Munich Quantum Valley

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Introduction

Although computers have become more and more compact and powerful over the past 50 years, there are still many problems that even the most sophisticated machines cannot solve. Transistors, the fundamental switching and storage components of computers, are currently getting close to the size of atoms, and we are approaching the point where the laws of classical physics are likely to put an end to Moore's Law. To create machines that are more powerful than the ones we already have, we need to use a fundamentally different method of data processing. Quantum computing is considered one of, if not the next, disruptive technology that has the potential to change the way organizations and businesses in various sectors operate. The field of quantum computing has developed rapidly in recent years. Many countries and digital corporations around the world have either announced new or expanded their existing quantum technology initiatives and have pumped significant resources into these ecosystems. The primary focus of such initiatives has been to harness quantum materials that manifest unique quantum effects, such as superposition and entanglement and exploit them to perform complex computing. While superposition is the ability of a quantum system to coexist in complementary states, i.e., in states which are mutually exclusive according to classical understanding, entanglement describes the behavior of quantum systems which do not act as separate systems anymore. An action on one of the systems can instantly affect its entangled "partners". Thereby, no kind of classical interaction occurs.

By definition, a quantum computer is thus a machine that uses the properties described by quantum physics to solve certain complicated computational problems within a reasonable time frame, ideally with an exponential improvement in speed over today's computers. As a result, the field of quantum information science and technology has emerged to find answers to the question of whether it is possible to achieve a benefit or "quantum advantage" over classical computation by storing, transmitting, and processing information encoded in quantum systems that exhibit distinct quantum behavior.

Munich Quantum Valley (MQV), funded by the Bavarian State Government's "Hightech Agenda Bayern Plus" program, establishes quantum-computing capabilities and provides quantum-technology expertise in Bavaria for research and development activities and general applications in industry and society. MQV brings together leading scientists from universities and research institutions, namely the Bavarian Academy of Sciences and Humanities (BAdW), the Fraunhofer-Gesellschaft (FhG), the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), the German Aerospace Center (DLR), the Ludwig-Maximilians-Universität München (LMU), the Max Planck Society (MPG) and the Technical University of Munich (TUM). MQV encompasses Bavaria at large. Important research clusters in quantum technology that complement the activities at the MQV member institutes are also located in Augsburg, Bayreuth, Regensburg and Würzburg.

The primary goal of MQV is to develop and operate competitive quantum computers in Bavaria. Further main goals are:

(a) Establishment of a center for quantum computing and quantum technologies in Bavaria through application-oriented R&D activities, the promotion of lighthouse projects and the transfer of results and technologies to industry.

(b) Realization of a quantum technology park, i.e. creation of the necessary technical infrastructure for the development and production of quantum devices and applications of quantum technology for industry, which should be accessible in particular to start-ups.

(c) Establish dedicated teaching, entrepreneurship, and outreach activities to create a quantum workforce and the next generation of quantum experts.

In the broadest sense, a classical computer can be understood as a machine that reads a certain amount of data encoded as binary bits (0s and 1s), performs calculations, and then outputs data again as 0s and 1s. Unlike a classical computer that works with binary bits, a quantum computer works with quantum bits (qubits). From the perspective of quantum physics, a qubit can be understood as a two-level system in which quantum information is stored. A qubit can be as simple as a single photon, electron, or ion. The distinctive property of a qubit is its ability to exist in either of two discrete states, 0 or 1, as well as in a coherent superposition of the two states. This unique property could allow quantum computers to have more memory capacity and higher computing power than classical computers.

Building a quantum computer requires the fabrication of qubits in well-defined quantum states with high fidelity, i.e., the actual state must closely resemble the intended state. The interactions between the qubits must be precisely controlled to carry out logical operations, and finally, the resulting states must be accurately determined to obtain the computational result. Since the qubits are very sensitive, all of this must be achieved while maintaining near-perfect isolation from the environment to prevent decoherence of their fragile quantum states. Decoherence refers to the interactions that a qubit experiences with its environment that lead to perturbations, such as the breakdown of the superposition of qubits and thus errors in quantum information. Many factors can contribute to the decoherence of a qubit, such as changing magnetic and electric fields in the environment, radiation from a nearby warm object, or unwanted crosstalk between neighboring qubits. To implement quantum code reliably, i.e., to build a so-called "general-purpose" quantum computer, quantum error correction must be integrated into the memory and gate operations of the qubits.

Researchers from all over the world have made enormous efforts to create systems with entangled qubits that meet all stringent technical requirements. As far as hardware for quantum computing is concerned, a few physical platforms have emerged as major contenders. These include trapped ions, superconducting circuits, neutral atoms, photons, quantum dots, and spins in solid-state hosts. Each of these platforms has demonstrated the ability to perform basic quantum-logic operations, with varying degrees of accuracy. Long coherence times and the ability to be stored in huge arrays make e.g. neutral atoms or trapped ions an ideal candidate for "quantum memory", while e.g. superconducting circuits or semiconductor quantum dots have the advantage of tailored properties and could be advantageous as "quantum processing units". However, a multitude of challenges remain. Key challenges include the scaling of existing systems to tens and hundreds of qubits, improving the precise controllability and manipulation of qubits (and minimizing decoherence), or performing operations with many gates (the logical operations performed on bits or qubits). In parallel with the development of quantum hardware, incredible progress has also been made in the field of quantum software and the development of quantum algorithms in recent years. Currently, we are in the realm of noisy intermediate-scale quantum (NISQ) computers, a term coined by John Preskill of the California Institute of Technology and referring to systems that do not yet have full error correction (i.e., are noisy) and have tens to thousands of qubits.

Since there is currently no clear winner for a unique strategy for quantum computing, MQV's quantum computing research encompasses three hardware platforms: superconducting qubits, neutral-atom qubits, and trapped-ion qubits – each with different characteristics and advantages for different use cases to ensure that the mutual benefits cross-fertilize when it comes to developing scalable platforms. The realization of the envisioned quantum computers will be addressed in a "full-stack" approach, with multidisciplinary consortia developing all layers of a quantum computer, from hardware and software to applications.

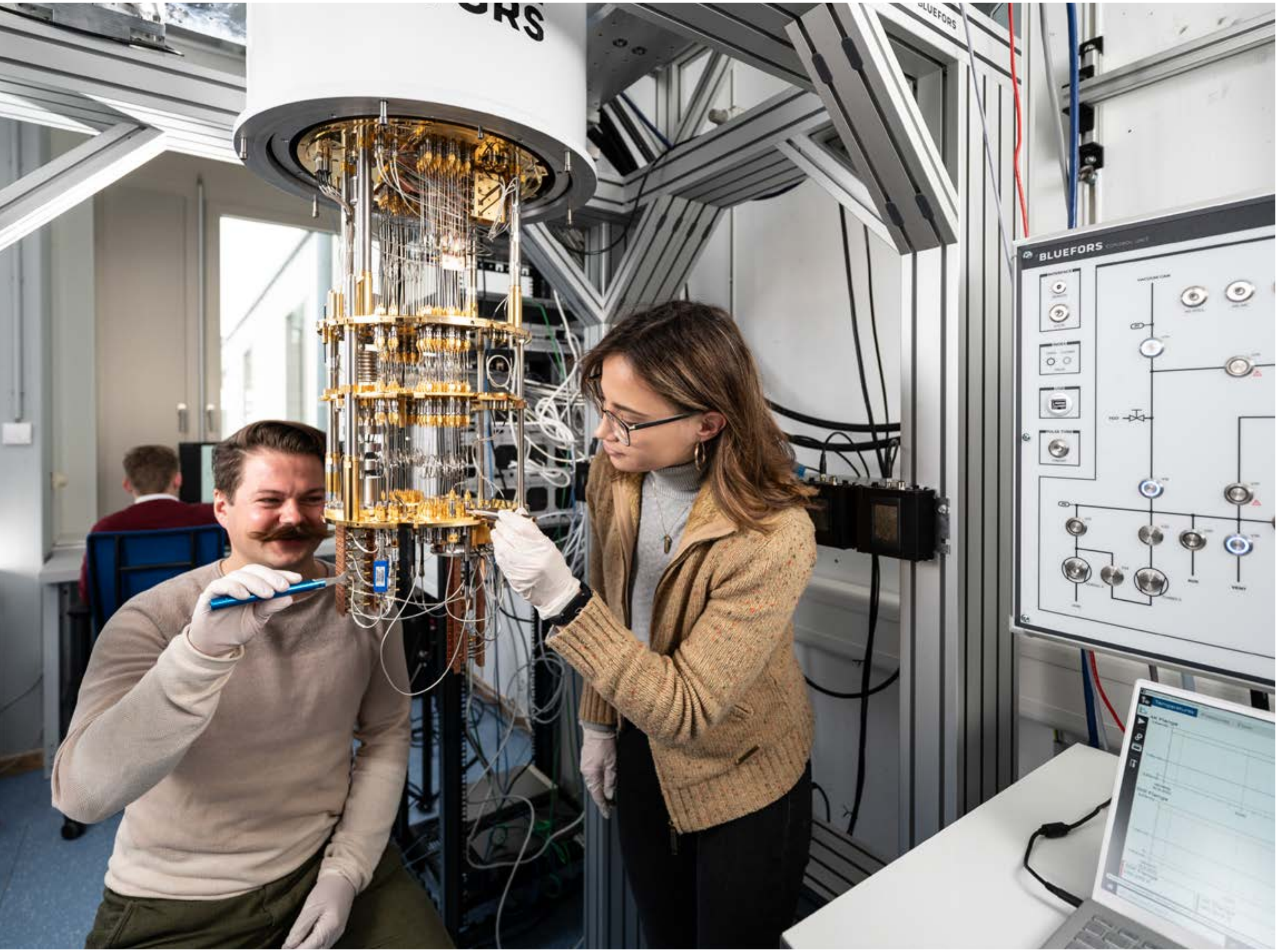
The Superconducting Qubit Quantum Computer (SQQC) consortium will provide superconducting systems known for their design versatility and excellent controllability. The Trapped Atom Quantum Computer (TAQC) consortium will provide neutral atom systems known for their potential to scale qubit registers and their high fidelity of entanglement. Trapped-ion systems have already demonstrated excellent performance and capability for integration into classical computing setups. As part of MQV, scientists will leverage years of experience with this hardware technology to use it as a testbed for integrating a quantum computer into a supercomputing environment. The Scalable Hardware & Systems Engineering (SHARE) consortium will provide the classical control technology needed for device scalability, such as fabrication of scalable integrated chip technology (superconducting quantum devices for SQQC, chip traps for TAQC, and fast electronic control for both). The Quantum Development Environment, System Software & Integration (Q-DESSI) consortium will integrate software stacks, create a comprehensive programming and runtime environment, and integrate quantum computing into high-performance computing (HPC) environments. The Quantum Algorithms for Application, Cloud & Industry (QACI) consortium will provide the tools, services and resources necessary for user training and integration. At the theoretical level, the Theoretical Quantum Computing (THEQUCO) consortium will develop hardware-independent theoretical foundations of quantum computing, while the Hardware Adapted Theory (HAT) consortium is tasked with platform-level quantum control and platform-level quantum error mitigation and quantum error correction. Thus, a holistic approach is taken where software engineering interfaces with the hardware-related tasks and connects them to the high-level application.

The first year in the consortia

Superconducting Qubit Quantum Computer (SQQC)

Superconducting qubits are one of the most prominent candidates for quantum processors. Their high technology-readiness level, their fast operation speed in combination with relatively long life-times and their potential for scalability single out superconducting quantum devices as promising way for industrial efforts worldwide. By now, this has led to the successful demonstration of a variety of quantum algorithms ranging from quantum chemistry simulations to machine learning tasks on those platforms. The main goal of the SQQC consortium is therefore to develop the relevant technology to operate advanced superconducting quantum processors within MQV: A five-qubit demonstrator is planned within the first two project years and access to a 24-qubit processor will be provided after five years. These processors will allow to execute proof-of-principle algorithms and enable the demonstration of basic principles of error correction schemes, relating to the theory and algorithmic developments within MQV.

The SQQC consortium aims to improve materials and fabrication processes to provide superconducting qubits with enhanced coherence times. Moreover, the consortium explores alternative ways to realize superconducting qubit architectures, which avoid current challenges related to unwanted interactions and loss of quantum information. Within the first year of MQV, SQQC has focused on setting up the infrastructure required to reliably operate a superconducting quantum computer. Since superconducting qubits are sensitive to room-temperature radiation, the system must be brought to very low temperatures, both for the operation as a quantum computer but also for analyzing and improving the qubit properties. SQQC has therefore set up a cryogenic measurement apparatus that enables fast testing of key components at 10 millikelvin, a temperature more than a hundred times colder than outer space. A second system has been equipped with the required control electronics to operate up to ten superconducting qubits. In combination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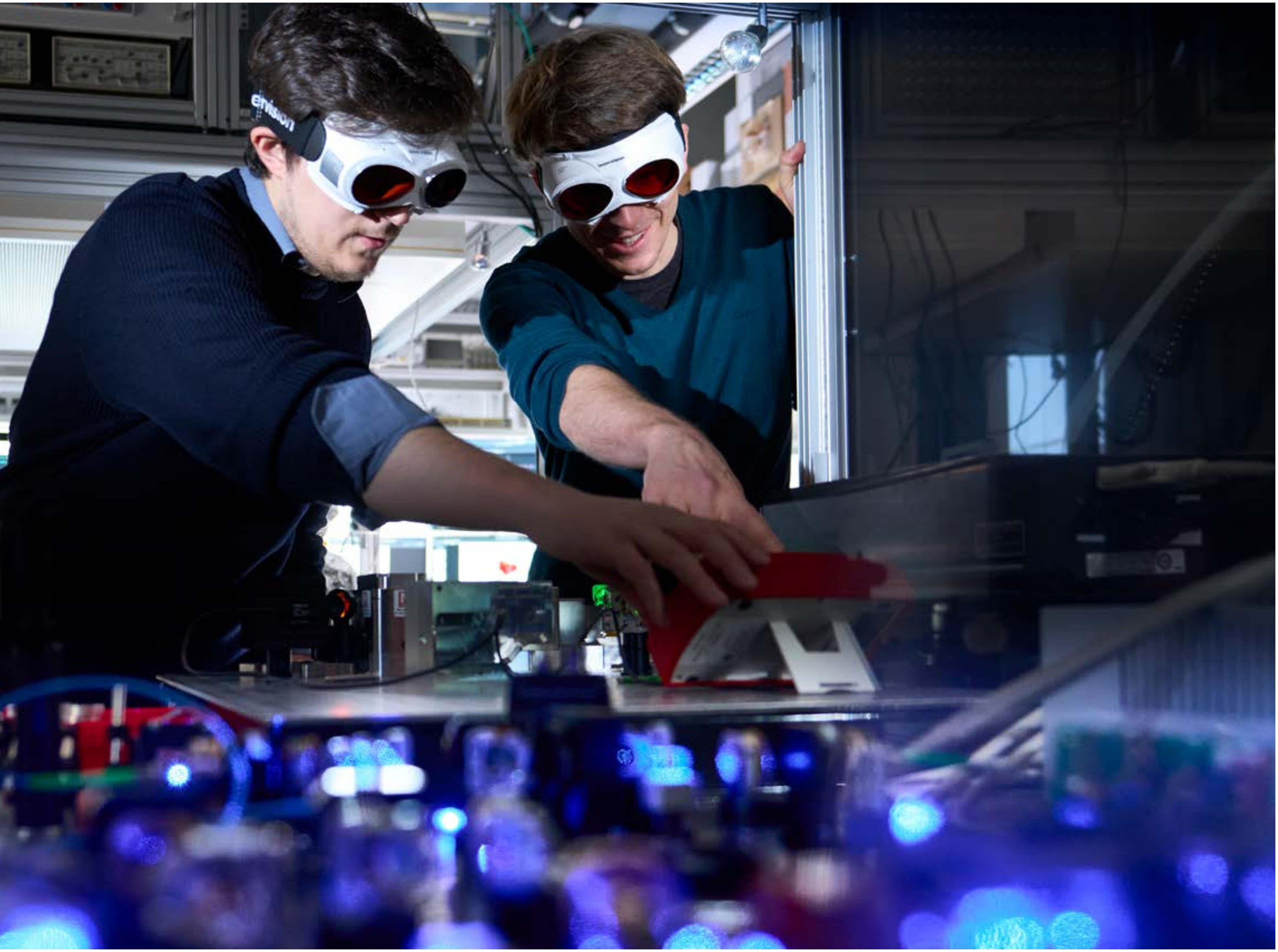
with the ongoing developments of scalable control software, SQQC could already demonstrate single and two-qubit operations with low error rates.

To further improve the quality of operations, the SQQC consortium is investigating losses at material interfaces as a dominant error source for the quantum processors. For example, when exposing the superconducting metal, which forms the qubit, to air, surface oxidation significantly reduces the lifetime of the quantum states. By developing cleaning processes, impurities can be avoided and subsequent coating of the surfaces ensures that the material interfaces do not degrade over time. By optimizing these processes at the cleanroom facilities at the Walther-Meißner-Institute (WMI), SQQC could reach relevant breakthroughs and quintuple the quality factors, a typical measure for robustness against loss, of superconducting quantum circuits up to almost five million. This corresponds to a lifetime of a quantum state of more than 150 micro seconds, a factor of ten thousand longer than the duration of typical logical operations, so-called gates, on the qubits. This surpasses a first milestone of MQV.

One of the most intriguing features of superconducting qubits is their flexibility in design. As each quantum processor is individually fabricated, this opens up the possibility to design novel types of qubits with improved properties. In parallel to standard qubit architectures, WMI has therefore realized an alternative qubit-type, the so-called fluxonium, that provides a very high potential for a scalable architecture. Moreover, the FAU has started modeling elements for other qubit architectures, which may lead to intrinsically robust qubit designs with even lower error rates. To tackle the challenge of measuring a large number of qubits, TUM is developing devices that improve speed and quality of measuring quantum states. These devices are based on novel quantum materials that allow signal currents to traverse only in one direction, an essential feature to efficiently gather information about the qubit state while protecting it from the influence of noise. Together with broadband amplifiers which enhance the microwave signals, used to address the qubits, without adding extra noise to it, these devices will allow for the simultaneous measurement of all qubits with high fidelity.

The work in the SQQC consortium is complemented by the BMBF-coordinated project Munich Quantum Valley Quantum Computer demonstrators – Superconducting Qubits (MUNIQC-SC) with its focus on scalability of superconducting quantum processors. The key innovation directions are the development of a qubit fabrication technology that is suitable for industry in terms of process chains to reliably fabricate low-error-rate qubits in large quantities. Its final goal is to scale the current devices with few qubits up to setups with 100 or more qubits within the next five years and to make them available to a broad audience by the means of cloud access. Hence, the main objectives of MUNIQC-SC well align with those of the SQQC consortium and spark fruitful information transfer between all consortia and partners.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Trapped Atom Quantum Computer (TAQC)

The TAQC consortium, formed by Max Planck Institute of Quantum Optics, LMU, Fraunhofer Institute for Integrated Circuits and the University of Heidelberg, aims at constructing the hardware for a quantum computer based on neutral atoms. The main advantage of this hardware technology is the potential of scaling to larger numbers of qubits already in the coming years. In the TAQC approach, the basic calculation unit of the quantum computer, the qubit, is stored in two different quantum states of a strontium atom. The atoms hover in almost perfect isolation from the environment inside an ultrahigh vacuum, where they are positioned in so-called optical tweezers. These optical tweezers can be imagined as tiny traps for the atoms, which are created by tightly focused laser beams. These traps fix the position of the qubits tightly during operation.

To perform calculations, the qubit states are manipulated using laser beams impinging on the atoms. These beams are generated from highly sophisticated lasers, which are among the most coherent light sources that can be built. They are delivered to the atoms through extremely precise microscope objectives, which allow focusing the light to spots a few hundred nanometers small – close to the fundamental limit allowed by the laws of physics.

In order to create the entanglement that underlies all quantum algorithms, the atoms in the TAQC technology are excited to high-lying states, so-called Rydberg states. Such Rydberg states can be thought of as inflated states of the atoms, which as a result feature very strong interactions over large distances. This means that two atoms promoted to their Rydberg states can feel each other's presence even if they are far away from each other. Consequently, these states have long been discussed as valuable tools to realize controlled atomic entanglement. For a working neutral-atom quantum computer, all of the above technologies have to be mastered and optimized.

The first year of the core effort within the TAQC consortium has been focused on the detailed planning and construction of the sub-systems that eventually will be assembled to become a digital quantum processor for neutral strontium atoms. Here, “digital” means that the quantum processor executes discrete sequences of laser manipulations on the atoms, which form quantum gates. Particular emphasis was put on those aspects that will eventually allow to build a usable device that can be accessed externally. In particular, the TAQC consortium aims at improving the technology readiness level of devices that have already been demonstrated in its quantum optics labs for basic academic research, while at the same time it also aims at further developing and tailoring them for constructing a quantum computer. One of the most important steps for the quantum computer is a more robust design: Right now, all machines in operation require a few highly trained PhD students or postdocs to be maintained. Eventually, these machines should be able to run completely autonomously and be controllable by remote users. Furthermore, TAQC wants to standardize more modules, which will allow for a more dedicated development effort of individual sub-modules.

TAQC developed a customized and standardizable vacuum apparatus, in order to protect the strontium atoms from all external influences. To allow for a scalable processor, the atoms must be placed in an ultrahigh vacuum environment that contains even fewer remaining atoms per unit volume than outer space. TAQC also carefully selected laser systems that fulfill the stringent requirements on spectral quality as well as level of integration. Contrary to the method of assembling sub-modules formed by dozens of mirrors on large optical tables, TAQC carefully works towards constructing specialized modules. Both the lasers and also the planned optics modules are fully compatible with the integration in a standard 19" rack, a type of enclosure also found in modern supercomputing centers. Along the lines of integrating more and more of the setups, the consortium also started a joint development on so-called “integrated optics”. This technology will allow, in the long-run, the integration of much of the presently used technology on dedicated chips, which can route and switch light with unprecedented flexibility and speed. As such, it is another very important step towards the miniaturization and modularization of neutral-atom quantum-computing hardware.

Finally, an important part of the work within the first year has been to identify interfaces between the different consortia within MQV, which have the goal to connect the hardware developments all the way through the full stack with the users, which will obtain access to TAQC hardware as soon as it is fully operational. Along these lines, the TAQC consortium has established collaborations with the Fraunhofer-Gesellschaft as well as the Leibniz Supercomputing Centre in order to develop novel control hardware for a trapped-atom quantum computer as well as a general access portal, which will be the gateway for external users to use the quantum computer developed within MQV.

In development efforts separate from the main one to build a digital quantum processor, TAQC aims to explore alternative strategies to exploit entanglement generated between tweezer-trapped atoms, and to make entanglement generated in the devices more immune to external perturbations, such as electrical or magnetic fields. Two alternative applications for exploiting entanglement encompass an alternative approach to quantum computation that is analog, rather than the more conventional digital approach, as well as the realization of novel, “quantum-enhanced atomic clocks”. In analog quantum computation, the goal is to emulate the behavior of complex quantum systems in an analog fashion rather than using a digital, gate-based sequence. In an already existing experimental setup, the consortium was able to trap and image more than 240 single strontium atoms, which form the basis of these analog quantum simulators. In a next step, the system will be controllably excited to Rydberg states, which is required to create entanglement in the system and perform simulations. In order to explore approaches to better protect quantum information against external influences, the TAQC consortium has begun to build a quantum-computing platform based on ytterbium atoms. In this element, the quantum information can be stored in spin states of the atomic nucleus, where the outer electrons shield any external influences and thus render the qubits extremely stable. Eventually, it may well be that a combination of the above technologies will be the one that can realize the full potential of neutral-atom quantum computing.

The TAQC activities are complemented by the BMBF-funded MUNIQC-Atoms project, which has the goal to significantly scale the qubit numbers achievable in neutral-atom quantum processors to more than 400 qubits using optical lattices. MUNIQC-Atoms includes the required technical developments in a consortium of 18 partners, whose joint expertise will pave the way for the future scalability of neutral-atom quantum processors.

Theoretical Quantum Computing (THEQUCO)

On the way to a competitive quantum computer, many fundamental questions arise on the theoretical level. These include the question of usefulness and usability of certain noisy quantum device as well as to what extent and for which problems can a quantum computer be more powerful than a classical computer?

First prototypes of quantum computers have been built and demonstrated in various labs worldwide. However, the quantum devices we have today and that will be built in the near future are not perfect. Due to their inherent sensitivity to external disturbances and influences, qubits are not stable and quickly lose the quantum properties one wants to exploit during computation. That ultimately leads to noise and errors on their manipulations. This raises more questions: Can we characterize the noise that is present in the devices? How does it affect the computational power? Provided the error rate is low enough, one can use certain error correction schemes, ultimately leading to a fault-tolerant quantum computer, that is, a quantum computer that delivers usable and reliable results despite occurring errors. For such a quantum error correction, several physical qubits are usually combined into one logical qubit. If the state of a physical qubit is unintentionally changed by occurring errors and its quantum information therefore lost, the information can be restored using the redundant information in the other qubits. However, the operations for correction themselves must also be corrected. Therefore, a full error correction requires, besides low noise levels, a significant overhead in the number of qubits. This is currently out of reach for near-term devices. Are there better schemes for error correction? And how can we make the algorithms robust to noise? Various groups in the THEQUCO consortium address such questions as raised above on a theoretical level, mostly independent of the actual platform. In the following, some of the results of the past year are highlighted.

A detailed understanding of noise processes in a physical system is a basic requirement for quantum fault-tolerance. Traditional methods such as process tomography – known quantum states are prepared as input to the process and measured afterwards to find out how the process can be described – are experimentally costly and the necessary steps “state preparation and measurement” are themselves subject to errors. Moreover, the traditional methods do not provide a mathematical model that can be used to predict a device’s behavior at different evolution times. A newly proposed procedure overcomes this difficulty and automatically produces a mathematical model for the evolution of the system from experimental data. At TUM this tool has been refined to make it resilient to noise in both initial state preparation and measurement. This provides a universally and easily applicable method for gathering information about noise processes trough experimental observations. Such information serves as the basis for the design of suitable error-correction procedures.

By utilizing both so-called quantum-control and quantum-resource theory, researchers at TUM investigated how time evolution can result in certain target states through coherent control operations plus switchable couplings to a thermal resource. The formal framework for addressing these types of engineering questions is meant to be part of the emerging quantum version of a systems theory that provides the underpinning for training “quantum engineers” in the near future.

Members of the Max Planck Institute of Quantum Optics analyzed the behavior of a quantum computer when it is simulating the dynamics of a many-body quantum system in the presence of some error rate. They showed that above some value of the error rate, it is possible to simulate the quantum many-body system very efficiently with classical computers, and thus quantum computers do not offer a big advantage. In contrast, below some other value the quantum advantage still remains for some specific many-body systems. The precise value of the error rate for which all this occurs depends on the geometry of the quantum computer. In summary, their results show that there is a transition in how well a quantum computer performs in simulating complex systems depending on the error rate.

As mentioned above, the long-term goal is to correct the errors, just like any ordinary computer does, where the error rates are however many orders of magnitude smaller. In this active research area, one tries to increase the threshold below which error correction is physically feasible. Exploring error-correction codes that can correct for higher error rates is closely related to the study of quantum phases of matter. A particularly interesting and unexplored set of models, which provide examples of novel quantum phases of matter, are so-called fracton models. At LMU it was found that a prime example of such a fracton-based error-correction code displays a minimum error threshold that is much higher than for codes that are currently considered the most promising ones. They conjecture that there is further room for improvement within these models.

Meanwhile, a common strategy used on present day quantum computers is to directly prepare certain target states of interest, for example quantum ground states of various condensed matter systems. To achieve this, one can variationally optimize a parametrized gate sequence. Since already short gate sequences can generate states with very strong quantum correlations, such variational gate sequences are promising candidates for near-term quantum algorithms. As a specific example, at FAU it was shown that the gate sequences needed for preparing the ground state of a certain quantum spin model, which is known to be extremely challenging to calculate classically, can be shorter than one might guess at first. It was demonstrated that the expected growth of gate number with system size is moderate, making the model an ideal candidate for targeting quantum advantage in ground-state preparation.

The study of quantum phases of matter is central to different research fields within quantum sciences. So-called Quantum Convolutional Neural Networks (QCNNs) have been introduced as classifiers for a certain kind of quantum phases of matter. Researcher at TUM proposed a model-independent protocol for training QCNNs to discover order parameters which are used to describe phase transitions in a physical system. Their protocol paves the way toward hardware-efficient machine learning of quantum phase classifiers on a programmable quantum processor.

Quantum Development Environment, System Software & Integration (Q-DESSI)

The Q-DESSI consortium focuses on developing a comprehensive software stack for quantum computing. The consortium is led by the Leibniz Supercomputing Centre (LRZ) and also includes several research groups at TUM and LMU. The software is targeted to be open source (where possible) and contains all needed components, including the compilation and transpilation chain with extension for optimization techniques, the runtime and scheduling environment, as well as the needed integration of quantum computers into high-performance computing environments (HPC–QC) to enable quantum acceleration in the form of hybrid HPC–QC applications.

On the application side, the software stack is designed to support a wide range of users. This includes the applications developed within the QACI consortium as well as associated projects, like the federally funded QuaST and the Bavarian project BayQS. Further, the software stack will support LRZ's wide user base across all its current and future quantum-computing systems, from users at Bavarian universities to the European EuroHPC user community.

On the hardware side, the developed software stack is targeted towards the hardware work in the consortia SQQC and TAQC, the developments of control hardware in the SHARE consortium as well as Q-DESSI's own control processor developments. Additionally, the Q-DESSI stack also targets the German and EU quantum-computing systems at LRZ, i.e., the federally supported Q-Exa and the EuroHPC quantum-computing system Euro-Q-Exa. Further, LRZ leads several EU-wide integration efforts, which will also build on the ideas and concepts of the MQV software stack in Q-DESSI.

The work in Q-DESSI is split into four main areas: First, the programming environment, including quantum compilers, runtime and development tools, all implemented as part of a generalized framework that can then be extended using plugin mechanisms both for high-level optimization and template extensions, as well as for low-level transpilation passes. Second, the runtime and execution environment, including the necessary system software to enable management, monitoring and scheduling of quantum-computing resources, providing the necessary interfaces for users, administrators and facilities to enable quantum-computing usage in production. Third, the development of novel hardware control, including the development of an architecture to execute quantum control programs, which can be integrated as part of quantum computing systems, as well as the needed firmware. Forth, the integration of quantum computing into the HPC ecosystem and the ability for hybrid usage, encompassing many aspects from the physical connection between systems, to the software setup for distributed control, a common scheduling environment as well as approaches for hybrid programming approaches.

Additionally, a goal of Q-DESSI is to establish a laboratory and test environment as part of the MQV Quantum Technology Park (QTP). This test environment is being established at LRZ's Quantum Integration Center (QIC), bringing quantum technologies into the data-center environment. This laboratory will offer multiple quantum technologies – currently planned are superconducting and ion-trap technologies – coupled with an HPC testbed, itself heterogeneous with multiple accelerator technologies. Q-DESSI will have full (root) access to all system, which will enable not only the direct use of both systems, but also reconfigurations of key components like the system scheduler.

In the first year, Q-DESSI has already made significant advances, from novel techniques for circuit optimization and verification, to investigation of new programming models for hybrid operations, and from the establishment of initial laboratory support with a first superconducting quantum-computing testbed almost in operation in the LRZ QIC alongside first HPC resources, to the establishment of new scheduling and operation methodologies for hybrid HPC–QC systems. The latter included the development of a novel scheduling simulator capable of covering HPC–QC integration needs. Additionally, significant work went into the definition of the software stack, its components and the needed interfaces.

The work from Q-DESSI has been published in several papers as well as presented in numerous talks at conferences and outreach events. Further, members of the Q-DESSI consortium co-organized several international events, including the ARCS computer architecture conference, held in September 2022 at the TUM campus in Heilbronn with the theme "Quantum Computing: The Dawning of a New Age?" as well as two well-received workshops on HPC–QC integration at IEEE Quantum Week in October 2021 and September 2022.

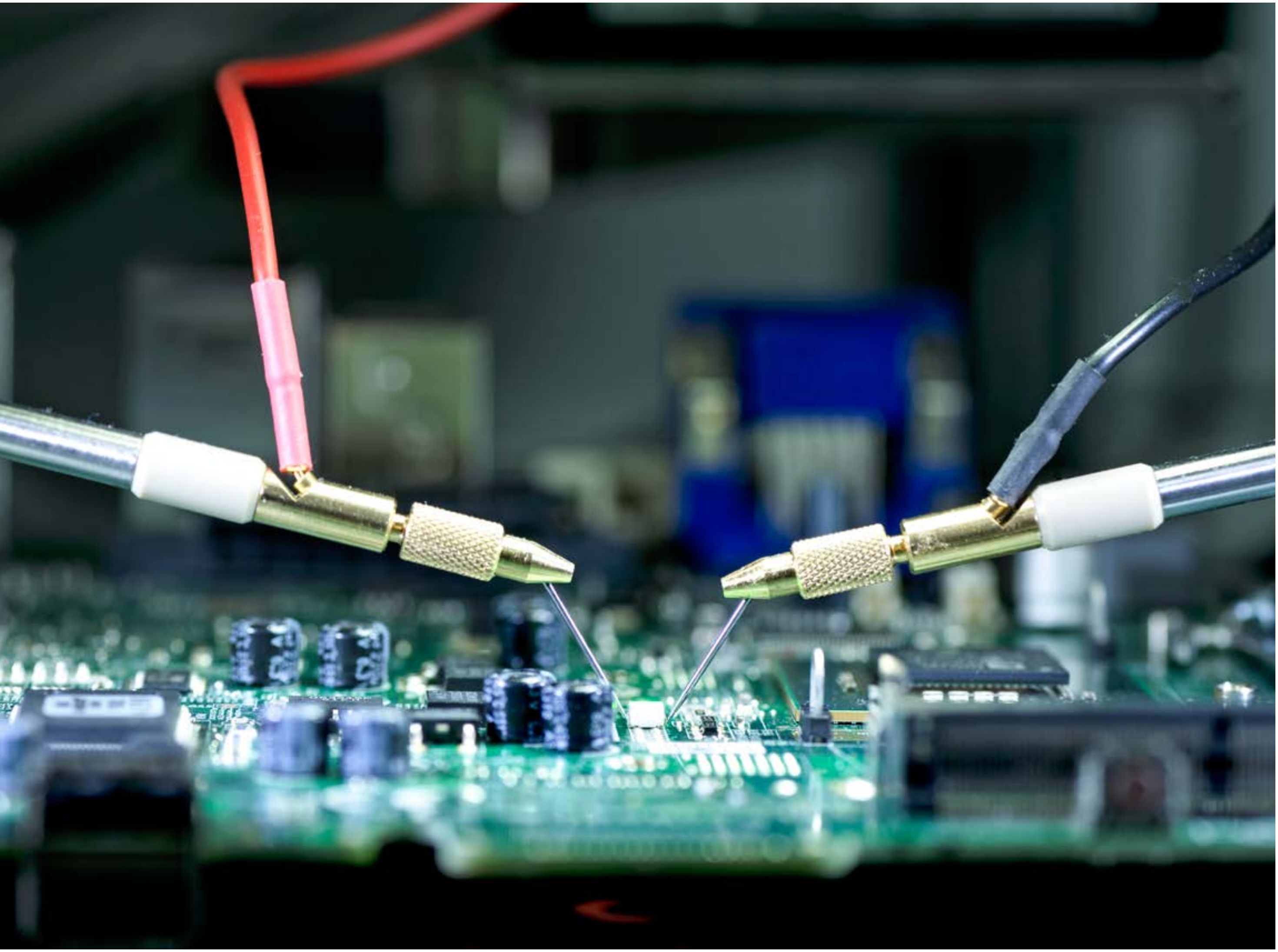
Scalable Hardware & Systems Engineering (SHARE)

The SHARE consortium unites three Fraunhofer research institutes and two universities. In close collaboration with the hardware-platform consortia SQQC and TAQC, SHARE develops electronic systems and qubit devices as well as scalable manufacturing processes for superconductive qubit systems. SHARE works towards establishing a silicon-based pilot line for manufacturing and integration technologies required for scaling and industrializing quantum computing hardware for superconducting qubits as well as scalable electronics needed for the control of trapped-atom qubit systems.

The work of SHARE aligns along two central tasks: (i) the development of electronic components and systems as well as (ii) providing semiconductor technology and integration for functional and scalable quantum-computing hardware.

The partners for the first task (i) started the intensive work for the architecture-definition for the SQQC and TAQC consortia. The elaborated document represents the requirements for transmon and neutral-atom-based qubit technologies. The derived high-level requirements and the architecture serve as guidelines when breaking down the development work and deriving the sub-block specifications which will be designed, implemented and deployed on the test-sites during the project. The document was worked out stepwise with the specialists of the partners and finally reviewed by the Walther-Meißner-Institute within SQQC. This first version of the document will be further revised once new findings and technological decisions require new and more detailed aspects.

As electrical material parameters are unknown for cryogenic temperatures, an electromagnetic-simulation



model was established at the Fraunhofer Institute for Integrated Circuits (IIS). This is to gain a reliable prediction about the expected parameters of the whole radio-frequency chain, such that signal crosstalk, loss and reflections can be reduced to a minimum. A shielding chamber housing for the neutral-atom qubits was designed and a compatible simulation model established to address these issues.

Fraunhofer IIS looked into radio frequency digital-to-analog converters as one key element controlling superconducting transmon qubits and required to operate at 4 Kelvin. A dedicated model was developed and design parameters were derived to achieve a better understanding of the behavior of cryogenic transistors. At the same time, the frequency synthesis performance has been analyzed and the Fraunhofer Research Institution for Microsystems and Solid State Technologies (EMFT) made first feasibility-studies. Circuit-level simulations have been carried out for the phase-locked loops, which is a control system that generates an output signal whose phase is related to the phase of an input signal.

FAU works on High Fidelity Control Electronics for cryogenic temperatures. With literature research regarding topologies operated at temperatures a fraction of a Kelvin, possible basic building blocks for the control of superconducting qubits were identified and they started the integrated-circuit design of these building blocks at room temperature. Using specialized simulation techniques developments of a dedicated monolithic microwave integrated circuit, a type of integrated circuit device that operates at microwave frequencies, have started.

The Fraunhofer Institute for Integrated Systems and Device Technology (IISB) develops and tests efficient amplifiers for qubit readout. Test structures for new low-noise amplifiers operated at 4 Kelvin were designed and the tape-out is planned in the near future.

In the first year the partners for the second task (ii) around Fraunhofer EMFT focused on the transfer from research to industry-like processes and facilities. Here, Fraunhofer EMFT successfully developed and fabricated superconducting aluminum resonators on 200 mm wafer scale, achieving state of the art quality factors in the single photon limit. Additionally, Fraunhofer EMFT carried out concept studies regarding the hetero-integration of superconducting qubits. Especially the simulation of characteristic properties of “3D qubits” will be built on in the next project phase.

A scientific highlight of the Fraunhofer EMFT has also been the realization of a roll-to-roll process. With this process, first prototypes of planar flexible cables consisting of a niobium metal sheet on a polyimide substrate have been manufactured, turning super-conductive at around 7.5 Kelvin. Future development is targeting the realization of 100 cable connections per inch.

TUM investigated promising alternative materials for qubits. Here the successful fabrication of resonator test structures has been realized via wet chemical and dry plasma etching processes. A further promising result has been the deposition of organic self-assembled monolayers towards surface passivation.

At the Walter Schottky Institute (WSI) from TUM the possibility to structure materials on an atomic level leading to fundamental physical properties of atomistic 2D materials with a specific focus on semiconducting nanomaterials has been explored. The research focused on single-atom circuits for a microwave-to-photon quantum transduction architecture. Additionally, WSI focused on the heterogeneous integration of novel 2D-semiconductors and their heterostructures into hybrid photonic and superconducting quantum circuits. The research aimed to simultaneously couple ensembles of atom-scale and optically active paramagnetic centers to photons in the visible and microwave regimes (quantum transduction). Finally, WSI developed ultrasensitive techniques to observe, microscopically identify and quantify paramagnetic defects and their detrimental effects on transmon qubits via spin-dependent transport processes. A reduction in the magnetic resonance signal was observed upon organic functionalization of the silicon substrate, treatment in HF removes the surface dangling bonds completely.

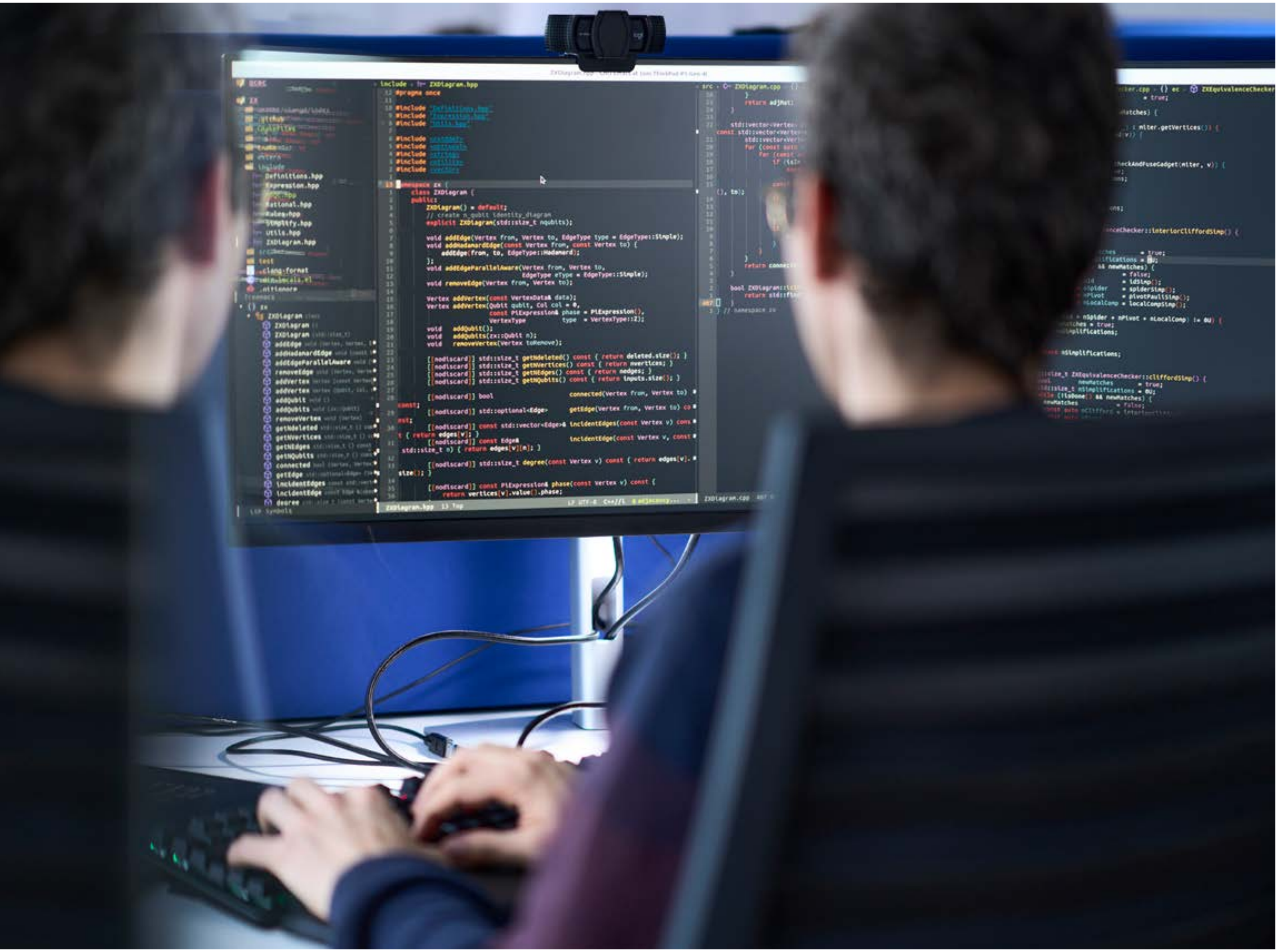
SHARE's combined efforts have resulted in several publications in high-impact peer-reviewed journals, scientific lectures, and posters. SHARE has also taken part in a number of workshop events, outreach initiatives, and hosted a workshop during the past year.

Quantum Algorithms for Application, Cloud & Industry (QACI)

The QACI consortium is one of the consortia most directly interfacing with the end users of quantum computing. It is the mission of the QACI consortium to provide users in academia and industry with all the knowledge, tools, services, and resources needed to solve their application problems on one of the full-stack quantum computers jointly developed by MQV consortia. This mission rests on three distinct pillars or central tasks the consortium hopes to achieve. Firstly, the identification of relevant industry use-cases, the subsequent prototypical implementation of suitable quantum algorithms along with a critical evaluation with respect to key performance indicators relevant to the users. Secondly, QACI seeks to develop supporting software tools and processes to enable also non-expert end users to implement and solve their quantum-computing application problem themselves, in a way that is very natural to their respective problem domain. Finally, the third central task is about providing infrastructure access to quantum-computing hardware and high-performance simulators along with user support and training.

The first project year of QACI has been dominated by recruiting and building the project team while kicking off the work packages and establishing collaborations and projects within the MQV family.

For the first central task, the industry use cases, a lot of work went into identifying use-cases within the focus areas of the respective partners and matching them suitable quantum-algorithm classes. Within the identified application areas, literature research has been completed, re-implementation and initial analysis of published algorithms have been done and the evaluation of simplified datasets and problems has been started. Most of the use cases considered within QACI are related to applications of quantum machine learning while, for example, optimization problems



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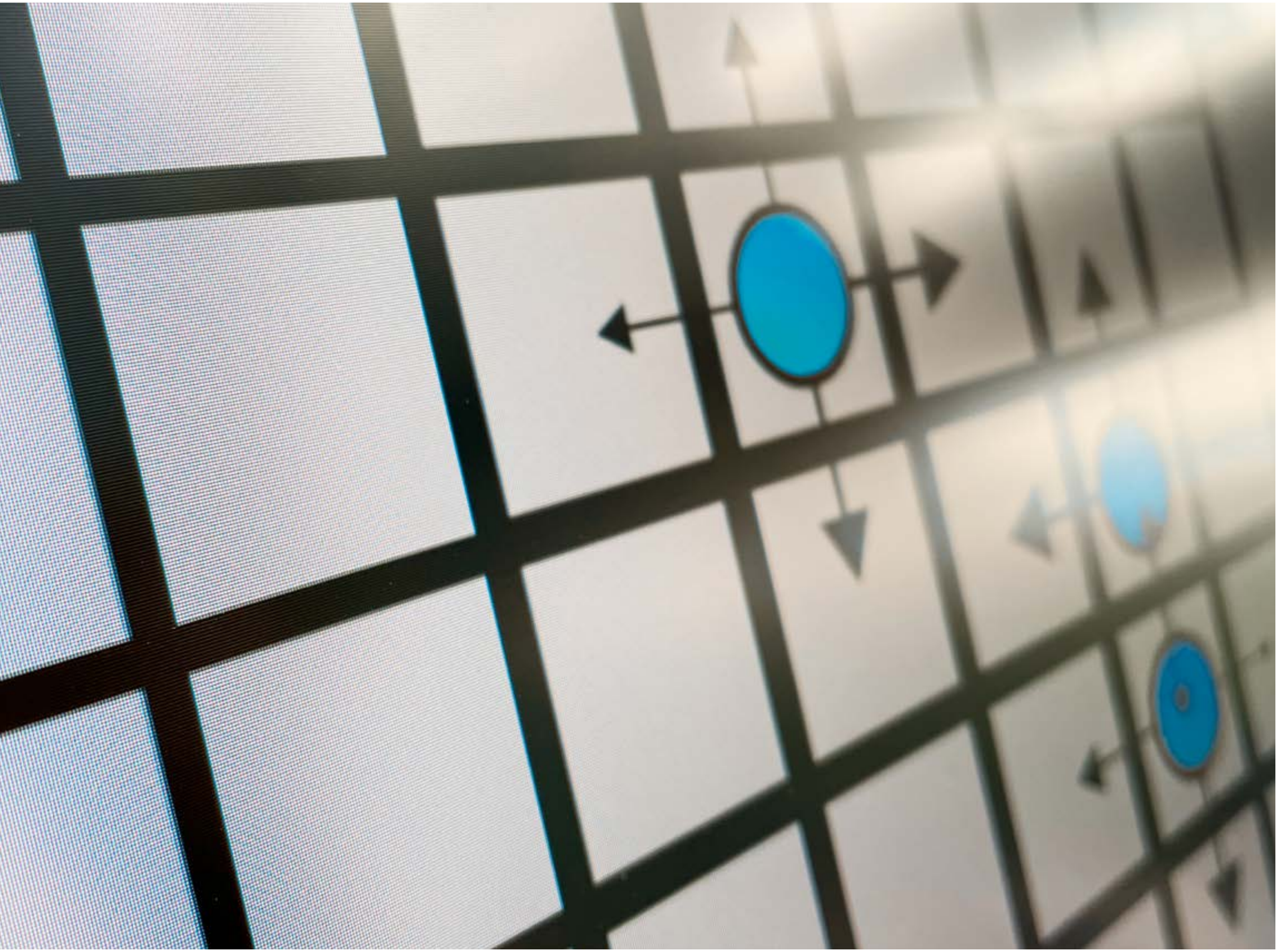
are considered in associated projects like QuaST. The machine-learning problems covered by QACI range from application of predictive maintenance in production, anomaly and fraud detection in the finance and insurance industry to applications in medical diagnostics or robotics. For these applications speed-up is not the only potential quantum advantage that should be considered. Also quality and reliability of the obtained solution or the amount of necessary training data are relevant benchmarks. Various interdisciplinary topics have been identified relating, for example, to the problem of encoding classical data in a quantum circuit. Notably, this resulted in a deeper technical exchange with the THEQUCO consortium bringing together current state-of-the-art methods in data encoding in quantum machine learning and numerical techniques from many-body-physics.

In the second central task, concerning tools and processes, much of the groundwork has been laid in the working package related to core methods and data structures. These core methods are the foundation for many of the tools concerning the development of application-aware quantum-circuit optimization routines, application libraries, automation tools as well as tools related to application-specific evaluation and verification methods. This was also accompanied by the first “MQV-branded” release of a series of tool kits by TUM researchers. There is for example MQT QCEC, a tool for quantum-circuit equivalence checking or MQT Bench, a library containing around 50,000 benchmarking circuits ranging from 2 up to 130 qubits on different abstractions levels and covering a variety of applications and standard algorithms. Furthermore, also here compilation and vertical integration were identified as core inter-sectional topics with other consortia, resulting in a first technical exchange meeting and a hackathon to explore integration of all the MQV-built tools so far into a working end-to-end pipeline getting a specific application up and running on a chosen quantum-computing hardware platform.

Concerning the infrastructure and support task, a requirements analysis of the different user groups and their various use cases with respect to the availability of (HPC-) simulators, their capabilities and supporting software and software-development tools has been started. Additionally, in the last quarter of 2022, this process was accompanied by providing classroom training sessions for researchers with hardware and commercial software providers.

A lot of the initial work already found its way into publications and conference contributions (e.g., Conference on Quantum Information Processing, Design, Automation and Test in Europe Conference, Design Automation Conference, IEEE International Conference on Quantum Computing and Engineering) with some more contributions accepted for publication in the beginning of 2023.

Finally, many partners of the consortium were actively participating in a variety of outreach events, presenting their works, for example during the World of Quantum trade fair, the Munich Tech Days or the “Lange Nacht der Wissenschaften” in Nuremberg.



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Hardware Adapted Theory (HAT)

Building a practically useful quantum computer is a formidable challenge, as the requirements in working precision and isolation against environmental noise are very demanding. These errors can significantly limit the performance and capabilities of quantum computing hardware. The HAT consortium aims to provide application-oriented theory support for the different experimental quantum computing platforms within MQV to enable the optimal execution of quantum algorithms.

In the first year of MQV, HAT has developed a stimulating environment through multiple meetings and exchanges. Besides many internal scientific collaborations, HAT is highly entangled with other theoretical and experimental consortia of MQV. Scientists from HAT work very closely with the consortia dealing with quantum-computing hardware based on superconducting qubits (SQQC) and neutral atoms (TAQC). These quantum devices, in general, need to be controlled precisely for implementing different quantum operations. HAT members at TUM work with these experimental teams to design noise-robust control fields (electromagnetic pulses) using different analytical and numerical techniques. The design of so-called 'control fields' is not a straightforward task but requires a detailed understanding of the physics behind these quantum devices.

In many cases, the quantum devices cannot be sufficiently experimentally characterized. These issues can be solved by including feedback from the quantum devices and reacting to the outcomes of those quantum measurements to design control fields. At FAU and the Max Planck Institute for the Science of Light (MPL), this was achieved by introducing a new numerical technique to find such optimal feedback strategies for quantum devices through the combination of reinforcement learning and quantum-control methods. With this new tool in hand, a large variety of important situations can be explored where feedback is used to counteract noise.

It is also an important task to numerically model the hardware components of a particular quantum-computing device. This will allow for predicting the behavior of an experimental setup as accurately as possible. In this regard, at FAU work has started to develop a numerical library for modeling building blocks of superconducting quantum devices as well as in designing algorithms that can be implemented on a particular quantum-computing hardware. A renormalization-group approach has been developed to tackle quantum-optimization problems. This approach divides the original problem into smaller sub-problems and combines the candidate solutions into a condensed, smaller-size optimization problem, which allows for solving these optimization problems more efficiently.

With the rapid progress in quantum technologies, developing new and improved methods for benchmarking and certification of quantum devices is essential. Benchmarking tools help to compare different quantum computing hardware at different levels. Randomized benchmarking has become a bread-and-butter technique for benchmarking quantum operations and has played a key role in famous quantum-advantage experiments. No fewer than 34 different variants of randomized benchmarking are known to date. As part of the HAT work at Freie Universität Berlin a comprehensive framework of randomized benchmarking was provided. Not only is the scheme general enough to capture all the previously known schemes. But it – in a very precise way – evaluates what randomized benchmarking delivers, with accurate error bounds, in a research field where precision and accuracy are the core point of it. From a practical perspective, it provides a starting point for developing new techniques of randomized benchmarking beyond the scope of known schemes.

Altogether, the entire HAT team is involved in providing hardware-based theory support to the experimental units of MQV for developing a quantum computer that can be used for near- and long-term applications.

Quantum Science & Technology – Education in Bavaria (QST-EB)

QST-EB educates the next generation of researchers and users of quantum technology and quantum computing in Bavaria, both at the level of Master's students as well as doctoral candidates. Equally, it reaches out to the public for a general awareness about QST.

The sub-project QST-EB-Teaching includes application-oriented internships; an excellence-focused international doctoral fellowship program across the departments of physics, chemistry, computer science, mathematics, and electrical engineering open to all Bavarian universities; advanced practical lab experiments at Bavarian universities; as well as master-level fellowships. The latter comprise a program for excellent female students, and one for exchange students of the Munich Master's program Quantum Science & Technology (QST). The overall goal is to attract worldwide top talents to MQV sites and to further educate them in quantum technology and quantum computing.

This year, QST-EB-Teaching financed seven advanced practical training setups one of each at the universities of Augsburg, Bayreuth, Erlangen, LMU and TU in Munich, Regensburg, and Würzburg with a value of € 144,000 each. With the help of the trainings, students gain both hands-on experience and essential insights into quantum technological and scientific mechanisms as well as experiments. In turn, the students are educated on MQV-relevant topics in Bavaria, such as the quantum mechanical entanglement of photons and the construction of atom-based quantum simulators.

In order to increase the proportion of women in the QST subject area, QST-EB-Teaching awards five scholarships each year to outstanding female students of the Munich QST Master's program. With over 70 students in the current QST Master's cohort, a proportion of almost one third is female, and a total of two thirds are international students. Both val-

ues are outstanding for a Master's degree program with a technical and scientific background.

With the help of the MQV-industrial internships, QST students can gain their first industrial experience with MQV partners. Hereby, QST-EB-Teaching serves both the students, who want to get in touch with the quantum-technology-oriented industries, and the companies who need young talents with an appropriate quantum-technology background. All internships are offered and regularly updated online on the MQV website (https://www.munich-quantum-valley.de/service/internships).

In the last year, QST-EB-Teaching also awarded six outstanding young scientists with doctoral scholarships as part of the MQV Doctoral Fellowship Program. The MQV doctoral fellows were selected through a highly competitive, international selection round with about 150 applications this year. The successful fellows receive a three-year ad-personam scholarship to pursue their research interests in the field of quantum science and quantum technology. After completing the selection process, the fellows were able to apply freely to any thematically appropriate research group at a Bavarian university. The introductory presentations by the applicants took place virtually and were open to the public. Thus, they could also be used for recruitment purposes by Bavarian research groups that had to fill self-financed doctoral positions. In this way, in addition to the above-mentioned fellows, eight other excellent applicants found doctoral positions within the MQV environment.

The sub-project QST-EB-Outreach aims to increase the visibility of MQV and to make quantum technologies and quantum computing accessible to a broad public. For this purpose, an MQV visual identity and website (https://www.munich-quantum-valley.de) were designed and implemented and a social-media presence (@munichquantum) was set up on LinkedIn, Twitter and Instagram.

A highlight of the year was the presence of MQV at the first trade fair for quantum technologies “World of QUANTUM” in Munich, which took place in April 2022 and led to many exchanges with both international scientists and science organizations as well as, with companies and start-ups from the quantum-technology sector.

In order to bring quantum technologies to the general public, the MQV actively participated in, the “Girls' Day”, the “forscha” (“Münchner Wissenschaftstage”), and the “Festival of the Future” at the Deutsches Museum. There, the interest of children and adults was catched with hands-on experiments on quantum effects. Furthermore, the outreach team teamed up with the PhotonLab (Max Planck Institute of Quantum Optics) to develop interactive books on quantum science for high school students as well as to produce an audio play for smaller children called “Alice im Quantenland” that confronts them with quantum effects in a playful way. In addition, first steps of setting up an “MQV Quanten-Labor” have been taken, to offer a truly quantum learning experience to high school students, expanding the existing students lab PhotonLab.


SOLUTION
UNIQUE VALUE PROPOSITION
UNFAIR ADVANTAGE
CUSTOMER SEGMENTS
LEAN DPS CANVAS
AI POTENTIAL
KEY METRICS
DATA-GENERATING MVE
EARLY ADOPTERS

Quantum Technology Park & Entrepreneurship (QTPE)

The key objective of QTPE is to establish two core cross-functional elements in MQV's endeavor to create a leading ecosystem for quantum technologies in Bavaria: First, a Quantum Technology Park, providing state-of-the-art technological tools and engineering know-how for realizing quantum technology. Second, a Quantum Entrepreneurial Center to translate scientific research into innovative, scalable businesses and to develop tailored entrepreneurship activities, accelerating the commercialization of quantum technologies for the society.

The Quantum Technology Park is the key component to improve the available infrastructure for quantum-technology research and product development. It will bring together several locations into one comprehensive setup. The entrepreneurship module is fully focused on supporting researchers with their plans to commercialize their technologies and on driving the entrepreneurial mindset in the field.

Quantum Technology Park

In order to finish the realization of the Quantum Technology Park as soon as possible, all involved institutions focused on speeding up planning processes for new infrastructure and on advancing or even finishing ongoing construction efforts. In parallel, the coordination of the various infrastructure elements operated by different institutions at different locations has been started.

Regarding the individual elements, the Fraunhofer Research Institution for Microsystems and Solid State Technologies (EMFT) managed to secure the funding for their new building on the campus Garching, allowing EMFT to move operations entirely to Garching. The new EMFT building will include clean room facilities and laboratories for the topics "Quantum Technologies and Trusted Electronics". Completion of the construction is envisioned for 2027/2028.

The Max Planck Society (MPG) is within the final year of setting up their new Semiconductor Laboratory (HLL) at the Garching Research Campus and is planning to complete the efforts in October 2023. The construction of the new MPG HLL building is within the planned time line. Slight modification of the lab layout and the initiation of the purchase of large equipment is ongoing. A key focus of the MQV-related activities of MPG HLL will be integrated photonics.

LMU is currently in the process of refurbishing and re-designing the existing clean-room facility of the Center for NanoScience (CeNS) operated by the Faculty of Physics at Schellingstraße in Munich. Several orders for equipment have already been placed and delivered. The technical infrastructure is adapted to the new research focus on "2D quantum materials" and related quantum technologies. The clean room with an area of 120 m² is designed for chip-sized processing, study, design and state-of-the-art fabrication of quantum materials and nanoscopic structures as well as their preparation for integration into large and complex interacting quantum technologies.

In a joint effort, TUM and Walther-Meißner-Institute/BAdW aim to establish a Quantum Technology Center focusing on superconducting and spin-based quantum technologies. The center will also provide office space for MQV researchers as well as office and laboratory space for entrepreneurs. This includes local teams incubated through the Venture Lab Quantum, the innovation center for quantum technology in Munich, as well as start-ups aiming to establish a presence in Bavaria through a Quantum Landing Pad framework. The concept for a new building has been drafted and the planning phase has started, including feasibility studies for different locations on the Garching Research Campus.

Entrepreneurship

To support quantum researchers on their potential entrepreneurial journey, the Venture Lab Quantum (VLQ) is currently extending its team, refining and extending the offerings for students and founders and consistently increasing its network of experts and industry connections.

The Venture Lab's pipeline contains about ten teams that are currently incubated through different programs and support models. With the Max Planck Institute for Quantum Optics spin-off planqc, the first start-up from MQV has been incorporated this summer and received their first funding from venture capital investors. The recently incorporated TUM spin-offs QuantumDiamonds and Munich Quantum Instruments complete the current list of start-ups which were successfully incubated with the support of the Venture Lab Quantum and MQV.

Concerning entrepreneurship education, the Venture Lab's flagship program "Quantum Entrepreneurship Lab" has been upgraded to an in-person format and restarted with 30 students this winter semester. The program is now officially partnering with the German industry consortium QUTAC to engage the students with high-profile challenge partners. Additional educational programs targeting more senior researchers are in the concept phase. Beyond these efforts, the VLQ team keeps increasing the network of relevant investors and key industry partners.

List of speakers, principal investigators, and leading scientists

Adel	Hans	FhG-IIS	SHARE
Aidelsburger	Monika	LMU	TAQC
Altmann	Philipp	LMU	QACI
Bauer	Karin	FhG-EMFT	SHARE
Bhatotia	Pramod	TUM	Q-DESSI
Blatt	Rainer	MQV	Scientific Director
Blatt	Sebastian	MPQ	TAQC
Bloch	Immanuel	LMU, MPQ	TAQC
Boche	Holger	TUM	THEQUCO
Brandt	Martin	TUM	SHARE
Burgholzer	Lukas	TUM	QACI, Q-DESSI
Carlowitz	Christian	FAU	SHARE
Cirac	Ignacio	MPQ	THEQUCO
Debus	Pascal	FhG-AISEC	QACI
Deppe	Christian	TUM	THEQUCO
Eckert	Claudia	FhG-AISEC	QACI
Eckstein	Martin	FAU	THEQUCO
Edelhäußer	Thorsten	FhG-IIS	SHARE
Efetov	Dmitri	LMU	QTPE
Eisert	Jens	FUB	HAT
Filipp	Stefan	TUM, WMI	SQQC
Finley	Jonathan	TUM	SHARE
Fölling	Simon	LMU	TAQC
Fürlinger	Karl	LMU	QACI
Glaser	Steffen	TUM	HAT, THEQUCO
Graebnitz	Christoph	FhG-AISEC	QACI
Gross	Rudolf	TUM, WMI	QTPE, SQQC

Hagelauer	Amelie	FhG-EMFT	SHARE
Hartmann	Michael	FAU	HAT, SQQC, THEQUCO
Holleitner	Alex	TUM	QST-EB, SQQC, SHARE
Hrdá	Barbora	FhG-AISEC	QACI
Huebl	Hans	WMI	SQQC
Jirauschek	Christian	TUM	SQQC
Kaul	Maximilian	FhG-AISEC	QACI
Knap	Michael	TUM	THEQUCO
Knolle	Johannes	TUM	SQQC, THEQUCO
Koch	Robert	FhG-IIS	SHARE
Koenig	Robert	TUM	THEQUCO
Kranzlmüller	Dieter	TUM	QACI, Q-DESSI
Kutter	Christoph	FhG-EMFT	SHARE, QTPE
Lang	Simon	FhG-EMFT	SHARE
Lapichino	Luigi	LRZ	QACI, Q-DESSI
Linnhoff-Popien	Claudia	LMU	QACI, Q-DESSI
Lorenz	Jürgen	FhG-IISB	QACI, SHARE
Lorenz	Jeanette	FhG-IKS	QACI
Marquardt	Florian	FAU, MPL	HAT, QST-EB, THEQUCO
Matic	Andrea	FhG-IKS	QACI
Meltzer	Elias	FhG-EMFT	SHARE
Mendl	Christian	TUM	HAT, QACI, Q-DESSI
Müller	Markus	FZJ	HAT
Nagy	Roland	FAU	SHARE
Nebrich	Lars	FhG-EMFT	SHARE
Ninković	Jelena	MPG-HLL	QTPE
Nötzel	Janis	TUM	THEQUCO

Pernice	Wolfram	eHEI	TAQC
Pollet	Lode	LMU	THEQUCO
Pollmann	Frank	TUM	THEQUCO
Pomplun	Nikolas	DLR	HAT
Rosskopf	Andreas	FhG-IISB	QACI
Schellenberger	Martin	FhG-IISB	QACI
Schilling	Christian	LMU	THEQUCO
Schmidt	Kai Philipp	FAU	THEQUCO
Schollwöck	Ulrich	LMU	THEQUCO
Schulte-Herbrüggen	Thomas	TUM	THEQUCO
Schulz	Martin	LRZ, TUM	Q-DESSI
Schulz	Laura	LRZ	QACI, Q-DESSI
Seidl	Helmut	TUM	QACI, Q-DESSI
Sturm-Rogon	Leonard	FhG-EMFT	SHARE
Thönes	Thomas	FhG-IIS	SHARE
Tornow	Marc	TUM	SHARE, SQQC
Trummer	Christopher	TUM	QTPE
Ufrecht	Christian	FhG-IIS	QACI
von Delft	Jan	LMU	QST-EB, THEQUCO
Wagner	Friedrich	FhG-IIS	QACI
Weber	Johannes	FhG-EMFT	SHARE
Weissenbäck	Markus	FhG-IIS	QACI
Werninghaus	Max	WMI	SQQC
Wilk	Tatjana	MCQST	QST-EB
Wille	Robert	TUM	QACI, Q-DESSI
Zahn	Daniela	FhG-EMFT	SHARE
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