Munich Quantum Valley

Public Annual Report

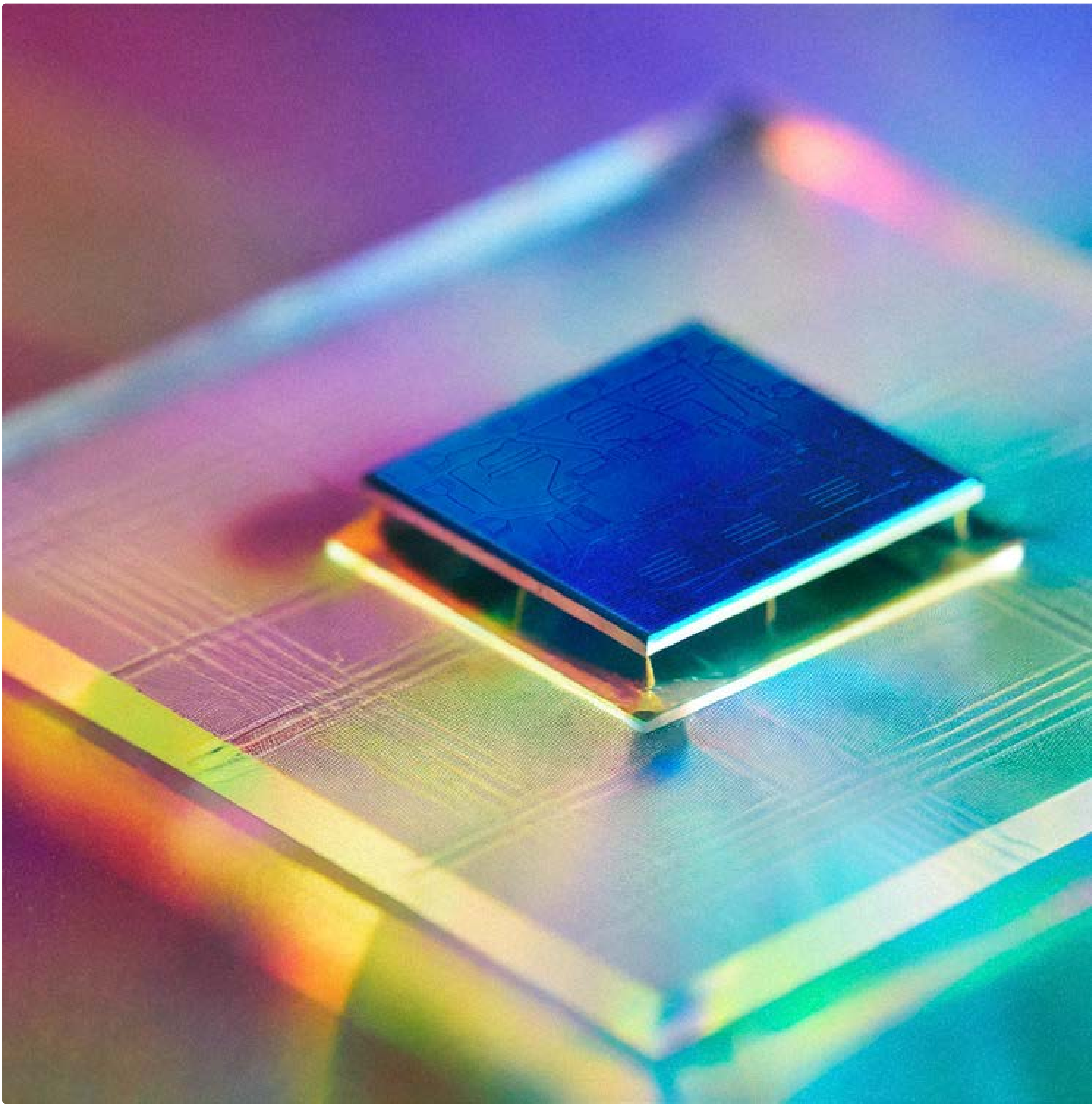
2023

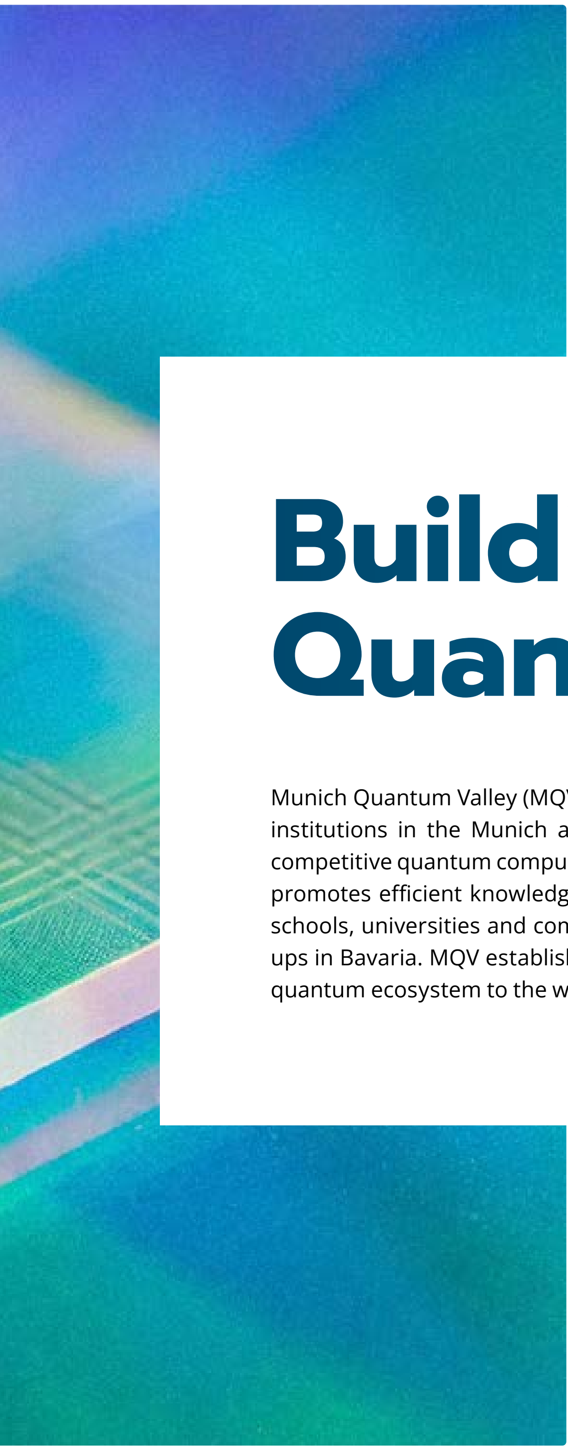
www.munich-quantum-valley.de

Munich Quantum Valley

Public Annual Report 2023

29 February 2024





Building a Quantum Future

Munich Quantum Valley (MQV) leverages decades of experience in quantum science at universities and research institutions in the Munich area and throughout Bavaria with the primary goal of developing and operating competitive quantum computers in close cooperation with strong industry partners and visionary start-ups. MQV promotes efficient knowledge transfer from research to industry, complemented by educational programs for schools, universities and companies, as well as tailored entrepreneurial support for quantum technology start-ups in Bavaria. MQV establishes a network with international reach and strives to propel Bavaria and its unique quantum ecosystem to the worldwide forefront of quantum technology.

Welcome address of the Bavarian Minister for Economic Affairs, Regional Development and Energy

– Hubert Aiwanger

Quantum technologies have enormous potential to revolutionize various industries and catalyze scientific progress. Bavaria, as a leading innovation region, recognizes the importance of embracing and developing quantum technologies to further strengthen its position as a global hub for innovation.

As part of its Hightech Agenda, Bavaria is funding Munich Quantum Valley. This initiative leverages the region's strong scientific, technological and economic capabilities. Bavaria already boasts an impressive ecosystem of universities, research institutes and cutting-edge technology companies, providing a solid foundation for building a thriving quantum industry.

I appreciate the efforts of Munich Quantum Valley over the past two years. The scientific and technological progress has been impressive. I am particularly pleased that a significant number of start-ups have already been spun off from Munich Quantum Valley and that a network of industrial partners has been established.

Munich Quantum Valley is a project that aims to build and operate quantum computers, placing Bavaria at the forefront of quantum technology worldwide. May it produce groundbreaking discoveries, foster collaboration and networking among scientists, and attract investment and talent from around the world. I wish Munich Quantum Valley every success in its mission to advance quantum technology and create a vibrant and thriving quantum ecosystem in Bavaria!

HIGHTECH Agenda Bavaria

Bavarian Ministry of Economic Affairs, Regional Development and Energy

Welcome address of the Bavarian Minister for Science and the Arts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– Markus Blume

In the coming years, quantum computers will develop into a groundbreaking technology that will have a major impact on science, the economy and our everyday lives. With Munich Quantum Valley, Bavaria is taking a quantum leap to the forefront of international quantum research. Over the past two years, as part of the Bavarian Hightech Agenda, we have succeeded in establishing a multi-faceted quantum ecosystem that focuses on broad quantum education, excellent research, technology transfer and innovative applications.

Munich Quantum Valley is a unique scientific flagship. It brings together excellent research groups from Bavarian universities and research institutions, who are working in consortia to pursue a common mission: the construction of a Bavarian quantum computer. Efficient technology transfer is particularly important at the interface between research and application. I am very pleased about the close cooperation between the consortia, companies and emerging start-ups in the quantum field. The Lighthouse Projects of Munich Quantum Valley bring together additional stakeholders from science and industry to jointly explore key aspects of quantum research.

With Munich Quantum Valley, we also strive to expand quantum expertise in Bavaria. The program has created nine new professorships to teach quantum physics to students at our universities. The doctoral fellowship program attracts outstanding young quantum scientists from all over the world.

I would like to express my deepest gratitude to all members of Munich Quantum Valley for their passion and outstanding research achievements. For the years to come I wish you continued deep insights, scientific success and good progress in the development of the Bavarian quantum computer!

HIGHTECH Agenda Bavaria

Bavarian State Ministry of Science and the Arts

Establishing a world-leading quantum hub in Bavaria

Foreword of the Munich Quantum Valley Scientific Director

– Rudolf Gross

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Rapid advances in quantum science and technology allow us to engineer and manipulate quantum systems in a controlled manner. This provides the basis for a variety of novel quantum technologies, having the potential for disruptive innovations and even shaping a new technology era. Now is the time to promote the transfer of quantum technology research into applications.

The Munich Quantum Valley was founded in 2021 to establish Bavaria as one of the world's leading regions for quantum technology. It propels joint research and development efforts at universities, research organizations, and industry. MQV aims to develop full-stack quantum computers, realize efficient infrastructures for quantum technologies, establish a globally unique quantum ecosystem, develop educational programs for schools, universities, and companies, provide tailored entrepreneurial support for quantum technology start-ups and explore novel concepts and quantum-enabling technologies in focused Lighthouse Projects.

We have compiled this report to give you an overview of our activities over the past year. And we are proud of what has already been achieved by joining forces in the Bavarian quantum ecosystem.

Munich Quantum Valley

Promoting quantum computing, quantum technologies, and quantum applications in Bavaria

Munich Quantum Valley promotes quantum science and quantum technologies in Bavaria with the primary goal of developing and operating competitive quantum computers. It connects research, industry, funders, and the public: MQV promotes an efficient knowledge transfer from research to industry, establishes a network with international reach and provides educational offers for schools, universities and companies.

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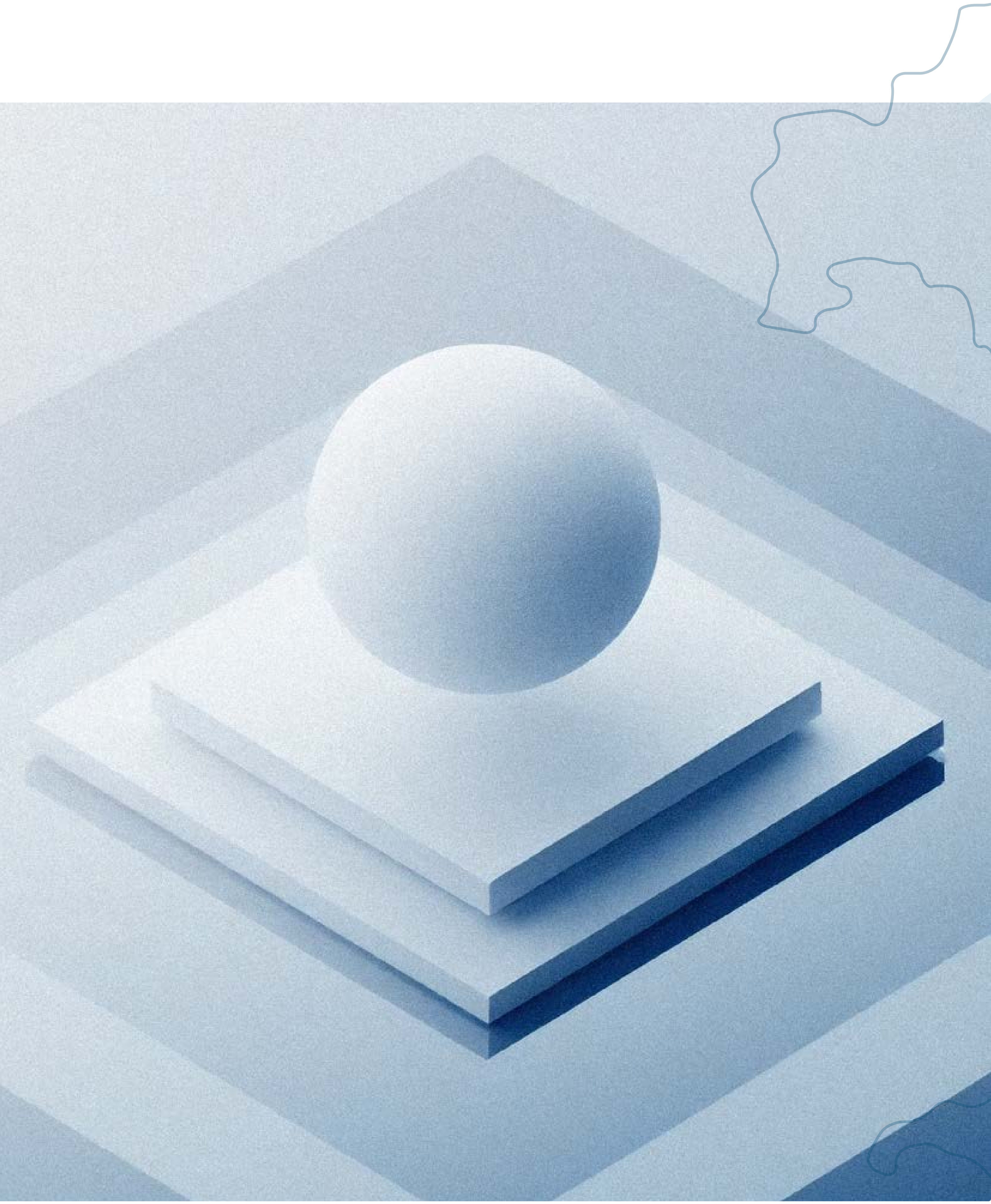


Chapter 1

About Munich Quantum Valley

Munich Quantum Valley (MQV) is organized as a registered association and supported by the Bavarian state government with funds from the Hightech Agenda Bavaria. It combines the research capacities and technology transfer power of three major universities and key research organizations in Bavaria in an unprecedented intensity of cooperation.

The founding members of Munich Quantum Valley e. V.:

- Bavarian Academy of Sciences and Humanities (BAdW)
- Fraunhofer-Gesellschaft (FhG)
- Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)
- German Aerospace Center (DLR)
- Ludwig-Maximilians-Universität München (LMU)
- Max Planck Society (MPG)
- Technical University of Munich (TUM)

Bavarian universities and research institutions contributing to MQV

- Fraunhofer Institute for Integrated Circuits IIS
- Fraunhofer Institute for Integrated Systems and Device Technology IISB
- Friedrich-Alexander-Universität Erlangen-Nürnberg
- Max Planck Institute for the Science of Light
- Technische Hochschule Nürnberg Georg Simon Ohm

- Julius-Maximilians-Universität Würzburg

- Ostbayerische Technische Hochschule Regensburg
- University of Regensburg

- Augsburg University

- Fraunhofer Institute for Applied and Integrated Security AISEC
- Fraunhofer Institute for Cognitive Systems IKS
- Fraunhofer Institute for Electronic Microsystems and Solid State Technologies EMFT
- Leibniz-Rechenzentrum LRZ
- Ludwig-Maximilians-Universität
- Max Planck Institute of Quantum Optics
- Max Planck Semiconductor Laboratory
- Munich Center for Quantum Science and Technology
- Research Institute CODE
- Technical University of Munich
- Universität der Bundeswehr München
- Walther Meißner Institute

Munich Quantum Valley e. V. Partner Network

Munich Quantum Valley has established a rapidly growing partner network, bringing together stakeholders from research institutions, universities, and companies whose common goal is to promote quantum science and quantum technologies in Bavaria. → 4.6

A Brief History of Munich Quantum Valley

2022
January

Munich Quantum Valley e.V. established as a registered association

2021
October

MQV funding has been granted until September 2026

2021
July

MQV funding proposal submitted to Bavarian State Government

2021
February - June

Development of MQV research agenda

2020
November

Strategy Paper submitted to Bavarian State Government, funding of €300 million within HIGHTECH Agenda Bavaria has been announced.

2021
January

Memorandum of Understanding signed

1.1 Munich Quantum Valley: Vision, Mission, and Roadmap

1.1.1 Vision

Munich Quantum Valley (MQV) aims to create the world's foremost ecosystem for industrializing quantum technologies. It combines research, technology development, graduate training, and educational outreach in quantum science and technology (QST) by establishing a tight network of research institutions, industry, incubators, funding agencies, and the public. By uniting public and private efforts in a shared enterprise and attracting the world's best scientists and engineers, MQV aims to develop and operate competitive quantum computers and achieve breakthroughs in QST that will transform our future. It will accelerate technological disruption by promoting knowledge transfer between science and industry to foster quantum applications and push Bavaria and Germany to the forefront in QST. MQV will build on the most promising hardware platforms and technologies developed within MQV and by European partners to realize full-stack scalable quantum computers. On a medium-term basis (5–10 years), MQV will fabricate systems with up to 1000 qubits, integrate them into the powerful Bavarian high-performance computing infrastructure (HPC), and make them available to users via cloud access. The long-term goal is to develop fault-tolerant quantum computers, which can solve a wide class of practical problems and hence are of broad use for both the economy and society.

1.1.2 Mission

Creating a powerful quantum ecosystem in Bavaria

As a hub between research, industry, funding agencies, and the public, MQV establishes a powerful quantum ecosystem in Bavaria to promote efficient knowledge transfer between academia and industry and operates an internationally leading center for developing the full spectrum of quantum technologies. MQV explores novel concepts in QST in focused Lighthouse Projects, operates a world-class research high-tech infrastructure, offers tailored educational programs for schools, universities and companies, a platform for international networking, and targeted entrepreneurial support for start-ups.

Developing quantum computing and quantum technologies for real-life applications

Using innovatively engineered superconducting, neutral-atom and trapped-ion platforms, the overarching mission of MQV is to realize full-stack quantum computer demonstrators, remotely accessible to researchers and industry through seamless integration with local high-performance computing infrastructure. By jointly developing hardware and software, MQV will provide the quantum computing tools allowing to address challenging real-life problems. On a medium-term basis (5–10 years), MQV will focus on noisy intermediate-scale quantum computers with up to 1 000 qubits, while the long-term goal is to develop fault-tolerant quantum computers capable of solving practical problems relevant to the economy and society. Besides an ambitious focus on quantum computing, MQV will create innovation in many related technology fields.

Building on unique Bavarian strengths

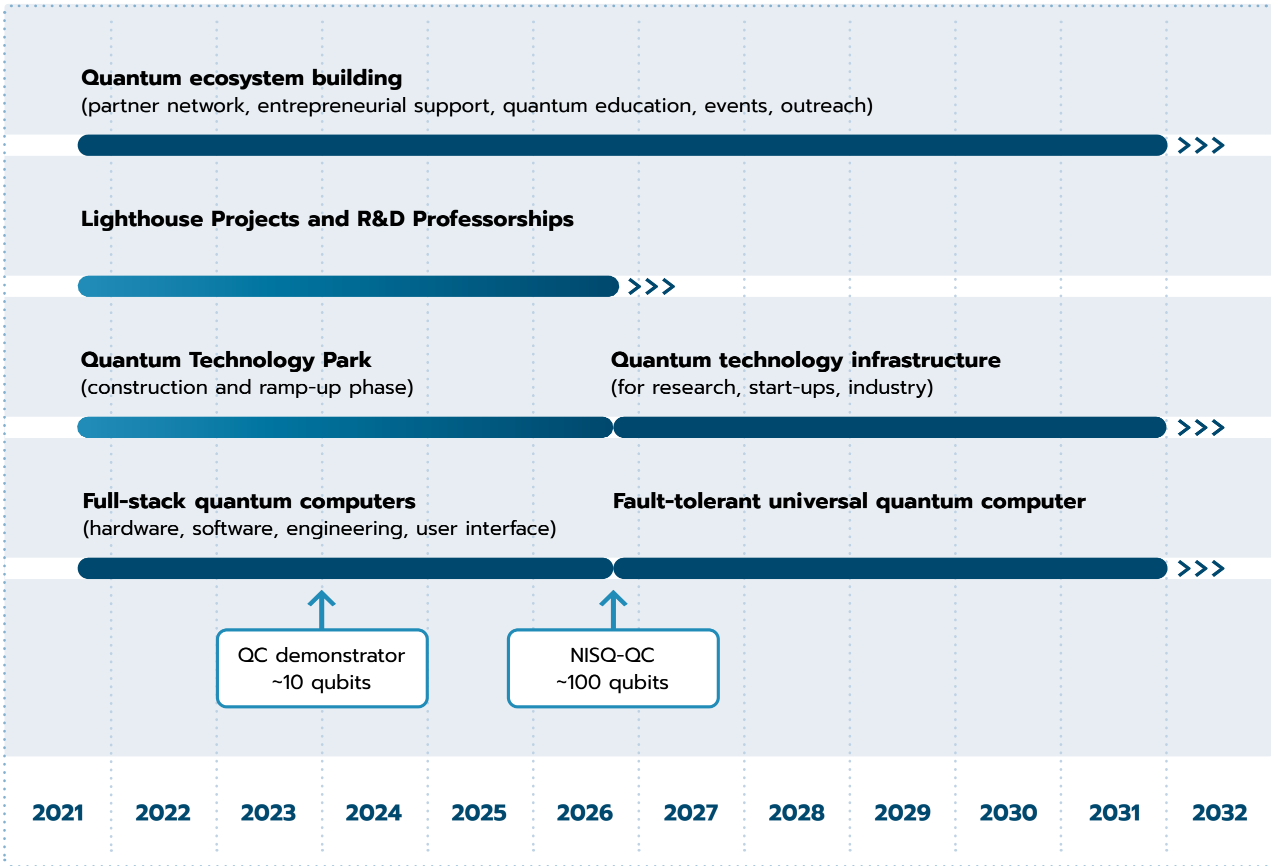
MQV builds on the longstanding tradition and outstanding excellence of its founding members, covering all fields of QST, and an exceptional industrial high-tech environment. By coordinating efforts of academia, industry and funding agencies, MQV provides a unique ecosystem, enabling efficient knowledge transfer between research and industry and establishing a network of high international visibility. MQV provides the tools and services to drive the commercialization of quantum technologies and to catalyze their transition from theoretical concepts to tangible real-world applications.

1.1.3 Roadmap

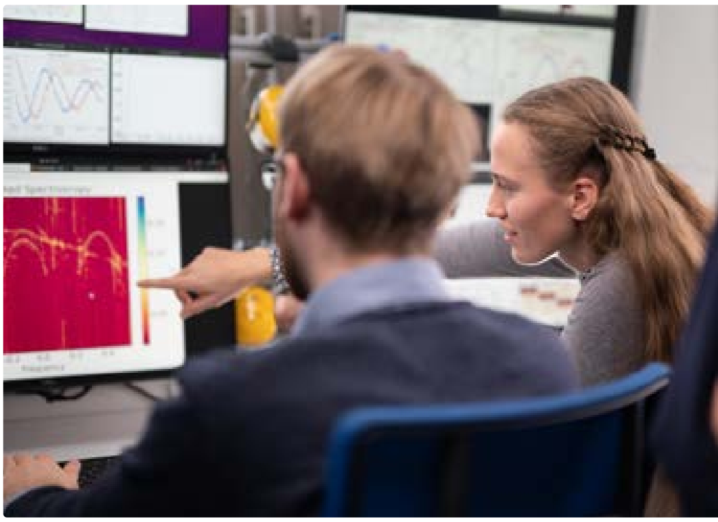
It is expected that quantum technologies will be era-defining, similar as digital technologies are shaping the information age. Therefore, the development of quantum technologies will extend over a longer period and most likely will also be accompanied by technology disruptions. Therefore, the MQV roadmap has been planned for an intermediate to long time scale from the beginning.

MQV will play a leading role in the long-term development of quantum technologies and enable Bavaria to take a leading role in the industrialization of this important future technology. In other words, MQV will enable Bavaria to be an active player in the coming quantum era and not just a passive visitor.

The world-leading know-how built up and concentrated within MQV will provide industry and start-ups a competitive advantage by having immediate access to this know-how. Moreover, the vibrant MQV quantum ecosystem is expected to be a decisive factor for Bavaria's competitiveness in attracting quantum industry and start-ups, as well as fostering investments.



The MQV Roadmap with the key program components implemented by MQV. Important milestones regarding the development of full-stack quantum computers in the first program phase (2021–2026) are a quantum computer demonstrator with about ten qubits and a Noisy Intermediate-Scale Quantum Computer with about 100 qubits.



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Important intermediate goals and most relevant milestones of the first program phase (2021–2026) of Munich Quantum Valley

2022

- implement hardware–software codesign approach
- start tailored venturing support for quantum start-ups
- launch quantum educational programs like Future Academy, MQV doctoral, masters and exchange fellow-ships and industrial internships

2023

- 1st generation MQV demonstrator
- demonstrate the scalability of technology and suppression of qubit cross-talks
- develop novel error correction protocols and stabilizer read-out strategies
- set up an initial pro-gramming environment

2024

- develop integrated optoelectronic and photonic switches, cryogenic electronics, and wafer-scale chip development
- demonstrate noise robust pulses and high-fidelity quantum gate operations
- machine learning and quantum tool-box for optimized circuit knitting

Within the first funding period (October 2021 to September 2026), Munich Quantum Valley aims to

- develop full-stack quantum computers based on different hardware platforms
- realize high-tech infrastructures and enabling technologies for quantum research within an open-access Quantum Technology Park
- provide tailored entrepreneurial support for quantum technology start-ups
- develop targeted programs for educating the next generation of quantum scientists and engineers
- explore novel concepts and quantum-enabling technologies in focused Lighthouse Projects
- strengthen quantum science at universities by additional R&D Professorships

2025

- 3D integration of 17(+x) qubit device into HPC system
- Quantum Technology Park with access to MQV users operational
- unified framework for quantum compilers established
- quantum algorithm implemented on MQV hardware

2026

- 2nd gen MQV NISQ demonstrator
- benchmarking algorithms developed
- comprehensive catalog on use cases ready
- quantum computing cloud access to all academic users

2026+

- 100+ qubit NISQ devices operational
- implement error correction implemented on superconducting and neutral atom platforms
- fault tolerance protocol implemented

1.1.4 Future fields of action – the MQV Roadmap 2026+

The translation of quantum technologies into useful applications – in particular in the field of quantum computing – will be a highly competitive marathon race. It requires endurance, the availability of high-tech infrastructure, and joining forces in interdisciplinary networks. Regarding the roadmap for 2026+, MQV identifies the following fields of action:

Operating an internationally leading quantum hub

Establishing a thriving quantum ecosystem and positioning Bavaria as a key player in the development and commercialization of quantum technologies, the continuous fostering and extension of the quantum ecosystem will be an important cornerstone of the MQV mission beyond 2026 in order to

- maintain Bavaria as a leading global innovation hub for quantum technologies, joining key stakeholders from academia, industry partners, and start-ups,
- intensify connections to a high-tech-oriented network of science and technology experts, industry leaders, and government officials,
- establish Bavaria as a key partner and incubator for national and EU quantum R&D efforts,
- provide a world-class quantum high-tech infrastructure,
- coordinate courses and practical training for quantum scientists and engineers, and support targeted graduate programs at universities,
- provide access to talents in quantum science and engineering by leveraging the talent pools of universities, research institutions, and local high-tech industries.

Developing quantum technologies and quantum computing for real-life applications

A key mission of MQV is to jointly develop quantum computing hardware and software, allowing us to solve challenging real-life problems. Until 2026, MQV focuses on the realization of full-stack noisy intermediate-scale quantum computers with up to 100 qubits and integrating them into the HPC infrastructure, while the long-term goal is to scale up these systems and finally develop fault-tolerant quantum computers capable of solving practical problems relevant to the economy and society. To this end, the major building blocks of the MQV roadmap for 2026+ will be to

- establish foundry-compatible fabrication processes,
- realize automation and scaling tools as well as advanced characterization techniques suitable for systems with more than 1 000 qubits,
- develop and implement quantum-error correction schemes aiming at the
realization of fault-tolerant quantum computers,
- establish fast feedback loops from quantum-to-classical processing units for stable operation of advanced quantum-computing systems and
- develop algorithms tailored to user applications.

Commercialization of quantum technologies

Besides having an ambitious focus on quantum computing, MQV aims to create innovations in many related technology fields such as quantum sensing, communication, and metrology. In order to establish an efficient knowledge transfer between academia and industry and to transfer quantum technologies into industrial applications, the MQV roadmap for 2026+ aims to

- provide quantum computing infrastructure for users developing quantum applications,
- develop concepts to make quantum technologies available to industrial users and start-ups,
- provide entrepreneurial training and operate a Quantum Landing Pad as a strategic endeavor designed to position Munich as a leading hub for quantum technology start-ups,
- offer support services specifically tailored to meet the needs of innovative high-tech companies,
- operate test laboratories allowing developers of software, control systems, and other quantum hardware components to benchmark and qualify their products.

Laying the foundations of the next generation of quantum technologies

Developing useful quantum computers and other quantum applications is a highly demanding long-term challenge, requiring the continuous advancement of the underlying concepts, materials, and technologies. The MQV roadmap 2026⁺ supports these long-term developments by

- the development of advanced quantum technologies and novel concepts in quantum theory,
- focused lighthouse projects to foster breakthroughs in quantum computing, communication, cryptography, metrology, and sensing,
- research professorships at universities,
- scholarships and targeted training for doctoral students.

Quantum Technology Park (QTP)

Presently, MQV establishes a distributed QTP by jointly using the already existing technology infrastructure at partner institutions such as the Walther Meißner Institute of BAdW, the Center for NanoSciences of LMU Munich, and the Center for Nanotechnology and Nanomaterials of TUM. Key objectives of the MQV roadmap for 2026⁺ are to improve the available tech infrastructure both regarding quality and quantity. Particular measures are

- the extension of the Superconducting Quantum Technology Center at WMI, which is urgently required to keep pace with the rapid progress in this field of technology,
- the integration of the new Center for Quantum Engineering (TUM) and Semiconductor Laboratory (MPG) into the distributed QTP,
- the further strengthening of the MQV-QTP by the planned FhG-EMFT building (completion: 2029/30) with the goal to establish foundry-compatible fabrication processes.

Preparing the public for the coming quantum era

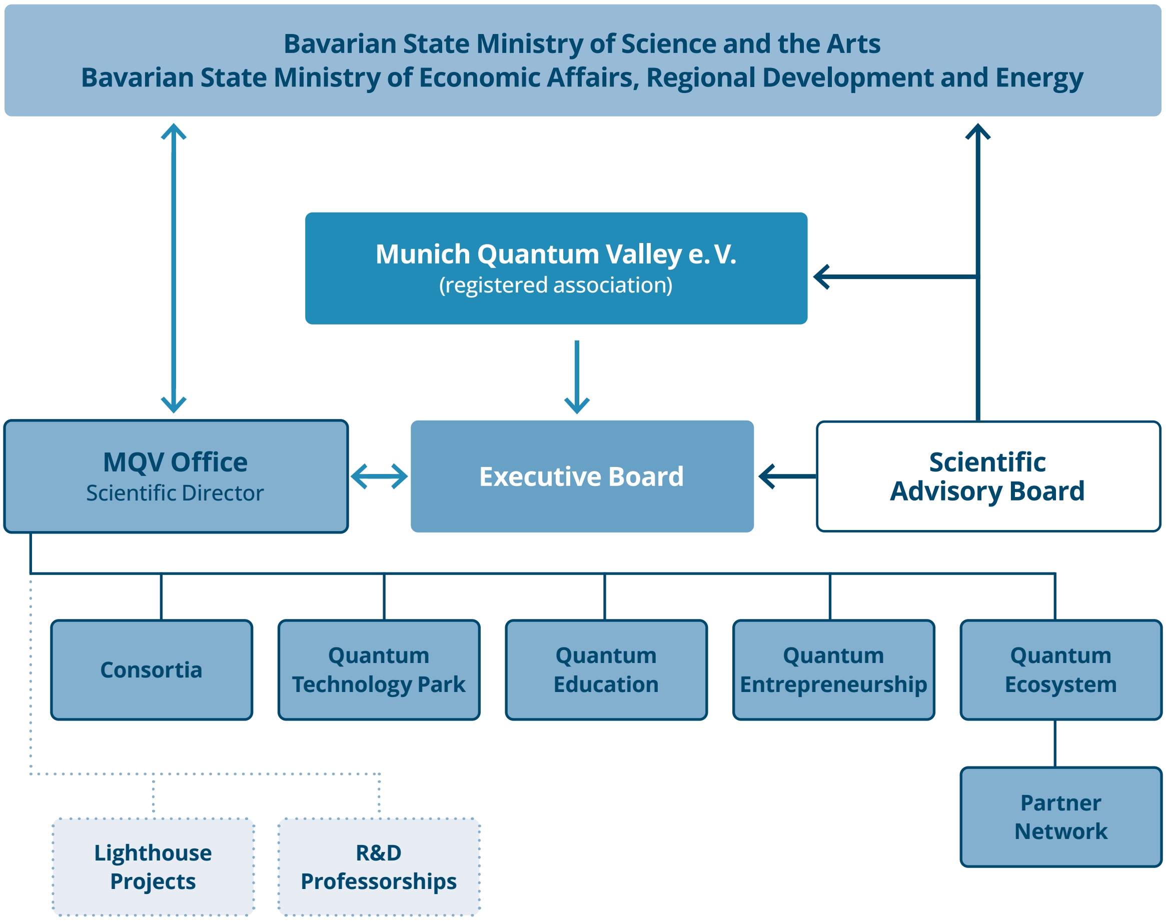
Already today, MQV is developing targeted outreach activities to engage the public in quantum science and technology and to address the potential societal impact of quantum technologies. This key mission of MQV will continue to be a central part of its roadmap for 2026⁺. → 5

1.2 Organizational Structure

The organizational structure of Munich Quantum Valley (MQV) must allow for flexible and efficient management of the different program parts.

For the legal structure, a registered association has been chosen, with the presidents of the member institutions being association members. The association's General Meeting implements an Executive Board and a Scientific Director, who are responsible for steering and supervising the MQV project parts with the administrative support of the MQV Office.

The budget of the project parts is granted by the Bavarian State Ministries directly to the member institutions. The progress of the different program parts is regularly evaluated by the Scientific Advisory Board, advising the MQV General Meeting and Executive Board and the Bavarian State Ministries.



1.2.1 Munich Quantum Valley e.V.

Munich Quantum Valley e.V. was founded on 27 January 2022 as a registered association to manage and coordinate the efforts within MQV towards developing and operating competitive quantum computers in Bavaria and promoting quantum technology and quantum science. Following the seven founding members:

Bavarian Academy of Sciences and Humanities (BAdW)

Fraunhofer-Gesellschaft (FhG)

Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

German Aerospace Center (DLR)

Ludwig-Maximilians-Universität München (LMU)

Max Planck Society (MPG)

Technical University of Munich (TUM)

The members of the association are represented by their presidents.

1.2.2 Executive Board

Each of the seven founding institutions of Munich Quantum Valley e.V. appoints one member of the Executive Board.

Prof. Claudia Felser, Chairwoman
Max Planck Society (MPG)

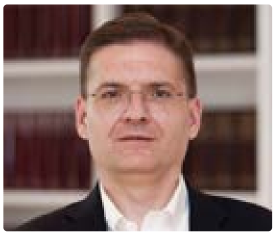
Dr. Robert Axmann
German Aerospace Center (DLR)

Prof. Arndt Bode
Bavarian Academy of Sciences and Humanities (BAdW)

Prof. Raoul Klingner
Deputy Chairman
Fraunhofer-Gesellschaft (FhG)

Prof. Gerhard Kramer
Technical University of Munich (TUM)

Prof. Jürgen Schatz
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)



Dr. Sigmund Stintzing
Ludwig-Maximilians-Universität München (LMU)

The Scientific Director is participating in the Executive Board meetings as regular guest. The Executive Board and the Scientific Director are responsible for steering and supervising the MQV project parts with the administrative support of the MQV Office.

1.2.3 Scientific Advisory Board

The Scientific Advisory Board (SAB) consists of internationally recognized external experts. It regularly evaluates the research activities within MQV. The results of the SAB meetings are used by the Executive Board, the Scientific Director and the Bavarian State Ministries in making strategic decisions regarding present and future MQV projects.

The independent evaluation by the SAB provides quality assurance of the MQV projects and public accountability for the appropriate and effective use of funds.

Prof. Christine Silberhorn, Chairwoman
Paderborn University, Germany

Manuel Alves Mendes
NXP, Germany

Prof. Markus Aspelmeyer
University of Vienna, Austria

Prof. Per Delsing
Chalmers University of Technology, Sweden

Dr. Volkmar Denner
fmr. CEO of Robert Bosch GmbH, Germany

Dr. Bettina Heim
NVIDIA, Switzerland

Prof. Kurt Mehlhorn
Max Planck Institute for Informatics and Saarland University, Germany

Prof. Roee Ozeri
Weizmann Insititute of Science, Israel

Prof. Anita Schöbel
Fraunhofer Institute for Industrial Mathematics ITWM, Germany

Prof. Andreas Tünnermann –
Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Germany

Prof. Stephanie Wehner
Delft University of Technology, The Netherlands

Dr. Sabine Wölk
German Aerospace Center, Germany

Prof. Peter Zoller
University of Innsbruck, Austria

1.2.4 MQV Office

The MQV Office supports the Executive Board, the Scientific Director, and all members and partners in administrative tasks, fundraising and application processes. It gives Munich Quantum Valley (MQV) a unified voice in communication with the press, funding agencies, investors, industry partners, politics, and the general public.

The MQV Office is the first point of contact for all internal and external inquiries from MQV members, industry partners, ministries, and funding agencies. Together with the MQV Scientific Director, it is responsible for the overall management and strategic coordination of MQV. It oversees the supervision and steering of the MQV research program, including the survey of the project progress regarding deliverables and milestones, periodic reporting, and budget spending. It also takes care of the preparation of annual reports and recommendations for the Scientific Advisory Board and the involved Bavarian State Ministries.

The MQV Office also engages in public outreach to create a broad public understanding of quantum technologies and their benefits to society, as well as to make MQV and its research and development program visible on a national and international level. It develops educational, social media, and online content, collaborates with the media, and organizes events for a wide range of audiences.

Coordination and Administration

- contact point for ministries, consortia and partners
- budget supervision
- support of MQV Scientific Director and Executive Board

Project Steering and Supervision

- internal quality assurance
- supervision of milestone plan
- adjustment of project plans

Partner Network and Quantum Ecosystem

- fostering a quantum ecosystem
- setup of industry partner network
- national and international collaboration

Education and Entrepreneurship

- coordination of educational programs for industry
- support of entrepreneurial activities
- support of start-ups

Public Engagement and Events

- event support and organization: e.g. symposia, workshops, fairs, open days
- press workshops
- social media and online content

People at MQV Office. © MQV | Tatjana Wilk

1.3 Key Scientific, Technological and Structural Objectives

The development of quantum mechanics about a century ago led to the first quantum revolution, allowing us to describe physical systems within the framework of quantum theory. Only within the past few decades, we have learned to precisely engineer, control, and manipulate quantum systems. This led to the second quantum revolution, denoted as Quantum $^{2.0}$, where the deliberate engineering and control of tailored quantum systems allow for a wide variety of useful applications in quantum computing, simulation, communication, metrology, and sensing.

Meanwhile, quantum technologies belong to the most important key technologies of the 21st century. The transfer of quantum technologies into applications is expected to significantly impact our lives and lead to disruptive changes in markets.

Universities and research institutions in Bavaria have been pioneering many quantum science and technology developments for decades. They put Bavaria in an excellent position to take a leading role in shaping the second quantum revolution and translating quantum technologies into useful applications. Munich Quantum Valley (MQV) builds on these unique strengths and joins the efforts of leading research institutions and high-tech companies to make Bavaria an internationally leading science and economic location for quantum technologies. By combining the established network of excellent quantum research with high-tech industry and start-ups, MQV is predestined to play a leading role in industrializing quantum technologies, developing profitable products and services, and using their large potential for innovation and creating added value. Based on the joint action of academia, industry and politics, MQV can propel Bavaria to the forefront of the emerging quantum markets and make it a leading player in the international competition for ideas, brains, markets, and venture capital.

Based on a well-defined long-term strategy and result-oriented technology roadmap, MQV has established clear priorities for key measures described in the following.

1.3.1 Building quantum computers

A key goal of MQV is to develop and operate competitive quantum computers in Bavaria.

Whereas classical computers encode and process data in binary bits (0s and 1s), quantum computers work with quantum bits (qubits). The distinctive property of a qubit is its ability to exist in either of two discrete states, 0 or 1, as well as in any coherent superposition of the two states. This unique property gives quantum computers more memory capacity and higher computing power than classical computers.

Building a quantum computer requires the fabrication of qubits using a suitable hardware platform and the preparation of well-defined quantum states with high accuracy. To realize logical operations, interactions between the qubits must be precisely controlled, and finally, the resulting states must be accurately determined to obtain the computational result. A major problem is the sensitivity of qubits to environmental noise, leading to decoherence by perturbing the fragile superposition states and thus errors in quantum information. Overcoming this problem requires near-perfect isolation of the qubits from the environment during manipulation. However, since this is difficult to achieve in practice, 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.

At present, it is not clear which hardware platform will show the best overall performance in the long term. Therefore, MQV will build and operate quantum computers based on three different platforms: ***superconducting quantum circuits***, ***trapped ions***, and ***neutral atoms***. Each platform has demonstrated the potential to perform basic quantum-logic operations with varying degrees of accuracy. However, a multitude of challenges remains. At present, the scaling of quantum processors to a larger number of qubits without deteriorating the precise controllability and manipulation of qubits or the ability to perform operations with many gates, are key challenges that are addressed by the MQV research program. In parallel with the development of quantum hardware, tremendous 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 so-called 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 and have tens to thousands of qubits. On a longer time scale, error correction is expected to become feasible, allowing for the realization of fault-tolerant quantum computers.

MQV develops and will operate full-stack quantum computers by the strongly interleaved R&D program of the following multidisciplinary consortia, developing all layers of a quantum computer, from hard- and software up to applications, thereby creating maximum synergy:

SQQC – Superconducting Qubit Quantum Computer

TAQC – Trapped Atom Quantum Computer

SHARE – Scalable Hardware & Systems Engineering

Q-DESSI – Quantum Development Environment, System Software & Integration

QACI – Quantum Algorithms for Application, Cloud & Industry

THEQUCO – Theoretical Quantum Computing

HAT – Hardware Adapted Theory

MQV takes a holistic approach, where software engineering goes hand in hand with the hardware-related tasks and connects them to the high-level application.

1.3.2 Establishing a powerful quantum ecosystem

Developing a successful industrial cluster for quantum technologies and applications in Bavaria in the long term is only possible by joining forces in science and industry. Therefore, the continuous fostering and extension of a vibrant quantum ecosystem and positioning Bavaria as a key player in the development and commercialization of quantum technologies are important cornerstones of the MQV mission.

In the field of fundamental science, a successful ecosystem has already been developed in the past two decades in Munich and throughout Bavaria within coordinated research programs of Collaborative Research Centers, Graduate Schools, and Excellence Clusters, joining the efforts of different universities and research institutions and researchers from different disciplines. There are also strong links on the national level, for example, within the Quantum Alliance – a network of the quantum-related excellence clusters in Germany – and several BMBF-funded projects. On the international level, there are fruitful collaborations within several projects of the EU Quantum Flagship.

An important aspect of the MQV mission is to extend the quantum ecosystem to industrial partners, investors, and potential users of quantum technologies. Measures that have been successfully started are the Partner Network, which brings together stakeholders from research institutions, universities and companies to promote quantum science and quantum technologies in Bavaria.

1.3.3 Establishing a Quantum Technology Park

A key objective of MQV is to establish core cross-functional elements to create a leading ecosystem and state-of-the-art infrastructure for quantum technologies in Bavaria. The Quantum Technology Park, providing the technological tools and engineering know-how for realizing quantum technology and enabling product development, is one of these core elements. In order to finish the realization of the Quantum Technology Park as soon as possible, the MQV member institutions focused on speeding up planning processes for new infrastructure and on advancing or even finishing ongoing construction efforts. Coordinating the various infrastructure elements operated by different institutions at different locations has been started in parallel. → 4.4

1.3.4 Fostering quantum entrepreneurship

Translating world-class fundamental research in quantum science and technology into innovative, scalable businesses and accelerating the commercialization of quantum technologies for society, are key components of the MQV mission. To implement this mission, tailored entrepreneurship activities are considered most promising, since the gradual transfer of know-how from research to the existing industry is often slow and hardly possible due to a lack of already available experts. Therefore, a key task of MQV is fostering quantum entrepreneurship. The entrepreneurial efforts of MQV fully focus on supporting scientists and engineers in their plans to commercialize technologies and on driving the entrepreneurial mindset in the quantum community. They are driven by the Venture Lab Quantum which is also part of the larger TUM Venture Lab initiative, supporting deep tech and life science start-ups across different domains. → 4.5

1.3.5 Educating the next generation of quantum scientists and engineers

Whenever new technology fields are starting up, the lack of a sufficient number of skilled experts is often limiting development speed. Therefore, the early education of the next generation of quantum scientists, engineers, and technicians is as important as the further education of the already existing workforce in companies. In close collaboration with universities and partners in federally funded projects, MQV develops and offers targeted training and re-education programs on all aspects of quantum technologies. → 4.3

1.4 Munich Quantum Valley in numbers

18 Industrial partners

13 Academic partners

6 Patents

227 Scientific publications

Find a non-exhaustive list of MQV publications on our website.

Social Media Follower
(31 Dec 2023)

LinkedIn	Instagram	Mastodon	X
7332	683	101	1258

11
Talks within MQV Colloquium

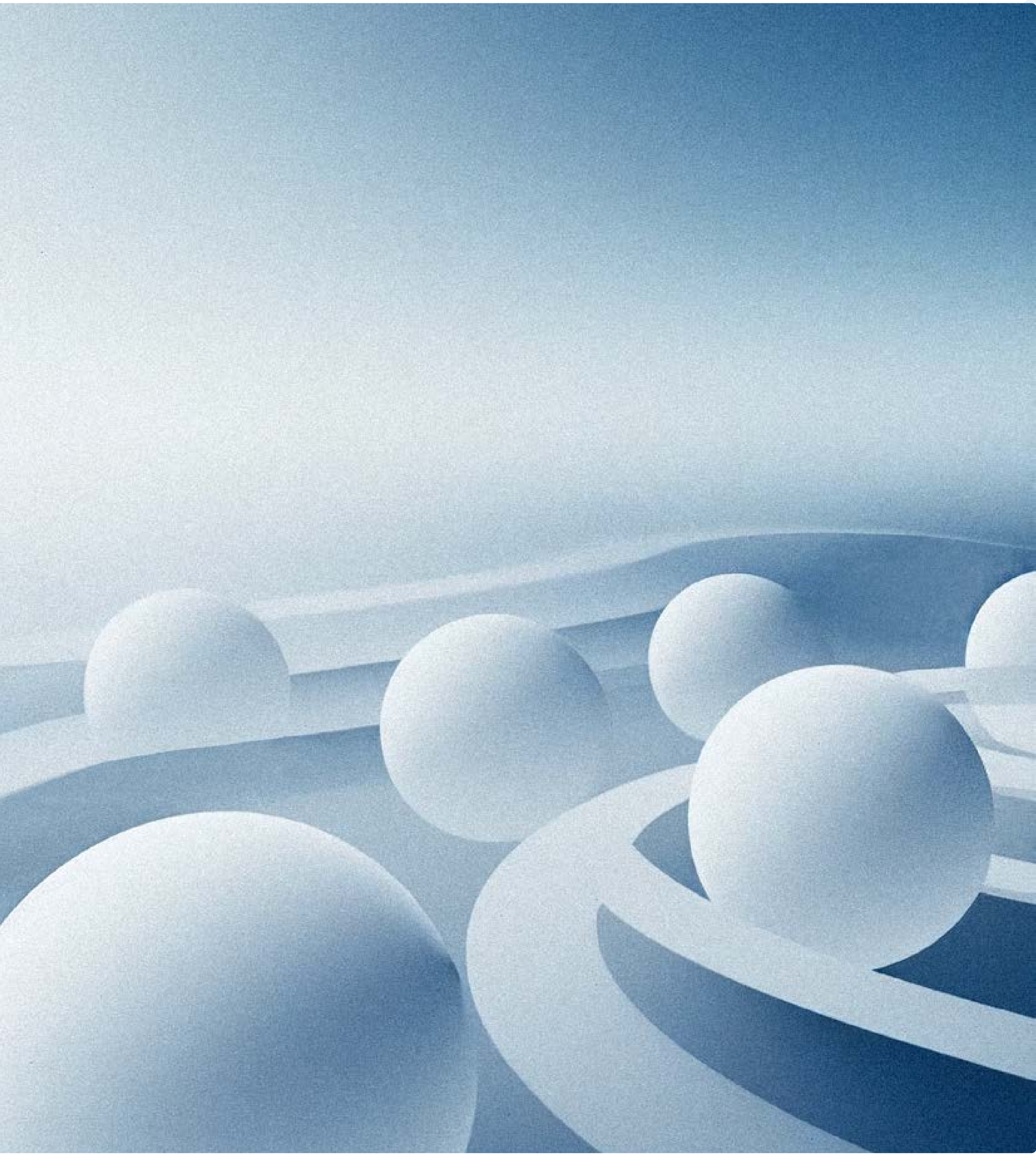
14
Public events

192
Scientific talks

400
Scientists

17
Research institutes

Impressions from the Walther Meißner Institute. © MQV | Mikka Stampa



Chapter 2

2 Spotlights

2.1 Remote access to the first German six-qubit quantum processor

In the pioneering effort of the superconducting qubit research within Munich Quantum Valley, the Walther Meißner Institute (WMI) and the Technical University of Munich (TUM) have recently demonstrated remote access to their quantum processors. For the first time, a quantum computer developed entirely in Germany will be available to collaborators and registered users to program quantum experiments and run them live on a six-qubit processor.

In the WMI laboratories, quantum processors are controlled by sending carefully designed microwave pulses to a chip that is cooled to 273 degrees Celsius below zero. This temperature is achieved by a so-called dilution refrigerator, which uses a transition between superfluid helium phases for cooling. Such low temperatures are necessary to preserve the fragile quantum states that carry the information of the computation, which must be protected from all sources of noise, including heat.

In the WMI-built quantum processor, the six qubits are arranged in a ring-shaped connectivity architecture. To control interactions between neighboring qubits, tunable coupling elements that can be modulated or shifted in frequency are used to mediate the interaction strength and to realize two-qubit operations. On the current device, single-qubit gates can be operated at 99.8% and two-qubit gates at 94% fidelity. The average qubit lifetime amounts to 36 microseconds, which would theoretically allow about one hundred qubit operations.

By carefully characterizing the operations on the qubits, researchers at WMI can provide a set of operations – which act as logical quantum gates – that can be put together into a full-fledged quantum algorithm. While such operations are very similar to basic logical operations on classical computers, classical computers hide this layer of access from the user by translating the actual program code, through several compiler stages, to this basic logic language. However, with currently available quantum computers, users can directly apply sequences of fundamental logic operations, the qubit gates, by applying microwave pulse signals to individual qubit units in order to manipulate the quantum state and observe its dynamics in real time.

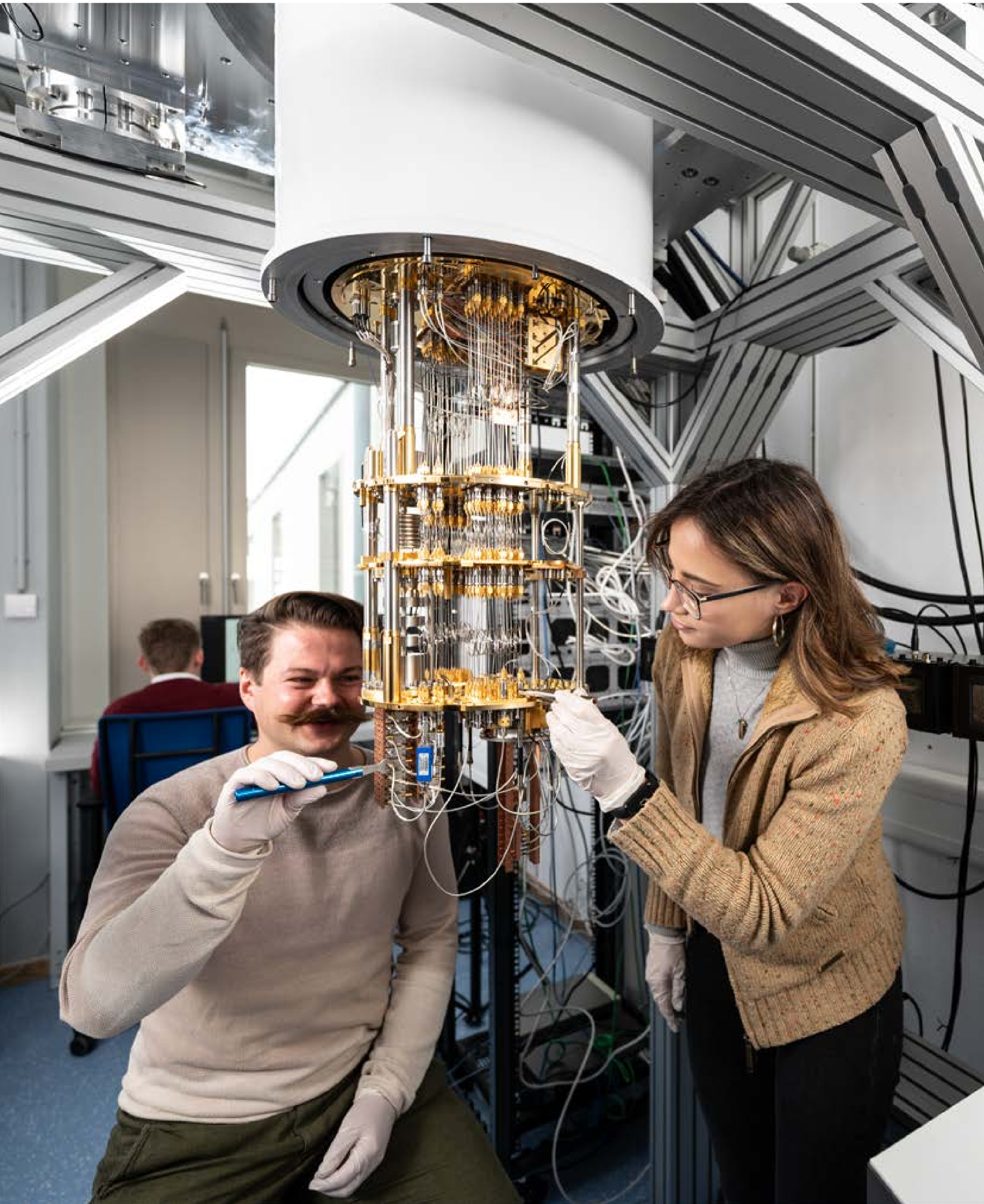
For application-oriented researchers, it is of great interest to have access to quantum hardware and instead of running numerical simulations, to test directly how a real quantum system behaves. By working directly with quantum computing hardware, problems such as the influence of noise on quantum computation or the need to consider certain implementation details can be studied, solved, and improved.

Access to the hardware can vary in its level of abstraction. Since currently available quantum hardware is not yet capable of running practical algorithms, the WMI cloud interface allows more fundamental quantum experiments to be performed. To guide users in this process, WMI has created a collection of pre-designed experiments that provide an introduction and explanation of the experiments that users can perform on the quantum hardware. A well-known example is the Rabi experiment: By incrementally increasing the amount of energy that is sent to the qubit by varying the amplitude of a microwave control pulse, one can cause the quantum state to evolve. This can be observed from an oscillating signal, which is plotted as a function of the signal amplitude and represents the probability that the qubit is prepared in the excited state. This level of control is crucial for preparing one of the key capabilities of the quantum computer, which is to prepare quantum bits in a superposition state, meaning that the qubit exists simultaneously in the logical states of 0 and 1.

The second unique feature of a quantum computer is its ability to create entangled states which can only be observed when more than one qubit is used. Entangled qubits can no longer considered separate entities but rather represent a combined quantum state, with exponentially increased information content.

The creation of entanglement in the system requires precise control of the interaction between two or more qubits. Another experiment in WMI's cloud environment can create a Greenberger–Horne–Zeilinger (GHZ) state, a state with a particularly high entanglement value. Using quantum tomography methods, the creation of this GHZ state could be verified with an accuracy of 96 %, demonstrating the entanglement capabilities of the quantum computer at WMI.

Based on these experimental templates, users can design their own experiments and quantum algorithms to gain insight into the operation of quantum algorithms on superconducting qubits. Currently, access to the device is prioritized for the realization of experiments within Munich Quantum Valley. In the coming years, the researchers at WMI plan to gradually increase the number and the performance of quantum processors that will become available to the public. Together with the partners of MQV, including the LRZ, the computer science departments of TUM, and the theory collaborations within MQV, this cloud access demonstrator will be used as a learning device for all partners to align on interfaces, standards, and methodology.



2.2 Pushing quantum technology towards industry requirements

The SHARE consortium aims to develop electronic components and system components for future quantum computers. This includes semiconductor technology and functional and scalable quantum computing hardware integration. In 2023, already major steps in this direction have been made.

Superconducting ultra-high density wiring

Within the SHARE consortium, the Fraunhofer Institute for Electronic Microsystems and Solid State Technologies (EMFT) in collaboration with the Fraunhofer Institute for Integrated Circuits (IIS) and the Fraunhofer Institute for Integrated Systems and Device Technology (IISB) succeeded in the first full fabrication of shielded, flexible superconducting cables and connectors. This development is of key importance as large-scale quantum processors (> 30 qubits) require a much higher number of microwave signal lines for qubit control and readout. The flexible cables developed by SHARE enable

- increasing the signal-line density due to small signal-line pitches and cross-sections,
- scalable manufacturing due to the highly automated fabrication process based on a reel-to-reel process,
- simple installation of the cables high integration level due to the high flexibility of the cables, and
- integration of additional components such as attenuators and filters directly within the cable.

Photo of a flexible superconducting cable and associated connector.

Fabrication of superconducting qubit chips on 200 mm silicon wafers

The scaling of superconducting quantum processors to larger qubit numbers requires the development of fabrication processes on 200 mm silicon wafers using industry-scale tools. Within the SHARE consortium, Fraunhofer EMFT in collaboration with Walther Meißner Institute of SQQC consortium demonstrated the fabrication of the first qubit chips on 200 mm silicon wafers. This step is important to evaluate the capability of the production line at Fraunhofer EMFT for qubit fabrication. It is also a prerequisite for the subsequent technology developments and optimization steps that are needed for reliable, reproducible, and device-matching fabrication of superconducting qubit components at the industrial-scale.

Proof-of-concept test chips for scalable control hardware

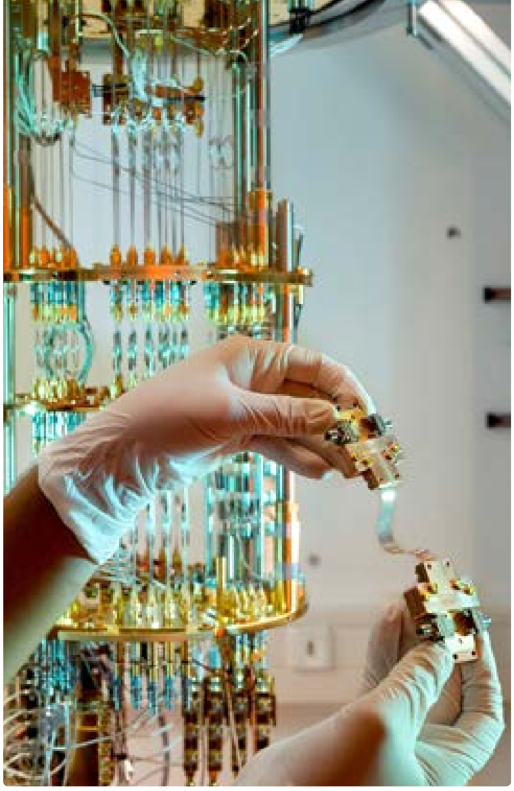
Working towards SHARE's goal of developing novel integrated circuits, the crucial first step involves the construction of test chips and device structures. These test chips serve as the basis for further exploring new possibilities to drive innovations in quantum computing by operating control electronics at extremely low temperatures, only a few degree of kelvin above absolute zero.

Fraunhofer IIS has successfully completed the tape-out of two test chips for the consortium's quantum computing project. The first test chip features a radio-frequency digital-to-analog converter (RF-DAC) designed to operate at cryogenic temperatures (4 kelvin). This RF-DAC is accompanied by a radio-frequency (RF) mixer circuit, enabling precise control of a single qubit within the frequency range of 4–8 GHz. This corresponds to the typical operating range of so-called superconducting transmon qubits, which are currently being developed by SHARE's partners in the SQQC consortium. The test chip serves as a proof-of-concept for the long-term scaling plans of the SHARE consortium, which aim to develop control circuits for thousands of qubits. To this end, the proximity of the control electronics to the qubit chips is crucial for achieving this scalability.

Fraunhofer IIS has also taped-out a second test chip that incorporates a complete analog RF chain capable of generating RF pulse signals ranging from 2–9 GHz at room temperature. This test chip demonstrates the integration of the analog part of a qubit drive channel, as can be found in commercially available qubit control hardware, into an application-specific integrated circuit (ASIC). It showcases the path toward future scalability of laboratory tools utilized in qubit chips with high qubit numbers (>100). These tape-outs represent significant milestones in SHARE's project, pushing the boundaries of quantum computing and laying the foundations for future advancements in the field.

Test structures for single transistors and transistor switches for multiplexing

With SHARE, the Department Elektrotechnik-Elektronik-Informationstechnik (EEI) of the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) has designed and manufactured test structures for single transistors and transistor switches for multiplexing. The assembled boards are ready for characterization at cryogenic temperatures and technology verification at the mK temperature range. Here, lumped component low-noise amplifiers (LNAs) have been designed and manufactured for switched amplifier concept verification.



A flexible superconducting cable interfacing two microwave connectors.

A signal processing platform prototype for controlling an optical modulator

Within SHARE, Fraunhofer IIS in collaboration with TAQC has integrated all necessary building blocks, components and modules into a running laboratory demonstrator of a signal processing platform prototype for controlling an optical modulator. Here, a dedicated software was developed for running the demonstrator, where arbitrary pulses are generated at arbitrary timestamps. The interfacing electronics drive a connected acousto-optic modulator (AOM) and later an electro-optic modulator (EOM). Laser signals were received and read-back via a photodetector that was also electronically interfaced to the platform device.

2.3 Discovery of quantum-error-correction codes with machine learning

Quantum states are inherently sensitive to interactions with the environment. While this can be useful for applications in quantum sensing and metrology, it also poses a major challenge in the design of quantum-computing devices: qubits need to be isolated from the rest of the world, while at the same time they need to be controlled to implement a quantum circuit.

Any undesired interaction of the qubits with the environment, for example from fluctuations of the electric or magnetic fields, can perturb the state of the qubits. It leads to wrong results of the computation and is thus considered as noise. Classical bits have only two discrete values, say “on” at a high voltage or “off” at a low voltage, and small fluctuations around the high and low values do not matter and can be easily corrected. In contrast, quantum bits can be in continuously tunable superposition states, and measuring the state even causes the wave function to collapse, changing the state of the qubit. Developing strategies to cancel these effects remains an important open challenge for the realization of more powerful quantum devices.

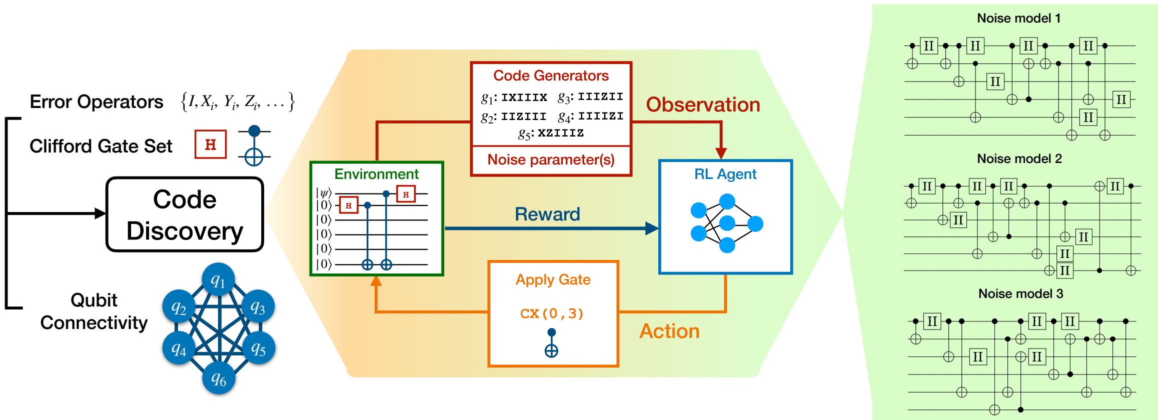
The current generations of quantum devices developed at Munich Quantum Valley (MQV) and worldwide aim at further reducing the noise and improving the level of control. However, one needs to think more generally about how to correct errors in quantum devices, which is the long-term perspective of ***quantum-error correction***. In this approach, many physical qubits implemented in the quantum hardware are combined in clever ways to encode the quantum information of one (or a few) logical qubits in a subspace, often called the “code space”, on which the desired computations are ultimately performed.

This code space must be chosen in such a way that errors on the physical qubits bring the state into mutually orthogonal subspaces, which is ensured by satisfying a set of equations, the so-called Knill-Laflamme conditions. Provided that the noise rate on the physical qubits is low enough, the errors can then be detected by partial measurements and ultimately be corrected to recover the original quantum information of the logical qubit, making the whole computation error-free.

Quantum-error correction is only possible at the cost of a significant overhead of combining a large number of physical qubits into a single logical qubit. Different hardware platforms have different connectivities between the qubits, and each device has its own characteristic level of noise that needs to be corrected. It is therefore important to choose the encoding into the logical code space that is tailored to the specific hardware and noise type. This motivated researchers at the Max Planck Institute for the Science of Light (MPL) to automate the discovery of quantum-error-correcting codes adapted to these needs using reinforcement learning, a machine-learning technique that excels at finding optimal action sequences in hard decision-making problems.

In the reinforcement learning setup, an agent in the form of a deep neural network is trained to make decisions. The agent chooses gates to be applied to the physical qubits from the set of gates allowed by the hardware. In this way, it gradually builds a quantum circuit that represents the encoding of the logical qubits into the space of the physical qubits. How well the agent performs is measured by a reward function, for which the researchers directly used the Knill-Laflamme conditions as a fundamental criteria for a suitable code space. This makes their strategy very general, allowing in principle to discover ***any*** stabilizer code. Unlike other machine-learning techniques, the training of the agent does not require large amounts of existing data that can bias the training. Rather, the agent explores new ideas in many iterations of trial and error until it finds a suitable strategy and consistently performs well, at which point the training is stopped.

Using this setup, the researchers at the MPL are able to discover many quantum-error-correction codes. They can also rediscover known codes from the literature, including the Shor code, Steane’s code, and Laflamme’s perfect code. Since their training gives them an efficient way to discover ***all*** stabilizer codes with different code families, they are even able to classify them. Moreover, the researchers at MPL demonstrated another very powerful aspect of the reinforcement-learning-based encoding and code discovery: One and the same agent can learn to switch its encoding strategy depending on some parameter characterizing the noise in the physical hardware. For uniform error rates, the agent finds conventional symmetric encoding strategies. In contrast, if certain errors have a higher probability than others, this noise-aware agent will be able to find encodings corresponding to asymmetric quantum codes that best protect the quantum information in this biased noise setting. This tailored quantum-error correction may provide useful strategies for error correction in near-term quantum devices.



Scheme for reinforcement-learning based discovery of quantum-error-correction codes and encoding circuits.

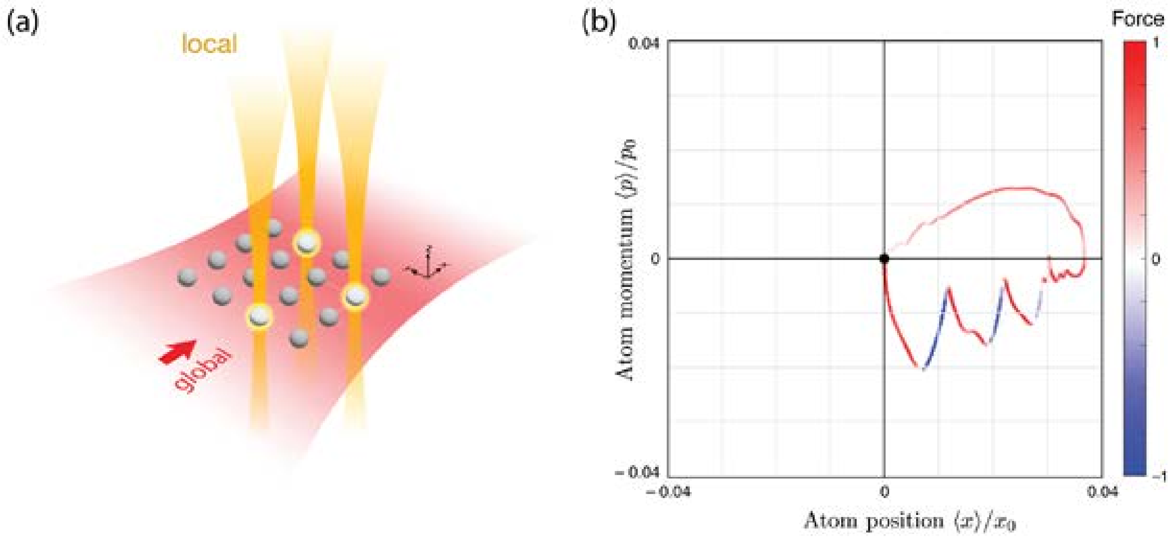
2.4 Design of novel high-fidelity quantum gates

Quantum technology based on strontium atoms is well established for precision time measurement and geodetic applications: The frequency of a very stable laser is compared to the resonant frequency of an ultra-narrow atomic transition, enabling today's most precise clocks. The ultra-narrow transition naturally defines two atomic states that can be used to store and manipulate the qubit. This is called an optical qubit.

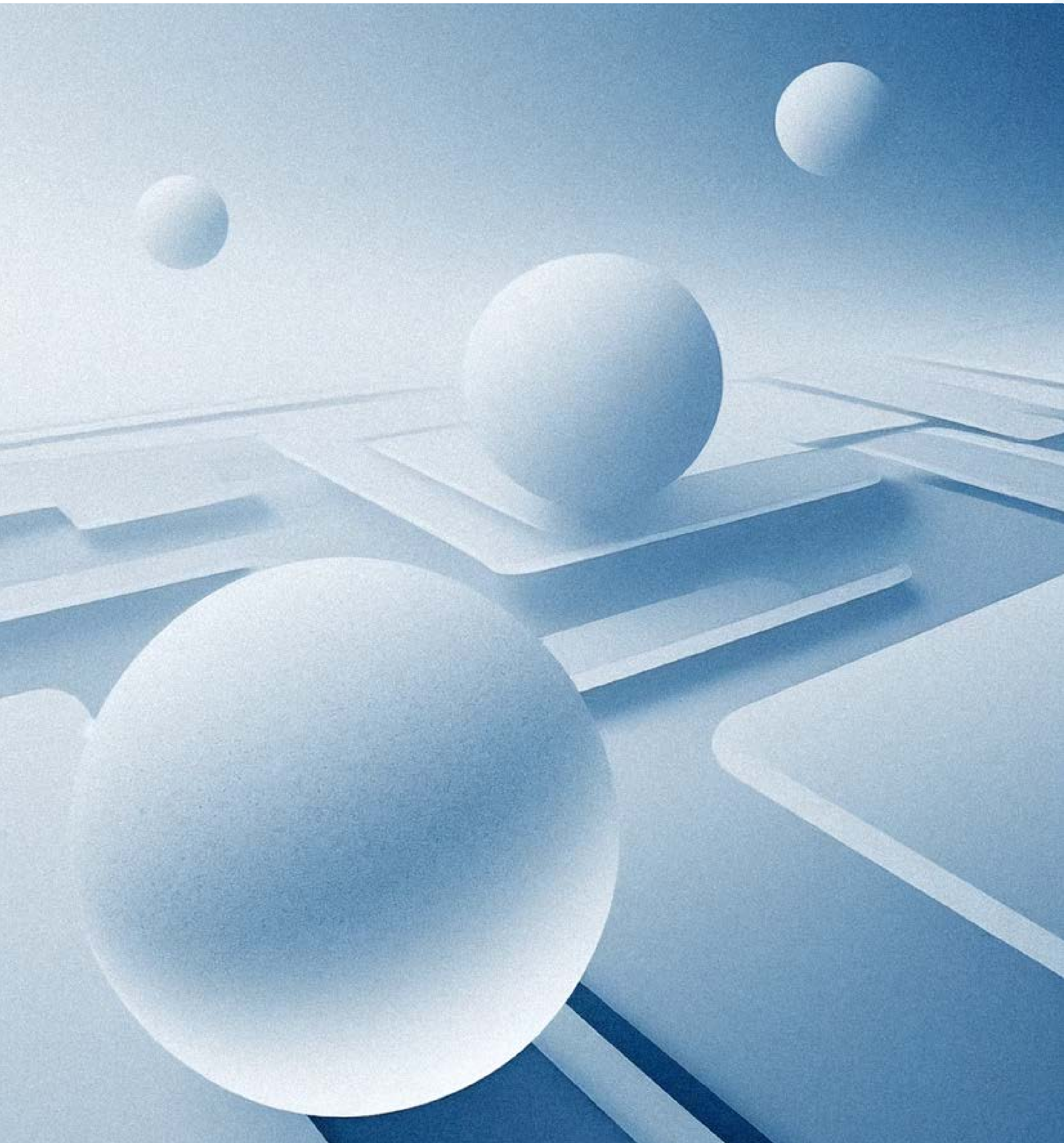
Although optical qubits offer a long coherence time, they pose significant challenges for the realization of scalable quantum computers. In contrast to optical clock technology, the ultra-narrow transition must be driven in the shortest possible time in order to connect many quantum gates in series. However, the fast driving of the optical qubit leads to a heating of the atoms due to the momentum of the absorbed photons (i.e. the light quanta of the excitation laser). Moreover, the fast driving of the optical transition makes the gate more susceptible to errors caused by the inhomogeneity of the laser intensity in the qubit array, because the central frequency of the ultra-narrow transition is shifted differently for each qubit of the quantum register depending on the intensity. These inhomogeneous shifts of the transition frequency lead to decoherence of the optical qubit. The suppression of these error sources, motional heating and inhomogeneous frequency shifts, is crucial to realize long sequences of coherent gates with the quantum-computer demonstrator TAQC of Munich Quantum Valley (MQV).

In collaboration with the quantum-control group from the consortium HAT, TAQC has designed a novel scheme that overcomes the challenges inherent to optical qubits, thus opening the way to parallel, high-fidelity quantum gates on a scalable atom array. The basic idea is sketched in Figure (a), where fast gates addressing individual atoms are combined with the optical ultra-narrow transition, which acts globally on the entire quantum register. Errors due to inhomogeneity of the global laser excitations can be precisely eliminated by controlling the fast, local gates for each atom individually in the pulse sequence, while the heating effect on atoms can be mitigated by using optimal quantum control to modulate the frequency of the excitation laser. The frequency modulation ensures that the motional state of each qubit, i.e., the position and velocity of the corresponding atom, is left virtually unchanged after performing the gate, as shown in Figure (b), thus preventing heating of the atoms. Eliminating atoms' heating is crucial to extend the number of gates that can be coherently executed into the hundreds. This large number of coherent gates is required for the application of quantum-error correction codes.

The novel scheme not only paves the way for large-scale quantum computing with optical qubits, but also holds potential for better control of analogue quantum simulators taking advantage of the same ultra-narrow transition, and for programmable optical clocks that use quantum entanglement as a resource for more precise timekeeping. The novel scheme will be demonstrated experimentally by TAQC next year.



(a) A laser beam globally drives an optical transition of strontium atoms for the entire quantum register, while tightly focused laser beams enable l ocal control of the individual atoms that form the quantum register. (b) Diagram showing the state of motion of the atom during the execution of a quantum gate. After performing the gate, both the atom's position and momentum (i.e., velocity) return to the original state in the origin.



Chapter 3

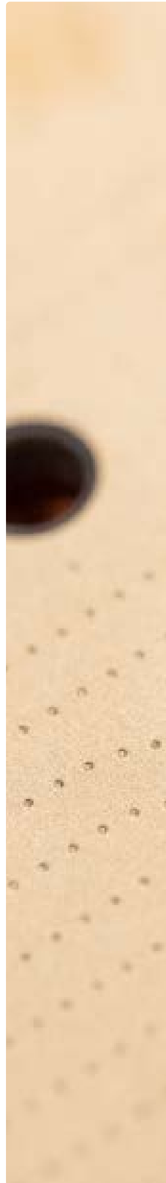
Research and development

To reach its primary goal of developing and operating competitive quantum computers, Munich Quantum Valley (MQV) follows a "full-stack" approach: Multidisciplinary consortia develop all layers of a quantum computer, from hardware and control to software and applications. On the hardware side, MQV's quantum-computing research encompasses three different platforms: superconducting qubits, neutral-atom qubits, and trapped-ion qubits – each with different characteristics and advantages for different use cases. This MQV approach ensures that the mutual benefits cross-fertilize when it comes to developing scalable platforms.

The Superconducting Qubit Quantum Computer (SQQC) consortium provides superconducting quantum systems known for their design versatility and excellent controllability. The Trapped Atom Quantum Computer (TAQC) consortium provides 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 these hardware technologies to use them 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 the fabrication of scalable integrated chip technology (superconducting quantum devices for SQQC, chip traps for TAQC, and fast electronic control for both). The Quantum Development of 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 consortia are funded by the Hightech Agenda Bavaria and collaborate internally as well as with matching associated projects funded by the German Federal Ministry of Education and Research (BMBF), the German Federal Ministry of Economic Affairs and Climate Action (BMWK) and the European Union.

3.1 Superconducting Qubit Quantum Computer (SQQC)



Superconducting qubits are promising candidates for large-scale quantum computers and are at present in the focus of intense research, development, and commercialization activities. Systems with more than 400 qubits have already been realized in 2022 by international industrial players. However, while ground-breaking new developments in terms of the performance of superconducting quantum computers are to be expected in the upcoming years, many technical challenges still loom on the horizon and could eventually hinder scaling to millions of qubits.

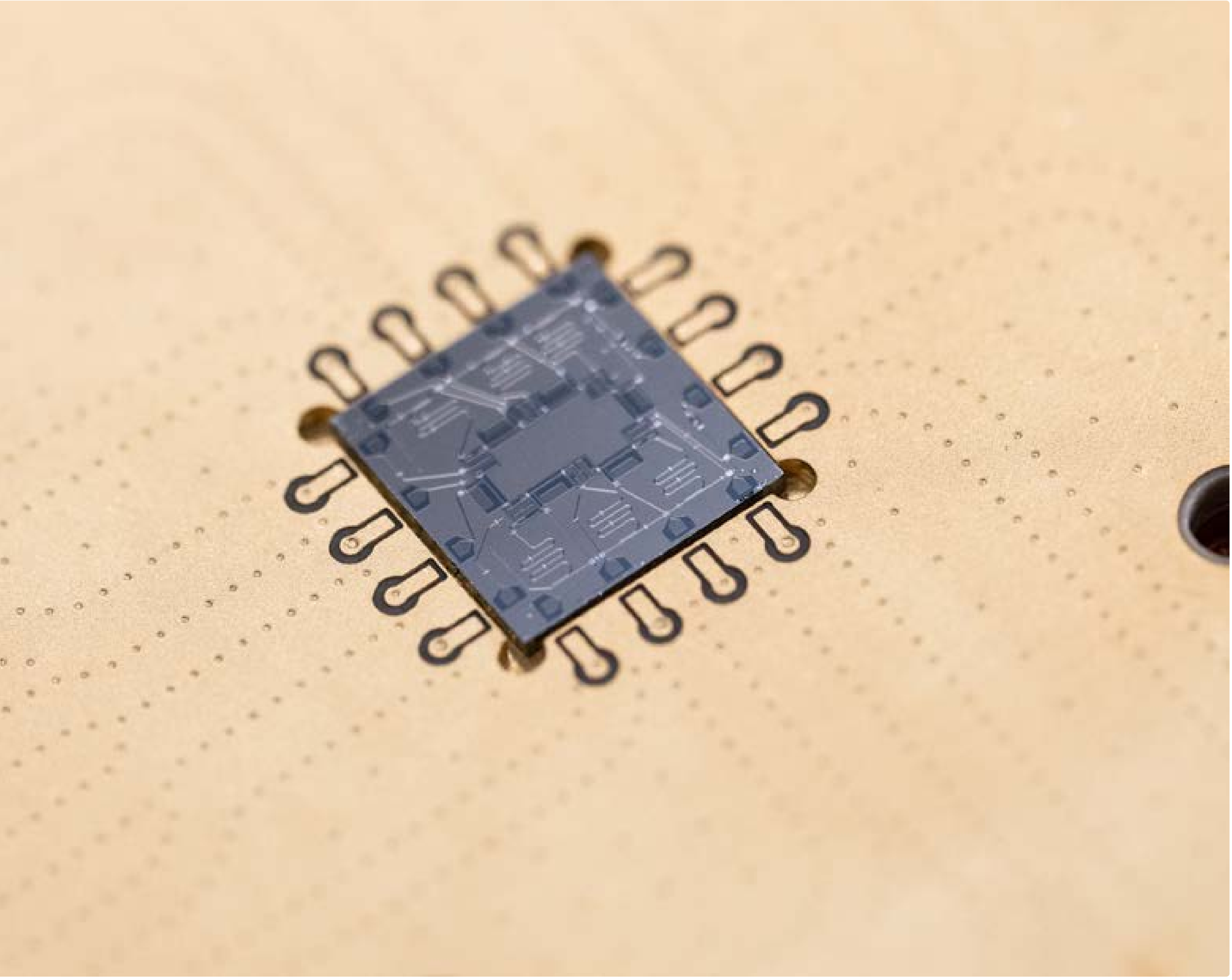
To solve these challenges and eventually enable competitive quantum computers, the SQQC consortium is developing scalable quantum processors as well as novel types of superconducting qubits within Munich Quantum Valley (MQV), as well as supporting technology for the whole quantum-computing pipeline. A six-qubit quantum computer, developed in collaboration with the federally funded GeQCoS and MUNIQC-SC projects, is already in operation and is being used to push the limits of both hardware and software. Eventually, a 24-qubit processor will be provided after five years. These quantum processors will enable us to execute proof-of-principle algorithms and allow for the demonstration of basic principles of error correction schemes, relating to the theory and algorithmic developments within MQV.

For the development of larger quantum-computing devices, the SQQC consortium has adapted a two-stream research strategy dividing the efforts into two distinct branches: First, following the success in the industry, a scaling branch aims to use the conventional transmon qubit to explore the challenges associated with upscaling of quantum systems. A second stream focuses on the development of novel qubit types, so-called generalized flux qubits or fluxonium qubits. These circuits have demonstrated advantages over transmons in terms of coherence time and control at the cost of increased complexity and fabrication requirements.

On the scaling branch, the aforementioned six-qubit chip is a current highlight within MQV. It presents the first German fabricated quantum computer with remote access via a cloud infrastructure and can execute quantum operations, so-called gates, with high fidelity. The quantum computer has been manufactured at the Walther Meißner Institute (WMI) and the Technical University of Munich (TUM). It consists of six qubits arranged in a ring-shaped connectivity architecture. Qubit couplings are controlled by tunable coupling elements that can be modulated or moved in frequency to induce interactions between the two qubits. One of the unique key features of a quantum computer is its ability to create entangled states which can only be witnessed when using more than one qubit. Loosely speaking, it can enforce the state of one qubit to depend on the measurement of another qubit. To showcase the capabilities of the quantum computer at WMI, the researchers have created a so-called Greenberger–Horne–Zeilinger (GHZ) state – a state with particularly high entanglement value – with an accuracy of 88 % (→ 2.1).

Fluxonium qubits represent a fundamentally different qubit type in the realm of superconducting quantum circuits. At the heart of a fluxonium is a superinductance component, typically realized through an array of Josephson junctions. This additional component, although adding a layer of complexity and fabrication challenge to the circuit, offers notable advantages. Specifically, the fluxonium features a non-trivial energy level landscape, enhancing its resistance against leakage out of the computational subspace, allowing therefore very fast, and high-fidelity operations. Notably, the longest coherence times ever recorded in superconducting circuits have been achieved recently using this design. Over the past year, WMI has made significant progress in fabricating single fluxonium qubits. Qubit lifetimes of up to 200 μs have been achieved, demonstrating excellent control with an error rate of less than 0.1 %, thereby enabling impressive 4000 operations before the qubit loses its quantum-information content. Building on this success, WMI is delving into these circuits' scaling behavior, advancing towards two-qubit gates, and exploring their full potential for quantum processing units.

To move to larger quantum devices, the clean-room facilities of the SQQC partners have been improved and fabrication processes have been optimized: the internal quality factors of superconducting quantum circuits, a typical measure of robustness to loss, are now approaching nine million, up from five million at best in recent years – surpassing values reported in the international community. This shows that SQQC has made considerable progress by optimizing fabrication process parameters and surface-cleaning recipes, which in turn translate into higher quality qubits with



A quantum-computer chip with six superconducting qubits (and tunable couplers) oriented in a ring-like architecture.

lifetimes over 200 μs on average and record coherence times over 300 μs on average. Coherence time refers to the time over which qubits can maintain their quantum mechanical state and is now ten thousand times longer than the duration of typical gates on the qubits. The major remaining limiting factors towards achieving even higher coherence times are losses due to so-called two-level system (TLS). Those losses stem from exposing the superconducting metal, which forms the qubit, to air. By developing cleaning processes, impurities can be avoided and subsequent coating of the surfaces ensures that the material interfaces do not degrade over time, leading e.g. to a reduction of the quality factor to 80 % of its initial value when exposed to air for over a week. This highlights the importance of the passivation of the resonators, guaranteeing stable quality factors over time. This method of passivation, developed at the Technical University of Munich, can be made compatible with existing device-fabrication methods. It can be well transferred to industrial, wafer-scale pilot-line fabrication.

However, good control and measurement of the quantum states are equally vital for the execution of quantum algorithms and future applications. In fact, at the end of each quantum algorithm, the state information must be measured with high fidelity. This operation is done by probing the qubits with ultra-low power microwave signals, which need to be amplified in order to be detectable with standard room-temperature measurement equipment. The SQQC consortium is therefore improving on amplifiers by numerical and analytical modelling to find optimized operation conditions. With the support of the BMBF project GeQCoS, ultra-low noise broadband amplifiers are experimentally realized, which allow for the readout of multiple qubits at once.

Furthermore, SQQC is engaged in close collaborations with the other consortia at MQV, for example with THEQUCO on novel qubit couplers, which have been theoretically designed to allow for very low error rates, and with HAT on improved routines for an optimal control of the qubits. Even outside of MQV, joint activities with the associated quantum-computer-demonstrators project on superconducting qubits, MUNIQC-SC, which focuses on the scalability of superconducting quantum processors, create a beneficial platform where the researchers of MQV can engage with industrial partners.

A cryostat to cool down quantum devices to cryogenic temperatures as low as 40 millikelvin. © MQV | Mikka Stampa

Researchers at Walther Meißner Institute performing experiments on a superconducting qubit. © MQV | Mikka Stampa

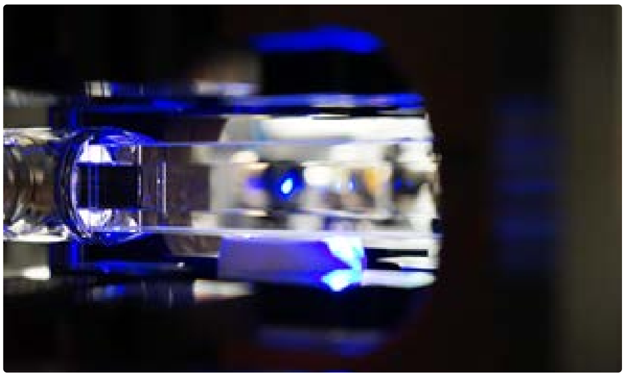
3.2 Trapped Atom Quantum Computer (TAQC)

The consortium TAQC aims at constructing the hardware for a quantum computer based on neutral atoms. In this technology, the basic calculation unit of the quantum computer, the qubit, is stored in two different quantum states of a strontium atom.

These atoms hover in almost perfect isolation from the environment inside an ultrahigh vacuum environment, where they are positioned in so-called optical tweezers. These optical tweezers can be thought of as tiny traps for atoms created by tightly focused laser beams. These traps fix the position of the qubits tightly during operation. The qubit states are manipulated using laser beams impinging on the atoms to perform calculations. 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 in size – 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.

In the second year, the TAQC consortium focused on integrating all the previously designed and planned systems into 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 so-called quantum gates. Building on the preparatory work in the first year of MQV, TAQC put particular emphasis on those aspects that should eventually allow for the creation of a usable device that can be accessed externally. This involves developing a dedicated rack system for laser frequency and intensity distribution. Contrary to the usual strategy of TAQC members to assemble sub-modules formed by dozens of mirrors on large optical tables, the consortium carefully works towards constructing specialized modules. Both lasers and also the planned optics modules of the TAQC setup are fully compatible with the integration into a standard 19" rack, which is a type of enclosure also found in modern supercomputing centers. Also, TAQC paid particular attention to designing a vacuum system that would allow for extremely low vacua, even lower than the vacua in outer space. For this purpose, TAQC used Titanium as a special material to achieve low pressures. In parallel, members of the consortium prepared all electronic systems required for the system to run autonomously, without manual adjustments during operation.



Magneto-optical trap of laser-cooled atoms. The temperature of the atoms in this cloud is just a fraction above the absolute temperature zero at –273.15 °C.


© MQV | Jan Greune

After assembling the core part of the system, the vacuum chamber, the researchers performed a so-called bake-out in order to remove any residual water adsorbed on the surfaces of the vacuum system. This step is always required in order to reach the required ultralow vacuum levels in the ultrahigh vacuum range.

After the successful bake-out, the optical systems required to deliver the most important laser beams for laser cooling and trapping were installed in the vicinity of the glass cell of the system, and a first signal of a laser-cooled atomic cloud was searched for. Eventually, researchers were able to find the so-called “blue magneto-optical trap”, where one can see a cloud of atoms hovering in vacuum, held by lasers and magnetic fields and at temperatures just 0.001 degrees above the absolute temperature zero. This magneto-optical trap is the starting point for all further steps in the consortium’s experiments and is an utterly important milestone for constructing the quantum-computing demonstrator.

After realizing the first magneto-optical trap, a high-resolution objective was quickly installed to create the optical tweezers that form the register for holding individual atoms. Once the objective was in place, TAQC members were able to form the first array of optical tweezers that could be used to trap atoms. It was then possible to observe how few atoms jump from the magneto-optical trap in the optical register, where they can then be made visible by shining near-resonant light to make the atoms fluoresce. The emitted fluorescence can be collected with the very same objective that also forms the optical tweezers in the first place.

Along the lines of miniaturizing and standardizing the major part of TAQC’s system, the members also started a joint development on so-called integrated optics. In the long run, this technology will allow 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. In the past year, the consortium was able to test the first versions of these photonic integrated devices. One of the most important questions for the application of these devices in neutral-atom quantum computers is their power durability. Therefore, researchers conducted careful tests of how much light intensity could be sustained by the integrated chip, which exceeded their expectations and is a promising lead for future studies.

Finally, an important part of TAQC’s work has been to collaborate closely with other partners within MQV. The main development thrusts in this regard are novel schemes to perform single-qubit gates. A key observation in this regard is the possibility to perform single-qubit operations on an optical clock transition without imparting a kick to the atom, which is usually the case for standard gates on optical transitions. TAQC is planning to benchmark these schemes also experimentally on their machine in the near future. A second important collaboration concerns the integration of the neutral-atom quantum computer into the higher-stack activities researched within MQV as a whole. In particular, in order to make the hardware accessible for users and problems formulated at an abstract circuit level, a compiler that performs a translation from the layer of the end-user to the low-level hardware is required.

Together with tool developers from the computer science department, the consortium laid out the hardware capabilities offered by neutral atoms, and developed a compilation flow that can be used to develop a fully-fledged compiler in a next step, thus connecting all partners 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 TAQC's strontium Ising simulator, researchers implemented an optical lattice to allow for high-fidelity and low-loss imaging of strontium arrays by pinning them in the lattice. This is a prerequisite for picking up atoms and moving them to arbitrary locations in the lattice grid. 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.

The efforts to realize a platform with the quantum information encoded in well-protected nuclear states of ytterbium-171 are also moving along smoothly. The experimental setup has been laid out and built, and is currently undergoing bake-out. After the ultra-high vacuum is established, the first laser cooling of the atoms will be performed with the goal to observe a magneto-optical trap. Afterwards, a tweezer array will be realized and first manipulation of the qubits performed.

The TAQC consortium closely collaborates with the recently founded quantum computing startup planqc, which is a spin-off from the Max Planck Institute of Quantum Optics. This collaboration provides a direct link between the fundamental research performed within MQV and the startup quantum ecosystem in Munich and Bavaria, making the findings of TAQC and MQV in general accessible to the end-user and bridging the gap between fundamental research and a commercial product.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3.3 Hardware Adapted Theory (HAT)

To address the main challenges in building a functional and beneficial quantum computer, including extreme precision and protection from outside interference, the HAT consortium has a crucial mission: to provide application-oriented theory support for the experimental platforms of Munich Quantum Valley (MQV) to enable the optimal execution of quantum algorithms.

This includes the numerical modeling of hardware, the use of optimal-control and machine learning approaches to design quantum gates, the tight integration of hardware and software development in co-design, quantum-error correction, quantum algorithms, as well as characterization, benchmarking, verification, and validation of gate operations, circuit building blocks and algorithms.

In the second year of MQV, HAT has made substantial advancements in its objectives by engaging in collaborative efforts within and outside the consortium. Researchers from the consortium have established close partnerships with hardware experts within the MQV project. Here, some of the key achievements from this year are highlighted.

To support hardware development, HAT is developing software libraries for numerical modeling of hardware components used in superconducting qubit (SQQC) and trapped atom (TAQC) quantum computers. Accurate numerical modeling and simulation of individual hardware components are essential to enhance the efficiency of fabrication and testing, ultimately leading to more reliable hardware. On this front, HAT has successfully delivered software libraries to SQQC, and work is actively continuing for TAQC.

Controlling individual qubits precisely is an important and yet, at the same time, challenging task. Developing and using the existing tools of optimal control to design noise-robust 'control pulses' is crucial to achieving better gate performances. In alignment with this objective, researchers from HAT are collaborating closely with hardware teams of SQQC and TAQC to understand the underlying physics of their hardware, which is required to design new protocols for control. With TAQC, HAT has successfully designed novel time-optimal control pulses capable of executing arbitrary single-qubit quantum gates. These new pulses exhibit robustness against the experimental fluctuations (noise) and go beyond the existing methods to minimize the entanglement between qubit subspace and motional states, a factor critical for gate performance. This collaboration has resulted in sharing a software library with TAQC, facilitating further development with enhanced capabilities. Simultaneously, in an ongoing effort with SQQC, HAT is designing control pulses to achieve noise-robust, high-fidelity single-qubit quantum gate operations with minimal leakage to unwanted quantum states. The ultimate aim is to create pulses that outperform existing methods while aligning with the specific constraints of experimental setups.

Along these lines, scientists from HAT are actively working on the development of an approach to implement algorithms for optimizing control sequences directly on a quantum device. This approach serves to enhance performance by adapting solutions based on direct feedback from the quantum device itself. Furthermore, HAT is both utilizing and advancing reinforcement learning tools to optimize control pulses for the execution of two-qubit gates in superconducting qubit hardware.

In an effort towards a hard- and software co-design approach, researchers from HAT have concentrated their efforts on developing shallow gate sequences for digital quantum simulations. This type of simulation, particularly the time evolution aspect, holds great promise for achieving quantum advantage. They created a method for classically optimizing gate sequences, which requires no quantum resources, making it viable for near-term quantum devices. This method demonstrates an enhancement in both efficiency and accuracy compared to established methods. The developed methods are not only beneficial for digital quantum simulations but also hold importance for fundamental issues in quantum optimization, particularly in addressing sampling problems through classical pre-processing.

Another crucial objective for enhancing the efficiency of quantum computers is quantum compilation. This process converts high-level quantum algorithms into a streamlined and executable format suitable for quantum computer implementation. In an ongoing effort within MQV, researchers from the HAT consortium are actively engaged in designing and devising strategies to achieve this goal, not only for the hardware developed within MQV but also for broader applications.

Quantum computers are highly susceptible to error, and designing strategies to mitigate or correct them is an important aspect of quantum computing to achieve fault tolerance. To this end, HAT scientists have introduced a novel family of quantum-error-correcting codes called lift-connected surface (LCS) codes. These new LCS codes exhibit competitive error rates compared to the well-established surface code and require approximately one-fourth of the physical qubits for the same code parameters while achieving a similar error threshold compared to the surface code. This makes them very attractive for error correction experiments on near-term devices. Along these lines, HAT researchers, in the past year, have developed a novel protocol for fault-tolerant code-switching for near-term quantum devices. They have created a toolbox for these protocols, offering a promising route to achieving fault-tolerant universal quantum computation. An experimental demonstration of these protocols on trapped-ion quantum devices is underway. HAT also uses a feedback-driven strategy to pursue error correction protocol development. This so-called 'feedback-based' approach directly integrates with the experimental device and adapts in real-time using feedback from quantum devices. To support this approach, they are using an in-house developed feedback-GRAPE (Gradient Ascent Pulse Engineering) algorithm, which draws inspiration from model-free reinforcement learning concepts. For superconducting qubits as developed in SQQC, the main error-correcting code is the surface code, which requires measurements of four-qubit correlations to detect and then correct errors. These measurements are carried out via a sequence of four two-qubit gates. HAT researchers have now developed a strategy to condense this process into only two quantum gates. Since the considered error detection process needs to be executed extremely often in computation, this reduction is expected to accelerate error correction substantially and enhance the capabilities of future fault-tolerant quantum computers.

Carrying out quantum-error correction in near-term quantum devices presents significant experimental challenges. In response, quantum error mitigation emerges as an alternative approach, comprising a set of techniques geared toward reducing errors. However, HAT scientists have identified strong limitations regarding the effectiveness of mitigating quantum noise, particularly for larger system sizes involving many quantum operations or gates. This sensitivity has critical implications for error mitigation, emphasizing the need for the development of alternative methods to reduce noise.

Lastly, it is crucial to achieve precise hardware characterization to construct accurate numerical models for the quantum platforms, design optimal control sequences considering real noise models, facilitate co-design, and implement hardware-specific error correction. Additionally, to ensure the functionality of proposed algorithms in practical applications, it is imperative to establish efficient and feasible benchmarking, verification, and validation protocols. HAT scientists have focused on crafting user-friendly, efficient tools for benchmarking and verification in quantum experiments to address this. They showcased a methodology that offers a suite of diagnostic techniques for evaluating quantum system performance using experimental data. Their innovative approach challenges the traditional notion that estimating quantum properties requires the application of complex global Clifford operations, which can be less practical. Instead, they advocate employing logistically shallow circuits (fewer operations) for dependable and efficient property estimation, presenting a more pragmatic approach for quantum experiments. HAT scientists have also developed methods to efficiently verify the outcomes of sampling experiments, a potential application for proving a computational advantage using quantum computers over their classical counterparts. They also experimentally demonstrated it on the trapped-ion quantum computers.

In summary, HAT scientists' research and development efforts have led to highly promising new approaches to increase the performance of the MQV hardware platforms. Their efforts have led to 27 peer-reviewed publications and 26 pre-prints, complemented by many scientific presentations at various conferences and outreach initiatives. HAT efforts are linked to multiple German quantum technology projects funded by the BMBF. These include the large hardware development efforts in the MUNIQC-ATOMS and MUNIQC-SC project, the "German Quantum Computer-based on Superconducting Qubits (GeQCoS)" project, as well as algorithm development efforts within the "Effiziente Materialsimulation auf NISQ-Quantencomputern (MANIQU)" and "Efficient Quantum Algorithms for the Hubbard Model (EQUA-HUMO)" projects, which all include direct collaboration with industrial partners. HAT has further tightened its collaboration across all MQV consortia to help the development of a full-stack efficient and beneficial quantum computer.

3.4 Scalable Hardware & Systems Engineering (SHARE)

The consortium Scalable Hardware & System Engineering (SHARE) is dedicated to advancing classical control technology needed for scalable quantum devices and circuits, particularly in the realm of SQQC and TAQC. The consortium specializes in the fabrication of scalable integrated chip technology, including superconducting quantum devices for SQQC, chip traps for TAQC, and fast electronic control for both.

In the pursuit of enabling scalable electronics in superconducting quantum computers, SHARE has developed a concept that revolves around integrating critical radio-frequency electronics into application specific integrated circuits (ASICs). Building upon the accomplishments of the first project year, where the consortium collaborated closely with Walther Meißner Institute (WMI) to define an architecture specification for the control and read-out of transmon-based, superconducting qubits, the Fraunhofer Institute for Integrated Circuits (IIS) and its partners have delved deeper into the design work for ASIC test chips. These test chips are designed to operate under different temperature requirements, as SHARE is aiming to utilize the advantageous physical properties at cold temperatures, especially with regards to signal noise, and bring the electronics as close as possible to the QPU (quantum processing unit). Typical semiconductor processes are not qualified for the extreme temperatures that occur near the qubit chip at just a few millikelvin, making it necessary to correctly model and simulate basic circuit components such as transistors and passive elements.

The three taped-out test chips encompass custom-built digital elements, passive structures such as so-called "Baluns" and active filter components (1), an 8-bit radio-frequency digital-analog converter (RF-DAC) targeted for operation at four kelvin and RF-mixers to up-convert into the GHz frequency range (2), and various integrated blocks and prototype structures for 4 K operation (3).

Additionally, SHARE's concept relies on electromagnetic simulation to develop highly integrated "flex-lines", that can later provide access to hundreds of qubits. Traditionally, four signal lines coming from room temperature signal generators were required to control each qubit, but this approach becomes impractical when dealing with more than a hundred qubits. To meet this challenge, SHARE is working to replace conventional cables with smaller, flexible cables made of superconducting material that can accommodate 100 signal lines per inch. Fraunhofer IIS has designed and simulated various aspects of the flexible waveguide, successfully measuring the permittivity of PCB and substrates. RF-filters have been designed, measured, and will be integrated into the cable to prevent undesired coupling and attenuation. The consortium's design specification document summarizes the progress in this area. The RF-design will undergo further optimization, and the manufacturing data will be finalized in the coming months.

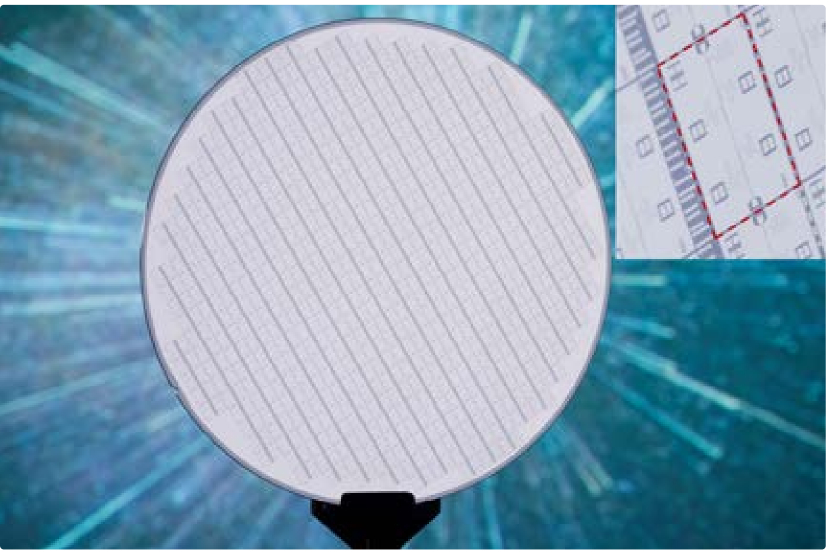
In SHARE's pursuit to achieve scalability for trapped atom quantum computers, researchers have made significant advancements in optical multi-channel switches tailored specifically for this purpose. By leveraging laser pulses, SHARE is able to execute logical gates on this type of quantum computer. The simultaneous execution of multi-channel signal processing, coupled with a multi-channel photonic circuit serving as the light modulator, facilitates seamless integration of the essential signaling channels. This integration, in turn, enables scientists to increase the number of addressable qubits, a crucial step towards achieving scalability. At Fraunhofer IIS, the consortium's contribution entails designing a multi-channel control unit equipped with FPGAs for digital signal processing and high-performance RF electronics to ensure the generation of high-quality signals. Additionally, SHARE is responsible for developing a carrier board tailored to the photonics chip. This collaborative effort involves essential partners such as the Max Planck Institute of Quantum Optics (MPQ) and Heidelberg University (HEI). HEI specializes in designing and fabricating multi-channel photonic integrated circuit (PIC) chips, which serve as optical signal modulators for the gate operations of the quantum-computer demonstrator. Moreover, they are designing a multi-path optical splitter to efficiently distribute the light from a single laser source to all the individual channels that will be independently controlled. On the other hand, MPQ is responsible for testing, qualifying, and integrating the optical switching device into their quantum-computer-demonstrator setup.

In addition to SHARE's focus on the neutral-atom quantum computing approach, the consortium is also actively involved in designing and developing the signal-processing platform and base-band electronics. These components hold potential for utilization in the superconducting-based system architecture, fostering collaboration between SHARE and

SQQC. By combining our expertise and collaborative efforts, the researchers are paving the way toward scalable quantum-computing systems, revolutionizing the realm of advanced computing technology.

SHARE is actively working on developing system integration technologies that will enable the scaling and industrialization of quantum-computing hardware. The focus is on enhancing the scalability and performance of superconducting qubit systems while paving the way for their future commercialization.

To achieve the scaling of quantum processor units (QPUs), scientists are exploring alternative concepts for fabricating Josephson junctions, which are key components of QPUs based on superconducting qubits. SHARE's goal is to use industry-scale tools on 200 mm silicon wafers for the fabrication process. In collaboration with consortium SQQC (WMI, TUM School of Computation, Information and Technology (CIT)), SHARE has successfully carried out the first full fabrication of Al-based qubit chips on 200 mm silicon wafers.



Aluminium-based superconducting qubit chips fabricated on 200 mm silicon wafers. © Fraunhofer EMFT | Bernd Müller

This milestone achievement has been made possible through close collaboration and the utilization of simulation results and the pre-characterization of individual chip components. In SHARE's pursuit of developing larger quantum-computing systems (> nine qubits) through 3D-integrated quantum processor architectures, researchers have also made significant progress in the development of a silicon-based interposer.

This interposer relies on two main technologies: superconducting through silicon vias (TSV) and advanced micro-bumps using superconducting indium. SHARE is actively working on fabricating these technologies on 200 mm wafers using industry-scale facilities to ensure a smooth transition to industrial applications.

One main challenge the consortium faces is ensuring that the interposer and its connecting technologies, which are fabricated at room temperature (and above), reliably perform in the extremely low-temperature range required for QPU operation.

In the initial stages of research, SHARE has successfully developed superconducting TSV test structures and achieved considerable optimization of fabrication parameters. These test structures consist of Si trenches covered with TiN superconducting metal. Additionally, SHARE has designed a TSV technology demonstrator in collaboration with SQQC, which is currently being fabricated at the clean-room pilot-line facility of the Fraunhofer Insitute for Electronic Microsystems and Solid State Technologies (EMFT). Furthermore, the consortium has worked on developing micro-bump interconnects for quantum processor integration at the chip level, and the fabrication of the first test structures for these interconnects is underway. This progress has been made possible through the combined technical and scientific expertise of SHARE and SQQC. Within SHARE, Fraunhofer EMFT has developed all the process steps towards the fabrication of flexible superconducting cables based on a trilayered design developed at Fraunhofer IIS. Moreover, it was possible for the first time to combine all the individual fabrication steps into one overall process and the first trilayered cables were fully produced. → 2.2

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

Fulfilling the promise of full-stack quantum computing within MQV requires not only cutting-edge hardware advances, but also – and equally important – the design, deployment and maintenance of the necessary software environments.

The Q-DESSI consortium as part of MQV, works on this key aspect and is creating the Munich Quantum Software Stack, enabling both direct and HPC integrated programming and execution environments. This software stack will ultimately connect application developers on one side, working on higher levels of abstraction and hybrid HPC workflows, with one or more hardware implementations on the other side. With that it will offer a production ready environment for the efficient execution of quantum codes not only on MQV hardware, but for quantum systems in general.

Users can access the system either via a dedicated portal with multiple language backends or via HPC systems using traditional schedulers like SLURM, which drive hybrid applications capable of offloading parts of their computation to QC backends. The relevant parts of the programs are then processed via a quantum resource manager as well as corresponding quantum design tools. Finally, the resulting quantum circuits are executed by a suitable backend system. This workflow is transparent for the user, hides the particular complexities, and still enables "expert paths" for experimental computations.

The presented software stack is currently being developed within Munich Quantum Valley (MQV) and deployed at the Leibniz Supercomputing Centre via its "Quantum Integration Centre" (QIC). A first prototype has been tested using the five-qubit superconducting system of the Leibniz Supercomputing Centre (LRZ), which has been installed in a collaboration between LRZ and IQM Quantum Computers as part of the project "Digital-Analoge Quantencomputer" (DAQC) by the Federal Ministry for Education and Research (BMBF). This successful test has been supported by a range of new developments in Q-DESSI over the last year:

Prototype of Bavarian Quantum Portal (BQP) deployed at LRZ enabling users to request personalized tokens for execution on MQV systems and then use the tokens either to drive Qiskit scripts or to directly submit quantum circuits. These are then run through the machinery of the quantum software stack for execution on one of the available backends.

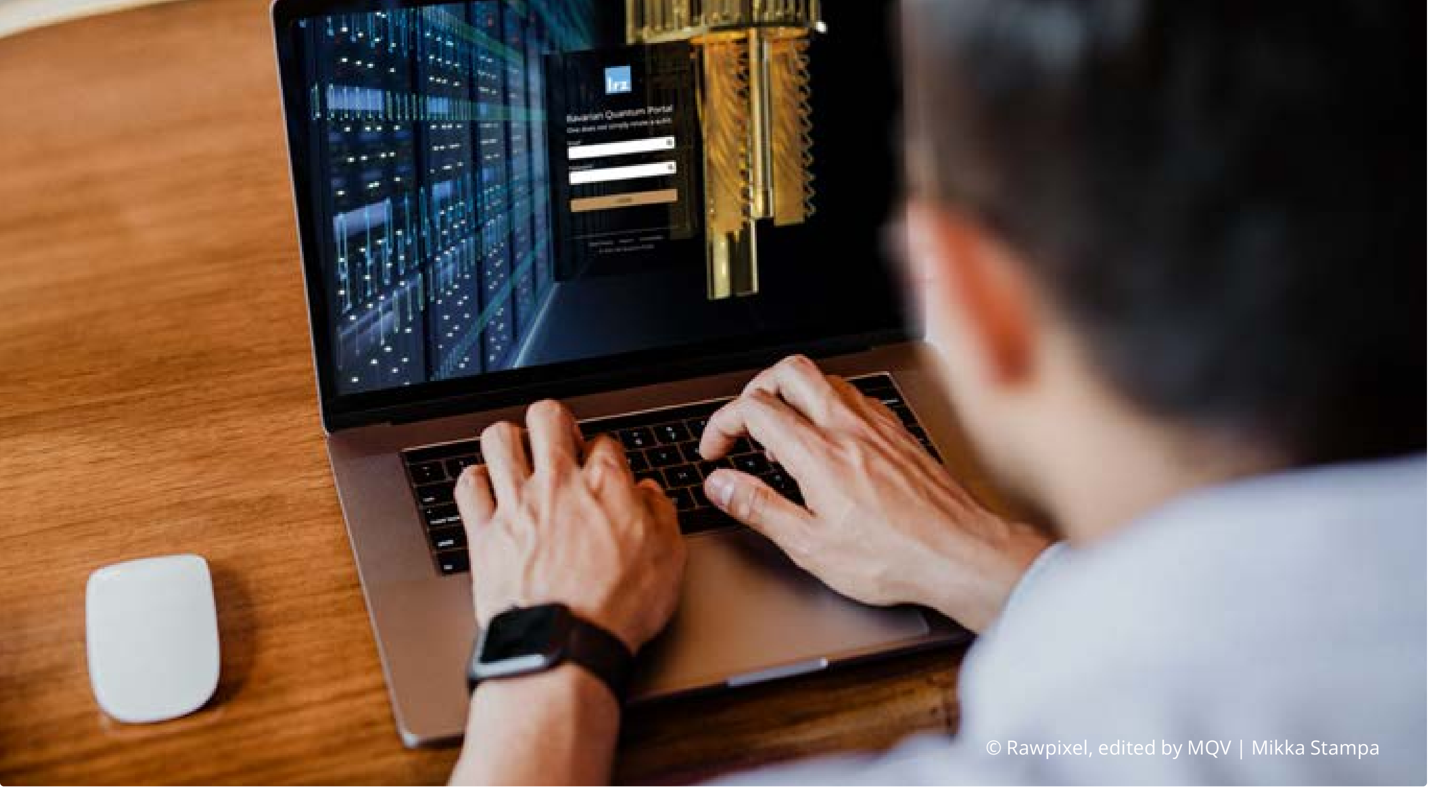
Large strides in HPC-enabled programming interfaces: over the last year, three groups have experimented with different approaches in embedding quantum programming into classic host languages with the goal of supporting the acceleration paradigm: QPI (Quantum Programming Interface, LRZ) offers an API driven offload mechanism, the integration into OpenMP (TUM/Schulz and LRZ) enables to use of standard HPC programming models, and higher-level of abstractions using ZX-calculus (LMU/Kranzlmüller) offer new ways to efficiently express quantum programs.

Defining a comprehensive compiler infrastructure, to enable efficient dynamic compilation and scheduling, while supporting the flexible deployment of independent compiler passes (TUM/Schulz/Wille/Mendl/Seidl and LRZ). The efforts are based on QIR, the Quantum Intermediate Representation, which enables a vendor neutral representation of quantum circuits along the entire compilation and optimization process, as well as cleanly integrates with classic compilers based on LLVM enabling hybrid code compilation.

A Quantum Virtual Machine (QVM), developed by TUM/Bhatotia, offers an abstraction of a large quantum system consisting of a set of distributed and small QPUs. QVM uses the recently introduced gate-virtualization circuit cutting and knitting technique, a divide-and-conquer method for executing larger circuits with higher fidelity. The approach has been prototyped and results submitted to a major conference.

Extensions to the Munich Quantum Toolkit (MQT)**,** a collection of design automation tools and software for quantum computing developed at TUM/Wille. It includes high-level support for end users in realizing their applications as well as efficient methods for the simulation, compilation, and verification of quantum circuits.

Feedback-guided compilation using figures of merit, queried online from live system data established the needed interface between systems and the connected instrumentalists on one side compiler/tools and their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developers on the other side. Initial work by TUM/Wille/Schulz and LRZ is being written up for submission to a major conference.

QDMI as a flexible backend interface: LRZ has defined a backend interface that a) enables the execution of quantum circuits on any platform, b) offers MQV and non-MQV platform providers a simple interface to integrate into the Munich Quantum Software Stack, and c) enables the querying of live data to support the delivery of figures of merits to the software stack.

The Munich Quantum Software Stack, developed by Q-DESSI, is not only intended for the specific scope of MQV and its systems, but targets a general audience supporting any kind of hardware and type of installation. In particular, it is already recognized as the leading effort world-wide in HPC/QC integration with its unique approach of tightly bridging the two worlds. This ambition, of offering a comprehensive and widely used and applied solution, is also reflected in its connections, participations and partnerships.

The project works closely with all other consortia within MQV, not only through common meetings, including a regular technical exchange meeting defining the cross consortia connections, especially to the hardware, but also common developments by shared PhD students, such as the development of a quantum control processor interfacing with MQV's arbitrary-waveform-generator (AWG) efforts, with low-level firmware and control system work, and by providing the needed interfaces to enable the use of MQV systems for the applications consortia.

Connected to the MQV core projects, the Munich Quantum Software Stack is also used as well as contributed to by a series of local projects, including MUNIQC-SC (adding specific support superconducting systems), MUNIQC-ATOMS (adding specific support for neutral atoms), QuaST (investigating performance models as well as higher-level of abstractions for optimization problems) as well as Q-Exa and DAQC (in both cases contributing backend development and stable support for the respective systems). Combined, all efforts together form and define the Munich Quantum Software Stack.

On the European-level, the LRZ and its quantum software development team participate in several projects, including the flagship projects Millenion and OpenSuperQPlus. Also in these projects, the goal is to use and extend the Munich Quantum Software Stack for the respective systems as well as help to drive EU-wide HPC/QC efforts. The latter is particularly critical for the newly started Euro-Q-Exa system deployment for which the LRZ was chosen as the EuroHPC hosting site and which requires the existence of a stable software stack.

Finally, several members of the Q-DESSI team contributed to the efforts as part of the IEEE Quantum Initiative, especially the newly founded IEEE Quantum – HPC Working Group.

3.6 Theoretical Quantum Computing (THEQUCO)

On the way to a competitive quantum computer, many fundamental questions arise on the theoretical level. To define the goal, one can ask the overarching question of quantum advantage: Which algorithms can be executed more efficiently on quantum computers than on classical hardware?

This question opens several research directions. The so far theoretical model of a noise-free quantum computer implementing a universal set of quantum gates is known to have a quantum advantage over classical Turing machines for certain classes of problems. On a more practical level, the question of quantum advantages asks for the development of new quantum algorithms to potentially extend the classes of problems that can be solved efficiently on a quantum computer. Moreover, the development of new classical simulation techniques of quantum many-body systems can potentially continuously raise the bar for a quantum advantage, but it can also help to characterize, validate, and certify quantum devices. However, the current and near-term generations of quantum devices 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? And how does it affect the computational power? If the error rate is low enough, one can use certain error correction schemes, ultimately leading to a fault-tolerant quantum computer, 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 is 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. Various groups in the THEQUCO consortium address all of these questions on a theoretical level, mostly independent of the actual platform.

In 2023, the THEQUCO consortium made broad progress in several subfields. In the following, some of the past year's results are highlighted.

One promising near-term application of digital quantum computers is the simulation of quantum many-body systems and quantum chemistry. Those systems intrinsically possess an exponential complexity due to the quickly growing Hilbert space, the mathematical space in which the state of a quantum system is expressed mathematically. While this growth hinders the simulation on classical computers, quantum computers are built to exploit exactly this very same Hilbert space growth, and thus are naturally suited to efficiently simulate such systems. One important question is how one can efficiently prepare finite temperature states of such quantum many-body systems on quantum hardware, in other words prepare a mixed state with statistics resembling thermal fluctuations present in these physical systems. A group of researchers at Max Planck Institute of Quantum Optics (MPQ) in Garching has developed a provable efficient quantum algorithm for preparing finite temperature states in short quantum circuits. Minimizing the depth of the circuits – given by the number of gates – is crucial for the possibility of near-term applications since the probability of errors in the application of the gates on the imperfect devices increases drastically with the circuit depth. A key ingredient for the finite temperature states is that the so-called Loschmidt echo needs to be evaluated on a quantum machine, for which multiple strategies have been developed.

In fact, the same trick used to evaluate the Loschmidt echo can be applied to quantum-inspired classical algorithms for simulating quantum many-body systems and quantum chemistry at finite energy densities. The short evaluation times require a limited amount of entanglement, allowing for an efficient, compressed representation of the quantum state by tensor networks. Researchers at the Technical University of Munich (TUM), MPQ and Ludwig-Maximilians-Universität München (LMU) continued developing simulation techniques based on such tensor networks. The subclass of matrix product states is the state-of-the-art method for simulations of one-dimensional physical models that appear, e.g., in strongly correlated electron systems. MQV researchers showed that quantum states represented by matrix product states can be prepared ultra-fast on quantum devices with measurement-assisted state preparation in only logarithmic time in system size. Moreover, they continued the development of algorithms based on isometric tensor networks in higher dimensions, and showed that these states can also be prepared efficiently on quantum computers. It is important to note that the expertise in the development of classical simulation techniques for those physical systems present in MQV thus leads to a very fruitful interplay with the development of quantum algorithms. The compression by tensor networks translates to less stringent requirements for qubit number and circuit length on without destroying the information saved in the logical qubits. To automate the discovery of error correction codes, the researchers at MPL relied on reinforcement learning, a powerful machine learning approach to automatically discover strategies. They fixed an error model, the allowed gate set, and the qubit connectivity. This can be chosen depending on the hardware for which the error correction code should be found. Afterwards, a neural-network agent is then allowed to modify the gates of a quantum circuit until a code that protects against those errors is found depicting the whole training loop. In that way, the agent simultaneously discovers a suitable error correction code and

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the quantum hardware, making them accessible for the current and near-term generations of quantum devices.

Contributing towards the long-term goal of efficient quantum-error correction, researchers at Max Planck Institute for the Science of Light (MPL) used machine learning tools to investigate the automatic discovery of error correction codes. In contrast to classical bits, a quantum-state measurement implies the infamous collapse of the wave function, altering the state. Moreover, a quantum state can not simply be copied as one is used to from classical bits. Hence, very carefully designed schemes of partial measurements are necessary to both detect and correct for the errors its encoding circuit. The researchers demonstrated that the agent cannot only discover efficient preparation circuits leading to known codes described in the literature before, but can also become a meta-agent that can produce codes and circuits for a whole class of error models with variable noise strengths. In this way, it is able to recommend adapted strategies for asymmetric noise channels which are much less studied so far. More detailed information on the reinforcement-learning method for the automatic discovery of quantum-error-correction codes can be found in Section 2.3.

3.7 Quantum Algorithms for Application, Cloud & Industry (QACI)

The Quantum Algorithms for Applications, Cloud, and Industry (QACI) consortium plays a pivotal role in establishing a direct interface with end-users, bridging the gap between quantum technology and its practical applications. QACI's mission is to equip users in academia and industry with the knowledge, tools, services, and resources necessary to solve their application problems on one of the full-stack quantum computers jointly developed by the MQV consortia.

QACI has defined three central tasks to fulfill this mission: ***Quantum Computing Application Algorithms for Industry Use-Cases***, ***Supporting Software Tools and Processes***, and ***Infrastructure Access and User Support***.

This is also reflected in two overarching goals and key deliverables that QACI aims to provide for the development of full-stack quantum computers. On a two-year scale, the goal is to develop high-level libraries as well as software- and cloud-interfaces for user-friendly quantum application development tools. On a five-year scale, QACI aims to develop a suite of optimized demonstrator quantum computing algorithms.

The two-year goal has been achieved this year: Many different tools ranging from circuit optimization and equivalence checkers to circuit simulators, in particular those under the Munich Quantum Toolkit umbrella, are already released as open source software. They are readily available on GitHub or python package repositories which makes them very convenient to use for non-experts. Regarding infrastructure access and user support, a portfolio of different quantum computing simulators is available and accessible at the Leibniz Supercomputing Centre (LRZ) and the first quantum computers were set up on the premises of LRZ. Furthermore, multiple pieces of training have been conducted and the prototype ***Bavarian Quantum Portal*** for cloud access has been demonstrated to work during the last review meeting in September 2023.

In 2023, QACI started several activities designed to foster collaboration and integration across the MQV tech stack and with external industry partners. These activities include the creation of a quantum use-case catalog and the setup of the cross-sectional topic Application-driven Benchmarking of Quantum Computers (→ 4.1). Intensified outreach activities were also particularly important for QACI as the end-user interface consortium.

First, a use-case description template was developed that allows to characterize use cases with respect to several application and implementation relevant dimensions. QACI members then established an inventory of all the use cases that were considered or already implemented resulting in an initial use-case catalogue spanning a variety of application domains such as finance and insurance, chemistry, security as well as energy and production networks. It must be noted that QACI's efforts in providing application algorithms for industry use cases do not cover the whole field of possible application domains and problem classes. Instead, use cases are spread across multiple complementary, associated projects within the MQV ecosystem. The most important among those are "BayQS" and the Lighthouse Project "BenchQC" → 4.1, both funded by the Bavarian government, as well as "QuaST", funded by the Federal Ministry for Economic Affairs and Climate Actions (BMWK). The use-cases catalogue will therefore continuously grow also with contributions of these associated projects. The purpose of this use-case catalog is not just documentation and illustration but is also used for automation and tool validation within the task of providing infrastructure access and user support. In addition, the catalog is the starting point for QACI's benchmarking topics.

The use of those benchmarking methodologies is paramount, allowing us to gauge the practical utility of quantum computers in real-world applications. At the heart of this approach lies the identification of use cases, underpinned by a mathematically formulated problem statement, as also contained in the above-mentioned use-case template. The mathematical formulation should strive for generality, allowing it to cater to a wide spectrum of applications. This also provides a natural interface to the work packages in the theory consortia THEQUCO and HAT: Here, QACI already had fruitful discussions on error propagation in application algorithms running on noisy quantum devices. Extending the mathematical formu-


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lation to the question of data encoding there is also an exchange on data compression using so-called tensor-network-inspired quantum circuits.

Another important aspect of the benchmarking approach is the inclusion of classical baseline implementations. Comparing quantum solutions with their classical counterparts is fundamental in understanding the advantages quantum hardware can offer. Furthermore, the development of simulator-based solutions allows us to disentangle quantum hardware's unique capabilities from the intricacies of the algorithms themselves. To that end, a collaboration project has also been set up with partners from LRZ and Fraunhofer Institute for Cognitive Systems (Fraunhofer IKS) to have a benchmark comparison of both hardware and software quantum-computing simulators on a simple yet representative range of use cases, e.g., molecular simulations, quantum convolutional neural networks, and optimization problems. The high-performance-computing performance will be analyzed on the hardware available at LRZ, thus showcasing for the users the available simulator portfolio of the center.

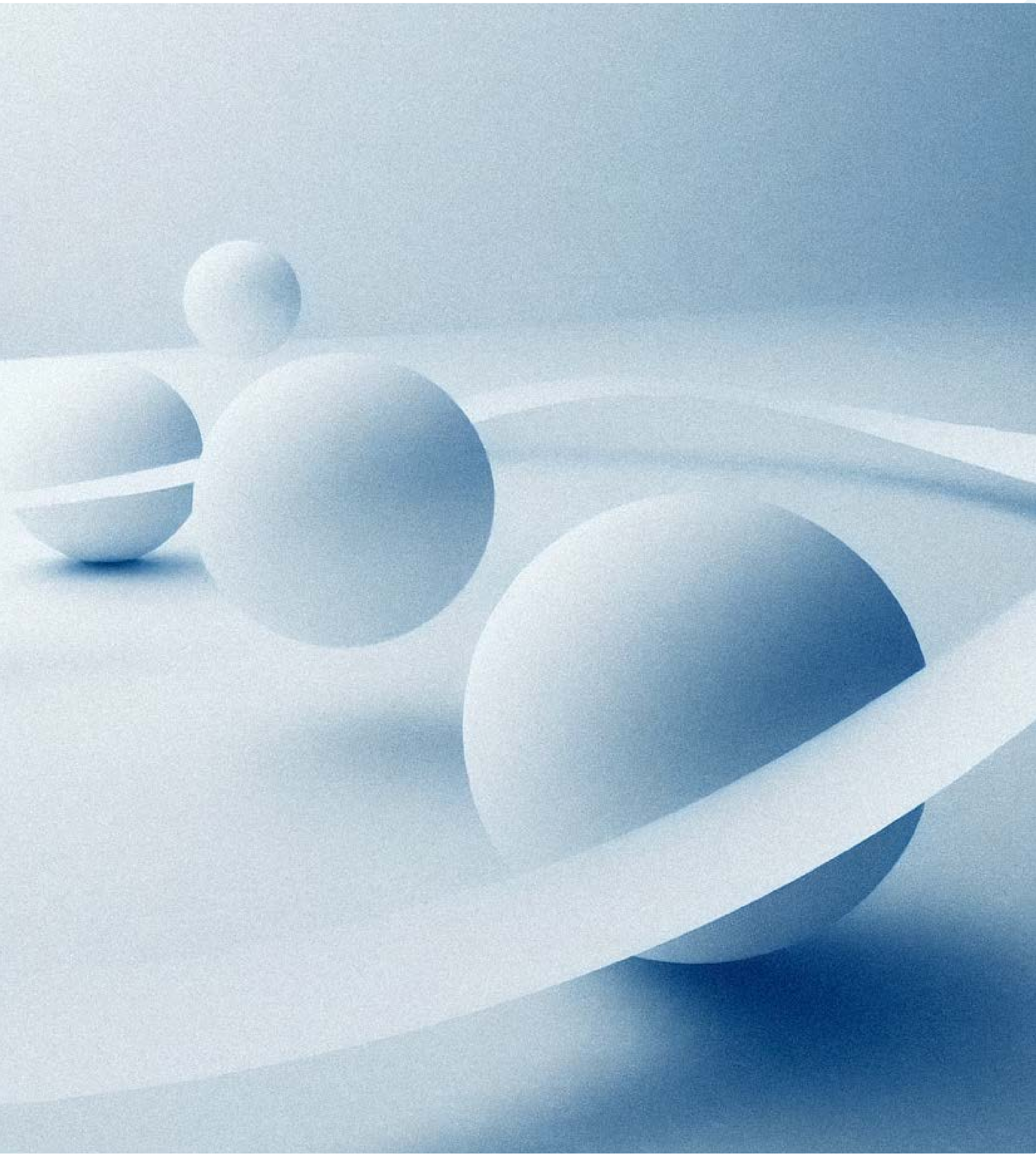
To assess the performance of quantum hardware comprehensively, a diverse array of metrics has been considered, prioritizing application-relevant end-to-end measurements. Some of these metrics must come from the industry end-users, as they are the most relevant for a business case of quantum-computing applications.

This approach provides a more holistic view of quantum computing's viability in practical scenarios. The inclusion of ablation studies further refines the understanding by dissecting the impact of individual components and parameters on overall performance. The data collected allows QACI to derive hardware requirements, identify scaling behaviors, and assess parameter sensitivity. These insights are pivotal for refining and optimizing quantum-hardware design. Co-design potentials, where hardware and algorithms are developed in tandem to maximize performance and efficiency, become evident through these comprehensive investigations.

As a first step towards this goal, many of the work packages in the central task of providing application algorithms for industry use-cases not only just implement algorithms, but perform ablation studies with respect to various parameters and metrics on different available hardware (e.g. IBM Q Systems, AQT machines) to come up with application-specific hardware requirements. Here, also the first application-oriented benchmarks of SQQC hardware was performed this year.

Concerning outreach activities, QACI organized the first ***Quantum Computing Application Symposium*** this year with many industry partners presenting their quantum use cases. The consortium also took the opportunity to conduct a short survey with the application symposium participants to find out what the most important benefits of joining the newly founded Partner Network (→ 4.6) are and how they could contribute. The bottom line of the survey is that there is a great interest in being In the MQV activities' information loop, participate in events, get hardware access, or cooperate in funded projects. All these activities are also part of the Partner Network task force currently consisting of the consortia SQQC, TAQC, QACI, and the MQV Office that tries to find suitable development directions for the Partner Network.

Lastly, 2023 has also been a productive year for QACI in terms of publication output. Notably, MQV-affiliated partners managed to contribute more thana dozen technical papers, including two best paper award rankings. With almost 10% of the papers coming "from the valley", MQV was well-represented within the community this year.



Chapter 4

Fostering excellence in quantum science and technology

The overarching mission of Munich Quantum Valley (MQV) is to create the world's foremost ecosystem for industrializing quantum technologies and to develop and operate competitive quantum computers.

To implement this mission, MQV promotes excellence in quantum science and technology in Bavaria through several targeted measures. Beyond the research and development program of the consortia developing full-stack quantum computers (→ Chapter 3), MQV fosters various exchange and partnership formats to link research with industry, coordinates Lighthouse Projects addressing topics besides quantum computing, and fosters R&D Professorships. Moreover, MQV sets up a Quantum Technology Park providing tailored high-tech infrastructure for developing and producing quantum devices. Finally, MQV supports dedicated educational and entrepreneurial activities to train the next generation of quantum experts and to foster start-ups.

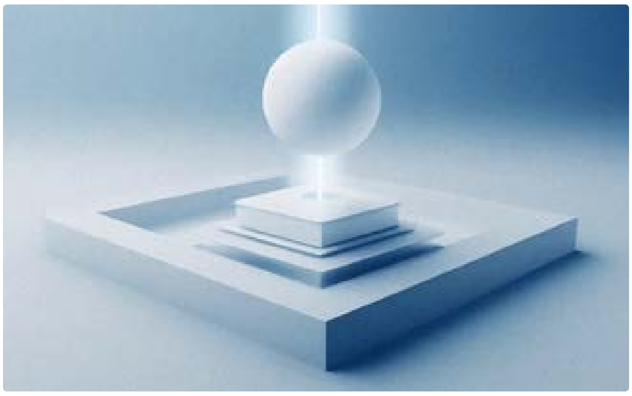
4.1 Lighthouse Projects

The Lighthouse Projects, funded by the Hightech Agenda Bavaria, complement the research program of Munich Quantum Valley (MQV) towards the goal of developing, operating, and providing access to quantum computers in Bavaria. The universities, research institutions, and industry partners are jointly investigating enabling technologies and theoretical foundations in the fields of quantum computing, simulation, communication, sensing, and metrology. In the course of 2023, seven Lighthouse Projects have started their research activities.

Application-driven Benchmarking of Quantum Computers (Bench-QC)

The practical usability of quantum-computing hardware in industrial applications depends strongly on the combination of the application, the algorithm used, the mathematical problem formulation and the given hardware parameters. The MQV Lighthouse Project Bench-QC aims to develop and implement a framework for the quantitative comparison of entire solution path for industrial problems using quantum computing. Bench-QC is a collaboration of two institutes of the Fraunhofer Society, the Fraunhofer Institute for Cognitive Systems (IKS), and Fraunhofer Institute for Integrated Circuits (IIS), and various industry partners: ML Reply (consortium lead), BMW, Optware and Quantinuum.

This work will extend the QUARK framework that was originally proposed by BMW to benchmark different possibilities to solve industrial-relevant optimization tasks via a quantum-assisted solution. In a first step within the Bench-QC project, this framework was extended to also consider generative quantum-machine-learning scenarios.



Free-Electron States as Ultrafast Probes for Qubit Dynamics in Solid-State Platforms

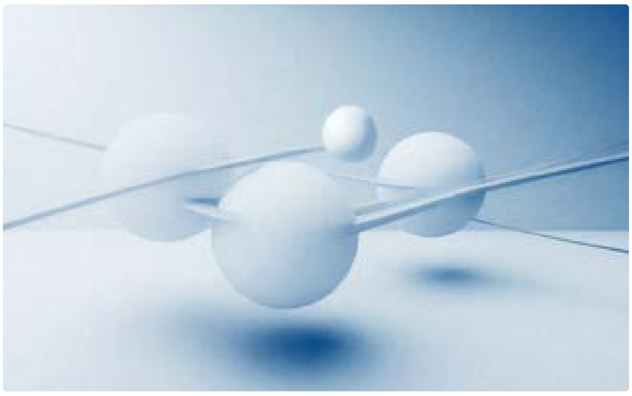
Electron microscopy has become a mature experimental technique to image the atomic-scale structure of solid-state systems, ranging from catalytic nanoparticles to functional electronic devices. However, up to now, electron microscopy is not able to measure the quantum state of a solid-state nanosystem. In recent years, the team has developed a time-resolved variant of electron microscopy, so-called ultrafast transmission electron microscopy (UTEM), in which the continuous electron beam used for imaging is replaced by electron pulses as short as 200 fs. With such an experimental tool, the team could already image transient structural, magnetic and plasmonic states on sub-picosecond timescales. In the MQV Lighthouse Project, the team aims to extend this line of research to the interaction of electrons with nanoscale solid-state quantum systems, including localized exciton states in transition metal dichalcogenides and quantum dots. A crucial element in an efficient coupling will involve a tailoring of the photonic environment by TEM-compatible resonator structures which allows for a local enhancement of the electron evanescent field at the position of the quantum system.

Integrated Spin Systems for Quantum Sensors (IQ-Sense)

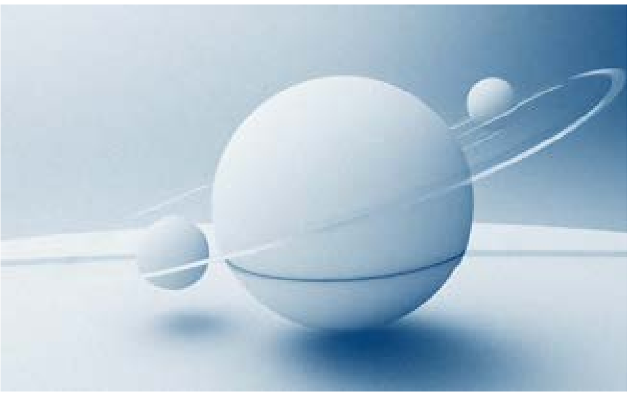
Sensors with the highest sensitivity are needed in many fields, especially in the life sciences. The MQV Lighthouse Project IQ-Sense focuses on developing and demonstrating integrated quantum sensors that surpass current sensors in terms of precision. To achieve this goal of tailoring quantum systems for the detection of different quantities to realize sensors with unprecedented sensitivity, researchers from the natural sciences are collaborating with scientists from the life sciences and medicine. IQ-Sense is a joint project of researchers from the Julius-Maximilians-Universität of Würzburg (JMU), the Walther Meißner Institute (WMI) of the Bavarian Academy of Sciences and Humanities (BAdW) and the Technical University of Munich (TUM).

Networked Quantum Systems (NeQuS)

The Lighthouse Project NeQuS aims at the development of novel quantum interfaces and transducers needed to connect different quantum systems together and take the first steps towards the quantum internet. Such networks built from interconnected quantum systems will have many advantages, transcending the various sub-fields of quantum information science and technology. Examples include inherently secure quantum communication in which parties can communicate without the risk of eavesdroppers intercepting their messages, linking quantum processors to build more powerful multi-core architectures, and quantum sensors and transducers in which remote systems can be measured with unprecedented sensitivity.



A major goal of NeQuS is to interconnect different quantum systems using photons propagating in glass fiber to build hybrid quantum networks. The project brings together ten groups from the Technical University of Munich (TUM), the Ludwig-Maximilians-Universität (LMU), the Bavarian Academy of Sciences and Humanities (BAdW), and the Max Planck Institute of Quantum Optics (MPQ). In the long term, the results of the project will pave the way to a global network of quantum computers that can perform distributed quantum tasks such as computing, communication, and sensing in an efficient, fault-tolerant, and provably secure manner. Such a “quantum internet” will have a similar transformative impact on quantum information science and technology as the development of the internet has had on classical information technology.



Quantum Communication Infrastructure (QuKomIn)

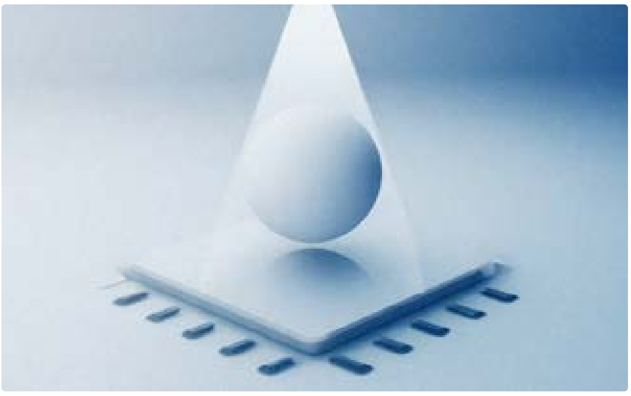
Ensuring safe communication in the future is the main goal of MQV Lighthouse Project QuKomIn, a joint effort of the Max Planck Institute for the Science of Light (MPL) and researchers from the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), the Fraunhofer Institute for Integrated Circuits (IIS), the German Aerospace Center (DLR), and the Ludwig-Maximilians-Universität München (LMU). The aim of the project is to establish a real test infrastructure for quantum communication in the form of a hybrid fiber-optic network with satellite links and application laboratories in the Erlangen/Nuremberg and Munich/Oberpfaffenhofen areas.

Quantum Circuits with Spin Qubits and Hybrid Josephson Junctions

It is still unclear which qubit concept and which quantum-processor architecture will ultimately be chosen to achieve universal and fault-tolerant quantum computing. In fact, it is quite likely that future quantum computers will use processors based on a combination of different qubit concepts, exploiting their specific advantages while avoiding or mitigating their individual weaknesses.

This Lighthouse Project addresses this mid-term perspective of quantum-processor development by aiming to demonstrate two leading solid-state qubit concepts – superconducting and spin qubits – in the same material platform. This demonstration may open new technological avenues by opening the door to combining superconducting and semiconducting quantum circuits while stimulating and accelerating the development of synergistic materials. Crucially, the material platform – germanium/silicon-germanium hybrid heterostructures – is fully compatible with semiconductor chip foundries.

The team at the University of Regensburg combines and connects the growth of superconductor/semiconductor hybrid heterostructures, the realization and the operation of both superconducting quantum circuits and semiconducting spin qubits in a joint effort of experimental and theoretical groups. The team is working to demonstrate both a noise-resistant fluxonium qubit architecture based on proximitized superconductivity in aluminum/germanium/silicon-germanium quantum circuits and a fully electrically controlled spin qubit in germanium/silicon-germanium.



Quantum Measurement and Control for Enabling Quantum Computing and Quantum Sensing (QuMeCo)

Quantum computing, simulation, sensing, and communication technologies rely on the ability to control and measure individual quantum objects while preserving their quantum-coherent properties. Thus, the overarching goal across all quantum technology platforms and application areas is to improve our ability to measure and control quantum systems while preserving their protection from ambient noise. The QuMeCo project aims to address this central challenge to realizing quantum technologies through research at the interface between the natural and engineering sciences. It aims to explore high-risk, high-gain alternatives to existing measurement and control solutions. Specifically, QuMeCo develops ultrafast photon detectors and single-photon sources, explores novel schemes for the readout of biological structures, develops measurement schemes for superconducting qubits, and uses molecules and color centers to detect fields and photons.

The QuMeCo team brings together twelve partners from the physics and electrical engineering departments of Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) and the Max Planck Institute for the Science of Light (MPL). Together, they cover a wide range of complementary research areas and offer excellent collaborative perspectives on various interdisciplinary challenges. In addition to novel measurement and control schemes for quantum computing, QuMeCo aims to develop new concepts and hardware for quantum measurement and control in the field of quantum sensing. The aim is to measure quantities such as magnetic or electric fields or to improve the resolution in imaging and spectroscopy by exploiting quantum effects such as superposition, entanglement, and sub-shot-noise correlations. QuMeCo will complement FAU's long-standing expertise in the field of quantum sensing, with the prospect of important Bavarian contributions to the second quantum revolution.

4.2 R&D Professorships

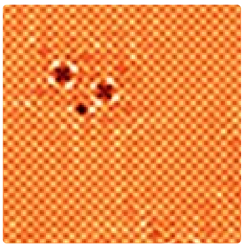
In order to strengthen research and education in the field of quantum science and technology and to attract the best brains to Bavarian universities, Munich Quantum Valley (MQV) promotes so-called research and development professorships. Already internationally recognized as a top location for quantum science and technology, the Free State of Bavaria is further broadening its basis to create expertise and educate future personnel with this program, which is funded by the Hightech Agenda Bavaria. So far, eight R&D Professorships have been awarded throughout Bavaria.

Prof. Milan Allan (LMU) — Experimental Quantum Metrology and Sensing

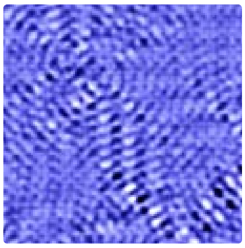
Prof. Milan Allan's research group develops one-of-its-kind quantum microscopes and uses them to understand the intriguing physics of quantum materials. In quantum mechanics, particles can be described as waves. Quantum materials are materials in which the world of quantum mechanics determines the macroscopic properties in unexpected ways. Often, the electrons form collective states, where they all form one quantum mechanical wave.

Allan's team uses scanning tunneling microscopes, which can investigate the properties of quantum materials atom by atom, to map out the wave functions. They also develop novel techniques, for example, measuring not only the electronic currents but also the fluctuations, locally and with extreme precision.

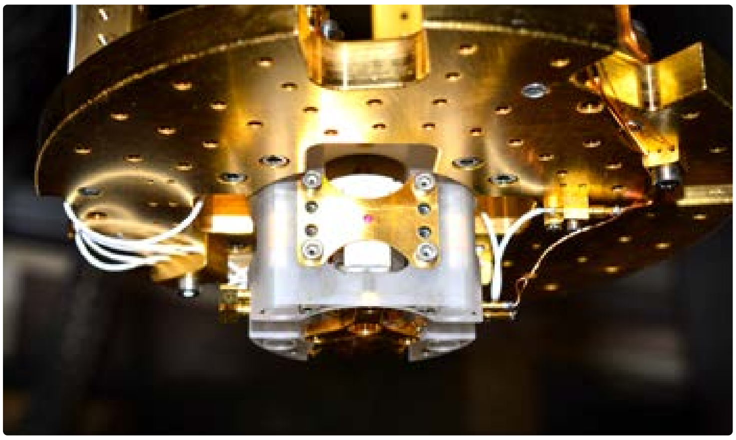
At LMU, his team will integrate new quantum sensors into their microscopes that use the interference of electron waves to measure tiny magnetic fields. One application of this microscope will be as a diagnostic tool for chips used in quantum computers.



Scanning tunneling microscopy image showing the sample topography with atomic resolution.



Interference pattern of quantum waves at a metal surface.



Photograph of the scanning tunneling microscope.

Prof. Wolfgang Mauerer (OTH Regensburg) — Quantum Algorithms and Quantum Information Science

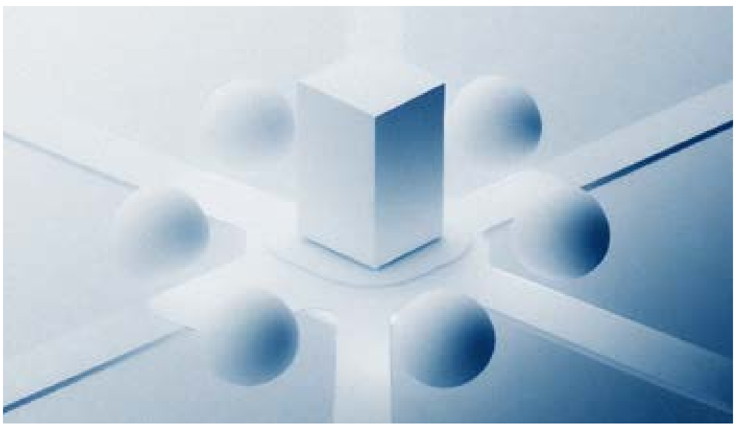
Prof. Wolfgang Mauerer

Prof. Wolfgang Mauerer's Laboratory for Digitalisation (LfD) primarily focuses on the intersection between quantum computing, systems engineering, and software engineering, with a wide range of international partners. Based on support at the European, national, and state level, and in commercially funded collaborations, he and his group contribute to clarifying fundamental quantum problems, developing quantum communication and software, as well as co-designing quantum applications. A highlight of the year was a novel quantum approach for finding optimal join orders in database systems, one of the most widely investigated and computationally challenging problems in the field. Apart from establishing a new strand of research in the community, an adaptation to quantum-inspired hardware could outperform decades of intensive research and commercial development, and tangibly improve the practical state of the art.

By helping establish a ***Special Interest Group on Quantum Computing*** at the Gesellschaft für Informatik e.V. (GI), and leading workshops on quantum machine learning and quantum database acceleration at high-profile conferences, Mauerer's team supports cross-disciplinary community building. Mauerer has introduced quantum computer science in OTH's computer science curriculum already nearly a decade ago. "Quantum Technology" as a new course of study, together with a currently procured quantum-key-distribution system and cross-faculty hands-on quantum labs, complement the quantum R&D efforts of OTH Regensburg and Mauerer's team.

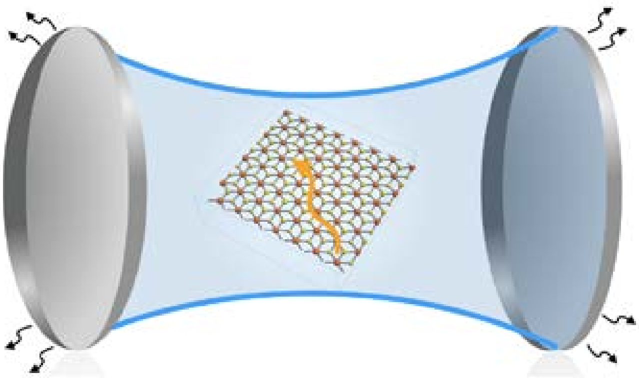
Prof. Roland Nagy (FAU) — Applied Quantum Technologies

Over the past decade, the research and development of applied quantum technologies such as quantum simulators, quantum computers, quantum sensors, or quantum networks has become a major endeavor in scientific research. The goal of these research activities is the quantum technology revolution, driven by the potential of quantum systems to outperform their classical counterparts. Quantum technologies are known to be more sensitive (quantum sensing), provide higher security (quantum network), or even enable functionality beyond a classical approach (quantum entanglement). In analogy to an "internet of things" these functionalities can be combined in a "quantum network of things". A quantum network of stationary quantum memory nodes, connected via photons can combine quantum computers, quantum simulators, and quantum sensors. As part of the ongoing research efforts, Prof. Roland Nagy and his team are focusing on realizing this task. They are using single spins (color centers) as communication qubits to realize a quantum network and nuclear spins as quantum memories.



Prof. Francesco Piazza (University of Augsburg) — Quantum Simulation, Quantum Optics and Quantum Control

The professorship deals with topics at the interface between quantum optics and condensed matter physics. A particular interest lies in collective phenomena that occur in the presence of strong light-matter interactions and their potential applications in the control of quantum material functions as well as in nonlinear quantum optics. Currently, the main focus is on recent experiments on implementing a new, non-relativistic quantum electrodynamics (QED) regime in quantum materials, achieved by confining light e.g. in a resonator. A reliable description of this many-body problem is a major challenge and is currently being developed by a continuously growing group of scientists. The group uses tailored field-theoretical approaches that extend methods from condensed matter theory and quantum optics and bring them together in a consistent, comprehensive and flexible framework. It works in close contact with the experimental groups where the latest developments occur, both in solids and ultracold atomic gases. While the former platforms will ultimately provide scalable quantum technologies to exploit QED effects, the latter will enable microscopically controlled exploration of the underlying phenomenology and a testbed for our theoretical understanding of novel collective behavior.



Quantum matter embedded in a resonator.

Prof. Peter Rabl (TUM/WMI) — Applied Quantum Theory

The realization of practical quantum technologies still faces many scientific and technological challenges, which arise, loosely speaking, from the incompatibility of fragile quantum states with the surrounding classical world. In his newly established group "Applied Quantum Theory", which is co-located at the Technical University of Munich and the Walther Meißner Institute, Prof. Peter Rabl approaches this challenge from a theoretical perspective and aims to develop novel protocols and control techniques to manipulate quantum systems in a more efficient and robust way. These methods will make it possible to preserve quantum superpositions longer, to build quantum processors with more and more qubits, and to reduce the immense classical control overhead still required to operate such systems.

> "… integrating many quantum systems into a single device"

Prof. Peter Rabl

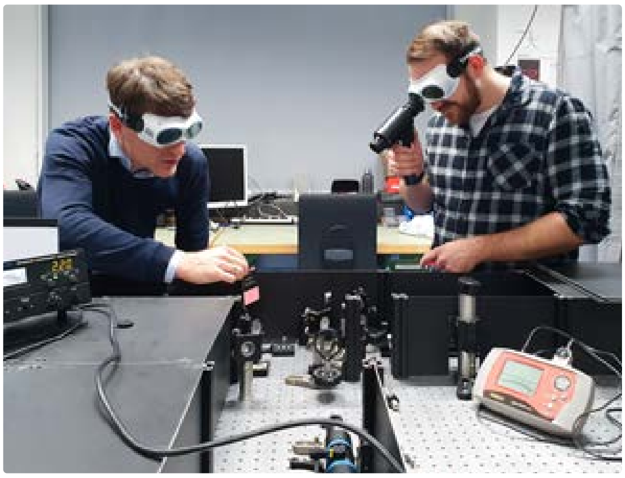
In this context, a specific focus is placed on the theory of hybrid quantum systems, with the long-term goal of integrating quantum systems realized on different physical platforms into a single quantum device or connecting them over long distances via the "quantum internet". Beyond this application-oriented research, Rabl's group is also interested in modeling novel quantum phenomena that are not yet accessible in nature but can be observed in artificial quantum devices with specifically designed interactions.

Prof. Giorgio Sangiovanni (JMU) — Computational Quantum Materials

Novel quantum materials can enable innovation in many technologies, as they promise, for example, significant improvements in energy efficiency. Prof. Giorgio Sangiovanni and his group are investigating such materials at the newly established Chair of Computational Quantum Materials at the JMU Würzburg, and are able to bridge the gap between theory and experiment through their extensive knowledge of the chemical composition of materials and the use of their computational tools. Together, they allow him to predict new phenomena emerging in complex materials due to the interactions of their electrons. His tools range from state-of-the-art many-body algorithms to artificial intelligence in order to explore quantum systems with a large number of interacting particles.

Prof. Andreas Stute (TH Nuremberg) — Optical quantum technologies

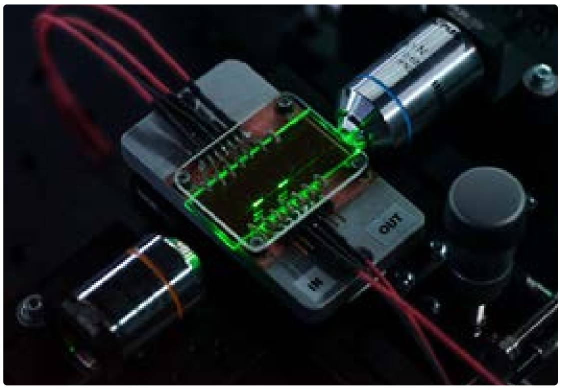
With the appointment of Prof. Andreas Stute to the R&D professorship for Optical Quantum Technologies, the Technische Hochschule Nürnberg Georg Simon Ohm joined MQV in May 2023. The applied research at TH Nuremberg in the area of optical quantum technologies focuses on the miniaturization and industrialization of photonic elements and optical systems for quantum devices. In order to enable this research, the investment in large-scale research equipment has been approved: On the one hand, a femtosecond laser system will be established for writing waveguides and diffractive structures in transparent materials such as optical fibers and bulk optical elements. Through wavelength conversion, this fs-laser could also be used for deterministic generation of vacancies in diamond or semiconductors for application in single-photon emitters or quantum sensing devices. On the other hand, a commercial multi-photon nanolithographic system will be acquired for the 3D printing of polymer optical elements. Both kinds of optical elements will serve as photonic subsystems that provide excitation light to or collect fluorescence light from atoms, ions and artificial atoms. In this way, the developed optical elements should serve as photonic enabling technologies in ion-trap or neutral-atom quantum computers, sensors based on vacancy centers, or photon sources for quantum key distribution. This interdisciplinary research will be realized through the activities of the Faculty of Applied Mathematics, Physics and Humanities and the Faculty of Electrical Engineering, Precision Engineering and Information Technology in collaboration with the Polymer Optical Fiber Application Center.



Prof. Stute and team member in quantum-optics laboratory at TH Nuremberg.

Prof. Tobias Vogl (TUM) — Quantum Communication Systems Engineering

Prof. Tobias Vogl studies optical quantum technologies. This involves using fluorescent defects in crystals that can generate quantum light at room temperature. These defects are combined with photonic integrated circuits to build compact quantum chips that can be used in various applications. Among applications being investigated is satellite-based quantum communication, where information is encoded in single-photon states of light and transmitted over very long distances through the atmosphere. This scenario is currently being evaluated as part of the QUICK^3 mission coordinated by Prof. Vogl. The goal is to develop a quantum-secured internet of the future with quantum communication links and network connections between distributed quantum computers.



Optical quantum chip used for quantum technologies. © University of Jena | Sebastian Ritter

Prof. Vogl aligns an optical quantum chip used for quantum communication. © University of Jena | Jens Meyer

4.3 Quantum education in Bavaria

An important goal of Munich Quantum Valley (MQV) is to provide and support educational programs for schools, universities, and companies in order to raise the next generation of researchers, engineers, integrators, and users of quantum technology and quantum computing in Bavaria and beyond. This is implemented within the Quantum Science and Technology Education in Bavaria (QST-EB) program as part of MQV.

At the master's and doctoral level, the QST-EB project pursues this goal primarily through application-oriented internships, an excellence-focused international doctoral fellowship program in the fields of physics, chemistry, computer science, mathematics, and electrical engineering that is open to all Bavarian universities, advanced practical laboratory experiments at Bavarian universities, and master's-level fellowships. The latter include a program for outstanding female candidates and a program for exchange students of the Munich Master's Program in Quantum Science & Technology (QST). The overall goal is to attract the world's top talents to the MQV sites and train them in quantum technology and quantum computing.

In addition, several training and education offers for industry professionals are being developed within the MQV ecosystem. To this end, the QST-EB project is collaborating closely with the complementary Quantum LifeLong Learning (QL3) training program, funded by the German Federal Ministry of Education and Research (BMBF), which targets specialists and managers from industry in the field of quantum technologies. Complementary to this effort, the Fraunhofer Institute for Cognitive Systems (IKS) is developing more customized quantum computing workshops that address the specific needs of individual companies to inspire quantum innovation within them. Furthermore, MQV also supports the development of educational offers for high-school students within the PhotonLab of Max Planck Institute of Quantum Optics (MPQ), which includes participation in teachers' training. Last but not least, the team at the MQV Office is also reaching out to the general public at science fairs and other public events (→ Chapter 5).

MQV doctoral fellowships

In an annual international competition, MQV awards highly prestigious doctoral fellowships to outstanding young researchers. The MQV doctoral fellows selected through this competition receive a three-year ad personam fellowship – they can join any research group at any Bavarian university but must find mentors who are willing to supervise their doctoral research. Many groups welcome them since they are fully funded for three years. They then join the graduate program with which their host group is affiliated.

The 2023 call received over 180 applications, which, after a multi-stage selection process by a jury of MQV members, resulted in 24 interview invitations and two waiting list entries.

In the end, five candidates (two female, two male, one diverse) were invited and four (two female, two male) were placed on a waiting list in March 2023. At the time of this report, four positions for a doctoral fellowship have been filled.

Anna preparing her materials in the clean room.

Gender

Not specified	4%
Female	29%
Male	67%

Field of interest

Theoretical physics	50%
Experimental physics	38 %
Computer science	8%
Electrical engineering	4%

Nationality of applicants

German	29%
Others	71 %

Overview of the distribution of gender, field of interest, nationality, and the place of graduation of the 24 interviewees for the 2023 MQV doctoral fellowships call.

Anna Rupp

MQV doctoral fellow in the Nanophotonics Group at the Faculty of Physics (LMU)

Anna studies materials, which are so thin they are called two-dimensional. They are made by stacking different layers, which consist of a single layer of atoms, vertically on top of each other. In the artificial crystals, exciting physical effects can be observed, which are promising for a plethora of applications. Some of these effects only occur when the materials are exposed to extreme conditions. For this reason, in her Ph.D., Anna is studying the 2D materials under extremely high pressure.

Quantum technology experiments for advanced practical training at Bavarian universities

Since the beginning of MQV, all seven Bavarian universities with a physics department have been equally funded with 120 000 € (plus 24 000 € overhead) to set up advanced practical training experiments addressing quantum technology topics of industrial relevance. The universities used the investments to provide quantum technology knowledge and training for several bachelor's and master's study programs with a focus on quantum science and technology. In addition, the LRZ plans to provide a first advanced practical training for TUM and LMU students of the Munich Master's Program in Quantum Science & Technology (QST) on one of the locally installed quantum computers.

MQV industrial and application-oriented internships

MQV offers industrial and application-oriented internships in collaboration with industry and the Fraunhofer-Gesellschaft. The internship portfolio is open to students from all Bavarian universities. The decision on which applicant is selected for a specific internship is made by the industrial partners offering the internship. Internship offers relevant to quantum technology and linked to MQV are updated by MQV throughout the year. At the end of September each year, students have the opportunity to apply for financial support during their internship within the framework of MQV's industrial and application-oriented internships.

MQV master's fellowships for women

The fellowship program for excellent female candidates supports up to five outstanding female students of the Munich Master's Program in Quantum Science & Technology (QST). The fellows were selected based on study achievements, quantum-technology activities, and individual interviews.

MQV exchange fellowships

Exchange scholarships are intended to support the exchange of master students with foreign partner universities. The scholarships can be used either for international students of selected partner universities (e.g. at Zurich, Paris, Barcelona) or for students of the Munich Master's Program in Quantum Science & Technology (QST) visiting a partner university.

In 2023, an exchange with ETH Zurich was supported within the framework of PushQuantum, as well as the participation in the European program Digitally Enhanced European Quantum Technology Master (DigiQ). The aim of DigiQ is to build a digital European Master's program in quantum education. The role of LMU and TUM is to provide access to the industrial and application-oriented internships of MQV for students of the partner universities.

Training and education for industry professionals

In general, the MQV-funded educational programs support students at the university level in Bavaria. Complementary, "Quantum LifeLong Learning" (QL3) is a joint project of TUM and LMU, funded by the Federal Ministry of Education and Research (BMBF) with the aim to establish a training and education program for specialists and managers from industry in the field of quantum technologies. The close proximity of the MQV member institutes (WMI, MPQ and the two universities) enabled them to welcome the QL3 participants for on-site visits and networking events.

In a complementary approach, the Fraunhofer Institute for Cognitive Systems (IKS) is targeting individual companies and their specific needs to create tailor-made quantum-computing workshops focusing on applications.

Judith Gabel giving a "Quantum Life Long Learning" (QL3) workshop. © MQV | Mikka Stampa

Participants of the Quantum Future Academy 2023 at the closing event in Berlin. © bundesfoto | Ole Heinrich

Quantum Future Academy for students from Israel and Germany

Together with the Munich Center for Quantum Science and Technology (MCQST), MQV was the local host of this year's Quantum Future Academy, a BMBF-funded initiative to introduce students to quantum science and technology. In 2023, the program brought together students from Israel and Germany. After the group spent a week together in Israel in February to explore the local quantum community, they were guests in Munich for another week in September to immerse themselves in the Bavarian quantum ecosystem. In addition to visits to research institutions with scientific presentations and lab tours, the students had the opportunity to visit companies and get in touch with local quantum start-ups. In a two-day workshop, the students learned what it means to start a company in quantum technology and had the opportunity to interact and discuss with founders. At the end of the week, they pitched their workshop ideas to a panel of BMBF representatives and experts from the quantum tech industry in Berlin. All participants enthusiastically agreed that it had been an amazing experience and that they would like to meet again.

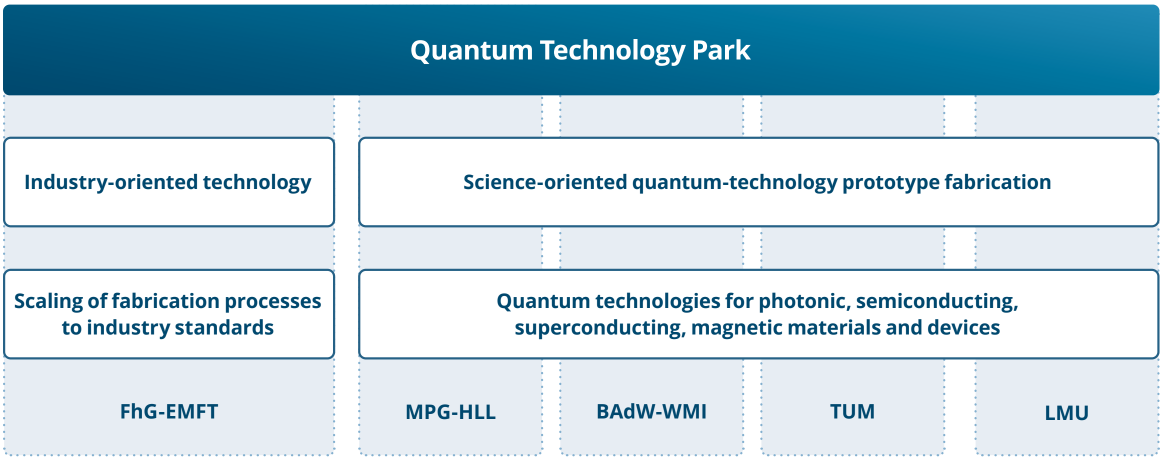
A quantum lab for high-school students

To make quantum science more accessible to a younger audience, MQV is actively supporting the PhotonLab, a laboratory for pupils located at the Max Planck Institute of Quantum Optics (MPQ), in the development of a new educational program called ***QuantenLabor***. By providing a new single-photon experiment and jointly developing appropriate educational materials, high school students and teachers will have access to a hands-on experience to learn about quantum technologies and quantum computing. First pilot classes have already visited this new setup, and it was also used in teachers' training. It helped both students and teachers gain new insights into quantum science by simultaneously showing wave and particle behavior in a single experiment.

4.4 Quantum Technology Park

A key measure of Munich Quantum Valley (MQV) is to set up a high-tech infrastructure providing state-of-the-art fabrication tools for quantum technologies.

To this end, the MQV Quantum Technology Park (QTP) combines already existing infrastructure at TUM, LMU, the Fraunhofer Institute for Electronic Microsystems and Solid State Technologies (FhG-EMFT), and the Walther Meißner Institute (WMI) of BAdW to create an infrastructure network that allows to advance new ideas for quantum devices from a proof-of-concept level to industrial production quality. Within the QTP program of MQV, the equipment of the already existing tech infrastructure is upgraded and new clean-room facilities at the Semiconductor Laboratory of the Max Planck Society (MPG-HLL) will be available until 2024. Moreover, Fraunhofer EMFT will obtain a new building with state-of-the-art tech infrastructure on the Garching Research Campus until 2029/2030. Whereas FhG-EMFT aims at the development of industry-scale fabrication processes, the other parts of QTP at MPG, BAdW, and the universities focus on science-oriented quantum-technology infrastructure for developing new materials and device concepts, as well as prototype fabrication.



The Quantum Technology Park of MQV consists of already existing/planned components at the Fraunhofer Gesellschaft (FhG-EMFT), the Max Planck Society (MPG-HLL), the Bavarian Academy of Sciences and Humanities (BAdW-WMI), and the Munich universities (TUM, LMU).

The present efforts within the QTP consortium mainly aim at the creation of a productive and accessible infrastructure network. The following three points are considered most important to achieve this goal:

1. **Creating transparency about capabilities, tools, and processes.** This allows for more effective use of existing equipment and better and coordinated purchasing decisions for new equipment. Moreover, it is the prerequisite to leverage the manufacturing process across different locations within or associated with the QTP.

2. **Providing access for internal and selected external stakeholders.** Enabling flexible access or at least the ability to leverage the capabilities of the QTP for all internal MQV stakeholders is a top priority. At present, also access regulations for external or "semi"-external stakeholders like spin-offs from MQV institutions, are being developed.

3. **Streamlining of processes across institutions.** Once access modalities are implemented, the individual technological capabilities are matched with important manufacturing processes to leverage the full potential of the QTP. In general, different locations will be used for different purposes across the development cycle of a technology from proof-of-concept to industrial production.

Four major construction projects are at the core of the Quantum Technology Park and presently are or will be implemented. They all contribute important technological capabilities to the MQV infrastructure required for developing quantum technologies further and to turning them into industrial-grade products.

1. **Refurbishment of the Quantum Materials and Devices Cleanroom at LMU.** The refurbishment of the Quantum Materials and Devices Cleanroom at the Chair of Experimental Solid-State Physics is close to completion. The clean room is primarily designed for fundamental research, allowing easy access to scientists and engineers with low process barriers. It allows rapid testing of research ideas and new quantum device concepts. It is particularly suited for the development of novel processes for quantum device fabrication, which, if successful, can be transferred to the more industry-oriented fabrication lines of QTP.

2. **New building on the Garching Research Campus for superconducting quantum technologies.** TUM and the Walther Meißner Institute (WMI) of BAdW are joining forces to extend the capabilities for superconducting technologies within the QTP. A new building in the direct vicinity of WMI is currently in the planning phase. The new building has to host dedicated tools for fabricating superconducting quantum circuits on four-inch wafers such as thin film deposition systems, electron beam and optical lithography, and infrastructure for 3D integration of chips. The concept phase as well as the feasibility studies are already completed. Unfortunately, limiting capabilities of the department of planning and building inspection result in considerable delays and strongly increasing construction costs become an important issue.

3. **New Semiconductor Laboratory of the Max Planck Society.** The new Semiconductor Laboratory was already under construction at the foundation of MQV and is planned to be completed early in 2024. Moving into the building and connecting all equipment to the supplies of the building will take another few months until the new laboratory is fully operational. A part of the 1500 m^2 industrial grade clean room will then support the development of new technologies within MQV, especially of photonic and superconducting quantum technologies.

4. **New building for Fraunhofer Institute for Electronic Microsystems and Solid-State Technologies (EMFT).** Fraunhofer EMFT is currently planning a new building on the northwest corner of the Research Campus Garching. The office and laboratory space requirements were already submitted at the beginning of the year. The new building will provide about 3400 m^2 for clean rooms, laboratories, and further technical infrastructure. The facility will run a clean room for silicon technology and will provide technologies for 3D integration of superconducting quantum circuits. It will allow industrial-scale fabrication of superconducting qubit chips on eight-inch silicon wafers.

4.5 Entrepreneurship

Turning world-class research into economic success and building a globally competitive quantum tech industry in Bavaria is one of the core goals of Munich Quantum Valley (MQV). Therefore, technology transfer is a key issue, and entrepreneurship is a key ingredient for its successful implementation since the gradual transfer of knowledge and capabilities from research to the incumbent industry is slow and often impossible due to a lack of talent concentration in existing companies.

The entrepreneurial efforts within MQV are driven by the ***Venture Lab Quantum (VLQ)*** which is part of the larger TUM Venture Lab initiative, supporting deep tech and life science start-ups across different domains.

Setting up the new Venture Lab Quantum headquarters

One key achievement in the last twelve months is the setup of the new headquarters for the Venture Lab Quantum and the founders within the program. This is especially important due to the considerable delays in the planning of the new quantum technology building on the Research Campus Garching and the dire lack of spaces on campus in general. With the new location in Münchener Straße 34, Garching, VLQ could add a state-of-the-art co-working space providing 24 workplaces, meeting rooms, call booths, and community areas on nearly 400 m^2. This will allow all founders in the Venture Lab Quantum program to have office space, while the location will simultaneously serve as the heart of the entrepreneurial quantum community.

The IdeaLab

The ***IdeaLab*** is an entrepreneurial education program tailored for Ph.D. students and postdocs in quantum-related disciplines. The format supports researchers with identifying and evaluating commercial applications of their academic work. Throughout a two-day workshop, twelve researchers get together in small groups to develop quantum-related start-up ideas, concluding in a pitch deck presentation. Additionally, the format imparts holistic knowledge on how to develop a deep tech start-up, spanning from IP management to customer acquisition.

After the inaugural IdeaLab in June 2023, a second session tooks place already in October 2023, with both dates attracting a total of 57 applications. The applicant pool consists of individuals from various academic backgrounds: 69% physics, 20% electrical engineering, and 11% computer science, all with quantum-related research topics. While the majority of applicants are from the workshop's target group of Ph.D. students (58%) and postdocs (15%), Bachelor's and Master's students amount to 27% of all applications. They are redirected to alternative educational platforms within the Venture Lab Quantum. From the program's first iteration, one team continued the work on their idea in stealth mode and is currently part of the Venture Lab Quantum Team.

Start-up pipeline and our class of 2022

Several start-ups were already supported by the Venture Lab Quantum (VLQ) during 2021 in the months before the actual start of MQV. As of today, the VLQ is supporting 15 founder teams across various maturity stages. In 2022, four of these teams incorporated and are currently on track to become successful businesses:

As a spin-off from the Max Planck Institute of Quantum Optics, **planqc** is the first true MQV start-up and aims to build quantum computers based on the MPQ's neutral atom platform with strontium atoms. After the incorporation in 2022, the team could raise more than €5 million from leading European Venture Capital funds and was successful in attracting a €29 million development contract from DLR QCI in April 2023 as well as a BMBF grant valued at €20 million later in 2023.

Quantum Diamonds, The spin-off from Prof. Dominik Bucher's chair for quantum sensing in Chemistry Department of TUM is developing a quantum sensing platform based on NV-Centers in diamond for applications in semiconductor industry. After successfully attracting support through EXIST, ESA, and a pre-seed ticket by Funding for Innovators, the team recently became part of one of MQV's industry-driven Lighthouse Projects and received funding through the prestigious EIC Accelerator program. In parallel, they run the first commercial pilots with leading semiconductor manufacturers and are close to closing the first investment round.

The start-up **Munich Quantum Instruments (MQI)** is a spin-off from the chairs of Prof. Kai Müller (Quantum Electronics and Computer Engineering) and Jonathan J. Finley (Semiconductor Nanostructures and Quantum Systems) building single-photon detectors based on superconducting nanowires. For these cutting-edge quantum detectors, MQI combines well-established know-how from the fields of Quantum Electronics and Quantum Physics and is well connected in the MQV ecosystem. Prior to their incorporation in the end of 2022, the team successfully applied for the EXIST Transfer of Research grant and is part of ESA-BIC. Since then, MQI started several research projects of ESA and with other companies in the quantum tech space.

Qlibri is a spin-off from Prof. Alexander Högele's chair at LMU and commercializes its microcavity technology in the form of hyper-sensitive absorption microscopes and through their quantum optics platform. The team was awarded the EXIST transfer of research grant already in 2020 and is growing organically now through collaboration with multiple researchers around the globe.

Driven by these successful examples, we could recently onboard multiple new founder teams to the Venture Lab Quantum program with ideas, ranging from new software solutions for quantum computing over quantum-enabled biomimicry of the sense of smell to novel concepts in microscopy.

The TechChallenge “Diagnose me, quantum-style”

During the summer semester 2023, the Venture Lab Quantum hosted a challenge within UnternehmerTUM’s “TechChallenge” program together with the start-up Quantum Diamonds. The program is open to students from all academic backgrounds and typically attracts around 200 students per semester. The challenge focused on using quantum sensing with NV-centers in diamond in medical diagnostics (and was named ***Diagnose me, quantum-style***. The challenge attracted the most students of any program partner, such that 30 students split into five teams tackled the challenge throughout the semester. With technical input from Quantum Diamonds CTO Dr. Fleming Bruckmeier and through PD Dr. Michael Seidel from TUM as well as methodical input from the Venture Lab Quantum team, the students discovered various specific use cases for the technology and worked on their initial (digital) prototype solutions.

This program introduced the basic concept of quantum technologies to a broad range of students. Most notably, three of the five teams were really intrigued by the power of this technology and decided to continue with their projects after the end of the program. The three teams (Bioqube, Biosense Quantum, Scentum) have since been onboarded to the core program of the Venture Lab Quantum and currently receive support during the first steps towards building the next quantum sensing start-up.

The Quantum Entrepreneurship Laboratory

During the winter semester 2022/23, the Venture Lab Quantum organized the fourth iteration of the course ***Quantum Entrepreneurship Laboratory (QEL)*** together with the student initiative PushQuantum. For the three roles of business developer, software engineer and quantum specialist, 30 students were selected from a pool of nearly 100 applicants. The participants were grouped into five teams, which tackled the challenges of our five challenge partners with a solution based on quantum computing. In this batch, the students were working with teams from Airbus, Infineon, Knuspr (e-Grocer), Merck KGaA and Volkswagen.

At the end of the semester, the five teams showcased their start-up concepts and technical solutions to the challenges at the QEL DemoDay in front of their challenge partners, their peers, and many external guests.

Quantum Future Academy workshop

Today's insights for tomorrow's experts – this is the motto of the Quantum Future Academy, a BMBF-funded initiative that aims to support and connect young quantum-enthusiastic students from different backgrounds. This year's program brought together a group of students from Israel and Germany. It was divided into a one-week stay in Israel (February) and a one-week stay in Germany (September) in order to get an introduction to both quantum ecosystems.

The centerpiece of the program in Germany was a Quantum Entrepreneurship Workshop organized by Venture Lab Quantum, where students fast-tracked concepts for quantum technology-based start-ups. They received support from a range of experts from leading companies in the Munich quantum ecosystem, including Menlo Systems, planqc, Quantum Diamonds and Munich Quantum Instruments. Within the limited time of two days, the teams succeeded in transforming rudimentary topic proposals into well thought-out start-up concepts. The culmination of their efforts and the entire week was the final event in Berlin, where the teams were able to present their start-up ideas in the presence of the State Secretary at the BMBF, Mario Brandenburg, the Israeli Ambassador, Ron Prosor, and many other distinguished guests.

Other activities

Besides the individual programs and activities mentioned above, MQV is continuously expanding its network with industry partners, investors, and other ecosystem supporters. With the key incubation and acceleration programs in Munich, such as Xplore and Xpreneurs at UnternehmerTUM or Intel Ignite, we collaborate closely to provide comprehensive support for the founders in our program.

Upcoming activities and outlook

The next efforts will focus on the extension of the VLQ team capacity and setting up the spaces in the new headquarter. In parallel, the support for the founders in the program will be enhanced by an expert speaker series which will cover topics from the mechanics of a Venture Capital fund to creating a strong culture in fast-growing teams. To further enrich the ecosystem, a concept for a ***Quantum Landing Pad*** has been created together with Invest in Bavaria. The go-live for the Landing Pad is planned for the beginning of 2024.

4.6 Partner Network

The Partner Network of the Munich Quantum Valley e.V. brings together stakeholders from research institutions, universities and companies with the common goal of promoting quantum science and quantum technologies in Bavaria. Over the past year, the network was continuously growing and meanwhile includes around 20 industrial and about 15 academic partners. While the majority of them joined the network through participation in related projects, such as Lighthouse Projects (→ 4.1) or BMBF-funded projects, a growing number of companies also joined through a new application process.

An MQV-internal working group, set up by the MQV Office (→ 1.2.4), is continuously working on the further development of the Partner Network and its benefits for its members to support an efficient knowledge transfer from research to industry and jointly develop educational offers for schools, universities, and companies.

Industry partners

Academic partners

4.7 Exchange with partners from academia and industry

In order to promote and foster the exchange with partners from scientific institutions and industry, both, internally within the MQV ecosystem and externally, MQV has launched a number of event formats and participated in a variety of academic conferences and industrial fairs.

Aimed primarily, but not exclusively, at a scientific audience, MQV has hosted nine monthly virtual ***MQV Colloquia*** with a total of eleven presentations by both internal and external invited speakers. To complement this series and to focus more on the needs of younger MQV members and to foster their exchange, MQV also organized several ***MQV Early Career Events***, where doctoral students presented their work and in-depth technical discussions were possible.

Addressing both academia and industry, MQV has launched a series of symposia having covered topics such as Quantum Computing meets Cyber Security and Applications of Quantum Computing.

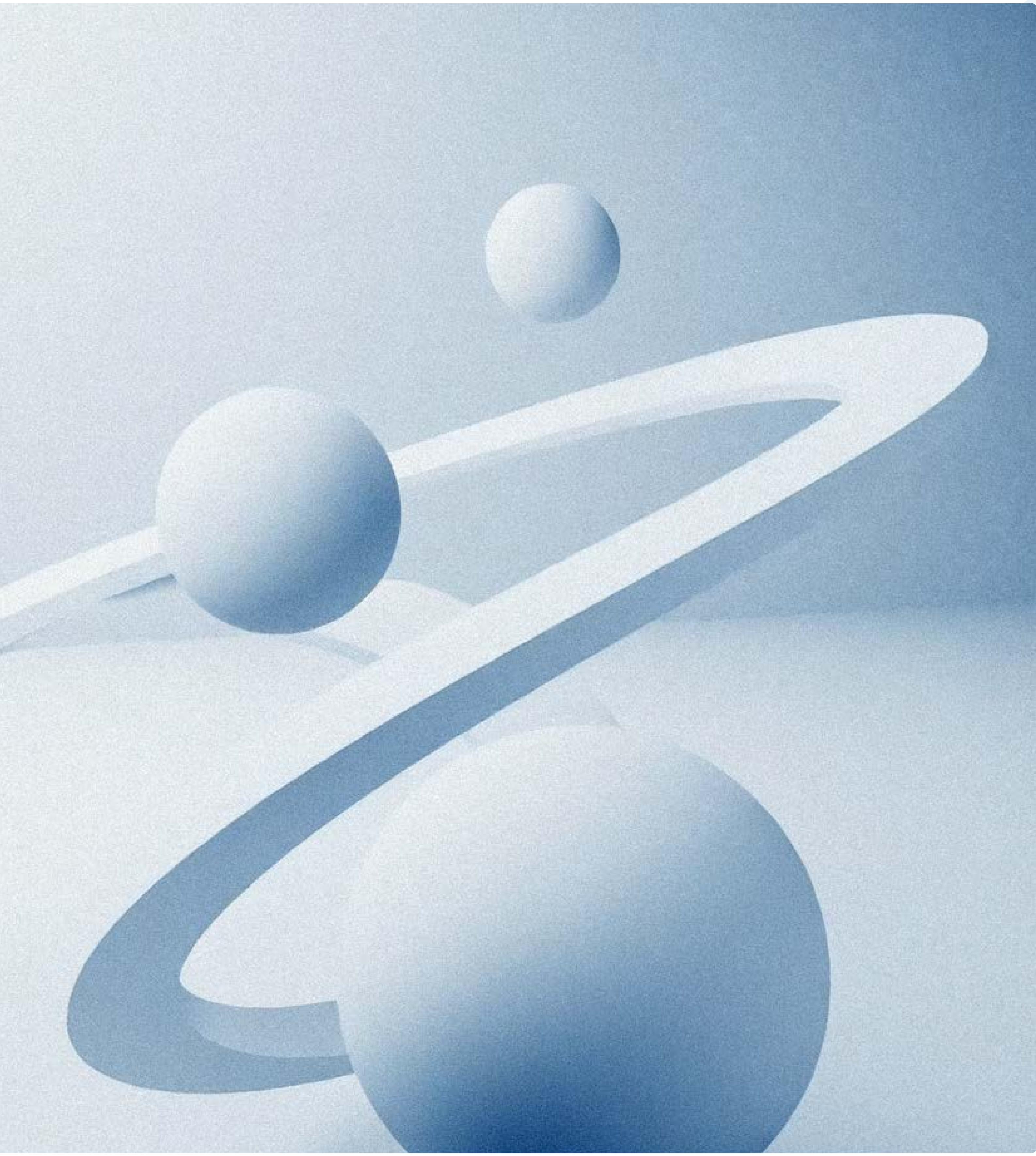
In order to increase MQV's visibility, to establish MQV as a role model for a quantum ecosystem, and attract new talent and new members to the Partner Network (→ 4.6), MQV has participated in a wide range of exhibitions, including the World of QUANTUM in Munich, the Spring Meetings of the American and German Physical Societies APS, DPG-SAMOP, DPG-SKM, the "Hannover Messe", and the European Quantum Technologies Conference, to name a few.

← Looking back at
World of QUANTUM 2023
on YouTube

Impressions from the World of QUANTUM
at Messe München. © MQV | Mikka Stampa

Impressions from the MQV symposia Quantum Computing Meets Cyber Security.
© MQV | Mikka Stampa

Impressions from the symposia Applications of Quantum Computing.
© MQV | Mikka Stampa



Chapter 5

5

Public engagement and the media

Engaging with the public by communicating the fascination of quantum science and technology and moderating the discussion about expectations, hopes, and possible fears is an important task for MQV. To create a basic understanding of quantum technologies and their benefits for society and provide insights into its research, MQV participated in various public events and launched its own outreach formats as well as new educational offers for high school students.

5.1 Public events and outreach activities

During the two science festivals "FORSCHA" and "Festival der Zukunft" at Deutsches Museum, which each lasted several days, as well as during the day of open house on the Research Campus Garching, MQV reached many visitors of all age groups. With experiments and exciting exhibits at the MQV booth, they could learn a lot about quantum technology and quantum computing and ask all their questions.

MQV researchers spoke in public formats about quantum computing and their own research more than a dozen times. They used a variety of opportunities to share their knowledge and insights, from public evening lectures to panel discussions, science slams, and podcast interviews.

The new monthly portrait series "MQV In Persona" is also aimed at a broad readership. It sheds light on the research of young postdocs and doctoral students, gives personal insights, and shows how diverse MQV's research is.

Special offers for high school students were also well received. Ten female students aged 14 to 16 took part in MQV's 2023 Girls'Day at Walther Meißner Institute to learn about basic principles of quantum physics, ultra-low temperatures, as well as the profession of scientists during an extensive lab tour.

As a further measure to make quantum science more accessible to younger audiences, MQV has supported the PhotonLab school laboratory at MPQ to establish a new "QuantenLabor" by purchasing a new single-photon experiment and supporting the development of related educational materials and programs for late high school students.


Julius

Smoking heads, cool experiments:

the MQV Girls'Day

What happens to an atom when we use it as a qubit? Can researchers estimate how likely a particular result is when measuring a quantum state, and can they influence quantum states? And how can we even prove that quanta can really be entangled over infinite distances?

Right from the start, the ten female students aged 14 to 16, who took part in MQV Girls'Day program at the Walther Meißner Institute (WMI), bombarded the scientists with questions. After introductory lectures and heated discussions on the basics of quantum science, the girls were given a cool-down – literally – with experiments involving liquid nitrogen. The girls could observe how different materials and gases behave at ultra-low temperatures. They were then allowed to dip flowers into the impressively swirling nitrogen and watch in fascination as they froze within seconds.

The day continued with a guided tour through the laboratories. And here, too, there was plenty on offer: Seeing the complex inner structure of cryostats up close, with helium pumps puffing in the background. Holding tiny computer chips in the hand and discovering the qubits on them.The lab tour again raised a number of questions for the girls, which they eagerly posed to the scientists.

At the end, the girls were given the opportunity to do "cookie lithography" using cookies as the "substrate", powdered sugar in analogy to metal particles, and paper masks for pattern transfer, which they had cut out themselves. In this way, they could experience what they had just learned in the lab about chip production.

When asked if they could imagine becoming a scientist themselves, some girls nodded eagerly and some even asked directly about internship opportunities. There could be no higher praise for the WMI scientists who took the time to present their work to the young aspiring researchers and answer their many questions.

← Julius Feigl showing the Girls'Day participants a cryostat at Walther Meißner Institute, explaining the cooling mechanisms. © MQV | Mikka Stampa

Impressions from the Girls'Day at Walther Meißner Institute. © MQV | Mikka Stampa

Amazing experiments and the fascination of quantum computing:

MQV at FORSCHA

From children at kindergarten age to retired physics teachers: At the MQV booth at this years' FORSCHA – an interactive festival of knowledge in Munich – young and old were able to gain an insight into quantum research and engage in experiments of their own.

The youngest visitors were particularly impressed by the effect of two polarization filters rotated against each other: ***Look, Dad, it suddenly gets dark!*** The effect, which looked like magic to the young visitors at first glance, could be explained by using an egg slicer as a "filter" and light waves from the 3D printer.

Those who were still not satisfied after the introduction to light polarization could delve deeper into the behavior of light in the quantum-eraser experiment and gain insight into wave-particle dualism. The green laser in the experiment seemed to magically attract children in particular. Even initially skeptical visitors found it difficult to escape the spell of the weird quantum effect as the explanation progressed. Parents often turned to their children for help, for whom this was nothing new: double slit, interference, no big deal.

Visitors at the MQV booth also learned that quantum properties are not only good for fascinating experiments, but also have a real application, e.g., in quantum computing. On a real quantum-computer chip provided by Walther Meißner Institute (WMI), tiny little qubits could be discovered. Built into a shiny golden holder, characteristic of the chandelier architecture of quantum computers with superconducting qubits, the chip made the abstract concept of quantum computing tangible.

← Richard Milbradt showing effects of polarization at the FORSCHA. © MQV | Mikka Stampa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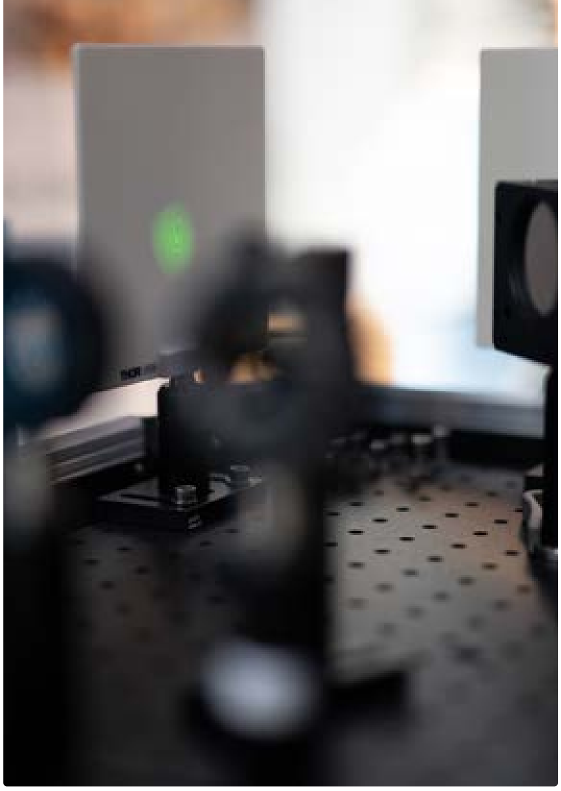
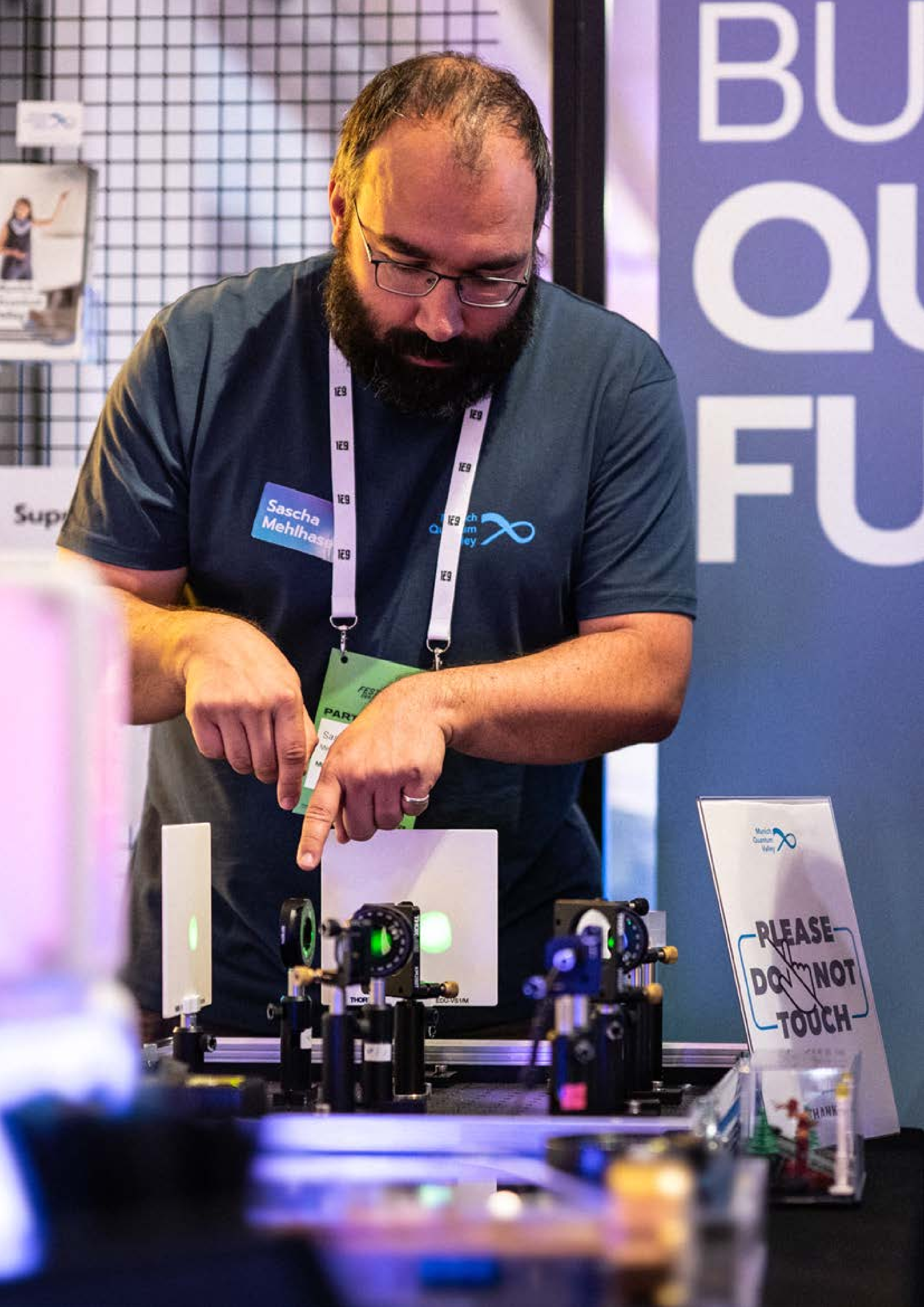


Impressions from the FORSCHA. © MQV | Mikka Stampa



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The future of quantum technologies:

MQV at the Festival of the Future

This year, MQV participated for the second time in the Festival of the Future on Munich's Museum Island – an event organized by 1E9 and Deutsches Museum, attracting representatives from science, business, politics, and the arts to discuss new technologies and ideas for a better future. At the booth, on panels and in workshops, MQV together with MCQST, PhotonLab and QL3 informed the diverse audience about the potential of quantum technologies and especially quantum computing.

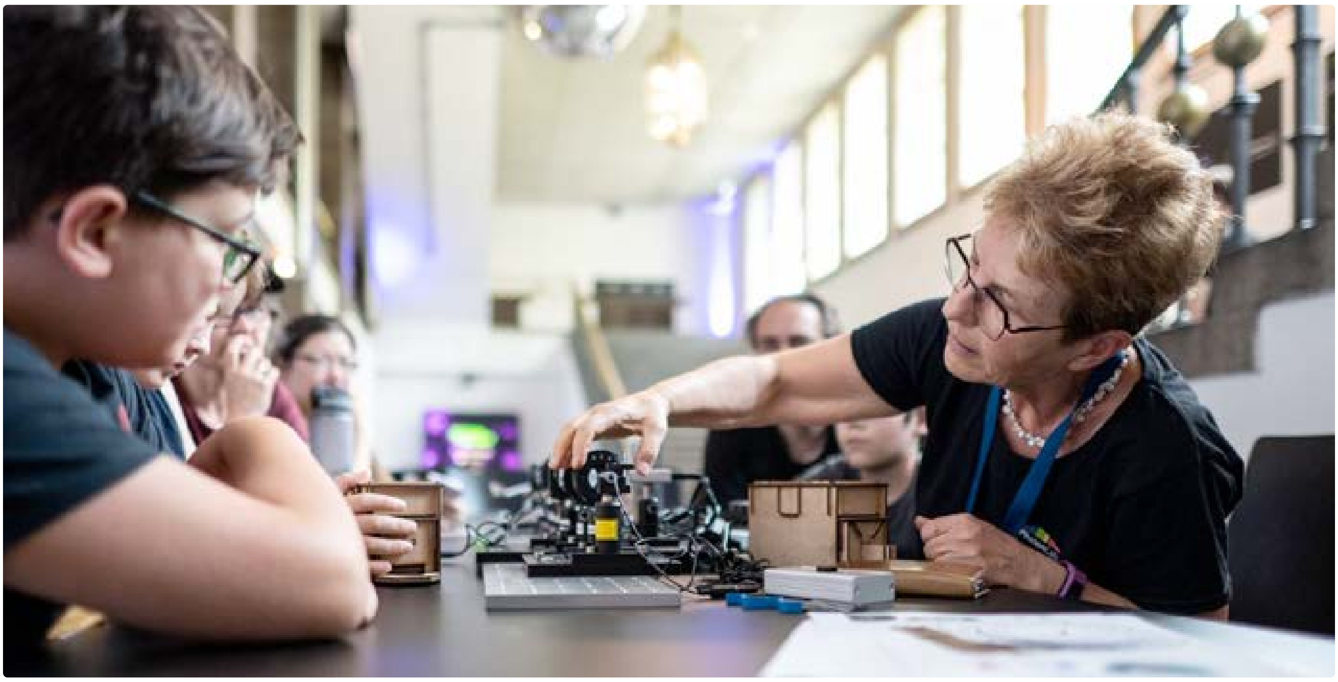
Visitors from very different backgrounds – natural sciences, IT, finance, design or communication, to name a few – shared a fascination for new technologies. At the MQV booth, the audience, some of whom were coming into contact with the field of quantum technology for the first time, was infected by the enthusiasm for this field of technology. The questions were as varied as the audience: while some were primarily interested in the basic principles of quantum science and learned about wave-particle duality from the quantum-eraser experiment, others inspected chips with superconducting qubits, visited a research lab for ultracold atoms with VR glasses and wanted to know details about the different technological approaches to realize quantum-computing hardware. Still others were primarily interested in potential applications and social as well as economical aspects of quantum computing. On the first day, the Bavarian State Minister of Science and the Arts, Markus Blume, also visited the exhibition. Furthermore, students took the opportunity to get information about Ph.D. projects and career opportunities at MQV and the Munich Cluster of Excellence MCQST.

MQV members also participated in two panel discussions. The panel "Beyond NISQ: How to harness the potential of quantum computers," explored the question of what further steps in research and development are necessary to move from error-prone quantum computers with a limited number of qubits to error-corrected, scalable devices. MQV member Robert Wille brought his perspective as a software expert to the table. Tatjana Wilk and Christopher Trummer contributed to the panel "Building an Industry: How to create a quantum valley" with their experience in education and promoting spin-offs.

The program was complemented by hands-on workshops offered by the PhotonLab and QL3, where participants from elementary school children to retirees learned about single-photon experiments, entanglement and quantum cryptography.

← Sascha Mehlhase explaining the quantum eraser experiment. © MQV | Mikka Stampa

← Looking back
at Festival der Zukunft
on YouTube



Impressions from the
Festival der Zukunft.
© MQV | Mikka Stampa

5.2 Munich Quantum Valley in the media

Munich Quantum Valley (MQV) and its associated researchers, projects and start-ups are regularly featured in news articles, both online and in print, in national and international media. About thirty individual news articles mentioning MQV were published in 2023, with many of them being picked up by several media outlets and in different languages. A non-exhaustive list of articles that provided a more in-depth look at MQV and its work can be found in the table on this page.

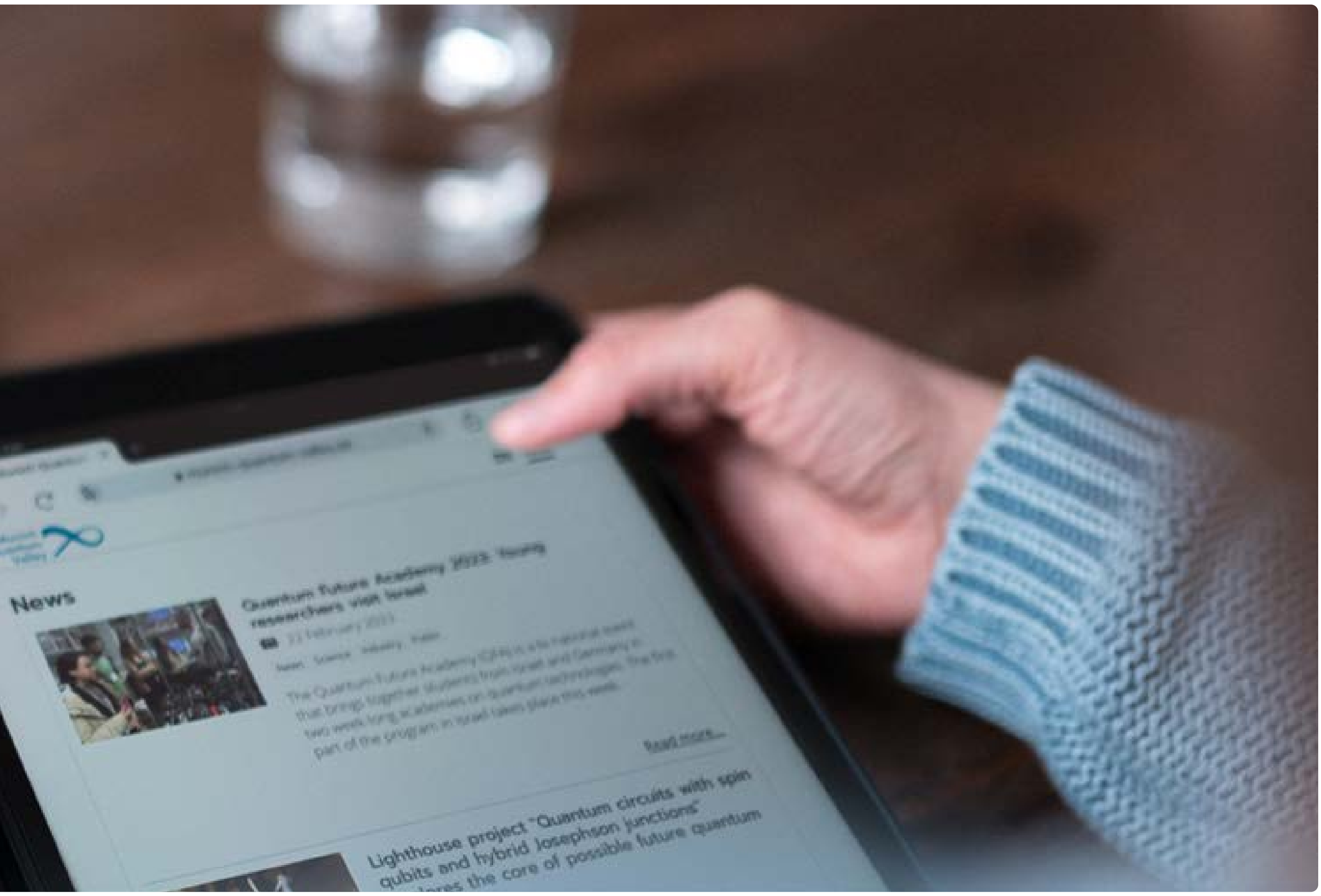
MQV has also been actively reaching out to the media with press releases announcing, e.g., the appointment of Prof. Rudolf Gross as the new Scientific and Managing Director and the acquisition of a quantum computer at the Leibniz Supercomputing Centre, based on trapped ions developed by the start-up company Alpine Quantum Technologies (AQT).

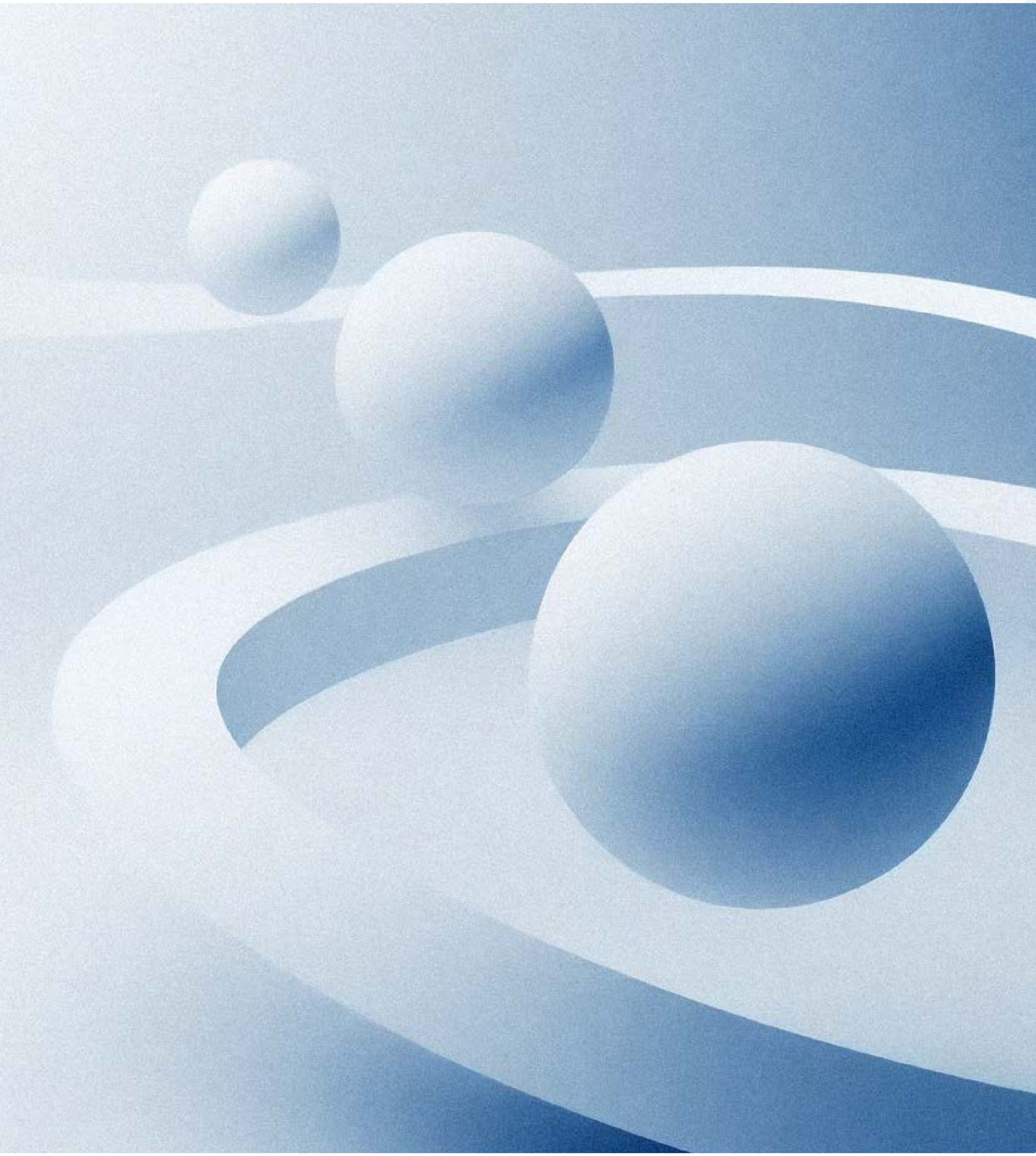
In addition to its presence in traditional media, MQV is also active on several social media channels. On Instagram, LinkedIn, Mastodon and X (formerly Twitter), MQV shares news and stories from the website, announces events, and provides colorful insights into its public engagement activities through photos and videos. MQV also promotes the activities of its member institutes and individual members in order to spread them further by acting as a multiplier. Over the past year, MQV has significantly grown its following on all platforms. The most important platform for MQV is LinkedIn, where the number of followers has almost doubled in the last year and currently stands at around 7300.

← Find selected articles and other media reports about Munich Quantum Valley on our website

© MQV | Mikka Stampa

Date	Media	Title
12 Dec	**pro-physik**	Ein Qantensystem auf Basis von Ionenfallen für das Munich Quantum Valley
23 Oct	**Mewburn Ellis**	Wie München sich einen Namen in der Quantentechnologie macht
14 Sep	**Businesswire**	REPLY bringt Quantum Computing in die Praxis
22 Mar	**Industriemagazin**	Quantencomputer für die Industrie: ein Gamechanger?
16 Mar	**Industrieanzeiger**	Industrielle Anwendungen im Fokus der World of Quantum
14 Mar	**HPC wire**	Leibniz QIC's Mission to Coax Qubits and Bits to work together
3 Mar	**NEWS | Rhode & Schwarz**	Superposition: Vast strides in quantum sensors and quantum metrology
24 Feb	**brutkasten**	planqc: Quantencomputer-Startup gewinnt Hermann Hauser als neues Board Member
22 Feb	**Süddeutsche Zeitung**	Quantencomputer: Alles nur ein Hype?
16 Feb	**Mirage**	How Quantum computers can become more reliable





Chapter 6

MQV life

MQV brings together a large number of scientists and developers from all over Bavaria. Professors, postdocs and Ph.D. students from a wide range of disciplines, company representatives, and start-up founders are all working towards the common goal of developing competitive quantum computers. Over the past year, the MQV community has grown even closer and scientific exchange has intensified.

From 26 to 28 September, all MQV members gathered in Eichstätt for the annual review meeting. In addition to the official program, the breaks and joint dinners provided time for exchange not only on a scientific but also on a personal level. Already knowing also the more distant colleagues from last year's meeting and the exchange, that took place in between, the atmosphere had something of a class reunion feel – with participants already looking forward to the next review meeting.

Several formats have been set up on a regular basis to promote exchange among members and allow the scientists to get to know each other and their work better. Seven of the eleven speakers at the nine virtual "MQV Colloquia" hosted by MQV this year were MQV scientist. Their talks invited a worldwide audience into the local quantum ecosystem. To focus more on the needs and exchanges of younger MQV members, MQV has organized several "MQV Early Career Events". The new monthly portrait series MQV In Persona, launched in July this year, also serves to introduce the young members and their work to one another. The portraits report on the work and lives of young scientists and describe their achievements as well as common challenges. At the same time, they show how diverse but also interconnected the research within MQV is.

Not only at internal events, but also at external fairs and conferences, MQV members met and performed together. For example, at this year's IEEE Quantum Week in Bellevue, Washington, where many MQV researchers from Technical University of Munich, Leibniz Supercomputing Centre, and Fraunhofer Institute for Cognitive Systems participated. The evening before the conference started, they were all invited to the MQV meet-up to kick off the conference week together and receive an MQV pin to show their MQV affiliation during the event.

MQV members also organized various workshops throughout the year, both for external audiences and especially for their own members. With their workshop "Quantum Machine Learning – Integrating Hardware and Software Developements", for example, MQV members from Friedrich-Alexander-Universität and Max Planck Institute for the Science of Light in Erlangen welcomed software as well as hardware developers to deepen their knowledge of neuromorphic quantum computing. Young MQV members in particular were invited to a workshop on certification and benchmarking for quantum computing. In addition, this year saw the start of a series of technical exchange meetings organized from within the consortia to address the tasks that require the input and collaboration of different consortia.

Impressions from the review meeting. © MQV | Mikka Stampa

In Persona

Munich Quantum Valley (MQV) follows a full-stack approach in developing quantum computers. In practice, this means an enormously diverse group of researchers and engineers with different backgrounds working on a variety of topics and problems.

Each of the researchers focuses on his or her specific area of expertise, but with strong collaboration and exchange across topics to achieve the common goal. Here are some of the projects and activities carried out by young scientists in the MQV network to highlight the wide range of research perspectives in the advancement of quantum computing.

“At the level below us, it’s really just the qubit chips”

Johan Tsayem

Fraunhofer Institute for Integrated Circuits (IIS)

Johan develops controller chips for quantum computers and thus works on the foundation of the technology. With his chips, Application Specific Integrated Circuits (ASICs), which he designs for specific applications, individual qubits can be controlled.

The quantum-control chips Johan Tsayem is developing at the Fraunhofer Institute for Integrated Circuits (IIS) in Erlangen are, in a sense, part of the foundation of quantum computers: “At the level below us, it’s really just the qubit chips. We are the people who build the control,” he explains.

The interdisciplinary exchange with MQV colleagues at the review meetings helped him as an electrical engineer to better understand the entire system, even if different worlds collided there for him: “What the software developers do, for example, is a great mystery to me. But I think it’s the same for them the other way around.” All the better to exchange ideas at regular meetings. “It’s always exciting to learn what the other groups are working on. It gets crazier and crazier.”

With the help of software, Johan develops the layout for his chip with the desired functions. © MQV | Veronika Früh

Lukas with his collegues Nils Quetschlich and Kevin Mato. The days in Munich are filled with numerous meetings and discussions. © MQV | Jan Greune

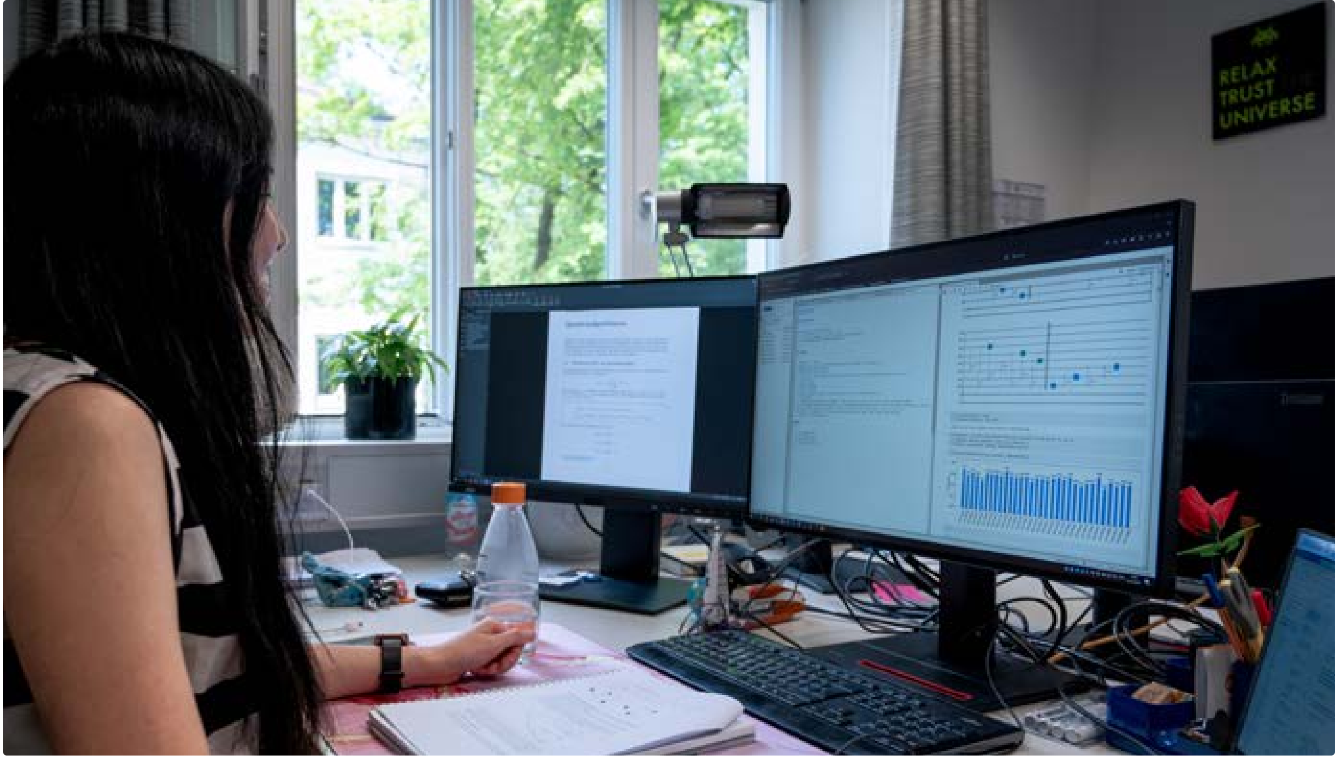
"Isolated solutions will not lead to succes"

Lukas Burgholzer

Chair for Design Automation (TUM)

Lukas develops methods and tools that help automate important steps in software development for quantum computers. One of his main focuses is on verification methods, i.e., the development of automated procedures that check programs for functionality. For example, an automated "equivalence check" can eliminate a compiler as a source of errors by verifying that source and machine code have the same functionality.

About 50 kilometers south in Munich, Lukas Burgholzer, postdoc at the TUM Chair for Design Automation, noticed a related phenomenon when talking to other researchers in the field of quantum computing: "When we as computer scientists talk to physicists, it takes a lot of time to make sure that both parties mean the same thing," says the 29-year-old, thinking back to meetings with several MQV scientists that focused on compilation. Everyone speaks a different language, but if you don't talk to each other, you run the risk of solving the wrong problems, Lukas warns. "In order to write a compiler that compiles to a particular hardware in the best possible way, we need characteristics of the physical systems that we can put into our models." You have to try to understand the physics a little more, he says, while the physicists have to create levels of abstraction and not throw around physical details. "We have to somehow come together on this, because isolated solutions will not lead to success."



Michelle in her element: programming with a view of the greenery. © MQV | Veronika Früh

Different levels of abstraction are also a concern of Xiao-Ting Michelle To. At the Institute of Computer Science at the Ludwig-Maximilians-Universität München (LMU), with a beautiful view into the greenery of the English Garden, the doctoral student is working on so-called quantum-algorithmic skeletons. “In principle, the aim is to hide the complicated quantum properties from programmers,” explains the doctoral student. In the end, users with basic knowledge of quantum algorithms should be able to work with more abstract, simpler formulations. She also hopes for new perspectives from her research. More people should dare to get to grips with quantum programming without having to delve too deeply. “Maybe others can still discover something new if they look at a problem from a different angle. We’re all in such a low-level perspective now, but you might just get some good ideas if you’re not quite that deep.” The fact that Michelle, as a member of Munich Quantum Valley, is a part of a larger whole motivates her even more: “I just know that my work as part of this big project is good for something. In the end, my part may not be directly visible, but you know that you did something in the background that helped. I think that’s cool.”

“The aim is to hide the complicated quantum properties from programmers”

Xiao-Ting Michelle To

Institute for
Computer Science (LMU)

Michelle’s research focuses on “Quantum Algorithmic Skeletons”. These are intended to make the complexity of quantum algorithms at the gate level invisible to programmers and thus enable their application to a broader field.

Being part of such a big project is also a strong motivation for Kiran Adhikari. With his research on distributed quantum networks, also known as quantum internet, the doctoral student is part of a consortium that is investigating the fundamentals of quantum computing. “There is a huge effort from MQV. Many things can happen in a short period of time, so you can see the results of your work having impact.” Working at the TUM Institute for Communications Engineering near downtown Munich, Kiran enjoys venturing into the physics of quantum networks from a strong information-theoretic perspective: “You are still doing physics, but in a more abstract way and that brings clarity.” For example, Kiran is looking for protocols on how to distribute quantum information as efficiently as possible over a quantum network. This is relevant not only for a future quantum internet, but also for scaling existing hardware. At this year’s review meeting, scientists developing the hardware within MQV were particularly interested in Kiran’s work, since connecting multiple processors together to scale up hardware is also a form of distributed computing. Kiran now has an invitation to visit one of their labs, perhaps to explore new possible collaborations.

“As theorists, we have to show that it is worth the effort”

Kiran Adhikari

Institute for
Communications Engineering (TUM)

Kiran researches distributed quantum networks, also known as quantum internet. He is investigating new applications as well as protocols for the efficient distribution of quantum information over large networks. His theoretical analyses help justify the enormous effort required to build up a quantum internet.

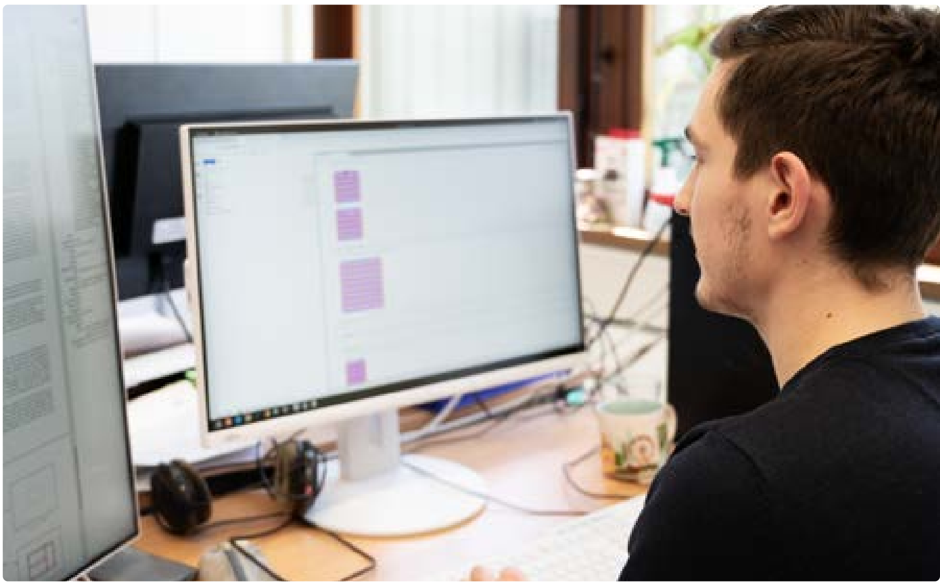
Kiran in his office showing elements of a new way to visualize a quantum internet protocol. © MQV | Maria Poxleitner

"I feel like I'm in the right place at the right time"

Leon Sander

Chair for
Quantum Theory (FAU)

Leon conducts research on Quantum Convolutional Neural Networks (QCNNs). He wants to find procedures that can efficiently detect and read out properties of quantum systems. Such procedures shall facilitate the characterization of complex quantum systems in the future.



Leon can let his creativity flow freely on the computer. His plots are reminiscent of a popular children's game. © MQV | Veronika Früh

Back in Erlangen, at the Friedrich Alexander University's Chair of Theoretical Physics, Leon Sander sits down in front of his computer and briefly types a few lines of code into the command line. "I'm trying to find a sequence of procedures that can efficiently extract properties from a complex quantum system. A Quantum Convolutional Neural Network (QCNN) helps by recognizing the property in question, so to speak, and developing it in such a way that the information can be read out with far fewer measurements than is traditional. To do this, I plot two-dimensional qubit lattices and apply operations to them," Leon explains, summarizing his research project. He jokes with his girlfriend that he's been playing four-in-a-row ever since she looked over his shoulder in his home office. And indeed: Leon presses Enter again and his grids appear on his screen, squares of red and blue circles that clearly remind of the game.

← Find all portraits in full length on our website.

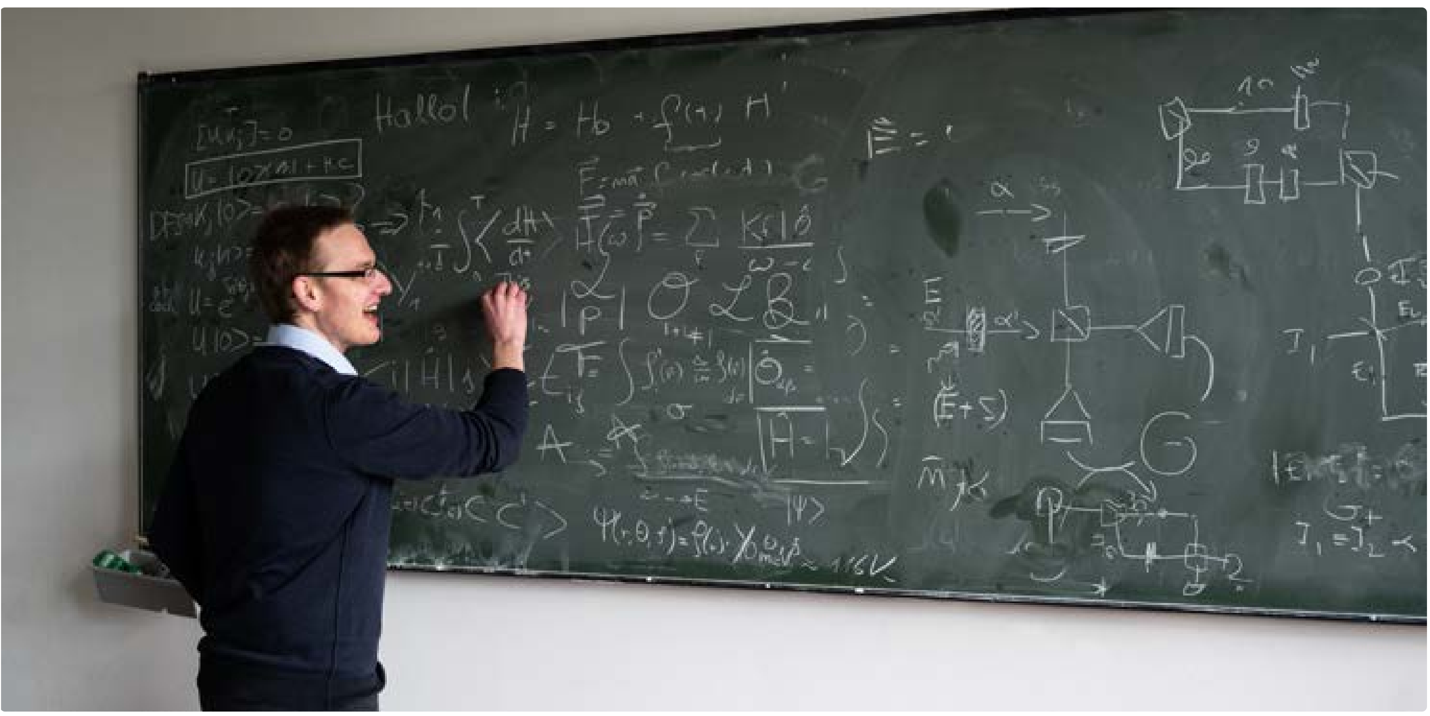
A few offices down on the same floor – fully scribbled blackboards and scientific posters alternate on the corridor walls – Timo Eckstein is studying quantum assembler algorithms. The subject of quantum in particular, he says, is like a hidden world: "Like a world map of knowledge, and you can play a bit of Columbus yourself," he adds, and his enthusiasm for playing a small part in discovering this world is evident. Specifically, he believes that his research will determine whether a particular quantum algorithm is actually more advantageous than its classical counterpart, or what conditions would have to exist in the future for it to be advantageous. When Timo talks about his research, he also talks a lot about the quantum community. It is this team spirit that he believes also makes good results possible in the first place. Collaboration is especially important for experiments and projects that are becoming increasingly complex. He also values the collaboration with other quantum researchers at FAU and as part of Munich Quantum Valley. The appointment of scientists from the field of quantum computing to professorships, partly within the framework of MQV, was an argument for him to stay in Erlangen for his doctorate.

"Physics is like real magic for me"

Timo Eckstein

Chair for
Quantum Theory (FAU)

Timo is studying quantum assembler algorithms in his research. He wants to find out under which conditions a quantum algorithm has advantages over a classical algorithm. He numerically computes new algorithm ideas or improvements for small systems before testing them with classical high-performance hardware and finally quantum hardware for larger scaled quantum systems.



Timo explaining a concept on one of the numerous fully written boards that decorate the chair of quantum theory – clearly they are well used. © MQV | Veronika Früh

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