HELMHOLTZ
RESEARCH FOR
GRAND CHALLENGES

QUANTUM TECHNOLOGIES IN THE HELMHOLTZ ASSOCIATION

Background and Strategy

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Preamble

This paper presents the long-term strategic goals of the Helmholtz Association 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 outlines 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 current ongoing investments in infrastructures and research groups, as well as proposals for necessary additional funding.

The research presented here builds on the synergy between the contributions of various Helmholtz Centres and their scientific cooperation on the topics irrespective of the formal assignment to Helmholtz research areas or programmes. In particular, the Helmholtz Centres 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 concrete 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.

From the multitude of existing and planned activities it becomes clear that substantial efforts will be necessary to remain at the forefront of technological development. Particularly in view of the very large investments made abroad in this area, both by governments and by private global players, central priorities should quickly and flexibly be strengthened and necessary infrastructures be promoted.

Thanks to its cross-cutting engagement, expertise and infrastructure throughout several centres and across different research areas, the Helmholtz Association is ideally positioned to enable our country to play a leading role in this emerging strategic field of science and technology at European and worldwide level.

Table of Contents

I. Mission

The Helmholtz Association’s mission is to contribute to solving great and pressing social, scientific, and economic issues through strategic, programmatic, cutting-edge research, including the operation of large-scale facilities. The development and comprehensive use of Quantum Technology (QT) is one of the most ambitious technological goals of today's science, with expected dramatic impact on the whole society and economy. Therefore, the goal of the Helmholtz Association is to be a national and European driver and 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 on all levels, ranging from fundamental science to system engineering and applications.

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

The Helmholtz Association has identified **five main fields of** Quantum Technologies in which the Helmholtz Centers are active:

- Quantum Computing
- Quantum Communication
- Quantum Sensing
- Quantum Materials and Fundamental Science
- Simulation and Numerical Techniques

These 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 III). Furthermore, we strongly interact with a wide range of researchers and potential users of Quantum Technologies to identify early adopters, make them fit for e.g. applications of quantum computers or novel sensors and learn from their needs to develop specific use cases together. 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.iv.), the Helmholtz Association develops tailor-made materials and designs quantum systems for Quantum Technology devices, e.g., qubits 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 functionalities for applications in novel Quantum Technology devices. Regarding Quantum Technology devices, the Helmholtz Association focuses in particular on the realization of **quantum computer** prototypes (Section II.i.), 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, developing – at the same time – relevant **simulation methods**, both at classical and quantum level (Section II.v.). Quantum computation development is closely integrated 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, high-energy physics, 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.ii.), in which terrestrial and 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 links to the development of **postquantum cryptography**.

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

It is typical for the Helmholtz Association to represent a large number of scientists from a broad multi- and interdisciplinary background, who will be early adopters of the scientific and technological developments on all stages of technological readiness. Therefore, the Helmholtz Association also provides early **prototype applications** of novel technologies and studies their applications in relevant scientific, societal and industrial **use cases** (highlighted in the relevant Sections II).

Finally, the Helmholtz Association conducts research with and develops new **large-scale facilities** (Section III). The use of high-end large-scale facilities available in the Helmholtz Centers will be a particularly strong asset, both for the fundamental research to be conducted, as well as for the development of devices and of use cases via user facilities 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]. Its five main fields of research and development of quantum systems and

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[1] https://qt.eu/

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

devices contribute directly to the focal points of these initiatives (Computation, Simulation, Communication, Sensing and Basic Science). In particular, researchers from Helmholtz Centers participate or even lead several Quantum Flagship Projects.

Research in 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 improvement of devices and together with the promotion of early adopter communities. We are convinced that this aspect will be crucial not only for the development and the application of quantum computing, but also for what concerns quantum simulations, communication and sensing.

Within its program-oriented research, the Helmholtz Association addresses Quantum Technology in different research fields with different foci. We cooperate across centers and research fields to promote 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), and the Deutsches Elektronen Synchrotron (DESY) and the Helmholtz Zentrum für Schwerionenforschung with its two satellite stations Helmholtz-Institut Jena (HIJ) und Helmholtz-Institut Mainz (HIM).

In accordance with the Helmholtz mission, research in the Helmholtz Centers is mainly program-oriented, nevertheless spanning a broad range from fundamental science to technology development, prototypes and applications. Depending on the different scientific foci of the Helmholtz Centers, the distribution of research topics is slightly different, which can partially be attributed to 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 at the Max Planck Society with the industry- and application-driven approach of the Fraunhofer Society. The Helmholtz Association cooperates closely with many universities and provides access and user support as a research partner to large-scale facilities, with a strong focus on method development to provide state-of-the-art research facilities.

II. Quantum Systems and Devices

i. Computing

Quantum computing promises unprecedented capabilities for certain computational tasks such as prime factorization and decryption. In addition, it might have a disruptive impact on fields that range from quantum simulations in chemistry, condensed matter and high-energy physics, to optimization problems and machine learning. Among the various quantum technologies, it probably represents the one with the longest time line, but also the one with the largest economic potential and impact on society. Despite major progresses in the field, quantum computing is today still in its infancy, resembling the status of classical computing in the 1950s. From 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 extremely few fully worded-out examples. The international competition in the field is extremely intense, and in countries such as China, USA and Canada it is propelled by substantial investments by the public and the private sectors. So far, Europe is at the rear of this race, but it has the competencies, the infrastructures and the human potential to quickly win positions in the competition.

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 this scope, it has formulated the following strategic goals:

Short-term (5 years)

- G1. To develop **approaches for optically interlinking qubits**, to realize networked multi-qubit modules.
- G2. To develop **prototype applications and use cases** that exploit quantum-advantage in real-world applications.
- G3. To create a **Quantum Computing User Community** to support the early adoption of quantum computing and annealing technologies for scientific and industry-oriented research.

Mid-term (10 years)

- G4. To systematically advance superconducting and semiconductor qubits to realize **small-scale demonstrators with tens of qubits** for quantum computing and simulation.
- G5. To pursue **research on innovative qubit platforms** with a potential for disruptively superior performance.

Long-term (beyond the 10-year horizon)

G6. To develop **highly scalable hardware and software tools** to control and calibrate thousands or even millions of qubits, with a particular focus on cryoelectronics.

G7. Scalable ion-based quantum computers including full application spectrum.

The given time scales target the achievement of significant results and do not imply the termination of actions connected to the goal.

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 and in the theory of quantum information, and access to frontier supercomputing facilities.

FZJ and KIT are carrying on a consistent effort on fundamental research 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. Experimental activities are complemented by theoretical ones aimed at a better understanding of the physical theory of qubits and at 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 which can be used through a web-interface for different applications by external partners. This research work is also supported by highly-parallel simulations on supercomputers of the highest performance class.

Another important aspect is the **development of the classical control tools (hardware and software)** that are needed to operate multi-qubit devices (KIT, FZJ, HIM). 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 cryoelectronics** tailored for this scope (FZJ) and working with extremely low noise (HIM). 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 a system context, thus allowing for milestone contributions to the field.

The Helmholtz Association is also sustaining **fundamental research on innovative qubit platforms** (see also Section II.iv). Examples are Majorana qubits based on topological insulators (FZJ), phase-slip qubits, high kinetic-inductance circuits (KIT) and molecular qubits (KIT). The rationale behind this broad approach is that up to now there is no 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, up to now 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 also 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), 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.ii), but target a much higher device complexity.

Research activities on the hardware of a quantum computer are paralleled by **research on prototype applications and uses cases** of quantum computing and quantum annealing (DLR, FZJ, DESY). Here the activities range from the search of application-driven quantum algorithms, to the investigation of multi-qubit architectures tailored to specific problems (e.g., the accurate simulation of molecular orbitals and of relevant models in condensed matter and high-energy physics) and of the corresponding quantum algorithms. Particular attention is dedicated to near-term quantum processor, i.e. devices with a few dozen of qubits, which are expected to unlock the first useful application of quantum advantage for science and industry.

Finally, the Helmholtz Association is strongly supporting the creation of a **Quantum Computing User Community** formed by scientists close to scientific computing and pursuing a pragmatic, heuristic approach to applied quantum computing. One main 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.

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 respect to the commercial D-wave machine, where the qubits exhibit only a low degree of coherence.

Another major activity is the foundation of JUNIQ - Jülich UNified Infrastructure for Quantum Computing (FZJ), which will provide remote access and user-support to commercial multi-qubit devices for quantum computing (e.g. IBM, Google, Rigetti Computing) as well as to a home-hosted D-Wave quantum annealer. The scope of JUNIQ, which will represent an infrastructure with 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.

Activities on quantum computing at FZJ will be further strengthened by the planned Helmholtz Quantum Center (HQC), which will bring most of the local activities under one roof and provide additional research infrastructure. It is planned to found a new Institute of Quantum Computing at FZJ which will concentrate on further development of supra-conducting or semiconductor qubits. Additionally, it is intended to establish a new Institute for Quantum Materials and Technology at KIT.

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 for what concern the development of the quantum hardware (with contributions from HZDR and HIM), and between FZJ, DLR, DESY, KIT, UFZ and HZB for what concerns the development of prototype applications and use cases. FZJ, KIT and RWTH Aachen University collaborate in the Initiative and Networking Fund of the Helmholtz Association 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 Leibnitz 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, and *An Open Superconducting Quantum Computer (OpenSuperQ*), as well as of the Cluster of Excellence *Matter and Light for Quantum Computing (ML4Q),* which has been successfully proposed by the Universities of Aachen, Bonn, Cologne and FZJ as part of the Excellence Strategy of the federal and state governments. The **EQUIPE initiative counts already 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).

ii. Communication

One of the central novel aspects in quantum communication is the **security of data transfer**, which will be enabled in a magnitude never known before. Quantum communication exploits the laws of quantum mechanics to build key distribution protocols for secure data transmission. Quantum key distribution is therefore not based on mathematical assumptions but on physical laws. The quantum states, however, are very fragile, and precise measurement is tricky, so that a transmission (within single chips or over longer distances) poses considerable technical challenges.

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 scope of allowing **worldwide quantum cryptographic connections** in the future. Our vision is the development of a **quantum internet** (quantum communication network) in which quantum repeater -powered terrestrial and space-based systems are connected, enabling unmatched known security. 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 our activities aim at **building blocks for quantum communication in general**, global scale **quantum key distribution**, **quantum repeater-based large-scale quantum networks,** distributed **quantum computing and quantum-resistant cryptography**.

Therefore, our specific goals are:

Short-term (5 years):

G1. Development of manageable photon sources and photonic integration

Mid-term (10 years):

G2. Develop quantum repeaters based on small quantum processes with optical interfaces
G3. Enable secure communication in the era of quantum computers using post quantum cryptography methods

Long-term (beyond the 10-year horizon):

G4. Enable secure communication on a global basis

Current Activities

G1 focuses on the **development of manageable photon sources and photonic integrations**, whereby we (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. Additionally we are looking into **enhancing and controlling light-matter interaction with optical microcavity compatible device architectures** (using graphene/carbon nanotube hybrids or SiC/AlN heterosctructures). We also work on **single quantum dots in III-V nanowires**, which have been suggested as on-demand sources of single photons or polarization-entangled photon pairs.

G2 – 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. We also work on the **realization of multi-qubit registers based on rare-earth-ion-doped crystals coupled to optical microcavities** as well as 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 centres 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 mediated by a single photon and storing quantum information over long time in nuclear spins.

G3 - the **security of current cryptosystems is compromised by attacks performed on quantum computers**. In order to ensure secure communication in the age of quantum computers, we (DLR) work on **quantum-resistant public-key cryptosystems** that are resilient against 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.

G4 - (Satellite-based) Global **Quantum Key Distribution** is focusing on the **development of a quantum communication system**. On one hand, the encryption methods currently in use are under concrete 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 is also 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**. We focus therefore on quantum communications with **respect to design, development and experimental demonstration of global satellite based 24/7 quantum key distribution systems**. Major challenges to tackle are the **very high link efficiency** that is needed for **useful key rates**, **effective filtering techniques** and **resilient protocols for daytime quantum communication, global network designs and protocols with and without trusted nodes**.

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

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 Sensors”** and the **“Galileo Competence Center”** it is therefore planned next to other things to focus on quantum communication and quantum cryptography and the associated information technologies at quantum level.

Prototype Applications and Use Cases

As a part of G1, we continue to improve technology of devices 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 (G2) 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 (G3 and G4).

Synergies

The described activities bring together the different expertise of the involved Helmholtz centres (DLR, KIT, HZDR, HIM and FZJ) – focusing on a common future vision “a quantum communication network”. DLR has intensive cooperation’s with the Ludwig-Maximilians-University Munich and the Max-Planck-Gesellschaft (MPI for the Science of Light). With the University of Canberra a collaboration for singlet states and the temporarily storage of a photon on the satellite was initiated.

In 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, THALES.

FZJ collaborates closely with partners at University of Bonn and Univ. of Cologne within cluster of excellence ML4Q and also with University of Bochum, Technical University of Dortmund and SNRC Paris and others.

HZDR cooperates with University of Vienna, National Institutes for Quantum and Radiological Science and Technology (Japan) and Stanford University on cavity-enhanced spin photon interfaces. HZDR also collaborates closely with Ioffe institute and 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.

iii. Sensing

Quantum sensors are a key application 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 excitingly new options based on a range of transformative approaches and initiates a revolution in sensing technologies of tomorrow and day after tomorrow. The activities of the Helmholtz Association stretch from space-bound and terrestrial applications in navigation and geodesy to autonomous mobility, communication and life science. They are combined in two main strategical directions: (1.) quantum sensing in space (DLR and HZDR) and (2.) integrated quantum sensors (HZDR, KIT, HIM, FZJ).

Strategic Goals

Short-term (5 years)

G1. **Self-calibrated solid-state magnetometry** for precise measurements of planetary magnetic fields in space missions as well as search of oil, metals and minerals.

G2. Miniature solid-state gyroscopes for autonomous driving

G3. **Lab-on-chip-technologies** for precise measurement of time and acceleration as well as **chip-scale molecular clocks** for highly stable and compact frequency/time references, which operate under space environment conditions.

Mid-term (10 years)

G4. **Compact quantum-cascade lasers** for the ultrasensitive heterodyne detection of atomic oxygen in space missions and trace gases in atmospheric research.

G5. A **compact room-temperature solid-state maser** with ultra-high quantum-limited sensitivity for deep-space communication, radio-astronomy and medical imaging.

G6. **Ultra-sensitive kinetic inductance detectors** of single photons in the spectral range from terahertz to X-rays.

G7. **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.

G8. **On-chip spectrometers with single-photon detection capability** for sensing applications in Earth observation, planetary research and astronomy.

Long-term (beyond the 10-year horizon)

G9. **Hybrid spin-mechanical system** with **zepto-scale gram sensing** to detect individual macromolecules with a resolution approaching the unified atomic mass unit.

G10. **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.

G11. **Prototype quantum imaging system** (UV to X-rays) with a broad range of applications ranging from solid-state physics up to biological and medical imaging.

G12. Dark matter detection by quantum-sensing optimized experiments.

Current Activities

DLR develops quantum optical instruments of the first and second generation, such as clocks and frequency references to measure distance and angle in space with ultrahigh precision. DLR also develops different types of accelerometer systems based on quantum properties of cold atoms and Bose-Einstein condensates. Because of spatial limitation on satellites, the goal is to achieve high degree of miniaturization using lab-on-the-chip technologies. These systems are designed for Earth observation and science missions, e.g., determination of gravity, time and orientation. HZDR develop 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 provide 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

Within the new DLR institutes “Institute for Satellite Geodesy and Inertial Sensors” and “Quantum technologies”, it is planned to focus on the development of **compact quantum instruments for space-based applications**. 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 mediates the communication between the quantum and classical worlds. KIT plans to implement arrays of **frequency multiplexed superconducting sensors,** i.e., with the ability to read out many sensors simultaneously, and 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 to monitor biomagnetic signals outside the laboratory scope and to provide industry-oriented miniaturized gyroscopes.

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 will foster research on **quantum metrology and optical clocks** for more precise and stable time signals. This will result in Technology Demonstration Missions in strong 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 test-beds 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 Universities of Hannover, Berlin and Ulm, DLR works on cold atom interferometry and Bose-Einstein condensates. HZDR cooperates with Ioffe Institute in Russia, University of Würzburg and National Institutes for Quantum and Radiological Science and Technology in Japan on the development of room-temperature masers and self-calibrated quantum magnetometers. HIM works together with PTB Berlin on sensors for biomagnetic experiments and 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.

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.

iv. Quantum Materials and Fundamental Science

At the current stage, technologies for creating and manipulating qubits for quantum computers are reaching maturity, but the step moving from the current qubit demonstrators to a full-blown quantum computer still remains a gigantic one. One of the challenges is that it is up to now unclear which qubit platform is most suitable for building a quantum computer. There is still room for drastic improvements, either incremental or disruptive, enabled by **new concepts** emerging from research on quantum phenomena in materials and systems that are characterized by **topology, entanglement** and **coherent control,** ultimately down to the atomic scale. These concepts also bear potential for quantum sensing**,** as well as quantum communication via **matter-light interaction**.

Strategic Goals

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):

G1. We want to explore the **fundamentals of quantum systems at the atomic and molecular scale** and engineer their quantum mechanical properties with atomic precision.
G2. We want to develop **innovative qubit concepts and material platforms**, which go beyond current solid-state qubit systems.
G3. We want to study the **dynamics of novel quantum states** arising at interfaces, in exotic materials, or in highly excited systems.
G4. We want to identify, understand, and overcome the **relevant decoherence mechanisms** in quantum systems to improve the performance of qubits and the quality of quantum sensors.
G5. We want to study the **coupling between solid state qubits and photons** for the coherent exchange of quantum information between matter and light.

Current Activities

The Helmholtz centers currently develop tailor-made designed quantum systems consisting of novel materials, complex interfaces and hybrid structures. These systems are based on paradigms involving spin 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, magnetism and other exotic orders. In the future we will build on this expertise in order to develop a suitable material base for Quantum Technology.

Future Activities

The first goal (**G1**) is crafting designed quantum systems at 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 freely explored and utilized. We will exploit atomic and molecular manipulation, chemical design and synthesis, and the creation of embedded single-atom scale defects as implementation 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 adsorbed on surfaces with atomic manipulation by scanning probe microscopes (FZJ). 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, compatibility with wafer-scale microelectronic fabrication technology (HZDR). 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 currently available, the second goal (**G2**) 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, we plan to investigate unconventional superconductors that can host a variety of exotic electronic states such as the long-sought pair-density-wave (KIT, HZB). We also will explore superinductors, engineered from materials close to superconductor-insulator transitions (KIT). We will study quantum magnets which support long-lived qubits since they host, e.g., quantum spin liquids that are defined by topological order rather than by conventional symmetry breaking (HZB, FZJ). Furthermore, we will explore materials and hybrid structures hosting Majorana states. In particular, we plan 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 must be demonstrated (FZJ, KIT). Another avenue are emergent quantum states in materials that combine intrinsic topology and magnetism, for instance, magnetic Dirac and Weyl semimetals (FZJ). Finally, we 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), 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 system (goal **G3**). In addition, it is intriguing to bring localized solitonic collective states, such as nano-skyrmions, to the quantum level. An idea 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). We will also study externally driven metastable and non-equilibrium states in quantum materials; this will help to understand the interplay of microscopic mechanisms and time scales in quantum materials. On this basis excitation protocols will be developed to establish and control emergent quantum order. The experiments require ultra-short light pulses over a broad wavelength range (FZJ). Furthermore, we will develop materials and interfaces for qubits based on the quantum anomalous Hall effect in magnetic topological insulators with the intention to raise the quantum anomalous Hall effect to room temperature (HZB). One-way quantum computing is another intriguing concept in the context of dynamics of quantum systems.

Therefore, we will explore solid-state materials containing Mössbauer nuclei with the goal of establishing qubits and logical gates. Specifically, we 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 (**G4**) 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 the quantum systems of the preceding goals (G1-G3) it is important to find ways to improve the coherence time. To this end, we will strive to identify the dominant sources of noise and design novel materials and systems which avoid these decoherence sources. Alternatively, smarter qubits and better manipulation protocols may be targeted (KIT, FZJ, HZB, HZDR, DESY).

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 **G5**). 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 wavelength 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 quantum materials will be incorporated in the planned **Helmholtz Quantum Center (HQC).** Similarly, the activities of KIT will be incorporated in the planned **Institute of Quantum Materials and Technology (IQMT)**. The use of high-end large-scale facilities that are available in the centers will be a particularly strong asset. The new Cluster of Excellence "**Matter and Light for Quantum Computing (ML4Q)**" in which the Universities of Köln, Bonn and Aachen and the FZJ collaborate will leverage further strong synergies. Finally, all Helmholtz Centers are involved in external collaborations with leading institutions in the field.

v. Simulation and Numerical Techniques

Simulations and numerical techniques are at the heart of the optimal and efficient usage of future quantum 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. This will **open completely new avenues** in science and allow to solve problems that **are not attainable today.**

Strategic Goals

In Quantum Technology, the Helmholtz Association plans to strengthen simulation as the third pillar next to theory and experiment. For this purpose, it has formulated the following strategic goals:

Short-term (5 years)

G1. To develop algorithms, methods and tools for disruptive computing devices to solve very hard and hitherto intractable computational problems in science and industry.
G2. To employ High Performance Computing-simulators to acquire essential knowledge of the operation of quantum computers and quantum annealers

Long-term (beyond the 10-year horizon)

G3. To develop, in a common effort of all Helmholtz Centers, a broadly useable software package which will help a wide community of researchers from various disciplines for performing efficient quantum computations.

Current Activities

We are developing the **quantum simulations** of interacting quantum systems in condensed matter and many body (FZJ) as well as high-energy physics (DESY), to study crucial properties of the most relevant models in these fields (G1). Equally important are the simulations of quantum materials (FZJ, KIT). In particular, our research portfolio includes simulations of critical phenomena in arrays of qubits; of strongly-correlated phenomena; of quantum dynamics in fermionic systems; of quantum many body systems; of models of high energy physics; as well as analog quantum simulations and quantum annealing. Further, we are developing analytical and numerical methods based on matrix-product and tensor-network states combined with machine learning algorithms, as well as quantum-circuit and classical optimization techniques (DESY, DLR, FZJ). We explore the power of Majorana qubits (FZJ, KIT) and cluster states (DESY), the latter as an alternative exploring the potential of one-way computing. We also develop means and techniques to diagnose two-level systems in qubits and to deduce recipes to mitigate them in future quantum circuits.

Future Activities

In order to overcome hardware restrictions of the next generation quantum devices, we will develop optimal ways to compile general quantum circuits with the goal to automate this process for a wide range of applications and hardware layouts. To achieve the strategic goals outlined above, we will design scalable hybrid classical-quantum simulation technologies which are robust against errors; we will support device and architecture design and platform evaluation with large-scale quantum computing in mind and we will generate high-quality control mechanisms of many-particle dynamics. In addition, we will employ advanced techniques of machine learning to gain a better design of quantum information devices and to expose the relation between quantum computing and artificial intelligence. We will 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 and solution algorithms will be developed on a great variety of quantum devices from which a large number of researchers within the Helmholtz Association and beyond will profit (DESY, DLR, FZJ, KIT, UFZ, HIM, HZB). This is considered crucial for all simulation and data-related activities in the Helmholtz Association and far beyond. These developments, combined with machine-learning algorithms, have the great potential beyond the 10-year horizon to lead to the **first application in quantum computing for real world problems** such as high temperature superconductivity or the standard model of high energy physics with a direct impact on society.

Prototype Applications and Use Cases

There are various **use cases** in the six Helmholtz Research Fields and through collaboration with universities, other research centres and industry in many other fields like finances, economics, and sociology. 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, DLR and FZJ with quantum computations in chemistry, condensed matter and high energy physics. DLR and Helmholtz Institute Ulm are working together on exploring **quantum simulations for battery research**.

Externally, there is a close collaboration with the Institute for quantum computing in Waterloo. There is also a long-standing collaboration for employing 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. Within OpenSuperQ FZJ develops simulation code for the simulation of a realistic model of the OpenSuperQ. 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. FZJ and DESY with Canadian partners have signed a MoU to consider the development of a Canadian and German cooperation **networks for quantum computing applications**.

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** of quantum materials as well as **device development** for quantum computing through 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)

G1. To advance **electron microscopy** to map the identity and **position of every atom** in a 100 nm cubed volume of material

G2. 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

G3. To perform **airborne and space borne experiments** in quantum communication

Mid-term (10 years)

G4. To employ **particle beams** to deliberately create defects and **implant single ions** at predefined locations

Long-term (beyond the 10-year horizon)

G5. To develop **neutron, laser, high-field, and synchrotron 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. With respect to G4, **electron beams** are used to create optically active spin defects in diamond and silicon carbide (HZDR). The Ernst Ruska-Center for Microscopy and Spectroscopy with Electrons (FZJ) is currently improving the **time resolution** to monitor switching processes in nanoelectronic devices under operating conditions (G1). The Karlsruhe Nano Micro Facility (KNMF) is developing new and improved diffraction imaging-based characterization approaches and improving time resolution as well as dose requirements for operando characterization techniques (KIT) (G1). **Tunable phase masks** will shape electron wave functions in space and time. 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**. The currently ongoing upgrade of BESSY II to the BESSY VSR variable pulse-length storage ring (HZB) will increase the time resolution by an order of magnitude (G5). Soft-x-rays probe spin textures of quantum materials and are complementary to **neutrons** which also give access to their complex **low-energy excitation spectra** (HZB, FZJ). The Helmholtz Nanoelectronic 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 (G2). **Aircraft and satellites** of DLR are involved in quantum communication, e. g., the CUBE project (see II.ii) (G3).

Future Activities

The Ion Beam Center (HZDR) will provide **precise positioning of single ions** (P-31, Si-29, C-13) with nm resolution for impurity-based quantum processors with nuclear spins (G4). 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 microscopy (FZJ). A new 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 (G5). 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 (G5), enabling us to precisely engineer them for use in future devices for quantum computing and quantum communication. Techniques for grazing incidence neutron scattering with full polarization analysis will be improved in order to **access quantum states at surfaces and interfaces** (FZJ). 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.i) (G2). JUNIQ, the user facility primarily for open innovation (see II.i, II.v), will offer users in science and industry **low-barrier access and support** to various quantum computer simulators and quantum computers (G2). Quantum computers and simulators will be integrated into the **modular HPC environment** of the Jülich Supercomputing Centre (G2). For single-photon quantum communication experiments, key distribution between airplane and ground will be extended to **satellite experiments** (DLR) (see II.ii). It is envisioned that a laboratory demonstrator for high encryption rates will be employed on board of the International Space Station (DLR) (G3).

Synergies

The synergy between infrastructures and their users is common to all large-scale facilities of the Helmholtz Association 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.v). 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.i). DLR activities are highly collaborative as well (see II.ii).

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 (s. pages 2-3 of the attached document “Quantentechnologien in Deutschland – Übersicht der vom Bund finanzierten Akteure und Aktivitäten”):

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 given essentially in each of the Quantum Technology areas addressed in 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 exploitation goals in all sub-areas of quantum technologies.

Partnerships between Helmholtz Centers and Fraunhofer institutes are being established. For instance, HZDR 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 centre for quantum technologies** at Physikalisch-Technische Bundesanstalt comprises these four fields of action with a focus on **quantum sensing, metrology and communication**.

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

In 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)"** in the Berlin area. The process is currently being intensively promoted with the aim of making quantum technologies a focal topic in 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 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-waves astronomy to nano-scale microscopy.

Advanced Imaging of Matter (**AIM**, University of Hamburg) will focus mainly on quantum physics but will include contributions coming 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.

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 and culminating research to design new methods and systems utilizing quantum technologies.

These five clusters have recently joined forces to pursue nationwide coordination activities, involving also other relevant centers of excellence in the Quantum Technology field such as the Center for Integrated Quantum Science and Technology (IQST, Universities of Ulm and 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 already existing through the involvement of the Helmholtz Association.

On the national level, it is important to also 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 supports 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 is the development of portable quantum sensors serving as magnetometer-based brain-machine-interface.

Quantum Flagship:

At the European level, the European Commission 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. Six of the 20 projects are coordinated by German partners, more than any other country (FR, AT, CH, ES, NL each have two project coordinators). 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 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.

- In the OpenSuperQ project (coordinated by Saarland University), an open-access state-of-the-art quantum computer with superconducting circuits is to be built. FZJ was selected as the location for this "European quantum computer".

The Helmholtz centres also take part in two flagship projects: AQTION, which develops a quantum processor based on ultracold ions (with the participation of HIM), and ASTERIQS, which will provide diamond-based quantum sensors (with the participation of FZJ).

<u>QuantERA:</u>

QuantERA is an ERA-NET Co-fund initiative in the field of Quantum Technologies, in which more than 30 organisations 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 20M euro call for projects in the four application domains and the cross-cutting domain of the Quantum Technology Flagship).

V. Structural Challenges

Exceptionally high degrees of interaction and cooperation are a prerequisite for 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 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 developed. Prerequisites are open funding schemes overcoming barriers between research areas and 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.

i. 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 heads, or by transferring heads between subfields. Furthermore, some quantum technologies, in particular the realization of quantum computers, represent an effort that goes substantially beyond the scale that the solid-state community is familiar with. As a result, to obtain major progresses 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 the decades to come).

The Helmholtz Association embraces the needed cultural change and it is committed to adopt appropriate governance structures. While fully-worked out solution are still under discussion, first steps have been made, for example, to lay out a detailed technical roadmap for activities addressing the strategic goals in the field of quantum computing. As the uncertainty is too high to define a simple linear progression of milestones, this roadmap is more like a road-network map, including alternative pathways and decision points to work towards the overarching goals laid out in Section II.i. The general idea is that activities are evaluated based on their likelihood to contribute to the overarching goals, with decision points serving to down select the approaches being examined. The roadmap will be updated and maintained by a board of internal and external experts, who will make recommendations to institutes and management boards of the Helmholtz Centers. The board of experts will also advise on the topic- and resource-allocation of the Helmholtz Association's internal funding instruments, in harmony with Program-Oriented Funding planning, but aiming for a higher level of detail and transcend programs and topics. It will also help to coordinate activities with other actors in the field.

ii. Transfer and Innovation Policy

International competition in the field of QT has become extremely intense in recent years. In countries such as China and the USA, very high investments have been made by the public but also by the private sector. Major industries such as 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, or by the other activities laid out in this roadmap document. For this, the centres of the Helmholtz Association are prepared to cooperate with industry either by joint projects and collaborations as well as by transfer of intellectual property rights through license contracts and transfer agreements. 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 marketable applications (Helmholtz Validation Fund). As an appropriate measure for the future development of quantum technology, the **set-up 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 as a particular important element the **establishment of a user community** and by **hosting an infrastructure for the access and dedicated user-support** (see sect. II.i). As a prerequisite for a prospective future development, we will also provide an **open research infrastructure**, which helps to bring in and to interact with outside know-how and partners in a prompt and flexible way as planned, 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 economically profit in a significant way: The technology for quantum computing is in many aspects fundamentally different from classical computing, which provides in fact a unique chance for Europe to re-enter the IT sector. However, for the next phase **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, both by public sector and industry, must start now.

iii. Disruptive Funding Instruments

Disruptive research which has the potential to initiate a complete restructuring of the economic environment or the research landscape, requires flexible and innovative support action for the interaction/ collaboration of research and industry.

This applies in particular to cooperation in which small and medium-sized enterprises and start-ups are involved. The overall strategy of Helmholtz Association offers the strategic superstructure to be able to use as wide a range of existing instruments as possible or to complement them creatively, as far as they are already included in the framework conditions for national project funding.

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

- Where existing funding instruments prove to be insufficient or 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 attached to ensuring that not only scientific staff from research institutions but also their management is involved in this exchange. 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.
- Especially the last step of a development into the market proves to be a special obstacle, because it has to be carried out as far as possible without financial support. Although there are, for example, bridge programmes 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 through the highest possible funding rates (including fully financed projects) and further 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 programme.
- Funding by different ministries depending on the technology readiness level 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, for example within the framework of expert conferences or workshops, should be aimed at in order to make optimal use of the diverse funding opportunities and sustainably support the innovation process.

iv. Brain Gain

Quantum technologies of tomorrow need quantum engineers and developers that are educated, trained and counseled already today. The realization of these strategical 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 arouse interest in quantum research and 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, quantum sensing etc.

- These educational laboratories should be connected with a **Helmholtz graduate school** for quantum technology, including summer schools, laboratory courses and tutorial video talks. The Helmholtz graduate school shall rotate between the centers engaged and involve partner universities. It can be strengthened with an international visiting programme for graduate students.
- The Helmholtz Association plans to form a **quantum community (Q@HGF)** from the experts in their own fields, who want to learn, understand and discuss crucial problems, novel ideas and future challenges with others in a surrounding, which fosters communication. Q@HGF shall be formed on the basis of virtual quantum campus with TED-like tutorial seminars, discussion-oriented workshops and a Helmholtz guest-programme to involve leading experts from all over the world.
- To strengthen the position of the Helmholtz Association in the field of quantum technology, **high potential researchers** in Germany and from abroad in early and middle stages of their careers will be **pre-selected through dedicated calls**. The goal is to make young scientist enter into the field, to grow community spirit, and to win in the battle of brain gain versus brain drain. To attract 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 implementation of the aforementioned educational concept.

VI. Current and projected additional resources

Currently nearly 500 people directly contribute with their work to the research on Quantum Technologies within the Helmholtz Association. As described above the centers have different topical focuses and thus contribute with different fractions to the 6 main fields. The current full annual costs sum up to a total of 77,42M€, which the Helmholtz Association already contributes to this important research topic. In addition, major investments and increases in the contributions are already planned for the next years.

The activities of the different centers are very diverse and range from hardware development over investigations of new materials to pure applications in relevant physical and chemical models.

This diversity is reflected in some degree of imbalance in the cost distribution in the table below, where the centers indicate partly very different financial support for the existing and requested financial means. Detailed figures per center and per topic are given in the table below.

	Costs in M€	DESY	DLR	FZJ	HIJ	HIM	HZB	HZDR	KIT
Quantum Computing	*Current Running Costs*	0.25	1.0	9.11		0.5			9.95
	Future Running Costs	0.5	*	12.91		0.5			9.95
	Future Investments (already approved)		**	5.09		1			7.5
	Future Investments (applied for)	0.5		24.47		1			
Quantum Communication	*Current Running Costs*		0.8	0.02				1.5	0.08
	Future Running Costs		*	0.02				1.75	0.08
	Future Investments (already approved)		**						

	Future Investments (applied for)								
Quantum Sensors	*Current Running Costs*		0.8	1.32	0.3	0.5		1.5	0.04
	Future Running Costs		*	1.32	0.4	0.5		1.75	0.04
	Future Investments (already approved)		**			1			
	Future Investments (applied for)					1			
Quantum Materials / Basic Science	*Current Running Costs*	0.5		13.55		0.2	4.0	6.0	9.42
	Future Running Costs	1.0		13.95		0.2	7.0	7.0	9.42
	Future Investments (already approved)	0.3		5.09		0.2			10.0
	Future Investments (applied for)	0.3		24.47		0.2			
Simulations / Numerical Techniques	*Current Running Costs*	0.3		0.72					0.1
	Future Running Costs	1.0		1.72					0.1
	Future Investments (already approved)								
	Future Investments (applied for)	1.0							
Large-Scale Facilities	*Current Running Costs*	0.25		5.21			4.0	5.0	0.5
	Future Running Costs	1.0		5.21			4.0	6.0	0.5+5.8***
	Future Investments (already approved)						3.0		50***
	Future Investments (applied for)	0.25				2			

*Numbers for DLR future yearly running costs will be primarily allocated within quantum sensing, quantum communication and to some parts into quantum computing, the actual distribution will be decided within the current funding process and HGF evaluation of the new DLR institutes. Overall DLR will be able to allocate ~ 37,8 Mio € yearly to the topic quantum technologies.

**Budget for DLR future investment once ~30 Mio. € in the context of the construction of new DLR institutes. Final budget for future investment is still to be decided.

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