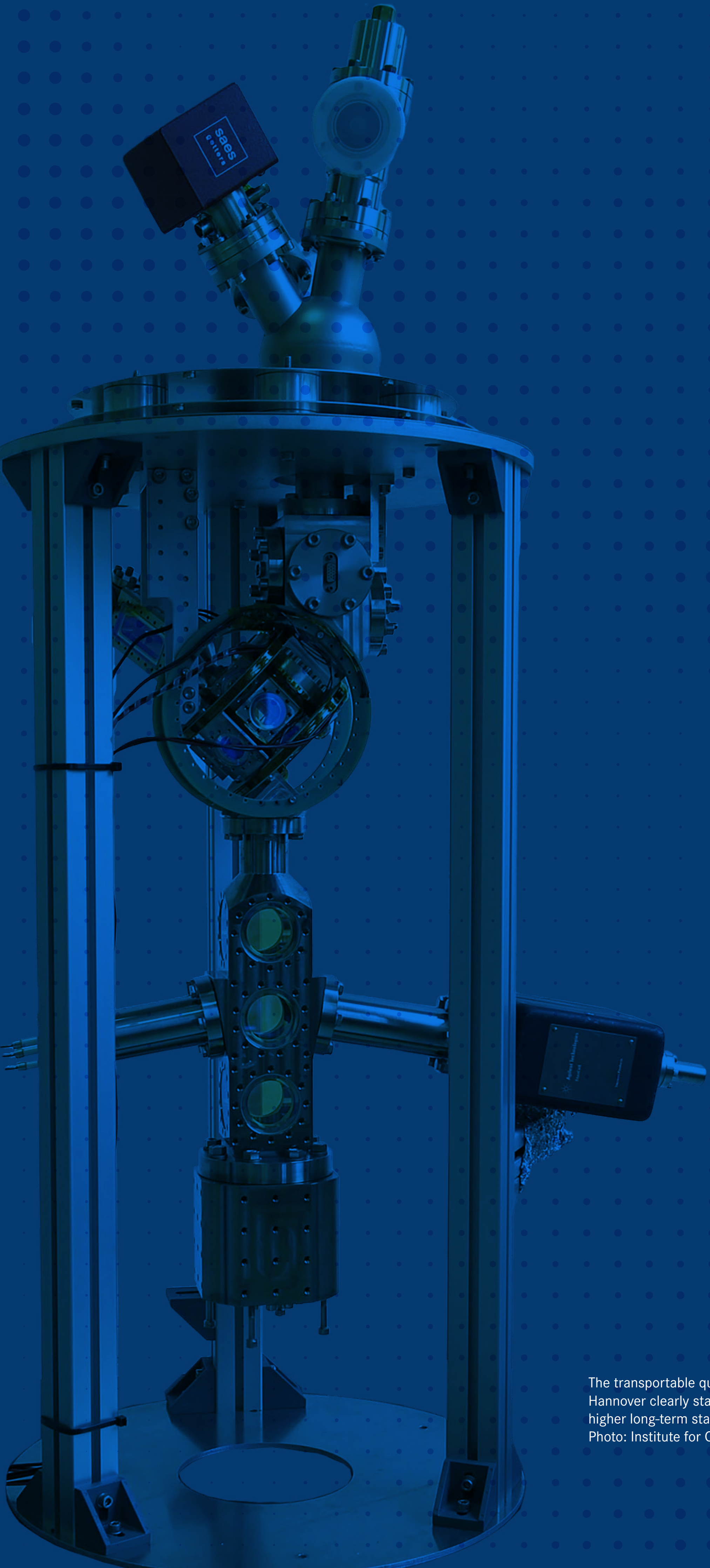
HELMHOLTZ QUANTUM

RESEARCHING THE SECOND QUANTUM REVOLUTION

Quantum technologies in the Helmholtz Association



The transportable quantum gravimeter QG1 developed in Hannover clearly stands out from classical gravimeters due to its higher long-term stability and higher measurement accuracy.
Photo: Institute for Quantum Optics, Leibniz Universität Hannover

Dear Reader,

It is by now widely recognized that Quantum Technologies will have a disruptive and long-standing impact on our digital society and economy, where collecting, analysing, exploiting and deploying data in daily activities, while protecting those very same data from unwarranted access, is crucial.

Photo: Gesine Born

Otmar D. Wiestler
President of the Helmholtz Association

Photo: Stefanie Herbst

Tommaso Calarco
Helmholtz Quantum Coordinator

Several of the 18 Helmholtz centres are actively contributing cutting-edge research to the different areas of Quantum Technologies: Quantum Computing, Quantum Communication, Quantum Sensing, Quantum Materials and Fundamental Science, as well as Quantum Simulations and Numerical Methods. Our creative scientists address for example fundamental quantum phenomena, investigate new quantum states and resources, and develop components for the realization and the deployment of fully functional quantum devices and prototypes.

The objective of the German national Roadmap "Quantum computing" is extremely ambitious: to provide in ten to fifteen years an error-corrected system for solving a universal class of problems to achieve broad benefits for the economy and society. Since such a machine will process information differently than a classical one, it is expected to make possible what is difficult or even impossible today to compute.

With a market value projected to reach tens of billions worldwide over the next decade, it is no surprise that leading companies (like IBM, Microsoft, Amazon and Google) have started investing heavily in the field; and that industry networks like the European Quantum Industry Consortium (co-initiated by the Forschungszentrum Jülich) are entering the space to establish a strong European quantum ecosystem.

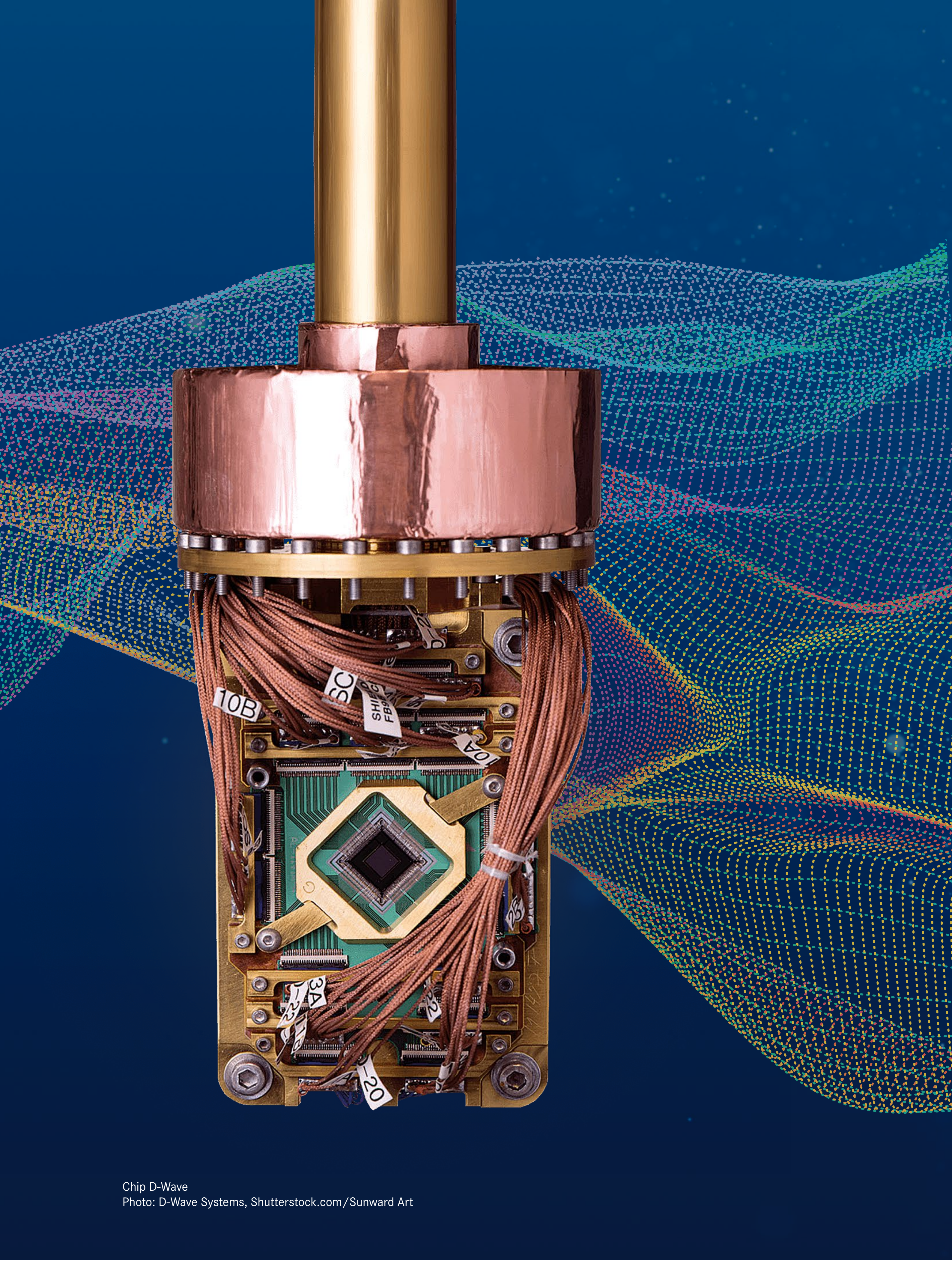
We fully realize that the ambitious goals ahead of us can only be reached in a long-term cooperation with the strongest partners in this challenging area.

The present brochure highlights what we have already achieved in this crucial research field; and, at the same time, lays down a strategy for further expanding our activities to to achieve our stated goals in a timely manner. Strong interactions with national initiatives and with European partners, in particular the German Quantum Computing programs and European Commission's Quantum Technology Flagship will be required to position Germany and Europe at the forefront of this international competition.

In the light of the Helmholtz Association's mission to contribute to solving pressing social, scientific, and economic issues through strategic, programmatic, cutting-edge research, and the operation of large-scale facilities, Helmholtz bears a special responsibility in the Quantum Technology field; this documents shall help to fully realize it.

Otmar D. Wiestler
President of the Helmholtz Association

Tommaso Calarco
Helmholtz Quantum Coordinator



Chip D-Wave
Photo: D-Wave Systems, Shutterstock.com/Sunward Art

HELMHOLTZ QUANTUM – JOINT COMPETENCES FOR QUANTUM TECHNOLOGIES

Quantum technologies are the key technology for the next digital disruption. In the light of the Helmholtz Association's mission to contribute to solving pressing social, scientific, and economic issues through strategic, programmatic, cutting-edge research, including the operation of large-scale facilities, Helmholtz bears a special responsibility in this field.

Several Helmholtz Centers are conducting research on the various applications of quantum technologies. Strategic recruitment, the establishment of numerous new institutes, and the development of infrastructures put the association in a position to make decisive contributions to the development of applicable and scalable quantum technologies.

With Helmholtz Quantum, the association has established a platform for its entire quantum expertise. The basis is laid by a common strategy. The platform enables the Helmholtz research centers to closely coordinate their research and its goals. At the same time, it is intended to be a nucleus for joint projects. Facilitated by the Helmholtz Quantum Coordinator, who networks the platform externally, especially with regard to German and European government strategies, a board of delegates representing each of the contributing Helmholtz research centers shapes the common activities and ensures the direct input from and in the various Helmholtz research groups that are active in this field. With Helmholtz Quantum and its board of delegates, with which it works closely, the association possesses a dynamic and powerful structure capable of making a serious and concerted contribution to the field of quantum technologies.

Helmholtz Quantum facilitates a new quality of exchange with other science organizations. It contributes to increasing networking across organizational boundaries within the German scientific community with those that share the goal of putting Germany and Europe at the forefront of developing this key technology for this important future field. It also provides partners with information and expertise from the Helmholtz Association. At the same time, the platform ensures that the Helmholtz strategy is shared with other players in the innovation landscape.

Helmholtz Quantum contributes its expertise to the scientific community and to public discourse. It also puts Helmholtz's entire capacity in service of supporting the implementation of overarching strategies. At Helmholtz Quantum scientific conferences, the association develops and establishes common goals and strategies that it then shares within Helmholtz and beyond. Representatives of Helmholtz Quantum play crucial roles in national and international structures and activities like the European Quantum Flagship; they contribute to the development of comprehensive strategies like the National Roadmap for Quantum Computing; and transfer knowledge gained from quantum technologies to society. Helmholtz Quantum acts as an important point of contact and facilitates exchanges between industry, politics, and society via a variety of target-group-specific formats.

I. MISSION AND VISION

In keeping with the Helmholtz Association's mission to contribute to tackling big challenges with strategic research, the goal of the Helmholtz Association is to be a national, European, and global driver, and a scientific-technological trend-setter in the landscape of quantum technology research. Together with partners from universities, research organizations, and industries, the Helmholtz Association intends to define **far reaching technological goals for the next 10 years and beyond** and to pursue them together at all levels, ranging from science fundamentals to system engineering and applications.

The Helmholtz Association deals with a broad spectrum of issues in the field of quantum technology. Current research ranges from the understanding of **fundamental quantum phenomena,** to the **design of quantum states,** through to the development of components for the **realization and deployment of fully functional devices and prototypes with the vision of also developing the first German quantum computer.**

Quantum Technologies in which the Helmholtz Centers are active:

- **QUANTUM COMPUTERS**
- **QUANTUM COMMUNICATION**
- **QUANTUM SENSING**
- **QUANTUM MATERIALS AND FUNDAMENTAL SCIENCE**
- **QUANTUM SIMULATIONS AND NUMERICAL TECHNIQUES**

These interconnected five fields of research are described in detail in **Section II.**. In addition to these five fields, it is the mission of the Helmholtz Association to develop, build, and provide large-scale research facilities for science. Some of these facilities have very specific contributions and relevance for quantum technology research (see **Section V.**). Furthermore, the association interacts with a wide range of researchers and potential users of quantum technologies to identify early adopters, make them fit for such purposes as the applications of quantum computers or novel sensors, and to learn from their needs in order to develop together specific-use cases. Therefore, specific examples of prototype applications and use cases are detailed in the respective fields in **Section II.**.

Based on **the fundamental understanding of quantum phenomena in materials** (**Section II.4.**), the Helmholtz Association develops tailor-made materials and designs quantum systems for quantum technology devices, e.g., for quantum computing, communication, and sensing. The Helmholtz Association also develops the necessary tools and methods for quantum state manipulation and detection, as well as improved functionality for applications in novel quantum technology devices. In relation to quantum technology devices, the Helmholtz Association focuses in particular on the realization of **first German quantum computer** (**Section II.1.**), and full-scale quantum processors together with their networks, pursuing a broad range of potential platforms for their realization. The Helmholtz Association will operate quantum computers of different levels of maturity including also commercially available systems where this serves research, developing in parallel relevant applications like **simulation and numerical methods**, both at the classical and quantum level (**Section II.5.**). Quantum computation development is closely interwoven with leading high-performance computer user platforms, ultimately providing **integrated hybrid and/or modular systems** together with their application in cutting-edge science, such as **quantum chemistry, condensed-matter physics, particle and high energy physics, matter under extreme conditions, space, aerospace and transport issues, optimization and machine learning.** Quantum computing networks depend on quantum communication, in which even few-qubit devices can be practically deployed, e.g., in quantum repeaters. Going beyond single devices, the Helmholtz Association envisions the development of a **quantum communication** network – a **quantum internet** (**Section II.2.**), in which terrestrial and ultimately space-based quantum repeaters will be connected, thus enabling long distance quantum-enhanced secure communication. Herein, the Helmholtz Association focuses on secure quantum communication systems in space and aviation while at the same time developing single photon sources. Secure (quantum) communication and quantum computing is linked to the development of **postquantum cryptography**.

Quantum sensors are also being developed with a potentially disruptive impact in a broad range of fields from basic science to applications in space-based geodesy and materials science to medical applications through to quantum state read-out (**Section II.3.**).

It is typical for the Helmholtz Association to connect as well as to reach out to a large number of scientists from a broad multi- and interdisciplinary background, who will be early adopters of the scientific and technological developments at all stages of technological readiness. Therefore, the Helmholtz Association also provides early **demonstrators and prototype applications** of novel technologies and studies their applications in relevant scientific, societal, and industrial **use cases** (highlighted in the relevant **Sections II.**). In fact, the current status of quantum computers that are superior to classical ones in synthetic benchmarks but not yet in applications makes them genuine large-research instruments.

Finally, the Helmholtz Association develops and conducts research with **large-scale facilities** (**Section III.**). The use of high-end, large-scale facilities available at the Helmholtz Centers will be a particularly strong asset, both for conducting fundamental research, as well as for developing devices and use cases via user facilities that are conceived as open innovation hubs.

For the Helmholtz Association, the currently most visible quantum technology initiatives are the recently started European Quantum Technology Flagship[1] as well as the German Federal Framework Program for Quantum Technologies,[2] and the German federal government's quantum computer initiative that is currently under discussion as part of its economic stimulus program.[3] Its five main fields of research and development of quantum systems and devices contribute directly to the focal points of these initiatives (Computer, Computation, Communication, Sensing, and Fundamental Science Research). Researchers from Helmholtz Centers also participate in or even lead several Quantum Flagship Projects.

Research at the Helmholtz Association is based on a strong basic understanding of fundamental quantum phenomena and of their application in novel and improved quantum technology devices. The close collaboration between fundamental research and prototype application enables the targeted evolution and improvement of devices and a synergy in the promotion of early adopter communities. The association is convinced that this aspect will be crucial not only for the development and the application of quantum computing but also for quantum simulation, communication, and sensing.

The Helmholtz Association addresses quantum technology in different research fields with different focal points. We cooperate across centers and research fields to advance the development of quantum technologies. The Helmholtz Centers which contribute substantially to the development of quantum technologies are the Forschungszentrum Jülich (FZJ), the Karlsruhe Institute of Technology (KIT), the Helmholtz-Zentrum Berlin (HZB), the Helmholtz Zentrum Dresden-Rossendorf (HZDR), the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the Deutsches Elektronen Synchrotron (DESY), and the Helmholtz Zentrum für Schwerionenforschung with its two satellite stations, the Helmholtz-Institut Jena (HIJ) and the Helmholtz-Institut Mainz (HIM).
In accordance with the Helmholtz mission, research at the Helmholtz Centers spans a broad range from fundamental science to technology development, prototypes, and applications. Depending on the Helmholtz Centers' different scientific focal points, the distribution of the quantum technology research topics varies and is connected with the differences in technological maturity of each field.

Within the German landscape, the research contributions of the Helmholtz Association connect the very fundamental scientific research conducted by the universities and by the Max Planck Society with the industry- and application-driven approach of the Fraunhofer Society. To close this gap, the Helmholtz Association cooperates closely with many universities and, as a research partner, provides access to and user support for large-scale facilities. In so doing, it pursues a strong focus on method development to provide state-of-the-art research facilities and their efficient use to a wide range of potential users.

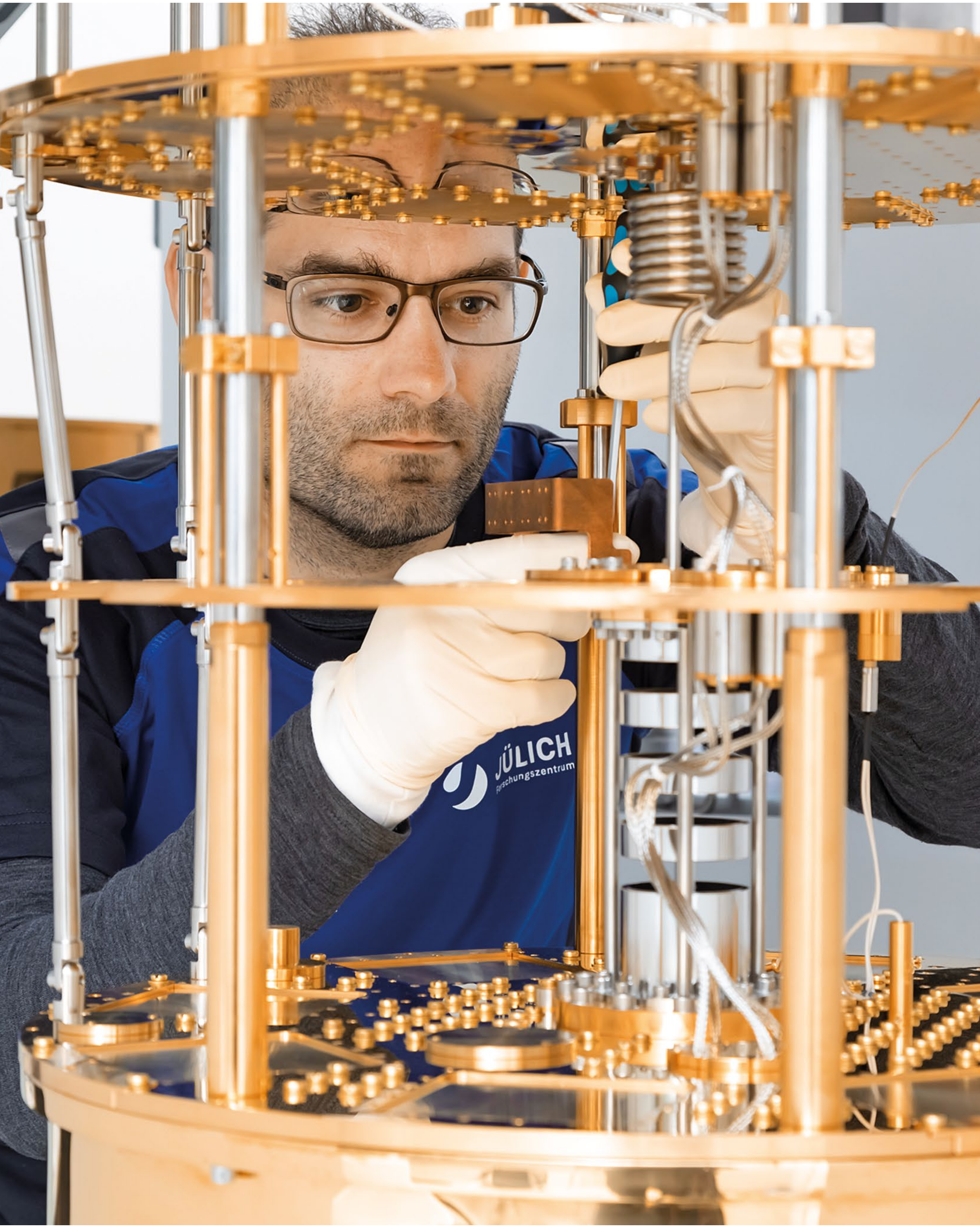
This paper presents the Helmholtz Association's long-term strategic goals developed in 2019 and updated in 2021 for the development of quantum technologies and provides an overview of current and future activities, as well as structural challenges to be met, towards reaching those goals. Rather than stating concrete milestones, it sketches important lines of action, whereas specific roadmaps for the respective strategic goals will still need to be developed in the future. The measures outlined include ongoing investments in infrastructures and research groups, as well as proposals for necessary additional funding.

[1] https://qt.eu/

[2] https://www.bmbf.de/de/quantentechnologien-7012.html

[3] https://www.bundesfinanzministerium.de/Web/DE/Themen/Schlaglichter/Konjunkturpaket/Konjunkturprogramm-fuer-alle/zusammen-durch-starten.html#collapsee4e62d3a-5fcd-4004-95f2-5c48fc8cbc22

II. QUANTUM SYSTEMS AND DEVICES


JÜLICH
Forschungszentrum

1. QUANTUM COMPUTERS

Quantum computers promise unprecedented capabilities for certain computational tasks. While many applications are still out of reach with current hardware disruptive impact is expected on fields that range from quantum simulations in chemistry, condensed matter and particle physics, to optimization problems and machine learning (see **Section II.5.**). Among the various quantum technologies, it most likely represents the one with the longest timeline with incremental improvements but also the one with the largest economic potential and impact on society. Despite major progress in the field, quantum computing today is still in its infancy, resembling the status of classical computing in the 1950s. At the current stage, the realization of a universal quantum computer remains a monumental task, representing possibly the biggest scientific and engineering challenge of our time. The development of prototype applications and use cases is also just at the beginning and while there are very many fields of research where quantum computing can have a huge impact, there are several examples on a lowest order approximation but extremely few fully fleshed-out examples. The international competition in the field is extremely intense, and in countries such as China, the USA, and Canada it is propelled by substantial investments by the public and the private sectors. So far, Germany and Europe are falling behind in this race, although it has the competencies, the infrastructures, and the human potential to quickly win ranking positions in the competition.

Physicist Markus Jerger from Jülich prepares the wiring to measure the quantum mechanical state of qubits.
Photo: FZ Jülich/Ralf-Uwe Limbach

STRATEGIC GOALS

The Helmholtz Association has the ambition of leveraging its critical mass within a use-inspired research-strategy to become a **leading force in quantum computing in Europe**. To accomplish this aim, it has laid out the following strategic goals:

Short-term (5 years)

1. Create a **“quantum computing user community”** to support the early adoption of quantum computing and annealing technologies for scientific and industry-oriented research by providing remote access to existing quantum computers.

2. Advance systematically the promising scalable platforms for the realization of multiple qubits to realize **small-scale demonstrators beyond the state of the art with up to 100 qubits and low error rates** for quantum computing and simulation.

3. Develop **approaches for (optically) interlinking qubits registers**, to realize networked multi-qubit modules.

Mid-term (10 years)

4. Create and apply innovative quantum algorithms for novel applications.

5. Develop a **medium-sized quantum computer system** as a large research instrument for both soft- and hardware that benefits from a clear quantum advantage.

6. Pursue **research on innovative qubit platforms** with a potential for disruptively superior performance.

Long-term (beyond the 10-year horizon)

7. Develop scalable quantum computers embedded in HPC solutions addressing the full application spectrum.

8. Perform large-scale research that complements Germany’s quantum computing industry.

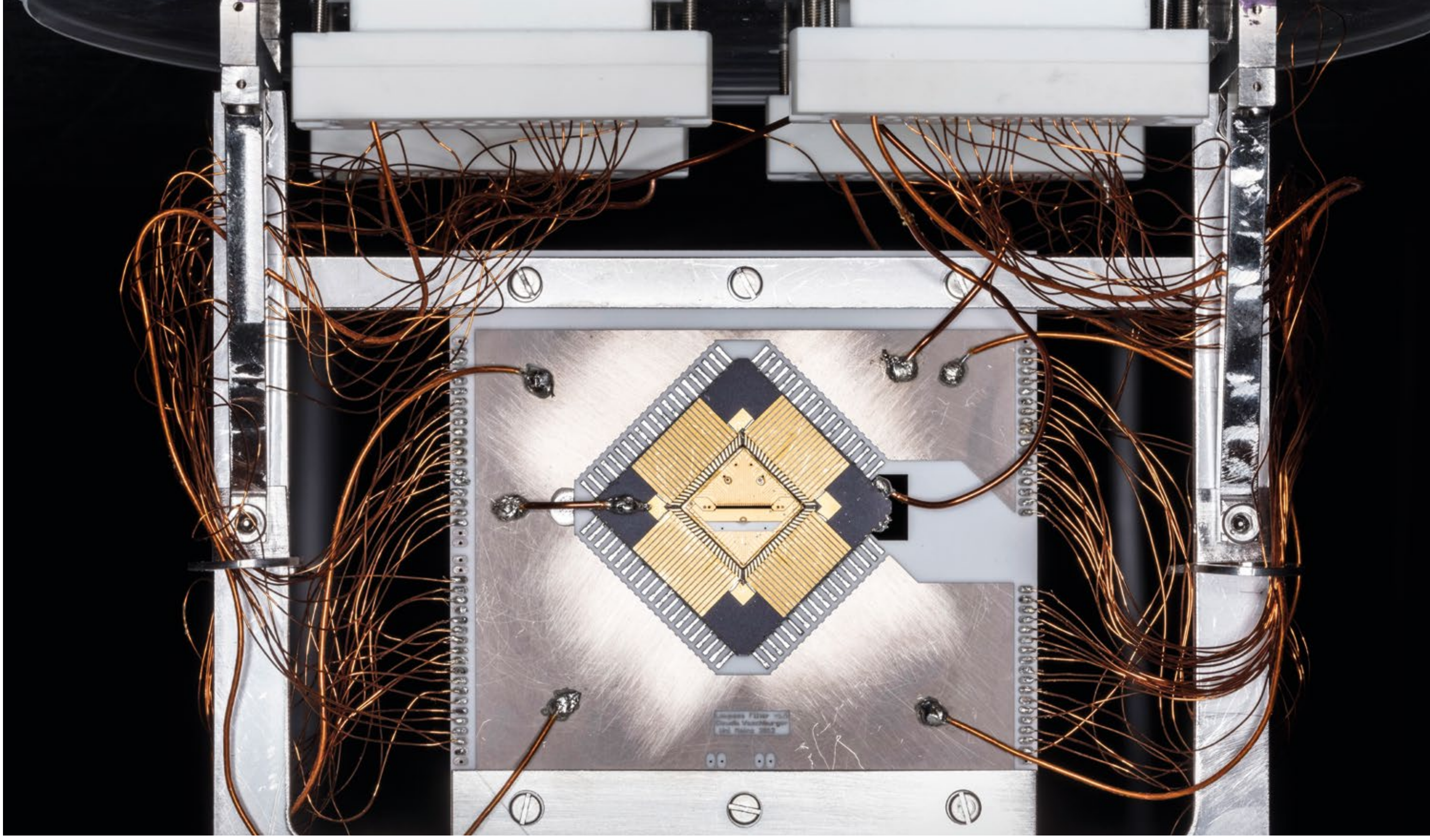
9. Develop **highly scalable hardware and software tools** to control and calibrate thousands of qubits and bejond, with a particular focus on highly integrated platforms.

The given time scales are intentionally conservative. The association nonetheless aims to achieve progress at the fastest pace possible, with the hope of meeting the stated goals ahead of the targeted dates.

CURRENT ACTIVITIES

Our activities in the field of quantum computing build on a unique combination of advanced fabrication and experimental capabilities, expertise in material research, superior knowledge of the theory of quantum information, as well as in access to frontier supercomputing facilities.

FZJ and KIT are carrying out fundamental research on how to **increase the performance and the reproducibility of well-established superconducting and semiconductor qubits,** with the goal of realizing and operating prototypes of gate-based quantum processors with few dozens of qubits and steadily improving their performance. Exper-



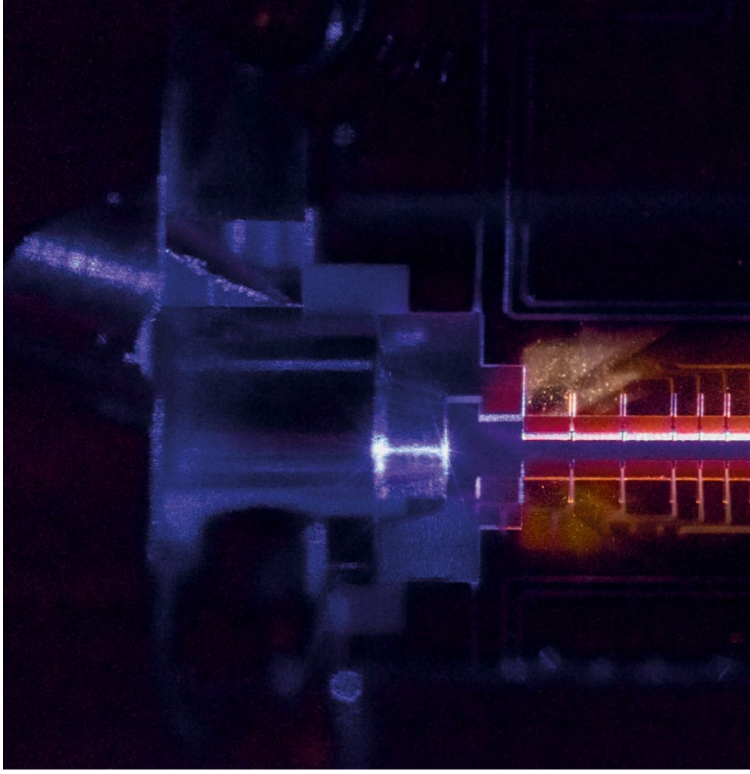
Wiring of a micro-segmented ion trap for quantum computing applications (JGUM). Photo: Thomas Klink – Fotografie

imental activities are complemented by theoretical ones aimed at a better understanding of the physical theory of qubits, the development of optimized quantum-control strategies, and new coupling schemes for multi-qubit systems. HIM works on **ion-based quantum computing** with the objective of building a 100-qubit processor, low latency connected to the HPC MOGON II, and offered by web-interface to external partners for applications, including as variational eigensover for chemical catalysis optimization. This research is supported by highly-parallel simulations on supercomputers of the highest performance class. DLR-SI develops scalable trapped-ion quantum processors based on highly integrated surface-electrode traps. A first machine employs ion species optimized for high fidelity operations and scalability with integrated photonics and will be made available to users. In parallel, DLR-SI will support a massive development of the required scaling techniques for integration of optical preparation and readout. Quantum gates are carried out using integrated microwave components with a scaling that is intrinsically already given by the underlying chip architecture.

Another important aspect is the **development of the classical control tools (hardware and software)** needed to operate multi-qubit devices (KIT, FZJ, HIM, DLR). While the current efforts mostly target few-qubit devices, the focus is on scalability, with the final goal of addressing millions of qubits. One innovative aspect in this context is the development of **ultra-low power cryo-electronics** tailored to this specific application (FZJ) and working with extremely low noise (HIM, DLR). The Helmholtz Association is one of the few organizations in the world that can sustain the co-development of quantum and classical hardware and software in the same system context, thus allowing for stepping stone contributions to the field.

The Helmholtz Association is also sustaining **fundamental research on innovative qubit platforms** (see also **Section II.4**.). Examples are Majorana qubits based on topological insulators (FZJ), phase-slip qubits, high kinetic-inductance circuits (KIT, DLR), and molecular qubits (KIT). The rationale behind this broad approach is the missing consensus on how to move from the current few-qubits prototypes to the final goal of a universal quantum computer with millions of qubits. It is not unexpected that in the long run some other, hitherto less explored (or even as yet unknown) platforms, might turn out to be ultimately superior. Pursuing different approaches on comparable footing will ensure playing a relevant contribution in the near and more distant future.

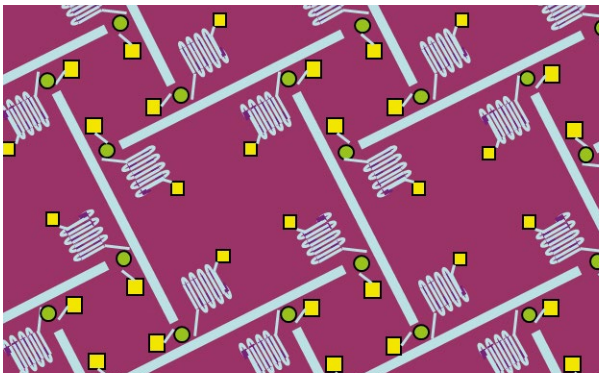
The exploration of innovative qubit platforms is closely related to the development of **techniques to optically couple distant qubits**, which will be instrumental for the realization of a quantum internet and for circumventing the limitations of monolithic qubit architectures. Systems pursued in this respect include quantum-dot qubits (FZJ), molecular magnets (KIT), ion-based qubits (DLR) as well as different types of defect centers (KIT, HZDR, HIM). These activities are closely related to those in the area of quantum communication (see also **Section II.2.**) but target a much higher device complexity.



For the mid-term and long-term realization of scalable quantum computing platforms it is necessary to develop techniques for the detection and correction of the errors that inevitably occur in any hardware implementation of quantum information processing devices. To this end, research on error mitigation techniques and on full-fledged quantum error correction (DLR) is paramount for enabling quantum computations at scales that exceed the regime that can be classically simulated.

Research activities on the hardware of a quantum computer are complemented by **research on prototype applications and use cases** of quantum computing and quantum annealing (DLR, FZJ, DESY, HZB, HZDR), as also described below in **Section II.5.**.

Another major activity is the foundation of JUNIQ – Jülich UNified Infrastructure for Quantum Computing (FZJ), which offers user support and will host and give access to quantum computing emulators and a variety of quantum computing systems, among them a D-Wave quantum annealer, the European OpenSuperQ system and a Pasqal simulator. JUNIQ is the platform to integrate quantum computers and quantum annealers in the form of quantum-classical hybrid computing systems into the modular HPC environment of the Juelich Supercomputing Centre. The scope of JUNIQ, which will represent an infrastructure for which there is currently no equivalent in the world, is to provide a unified platform for comparing different computing technologies and to support the adoption of quantum information processing technologies in real-world applications.
Finally, the Helmholtz Association supports the creation of a **quantum-computation user community** formed by scientists who are close to scientific computing and who are pursuing a pragmatic, heuristic approach to applied quantum computing. One important measure in this respect has been the creation of the interest group **EQUIPE – Enable Quantum Information Processing in Europe** (FZJ), with the mission of promoting the exploitation of quantum computing and quantum annealing technologies for scientific and industry-oriented research.



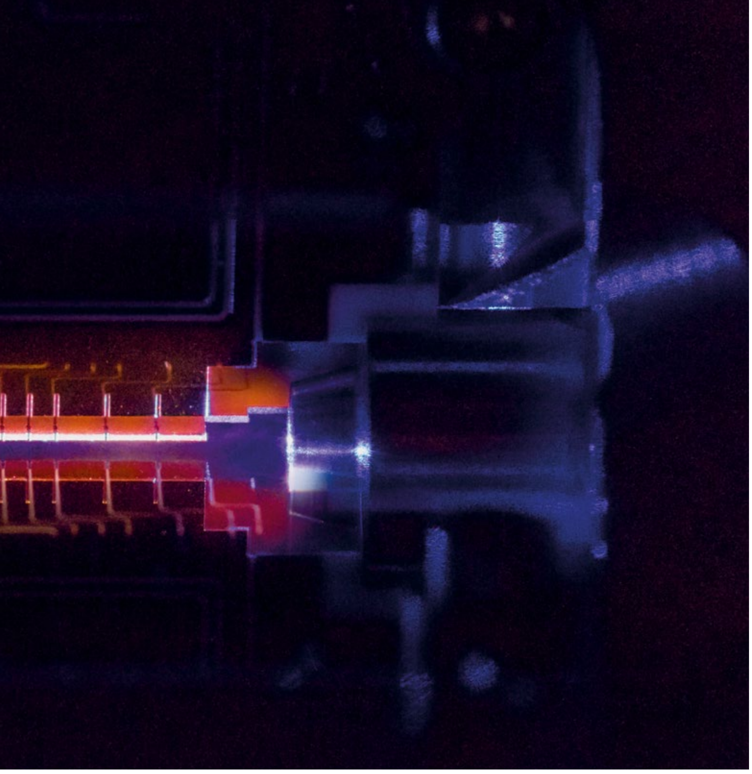
Detail from a two-dimensional integrated circuit component for error-tolerant quantum computing. The qubits are coloured green in the illustration. Photo: Forschungszentrum Jülich

FUTURE ACTIVITIES

The research portfolio described above will be enriched in the near future by the following activities:

KIT will investigate, in association with the Walther-Meißner-Institut (WMI) and the Leibniz Institute of Photonic Technology (IPHT) the realization of a coherent quantum annealer that might outperform classical processors on specific tasks with practical relevance, such as large parameter-set optimizations. The development of such a coherent annealer is technologically less challenging than that of a gate-based quantum processor, but it will represent a major advancement with respect to the commercial D-wave machine, where the qubits exhibit only a low degree of coherence, which is a disadvantage for some specific optimization tasks.

Activities on quantum computing at FZJ are further strengthened with the building of the Helmholtz Quantum Center (HQC), which will combine most of the local activities under one roof and provide additional research infrastructure. The negotiations for a new institute director for the Institute for Quantum Computing at FZJ are ongoing. The institute will concentrate on the system integration of mainly superconducting or semiconductor qubits. In addition, a new Institute for Quantum Materials and Technologies was founded at KIT.

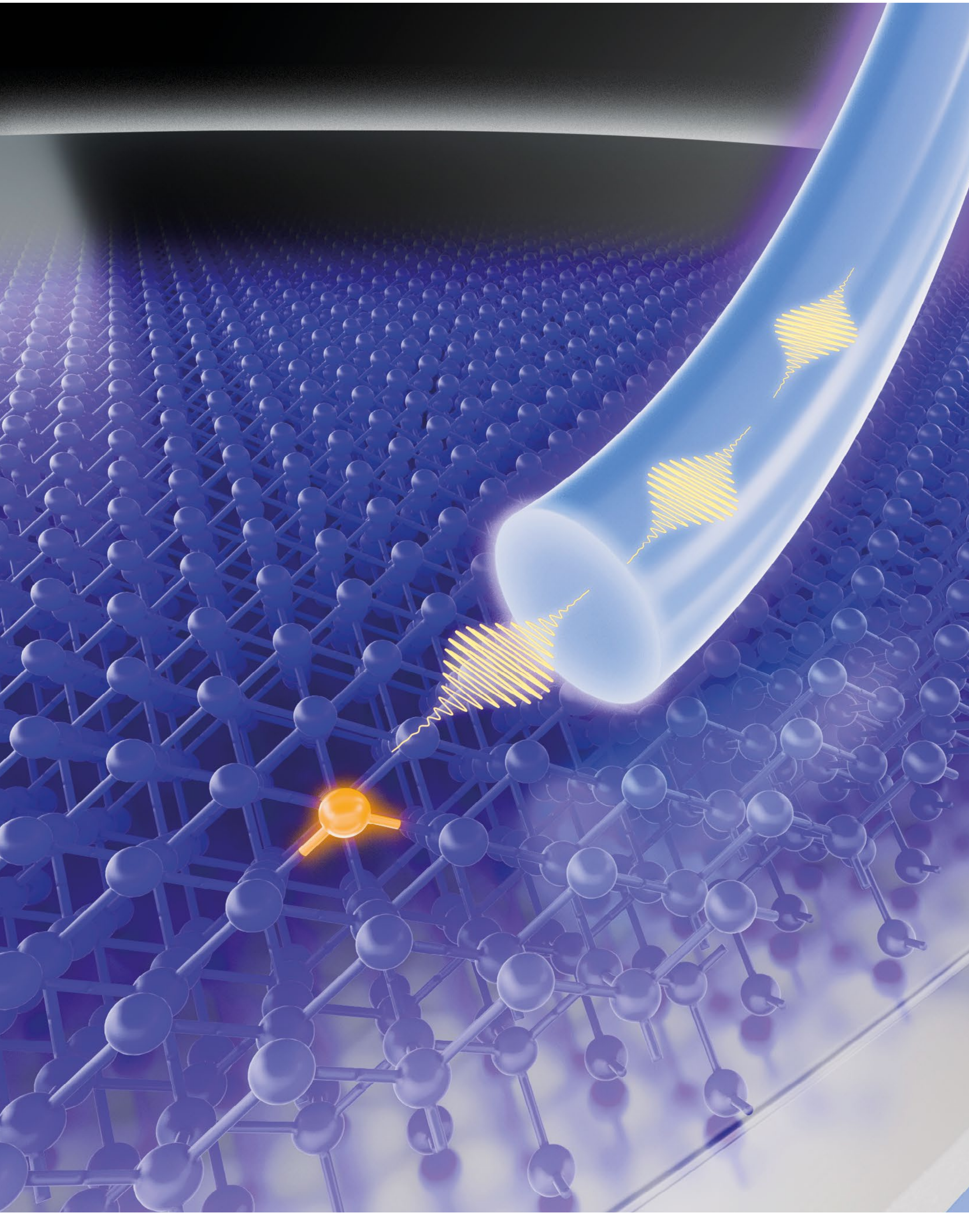


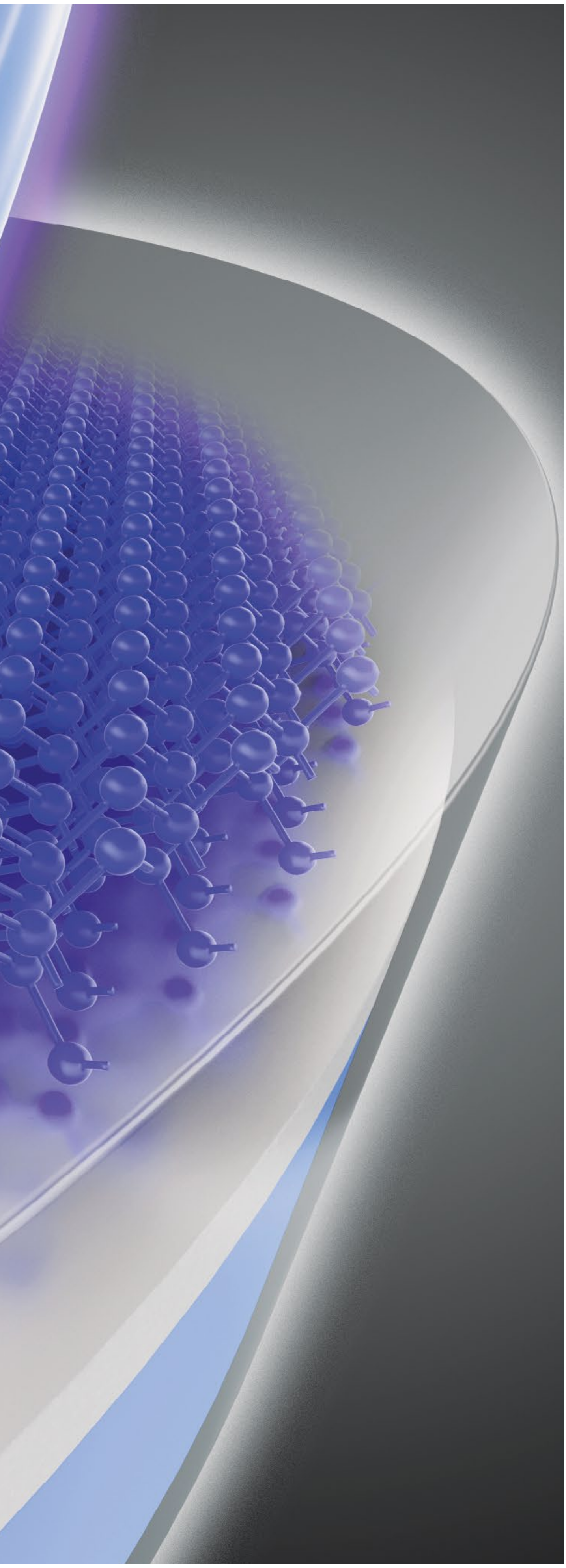
Trapped ion qubits are stored in a linear Paul trap and manipulated by ultraviolett and infrared laser beams. Photo: Thomas Klink – Fotografie

FZJ is planning to lead a quantum demonstrator project in the upcoming quantum computing program from the economic stimulus package, addressing the scientific and technological ecosystem of solid-state qubits. DLR plans to join this consortium with contributions in tailored quantum compilation, algorithms, and applications. In addition, DLR is establishing a consortia of start-ups and companies to form an ecosystem for and within quantum computing R&D.

SYNERGIES

The main asset for reaching our strategic goals in quantum computing is the set of synergies between involved Helmholtz Centers, in particular between FZJ and KIT with respect to the development of the quantum hardware (with contributions from DLR, HZDR, and HIM), and between FZJ, DLR, DESY, KIT, UFZ, and HZB for issues related to the development of prototype applications and use cases as well as software and algorithms. FZJ, KIT, HZB, and RWTH Aachen University collaborate in the Helmholtz Association's Initiative and Networking Fund through the research project Scalable Solid State Quantum Computing. In addition, the Helmholtz Association is cooperating with a large number of national and international universities, research associations (including the Fraunhofer Society and NASA Ames), and industry partners. For example, collaborations with industrial fabrication facilities, such as the Interuniversity Microelectronics Centre (IMEC) in Belgium, and the Leibniz Institute Innovations for High-Performance Microelectronics (IHP) are gaining momentum. Their scope is to establish highly reliable, industry-like fabrication procedures to increase device yield, complexity and quality. Similar partnerships are currently being explored with Infineon and Leibniz Institute of Photonic Technology (IPHT). Helmholtz Centers are also **central partners of the European FET Flagship projects** Scalable Rare Earth Ion Quantum Computing Nodes (SQUARE), which is coordinated by KIT, ScalableTrapped Ion Computer (AQTION) at HIM, and an Open Superconducting Quantum Computer (OpenSuperQ), which since February 1st, 2021 is coordinated by FZJ, as well as of the cluster of Excellence Matter and Light for Quantum Computing (ML4Q), which was established by the Universities of Aachen, Bonn, Cologne, and FZJ as part of the federal and state government's Excellence Strategy. In addition, the cluster of Excellence Complexity and Topology in Quantum Matter (ct.qmat) was established by the University of Würzburg, the TU Dresden, and HZDR. DLR-SI is cooperating with the cluster of excellence QuantumFrontiers which was established by the Universities of Hannover and Braunschweig and is member of the initiative Quantum Valley Lower Saxony (QVLS) which aims at creating ion-based quantum computers with more than 50 qubits within the next few years. The **EQUIPE initiative already has about 30 European partners**, including the Helmholtz Centers DLR, KIT, and DKFZ and companies such as Volkswagen, Airbus, Total, and Bayer. Furthermore, together with several Canadian partners, FZJ and DESY are promoting the joint development of an open **Canadian and German cooperation-network for quantum computing applications** (especially data analysis and machine learning). Within the BMBF quantum computing program, FZJ is participating in the projects German Quantum Computer based on Superconducting Qubits (Geqcos) with KIT, HIM is partner in the trapped ion processor (IQuAn), and in Digital-Analog Quantum Computing (DAQC) and is expected to lead a project on quantum artificial intelligence for the automotive industry Q(AI)2 with DFKI, Bosch, BMW, Mercedes, and Volkswagen. HIM is partner in the trapped ion processor (IQuAn). DLR is involved in establishing a cooperation network on quantum error correction technologies, including the University of Arizona in Tucson, QuTech (Delft University of Technology), and the Laboratoire d'électronique des technologies de l'information (CEA-Leti, in Grenoble).





2. QUANTUM COMMUNICATION

One of the central, novel aspects in quantum communication is the **security of data transfer**, which will be enabled at a magnitude heretofore unknown. Quantum communication exploits the laws of quantum mechanics to build key distribution protocols for secure data transmission. Quantum key distribution is therefore based not on mathematical assumptions but on physical laws. The quantum states, however, are very fragile, and precise measurement is tricky, such that a transmission (within single chips or over longer distances) poses considerable technical challenges.

Schematic representation of a single defect in a silicon wafer created by the implantation of carbon atoms, which emits single photons in the telecom O-band. Photo: HZDR/Juniks

STRATEGIC GOALS

The Helmholtz Association is currently focusing on **quantum communication systems in space and aviation,** addressing the challenges of **quantum key distribution** for secure communication with the aim of allowing **worldwide quantum cryptographic connections** in the future. Our vision is the development of a **quantum internet** (quantum communication network) in which quantum repeaters based on powered terrestrial and space-based systems are connected, enabling unmatched known security and global quantum connectivity. Security is also analyzed in light of the rise of quantum computers and their known attacks, making it mandatory to investigate the field of quantum-resistant cryptography. Thus, all of our activities aim at **building blocks for quantum communication in general**, global scale quantum key distribution, q**uantum repeater-based large-scale quantum networks,** distributed **quantum computing, and quantum-resistant cryptography.**

Therefore, our specific goals are:

Short-term (5 years)

10. Development of manageable photon sources and photonic integration.

Mid-term (10 years)

11. Develop quantum repeaters based on small quantum processes with optical interfaces.

12. Enable secure communication in the era of quantum computers using post quantum cryptography methods.

13. Enable quantum-cryptographic secure communication on a global basis.

Long-term (beyond the 10-year horizon)

14. Development of quantum-internet linking nodes, such as quantum computers or security end users.

CURRENT ACTIVITIES

Goal 1 focuses on the **development of manageable photon sources and photonic integrations,** whereby primarily KIT, HZDR, and FZJ focus on the development of **scalable, electrically-driven on-chip single-photon emitters** operating at room temperature and in the telecom band. In addition, the Helmholtz Association is looking into **enhancing and controlling light-matter interaction with optical microcavity compatible device architectures** (using graphene/carbon nanotube hybrids or SiC/AlN hetero-structures). The Association also works on **single quantum dots in III-V nanowires,** which have been suggested as on-demand sources of single photons or polarization-entangled photon pairs.

For **Goal 2** a key ingredient of quantum repeater protocols is quantum memories, which can be realized in spin and atomic systems, or in Bose-Einstein condensates. The **development of quantum repeaters based on small quantum processors** is currently realized by us (primarily KIT, HZDR, HIM and FZJ) through work on **cavity-enhanced spin-photon interfaces for quantum repeaters** based on color centers in diamond, silicon and silicon carbide, while DLR works on quantum memories based on atomic systems and BECs. We also work toward the **realization of multi-qubit registers based on rare-earth-ion-doped crystals coupled to optical microcavities** as well as the integration of molecular qubits towards on-chip manipulation with light.

As the number of qubits in individual quantum processors is very likely to be limited, we are trying to distribute the desired number of qubits into a number of quantum processors connected by **quantum channels** into a cluster. A prerequisite for these quantum channels are **optical interfaces between semiconductor spin qubit processors and photon qubits,** which are under development in our centers using **various platforms (quantum dots, donors and color centers in silicon).** Quantum processors equipped with optical interfaces can perform the function of a quantum repeater.

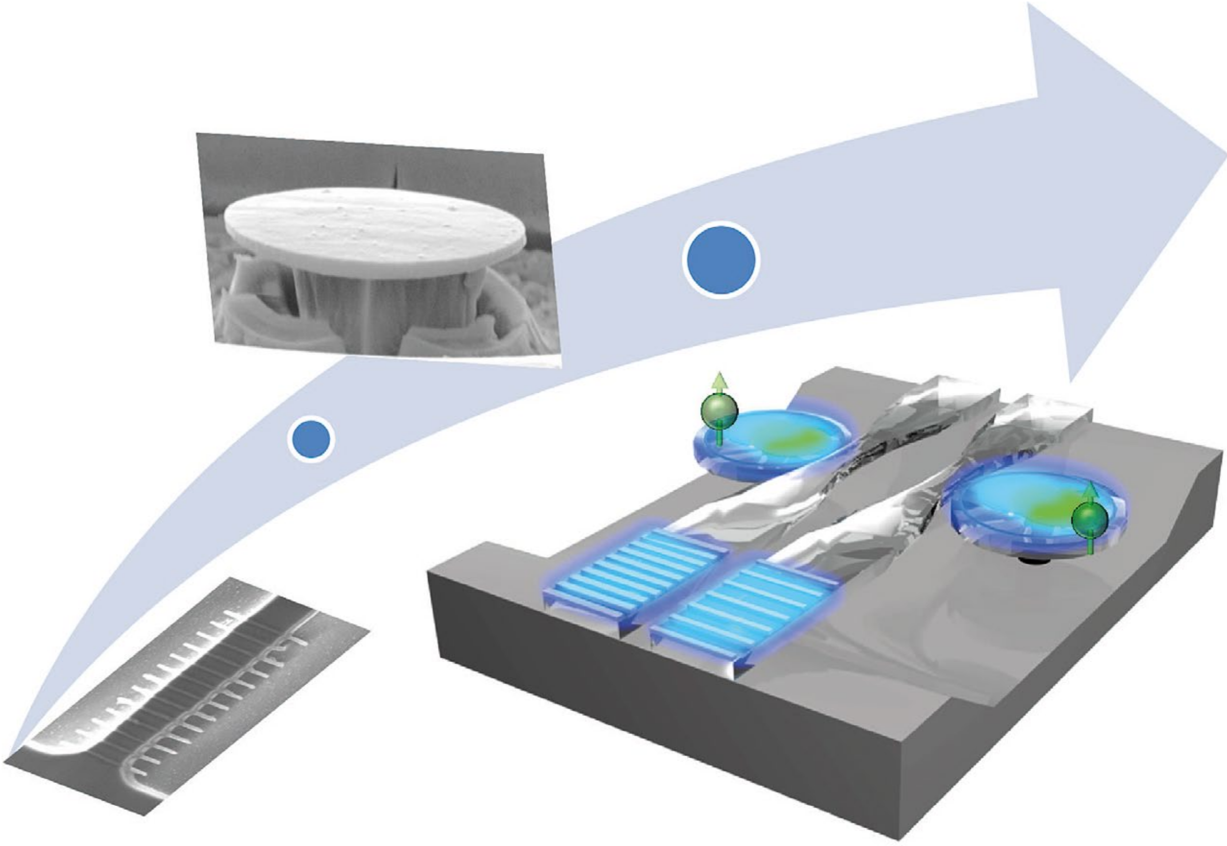
We work on the entanglement between multiple electron spin color centers on the same photonic chip that are mediated by a single photon and on storing quantum information for long periods in nuclear spins. Atomic, ensemble-based storage of quantum information is realized in vapor cells.

Goal 3 - The **security of current cryptosystems is compromised by attacks performed with quantum computers.** In order to ensure secure communication in the age of quantum computers, DLR works on **quantum-resistant public-key cryptosystems** that are resilient against known attacks performed on quantum computers. Although the security of quantum-resistant cryptosystems is not based on quantum effects, the progress in the field of quantum technologies has a major impact on the security of quantum-resistant cryptosystems.

Goal 4 - Global **Quantum Key Distribution (QKD)** is focusing on the **development of a quantum communication system.** On the one hand, the encryption methods currently in use are under threat from the development of a quantum computer running known or unknown attacks. Quantum cryptography shall be used to protect the critical infrastructure on the ground and in space, in particular, and will also be secure in the long term against attacks by a quantum computer. For quantum cryptographic connections over worldwide distances, to remote or mobile end users, satellites are necessary. On the other hand, satellites will also serve in the long term to connect quantum computers over long distances and thus become part of a **quantum internet in which terrestrial and space-based quantum repeaters are connected.** The Helmholtz Association (primarily DLR) therefore focuses on quantum communications with **respect to design, development, and experimental demonstration of global terrestrial and satellite based 24/7 quantum key distribution systems.** Major challenges to tackle are the **very hig- link efficiency** that is needed for **useful key rates, effective filtering techniques, and resilient protocols for daytime quantum communication, global network designs, architecture and protocols with and without trusted nodes.** It is important to **investigate and verify the practical security of the entire system and architecture.** QKD offers long-term protection against unknown attacks of quantum computers beyond what post-quantum cryptographie (PQC) can forecast. PQC and QKD supplement each other, providing overall security under all economical and security constraints.

Further research topics are the development of **sources for single photons, photon pairs, random number generators, and quantum relays.**

Goal 5 – This goal addresses the development of the network architecture and the relevant building blocks. Later on, the focus will be on concepts and on the implementation of the channel (e.g., satellite-based quantum teleportation), sources and receivers, quantum state converters, and the interface to the quantum computers. The architectural design has to take into account all available different physical and conceptual communication channels of quantum states and interfaces to stationary qubits and processors. The design will optimize a hybrid approach of terrestrial and space-based quantum repeater and direct-state transfer.



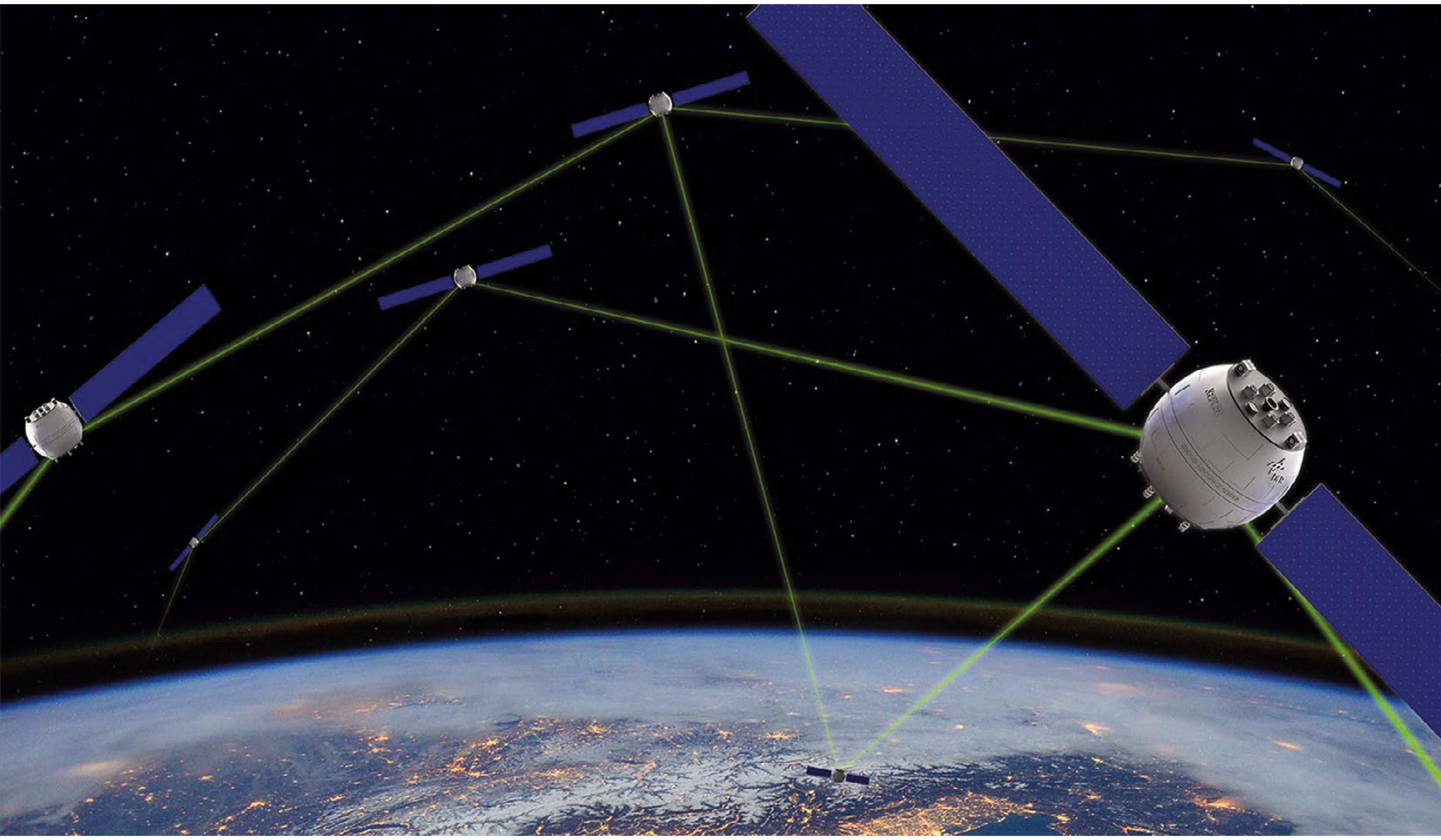
Connection of atomic systems via nanostructures and microcavities to a macroscopic integrated-optical device chip interface.
Photo: Forschungszentrum Jülich/AG Pawlis

FUTURE ACTIVITIES

Completely new perspectives arise from quantum sensor technology and metrology, as well as from quantum communication and cryptography. Within the **new DLR institutes Quantum Technologies, Institute for Satellite Geodesy and Inertial Sensing,** and the **Galileo Competence Center** it is therefore planned to focus on quantum communication and quantum cryptography and the associated information technologies at quantum level. DLR will also start to incorporate quantum communication methods in satellite operations. Starting with prototype implementations in various aspects of data flow at the ground segment level, e.g., interfaces between customers and the control centers and from there to the ground station, quantum communication can then be subsequently established in an operational workflow. Operating satellites with quantum key distribution units will be the final goal.

PROTOTYPE APPLICATIONS AND USE CASES

As a part of Goal 1, we continue to improve device technology based on epitaxial quantum dots in GaAs and single dopant atoms in ZnSe. These **optically active nanostructures are integrated in multi-layered heterostructures,** facilitating photonic and/or electronic integration. Both of these nanostructures have been demonstrated to work as sources of single photons, entangled photon pairs or sources of single spin-photon entanglement suitable for quantum communication. Regarding the improved connection between quantum processors (Goal 2) one of the first applications could be quantum repeaters whose operation is based on quantum error correction at the nodes of the networks. Secure communication in the age of quantum computers and even before will be a crucial topic in the future – providing the technical solutions (space-based infrastructures, optical-links and terrestrial infrastructure) coupled with quantum-resistant public-key cryptosystems will enable the secure long-distance communication of the future (Goal 3 and Goal 4).



DLR Space Research: Program Topic Communication, Navigation and Quantum Technology – System Kepler. Photo: DLR, ESA, NASA

SYNERGIES

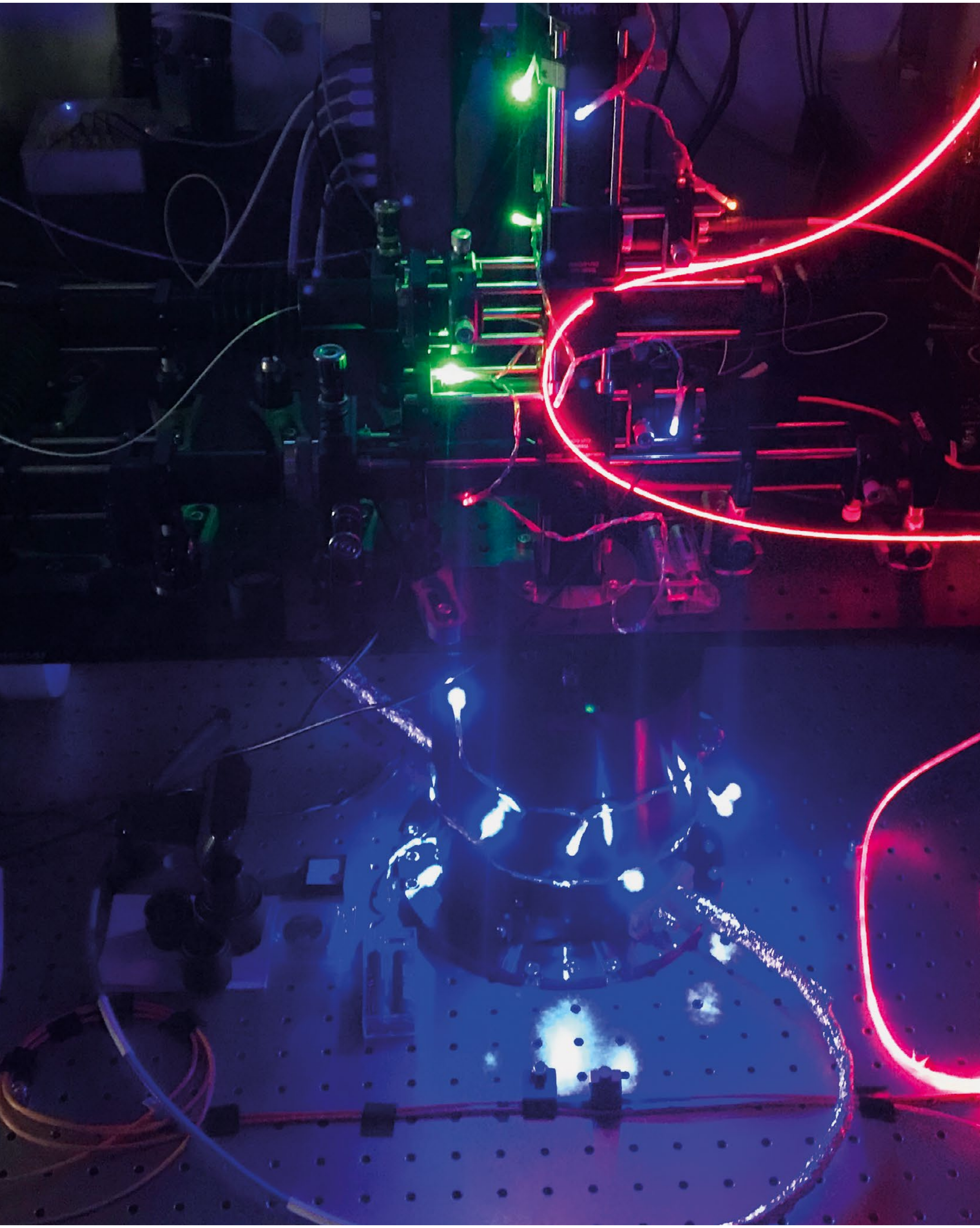
The described activities bring together the different expertise of the involved Helmholtz Centers (DLR, KIT, HZDR, HIM, and FZJ) – focusing on the common future vision of “a quantum communication network.”

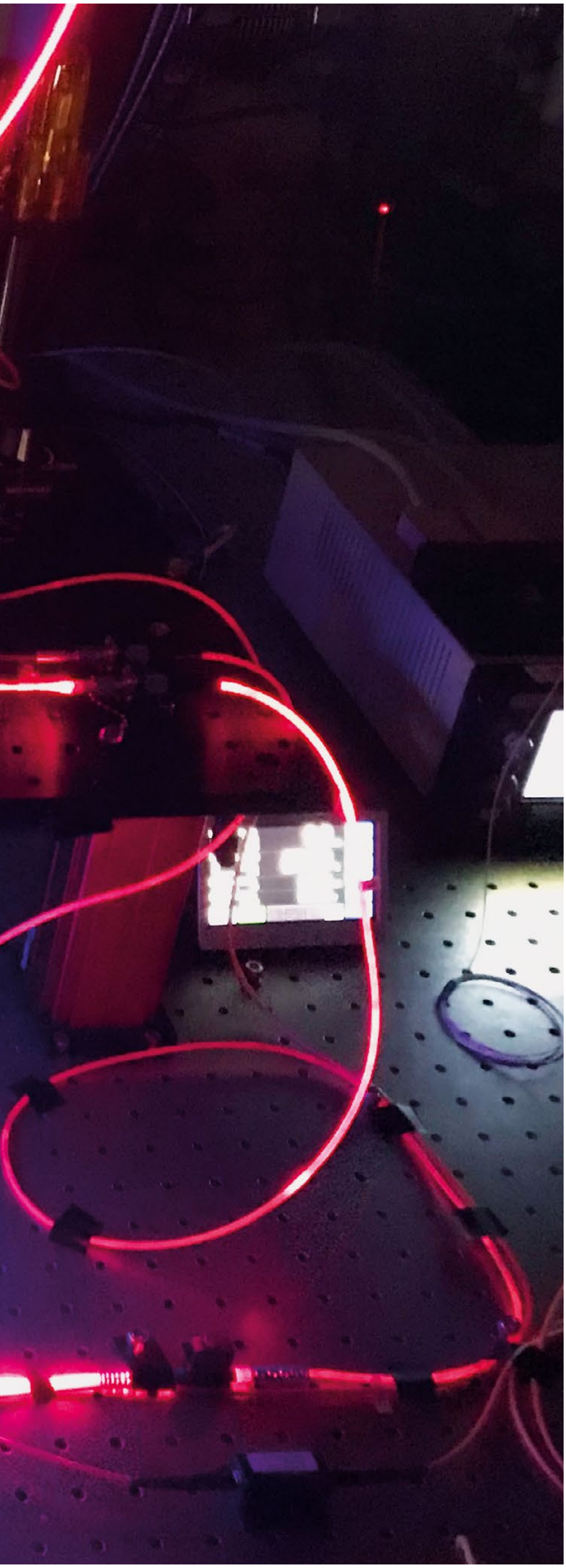
DLR cooperates closely with the Ludwig-Maximilians-University Munich, the Max-Planck-Gesellschaft (MPI for the Science of Light), and the Fraunhofer-Gesellschaft (IOF and HHI). Furthermore, DLR has the strong industrial partner Tesat Spacecom for the industrialization of laser terminals for classical and quantum space communications. Current projects related to QKD and quantum networks include QuNET (BMBF), QUBE (BMBF), OPENQKD (EU), QUARTZ (ESA), BayernQSat (StmWi), and SAGA (ESA).

The Quantum Technology Flagship Project SQUARE KIT is working together with Ecole Normal Supérieure (ENS) Paris, Aarhus, Stuttgart, Lund, The Institute of Photonic Sciences (ICFO) Barcelona, attocube, and THALES. KIT also contributes to the Germany-wide BMBF project Q.Link.X on realizing diamond-based quantum repeater links.

FZJ collaborates closely with partners at the University of Bonn and the University of Cologne within cluster of excellence ML4Q and also with the University of Bochum, the Technical University of Dortmund, SNRC Paris, and others. HZDR cooperates with the University of Vienna, the National Institutes for Quantum and Radiological Science and Technology (Japan), and Stanford University on cavity-enhanced spin photon interfaces. HZDR also works closely with Ioffe institute and the University of Crete on entangled photon sources.

The described activities are complementary to the BMBF project Q.Link.X where the focus is on Quantum repeater for tap-proof communication over long distances.





3.
QUANTUM SENSING

Quantum sensors are a key application in the field of quantum technologies, with an ever-increasing number of quantum-enabled sensing solutions expected to emerge over the next 10 years. With classical sensor systems increasingly reaching their inherent physical limits in terms of accuracy, sensitivity, speed and dimensionality, quantum sensors provide exciting new options based on a range of transformative approaches. They initiate a revolution in sensing technologies for tomorrow and for the day after tomorrow. The Helmholtz Association's activities stretch from space-bound and terrestrial applications in navigation and geodesy to autonomous mobility, communication, and life science, to applications in particle physics. They are combined in two main strategic directions: (i) quantum sensing in space and mobile platforms (DLR) (ii) integrated quantum sensors (HZDR, DLR, KIT, HIM, FZJ, DESY).

Quantum light microscope in operation.
Photo: HZDR/Michael Hollenbach

STRATEGIC GOALS

Short-term (5 years)

1. **Self-calibrated solid-state magnetometry** for precise measurements of planetary magnetic fields in space missions as well as the search for oil, metals, and minerals.
2. Miniature solid-state gyroscopes for autonomous driving.
3. Robust and miniaturized quantum optical systems **(lab-on-the-chip-technologies)** for high precision space, time, and acceleration measurement under rough space environment conditions.
4. Robust **quantum optical clocks and frequency references** on satellites with stability of several hours based on the iodine standard in combination with optical comb generators and cavities.
5. Optically read-out **inertial sensors** for use on GNSS and broader mass market.
6. **Lab-on-chip for biology, neuronal research and medicine:** Quantum magnetometry for fluidic applications.
7. Integration of quantum sensing in **searches for axions and dark matter** (magnetometry, optical atomic clocks, cryogenic particle detectors).

Mid-term (10 years)

8. **Compact quantum-cascade lasers** for the ultrasensitive heterodyne detection of atomic oxygen in space missions and trace gases in atmospheric research.
9. A **compact solid-state maser** for heterodyne detection with ultra-high quantum-limited sensitivity for long-distance communication, radio-astronomy, medical imaging, and quantum radars.
10. **Ultra-sensitive kinetic inductance detectors** of single photons in the spectral range from Terahertz to X-rays.
11. **Fully automatic generation of Bose-Einstein condensate accelerometers** with a high repetition rate for the high-precision measurement of the Earth's rotation rates as well as of non-conservative forces on satellites.
12. **Matter-wave based quantum gravimetry** for Earth, planetary research, and fundamental physics.
13. Demonstration of **optical atomic clocks in space** and optical frequency links.
14. **On-chip spectrometers with single-photon detection capability** for sensing applications in Earth observation, planetary research, and astronomy.
15. Realization and validation of **magnetomyography platform based on quantum sensors.**
16. **Prototype quantum imaging system** (UV to X-rays and atoms) with a broad range of applications ranging from solid-state physics to biological and medical imaging.
17. **Dark-matter detection and tests of general relativity** with quantum-sensing optimized experiments.

Long-term (beyond the 10-year horizon)

18. **Hybrid spin-mechanical system** with **zepto-scale gram sensing** to detect individual macromolecules.

19. **Room-temperature quantum chips** and **readout electronics** with a broad spectrum of applications ranging from quantum sensor arrays for automotive industry to building blocks for coherent quantum processors.

20. Highly stable **master clock in space for time and frequency distribution** with applications to **chronometric geodesy** (determination of the geoid below the centimeter level).

21. Realization and validation of **magnetoencephalography devices based on quantum sensors** (stationary and wearable).

CURRENT ACTIVITIES

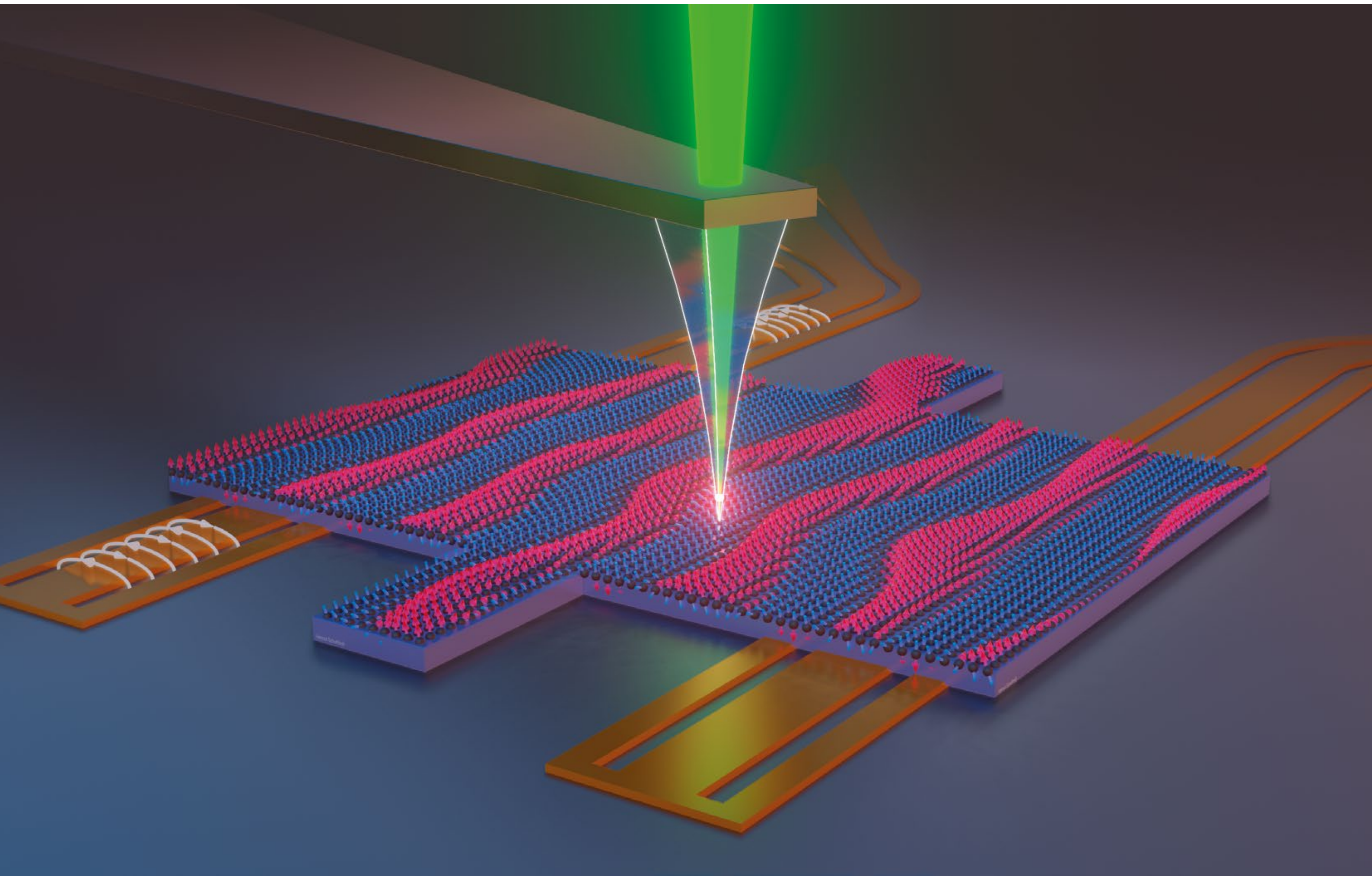
Within the two new DLR institutes Institute for Satellite Geodesy and Inertial Sensors and Quantum Technologies (founded in 2019), the focus is on the development of **compact quantum instruments, clocks and gravity sensors for space-based applications, and mobile platforms.** In addition, DLR-SI is studying "relativistic geodesy" for fundamental and applied research. Quantum metrological systems, based on quantum optical instruments of the first and second generation, such as clocks and frequency references measure distances and angles in space with ultra-high precision. Highly precise and compact accelerometer systems use cold atoms and Bose-Einstein condensates respectively as test masses (at DLR-SI) as well as fiber-optic based Fabry-Pérot interferometric optical readout of mesoscopic test masses (OMIS) at DLR-QT. Both are based on miniaturization technologies by lab-on-the-chip-approaches to account for spatial limitation on satellites. These systems are designed for Earth observation and science missions, e.g., the determination of gravity and new reference systems for time and navigation. Feasibility will be demonstrated by two "lighthouse-missions" within the next 5 years: BECCAL and COMPASSO on the ISS. DLR is also investigating concepts for distributed quantum sensing and is exploring quantum radar concepts. The Helmholtz Association is also studying the prospect of diffraction of fast atoms and ions through 2D materials for a wide range of sensing applications. HZDR develops a quantum sensor architecture based on spin centers in semiconductors. Because of their atomic scale, keen sensitivity to their environment and simple readability of their quantum states, these centers enable high precision measurements of various physical quantities at high speed and with high spatial resolution. HZDR selects material platforms, which maintain quantum properties under highly varying temperatures and radiation environments occurring in vehicle engine systems, power plants and space. KIT builds ultra-sensitive superconducting kinetic inductance sensors to implement single photon detectors in an extremely broad spectral range from terahertz to X-rays. Particular application examples are dark matter searches, astronomical observations of the cosmic microwave background and on-chip single photon detectors for quantum links.

HIM develops highly precise solid-state and alkali gas–based sensors. Special applications are the search for dark matter, the recording of biomagnetic signatures of the brain and the heart as well as the astronomical observation of the cosmic microwave background and the development of on-chip single photon detectors for quantum links.

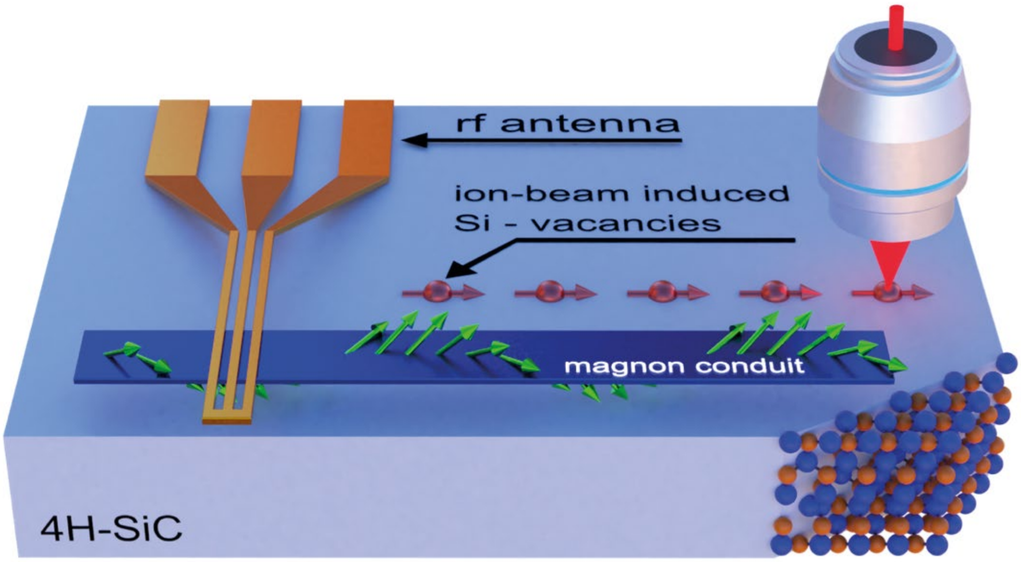
A further application of such ultra-sensitive, cryo-cooled µ-calorimeter is precision spectroscopy at ion storage rings as it is done by HIJ. There, dedicated detectors for imaging applications at short wavelengths are currently developed in close collaboration with KIT and the IPHT Leibniz/Jena.

FUTURE ACTIVITIES

DLR will develop a new kind of atom interferometry based on optical clock transitions and investigate longer-term applications in space. For the next generation of gravimetry/gradiometry missions for Earth observation hybrid concepts involving laser ranging and cold atom interferometers will be explored. HZDR plans to develop **hybrid quantum sensors**, where spin centers are integrated into electronic circuits, photonic structures, microwave cavities, and mechanical resonators to combine the advantages of dissimilar quantum degrees of freedom as well as to mediate the communication between the quantum and classical worlds. Magnonic-based circuits could convert small DC signals in microwaves on the chip level as well as focus and steer the microwaves in nano-circuits to the desired place. Compared to the power cryoelectronics, the wavelength will be orders of smaller magnitude, allowing for much better localization of the microwaves and less crosstalk between qubits, facilitating a compact design. KIT plans to implement arrays of **frequency multiplexed superconducting sensors,** i.e., with the ability to read out many sensors simultaneously, and to develop room temperature readout electronics. FZJ will develop **optimal quantum control techniques** for various quantum systems to improve their sensing performance. Cryo-cooled, µ-calorimetric single-photon detectors equipped with pixel arrays for XUV radiation will be developed by HIJ and commissioned. Along with compact coherent XUV light sources a prototype quantum imaging system will be setup. This system will also exploit the possibility of ghost imaging with entangled or correlated photon pairs at exotic wavelengths. HIM develops portable high-performance, diamond-based quantum sensors that monitor biomagnetic signals outside the laboratory scope and that provide industry-oriented miniaturized gyroscopes.



Scanning quantum magnetometry. Photo: HZDR/Helmut Schultheiß



Artistic view of an on-chip quantum magnetometry to probe magnetic excitations. Photo: HZDR/Helmut Schultheiß

PROTOTYPE APPLICATIONS AND USE CASES

Quantum sensing will lead to new applications in the field of **Earth observation** in terms of very precise gravity measurements to **track Earth's water movement**. Examples include, among others, monitoring changes in underground water storage, the amount of water in large lakes and rivers, soil moisture, ice sheets and glaciers, and sea level caused by the addition of water to the ocean. The new DLR institute for Quantum Technologies fosters research on **quantum metrology and optical clocks** for more precise and stable time signals. This will result in Technology Demonstration Missions in close cooperation with the planned Galileo-Competence-Center. The technological readiness of these developments will be proven, and they will be introduced into concepts for Europe's future **European Global Navigation Satellite Systems (GNSS)** efforts.

In the **long term**, quantum sensing might also lead to various **use cases** in other fields like materials science, chemistry, biology, medicine, and mobility/navigation.

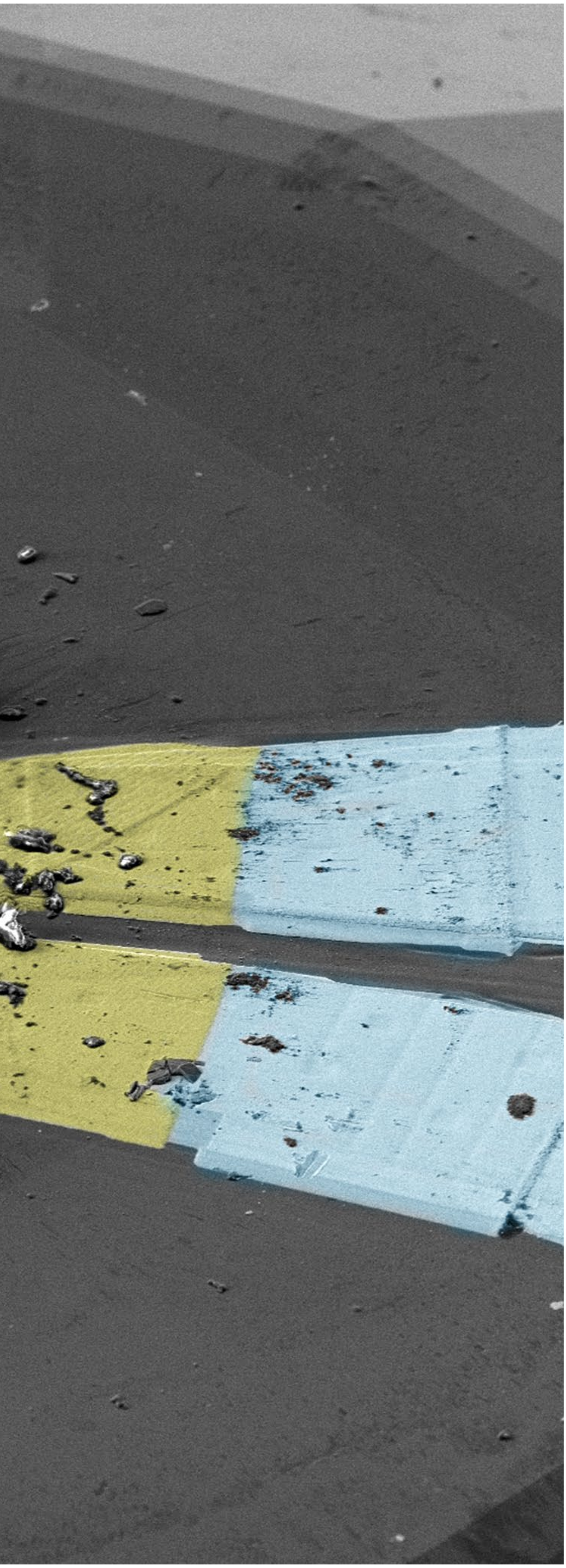
SYNERGIES

DLR internally developed testbeds to determine performances of quantum-optical systems for gravity sensing missions in cooperation with GFZ (Geoforschungszentrum Potsdam). DLR and KIT cooperate in terms of lab-on-the-chip technologies for acceleration metrology.

The Helmholtz Association is also involved in national and international cooperation. FZJ and HIM are partners of the European Flagship project ASTERIQS.DLR cooperates with PTB (Physikalisch-Technische Bundesanstalt) on highly precise quantum-metrological methods for dilatometry. With the Leibniz University of Hannover, the University of Ulm and Humboldt University of Berlin, DLR works on cold atom interferometry and Bose-Einstein condensates. HZDR cooperates with Ioffe Institute in Russia, the University of Würzburg, and the National Institutes for Quantum and Radiological Science and Technology in Japan on the development of quantum microwave amplifiers and integrated quantum magnetometers. HZDR works with PDI Berlin on acoustically controlled qubits. HIM works with PTB Berlin on sensors for biomagnetic experiments and for the detection of bosonic dark matter.

For its space missions, DLR cooperates with the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the European Global Navigation Satellite Systems Agency (GSA). This cooperation integrates research and development efforts from various international research institutes and industry, such as JPL, Airbus, OHB, and STI. DLR's other industry partners include Menlo Systems, TESAT, Bosch, Hensoldt, and Daimler.

At the research campus in Jena there is a network of research institutes consisting of HIJ, Fraunhofer Institute IOF, Leibniz IPHT, and FSU Jena. The joint activities also focus on detectors at the quantum limit and cryo-sensors in cooperation with the KIT and the Kirchhoff-Institute for Physics Heidelberg.



4. QUANTUM MATERIALS AND FUNDAMENTAL SCIENCE

Quantum materials display properties that result from complex electronic states that involve several inter-twined degrees of freedom such as charge, spin, orbit, and lattice. Such materials are consequently at the focus of a large number of activities at the Helmholtz Association. To enable future quantum devices, quantum materials must be discovered, characterized, and further developed – a long and costly process involving the Helmholtz Association's highly qualified researchers and large-scale facilities. Quantum materials are our key toward realizing the vision of quantum supremacy, especially beyond current proof-of-principle experiments. While qubits have been demonstrated based on materials discovered in the past century, the step of moving to a fully functional quantum computer remains an immense challenge. There is a need for serious improvements, either incremental or disruptive, enabled by new discoveries and a new level of understanding and control of quantum materials. Our research in this direction leaves behind the established view of condensed matter in at least two ways. First, using strong interactions between electrons, we realize conceptually new states characterized by frustration, entanglement, and coherence, and secondly, we explore non-trivial topologies of the wave functions to guarantee the exceptional stability of the relevant states. Both properties are of major interest with respect to tailoring functionalities for new computing paradigms and bear potential for quantum sensing and quantum metrology as well as quantum communication via matter-light interaction.

Quantum materials under extreme conditions: high pressure, high magnetic field. Photo: HZDR/Toni Helm

STRATEGIC GOALS

To realize quantum technologies, the Helmholtz Association will strive to develop tailor-made materials and design quantum systems guided by the following strategic goals (which, owing to their more fundamental nature, all have a time horizon of 10 years and beyond):

1. Explore the **fundamentals of quantum systems down to the atomic and molecular scales** and engineer their quantum mechanical properties with atomic precision, thereby optimizing quantum coherence in nanostructures for potential use in quantum technologies. This includes demonstrating their phase-coherent control and coupling to a quantum network.

2. Explore novel **materials as a source for novel metrological standards and innovative qubit concepts,** which go beyond current solid-state qubit systems. Establish systematic multidimensional phase diagrams for materials candidates in terms of electronic and magnetic properties, topology, and potential functionality.

3. Study the **dynamics of novel quantum states** arising at surfaces and interfaces, in exotic materials, in highly excited systems, and in emergent topologically protected magnetic and polar structures, and consider their potential for future quantum devices.

4. Identify, understand, and overcome the **relevant decoherence mechanisms** in quantum systems to improve the performance of qubits and the quality of quantum sensors.

5. Explore the **limits of** validity of **quantum mechanics**, such as in the interferometric tests of collapse models.

6. **Couple solid-state qubits and photons** for the coherent exchange of quantum information between matter and light. Realize solid-state quantum emitters (single and entangled photon sources in a broad wavelength range) and quantum sensors.

CURRENT ACTIVITIES

The Helmholtz Centers currently develop tailor-made quantum systems based on novel materials, complex interfaces, and hybrid structures (e.g., molecular devices) in a synergetic experiment/theory approach. These systems are based on paradigms involving spin, charges, and other quantum degrees of freedom, as well as topology, configurations, and correlations. They exhibit a wealth of non-trivial quantum ordering phenomena, including superconductivity and magnetism, on which many quantum technologies already rely. In novel exotic phases competing or intertwined orders offer additional tuning knobs to manipulate the electronic state of quantum devices.

To go further, to optimize the existing technologies, assess the technological potential of novel materials and finally to design and tailor the electronic properties and responses of dedicated devices, the Helmholtz Association can rely on a unique combination of state-of-the-art experimental infrastructure. The association has been continuously developing experimental methods to synthesize new quantum materials and molecules, and to enable the in-depth exploration of their physical properties at all relevant time and length scales. In particular, most powerful X-ray-based methods are developed and employed to probe the inner workings of quantum materials and devices at highest spectral resolution and at the shortest relevant time and length scales (HZB – BESSY II and DESY – PETRA III, FLASH).

Quantum materials are fabricated in single crystalline, thin film, and heterostructure form to generate novel hybrid quasiparticles and explore their electronic properties under extreme conditions (FZJ, HZB, HZDR, KIT) and in operando (DESY). Topologically protected materials in 2D and 3D are explored to understand their fundamental properties and functionalize them with magnetism and superconductivity for use in quantum technologies (FZJ, HZB).

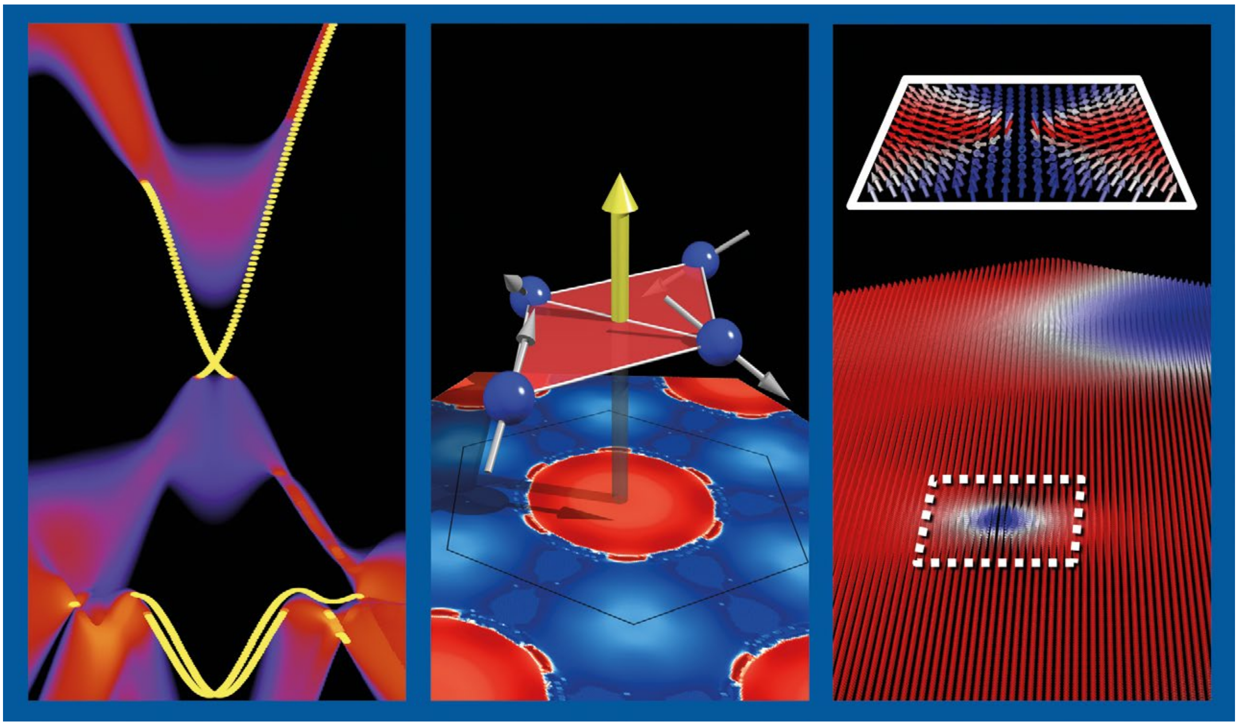
We study emergent phenomena, relaxation and decoherence mechanisms in unconventional magnetic systems, such as the quantum spin liquid state (HZB, HZDR, KIT, DESY) and magnetic and polar topological textures, such as skyrmions (HZB, FZJ, HZDR). These exhibit long lifetimes, easy coupling to quantum signals carried by spins, charges, and photons, and strong interaction with other quantum states, such as superconducting wave functions. Their unique, strong, and precisely controllable quantum behavior, which often extends to room temperature, is explored for applications in quantum technologies and their interconnections to the classical world.

We develop and optimize superconductor-based quantum circuits (KIT). We synthesize and investigate novel unconventional superconducting phases, which can lead to a disruptive technology for quantum circuits at higher operation temperature that would permit the use of much simpler cooling technology and a higher integration density (KIT, HZB, HZDR, DESY). We entangle magnetization space with momentum-space topologies to explore novel quasiparticles with hybrid topologies (FZJ, DESY). In particular, superconductors are interfaced with topological and Chern insulators and skyrmion-carrying 2D van der Waals materials to create topological superconductors with Majorana zero modes for topological quantum computing (FZJ).

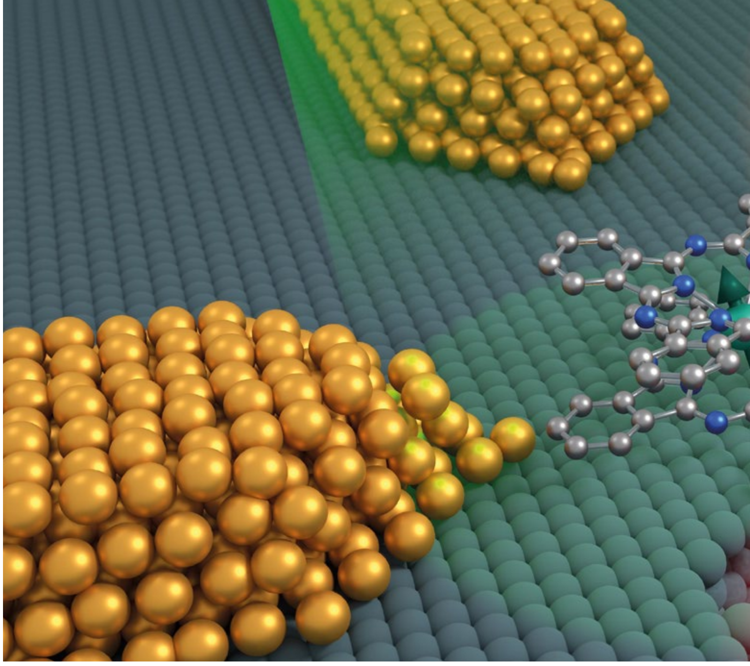
We develop the concept of quantum nanoscience, which has the potential to form a bridge between quantum materials research and the development of nanoscale quantum devices, and create custom-built metastable quantum-material structures on atomic and molecular length scales with wave function control (FZJ). We create and functionalize molecular systems that are embedded in quantum circuits to serve as buildings blocks for quantum technologies (single and entangled photon sources, qudits or optically addressable spins) (KIT). We create novel non-equilibrium and Floquet-Bloch quantum states and track their ultrafast dynamics in time domain and energy-momentum space (FZJ, DESY).

FUTURE ACTIVITIES

The first goal **(Goal 1)** is crafting designed quantum systems down to the atomic and molecular scale, thus realizing arbitrary (metastable) structures with intrinsically quantum-dominated properties. This enables quantum state engineering with atomic precision, such that the concepts of entanglement, coherent control and quantum measurements can be explored and utilized with fewer constraints. We will exploit atomic and molecular manipulation, chemical design and synthesis, and the creation of embedded single-atom scale defects as implementation



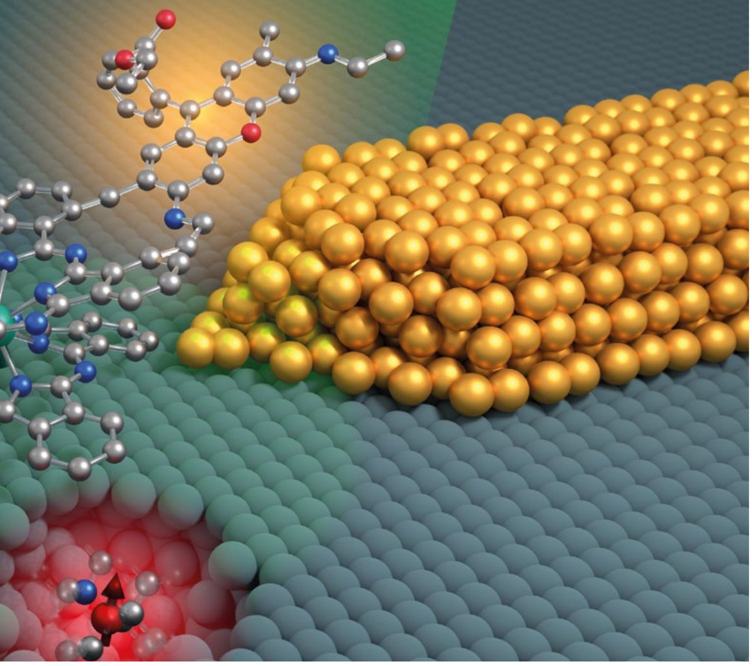
Quantum Materials such as topological matter has fascinating properties and great potential for use in information technology.
Photo: Forschungszentrum Jülich



routes. In particular, we plan to develop and construct a first qubit demonstrator that utilizes the electron or nuclear spin of a single atom or molecule absorbed on surfaces with atomic manipulation by scanning probe microscopes (FZJ, KIT). Furthermore, using chemical design, we target the production of billions of atomically identical molecular qubits based on nuclear spin states or multilevel-state qubits (qudits), all exhibiting long coherence times and very large Hilbert space (KIT). We will also utilize embedded quantum dots as well as atom-scale defects in isotopically purified silicon for integration into semiconductor circuits, owing to their potential for long coherence times and compatibility with wafer-scale microelectronic fabrication technology (HZDR, HZB). Based on demonstrated nm-precise single ion implantation (HIM), we will generate tailor-made structures of quantum devices in ultra-pure Si, YAG and diamond crystals.

Since future quantum computers require higher quality qubits then is currently available, the second goal **(Goal 2)** is to explore a wide variety of different material systems, including those with tunable exotic electronic order, quantum magnets, interfaces of highly correlated and topological matter, and molecules. In particular, it is planned to investigate unconventional superconductors that can host a variety of exotic electronic states such as the long-sought pair-density wave and understand the role of extended defects for flux pinning (KIT, HZB, HZDR, DESY). The Helmholtz Association will study quantum magnets which are capable of supporting long-lived qubits since they can host novel emergent states, e.g., in quantum spin liquids, that are not defined by conventional symmetry breaking but rather by topological order which protects them from decoherence. The association will also study various topological textures in thin films and heterostructures which can be used to couple to other quantum states (HZB, FZJ, DESY, HZDR). Dedicated synthesis facilities for quantum materials with topological properties will be developed including in situ characterization to control their quantum and topological properties (HZB). Tools to resolve emergent states in space, time, and energy will be developed at BESSY II (HZB) as well as at PETRA III and FLASH (DESY). Integration of topological textures into two- and three-terminal sub 1 µm devices will be done on Si wafers (HZB) with the development of dedicated processes for the nanopatterning of quantum heterostructures (HZDR, HZB, DESY). Furthermore, the association will explore materials and hybrid structures hosting Majorana states. In particular, the Helmholtz Association plans to study the Majorana zero modes at the end points of superconducting nanostructures in contact with topological insulators; as a key experiment, braiding of Majorana zero modes shall be demonstrated (FZJ, KIT, DLR) as well as the creation of Majorana zero modes caused by fluxon solitons in long Josephson junctions (KIT). Another avenue is emergent quantum states in materials that combine intrinsic topology and magnetism such as magnetic topological insulators, Dirac and Weyl semimetals. These materials permit innovative qubit designs with high readout speed and they enable innovative metrological standards via the quantum anomalous Hall effect (FZJ, HZB, HZDR, KIT, DESY). Finally, the association will investigate the coupling of different types of qubits in order to transfer quantum information between them. This can be explored in hybrid structures consisting of magnetic and superconducting degrees of freedom (KIT, HZDR), semiconductor and superconductor hybrid structures (KIT, FZJ, HZDR), as well as molecular systems and other qubits (KIT).

The study of state dynamics is crucial for any quantum material and quantum system **(Goal 3)**. Another promising avenue of research is the attempt to bring localized solitonic collective states, such as nano-skyrmions, to the quantum level. One approach in this context is to create novel “dynamical” topological states, e. g., Majorana modes as a result of the interaction between spin solitons and superconductors (FZJ, KIT). The Helmholtz Association will also study externally driven metastable and non-equilibrium states in quantum materials. To this end, the association will use a suite of (soft) X-ray spectroscopic techniques with femtosecond time resolution to selectively probe the involved subsystems (spin, charge, orbital, ...) at the active elements and their dynamic coupling to the other quantum reservoirs, i.e., potential decoherence pathways. This will help to understand the interplay of microscopic mechanisms and time scales in quantum materials (HZB, DESY). On this basis, excitation protocols will be developed



Pictorial representation of an optoelectronic device with a douple-Decker molecule containing a rare-earth ion in the centre. Photo: KIT/Wolfgang Wernsdorfer

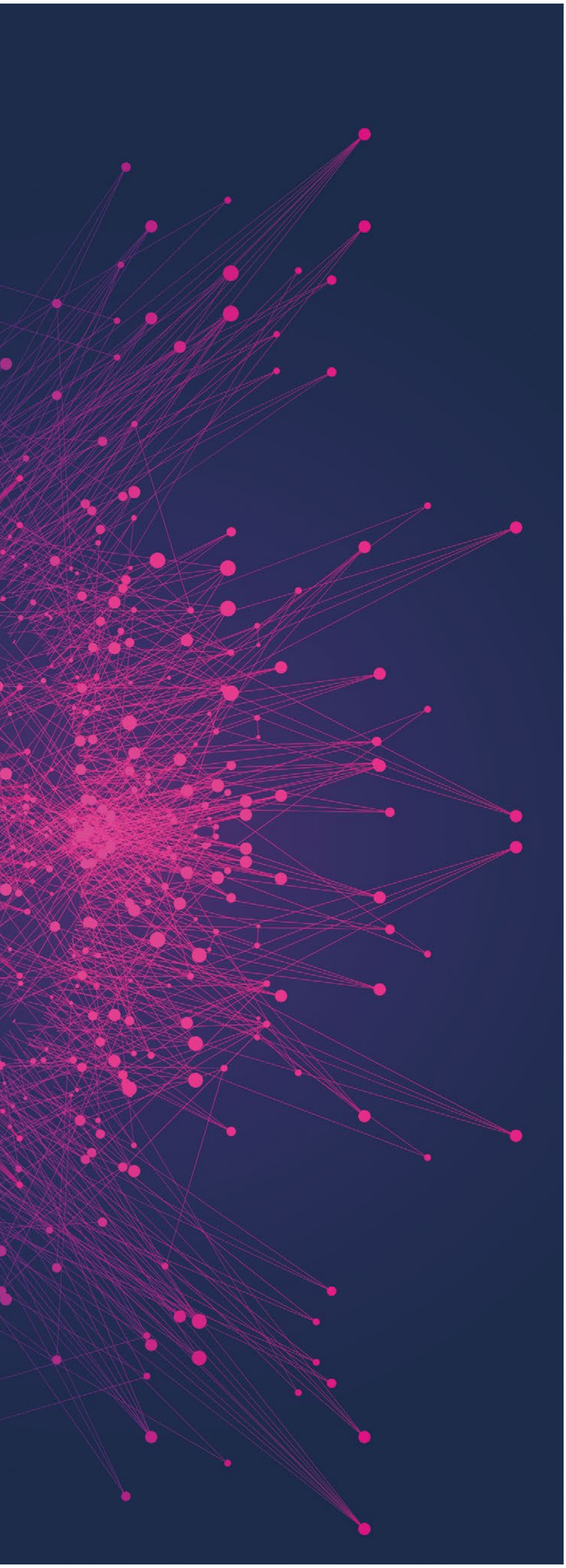
to establish and control emergent quantum order. The experiments require ultra-short light pulses over a broad wavelength range (HZB, DESY) and include the implementation of novel spectroscopic techniques using low energy excitations that preserve the superconducting state, such as Higgs spectroscopy (FZJ, HZDR). One-way quantum computing is another intriguing concept in the context of dynamics of quantum systems. Therefore, the association will also explore solid-state materials containing Mössbauer nuclei with the goal of establishing qubits and logical gates. Specifically, the association will prepare nanostructured ensembles of Mössbauer nuclei as atomically identical photon emitters that could serve as quantum registers with long coherence times. Multiphoton excitation of these ensembles by X-ray pulses from a source like the European XFEL will create highly entangled states of excited nuclei, leading to emission of photons for quantum information transfer (DESY).

A major goal **(Goal 4)** required for the establishment of any quantum material system as qubit device or quantum sensor is the identification of the most relevant decoherence mechanisms. Specifically, for all of the quantum systems related to the aforementioned goals (G1–G3) it is important to find ways to improve the coherence time. To this end, the Helmholtz Association will strive to identify the dominant sources of noise and design novel materials and systems which avoid these sources of decoherence, e.g., via topological protection. Alternatively, smarter qubits and better manipulation protocols may also be targeted (KIT, FZJ, HZB, HZDR, DESY).

The emergence of classicality in descriptions of the everyday macroscopic world and the limits of validity of quantum mechanics are intriguing questions on the foundation of physics. DLR will develop molecular interferometers to test gravity-induced collapse models **(Goal 5)**, which may also have applications for inertial sensing and material analysis. In future quantum computing devices, the information processing will be based on solid-state quantum registers, whereas the control, transfer and communication will be performed by photons. For this reason, coupling schemes between solid-state and photon qubits are essential and will be investigated **(Goal 6)**. As a specific example, we will design semiconductor devices for short and mid-range qubit coupling (HIM), as well as long-distance qubit coupling through spin-photon entanglement (HZDR). Moreover, scalable electrically-driven on-chip single-photon emitters based on rare-earth qubits using carbon materials (nanotubes, graphene, graphdiyne) will be developed (KIT, HZDR, HIM). Additionally, the monolithic integration of on-demand entangled photon sources at wavelengths used in telecommunications is envisaged (FZJ, HZDR).

SYNERGIES

Bringing together the expertise of several Helmholtz Centers in a single roadmap will leverage considerable synergies. Their respective expertise are characterized by a high degree of complementarity. By combining forces, the involved players will create a joint research program with worldwide visibility. The activities of FZJ in the field of quantum materials will be incorporated in the planned **Helmholtz Quantum Center (HQC)**. Similarly, the activities of KIT have been incorporated in the recently founded (2020) **Institute of Quantum Materials and Technologies (IQMT)** and those of HZB in the new **Division Quantum and Functional Materials.** Quantum materials research at KIT is embedded in the recently funded transregional collaborative research center TRR-288 Elasto-Q-Mat. The use of high-end large-scale facilities that are available in the centers such as the storage rings BESSY II and PETRA III and the free-electron laser FLASH will be a particularly strong asset. The Clusters of Excellence **“Matter and Light for Quantum Computing (ML4Q)”** in which the Universities of Köln, Bonn, and Aachen, and the FZJ collaborate and **“Complexity and Topology in Quantum Matter (ct.qmat)”** established by the University of Würzburg, the TU Dresden, and HZDR will leverage further strong synergies. Finally, all Helmholtz Centers are involved in external collaborations with leading institutions in the field.



5. QUANTUM SIMULATIONS AND NUMERICAL METHODS

Simulation and numerical methods are at the heart of the optimal and efficient usage of future quantum computer devices. Firstly, **simulation, benchmarking, and control of many-qubit systems** are essential in order to develop quantum devices of the future with a large number of qubits. Secondly, **hybrid classical-quantum simulations with optimized numerical techniques** in physics, chemistry, biology, and even beyond these research areas will provide a proof of the usability of quantum computing devices next to classical computers. Thirdly, quantum algorithms for use-cases from academia and industry, such as machine learning or optimization, will be developed towards the demonstration of a quantum advantage for useful applications. This will **open completely new avenues** in science as well as in industry and allow solutions to problems that **are not attainable today**.

Photo: Shutterstock.com/BAIVECTOR

STRATEGIC GOALS

In quantum technology, the Helmholtz Association plans to strengthen simulation next to theory and experiment, as well as realizing quantum computing applications. For this purpose, it has formulated the following strategic goals:

Short-term (5 years)

1. Develop **algorithms, methods, and tools** for disruptive computing devices to solve very difficult and hitherto intractable computational problems in science and industry.
2. Develop **prototype applications and use cases** that exploit quantum-advantage in real-world applications.
3. Employ **high performance computing emulators** to acquire essential knowledge of the operation of quantum simulators, quantum computers and quantum annealers.
4. Assess the quantum advantage by **benchmarking** various quantum platforms (including quantum simulators and NISQ devices) in contrast to quantum-inspired classical simulation methods.
5. Develop **error mitigation and quantum circuit expressivity** methods to minimize noise on quantum devices.

Long-term (beyond the 10-year horizon)

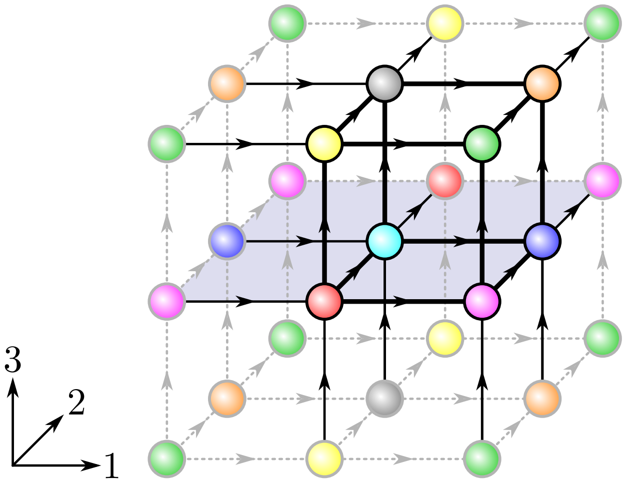
1. Develop, in a common effort with all Helmholtz Centers and with external partners, a **broadly useable software package** which will help a wide community of researchers from various disciplines and industry perform efficient quantum computations.

CURRENT ACTIVITIES

Helmholtz Centers are developing a **quantum simulation** of interacting quantum systems in condensed matter and many-body systems (FZJ, HZDR) as well as in nuclear and particle physics (HZDR, DESY), to enable the study of crucial properties of the most relevant models in these fields (G1). Equally important are the simulation of quantum materials (FZJ, KIT, HZB, HZDR). In particular, the research portfolio includes simulation of critical phenomena in arrays of qubits; of strongly-correlated phenomena; of quantum dynamics in fermionic systems; of quantum many-body systems; of models in particle physics; of matter under extreme conditions. Research at the Helmholtz Centers also addresses analog quantum simulations and quantum annealing; the development of analytical and numerical methods based on matrix-product and tensor-network states combined with machine learning algorithms; and quantum-circuit and classical optimization techniques (DESY, DLR, FZJ, HZDR). In addition, the Helmholtz Centers also study the power of Majorana qubits (FZJ, KIT) and cluster states (DESY), the latter as an alternative exploration of the potential of one-way computing. They also pursue activities to develop the means and techniques to diagnose two-level systems in qubits and to deduce recipes to mitigate them in future quantum circuits. Finally, research conducted at the centers also develop algorithms of error mitigation and methods to analyze the expressivity of quantum circuits.

Multiple research groups at the Helmholtz Association work on **prototype applications and use cases** of quantum computing and quantum annealing (DLR, FZJ, DESY, HZB, HZDR). Here, the activities range from developing application-driven quantum algorithms (e.g., for planning problems, machine learning, and quantum simulation), to the investigation of multi-qubit architectures tailored to specific problems. These activities are performed in a wholesome approach including hardware (Section II.1.), algorithms, and applications towards the demonstration of useful applications with quantum computing devices (hardware-software-codesign).

DLR recently launched multiple projects for investigating possible quantum advantage for applications from aerospace research. This includes the development of tailored algorithms as well as error mitigation and compilation strategies for use-cases from satellite mission planning, computational fluid dynamics, battery and fuel cell research, image processing and anomaly detection.



A 3-dimensional periodic lattice as used for simulations of models of theoretical particle physics on a quantum computer. Source: https://arxiv.org/abs/2105.06019

FUTURE ACTIVITIES

In order to overcome hardware restrictions related to the next generation quantum devices, optimal ways will be developed to compile general quantum circuits with the goal of automating this process for a wide range of applications and hardware layouts. To achieve the strategic goals outlined above, it is necessary to design scalable hybrid classical-quantum simulation technologies which are robust against errors and to provide support for device-, architecture- and quantum circuit design and platform evaluation. In addition, advanced techniques of machine learning will be employed and further evolved to quantum machine learning to gain a better design of quantum devices and to expose the relation between quantum computing and artificial intelligence. The quality of quantum operations performed over the quantum register strongly depends on the fidelity of quantum gates and degradation due to the interaction with a noisy environment. We will test this environment on the basis of modern classical HPC facilities, which are capable of running massive Monte Carlo simulations of 30+ qubits systems afflicted by various types of quantum noise (HZDR). Depending on noise properties, a suitable error correction code can be selected on the fly to improve computation accuracy of standard or custom quantum algorithms. The simulation results can then be directly benchmarked against quantum state tomography of real qubits and gates. The Helmholtz Association plans to develop a software infrastructure to **realistically simulate spin-qubit devices, control procedures, and circuits** (FZJ). A special emphasis is laid on **JUNIQ which serves as a nucleus** to explore different quantum computer technologies and quantum simulators. Within JUNIQ, software tools, modelling concepts, benchmarking methods, and algorithms will be developed and applied on a great variety of quantum devices. A large number of researchers at the Helmholtz Association and beyond will benefit (DESY, DLR, FZJ, KIT, UFZ, HIM, HZB, HZDR) as a result. In addition, with the planned DESY Applied Quantum Lab, a complementary activity within the Helmholtz society focusing on quantum simulations and use cases will be established. This is crucial for all simulation and data-related activities at the Helmholtz Association and beyond. These developments have great potential beyond the 10-year horizon considered here to lead to the **first application in quantum computing for real world problems**. These can, for example, **lie in the area of high temperature superconductivity, the standard model of particle physics, in production management or in planning problems, such as traffic management or logistics** with a direct impact on society. Developing the necessary methods and algorithms and **integrating quantum hardware into existing HPC infrastructures** will enable practical use of **quantum-classical hybrid computing models**, a prerequisite for any practical application.

SYNERGIES

On the **variational quantum simulation** side there is expertise at DESY, HIU, DLR, and FZJ with quantum computations in chemistry, condensed matter, and particle physics.

At the international level, DESY collaborates closely with the Institute for Quantum Computing in Waterloo and with the Quantum Initiative of CERN OpenLab. The Helmholtz Association also has a long-standing collaboration for em-ploying DESY's tensor network techniques with the Perimeter Institute in Waterloo and the MPQ in Garching. DLR is closely collaborating with NASA Ames on software and algorithms for quantum compiling and quantum computing. FZJ contributes to the development of quantum simulators in the flagship project PASQuanS. Within OpenSuperQ, FZJ develops simulation code for the simulation of a realistic model of the OpenSuperQ devices. In collaboration with the universities of Chalmers, Saarland, and the Basque Country, FZJ uses this code to simulate quantum circuits for applications in quantum chemistry, optimization, and machine learning. DESY has a close collaboration with CERN Openlab working jointly on quantum computer applications for particle physics experiments.

III. LARGE-SCALE FACILITIES

A core competence of the Helmholtz Association is the planning, setup, and operation of large-scale-facilities. Photons, neutrons, ions, electrons, and high electromagnetic fields are important for **materials research** related to quantum materials, **device development** for quantum computing, and to most **advanced spectroscopy and imaging methods**. Supercomputers are essential for the **simulation of quantum materials and devices** as well as for quantum computer benchmarking. Quantum computing requires a **user infrastructure** and a **hardware infrastructure** in **central facilities**. In quantum communication, large-scale infrastructures enable **airborne and spaceborne experiments**.

STRATEGIC GOALS

The Helmholtz Association is developing large-scale facilities for quantum technologies with the following strategic goals:

Short-term (5 years)

1. To advance **electron microscopy** to map the identity and **position of every atom** in a 100 nm cubed volume of material.
2. To develop and operate **quantum computing** devices and to provide access and support for quantum computer simulators and quantum computers with different degrees of technological maturity.
3. To perform **airborne and spaceborne experiments** in quantum communication.
4. To develop advanced facilities for the **synthesis** of quantum materials including those with capabilities of *in situ* **characterization** at the atomic scale of their structure/defects and quantum properties.
5. To employ **particle beams** to deliberately create defects and **implant single ions** at predefined locations.

Mid-term (10 years)

6. Advance **high-field and neutron scattering capabilities** to probe exotic quantum behavior uniquely accessible by these methods.

Long-term (beyond the 10-year horizon)

7. Develop **laser, synchrotron, and X-ray free-electron laser radiation sources** for the study of electronic states with respect to **all quantum numbers** at ultimate time and length scales.

CURRENT ACTIVITIES

Helmholtz Centers are already actively pursuing each of these strategic goals. The Ernst Ruska-Center for Microscopy and Spectroscopy with Electrons (FZJ) is currently improving the **time resolution** to monitor switching processes in nano-electronic devices under operating conditions **(G1)**. The Karlsruhe Nano Micro Facility (KNMF) is developing new and improved diffraction imaging-based cha-racterization approaches and improving time resolution as well as dose requirements for operando characterization techniques (KIT). **Tunable phase masks** will shape electron wave functions in space and time. The Helmholtz Nano Facility (FZJ) is developing alternative approaches for **high resolution lithography** down to 5 nm and for atomic layer etching processes **(G2)**. The Jülich Supercomputing Centre (FZJ) provides high performance computer capacity for users in science and industry, develops quantum computer simulators, and benchmarks quantum computers. **DLR aircraft and satellites** are involved in quantum communication, e. g., the CUBE project (see **II.2.**) **(G3)**. The integration of guided design, synthesis, and analysis with soft-X-rays are currently being developed with a first focus on energy materials (HZB) **(G4)**. **Ion and electron beams** are used to create optically active spin defects in diamond, silicon, and silicon carbide (HZDR) **(G5)**. The nature of these induced defects can by revealed using the positrons at ELBE (HZDR). High magnetic fields at HLD (HZDR) provide an excellent opportunity to study complex quantum matter under extreme conditions **(G6)**. **Neutrons** give access to their complex **low-energy excitation spectra** of spin textures of quantum materials **(G6)** and are complementary to soft X-rays which, especially at high coherence, are also capable of probing quantum states in thin films and nanometer-scale devices (HZB, DESY, FZJ) **(G7)**. The capabilities of the strong THz sources at ELBE (HZDR) help to explore fundamental low-energy excitations, their relaxation, and decoherence mechanisms in quantum materials on all relevant time and length scales. Pulsed laser sources will enable detailed studies of electronic states by **momentum microscopy** at short time scales (FZJ). Time resolution is also essential to access excited electronic states by **soft X-rays** with element and spin selectivity and address structural dynamics in the same experiment via photoelectron diffraction. At BESSY II, PETRA III, and FLASH, a broad range of soft-X-ray spectroscopy and imaging techniques (among them ARPES/momentum microscopy, REXS, RIXS and XMCD) provide deep insights into the spin, charge, and orbital degrees of freedom of **emergent states** and their **dynamics** in quantum materials and are currently leading to the discovery of a large number of quantum materials with topologically protected states (HZB, DESY, FZJ).

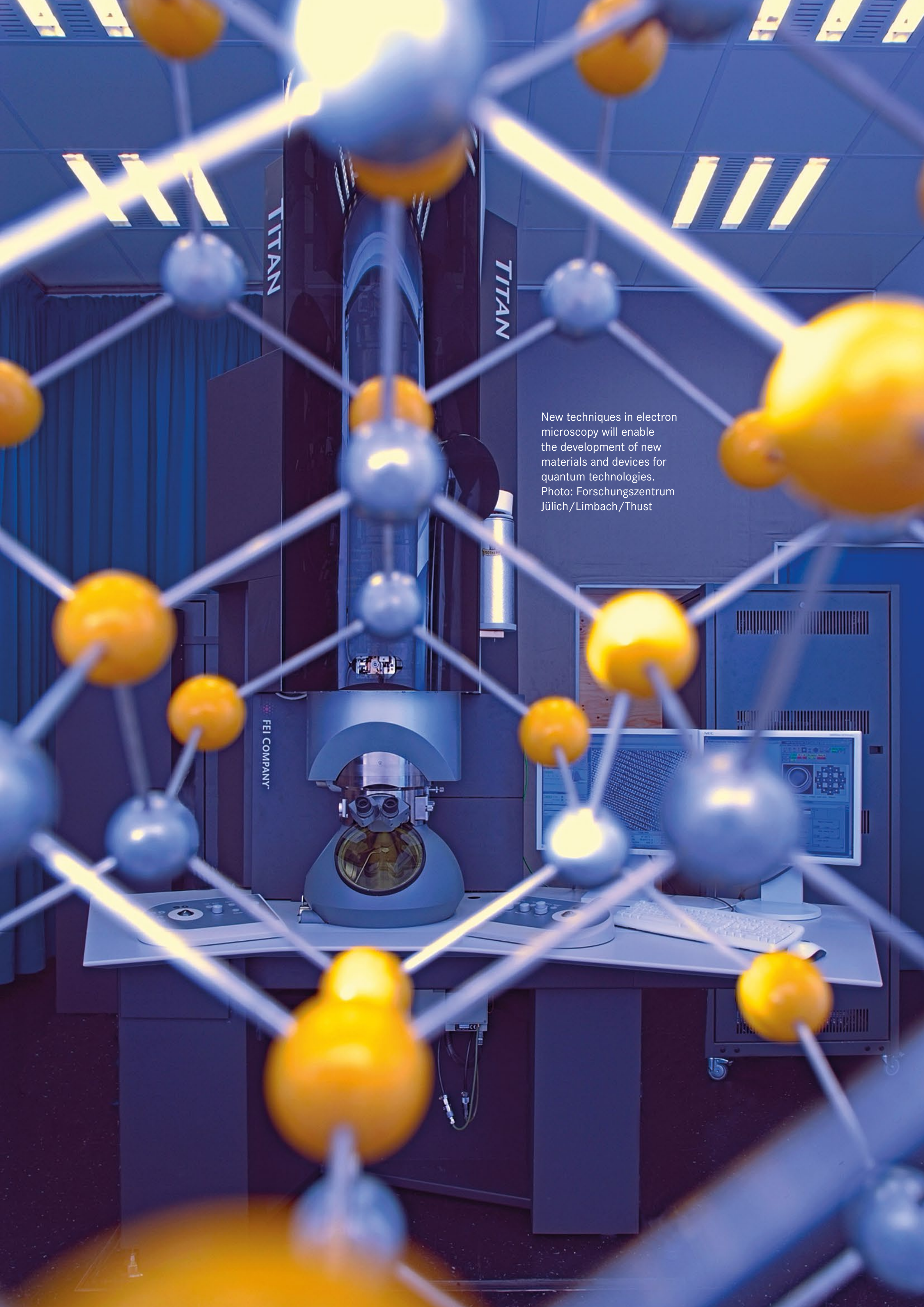
New JUNIQ building to host the different Quantum Computers such as a D-Wave Quantum Annealer of the Jülich UNified Infrastructure for Quantum computing. Photo: Forschungszentrum Jülich

FUTURE ACTIVITIES

Electron microscopy (FZJ, KIT) will be enabled to map the identity and position of every atom in a 100 nm cubed volume of material **(G1)**. Moreover, **time-resolution and coherent quantum control** will be introduced into transmission electron microscopy as well as scanning tunneling and atomic force microscopy (FZJ, HZDR, KIT). The Helmholtz Nano Facility (FZJ) will be associated with the Helmholtz Quantum Center (FZJ) which shall **centralize** and extend the ongoing **quantum computing device research** and enable scientists to span the full spectrum from materials design to quantum computer prototype operation (OpenSuperQ, see **II.1.**) **(G2)**. JUNIQ, the user facility primarily for open innovation (see **II.1., II.5.**), will offer users in science and industry **low-barrier access and support** to various quantum computer simulators and quantum computers. Quantum computers and simulators will be integrated into the **modular HPC environment** of the Jülich Supercomputing Centre. For single-photon quantum communication experiments, key distribution between airplane and ground will be extended to **satellite experiments** (DLR) (see **II.2.**) **(G3)**. It is envisioned that a laboratory demonstrator for high encryption rates will be employed on a LEO satellite (DLR). Furthermore, the DLR Optical Ground Station Oberpfaffenhofen is upgraded to serve for satellite-ground quantum communication experiments. At HZB dedicated synthesis facilities for quantum and topological materials will be integrated with soft-X-ray synchrotron radiation **(G4)**. The Ion Beam Center (HZDR) will provide **single ion implantation** with nm precision for the deterministic creation of spin qubits and single photon emitters **(G5)**. Techniques for grazing incidence neutron scattering with full polarization analysis will be improved in order to **access quantum states at surfaces and interfaces** (FZJ) **(G6)**. Positron annihilation spectroscopy will enable volumetric characterization of electron density distortions and generated extended defects originating from impurity introduction (HZDR). The use of high-pulsed magnetic fields with synchrotron radiation will be developed to element-specifically investigate and fine tune topological properties of quantum materials (HZB, HZDR). Upgrades to the THz sources at HZDR, leading to the new DALI light source, will enable unprecedented control of low-energy degrees of freedom of various states of matter and the ability to precisely prepare exotic quantum states **(G7)**. The extensive range of probing techniques, from near-field microscopy to time-resolved ARPES, that will be implemented, allows comprehensive investigations of the underlying dynamics (HZDR). A new high-coherence diffraction-limited storage ring, BESSY III (HZB), shall enable **nanometer spatially resolved experiments with meV spectral resolution**, e. g., for the control of band bending effects at device interfaces or the study of topologically protected edge states. New pulsed free-electron laser sources and ultrafast detectors (DESY) will push these capabilities into the **femtosecond temporal domain**. The next-generation synchrotron radiation source PETRA IV (DESY) will deliver diffraction-limited, highly brilliant beams of hard X-rays to reveal **structure and function** of quantum materials, enabling us to precisely engineer them for use in future devices for quantum computing and quantum communication.

SYNERGIES

The synergy between infrastructures and their users is common to all of the Helmholtz Association's large-scale facilities as is the cooperation between its centers. The Helmholtz Energy Materials Foundry and Characterization Platform will be extended for quantum materials research. FZJ and KIT will collaborate to advance electron microscopy. The Helmholtz Nano Facility (FZJ) has strong relations with equipment manufacturers Oxford Instruments, Leybold, Raith, and Swiss Litho. The Helmholtz Quantum Center (FZJ) will host the Central Quantum Computing Laboratory (OpenSuperQ), which will bring together university and industry partners (see II.5.). The Jülich Supercomputer Center (FZJ) cooperates with leading hardware vendors, software companies and system integrators, such as IBM, NVIDIA, Intel, Atos, and ParTec. The interest group EQUIPE (FZJ) with about 30 partners from science and industry will support, i.a. the co-design of quantum algorithms and applications within JUNIQ (see II.1.). DLR activities are highly collaborative as well (see II.2.).



New techniques in electron microscopy will enable the development of new materials and devices for quantum technologies. Photo: Forschungszentrum Jülich/Limbach/Thust

IV. MAJOR NATIONAL AND EUROPEAN ACTIVITIES

Research in the field of Quantum Technologies is carried out by a broad range of actors throughout Germany, whose roles can be summarized as follows:

The **Max Planck Society (MPG)** sees its contribution to the national quantum technology strategy above all in the continuation and expansion of **excellent basic research**. This also includes the development of new topics, the focus on the patenting of new ideas, as well as the participation in national and international research networks. The Max Planck Society is willing to contribute to the transfer of fundamental phenomena of the second quantum revolution into application-relevant technologies.

Given the broad spectrum of the Max Planck Society's activities, opportunities for collaboration are essentially given in each of the quantum technology areas addressed at the Helmholtz Association. Already established partnerships involve, for instance, MPI of Quantum Optics/DESY in the field of numerical techniques and simulations, as well as MPI for the Science of Light/DLR in the context of large-scale facilities.

With the establishment of a **nationwide transfer and exploitation infrastructure**, the **Fraunhofer-Gesellschaft (Fraunhofer)** is positioning itself as Europe's largest institution for applied research as an intermediary between cutting-edge research and industry. Through the strategic bundling and networking of twelve Fraunhofer Institutes from the fields of materials science, photonics, and microelectronics as well as communication and information technologies, an interdisciplinary competence network will be established. This addresses economic and socially relevant goals in all sub-areas of quantum technologies.

Partnerships between Helmholtz Centers and Fraunhofer institutes are being established. For instance, DLR is working closely with the Heinrich-Hertz-Institut in the area of quantum receivers and quantum sensors focusing on space activities and quantum repeaters. Cooperation with further Helmholtz Centers are possible in the fields of quantum sensing, quantum communication and quantum computing with super- and semiconductors.

The **Physikalisch-Technische Bundesanstalt (PTB)** combines an internationally competitive, strong technical competence in the field of quantum sensor technology with the official mandate to support German industry in the field of metrology for quantum technology, i.e., through services, technology development, the creation of metrology infrastructure and technology transfer and training. A planned **competence center for quantum technologies** at Physikalisch-Technische Bundesanstalt comprises these four fields of action with a focus on **quantum sensing, metrology, communication, and computing**.

Synergy with the Helmholtz Association already exists through a cooperation FZJ/Physikalisch-Technische Bundesanstalt. Strong cooperation is expected in the context of Quantum Sensors and Metrology.

At the **Leibniz Association**, a number of institutes carry out research and development work in the field of quantum technologies and the enabling technologies required for them. The research focuses on photonic technologies and the development of solid-state quantum circuits in the fields of computing and metamaterials. This research is carried out in close cooperation with local universities and industrial partners but also in international collaborations. At the level of the Leibniz Association, a strategy process has begun, the first result of which is the application for a **Leibniz Science Campus "Photonic Quantum Technologies Berlin (QuantecB)"** within Berlin. The process is currently being intensively promoted with the aim of making quantum technologies a key point of research at the Leibniz Association.

The development of quantum materials as well as quantum computing and quantum simulations are potential fields of cooperation between the Leibniz Association and the Helmholtz Association.

EXCELLENCE STRATEGY OF THE GERMAN FEDERAL AND STATE GOVERNMENTS

Five clusters have been granted that focus on different aspects of quantum technologies:

MATTER AND LIGHT FOR QUANTUM COMPUTING

(ML4Q, Universities of Cologne, Bonn, Aachen, and FZJ) will focus on quantum communication and quantum computing which shall provide blueprints for modular and fault-tolerant quantum information devices as a basis for a quantum internet. The ultimate aim is the formation of a high-grade topological qubit.

QUANTUM FRONTIERS

(Universities of Hannover and Braunschweig) will develop measuring devices to apply in various fields ranging from gravitational-wave astronomy to nano-scale microscopy.

ADVANCED IMAGING OF MATTER

(AIM, University of Hamburg) will focus mainly on quantum physics but will also include contributions from chemistry and structural biology to study quantum simulations, topological order, cold gases, dynamic quantum control, and hybrid states of both molecules and light.

COMPLEXITY AND TOPOLOGY IN QUANTUM MATERIALS

(ct.qmat, Universities of Würzburg and Dresden) will focus on topology in condensed-matter physics and will study strongly correlated electron systems, skyrmions, and topological photonics, to name a few; it aims at realizing devices building on topological phenomena. Control shall be gained over functionalities to apply quantum materials to all modern technologies, be it medical engineering or information processing. HZDR has partnered with this cluster. HZDR ‘s large-scale facilities offer a special framework of possibilities for working on the topics under ct.qmat.

MUNICH CENTER FOR QUANTUM SCIENCE AND TECHNOLOGY

(MCQST, Ludwig-Maximilians-University, MPI of Quantum Optics, and Technical University Munich) will focus on a range of topics (quantum information, computational methods, quantum nano-systems, quantum optics). It aims at building common workshops, culminating in research, to design new methods and systems utilizing quantum technologies.

These five clusters have recently joined forces to pursue nationwide coordination activities involving other relevant centers of excellence in the quantum technology field such as the Center for Integrated Quantum Science and Technology (IQST, Universities of Ulm, Stuttgart, and MPI for Solid State Research), under the umbrella of the so-called “Quantum Alliance.” This will offer additional opportunities for synergies beside those that already exist through the involvement of the Helmholtz Association.

Different regional cluster initiatives have been started, with a focus on the development of quantum computing, complemented by the setup of infrastructures for the exchange of ideas and technology transfer in the field of quantum sciences, and excellent education and training opportunities. The **Munich Quantum Valley** and the **Quantum Valley Lower Saxony** have been established, while the **Center for Quantum Science and Engineering (CQSE) in NRW** has applied for funding in the structural change program for Rheinisches Revier and the second of the three-stage process has already been approved.[4]

At the national level, it is also important to mention the Q.Link.X network, a consortium of 21 universities and research institutes and two industrial partners, funded by BMBF. It investigates the physical systems necessary for the construction of a so-called quantum repeater (QR) line and aims to quantitatively prove the Quantum Repeater advantage for line lengths between 10 and 100 km. Furthermore, the technical connection to the important telecom band for fiber-based communication will be investigated and both quantum information and communication technologies will be prepared. In cooperation with a consulting group from industry, a "Roadmap Scalable Quantum Repeater" will be developed at the end of the project. The involvement of KIT, MPI of Quantum Optics, Fraunhofer's Heinrich-Hertz-Institute for Telecommunications and Leibniz's Institute for Solid State and Materials Research makes Q.Link.X an ideal example of successful cooperation across German research institutions.

Since 2017, HIM has supported the project BrainQSens (one of three QUTEGA pilot projects) with the universities of Ulm and Stuttgart as well as the industrial partners Zeiss and Bosch. The aim of this cooperation is the development of portable quantum sensors that serve as magnetometer-based brain-machine-interface.

The goal of the QUASAR project is to implement and demonstrate a microarchitecture that overcomes previous geometric scaling limits at the quantum level with the semiconductor technology currently available in Germany.

The partners of the GEQCOS collaborative project are pursuing a new approach to generate qubits based on superconducting circuits. The goal is to realize a quantum processor that can be used to demonstrate the functionality of the chosen concept.

In the IQuAn project, HIM and QUANTUM Mainz build a scalable trapped ion co-processor, connected with latency to the MOGON II HPC at HIM. This combination of HPC and quantum co-processor is expected to be an ideal setting for variational eingensolver problems, with used cases in chemical reaction and catalysis calculations. In the HFAK project, a collaboration with Covestro, also funded by BMBF, the Helmholtz Association adapts software to be run on this HPC-QC setup.

The intended main goal of the VERTICONS project is to provide a complete, coherent, documented and tested quantum-control architecture. This includes a flexible real-time control system and the corresponding software design for automated control strategies.

The collaborative project SiUCs is now pursuing a radically new approach to qubits using very strong light-matter coupling. The approach of this ultra-strong coupling will allow qubits to be manipulated much faster, significantly increasing the computational depth of a quantum computer.

Above a certain signal-to-noise ratio, information retrieval using conventional classical microwave signals is no longer possible. QUARATE aims to further improve information retrieval by using quantum microwaves and the resulting new correlation possibilities.

The goal of DAQC project is to combine the flexibility of digital circuits with the robustness of analog computational blocks for the fabrication and continuous operation of a digital-analog quantum computer, as well as the associated calibration and control technology. This quantum computer will be integrated into a high-performance computing environment in which the quantum processor will assume the function of a computing accelerator. Thus, not only quantum supremacy, but a real quantum advantage is to be achieved by means of DAQC already within the next few years.

[4] As of June 2021

EUROPEAN QUANTUM FLAGSHIP

At the European level, the European Commission has started a large FET Flagship Initiative on quantum technologies, planned for ten years with a budget of at least one billion euros. In February 2018 the first call for projects of the EU Quantum Flagship closed. In total, research and innovation projects in the fields of quantum communication, quantum computing, quantum simulation, and quantum sensors/metrology were funded with EUR 110 million, basic quantum technology research with EUR 20 million and a coordination project (CSA) with EUR 2 million.

German applicants and in particular non-university research institutions were very successful. Seven of the 24 projects are coordinated by German partners, more than any other country. These include the coordination project (led by VDI-Technologie Zentrum) and two basic research projects (one coordinated by KIT) as well as three innovation projects.

The basic science project Scalable Rare Earth Ion Quantum Computing Nodes (SQUARE), coordinated by KIT, aims at the development of materials to be used as a resource for quantum coherence which can be controlled by rare earth metal ions. Rare earth metal ions demonstrate a unique potential as extended quantum register and fast quantum gate which can be connected to quantum processors within a quantum network by optical photons at telecommunication wavelengths.

The innovation projects are:

- The **METABOLIQS** project (coordinated by Fraunhofer Institute for Applied Solid State Physics) uses quantum effects in diamond defects for safe, multimodal heart imaging.
- The project **PASQuanS** (coordinated by the MPI of Quantum Optics) aims at the realization of a programmable quantum simulator based on ultracold atoms (with participation of FZJ).
- In the **OpenSuperQ** project (coordinated by Saarland University until January 2021, now by FZJ), an open-access, state-of-the-art quantum computer with superconducting circuits is to be built. FZJ was selected as the host location for this “European quantum computer.”

The Helmholtz Centers also take part in three additional flagship projects:

- **AQTION**, which develops a quantum processor based on ultracold ions (with the participation of HIM),
- **ASTERIQS**, which will provide diamond-based quantum sensors (with the participation of FZJ and HIM) and the
- **QLSI** project (with the participation of FZJ), which aims to demonstrate that silicon spin qubits are a compelling platform for scaling to very large numbers of qubits.

EuroHPC JU pilot on quantum simulator:

The project **HPCQS** (coordinated by FZJ) aims to build a European pilot infrastructure providing tightly coupled systems of Pasqal quantum simulators and supercomputers for quantum HPC hybrid simulations. The infrastructure is being developed in a co-design process together with selected use cases.

QuantERA:

QuantERA is an ERA-NET Co-fund initiative in the field of quantum technologies, in which more than 30 organizations from 26 EU and associated countries build a network with the support of the European Commission to coordinate and support international research projects. By alignment of funding schemes and coordination of both national and international programs, QuantERA is complementing the Quantum Technology Flagship to leverage Europe's competitive advantages. Proposals can be submitted upon designated calls (there is currently a EUR 20M call for projects in the four application domains and in the cross-cutting domain of the Quantum Technology Flagship).

The latest version of the **Horizon Europe Work Programme** contains, under Cluster 4 "Digital, Industry and Space" of Pillar II, new calls for quantum technologies. The total estimated budget is EUR 243.3M with openings in the years 2021 and 2022. This budget includes calls within the Quantum Flagship initiative as well as a call in the global-space infrastructures program titled "Quantum Technologies for Space Gravimetry."

The instruments chosen are:

- Framework Partner Agreements (FPA), long-term cooperation mechanisms between the commission and the beneficiaries of grants, in which they specify the common objectives, the nature of actions planned on a one-off basis or as part of an approved annual work program, and the procedure for awarding specific grants.
- Research and Innovation Actions (RIA), research activities aiming to establish new knowledge and/or to explore the feasibility of a new or improved technology, product, process, service or solution.

Additional funding is envisioned as part of the Digital Europe Work Programme; more specifically for:

- The deployment of a secure European Quantum Communication Infrastructure (EuroQCI), with an estimated budget of EUR 174M using the main instrument of SMEs support grants.
- The deployment of a world-leading federated, secure, and hyper-connected supercomputing, quantum computing, service and data infrastructure within the EUroHPC Joint Undertaking, with an estimated budget and instruments that are still being determined.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V. STRUCTURAL CHALLENGES

Exceptionally high degrees of interaction and cooperation are a prerequisite for accomplishing the very long-term goals of developing quantum technologies. Some of these goals, such as the development of a fully error corrected universal quantum computer, may even be the most complex scientific tasks today. Thus, novel measures need to be developed and implemented for coordinating and supporting research and development from fundamental sciences to innovative engineering. These measures include governance structures for highly complex research and development projects as well as framework conditions for the efficient transfer and outreach to industry. Furthermore, the existing high potential of young scientists and future experts needs to be nurtured and evolved. Preconditions are open funding schemes overcoming barriers between research areas as well as between science and industry. The following paragraphs summarize the main challenges that will need to be addressed to create effective structures that can support the development of quantum technologies. With a focus on quantum computing the expert commission established by chancellor Merkel has proposed a number of measures as part of the "Roadmap Quantencomputing."[5]

[5] https://www.quantentechnologien.de/fileadmin/public/Redaktion/Dokumente/PDF/Publikationen/Roadmap-Quantencomputing-bf-C1.pdf

1. GOVERNANCE

Quantum technologies have only recently emerged as a technology- and application-driven field from fundamental research. In many regards, the transition is far from complete. This situation leads to a coexistence of different cultures and to the need of transferring insights from basic-science to engineering-oriented activities – either by transferring knowledge between minds, or by exchanging knowledgeable minds between sub-fields. Furthermore, some quantum technologies, in particular the realization of quantum computers, represent an effort that goes substantially beyond the scale that some science communities are familiar with. As a result, to obtain major progress in the field it will be necessary to develop governance structures that are effective at formulating and implementing a technology-focused strategy, while maintaining an openness to basic science (which is expected to continue providing highly relevant insights for decades to come).

The Helmholtz Association embraces the needed cultural change, and it is committed to adopting appropriate governance structures. While fully-worked out solutions are still under discussion, first steps have already been made. With Helmholtz Quantum, the association has established a platform for its entire quantum expertise, as is already detailed in the introduction. Furthermore, detailed technical roadmaps for activities addressing the strategic goals in the field of quantum computing and quantum communication are being compiled. As the uncertainty is too high to define a simple linear progression of milestones – it is not clear, for example, which technology will emerge as the best for a quantum computer – these roadmaps are more like a road-network map, including alternative pathways and decision points to work towards the overarching goals laid out in **Section II.1.**. The general idea is that activities are evaluated based on their likelihood to contribute to the overarching goals, with decision points serving to select the approaches being examined. These roadmaps will be updated and maintained by a board of internal and external experts, who will make recommendations to institutes and management boards at the Helmholtz Centers. In keeping with already existing plans for program-oriented funding, the board of experts will also advise on the Helmholtz Association's internal funding instruments, including determining topics for research and resource allocation. but aiming for a higher level of detail and transcend programs and topics. It will also help coordinate activities with other national and international actors in the field.

2. TRANSFER AND INNOVATION POLICY

International competition in the field of quantum technology has become extremely intense in recent years. In countries such as China and the USA, substantial investments have been made from both the public and private sectors. Major industries like Google, IBM, Microsoft, Intel, and Alibaba are aiming for global leadership in quantum technologies.

Technological independence in the area of quantum technologies is of strategic importance to Europe and its member states. In order to successfully use the paradigm shift to quantum computing, quantum communication and quantum sensing as a lever, all European players have to work together in a concerted action. The Helmholtz Association is prepared to play its part, e.g., by helping to develop a prototype of a European quantum computer and to provide access to a broad user community from academia and industry by actively informing small- and medium-sized businesses (SMEs) about the prospects of quantum computing as well as through the other activities laid out in this roadmap document. The Helmholtz Centers are prepared to cooperate with industry either with joint projects and collaborations or with the transfer of intellectual property rights through license contracts and transfer agreements. For example, the DLR Institute of Quantum Technologies in Ulm works with regional partners (Fraunhofer Stuttgart/Freiburg, IQST Ulm/Stuttgart, FZI Karlsruhe, Hahn-Schickard) on establishing a European Digital Innovation Hub on quantum technologies (EDIH-QT) to support SMEs to evaluate, access, and adopt quantum technologies. Other transfer channels include the active support of **establishing high-tech spin-offs** or by **initiation of validation projects** that bridge the gap between research results and commercial applications (Helmholtz Validation Fund). As an appropriate measure for the future development of quantum technology, the **setup of Open Innovation Labs** is envisioned in order to get corporate partners involved in joint development projects with a long-term perspective. In fact, European and especially German companies are already investigating quantum computing use-cases and are expected to be among the early commercial users of quantum computers. For this, we consider the **establishment of a user community** and the **hosting of an infrastructure for open access and dedicated user-support** (see **sect. II.i**) of particular importance. As a prerequisite for a prospective future development, an **open-research infrastructure will be provided**, which will help bring in and interact with outside know-how and partners in a prompt and flexible way, e.g., in the Helmholtz Quantum Center (HQC), which links basic research with device and systems fabrication, the co-design of hardware and software, as well as testing and user facilities (see **sect. II.i**).

Although there are only a few pure computing companies based in Europe, our region can profit economically in a significant way: The technology for quantum computing is in many aspects fundamentally different from classical computing, which provides a unique chance for Europe to re-enter the IT sector. For the next phase, however, **a European industry consortium, a "Quantum Airbus," is desirable.** Only if Europe undertakes activities along the complete value chain from research and development to production will it be possible to keep and further develop the know-how on all aspects of quantum technologies in Europe in the long run. It is not yet too late to expand capacities in this area in Europe, but investments, from both the public sector and industry, must start now.

From this perspective, the launch of the **European Quantum Industry Consortium (QuIC)** on 14 of April 2021, which includes more than 100 members from all sectors of the quantum technologies industry in Europe, with more expected to join in the coming months, is particularly timely and important. FZJ played a crucial role in QuIC's foundational phase, both as an initiator (through the Quantum Community Network) as well as a financial contributor (through applying with the regional ministry of economic affairs for funding).

3. DISRUPTIVE FUNDING INSTRUMENTS

Disruptive research with the potential to initiate a complete restructuring of the economic environment or the research landscape, requires flexible and innovative measures to support such things as: collaboration in research specifically and in the industry in general; the generation of spin-offs from the centers; and the support of start-ups.

This applies in particular to cooperation in which small and medium-sized enterprises and start-ups are involved. The Helmholtz Association's overall strategy offers a strategic, high-level structure along with a wide-range of existing instruments. As such, it either makes use of those structures and instruments that are already included within the framework conditions for national project funding, or it complements them creatively.

There are challenges which are decisive for the success of disruptive research topics:

- Where existing funding instruments prove to be insufficient or are no longer applicable, more frequent use should be made of the possibility of project-funding institutions to develop tailor-made programs in dialogue with the respective ministries and science.
- Particular importance should be paid to ensuring that not only scientific staff from research institutions but also their management is involved in this exchange of novel ideas for disruptive funding schemes. This should be done at an early stage in accordance with requirements of the relevant funding guidelines.
- It would be particularly important for the scope of shaping disruptive research topics, such as quantum technology, to adapt national research funding more closely to EU criteria with regard to the accepted risk factor and the financial possibilities on the way to the market.
- The last step of a development into the market is a special obstacle, because it has to be carried out as far as possible without financial support. Although there are, for example, bridge programs for start-ups, more capital-intensive follow-up steps are still difficult in many respects. The aim should, therefore, be to make it easier for start-ups and small and medium-sized enterprises to enter the market aided by the highest funds possible (including fully financed projects) and other sources of additional support.
- It would also make life easier for science if the entire value chain, from basic research to the final product, were to be represented on the market by an integrated funding program.
- Funding by different ministries, depending on the level of technological readiness, is a foreseeable problem, especially for a disruptive topic such as quantum technology.

An intensive and early exchange between funding bodies, project-funding organizations and potential funding recipients – within the framework of conferences or workshops, for instance – should be aimed at in order to make optimal use of the diverse funding opportunities and to provide the sustainably needed to support the innovation process.

4. BRAIN GAIN

Quantum technologies of tomorrow need quantum engineers and developers that are already educated and trained. The realization of these strategic goals is only possible with local and national partnerships between educational institutions, research centers, and high-tech companies. The main goals are to create a structure for education and innovation as well as to raise interest in quantum research and to contribute to a more modern image of quantum science in society.

- The Helmholtz Association, as a whole, aims at building a bridge between fundamental quantum mechanics, as it is being taught in universities, and applied quantum mechanics, as required for practical applications. The curriculum shall be developed based on experimental observations rather than on historic development or formal structures. The Helmholtz **educational quantum laboratories** should offer space for the experiments demonstrating practical applications such as, but not limited to, quantum cryptography, quantum algorithms, and quantum sensing.

- These educational laboratories should be connected with a **Helmholtz graduate school** for quantum technology, featuring summer schools, laboratory courses and tutorial video talks. The Helmholtz graduate school events shall rotate between the relevant centers and involve partner universities. It can be strengthened with an international visiting program for graduate students. A first endeavor in this direction is planned at FZJ.

- To strengthen the position of the Helmholtz Association in the field of quantum technology, **researchers with evident high potential** in Germany and from abroad, who are in the early and middle stages of their careers, will be **pre-selected through dedicated calls.** The goal is to attract young scientists to the field, to grow community spirit, and to win in the battle of brain gain versus brain drain. To attract such excellent scientists, they should receive competitive offers. The model of jointly appointing professors between the Helmholtz Centers and the universities fully supports the building of quantum networking and the implementation of the aforementioned educational concept.

5. STRUCTURAL EMBEDDING IN HELMHOLTZ

The research presented here builds on the synergy between the contributions of various Helmholtz Centers and their scientific cooperation on the topics irrespective of the formal assignment to Helmholtz research areas or programs. In particular, the Helmholtz Centers DLR, DESY, FZJ, HZB, HZDR, HIM, and KIT contribute with their work from basic research to the development of specific quantum technologies.

A large part of the work belongs to the research area “Information” and, for specific applications in particular, within the research area “Aeronautics, Space and Transport.” In addition, valuable contributions and strong support come from the research area “Matter” with its significant number of large-scale research facilities. Furthermore, other research areas are connected both directly and indirectly as users of the new technologies.

Currently, nearly 500 people directly contribute with their work to the research on quantum technologies at the Helmholtz Association. As described above, the centers have different topical focuses and thus contribute with different divisions to the 6 main fields. The activities of the different centers are very diverse and range from hardware development to investigations of new materials to pure applications in relevant physical and chemical models.

With its commitment, expertise, and infrastructure, the Helmholtz Association is ideally positioned to enable our country to play a leading role in this emerging strategic field of science and technology, within Europe and worldwide.

HELMHOLTZ QUANTUM

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Layout
Helmholtz/Stephanie Lochmüller

Credits
Cover: Shutterstock.com/Yurchanka Siarhei; S. 8–9, 12–13, 42–43, 48–49, 56–57: Pixabay.com/Tomislav Jakupec

Paper
Circle silk Premium White

Status
August 2021

carbon neutral print production | through CO_2 offsetting | www.natureoffice.com/DE-140-856628

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