WACQT Mid-Term Report Summarising 2018–2023

WACQT | Wallenberg Centre for Quantum Technology

In this document, we provide an overview of the progress made in the Wallenberg Centre for Quantum Technology (WACQT) during its first six years and its status at the end of 2023.

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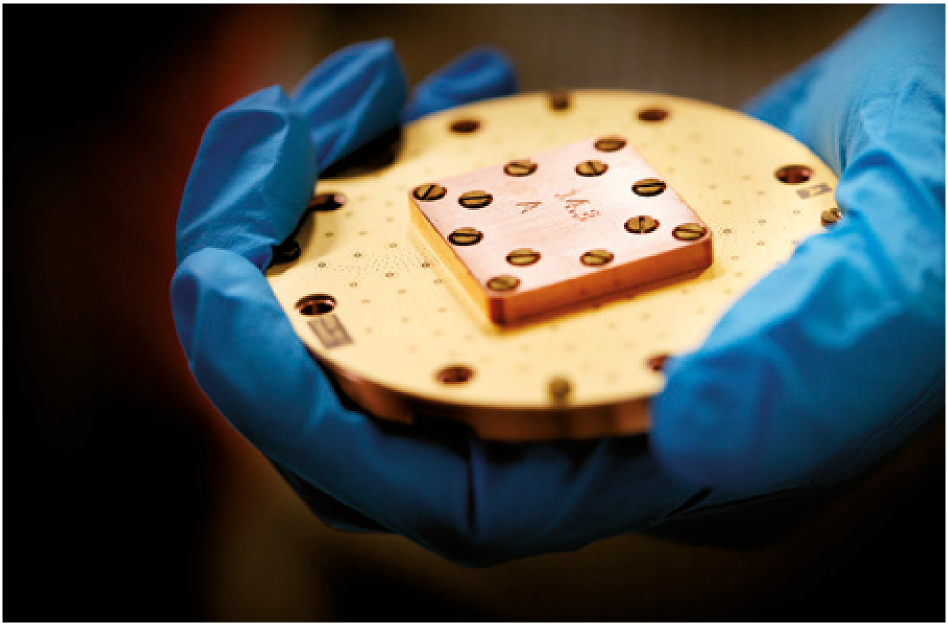
Introduction

The world is on the verge of a second quantum technology revolution, with extremely powerful computers, intercept-proof communication, and hyper-sensitive measuring instruments in sight. WACQT is a 12-year, SEK 1.4 billion research effort, funded mainly by the Knut and Alice Wallenberg Foundation (KAW). The Centre aims to take Swedish research and industry to the forefront of this very rapidly expanding area of technology. Through an extensive research programme, we are developing and securing Swedish expertise within the four pillars of quantum technology: quantum computing, simulation, communication, and sensing.

WACQT has two main parts: the Core project, which has the overall goal of developing a quantum computer based on 100 superconducting qubits; and the Excellence programme, which has the overall goal of building a broad competence base for quantum technology in Sweden. The Excellence part is where you will find most of our industry collaborations; the Graduate School, EDI-WACQT, where we focus on equality, diversity, and inclusion; the guest researcher programme; the recent Quantum Technology testbed; and our effort to strengthen education in Quantum Technology.

Academic partners are Chalmers University of Technology (coordinator), the University of Gothenburg (GU), KTH Royal Institute of Technology, Linköping University (LiU), Lund University (LU), and Stockholm University (SU). Our industry partners are large companies that are potential end-users of quantum technology with a substantial level of activity in Sweden: SAAB, Volvo Group, AstraZeneca, Hitachi Energy, Ericsson, and Jeppesen. WACQT also collaborates with Swedish enabling technology partners such as Deep Light Vision, RISE, Spectracure, Sahlgrenska University Hospital, and Intermodulation Products. These partners offer key competence for the realisation of WACQT projects, including by developing and manufacturing relevant hardware or software.



25-qubit quantum processor chip packaged in a specially designed sample holder.
Photo: Anna-Lena Lundqvist

Some highlights from the first six years of WACQT:

- We have created a large and diverse team (over 200 people, of which 2/3 are salaried via WACQT), attracting scientists and engineers from all over the world (48 countries) to Sweden.
- 57 PhD students have been recruited, of which 10 are industry PhD students. An additional 24 PhD students are affiliated with WACQT. In total this means 81, of which 18 are women (27%).
- We have received over 40 visits by senior guest researchers from around the world.
- Within the Core project, WACQT has developed a 25-qubit quantum computer in-house.
- A Swedish Infrastructure for Quantum Communication is being deployed.
- Five companies and an IP holding company have been spun off based on results from WACQT.
- Over 150 peer-reviewed articles have been published.
- Some new courses and Masters' level profiles in quantum technology have been started.
- WACQT Principal Investigator (PI) Anne L'Huillier received the 2023 Nobel Prize in Physics.
- WACQT researchers have contributed to writing the Swedish Quantum Agenda[1].

[1] https://www.vinnova.se/en/publikationer/a-swedish-quantum-agenda

PhD student Hangxi Li and group leader Giovanna Tancredi dismounting part of the cooling system. Photo: Anna-Lena Strandqvist.

Introduction to quantum technology

The quantum world – at the scale of atoms and down – is paradoxical and bizarre. Particles seem to be both here and there at the same time or mysteriously intertwined at a distance. Quantum technology is about harnessing and manipulating these strange quantum mechanics phenomena to create entirely new technologies with extraordinary possibilities.

From theory to revolution

By the 1930s, the mathematical formulation of quantum mechanics was largely complete. The understanding of the quantum properties of light and matter led to the invention of the laser and the transistor – which led to information technology. Computers and the Internet have drastically changed our lives. Today we call this the first quantum revolution.

It was long thought impossible to control quantum systems such as single atoms, electrons or light particles (photons). In the 1980s, researchers began developing methods and equipment to measure and control individual atoms, electrons, and photons. The ability to exploit the properties of individual quantum systems opens the door to entirely new technologies – a second quantum revolution.

Central phenomena

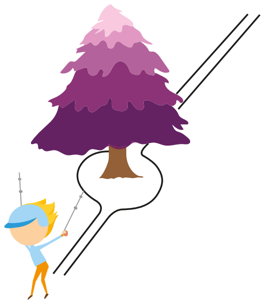
The extraordinary properties of the emerging quantum technology are all based on the non-intuitive phenomena of quantum mechanics. Some of the most important are:

Superposition, interference, and decoherence

If an electron could ski, it would be perfectly normal for it to ski on either side of a tree. In the world of quantum mechanics, it is entirely possible for particles to be in several different places at the same time, or to be, for example, simultaneously in states that have different energies or different polarisations. This is called superposition. You can count on probabilities for where a quantum particle is, but you do not know where it is without measurement.

Probabilities for the different states form superpositions (compare with the superposition of waves) and this is expected to enable, for example, massive parallel computing power in quantum computers. Effective calculations are then based on algorithms that act as choreography to maximise the constructive and destructive interference of the various states.

However, small disturbances can cause the superposition to diminish and eventually collapse. This process is called decoherence and is one



Superposition: If electrons could ski, they could ski on both sides of a tree. Yen Strandqvist, Chalmers

Entanglement can mean superposition over very large distances.
Yen Strandqvist, Chalmers

of the biggest challenges in quantum technology. This is because there is an inherent contradiction between the need to be able to manipulate a quantum system and to isolate it to avoid decoherence.

Entanglement

Superpositions can extend between multiple particles, and a special type is called entanglement. The manipulation of a particle affects its entangled partner immediately, even at long distances. The experimentalists who showed this were awarded the Nobel Prize in Physics in 2022.

Squeezed states

In quantum physics, there is a limit to how precisely you can simultaneously know coupled variables, such as the frequency and time, of an object. The uncertainty is often distributed equally between the two coupled variables. But by manipulating the object's quantum state so that it ends up in a squeezed state, the uncertainty can be made to primarily affect one variable. Then the other variable can be measured more precisely.

Qubits

In a quantum computer, the information is in qubits (quantum bits). When these qubits are entangled, the number of states that the quantum computer can handle doubles for each additional qubit, unlike a classical computer where you must double the number of bits. This means that in some cases, quantum computers are anticipated to be much more efficient than classical computers.

The four pillars

Quantum computers have the potential to perform calculations more efficiently than a classical computer, such as solving difficult optimisation problems. A future large (with millions of qubits) quantum computer would be able to crack encryption codes much faster by figuring out which prime numbers are used. Quantum computers are very good at searching unsorted data; the problem however is getting large amounts of data into a quantum computer.

(Then) Postdoc Anstasiia Ciers and professor Witlef Wieczorek setting up an experiment in the Quantum sensing and foundations lab at MC2/ Chalmers. Photo: Henrik Sandsjö.

Quantum simulations of complex molecules can help us develop new drugs or catalysts. It can also help us design new materials. The idea is to use a quantum system (the quantum computer) to simulate (with quantum algorithms) another quantum system (for example molecules or proteins) and thereby speed up and improve the development of drugs, batteries, and catalysts, among other things.

Quantum communication uses entangled states to send messages that cannot be intercepted. In the long-term perspective, a new internet built for quantum information is being discussed. Even in the shorter term, the technology is interesting for the secure sharing of data within, for example, the health and safety sectors.

Quantum sensors can enable significantly more accurate measurements. Better atomic clocks used in GPS are one example, sensors for medical diagnostics are another. In general, coherence is used to measure a physical quantity or entanglement to improve measurements beyond what can be done with classical sensors.

What can it be used for?

There is a lot of research and development going on around quantum technology. A big question is: in which areas does quantum technology of the second revolution provide an advantage ("quantum supremacy" or "quantum advantage") over previous/existing technologies? This advantage is based on the central phenomena that are expected to provide more efficient (quantum) computers and algorithms as well as more sensitive sensors. Currently, however, simulations are done on simple systems because quantum computers are still small (in terms of the number of qubits) and suffer from relatively fast decoherence, which creates errors in the calculations.

Here are some applications where it is believed quantum technology would provide an advantage:

"A future quantum computer with the right algorithm could break the encryption key relatively easily."

Measurement of oxygenation in the heart and brain

Quantum structures that reduce the speed of light to a few tens of kilometres per second can be used to enable optical imaging deep inside the body. In particular, the aim is to measure oxygenation in the anterior heart wall and in the brain, which would be of great help in quickly diagnosing stroke.

Simulation of medicines and other materials

It is difficult and time-consuming to predict reactivity and other properties of drug molecules to design new molecules and select drug candidates. Here, there is a chance that quantum computers would make a big difference, because medicines can be seen as quantum systems.

In a similar way, one could simulate old and new materials for catalysts, batteries, and solar cells to understand how they work and to develop better materials.

Cyber-security and Quantum Key Distribution

The encryption algorithms used today rely on the fact that it is very difficult to crack the encryption keys. A future quantum computer with the right algorithm could break the encryption key relatively easily. One problem is transferring the key without an unauthorised person getting hold of it. In quantum communication, this is solved by transmitting the encryption key with quantum particles, via the quantum key distribution (QKD) scheme. It is impossible to measure or copy the state of a quantum particle without noticeably changing it. Therefore, one can always be sure of detecting eavesdropping.

Research and development

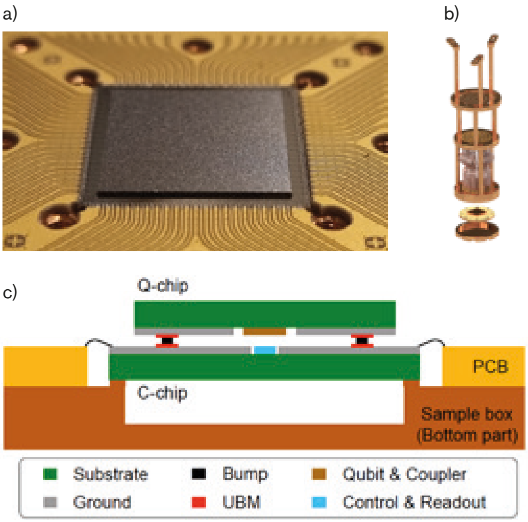
The core project and its enabling technologies

25-qubit processor and its enabling technologies
The main goal of the Core project is to build a 100-qubit quantum computer based on superconducting qubits. We aim to make it compatible with surface-code error correction.

In the quantum computing hardware team, led by Giovanna Tancredi, Jonas Bylander and Per Delsing, we have focused our research efforts on tackling several challenges that need to be faced when building a 100-qubit processor. One of the biggest challenges is the fight against qubit decoherence – the loss of quantum information. We have investigated this in depth by examining different processor designs, improving our fabrication processes, and looking into using better materials for the processor fabrication. We can now reproducibly fabricate some of the best superconducting qubits in the world. The average decoherence time for a processor chip is about 100 microseconds (µs), whereas individual qubits now reach 270 µs[2].

We have demonstrated the successful execution of algorithms in 2- and 3-qubit quantum processors, solving a model combinatorial optimisation problem for routing flights[3] and performing our first quantum chemistry simulations[4]. The quantum chemistry simulations represent method development that will inform how we validate larger quantum computations once the system is so large that we cannot just simulate it classically. Aiming to reduce the execution time of our algorithms, we have experimentally demonstrated a three-qubit operation[5] that, combined with the single- and two-qubit operations, allows us to decrease the run-time and increase the performance of our algorithms.

We are also actively working to realise better and faster measurements of the qubits' quantum states. We have developed novel measurement techniques[6] that allow us to push the limit of how fast we can measure the qubits' states. We are also working on building a special type of cryogenic amplifier[7] that will further boost our processors' performance. To reach our goal of building a 100-qubit quantum processing unit (QPU), we had to develop a new way to fabricate the processor itself. Now, all the necessary components are built on two different chips that are then integrated as shown in the above figure. In 2021, we reported our first generation of such a quantum processor module, demonstrating very good performance[8]. Since then, we have fabricated and tested several processors containing 25 qubits to optimise both



The WACQT 25-qubit processor. a) Quantum processing unit (QPU) flip chip module. b) Sample holder for the QPU. c) Schematic of the QPU from the side (not to scale).

the design and the fabrication process to attain ever-better performance. We are also developing control software that will allow users to characterise the processor in an automated way and perform the desired algorithm on it.

Software stack

Quantum computer demonstrators are key tools for showcasing state-of-the-art noisy intermediate-size quantum (NISQ) technology to a broader audience. Current quantum processors are inherently lab-only devices, constraining their deployment and usage not only in terms of the necessary lab equipment, but also in terms of physical access, their single-user nature, and the requirement for cutting-edge experimental skills to operate them. A software stack, comprised of various software layers, addresses these limitations by providing remote access, a queueing mechanism, and raising the level of abstraction from the language of voltages and frequencies to logical operations with a computational meaning.

At the halfway point of the WACQT project, the quantum computing software team led by Miroslav Dobsicek has successfully developed a complete research prototype of a software stack. This software allows remote users to send simple quantum circuits generated by the well-known Qiskit tool directly to a lab located at Chalmers University of Technology in Gothenburg. The software stack has evolved alongside the underlying hardware. We began with quantum chips featuring 2 and 5 qubits, and we now support the latest 25-qubit chip. A key com-

[2] DOI: 10.48550/arXiv.2310.06797
[3] DOI: 10.1103/PhysRevApplied.14.034010
[4] DOI: 10.1021/acs.jctc.2c00807 & 10.1039/D3SC05269A
[5] DOI: 10.1038/s41534-023-00711-x
[6] DOI: 10.1038/s41534-023-00689-6
[7] DOI: 10.1103/PhysRevApplied.19.044056 & 10.1063/5.0127690
[8] DOI: 10.1088/2058-9565/ac734b

ponent enabling this progress is the use of automatic tune-up routines. Our work on single-qubit tune-up operations is on par with, or even surpasses, the speed and quality of commercial solutions. The work is currently focused on enabling automated tune-up of all operations on the Quantum Processor Unit (QPU).

In 2024, the research prototype of the software stack will transition to operational use and further development at the WACQT Quantum Technology Testbed, in collaboration with a newly started company, Chalmers Next Labs. The entire software stack will be open source to benefit the broader community[9]. We hope this move will attract further development.

WACQT Quantum Technology Testbed

The testing of quantum algorithms and the development of quantum computer software require a dedicated quantum computer system with sufficient availability for users. To this end, the new Testbed is envisioned as an important complement to our experimental systems used for the development of quantum hardware. It is envisioned as open infrastructure for Swedish industry and academia, where external users can book time on the Testbed, either to develop quantum algorithms or to test quantum hardware. WACQT/Chalmers will own the infrastructure, and the newly started company Chalmers Next Labs (CNL) will operate it and employ the staff needed.

The Testbed has two parts: one for quantum algorithms and one for hardware related to quantum technology. The installations started in 2023, with the hardware testbed starting in March 2024, i.e. for those who want to test components and similar devices in a cryostat at low temperature (< 1K). Most of the enabling equipment will be ready and installed, including the copy and fine-tuning of the 25-qubit processor, to launch the algorithm testbed in January 2025.

Another important part of the Testbed is the Quantum Helpdesk, a customer support team, in operation since March 2024, to which users can turn for help in developing and adapting quantum algorithms that address the problems they want to solve. In a similar way, the testbed will also help users who want to test hardware with cryogenic and measurement expertise. In early 2024, WACQT entered into a five-year agreement with IBM for the execution of quantum algorithms on IBM Quantum Services, which feature several QPUs.

[9] The software stack, Tergite, was posted on Github in June 2024: https://tergite.github.io

CNL staff showing the Testbed to visitors.

Computation (other approaches)

Since it is still an open question which qubit platform will perform best, we are working on alternative quantum computing approaches such as continuous variable (CV) quantum computing with superconducting circuits (Simone Gasparinetti, Chalmers), and trapped ion qubits via Rydberg interaction (Markus Hennrich, Stockholm University).

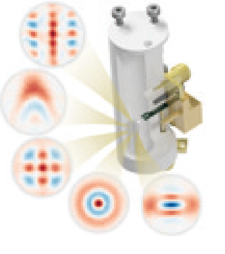


Figure showing 3D aluminium cavity hosting various nonclassical states of light, represented by their experimentally measured Wigner functions.

Continuous variable quantum computing

The performance of today's quantum processing units is limited by errors occurring in the quantum systems used to encode the information. To cope with these errors more efficiently, an emerging approach is to replace qubits with harmonic oscillators. In contrast to qubits, which can exist in arbitrary superpositions of only two states, harmonic oscillators possess a very large (ideally, infinite) number of states. There are, therefore, multiple possibilities for encoding logical information in oscillators, some of which lead to hardware-efficient error correction protocols.

3D cavities: WACQT researchers demonstrated a logical gate on two-encoded qubits as well as experimentally implemented a new quantum process tomography protocol.

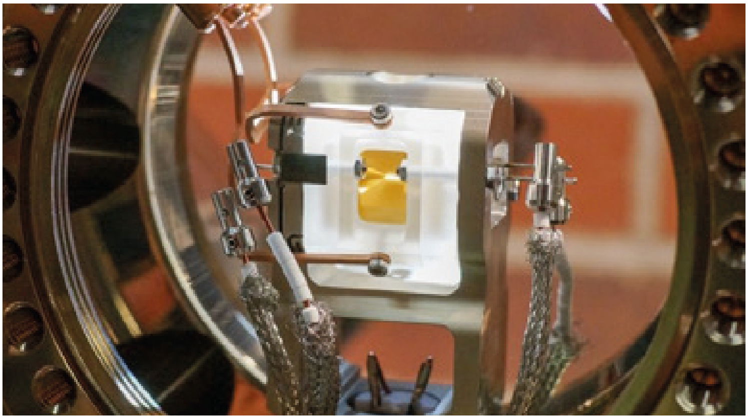
Planar resonators: WACQT researchers first suggested and demonstrated the use of planar superconducting circuits comprising a nonlinear element, known as SNAIL, to achieve fast and tuneable nonlinearities, leading to a universal gate set for quantum computing[10].

Rydberg ions

Trapped ions excited to highly excited electronic states, known as Rydberg states, are a novel quantum computing approach. This technology combines the benefits of both trapped ion and Rydberg atom technologies. Trapped ions are excellent for storing quantum information for relatively long periods, from seconds and even to hours, and can be precisely manipulated with low error rates using laser pulses. The strong interaction between the Rydberg ions speeds up processing in trapped ion quantum computers, making operations up to two orders of magnitude faster compared to other trapped ion approaches.

A noteworthy achievement of the WACQT team is the demonstration of two-qubit gates via Rydberg interaction in less than a microsecond[11]. Furthermore, the team has demonstrated that these operations can be performed on strings of more than 10 ion qubits. The Rydberg ion approach does not suffer from the limitation of slowing down as the number of qubits increases, unlike standard trapped ion operations. The Stockholm team is currently building a cryogenic Rydberg ion setup. This will extend the lifetime of Rydberg states and reduce ion losses due to thermal radiation.

Trapped Rydberg ions have the potential to simulate complex quantum systems and molecular dynamics. Their strong coupling to motion and the ability to continuously cool an ion crystal through laser cooling and controlled environmental coupling make them particularly useful for these applications.



Rydberg ion setup (Markus Hennrich, SU). Ion trap inside a vacuum chamber.

[10] DOI:10.1038/s41467-024-46507-1
[11] DOI: 10.1038/s41586-020-2152-9

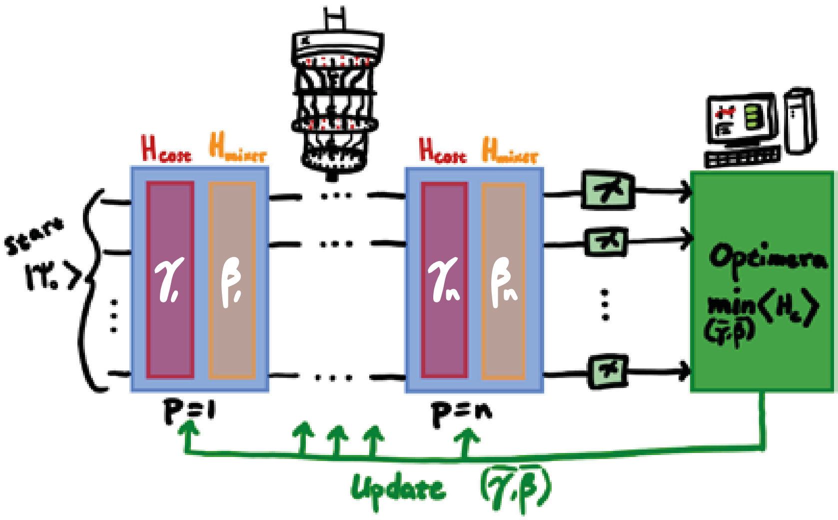
“Topological analysis of electron densities may be useful for benchmarking future quantum computation of materials.”

Simulation and theory

In the quantum computing theory team, led by Göran Johansson, Giulia Ferrini and Anton Frisk Kockum, we aim to develop algorithms based on use cases from the industry and help the development of the quantum hardware through circuit-level modelling, gate optimisation, and benchmarking. Efforts are also devoted to exploring the origins of quantum advantage, as well as quantum error-correction protocols adapted to our hardware.

Use cases

Quantum Algorithm for Scheduling Optimisation: In collaboration with Jeppesen, WACQT researchers evaluated the quantum approximate optimisation algorithm’s (QAOA) performance for optimising realistic airline scheduling instances. An experimental demonstration solved a small two-qubit scheduling problem on Chalmers hardware. Larger scheduling instances were also addressed using the 5000-qubit D-WAVE quantum annealer.



Schematic representation of an iterative approach between performing algorithms in a quantum computer (left side) and a classical computer (right side). Hanna Linn, Chalmers.

Quantum Chemistry Calculations: The quantum chemistry theory group, researchers from AstraZeneca and the quantum computer hardware teams at Chalmers together performed Sweden's first quantum chemistry calculations. They explored potential energy surfaces for dissociating the H_2 and HeH+ molecules and calculated molecular electron densities on a quantum computer. Topological analysis of electron densities may be useful for benchmarking future quantum computation of materials.

Protein Folding Resource Estimate: Researchers at Chalmers estimated resource requirements for coarse-grained protein folding on quantum computers, for different coarse-grained models and encodings.

Modelling

In 2021, the theory team at Chalmers introduced novel three-qubit gates. These gates operate similarly to two-qubit gates but with improved efficiency, as experimentally demonstrated at Chalmers. They explored gate fidelity in quantum computers affected by weak Markovian noise. Additionally, the team developed quantum process tomography protocols by studying Kraus operators through gradient descent. This work resulted in a collaborative project with the Continuous-Variable (CV) experimental group.

Quantum advantage

Researchers led by Giulia Ferrini (Chalmers) showed that certain CV circuits, despite displaying an apparent resourcefulness, cannot provide quantum advantage. These circuits are made of Gottesman-Kitaev-Preskill states and Gaussian operations. However, supplementing them with a simple resource like vacuum restores quantum advantage.

Quantum error correction

Researchers led by Mats Granath (University of Gothenburg) introduced new quantum error correcting codes similar to the surface code. Using graph neural networks, they also invented novel decoders that are both fast and accurate, and can learn from experimental data. The group has also established rigorous thresholds for surface codes.

Quantum Communication and NQCIS

Quantum communication research within WACQT is led by Katia Gallo (KTH) and Stefan Kröll (Lund). It comprises several research groups that work with various aspects of quantum cryptography: quantum key distribution, entangled photon sources, increasing the transfer rate, etc. We are also involved in the National Quantum Communication Infrastructure in Sweden (NQCIS), which is part of the European Quantum Communication Infrastructure (EuroQCI).

We work in four thematic areas: 1. Integrated quantum photonics, 2. QKD devices and systems, 3. Quantum repeaters, and 4. Quantum transducers. This includes 10 PhD and postdoc projects (distributed among KTH Royal Institute of Technology, Chalmers University of Technology, Linköping University and Stockholm University) and is fully in line with its targets. Progress and renewal have been furthered by the strategic recruitment of three new WACQT group leaders who are working on hybrid quantum photonics (Assoc. Prof. Ali Elshaari, KTH, 2021), quantum microwave-to-optics transduction (Asst. Prof. Raphael van Laer, Chalmers, 2021), and squeezed light for quantum communication and sensing (Asst. Prof. Vaishali Adya, KTH, 2023).

Recent scientific highlights include the demonstration of:

- *deterministic single-photon sources at room temperature* by integrating hexagonal boron nitride in silicon-nitride waveguides – an important step forward since previous sources operated at cryogenic temperatures
- *high extraction efficiency sources of photon pairs* based on a quantum dot embedded in a broadband micropillar cavity
- *clamped silicon optomechanical crystals* affording ease of manufacturing and improved thermal anchoring, operating in the sideband-resolved regime at frequencies commonly used in superconducting qubits
- *hybrid integrated circuits* combining lithium niobate and superconducting single photon detectors – a promising architecture for future, densely packed, wavelength-multiplexed quantum communication systems-on-a-chip
- *quantum random number generation with a perovskite light emitting diode*, proving the capability for such simple and affordable light sources to deliver high bit rates and performance in quantum information tasks.

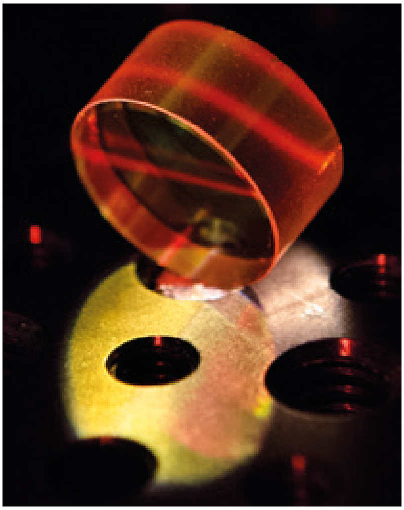

Planned route of existing optical fibres to create a quantum network for quantum secured communication in Sweden with tentative routes to Denmark and Finland.

Finally, the WACQT Quantum Communication pillar has been the driving force for the EU award to Sweden of a project to build a National Quantum Communication Infrastructure in Sweden (NQCIS). NQCIS is a EUR 9.8 million initiative spanning the period 2023–2025, co-funded by the EU (50%), VINNOVA, and the WACQT Quantum Communication pillar in addition to the participating parties. The consortium, led by the WACQT quantum communication PI (Prof. Katia Gallo) brings together researchers at KTH Royal Institute of Technology, Ericsson, Chalmers University of Technology, Linköping University, Stockholm University and two Swedish SMEs. Its goal is to deploy a national testbed and train a considerable number of users in quantum communication technologies, integrate the latter with existing quantum communication networks, and prepare for the deployment of the large-scale Euro-

NQCIS Sweden

https://nqcis.eu

pean Quantum Communication Infrastructure (EuroQCI). The long-term goal is to build a quantum communication infrastructure across Europe, boosting Swedish and European capabilities in quantum technologies, cybersecurity, and industry competitiveness.



Rare-earth ion doped crystal for quantum metrology, quantum memories and quantum life science. Adam Kinos, LU.

Sensing

Quantum-enhanced sensing typically uses non-classical states or quantum-enabled preparation techniques to achieve sensitivities, precisions, and accuracies not achievable with traditional, classical approaches. The WACQT quantum sensing activities include strong activities in Sweden on quantum metrology and quantum control. In 2018, WACQT Quantum Sensing started to support work on micro-mechanical resonators for quantum-enhanced sensing, e.g. for the measurement of extremely weak forces (Witlef Wieczorek, Chalmers), the generation and detection of single microwave photons (Ville Maisi, Lund), quantum sensing with trapped Rydberg ions (Markus Hennrich, Stockholm University), atto-second quantum physics (Anne L'Huillier, Lund), and quantum information using rare earth crystals (Stefan Kröll, Lund).

The activities have generally developed very well. Group leaders Wieczorek and Maisi have both received prestigious Consolidator grants from the European Research Council (ERC) Excellence Programme in connection with their projects. WACQT is of course proud to support the development of quantum state control and characterisation within the atto-second physics group led by Anne L'Huillier as one of the areas it supports. A quantum-enabled technique for the optical imaging of tissue oxygenation in the human body developed by the Kröll group has resulted in a spin-off company (Deep Light Vision) that is presently expanding its activities.

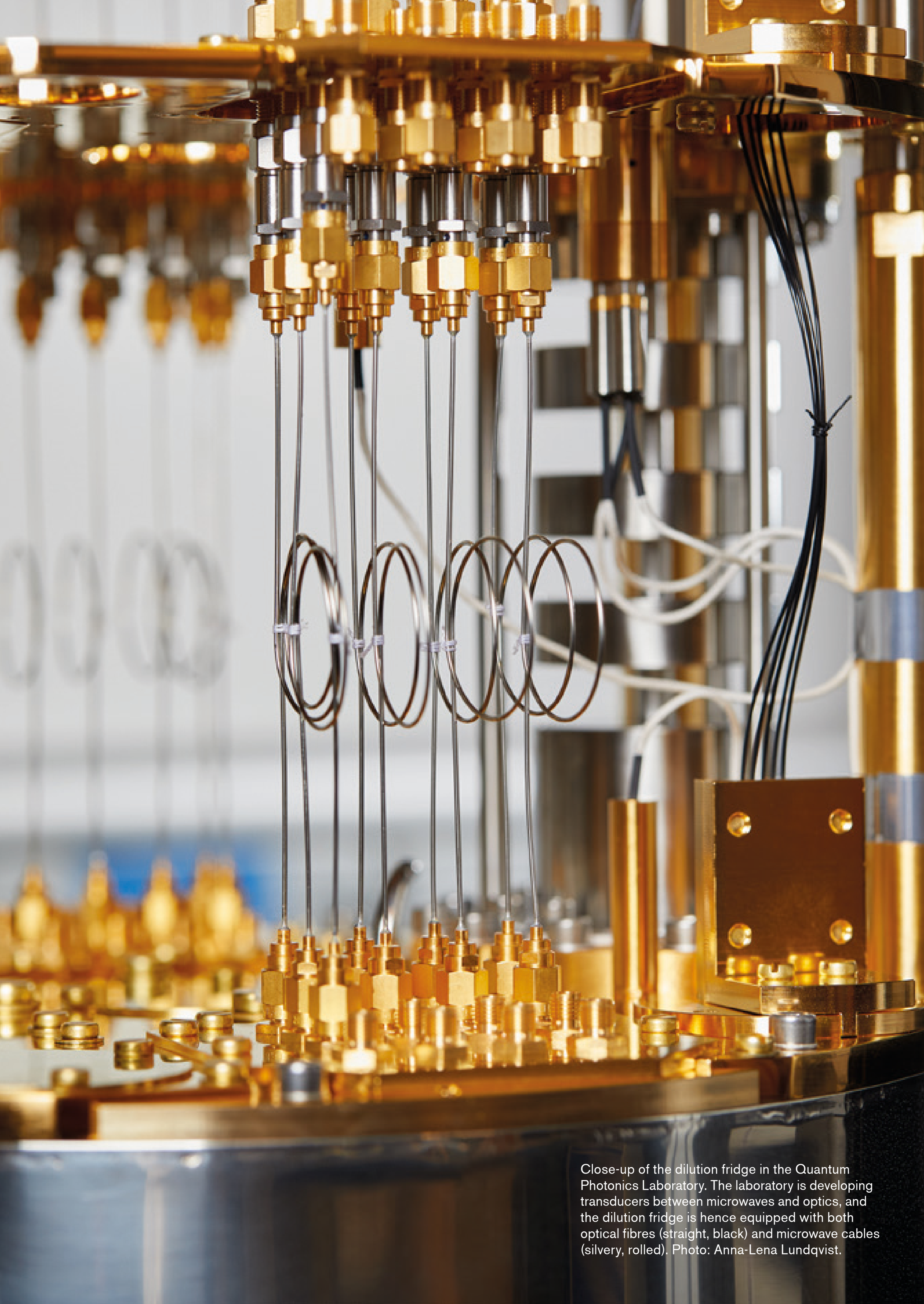
During the third year, the quantum sensing activities started to expand. National online conferences were organised where research groups in quantum sensing, or closely related fields, were given the opportunity to present their work. This provided a good overview of the efforts in this field in Sweden. The ongoing experimental work on single microwave photon generation and detection was enhanced by theoretical efforts to strengthen the project. WACQT also started to support national activities in the internationally rapidly developing area of sensing, employing colour centres in diamonds and other hosts, e.g. silicon carbide (SiC). These colour centres are developed as sensors for a variety of applications, including studies of cell metabolism and processes inside the body. WACQT thereby supports the partly interdisciplinary cooperation between quantum optics activities in the Bourennane group at KTH, the colour centre growth activities in Linköping (Ul-Hassan), and the Abrikosov material property theory group in Linköping.

Time and frequency are the quantities humans can measure the most accurately. These measurements use extremely well stabilised lasers. A quantum metrology project in cooperation with the Metrology Division at RISE is being supported to stabilise lasers using slow light techniques, where the speed of light is reduced by 5–6 orders of magnitude. This project is also linked to European activities in the quantum metrology area through the European Metrology Programme for Innovation and Research (EMPIR) within the NEXTLASERS project for the next generation of ultra-stable lasers.

In line with WACQT's ambition to secure future competence in quantum technology, WACQT also supports two tenure track positions with activities partly related to quantum sensing: Armin Tavakoli on quantum information and the foundations of quantum theory at LU; and Vaishali Adya (in the communication pillar), who is in part working on squeezed light generation in waveguide systems and in part on the development and characterisation of integrated squeezed light sources for gravitational wave detection and biosensing at KTH.

WAQCT has initiated and/or strengthened new research areas in quantum sensing, metrology and control in Sweden over the last 6 years. These efforts will influence Swedish research for a significant period of time. We would like to highlight the following fields:

- Quantum optomechanics: Witlef Wieczorek, Chalmers
- Quantum metrology in the atto-second regime: Anne L'Huillier, LU
- Development and applications of solid-state colour centre materials: Igor Abrikosov, LiU; Mohamed Bourennane, SU; Stefan Kröll, LU
- Single microwave photon detection: Ville Maisi & Peter Samuelsson, LU; Sergey Kubatkin, Chalmers
- Microwave and electric field sensing with Rydberg ions: Markus Hennrich, SU
- Nonlocality, entanglement, quantum communication and quantum thermodynamics: Armin Tavakoli, LU.



Close-up of the dilution fridge in the Quantum Photonics Laboratory. The laboratory is developing transducers between microwaves and optics, and the dilution fridge is hence equipped with both optical fibres (straight, black) and microwave cables (silvery, rolled). Photo: Anna-Lena Lundqvist.

Collaborations

Industry engagement

One of the two main goals of WACQT is to increase the general competence level for quantum technology in Sweden. We are working with our Industrial Advisory Board (IAB) to strengthen the interaction between WACQT and our industry partners. Since 2019, we have had different levels of offers to industrial partners with updated conditions finalised in 2023, now with only one type of association. The WACQT Testbed described above is a recent addition to the industry collaborations.

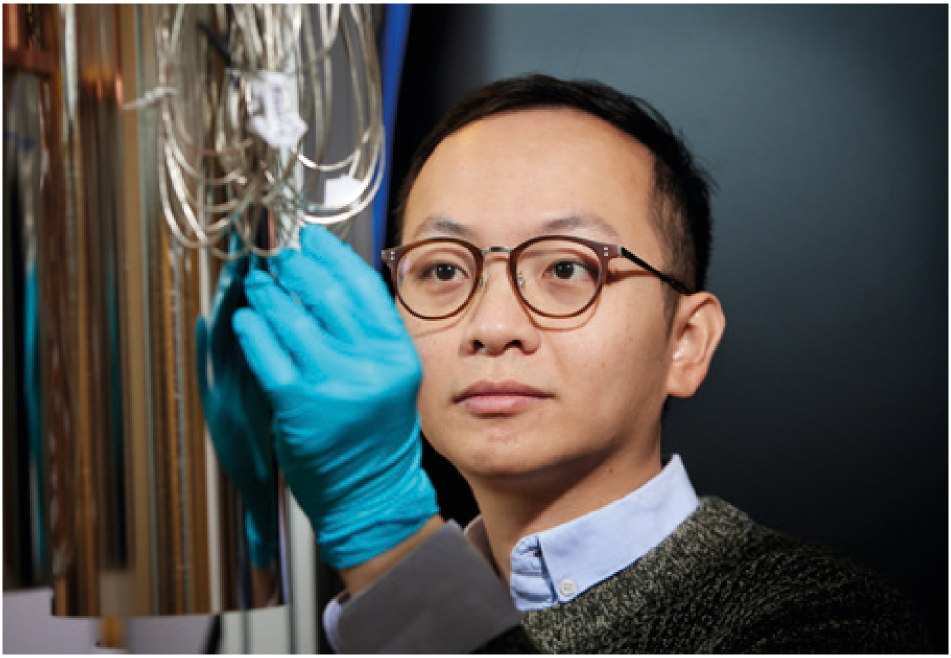
We have held many short seminars and courses with potentially interested companies, mainly in a one-hour online format. When seminars and courses have been held on-site, they have been combined with a lab visit. We arrange workshops for current and future partner companies with the intention of digging deeper into use cases and what quantum technology could offer them.

The main link between research groups within WACQT and our industry and enabling-technology partners is industry PhD students (since 2019) and industry postdocs (since 2023). The initial batch of 10 industry PhD students are expected to have defended their theses by the end of 2024. Subsequently, discussions about new partners and setting up new projects will continue. Since 2023 we have industry postdocs at Deep Light Vision and AstraZeneca.

The companies with a substantial presence in Sweden are of two types. The first type is large end-users that do not necessarily develop their own quantum technology. Their main reason for joining WACQT is to study potential use cases of quantum technology (ABB/Hitachi Energy, Volvo Group, SAAB, AstraZeneca, and Jeppesen). The other type is enabling companies that either develop hardware and/or software needed for quantum technology (SpectraCure/Deep Light Vision, and Intermodulation Products) or have important know-how in the field (RISE and Sahlgrenska University Hospital).

Swedish-Finnish postdocs

KAW supports an additional grant for improving collaborations between Sweden and Finland via a programme for sharing postdocs between universities. Six postdoctoral fellowships have been started, involving Chalmers University of Technology, KTH Royal Institute of Technology, and Lund University in Sweden; and VTT, Aalto University, the University of Finland and Bluefors in Finland.



Former postdoc Sandoko Kosen working on a quantum computer.
Photo: Anna-Lena Lundqvist.

Scientific collaboration with others

With over 150 published peer-reviewed articles (excluding reviews), it is no surprise that these are based on collaborations between several authors, groups, and organisations spread over many countries. All in all, close to 200 organisations in 33 countries were involved in these 150 articles. 14% of the publications were generated from industry-academia collaborations, 66% from international collaborations, 13% from national-only collaborations, and 20% from a single institution. Roughly half of the publications originate from physics, but other areas are also represented such as materials science, chemistry, and biochemistry.

Figure 1
Collaboration countries

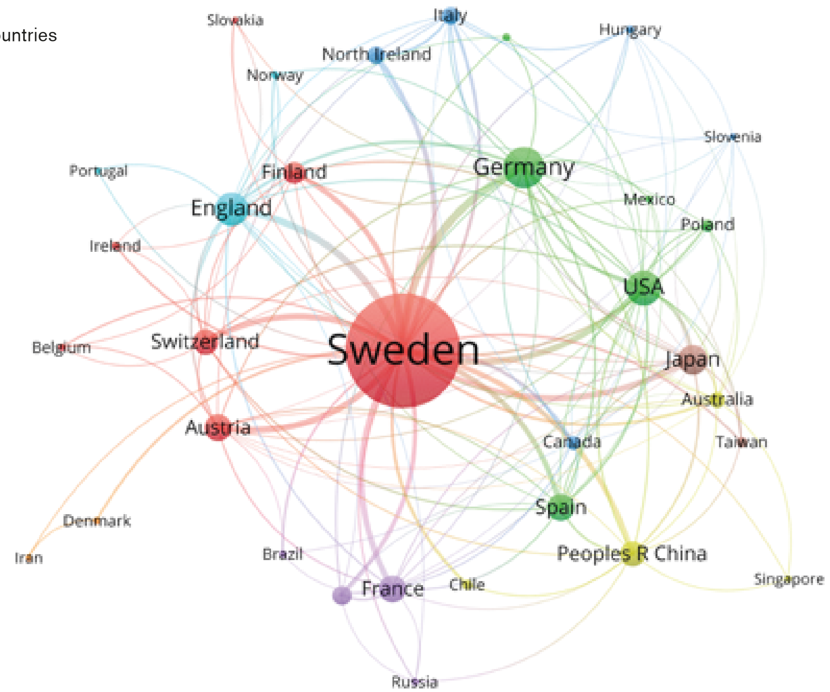


Figure 2
Collaboration affiliations

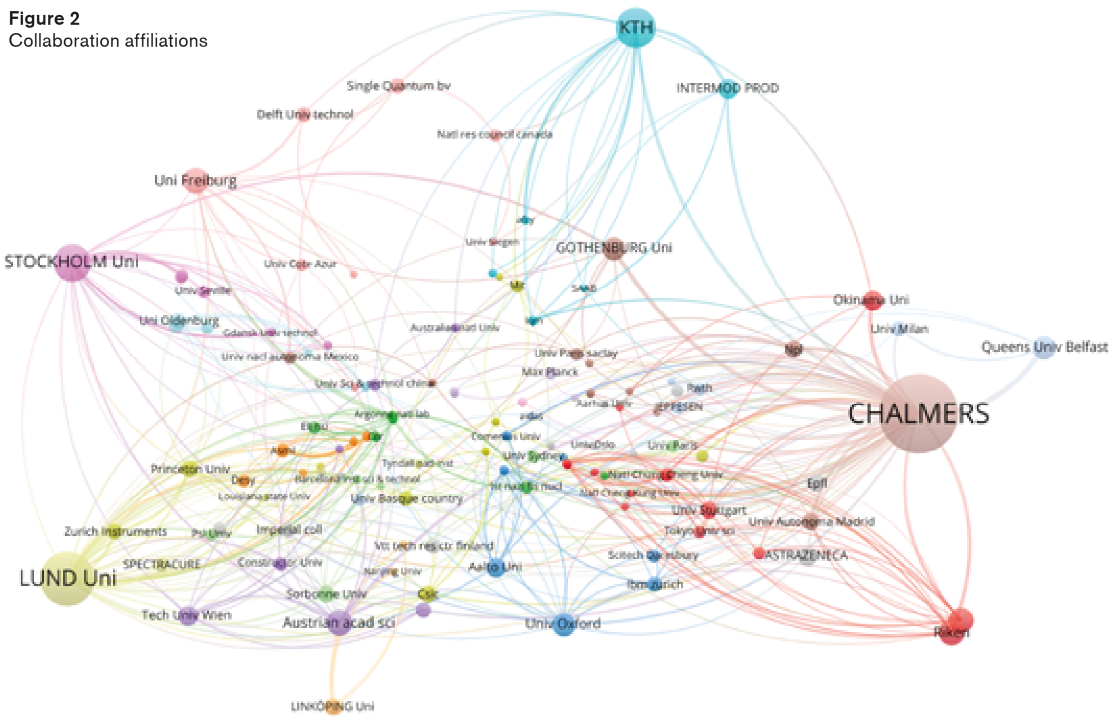


Figure 3
Publications subjects

Figure 1 – Opposite page top:
Network of collaboration between countries based on co-authors' affiliations. Thicker lines imply a higher level of collaboration, at least in terms of shared publications.

Figure 2 – Opposite page bottom:
Network of co-authorship per organisation. Bigger circle means more output and thicker line means more instances of co-authorship. WACQT partners are in all caps.

Figure 3 — Top:
Subject categories covered by WACQT publications (SciVal).

Working with other initiatives

National and Nordic collaboration

Within Sweden, WACQT is collaborating with several of the other strategic initiatives supported by the Knut and Alice Wallenberg Foundation (KAW). WACQT and WASP/AI have a common project on Quantum Machine Learning. Discussions between WACQT and the materials programme WISE have started, and joint activities are expected to start in 2024.

At the Nordic level, WACQT also collaborates with similar initiatives in the other Nordic countries within Nordic Quantum. The Wallenberg Initiative on Networks and Quantum Information (WINQ) is also part of this collaboration. Discussions are under way to formalise a Nordic network – Nordic Quantum – with initial interest mainly from academia but which might be expanded to include industry. Several researchers in WACQT are involved, including the writing of a white paper on Nordic collaboration and actions, to be published in 2024. https://nordita.org/nordic-quantum

European projects

Researchers within WACQT are also involved in a large variety of EU-funded projects. Some examples of projects that align with the scope of WACQT follow below.

WACQT's quantum computer development has greatly benefited from participating in the EU Quantum Flagship. The PIs of WACQT were instrumental in organising the European community and co-leading the projects OpenSuperQ and OpenSuperQPlus (with EUR 4.5 million in funding to Chalmers). We aligned the projects with WACQT's quantum computer roadmap and are working in collaboration and competition with most of the best groups in Europe. Highlights include the demonstration of Chalmers' first 25-qubit in-house developed quantum processor with state-of-the-art qubit coherence times.
WACQT researchers have also been one of the driving forces behind the Quantum Flagship project SQUARE on quantum computing in rare-earth-ion doped crystals. Within the project, the Lund group has led the work to develop a roadmap for quantum computing in rare-earth-ion doped solid state systems. An ERC Advanced Grant for Quantum Physics with Attosecond Pulses (QPAP) is supporting the Lund activity in ultrafast quantum physics.

The WACQT PI in quantum communication has been the driving force behind Swedish participation in EuroQCI and the award of the national project to build a quantum communication testbed and infrastructure in Sweden (NQCIS, with EUR 9.75 million in funding to the

“The development of the quantum computer software stack has been demonstrated through multiple online demonstrations and a growing number of collaborators.”

Swedish consortium, including Ericsson, for the years 2023 to 2025). The Rydberg ion group at Stockholm University is coordinating the European EIC Pathfinder project BRISQ on realising the prototype of a fast Rydberg ion quantum processor.

The development of the quantum computer software stack has been demonstrated through multiple online demonstrations and a growing number of collaborators. In 2022, a collaboration with the Nordic-Estonian Quantum Computing e-Infrastructure Quest (NordIQuEst) showcased a cross-border connection and hybrid quantum-classical workflow. This demonstration involved using the LUMI supercomputer in Finland as a powerful pre- and post-processor for the quantum data from the WACQT quantum computer demonstrator. A further demonstration utilised the experimental system eX3 in Norway, where the quantum computer repeatedly provided quantum random numbers to a Monte Carlo simulation running on an HPC node. In 2023, we increased the task complexity to a simple machine-learning demonstration over a handful of qubits, showcasing it live at the EU Digital Assembly at Arlanda XPO.

In hindsight, the best thing about these demonstrations was tapping into the potential and excitement of people who would like to contribute to the development of quantum computing but are not physicists themselves. The software stack facilitated collaborations with researchers working on large-scale computer infrastructures, computer scientists working on compilers, and application scientists looking at optimisation problems and chemistry calculations. These successful collaborations led to further funding opportunities with more partners, including the “QuantumStack” project funded by SSF FuSS, OpenSuperQPlus under the Horizon Europe programme, and the EUROQHPC-Integration project funded by the Digital Europe programme, where the EuroHPC JU decided to support the integration of HPC and quantum computer demonstrators at scale.

Guest reseacher programme

The purpose of the guest researcher programme (GRP) is to invite international experts, from both academia and industry, for shorter or longer periods to interact with WACQT researchers and students. The long-term mission of the GRP is to create attractive places to meet where a significant number of international scientists choose to participate at the same time. This includes workshops in which important problems in quantum technology with relevance for WACQT may be discussed.

The GRP is led by Mats Granath, University of Gothenburg.

The GRP is led by Mats Granath, University of Gothenburg.

We have had more than 40 visitors to WACQT nodes. Notable guests include John Martinis (Google and UCSB), Anton Zeilinger (prior to the Nobel Prize 2022), Peter Shor (MIT), and David Wineland (NIST, Nobel laureate 2012).

Among the supported workshops/conferences we can note:

Nobel symposium on Emerging Quantum Technologies, August 2022 in Malmö.
Organised by Martin Leijnse and several other WACQT researchers.

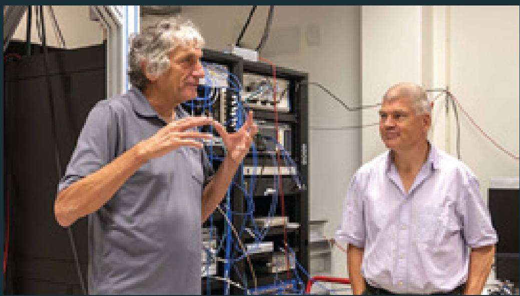
Machine Learning for Quantum Control and Quantum Computing, September 2022.
Mats Granath and Anton Frisk Kockum were co-organisers.

Frontiers of near-term quantum computing, 2023.
Laura Garcia Alvarez, Werner Dobrautz, Alexandru Gheorghiu were co-organisers.

Quantum Natural Language Processing, 2023.
Devdatt Dubhashi and Mats Granath co-organised with Quantinuum.

Rare-Earth-Ion Doped Crystals for Quantum Information, 2023.
Organised by Stefan Kröll, with co-organisers Lars Rippe and Andreas Walther.

Einstein '23 symposium, GRP was a co-sponsor.
Organised by Göran Johansson.



John Martinis (Google, left) in discussion in the quantum computer lab with Per Delsing (Chalmers, right) and others during John's visit to Chalmers in 2023.

Peter Shor giving a presentation about quantum mechanics at his visit to Chalmers in 2023.

Exploitation

The utilisation of research results to create impacts in society is a key element in WACQT, and researchers, apart from excelling in research output, also inv10 significant effort into innovation and utilisation-related activities. During the first six years of the WACQT programme, at least five spin-offs were founded. Many of these spin-offs are already offering services and products to a wide client base.

WACQT-IP

https://wacqt-ip.com

WACQT-IP was created with the goal to assist WACQT researchers to protect early steps in quantum technology via patenting, building up a patent portfolio, and venture creation based on the research results from the involved researchers. It also assists researchers with early-stage commercialisation actions based on results and IP developed within WACQT. This holding company started operations in 2022 with financing from Chalmers Ventures and Navigare Venture, and participation by WACQT researchers via the company WACQT Researchers AB: https://wacqt-ip.com/wacqt-researchers-ab. WACQT Researchers own 70% of WACQT-IP. The operations manager of WACQT-IP is Mats Rydehell and its board is chaired by Pontus de Laval. In total, 30 researchers and two administrators opted to sign up. Note that under Swedish law it is the researcher, not the university, who owns their inventions due to the 'teachers' exemption'. It is optional for WACQT researchers to join WACQT-IP by buying shares in WACQT Researchers AB.

Chalmers Next Labs AB

https://chalmersnextlabs.se

Chalmers Next Labs (CNL) bridges the gap between cutting-edge research and real-world applications. CNL works directly with Chalmers University's research groups, external funding bodies, and industry partners to tackle critical challenges. Its team of highly skilled technical specialists thrives in a dynamic international environment. Chalmers Next Labs packages the expertise of Chalmers' researchers into practical solutions. CNL operates the WACQT Quantum Technology Testbed (see above) that is owned by Chalmers University of Technology AB.

IP protection
During 2020 and 2021, a series of five seminars on IP-based utilisation was held. The speakers came from the Swedish Intellectual Property Office (PRV), Chalmers Innovation Office, Chalmers Ventures, Wallenberg Launch Pad, LU Innovation, and KTH Innovation. In 2022, one workshop entitled ‘Thinking about Intellectual Assets’ was held, focusing on how to handle the intellectual assets that may be generated in the environment.

Even though several spin-offs have been started, only relatively few patent applications have been filed from the researchers involved in WACQT. At least 10 patent applications have been filed, of which most are for components used in quantum computers, with two for quantum sensing and two for quantum communication.

Spin-offs
At least the following spin-offs are based on results from WACQT during its first six years:

Atlantic Quantum
https://www.atlantic-quantum.com
Aiming to develop fault-tolerant quantum computers based on superconducting qubits, Atlantic Quantum is a spin-off of MIT and Chalmers University of Technology. It is headquartered in Cambridge, Massachusetts, with a subsidiary in Gothenburg. The company secured a SEK 95 million seed investment in 2022, money which will fund the expansion of Atlantic Quantum’s team both in the USA and Sweden. Co-founded by Jonas Bylander, Chalmers University of Technology.

ATLANTIC
QUANTUM

Deep Light Vision
https://deeplightvision.com
Deep Light Vision is developing a new form of medical imaging method called Ultrasound Optical Tomography that can provide the option to image the oxygenation inside organs such as the brain, heart, or parts of the body with suspected cancer. The method, which utilises narrowband optical quantum-engineered rare-earth crystal filters as a key component, aims to provide a faster and easier diagnosis of medical conditions such as stroke, heart attack, cancerous tumours, and other medical conditions. Three filed patent applications. Co-founded by Stefan Kröll, Lund University.

DEEPLIGHT
VISION

quCertify

quCertify AB is a Swedish quantum technology startup that provides solutions for secure communication and quantum networks for the IT security industry. It is a spin-off of the quantum information and quantum optics group in the Physics department at Stockholm University. It benefits from 25 years of experience in quantum communication. quCertify AB develops, validates, and commercialises enabling technologies such as quantum random number generation, entanglement sources, picosecond pulsed lasers, multifold coincidence counting, and time-tagging instruments.

quCertify AB is a partner in the National Quantum Communication Infrastructure in Sweden project. quCertify AB's projects have received support from the EU and Vinnova.

quCertify

SCALINQ AB

https://www.scalinq.com

SCALINQ aims to provide complete packaging solutions to enable large-scale superconducting quantum processors. Its first product, Linqer, which is already for sale, can scale up to 596 microwave control lines. It is a patented sample holder designed with extreme precision and flexibility to fit a variety of quantum processor designs with high-end performance output. Interest from the community has been huge, and SCALINQ has released several additional prodcuts since incorporation. Co-founded by Robert Rehammar, Giovanna Tancredi, and Sandoko Kosen from Chalmers University of Technology.

SCALINQ

Sweden Quantum AB

https://www.swedenquantum.com

Its first product-in-prototype and patent pending is the High-Energy Radiation Drain (HERD), a new type of infrared-blocking filter for quantum computing applications. Unlike commonly used copper-powder or Eccosorb filters, HERD combines very low ripples and insertion loss in the passband with high rejection in the stopband. Co-founded by Simone Gasparinetti and Robert Rehammar, Chalmers University of Technology.

Sweden Quantum

Training

Graduate school

The objective of the Swedish Graduate School in Quantum Technologies is to foster the next generation of Swedish quantum researchers and engineers. Over the duration of WACQT, the graduate school will fund 95 PhD studentships, of which at least 30 are industry PhD students. In the first six years, 81 PhD students have started in WACQT, of which 24 are affiliated and ten are industry PhD students. Two industry PhD students defended their PhD theses and one licentiate. Six PhD students defended their theses. Of the alumni we know where they went, 80% are still in quantum technology, 70% stayed in Sweden and 1-in-4 went to industry.

Both WACQT and affiliated PhD students should meet the same requirements:

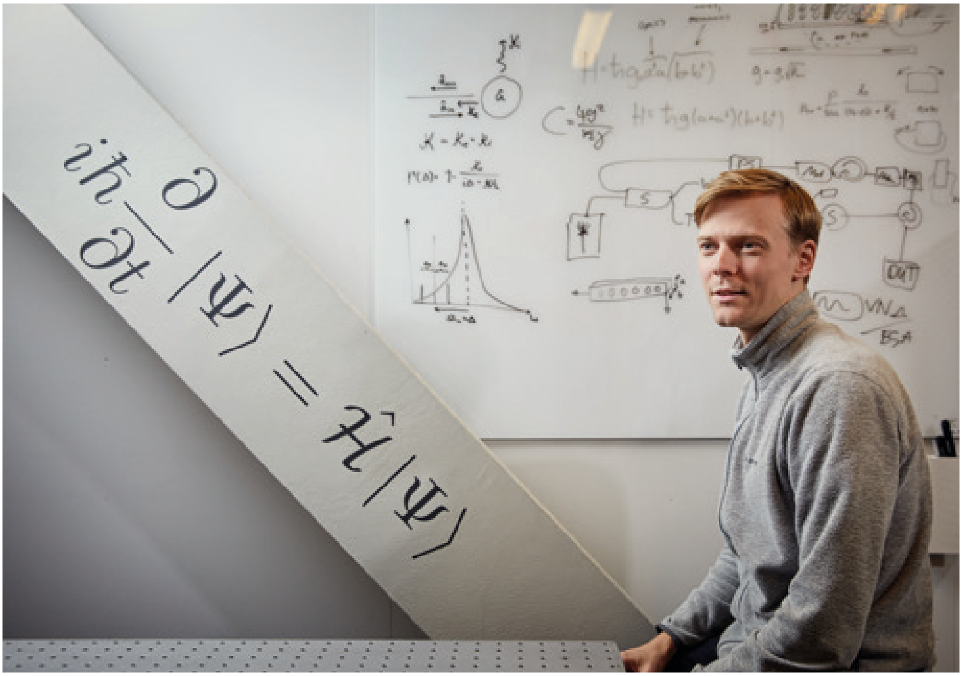
- Take courses amounting to at least 15 credits in quantum technology during their PhD studies.
- Take the WACQT lab course, 6 credits (counts towards the 15 credits).
- Attend the biennial summer schools (counts towards the 15 credits).
- Attend the field trips to visit other quantum technology sites.
- Attend the WACQT annual meetings.

The postdocs in WACQT may (if space allows) attend the relevant graduate school courses and are encouraged to participate in the summer schools and other graduate school events.

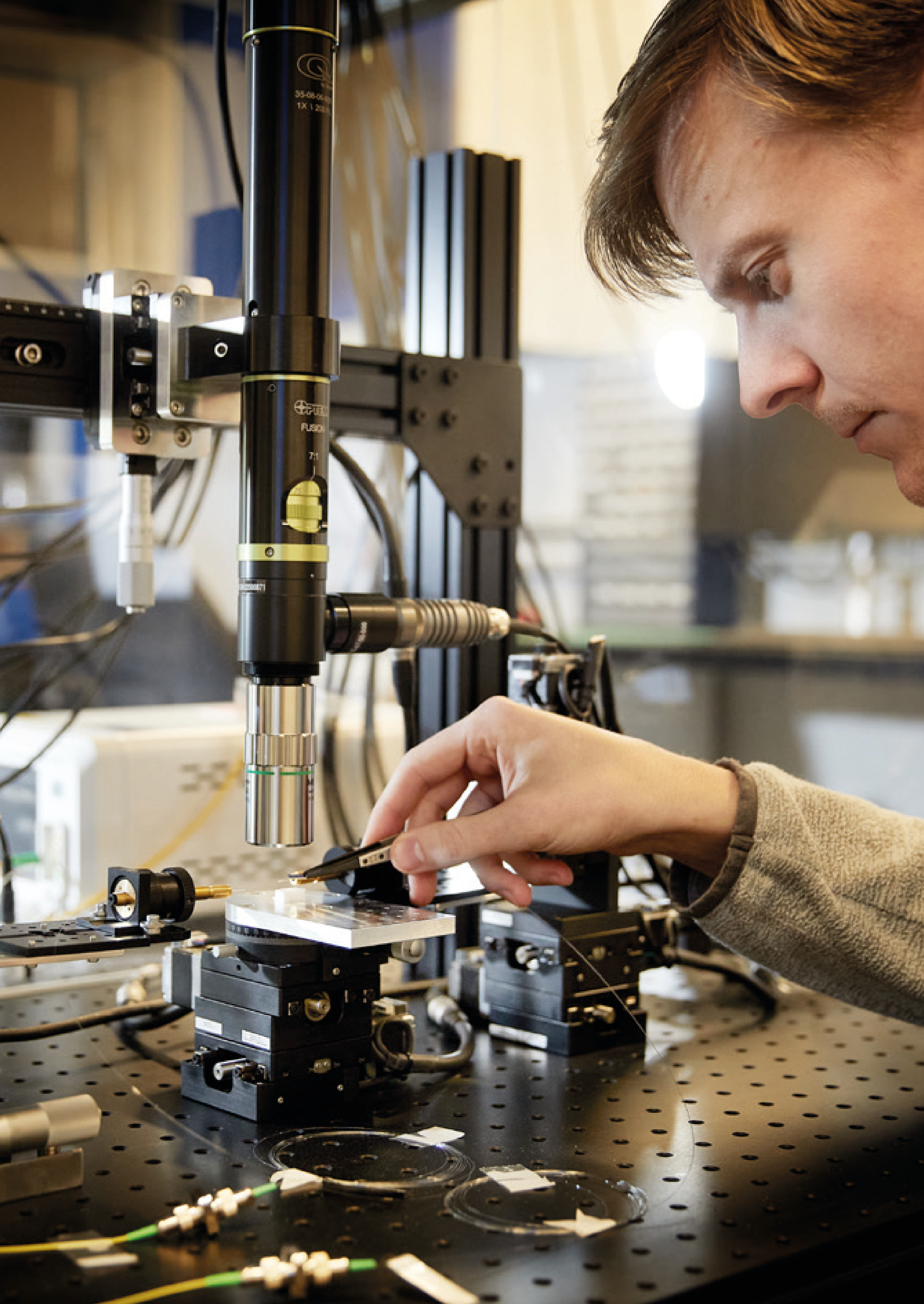
Additionally, the faculty funded by the programme will develop several specialised courses that are elective for all students at the Graduate School, the first being a course on Advanced Quantum Algorithms developed by Giulia Ferrini and Anton Frisk Kockum at Chalmers University of Technology, offered for the first time in winter 2019. The lectures were recorded and are available on WACQT's YouTube channel. The research school also supports local existing courses within quantum technology to ensure their quality.

Opportunities for students to present their work, interact with international experts from academia and industry, and form a professional network include:

- a biennial international summer school with leading international speakers covering a broad range of topics in quantum technology
- field trips to sites in neighbouring countries with visits to universities, institutes, and companies active in quantum technology
- The annual WACQT May meeting.



PhD student Johan Kolvik in the Quantum Photonics Laboratory talks about his research (above) and demonstrates an experiment with optical fibres (opposite page). Photo: Anna-Lena Strandqvist.


FUSION

At Chalmers University of Technology, a new Quantum Technology specialisation was developed for the Physics Masters' programme that started in 2022. It mainly consists of existing courses but includes a new course on 'Open quantum systems', offered for the first time in spring 2023.

Available Master's programmes and profile tracks, and individual courses on quantum technology are listed at https://www.chalmers.se/en/centres/wacqt/education

WACQT Summer (and winter) schools

The summer schools have been held every second year since 2019. They include presentations by a handful of experts from around the world, with a final quiz. The schools also include soft skills development, such as a career panel discussion, two-minute pitch talk by all students, and unconscious bias. Around 60–70 students attend these each time. The most recent school took place in summer 2023 outside Ystad in southern Sweden.

During the pandemic, a winter school with industry participation was organised as four half-day events. All PhD students were given the opportunity to present their research and receive feedback. The industry participation was transformed into six very successful webinars given by our industry partners during autumn 2020, sharing their views on quantum technology.

WACQT autumn lab course

The Graduate School has developed a hands-on course based on four lab sessions at Linköping University, Lund University, KTH Royal Institute of Technology, Stockholm University, and Chalmers University of Technology, where the students also get an overview of the local research in Quantum Technology. This was offered for the first time in autumn 2019 and is offered every second year. This facilitates development of a common language among the students, multi-disciplinary skills, and a strong sense of belonging to the community of Swedish quantum technology researchers and engineers. In the latest lab course, the following lab sessions were given:

- 'Quantum information with attosecond light pulses' at Lund University, supervised by David Busto and Anne L'Huillier.
- 'Quantum Algorithms and Quantum Key Distribution' at Linköping University, supervised by Jan-Åke Larsson, Guilherme Xavier, and Niklas Johansson.
- 'Quantum Information with Photons and Atoms' at KTH Royal Institute of Technology and Stockholm University, supervised by Ali Elshaari and Marcus Hennrich.
- 'Quantum Information in Superconducting Circuits' at Chalmers University of Technology, supervised by Giovanna Tancredi and Simone Gasparinetti.

WACQT Graduate School during a visit to Niels Bohr Institute.

Study visits

In 2023 we arranged the first study visit (field trip) to the Niels Bohr Institute together with WINQ. The visit took place in March 2023, and included most of the PhD students and a few additional WACQT researchers, completely filling the lecture room capacity of 60 people. The participants were informed about quantum technology research at the Niels Bohr Institute and DTU, the NovoNordisk foundation's quantum initiative, the NATO Quantum Technology Centre, and Danish undergraduate level quantum technology teaching.

Marianne och Marcus Wallenbergs Stiftelse

Education and EDU-WACQT

The Graduate School Committee supervises a project called EDU-WACQT funded by the Marianne and Marcus Wallenberg Foundation, granted in December 2022.

This additional SEK 13 million in funding enables support to undergraduate quantum technology activities such as:

- Summer jobs available to all quantum technology researchers in Sweden, to give more undergraduate students a hands-on experience in quantum technology. The first round of summer job grants, in total 14, were awarded in 2023. In the second round, for the 2024 summer, 12 job grants have been awarded. The last round will be for the 2025 summer.
- Tuition fee scholarships for master students in quantum technology from outside of the EU/EEA, recruiting talent from a more diverse pool of students. The scholarships – at Chalmers, KTH, SU and LU – have been announced and the process of selecting the best applicants is ongoing. The scholarships will start in autumn 2024.
- National coordination and support for the development of courses and course modules in quantum technology, which could be shared between universities.

Diversity and EDI-WACQT

Right from the Centre formation stage, we have striven to build up a diversified and gender-balanced team at the different universities. We are aware that women are underrepresented within quantum technology worldwide and in Sweden and we are actively working to increase the number of women. The participating universities already have statements on equal opportunity when posting ads for new positions. In 2023 the management team decided to mandate the inclusion of the following statement in ads for WACQT-funded positions:

‘This position is supported by the Wallenberg Centre for Quantum Technology (WACQT), which receives funding from the Knut and Alice Wallenberg Foundation. WACQT is a 12-year, billion-SEK initiative with the purpose of advancing Swedish academia and industry to the forefront of quantum technology, and to build a Swedish quantum computer. WACQT is committed to promoting career development, diversity, and gender equality through networking and supporting activities.’

To ensure that the policies are followed, regular discussions among the WACQT participants on these issues and other values and alerting them to deviations from these policies are good ways to spread good attitudes and behaviours in the organisation. WACQT relies on the gender equality and equal opportunity policies that have been adopted at the participating universities as the basis for operational decisions. While the policies and action plans differ somewhat between the universities, they are similar in spirit.

Initially, these activities were under the banner of Women in WACQT (WWACQT) with the aim to foster the careers of women within the Centre by enhancing their visibility and by providing support for networking and mentoring. The most prominent action that WWACQT has undertaken, in 2020, was to establish a mentorship programme for the junior female researchers in WACQT at Chalmers. The programme was conceived in collaboration with the Women in Science (WiSE) network, also based at Chalmers, and has therefore been named the WiSE-WWACQT Mentorship Programme. The programme is also supported by the Gender Initiative for Excellence (GENIE) at Chalmers.

The WiSE-WWACQT Mentorship Programme aims to provide support for female PhD students and postdocs at either the Chalmers’ Electronics Department or WWACQT through mentorship. It provides a one-to-one connection between junior and senior scientists working at different departments at Chalmers. It fosters opportunities

PhD students Ariadna Soro in the Applied Quantum Physics group and Jiaying Yang in the Quantum Technology Lab discuss quantum photonics. Photo: Anna-Lena Strandqvist.

to exchange ideas, discuss challenges, get career coaching, and an avenue to report problems if needed. In its fourth round, the Programme had 30 mentees and 30 mentors.

In 2023 WWACQT changed its name and scope to EDI-WACQT, where EDI stands for Equality, Diversity, and Inclusion. The network includes representatives from Stockholm University, KTH Royal Institute of Technology, Linköping University, Lund University and Chalmers University of Technology.

In recent years, EDI-WACQT has organised seminars for young researchers, especially during the summer school and autumn lab courses. These include a workshop on unconscious bias, panel discussions with established researchers about career challenges, a workshop on negotiation, one on work-life balance, mental health and impostor syndrome; and one on the values driving one's research.

These activities have been led by Giulia Ferrini (Chalmers) and Katia Gallo (KTH) up to 2024, with Vaishali Adya (KTH) taking over from 2024 onwards. The EDI-WACQT group includes representatives from all academic partners, representing the researchers, PhD students, and postdocs.

Promoting quantum technology

National

By the end of August 2022, the Minister for Education Anna Ekström came for a half-hour visit to the quantum computer project at WACQT. In October 2023 the Minister for Defence Pål Jonsson came for a similar visit.

During 2022 and 2023, several of the WACQT researchers and the chair of the WACQT board, Lena Gustafsson, spent considerable time working on a Quantum Agenda for Sweden[12]. Hopefully, this will impact Sweden's quantum technology focus during the coming years. This work has been done in close collaboration with VINNOVA, Quantum Life Science at the Karolinska Institutet, RISE and the Swedish Research Council (VR). The Agenda was presented to the Minister for Education Mats Persson in March 2023.

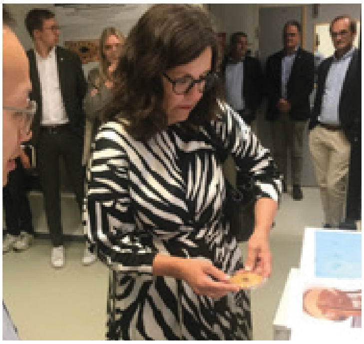
From the start in 2023, WACQT partners have been involved in the Quantum Sweden Innovation Platform (QSIP[13]) led by Chalmers Industriteknik.

Nordic

The informal academic network Nordic Quantum started to meet in 2022 and is working on a Nordic white paper and an assessment of needs and priorities. The discussions have mostly been around how to best share ideas on education and what we could do together apart from ongoing research collaborations. The network meets twice a year to discuss ways forward.

In spring 2023, two workshops were held back-to-back with Nordic Quantum and a wider policy event with academia, industry, and policymakers in Brussels with participants from the Nordic and Baltic regions.

Recently, discussions on standardisations within quantum life sciences have started with the Nordic standardisation bodies.



Postdoc Sandoko Kosen showing the Minister om education Anna Ekström the quantum computer lab, accompanied by Chalmers' president Stefan Bengtsson and professor Göran Johansson.

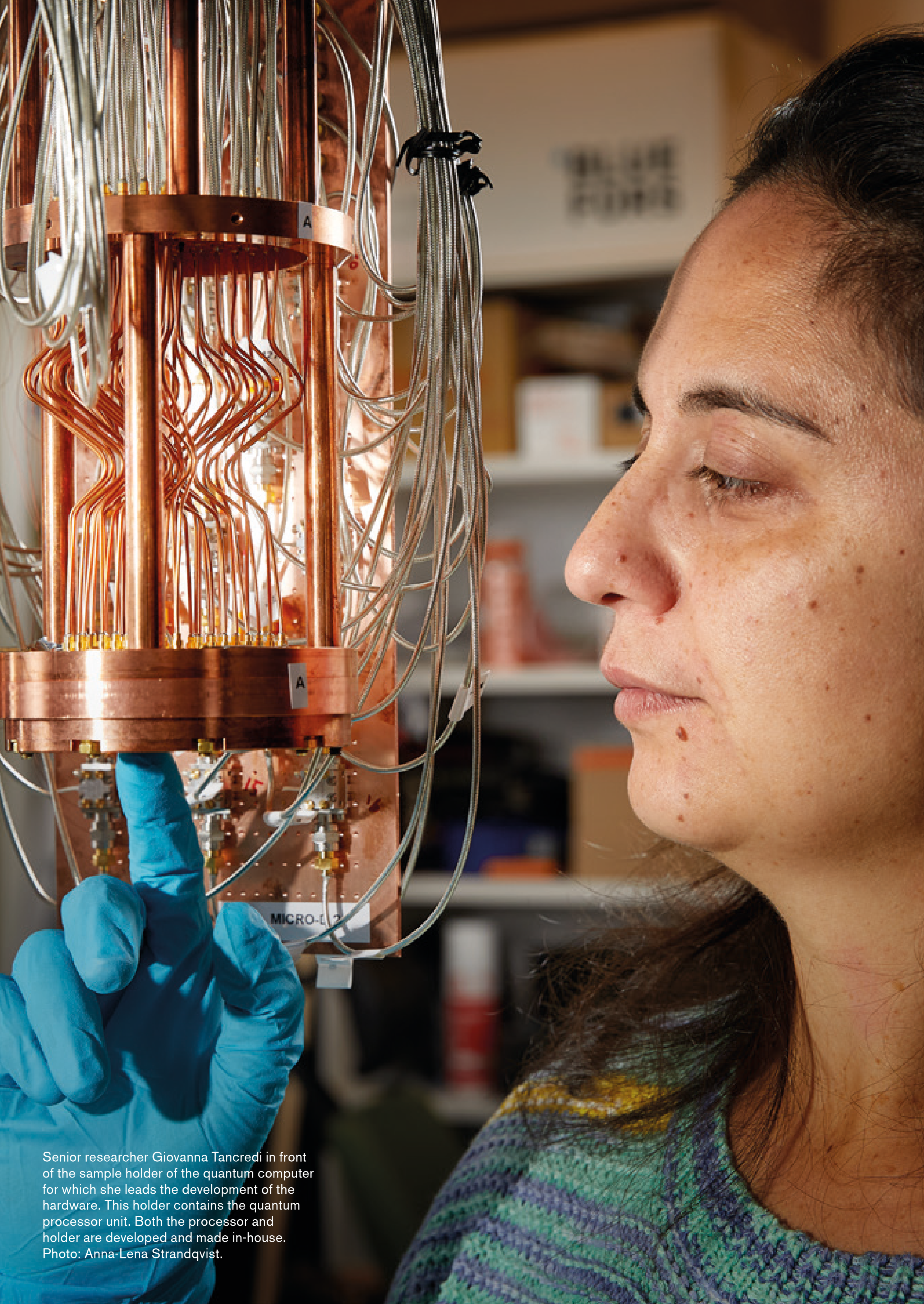
American embassador Erik D. Ramanathan visiting the quantum computer lab in 2022. From left to right: Per Delsing, Anton Frisk Kockum, Göran Wendin. Göran Johansson, Jonas Bylander and the embassador. Photo Carina Schultz

European
WACQT researchers have been involved in various policy including the European network of national quantum initiatives (EuroNQI), which since 2023 also includes people from the Swedish Government cabinet and the Swedish Research Council. Within this forum, discussions have been held on many issues including risk assessments, the work programme of the recently started Chips Act Joint Undertaking[14], and the quantum pact (quantum declaration) that Sweden signed in late 2023[15].

Up until 2023, Chalmers was the only Swedish member of the European Quantum Industry Consortium[16] (EuroQUIC) whose mission is to boost the European quantum technology industry's competitiveness and economic growth in Europe.

International
The US ambassador visited WACQT in March 2022. The Swedish Minister for Education, Anna Ekström, signed a joint statement on quantum information science and technology with the US ambassador in April. In May, the USA hosted a roundtable meeting at the White House with its eleven partner countries in quantum technology: Canada, Japan, Australia, Sweden, Denmark, Finland, the Netherlands, Switzerland, Germany, France, and Great Britain. WACQT Director Per Delsing was invited as one of two representatives from Sweden to attend the meeting.

[12] https://www.vinnova.se/en/publikationer/a-swedish-quantum-agenda
[13] https://qsip.se
[14] https://www.chips-ju.europa.eu
[15] https://digital-strategy.ec.europa.eu/en/library/european-declaration-quantum-technologies
[16] https://www.euroquic.org



Senior researcher Giovanna Tancredi in front of the sample holder of the quantum computer for which she leads the development of the hardware. This holder contains the quantum processor unit. Both the processor and holder are developed and made in-house. Photo: Anna-Lena Strandqvist.

Outreach and media

Since the start of WACQT, there has been a lot of media coverage as well as other activities communicating the formation and plans of WACQT. WACQT representatives receive many invitations to present our activities, and many want to visit us. We also have outreach activities targeting industry (see the heading Industry engagement).

Media

There have been plenty of news articles about WACQT and our researchers, often as follow-up to the WACQT-related press releases. Activities within WACQT have mainly been reported on by local and national media but also internationally, especially in topical outlets. See list with links at https://wacqt.se

Visits

A wide range of interested parties contact us for visits, including high schools, university students – national and international – policymakers in science and technology, ambassadors, etc. The visitors usually get a short presentation on quantum technology followed by discussion and a lab visit. See also the Guest Researcher Programme.

Outreach

Outside the policy context we have outreach activities, such as giving presentations or posts on our social media channels. On YouTube https://www.youtube.com/@wacqt we mostly post recordings of our courses or online seminars. On our X/Twitter channel we post our newsletter, ads for vacant positions, recent publications, and more.
https://twitter.com/wacqt_sweden

Popular science presentations have been held, e.g. by Anton Frisk Kockum, Mats Granath and Witlef Wieczorek at the International Science Festival 2022, and Jonas Bylander at TEDxGöteborg in 2021. Giulia Ferrini, Hanna Linn, and Markus Hennrich organised virtual lab tours for schools during the pandemic in 2021 together with "Hello World!".

Newsletter

Our newsletter is sent out three times per year. In it, we cover updates from the Centre and some quantum technology highlights from around the world. Sometimes we include an in-depth article focusing on a specific topic. Anyone can read and sign up for it:
https://www.chalmers.se/en/centres/wacqt/newsletter

Website

The website was redesigned in 2023 and now includes more information in Swedish about WACQT and quantum technology. The graduate school and education parts have received plenty of updates with more information about courses and requirements. https://wacqt.se

Financials

The main source of funding is the Knut and Alice Wallenberg Foundation (KAW) and co-financing from our partners. The Marianne and Marcus Wallenberg Foundation (MMW) has awarded an additional grant of SEK 13 million for education support. For all grants combined from KAW and MMW, the expected funding amounts to close to SEK 1400 million. The KAW grants are awarded in periods (3, 4, 3, and 2 years). For each, we need to re-submit an application defining the scope and budget for each period. After six years, approximately one third of the funding has been paid out. The partners have contributed approximately a quarter of the total reported costs. The first half of WACQT has been a steady ramp-up of activities and recruitments. As of 2023, we are close to a steady-state in terms of personnel, with some remaining tenure-track positions to be filled and the recruitment of more industry postdocs.

Annual May meeting

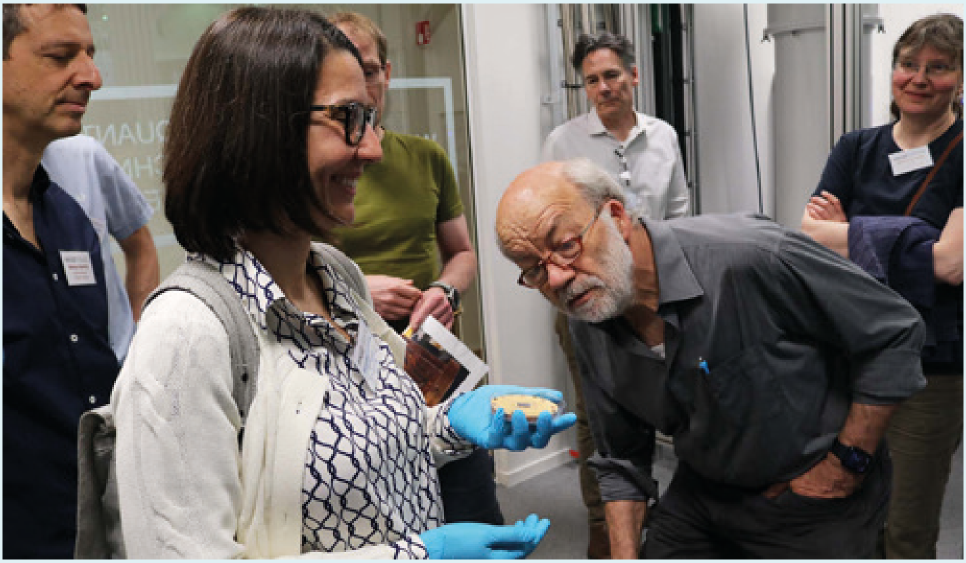
The WACQT team meet up with the boards over a three-day annual review meeting in May during which we gather to discuss science and progress. The junior researchers either prepare a poster or give a presentation. We try to give everyone, including the boards, time and opportunities to meet up to discuss science and other issues. The Scientific Advisory Board (SAB) has a dedicated lunch with the junior researchers.

The programme includes social activities as well as board meetings. Some members of the boards also give scientific presentations. Apart from the scientific presentations, we also hear from the graduate school, EDI-WACQT, guest researcher programme, collaboration with industry, and WACQT-IP.

Members of the Board, SAB,
and IAB at the May meeting in 2024.

From left to right:
Steve Girvin, SAB
Gerd Leuchs, SAB
Catrin Granbom, IAB/Board
Erika Andersson, SAB
Maria Lanne, IAB/Board
Lena Gustafsson, Board
Stefan Filipp, Board
Elisabeth Giacobino, Board
Jörg Wrachtrup, SAB
Anders Broo, IAB/Board
Will Oliver, SAB
Per Delsing, Director
Harry Buhrman, SAB
Eleni Diamanti, SAB
Pontus de Laval, Board

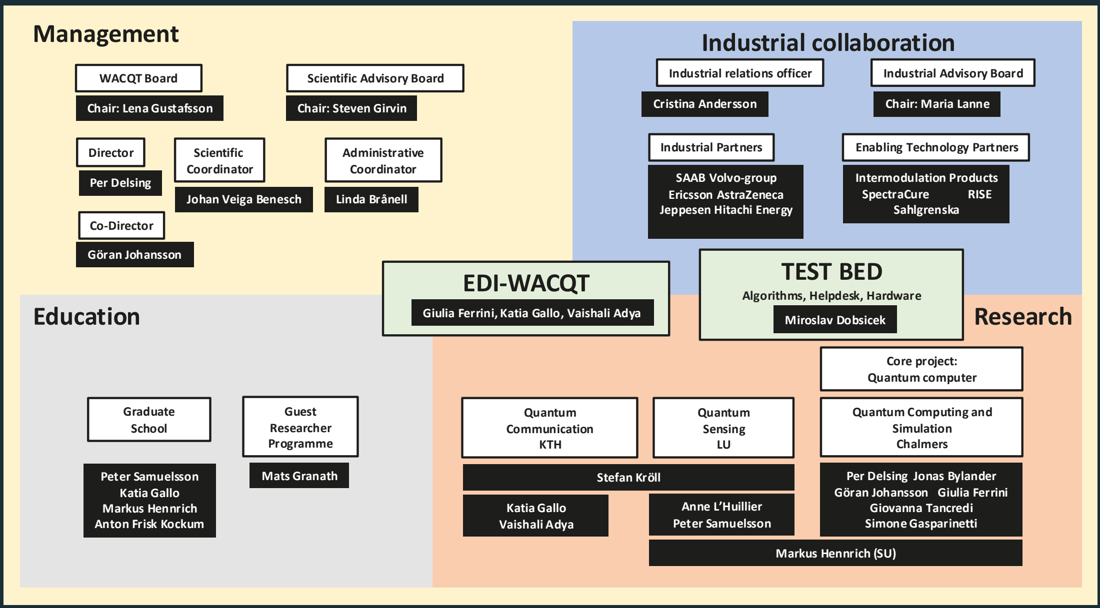
Group photo from the May meeting 2024 at Chalmers.



Checking that everything looks fine.
Lab visit during the May meeting 2024.
From left to right: Markus Hennrich,
Beatriz Grafulla, Miroslav Dobsicek,
Gerd Leuch, Will Oliver and Erika
Andersson.

Organisation

The overall structure was settled early in the programme, but there have been some changes in which individuals have specific roles.



WACQT organisational chart with lead roles, industry partners, and main nodes of the four quantum technology pillars. Check wacqt.se for updates.

Board

The task of the Board is to make strategic decisions that will steer WACQT in a successful direction. All board members have extensive experience of leading and running large research or development initiatives, either in academia or in industry, including international scientific experts.

Lena Gustafson
Chair, Umeå University

Pontus de Laval
Vice-chair, KAW

Anders Palmqvist
Chalmers

Elisabeth Giacobino
Lab Kastler Brossel

Stefan Filipp
TU Munich & WMI

Maria Lanne
SAAB

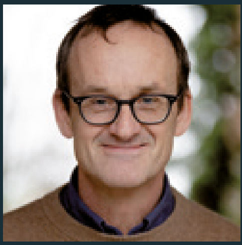
Anders Broo
AstraZeneca

Catrin Granbom
Ericsson

Management group

WACQT is managed by a Director and a Vice-director together with several principal investigators (PIs), the scientific coordinator and the administrative coordinator. Quite frequently, its meetings also include the chairs of the Visiting research fellow programme and graduate school, or our industry relations officer.

Per Delsing
Director until 2024, Chalmers



Göran Johansson
Vice-director, Director from 2025, Chalmers

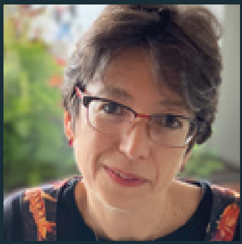
Simone Gasparinetti
Chalmers

Giovanna Tancredi
Chalmers

Giulia Ferrini
Chalmers

Stefan Kröll
Lund University, until 2024

Markus Hennrich
Stockholm University



Katia Gallo
KTH

Anne L'Huillier
Lund University

Jonas Bylander
Chalmers

Peter Samuelsson
Lund University, from 2025

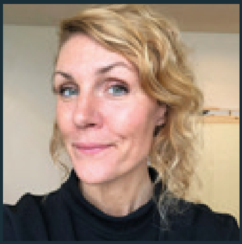
Vaishali Adya
KTH, from 2025

Administrative support


Johan Veiga Benesch
Scientific coordinator


Linda Brånell
Administrative coordinator

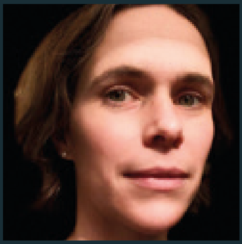

Susannah Carlsson
Website


Lovisa Håkansson
Communications


Cristina Andersson
Chalmers, WACQT
Industry Relations Officer


Ingrid Collin
Financials


Eva Strandberg
Financials


Ingela Roos
Communications

Scientific Advisory Board (SAB)

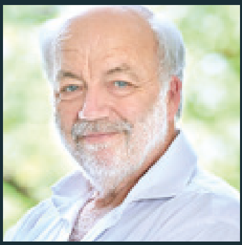
In the still largely unexplored realms of quantum technology, there are many complex issues and crucial decisions to be made. In such situations, we get extremely valuable and competent advice from the quantum experts on our Scientific Advisory Board. They meet the boards, management, and the researchers during the annual review meeting in May. They file an annual report with insights and recommendations after the May meetings.

Steve Girvin,
Chair, Yale University

Erika Andersson
Herriot Watt University

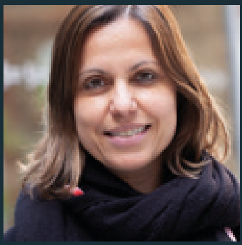
Harry Buhrman
Quantinuum, QuSoft and University of Amsterdam

Jörg Wrachtrup
University of Stuttgart



Gerd Leuchs
University of Erlangen–Nuremberg

Will Oliver
MIT



Eleni Diamanti
CNRS Sorbonne University

Industial Advisory Board (IAB)

Our Industrial Advisory Board is comprised of one member from each of our end-user industry partner companies. The purpose of the Industrial Advisory Board is to give strategic advice, and industry perspectives, in questions related to industry collaboration and to increase the understanding between the academic groups and the industry research efforts. The discussions also lead to important insights and affect the topics under investigation.

Maria Lanne
SAAB, Chair

Anders Broo
AstraZeneca

Catrin Granbom
Ericsson

Mikael Rönnholm
Volvo Group

Peter Sutton
Jeppesen/Boeing

Cristina Andersson
Chalmers, WACQT
Industry Relations Officer

Besides these, the following have also been involved during the first six years:

Admin:
Anton Frisk Kockum and Philip Krantz as scientific coordinator, at Chalmers.

Management group:
PI Gunnar Björk: KTH and PI and senior advisor Göran Wendin: Chalmers.

Board and SAB:
Charles Marcus, NBI

IAB:
Michele Luvisoto: Hitachi, Jenny Ernman: Volvo Group, and Azimeh Sefidcon: Ericsson.

Wallenberg Centre for Quantum Technology

WACQT is a national research programme, coordinated from Chalmers, that aims to take Swedish research and industry to the forefront of quantum technology. Our main project is to develop a high-end quantum computer that can solve problems far beyond the reach of the best conventional supercomputers.

Contact WACQT
Johan Veiga Benesch, scientific coordinator
E-mail: johan.benesch@chalmers.se
Tel: +46-31-772 32 93

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