Federal Ministry of Education and Research

Action concept Quantum technologies

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1. Use the potential of quantum technologies for Germany

New technologies have an enormous influence on our everyday lives: They are the basis for the diverse possibilities of the digital world, the basis for effective energy generation, new forms of mobility and innovative medical technology. For a future-proof and technologically sovereign Germany, it is crucial to identify upcoming technologies and their potential as early as possible, to create excellent framework conditions for future design and use and to actively shape technological advances.

Quantum technologies are a future technology with disruptive potential and particularly promising application prospects. Although they are still in a comparatively early stage of development, innovative potential uses in business and society are already emerging that also address the challenges mentioned above.

The time horizon and the expected effects of different technology strands within quantum technologies are different[1]: In the basic technologies and basic components for quantum technologies, there is already a corporate landscape of start-ups and large companies in Germany. The first products in quantum sensors, quantum materials and quantum communication have already reached market maturity. In contrast, widespread use of quantum computing is only expected in the medium to long term, but this brings with it enormous development potential[2,3]. Like any other new technology, quantum technologies not only present opportunities, but also challenges. These are important to keep an eye on. For example, in the long term, quantum computers will be powerful enough to endanger the security of classic digital communication with the cryptography used today. The migration to quantum computer-resistant cryptographic methods is therefore unavoidable and must already be considered today.[4]

Germany has a good position in quantum technologies. Due to the proven research landscape, Germany ranks fourth in an international comparison for corresponding publications behind the USA, China and Great Britain, and has the most publications of European countries[2]. When it comes to patent families, Germany is also in the top four behind China, the USA and Japan. The focus of the German patent families is in the areas of quantum measurement technology and quantum electronics[5]. It is important to use this strong basis.

Against this background, the Federal Government's aim is to bring Germany and Europe to a leading international position in quantum technologies with targeted, long-term support and to consolidate this position. In quantum computing, it is important to catch up with the technology leaders. This ensures technological sovereignty, increases value creation potential and opens up great opportunities for the use of technology in the economy and society.

To this end, the application-oriented development of quantum technologies in Germany must be promoted in a targeted manner. It applies

- ÿ to secure and expand Germany's innovative strength and technological sovereignty in quantum technologies,
- ÿ work towards the development and production of marketable products,

[1] Kagermann, H. / Süssenguth, F. / Körner, J./ Liepold, A.: Innovation potential of second-generation quantum technologies (acatech IMPULS), Munich 2020
[2] Quantum Technology Monitor, McKinsey & Company (accessed on November 22, 2022)
[3] What Happens When 'If' Turns to 'When' in Quantum Computing?, Boston Consulting Group (2022)
[4] "Making cryptography quantum secure", www.bsi.bund.de/PQ-Migration, Federal Office for Information Security (BSI) (2021)
[5] Quantum Technologies Patents, Publications & Investments, Michel Kurek, Ecole Polytechnique Paris (2020).

- ÿ Contributions to overcoming social challenges with quantum technologies climate research, energy, health, mobility and security,
- ÿ Train and recruit skilled workers and develop Germany as an attractive employment location for quantum technologies,
- ÿ to bring quantum technologies closer to people, to convey the opportunities and thereby to demonstrate impacts, and
- ÿ to ensure coordinated, joint action by the federal government.

The key to this is to establish a powerful ecosystem in which all relevant players along the value chain work together in a closely networked manner. The interlinking of basic and applied research as well as the early involvement of end users ensure that technology development keeps the actual needs in mind. The integration of partners from business is an important component. Active positioning in the development of standards and the development of the required quantum metrology are also of great importance. The aim is to tap into the expected enormous market potential in this area of application1. The consequences for cybersecurity – and thus for the digitalization of Germany – must also be assessed at an early stage.

that arise from the development of quantum technologies must be taken into account.

With this action plan, the federal government is giving itself a political framework for its measures in the field of quantum technologies until 2026. At the same time, the concept is part of a long-term strategy. In order to fully utilize the potential of quantum technologies, further steps will be necessary that go beyond the action plan (see also *Vision 2036* in Chapter 3).

The federal ministries are responsible for implementing the individual components of the federal government's interdepartmental action plan. You will check the success of the respective measures based on measurable goals and milestones. These indicators are continuously monitored, checked and successively updated at the level of measures and action plans and thus take into account the dynamic development in quantum technologies.

To overcome the key challenges, the federal government is pursuing **three central strands of action.** These rely primarily on public co-financing with the aim of triggering, strengthening and accelerating private initiatives and investments in Germany. Depending on the area of application, this takes different forms, for example through contracts, direct project funding or investments (especially venture capital) from the public sector.

A. Making quantum technologies usable for business, society and government institutions:

We will stimulate market development and the use of technologies for socially relevant issues. By 2026 we want to do this in Germany:

ÿ Significantly expand the usability and application of quantum technologies in all technology strands.	*All Departments*
ÿ Develop quantum computing for practical applications in business, administration and society in Germany and Europe. The long-term goal of technological sovereignty in quantum computing in Germany and the EU is based on all aspects that build on one another Components and levels *(full stack)* are considered.	*BMBF, BMWK*
ÿ Strengthen skills for the design and development of quantum algorithms across different research areas, for example in the area of optimization or quantum machine learning.	*BMBF, BMWK*
ÿ develop application-suitable quantum communication components and bring them onto the market, creating a well-networked quantum communication industry	*BMBF, BMF,*

Building up Germany and transferring know-how from science secure the economy.	*BMI, BMWK*
ÿ Drive the migration to quantum-secure cryptography *(post-quantum cryptography, PQK)* in Germany, especially in relevant areas (e.g. critical infrastructures6).	*BMI, BMVg, BMBF*
ÿ Marketable products in quantum sensing with lighthouse applications create.	*BMBF, BMWK*
ÿ Develop optical clocks for the next Galileo generation and, together with European partners, advance the development of the next generation of satellite-based gravity field quantum sensors (up to *Technology Readiness Level (TRL)* 5).	*BMWK*
ÿ Investigate the effects and benefits of quantum technologies in public administration, especially in communication security, and implement appropriate measures.	*BMI, BMF*

B. Drive forward technology development in a targeted manner with a view to future application:

Due to the early development stage of many technology strands, far-sighted and long-term measures are necessary to drive forward research and development with a clear application perspective. By 2026 we want to do this in Germany:

ÿ use targeted measures to strengthen Germany's strong position in the Secure and expand basic technologies.	*BMBF, BMWK*
ÿ Develop next-generation chips for quantum technologies, e.g. for quantum computers or quantum sensing applications.	*BMBF, BMWK*
ÿ Develop quantum computing hardware in an application-oriented manner based on various approaches. We are striving for a universal quantum computer on par with international developments and at least 100 individually controllable qubits, which can be scaled to 500 qubits in the medium term. In addition, powerful special hardware will also be developed for suitable fields of application.	*BMWK, BMBF*
ÿ Strengthen skills for the design and development of quantum algorithms across different research areas, for example in the area of optimization or quantum machine learning.	*BMBF, BMWK*
ÿ develop space-suitable and marketable key components for sensors, navigation and communication and bring them onto the market.	*BMWK*
ÿ Establish a quality infrastructure and reliable quantum metrology in order to create independent characterization, qualification and standardization for specific components for quantum technologies.	*BMWK, BMBF*

6 This is also a goal of the cybersecurity strategy for Germany 2021.

C. Creating excellent framework conditions for a strong ecosystem:

In international competition, it is crucial that attractive and stimulating framework conditions are set in Germany and Europe. By 2026 we want to do this in Germany:

ÿ Close networking of all actors and activities in science and business and ensure politics.	*All Departments*
ÿ Strengthen the education and training of professionals in the field of quantum technologies with a coherent program that includes young academics, technical staff and professional development.	*BMBF, BMWK*
ÿ create a positive start-up climate to encourage spin-offs from the academy to support.	*BMBF, BMWK*
ÿ Work towards close integration with European partners at all levels. This includes both cooperation on technological issues and the development of common standards, including responsible use and common standards to Quality infrastructure.	*All Departments*

The quantum technologies action plan contributes to the goals of the Federal Government's "Future Research and Innovation Strategy". It contributes to securing the technological sovereignty of Germany and Europe in future technologies. In operational implementation, depending on technological maturity and application focus, it is supported by the specialist programs as well as the specific implementation concepts and measures of the departments involved. The appendix provides an overview of the status quo.

2. Great challenges, extraordinary potential

Quantum technologies, i.e. the targeted control of quantum mechanical effects and their technological use, promise enormous progress for applications in business, society and government institutions. Depending on the technology strand (quantum computing and quantum simulation, quantum communication and post-quantum cryptography, quantum sensors and quantum metrology as well as the associated basic technologies), the application maturity and possible uses vary:

Quantum computing and quantum simulation

The enormous potential is most clear in quantum computing. Classic computers will reach their limits in the long term, for example when simulating chemical reactions and compounds (material science, drug design) or optimizing complex systems, such as logistical systems. Through new algorithms based on qubits (quantum bits) instead of classical bits, quantum computers could provide decisive advantages here. Potential is also seen, for example, in bills for weather services and modeling of climate change and its consequences.

Therefore, there is research work on a wealth of technologically different implementations of quantum computers (see also information box "Quantum computing") and possible applications.

It cannot be reliably predicted which approaches will ultimately be successful or whether different implementations will stand out in certain use cases. However, the technologies have the potential to create completely new possibilities for products and services in a wide variety of application areas and industries and thus have a significant influence on international competition. In the long term, studies assume an annual market volume of several hundred billion euros in quantum computing alone.3 This explains the high level of attention worldwide and the considerable financial commitment to the topic. However, fundamental challenges still need to be overcome during development, both in terms of hardware and software, which require long-term research and development activities.

Post-quantum cryptography and quantum communication

Even if it is not a quantum technology itself, post-quantum cryptography plays an important role in this context. From an IT security perspective, the development of powerful quantum computers represents a threat: the so-called *Shor algorithm,* a quantum information technology method, would be able to break the public key cryptography used today. The quantum computing hardware required for this does not yet exist. However, once this is available, this would pose an incalculable risk, as such encryption methods are currently used to secure our confidential communications and security-relevant data. Encrypted data could already be intercepted and recorded in order to be decrypted with future quantum computers ("store now, decrypt later"). This makes the development and introduction of new, quantum-secure cryptographic methods ("post-quantum cryptography") absolutely necessary, which should offer at least as high a level of security compared to quantum computers as the classical methods mentioned above do today. It should be noted that post-quantum cryptography can be implemented on classical hardware just like the public key methods currently used.

This significantly distinguishes them from quantum communication methods and allows them to be used even in situations in which quantum communication is not possible, for example due to physical limitations.

Quantum communication offers enormous potential to secure confidential communication most effectively. For quantum encryption, quantum physical effects such as entanglement or the incomplete copyability of individual photons are used to exchange keys in order to transmit data securely. In contrast to common cryptographic methods, the high security of quantum cryptography is based on physical laws of nature and not on mathematical ones

Assumptions. A wide variety of quantum communication methods have now been demonstrated in applications, both in optical fibers and between satellites and in terrestrial free-beam connections. However, range and data rate still represent a challenge for broad application relevance. For this reason, the development of quantum repeaters, which are required as nodes to extend transmission routes, is essential as a key component for quantum communication over long distances.

Quantum sensing and quantum metrology

Quantum-based measurement technology is probably the field with the highest technological maturity in the field of quantum technologies. For example, nitrogen vacancy centers in diamond are already used in special microscopes. The first quantum gravimeters are also available on the market and enable the measurement of the Earth's gravity field for applications in geology or geodesy.

Quantum sensors also offer new applications that are complementary to classic technologies. By directly relating the measurement methods to natural constants, which are defined without uncertainty by the recent redefinition of the SI system of units (2019),[7] they offer novel possibilities for reliable, ubiquitous and highly precise sensor technology. Overall, quantum-based measurement technology is a heterogeneous field with a wide variety of technologies and numerous promising, some of which are already market-ready, application options.

However, quantum metrology is not only limited to quantum sensing. It is generally concerned with making high-resolution and high-sensitivity measurements of physical parameters using quantum effects such as quantum entanglement. Quantum metrology thus promises the development of measurement techniques that enable greater precision than the same measurement using classical methods. For example, electrical quantum metrology can develop conventional measurement technology into a comprehensive quantum measurement technology. Among other things, programmable “quantum voltmeters” are already available on the market.

Basic technologies

The cross-sectional field of basic technologies (“Enabling Technologies”) is particularly indispensable for the further development of quantum technologies. It is already developing economic potential: the first markets for special lasers, control electronics and cooling technology for quantum systems have already emerged. In particular, highly specialized start-ups and small and medium-sized enterprises (SMEs) are able to generate their first sales. The future challenge will be to develop innovative overall systems from this sum of individual components and to open up further possible uses.

As a cross-sectional task, independent metrological characterization and qualification of components[8] must also be considered and developed from the outset for a stable, trustworthy and reliable value chain in the emerging quantum technology industry.
This ensures the guarantee of quality, traceable and secured performance parameters and the comparability of QT components.

State of technology in international comparison

In international comparison, the USA is currently the world leader, particularly in quantum computing. Large corporations such as Google and IBM currently represent the state of the art in the field of superconducting quantum computing. The USA also has the highest number of start-ups in quantum technologies (92), the highest venture capital raised ($2.2 billion from 2001 to 2021) and the most academic research groups (64)2. The national funding is distributed across a wide range of national agencies and organizations (including NIST, NASA, DARPA) with different thematic and strategic focuses. Total government funding in 2022 was approximately $0.9 billion.[9]

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[7] https://www.pro-physik.de/nachrichten/das-neue-mass-der-units
[8] https://www.nature.com/articles/s41567-022-01659-z
[9] https://fedtechmagazine.com/article/2022/06/where-quantum-technology-going-federal-government

With a total of $15 billion, China has announced by far the highest government funding in an international comparison. Specific structures and strategies are less transparent, but important work has already been published on a scientific and technological level. With the help of the Micius research satellite, an intercontinental key exchange using quantum cryptographic methods was demonstrated in 2018.10 There are also increasing developments in quantum computing that indicate a high technological level.

Significant public funding for quantum technologies has currently been announced in the European Union ($7.2 billion in the EU versus $1.9 billion in the USA). In Germany alone, 2 billion euros are available for research and development in quantum technologies as part of the federal government's future package. However, there is significantly less venture capital available, especially compared to the USA (0.3 billion compared to $2.2 billion). In terms of scientific publications, the European Union is a leader, both in academic quality and breadth. The number of start-ups has also more than tripled since 20152.11, but is far below the US figures.

It is important for Germany to benefit economically and socially from the development of quantum technologies and to establish sovereign access to this future technology. The initial situation is assessed as follows:

Strengthen	**weaknesses**
• Distinctive industrial sector with many potential users of the technology • Embedding in the European internal market • high public investment in the Development of quantum technologies • strong basic research • good culture of collaboration between Science and business within the framework of Collaborative research • ongoing research work on almost all relevant technology platforms • established quantum metrology • Dual education system and strong universities Training	• Only a few works in the area Quantum information theory (lack research activity) • Potential users are still reluctant Use of quantum technologies • State of applied computer technology especially in the field of quantum computing behind the North American company • Less in international comparison venture capital as well as higher administrative Hurdles for start-ups and their support • expandable promotion of talent

[10] https://arxiv.org/ftp/arxiv/papers/1801/1801.04418.pdf
11 without Enabling Technologies

opportunities	Risks
• Germany's manufacturing industry could benefit disproportionately from the use of the technology • Good co-design opportunities for providers and users of the technology • new markets for German medium-sized businesses Manufacturer of special components • great economic potential of the domains Communication, sensors and computing, through novel applications • Technological sovereignty in Europe Broad coverage of the technology is generally achievable	• Skilled labor shortages and brain drain Scientists, especially top experts • possible development of a critical one Dependence on non-European hardware and software • Dangers for Germany's sovereign and critical infrastructures and technologically leading companies due to the use of quantum computers by other states • Lack of quality and trust in the Technology with a lack of comparability and independent qualification of Quantum technology components • Standards are set outside Europe and are incompatible with German products

This rough analysis shows the great potential that Germany has due to its strong basis in quantum technologies. It forms the basis of the Federal Government's measures outlined below to bring Germany into a leading international position in quantum technologies and to secure this.

Technology strands

Quantum computing and quantum simulation

While conventional computers work with bits that have the values (0) or (1), quantum bits (qubits) are used in a quantum computer. These are quantum mechanical systems that are in two states (0) and (1) or in a superposition thereof due to the quantum physical effect of superposition. Qubits can therefore assume any combination of the two states. In addition, two or more qubits can be "entangled" with each other so that they assume a special common overall state. A change to a qubit then has immediate effects on the qubits entangled or interacting with it, even if they are spatially far apart from one another. This is a fundamentally different computing principle than that of classic computers. Due to the enormous scaling with the number of qubits associated with this approach, enormous potential for certain computing operations is expected even in quantum computers with just a few qubits.

A quantum computer is defined not only by the sheer number of usable quantum bits (a measure of the problem size), but also by the error rates of an operation (it helps to estimate the quality of the result) and the so-called depth of the circuits that can be implemented (i.e. the calculation processes of the quantum operations on the qubits). Circuits with many operations in a row ("great depth") enable more complex calculations. The depth of the circuit depends, among other things, on how long certain physical states can be maintained (so-called decoherence time).
Quantum computers are inherently parallel and suitable for huge task sizes, while classical computers only enable parallelism through many functional units working in parallel and are limited by their memory in terms of the size of the problems that can be processed. By using the quantum mechanical principles of entanglement and superposition, quantum computers can handle certain tasks that push classical computers to their limits. A quantum advantage can therefore be achieved in these tasks, for example in the sense of a massively reduced computing time, which in many cases makes a solution possible in the first place. In principle, but also in the long term, quantum computers should be seen as special hardware for certain areas and not as a replacement for previous microelectronic computers for a wide range of users.

The development of a practical quantum computer requires the creation and control of numerous qubits. These must not lose their quantum properties through interaction with the environment for as long as possible (so-called decoherence), but at the same time they must be able to be prepared, entangled and read out in a controlled manner. For this purpose, a wide variety of physical implementations of architectures for qubits are being developed, from ion traps to electrons in semiconductor structures, superconducting systems to nuclear spins or photons and topological states. All technical implementations have their advantages and disadvantages and it is impossible to predict which of the technological approaches will prevail. For a universally programmable computer, complex further developments of hardware and algorithms are still necessary. Since many quantum algorithms react very sensitively to disturbances, the ability to correct errors is also a crucial factor. In addition to robust qubits, special algorithms are also being developed that improve the efficiency of the hardware.

In contrast to a universal quantum computer, quantum simulators represent a controllable system developed for a specific problem. It is used to imitate another quantum system and thus simulate specific processes. Quantum simulators are therefore able to model properties relevant to practice, for example in materials research.

Quantum communication

In quantum communication, quantum states are the basis for the secure transmission of information. Quantum states are used for key distribution in quantum cryptography. According to the so-called "no-cloning theorem," it is impossible to copy unknown quantum states or measure them without interference. For this reason, it can be determined for individual and entangled quanta whether the information they transport has already been read out. This makes it possible to detect a possible eavesdropping attack on communication that was believed to be secure. In comparison to previous encryption concepts, data transmission security against interception is not based on assumptions of complexity of certain mathematical problems, but on quantum mechanical principles.

Since quantum states are very fragile, their transmission poses significant technical challenges. For example, quantum signals can be maintained over long distances and interference can be reduced.

In order to be able to use the advantages of quantum communication, it must be tested qualitatively and quantitatively in existing IT and communication infrastructures and gradually integrated. In order to maintain the reliability and availability of communication infrastructures, quantum systems must also reach a level of maturity that corresponds to that of classic IT. Possible points of attack include, for example, the interfaces between quantum and classical IT.

For future interoperable applications and for a uniform understanding of the security of quantum communication, the standardization of basic building blocks such as the protocols used, key management, the integration of quantum repeaters as nodes to extend communication distances and other network elements is also required.

Quantum sensing and quantum metrology

Quantum states are very sensitive to influences from their environment. In quantum computing and quantum communication, this means that qubits are very difficult to control for long enough. But what is a challenge there can be a great advantage elsewhere. On the other hand, it is precisely this sensitivity to external influences that can be used for highly precise measurement of the underlying physical quantities - for example electric and magnetic fields, gravity or temperature.

A basic idea of quantum sensing is to use two states in a quantum system whose spectroscopically measurable energy difference depends on the size of the external influence. Other measuring principles make use of the wave properties of matter. In quantum optics, the entanglement of photons allows extremely precise measurements and enables imaging in previously inaccessible spectral ranges. Quantum-based measurement technology can achieve a new kind of precision that remains unattainable with classic measurement technology. One challenge is to shield all environmental influences that could distort the measurement.

Quantum metrology is closely linked to this: it uses quantum to determine units of measurement and for other high-precision research work. Quantum mechanics sets the ultimate limit on the accuracy of any measurement. Quantum metrology therefore uses quantum effects to increase precision beyond that possible with classical approaches or to make measurements possible in the first place.

Furthermore, quantum metrology, also through the redefinition of the SI units, offers the possibility of drift-free, self-referenced and SI-traceable quantum sensors. These can offer significant advantages over classic solutions, for example as (pressure) sensors in process automation or quantum electronic components that directly implement the newly defined SI units and derived quantities such as the volt and the ampere.

3. Technology at the highest level for creative power and technological sovereignty

Quantum technologies are a future key technology in which Germany is building on a strong foundation. The aim of the federal government is to take advantage of the opportunities that arise and to establish Germany and Europe as world leaders in this area. Through targeted measures, quantum technologies are made usable for society and the economy and technological sovereignty in this field is secured. The federal government is oriented towards a long-term target in which an advanced level of technology with a wide range of applications will be established by 2036.

Vision 2036

The development of quantum technologies from a future technology into a central key technology requires a time horizon that significantly exceeds the time frame of this action plan. The Federal Government is therefore relying on further development of the measures and long-term, sustainable support and development of the technology, as also called for by the Research and Innovation Expert Commission1,12 . In the case of quantum computing, a technology-neutral approach is particularly important until it becomes clearer which implementation of qubits is most advantageous for the further development of quantum computers. It is also conceivable that different hardware platforms will be particularly suitable for different applications.

In the long term, quantum technologies should be established as a key technology in a wide range of application areas. For the year 2036, ten years after this action plan expires, our target image is:

- Quantum technologies are core components in a wide range of economic application sectors. They make significant contributions to value creation in Germany and to dealing with the pressing future issues of our society, including:

  - o Quantum sensors have become established in a variety of economic and socially relevant applications. The construction industry benefits from innovative sensor types in soil exploration, in medical technology quantum sensors enable novel diagnostic options and in information and communication technology improved signal processing is achieved through the use of high-precision atomic clocks.

  - o Complex use cases are solved on universal error-corrected quantum computers manufactured in Germany. Quantum computers and special computers, for example quantum simulators or. Quantum annealers play a significant role in several industries, such as the chemical and pharmaceutical industries, the financial sector and the automotive sector.

  - o Sensitive data in administration and security authorities is exchanged via internal administrative networks that are based on quantum computer-resistant cryptography processes. The internal administrative networks have secure and defined transitions to other communication partners. Sensitive data from critical infrastructures and the economy are protected by quantum computer-resistant cryptography processes and, in some areas, additionally secured by quantum communication. Locations of economic, scientific or sovereign relevance are connected via a secure EU-wide quantum communications network.

[12] Annual report on research, innovation and technological performance in Germany 2022, Research Expert Commission and Innovation (EFI) (2022)

- o The German activities in the area of standardization and the significant increase in precision in time, mass and current standards through quantum metrology form the basis for an international quantum-based standardization system.
- • Quantum technologies make their contribution to the German economy also in the year By 2036, it will be one of the world's ten most innovative economies13 . Together with partners from the European Union, we are technologically independent in the production of products and applications of quantum technologies or produce critical elements of international value chains14 (technological sovereignty).

The federal government's measures are divided into three strands:

A. Making quantum technologies usable for the economy, society and government institutions

Quantum technologies will open up a wide range of new possibilities: from the simulation of new active ingredients to secure communication to new types of sensors that detect unexploded bombs or enable navigation without satellite support. Against this background, targeted development of the technology is necessary, which always keeps the possible application scenarios in mind.

The focus of the Federal Government's action plan is therefore on measures that stimulate, strengthen or accelerate private investments in Germany through public co-financing. Depending on the area of application, support from the public sector takes different forms.

To achieve this, the federal government uses three complementary and coordinated funding instruments:

- For research-related topics that are of significant federal interest, research and development in companies, universities and research institutions is supported with grants through project funding. These non-repayable grants are primarily aimed at application-oriented project consortia that cover the value chain from technology development to the end user.

- By specifically awarding orders for marketable products, the public sector acts as a central anchor and reference customer for companies that develop and manufacture such hardware in Germany. An example of this is the basic financed German Aerospace Center (DLR), which procures innovative quantum computers for its own use through research contracts on the market by awarding contracts worth around 600 million euros from the economic stimulus package. Positive results from previous calls for proposals show that the novel approach of the DLR quantum computing initiative has proven to be a good way to promote an entrepreneurial quantum computing ecosystem in Germany.

- The financing needs of young companies that bring new developments to market maturity can also be covered through direct public sector investments. With the new Deep Tech and Climate Fund (DTCF) as part of the future fund approved in 2021, the federal government is expanding the established financing instruments for start-ups. The fund, which can grow to up to 1 billion euros, invests directly in deep tech companies on pari passu conditions with a longer-term investment perspective and covers, among other things, the content

13 In 2021, Germany is in fourth place in the Bloomberg Innovation Index with a value of 86.45, behind South Korea (90.49), Singapore and Switzerland. The rest of the top 10 most innovative countries with index values above almost 84 are quite close to Germany.

14 For example, the latest generations of semiconductors are currently not manufactured in Europe, but in Southeast Asia. However, it depends Production depends largely on lithography systems from the European Union, to which German suppliers contribute essential components.

also quantum technologies. In addition to the established High-Tech Gründerfonds (HTGF), the DTCF is an example of direct public sector investments in the area of venture capital.

In order to focus on the ambitious techno-economic goals of the action plan for quantum technologies and to do justice to the budgetary priority of private funds over public funding, the funding measures gradually also take into account the increasing levels of technology maturity in their framework conditions.

The aim of the action plan is to create a close network of actors who can quickly establish the first products on the market through joint research and development. Germany can particularly benefit from a large number of potential users from many different industries.1 The rapid and interrelated development of initial pilot applications as well as testbeds[15] and standards will allow the technology to be tested under real usage conditions

testing.

The Federal Government sees great potential in particular in the following areas:

ÿ Economic innovation The development of

quantum technologies has now progressed to such an extent that they will find their way into more and more areas of economic life in the coming years.
In the future, the successful application of quantum technologies offers enormous market potential for German companies that can use them to offer innovative products and services. In addition to the development and sales of the technology, a variety of other new application possibilities open up across industries, from product development to service offerings.

In the area of **quantum sensors and communication,** where the first products are already on the market, the economy can benefit both in sales and in the use of new technologies.

The Federal Government will lay the foundations for this within the framework of this action plan
Research and business create to

ÿ to bring the first applications onto the market with lighthouse projects in quantum sensors, for example in the exploration of raw materials, the clarification of subsoil or the use of high-precision inertial positioning and navigation systems,

ÿ a well-networked quantum communications industry through targeted support
Material and component levels, module and network levels, cybersecurity and application-suitable software to build first
Bringing quantum communication components from Germany onto the market

ÿ to further develop the technology so that at the end of the term this
Action concept Possible uses for products in at least five different ways
Sectors are specifically tracked,

ÿ through quantum metrology prerequisites for quality assurance in the area
to create quantum technologies.

Due to greater development needs, the application perspective in **quantum computing** is more of a medium to long-term nature with a possible time horizon of five to 15 years (see also information box “Quantum computing technology lighthouse”). According to studies, this could...

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[15] For example, the European consortia within the framework of the “Framework Partnership Agreements” *Qu-Test* (https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101080035/program/43108390/details=) and *Qu-Pilot* (https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/org-details/999999999/project/101079926/program/43108390/details)

Established application first in optimization problems in industry and logistics (e.g. via quantum annealers), subsequently in the simulation of chemical processes, in AI-based evaluation of large amounts of data and later in quantum cryptography16. Experts predict that the actual added value will not lie in the development of the hardware, but rather in its application in the next wave of digitalization1, which will affect numerous industries. Particularly in the areas of the chemical and pharmaceutical industries, significant economic potential is seen even at an early stage of development2.

Ammonia synthesis for the production of fertilizers and fine chemicals causes around one to three percent of global energy consumption and corresponding process-related CO2 emissions17. Even an optimization of a few percentage points in efficiency via improved catalysts developed with the help of quantum simulations would have a significant global impact on energy efficiency and climate protection.

The Federal Government will support the targeted development of
Technologies and possible applications create a strong basis for quantum computing (see also information box “Quantum computing technology lighthouse”):

ÿ In Germany and Europe, quantum computing is to be developed for practical applications in business and society through technology-open development.

ÿ The federal government supports the development of all interconnected components and levels of quantum computing (“full stack”), in particular algorithms and application software. The early involvement of users is of utmost importance.

ÿ Building on these activities, the federal government aims to achieve quantum advantages with European hardware solutions in specific use cases by companies in Germany by 2032.

ÿ A quality infrastructure for quantum computing is being built that promotes characterization, comparability through benchmarking, standardization, conformity and standardization.

ÿ Social challenges

Societies around the world are facing major challenges:

Climate change is a global phenomenon. Fighting it and dealing with the consequences require joint global, European, national, regional and local action. A better understanding of the Earth system, the individual components of the climate system as well as the key factors influencing the climate as well as the need to adapt to the expected or already foreseeable consequences of climate change will help to find adequate and tailor-made solutions to the challenges. Securing the energy supply is also a global task due to diverse international connections and limited resources, which, in addition to overcoming the current energy crisis, must also be addressed in the long term at international, national and local levels.

Closely linked to these aspects is the question of mobility. A globally networked society and economy are inconceivable without mobility. Mobility is the backbone of the supply of essential goods, a prerequisite for inclusion, for access to work, training and health care. At the same time, mobility is also fundamental for equal opportunities

[16] Quantum Computing. When will the breakthrough come? Roland Berger GmbH, 2021
[17] Energy consumption in the production of mineral nitrogen fertilizer (WD 8 - 3000 - 088/18), Scientific Services of the German Bundestag, 2018

between the sexes and for disadvantaged population groups. All economic sectors are also dependent on functioning transport and logistics, as without these economies and the sale and distribution of goods would be impossible. In this respect, there is also a double-sided dependency on mobility and energy supply. Mobility therefore has a significant impact on economic and social development. The current technological advances have initiated a fundamental change in the mobility sector and the energy sector.

In the area of health, demographic change, increased travel, infectious diseases and illnesses resulting from the changing world of life, climate change and changing nutrition and lifestyle habits are constantly presenting medical care with new challenges.

Quantum technologies can make important contributions in these subject areas and sectors:

Climate research: With new quantum sensors, the monitoring of climate changes can be significantly improved in the medium term (e.g. changes in water resources using gravimeters for earth observation). In the long term, quantum computing is also seen as having potential for improvements in the simulation of climate change.

Energy supply: The future energy supply will be highly decentralized. Here, distributed energy networks and local renewable energy providers as well as private households will work together in a complex system. The interaction of supply and demand is a complex optimization problem that quantum annealers and future quantum computers could be particularly suitable for solving.

Mobility: Improved sensor technology opens up new possibilities in various areas of mobility, for example through improved position stabilization with quantum gyroscopes (application for autonomous driving in road traffic to space travel). In the long term, quantum computing can create new approaches to optimizing traffic flows. Quantum technologies will make important contributions to hyper-connected, smart and autonomous mobility, which relies on security and stability in all its components and interactions and is also based on real-time data exchange in rapidly increasing quantities.

Health: The development of quantum sensors can create access to improved or novel therapy and diagnostic options in medical technology in the short and medium term. New imaging methods will be particularly important in laboratory analysis or intraoperative diagnostics. In the long term, quantum sensors can e.g. B. can be developed for controlling prostheses. The development of drugs or vaccines can be accelerated and/or improved through the use of quantum computers.

Digitalization and artificial intelligence: The development of system responses based on massive data in areas such as personalized medicine, autonomous driving or control in the infrastructure of cities requires fast decision-making algorithms that benefit immensely from quantum simulators and quantum algorithms in terms of their performance and accuracy can be superior to classic methods.

The federal government will promote the development of all strands of technology. in particular she will

ÿ create new possibilities for medical diagnostics and imaging with lighthouse projects in sensor technology,

ÿ the preparation of a European earth observation mission to monitor Supporting climate change based on quantum gravimetry/gradiometry and supporting the development of the next generation of satellite-based gravity field systems advance quantum sensors (up to TRL 5), ÿ the development of optical clocks for satellite navigation systems and Bringing quantum gyroscopes for inertial sensing to application maturity.

ÿ Security and sovereignty

The changes expected from quantum technologies are likely to have profound consequences in the area of digitalization and (information) security. This applies, for example, to aspects of communication, cryptography and elements of sensor technologies. Nationally and internationally there are increasingly strict security requirements.

Germany must master these future technologies in order to be able to act sovereignly. Against this background, the federal government will create the conditions to ensure data security for business and public administration, security authorities and the Bundeswehr through post-quantum cryptography and, in addition, quantum communication.

The federal government will do this

ÿ promote migration to post-quantum cryptography in Germany,

ÿ promote the development of quantum-resistant cryptographic systems and their Ensuring quality through standards

ÿ promote quantum key distribution as a technology that complements post-quantum cryptography and quantum communication,

ÿ examine the use of quantum technologies in federal/government networks and in particular consider the effects on communication security,

ÿ the networking of cities and scientific and scientific communities with lighthouse projects Advance government locations with quantum communication links,

ÿ the research and development of quantum repeaters for long-range promote quantum communication links (>200 km),

ÿ promote research into the security of quantum communications in practical applications, the analysis of potential attacks and effective countermeasures,

ÿ promote research into security technologies based on quantum mechanical principles, such as quantum effect-based security tokens,

ÿ agile certification by bringing together relevant actors Quantum communication and quantum sensing technologies for the trustworthy Accelerate use in business and authorities,

ÿ Provide the first infrastructure necessary for quantum communication.

B. Drive forward technology development in a targeted manner with a view to future application

ÿ Pushing technological boundaries

Great progress has been made in quantum computing in recent years. However, many development steps are still necessary before a universal error-corrected quantum computer can reach application maturity. The federal government is therefore pursuing this goal with a long-term development strategy (see also information box “Quantum computing technology lighthouse”). This includes system development at all levels (“full quantum computing stack”). In particular, novel approaches must be found to scale quantum computing chips into universal computing units.

Developments in quantum sensing and quantum communication are already more advanced and closer to application. Nevertheless, there is a need for further research and development in improving the technological parameters, measurement methods and readout protocols as well as in standardization and certification. In addition, the focus is on improving the robustness, integrability, miniaturization and applicability of the technologies.

In addition to the targeted further development of usable systems, the Federal Government also supports research work on the basic technologies that are absolutely necessary as a basis for further progress. This includes materials, components and manufacturing technologies, but also fundamental modules for the preparation, control, manipulation and detection of quantum states. Example technologies of central importance are beam sources, detectors, microwave technology, cryogenics or controlled layer growth.

The federal government will do this

ÿ Germany's strong position in basic technologies through targeted funding secure and expand,

ÿ develop and bring onto the market marketable photonic and optoelectronic key components suitable for space travel for sensors, navigation and communication, e.g. micro-integrated lasers, quantum sources, detectors, modulators or frequency combs,

ÿ Promote the development of quantum computing hardware in a technology-neutral manner, based on various realizations of qubits, from basic research to applications in computing technology. This is being done with the aim of developing a universal quantum computer in Germany on par with international developments and at least 100 individually controllable qubits by 2026, which can be scaled to 500 qubits in the medium term. In addition, powerful special hardware will also be developed for suitable fields of application.

ÿ Set standards

Issues of standardization and standardization will play a crucial role in the future development, mastery and dissemination of the technology. In this way, commercial companies can be supported by building a quality infrastructure for quantum technologies and thereby set quantum technologies “made in Germany” as a quality feature worldwide.

In international standardization committees, specifications of new technologies are determined and thus have a decisive influence on the design and ultimately on access to the market. Against this background, there is a strong commitment to building a metrological quality infrastructure and increased at the technological forefront

Continuation of ongoing activities18 in this area is required12,19. A roadmap from the CEN-CENELEC Quantum Technology Focus Group analyzes the needs for standardization in this area and proposes a coherent framework that enables effective standardization in all domains (computing, communication, sensors) and helps avoid duplication. Concrete examples include characterization parameters for components for quantum communication or for ion traps for quantum computers, as well as initial approaches to quantum computer benchmarking. Based on this preparatory work, a "Joint Technical Committee" JTC 22, requested by DIN, was recently set up at CEN-CENELEC. The increased international measures in the area of quantum technologies and related areas are already reflected in the first standard setting20 21.

In this context, the development of suitable *benchmarks* and characterizations of quantum technology components also plays an important role in order to be able to carry out quantitative comparisons of performance across architectures and technologies, particularly in the area of quantum computing. The first approaches are currently taking place at DIN22. Independent qualification of components is also an important prerequisite for stable value chains and thus for unlocking economic potential. In addition, such an infrastructure helps build trust in quantum technologies and prevents excessive expectations.

Standardization and standardization require that the companies involved interact on an equal footing, expect significant economic benefits from the results and have sufficient financial and personnel strength for intensive committee work. The influence of an economic area in the international standardization committees fundamentally depends on the number and weight of such companies involved. Against this background, the Federal Government will work together with its European partners to ensure greater German and European involvement in the standardization committees. By promoting an entrepreneurial ecosystem for quantum technologies, prerequisites for work on standardization and standardization are ultimately specifically supported. The needs for standards18 that have already been identified in initial approaches, for example for relevant parameters of quantum technology components for "reliable data sheets", provide the basis for harmonized and jointly developed characterization and qualification at the European level as well as the use of testbeds23,15 .

The federal government will therefore

ÿ Support standardization activities in the area of quantum technologies and work towards greater German and European involvement in the standardization committees,

ÿ Build a quality infrastructure for quantum technologies that creates an advantage for the emerging quantum industry in Germany through objective, independent characterization, qualification and standardization of quantum technology components and comparative architecture-independent benchmarks of quantum computers.

[18] https://www.cencenelec.eu/areas-of-work/cen-cenelec-topics/quantum-technologies/, https://arxiv.org/abs/2203.01622, https://www.etsi.org/committee/qkd

[19] Position paper "THE WHO DESIGNS THEM DOMINATES THE MARKET: NORMS AND STANDARDS", Fraunhofer Society for the Promotion of applied research eV (2021)

[20] https://csrc.nist.gov/Projects/post-quantum-cryptography

[21] ~~ISO - ISO/IEC CD 4879 - Information technology — Quantum computing — Terminology and vocabulary~~

[22] https://www.din.de/de/forschung-und-innovation/din-spec/alle-geschaeftsplaene/wdc-beuth:din21:358848855

[23] EMN-Q - The European metrology network for quantum technologies: https://www.sciencedirect.com/science/article/pii/S2665917421003111

Technology lighthouse: quantum computing Compared to the other branches of quantum technologies, quantum computing is expected to have the highest disruptive potential in applications1. At the same time, the technology is still at a comparatively early stage. The first quantum computers are already able to carry out simple calculation operations. However, these systems still have limited computing power, are prone to errors and can only be used for special tasks. The full potential of the technology can only be exploited when a universally programmable and error-corrected quantum computer is available and works alongside existing computer architectures. Numerous further development steps are necessary for this24. Experts estimate that the necessary steps will take at least ten to fifteen years. Economically usable interim results in the fields of application can be expected beforehand, within the next five to fifteen years25. With regard to the technological uncertainties, these time scales represent an initial rough estimate that takes into account forecasts from public institutions26 and industry 27, 28, 29 as well as the current pace of development.

Today, cutting-edge technology is organized in global value chains. In technically demanding and highly investment-intensive areas, available economic resources can be a limiting factor that requires international cooperation. At the same time, the COVID-19 pandemic and the Russian war of aggression in Ukraine have shown how fragile and vulnerable global supply chains can be and the value of technological sovereignty in a world that has become uncertain. The federal government will therefore support technology development in quantum computing in the long term. Based on the roadmap of an independent council of experts, the federal government is implementing an ambitious package of measures as part of the economic stimulus and future package that aims to achieve *technological sovereignty* for Germany and Europe in the field of quantum computing. This could mean that Germany, together with partners from the European Union, becomes technologically independent in the production of corresponding hardware and software.

A central role in critical elements of international value chains for quantum computing can also ensure that Germany, as an important partner, can always maintain access to economically essential quantum resources. A balance must be found between competition and cooperation.

In the short and medium term, the measures aim to develop the first quantum computers in Germany that are state-of-the-art in research and technology. They need to be scaled and improved until they provide a quantum advantage in practical applications. Building on this, the aim is to develop a universal, error-corrected system. The federal government is relying on a technology-open approach, as it is not yet possible to foresee which technological basis is best suited for the various areas of application and can be scaled up. We check at regular intervals which of the technology strands are promising and adjust the portfolio of measures accordingly.

Within this action plan, the federal government aims to develop a quantum computer on a par with international developments and at least 100 individually controllable qubits by 2026, which is scalable to 500 qubits in the medium term. In addition, powerful special hardware will also be developed for suitable fields of application.

The work in hardware development is accompanied by measures to develop software and algorithms for these new types of computers in order to be able to take advantage of speed and quality advantages.
This is particularly important given that expert estimates indicate that the significant value creation potential is not in the hardware and software, but in the next wave of digitalization

[24] Quantum computer development status, Federal Office for Information Security (2020)
[25] Roadmap Quantum Computing, VDI Technologiezentrum GmbH (2021)
[26] Bundestag printed matter 19/25208 and 19/26340
[27] https://www.ibm.com/quantum/roadmap, accessed September 2022
[28] https://www.dwavesys.com/media/xvjpraig/clarity-roadmap_digital_v2.pdf
[29] https://blog.google/technology/ai/unveiling-our-new-quantum-ai-campus/

see it in the applications1. At the same time, quantum simulators are being further developed, which can provide similar quantum advantages to quantum computers in some specific areas, for example in materials research or in improving chemical processes such as the energy-intensive production of fertilizers1.

Specifically, the federal government is pursuing the following measures for the development of quantum computers “made in Germany”:

- Development of the basic technology platforms for quantum computers in competition: As part of research projects, the development of hardware components as well as the conception and implementation of demonstration setups based on the various technology platforms are publicly funded.
- At the same time, the industrialization of technically more mature technologies is taking place within the framework of contracts, in particular through the DLR's quantum computing initiative.
- Building a network for quantum algorithms and software. The focus here is on industry-specific applications that particularly address optimization problems and methods that address research in large data pools.
- Development of basic technologies: In addition to the fundamental technological developments of quantum computing, suitable technical equipment is required, among other things, to control the sensitive quantum states.
- Development of metrological foundations for the comparability of quantum computer hardware, such as the reliable measurement of qubit properties, coherence times, etc.
- Funding for the development of skilled workers: It is important to use outreach activities to arouse interest in quantum technologies in schools, to get students excited about the field and to develop funding formats for both academic and career paths in business.
  Tailor-made programs at the postgraduate level help to train qualified specialists for the development of quantum technologies.
- Support for spin-offs from universities and research institutions. The goal is to build a holistic, internationally competitive, entrepreneurial ecosystem for quantum technologies.

C. Create excellent conditions for a strong ecosystem

ÿ Create interfaces: Strengthen the ecosystems

In order to make the new technologies ready for application and therefore usable for the economy and society, the development of a functional, comprehensive ecosystem is necessary: from basic research to technology development to the user, in the training of technical specialists to engineering, computer science and physics, but also with accompanying networking measures and the development of a metrological quality infrastructure.

Germany brings with it a number of strong players in all relevant areas. The federal government's goal is to create close networking in all parts of the value chain in the form of an entrepreneurial ecosystem. This is intended to enable the targeted and synergistic development of quantum technologies that are economically self-sustaining in the long term.

The federal government is strengthening the quantum technology ecosystem with the following means:

ÿ Direct project funding from the federal government is generally aimed at associations from business and science. Project consortia are supported that cover as many parts of the value chain as possible. Through joint research and development work, close bonds are created between basic researchers, developers and users and ideas are pursued in a targeted manner. The development of characterization, qualification and standardization of quantum technology components of the value chains is considered from the outset and included in the measures.

ÿ At the same time, the entrepreneurial ecosystem is stimulated by co-located research contracts: innovative quantum computers for the DLR's own needs are procured through research contracts. In the European partnership EuroHPC, which is co-financed by the federal government, quantum computers for locations of the Gauss Center for Supercomputing in Germany are also being procured with a comparatively lower financial volume. With this instrument, more technologically mature approaches will be developed by companies, especially start-ups, in the medium term. Close cooperation with the DLR also creates incentives for highly innovative companies from the European economic area to locate research, development and production in Germany.

ÿ Focused networking meetings, seminars and symposia accompany the research and development activities within the technology strands. They enable exchange and synergies across individual project consortia. In addition, comprehensive exchange forums and seminars are offered, an accompanying analysis of the ecosystem is created and cross-sectional topics are discussed in joint workshops in order to create a powerful ecosystem. This also ensures that synergies are created and the resources used are used efficiently.

ÿ Strengthen start-up culture and innovative companies

Start-ups and research-focused small and medium-sized companies will play an important role in technology development. Cooperation models with large companies are also proven success factors.

The federal government supports young, innovative companies in this regard ÿ Specific funding that allows spin-offs from universities and research institutions in the field of quantum technologies to develop innovative ideas towards a application and commercial exploitation30,

ÿ the expansion of technology transfer in all facets at the level of institutional and strategic development of publicly funded research institutions, especially through spin-offs,

ÿ specific support31 and targeted approach to small and medium-sized companies,

ÿ Easier access, especially for young companies, startups and small and medium-sized companies, to existing quantum technology expertise and infrastructure at universities and research institutions. This is particularly necessary in the deep tech field of quantum technology in order to effectively bring Germany's excellent starting position in research1,2 into application and the market.

ÿ Networking with public venture capitalists (in particular the High-Tech Gründerfonds, DeepTech & Climate Fund, SPRIN-D Federal Agency for Leap Innovations) as well as long-term oriented, local private investors.

ÿ Arouse interest, attract skilled workers

Quantum technologies are still a comparatively abstract topic that requires explanation, and communication represents a major challenge. However, a discussion of the technology and its applications requires a generally understandable approach.
In addition, there is a need for realistic expectations regarding the potential, the pace of development and the limits of the technology, especially among decision-makers from business and politics. Generally understandable information and specific knowledge about the applications of quantum technologies are therefore also necessary in general and school education.

There are already signs of bottlenecks in recruiting suitable academic specialists2 .
Communication concepts that are appropriate to the addressee are therefore extremely important. The aim is to arouse interest at a low threshold in order to inspire the specialists of tomorrow, as well as to show the potential to non-specialist users. Employees in companies must be empowered to use the technology. And of course there is also a need for highly qualified specialists, especially for the further development of the technology. Therefore, it is important

- to show opportunities and possibilities for different professional development paths,
- the needs of in the sense of an evidence-based education and research policy To analyze developers and users of quantum technologies in Germany as well as the relevant capacities in the area of skilled worker training in order to to estimate the extent of the necessary measures,
- To facilitate access to quantum technologies in disciplines outside of physics, especially in related areas such as computer science and the engineering sciences,
- To support the training and further education of specialists in quantum technologies. The focus is particularly on the qualifications of experienced professionals.

The federal government has already put together a broad package of measures. Under the umbrella brand “Quantum Futur” 32 , various measures are being taken to build up a skilled workforce: young scientists can have their first small

30 Funding Guideline “Enabling Start-up – Start-ups in Quantum Technologies and Photonics - Quantum Technologies”
31 Funding guidelines https://www.quantentechnologies.de/forschung/foerderung/kmu-innovativ-photonik-und-quantentechnologies.html
32 https://www.quantentechnologie.de/nach Growth.html

Setting up a working group, training and further education concepts are being implemented and younger students are also getting excited about the topic at an academy and an award ceremony. Intuitive and participatory outreach concepts for quantum technologies should also appeal to broader sections of the population.

As part of this action plan, these measures will be further developed together with new ideas for knowledge transfer and civil society participation. The biggest challenge in the future will be to address and reach different target groups.
This is the only way to ensure that tomorrow's skilled workers are available in sufficient numbers, that the right decisions can be made when dealing with the topic and that social acceptance of the topic can be created.

One focus of the activities will be on the increased support of excellent young talent: starting with the networking of outstanding students and the specific support of doctoral students through to targeted measures such as “Quantum Fellowships” or academic junior groups for excellent postgraduates, who are particularly urgently needed for technology development . In addition, particular attention should be paid to young people who can provide the next generation of skilled workers in the emerging quantum technology market. To this end, age-appropriate, activating formats of research-based learning should be developed, for example through participatory activities in schools.

At the same time, the further training of experienced professionals and technical staff from thematically related fields should be promoted, as particularly good prospects for broadening the skilled worker base are seen in this area2.

ÿ Keep an eye on impacts: identify opportunities and consider impacts

In order to build future technology, new developments must be recognized early and taken into account strategically. For its measures, the federal government relies on the results of broad agenda and strategy processes with the participation of experts from science and business.25,33 The positions of expert commissions12, academies1 and associations34,35 are also taken into account.

Due to the rapid development of technology, the federal government is in constant communication with the specialist community in order to be able to take new developments into account at an early stage. For this purpose, specialist committees with external expertise are used, sometimes in fixed advisory groups, sometimes in technical discussions on specific subject areas. As part of the accompanying research, systematic, continuous monitoring of the ecosystem is also set up.

At the same time, the participation of citizens in order to accept new quantum technologies must accompany technology development. Direct and early collaboration between researchers and future users as part of participatory technology development promotes practical and needs-oriented technical solutions. Quantum technologies will change society in many places: from direct contact with the new technology in medicine, mobility and communication to questions of resilience to questions of internal and external security - citizens and the economy, state and society will be affected in a variety of ways be affected by new developments. So far, the discussion has focused on the opportunities and options offered by the technology. Risks are currently mostly seen in the sense of lagging behind in development compared to competing ones

[33] “Agenda Quantum Systems 2030”, VDI Technology Center (2021)
[34] “Developing Europe into a leading location for quantum technologies”, Federal Association of German Industries (BDI) (2021)
[35] “Quantum technologies in companies”, Bitkom eV (2022)

countries discussed. As technologies mature and are used, questions will increasingly arise about social and cultural influences, technology assessment and the prevention of adverse side effects.

In addition to questions about social effects on society as a whole due to the impact on everyday life and the world of work, the focus in the area of innovation management, for example, is on discussions about the impact of access to quantum technologies (e.g. by small and medium-sized companies), what effect quantum technologies have on individual industries and supply chains, etc have on national security preparedness and what specific innovations they bring about.

Last but not least, quantum technologies will have a significant impact on modern cryptography. As soon as powerful quantum computers become available, the security of standard cryptographic methods used today will no longer be guaranteed.
Quantum communication can solve this problem through quantum-based key agreement36. In combination with post-quantum cryptography based on mathematical principles, the confidentiality of sensitive information can be maintained in the long term. However, the new risks arising from technology, particularly for information security and data protection, must be evaluated, monitored as technology develops and effective countermeasures designed.

Overall, it is important to keep an eye on the consequences at an early stage, to counteract possible undesirable developments promptly and to have an open discussion with social actors.

[36] Economic-technological revolution through Quantum 2.0, Deutsche Bank Research (2021)

4. Act together – act confidently

ÿ Joint action by the federal government

The federal government coordinates its measures in quantum technologies at various levels in an interdepartmental manner. The aim is to avoid duplication of work, to define interfaces and handover points and to bring together development strands beyond the respective areas of responsibility of the departments.

The activities of the departments are thought of together from the outset and are regularly coordinated at management and working levels. The central committee at working level is a departmental group in which all thematically involved departments work together on current developments and planned measures in a topic-oriented manner.

In addition, as part of project funding, activities are coordinated together and at an early stage in order to create synergies. This includes joint, cross-departmental activities to strengthen ecosystems and networking between various funded actors.

With increasing technological progress and greater proximity to applications, the federal government expects the commercial sector to gradually assume increasing responsibility for the ecosystem and research and development activities. The Federal Government will accompany this development through accompanying analyzes and adapt and further develop its measures on this basis.

ÿ Interdisciplinary interfaces

The interdisciplinary field of quantum technologies has points of contact with several other key technologies. The ability to connect to existing technologies is also important, for example the embedding of quantum computing in the infrastructures of "High-Performance Computing" (HPC), the creation of "software stacks", or the embedding of quantum communication in modern information and communication technology, in particular at the interface to artificial intelligence. In addition, it requires

Further development also includes technological advances, for example in the areas of microelectronics, photonics and cryogenics. This anchoring is ensured through joint projects in the interfaces and placement in the relevant research programs. Consequently, there are intersections with various other programs of the federal government or individual departments, for example in the areas of microelectronics, high-performance computing, cyber and IT security or space research (see also appendix "Research programs, strategies and measures of the departments with reference to the action concept").

ÿ Networking with national actors

The measures are closely linked to the activities of institutions funded by the federal government that are active in the field of quantum technologies. An overview of the measures taken by these institutions is provided in the appendix.

There are strong regional centers in Germany that are supported by targeted measures from the federal states. Close networking with the specific measures and priorities of the federal states is ensured in regular coordination rounds at working level. Important impulses also come from close contact with academies and associations.

ÿ Build strong international partnerships and secure technological sovereignty

The aim of the federal government is to promote an entrepreneurial spirit through holistic support Quantum technology ecosystem has sovereign access to all relevant building blocks of this To secure future technology and its development and application at eye level and in the to help shape our values. The Federal Government is relying on a strategic European approach with the political goal of technological sovereignty.[37]

European measures that are dedicated to quantum technologies have been brought together at the European level since 2018, mainly in the Quantum Flagship, supplemented, for example, by European funding for metrological aspects within the framework of Euramet[23,38]. After the ramp-up phase of the flagship has been completed, the course should now be set for successful implementation. To this end, research and development as well as the development of infrastructure are supported as part of the Horizon Europe and Digital Europe programs. Networking of national and European funding measures takes place at different levels. Transnational funding projects are supported as part of the QuantERA initiative. This also applies to larger structural measures such as the pan-European procurement of quantum computers and their integration into an HPC environment in EuroHPC [39] or the development of a European quantum communications network (EuroQCI) [40]

and its space component SAGA, there is close coordination with the EU Commission, ESA and other EU member states as well as a pooling of national and European funds. Furthermore, the Framework Partnership Agreement for “open testing and experimentation” was launched, which aims to bring together European testbeds for quantum technologies[15] . In the area of standardization, the publication of the roadmap on standardization needs of the European CEN-CENELEC is expected in the next few months[10, 18].

It is important to continue to coordinate closely with European partners, particularly on questions of technological sovereignty. The aim is to achieve a leading position in global competition with European partners, particularly in quantum computing and quantum communication, and to position Europe as a technology provider. This is also intended to prevent Europe from falling into critical dependencies.[41]

The Federal Government is strengthening these European initiatives through targeted bilateral and multilateral activities with partners. The prerequisite for these initiatives is that they:

- ÿ allow collaboration in the spirit of our values and on an equal footing,
- ÿ are conducive to the goal of technological sovereignty, and
- ÿ a mutual added value of the cooperation through the complementary complementarity of skills and technologies can be expected.

In combination with national and European activities, targeted impulses can be set and the ecosystem strengthened.

In addition to the targeted strengthening of cooperation, the risk of know-how draining to non-European countries must also be taken seriously. Against this background, the Federal Government is pursuing various approaches in its measures to prevent the outflow of technological expertise in this future technology, for example through the instrument of back-licensing for contractors as part of the DLR quantum computing initiative, through appropriate project funding regulations and through measures in the Framework of foreign trade law.

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[37] Shaping the future with technological sovereignty – BMBF impulse paper on technological sovereignty (2021)
[38] https://www.euramet.org/about-euramet
[39] https://eurohpc-ju.europa.eu/new-calls-first-eurohpc-quantum-computers-and-upgrades-existing-eurohpc-systems-2022-03-31_en
[40] https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci
[41] https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_de

5. Milestones and resource planning

The success of the action concept is measured by milestones that serve as a research policy level for monitoring goal achievement. They are regularly reviewed and, if necessary, adapted to the dynamic development of the international research field. By the end of the action plan's term in 2026, the following milestones should have been achieved in Germany, depending on the technology strand:

ÿ **Quantum computing**

The aim is for Germany to become one of the leading technological players in quantum computing outside the EU. This is primarily about competitiveness in a purely technical sense, such as the availability of quantum hardware, its performance and an estimate of potential for scaling, error rates and error correction. Measurable technology goals in 2026 include:

- Availability of an internationally competitive quantum computer with at least 100 individually controllable qubits, scalable to 500 qubits.
- Development of powerful special hardware for suitable application areas of quantum computing.
- In addition, the techno-economic development of the entrepreneurial ecosystem for quantum computing in Germany should be among the top three within the EU and at least reach the level of important non-European industrialized countries such as the USA or Japan. Related quantitative indicators include

  ÿ Sales, number of employees and profitability accumulated across the companies ecosystem in Germany

  ÿ Development of the number of patents related to quantum computing by companies in the ecosystem and by German research institutions

  ÿ Degree of coverage of QC-relevant technology sectors by companies ecosystem

  In addition, the degree of networking of the companies in the ecosystem should be recorded in the sense of how many companies or scientific partners there are on average Cooperation or other economic networking such as equity investments, spin-offs, etc.

- At least 60 end users in Germany are active in quantum computing, including in business, science and civil society.

ÿ **Quantum sensing:**

In quantum sensor technology, the federal government wants to apply promising technological developments in the economy, society and government institutions. The following level of development should be achieved in Germany in 2026:

- Five new products in quantum sensing on the market, as well
- Optical clocks that meet the requirements of the next generation of Galileo clocks.

ÿ **Quantum communication and post-quantum cryptography:**

The federal government wants to achieve the following milestones in quantum communication and post-quantum cryptography by 2026:

- Establishment of the first tap-proof, i.e. quantum-encrypted, Communication test routes between selected authority locations. • Other start-ups/ companies are in the field of quantum communication in Germany founded.
- Realization of a nationwide fiber optic backbone for quantum communication and the Time and frequency distribution.

- Demonstration of the first quantum repeater test tracks.
- Launch of the first test satellites for quantum key distribution.
- Creation of a federal government strategy for migration to post-quantum cryptography in Germany.
- Continuation of the migration to post-quantum cryptography for high-security areas.
- Initiate migration to post-quantum cryptography in other security-critical areas areas.
- Integration of post-quantum cryptography processes into practical IT security solutions.

For a later transfer into productive systems, further steps are required in the area of testing, approval and technical upgrading of the components and infrastructure involved.

ÿ **Characterization and standardization**

The aim is to establish quantum technologies “made in Germany” as a global quality feature Federal government until 2026

- Establishment of a quality infrastructure for quantum technologies for objective, independent characterizations, qualification and standardization of quantum technology components and comparative benchmarks.

In addition, the effects of the federal government's measures are monitored using other overarching and topic-specific indicators, which are evaluated as part of evaluations of the programs on which this action plan is based (see also the appendix).

Funding planning

Overall, during the term of the action plan for the further development of quantum technologies in the departments involved, budget funds amounting to approximately 2.18 billion euros are earmarked in the current financial planning. The measures are supplemented by the activities of the scientific organizations co-financed institutionally by the Federal Government, which plan to invest around 850 million euros in research in quantum technologies during this period.

A general financing reservation applies. To the extent that specific measures or subsequent future measures lead to expenditure in the federal budget, they are subject to available budget funds or positions/ positions and do not prejudge current or future budget negotiations. The departments support the implementation of the strategy according to their responsibilities and financial resources. Any additional requirements for material and personnel resources must be financed financially and in terms of staff within the respective individual plan; additional funds are not available.

6. Appendix

ÿ Departmental research programs, strategies and measures related to the Action concept

ÿ Future research and innovation strategy of the Federal Government

The future research and innovation strategy creates the basis for Germany and Europe to play a decisive role in the major research and innovation policy issues of the coming years. On this basis, we want to use impulses and experiences and learn from the current crises as drivers of social change processes.

ÿ The Federal Government's digital strategy 42

The digital strategy brings together the federal government's political priorities on the cross-cutting issue of digitalization under one roof and forms the overarching framework for digital policy until 2025. The strategy provides an overview of the key digital policy projects that each department is responsible for

implemented.

ÿ "Quantum systems research program – developing cutting-edge technology. Future design." 43

The research program "Quantum Systems – Developing Cutting-Edge Technology. Shaping the future." sets the strategic framework for research funding by the Federal Ministry of Education and Research (BMBF) in the future technologies of photonics and quantum technologies over the next ten years. The funding follows the mission of the research program: to make Germany a world leader in the European network in quantum computing and quantum sensors in the next decade and to expand Germany's competitiveness in quantum systems. The aim is also to secure technological sovereignty and to use the opportunities offered by quantum systems for a modern and sustainable economy and society.

ÿ "Digital. Safely Sovereign"44 - the Federal Government's research framework program for IT security

With the research framework program "Digital. Secure. Sovereign.", the federal government is strengthening excellent research for IT security and privacy and paving the way for economic prosperity and technological sovereignty in Germany and Europe.

Research funding on quantum communication is an important part of the supporting program. The goals with regard to quantum communication are, above all, the improvement of the performance of quantum communication components and other quantum mechanically based security and robustness from concepts, the development of hybrid quantum communication systems based on various transmission and storage technologies and the further development of secure and efficient concepts for quantum networks and their integration into the existing classical communication and IT infrastructures. To the

In order to meet the challenges of decryption using quantum computers, research will be carried out in parallel with how a migration to post-quantum cryptography can take place. In addition, possible attack strategies on quantum information systems will be analyzed and effective countermeasures will be developed.

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[42] https://digitalstrategie-deutschland.de/static/1a7bee26afd1570d3f0e5950b215abac/220830_Digitalstrategie_fin-sperrfrei.pdf
[43] Quantum Systems Research Program, BMBF (2021)
[44] Digital. Secure. Sovereign. - Federal Government Research Framework Program on IT Security, BMBF (2021)

ÿ **“High-performance computing for the digital age. Research and Investments in high-performance computing.”**
With the program, the BMBF promotes the expansion of computing infrastructure into the exascale range and innovations in high-performance computing, advances applications in business and strengthens high-performance computing at universities. This is accompanied by research approaches to develop efficient and powerful hardware and software for future computer systems and applications. In order to bring new computing technologies such as quantum computing into application more quickly, they should be integrated into the existing ecosystem of high-performance computing. Furthermore, centers for supercomputing, such as the locations of the Gauss Center for Supercomputing, provide good conditions for the integration of quantum computers.

ÿ **“Microelectronics. Trustworthy and sustainable. For Germany and Europe.” Federal Government Framework Program for Research and Innovation 2021-2024[45]**
An important technological and structural interface exists particularly in the area of microelectronics, which is supported in the framework program “Microelectronics.
Trustworthy and sustainable. For Germany and Europe” is anchored. The classical electronics addressed there are an important enabling technology, especially for controlling quantum computer chips. There is also an overlap in terms of process technology in the production of semiconductor-based quantum chips.

ÿ **Cybersecurity strategy for Germany 2021[46]**
The cybersecurity strategy published in 2021 forms the strategic framework for the federal government's actions in the area of cybersecurity for the next five years. It describes the fundamental, long-term orientation of the federal government's cybersecurity policy in the form of guidelines, areas of action and strategic goals. It has an active, creative character and is intended to enable and promote targeted and coordinated cooperation between all actors. The cybersecurity strategy for Germany and the cybersecurity strategies of the federal states complement each other and thus intensify federal cooperation. Embedded in the European cybersecurity strategy, the cybersecurity strategy for Germany also contributes to shaping Europe's digital future.

ÿ **“National Program for Space and Innovation” – The Federal Government’s space program**

The BMWK promotes German space research through the DLR Space Agency on the basis of the National Program for Space and Innovation in research and development projects by German companies, research institutions and universities.
Over the past two decades, a high level of technology development expertise for space quantum technology has been built up in basic research projects. The results and competencies are now being transferred into applications while expanding Germany's leadership role and the potential of quantum technology for satellite navigation (optical clocks and inertial navigation), satellite communication (quantum key distribution), earth observation (gravimetry/gradiometry)

as well as

Automation technology and robotics (quantum computing to increase the autonomy of future space systems).

ÿ **Technology program “Quantum Computing – Applications for Business” and Major project “PlanQK - platform and ecosystem for quantum-supported artificials Intelligence"**

45 Microelectronics. Trustworthy and sustainable. For Germany and Europe.” Federal Government Framework Program for Research and Innovation 2021-2024, BMBF (2021)
46 Cybersecurity strategy for Germany, BMI (2021)

With this technology program, the BMWK supports research, development and innovation projects that prove and demonstrate the technical feasibility and economic viability of quantum computing using the example of relevant, practical use cases, particularly for medium-sized companies. The addressed ones

Quantum computing applications include, among other things, material simulation for hydrogen research, machine learning for the evaluation of used vehicles and the optimization of processes in production and logistics. In addition, within the funding measures, the foundations for GDPR-compliant cloud solutions for quantum computing operated in Germany and Europe are being developed. In addition, the platform developed in the major project "PlanQK - Platform and Ecosystem for Quantum-Based Artificial Intelligence" already offers users and developers of software for

Quantum computing provides public access for the use and joint implementation of quantum computing solutions. In total, 10 collaborative projects with a total of 67 partners from business and science will be funded with around 50 million euros.

ÿ Overview of activities of subordinate authorities, agencies and institutionally supported institutions

ÿ Agency for Innovation in Cybersecurity GmbH (Cyber Agency)

The cyber agency finances and promotes medium to long-term research projects with high disruptive potential in the field of cybersecurity and related key technologies. The cyber agency should consciously act in a risk-taking manner (open innovation and venture culture) with high technological ambition. The cyber agency is not a university research institution and does not conduct independent research within the framework of programs and projects. Its aim, within the framework of its entrepreneurial and scientific freedom, is to advance topics of cybersecurity and related key technologies of internal and external security in a needs-based and application-oriented manner and thereby make a contribution to Germany's technological sovereignty in the cyber and information space.

As part of the cyber agency's current strategy (2022-2025), research projects to promote cybersecurity in the field of quantum technologies are also to be advertised.

ÿ Federal Office for Information Security (BSI)

The BSI recommended the first quantum-safe processes in March 2020 and published more detailed assessments and recommendations on migration to quantum computer-resistant processes in its guide "Making cryptography quantum-safe" from December 20214. Approved products that have implemented quantum computer-resistant processes are already available in the high-security area. In addition, the BSI carries out projects to investigate the security of quantum key distribution, which are intended to contribute to the development of trustworthy and secure products.
The BSI is involved in the standardization of the quantum-safe processes FrodoKEM and Classic McEliece recommended by it at ISO/IEC. In October 2022, a preliminary work item for the project "Inclusion of key encapsulation mechanisms for PQC in ISO/IEC standards" was launched in ISO/IEC SC27 WG2 following a proposal from the BSI.
This project will produce ISO standards for FrodoKEM and Classic McEliece.
In order to continue to monitor the state of research on quantum computers, the project "Ongoing update of the quantum computer development study" will annually over the next three years revise the "Quantum computer development status" study, which was created in 2017 and has already been updated twice (https://bsi.bund.de/ qc study) carried out. In the first revision of the study, the NISQ area (Noisy Intermediate Scale Quantum) will be dealt with more intensively and the developments in the

Error correction discussed. In addition, an expanded understanding of operational Criteria are obtained and the descriptions of algorithms, error correction and platforms are updated. Once the revision is complete, the new version will be available on the above website.

As part of the BSI project "Secure implementation of a general crypto library", which was completed in 2017, a BSI development branch including detailed crypto documentation for the Botan crypto library was created. In the current BSI project "Maintenance and further development of the Botan crypto library", a selection of quantum computer-resistant processes is now being implemented in Botan, taking into account current developments in the NIST standardization process and the BSI recommendations.
The aim of this is to create a crypto library that has been tested according to current knowledge for the application and use of post-quantum cryptography in order to promote the widespread use of quantum computer-resistant cryptography.
In the current BSI project "Integration of post-quantum cryptography into the email client Thunderbird" quantum computer-resistant end-to-end encryption (E2EE) is being implemented with encrypted and digitally signed emails. For this purpose, the OpenPGP-based public key cryptography of the popular email client Thunderbird is expanded to include encryption and signature procedures from post-quantum cryptography.
In addition to the implementation activities, a large part of the project is a corresponding standardization draft in the form of an RFC Internet Draft, which is intended for submission to the OpenPGP working group of the Internet Engineering Task Force (IETF).
In the feasibility study "Quantum computer-resistant authentication for VS-IT systems", which runs until February 2023, the implications of quantum computer-resistant authentication procedures on existing and VS-IT systems under development are being examined by an external contractor. The signature algorithms currently in the NIST standardization process as well as the products of the manufacturers of VS IT systems known to the BSI are considered. In particular, limitations such as the performance of the signature algorithms, cryptoagility and the migration capability of the VS IT systems are taken into account in this feasibility study.

In collaboration with the European Telecommunications Standards Institute (ETSI), the BSI has pushed forward the creation of the first protection profile for quantum key distribution (QKD) modules according to Common Criteria. The Protection Profile, which is limited to the consideration of prepare-and-measure protocols and point-to-point connections, is now available in an initial version and will be certified soon. It represents a first step towards an evaluation methodology, but requires the development of further standards and background documentation until certification of specific products is actually possible.

Achieving a secure implementation of QKD protocols requires a solid understanding of the possible side-channel attacks on QKD modules, which have already been demonstrated for many concrete implementations. To this end, the BSI has commissioned the creation of a study that is intended to present the current state of scientific research on side channel attacks on QKD systems in a uniform and complete manner. This is a necessary first step toward establishing an evaluation methodology for QKD side-channel attacks.

The BSI, in close collaboration with the PTB, is involved in the coordination of the BMBF-funded “Umbrella Project Quantum Communication Germany”. The central goal of the umbrella project Quantum Communication Germany is to establish quantum communication as a technology that can be used in practice, is secure and commercially available in Germany and Europe. The BSI focuses on the early consideration of aspects of information security (e.g. the security of QKD protocols).

- **Bundesdruckerei GmbH**

Bundesdruckerei GmbH and its subsidiary Maurer Electronics GmbH are a leading German high-tech security company headquartered in Berlin. It protects identities and data with innovative solutions, products and technologies “Made in Germany”. In this way, it creates trust and legal certainty in the digital society - and enables states, companies and citizens to act sovereignly in the analog and digital world. As a company in the Bundesdruckerei Group and with over 250 years of experience, the company is paving the way to a secure digital future. Bundesdruckerei GmbH currently owns over 4,100 national and international patents, currently employs around 2,600 people and achieved sales of 642 million euros in 2021.

Bundesdruckerei has been working with quantum technologies since the PlanQK and PoQuiID projects. The interest in both projects was a proof of concept for application scenarios with the project partners' quantum computing capacities that are currently being developed. In 2021, the Qu-Gov project – quantum technologies for the federal administration was added, a direct commission from the Federal Ministry of Finance. A top-down approach is pursued here, in which proof-of-concepts or proof-of-values are developed for use cases from the sovereign and official environment and evaluated in a platform-open manner. Quantum technologies for the federal (finance) administration will be evaluated, researched and initial use cases tested by the end of 2024. The main topics here are

- Quantum information/security, quantum
- analytics and •

quantum-related (data) sovereignty.

The project relies on partners from science, industry, start-ups and administration and on collaborations. The first partners have already been found or are being selected.

This project represents an interface between science, industry and administration and sees itself as an enabler for a modern, future-oriented administrative structure, which should seamlessly tie in with digital topics such as the Federal Data Atlas and the Federal AI Competence Center.

At this time, the Bundesdruckerei founded the “Federal Quantum Alliance” (BQA) with DB Systel in order to research quantum technologies for the federal administration with federal or federally affiliated companies beyond the project. The BQA is currently in discussions with other federal institutions such as PTB and BAM. This federal quantum alliance is therefore a useful addition to the various “quantum alliances” communicated to date in Germany, as it explicitly addresses federally owned companies and authorities and can multiply the knowledge gained in the Qu-Gov project. Further information at www.bundesdruckerei-gmbh.de.

- **BWI GmbH**

As a wholly owned federal company, BWI GmbH is the Bundeswehr's IT system house. As a link between the military and industry, BWI operates and develops the IT of the German armed forces, carries out and tests digital transformation projects
and implements innovative use cases. Particularly in the latter case, BWI's focus is on the early and application-oriented use of new technologies. The BWI clearly differentiates itself from research in its service portfolio; the BWI primarily relies on research results and enables the subsequent implementation of these into practice. For this purpose, the Competence Center Quantum Enabled Technologies was founded in BWI's Innovation & Technology department.

The declared goal is to raise awareness of quantum technologies in the BWI and Bundeswehr environment. Through market and technology screenings, knowledge transfer from consulting projects and isolated tests, concrete recommendations for action are derived for the BWI service portfolio.

ÿ **German Research Foundation (DFG)**

The primary task of the DFG is to promote cutting-edge, insight-led research. The DFG is particularly active in those areas where research finds its own topics and follows the dynamics of scientific knowledge processes. Individuals, groups or institutions who are eligible to apply can therefore submit funding applications to the DFG at any time and on any topic. The increasing demand both in individual funding and within the framework of coordinated programs and the associated increasing volume of approvals in the field of quantum technology show that the DFG's instruments address the needs across the entire spectrum of funding.

In 2021, a total of 149 projects with an annual approval amount of 58.6 million euros with a direct connection to the research field of "quantum technology" were in ongoing funding. Of this, 40.4 million euros went to clusters of excellence47. This corresponds to an increase of around 11% within three years.

In coordinated programs (collaborative research areas, graduate colleges, clusters of excellence), individual research areas are often heavily influenced by quantum technology, while the entire consortium pursues basic research in the natural sciences and engineering.

As part of its creative and strategic activities in the European Research Area, the DFG participates in the ERA-Net QuantERA (www.quantera.eu). The EU-funded network of 39 research funding organizations from 31 countries supports research on quantum technologies, particularly through calls for proposals for transnational projects.

In the last call for proposals, the DFG was responsible for funding participation from Germany in basic science-oriented projects. The 19 projects partially financed by the DFG will start in 2022. The next call for proposals in which the DFG plans to participate will take place in 2023.

As part of two large-scale device initiatives to research quantum technology that were launched in 2021, the DFG is supporting eight universities with a total of approximately 17.7 million euros. The aim of large-scale equipment initiatives is to make the latest technology usable for research. Two calls were launched: "Spin-based quantum light microscopes" and "Testbeds for Quantum Communication" (QCDE).

In addition, since 2021, the DFG has been funding the graduate school "PhD experts in photonic quantum technologies", which aims to establish a new professional group of "photonic quantum engineers". (https://gepris.dfg.de/gepris/projekt/431314977).

ÿ **German Weather Service (DWD)**

Due to their need for computing power and storage capacity, weather and climate simulations represent a primary use case for the use of high-performance computing (HPC) infrastructures. With the ICON-Consolidated development line, the DWD and its partners from the ICON consortium (MPI-M, DKRZ, KIT) also presents the weather and climate model ICON for future HPC architectures. If the technology is sufficiently mature, this will also happen for architectures based on quantum computing. The expected extreme increase in computing power will be even more precise

[47] The following clusters of excellence have a very strong connection to quantum technologies:
- ~~Complexity and topology in quantum materials (CT.QMAT)~~
- ~~QuantumFrontiers - Light and matter at the quantum frontier~~
- ~~CUI: Advanced Imaging of Matter~~
- ~~Munich Center for Quantum Science and Technology (MCQST)~~
- ~~Matter and Light for Quantum Information (ML4Q)~~

Allow simulations of atmospheric processes at a resolution that has never been achieved and at the same time better quantify the uncertainties. The development of quantum computing for the application of solutions to mathematical equations that describe processes in the atmosphere is therefore very useful and necessary.

ÿ **Research Institute Cyber Defense and Smart Data (FI CODE) at the University of Bundeswehr Munich**

The FI CODE has been a so-called IBM Quantum Hub since 2018 until 2023 and thus has one of only a few exclusive accesses to the IBM quantum computer infrastructure in the world.

The current availability of small, noisy quantum computers enables researchers at FI CODE to develop quantum algorithms and
to test heuristics and error reduction schemes and to carry out experiments to research and apply quantum information processing.
On the way to the practical relevance of quantum computing, FI CODE is pursuing various applications in the areas of optimization, machine learning and quantum simulation and developing methods for circuit optimization and error reduction.
FI CODE intends to extend the cooperation with IBM as IBM Q Hub beyond 2023.

ÿ **Fraunhofer Society for the Promotion of Applied Research e. V. (FhG)**

The Fraunhofer-Gesellschaft is the world's leading organization for application-oriented research. With its focus on future-relevant key technologies and on the exploitation of the results in business and industry, it plays a central role in the innovation process.

Quantum technologies are currently in the crucial initial phase of the second quantum revolution, which will trigger disruptive changes in science, business and society. The **Fraunhofer-Gesellschaft** is addressing this challenge in quantum technologies in the following way:

• The Fraunhofer Society Based on its application expertise, **it identifies quantum added value** in communication, computing, imaging and sensing in close cooperation with business partners . **empowers** technology platforms in a

• The Fraunhofer Society holistic under use more established approach

o Science for excellent basic research o and the economy

for outstanding innovations in quantum technologies. • The Fraunhofer Society **qualifies** graduates in a cross-disciplinary and cosmopolitan manner in close cooperation with universities

existing specialists in the natural and technical sciences and actively contributes to community building. • The

Fraunhofer-Gesellschaft **operates** active **patent portfolio management** and **promotes the founding** of companies in quantum technologies as part of the programs of its performance centers .

• The Fraunhofer Society **supports the development of technologies** in the field of quantum computing, particularly through the establishment of a Germany-wide quantum computing competence network and as part of its cooperation with IBM Deutschland GmbH. It uses considerable resources of its own to make the system in Ehningen available to the scientific community, business, SMEs and start-ups and conducts research in the field of quantum computing - alone and in consortia. The aim is to continue the collaboration with IBM beyond the current contract (02/2020 - 02/2024).

The Fraunhofer-Gesellschaft has been intensively dedicated to this key technology since 2016 and supported the first large-scale research activities in 2017 with the lead project QUILT (focus: quantum imaging, with high standards of scientific excellence and strong application potential).

In addition, the Fraunhofer Society offers the German R&D landscape access to an existing quantum computer under German/European legal and data bases and data locality.

In the future, too, the Fraunhofer-Gesellschaft wants to specifically exploit the potential of promote quantum technologies in Germany and Europe and sees opportunities for this in particular in the following areas:

ÿ **Targeted development of system competence** to help shape a scientific and technological paradigm shift.
Participation in a sovereign, pan-European digital infrastructure with quantum-secure networks to protect the state, industry & civil rights and quantum-supported computing capacities for R&D in energy, climate & health.
ÿ **Portfolio of intellectual property rights & IP pooling** for “freedom-to-move” in Europe. ÿ **Establishing fabs & pilot lines for closed supply chains** in one competitive & autonomous German-European economic area, including the Research Factory Microelectronics Germany (FMD) with the module “Quantum and Neuromorphic Computing”.

ÿ **Helmholtz Association of German Research Centers e. V. (HGF)**

The Helmholtz centers that contribute to research in quantum technology48 are organized in the “Helmholtz Quantum” platform, which has published an overarching strategy for the Helmholtz Association49. It identifies five quantum technology fields in which the centers conduct their research contribute with different focuses: 1. quantum computing, 2. quantum communication, 3.

quantum sensing, 4. quantum materials and basic research and 5.
Quantum simulations and numerical methods.

Current research ranges from understanding fundamental quantum phenomena to the design of quantum states to the development of components for the realization and use of fully functional devices and prototypes. The plan is to develop and provide infrastructure together with the user communities, including exchange platforms and qualification programs, in order to leverage potential for the implementation of applications, co-design and future personnel. These include material characterization platforms, quantum computing high-performance computing centers, or the development of a broadly usable software package for quantum computing. Strong in materials expertise is necessary in the long term for excellent, disruptive technologies, while the integration of quantum computers in high-performance data centers both makes the full potential of quantum computing accessible and connects the user community at an early stage.

Large software packages now reach the complexity of infrastructures and are

48 German Electron Synchrotron (DESY), German Aerospace Center (DLR), Research Center Jülich (FZJ), GSI Helmholtz Center for Heavy Ion Research (GSI), Helmholtz Center Berlin (HZB), Helmholtz Center Dresden Rossendorf (HZDR), Karlsruhe Institute of Technology (KIT)

49 Quantum Strategy Brochure: https://www.helmholtz.de/forschung/im-focused/quantentechnologie/, Helmholtz Association of Germans Research centers (2021)

a requirement for users. In the field of sensor technology, one of the declared goals is the lab-on-chip integration of quantum sensors for application areas such as biology or medicine.

Together with partners from universities, research organizations and industry, the Helmholtz Association wants to define far-reaching technological goals for the next 10 years and beyond and pursue them together at all levels, from the scientific fundamentals to systems technology and applications.

In recent years, additional outstanding international scientists have been recruited to the community. Many centers are building new institutes to research quantum technologies, and the community is investing in core infrastructure that will serve as a technological hub to enable major advances. In the Helmholtz Association (as of 2021) around 500 people are already working directly on research into quantum technologies. The researchers lead and participate in small and large projects that are funded, for example, by the BMBF, the EU or Helmholtz itself, and are therefore closely integrated into the national and European strategy.

Examples of concrete goals for the next five years, as formulated in the strategy paper:

- Systematic further development of the promising scalable platforms for the realization of multiple qubits in order to realize small-scale demonstrators that go beyond the state of the art with up to 100 qubits and low error rates for quantum computers and simulations.

- Development of manageable electrically powered on-chip single photon emitters operating at room temperature and in the telecommunications band.
- Robust and miniaturized optical quantum systems (lab-on-the-chip technologies) for high-precision space, time and acceleration measurements under harsh space conditions. 50

- Exploring novel materials as a source for new metrological standards and innovative qubit concepts that go beyond current solid-state qubit systems. Creation of systematic multidimensional phase diagrams for Material candidates in terms of electronic and magnetic properties, topology and potential functionality.
- Development of algorithms, methods and tools for disruptive computing devices to solve very difficult and previously unsolvable computing problems in science and industry.

- Research into the technological basis for a tap-proof system Quantum communication network in Germany and Europe.51

An additional contribution from the DLR outside of the HGF's program-oriented research funding is the DLR's **Quantum Computing Initiative, which is funded with around 740 million euros from the economic stimulus package for the construction of quantum computer systems, development of software and initial applications.** The initiative's approach is to implement the systems by commissioning companies, especially start-ups. In addition, 80% of the funds flow into companies that cover their full costs and can even achieve a profit margin. This is particularly important for financially weak small and medium-sized companies or start-ups. In this way, an industrial ecosystem is being built in parallel through the development of quantum computers for the DLR's research fields. At the same time, the results (intellectual property) should

[50] https://www.dlr.de/content/de/artikel/news/2021/03/20210715_neue-uhren-fuer-die-satelliten-navigation-der-zukunft

[51] https://www.dlr.de/content/de/artikel/news/2021/03/20210810_erste_quantengesichere_videokonzept_zwischen_bundesbehoerden.html

and co-determination rights in this potentially sensitive technology area are secured for DLR, but the executing companies are given freedom of action through a back license. In addition, collocations at the DLR institutes in Hamburg and Ulm provide incentives for relevant innovative companies from the European economic area to settle in Germany.

ÿ **Max Planck Society for the Advancement of Science e. V. (MPG)**

The Max Planck Society (MPG) began early on to promote basic research on quantum science and technology (QST) in the spirit of the second quantum revolution. The Max Planck Institute (MPI) for Quantum Optics was founded in Garching in 1981, the experimental sub-institute of the MPI for Gravitational Physics in Hanover in 1993, the MPI for the Physics of Complex Systems in Dresden in 1994 and the MPI for the Physics of Light in Erlangen in 2009. In addition, the Max Planck Institutes for Solid State Research in Stuttgart, for Computer Science in Saarbrücken, for Nuclear Physics in Heidelberg, for Multidisciplinary Natural Sciences in Göttingen, for the Chemical Physics of Solids in Dresden, and for the Structure and Dynamics of Matter in Hamburg are also involved , for microstructure physics in Halle, for mathematics in the natural sciences in Leipzig, for intelligent systems in Tübingen, for security and privacy in Bochum and the Fritz Haber Institute in Berlin, some of which deal with aspects of this topic. With the basic research on QST at all of these institutes, the MPG sees itself as a pioneer and supporter of the current specialist programs for quantum technologies.

The MPG sees QST as strategically important topics, not only in terms of basic research, but also in terms of potential economic benefits. Germany is excellently positioned in the area of fundamentals and can take a leading role in the global competition for QST.

The MPG contributes central know-how in the area of QST, including in the following fields:

• ***Quantum computing*** (Garching, Erlangen, Bochum, Tübingen) •
Quantum simulation (Garching, Erlangen, Dresden, Hamburg) •
Quantum cryptography, quantum communication, quantum internet (Garching, Erlangen, Bochum)
• ***Quantum information theory*** (Garching, Leipzig, Saarbrücken) •
Quantum sensing, quantum metrology, quantum imaging (Stuttgart, Hanover, Heidelberg, Garching, Göttingen) •
Quantum components (Halle, Stuttgart, Dresden, Garching, Erlangen) •
Quantum materials (Stuttgart, Hamburg, Halle, Dresden)

The MPG sees its contribution to the national strategy primarily in the continuation and expansion of excellent basic research. This also includes the development of new subject areas, attention to patenting new ideas, the promotion of spin-offs and startups, and participation in national and international research networks. The MPG makes significant contributions to the transfer of fundamental phenomena of the second quantum revolution into application-relevant technologies.

The MPG was significantly involved in the expert council, which identified the central challenges in the field of quantum computing and made recommendations for future action in the form of a national roadmap at the beginning of 2021.

The MPG has sharpened its strategy regarding quantum sciences and technologies (QST); Extensive activities were launched both internally and externally, two of which are briefly explained below:

- *Max Planck Quantum Alliance (MPQA)*

An important part of a sustainable long-term strategy for the MPG in the area of QST is the establishment of an internationally visible umbrella organization that unites the various activities (new and existing) within the MPG and offers a platform for the implementation of further measures. This MPQA initiative aims to increase the global visibility of the MPG in QST, to strengthen the cooperation of the departments involved in the area of QST within the MPG, and to increase the competitiveness in attracting internationally very competitive top talent. Since some of the QST research topics lie between the core areas of different institutes (especially in terms of the scientific concepts and/or the required technological infrastructures), the interdisciplinarity of the QST represents a constant challenge.

- *Munich Quantum Valley (MQV)*

The MPG is the driving force behind the Munich Quantum Valley initiative, which aims to establish quantum computing and quantum technologies in Bavaria as a network of its kind that is unique in Europe. The members of the initiative (the Bavarian Academy of Sciences (BAdW), the Ludwig Maximilian University of Munich (LMU), the Technical University of Munich (TUM), the Friedrich Alexander University Erlangen-Nuremberg (FAU), the Fraunhofer Society (FhG), the German Aerospace Center (DLR) and the MPG) signed the founding certificate of the MQV association on January 27, 2022. The Free State of Bavaria is supporting the initiative with 300 million euros in funding from the Bavarian High-Tech Agenda until 2025. In addition, there is over 80 million euros from the funding programs of the Federal Ministry of Education and Research (from the Quantum Technologies Future Package) and the Federal Ministry of Economics and Climate Protection, which were raised through joint applications from the members of the initiative. To date, over 40 scientific institutions, research institutes and companies have come together under the MQV umbrella.

The main aim of the initiative is to establish a Center for Quantum Computing and Quantum Technologies (ZQQ) over the next five years. This center aims to provide access to computers based on the three most promising technologies in quantum computing today: superconducting, ionic and atomic qubits. Research and industry are closely linked to ensure efficient technology transfer and to promote the establishment of start-up companies. The initiative also envisages the establishment of a quantum technology park that can be used by research institutions together with the more than 20 German and European high-tech companies in the greater Munich area that show great interest or are already active in the field of QST. These include companies such as Airbus, attocube, BMW, Fujitsu, Google, Huawei, Infineon, Menlo Systems, Microsoft, OHB, Rohde & Schwarz, Siemens, Toptica Photonics and Volkswagen. Research capacities are pooled together and scientific findings are quickly converted into marketable products. These activities are also supported by qualification and training offers as well as funding programs for quantum technology start-ups.

ÿ **Physical-Technical Federal Institute (PTB)**

Within the framework of its statutory mandate, the Physikalisch-Technische Bundesanstalt (PTB) is responsible for traceability in the area of measurement and the provision of services, including in the area of quantum technologies. Examples of PTB-relevant quantum technologies are high-precision quantum standards for electrical quantities (resistance, voltage), highly accurate sensors for magnetic fields, for pressure or for temperature, single electron pumps with highly non-classical properties as well as single photon sources and detectors for quantum radiometry and quantum cryptography. Furthermore, ultra-stable and precise optical clocks with extensive fields of application in communication, navigation and geodesy are among PTB's important research results. In the past, PTB has consistently expanded the further development of quantum metrology and quantum sensors as part of its regular strategic planning due to the enormous economic potential and the expected demand from research and industry.

As part of the presentation of the SI units, which have been largely based on quantum physics since 2019, **the PTB brings together the most important fields of quantum technology** (QT) under one roof in a technologically leading position and is characterized by a long-standing, **close collaboration with industry** out of. This puts PTB in a position to support the German economy in a unique way. In this way, **new economic fields** that are unique in the world can be developed in Germany and thus a clear location advantage can be developed **in Germany .**

For this purpose, the **quantum technology competence center QTZ,** which is part of the framework program “Quantum technologies – from the basics to the market”, has been established since 2019 built as a PTB interface for access to QT expertise and infrastructure for partners from industry and science. The central goal is to **support the development of QT with economic potential.** This makes it possible to effectively use PTB's expert knowledge and its role as a national metrology institute to exploit the potential of quantum technologies in order to generate optimal **social and economic added value .**

The QTZ focuses on the fields of action briefly explained below.

1. **Robust components and technologies.** For the application of QT in the market, robust and user-friendly QT components and devices are required that can also be used by non-experts in the harsh environment of an industrial company. The PTB enables the further development of QT components already established at the PTB (and other research institutions) for this practical use.
2. **Calibrations and Services.** An important prerequisite for commercial use is reliable and comparable QT components and the assurance and certification of quality assurance specifications through calibration and characterization. With these original services from PTB as an independent, national metrology institute, PTB creates an important, resilient basis for QT's path into the market.

3. **User platforms in the QTZ.** The user platforms offer robust and user-friendly measuring stations in key areas of QT and should be able to be used by external partners, supported by PTB staff and infrastructure. The goal here is to enable partners to have their own experiences in QT without them having to build the infrastructure themselves, which typically requires very high investments and lead times, especially in QT. A lack of contact and experience with the technologies used or their time-consuming setup represent a further challenge, especially for small and medium-sized companies (SMEs). Especially in a potentially very dynamic and disruptive field like QT, this can be a major disadvantage that is difficult to make up for in the competitiveness that the QTZ is intended to help bridge.

4. **Hands-on training, quantum education and support for start-ups.** The implementation of QT on the market requires well-trained personnel, for whom there are currently no sufficient training offers. Those already at PTB

Existing connections with key industry players provide an excellent starting point for training such a “quantum work force” in a timely manner and as needed, using user platforms particularly suitable for this purpose. Another possibility for knowledge transfer is to encourage and promote start-ups.

In the recent past, PTB has become increasingly involved in various QT activities in order to implement the aspects above:

The PTB is a founding member of the **Quantum Valley Lower Saxony** (www.qvls.de). Recent initiatives to strengthen the industry have emerged from this evolving QT ecosystem:

ÿ The PTB operates a QT high-tech incubator (hti.qvls.de) together with the QVLS partners. Through funding from the state of Lower Saxony, 14 teams (startups and young companies) are currently being granted stimulus funding including the use of technical infrastructure and other support.

ÿ The recently selected future cluster QVLS-iLabs (ilabs.qvls.de, expected to start in March 2023) complements the high-tech incubator through collaboration with established industry.

The PTB coordinates, in close collaboration with the BSI, the BMBF-funded “Umbrella Project Quantum Communication Germany”. The central goal of this project is to fuel the coherent development of quantum communication, to act as a platform for all relevant partners from Germany and thus to ensure a strong role for Germany and Europe in the commercialization of quantum communication. In this way, synergies are achieved, duplication is avoided and the optimal use of resources from research and industry is ensured, thereby significantly strengthening the competitive position in the international environment and securing technological sovereignty in the future. DIN is directly involved in the project via subcontracting.

In addition to the umbrella project, the metrology necessary for industrial implementation is also being developed from the outset in various current research programs, for example quantum computer demonstrators. These activities are technology-open and extend across diverse architectures.

Participation in standardization is an important factor for the industrial development of QT - standards that are set outside Europe must not limit the compatibility of QT components developed in Europe. It is in the interest of Germany's strong position to participate in standardization. The PTB is involved in various standardization activities, for example the PTB has co-chaired the Focus Group on Standardization of CEN-CENELEC since 2019 (https://www.cencenelec.eu/areas-of-work/cen-cenelec-topics/ quantum-technologies/), DIN provides the secretariat. Based on this preparatory work, a “Joint Technical Committee” JTC 22 at CEN-CENELEC, which DIN applied for, was recently approved and will hold its founding meeting in Berlin in March 2023.

The PTB also develops further training offers for industry together with various partners (https://www.quantum-training-alliance.de/home). The aim here is to support a coherent and well-coordinated development of offers in Germany, to avoid duplication and to provide interested parties from industry with effective and easy access, beyond thematic or regional interests.

ÿ **Gottfried Wilhelm Leibniz Scientific Association e. v.**

The institutes of the Leibniz Association cover the value chain from basic research to quantum phenomena and materials to materials and

Component development and systemic heterointegration through to prototype solutions. You research a wide variety of material systems and technology approaches to develop innovative solutions. Completely new possibilities arise, for example, in the practical combination of research in microelectronics and materials science. New oxidic, metallic, organic and hybrid functional and nanomaterials and structures are being researched here that have great potential for future micro- and nanotechnologies and thus address aspects of integrated smart systems, nanoelectronics and quantum computing.

In the Leibniz Association, the following institutes essentially conduct research in the field of quantum technologies: The Ferdinand Braun Institute – Leibniz Institute for High Frequency Technology (FBH), the Leibniz Institute for Solid State and Materials Research (IFW), the Leibniz Institute for Innovative Microelectronics (IHP), the Leibniz -Institute for Crystal Growing (IKZ), the Leibniz Institute for Surface Modification (IOM), the Leibniz Institute for Photonic Technologies (IPHT), the Paul Drude Institute for Solid State Electronics (PDI) and the Weierstrass Institute for Applied Analysis and Stochastics (WIAS).

In addition, within the disciplinary breadth of the Leibniz Association, economic and social science aspects of the new technologies are also considered and new areas of application in natural, environmental and life sciences are opened up.

The interdisciplinary Leibniz Institutes conduct research in the three main areas of quantum communication, quantum metrology and sensing and quantum computing, as well as “enabling” technologies, in particular photonics, laser, microwave, signaling and cryogenics, control electronics, integrated systems and new software algorithms . You develop materials for quantum technologies and characterize the corresponding optical, electrical and structural properties, research the effects of light-matter interaction and phenomena of quantum and nanophotonics and thus make a fundamental contribution to knowledge-oriented research questions in quantum physics. The Leibniz Institutes also supply European research institutes with critical material systems such as: B. isotopically pure semiconductors and thus make an important contribution to increasing the resilience of the European research area. With the help of innovative processes and process technologies, but also through modeling and simulation, it is possible to design and develop new components: electronic or opto-electronic semiconductor components, multi-qubit circuits, quantum sensors and detectors, qubit control, control and Readout circuits.

Individual Leibniz Institutes have mastered the systemic and hybrid integration of these components and enable proof-of-concept demonstrators, complex systems, industrial prototypes through to small series production. To ensure secure transmission of encrypted information, the institutes in the field of quantum communication are researching photonic modules and their microintegration. In quantum metrology and sensor technology for navigation, synchronization of networks, medical diagnostics and highly sensitive imaging techniques, atomic quantum sensors, quantum sensors based on optically pumped magnetometers and based on defect centers as well as sensory surfaces are researched and developed. In the

In the field of quantum computing, which is important for potential tasks in critical application fields such as chemistry, meteorology, finance and for material or drug development, the institutes research both superconducting and spin-based quantum bit systems as well as components and modules for optical photonic quantum computing as well as for quantum computing based on isotopically pure semiconductor systems and ions.

The Leibniz Institutes work nationally in relevant projects, such as the Cluster of Excellence ct.qmat - Complexity and Topology in Quantum Matter, the research factory

Microelectronics Germany, QSolid - quantum computers in the solid state, MUNIQC-SC - Munich Quantum Valley quantum computer demonstrators - superconducting qubits or QYRO - nuclear spin-based quantum gyroscopes for new space applications as well as internationally, such as BECCAL - Bose-Einstein Condensate and Cold Atom Lab on the international space station. Since 2021, under the umbrella of the Leibniz Strategy Forum "Technological Sovereignty", the Leibniz Institutes have begun to pool their expertise on, among other things, "quantum technologies" in a cluster and to deepen their collaboration.

ÿ **Center for Digitalization and Technology Research of the Bundeswehr (dtec.bw)**

The dtec.bw is a scientific center supported by both Bundeswehr universities and is part of the federal government's 2020 economic stimulus program "Combat the consequences of Corona, secure prosperity, strengthen future viability".
It is subject to academic self-administration. The funds with which the dtec.bw was provided by the BMVg division are used at both Bundeswehr universities to finance research projects and knowledge and technology transfer projects. One of the ongoing projects is MuQuaNet: The Quantum Internet in the greater Munich area.

The aim of the project is, with the UniBw Munich as the core, to develop, build and operate a quantum-secure communications network for research and evaluation and to make it available to other research institutions, authorities and Bundeswehr departments. Made up of different components, it is intended to prepare for seamless integration into today's network communication, demonstrate the diverse possible uses and serve as a blueprint for the construction of tailor-made, highly secure communication networks.

7. Glossary

Defects in diamond or *NV centers:*

Contamination of a diamond lattice by individual foreign atoms, such as nitrogen ("nitrogen vacancy"). This creates an excitation spectrum that can be used - even at room temperature - as a single photon source, as a computing unit in a quantum computer, or as a highly sensitive sensor due to its sensitivity to magnetic fields.

R&D: research and development

Mainly refers to pre-competitive work in a company or company Research facility with a significant technical risk. In contrast to competitive or experimental development, as well as product development.

Full stack

Describes the sum of all the components of a platform or an overall technical system that build on one another. The origins of the term lie in software development. In relation to quantum computing, the hardware components are also included.

Galileo

A system of navigation satellites operated by the European Union comparable to the American GPS (Global Positioning System).

SMEs: Small and medium-sized companies

According to the EU definition, companies with fewer than 250 employees and an annual turnover of no more than €50 million or a balance sheet total of no more than €43 million.

NISQ: Noisy Intermediate Scale Quantum Computer

Interim goal of realizing "medium-sized" quantum computers with 50 to a few 100 qubits. These are intended to show the potential of quantum computers beyond simulations, but will still be severely limited in their computing power due to a lack of control over all qubits.

Optical clock:

Also atomic clock. The frequencies of atomic transitions, usually cesium or rubidium, can be used to calculate a highly precise time signal. The method has been used for decades to measure world time. Further technological advances in the process could also make it suitable for future use in telecommunications or for measuring the absolute height in the terrain (relativistic geodesy).

PQK: Post-Quantum Cryptography

Describes the need to further develop or replace current encryption methods if they can no longer be considered secure based on the new computing capabilities of quantum computers.

Quantum gyroscope:

Describes a measuring device that uses quantum effects to measure rotational movements and their rotation rates. The area of application for (quantum) gyroscopes is, in particular, navigation applications.

QKD: Quantum Key Distribution

Encryption technology for data communication. In contrast to currently used methods, QKD uses the quantum mechanical property of the entanglement of states during data transmission and is therefore intrinsically secure against eavesdropping, or eavesdropping could always be detected and would lead to a breakdown in communication.

Qubits: Quantum Bits

Smallest logical computing unit of a quantum computer, analogous to the bits of the classical computer. In contrast to these, qubits can assume any state between “0” and “1”, which is one of the essential features and potential advantages of a quantum computer.

TRL: Technology Readiness Level

Describes the level of maturity of technologies. The scale ranges from TRL 1 (description of the functional principle) to TRL 9 (qualified system with proof of successful use). TRL 5 describes an experimental setup in an operational environment.

8. Imprint

editor

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