2018

Annual Report

COLOPHON

Annual Report

In accordance with the 'Partnerconvenant QuTech'

Cover photo

Marieke de Lorijn

Text editor

DBAR science writer & editor

Graphic design

Simon Droog (SD // simondroog)

QuTech

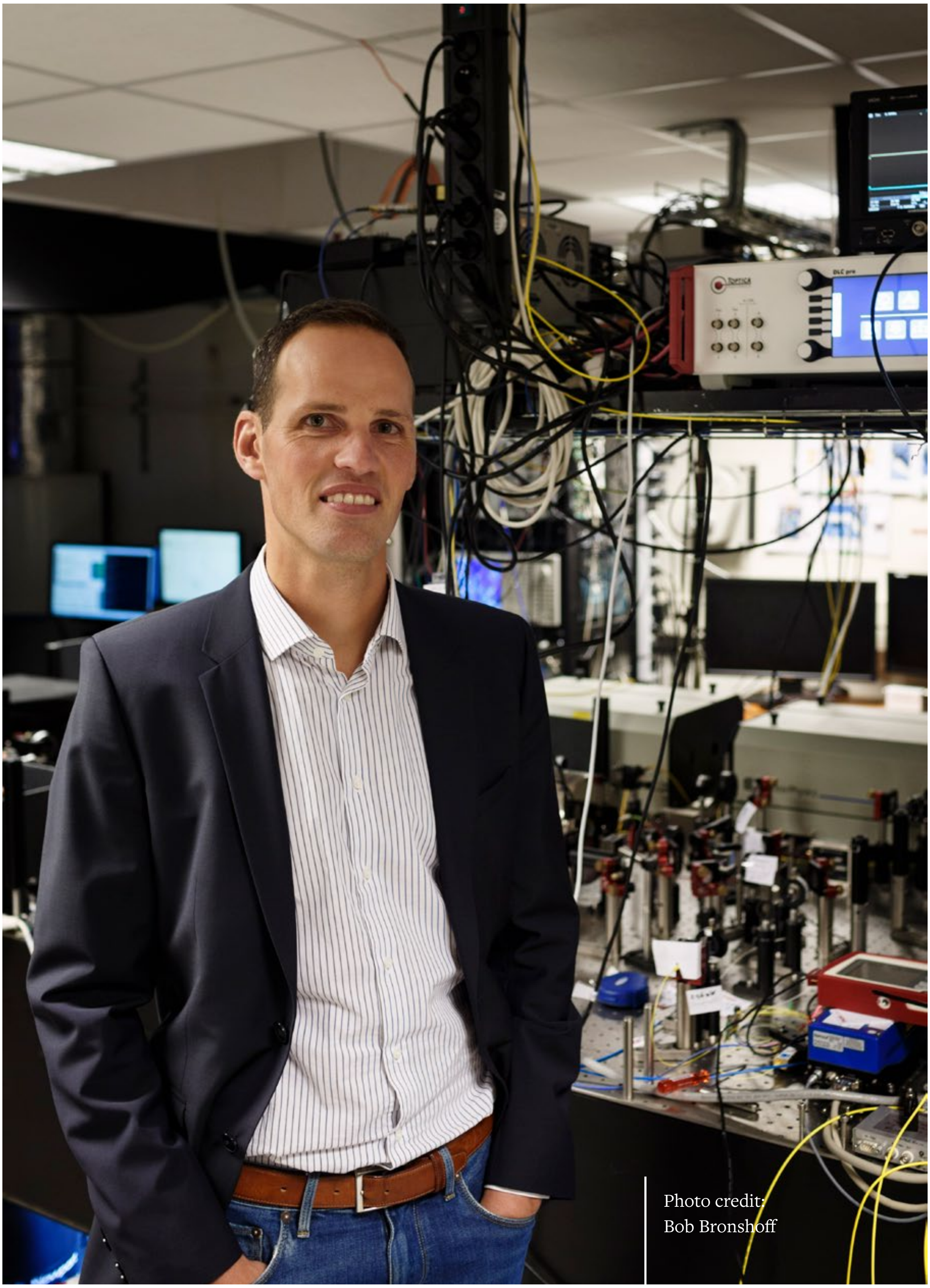
Lorentzweg 1

2628 CJ Delft

+31 15 27 86 133

QuTech@tudelft.nl

Contents



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Foreword

On behalf of the whole of QuTech, I am proud to present the annual report for 2018. It presents an overview of developments in QuTech's research roadmaps along with several other activities, such as QuTech partnerships, outreach and Academy.

At QuTech we work on one of the grandest and most exciting challenges of this time: to realize technological breakthroughs based on the fundamental laws of quantum particles. Looking back, 2018 was an excellent year that in many ways shows our transition from a 'start-up phase' to a more efficient and powerful organization. Besides the many research highlights described in this report, let me highlight the following developments.

We have worked hard to adapt the governance of QuTech to empower the organization in light of the growth from about 70 people in 2014 to about 200 today. I am very happy that we have been able to attract excellent people for the new positions of Business Director (Kees Eijkel) and Operations Director (Charlotte van Hees), see page 56.

Our demonstrator projects are running at full speed (page 23). It was my privilege to officially open our first online platform for quantum computing, Quantum Inspire, in the summer. This feat was repeated for outside users by the State Secretary at the InnovationExpo in the fall. Now, users from all over the world can connect to our platform, and we aim to connect our first quantum hardware to it in 2019. For the quantum Internet, a first link is set up to connect Delft to The Hague, in collaboration with KPN. In 2019, we hope to see the first quantum signals being sent over commercial fibre.

Talking about quantum internet: in October, the European Commission announced that its Quantum Flagship Programme will fund the development of a blueprint for a future quantum internet. This €10 million programme is run by the Quantum Internet Alliance (QIA, page 12, a large consortium of universities and industry. QuTech is proud to lead this effort, in the person of Stephanie Wehner.

Finally, we performed an extensive self-evaluation of our institute in preparation of the mid-term review by an international expert committee chaired by Robbert Dijkgraaf and Albert van den Berg. The site visit of the review committee took place in January 2019. At the time of writing the outcomes have just been presented: the committee gives QuTech the highest score on all aspects! We are delighted that the committee strongly endorsed our institute and we are extremely grateful for the advice for our future development. The committee's full report is made publicly available.

I hope you will enjoy reading this annual report.

Ronald Hanson
Scientific Director QuTech

About QuTech

QuTech is a mission-driven research centre that aims to develop scalable prototypes of a quantum computer and an inherently safe quantum internet. To achieve these ambitious goals, world-class scientists, engineers and industry work together in an inspiring environment. QuTech was founded in 2014 as a collaborative institution of Delft University of Technology (TU Delft) and the Netherlands Organisation for Applied Scientific Research (TNO). Within TU Delft, both the Faculty of Applied Sciences and the Faculty of Electrical Engineering, Mathematics and Computer Sciences are involved in QuTech. Within TNO, the departments Quantum Technology, Radar Technology, Optics, Optomechatronics, Nano Instrumentation and Distributed Sensor Systems contribute to QuTech.

The decision to establish the QuTech advanced research centre was presented in October 2013 after an extensive internal and external consultation process. At that time, Delft already had a very strong scientific competence in the field of quantum information solid-state physics. This was a result of a long tradition of excellence in quantum and nanoscience fuelled by strategic investments by the university and NWO (in particular through a FOM Focus Group 2004-2013). In 2012, a consortium of TU Delft and Leiden was awarded an ERC Synergy Grant for a Quantum Computing Lab, providing an excellent basis for strongly synergetic research between the Delft scientific groups of Prof. Leo Kouwenhoven, Prof. Ronald Hanson, Prof. Lieven Vandersypen and Prof. Leo DiCarlo working on different solid-state qubit technologies, in collaboration with Prof. Carlo Beenakker of Leiden University. To advance this core of excellent quantum information research towards technology, the need was identified to expand the competences through adding other disciplines, including computer science, quantum information theory and electrical engineering. Moreover, a different complementary mindset – that of applied engineering towards higher technology readiness levels (TRL) – was desirable. This starting point was written down in a proposal for QuTech, that resonated within the faculties and with The Ministry of Economic Affairs, TNO and the Netherlands Organisation for Scientific Research (NWO).

In 2014, QuTech was awarded the National Icon status by the Dutch government because of its pioneering and innovative character, the economic potential for

QUANTUM WHAT?

After decades of hard work in science and engineering, new quantum technologies are now coming within reach. They have the potential to radically change many technological fields, from imaging to computation, as well as to profoundly affect many societal issues such as health and security. That is why countries and industries around the world are scrambling to stay ahead of developments in the quantum field. So, what is this technology actually about?

At the scale of single atoms and electrons, many of the well-known laws of classical mechanics, which describe how things move and behave at the human scale, reach their limits. Instead, we have to turn to the laws of **quantum mechanics**. Quantum mechanics is the branch of physics that deals with the behaviour of matter and energy on the scale of atoms and subatomic particles.

Based on the (often counterintuitive) laws of quantum mechanics, **quantum technologies** work in a fundamentally different way than their 'classical' counterparts and, therefore, they have the potential to perform tasks that would otherwise be unattainable.

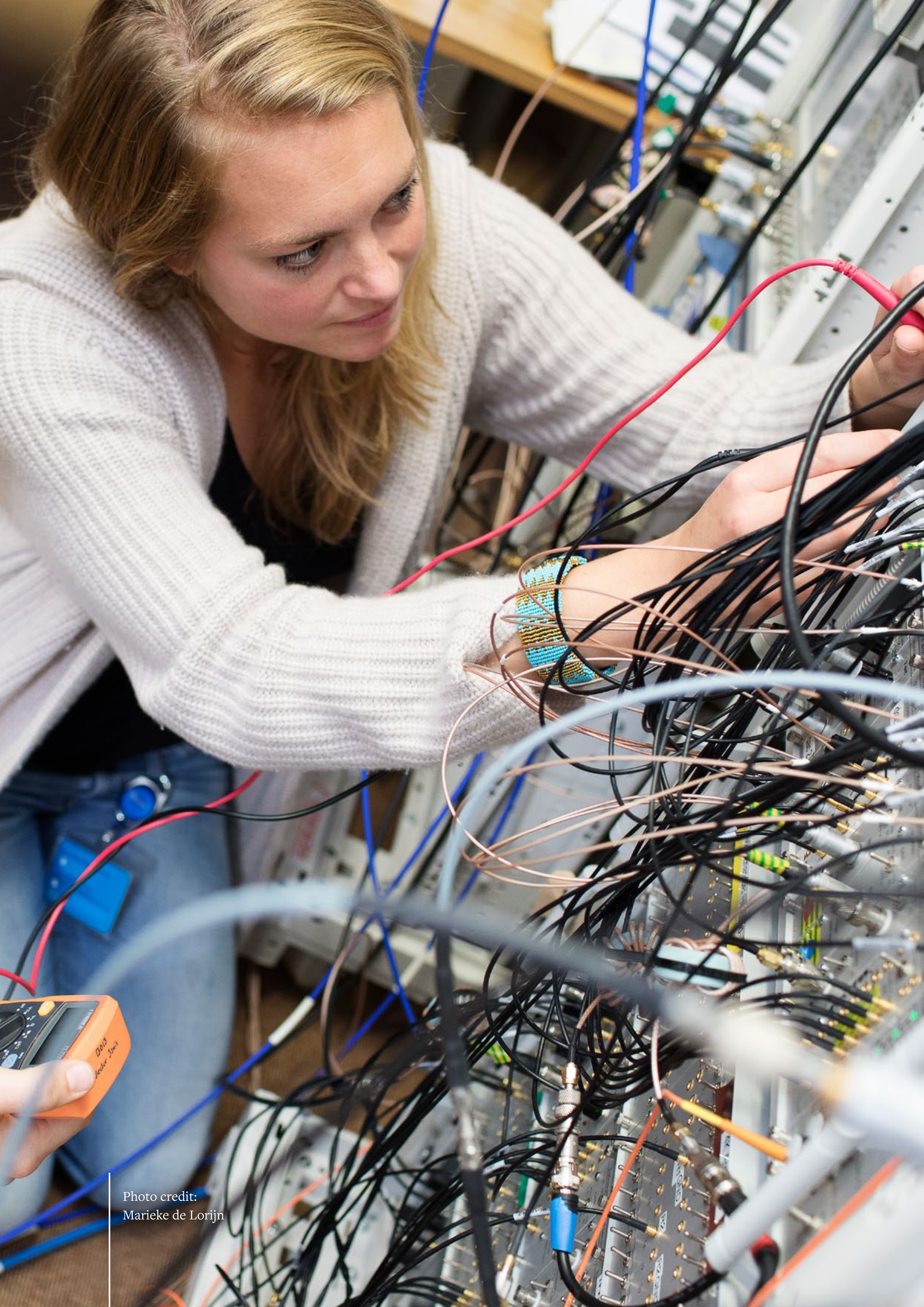
Whereas current classical computers and internet are based on bits that can take the value 0 or 1, quantum technologies are based on quantum bits (qubits) that can be in superposition states: it is like they are in '0' and '1' at the same time. Even more, they can be 'entangled': their fates are merged in such a way that a measurement of one instantaneously affects the other. By performing calculations based on such qubits, a **quantum computer** loosely speaking acts as a massive parallel device with an exponentially large number of computations taking place at the same time. This way, a quantum computer can solve problems that are out of reach of the best classical supercomputers we will ever build.

The vision of a **quantum internet** is to fundamentally enhance internet technology by enabling quantum communication between any two points on earth, via the quantum property of entanglement. A quantum internet may operate in parallel to the internet that we have today, and connect quantum processors in order to achieve capabilities that are impossible using only classical means, such as quantum encryption and distributed quantum computing.

There is no doubt that quantum computers and the quantum internet will have a great impact on our world. We have some ideas of what exciting prospects lie ahead, but, as with traditional computers and internet, we will likely see the full benefits only once the technologies become mature.

the Netherlands and the possible contribution to major social challenges such as Energy Supply and Safety.

In the covenant of QuTech of June 2015, the Minister of Economic Affairs, the Minister of Education, Culture and Science, TU Delft, TNO and NWO undersigned their intention to support QuTech for the period 2015-2025. The top sector High Tech Systems and Materials (HTSM) is also a partner in the covenant QuTech. HTSM is one of the nine key economic areas (the top sectors) established and supported by the Dutch government to further strengthen the Dutch international position through the "golden triangle" formed by companies, research institutes and government.



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Marieke de Lorijn

Research

QuTech's research is organized along three mission-driven science & technology roadmaps: **Fault-Tolerant Quantum Computing (FTQC)**, **Quantum Internet and Networked Computing (QINC)**, and **Topological Quantum Computing (TOPO)**. These roadmaps work towards the primary R&D goals of QuTech: to develop scalable prototypes of quantum computers and quantum internet. In addition, QuTech has three cross-cutting activities: the Shared Technology Development (SD) roadmap, the Quantum Software & Theory group, and the QuTech Academy. In this chapter we will discuss the achievements in these roadmaps. Outcomes and solutions generated by the Quantum Software & Theory group are integrated into the research activities of the three science & technology roadmaps. The QuTech Academy is described separately.

ROADMAP

Fault-Tolerant Quantum Computing FTQC

> ROADMAP LEADERS: **LIEVEN VANDERSYPEN, LEO DICARLO**

INTRODUCTION

The mission of the Fault-tolerant Quantum Computing (FTQC) roadmap is to achieve the grand goal of a scalable, fault-tolerant quantum computer, i.e. a system that uses quantum superposition and entanglement to reliably solve otherwise insurmountable problems by correcting the unavoidable errors from decoherence along the way. The roadmap's current qubit workhorses are silicon spin qubits and superconducting transmon qubits.

In 2018, a major achievement of FTQC was to bring the various developments in the roadmap together in two (so far internal) demonstrators, whereby both superconducting and silicon spin qubits are programmed via a web interface and our quantum computer architecture.

RESULTS 2018

Spin qubits // In 2018, we defined the state of the art by implementing quantum algorithms for the first time in two-qubit device based on Si/SiGe quantum dots (*Nature* 2018). We also prepared two-qubit entangled states with state fidelities up to 90%. Very recently, we extracted a CPhase fidelity of 92% using interleaved randomised benchmarking (*arXiv:1811.04002v1*) using a novel randomised benchmarking protocol introduced by the Wehner group at QuTech (*arXiv:1806.02048*).

We continued our work to realize our vision in which local registers of silicon spin qubits are networked on-chip in a scalable fashion. In 2018, we demonstrated strong coupling of a single electron spin and a single on-chip photon (*Science* 2018) which provides the basis for two-qubit gates between distant spins. Together with Intel we created a compelling vision for large 2D arrays using shared control lines (word/bit lines, *Sci. Adv.* 2018).

We demonstrated the promise of germanium as an alternative to silicon for hosting high-fidelity spin qubits, based on locally grown Ge/SiGe quantum wells (*Nature Comm.* 2018). Holes in germanium benefit from strong spin-orbit interaction, low hyperfine interaction (with the option of isotopic purification), low effective mass and high mobilities (500,000 cm2/Vs).

We also demonstrated long spin lifetimes at elevated temperatures (*Phys. Rev. Lett.* 2018), providing scope for quantum integrated circuits hosting both the qubits and the classical control electronics.

Superconducting qubits // In 2018, we made decisive proofs-of-principle toward our core mission to build a scalable quantum computer with surface-code quantum error correction, validating our previously proposed architecture (*Phys. Rev. A* 2017) at the heart of our IARPA-funded project and QuTech-Intel partnership. Key highlights include the development of a fast (40 ns), high-fidelity (99.1%), and low leakage (0.1%) conditional-phase gate using a novel flux-pulsing scheme we term Net-Zero (*arXiv:1903.02492*), and fast (400 ns), high-fidelity (99%) single-shot qubit readout (manuscript in preparation). Integrating these developments has allowed us to realize multi-round quantum parity checks which successfully create and stabilize entanglement in a three-qubit circuit, a first for superconducting qubits (manuscript in preparation). These experiments all use the scalable control electronics developed in-house and in collaboration with Zurich Instruments. A final important development in control electronics for 2018 is the realization of central controller units capable of fully orchestrating operations in 7- and 17-qubit surface-code chips.

Other exploratory projects using superconducting quantum circuits include entanglement of qubits on separate chips using engineered measurement fields (*Phys. Rev. B* 2018), extending the coherence of hybrid superconducting-semiconducting transmon qubits in a magnetic field (*Phys. Rev. Lett.* 2018), and mitigating errors in a variational quantum eigensolver by a novel technique we term ‘symmetry verification’ (*Phys. Rev. A* 2018 and *arXiv:1902.11258*).

Cryogenic electronics // Currently, the qubits are controlled by conventional electronics operating at room temperature. The thermal gap can be readily bridged by a few cables due to the small qubit count in today’s quantum computers. However, practical quantum computers will require thousands of qubits, making this approach impractical.

To enable the reliable design of complex circuits at deep-cryogenic temperatures, we developed the world’s first compact models of nanometre bulk CMOS devices down to 100 mK, and validated them at 4 K by experimental characterization of complex circuits (*IEEE J. Electron Devices Society* 2018). Furthermore, we experimentally demonstrated the operating limits at cryogenic temperature of core devices, i.e. BJT, MOS, DTMOS (*IEEE J. Electron Devices Society* 2018). We designed and experimentally characterized cryogenic CMOS (cryo-CMOS) circuits down to 4 K, aimed at the read-out, control and digital processing for quantum processors, including a cryo-CMOS Low-Noise Amplifier (LNA) for spin-qubit reflectometry, a 6-GHz digitally-controlled oscillator, a single-photon avalanche diode (*IEEE J. Solid-State Circuits* 2018), ultra-low power logic circuits and processors and stable voltage references (*IEEE J. Electron Devices Society* 2018). In addition, we demonstrated the cryogenic operation of a large number of off-the-shelf logic and mixed-signal systems, including FPGAs (*RSI* 2017, *Transactions on CAS* 2017, *ICFPT* 2017) and passives (*Cryogenics* 2018).

Quantum Computer Architecture: full-stack // In the context of the QuTech-Intel partnership, we designed, developed and integrated the different architectural layers (software and hardware) required for running a quantum algorithm on a superconducting or a spin qubits quantum chip: a so-called full-stack quantum computer. These layers include a high-level programming language and compiler (OpenQL), a (low-level) quantum assembly language (QASM), a quantum instruction set architecture (QISA), and a control microarchitecture (QuMA). In 2018, we showed that the OpenQL compiler is capable of producing c-QASM (common QASM; *Quantum Sci. Tech.* 2018) that can be executed on a quantum simulator and e-QASM, an executable quantum instruction set architecture executed on the microarchitecture targeting quantum hardware.

Quantum theory and software // Several international groups working on superconducting qubits are interested in encoding qubits into oscillators. In 2018, we showed, for the first time, how one can formulate a scalable architecture based on such encoding. The results show that when we encode a qubit into an oscillator via a so-called Gottesman-Preskill-Kitaev (GKP) code, we can use the surface code on such GKP qubits to suppress the error rates to arbitrary low strength with growing surface code lattice. Our results show that GKP oscillator states are required with at least 4 photons for this scheme to be below threshold (to be published).

One of the near-term applications of quantum processors is to determine the ground state and ground-state energy of quantum chemical or strongly-interacting Hamiltonians. When the Hamiltonian is stoquastic, i.e. has no sign problem, it is expected that a quantum processor may not provide strong benefits beyond classical computers. In 2018, we have developed efficient classical algorithms for subclasses of Hamiltonians to decide whether they are stoquastic (Klassen & Terhal). The workhorse behind ground-state energy estimation on a quantum processor is the algorithm of quantum phase estimation. We have shown how classical processing can be used to reduce the cost (in terms of circuit depth) of phase estimation, thus leading to a more efficient hybrid quantum-classical algorithm. We numerically explored how well the algorithm will perform on current superconducting hardware at QuTech (*New J. Phys.* 2019).

OUTLOOK 2019

For 2019, we plan to work on extending silicon and germanium quantum dot arrays for computation and simulation to linear arrays with 3-5 dots, and to two-dimensional arrays of 2x2 dots. We will also aim to improve the two-qubit gate fidelity and take next steps in schemes for entangling two spin qubits located in well-separated registers on the qubit chip. Finally, we aim to show qubit operation using quantum dots fabricated in a 300 mm industrial cleanroom at Intel.

In superconducting qubits, our main objective will be to extend the demonstrated generation and stabilization of entanglement using multi-round parity checks to a 7-qubit circuit (Surface-7). This will allow stabilizing an entangled two-dimensional subspace (thus a logical qubit) and to detect (but not yet correct) errors in the constituent qubits. A further goal will be to extend the stabilization to a 17-qubit circuit (Surface-17), which will allow full quantum error correction on the logical qubit. The key challenge to meeting these goals is realizing the requisite quantum hardware, which we pursue in strong collaboration with Intel. The room-temperature control electronics and software are already largely in place.

On the cryogenic control side, a major objective is to control a single spin qubit using the cryogenic CMOS control chip we designed together with Intel colleagues in 2018. In parallel, we will design a next-generation control chip that provides increased on-die functionality, e.g. integrating read-out and extended control in a single cryogenic CMOS chip.

Photo credit:
Marcel Krijger

STAFF DEVELOPMENTS

Leo DiCarlo appointed as Antoni van Leeuwenhoek professor

In June, TU Delft appointed Leo DiCarlo as Antoni van Leeuwenhoek full professor. The Antoni van Leeuwenhoek chairs promote young outstanding researchers so that they can optimally develop their academic careers. DiCarlo started in Delft in 2010 as assistant professor in the Department of Quantum Nanoscience (TNW). He was promoted to associate professor in 2015. His research focuses on quantum computing with superconducting circuits. It is his ambition to realize the first scalable prototype of a quantum computer, with integrated quantum hardware, control electronics and software. This research combines traditional solid-state physics with electrical and computer engineering. DiCarlo and his team pursue this goal working closely with academic and non-academic engineers in QuTech, as well as key industrial partners such as Intel and Zurich Instruments.

ROADMAP

Quantum Internet and Networked Computing QINC

> ROADMAP LEADER: **STEPHANIE WEHNER**

INTRODUCTION

The mission of the Quantum Internet and Networked Computing (QINC) roadmap is to build and apply fundamentally new network technology by enabling quantum communication between any two points on earth. Over short distances, such networks provide a scalable path to building large-scale quantum computing systems by networking small quantum processors into one big quantum computing cluster. Over long distances, a quantum internet will – in synergy with the 'classical' internet that we have today – connect quantum processors at a distance in order to achieve unparalleled capabilities that are impossible using classical systems, such as communication channels with security guaranteed by the laws of physics.

Achieving this goal poses formidable challenges, which demand unique solutions spanning physics, material science, computer science and engineering. To realize this vision, we work on an extensible architecture for entanglement-based quantum networks with a team covering expertise from physics, optical engineering, systems engineering and computer science. A demonstration outside the lab of a multi-city network is planned to be realized by the end of 2020. QINC is a research and development roadmap featuring both cutting edge long-term research towards a large-scale quantum internet, as well as near-term technology development capable of enabling quantum security in the Randstad.

RESULTS 2018

Over the past year, we made significant progress in all elements of quantum networks. These advances now put us on the verge of being able to link up larger multi-node networks over long (~100 km) distances. Additionally, several important steps were made to program and use such networks for actual applications, and to start laying out the blueprints for large networks.

Blueprints for the quantum internet // To start shaping the future quantum internet, we defined a roadmap for the stages of quantum network development in an invited perspective to Science (*Science* 2018), taking up a role as a thought leader in defining the field of quantum networks. Additionally, starting 2018, QuTech leads the European Quantum Internet Alliance (QIA) consortium in the EU Flagship on Quantum Technologies. In October, the European Commission announced that its Quantum Flagship Programme will contribute 10 million euro to the development of a blueprint for a future quantum internet. The blueprint will be developed by QIA, a consortium of twelve leading research groups at universities from eight European countries, in close cooperation with over twenty companies and institutes.

Network links // Key progress towards fast network links, quantum repeaters and multi-node networks was made. First, we realized a remote entanglement protocol based on the detection of single photon (*Nature* 2018), which has increased entanglement rates to 40 Hz, an orders-of-magnitude improvement over previous methods. Second, we further developed quantum memories based on nuclear spins that can robustly store quantum states while entanglement is distributed between the nodes (*Phys. Rev. A* 2018) and demonstrated coherence times exceeding seconds (*Nature Comm.* 2018). This combination of results means that we can now enter a new territory: entanglement can be generated faster over the network than the decoherence rate of the quantum memories in the nodes, so that quantum repeaters and larger multi-node networks become feasible.

At the same time, we made key steps to further enhance entanglement rates by incorporating the network qubits in an optical cavity. We have designed and characterized the first of such integrated devices that may enable several orders of magnitude gain in speed in the near-future (*New J. Phys.* 2018). Another important advance was our demonstration of quantum-frequency conversion of a single photon from a NV centre to the telecom wavelengths: this will enable extending our quantum networks to over distances up to ~100 km (*Phys. Rev. Applied* 2018).

On the theory side, several breakthroughs were made in assessing and optimizing the performance of future quantum repeaters and quantum networks. First, building on work to estimate decoherence, we introduced a new method called capacity estimation that allows us to characterize quantum memories, error-correction codes and quantum repeaters in the presence of arbitrarily correlated errors (*Nature Comm.* 2018).

On a lower level, we developed ways to analyse and optimize entanglement distillation and quantum repeaters (*Nature Comm.* 2018). We analysed near-term experimental quantum repeaters and identified promising schemes to surpass the capacity - the highest secret-key rate achievable with direct transmission in the near future (*Quantum Sci. Technol.* 2018). Furthermore, we presented multiple methods to assess entanglement distillation schemes, optimize the trade-off between the fidelity to the target state and the success probability (*Phys. Rev. A* 2018), and analyse parameter regimes for a single sequential quantum repeater (*Quantum Sci. Technol.* 2018). Finally, we showed an optimal protocol to generates multipartite GHZ states when utilising nearby nodes (*arXiv* 2018).

Multi-qubit nodes // In parallel to the developments of the quantum network links, we enhanced the number of qubits – and control over these qubits – in the end nodes that store and progress quantum states.

Importantly, we realized coherence times well over one second, even in a system containing ~10 qubits (*Nature Comm.* 2018), paving the way to more precisely understanding decoherence, improving fidelities by optimizing gates, and control over many (10+) qubits per node.

On the material side, we set up our own dedicated diamond growth. This will enable us to grow precisely controlled layers of defect spins (our qubits) for new diamond devices with improved coherence properties and quantum memories.

On the theoretical side, we showed that the fidelity of a quantum gate can be estimated efficiently using randomized benchmarking, making it possible to benchmark network nodes and quantum processors with many qubits (*arXiv:1701.04299*). We also introduced a new method called character randomized benchmarking (*arXiv:1806.02048*), which is a very general method to characterize complex gates more easily.

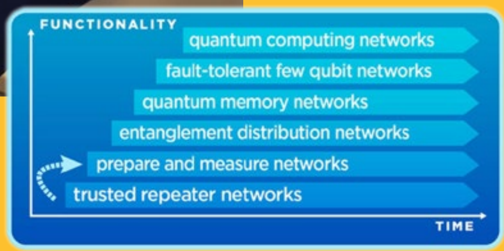
Network Design and Tools // Towards the development of what may become the world's first network and software stack, we released SimulaQron, which provides an essential tool for software development for a quantum internet (*Quantum Sci. Technol.* 2018). It can be used in all areas ranging from the implementation of the actual applications, development of application-level abstractions and programming libraries, to exploring the implementation of a quantum network stack (*www.simulaqron.org*).

We also developed NetSquid, a discrete-event simulation platform built specifically for quantum networks. This is presently the only discrete-event simulation platform for quantum networks in the world, and is now actively being used to bridge the gap between high- and low-level analysis, to validate theoretical modelling, and to test the performance of control pane protocols (*www.netsquid.org*).

Applications // An important ambition within QuTech's QINC roadmap is to enable useful applications on quantum networks. As an example, in 2018, we analysed Anonymous Quantum State Transmission in the presence of noise in the network and developed a novel protocol that tolerates more noise and achieves higher fidelities of transmitted quantum message than existing protocols (*Phys. Rev. A* 2018). Furthermore, we proved the security of quantum devices even when the devices used are not trusted (*Phys. Rev. A* 2018). Finally, we proposed and proved unconditional security of Conference Key Agreement, a cryptographic protocol that is suited for quantum networks, while giving security guaranty in the most paranoid scenario (*Phys. Rev. A* 2018).

OUTLOOK 2019

For 2019, we aim to achieve the first multi-node quantum network by connecting three nodes. Also, we will take the first step towards a quantum network stack by developing a link layer protocol. We will perform a world distance record test for entanglement generation between Delft and Den Haag in preparation of the 2020 network. Finally, we will release our simulation platform NetSquid to a wide development audience.



ROADMAP FOR QUANTUM INTERNET DEVELOPMENT

A quantum internet may very well be the first quantum information technology to become reality. It is set to revolutionize communication technology by exploiting phenomena from quantum physics, such as entanglement. In "Quantum Internet: A vision for the road ahead" (*Science 262, 6412*), Stephanie Wehner, David Elkouss and Ronald Hanson present a comprehensive guide towards realizing such a quantum internet.

Their roadmap consists of six phases, starting with simple networks of qubits that could already enable secure quantum communications – a phase that could be reality in the near future. The development ends with networks of fully quantum-connected quantum computers. In each phase, new applications become available such as extremely accurate clock synchronization or integrating different telescopes on Earth in one virtual 'super telescope'.

This work creates a common language that unites the highly interdisciplinary field of quantum networking towards achieving the dream of a world-wide quantum internet. In addition to providing a guide to further development, it sets challenges both to engineering efforts and to the development of applications. "On the one hand, we would like to build ever more advanced stages of such at network", says Wehner, "and on the other hand, quantum software developers are challenged to reduce the requirements of application protocols so they can be realized already with the more modest technological capabilities of a lower stage." Hanson adds: "This work establishes a much-needed common language between the highly interdisciplinary field of quantum networking spanning physics, computer science and engineering."

The first true quantum networks, allowing the end-to-end transmission of quantum bits, are expected to be realized in the coming years, heralding the dawn of a large-scale quantum internet.

STAFF DEVELOPMENTS

New colleague: Wolfgang Tittel

In April 2018, Prof. dr. Wolfgang Tittel joined QuTech in the development of the world's first quantum internet. He obtained his PhD in 2000 at the University of Geneva, worked as a postdoc at the University of Aarhus and the University of Geneva and joined the University of Calgary in 2006 as Industrial Research Chair. He engaged in ground-breaking experiments since the start of the field of quantum communication and cryptography and worked on the edge of science and technology. At QuTech, he will take the step towards the quantum internet as a mature technology. Tittel: "It is my dream to participate in the true development of a quantum network."

Photo credit:
Marieke de Lorijn

New programme manager: Ingrid Romijn

Dr. Ingrid Romijn started in October 2018 as programme manager. Within QINC, Ingrid promotes and manages technology transfer and industrialization of quantum internet technology. Ingrid received her PhD from Leiden University in Solid State Physics on metal-insulator transitions in conducting polymers and composite materials. Before joining QuTech she worked for ECN Solar Energy as project leader and programme manager.

Photo credit:
Marieke de Lorijn

Photo credit:
Klapstuk

ROADMAP

Topological Quantum Computing

TOPO

> ROADMAP LEADER: **MICHAEL WIMMER**

INTRODUCTION

The mission of the Topological Quantum Computing (TOPO) roadmap is to develop, build and demonstrate the first topologically protected quantum bit based on Majorana-bound states. Such qubits promise protection from errors by design, without the need for external error correction.

Topological qubit designs always involve hybrid semiconducting/superconducting devices harbouring Majorana bound states. This often leads into uncharted territory and our main challenge is to push the development of new materials and fabrication techniques to unravel the fundamental physics of these novel devices.

RESULTS 2018

Nanowire devices // TU Delft pioneered the field of Majorana bound states in condensed matter with the detection of Majorana signatures in hybrid nanowire devices in 2012. In 2018, our efforts to bring material quality and fabrication techniques to a higher level allowed us to chart the topological phase diagram, ruling out alternative explanations for the zero-bias peak (*Nature Nanotech.* 2018).

In parallel, we developed a new Majorana platform based on epitaxial aluminium on InSb nanowires, where, in 2018, we observed quantized conductance due to Majorana bound states (*Nature* 2018) – a long-standing open question in the field. In fact, this quantized conductance is the hallmark of coupling to a single Majorana bound state which is also the prerequisite for topological braiding operations. In this platform we were also able to observe well-defined parity states in Coulomb islands, compatible with topologically protected Majorana bound states (*Nature Comm.* 2018).

While the experimentally most investigated signature of the topological phase transition is the conductance peak at zero bias voltage, prospective topological quantum bits require charge parity-conserving measurements, which do not involve quasiparticle tunnelling. We observed the topological ordering by the flux-periodicity doubling of the supercurrent, commonly referred to as the 4π-periodic Josephson effect (*Nature Comm.* 2019). This experiment is the missing link between quasiparticle tunnelling experiments and the coherent manipulation of topological quantum bits.

Building and operating a topological Majorana-based qubit requires to go beyond single-nanowire devices. Together with Microsoft and key collaborators we outlined a series of experiments towards topological quantum computation (*Nature Rev. Mat.* 2018). In particular, this requires a platform for scalable nanowire networks and we drive new material development in collaboration with Microsoft. In particular, we built an advanced molecular beam epitaxy facility in Delft and obtained first promising results on nanowires networks based on selective area growth (*Phys. Rev. Mat.* 2018).

The Andreev bound states are the basis of the modern understanding of nanoscale superconductivity. Localised to a weak link, they are single electronic degrees of freedom, which can be occupied by zero, one or two electrons. This localised state can therefore store a quantum bit in a nanoscale superconducting junction. We demonstrated the first coherent manipulation of the Andreev levels, which showcases the technological relevance of this novel superconducting qubit technology (*Phys. Rev. Lett.* 2018). This work was a collaboration between the University of Copenhagen, the QDEV group at Yale University and QuTech.

Alternative Majorana platforms and enabling technologies // An alternative realization of complex Majorana-based circuits is by using superconductor-semiconductor hybrids based on two-dimensional electron gases (2DEGs). In 2018, we demonstrated the important role of non-topological edge states in InAs-based 2DEGs (*Phys. Rev. Lett.* 2018). We also developed numerical methods for simulating the physics of 2DEGs and found an unexpected robustness of topological edge states in quantum spin Hall systems to magnetic field (*Phys. Rev. B* 2018), clarifying the parameter regime in which these systems can be used as a Majorana platform.

Observing new physical phenomena with small excitation energies in quantum nanoelectronics demand efficient cooling methods, which can bypass the phonon barrier imposing a typical limiting electron temperature of 10 to 100 mK. We demonstrated that the demagnetization cooling of the nuclear spins in indium leads to an electron temperature of 3.2 mK, which paves the way to the unexplored regime of sub – 1 mK nanoelectronics (*arXiv:1811.03034*).

A transmon qubit insensitive to magnetic field is a crucial element in topological quantum computing. Here we created graphene transmons by integrating monolayer graphene Josephson junctions into microwave frequency superconducting circuits, allowing it to operate in a parallel magnetic field of 1 Tesla (*Nature Comm.* 2019).

OUTLOOK 2019

We will continue our efforts towards implementing a topological qubit, following the parallel paths that we have established in the roadmap: selective area growth nanowire networks, two-dimensional electron gases and Andreev qubits. The close integration of theory and experiment within our roadmap, as well as our close collaboration with Microsoft will be crucial to our success.

STAFF DEVELOPMENTS

New roadmap leader: Michael Wimmer

From 2013-2017, Dr. Michael Wimmer was employed by the Dutch Organization for Fundamental Research on Matter (FOM), from 2015 onwards working full-time at QuTech as tenure-track team leader. In 2018, he became Principal Investigator and TOPO Roadmap Leader, employed by QuTech. Wimmer did his PhD in 2008 at the University of Regensburg. After postdoctoral appointments at the University of Regensburg and Leiden University he moved to TU Delft.

New programme manager: Csilla Buiting-Csikós

Photo credit:
Marieke de Lorijn

Ir. Csilla Buiting-Csikós has been working at TU Delft since 1992: first as an assistant professor at the Faculty of Mechanical, Maritime and Materials Engineering (3mE), later as deputy department head. Beginning of 2018 she joined QuTech as a programme manager mainly to support the TOPO roadmap.

Photo credit:
Klapstuk

ROADMAP

Shared Technology Development SD

> ROADMAP LEADER: **GARRELT ALBERTS**

INTRODUCTION

In the Shared Technology Development (SD) roadmap, technology developments are managed for the three scientific roadmaps of QuTech. Furthermore, the SD roadmap facilitates the taking of quantum technology to market (technology push).

RESULTS 2018

Together with the TOPO roadmap // We developed new technologies to create a Majorana device, which can act as a very stable and scalable qubit. In 2018, we made steps in the hardware development for Majorana devices as well as in the software development for simulation and measurement support purposes.

- The hardware development concerned realizing hardware for InSb 2DEG-based Majorana devices. This 2DEG approach involves mesa etching (wet chemical etching) to define 1D channels. Advantages of this approach are the design versatility and the fact that high 2DEG mobility is retained. This development supports the long-term goal of developing a scalable 2DEG-based qubit system for quantum computing hardware with Majoranas.
- The software development concerned architectural enhancements for visualisations in the kwant simulator (*www.kwant-project.org*), as well as the development of automated alignment of magnetic fields that support device measurements. The kwant enhancements regarding the visualisation functionality enable to gain better insights in quantum transport phenomena. The automated magnet alignment enables to perform device measurements more quickly and robustly.

Together with the FTQC roadmap // We supported the fabrication of spin qubit devices. This is a critical aspect for both Intel and QuTech, as device fabrication is currently the bottleneck in the functional demonstration of quantum computing. In 2018, we successfully set up semi-routine fabrication of many of the preliminary steps to build full devices. A full development line was also set up to use purified Si as substrate material. A new ALD tool was purchased and set up to improve the quality of devices. We developed software tools for the automated calibration and tuning of spin qubits. This resulted in 2018 in the release of the QTT software tool (*https://qtt.readthedocs.io/en/latest/*) for use by the wider community. These activities were also extended toward the Quantum Infinity platform (the Quantum Computing demonstrator based on transmons) as well as topological qubits. We designed transmon chips to improve the functionality of both Intel and QuTech transmon chips. In 2018, the best chip manufactured demonstrated 6 functional qubits (out of 7). It is expected that functional 7-qubit chips could be available in 2019. We described on a fundamental level the computational possibilities and manipulation of electron spin qubits and transmon qubits. We evaluated the potential of stabilisation mechanisms in surface codes.

Together with the QINC roadmap // We demonstrated the feasibility of a technology that converts the frequency of single photons from an NV centre to telecommunication wavelengths. We successfully integrated microwave lines in qubit cavities, which is essential for qubit control. The implantation of NV centres at predefined locations in a diamond was achieved, opening new avenues towards isolated quantum memories. A new NV production method was developed to produce cavity-enhanced NV centres that have an expected 40-fold increase in single-photon emission.

Furthermore, we developed NetSQUID (*www.netsquid.org*), a quantum network simulator for researching quantum internet protocols. An optical breadboard was developed to manufacture spherically shaped indentation in optical fibre strands. An indented fibre in combination with the newly developed NV centres produce a cavity that increases the number of emitted photons. The indentations can be manufactured with high accuracy and reproducibility using a high-power CO2 laser to ablate the fibre material and cameras to perform metrology.

Prototype and demonstrator development // We defined a fully functional and architectural breakdown for Quantum Inspire (*www.quantum-inspire.com*), a

Photo credit:
Marieke de Lorijn

full-stack prototype quantum computer, as well as a quantum internet demonstrator (quantum link). Quantum Inspire is a full-stack quantum computer demonstrator on which quantum algorithms can be executed on different qubit varieties, such as transmon qubits, electron spin qubits and NV centres. The control hardware has been procured and partially installed and tested, the control software has been hooked up to a quantum simulator as a first qubit. Furthermore, we supported the development of the Quantum Infinity demonstrator, which is based on transmon qubits.

Together with the QINC roadmap, a quantum network link prototype was developed. All equipment for two quantum nodes has been purchased and the design of the link architecture has been patented. Breadboards of several subcomponents in the design were produced to validate the individual components. Our experience in breadboard building will be used to build the quantum nodes which started Q4 of 2018.

Bringing quantum technology to society // Quantum technology development support for the Intel and the QuSurf (an international consortium consisting of QuTech, ETH Zurich and Zurich Instruments) projects continued in 2018. We performed several consultancy activities related to quantum computing and communication for the Dutch Ministry of Defence.

TU Delft — TNO

STAFF DEVELOPMENTS

Our new man from TNO: Klaas Jan de Kraker

Dr.ir. Klaas Jan de Kraker joined QuTech as a senior project manager in the SD roadmap, focusing on the activities related to the QINC and TOPO roadmaps.

After graduating from TU Delft in 1997, Dr.ir. Klaas Jan de Kraker embarked on a career

We cooperated with SURFsara in Amsterdam to make quantum technology available to the Dutch academic community. The first step involved making QuTech's quantum simulators (QX and NetSquid) available by porting them to SURFsara's national supercomputer.

OUTLOOK 2019

In 2019, the Quantum Inspire platform will be fully launched, after the prelaunch took place in September 2018. This platform is making a quantum emulator and qubit hardware developed by QuTech available to society. It is envisioned that this platform will host different kinds of quantum computing qubits that have been developed at QuTech and that it will grow into a first public prototype of a Quantum Computing Cloud service. It is also planned to have the first two-city Quantum Link established between Delft and The Hague. Furthermore, the blueprint for the quantum internet will be developed in the Quantum Internet Alliance project. The development of this blueprint will be based on QuTech's NetSquid quantum internet simulator. NetSquid 2.0 will be released in 2019. Finally, the first breadboard prototypes of new key components of the quantum internet, such as an efficient quantum memory for light, will be developed and tested in the QuTech laser labs.

as software engineer, technical consultant and technical project leader. In 2004 he joined TNO as research scientist and project leader. In 2018 he moved to TNO Delft, and now works at QuTech as project manager.

Why QuTech? // I love doing new things. I find it fascinating to get to know the world of quantum technology and to support the ground-breaking research done at QuTech. And I really want to help realise the innovations promised by quantum technologies.

How familiar were you with the quantum topic? // I've always worked on modelling and simulation topics, so, on software. As the quantum software is getting more and more important alongside the hardware, QuTech fits well with that background.

What is TNO's and specifically your role within QuTech? // For TNO, the main task is to bring research results to the market, so, to engineer these results into products. Challenges involve designing the business development and translating the opportunities offered by this business into a new focus for the engineering efforts. As project manager I try to organise the various aspects of the work as efficiently as possible. This isn't just about time, money and quality, but also about making sure that my colleagues can do their jobs in a good environment. I also spend time on coordinating the TUD/TNO collaboration.

Is that collaboration a challenge? //Although QuTech is developing its own specific culture, TNO and TUD traditionally each have their own way of working. So, successful collaboration requires mutual understanding and some adjustment. I know both cultures very well, and I try to exploit that experience to support the collaboration.

What makes QuTech a unique place to work? // Is that a serious question??

HIGHLIGHTED PUBLICATIONS

In this section, we highlight several publications of particular impact. A full list of peer-reviewed publications is included as appendix to this report (page 68).

A programmable two-qubit quantum processor in silicon

T.F. Watson, S.G.J. Philips, E. Kawakami, D.R. Ward, P. Scarlino, M. Veldhorst, D.E. Savage, M.G. Lagally, M. Friesen, S.N. Coppersmith, M.A. Eriksson, and L.M.K. Vandersypen
Nature **555**, *633–637 (2018)*

Quantum technology is making a great leap forward. While scientists can control a few qubits with great reliability, it doesn't yet look like a real computer. To be able to perform universal quantum calculations, operations that control the state of individual qubits and intertwine multiple qubits in a controlled way are required. Programmability implies that this set of operations is available in such a way that they can be placed in any order to perform different algorithms. We realized a programmable two-qubit quantum processor in silicon, successfully implementing two quantum algorithms.

Quantized Majorana conductance

H. Zhang, C.X. Liu, S. Gazibegovic, D. Xu, J.A. Logan, G. Wang, N. van Loo, J.D.S. Bommer, M.W.A. de Moor, D. Car, R.L.M. Veld, P.J. van Veldhoven, S. Koelling, M.A. Verheijen, M. Pendharkar, D.J. Pennachio, B. Shojaei, J.S. Lee, C.J. Palmstrom, E.P.A.M. Bakkers, S. Das Sarma, L.P. Kouwenhoven
Nature **556**, *74-79 (2018)*

Majorana zero-modes—a type of localized quasiparticle—hold great promise for topological quantum computing. In tunnelling spectroscopy, a Majorana zero-mode should show up as a zero-bias peak in the differential conductance, of which the height is predicted to be quantized. The Majorana symmetry protects the quantization against disorder, interactions and variations in the tunnel coupling. We developed a new Majorana platform based on epitaxial aluminium on InSb nanowires, where we observed the expected quantized conductance. The observation of a quantized conductance plateau strongly supports the existence of Majorana zero-modes in the system, paving the way for future braiding experiments that could lead to topological quantum computing.

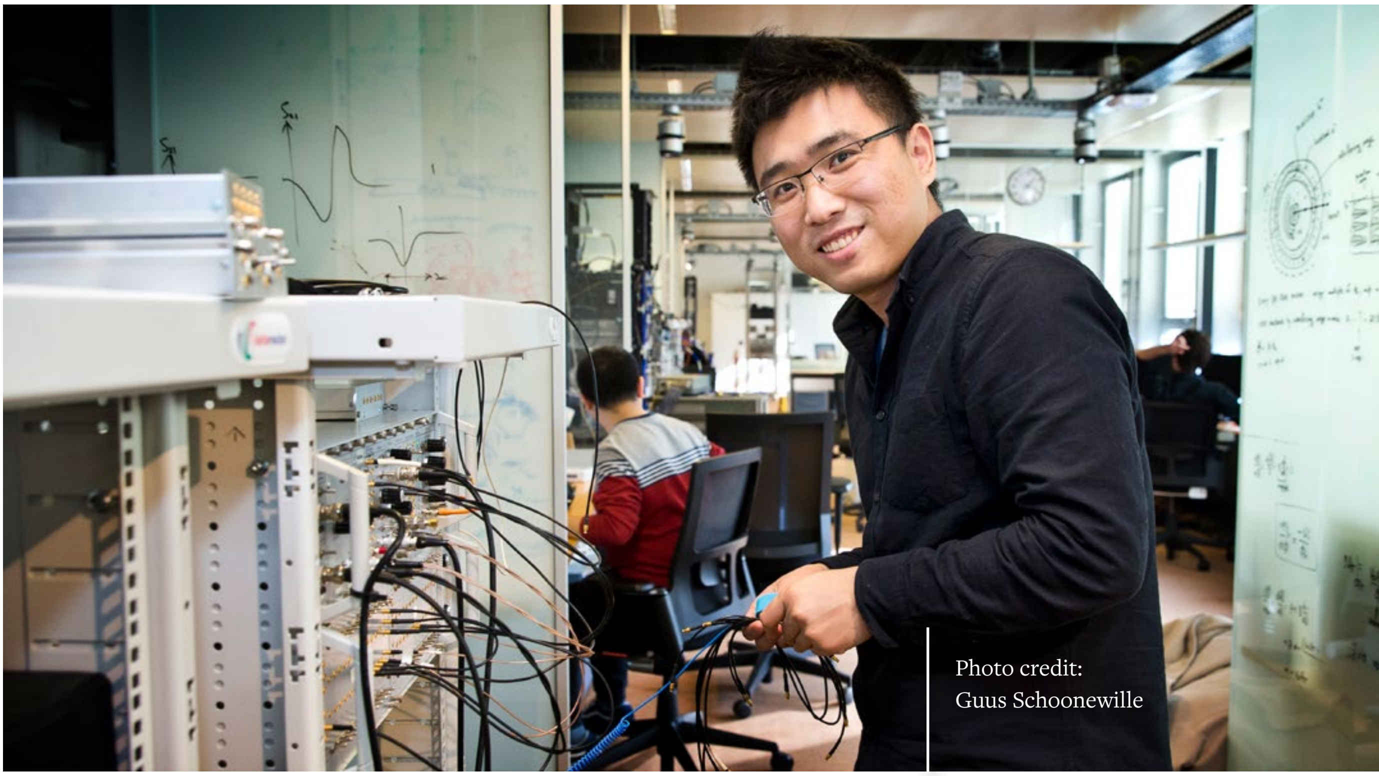


Photo credit:
Guus Schoonewille

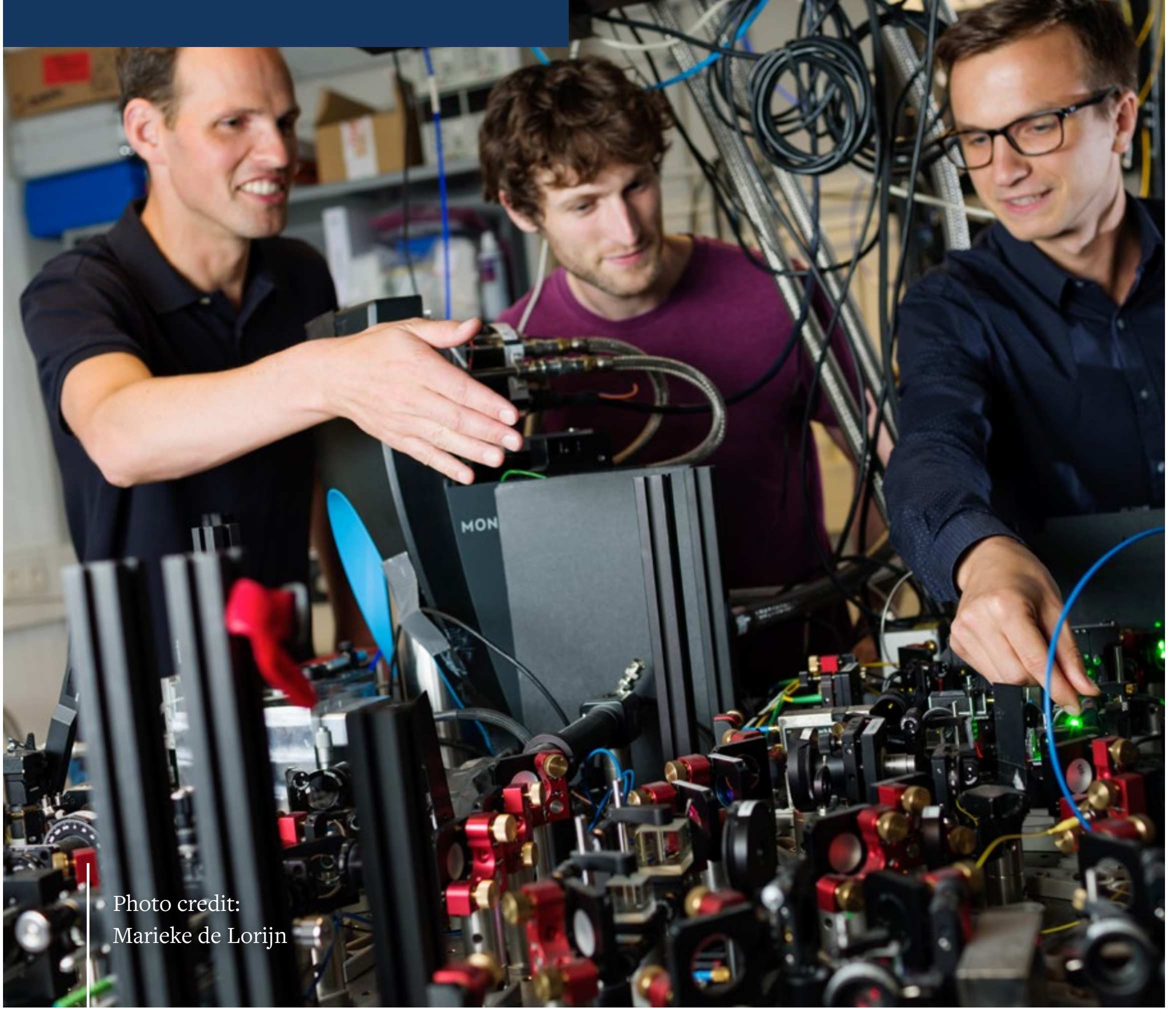


Photo credit:
Marieke de Lorijn

Deterministic delivery of remote entanglement on a quantum network

Entanglement – once referred to by Einstein as "spooky action" – forms the link that will provide a future quantum internet its power and fundamental security. By exploiting the power of quantum entanglement, it is theoretically possible to build a quantum internet that cannot be eavesdropped on. We have now succeeded in generating remote entanglement in a fraction of a second. In combination with a smart way of protecting the quantum link from external noise, the experiment has now surpassed a crucial threshold: for the first time, entanglement can be created faster than it is lost. With this, the experimental setup is can deliver entanglement 'on-demand', paving the way for quantum networks with more than two nodes.

Peter C. Humphreys, Norbert Kalb, Jaco P. J. Morits, Raymond N. Schouten, Raymond F. L. Vermeulen, Daniel J. Twitchen, Matthew Markham, and Ronald Hanson

Nature **558**, *268–273 (2018)*

Strong spin-photon coupling in silicon

N. Samkharadze, G. Zheng, N. Kalhor, D. Brousse, A. Sammak, U. C. Mendes, A. Blais, G. Scappucci, L. M. K. Vandersypen
Science **359***, 6380, 1123-1127 (2018)*

In the worldwide race to create more, better and reliable quantum processors, a key challenge is related to making large numbers of qubits. To use a lot of qubits at the same time, they need to be connected to each other. At present, the electrons that are captured as qubits in silicon can only make direct contact with their immediate neighbours. Other quantum systems use photons for long-distance interactions. In this publication, we showed that a single electron spin and a single photon can be coupled on a silicon chip, which makes it possible in principle to transfer quantum information between a spin and a photon. This is an important step to connect distant quantum bits on a silicon chip, thereby paving the way to upscaling quantum bits on silicon chips.

Photo credit:
Marieke de Lorijn

Ballistic Majorana nanowire devices

Önder Gül, Hao Zhang, Jouri D. S. Bommer, Michiel W. A. de Moor, Diana Car, Sébastien R. Plissard, Erik P. A. M. Bakkers, Attila Geresdi, Kenji Watanabe, Takashi Taniguchi and Leo P. Kouwenhoven
Nature Nanotechnology **13***, 192–197 (2018)*


Photo credit: QuTech, TU Delft, Scixel

In 2012, the world of physics was rocked by our first observation of the exotic Majorana quasiparticle. These particles are a promising candidate for robust quantum bits in a topological quantum computer of the future. However, making and regulating these Majoranas on the way to creating this topological quantum computer is still in its infancy. A major challenge that lies ahead is how to manufacture usable, error-free quantum chips. We have used new manufacturing methods to create a clean nanowire, featuring improved contacts that leave the nanowire intact at almost atomic level. This system allows improved Majorana measurements about the presence of Majoranas. This is an important step towards developing a topological quantum computer.

Capacity estimation and verification of quantum channels with arbitrarily correlated errors

Corsin Pfister, M. Adriaan Rol, Atul Mantri, Marco Tomamichel, and Stephanie Wehner
Nature Communications **9**, *27 (2018)*

To realize a future quantum computer and quantum internet, quantum bits must be sent over quantum communication channels, and need to be stored in quantum memories. Quantum bits, however, are highly delicate and must be protected against noise and imperfections. How well a quantum memory succeeds in storing quantum information is captured by its so-called quantum capacity. In this publication, we proposed the first method to directly estimate this capacity for storing quantum information, even if the noise is arbitrarily correlated. The method also to give insights into the performance of the implementations of quantum error correction schemes, and quantum repeaters – which enable the transmission of quantum bits over long distances.

QuTech's electronics guru: Raymond Schouten

What's your role at QuTech? // "Together with my colleagues Raymond Vermeulen and Marijn Tiggelman I work on improving experimental research by giving advice, troubleshooting and developing electronics instrumentation for QuTech as a whole. I also teach the PhD course "Electronics for Physicists" and first-year student workshops on sensors and chips."

How does new instrumentation come about? // "The most productive environment for new ideas on instrumentation is one with a lot of people running into measurement limitations or problems. Development within QuTech is always done in interaction, which improves the efficiency of the effort and the quality of the result. Outside Qutech, we profit from electronics experts at TU Delft and from outsourcing the production of prototypes or small series."

What has been your best design thus far? // "While it's quite easy to come up with complex solutions, it is much more rewarding to find the bare minimum needed. That requires getting to the essence of the problem. It happened that a researcher suggested to develop a new type of amplifier, but after some discussion we both concluded that a simple resistor worth 5 cent could do the job. In a way, that could have been my best design."

Are you considering starting a spin-out company for the electronics you've developed? // "Our most popular system by far, the IVVIrack for low-noise electronic signal handling, has found its way to quite a few universities worldwide. Personally, I like to be creative and work closely with researchers to reach the highest technical levels in their measurement setups. Starting a company would only distract me from that, and possible financial advantages are of no interest to me."

Photo credit:
Klapstuk

ROADMAP

QuTech Academy

> ROADMAP LEADER: **MENNO VELDHORST**

With the QuTech Academy we strive to provide top-quality education in order to bring about generations of excellent quantum scientists, to inform the public and policymakers about quantum technology, and to further quantum information science across the globe.

In 2018, a series of four courses were given at TU Delft in the MSc programme, introducing students to the field of quantum technology. These courses provide the fundamentals of quantum information, teach about quantum communication and cryptography, and introduce students to the required quantum hardware to realize a quantum computer and quantum internet. In addition, we started a special topics course for MSc and PhD students, focussing this year on theoretical modelling of superconducting devices. A total of four Massive Open Online Courses (MOOCs) were provided, including three new MOOCs targeting different audiences with different levels of expertise. Many QuTech PIs, postdocs, PhDs and students were involved in these online courses provided to more than 50,000 enrollers over the past years.

As a pilot run for upcoming QuTech scholarships, three students were provided with a QuTech scholarship. These were awarded to excellent international students enabling them to study at TU Delft and to follow the QuTech Academy courses.

MOOC NEW IN 2018

The Building blocks of a quantum computer: Part 1

by Menno Veldhorst, Lieven Vandersypen, Koen Bertels, Leo Di Carlo, Attila Geresdi, Giordano Scappucci, Tim Taminiau and Michael Wimmer

7169 ENROLLED

The building blocks of a quantum computer is a series of two MOOCs, introducing students to all the layers of a quantum computer and internet. In the first part, the most promising qubit platforms are introduced and discussed how to quantum operations on physical qubits.

MOOC NEW IN 2018

The Building blocks of a quantum computer: Part 2

by Menno Veldhorst, Koen Bertels, Carmen G. Almudever, David Elkouss, Nader Khammassi, Fabio Sebastiano and Barbara Terhal

7169 ENROLLED

The second part of the series the building blocks of a quantum computer has the focus on the architecture behind a quantum computer and a quantum internet, discussing quantum-classical interface, micro-architectures, quantum error corrections, networks and protocols and quantum algorithms.

MOOC

Quantum Cryptography

by Stephanie Wehner and Thomas Vidick

9047 ENROLLED

Stephanie Wehner and Thomas Vidick (California Institute of Technology) created this interdisciplinary course as an introduction to the exciting field of quantum cryptography. The course answers the question 'How can you tell a secret when everyone can listen in?' Participants learn how to use quantum effects, such as quantum entanglement and uncertainty, and to implement cryptographic tasks with levels of security that are impossible to achieve classically.


Photo credit: Anne Reitsma

MOOC **NEW IN 2018**

Quantum Internet and Quantum Computers: How Will They Change the World?

by Menno Veldhorst, Stephanie Wehner and Lieven Vandersypen

8125 ENROLLED

This new MOOC deals with the basic principles and promises of the quantum computer and quantum internet, and about how these new technologies will change the world.

ON-CAMPUS

Quantum Hardware

by Lieven Vandersypen, Ronald Hanson and Barbara Terhal

35 STUDENTS

This class delved into how qubits and quantum operations can be realized in real quantum hardware. Students learned the critical challenges in achieving quantum hardware and technology. The course provided an overview of the current state of the technology and explained the most promising approaches to realizing quantum hardware. A critical assessment of the strengths and weaknesses of each approach followed. Conceptual similarities and differences between the various technologies were also discussed.

ON-CAMPUS

Electronics for Quantum Computation

by Carmen G. Almudever and Fabio Sebastiano

27 STUDENTS

To make a quantum computer and quantum internet function, hardware and software is needed to control and instruct the quantum device. In this class, students learned about the relevant concepts while practising to interface with a quantum computer.

ON-CAMPUS

Fundamentals of Quantum Information

by Leo DiCarlo and David Elkouss

101 STUDENTS

In this class, students were taught the fundamentals of qubits, quantum gates and measurements. An introduction is given to quantum entanglement, as well as quantum teleportation, how properties of quantum information can be applied to construct some of the most well-known quantum algorithms, and the basics of quantum error correction.

ON-CAMPUS

Quantum Communication and Cryptography

by Stephanie Wehner

28 STUDENTS

Students who have learned the fundamentals discover how quantum communication can be used to solve cryptographic problems. This course explained some of the most well-known quantum cryptographic protocols, such as quantum key distribution. Students were taught how general quantum cryptographic techniques could be used to design and analyse quantum protocols at large.

ON CAMPUS NEW IN 2018

Special Topics in Quantum Technology

by Barbara Terhal

8 STUDENTS

This course is for MSc students and PhDs, focussing in 2018 on theoretical modelling of superconducting devices.

OUTLOOK 2019

Next year, we will start with QuTech scholarships to attract top talents in the field of quantum technology. We will expand our on-campus teaching by offering a Minor in Quantum Science and Information for technology students to get introduced to the exciting field of quantum technology. We are expanding our outreach activities and are working on an online platform with the goal to become the starting point for anyone to learn about quantum technology.

Social Activities

The QuTech community comes together not just to work but also to have fun. In 2018, several social activities were organized, such as a Summer BBQ, a three-day group outing to the isle of Texel and a Christmas Party, featuring QuTech's own band 'Q2'. With the slogan "Quantum Speed Up? My measurements are running too!" printed on their t-shirts, a QuTech delegation participated in the Golden Tenloop, a running competition in Delft. Similarly, QuTech students competed in (and won!) the annual TU Delft Applied Physics Student Association sports day.

Photo credit:
Marieke de Lorijn

Partnerships

In addition to QuTech's collaboration with (inter) national universities and knowledge institutions, for instance within the Dutch Quantum Software Consortium (QSA, started in 2017) and the European Quantum Internet Alliance (QIA, started in 2018), QuTech develops technology for quantum computing and communication in close collaboration with strategic partners from industry.

Microsoft

In 2017, TU Delft with TNO as subcontractor and Microsoft have renewed their long-term collaboration on the development of topological qubits, which have the potential to become the building blocks of a future quantum computer. As part of this collaboration in 2018, the first joint research projects started, which already led to many interactions between Microsoft and QuTech researchers and engineers.

Intel

In 2015, QuTech and the US-based chip manufacturer Intel Corporation started a 10-year collaborative relationship to accelerate advancements in quantum computing. The combination of the expertise of both Intel engineers and QuTech scientists has already shown to be successful in the first years of the collaboration, which has led to joint publications in important scientific journals and has generated joint inventions. In January 2018, the CEO of Intel showed a 49-qubit superconducting test chip co-designed with QuTech at the Consumer Electronics Show in Las Vegas. Another highlight in 2018 was the collaboration of QuTech and Intel in the development of an integrated cryogenic control chip, to control both superconducting qubits and spin qubits.

An exciting new development is the establishment and growth of a Quantum Campus in Delft for which the plans were further shaped in 2018. The ambition is to grow a vibrant ecosystem around QuTech where students, researchers and entrepreneurs benefit from their proximity and top-of-the-line facilities in achieving their respective goals in the development of quantum technologies. Several companies have already joined the Quantum Campus. In 2018, three new and exciting partners decided to join this effort:

Microsoft Station Q Delft

In addition to the renewed research collaboration, work was done in 2018 on the realization of a Microsoft lab on the TU Delft campus. The Station Q Delft lab will be led by Prof. Leo Kouwenhoven, in his capacity of principal investigator at Microsoft. The lab was officially opened early 2019.

Bluefors

On 4 October 2018, during the Innovation Expo in Rotterdam, the Finnish company Bluefors announced that it will join the Delft quantum technology community and open an R&D office in Delft. After Microsoft, Bluefors is the second international company to come to the Q-campus Delft. Their mission is to develop cryogenic technology for quantum computers. The Bluefors lab will be located in the former Applied Sciences building where QuTech is also housed.

QBlox

In 2018, a PhD student and an engineer from QuTech's DiCarlo group set up start-up company QBlox focused on room-temperature control electronics for qubit control. First product offerings will be based on licensed technology developed within QuTech. QBlox aims to open its R&D office on the Q-campus Delft in 2019.

Microsoft Quantum Lab Delft

PROGRESS 2018

Photo credit:
Marco de Swart

After a new phase in the collaboration between Microsoft and TU Delft/QuTech was formalized mid 2017, 2018 saw a lot of preparatory work being done to kickstart new joint research projects and towards the official opening of the Microsoft Quantum Lab Delft in early 2019.

The Microsoft Quantum Lab Delft aims to achieve scientific breakthroughs in the field of quantum computing through physics research based on Majorana particles. The lab is strategically situated on the TU Delft campus to support collaboration between Microsoft researchers and PhD students, academic researchers and other employees at TU Delft.

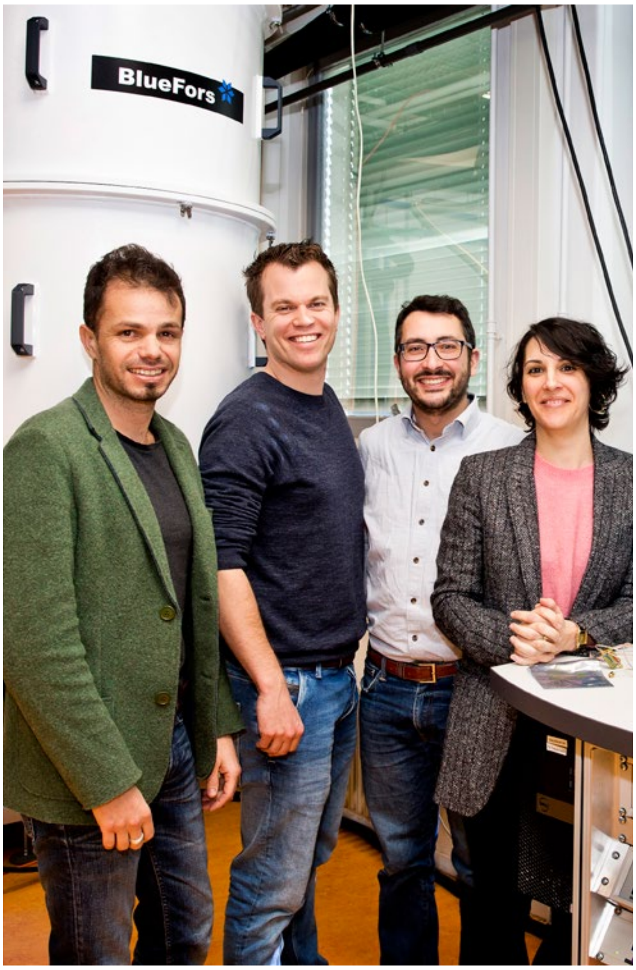
To house the new lab, the C wing of the Applied Physics building of TU Delft was fully renovated, from basement to roof. The result is a state-of-the-art laboratory space housing among others several dilution refrigerators, a transmission electron microscope, a scanning electron microscope and a focused ion beam microscope.

Photo credit:
fvdb

Grants and prizes

In 2018, QuTech scientists were awarded several grants and prizes. Some of the highlights are described on the next pages.

Open Technology Programme Grant for silicon qubits



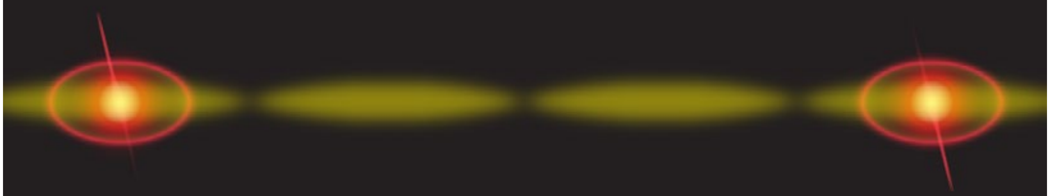
Menno Veldhorst (lead PI), Fabio Sebastiano, Giordano Scappucci and Carmina Almudever (co-PIs) received an Open Technology Programme project grant from NWO (domain Applied and Engineering Sciences). The team received a budget of over 1.2 M€ for 5 years to construct quantum bits that are based on silicon transistors, the most replicated man-made structure in the history of mankind. Large qubit arrays will be fabricated in partnership with Intel Corporation, while cryogenic electronics will be developed together with BlueFors. These together will enable the team to demonstrate quantum operations on a large quantum chip, laying down the path towards a quantum era for computation.

Horizon 2020 grant for Andreev qubits for scalable quantum computation

A Horizon 2020 FET Open grant of 3.5 million euros was awarded to a European consortium coordinated by Attila Geresdi to establish the foundations of a radically new solid-state platform for scalable quantum computation, based on Andreev qubits. This platform is implemented by utilising the discrete superconducting quasiparticle levels (Andreev levels) that appear in weak links between superconductors. The research consortium consists of academic partners at Budapest, Copenhagen, CNR Pisa, CEA Saclay, Basel, Madrid and Delft. The device technology, based on high-quality semiconductor nanowires and planar heterostructures in combination with clean superconductor leads is of key importance for the flexibility and the potential of scalability of the Andreev qubit platform. These aspects will be covered by the broad range of competences in the consortium, spanning from theoretical device modelling and materials science to quantum transport and quantum bit measurements.

Ten million euro for European Quantum Internet Alliance to speed up development of a quantum internet

In October 2018, the European Commission announced that its Quantum Flagship Programme will contribute 10 million euro to the development of a blueprint for a future quantum internet. Applications of networks based on quantum entanglement include improving the security of for instance financial transactions, and could give inherently secure networks. The blueprint will be developed by the Quantum Internet Alliance, a consortium of leading quantum research groups and high-tech companies in Europe led by QuTech. The aim of the consortium is to develop the technology needed for such a quantum internet, ensuring a leading role for European industry in this emerging field of technology. The funds granted by the EC are part of a first phase of funding from the ten-year, 1 billion euro Flagship programme.



NWO Projectruimte funds for Menno Veldhorst and Giordano Scappucci

Menno Veldhorst and Giordano Scappucci receive 600,000 euro from NWO to study macroscopic entanglement between spins in germanium. In this combined materials science and physics project, germanium will be explored as quantum material to integrate superconductivity and quantum dots. Novel hybrid systems will be created with the goal to demonstrate entanglement between two spins over a macroscopic distance on a single chip. A superconducting resonator will be constructed that can be directly coupled to hole spins in germanium, maximising coupling and minimising loss. Spin-orbit coupling will act as driving force for fast electrical qubit rotations, while creation of entanglement between two spins will be mediated by microwave resonator photons.

Menno Veldhorst on MIT Technology Review's 2018 Innovators Under 35 List

Menno Veldhorst has been named to MIT Technology Review's prestigious annual list of Innovators Under 35. Veldhorst invented a faster path to real-world quantum circuits by making it possible for them to be printed on silicon – the way computer chips have been printed for decades. Prior to Veldhorst's innovation, it was considered impossible to make usable, semiconductor-based quantum circuits on silicon that would be stable enough to perform useful calculations.

Photo credit:
Marieke de Lorijn

Martinus van Marum Prijs 2018 awarded to Bas Hensen

The Royal Netherlands Society of Sciences (Koninklijke Hollandse Maatschappij der Wetenschappen) awarded the Van Marum Prijs 2018 to Dr. Bas Hensen for his 2016 PhD thesis ‘Quantum Nonlocality with Spins in Diamond’. In it, Hensen describes the first ever demonstration of the loophole-free Bell Test. Using entangled quantum particles in two diamonds located 1.3km apart, this was the first successful Bell Test to close all possible loopholes that could invalidate the proof. Besides their profound philosophical implications, the results are important to the application of entanglement to encryption in a future internet. Hensen previously won the 2017 NWO Physics Thesis Award.

ERC Starting Grant for Attila Geresdi

The European Research Council awarded an ERC Starting Grant to QuTech’s Attila Geresdi. The grants (1,5 million euros for a five-year programme) are intended to support excellent early-stage scientists.

Geresdi and his team will work on the concept of topological protection by Majorana bound states.

He will specifically utilise a well-understood and flexible platform: a linear array of quantum dots. In this system, the quantum behaviour of the electrons in the dots maps to a one-dimensional topological superconductor, hosting a Majorana state on each end of the chain. This concept of analogue quantum simulation enables the investigation and control of complex quantum systems, even those that are inaccessible for classical computer simulations.

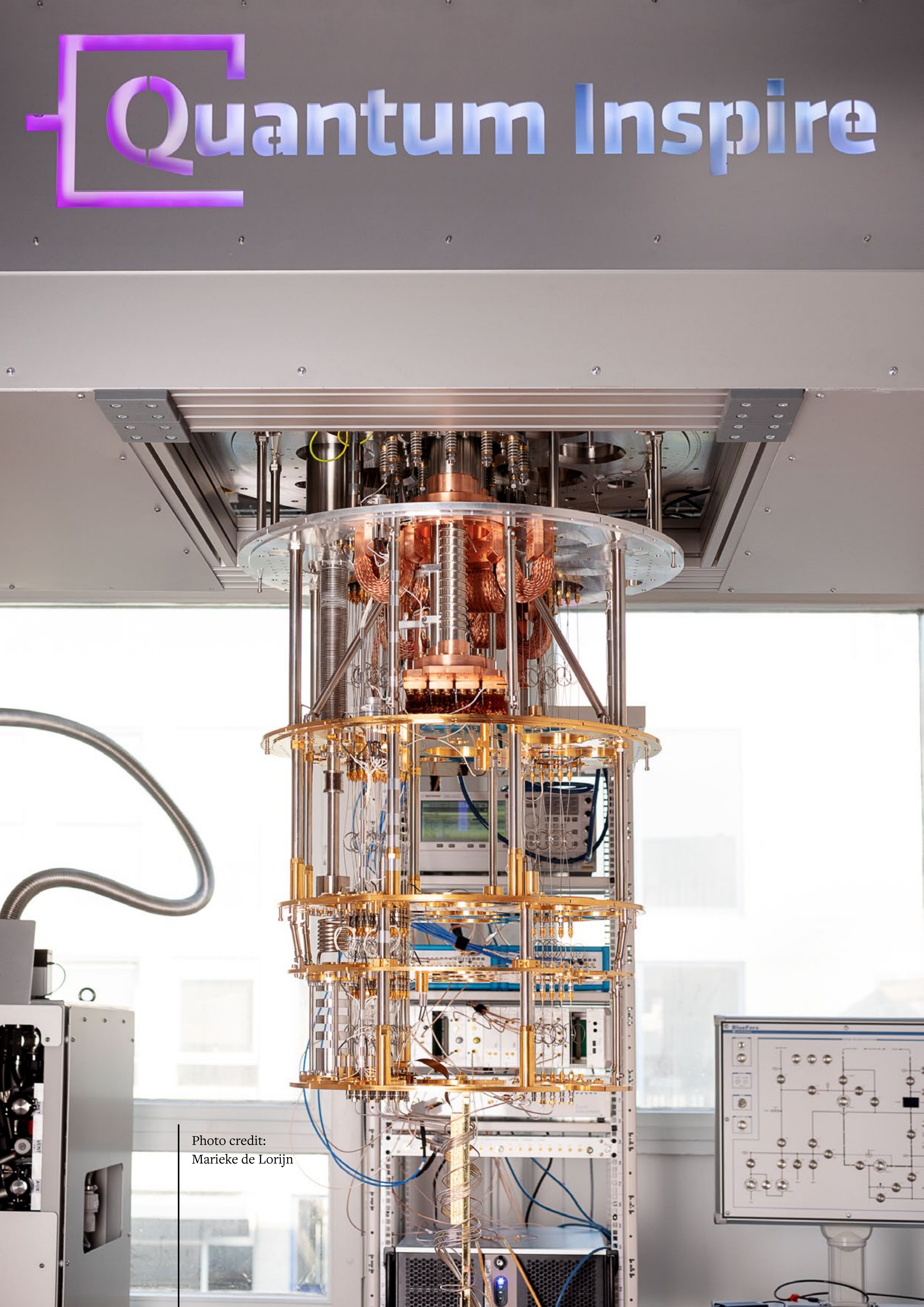


Photo credit:
Marieke de Lorijn

Outreach

QuTech strongly believes in the importance of science communication and outreach activities to the general public and society. QuTech researchers are asked frequently by media, companies, governments and other national and international stakeholders to give their expert view on the field. In this section we list the most important outreach activities of 2018.

In-company presentations

To inform companies about the state-of-art of quantum technologies, several in-company presentations were given by QuTech researchers, among which at Alten (Eindhoven), Zeiss (Oberkochen), Gartner (Amsterdam) and Centric (Gouda).

Photo credit: Martijn Beekman

Innovation Expo

During the Innovation Expo, an annual large brokerage event for Dutch innovators organized by the Dutch government, QuTech presented itself to a public of 4000 participants from various fields of innovation. With a booth and plenary session, QuTech presented its core R&D, businesses established on campus and the Quantum Inspire to the general public. As part of the plenary session, State Secretary Mona Keijzer performed the official public launch of Quantum Inspire. The ambition is to engage in these kind of outreach events more often, for instance at the Q2B conference in San Francisco and the Hannover Messe in 2019.

8
JANUARY 2018
QuTech-Intel quantum chip at the Consumer Electronics Show

At the 2018 Consumer Electronics Show in Las Vegas, Intel CEO Brian Krzanich presented a 49-qubit chip co-designed between Leo DiCarlo's team at QuTech and Jim Clarke's team at Intel.

11
FEBRUARY 2018
Paradiso lecture by Ronald Hanson

24
MARCH 2018
TEDx UHasselt

'Quantum Science Enters Society' by Julia Cramer.

https://youtu.be/I6VJBbhJbhE

3
APRIL 2018
FameLab competition

QuTech's Ben Criger competed in the Dutch finals of this international science communication competition.

13
APRIL 2018
FYSICA Young Speakers Contest

QuTech PhD student Guoji Zheng made it to finals.

15
MAY 2018
Visit of the Federal President of Germany Frank-Walter Steinmeier to QuTech

6
JUNI 2018
International Festival of Technology, Delft

Quantum Escape Room experience.

17
OCTOBER 2018
'Fun facts about quantum computing' in the Financial Times

Based on interviews with Intel's Jim Clarke and QuTech's Lieven Vandersypen.

20
OCTOBER 2018
Ronald Hanson featured on "Klaas Kan Alles"

https://youtu.be/ESGCJ3MRXa8

3
NOVEMBER 2018
Julia Cramer at the Skepsiscongres 2018

on the misuse of the word 'quantum'.

14
NOVEMBER 2018
Ronald Hanson at the Betweter Festival

https://youtu.be/wzNNpdp0a0M

13
DECEMBER 2018
Kindercollege (Kids' Lecture) by Julia Cramer

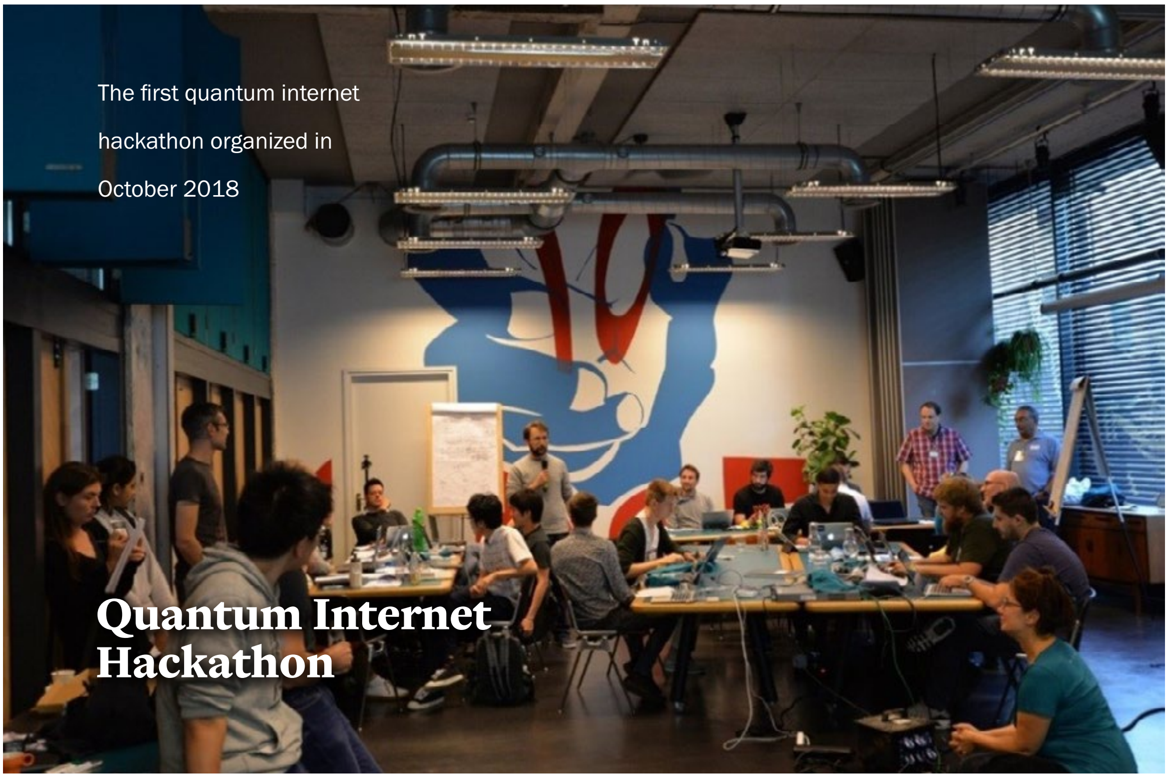
at the Sultan Ahmet mosque in Delft.

International Conference Quantum Information Processing 2018

In January, the 21st International Conference on Quantum Information Processing (QIP) was hosted by QuTech and TU Delft. QIP is the world's largest meeting for theoretical research on quantum information. This was the first time the conference was held in the Netherlands. Over 500 leading quantum scientists filled the auditorium of TU Delft for one week.

Quantum Internet in international media

The publication of a vision paper by QuTech, the announcement of EU Flagship funding and the publication of deterministic entanglement generation led to interviews of Stephanie Wehner in various international media and coverage on Dutch national evening TV news with an interview of Ronald Hanson.



The first quantum internet hackathon organized in October 2018

Quantum Internet Hackathon

One of the highlights of the outreach and industry engagement activities as part of the QINC roadmap was the first Quantum Internet hackathon in October 2018. The hackathon was organized together with RIPE NCC and sponsored by Juniper networks. It used QuTech's open-source simulator SimulaQron. During a whole weekend, participants from all over the world worked on topics such as a library for performing measurement-based quantum computation including blind quantum computation on a remote server, and a visualisation tool for quantum key distribution.

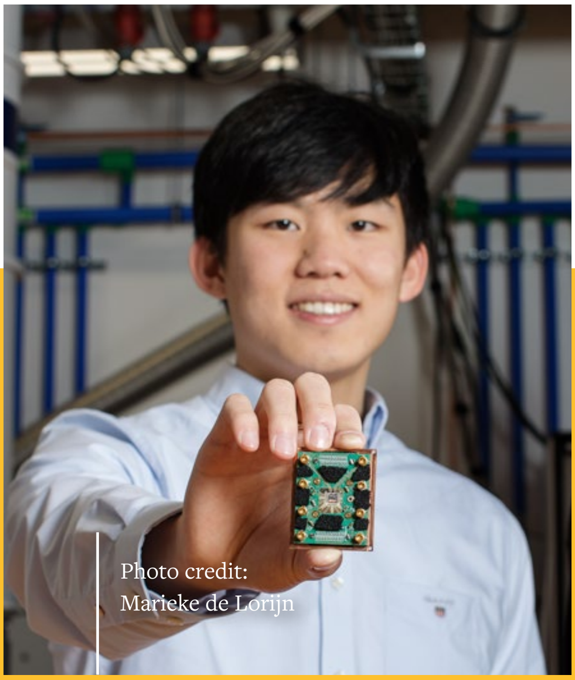


Photo credit:
Marieke de Lorijn

PhD life at QuTech

GUOJI ZHENG *is PhD student at QuTech. During his Applied Physics study at TU Delft, he wrote his own PhD proposal, which got him a Casimir PhD grant to work at QuTech.*

What made you choose QuTech for your PhD? // I did my final MSc project at QuTech and I could picture myself working in such an environment. The groups are among the best in the world with many years of experience in quantum physics, quantum computers and quantum internet.

What do you like best about working at QuTech? // If I look around, I see a vast amount of expertise, which is very helpful for my PhD. QuTech also offers a lot of technical resources, which enables one to fabricate complex devices and perform sophisticated measurements. My favourite social event at QuTech would be the 'QuTech uitje', which is a trip of 2-3 days filled with lots of fun activities.

You were in the finals for the Young Speaker contest of the FYSICA event? // Yes, and it was a fantastic experience. Speaking to a rather general audience, my first goal was to teach and get them excited about quantum computers. The second goal was to tell them about our recent achievement, where we showed a very strong interaction between two quantum systems on a silicon chip: an electron spin and a photon. This coupling could enable the transfer of quantum information between them. Connecting distant quantum bits on a silicon chip via a photon could make it easier to build large chips with many quantum bits.

If you could change one thing about QuTech, what would it be? // Everyone works very hard at QuTech, I think it would be nice to be able to relax now and then, for example by creating a recreation room. This also has a social advantage of bringing people together with common interests outside science.

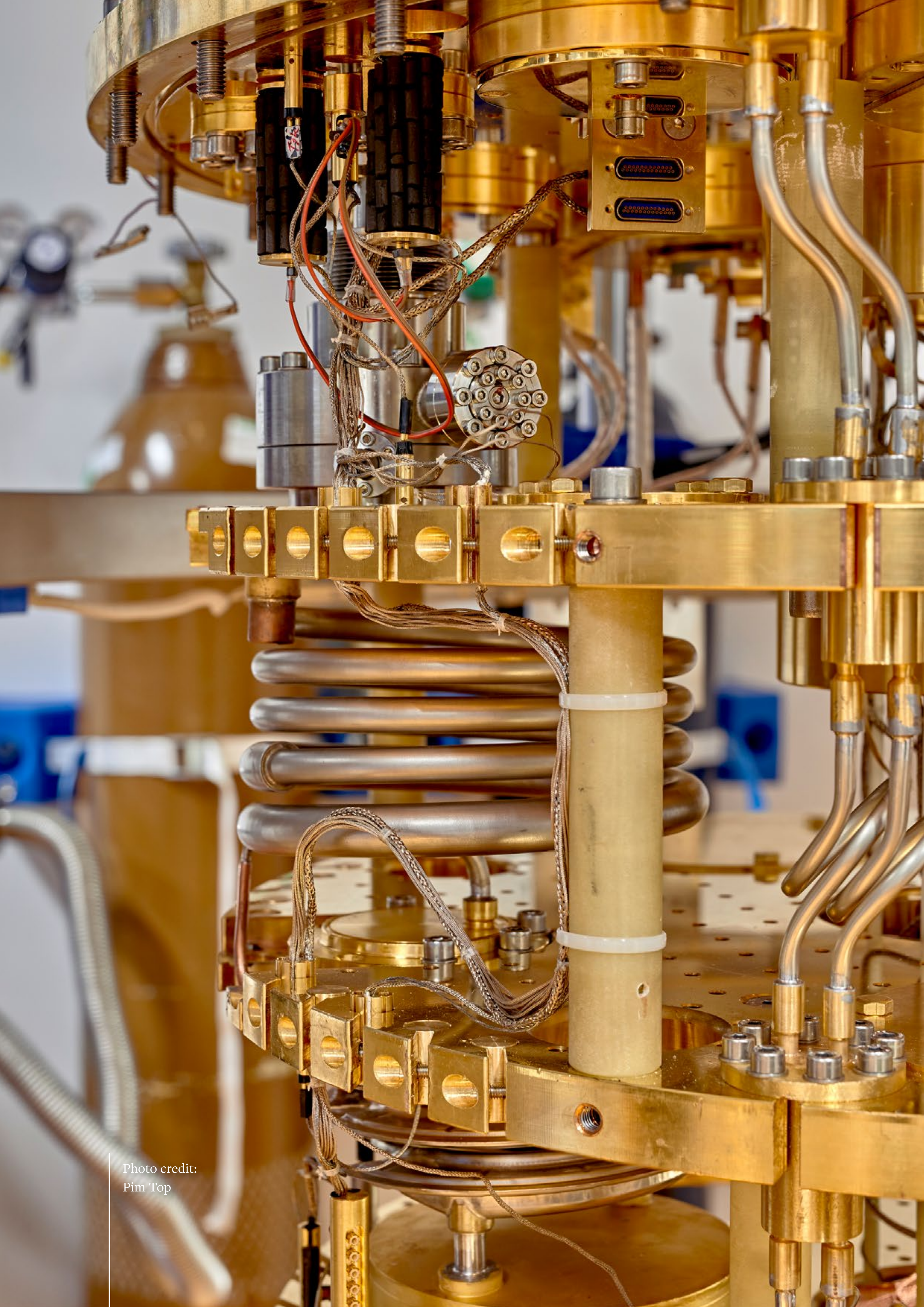


Photo credit:
Pim Top

Organization

GOVERNANCE

QuTech is not a legal entity, but a collaboration between TU Delft and TNO, governed by the 'Samenwerkingsovereenkomst QuTech'. In 2018, this covenant was amended in order to move to a new governance structure. A new team of directors was formed as a response to the growth of QuTech in terms of staff and projects and the many opportunities identified for further collaborations.

Until 2018, the Scientific Director together with the Managing Director and the roadmap leaders formed the management team of QuTech. A supervisory board steered and supervised the research of QuTech. From 2018 onwards, the governance structure of QuTech is divided into three parts: Research, Operations and Business Development, each with a director, together forming the QuTech Management Board ('Directie'). The Research Director acts as primus inter pares. The QuTech Management Board reports directly to the TU Delft Executive Board. The TU Delft Executive Board consults the Executive Board of TNO where appropriate, for example on decisions with financial consequences. The Scientific Director and Operations Director are employed by TU Delft, the Director Business Development is employed by TNO.

As result of this change in governance structure, we have recruited a new Director of Operations (Charlotte van Hees) and Director of Business Development (Kees Eijkel). Both started on 1 December 2018, thereby completing the QuTech Management Board. The three directors lead QuTech in consultation with the roadmap leaders.

Meet QuTech's new directors

The QuTech Management Board: Kees Eijkel (left), Ronald Hanson (middle) and Charlotte van Hees (right)

Photo credit: Marieke de Lorijn

Kees Eijkel

Director of Business Development

“I did my Master’s in Mathematics and Experimental Physics in Amsterdam, after which I graduated in microsystems at the University of Twente. After a period as assistant professor, I became head of the cleanrooms in Twente, and helped spin out the first microsystems companies from there. In 2000, I became technical-commercial director of the MESA+ institute for Nanotechnology, building the institute, spinning out more companies and helping to create the first national nanotech programme NanoNed. After that, I was CEO of Kennispark, the Twente innovation ecosystem, and the Science Park. QuTech brings all of my experience together. That, combined with the excellence, width and drive of the institute and its people, convinced me that this is the place to be. Choosing QuTech just took a second. The coming years, I aspire to move the QuTech ecosystem, its external partnerships (both private and public) and its start-up production to a higher level, and as such, contribute to QuTech’s mission. It is an honour and an exciting adventure to be part of QuTech!”

Charlotte van Hees

Director of Operations

"Within QuTech I am responsible to support the research and innovation agenda with smooth operational design and processes. The drive of the whole team – scientists, engineers and support staff – to engage in something new, to pool resources and expertise, to actually build a quantum computer and quantum internet, is what attracted me to QuTech. Before coming to Delft, I worked for the United Nations, the Association of Dutch Universities and Leiden University of Applied Sciences. Trained as an organizational anthropologist I like to travel, go places, observe, learn from other cultures, habits, value systems. I enjoy building teams and get them in sync with the rest of the organization. In this respect, QuTech poses a challenging and exiting environment with scientists and engineers from around the world, in a partnership between public and private sectors, all working together towards one mission.”

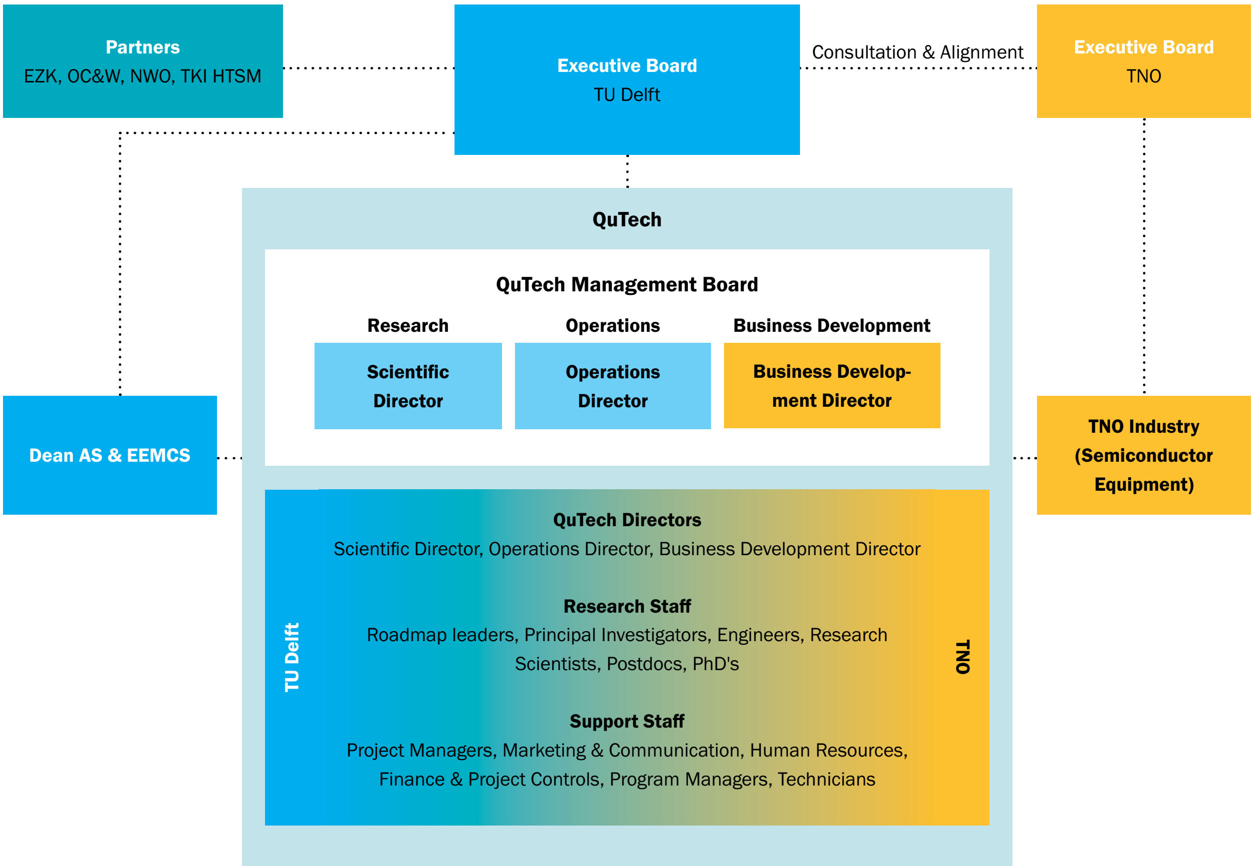


Figure 1 // Governance structure of QuTech

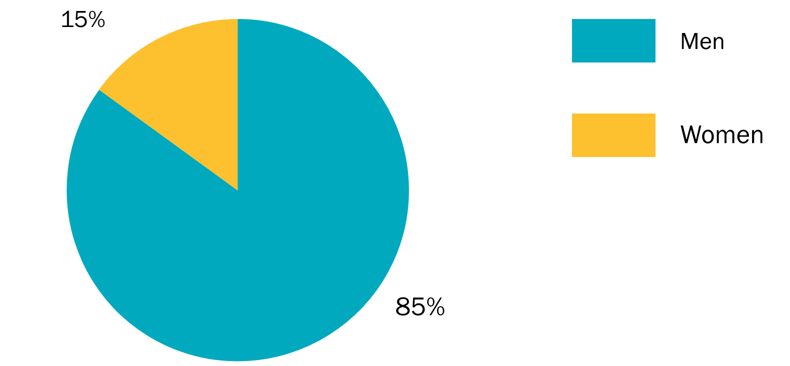
QuTech Management	
Scientific Director	Ronald Hanson
Business Development Director	Kees Eijkel
Operations Director	Charlotte van Hees
Roadmap Leaders	Leo DiCarlo, Lieven Vandersypen, Garrelt Alberts, Stephanie Wehner, Michael Wimmer, Menno Veldhorst

QuTech is mostly organized around roadmaps, where a large part of the activities takes place. General support is organized centrally. Each roadmap has a roadmap leader, who is responsible for the principal investigators, post-docs, PhD candidates, MSc students, engineers and roadmap-dedicated technicians.

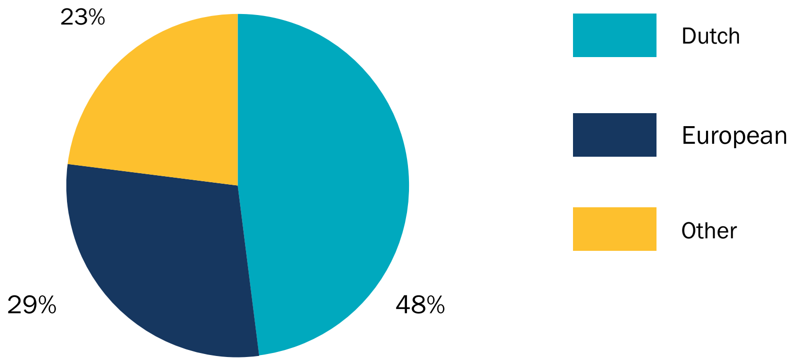
Personnel

In December 2018, QuTech personnel comprised 210 FTE (remunerated and non-remunerated), compared to 180 in 2017. This number is expected to increase to about 250 in 2020. Below we illustrate the composition of the QuTech community, using pie charts on the basis of FTEs.

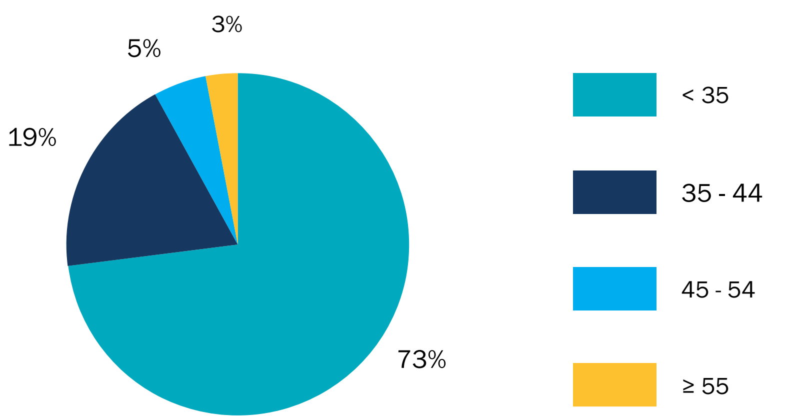
GENDER



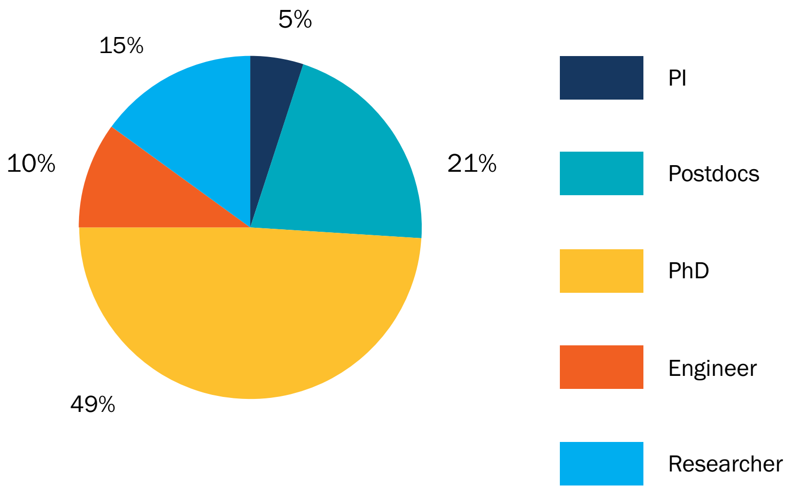
NATIONALITY



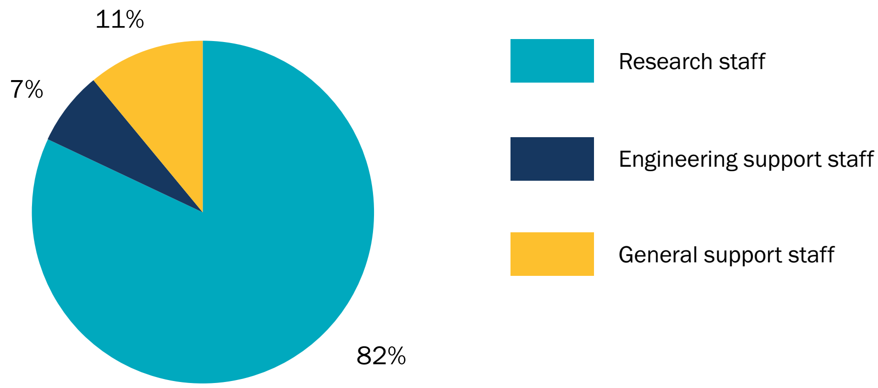
AGE STRUCTURE



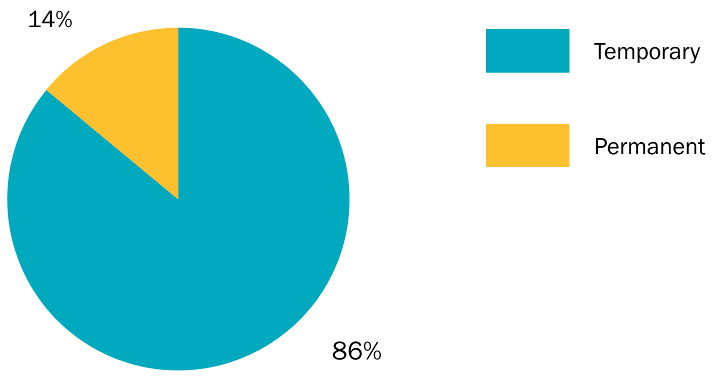
RESEARCH ACTIVITIES



STAFF CATEGORIES

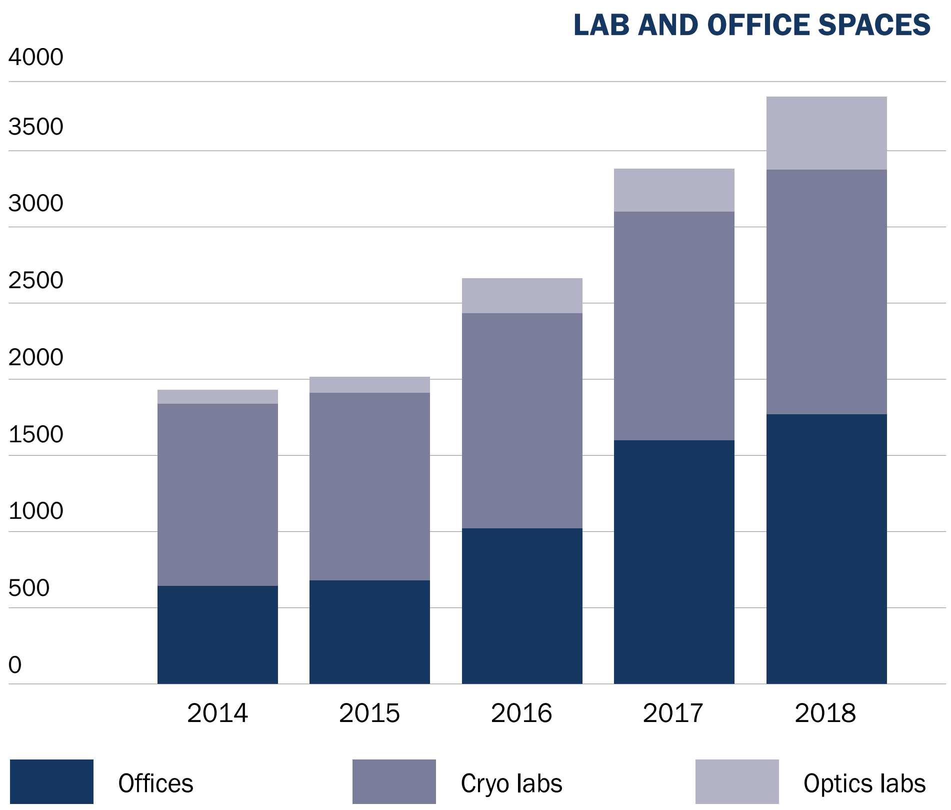


TEMPORARY/ PERMANENT CONTRACT



Research infrastructue

Growth (M2) in lab and office spaces



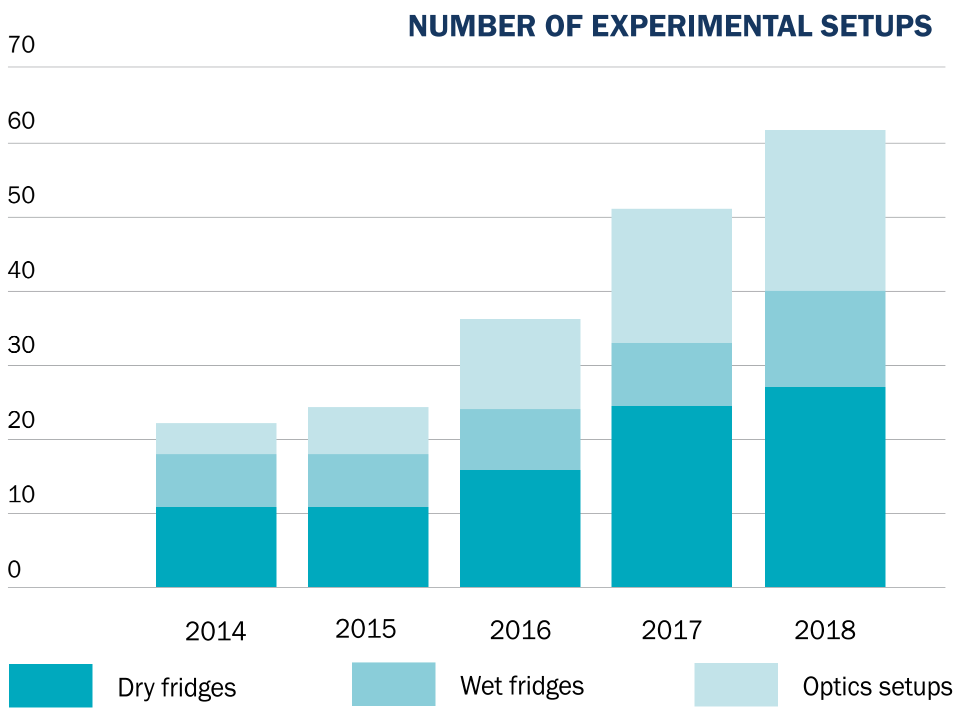


Photo credit:
Anne Reitsma

Financial overview

This section provides further information regarding QuTech's finances, based on the framework of a partnerconvenant established in 2015. It includes the following partners:

- The Ministry of Economic Affairs and Climate (MinEZK)
- The Ministry of Education, Culture and Science (MinOCW)
- The Netherlands Organisation for Applied Scientific Research (TNO)
- Delft University of Technology (TU Delft)
- The Netherlands Organisation for Scientific Research (NWO), specifically:
    - NWO domain Applied and Engineering Sciences (NWO/TTW; formerly Technology Foundation STW)
    - NWO domain Science (NWO/ENW; formerly Foundation for Fundamental Research on Matter, FOM)
- TKI Holland High Tech (formerly the Foundation TKI High Tech Systems and Materials)

The partners agreed to financially support QuTech for the 10-year period from June 2015 to June 2025. Allocation of the 2020-2025 budgets takes place in 2019 after the midterm evaluation. This financial overview does not take funding from other grant providers or partners (Microsoft, Intel) into account.

Scientific, engineering and support staff at QuTech, as well as all operating budgets and investments, are currently funded through four primary sources:

1. TU Delft
2. TNO
3. Industry funding
4. Ministry of Economic Affairs and Climate Policy, TKI Holland High Tech, NWO/ENW (formerly FOM) and NWO/TTW (formerly STW).

In addition to funding from the above contributing parties, QuTech researchers receive funding for PhD students, postdocs, running budgets and investments via research grants applied for through the NWO, the European Union (ERC grants, FP7 and H2020 grants), IARPA, ARO, etc.

The 10-year budget established in 2015 included the following in-kind and in-cash contributions by partners:

TU Delft in-kind	29	M€
TU Delft in-cash	20	M€
TNO in-cash*	50.75	M€
NWO/ENW*	36.18	M€
STW in-cash	9.6	M€
Total	**145.53**	**M€**

**The TKI Holland High Tech allowance is included in the budgets of TNO and NWO/ENW (formerly FOM).*

TU DELFT BUDGET

The 10-year commitment of TU Delft includes:

- In-kind contribution (29 million euro)
    - Provision for housing, energy, cleanroom, infrastructure and professors/ researchers/personnel from the TU Delft faculties Applied Sciences (TNW) and Electrical Engineering, Mathematics & Computer Science (EWI).
- In-cash contribution (20 million euro)
    - Provided from TU Delft strategy funds.

The budgeted in-cash contribution of TU Delft for 2018 (2 million euro) was allocated according to QuTech purposes (scientific and support staff, equipment).

TNO BUDGET

The 10-year TNO budget consists of:

- TNO strategic funds (29.75 million euro)
    - SMO (Samenwerkings Middelen Onderzoek) from the High Tech Systems and Materials roadmap and ICT roadmap
    - Early Research Programme
- MinEZK via TNO (11.75 million euro)
    - This is the MinEZK fund allocated to TNO for QuTech purposes
- TKI allowance via TNO (9.25 million euro)
    - This is based on the contribution of 1 million euro/year from private companies

NWO/ENW BUDGET *(formerly FOM)*

The 10-year NWO/ENW budget consists of:

- NWO/ENW (3.75 million euro plus a further 3.75 million euro pledged).
  This budget is and will be largely spent on the start-up packages for three QuTech PIs (two senior researchers and one full professor).
- NWO/ENW Industrial Partnership Programme (3.75 million euro plus a further 3.75 million euro pledged).This part of the budget reflects the Industrial Partnership Programme with Microsoft, explicitly included in the partner covenant according to the stipulation of MinEZK and HTSM partners for a private contribution exceeding 2 million euro/year in order to participate in QuTech. This budget is to fund 6 PhD positions, 6 postdoctoral years, one 5-year technician position and one senior researcher position, as well as for materials and equipment required for the research within the programme. The private contribution funds another 8 PhD positions, 16 postdoctoral years, 10 technician years and a senior researcher year, as well as materials and equipment required for the research within the programme.
- TKI-allowance via NWO/ENW. This allowance, generated from the IPP project collaboration between Microsoft, TU Delft, NWO/ENW, was intended to be routed via NWO/ENW (FOM). In 2017, QuTech, NWO/ENW and TKI Holland High Tech agreed to grant the allowance directly to QuTech, where it will be spent on PhD and postdoctoral positions and running budgets as described in the research programme approved by TKI Holland High Tech.

NWO/TTW BUDGET (formerly STW)

The 10-year NWO/TTW budget consists of:

- For the period 2014-2019, NWO/TTW (STW) granted 2.6 million euro. The budgeted costs (PhD students, materials, equipment, cleanroom, engineers) have now been mostly spent. QuTech and NWO/TTW will review how to spend the remaining budget in line with the purpose of the budget and keeping the mission of NWO/TTW in mind.
- Allocation of the 2020-2025 NWO/TTW budget takes places after evaluation of QuTech in 2018.

TKIs EXPLAINED

Within the Top Consortium for Knowledge and Innovation (TKI) Holland High Tech (formerly High Tech Systems and Materials), knowledge institutions and industry collaborate on a public/private-funded multi annual TKI programme. A TKI programme includes fundamental research, industrial research, experimental development, or a combination of these types of research. With the TKI allowance, the Ministry of Economic Affairs and Climate stimulates private-public collaboration between research organizations and industry. The basic principle is simple: for every euro the private sector invests in R&D at a knowledge institute, the TKI receives 25 cents. The TKI uses these revenues for new public-private research.

Photo credit:
Marieke de Lorijn

Appendices

List of peer-reviewed publications 2018

JANUARY

2 January 2018

Capacity estimation and verification of quantum channels with arbitrarily correlated errors

Corsin Pfister, M. Adriaan Rol, Atul Mantri, Marco Tomamichel, Stephanie Wehner

Nature Communications 9, 1 (2018)

5 January 2018

Non-linear and dot-dependent Zeeman splitting in GaAs/AlGaAs quantum dot arrays

V.P. Michal, T. Fujita, T.A. Baart, J. Danon, C. Reichl, W. Wegscheider, L.M.K. Vandersypen, and Y.V. Nazarov

Phys. Rev. B 97, 035301 (2018)

15 January 2018

Ballistic Majorana nanowire devices

Ö. Gül, H. Zhang, J.D.S. Bommer, M.W.A. de Moor, D. Car, S.R. Plissard, E.P.A.M. Bakkers, A. Geresdi, K. Watanabe, T. Taniguchi and L.P. Kouwenhoven

Nature Nanotechnology 13, 192-197 (2018)

25 January 2018

The cryogenic temperature behavior of bipolar, MOS, and DTMOS transistors in standard CMOS

Harald Homulle, Lin Song, Edoardo Charbon and Fabio Sebastiano

IEEE Journal of the Electron Devices Society 6, 263–270 (2018)

26 January 2018

h/e superconducting quantum interference through trivial edge states in InAs

F.K. de Vries, T. Timmerman, V.P. Ostroukh, J. van Veen, A.J.A. Beukman, F. Qu, M. Wimmer, B.-M. Nguyen, A.A. Kiselev, W. Yi, M. Sokolich, M.J. Manfra, C.M. Marcus and L.P. Kouwenhoven

Phys. Rev. Lett. 120, 047702 (2018)

FEBRUARY

6 February 2018

Fully device-independent conference key agreement

Jérémy Ribeiro, Gláucia Murta, Stephanie Wehner

Physical Review A 97, 022307 (2018)

13 February 2018

Chip-to-chip entanglement of transmon qubits using engineered measurement fields

Christian Dickel, Jaap Wesdorp, Nathan Langford, Sarwan Peiter, Ramiro Sagastizabal, Alessandro Bruno, Ben Criger, Felix Motzoi, and Leo DiCarlo

Phys. Rev. B 97, 064508 (2018)

14 February 2018

A programmable two-qubit quantum processor in silicon

T.F. Watson, S.G.J. Philips, E. Kawakami, D.R. Ward, P. Scarlino, M. Veldhorst, D.E. Savage, M.G. Lagally, M. Friesen, S.N. Coppersmith, M.A. Eriksson, and L.M.K. Vandersypen

Nature 555, 633-637 (2018)

MARCH

1 March 2018

General method for extracting the quantum efficiency of dispersive qubit readout in circuit QED

Niels Bultink, Brian Tarasinski, Niels Haandbaek, Stefano Poletto, Nadia Haider, David Michalak, Alessandro Bruno, and Leo DiCarlo

Appl. Phys. Lett. 112, 092601 (2018)

9 March 2018

Strong spin-photon coupling in silicon

N. Samkharadze, G. Zheng, N. Kalhor, D. Brousse, A. Sammak, U.C. Mendes, A. Blais, G. Scappucci, and L.M.K. Vandersypen

Science 359, 1123-1127 (2018)

9 March 2018

Evolution of nanowire transmon qubits and their coherence in a magnetic field

Florian Luthi, Thijs Stavenga, Oscar Enzing, Alessandro Bruno, Christian Dickel, Nathan Langford, Adriaan Rol, Thomas Jespersen, Jesper Nygard, Peter Krogstrup, and Leo DiCarlo

Phys. Rev. Lett. 120, 100502 (2018)

APRIL

5 April 2018

Quantized Majorana conductance

H. Zhang, C.X. Liu, S. Gazibegovic, D. Xu, J.A. Logan, G. Wang, N. van Loo, J.D.S. Bommer, M.W.A. de Moor, D. Car, R.L.M. Veld, P.J. van Veldhoven, S. Koelling, M.A. Verheijen, M. Pendharkar, D.J. Pennachio, B. Shojaei, J.S. Lee, C.J. Palmstrom, E.P.A.M. Bakkers, S. Das Sarma, L.P. Kouwenhoven

Nature 556, 74-79 (2018)

11 April 2018

Parameter regimes for a single sequential quantum repeater

Filip Rozpędek, Kenneth Goodenough, Jérémy Ribeiro, Norbert Kalb, Valentina Caprara Vivoli, Andreas Reiserer, Ronald Hanson, Stephanie Wehner, David Elkouss

Quantum Science and Technology 3, 304002 (2018)

13 April 2018

Continuous-variable protocol for oblivious transfer in the noisy-storage model

Fabian Furrer, Tobias Gehring, Christian Schaffner, Christoph Pacher, Roman Schnabel, Stephanie Wehner

Nature Communications 9, 1450 (2018)

16 April 2018

High-performance back-illuminated three-dimensional stacked single-photon avalanche diode implemented in 45-nm CMOS technology

Myung-Jae Lee, Augusto Ronchini Ximenes, Preethi Padmanabhan, Tzu-Jui Wang, Kuo-Chin Huang, Yuichiro Yamashita, Dun-Nian Yaung and Edoardo Charbon

IEEE Journal of Selected Topics in Quantum Electronics 24, 6 (2018)

24 April 2018

Light, the universe and everything – 12 Herculean tasks for quantum cowboys and black diamond skiers

Girish Agarwal, Roland E. Allen, Iva Bezděková, Robert W. Boyd, Goong Chen, Ronald Hanson, Dean L. Hawthorne, Philip Hemmer, Moochan B. Kim, Olga Kocharovskaya, David M. Lee, Sebastian K. Lidström, Suzy Lidström, Harald Losert, Helmut Maier, John W. Neuberger, Miles J. Padgett, Mark Raizen, Surjeet Rajendran, Ernst Rasel, Wolfgang P. Schleich, Marlan O. Scully, Gavriil Shchedrin, Gennady Shvets, Alexei V. Sokolov, Anatoly Svidzinsky, Ronald L. Walsworth, Rainer Weiss, Frank Wilczek, Alan E. Willner, Eli Yablonovitch & Nikolay Zheludev

Journal of Modern Optics 65, 1261-1308 (2018)

MAY

3 May 2018

Quantum error correction in crossbar architectures

Jonas Helsen, Mark Steudtner, Menno Veldhorst, Stephanie Wehner

Quantum Science and Technology 3, 3 (2018)

4 May 2018

A 2×2 quantum dot array with controllable inter-dot tunnel couplings

U. Mukhopadhyay, J.P. Dehollain, C. Reichl, W. Wegscheider, and L.M.K. Vandersypen

Appl.Phys.Lett. 112, 183505 (2018)

28 May 2018

Transforming graph states using single-qubit operations

Axel Dahlberg, Stephanie Wehner

Philosophical Transactions of the Royal Society A 376, 2123 (2018)

28 May 2018

The Small Stellated Dodecahedron Code and Friends

J. Conrad, C. Chamberland, N. Breuckmann, B.M. Terhal

Phil. Trans. R. Soc. A 376, 2123 (2018)

JUNE

5 June 2018

Device-independence for two-party cryptography and position verification

Jeremy Ribeiro, Le Phuc Thinh, Jedrzej Kaniewski, Jonas Helsen, Stephanie Wehner

Physical Review A 97, 062307 (2018)

5 June 2018

Valley dependent anisotropic spin splitting in silicon quantum dots

R. Ferdous, E. Kawakami, P. Scarlino, M.P. Nowak, D.R. Ward, D.E. Savage, M.G. Lagally, S.N. Coppersmith, M. Friesen, M.A. Eriksson, L.M.K. Vandersypen, and R. Rahman

npj Quantum Information 4 , Article number: 26 (2018)

7 June 2018

Fermion-to-qubit mappings with varying resource requirements for quantum simulation

Mark Steudtner, Stephanie Wehner

New Journal of Physics, 20 (2018)

11 June 2018

Transport regimes of a split gate superconducting quantum point contact in the two-dimensional LaAlO3/SrTiO3 superfluid

Holger Thierschmann, Emre. Mulazimoglu, Nicola Manca, Srijit Goswami, Teun M. Klapwijk & Andrea D. Caviglia

Nature Communications 9, 2276 (2018)

13 June 2018

Deterministic delivery of remote entanglement on a quantum network

Peter C. Humphreys*, Norbert Kalb*, Jaco P. J. Morits, Raymond N. Schouten, Raymond F. L. Vermeulen, Daniel. J. Twitchen, Matthew Markham, Ronald Hanson

Nature 558, 268–273 (2018)

14 June 2018

Impact of valley phase and splitting on readout of silicon spin qubits

M. L. V. Tagliaferri, P. L. Bavdaz, W. Huang, A. S. Dzurak, D. Culcer, M. Veldhorst

Phys Review B 97, 245412 (2018)

19 June 2018

Quantum Frequency Conversion of Single Photons from a Nitrogen-Vacancy Center in Diamond to Telecommunication Wavelengths

Anaïs Dréau, Anna Tchebotareva, Aboubakr El Mahdaoui, Cristian Bonato, and Ronald Hanson

Phys. Rev. Applied 9, 064031 (2018)

20 June 2018

Dephasing mechanisms of diamond-based nuclear-spin memories for quantum networks

N. Kalb, P. C. Humphreys, J. J. Slim, and R. Hanson

Phys. Rev. A 97, 062330 (2018)

21 June 2018

Optimizing practical entanglement distillation

Filip Rozpędek, Thomas Schiet, Le Phuc Thinh, David Elkouss, Andrew C. Doherty, Stephanie Wehner

Physical Review A, 97, 062333 (2018)

29 June 2018

One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment

M. H. Abobeih, J. Cramer, M. A. Bakker, N. Kalb, M. Markham, D. J. Twitchen & T. H. Taminiau

Nature Communications 9, 2552 (2018)

JULY

6 July 2018

A Crossbar Network for Silicon Quantum Dot Qubits

R. Li, L. Petit, D.P. Franke, J.P. Dehollain, J. Helsen, M. Steudtner, N.K. Thomas, Z.R. Yoscovits, K.J. Singh, S. Wehner, L.M.K. Vandersypen, J.S. Clarke, and M. Veldhorst

Sci. Adv. 4, eaar3960 (2018)

13 July 2018

Representations of the multi-qubit Clifford group

Jonas Helsen, Joel J Wallman, Stephanie Wehner

Journal of Mathematical Physic, 59, 072201 (2018)

16 July 2018

Automated tuning of inter-dot tunnel coupling in double quantum dots

C.J. van Diepen, P.T. Eendenbak, B.T. Buijtendorp, U. Mukhopadhyay, T. Fujita, C. Reichl, W. Wegscheider, and L.M.K. Vandersypen

Appl.Phys.Lett. 113, 033101 (2018)

19 July 2018

Gate-controlled quantum dots and superconductivity in planar germanium

N.W. Hendrickx, D.P. Franke, A. Sammak, M. Kouwenhoven, D. Sabbagh, L. Yeoh, R. Li, M.L.V. Tagliaferri, M. Virgilio, G. Capellini, G. Scappucci, M. Veldhorst

Nature Communications 9, 2835 (2018)

23 July 2018

Direct Microwave Measurement of Andreev-Bound-State Dynamics in a Semiconductor-Nanowire Josephson Junction

M. Hays, G. de Lange, K. Serniak, D.J. van Woerkom, D. Bouman, P. Krogstrup, J. Nygård, A. Geresdi, and M.H. Devoret

Phys. Rev. Lett. 121, 047001 (2018)

AUGUST

14 August 2018

Spin Lifetime and Charge Noise in Hot Silicon Quantum Dot Qubits

L. Petit, J.M. Boter, H.G.J. Eenink, G. Droulers, M.L.V. Tagliaferri, R. Li, D.P. Franke, K.J. Singh, J.S. Clarke, R.N. Schouten, V.V. Dobrovitski, L.M.K. Vandersypen, and M. Veldhorst

Phys. Rev. Lett. 121, 076801 (2018)

14 August 2018

Spin and orbital structure of the first six holes in a silicon metal-oxide-semiconductor quantum dot

S. D. Liles, R. Li, C. H. Yang, F. E. Hudson, M. Veldhorst, A. S. Dzurak & A. R. Hamilton

Nature Communications 9, 3255 (2018)

29 August 2018

Quantum technologies with optically interfaced solid-state spins

David D. Awschalom, Ronald Hanson, Jörg Wrachtrup and Brian B. Zhou

Nature Photonics 12, 516 (2018)

SEPTEMBER

7 September 2018

Spin-orbit interaction and induced superconductivity in a one-dimensional hole gas

K. de Vries, J. Shen, R. J. Skolasinski, M. P. Nowak, D. Varjas, L. Wang, M. Wimmer, J. Ridderbos, F. A. Zwanenburg, A. Li, S. Koelling, M. A. Verheijen, E. P. A. M. Bakkers, L. P. Kouwenhoven

Nanoletters 18, 6483-6488 (2018)

12 September 2018

SimulaQron – A simulator for developing quantum internet software

Axel Dahlberg, Stephanie Wehner

Quantum Science and Technology 4, 015001 (2018)

27 September 2018

Capacitance spectroscopy of gate-defined electronic lattices

T. Hensgens, U. Mukhopadhyay, P. Barthelemy, S. Fallahi, G.C. Gardner, C. Reichl, W. Wegscheider, M.J. Manfra, and L.M.K. Vandersypen

J. Appl. Phys. 124, 124305 (2018)

OCTOBER

October 2018

Cryogenic low-dropout voltage regulators for stable low-temperature electronics

Harald Homulle and Edoardo Charbon

Cryogenics 95, 11-17 (2018)

19 October 2018

Quantum internet: A vision for the road ahead

Stephanie Wehner, David Elkouss, Ronald Hanson

Science 362 (6412), eaam9288 (2018)

31 October 2018

Electric field tunable superconductor-semiconductor coupling in Majorana nanowires

M.W.A. de Moor, J.D.S. Bommer, D. Xu, G. Winkler, A.E. Antipov, A. Bargerbos, G. Wang, N. van Loo, R. Op het Veld, S. Gazibegovic

New Journal of Physics 20 (2018)

NOVEMBER

5 November 2018

Magnetic field compatible circuit quantum electro-dynamics with graphene Josephson junctions

J.G. Kroll, W. Uilhoorn, K.L. van der Enden, D. de Jong, K. Watanabe, T. Taniguchi, S. Goswami, M.C. Cassidy & L.P. Kouwenhoven

Nature Communications 9, 4615 (2018)

5 November 2018

A graphene transmon operating at 1 T

J.G. Kroll, W. Uilhoorn, K.L. van der Enden, D. de Jong, K. Watanabe, T. Taniguchi, S. Goswami, M.C. Cassidy, L.P. Kouwenhoven

Nature Communications 9, 4615 (2018)

9 November 2018

Magnetic-field-dependent quasiparticle dynamics of nanowire single-Cooper-pair transistors

Jasper van Veen, Alex Proutski, Torsten Karzig, Dmitry I. Pikulin, Roman M. Lutchyn, Jesper Nygård, Peter Krogstrup, Attila Geresdi, Leo P. Kouwenhoven, and John D. Watson

Phys. Rev. B 98, 174502 (2018)

9 November 2018

Renormalization group decoder for a four-dimensional toric code

K. Duivenvoorden, N.P. Breuckmann, B.M. Terhal

IEEE Transactions on Information Theory (2018)

16 November 2018

Anonymous transmission in a noisy quantum network using the W state

Victoria Lipinska, Gláucia Murta, Stephanie Wehner

Phys. Rev. A 98, 052320 (2018)

20 November 2018

Optimal design of diamond-air microcavities for quantum networks using an analytical approach

Suzanne B. van Dam, Maximilian T. Ruf, Ronald Hanson

New J. Phys. 20, 115004 (2018)

DECEMBER

19 December 2018

Fundamental limits on the capacities of bipartite quantum interactions

Stefan Bäuml, Siddhartha Das, and Mark M. Wilde

Physical Review Letters 121, 250504 (2018)

28 December 2018

Low-cost error mitigation by symmetry verification

Xavier Bonet-Monroig, Ramiro Sagastizabal, Malay Singh, and Thomas O'Brien

Phys. Rev. A 98, 062339 (2018)

December 2018

Spooky Quantum Action Passes Test

Ronald Hanson and Krister Shalm

Scientific American (December, 2018)

Graduates

The following PhD researchers and students graduated from QuTech in 2018:

Date	PhD defense
January 10	**Toivo Hensgens** – Emulating Fermi-Hubbard physics with quantum dots (*cum laude*)
April 5	**Norbert Kalb** – Diamond-based quantum networks with multi-qubit nodes
September 25	**Christian Dickel** – Scalability and modularity for transmon-based quantum processors

MSc	
Malay Singh	Hans Bartling
Eduardo Alvarez	Mark Noordam
Roeland ter Hoeven	Romy van Es
Eric Leerssen	Jarn de Jong
Kiefer Vermeulen	Steven van Gemert
Tim Stegwee	Michael Borst
Marta Pita Vidal	Remon Berrevoets
Max Kouwenhoven	Mark de Kruijff
Joep Assendelft	Patrick Jonk
Marc Beekman	Roel Horeman
Kanvi Parekh	Constantijn Molengraaf
Mark IJspeert	Leon Wubben
Senja Ramakers	Lieuwe Stek

BSc	
Thom Fronik	Kamiel Dankers
Reinier de Bruin	Tumi Aluko
Michael Chan	Jildou de Jong