Finnish Quantum Agenda

Institute Q

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Executive Summary

Quantum technology has the potential to realize sensing, computing and communication solutions that are faster, more powerful, more precise, and more secure than traditional technologies. Finland has a strong base in research and innovation activities in quantum technologies, and it is important to strengthen the investments in research and innovation in quantum technology to maximize the benefits of this area for Finland and globally.

Quantum technology is based on fundamental understanding of quantum phenomena and materials, and on novel ways of controlling and manipulating them. The technology makes it possible to build devices that have great potential to positively impact society. The area has in the last decade grown significantly, and both public and private investments in the field are booming. Governments follow the technology development with growing attention, and most of the advanced nations actively participate in the development through funding initiatives. National strategies and initiatives are published around the world.

Research and innovation activities in Finland in the area of quantum technologies are of high quality. The Finnish quantum ecosystem is internationally recognized and competitive. This means that Finland has the potential of being an important actor in this area. To utilize the full potential of the area requires, however, concentrated action from all stakeholders, access to international talent, innovation, and supply chains. There is a clear need to support people, infrastructure, investments, favourable regulatory environment, national and international cooperation in this field. The crucial components are the availability of world-class experts, both in research and in innovation, and an excellent development and operating environment, with special emphasis on research and innovation infrastructure.

This Finnish quantum agenda is the result of work done by a working group formed in September 2022 by the Finnish quantum community (see Appendix 1). It gives a short description of quantum technologies, describes the status of research and innovation activities in Finland, and lists recommendations for further development of the area. The recommendations involve universities, research institutes, companies, funding agencies, and the government.

The working group recommends the following set of interconnected activities to address the opportunity and realize the potential of quantum technology for the Finnish society:

1. **A coordinated research and innovation funding programme.**
2. **Long term programme and a roadmap for research and innovation infrastructures.**
3. **Targeted development of the Finnish quantum technology ecosystem.**
4. **Increase of education and development of the educational offerings in quantum technologies.**
5. **Support for national and international cooperation.**

To best foster the development of the field, the agenda also suggests the preparation of a full national quantum strategy by the government. A visible state-level commitment is required for maintaining Finland's position as a leading actor.

Introduction

Quantum physics was born in the first decades of the 20th century, and soon the development of the theory itself led to remarkable successes in technology that have deeply changed the society. We have already witnessed the first quantum revolution, which provided us with devices we use every day: from the transistors inside our computers and telephones, to the lasers in barcode readers and to the advanced medical imaging systems such as magnetic resonance imaging.

We are now living the second quantum revolution. Advances in scientific and technological research have made the development and deployment of new devices possible, in particular thanks to the - rather recent - ability to detect and manipulate individual quantum objects.

Second generation quantum technology can lead to a new wave of breakthroughs that will most likely shape our economy and society. Fundamental and applied research has led to the discovery of devices and methods that promise to outperform traditional methods of computing, communication, sensing and simulation.

The field is still evolving rapidly, and it may take several decades for the potential of the technology to be fully realized and its societal impact visible. However, several second-generation quantum technologies are already available for use and many more will be accessible in the next five to ten years.

The Finnish Academy for Science and Letters is currently preparing a document on the potential societal impact of quantum technology[1], and thus this agenda does not cover that issue in any depth.

While many fundamental research questions remain to be answered, quantum technology already offers a wealth of opportunities. Thanks to the rapid advances in the last years, investments in the field around the world are booming, both in the public and private sector[2]. In tandem, national education efforts specifically focused on quantum technologies are emerging[3]. Governments are following technology development with growing attention. Quantum technology is a global field, with North America and Europe at the forefront, while China, Japan, and some other countries in the Asia-Pacific region are rapidly catching up. Europe has a long academic tradition of quantum science research, and with the establishment of the Quantum Flagship[4] in 2018, the European Union has taken serious steps to meet the challenge of being competitive in the sector of quantum technology with its possibly disruptive scientific, technological, and economic impact.

In the international landscape, national institutes and initiatives[5] are being formed, and national strategies[6] are published around the world. Such national strategies and

[1]Suomalainen Tiedeakatemia, Kvanttiteknologian yhteiskunnalliset vaikutukset ja mahdollisuudet Suomen kannalta – katsaus päätöksentekijöille, Helsinki 2023.
[2]McKinsey & Company, The Quantum Technology Monitor, June 2022.
[3]Kaur, M., & Venegas-Gomez, A., Defining the quantum workforce landscape: a review of global quantum education initiatives, Opt. Eng. 61(8), 081806 (2022).
[4]https://qt.eu
[5]National Institutes for Quantum and Radiological Science and Technology (JP), https://www.qst.go.jp/site/qst-english/; National QIS Research Centres (US), https://science.osti.gov/Initiatives/QIS/QIS-Centers; National Quantum Computing Centre (UK), https://www.nqcc.ac.uk; Quantum Delta (NL), https://quantumdelta.nl/delft/; Quantum Alliance (DE), https://www.quantum-alliance.de; Wallenberg Centre for Quantum Technology (SE) https://www.chalmers.se/en/centres/wacqt/;
[6]See Appendix 2

initiatives are vital for the development of the area. Furthermore, they deliver a strong message to researchers and companies in this field: long-term initiatives indicate that the area is important for the country, and that the country is a good location for research and innovation in quantum technology. Thus, also Finland should signal the importance of quantum technology with a national strategy and long-term funding initiative.

The potential of modern quantum technology is so powerful that these technologies are viewed as important elements of national security and self-sufficiency. This means that there is a need for systematic and coordinated collaboration between national quantum ecosystem players, government officials, policymakers, and funding agencies. The national security angle influences the international context, calling for collaboration with likeminded techno-democracies.

Motivation for public and private investment in quantum technologies in Finland can be summarized as follows:

- The field has a very high potential in various application areas and thus in improving the competitiveness of Finland.

- The research and innovation community in quantum technology in Finland has excellent quality, including both academic and industry leaders, and is large compared to the size of the country.

- The long tradition in excellent research, leading innovation activities, the seamless collaboration between research and innovation, and the thriving ecosystem in Finland in quantum technologies gives us a competitive advantage.

- While the research in quantum technologies requires investments in infrastructure, the area is such that even smaller countries and companies can have a significant impact.

The development of the area faces challenges as well, including the following:

- Securing the availability of skilled workforce to Finnish society, economy, and academia in the global arena where experts are the most competed resource.

- Maximizing the opportunities of Finnish industries to succeed and benefit from a competitive advantage of the national ecosystem.

- Securing access to the resources: the latest quantum technology including parts, innovation, and intellectual property.

- Influencing the international trade and related regulations so that they are aligned with Finland's interests.

- Increasing the diversity of the workforce in the field; Finland as a model high-tech country of equal opportunities.

Thus, Finland is in the forefront of research in several key areas of quantum technology. We have a very strong research and innovation ecosystem in the area. To take full advantage of this strong position rooted in basic research on quantum science, we must act now to secure Finnish opportunities in the development of emerging second-generation quantum technologies.

This agenda is a result of cooperative action from the Finnish quantum community. It has been prepared by a working group having representatives both from the research and innovation branches. For the list of members, see Appendix 1.

The agenda gives an overview of the area, an assessment of the status of the work done in Finland, and suggestions for actions in the public sector for further development of the area.

Structure of the area

Quantum technology is a field where quantum effects are controlled and exploited for practical applications. Many of the devices that we use in daily lives are based on quantum phenomena that are well known by the scientist for a century. Examples of such technologies are transistors, light emitting diodes (LEDs), photodetectors, lasers, GPS/atomic clocks, MRI/MEG scanners for medical imaging, and solar panels. These technologies are based on manipulating quantum particles in well-designed settings.

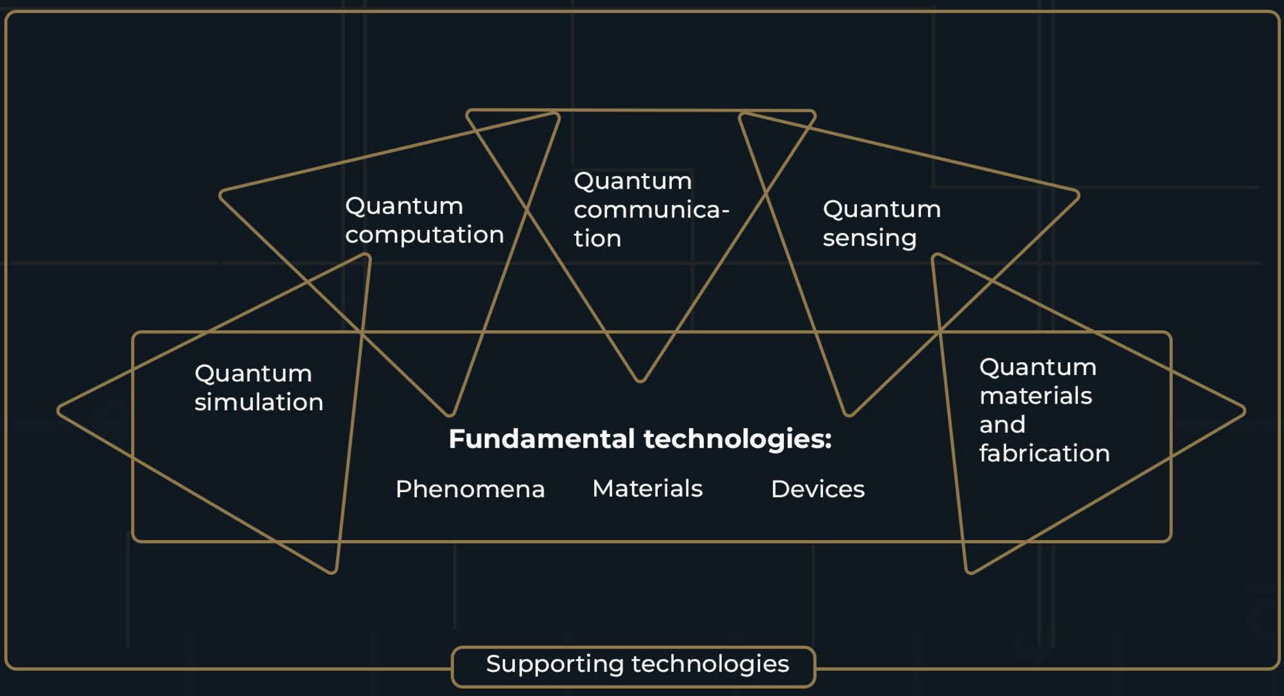
However, there are several peculiar and fragile quantum phenomena, such as entanglement and superposition, that only today are captured and shielded from noise with precise enough technological methodology to be translated into real life applications. Capability to manipulate, control individual quantum objects (atoms, electrons, photons) has led to the emergence of the so-called second quantum revolution. This change is not happening by chance. Rather, it is based on decades of persistent work to understand the quantum realm, to develop fabrication processes and methods for nano-scale devices, and to develop theories and computational methods that help to interpret and understand what is really happening and what could be achieved next.

Modern quantum technology aims at harnessing these phenomena and to build new types of devices and systems based on them. Quantum systems make use of properties that are not available in our current appliances. This implies that to develop, for example, a quantum computer, it is not enough to build quantum hardware, but it is also essential to create completely new software and algorithms. Software running on conventional computers cannot simply be adapted as the rules for information processing in the quantum realm are radically different. Especially in the near term, when quantum hardware capabilities will still be limited, quantum algorithms and dedicated software will play a crucial role in harnessing their power for solving useful problems.

Subareas of quantum technology are schematically depicted in **Figure 1.**

Quantum technology is anticipated to permit more powerful computing, provably secure communication, unmatched simulation capabilities, new types of sophisticated materials with tailored properties, higher sensitivity and precision sensing, and new measurement types, from atomic up to macroscopic length scales. It is expected to provide unparalleled technological and societal impacts in sectors ranging from high performance computing to secure telecommunications and from chemistry/drug development to more efficient materials.

Figure 1.



Quantum technology sub-areas

Fundamental technologies

Fundamental technologies consists of deep understanding of quantum phenomena, materials science, device fabrication and quantum information, which are all rooted on the top level basic research on quantum science in Finland. This understanding enables to determine what is ultimately possible with quantum technologies.

The fundamental technologies are at the core of other subareas of quantum technology. For example, techniques for controlling decoherence provide long enough lifetimes for fragile quantum resources, such as entanglement, which makes quantum computing, quantum simulation and communication possible.

Quantum materials and fabrication

Quantum materials are substances that generally exhibit some quantum mechanical asset that has no counterpart in the classical world. A new generation of functional quantum materials is emerging. These materials can be engineered even at the atomic level, incorporated to induce designed quantum phenomena, and utilized to create novel functional quantum devices and systems.

Applications of these materials and technologies could result in revolutionary improvements in terms of capacity, efficiency, sensitivity and speed, and will be the decisive factor for success in many industries and emerging markets. Control and development of quantum materials requires specific focus on fabrication environment, processes, and know-how, as well as extensive characterization capabilities.

Quantum computing

Quantum computing is developed on different physical platforms, that all use the same principle: they have a processor in which quantum two-level systems (qubits), or more complex quantum objects can be isolated and manipulated. This means that quantum computers can exploit quantum phenomena to process data in a radically different way from classical information processing. Quantum computers are fundamentally different from conventional computers and are foreseen to be used either as systems for special purpose computing or as accelerators for high-performance computing systems.

Quantum computing is among the most challenging and far-reaching quantum technologies, even if noisy intermediate-scale quantum computers have already been built. Presently, researchers and engineers from companies such as IBM and Google, as well as the world of startups and academia are racing to develop quantum computers with a larger number of qubits. At the same time, they aim to demonstrate that even quantum computers with a smaller number of qubits can solve useful problems beyond capabilities of conventional computers. To enable useful quantum advantage with present and near-term quantum computers, efficient quantum algorithms (i.e., algorithms that work for increasingly large numbers of qubits) are necessary.

As in classical computing, the role of software is crucial in quantum computing, as the hardware alone computes nothing. Indeed, quantum computing means the combination of the hardware and the software. Software for quantum computers involves specific themes that are not present in software for classical computers. Quantum algorithms are fundamentally different from classical ones. Also, the issues of middleware between the hardware and algorithms are intricate. Research and development in quantum software is currently very active.

Besides supporting hardware, extensive effort in developing the necessary quantum software and computational infrastructure allowing the technology adaptation for real applications is necessary.

Quantum simulation[7]

Quantum simulation is closely related to quantum computing. In fact, quantum simulators can be regarded as specialized quantum computers, i.e., quantum devices specifically designed to handle predefined tasks. They can solve specific problems that are difficult to simulate on classical computers because they directly exploit the quantum properties of real particles. For example, one quantum simulator might find the chemical properties of a complex molecule and another the best strategy for delivering products between multiple addresses. Conversely, a quantum computer could be programmed to perform any calculation, including those described above.

Quantum simulators are used as a kind of test laboratory. They model simple quantum systems to provide insights into more complicated quantum systems that are difficult to test.

Quantum sensing[7]

Quantum sensing exploits quantum phenomena to design and manufacture ultra-precise measuring devices. These devices are even more precise than the limits

[7] Descriptions by QPlayLearn, a platform of multilevel educational resources developed by partners in InstituteQ.

reached by current sensor technology, and/or they can exploit different and more efficient measurement protocols for faster operation. Many measuring devices already exploit quantum properties, such as nuclear magnetic resonance, but the key idea is that, with new technological advances, individual quantum systems can be used as measuring devices to reach ultimate sensitivity.

Solid-state quantum sensors or photonic systems can already be used in various applications, ranging from biosensors to microscopy and imaging, positioning systems, defect detection in materials, magnetometry and thermometry, interferometry and polarimetry, and geophysical research in seismology.

Quantum sensors are used in quantum metrology to create high-resolution and high-sensitivity measurements for physical and standard parameters, such as time, gravitational wave detection, electrical and optical measurements, or fundamental physical constants

Quantum communication

Quantum computing poses a threat to much of modern digital encryption. Sufficiently mature quantum computers could break many of the encryption protocols that are in use in society. A possible solution to this is quantum communication. Quantum communication seeks to understand and develop ways to transmit information between distant locations using the principles of quantum physics, and how to increase the cyber security in the quantum era.

Quantum cryptography uses encryption methods that are unbreakable, even by quantum computers. This could provide an ultimate solution to cyber-attacks. The power of quantum cryptography lies in the fact that it is impossible to copy or read data encoded in a quantum system without disrupting the system itself. As a related branch of technology, methods to secure communication on classical computers in quantum era are under development, known as post-quantum cryptography.

A part of quantum communication is quantum key distribution (QKD), which uses quantum properties of photons to distribute encryption keys securely between users. In QKD it is impossible to copy or read data without disrupting the system itself.

Current quantum communication protocols have been demonstrated over distances of a few hundred kilometers with direct communication and over thousand kilometers with a satellite link. The ultimate goal is to extend these techniques to global distances and build a quantum Internet.

Supporting technologies

Supporting technologies include a range of fields that are critical for the development of quantum technologies. These include e.g., micro- and nanoelectronics, micro- and nanomechanical engineering and manufacturing, process control and control engineering, ICT engineering, cryogenics, photonics, vacuum technologies, and experimental control technologies. For quantum technologies, a wide variety of conventional devices and components are needed, together with the quantum devices, to deliver complete systems.

Availability of experts and infrastructures for product development, system integration and device packaging, as well as the security of supply chains, will be critical for the growth of the ecosystem.

Remarks

As noted above, the subareas of quantum technology are not isolated; rather, there are many interconnections between them. Among these subareas, the research and innovation activities are intimately connected. This is especially true in Finland, and it forms one important part of the current competitive advantage of the Finnish quantum ecosystem.

Global investments briefly

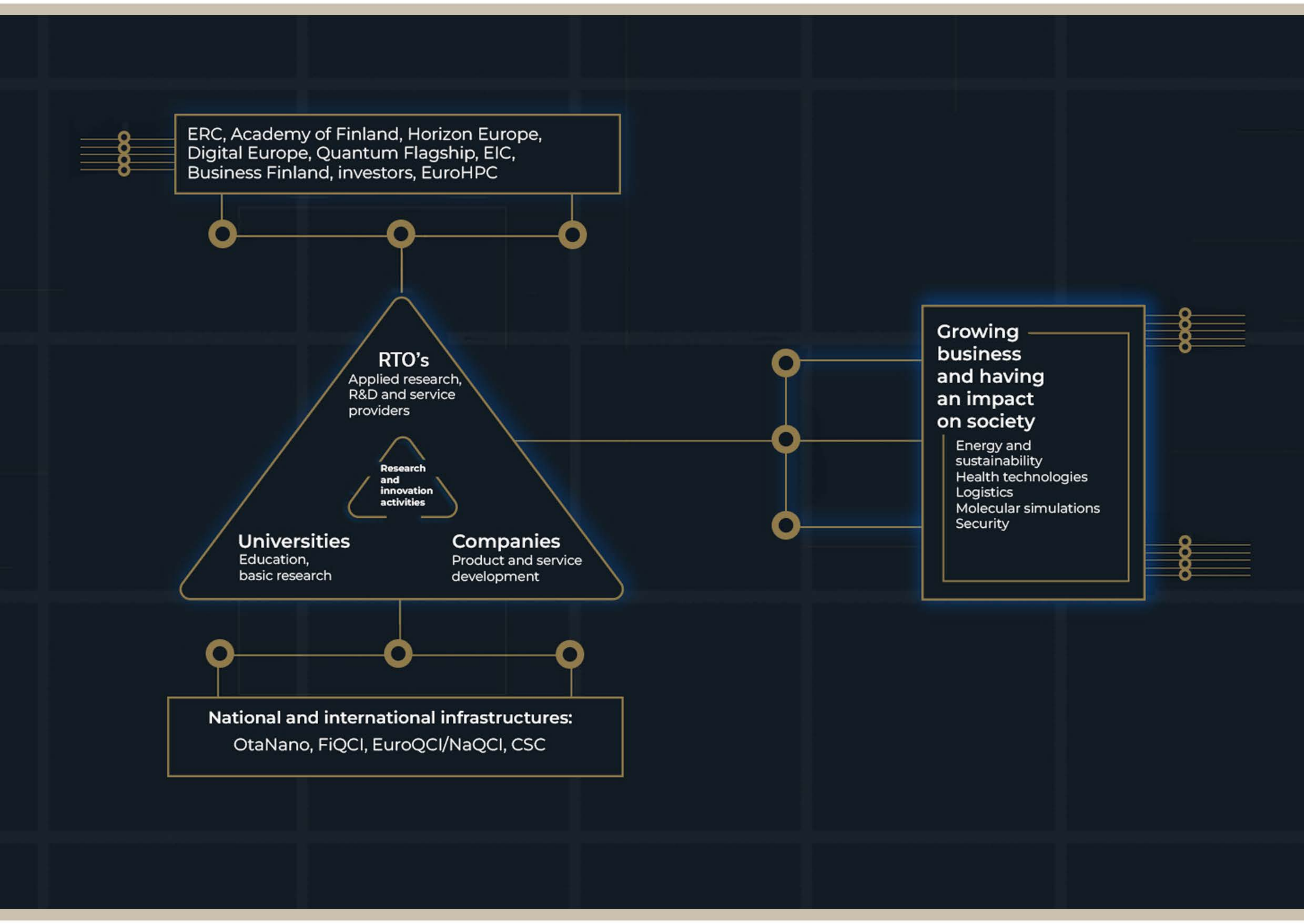
Global investments for the field of quantum technology are rising continuously. Mc Kinsey & Company estimate the worldwide public quantum efforts exceeding US$31 billion.[2] Recent openings include e.g., the Swedish Wallenberg Foundation investment of SEK 1,3 billion (~ € 130 million) for 12 years (2018), the Dutch Government investment of € 615 million for 6 years (2021), and the Danish Novo Nordisk Foundation investment of US$ 200 million (~ € 192 million) for 12 years (2022). Annual funding for quantum technology startup investments has doubled during past years, surpassing US$ 1.4 billion in 2021.[2]

The global investments give insight into the level of attractiveness and activity in quantum technologies. Estimates of existing research volumes around the world are difficult to obtain, partly because the field is strongly multidisciplinary: it involves research activities that extend from theoretical and experimental physics, mathematics, and computer science to engineering. These fields are contributing with varying intensity to research activities in quantum technologies.

Status of the area in Finland

Finland has a strong and globally unique research tradition in quantum science and technology. For decades our research groups have pursued theoretical, computational, and experimental efforts, with the goals of modelling and controlling charge, flux, phonons, photons, quantum and classical noise, microwave radiation and plasmons in fabricated nanostructures. The work has led to accumulated expertise in quantum phenomena, materials, and devices, as well as development of component, sensor, and detector applications. In recent years, this research expertise has been instrumental in building a strong research and innovation ecosystem. Besides know-how on quantum hardware and devices, decades of fundamental research in quantum information theory have generated unique expertise in the area of quantum algorithms, that has led to world-class innovations in this area.

Figure 2.



Schematic illustration of the Finnish quantum ecosystem

Some properties of the research and innovation ecosystem are given below.

• The current research volume of quantum technologies in Finnish universities and research and technology organizations is about 45 million euros per year[8]. A large majority of this funding comes from nonthematic funding programs of the Academy of Finland and the European Union. In addition to this, becomes the private investments in R&D by companies.

• The volume corresponds to about 2-3 % of the whole research funding of universities and research institutes.

• The number of research publications in quantum technology in Finland (2017-2022) is about 61 % and 79 % of the corresponding numbers for Sweden and Denmark, respectively (see Table 1).

• The citation indices of publications for Finland are clearly above the world average.

• Quantum technology researchers have obtained about 9-13 % of all the ERC grants in Finnish organizations.

• There are currently about 11 companies working more or less exclusively on quantum-related themes, and their estimated current total revenue is € 130 million (see Table 3).

• The start-up funding for quantum technology in Finland is about € 280 million since year 2000 (see Table 3).

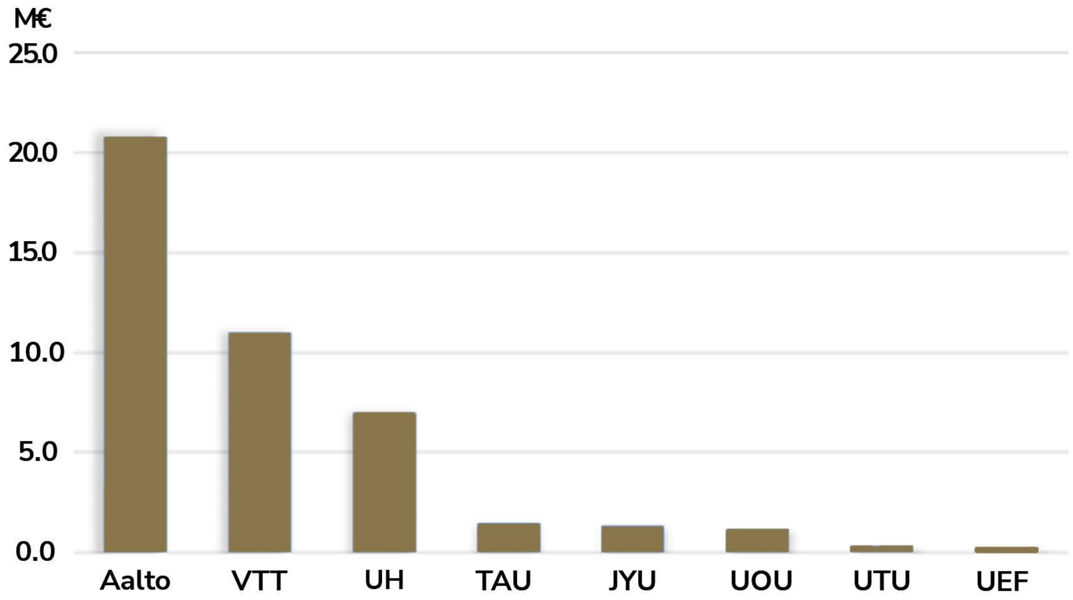
• The total number of RDI personnel working on quantum technology in Finnish universities and VTT is close to 550 (2022).

[8] Based on data collection and estimations from the host organizations of the Finnish Quantum Agenda working group, concerning years 2022-2027.

The volume and quality of quantum technology research in Finland

The total amount of research funding used for quantum technology in universities and research and technology organizations in Finland in 2022 is about €45 million. The distribution of the research funding between organizations is shown in Figure 3.

Figure 3.



Volume of quantum technology related research activities in Finnish universities and research organizations in 2022, based on survey made by the Finnish Quantum Agenda working group. The numbers do not include investments in research infrastructures.[9]

The largest actors in the research area are Aalto University, VTT, and University of Helsinki. Quantum technology has also been identified as a topic of interest in the Universities of Tampere, Jyväskylä, Eastern Finland, Turku, and Oulu. Various aspects of quantum foundations, materials, devices, and components, as well as algorithms and software, are studied experimentally and theoretically with different intensities at these universities.

The research funding of about 45 million euros per year is largely obtained from competitive nonthematic funding sources, such as the general calls of the Academy of Finland and of the EU. On average 30-35 % of this funding is organizations' own budget funding (including professorships). The full volume corresponds to about 2-3 % of all the research funding used in Finnish universities and research institutes.

[9] According to the completed survey, the anticipated average full volume is settled around €45 million/ year during 2022-2027. The estimates of individual organizations may vary between years.

The research done in Finland in quantum technology is of high quality. This can be seen for example by looking at data on ERC grants. Researchers in quantum technologies have obtained about 9-13 % of all ERC grants in Finland. This should be compared with the above fact that the overall funding of the area is only about 2-3 % of the whole research done in universities and research institutes, about 5 times more than expected based on their share of the research volume.

The high quality of the quantum technology research in Finland can also be seen in the Academy of Finland centre of excellence in Quantum Technology QTF[10], containing groups from Aalto University, VTT, and University of Helsinki. It is the third successive centre of excellence in the area of quantum physics and devices.

We also note that the Photonics Research and Innovation (PREIN) flagship of the Academy of Finland[11] launched a separate work package on quantum technologies in 2022. PREIN is hosted by Tampere University, University of Eastern Finland, Aalto University, and VTT.

While bibliometric data is not well suited for the analysis of emerging areas, we present some data on publication activity as well. Table 1 compares the Finnish publications with those from countries with strong research background (the Netherlands, Denmark, and Sweden) and with one without such background (Norway).

Table 1.

Country	WoS Docs	CNCI	Top10 index	Top1 index	% Internat. Collab
Netherlands	1773	1.88	22.17	3.84	75.0
Sweden	1266	1.42	17.30	2.05	79.5
Denmark	976	1.64	21.52	2.97	75.1
Finland	770	1.34	14.29	2.21	72.2
Norway	283	1.02	12.37	0.71	73.9

Bibliometric data on publications on quantum technologies from Finland, Sweden, Denmark, Norway, and the Netherlands in 2017-2022, using IEEE keywords. Source: Aalto University library. Column explanations: WoS Docs: number of documents in Web of Science database; CNCI: category normalized citation impact; Top10 index: percentage of publications in the most cited 10% of the publications; Top1 index: percentage of publications in the most cited 1% of the publications; Internat. Collab: percentage of publications that are international collaborations.

We note that especially the top1 index is high in all the countries except Norway.

[10] https://qtf.fi
[11] https://prein.fi/

Innovation activities

Globally, quantum technology is considered critical both technology-wise and geopolitically. All major powers, China, US and EU, have initiated programs of billions of euros to advance the technology. Technology-wise the US still holds some advantage, but both EU and China are advancing fast. In intellectual property, the US covers for almost half of the patent applications, with China as number two, with about one third of applications. The European and Japanese companies file both about 10 percent of patent applications.

For assessing Finland's position in the field, a comparative study of innovation funding and activity is presented here. The study considers major European quantum technology hubs and countries comparable to Finland, namely Sweden, Denmark, Netherlands and Germany.

First of all, the national focused research, development and innovation funding programs for quantum technology vary a lot (see Table 2). The Finnish focused quantum funding is the smallest, including the Finnish quantum computer development program and minor, single-shot calls from Academy of Finland and Business Finland. Rather, most of the research in quantum technology in Finland is funded through non-focused, bottom-up calls, not included in this table. Note that the programs below are long term, e.g., in Sweden the Wallenberg program is for 12 years.

Table 2.

Country	RDI	Infra	Education/ societal	Ecosystem development	Unknown	Total
Finland	35					35
Sweden[12]	(150)					150
Denmark	180	50				230
Germany[12]	(2600)					2600
Netherlands	223	150	61	182	150	765

Summary of national focused RDI funding programs in quantum technology (M€).[13]

The quantum technology business ecosystem is strongly emerging in Finland. Table 3. summarizes the private investment and company activity in the countries. The high numbers are especially due to two growth companies, Bluefors and IQM, which both arise from the long term quantum technology research in Finland, i.e. the success represents past, long term public funding, not current or future funding. With the current large programs in Sweden, Netherlands and Denmark, the Finnish ecosystem is facing serious competition. Especially the wide approach taken by the Netherlands, where already a vibrant RDI ecosystem including universities (TU Delft), RTOs (TNO) and companies exists, promises to create a strong ecosystem, with stated goal of 100 start-up companies by 2027.

[12]Actual division not known but focus mostly in RDI.
[13]Sources: Novo-Nordisk Foundation, Wallenberg foundation, Quantum Delta, Heinrich Böll Stiftung, Qureca

Table 3.

Country	Com-panies	Turn-over (M€)[14]	Emp-loyees[14]	Start-up[15] funding (M€)	Granted Patents w/o global companies[16]	Patent applications w/o global companies[17]	Applications and grants with global companies[18]
Finland	11	130	460	280	14	15	29
Sweden	4	10	20	9	2	8	11
Denmark	7	60	250	2.3	2	3	8
Germany	32	180	1 200	450	18	50	141
Netherlands	13		130	12	11	6	26

Summary of quantum technology business ecosystems in selected reference countries.

Finland's relatively high number of patent applications emphasize a vivid innovation ecosystem with significant company RDI investments. It is worthwhile to note, that Netherlands and Germany also attract more foreign company patent applications, marking the potential market size and possibly more international company RDI in the countries.

Research infrastructures

Research infrastructures are crucial for high quality work in quantum technologies. The national OtaNano research infrastructure[19] is hosted and operated by Aalto and VTT. It is used by approximately 700 users annually. OtaNano is the key state-of-the-art resource for experimental quantum technology research in Finland. It forms one of the largest fabrication centres for micro- and nanoelectronic devices in the Nordic countries.

The large fabrication centre Micronova is part of OtaNano, and it provides significant asset of modern pieces of fabrication equipment that are needed for manufacturing high-end quantum technology components. In addition to quantum technology, the fabrication centre supports microelectronics especially in MEMS sensors, integrated photonics, RF technologies and 2D materials. VTT coordinates the quantum pilot line framework in the European quantum Flagship, that provides an important route for upgrading the existing pilot line facilities in Micronova.

The microelectronics industry in Finland is large (~ € 2 billion annual revenue[20]), and many of the growth SME companies rely heavily on the Micronova cleanroom environment for their research and development. Current cleanroom capacity is too small to allow for the growth of the microelectronics or quantum technology ecosystem,

[14] As many companies are young and mainly spending money, several companies reported no data – especially in the Netherlands. Their turnover and personnel number was estimated conservatively.
[15] JV / start-up funding estimates from literature were used. These estimates contain funding from start of QT era i.e., about year 2 000.
[16] IPC + CPC, INPAFAM/STN, granted patents, without foreign owners, priority date 2010 or after
[17] IPC + CPC, INPAFAM/STN, applications, without foreign owners, priority date 2010 or after
[18] IPC + CPC, INPAFAM/STN, applications and patents, with foreign owners, priority date 2010 or after
[19] otanano.fi
[20] https://teknologiateollisuus.fi/fi/teknologiateollisuus/toimialaryhmat/puolijohdetoimialaryhma

and hence additional capacity is needed around 2025 and forward.

The semiconductor industry group at Technology industries Finland and VTT have recently proposed a joint quantum technology and microelectronics clean room pilot line investment.[21] This would scale up the much-needed capacity and capabilities for the mutual benefit and development of both industry ecosystems in Finland.

OtaNano houses also excellent characterization setups which allows detailed imaging of the fabricated components and measurement of quantum devices in low temperature facilities with more than 20 sub-kelvin cryostats. The research infrastructure operates on open access principles and serves users as part of the European Microkelvin Platform (EMP). Also, VTT participates in the quantum testing and characterization framework of the European quantum Flagship, that provides a useful route for upgrading the existing testing facility. The annual acquisitions budget of OtaNano is about € 3,5 million, and the upkeep and personnel costs are about € 3,0 and 2,0 million per year, respectively.

The national quantum computer development has recently sparked the formation of the Finnish quantum computing infrastructure (FiQCI), with first devices installed and operational.[22] Their acquisition has been supported by a € 20,7 million grant from the government to VTT, and a further € 3,7 million research infrastructure funding from the Academy of Finland to the parties maintaining and developing FiQCI: VTT, CSC – the Finnish IT centre for science, and Aalto University. A central part of the infrastructure is its tight link to the high-performance computing (HPC) infrastructure operated by CSC. The quantum-computing infrastructure is built around the pan-European LUMI supercomputing infrastructure, hosted by CSC in Kajaani. Finnish researchers are the first in Europe with open access to a hybrid HPC+QC supercomputing environment. The ecosystem around LUMI is growing, with work to set up a pan-European distributed HPC+QC supercomputing environment starting in 2023. Beyond the emerging national infrastructure, online access to other available quantum computing resources is utilized for algorithm development scaled to larger quantum devices.

The Finnish quantum key distribution (QKD) network (NaQCI) is implemented as part of the European Quantum Communication Infrastructure[23], aiming at building a secure quantum communication infrastructure that will span the whole EU. Finland has signed the declaration to join the infrastructure in 2019 and the first stage investment is ongoing with a € 4,1 million national funding share. The work, led by VTT involves also CSC, ERVE[24] and Cinia[25] (state-owned special purpose companies).

The Nanoscience Centre (NSC)[26] at the University of Jyväskylä host research infrastructure, relevant for the development of the field. The NSC infrastructure includes a clean room with state-of-the-art nanofabrication instruments, 7 sub-kelvin cryostats, high-level microscopy systems, and a laser laboratory for ultrafast measurements. The facility is constantly being updated and improved, with an annual depreciation level of 0.9 M€. The NSC cleanroom facilities are currently being extended to cover 270 m^2, which will provide an excellent opportunity to take advantage of both the existing high-level NSC equipment and the future investments on the roadmap to benefit the national quantum technology community.

[21] https://www.vttresearch.com/fi/uutiset-ja-tarinat/suomeen-suunnitteilla-kansainvalinen-mikroelektroniikan-ja-kvanttiteknologian?utm_content=230414850&utm_medium=social&utm_source=twitter&hss_channel=tw-66325641
[22] https://www.vttresearch.com/en/news-and-ideas/finlands-first-5-qubit-quantum-computer-now-operational
[23] https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci
[24] https://www.erillisverkot.fi/en/
[25] https://www.cinia.fi/en/
[26] https://www.jyu.fi/science/en/nanoscience-center

The University of Eastern Finland and Tampere University host valuable photonics infrastructure for the national quantum technology development, spanning photon sources and sensors, photonic materials, and components, as wells as extensive clean-room facilities for micro- and nanofabrication. The photonics infrastructure belongs to FinnLight, which is part of the roadmap for Finnish research infrastructures (FIRI) established by the Academy of Finland.

Education

Building on strong tradition in research, several universities provide strong education in physics, engineering, mathematics, and computer science. Aalto University already runs Bachelor's and Master's levels majors in quantum technology. National level development of education has been started with a cooperation agreement on quantum technology education in the Helsinki metropolitan area (QuantEd), allowing undergraduate and postgraduate students to take courses from Aalto and University of Helsinki curricula[27] without additional costs. The first international master programs in quantum technology[28], and workforce retraining programs are emerging in EU funded initiatives, with Finnish parties involved.

Organization of the community

In 2021, Aalto University (Aalto), University of Helsinki (UH) and VTT established a collaboration called the Finnish Quantum Institute – InstituteQ[29] . The general mission of InstituteQ is to raise the readiness of Finnish society for the disruptive potential and implications that quantum technologies will have for society and the economy at large. By teaming up expertise and resources, the institute aims to carry, implement, and mutually benefit from front line research, education, innovations, and infrastructures, forming a competitive edge in the quantum race.

The work in Finnish universities and research organizations provides academic and technological research contributions on areas that are highly relevant to the development of the field in a long term. Altogether, close to 90 groups work in the areas relevant to this field, some with core activities and others with parallel activities supporting the field of quantum technologies.

Via its strategic national role, VTT has taken significant steps towards building the national quantum innovation ecosystem. In 2021, several Finnish companies and VTT signed a Memorandum of Understanding (MoU) launching coordinated development of the business ecosystem on quantum technologies in Finland (BusinessQ). The membership is open to interested stakeholders with no financial or legal commitments. BusinessQ operates as an independent collective within the framework of InstituteQ, based on common principles and expectations defined in the MoU. This is to make the membership as easy as possible to attract the wider business and other stakeholder communities.

[27] https://www.aalto.fi/en/research-art/study-quantum;
https://www2.helsinki.fi/en/researchgroups/instituteq-the-finnish-quantum-institute-university-of-helsinki/courses
[28] https://qt.eu/about-quantum-flagship/projects/education-coordination-support-actions/
[29] https://www.aalto.fi/en/news/finnish-quantum-institute-announced

BusinessQ brings together InstituteQ partners, companies with quantum expertise, as well as potential end-users[30]. It fosters the building of a national business roadmap with a goal to broaden the impact of quantum technology in industry and business in Finland. The business roadmap is aligned with the national agenda.

The quantum computing environment in Finland is developed in strong European collaboration. Here, CSC plays a central role in access provision to combined high-performance / quantum computing (HPC+QC) platforms. The work benefits strongly from the availability of the pan-European LUMI supercomputer, hosted by CSC.

Beyond the core area of quantum technology, the community extends to adjacent technology areas that play a key role in Finnish research, development, and industrial ecosystem. Those include the areas of micro- and nanoelectronics and photonics, telecommunications, and cybersecurity.

[30] https://instituteq.fi/business

Recommendations

Background

The following recommendations are aimed at providing long-term support for high-quality activities in the area. They concentrate on supporting the work of excellent researchers and innovators by providing them with good working conditions. The working conditions include the research and development infrastructures, the ecosystem of different organizations, the long-term availability of funding, quality of students, and any other relevant measures.

A long-term commitment by the Finnish government agencies and universities for quantum technology in Finland would send a strong signal to researchers and companies interested in working in Finland in this area. Such a commitment would imply that Finland is an attractive place for people and companies working in the area, both for those already here and for those looking for good destinations. The closest peer countries, Sweden, Denmark, and the Netherlands, have all published long-term funding programs. There is a real danger that Finland loses its image and status as the European quantum hub if the national funding and support for infrastructures remain mediocre or short-term. Thus, a coordinated support package covering all aspects of quantum technology, from RDI, education, infrastructure, and ecosystem to societal and applications development, is needed in Finland.

The recommendations do not make any choices between different subareas of quantum technologies. The boundaries between subareas are fluid, and the working group believes that it is important to provide support based on excellence and impact, not based on the subarea of quantum technologies. The thematic funding programmes are suggested to be allocated by existing agencies, Academy of Finland and Business Finland, using their criteria for excellence and impact, but with no hard constraints on the subareas.

Developing an area such as quantum technology cannot rely solely on short-term funding programs. As universities are the key actors in research and education, their commitment to the area is crucial. The commitment should be expressed by establishing professor positions, by creating and upscaling educational programs, and by improving research infrastructure. As for research institutes, VTT has a special position in developing quantum technology, and thus we also give a recommendation related to it.

Recommendations

1. **A coordinated research and innovation funding programme**

1.1. Establish research program for quantum technologies from the Academy of Finland.
1.2. Either in connection with above or separately, open a research program or calls from the Academy of Finland for cooperation with the Nordic countries and the USA[31].
1.3. Start innovation programs for quantum technology from Business Finland, targeted either to the whole area or to specific subareas.
1.4. The above research and innovation funding programs should be coordinated jointly by the Academy of Finland and by Business Finland, so that there is no gap between research and innovation activities.

2. **Research infrastructures**

2.1. Establish a long-term program for national and local infrastructures.
2.2. Universities and research institutes should commit to the funding for personnel and upkeep of the research infrastructures.

3. **Ecosystem development**

3.1. Start further development of the Finnish quantum technology ecosystem with funding from Business Finland.
3.2. Develop the Invest in Finland activities of Business Finland in the area of quantum technologies and include quantum technologies as an investment focus area of the Finnish Industry Investment Ltd (TESI).
3.3. Finland should participate in the standardization and regulation activities in the area to provide the companies and research performing organizations with a good operating environment.

4. **Education**

4.1. Strengthen university education in quantum technologies.
4.2. Support research, innovation, and education in quantum technologies by establishing professorships within the area.
4.3. Establish master's and bachelor's level educational programs in the area. It would be useful if the universities would cooperate in planning and running the programs[32]
4.4. Establish a national Ph.D. program funded, e.g., by the Ministry of Education and Culture.
4.5. Establish and promote retraining and upskilling courses to companies and industries engaging in quantum technology. Develop targeted and well-structured outreach initiatives on quantum science and technologies.

[31] International cooperation is suggested with likeminded techno-democracies beyond the existing opportunities provided by the mechanisms of the European Union. Countries that are suited within this scope include the Nordic countries, USA, United Kingdom, Switzerland, Canada, Singapore, Japan, and Australia.
[32] The fields of supporting technologies are also important when discussing the educational efforts.

5. **General recommendations**

The timespans of the recommendations are different, and some of them should be started immediately, while others can, or they must wait for some time. For the largest possible impact, the actions should still be coordinated and pursued as a coherent whole. Below we list some general recommendations, focusing on strengthening the existing actors within the quantum community.

5.1. A national quantum strategy for Finland would be highly desirable.
5.2. The role of VTT as a research institute and in facilitating the cooperation between the research and innovation activities is important and it should be fostered.
5.3. The important role of CSC as a service provider and a hub for quantum and hybrid quantum-classical computing should be supported and continued.
5.4. To facilitate cooperation within the area, the scope of InstituteQ should be expanded to cover all universities and research institutes that are relevant for quantum technologies, while maintaining its role as a light coordination entity.
5.5. The quantum technology community should continue to actively search for European and other international funding with the best possible partners. The community and the government should collaborate in influencing the European research and innovation agenda in this area.
5.6. If the Academy of Finland opens a new call for flagships, the quantum research community should form a focused application to that call.
5.7. Equality, diversity, and inclusion aspects should be actively pursued in this emerging area – here, universities play an important role, even if efforts are required by all stakeholders.

Suggested volume of the research programmes

The working group has estimated the volume of research and innovation programmes by using the current state of the area as the starting point. The bottom-up research funding is approximately € 45 million per year.

A research program for quantum technologies from the Academy of Finland could have a length of four years and with a total volume of about € 12 million, i.e., € 3 million per year.

For strengthening the attractiveness of Finland, it would be very useful if there would be a possibility of extension. The start date of the research program should be 2023 or 2024. In connection with this program a special research program for cooperation with the Nordic countries, the USA and other likeminded techno-democracies would be very useful, with a volume of, e.g., € 4 million.

Innovation programs for quantum technology from Business Finland, targeted either to the whole area or to specific subareas. The total volume of these programs could be € 20-30 million starting in 2023 for four years and possible continuation program of similar value.

If feasible, the research and innovation funding programs should be coordinated jointly by the Academy of Finland and by Business Finland. One of the strengths of the area in Finland is the seamless cooperation between research and innovation activities, and a jointly coordinated pair of programs could guarantee that this continues.

Professorships: a recommendation of 5-10 new professorships during 2023-2027. A reference can be obtained from Sweden. There the Wallenberg foundation gave a € 130 million (over a period of 12 years) donation to quantum research. The donation included a condition: the participating universities should establish at least 14 professorships in the area.

Details of the infrastructure investments

There are several kinds of infrastructure that is needed for successful development of quantum technology and its applications. The infrastructure needed for quantum technology can also be used in other areas, e.g., microelectronics and photonics.

These infrastructures are:

1) Cleanroom infrastructure for developing and manufacturing quantum devices, components, and systems. Cleanroom infrastructure is an extensive and expensive investment, including both the laboratory space with the required cleanliness as well as the processing equipment inside. The expected manufacturing volumes of quantum devices are quite low (in comparison to typical microelectronics fabrication facility outputs). Thus, it is advisable to invest in selected national clean room infrastructure that would serve both academia and SME companies in their research, development, and innovation actions in complementary areas.

The existing OtaNano cleanroom environment should be utilized and further developed to support quantum technology needs. The optoelectronics infrastructure in Tampere and the photonics and materials research infrastructure at the University of Eastern Finland could be utilized in strengthening quantum optics related research, development and innovation activities, while the facilities of Nanoscience Center at the University of Jyväskylä form a link of bioscience research to quantum technology. Development of these infrastructures would also support microelectronics, optoelectronics, and photonics companies to scale up in Finland.

As a new initiative, the recently proposed pilot line clean room[21] is crucial for the quantum technology ecosystem development and growth in Finland. It forms essential part of the quantum infrastructure investment plan, while also supports the large national microelectronics industry. It clearly extends the impacts of the investments beyond this agenda. Importantly, European funding to cover part of the public investment costs may be available since the pilot line also supports the European Chips Act goals of innovation leadership and security of supply. The investment includes both new process equipment and a new cleanroom area for companies for their own equipment and use. The plan combines public and private investments for best impact.

In addition to this, the commercially run cleanroom operated by IQM could serve as a fab that enables production level scale-up for new products.

2) Research, development, and testing infrastructure is critical for studying and characterizing the components manufactured and developed with the cleanroom environment, and in building functional systems and products out of the components. This infrastructure can be more distributed in different universities and institutes in Finland, with specific smart specialization. The typical investments required are cryostats, characterization equipment and control electronics. The testing and evaluation facilities should cover technologies from quantum communication (included e.g., NaQCI QKD test network) and quantum photonics (e.g., quantum photonic integrated circuits (QPICs)) to superconducting quantum systems, and quantum sensors. The testing and evaluation facility should be openly accessible for companies and academia to support ecosystem growth in the best manner possible. As a note, the testing capacity is already a bottleneck in quantum device, product, and service development, even though universities and VTT house several cryostats, for example. Companies also have special interest towards open-architecture infrastructure that allows plug and play testing of components and middleware operating the actual hardware.

3) Quantum computing infrastructure enables development of quantum algorithms, software, and the use of quantum computers for practical applications. This sets requirements of smooth integration with classical computing infrastructure, as well as development and integration of efficient quantum software and algorithms for near term quantum computers.

The quantum technology research and growing business ecosystem in Finland needs in-depth access to quantum computing infrastructure. This can be approached through building or buying quantum computers, or by providing access to quantum computers available on the cloud.

Building a quantum computer educates trained workforce and creates capabilities in hardware construction; such development work can create important knowhow and intellectual property that can be significant for the Finnish quantum ecosystem.

Through procurement, alternative hardware platforms can be made physically accessible for hardware and software developers in Finland. By remote access to the most advanced (academic or commercial) quantum computers in the cloud, efficient quantum algorithm development for larger quantum devices can be enabled.

Besides access to state-of-the-art hardware, expertise in quantum algorithms and in all layers of the software are crucial for developing useful applications of the devices. The development of such algorithms and software needs also strategic investments.

Also, the open access and open architecture should be taken into account in infrastructure investments: they would make it easier for researchers and smaller companies to participate in cutting edge research both in hardware and in software.

The landscape of quantum computation is changing rapidly, and it is hard to judge which technology platform will become the most successful one. The superconducting technologies, where Finland has its highest competence, are currently leading the field. Access to international quantum computing resources, alternative computing platforms and their software at all levels are all important to maximize the opportunities of the Finnish community.

We also remind of the possibilities in using the European resources made available via e.g., EU Quantum Flagship and EuroHPC calls, with their possible requirements for national matching funding.

4) National quantum communication infrastructure (NaQCI) is part of the European large-scale effort to build a quantum secure communication shield across the EU. The Finnish implementation forms the national section of this quantum-based combined terrestrial and space communication infrastructure. Ultimately, in 15-20 years, EuroQCI would evolve into a quantum Internet, linking quantum processors and sensors and enabling an EU-wide distributed quantum computing and communication capability. The development actions of NaQCI are carried out as joint efforts between the Member States and the European Commission. The next stage includes setting up a QKD network between Finland and Estonia or Sweden. NaQCI works also as a testing and development platform for quantum communications and QKD for Finnish universities, research and technology organizations and companies.

Estimates for the infrastructures

The cost of the instrumentation needed for the current cleanrooms and for the research development and testing infrastructure can be estimated on the basis of current depreciations (about € 3,5-5 million/ year at OtaNano) and planned extensions.

An infrastructure program, supporting the development of the fabrication facilities as well as development and evaluation facilities should be erected, with total volume of 50 M€ during the next eight years. This would support fabrication equipment investments with about 20 M€, and development and testing facilities with about 30 M€.

Furthermore, a one-time investment into microwave electronics and cryogenic upgrades for € 3-4 million would help in alleviating the acute problem in test capacity of low-temperature characterization at the universities.

A new cleanroom infrastructure for joint use by academia and companies, supporting both quantum technology as well as microelectronics, has an estimated cost of € 90 million[21]. Preliminary estimates include approximately half of this to be private investments, including the cleanroom building by a real estate developer. The approximately € 45 million of public funding would be needed in particular for the process equipment available for academic and industrial research and development. Additional needs for cleanrooms might result from an industry-led initiative for possible large-scale production of quantum circuits and other components. One such project, as mentioned earlier in this document, is the extension of the commercially run cleanroom operated by IQM with planned total investment size of € 280 million, of which 25% is currently budgeted by the company as funding from various public sources.

Quantum computer development towards first demonstration of quantum advantage with above 100 qubits in Finland is estimated to cost € 25 million in hardware and software development immediately after the current 50-qubit development project is finished i.e., in 2024. Raising the level of ambition further (estimated 300 qubits and industry relevant quantum advantage) could cost another € 45 million.

Development of a quantum computer in Finland with the goal of reaching quantum advantage would be useful for several reasons given above. However, it is also recommended that the rapid global development of quantum computers is closely monitored.

The 2nd stage estimates on EuroQCI implementation (2024–) have estimated national cost of € 4,1 million. Decision on joining the next stage is to be done separately.

In summary, the working group recommends that

(i) the current short-term needs of the quantum technology infrastructures are met with targeted infrastructure funding,

(ii) an infrastructure program is initiated for supporting the development of smaller scale infrastructure and for the larger cleanroom and quantum computing infrastructure, and

(iii) the infrastructure program is coordinated together with the research and innovation programs. As part of the coordination work, roadmap for all the infrastructures, should be created.

Appendices

Appendix 1: Finnish Quantum Agenda working group

The Finnish Quantum Agenda was produced by a working group during Sep-Dec 2022. The working group convened five times during that period. In addition, an infrastructure task force convened once for additional information gathering. A Finnish quantum community meeting (hybrid) was organized on 31 October to collect additional input to the agenda work.

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Appendix 2: National and international documents

Quantum technologies are identified as an emerging field of technology with broad potential impact in our society, requiring also political decision making. So far, the aspects of quantum technologies have been scattered around different national documents and covered only superficially. This agenda acknowledges following national level reports and declarations, that address quantum technologies to varying extent:

- Ministeriöiden tulevaisuuskatsaus 2022: Yhteiskunnan tila ja päätöksiä vaativat kysymykset, the futures review assessing projections and situations in society and examining issues involving political decision making, VN 2022:58. The review addresses a need to draft a national quantum strategy.

- Tekoäly 4.0 ohjelma 2020–2023, a national program on artificial intelligence. The reports of the program propose increase in long term research funding to quantum technologies, resourcing of universities and research organizations to secure a pioneering role in quantum computing, and a quantum campaign for companies and research organizations. In addition, low threshold education and information on quantum technologies is endorsed.

- Ecologically sustainable digitalization contributes to climate targets, final report of the working group preparing an ICT climate and environment strategy, Ministry of Transport and Communications, LVM 2020:19. The report addresses quantum technology as one of the emerging technologies that enable future ICT solutions and services, and with potential to lower the climate and environmental impact of various sectors.

- Societal transformation 2018–2037, 100 anticipated radical technologies, 20 regimes, case Finland, publication of the Committee for the Future, Parliament of Finland, 10/2018.

- D9+ Declaration: Leading the Way to Europe's Digital Decade, agreeing to encourage the development and deployment of disruptive technologies, such as quantum technologies, including through investments and strengthening their cybersecurity. TEM 2021.

- Finnish quantum computing development roadmap, VTT-R-01085-21, unpublished.

- Kvanttiteknologian yhteiskunnalliset vaikutukset ja mahdollisuudet Suomen kannalta – katsaus päätöksentekijöille, a review for decision makers on societal implications and opportunities of quantum technologies for Finland, Finnish Academy of Science and Letters 2023.

As a reference point for this agenda, several international agendas and strategies on quantum technologies exist. The European context of operation is acknowledged as defined in following documentation:

• Strategic Research and Industry Agenda (SRIA) 2022. A preliminary release of an update to the EU's quantum technology strategy, aligning the existing Strategic Research Agenda (SRA, 2020) and the Strategic Industry Roadmap (SIR, 2021), as well as the new and forthcoming programmes such as the European Chips Act and EuroHPC Joint Undertaking.

• EU's digital compass 2021. Communication from the European Commission to the European Parliament, the council, the European Economic and Social Committee and the Committee of the regions. Addressing the need to invest in new quantum technologies, development of quantum computers, and securing European sustainable federated supercomputing and quantum computing data infrastructure.

• The European Chips Act (target of acceptance early 2023). Availability of high-quality chips is a key asset for key industrial value chains. For quantum technology, the Act requires acknowledgement of both technologies for dedicated quantum chips as well as classical chips technologies for quantum (enabling technologies). The former includes development of innovative design libraries for quantum chips, pilot lines and testing/ experimentation facilities, and the latter integration, packaging, and development of e.g., cryogenic chips. The European community has successfully promoted the inclusion of this aspect to the Act.

The existing national agendas and processes benchmarked for the Finnish Quantum Agenda include:

- Danish quantum agenda (2022),
- Swedish quantum agenda work (ongoing in parallel with FQA),
- Dutch National agenda on quantum technology (2019),
- UK National Quantum Technologies Programme strategic intent (2020), and the preceding national strategy (2015),
- US National quantum strategy (2018),
- French Quantum Plan (2021),
- Australian National quantum strategy work (2022).

Institute Q