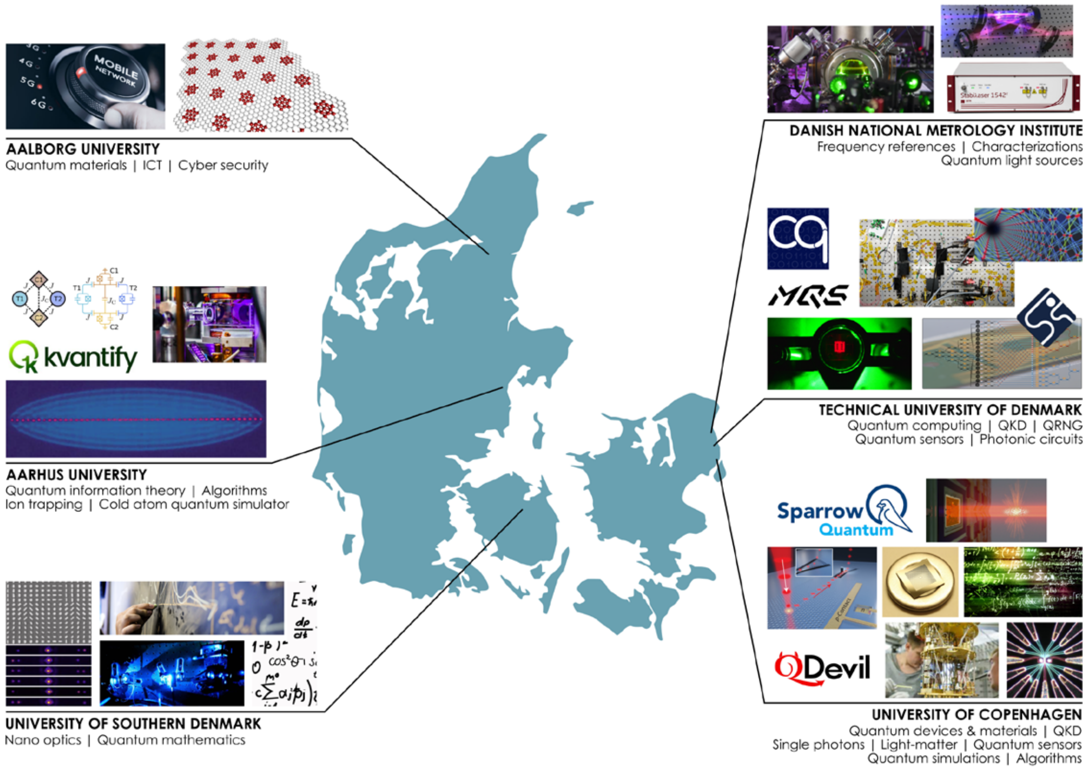


Figure 2: Overview of the Danish quantum research landscape indicating main activities and technology spinouts.

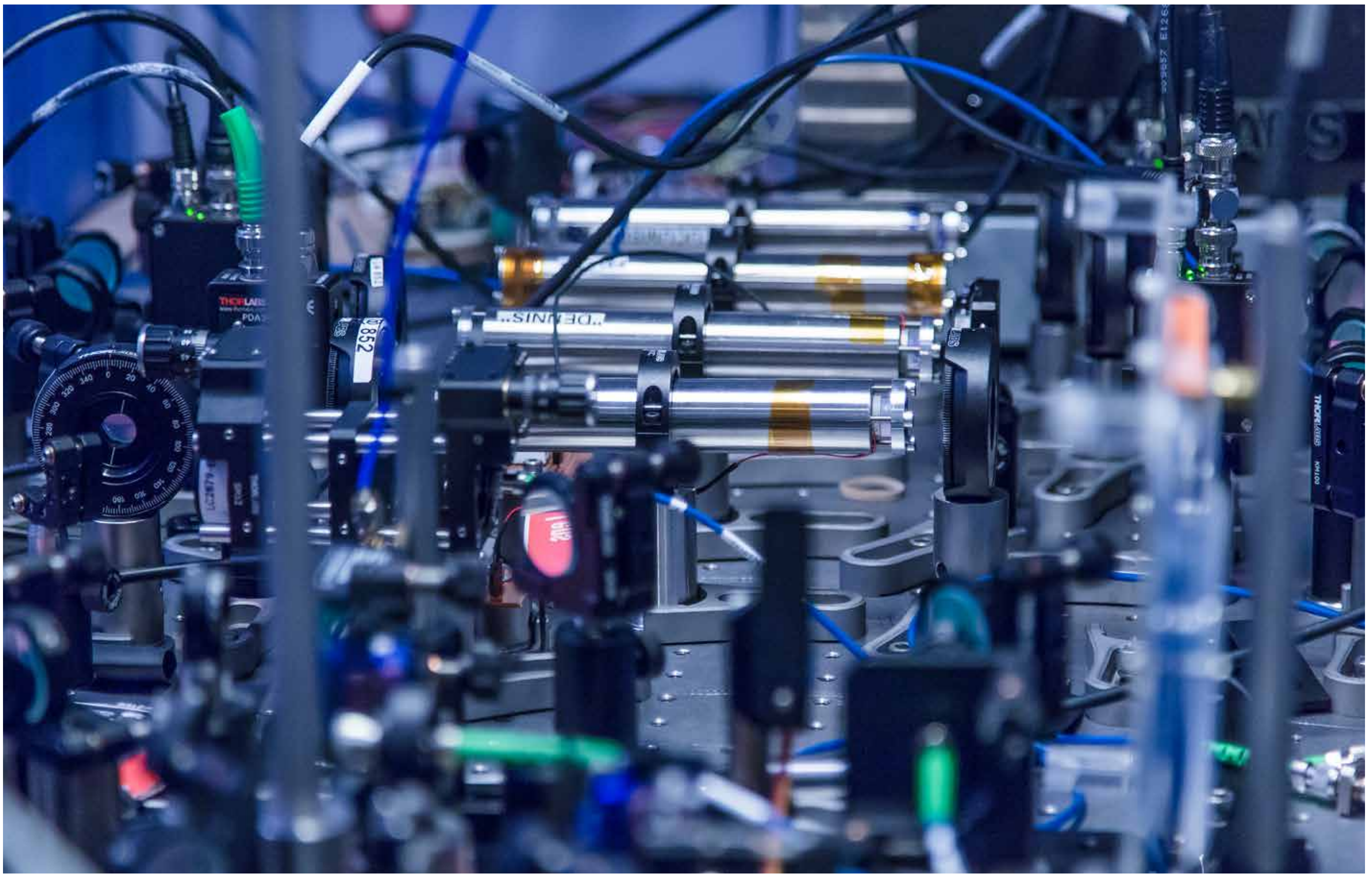
many international researchers into the area, both well-known names and up-and-coming talents. Therefore, there is no doubt that the Danish research capability on quantum technology is very strong, and Denmark is among the leading nations globally in academic quantum research. However, to bring this expertise out of the laboratory and into commercial use, we need a national strategy supporting investments into increasing the technology readiness level and into easing the transition from academic re-search to concrete applications in industry. This last step is cru-cial to ensure job creation outside of academia and consolidating Denmark's competitive edge as quantum technologies in the near future gradually transits from the laboratories into the real world. Therefore, we need a quantum technology roadmap and a Danish Quantum Agenda.

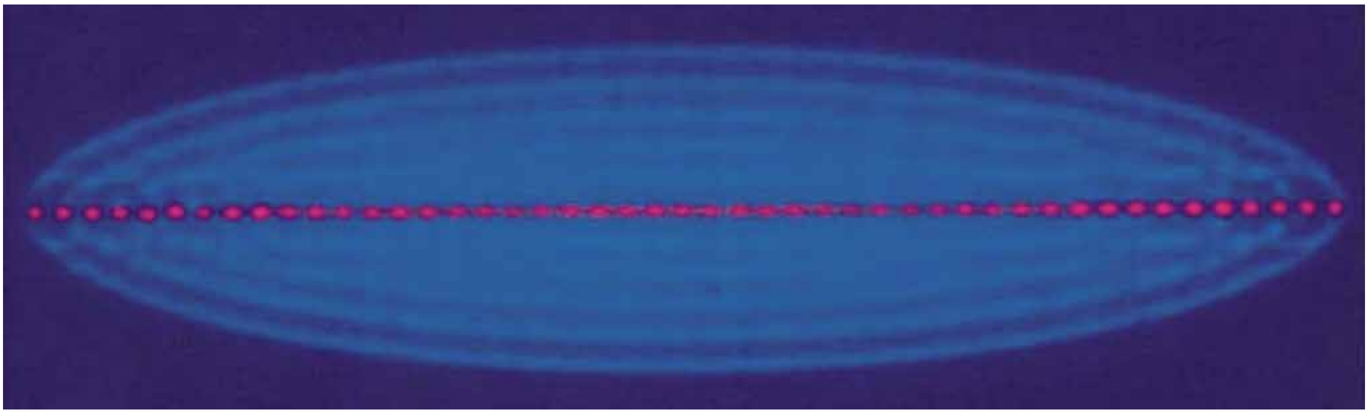
Relative to its size, Denmark has an exceptionally large output of candidates and postdoctoral scholars trained in the development and application of quantum technologies. In fact, Denmark is the leading nation in the world in terms of per capita 'quantum scientists' educated, with dedicated quantum technology MSc study programs being piloted at the universities. The quality of the many people trained in Denmark is extremely high and a large portion of the researchers are employed in the private sector in high-tech jobs around the world. Hence, Denmark is a net supplier of the specialized workforce that will drive and shape the second quantum revolution and bring quantum technology into large-scale applications. We have a great potential to start a strong push into quantum technology also at a commercial level. The workforce needed is already being trained in Denmark, and this workforce will be available for new initiatives supporting this Danish Quantum Agenda.

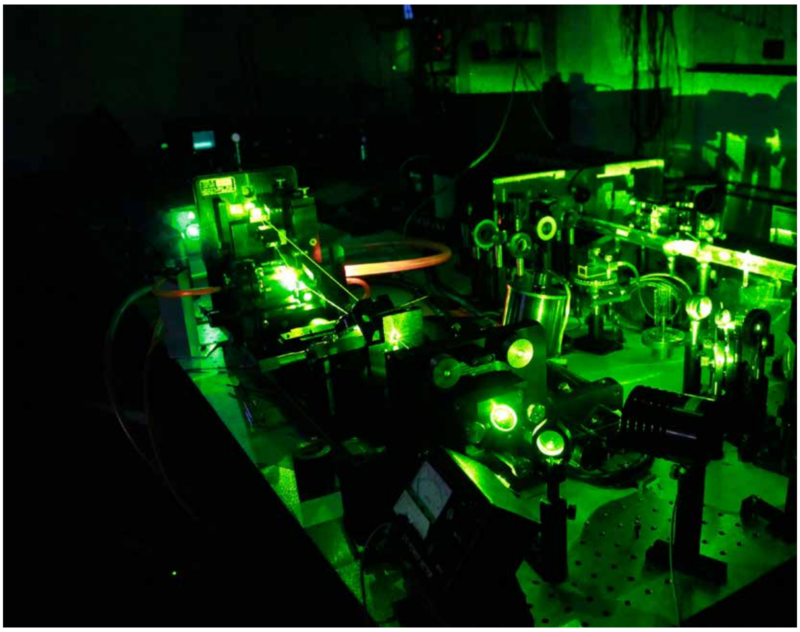
Globally, there is a clear sense of urgency regarding quantum technologies. Quantum technologies are enabling technologies, and it is extremely important to invest early on. The push needs to come before the first large-scale applications are clearly identified, otherwise we run the risk of getting left behind and losing a market that our strong starting point could justify. The worst-case scenario is that we forego the opportunity and will have to rely on imported quantum technologies as this becomes an industry standard in coming decades, leaving us with little know-how on the technical side as we are outcompeted by companies based in other countries.

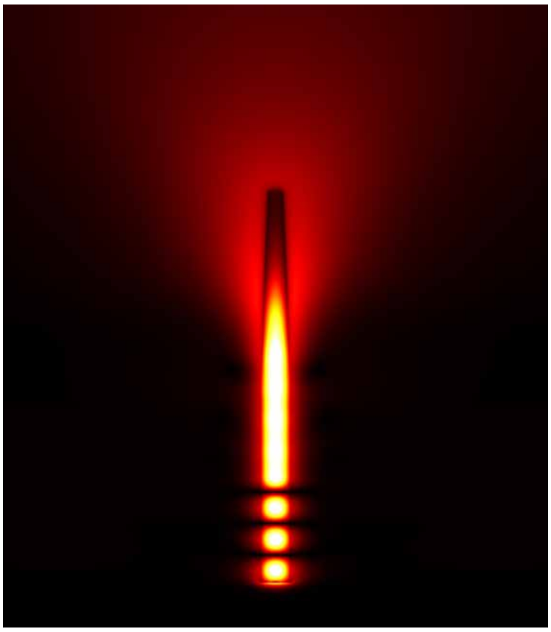
Today, we already have a strong presence of commercial players in quantum technology in Denmark, including IBM, KPMG, and Microsoft. We also have a fertile breeding ground for quantum technology ventures at the edge of academia and industry. However, we are still missing a very active start-up environment, and it is of utmost importance to allocate the resources at this relatively early stage to commercialize the inventions and know-how that Danish research environments continually generate.

We need to address applied research, innovation, business development, and private-public partnerships to ensure that Denmark will leverage its strong research position in a time of burgeoning interest in quantum technologies. The Danish Quantum Agenda outlines a path for how all these factors can be developed. It is important to be proactive and act early, we need to be on-board from the beginning to ensure a full value chain, from basic principles and multi-disciplinary research pursuits to large-scale applications in industry and government. Quantum technology has the potential to become a new commercial success for Denmark as a country if we invest at the right levels and at the right time.









2.0
VISION FOR A DANISH EFFORT ON QUANTUM TECHNOLOGIES

It is our vision, that Danish companies and public organisations can be among the first in the world to take advantage of the possibilities offered by second-generation quantum technologies. Denmark already holds a leading global position in digitalisation. Early adoption of advanced quantum technologies will be a natural evolution of our present position and contribute to creation of growth and wealth.

As Denmark already has a world-class public health care system and a strong industry within life sciences and med-tech, these sectors will most likely be some of the first to take advantage of the new possibilities. It may be in such diverse fields as improved quality of MRI scanners enabled by better sensors, increased cyber security to protect sensitive health data by utilizing quantum communications, and accelerated drug discovery using quantum simulators and quantum computers. Quantum technologies will also help resolve key challenges related to climate change, e.g., optimising logistics to save energy and time, and optimising complex power grids with contributions from renewable energy sources.

To realise this vision will require a concerted effort between industry, public enterprises, and researchers supported by public and private foundations. Based on the strong heritage of Niels Bohr, Danish research holds a world-leading position in basic research in quantum mechanics. We must act now to transform this position into innovation and commercial results. If we wait too long, Denmark runs the risk of falling behind and being reduced to a supplier of brainpower to other nations. The Danish Quantum Community proposes a three-step process for making Denmark a frontrunner in the second quantum revolution.

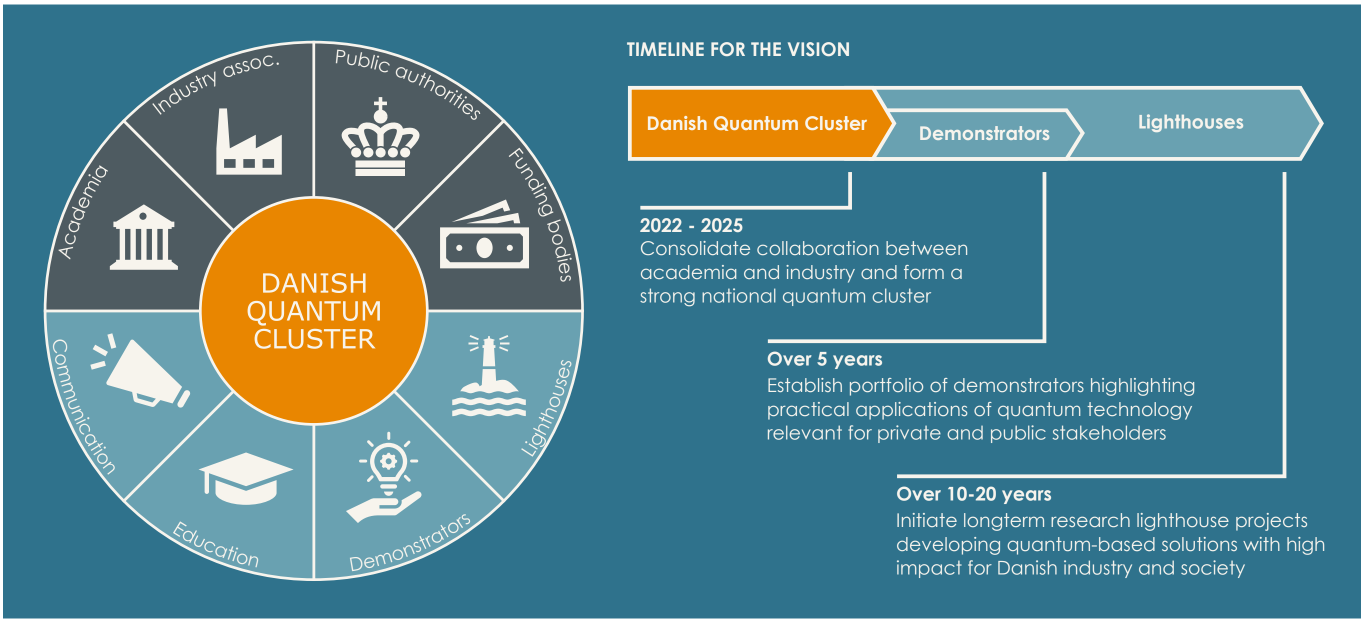


Figure 3: The vision for converting Danish positions of strength within quantum research into innovation by means of demonstrator projects tailored to investigate quantum technology use cases in Danish companies and public institutions.

1ST STEP

As a first step, the collaboration between academia and industry should be stimulated further to establish a Danish Quantum Cluster. The cluster will serve as a national point of contact and coordination, and actively work to strengthen the collaboration between industry and academia, build a quantum ecosystem, and create quantum awareness in society. The cluster will also maintain relations with similar organisations internationally, e.g., the Dutch network Quantum Delta NL and the European Quantum Industry Consortium. In 3-4 years, the cluster should be strong enough to become eligible for public cluster support.

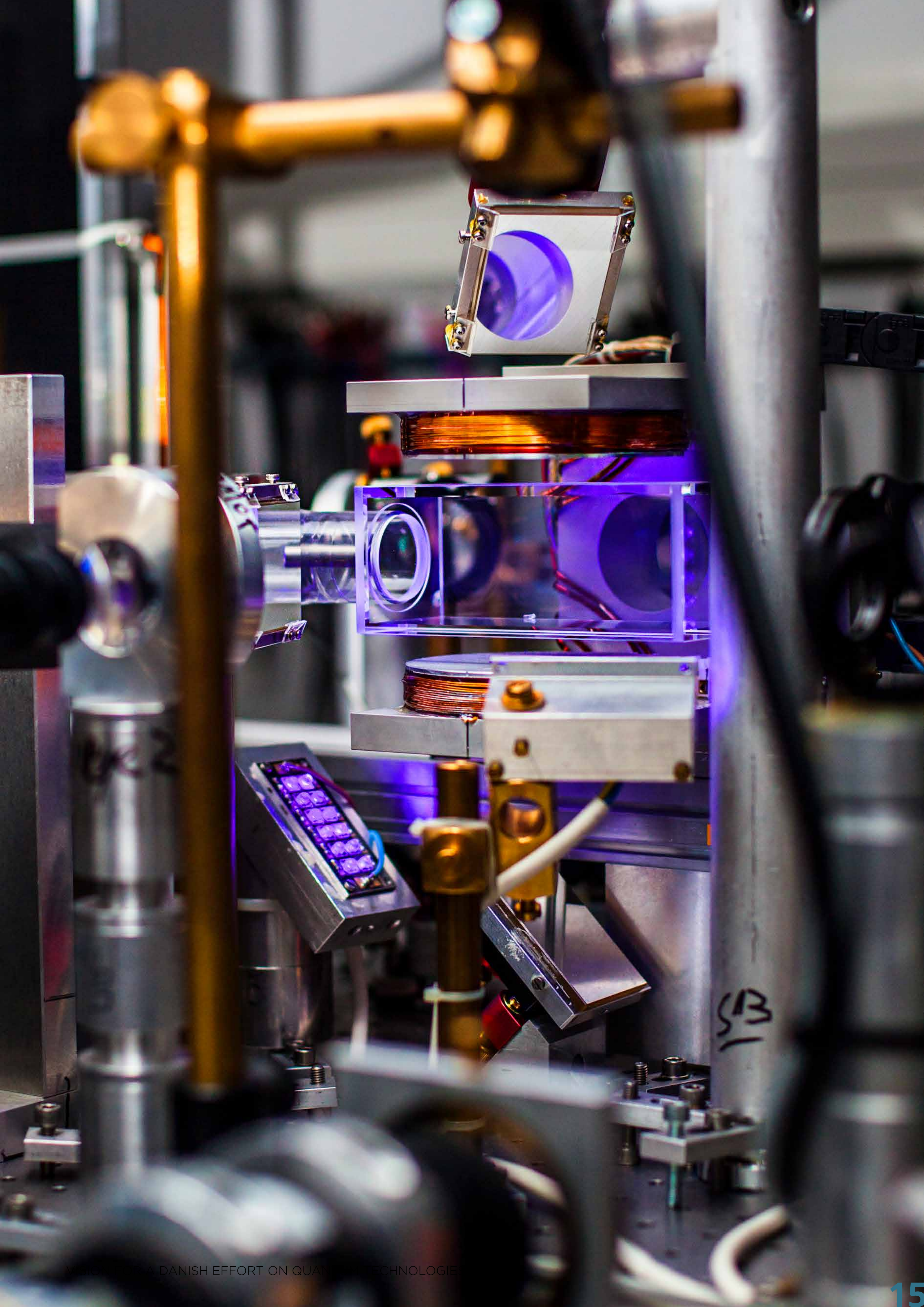
2ND STEP

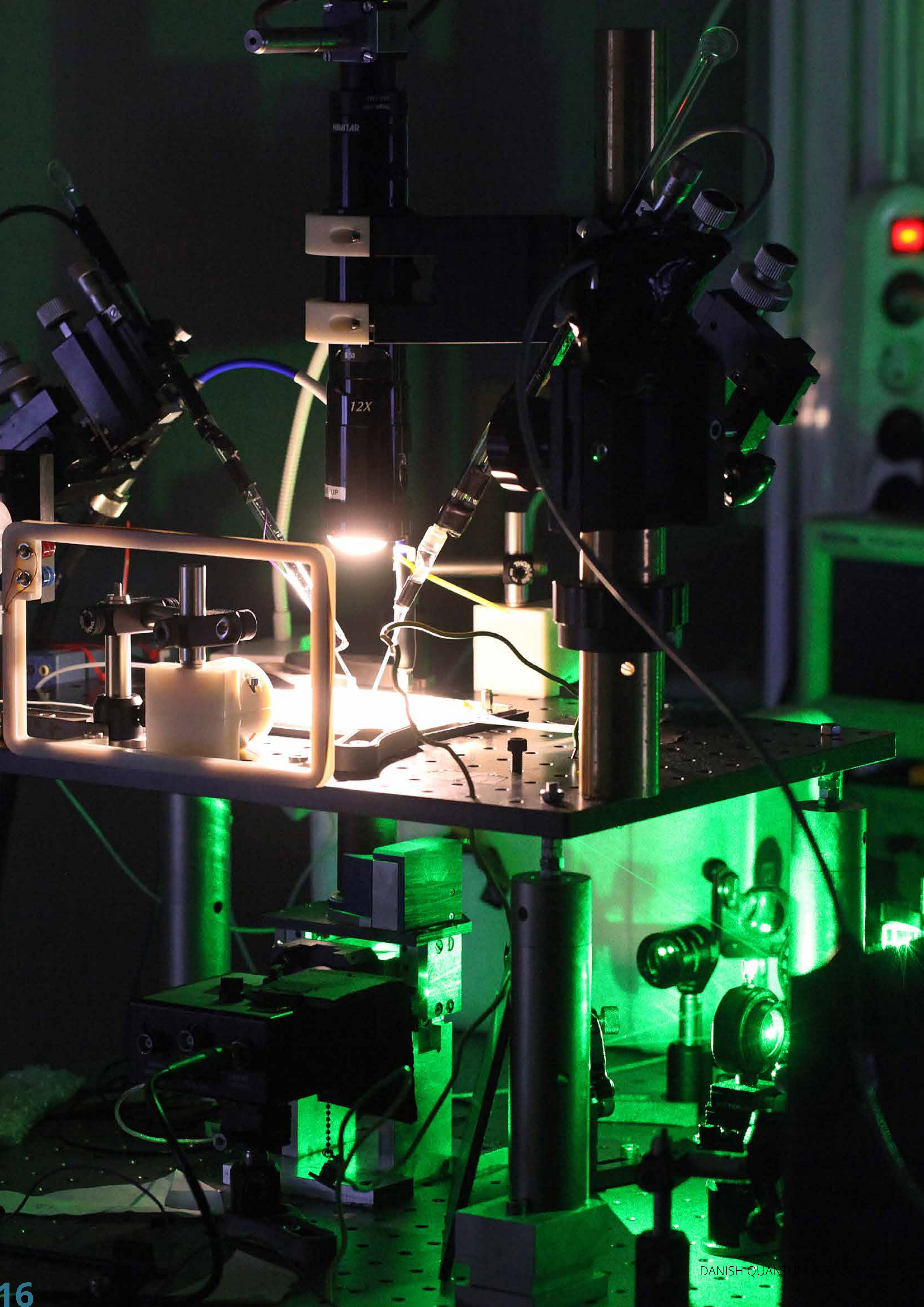
The second step will be to establish a portfolio of so-called demonstrator projects, selected to highlight practical use of quantum technologies relevant to Danish private and public organisations. The quantum cluster will help identify and match relevant end-users with Danish research teams in consortia that formulate the demo-projects and seek funding for them individually. It is envisioned that Danish public and private foundations will participate in the funding.

Executing demonstrator projects across the four main quantum technology areas: sensing, communications, simulations, and computing, will increase the awareness of the potential of quantum technologies in a Danish context and accelerate the adoption of quantum-based innovations in the participating companies. The end goal is to create sufficient awareness and know-how in Danish society to ensure that Denmark will take full advantage of the economic and societal potential offered by the emerging quantum technologies.

3RD STEP

The third step will be the initiation of a handful of ambitious, long-term, cross-functional 'lighthouse' research projects aiming at developing quantum-based solutions that will be relevant for Danish industry and society in 10 – 20 years. Examples could be an optical quantum computer with algorithms and software targeting applications in life sciences, or a quantum simulator enabling the development of an energy-efficient carbon capture process.

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3.0 QUANTUM TECHNOLOGIES SUPPORTING DANISH GROWTH AND JOB CREATION

In this chapter, the main quantum technology areas are addressed one by one. Recent developments and examples of active or suggestive use cases, both nationally and internationally, are mentioned, and the anticipated relevance to Danish industry and society is pointed out.

3.1 Quantum Sensors

Sensors are increasingly important resources in all sectors of society. They are vital sources of information e.g., for smart home technology and IoT, for autonomous vehicles, for optimization and analysis in agricultural and industrial production, for surveillance in security and defence, and for analysis and diagnostics in healthcare. The common theme for all the applications is getting the information fast enough and with sufficient detail and precision, preferably from a sensor with low size, weight, and power consumption. Consequently, there is an increasing demand for miniature, high-speed, and ultra-sensitive sensors.

Quantum sensors exploit quantum physics to obtain sensitivity to specific physical properties beyond the limitations of classical technologies e.g., electric or magnetic fields, forces, pressure, etc.

Danish research is at the very forefront of several quantum sensing technologies including both atom and ion-based systems, solid state platforms like defect centres in diamond, and the generation and application of squeezed light. Quantum sensors are among the most mature quantum technologies and those closest to market, and Denmark thus has an opportunity to capitalise on previous investments into fundamental research. Being at the forefront of sensors development will provide Danish businesses an edge over their competitors and will open new markets.

Danish companies have a strong history of developing sensing technologies for applications in a broad range of sectors, e.g. Ambu (medical monitoring and diagnostics); Brüel & Kjær (sound and vibration); Dantec (fluid mechanics/combustion/spray & particle); FOSS (food analysis); GN Resound, Oticon, and Widex (hearing aids); Radiometer (medical analysis); Weibel and TERMA (defence and space). Building on a strong foundation in conventional sensing technologies would provide optimal conditions for take-up and commercialization of quantum sensors either in the form of entirely new disruptive technologies or integrated into hybrid devices. There is thus a strong incentive for a strategic effort to drive the technology transfer.

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3.1 USE CASES FOR QUANTUM SENSORS

CASE 1: Medical monitoring and diagnostics

Atomic gas sensors and sensors based on nitrogen-vacancy (NV) centres in diamond enable measurements of magnetic fields with extremely high sensitivity and resolution, respectively. Both technologies operate at room temperature providing a significant practical advantage over superconducting SQUID sensors.

One practical example already being studied in cooperation with Hvidovre Hospital is the enhancement of image quality of existing MRI-scanners based on monitoring of the magnetic field in the scanner during operation. By compensating for variations in the magnetic field during a scan, the image quality may be improved.

CASE 2: Quantum gravimeter

The French company MuQuans has developed a gravimeter capable of mapping underground features e.g., detecting underground cavities under roads or at construction sites. Scanning the underground conditions before starting major construction projects could provide significant cost savings and avoid delays.

3.2 Quantum Communications

Denmark is one of the highest-ranking countries in the world when it comes to digitalization, the public sector in particular. Danish society greatly benefits from that and as previously pointed out by Invest in Denmark, this makes the country a hotspot for ICT activities and developments. This is a window of opportunity for innovation that should be extended into the realm of quantum communication technologies.

The profound digitalization of society comes with remarkably high demands on data security. Denmark has already experienced the consequences of cyber security breaches several times in recent years. Not only should privacy be guaranteed for data transmitted right now, but in many cases confidentiality must also be safeguarded for many years into the future. Securing against "harvest now, decrypt later"-attacks requires an ambitious and long-term encryption strategy as one should not only account for algorithmic advances and the growth in conventional computational power, doubling every 18 months, but also prepare for an entirely new computational era approaching with the development of full-scale quantum computers.

Quantum key distribution (QKD) is an emerging quantum technology offering continued data security, even against quantum computer attacks, rooted in the laws of quantum physics rather than assumptions about mathematical hardness. Danish research is particularly strong in the field of QKD and related technologies, such as quantum random number generators (QRNG), and the maturity of those is signified by several current investments from the Innovation Fund Denmark into QKD research and development projects. However, to take advantage of our position and form a Danish industry around QKD, that significantly taps into the foreseen billion USD global market for quantum communication technologies, long-term strategic investment is required.

3.3 Quantum Simulators

While a large-scale universal information processor, capable of executing arbitrary quantum algorithms, is the ultimate goal for quantum computing, a compelling near-term approach for entering the regime where the potential of quantum computing can be exploited on an intermediate scale is the development of quantum simulators. Quantum simulators are controlled model systems tailored to mimic and simulate exactly the dynamics of specific problems that are intractable with current conventional computers. In other words, they are small-scale quantum computers capable of solving just one particular or a limited class of problems. Quantum simulators can be implemented on a variety of different physical platforms, such as trapped cold atoms, trapped ions, and photonic circuits. A broad range of applications of quantum simulators are foreseen e.g., in chemistry for simulation of reactions and electronic structures of molecules; in biotechnology for drug discovery, molecular docking, and potentially even protein folding; and in condensed matter physics for identification of ground states in the design of novel materials.

Recently, the Novo Nordisk Foundation has made a significant push for the development of quantum simulators, for tackling computationally hard problems in biotechnology, by awarding two new research centres addressing this challenge.

The first commercially available quantum simulator was introduced by the Canadian company D-Wave in 2011. D-Wave's products are based on the principle of quantum annealing and a technological implementation exploiting Josephson junctions. Quantum annealers (or adiabatic quantum computers) are not traditional gate-based quantum computers. Annealers can solve optimization problems, and they do not require the same extent of error correction as NISQ-devices. After the introduction of 'D-Wave One' in 2011, more versions followed. D-Wave Two and 2X in 2013 and 2015, respectively, and most recently the D-Wave 2000Q in 2017 and the Advantage platform in 2020. Most recently, D-Wave has announced that they offer access to their annealer through the cloud.

3.2 USE CASES FOR QUANTUM COMMUNICATIONS

CASE 1: QKD

QKD is one of the most mature quantum technologies with several systems already in use worldwide. Two recent examples of field-testing of commercial grade QKD-system are the Korean Electrical Power Research Institute, KEPCO, using QKD-products from ID Quantique for protection of the command-and-control system for the Korean power grid (November 2020), and the UK telecoms operator BT deploying QKD-systems from Toshiba for distributions of encryption keys to be used in classical encryption devises (October 2020).

Two Danish innovation projects funded by Innovation Fund Denmark targeting the development of QKD systems, are currently in progress. This is a concerted effort between the Niels Bohr Institute, Technical University of Denmark, Aarhus University, and Danish businesses such as Cryptomathic, Sparrow Quantum, Zybersafe, Danske Bank, and Energinet. Technology demonstrations including field tests are planned in the coming 2-3 years. Together, the ultra-secure communication technologies being developed cover both long-range links, potentially satellite-based, and fast short-range links suitable for metropolitan networks and data centre applications. Working towards compatibility with conventional optical fibre components and existing telecom infrastructures, the technologies represent a strong case for establishing a Danish QKD industry. Towards that goal, Danish research teams actively participate in the large-scale industry-heavy European project OpenQKD under H2020.

CASE 2: QRNG

Random numbers are a key component of present and emerging QKD cryptosystems as well is for a wealth of conventional computational applications.

Commercially available quantum random number generators (QRNGs) are available from several sources e.g., the Swiss company, ID Quantique. Several use cases have been reported including lottery draws by Swiss Lotterie Romande (2016), and online gaming by Ukrainian PokerMatch (2018).

The first mass deployment of a QRNG for communications is the use of a QRNG-chip developed by ID Quantique in Samsung's recent Galaxy A Quantum smartphone announced in May 2020.

Danish researchers are at the very forefront of developing ultra-fast QRNG technology, and spinouts serving this part of the market are expected to be established within the next couple of years.

3.3 USE CASES FOR QUANTUM SIMULATORS

CASE 1: Traffic optimization

Managing traffic in big cities is a computationally complex task since it must consider many different variables and possibilities. Quantum annealers are a good fit for these problems. In November 2019, Volkswagen and D-Wave conducted a pilot-project in Lisbon where the routes of 9 busses were optimized in real time using a D-Wave annealer, taking actual traffic conditions into account.

CASE 2: Optimal positioning of cell tower sites for mobile network

Telecom Italia Mobile, TIM, collaborated with D-Wave on developing an algorithm for D-Wave's quantum annealer that was used to plan 4.5G and 5G network parameters. According to TIM, this work resulted in performance 10 times faster than traditional optimization methods. https://www.insidequantumtechnology.com/news-archive/telecom-italia-teams-with-d-wave-for-first-telecommunications-operation-in-europe-that-integrates-quantum-computing-teams/

3.4 Quantum Computers

Quantum computing has received a lot of attention since Shor and Grover published their algorithms for prime factorisation and database search in 1994 and 1996, respectively, showing the ability to provide exponential (Shor) and quadratic (Grover) speed-up over traditional algorithms solving the same problem. The vision that a quantum computer will eventually be able to solve extremely complex problems in a short time has created a lot of hype. In recent years, it has become clear that the path towards a general-purpose quantum computer may be quite long i.e., take several decades. However, already today, so-called NISQ-devices with around 100 physical qubits are available and performance is improving every year. Simple quantum algorithms may already be implemented on NISQ-devices and will most likely be able to demonstrate so-called quantum advantage i.e., the ability to solve computational problems significantly faster than traditional computers in the next few years.

To date, no winning quantum computing technology has emerged. Several so-called qubit-technologies have been under development for the last 5-10 years, see fig. 4 below. Most of the qubit-technologies shown in the figure are operating at ultra-low temperatures close to 0 K, the only exception being the ion-trap qubits, which may operate at room temperature. Recently, optical quantum computing concepts have also emerged and are now being pursued by many research institutions and two VC-funded start-ups: Xanadu in Toronto and PsiQuantum in Silicon Valley. Most parts of an optical quantum computer will be able to op-erate at room temperature, however, single photon sources and detectors will most likely require cryogenic cooling.

Today's NISQ computers have limited functionality due to the sparse number of qubits, the relatively short lifetime of qubits, and the high error rates. This means that a computation must be finalized within a limited number of computing cycles put-ting severe restrictions on quantum algorithms for NISQ. Sev-eral techniques are being pursued to improve the performance of NISQ including quantum error correction, where one logical qubit is obtained from several physical qubits. However, no sim-ple solutions are in sight that will allow the NISQ to scale to millions of qubits. For that reason, many researchers believe that a large, fault-tolerant, gate-based quantum computer may still be decades away.

The first quantum computers are expected to act as accelerators to large-scale classical computers, most likely high-performance computers or data centers. Indeed, the first emerging quantum computers are used as accelerators. In such a system, the quantum computer is connected to a host where an elaborate quantum software stack is executed. The software allows for high-level representations of quantum algorithms to be translated into low-level physics-oriented actions that interact with the physically implemented qubits. Similarly, to act as an accelerator, new programming abstractions are required to allow programmers to update their existing computing software to benefit from the quantum computer. A dynamic environment is developed, where the classical computer is used where it has an advantage over the quantum computer, and the quantum computer is used where it has an advantage over the classical computer. The host software, including the quantum software stack, is an active research and development field with significant Danish efforts.

Quantum computers increase rapidly in scale. Most recently, two companies have announced that they see a path to scale to "millions of qubits". In September 2020, IBM announced its plans for an 1121 physical qubit device (Condor) delivering 10 – 50 logical qubits by 2023. IBM also indicated a roadmap to reach 1M+ physical qubits at some unspecified date. In November 2020, PsiQuantum announced that they are developing a fault-toler-ant photonic quantum computer with 1M physical qubits using semiconductor manufacturing technologies, however, very few details were revealed.

Microsoft initiated the collaboration with NBI on topological qubits in 2012 and in 2018 decided to place the company's quantum materials lab in Lyngby. Since then, Denmark has participated in the development of core components for quantum computers.

QUBIT TECHNO-LOGIES	SUPER-CONDUCTORS	ION TRAPS	TOPOLOGICAL SUPER-CONDUCTORS	SEMICONDUC-TOR SPINS	PHOTONICS
Current status	Most mature Basis of most commercial systems	Medium-sized systems have been implement-ed	Resource state reported Major investment First qubit yet to be realized	Two qubit algorithms implemented	Demonstrations in research and commercial systems
Strengths	Engineering maturity	Stability Qubit connectiv-ity Gate fidelity	Predicted stabili-ty and scalability	Stability	Scalability Operation at ambient conditions
Challenges	Scalability Qubit connec-tivity	Gate operation times Horizontal scaling beyond one trap	Proof of concept for functioning qubits Finding ideal material	Uniformity of qubits due to materials issues	Optical loss Inefficient qubit generation
Example commercial players	IBM, Intel, Goog-le, Rigetti, IQM	IonQ, Honeywell, Alpine QT	Microsoft, Nokia Bell Labs	Intel	PsiQuantum, Xanadu, QuiX

Figure 4: Comparison af various quantum computing platforms
Source: https://en.acatech.de/publication/the-innovation-potential-of-second-generation-quantum-technologies/

3.4 USE CASES FOR QUANTUM COMPUTERS

CASE 1: Next-generation lithium battery design

Daimler AG, Daimler-Benz's parent company, and IBM collaborate on the use of IBM's NISQ computers to develop next generation lithium-sulphur batteries for electrical vehicles.

CASE 2: Carbon capture, utilization and storage

Cambridge Quantum Computing and Total have entered a multi-year collaboration to develop quantum algorithms and quantum computing solutions for carbon capture.

4.0 ECONOMIC IMPACT

Quantum technologies are expected to have significant impact on many business sectors e.g.:

- Transportation/logistics – improved optimization of traffic routing and cargo loading; carbon dioxide reduction
- Communications – improved cyber security, initially via QKD and later on in a quantum internet
- Finance/fintech – precise time stamping, portfolio optimization, risk assessment, fraud detection (improved ML/AI)
- Pharma – speed up of drug discovery and clinical testing
- Energy – optimization of power grid efficiency
- Ingredients – computerized synthesis of new enzymes/proteins rather than trial-and-error
- Sensing – quantum sensors provide higher sensitivity and dynamic range than traditional sensors

Many of the Danish commercial strongholds in these sectors were founded more than 50 years ago. During the past 50 years, we have only witnessed the rise of a single new large Danish industrial position of strength.

Denmark has well-known positions of strength in transportation/logistics, pharma, wind energy, ingredients, and sensing. These sectors make up a significant part of the Danish economy, see below. Many of the Danish commercial strongholds in these sectors were founded more than 50 years ago. During the past 50 years, we have only witnessed the rise of a single new large Danish industrial position of strength, namely the **Danish wind energy sector** today having ~ 20,000 employees and a total revenue of ~ 120 BDKK. *Source: https://finans.dk/analyse/ECE11485543/bran-cheanalyse-vindmoelleindustrien-2019/*

DATA FOR TOP-10 COMPANIES FROM EACH SECTOR

Sector	Revenue 2018 [BDKK]	Employees 2018 [× 1000]	Largest companies in sector
Transportation	404	145	Mærsk, DSV
Pharma	158	57	Novo Nordisk, Lundbeck, Leo
Wind energy	117	16	Vestas, Siemens Gamesa
Ingredients	45	13	Novozymes, Chr. Hansen
Sensing	32	24	Oticon, Widex
Total	**756**	**255**	

Source: https://finans.dk/analyse/ and company annual reports.

As an example, we can take a closer look at Danish companies with sensors-based products.

TOP-10 DANISH SENSOR COMPANIES			
Company	Revenue 2018 [MDKK]	Employees 2018	Main activity
B&K Medical	406	123	Ultrasound imaging
Brüel & Kjær Sound and VIbration	821	439	Sound and vibration analysis
Dantec Dynamics	155	100	Flow measurements
Foss	2,150	1,522	Food analytics
GN Resound	3,587	605	Hearing aids
Oticon (Demant A/S)	13,937	14,250	Hearing aids
Radiometer Medical	3,793	1,063	Medical analytics
Terma	1.917	1,521	Defence systems/radar
Weibel Scientific	300	123	Doppler radar
Widex (T&W medical A/S)	4,466	4,217	Hearing aids
Total	**31,532**	**23,968**	

Source: overview of top-10 Danish companies from each sector as published at finans.dk and in annual reports.

Quantum technologies have the potential to positively impact several business sectors of importance to the Danish economy, representing a total revenue above 750 BDKK and employing more than 250,000 people. For reference, the total number of employees in the industrial sector is 374,000 (Q2/2020), source: Statistics Denmark. With the current Danish position of strength in quantum research, it will be possible to improve our current strongholds in the above sectors using quantum technologies and to create a number of Danish quantum providers as well, if we efficiently transform the research into innovation.

Quantum technologies have the potential to positively impact several business sectors of importance to the Danish economy, representing a total revenue above 750 BDKK and employing more than 250.000 people.

A central player in the defence and security sector is the industry association CenSec representing more than 130 SME members. In 2020, CenSec was granted government funding for establishing a new national cluster for defence, space, and security technologies. The association has already expressed clear interest in quantum technologies and mobilizing its members to engage in this new frontier for the sector, and the formation of a new national cluster is an excellent opportunity to promoting R&D activities in quantum sensing and communication.

4.1 Market

The players in the market for quantum technologies may be divided into two main groups: quantum providers and quantum users. Quantum providers provide quantum products (sensors, computers, software as well as classical supporting technologies) or services (cloud access to quantum computers, quantum communications) to the quantum users (banks, pharma companies, defence).

Today, the 'market' consists of three main contributions:

1 Investments into R&D at quantum providers – by public and private funds and/or VCs (large part)
2 Revenue from sale of products and/or services from quantum providers to quantum users (small)
3 Investments into applied research leading to increased productivity for quantum users (small)

As the markets are still very immature, the uncertainty even for near term market estimates is significant. Some both near-term and long-term market estimates are shown in figure 5-7.

An analysis of the impact on Danish economy in e.g. 20 years is beyond the scope of this report. Instead, two studies from The Netherlands and Australia respectively, are presented, see below.

SUMMARY OF TEN-YEAR FORECASTS OF QUANTUM SENSOR MARKETS, BY TYPE OF SENSOR ($ MILLIONS)

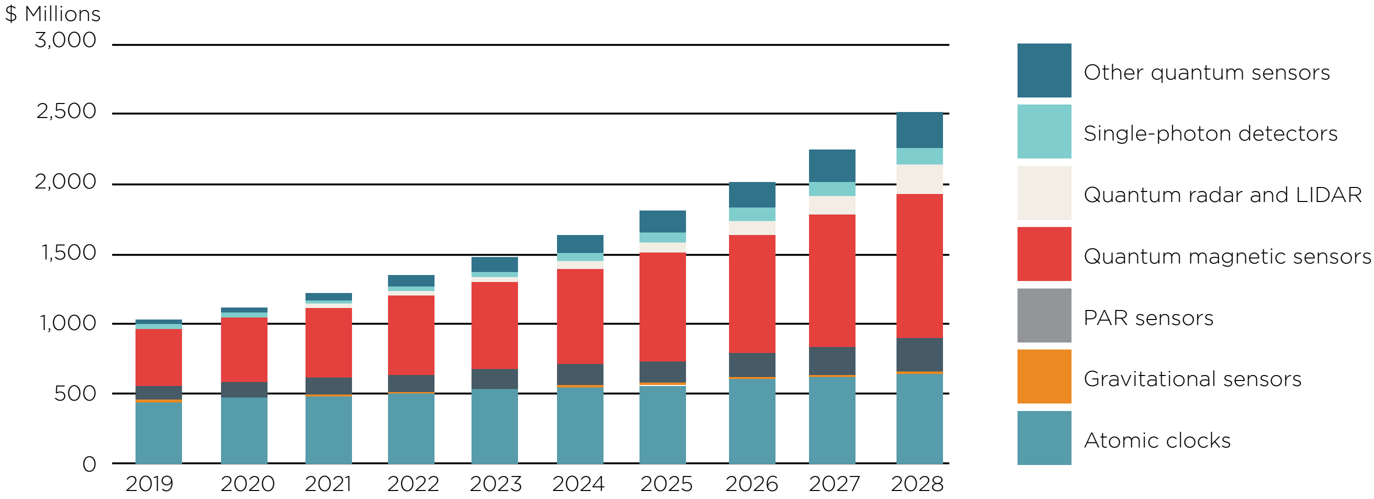


Figure 5: Global sensor market forecast by IQT, 2019, revenue of 1.5 BUSD in 2023 growing to 2.5 BUSD in 2028. Quantum magnetic sensors, PAR sensors and atomic clocks are commercially available today.

Source: Inside Quantum Technology, 2019.

QUANTUM SAFE PRODUCTS MARKET ($ MILLIONS)

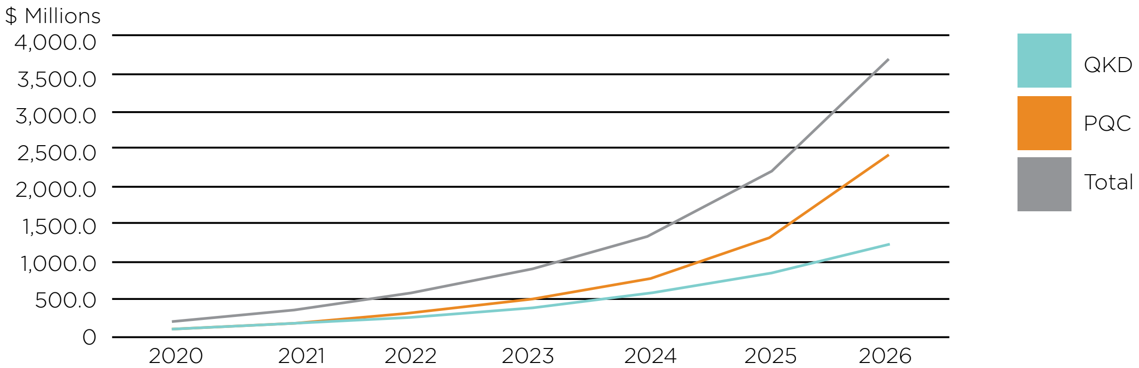


Figure 6: Market estimate for QKD and post-quantum-cryptography, PQC. Currency is US$. IQT October 2020.

Source: Inside Quantum Technology, 2020

TOTAL QUANTOM COMPUTER REVENUE ($ MILLIONS)

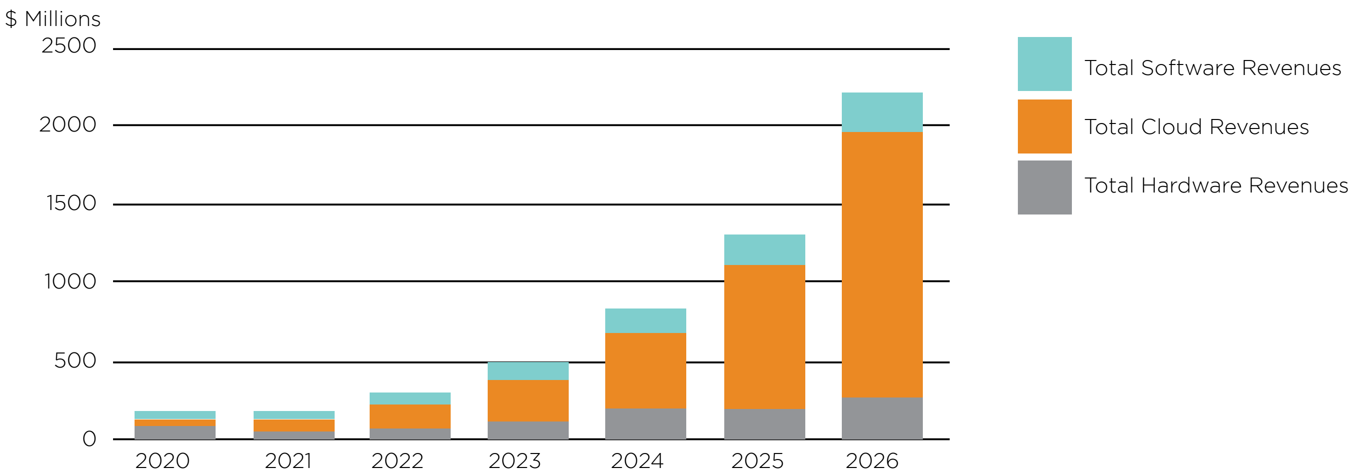


Figure 7: Market for quantum computing hardware, software, and cloud services. Estimate by IQT, October 2020

Source: Inside Quantum Technology, 2020

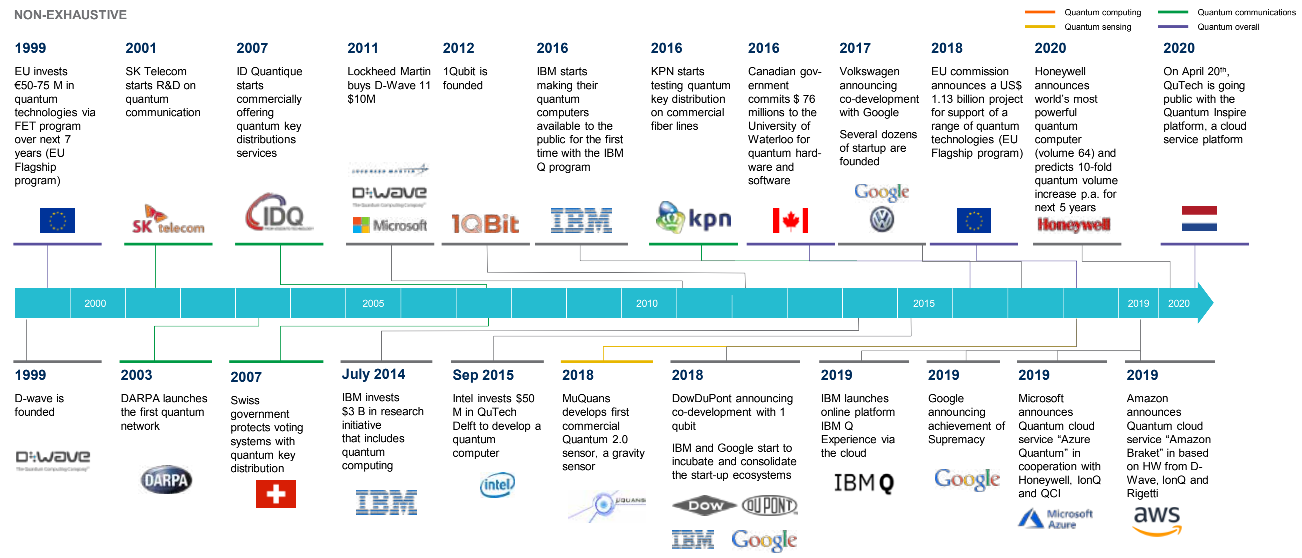


Figure 8: Investments in Quantum has increased significantly during the last 5 years. Recently cloud providers such as Microsoft Azure and AWS also started tapping into the quantum computing market.

Source Economic Impact of Quantum in The Netherlands, Quantum Delta NL, 2020:

A Dutch study from May 2020 gives the following long-term outlook for the global market by 2040: *https://quantumdelta.nl/TUQ/wp-content/uploads/2020/03/20200518-1400-QuTech_Economic-Impact-of-Quantum_vFinal_COMMENT_JR.pdf*

- **Quantum sensing** underway with many new applications expected in next decade, driving a global quantum sensing market of 1-5 BEUR by 2040
- **Quantum communications' global potential estimated to reach 1-6 BEUR by 2040,** subject to broad adoption of post quantum cryptography and QKD in 5-10 years. QKD is likely to become the first widely used quantum technology. Quantum internet may become relevant towards 2035 / 2040.
- **Quantum computing has highest impact opportunities (globally 8-80 BEUR, 2040)**, yet foundational breakthroughs are still needed, thus, it carries highest uncertainty; for example, there is not yet a clearly winning qubit concept; large-scale applications beyond 15-20 years

By 2040 the study estimates quantum technologies can support **the creation of 15-30,000 new jobs and a revenue of 1.5 – 3.0 BEUR in The Netherlands.**

An Australian study, also from May 2020, gives a more optimistic outlook for the same market: *https://www.csiro.au/en/Showcase/quantum*

- **Global quantum sensing market of ~ 12 BEUR by 2040** (assuming 3% of total sensing market).
- **Global quantum communications market of ~ 10 BEUR in 2040** (assuming 2% of total comms mkt.).
- **Global quantum computing market of ~ 30 BEUR in 2040** (assuming 4% of HPC market).

By 2040 the study estimates quantum technologies can support the creation of **16,000 new jobs and a revenue of 2.6 BEUR in Australia.**

4.2 International efforts

Over the last years there has been a significant increase in investments into quantum technologies worldwide. The timeline below illustrates the increased level of activities in recent years.

The global effort for public funding has been boosted as many countries have now recognised the value that will be generated by quantum technology. These countries are now investing to prepare their quantum ecosystems to address this opportunity.

The main public programs and efforts around the world are summarised in figure 9. Additionally, significant investments are made by tech giants such as IBM, Intel, Google, Microsoft, Alibaba and Tencent.

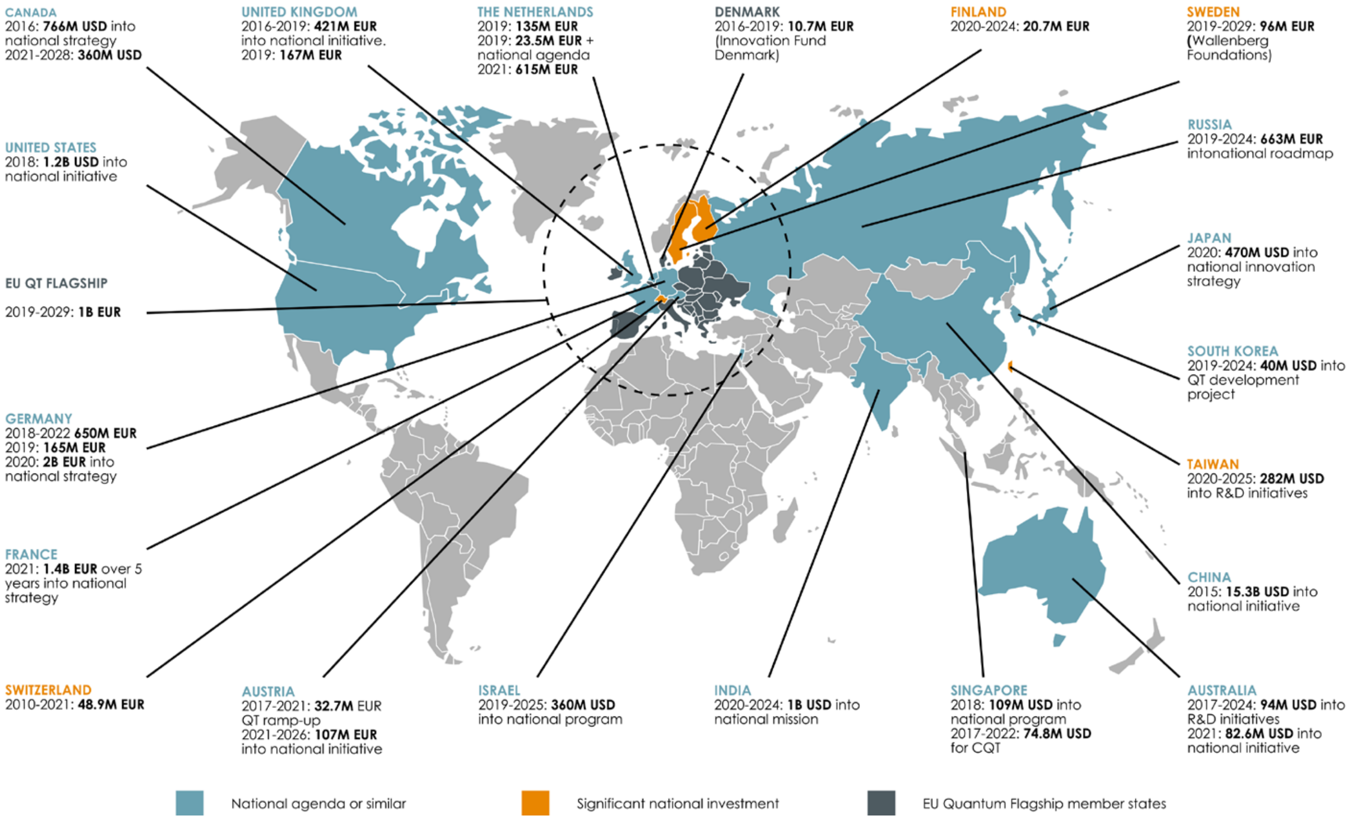


Figure 9: Main publicly funded quantum technology programs and efforts around the world. Global effort to date around 22.5 B USD, not counting the significant investments by private companies such as IBM, Google, Intel, Microsoft, Alibaba, Tencent etc.

4.3 Danish quantum technology providers and potential end-users

Several Danish companies are already actively engaged in quantum technologies and the first Danish start-ups developing quantum hardware and software are up and running

- SiPhotonIC – silicon photonic integrated circuits
- Sparrow Quantum – single photon sources
- QDevil – equipment for quantum research labs
- Molecular Quantum Solutions – quantum algorithms for pharma, biotech and chemistry
- Kvantity – quantum algorithms and software

Several Danish companies are already actively engaged in quantum technologies and the first Danish start-ups developing quantum hardware and software are up and running

All the four start-ups are university spinouts, reflecting the high-tech nature of their business. Initial customers are research groups at universities or large companies.

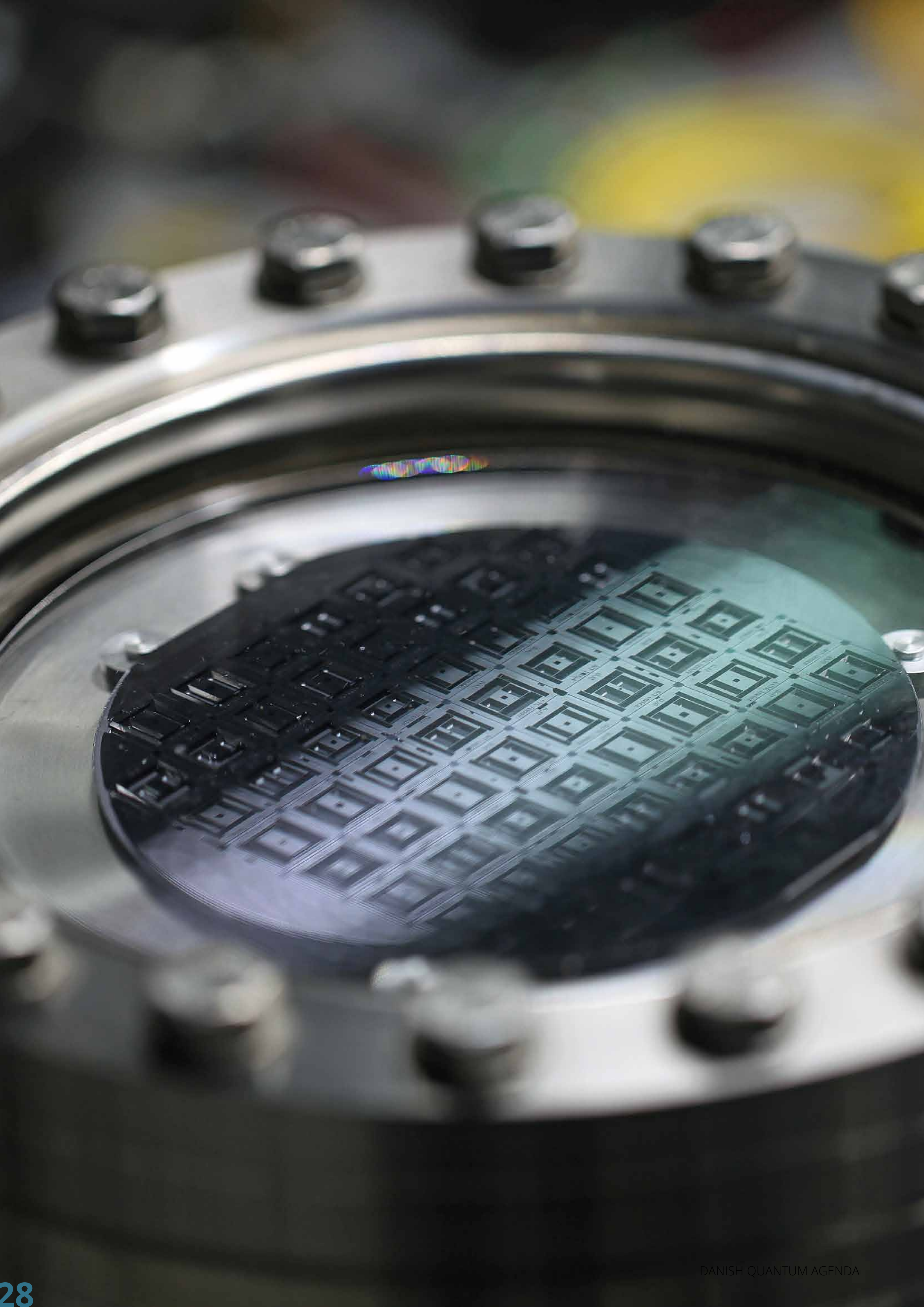
Larger Danish companies engaged in quantum:

- Cryptomathic – key management for quantum cryptography
- DFM – quantum metrology and ultra-stable lasers
- IBM DK – IBM's hub for post quantum cryptography, Nordic hub for quantum computing
- KPMG DK – KPMG's global quantum hub
- Microsoft DK – Quantum Materials Lab, close collaboration with NBI on topological qubits
- NKT Photonics – fibre lasers
- Quantum Wise – simulations software (now part of Synopsis)

Examples of companies who may benefit from using quantum simulation/computing/sensing

- Grundfos – simulations of water flow
- Mærsk/DSV – optimization of logistics (travelling salesman problem)
- Novo Nordisk/Lundbeck/Leo Pharma – drug discovery (protein folding)
- Oticon/GN ReSound/Widex – sensors for hearing aids
- Vestas/Siemens – simulations of air flow
- Defence/government/banks/utilities – increased cybersecurity by means of quantum communications, initially QKD
- FOSS/Radiometer – improved measurement accuracy

To date, only Novo Nordisk has embarked on a quantum readiness programme. Some of the actions proposed in section 5 of this paper is aiming at increasing the 'quantum awareness' among potential end-users.



5.0 PLAN FOR A DANISH EFFORT

5.1 Education

Education is an essential part of driving research and innovation in quantum technologies. Worldwide, increasing awareness of this fact is becoming evident as research teams in academia and industry alike are finding it exceedingly hard to recruit people with proficiency in quantum physics, quantum algorithms, and quantum engineering. In a recent survey by The Quantum Daily, 80% of the respondents reported that it is hard to hire the right people.

If Denmark is to build a vibrant and internationally competitive quantum technology ecosystem a targeted effort on education is required. This action should not only address the education of research specialists but also secure more broadly the formation of a quantum literate workforce through upskilling and retraining. Furthermore, awareness of the technological potential should be increased among decision-makers in industry and public endorsement of the quantum technology agenda should be stimulated.

Educating specialists

To build up and sustain a strong Danish ecosystem, it is of utmost importance that young talents are attracted to education relevant to quantum technology and retained. A recent survey shows that Denmark performs very well on this task, ranking number one in Europe by the number of graduates of quantum relevant studies per inhabitant.

However, maintaining this position will require the universities to develop and offer dedicated programmes in quantum technology of the highest quality. Several international high-ranking universities have already established such programmes and if Denmark does not follow, a loss of talent is to be expected.

Two approaches to the organization of university programmes in quantum technology can be envisioned:

– as a 2-years M.Sc. programme providing a basic education in the four main quantum technology pillars followed by a short specialization, building on top of qualifying B.Sc. degrees in

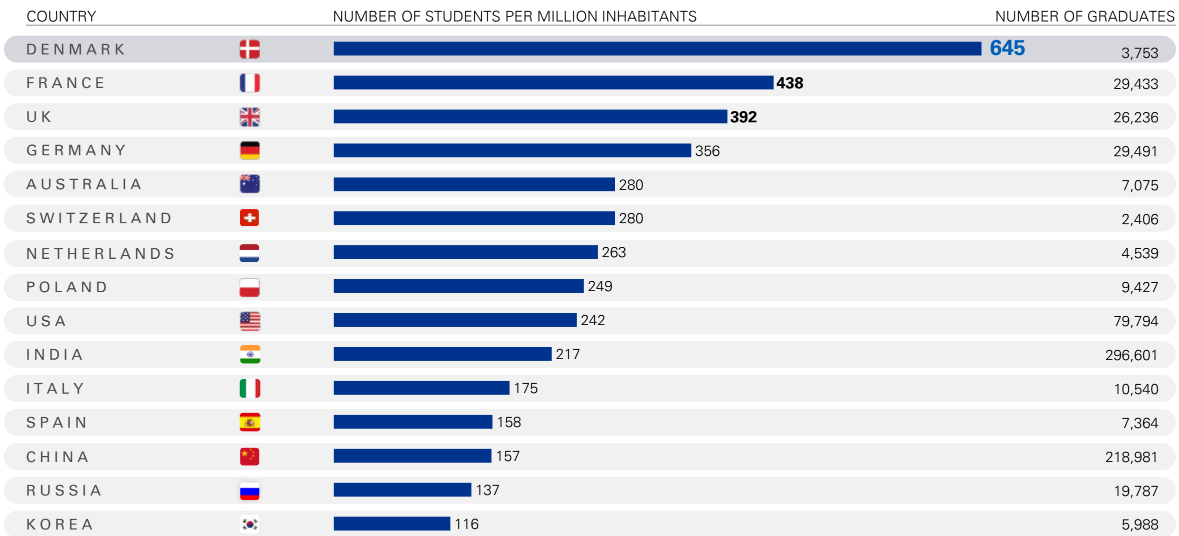


Figure 10: Graduates (master level) in quantum-relevant studies 2017. Courtesy of KPMG and ITB.

physics, engineering, or computer science. This programme is at present being piloted at the universities.

- as a 5-years programme commencing with a 3-years B.Sc. level education, providing a thorough background in all branches of quantum technology, followed by a 2-years M.Sc. specialization. This programme would also provide a pathway for pursuing a Ph.D. degree in quantum science.

To create awareness and gain the public's endorsement of the quantum technology agenda, researchers, journalists, and science communicators must join forces and provide the public with accessible explanations of quantum technologies, objective accounts for their potential and limitations, as well as realistic predictions for how, where, and when they are going to impact society.

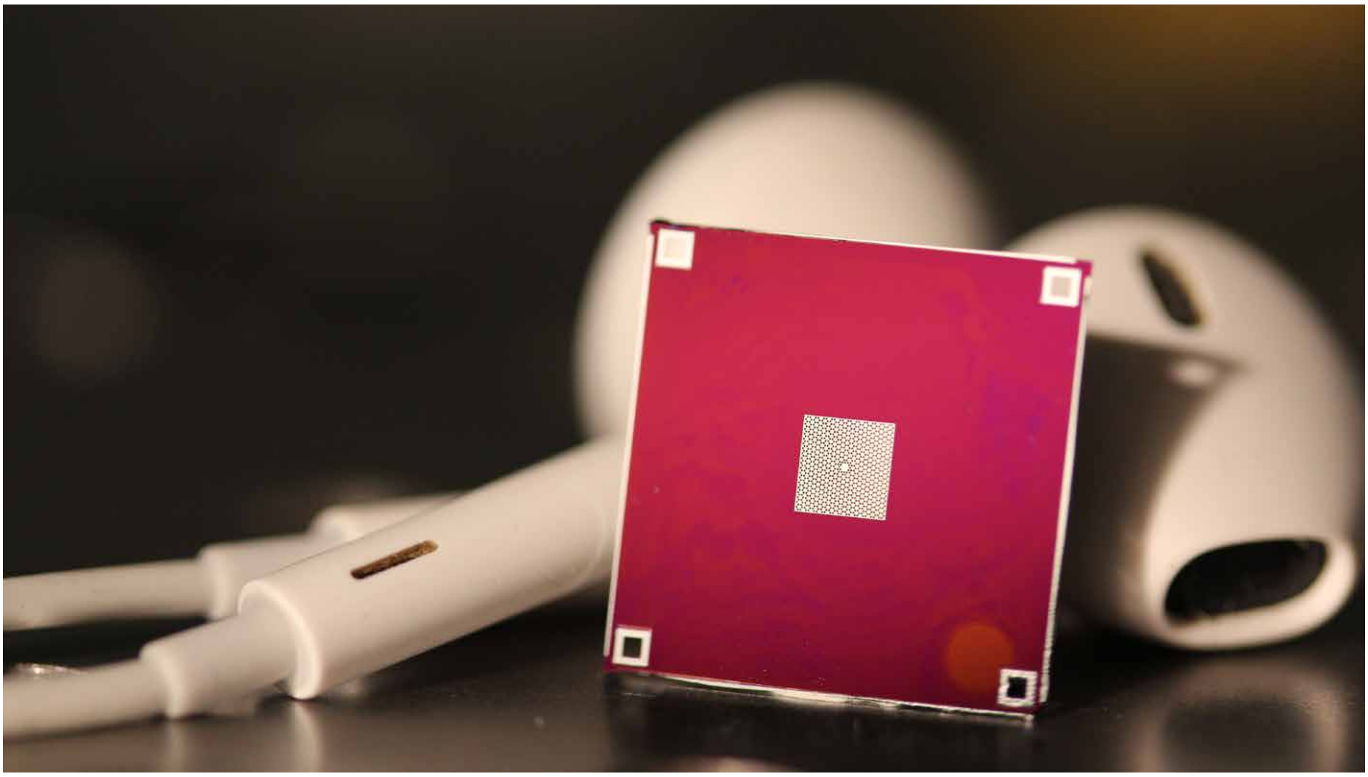
In either case, the technology and innovation aspect of the education should be supported by an internship programme providing students with the opportunity to conduct long- or short-term projects in collaboration with quantum technology companies. Internships could also be with start-up companies participating in a national quantum incubator, giving students hands-on experience with quantum innovation.

Retraining and upskilling

A quantum workforce involves not only highly specialised scientists but also a broad range of engineers and supporting technicians within electronics, optics, cryogenics, mechanics, nanofabrication, programming, etc. Many of those are already part of the current workforce but require supplementary education to best apply their expertise in quantum technology. To this end, retraining and upskilling courses should be established and promoted to companies and industries engaging in quantum technology, both as suppliers and users. An interdisciplinary applications-focused curriculum should be developed that explains quantum mechanics in a more common and accessible language while still providing a sufficient level of details for people to apply the knowledge in practice.

General awareness

Quantum physics is considered a difficult topic by the larger part of the population. To create awareness and gain the public's endorsement of the quantum agenda, researchers, journalists, and science communicators must join forces and provide the public with accessible explanations of quantum technologies, objective accounts for their potential and limitations, as well as realistic



predictions for how, where, and when they are going to impact society. In the long term, when quantum technologies have reached a sufficient level of maturity to provide indisputable benefits by solving relevant problems, they will naturally be adopted by society, just as most of us are happily using computers without worrying about the underlying technology. But in the intermediate phase, a steady flow of information from science to society is required to increase the level of awareness and educate the general population.

5.2 Innovation

Turning basic quantum research into products and/or services takes time and requires significant investments. Basic inventions and proof-of-concepts are often created in the university environment; however, this is only the first step in a long journey towards commercialization.

Strategic research carried out in collaboration between universities and industry leading to industrially meaningful demonstrators, could be a first step in this direction, and an important tool to convince industry about the potential of quantum technologies. Funding for such strategic research will be important to stimulate the growth of a Danish quantum cluster.

A few projects of strategic nature have been supported by Innovation Fund Denmark, mainly in the field of quantum communications. The Novo Nordisk Foundation has also taken a first step into strategic research in the autumn of 2020 by awarding around 110 MDKK to two Danish research groups working on quantum simulations for applications relevant to life sciences. Supporting this process even further, NATO has decided to place its DIANA quantum accelerator in Denmark addressing start-ups within so-called dual-use technologies having applications both in the civil and in the defence sector. Complementing this with a similar set-up for other quantum technologies could be a great step forward in the development of the Danish quantum eco-system.

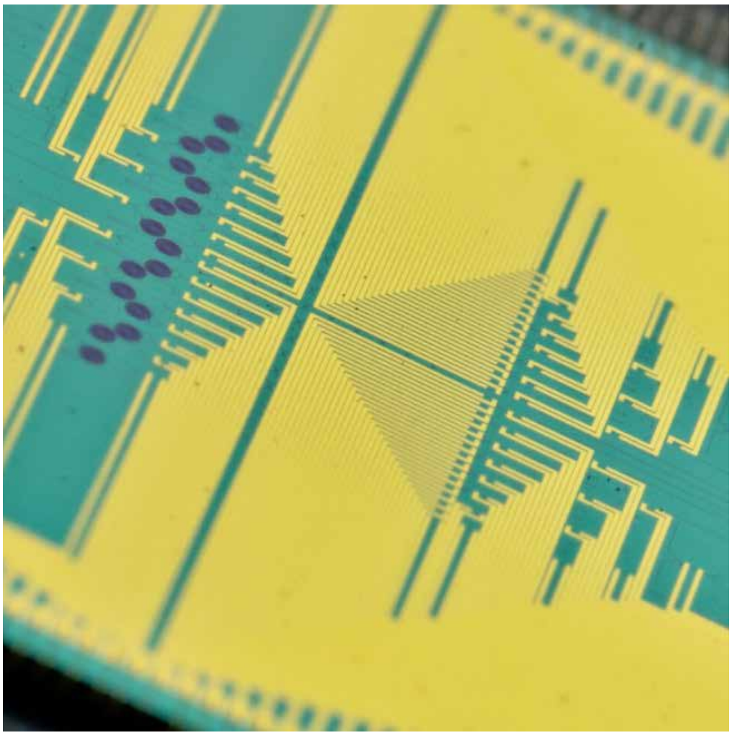
In addition to strategic research and accelerator/incubator facilities, it is necessary to address the long-term funding of quantum start-ups. As quantum technologies may be used to address many of the global challenges it seems natural to consider a public private partnership model, potentially also involving the pension funds.

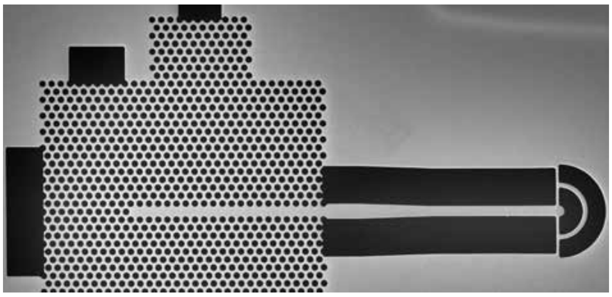
Public procurement may also be used to stimulate quantum innovation. Traditionally, Danish public institutions such as defence, police, hospitals etc. have been reluctant to engage in early-stage product development – much in contrast to what is happening in the US and UK. With the new political agreement on the Danish defence strategy we now see more positive signs towards supporting Danish research and procurement from Danish industry.

Danish Quantum Cluster

A few Danish companies are already engaged in development and sale of products based on quantum technologies, e.g. the start-ups Sparrow Quantum A/S, QDevil ApS and SiPhotonIC ApS as well as the mid-sized companies NKT Photonics A/S, Accelink Denmark A/S and DFM A/S (Denmark's National Metrology Institute). The large multinationals, IBM Denmark and KPMG Denmark are already offering various services related to second generation quantum technologies in the fields of quantum com-puting and quantum cryptography.

Already now, the above companies form the embryo of a Dan-ish quantum cluster developing in the Greater Copenhagen area.





Photos courtesy of SiPhotonIC (left), QDevil (top right), and Sparrow Quantum (bottom right).

Provided the right amount of support, this cluster could grow significantly over time e.g. to reach a size similar to the Danish robotics industry, originating from the cluster around Odense, now having evolved to ~ 8.500 employees in 292 companies across the country with a revenue of ~ 18 BDKK *https://www.odenserobotics.dk/reports-and-analyses/* .

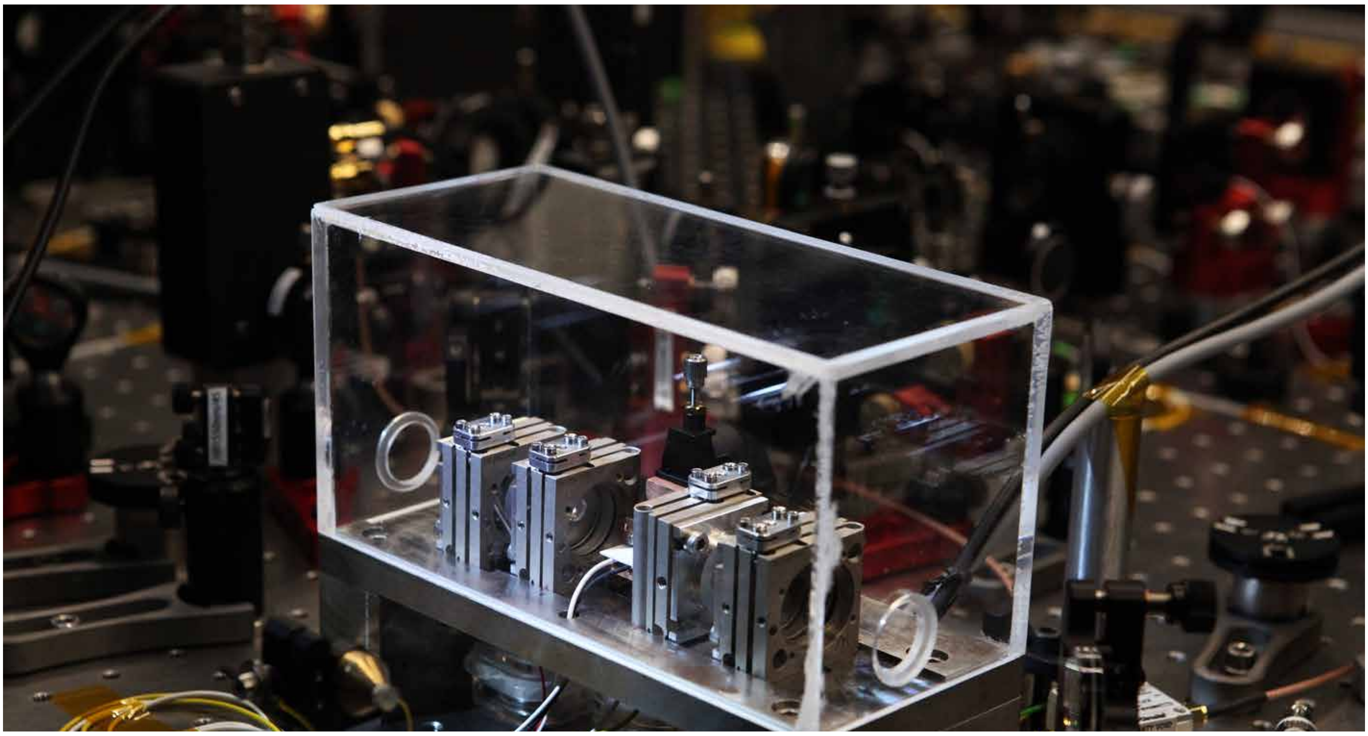
What can be done to stimulate the development of a Danish Quantum Cluster?

- Continue supporting basic quantum research to solidify Denmark's leading position.
- Strengthen university research in applied quantum technologies in cooperation with industry.
- Universities should patent strategic quantum inventions, even if they have a longer time to market.
- Strengthen university education in quantum sciences to ensure a steady supply of new talent.
- Create a quantum incubator in close collaboration with universities providing an environment with easy access to scientific and business development expertise as well as advanced test equipment.
- Provide easy access to cloud-based quantum computers for algorithm and software developers.
- Sponsor cross-functional projects based on use cases with relevance to Danish industry and society.
- Stimulate close cooperation between universities and 'quantum start-ups'.

New physical infrastructures are needed at a national level to support the quantum technology development. This includes test beds for quantum products as well as optical fibre networks for both large-scale tests of quantum communication hardware and protocols and for dissemination of ultra-precise time and frequency signals.

5.3 Industrial outreach – demonstrators for relevant use cases

According to research by IDC, International Data Corporation, only 7% of global industries are currently starting to investigate the potential use of quantum computing in their business. Additionally, 28 % are aware of the potential of quantum computing, but have no activity in this field yet https://blog-idcuk.com/quantum-computing-revolution-or-hype/. Therefore, a major awareness activity is necessary to make Danish industry realize the potential of quantum technologies.



Suggestions for action:

- Prepare a list of use cases relevant for Danish companies. Use case should potentially demonstrate 'quantum advantage' in 5-10 years
- Identity a Danish research team that is ready to engage in a demonstrator project. A demonstrator must show the technology working in a relevant environment
- Prepare high level use case and project presentation
- Contact major industrial players with a potential benefit from quantum and initiate awareness process
- Arrange dedicated meetings with relevant companies and present possibilities
- Arrange conferences for industry – present updated roadmap and use cases
- Study tours to international centres of excellence in cooperation with trade organisations

To bridge the gap between basic quantum research and the practical applications in industry, we have identified several use cases that are potentially relevant to the Danish industry and have solid backing from the research community (see Appendix A3).

5.4 Infrastructure

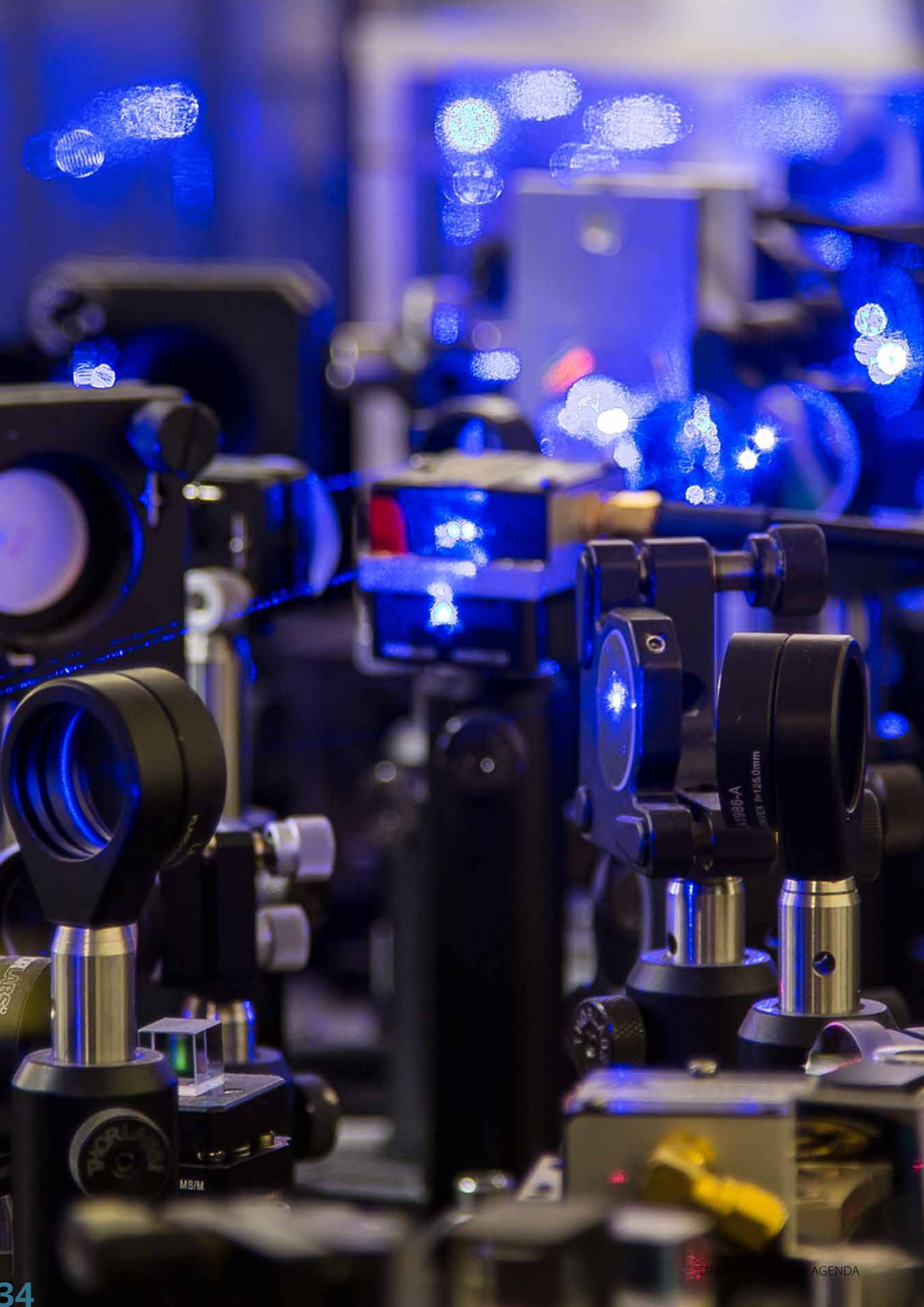
A successful transition from academic research to real-world applications and development of commercial quantum products requires a supporting infrastructure. Performance, reliability, and standardization are key elements for commercial success. Credible measurement and validation techniques are essential to ensure global acceptance of new quantum products. In addition, international standards are required for unique specification of interfaces between various quantum products. As an example, the quantum internet will require a range of components and sub-systems (e.g. quantum light sources, optical fibres, quantum repeaters, detec-tors) and they must all adhere to accepted standards to ensure flawless operation.

Active participation in international communities is important to gain new knowledge and exert influence in the standardization process. For instance, continued and increased Danish representation in international standardization committees is needed to ensure that future standards do not limit the acceptance of technology and products developed at Danish universities and companies.

Participation in the European Metrology Network for Quantum Technologies will also facilitate knowledge sharing, collaboration, and the uptake of measurement science in the development of quantum technology and lead to globally accepted measurement services for quantum technologies and devices.

In order to maximize the outcome of a national strategy for the transition from academic research to commercial applications, it is important to involve all relevant players in the Danish innovation system. The Danish government-approved Research and Technology Organisations (GTS institutes) play a key role in this system as the link between technology and business. They possess specialized and relevant knowledge in e.g. measurement science and software algorithms, as well as more generic competencies for the development of high-tech and deep-tech businesses, which can support the transition.

New physical infrastructures are needed at a national level to support the quantum technology development. This includes test beds for quantum products as well as optical fibre networks for both large-scale tests of quantum communication hardware and protocols and for dissemination of ultra-precise time and frequency signals. Access to accurate timing and ultra-precise optical frequencies is fundamental to research and development in quantum technology. Similar infrastructure is already established or being established in our neighbouring countries, and we need national facilities in order to remain competitive.



CONCLUSION

The world is facing tremendous challenges at a time when vital classical technologies are running out of steam. Quantum technologies offer a route forward by enabling solutions that go beyond the capabilities of classical technologies.

Today, we see the beginning of a new era, as several small-scale second-generation quantum applications are becoming available. Most quantum technologies, however, still require significant development before they are ready to provide real benefits to society. Denmark is in a strong position to take part in this process, and quantum technologies represent a significant opportunity for Danish society.

To properly address this opportunity, a financial framework accelerating this process is needed: It should invest in the basic research taking place at the universities. This support is needed now and 5-10 years into the future to bring the research at the universities to a mature level ready to be adopted by industry. Similarly, it should provide support for quantum innovation by funding cross functional research bridging basic research, innovation, societal needs, solutions, and end customers. Finally, it should support the establishment of a Danish IPR pool, respecting the longer time to market.

In addition, we propose the following activities:

– **Education** – educate new candidates and upskill existing staff in quantum technologies

– **Awareness** - generate increased awareness in industry and public organisations of quantum technologies' potential

– **Demonstration** – foster application demonstrations relevant to Danish end-users to stimulate early adoption of quantum technology

– **Eco-system** - stimulate the development of a Quantum Incubator and a Danish Quantum Cluster

– **Infrastructure** - provide funding for test beds and infrastructures required for full scale test of quantum technology

In this report, the Danish Quantum Community has presented a proposal for action that will lead to the creation of a Danish quantum ecosystem – a potential new stronghold for Danish economy.

APPENDICES

A1
Quantum technologies explained

Adapted from: EU Quantum Flagship - Final Report High-Level Steering Committee, June 2017 see https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=46979

About Quantum Sensing and Metrology

Quantum states are very sensitive to the environment and can therefore be used to make very accurate sensors. As a result of steady progress in material quality and control, cost reduction and the miniaturisation of components such as lasers, these devices are now ready to be carried over into numerous commercial applications. Solid-state quantum sensors, such as nitrogen vacancy centres in diamond, have been shown to be useful for measuring very small magnetic fields. This may help with multiple applications, from biosensors to magnetic resonance imaging and detection of defects in metals. Superconducting quantum interference devices (SQUIDs) are one example of an early QT now in widespread use, in fields as diverse as brain imaging and particle detection. Quantum imaging devices use entangled light to extract more information from light during imaging. This can greatly improve imaging technologies by, for example, allowing higher resolution images through the use of squeezed light or creating the ability to produce an image by measuring one single photon which is entangled with a second, differently coloured and entangled photon that is being used to probe a sample. Atomic and molecular interferometer devices use superposition to measure acceleration and rotation very precisely. These acceleration and rotation signals can be processed to enable inertial navigation devices to navigate below ground or within buildings. Such devices can also be used to measure very small changes in gravitational fields, magnetic fields, time, or fundamental physical constants. Quantum metrology employs intrinsically quantum mechanical features such as coherence and the Josephson and quantum Hall effects to perform precise measurements of e.g. time, frequency, voltage, current and resistance in quantum standards. Tremendous progress in this field over the past years culminated in the redefinition of the SI unit system in 2018. With this step, quantum standards directly profit from advances in quantum technology with an impact on a large range of commercial applications and society.

Applications of quantum sensing and metrology

- Natural resource exploration
- High resolution imaging techniques
- Self-driving vehicles
- Face recognition
- Precise measurement of time, e.g. for high frequency trading
- Precise and sensitive measurements on microscopic processes

About Quantum Communication

Communication security is of strategic importance to consumers, enterprises, and governments alike. At present, it is provided by encryption via classical computers, which could be broken by a quantum computer. This motivates the development of post-quantum cryptography, that is, encryption methods that quantum computers could not break. Secure solutions based on quantum encryption are also immune to attacks by quantum computers, and are commercially available today, as is quantum random number generation – a key primitive in most cryptographic protocols. But they can only function over distances up to 300 km: quantum information is secure because it cannot be cloned, but for the same reason it cannot be relayed through conventional repeaters. Instead, repeaters based on trusted nodes or fully quantum devices, possibly involving satellites, are needed to reach global distances. Trusted-node schemes are well suited to the protection of critical infrastructure networks, and they are already being installed. The advantage of quantum repeaters, exploiting multimode quantum memories, lies in extending the distances between trusted nodes.

The building blocks for fully quantum repeater schemes are twofold: a small quantum processor and a quantum interface to convert the information into photons similar to the optoelectronic devices used in today's internet, but with quantum functionality. These building blocks have already been demonstrated in the lab, but years of R&D are still needed for them to reach the market. As soon as this happens, true internet-wide quantum-safe security could become a reality.

Applications of quantum communications

- Financial transactions
- Cryptography
- Secure communications
- Cloud services
- Banking
- Health records
- Cybersecurity
- Blockchain

About Quantum Simulation

The design of aircrafts, buildings, cars, and many other complex objects makes use of supercomputers. By contrast, we cannot yet predict if a material composed of a few hundred atoms will con-duct electricity or behave as a magnet, or if a chemical reaction will take place. Quantum simulators based on the laws of quan-tum physics will allow us to overcome the shortcomings of super-computers and simulate new materials or chemical compounds, as well as solve equations in other areas, like high-energy physics. Quantum simulators can be viewed as analogue versions of quan-tum computers, specially dedicated to reproducing the behaviour of materials at very low temperatures, where quantum phenom-ena arise and give rise to extraordinary properties. Their main advantage over all-purpose quantum computers is that quantum simulators do not require complete control of each individu-al component, and thus are simpler to build. Several platforms for quantum simulators are under development. First prototypes have already been able to perform simulations beyond what is possible with current supercomputers, although only for some particular problems. This field of research is progressing very fast. Quantum simulators will aim to resolve some of the outstanding puzzles in material science and allow us to perform calculations that would otherwise be impossible. One such puzzle is the or-igin of high-temperature superconductivity, a phenomenon dis-covered about thirty years ago, but still a mystery in terms of its origin. The resolution of this mystery will open the possibility of creating materials able to conduct electricity without losses at high temperatures, with applications in energy storage/distribu-tion and in transportation.

Applications of quantum simulations

- Financial modelling and transactions
- Sustainable energy and agriculture
- Synthesis simulations e.g. for new materials
- Drug development & personalised drugs
- Energy consumption
- Distribution of resources
- Weather forecast

About Quantum Computation

Quantum computation is among the most far-reaching and challenging of quantum technologies. Based on quantum bits that can be zero and one at the same time and instantaneous correlations across the device, a quantum computer acts as a massive parallel device with an exponentially large number of computations taking place at the same time. There already exist many algorithms that take advantage of this power and that will allow us to address problems that even the most powerful classical supercomputers would never solve. Quantum computers using different platforms have been demonstrated over the last two decades. The most advanced are based on trapped ions and superconducting circuits, where small prototypes for up to ~ 50 quantum bits have already run basic algorithms and protocols. Many platforms and architectures have demonstrated the basic principles of quantum computing based on solid-state systems and on atomic and optical systems.

Due to technological interest and the evident limitations of existing approaches, referred to as the “end of Moore’s Law” of computational scaling, global IT companies have been taking an increased interest in quantum computing in the last decade. Advances in quantum computer design, fault-tolerant algorithms and new fabrication technologies are now transforming this “holy grail” technology into a realistic programme poised to surpass classical computation by ten to twenty years in some applications. With these new developments, the question companies are asking is not whether there will be a quantum computer, but who will build and profit from it. Realising quantum computing capability demands that hardware efforts should be complemented by the development of quantum software to obtain optimised quantum algorithms able to solve application problems of interest.

Applications of quantum computing

- Artificial intelligence - Machine learning speed up
- Blockchain
- Route optimization
- Big data
- Internet of Things
- Simulations
- Parallel processing
- Acceleration of calculations

A2
Quantum Roadmap

For an industry to assess the potential of quantum technologies for their individual businesses, it may be useful to establish an overview of when the various quantum technologies are expected to become commercially available using a so-called roadmap.

Below are two recent examples of roadmaps for quantum technologies, from two different sources: QuTech in Delft and OSA in the US. Not completely identical but relatively closely aligned. The largest uncertainty is related to the availability of the 'universal quantum computer' or the 'fault-tolerant gate-based quantum computer' predicted by the two sources to become available around 2035. At the time of writing this report, no qubit technology has yet emerged as a clear winner. Massive challenges related to scaling of most quantum computing concepts still need to be overcome.

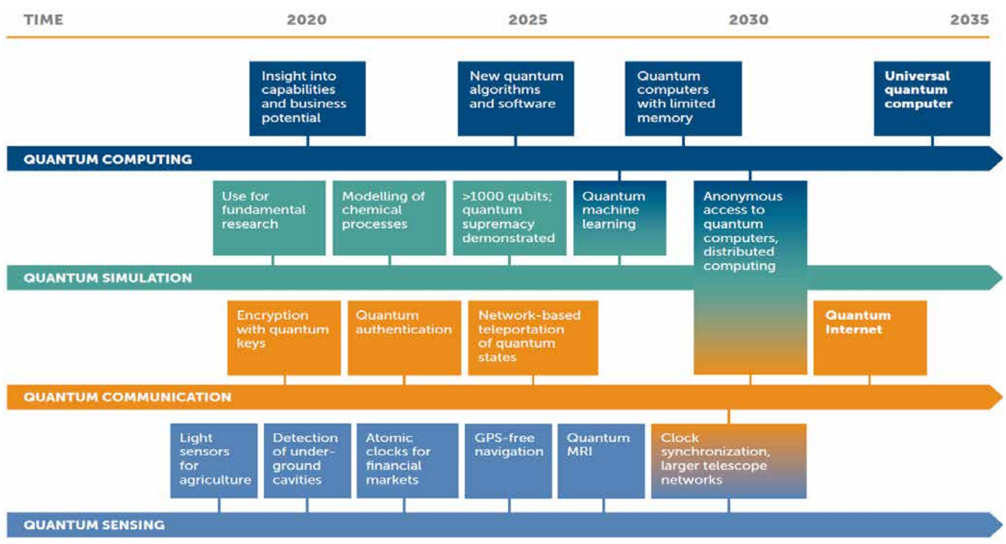


Figure 11: Forecast developments in quantum technology and the associated applications in the coming decades. From Dutch National agenda for quantum technology, September 2019. *Source:* https://qutech.nl/national-agenda-on-quantum-technology-the-netherlands-as-an-international-centre-for-quantum-technology/

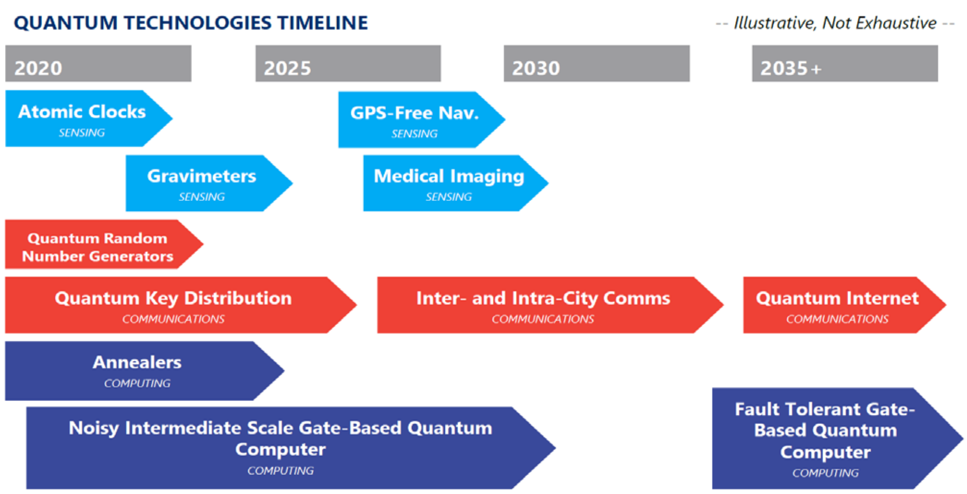


Figure 12: Optical Society of America Industry Development Associates' (OIDA) roadmap, March 2020. *Source:* https://www.osa.org/en-us/industry/industry_intelligence/oidaroadmap/

A3
Use cases

The following cases are examples of how one may presently envision that Danish industry will benefit from a national strategic effort in developing quantum technologies to gain a competitive advantage.

Photo: GOM Space

USE CASE: Improving MRI with hyperpolarization

Magnetometry has a wide range of applications in medical imaging and diagnostics, e.g. in magnetocardiography (MCG) for monitoring heart activity and anomalies, magnetoencephalography (MEG) for neuroimaging, and magnetomyography (MMG) for mapping of muscle activity, techniques that are already employed by Danish MedTech companies. Denmark is a European hub for MedTech and hosts quantum research at the very forefront in quantum magnetometry. There is thus a huge opportunity for synergy effects and/or formation of new Danish companies working in quantum MedTech.

Danish researchers strive to make hyperpolarization, i.e. the polarisation of nuclear spins, operational at room temperature by combining it with techniques from diamond-based quantum sensing. The hyperpolarization technique offers a factor of 10.000 increase in sensitivity of NMR imaging and was pioneered by the very same Danish researchers. There is currently a multi-billion USD global market for NMR. The targeted simplification of hyperpolarization, i.e. room-temperature operation, by application of quantum technologies has potential to obtain a share of this market.

USE CASE: Quantum-enhanced Raman spectroscopy

A well-established resource for enabling quantum-enhanced resolution or sensitivity in optical measurements is that of squeezed light. Denmark has a strong expertise in generation and application of squeezed light and a continuous wave squeezed light source has been developed in a form factor ready for use in the field.

An already demonstrated application of squeezed light is for quantum-enhanced stimulated Raman scattering (SRS) spectroscopy. It is a technique for non-invasive real-time vibrational imaging of living cells and organisms, which has also been applied to enhance the detection of lipid content in brain tissue for improved analysis of brain tumours. The ability of SRS spectroscopy to provide in-situ measurements of concentration of various molecules in a sample makes it a commonly applied technique for quality analysis of foods and pharmaceuticals and for monitoring cell culturing processes. Combining Danish expertise in squeezed light and conventional spectroscopy could lead to the development of a new generation of SRS microscopes with quantum-enhanced sensitivity, enabling imaging of weak Raman transitions without the use of markers or increasing the optical power, thus mitigating the risk of laser-induced cell damage.

USE CASE: Navigation in GPS denied environment

GPS technology has revolutionized navigation and timing and is by far the dominating technology due to its accuracy and simplicity of use. However, relying entirely on the availability of GPS signals is a huge vulnerability for the reliability and security of navigation, both in defence and civil transport, as the signals can be either blocked or jammed by adversaries. Quantum sensors offers a backup solution. Nitrogen vacancy (NV) centres in diamond are superb magnetic field sensors and can thus act as a compass. However, the NV centre not only measures the magnetic field strength but constitutes a so-called vector magnetometer, measuring both the field's strength and direction. This provides for a local uninterruptable navigation system without need for the vulnerable external communication. The compactness of the technology also enables a form factor compatible with drone technology. A focused effort into this emerging technology could open new business opportunities for the Danish companies developing and producing sensor technology for defence and security applications.

USE CASE: Quantum communication networks

The ultimate vision in quantum communication is the realization of a quantum internet, where quantum entanglement is distributed over long distances by photonic qubits. To reach this ambitious goal requires excellent single-photon and multi-photon sources, and deterministic light-matter interfaces - strong-hold positions of Danish research. The European Commission has initiated the establishment of a new quantum communication infrastructure called EuroQCI. EuroQCI is projected to be a pan-European infrastructure enabling quantum secure communication and transmission of quantum information, e.g. between quantum computer nodes.

Denmark has very strong academic expertise in quantum communication and cryptography, illustrated by the participation in 3 quantum communication consortia (The Quantum Internet Alliance, Uniqorn, CiViC) under the FET Quantum Flagship. In addition, Denmark has a research and development intensive ICT industry as well as one of the world's most digitized public sectors. There is thus a clear opportunity for public private collaboration on development, testing, and commercialization of technologies for the EuroQCI and a future global quantum internet. Current Danish innovation activities already target development of quantum technologies for secure point-to-point communication, pursuing both coherent light and single-photon approaches. The technology is mature, and the expected time to market is around 5 years. A strategic effort with a timeframe of 5-10 years would enable Denmark to extend its strong position in ICT into the quantum domain and secure a share of an emerging global market expected to reach 1-6 BEUR already by 2025, as estimated by recent studies by IQT and Toshiba, respectively.

USE CASE: Satellite communications

The quantum internet represents a challenging vision that aims at enabling ultra-secure quantum communication between any two hosts on Earth. While the demand for inter-connectivity is exponentially growing, half of the world still has no access to the Internet. In some cases, it is too expensive or impractical to extend current infrastructure or even build new backbone networks, and a global wired quantum network is still extremely challenging since single photons transmitted over long-distance optical fibers suffer from high losses.

Space Inventor is a Danish satellite engineering company who specializes in nano- and microsatellites. Space Inventor designs, builds, and tests a range of avionics products. To address the drawbacks of a wired network, we envision using the CubeSat technological paradigm, which has contributed to radically transform our way of understanding space. Specifically, the vision aims at developing a new global interconnecting infrastructure whose heart is a constellation of low-cost CubeSats each equipped with a high-tech miniaturized payload that will integrate a classic high-speed optical terminal and a quantum terminal to generate and transmit quantum states. The target infrastructure will be able to support the achievement of a global backbone quantum network, which is the indispensable prerequisite for the quantum internet. Current Danish innovation activities are already targeting free-space optical communication for data exchange. A strategic effort with a timeframe of 10 years would enable Denmark to extend its strong position into the satellite domain and secure a share of an emerging global market.

USE CASE:
Simulating natural processes with light

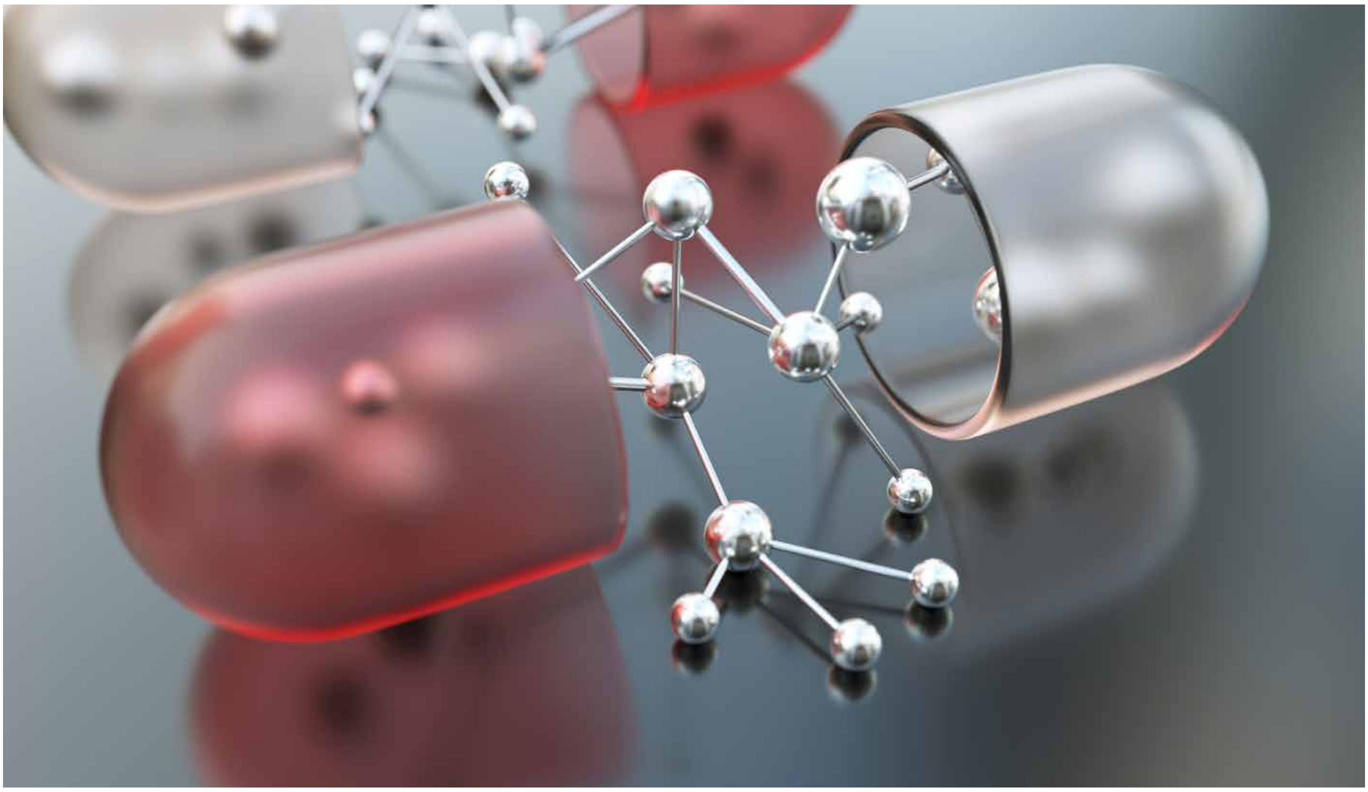
Denmark has the necessary scientific know-how in quantum photonics and integrated optics to develop photonic quantum simulator hardware within a 5-years period, based on both coherent light and single-photon approaches. This would then be applied to molecular vibronic spectra simulations and other known applicable problems, such as predicting molecular docking configurations, highly relevant to Danish companies working in drug discovery. A key step is to co-develop hardware and algorithms towards targeted applications, where the resource efficiency of the protocols is a key optimization parameter.

Much attention has been drawn to optical quantum simulators, in which the quantum statistical properties of light, in combination with multimode interferometric systems, is exploited for specific quantum computation tasks. Applications include computationally hard problems e.g., of relevance to network analysis and understanding of vibronic properties of molecules. The latter relates to light absorption properties, and the simulators can thus assist in assessing various molecules performance as solar cells or as dyes for either biological labelling or industrial processes. In Denmark, the company Molecular Quantum Solution develops efficient hybrid quantum algorithms to solve quantum chemistry problems, whereas the company SiPhotonIC develops a low loss silicon-based platform for quantum simulation hardware.

USE CASE:
Discovery of new materials

Understanding the physics of solid-state systems is essential for developing novel materials with tailored properties. Cold atoms trapped in optical lattices comprise an ideal system for quantum simulations of hard problems in solid state physics and for exploring the validity regime of commonly used theoretical models. In Denmark, researchers are already developing and exploring optical lattices for quantum simulations and significant expertise has accumulated in the field of cold atom physics, both experimentally and theoretically.

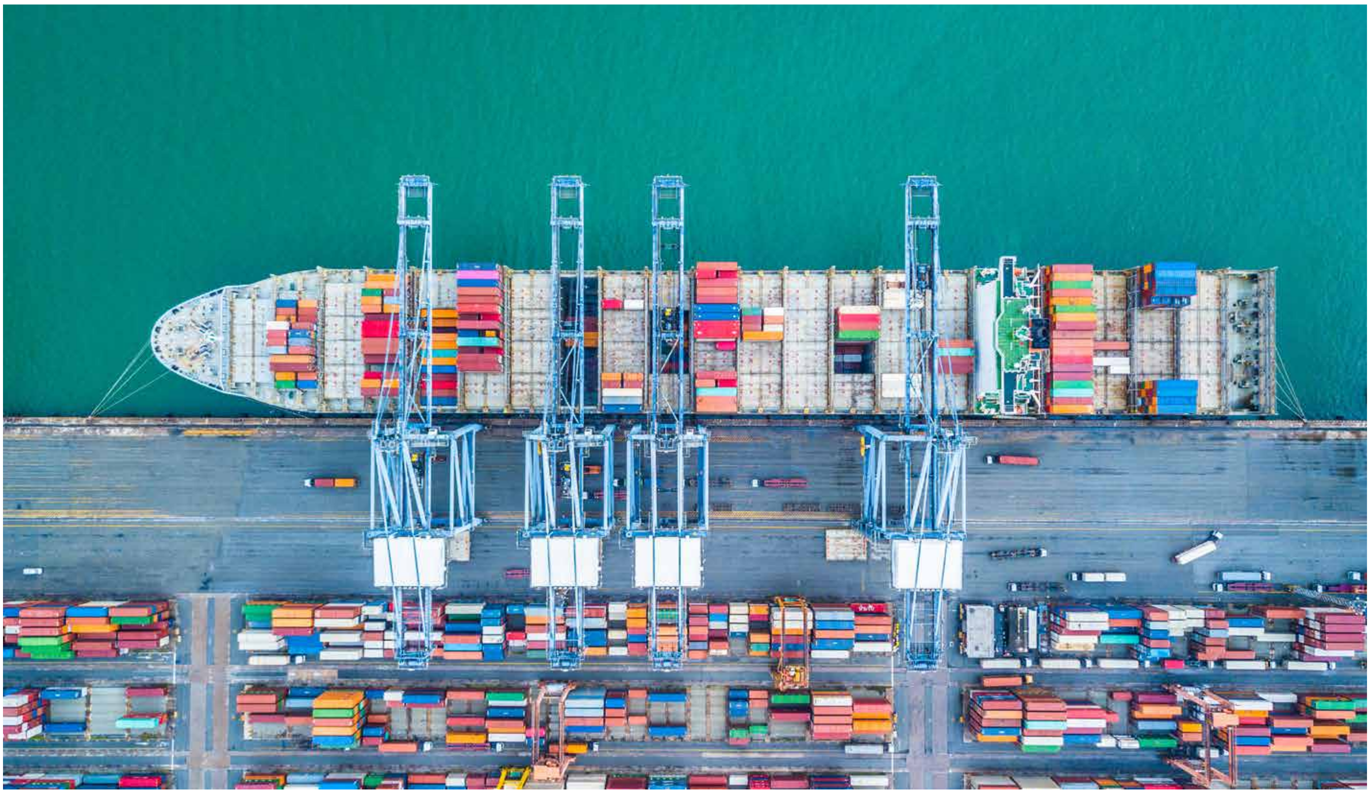
The development of sophisticated cold atom quantum simulators would provide a platform for developing materials with specific functionalities e.g. for catalysis (Haldor Topsøe), artificial photosynthesis, and energy storage (Ørsted and Energinet) with high sustainability.



USE CASE: Quantum computing algorithms tackling Danish industry challenges

As quantum simulator and computer hardware matures there will be an increasing demand for new algorithms exploiting the capabilities for solving relevant problems. In fact, this is already the case, as the applications of existing available gate-based (IBM and Google), photonic (Xanadu), and special purpose quantum computing platforms (D-Wave) are far from exhausted. As an example, it is believed, but not yet demonstrated, that Monte-Carlo simulations, relevant to a broad range of applications e.g., in finance, computational biology, and climate models, can be performed efficiently on a quantum annealer. Denmark has a strong research community within quantum mathematics and algorithms and a targeted effort on algorithms development could within 5 years result in applications of NISQ computation to the benefit of major Danish companies e.g., in logistics optimization (Mærsk and DSV), fluid dynamics (Vestas), biotechnology (Novo Nordisk) and finance (Danske Bank).

In parallel, investigations of the interface between density functional theory (DFT) and quantum computing e.g., hybrid DFT-NISQ approaches to simulation of strongly correlated many body problems and application of DFT in quantum computations, would be highly interesting and would have the potential to impact both fields significantly. DFT calculations for materials design is a Danish research stronghold and important for the development of high-efficiency catalysts (Haldor Topsøe).



Danish
Quantum
Community