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INSTITUTEQ
THE FINNISH NATIONAL QUANTUM INSTITUTE

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INTRODUCTION: QUANTUM SCIENCE AND TECHNOLOGY LANDSCAPE

The discovery of Quantum Mechanics is now about one hundred years old [1-4]. Although the interpretation of Quantum Mechanics, meaning the ontology underlying the postulates, still remains object of investigation and controversy see e.g. [5,6], the application of the mathematical formalism stemming from the postulates has not only permitted enormous advances in the understanding of Nature at molecular atomic and sub-atomic scales but has also triggered technological innovations that invest almost every sector of every day life. Quantum Mechanics made possible in the middle of last century the invention of the transistor, an event which may well epitomize what it is now commonly called the "first Quantum revolution". Microchips, broad-band internet and satellite navigation are tangible examples of the overwhelming societal and commercial impacts of the first quantum revolution. On their turn, these technologies have also paved the way for nanomanipulation protocols permitting control and application of previously untouched and fragile quantum phenomena [7]. Effects like superposition, in which particles seem to assume multiple states until they are observed, and entanglement, in which the properties of a multi-partite quantum system are tied together in a manner independent of the spatial separation of individual components, are now set to offer the potential for completely new technical solutions. A "second Quantum revolution" [8] is thus now underway. On the horizon is the possibility to fulfill the vision [9-12] of realizing Fault-Tolerant Large Scale Quantum computers (FT-LSQ) permitting to execute certain computational tasks exponentially (e.g. quantum Fourier transform and prime factorization using Shor's algorithm [13]) or polynomially (e.g. search in unsorted databases based on Grover's [14]) faster than on high performance classical computers (HPC): the so-called Quantum computational advantage. Very recent milestone experiments well illustrate the reasons for outlooks' relative optimism [15,16]. In the fall 2019 Google released the "Sycamore" [17] a quantum circuit consisting of 53 qubits and 20 cycles of unitary operations to demonstrate the experimental feasibility of a noisy sampling task. Just a few months later, a team led by Jian-Wei Pan (潘建伟) at the University of Science and Technology of China (USTC 中国科学技术大学) presented an experimental implementation of boson sampling with 50-70 detected photons by a device called "Jiuzhang" (九章) [18]. Boson sampling is a protocol proposed by Aaronson and Arkhipov [19] to use non classical light to generate quantum computational advantage. In September 2021, a second team also led by Jian-Wei Pan announced [20] that a 66-qubit two-dimensional superconducting quantum processor, called "Zuchongzhi (祖冲之) 2.1" is able to perform sampling tasks with a classical computational cost about 6 orders of magnitude and 5000 times higher than that of the hardest tasks on Google's Sycamore. Many experts interpret these results as indicating that quantum computing technologies are reaching the performance levels required for near-term applications of Noisy Intermediate Scale Quantum (NISQ) type [21]. In NISQ quantum gates' noise limits the size of quantum circuits that can be executed reliably. Up-to-date expert surveys [22-25] identify quantum simulation, quantum linear algebra for AI and machine learning, quantum optimization as archetypical problems that NISQ devices may help tackling with direct industrial impacts respectively in the pharmaceuticals, chemicals, automotive, and finance sectors. The NISQ stage of quantum computing is meant to be an intermediate step towards LS-FTQ [26]. Indeed, the achievement of quantum computational advantage will not consist of one-off experimental demonstration [20]. Rather, the aforementioned experiments are part of long-term competition between the development of new classical simulation algorithms (see e.g. [27]) and quantum devices. Even in the eyes of skeptical observers such competition is inherently triggering "major advances in human ability to simulate quantum physics and quantum chemistry" [28].

The benefit of introducing quantum hardware is only realised if accompanied by the development of new quantum algorithms. Information processing quantum and classical is thus set to play an essential role in the unfolding of the second quantum revolution. Shor's algorithm [13] by enabling exponential speedup of integer factorization poses a vital threat to the security of current public key cryptography. Although estimates vary on when a quantum computer powerful enough to realize this threat will be built [16], reports of many governmental agencies (see e.g. [29-31]) call for an accelerated transition to quantum resistant algorithms actively developed by ongoing research in post quantum cryptography (PQC).

Advances in material nano-manipulation also open new avenues to exploit the natural sensitivity to environment of quantum mechanical superposition states to device new generations of high accuracy sensors (see e.g. [32]). These techniques promise immensely important developments in fields as diverse as brain imaging and particle detection [23,33].

In order to sustain and accelerate the rapid advance of fundamental and applied research of quantum technologies, governments around the world have during the 10th of this century announced massive investments. Among leading public players [34], China has announced about $15 billion in funding as part of the 14. 5-year plan (2016-20), the European Union $ 7.2 billion summing the funding prominently coming from the EU-Quantum flagship research and innovation initiative started in 2018 [35] (about 14% of total) and from the German [36], French [37] and Dutch [38] national plans (respectively about 42%, 28% and 12% of the total investment).

As of 2021 US, UK, India and Japan governments have also announced funding directly devoted to Quantum technology of the order or slightly above $ 1 billion.

Corporate investments are also surging [34]. Google has publicly committed to attain quantum advantage with an investment of several billions dollars guided by roadmap aiming at the realization of a FT-LSC by 2029 [16]. IBM's roadmap [26] aims at delivering FT-LSC by 2030. On schedule, at the beginning of 2022, IBM announced breaking the 100-qubit barrier with the release of the Eagle processor [39]. Besides Google [40] and IBM [39], major corporations such as Alibaba [41], Amazon [42], and Microsoft [43] have also already launched quantum-computing cloud services [15]. Investments are not limited to big corporate. In 2021 alone, announced investments in quantum-computing start-ups have surpassed $ 1.7 billion, more than double the amount raised in 2020. The overall estimated value at stake for quantum-computing players is nearly $ 80 billion [34].

INSTITUTEQ AT THE CENTER OF THE QUANTUM TECHNOLOGY LANDSCAPE IN FINLAND

Finland has taken major steps to promote Quantum technologies via the establishment in 2018 of the na- tional Centre of Excellence (CoE) in research **Quantum Technology Finland (QTF)** [44] with a yearly operational volume of C12 million for 8 years (2018-2025) and, in June 2020 via a C20, 7 million acqui- sition grant from the Government to VTT to pursue a quantum computer. In November 2021, VTT then announced the entry into operation of **Finland's first 5-qubit quantum computer** [45].

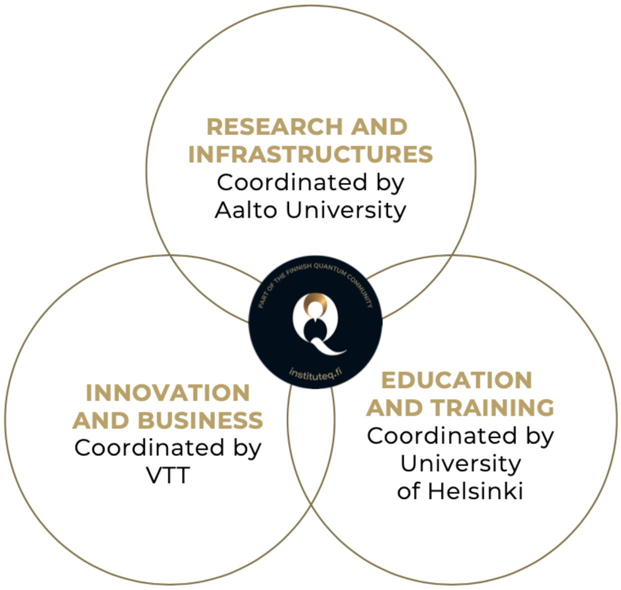
In order to coordinate national efforts by teaming up more broadly the existing expertise and resources, on March 31st 2021, the key players in quantum technologies - Aalto University, University of Helsinki and VTT Technical Research Centre of Finland (VTT) signed an agreement to collaborate on quantum science and technology, under the umbrella of **InstituteQ: The Finnish Quantum Institute** [46]. So far, close to 50 groups have joined the collaboration representing the versatile QT relevant expertise in theoretical, experimental, and applied physics, chemistry, computational science, mathematics, materials science and technology, nanoscience and nanotechnology, electrical engineering and electronics, neuroscience, eco- nomics, education and philosophy. The creation of the Institute has following general objectives:

- To enable the partners to develop, coordinate and carry out internationally highest-level research in quantum science and technology.
- To provide the best possible education for future workforce in this field, both in graduate and in- dustrial programs. To achieve this goal the institute will serve as platform for coordinating national training programs (Ph.D. & M.Sc.).
- To drive innovation and leverage the national ecosystem building in quantum technology.
- To foster the development of relevant national infrastructures in quantum technology.

The need to team up resources and expertise across a wide spectrum in a collaborative center to pursue goals akin to those of InstituteQ is also demonstrated by similar initiatives across the EU. To only mention few examples from countries of size comparable to Finland, the **Vienna Center for Quantum Science and Technology (VCQ)** [47] unites quantum physicists of University of Vienna, the Vienna University of Technology, the Austrian Academy of Sciences, and the Institute of Science and Technology Austria in order to set new impulses for research and teaching in Quantum Science and Technology. **The Quantum Delta NL** [38] consists of five major quantum hubs (Amsterdam, Delft, Eindhoven, Leiden, and Twente) and several universities and research centres to work together on the frontier of quantum technology. In Denmark, the Department of Physics and Astronomy at Aarhus University, Department of Physics at the Technical University of Denmark, and the Niels Bohr Institute at Copenhagen University initiated in January 2020 the **Danish Quantum Community** [48] with the aim of uniting all national stakeholders to advance the development of quantum technologies. Nevertheless, the fall 2020 report [49] of the danish Industriens Fond – KPMG emphasizes the need of further enhancing coherence among Danish quantum technology players. The case for a national Quantum institute is also there clear.

STRUCTURE OF INSTITUTEQ

InstituteQ is a "*virtual organization*" whose structure reflects the Institute's mission. The collaboration is led by *Leadership Committee* comprising of rectors of the university partners and the CEOs of the other partners. The Leadership Committee appoints a *Steering Group* supervising and steering the collaboration within InstituteQ. The development of the activities is led by an *Acting Director*, appointed from among the senior academic personnel of the coordinating partner. InstituteQ implements three main operation lines, one in research and infrastructures (*ResQ*), one in education and training (*EduQ*) and one in business and innovation (*BusinessQ*). The operations lines have appointed *Operations Leads* and *Working groups* in charge of coordinating and implementing the objectives of the institute. All personnel engaged in the collaboration are in an employment relationship with their host organization, and with double affiliation to InstituteQ by discretion of each party. Administration and services for the institute are produced by the partners subscribing the agreement. For the time being, the operations are in the preparation stage, and they will be ramped up, contingent



Areas of operation of InstituteQ. The collaboration is supervised by the InstituteQ Steering Group and Leadership Committee with members from all the participating institutions. Each area is coordinated by one of the partner organisation and developed by a working group.

upon funding confirmations by external sources as well as any commitments by the partner organizations. The main motivation of the collaboration is to set in motion coordinated development of the field and leverage longer-term resourcing of this field in Finland. Active members can best contribute by joining the working groups.

RESQ SUSTAINS RESEARCH

For decades research groups in Finland have pursued theoretical, computational, and experimental activities which altogether constitute an exceptionally strong and globally unique patrimony in quantum science and technology. For instance, Finland's long and successful research tradition in low temperature physics, sensor and cryogenic technologies is worldwide recognized.

The mission of the ResQ working group is to coordinate and foster top-level cross-disciplinary research. In fact, the emerging needs of quantum technologies now require to encompass a very broad spectrum of fields ranging from quantum machine learning and algorithms to philosophy and mathematical logic and from quantum materials to neuroscience and biomedical engineering [50]. An enormous potential for in- novative research stems from building synergies between groups affiliated to InstituteQ which are also part of Finnish centres of excellence such as the aforementioned QTF, **the Finnish CoE of Inverse Modelling and Imaging** (2018-25) [51] whose focus areas are nonlinear partial differential equations, geometry, and uncertainty quantification, and the very recently established **Finnish CoE in Randomness and Structures** (FiRST) (2022-29) [52] whose research themes are at the crossroads between probabilistic methods, quan- tum and conformal field theory, geometric and harmonic analysis, partial differential equations and analytic number theory.

Achieving international scientific success in a small country such as Finland requires utilizing efficiently available resources for the benefit of the community and collaborating with best partners around the world. Taking maximum advantage of funding opportunities and in particular those offered by the European Quantum Flagship plays an essential role. During 2014-2020 EU programs funded projects with Finland based coordinators got about 3% percent of all funding for quantum-relevant projects against a 2% of the gen- eral funding share obtained by Finland [49]. Whereas these data already witness the strength of Finland based research in Quantum related fields in comparison with other fields, they also indicate the existence of margin of improvement. Countries such as Denmark, Switzerland and Austria in the same time span respectively obtained 8%, 6% and 5% of the EU quantum funding share. One of the goals of ResQ is thus to enable enhanced research partnering in European Quantum Flagship calls.

Efficient use of intellectual resources concretely means ensuring the conditions to retain top scientists coming from the Finnish ecosystem and to attract talents from abroad at all research position levels. To this goal, InstituteQ is collaborating with other Quantum Science and Technology centres in the international landscape (for instance the Swedish **Wallenberg Centre for Quantum Technology - WACQT** [53]) and with companies to build a strong post-doc fellowship program, for example. The realization of the pro- gram is subject to European funding, for which the community recently submitted a proposal. Another envisioned initiative is the creation of

InstituteQ Chairs of Excellence to recruit outstanding researchers to develop new research directions, or to reinforce existing research themes. Other plans to sustain interna- tional collaborations include high profile visitor program and series of scientific events that serve the needs of the community.

An important part of the mission of ResQ is to foster the development and promotion of the Finnish research infrastructures in the area of quantum technology. A prominent example of such infrastructures is **OtaNano** [54], that is an open access research infrastructure jointly operated by Aalto University and VTT. It provides advanced fabrication, measurement and characterization tools for academic and commercial users working on quantum technologies. Building the new **Finnish Quantum Computing Infrastructure** (FiQCI) is expected to gain significant leverage from the use of OtaNano. The ResQ efforts focus on influencing the development of important infrastructures, as well as ensuring access to critical tools and hardware platforms. The community shall also look for models to enable efficient use of fabrication lines and sharing of know-how within the community.

EDUQ DEVELOPS EDUCATION, TRAINING AND OUTREACH

Current estimates [55] predict an exponential growth in job creation in the field of Quantum Science and Technology with a projection of more than half a million new jobs around 2040. The expected exponential growth poses multifarious challenges to education in Quantum Science and Technology. Many stakeholders and companies have already reported significant difficulty in recruiting a workforce with education and skills adapted to fill job market demands. The phenomenon, referred to as "Quantum bottleneck", has been highlighted even in general interest newspapers [56, 57]. Quantum related jobs require both a quantum-aware and quantum proficient workforce with education degrees starting from Bachelor level. Furthermore, Quantum Science and Technology is a broad, interdisciplinary field spanning a wide range of scientific areas. The recognition of these facts is motivating several Universities across the EU to join forces to establish common M.Sc. and Ph.D. programs in the field. Notable examples are the **Cluster of Excellence Munich Center for Quantum Science and Technology** [58] formed by Technical University Munich (TUM) and Ludwig-Maximilians University Munich (LMU) which offers among other initiatives M.Sc., Ph.D. and post-doc programs; the **Quantum Master Barcelona** [59] which is embedded in **Quantum-Cat** [60] a Quantum Technology hub formed by the community of universities, companies and research institutes of Catalonia with aims analog to InstituteQ.

EduQ working group has the mission of coordinating efforts to educate the new generation of quantum scientists and engineers and to develop quantum literacy for the general public and policy makers. The first concrete achievement in this direction is the agreement on "*Cooperation on quantum technology education in the Helsinki metropolitan area*" signed by the Aalto University and the University of Helsinki. The agreement is in place since September 1st 2021 and allows undergraduate and graduate students of the covenanting institutions to freely choose among quantum technology relevant studies organized by the same institutions. The agreement is expected to serve as an incubator of national doctoral (Ph.D.) and master's (M.Sc.) training programs. The establishment of national programs will put the

Finnish learning ecosystem in the position to compete with the educational offer emerging across the EU such as the aforementioned examples in Bayern and Catalonia. This is necessary to develop efficient educational study paths and contents that respond to the needs of the growing quantum sector. Also, it allows partners within InstituteQ to successfully respond to European funding opportunities supporting education in quantum science and technology.

InstituteQ's vision of national training programs is that students attached to the degree programs of their home universities have the multitude of national M.Sc. and Ph.D. studies easily available under the InstituteQ umbrella. The educational content is produced and developed in national collaboration with participating organizations. Development of knowledge and skills adapted to advance the careers of students interested in working not only in academia but also in industry and in government positions, is vital for the swift advancement of the field. To this goal InstituteQ will seek for opportunities of extended industry collaboration and to offer opportunities to internships and secondments as well as other forms of career development.

In order to overcome physical distances of students and lecturers, EduQ plans to devote significant efforts to favor the development of online courses and activities for both M.Sc. and Ph.D. students. In par- ticular, the EduQ working group is already participating to the **QTEdu Open Master** [61] a pilot project of the European Quantum Flagship aiming to give students from all across Europe access to courses, in- ternships, and even remotely supervised Master's thesis projects. Learning requires also networking and socialization of students. The plan is to integrate traditional formats such as summer conference and school with innovative digital formats such as an annual quantum game hackathon which EduQ would organize in collaboration with companies. Qplaylearn [62], the official outreach project of InstituteQ provides another example of digital innovation for educational purposes. **QPlayLearn** is an online platform containing mul- timedia resources for learning about quantum science and technologies in a playful way. The scope is to provide a tool of multilevel education to everyone, regardless of their age and background. While working for realizing the activities outlined above, EduQ team is also conscious [63] that reshaping degree programs offers a great opportunity to create more equitable and inclusive learning environments in disciplines that historically lacked in diversity. It is therefore paramount to cultivate a friendly and supportive learning environment for students which regards diversity as a richness. These considerations also inspire all EduQ outreach activities, such as the quantum exhibitions which includes workshops for school kids. A good example is the currently ongoing **Photonic Trail** [64] that is currently open in Kaarina. The aim is to open the exhibition in the Helsinki region around mid-April.

BUSINESSQ FOSTERS INNOVATION AND BUSINESS

Finnish quantum science and technology research has already brought about several academic spin-offs and even international success stories. The business idea that in 2008 led to the foundation of Bluefors [65], for example, emerged from the task of upgrading dilution refrigerator systems at the Low Temperature Labora- tory of the then Helsinki University of Technology, for which one of the later founders of the company had been hired around 2005. BlueFors quickly established itself as a market leader in the field of cryogen-free ultra-low temperature systems, running today operations with over 250 employees and an annual revenue of approximately C100 million.

In view of the growing international competition, broadening the impact of quantum technology in industry and business in Finland requires building a coherent ecosystem that makes it attractive for companies to work with, instead of contacting several separate university groups. The third objective of InstituteQ is thus to provide a forum for companies and industries interested in development, innovation and commer- cialization of new products and services related to quantum technology.

To this goal, **BusinessQ** operates as an independent collective within the framework of InstituteQ and with no financial or legal commitments. Its operations are based on a Memorandum of Understanding signed by the first members in August 2021. This is to make the membership as easy as possible to at- tract the wider business and other stakeholder community. The vision of BusinessQ defined jointly by the participating companies, is that Finland implements quantum technology in businesses by 2030. The collab- oration thrives for renewal of Finnish industries through quantum technology. The goal is to make Finland quantum-ready and quantum-safe. A growing number of members have joined BusinessQ, including the aforementioned Bluefors, the European multinational information technology service and consulting com- pany Atos [66], IBM, OP-bank [67] and a growing number of startups. Among the latter ones is Algorithmiq [68] whose business idea is the development of qubit architecture agnostic variational quantum algorithms, which industry experts consider as the most promising avenue for practical applications on NISQ devices [24, 23]. Another example of recent startup members of BusinessQ is IQM [69], a Finnish hardware com- pany building superconducting quantum computers. Both of them are recent spinouts from the InstituteQ research community. In many ways the emergence and success of such companies exemplifies the ob- jectives of InstituteQ to facilitate fundamental scientific findings in quantum science and technology and to apply them for the development of new commercial opportunities through the creation of an open and diverse human ecosystem.

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