Bundesministerium
für Bildung
und Forschung

Research program Quantum systems

Develop cutting-edge technology. Shaping the future.

Cover image: Artistic visualization of several one-dimensional chains of interacting particles, such as those found in ion trap-based approaches to realizing qubits for quantum computers.

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1. The mission of the quantum systems research program

The *quantum systems research program – 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 program is strictly aligned to a mission that will be measured by ambitious milestones.

The mission of the research program is to make Germany a world leader in the European network in quantum computing and quantum sensing over the next decade and to expand Germany's competitiveness in quantum systems.

In addition to strengthening competitiveness, it is also important to secure the technological sovereignty of Germany and Europe in quantum systems and to use quantum systems to increase the opportunities of technological change for the economy and society use and promote their sustainability.

Milestones

The mission of the quantum systems research program and its success is measured by milestones.
These are checked regularly and adjusted if necessary. This ensures that the milestones in this dynamic, international research field are always up to date and suitable as a benchmark for a mission-oriented research policy.

The following milestones were selected:

Quantum computing:

ÿ By 2026: internationally competitive quantitative computer with at least 100 individually controlled erable qubits, scalable to 500 qubits

ÿ By 2026: the number of start-ups in Germany will quadruple to ÿ20; ÿ60 end users in Germany, including in business, science and Civil society

ÿ By 2032: quantum advantage in at least two demonstrate practical applications in Germany

ÿ By 2032: remain the world leader in publications (Top 3) and join the top 5 in patents1

Quantum sensing:

ÿ By 2026: five new products on the market

ÿ By 2032: ÿ 60 companies involved, of which 10 start-ups

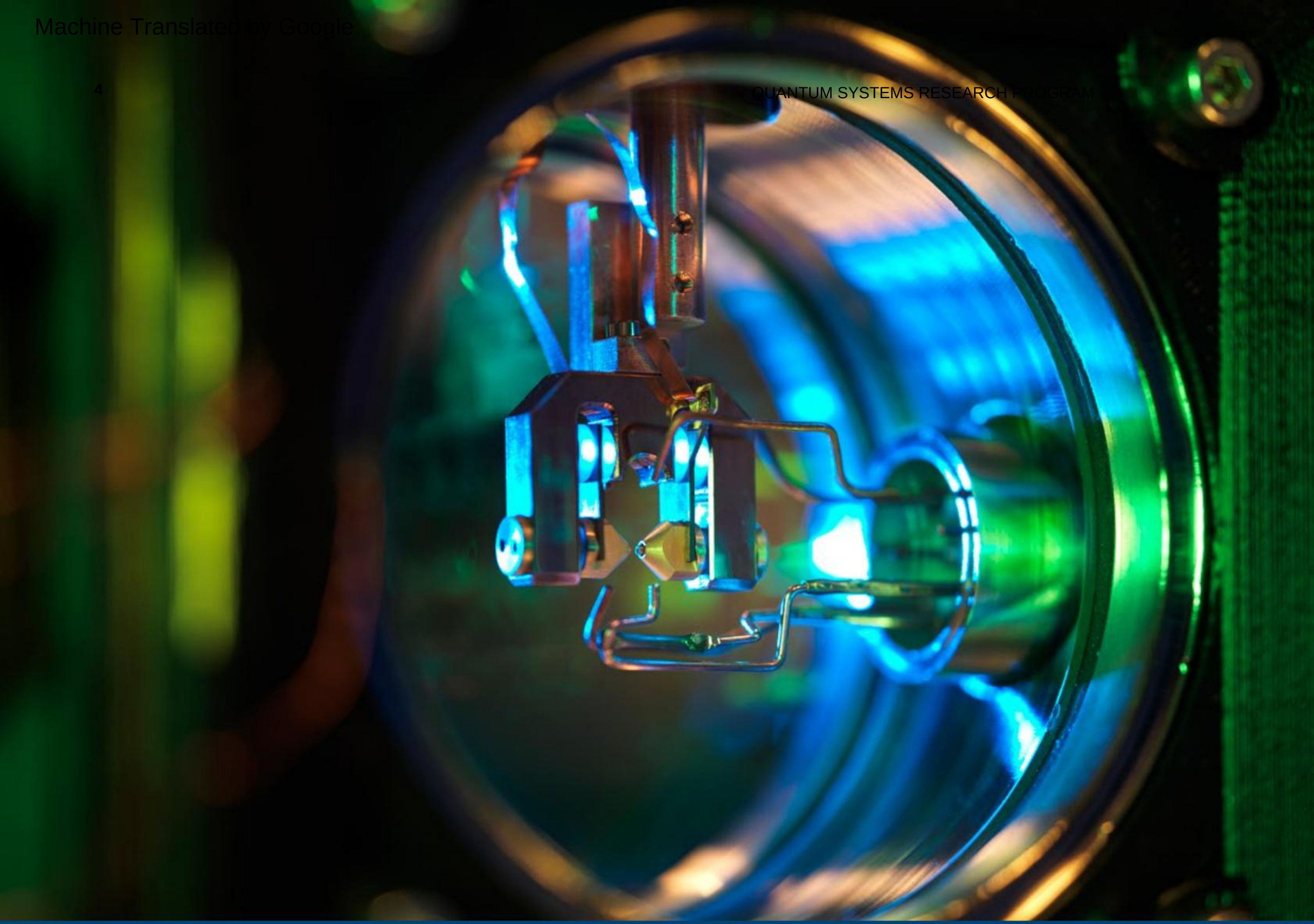
ÿ By 2032: remain the world leader in publications (Top 2) and join the top 5 in patents1

Photonics:

ÿ By 2026: ÿ30 photonics companies involved in quantum technologies

ÿ By 2032: ÿ a new, research-intensive one Lead market opened up for German photonics Industry

1 Measured by patent applications at the European Patent Office, determined based on a database search of logically linked ones keywords



2. Summary

With the *quantum systems research program – developing cutting-edge technology. Shaping the future.* The Federal Ministry of Education and Research (BMBF) is creating a common umbrella for successful research funding in photonics and quantum technologies over the next ten years. As the lead within the federal government for research policy in quantum systems, the BMBF intends to promote technology transfer and the expansion of ecosystems in this area strategically and in the long term. The funding follows the mission of the research program: to lead Germany to world leadership 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 (see Chapters 1 and 5).

The research fields of photonics and quantum technologies are central to the positioning of innovative German companies in growth markets. In
Photonics generated around 1,000 revenues in 2020
companies in Germany have an annual turnover of 40.1 billion euros and are important employers with around 160,000 employees. An estimated growth of around six percent of the approximately $750 billion

The global photonics market is constantly creating opportunities for research-based innovations, for example in production and mobility. The market for quantum technologies is still at a much earlier point in its development, but offers similarly great potential. Current estimates predict the emergence of quantum computing alone in the next 15 to 30 years a global market of 450 to 850 billion US dollars with segments such as logistics and finance (see Chapter 4). Application-oriented research for these growing and emerging markets will be specifically supported by the quantum systems research program.

Photonics and quantum technologies are also very important for solving social challenges. A foretaste of this is provided by sophisticated photonic technologies such as lasers, light-emitting diodes (LEDs) and photovoltaics, which are already shaping life and work in many areas today.

New solutions from photonics and quantum technologies will make a decisive contribution to developing new materials and active ingredients more quickly or to better understand and cure diseases. You will communicate faster and more securely and help to live, produce and move around more resource-efficiently in the future. This is also where the quantum systems research program comes into play and aims to put these new technologies into use (see Chapter 7).

Photonics and quantum technologies both developed from fundamental research in quantum physics and are thematically interlinked. In many cases, modern photonics makes the development of quantum technological solutions possible in the first place. The networking of actors, the joint research into technological components, the bundling and effective use of resources are important factors for the successful development of both areas. In order to specifically expand such synergies, the BMBF is funding both topics together for the first time with the Quantum Systems research program.

In order to leverage the high innovation potential of quantum systems, great efforts and a goal- and mission-oriented research policy are still necessary (see Chapter 1). The scientific and technical challenges are complex. Many solutions are currently taking their first steps from the laboratory into technical application (see Chapter 6). A successful technology transfer therefore requires high, long-term investments from all stakeholders. New fields of application, for example in the digital economy, production, mobility, medicine, due to the energy transition and in environmental protection, also need to be developed (see Chapter 7). In addition, there is a need for solidarity between business, science and politics, the securing of qualified specialists and an informed public with the courage to change (see Chapter 8). In order to make all of this possible, the BMBF supports the quantum systems specialist community with targeted funding and accompanying measures with this program (see Chapter 9). The program will in particular:

ÿ The transfer of innovations from the basic
Accelerate genetic research through to application

ÿ Promote spin-offs and start-ups
Pave the way

ÿ Enable more research and development in small and medium-sized enterprises (SMEs).

ÿ Make room for daring research ideas; also by regularly consulting disruptive perspectives from “pattern breakers” as well as innovative ones
Experts

ÿ The networking of the actors and the expansion of
Promote innovation ecosystems

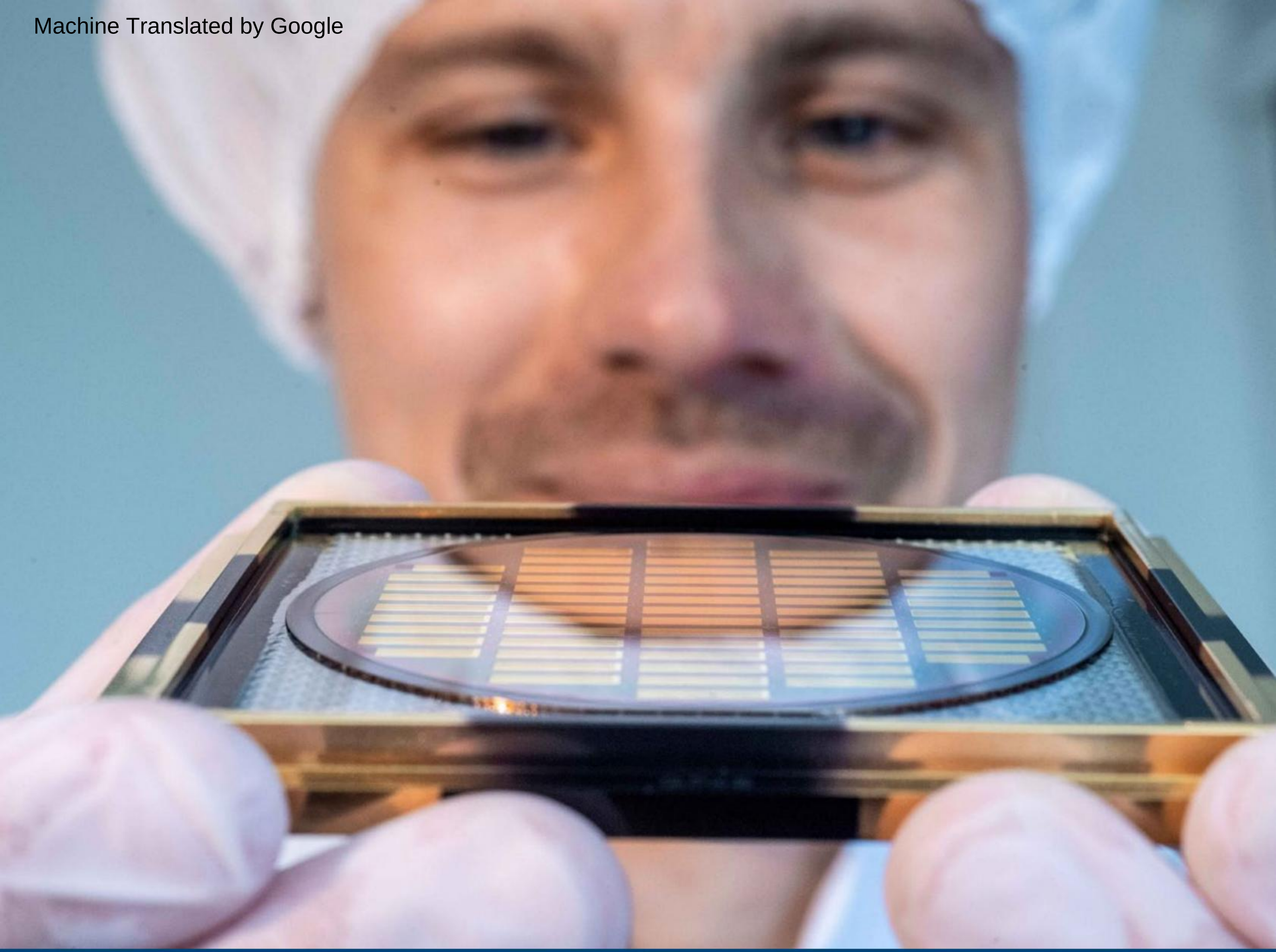
ÿ Germany as a science location in the
Further network quantum systems across Europe and internationally

ÿ Improve the training and further education of specialists for quantum systems

ÿ Exchange with science communication
strengthen with society

When developing the program, the BMBF used the findings from the *Quantum Systems 2030 Agenda* . In this, over 300 experts from science and industry have compiled the research needs and challenges of the coming years. Together with the specialist community, the BMBF will continually develop the measures and adapt them to changing requirements (see Chapter 10).

The research program enables the start of a mission-led decade of innovation for quantum systems.



3. Introduction: Germany in the quantum systems at 1st chapter bring to the top of the world

opener

Photonics and quantum technologies are increasingly becoming an innovation and growth engine for Germany as a business and science location as well as for modern society. As application technologies, they are closely linked in terms of content. This enables synergies that the Federal Ministry of Education and Research (BMBF) would like to specifically use to advance both technologies. Therefore, it has combined both topics under the term *quantum systems* . With the quantum systems research program, photonics and quantum technologies are now being jointly funded under one roof for the first time. In this way, the BMBF is laying the basis for the successful further development of quantum systems over the next ten years. It takes the entire value chain into account, relies on the strength of German medium-sized manufacturing companies and application-oriented research and specifically uses the synergies of the two topics. Particularly through its mission orientation, the program is intended to become a catalyst so that Germany can assert itself as a world leader in the two main areas of quan

Illustration 1:

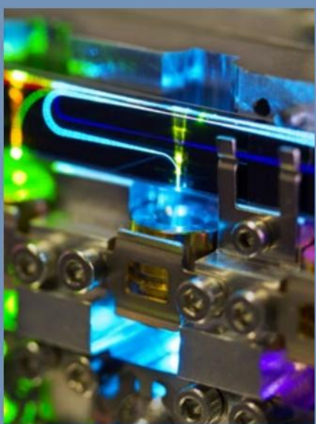
What are quantum systems?

Under the term quantum systems, the BMBF brings together the two closely interlinked research fields of photonics and quantum technologies in order to use synergies and pool resources.

Our world today is based in many places on digital technologies. But it doesn't just consist of zeros and ones; from quantum. Max Planck and Albert Einstein recognized this at the beginning of the 20th century. The carriers of physical interactions cannot be divided arbitrarily, but appear in a certain minimum size - as quanta. Our world is a quantum world in which the rules of quantum mechanics apply at the level of atoms and their components - strange rules that contradict our everyday understanding in some points.

Quantum systems

Photonics is the technical control of light in every form. The focus of photonics is on the generation, control, measurement and, above all, the use of light in numerous socially and economically important areas of application. The term "photonics" reflects the reference to the photon, the light particle or light quantum, just as the term "electronics" refers to the electron. The light has a number of extraordinary properties such as the most precise focusability, the highest (light) speed, the highest performance and undisturbed ability to superimpose. The key technology photonics makes these properties technologically usable in such diverse areas as production technology, energy and lighting technology, medical and environmental technology as well as information and communication technology.

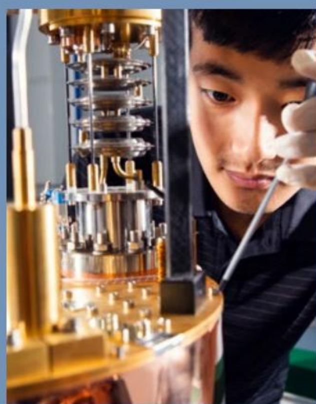


Photonic integrated circuit (PIC) for life science applications in the visible range. Source: TOPTICA Photonics AG

Photonics and quantum technologies are technologically closely related. Only in the last few years has it been possible to control and manipulate individual quantum states outside of highly complex laboratory setups. Photonic technologies such as sources for individual photons, detectors or highly integrated photonic components such as photonic integrated circuits are pioneers here. Photonics is a central basic technology for quantum technologies. In approaches such as quantum imaging or photonic quantum computing, it itself becomes quantum technology.

Ion trap for an atomic clock of the highest precision, which is read out with a laser. Source: Physical-Technical Federal Institute

The latest generation of **quantum technologies** uses the targeted control and manipulation of individual quanta, which has only recently become technically possible. This means that quantum physical effects such as entanglement and superposition are also moving into the area of technological usability. Quantum technologies offer the potential for completely new technical solutions. They will have a decisive influence on technological, economic and social development in the coming decades, for example in information transmission and processing, in highly precise measurement and imaging processes or in the simulation of complex systems. Research in quantum technologies currently focuses on four fields: quantum computers and simulation, quantum communication, quantum-based measur



Experimental setup for a quantum computer. Source: Bavarian Academy of Sciences/ Kai Neunert

In the first focus, photonics – that is, the use of light in innovative applications – many technologies have already reached everyday life. Smartphones or internet via fiber optic cables would not exist without photonics. Also

Photonic technologies such as lasers or imaging processes play a crucial role in modern chemistry, pharmacy and medical diagnostics. There are over 1,000 people working in these photonics application sectors in Germany alone

500,000 people. But the possibilities are far from exhausted. New findings from fundamental research in quantum physics are pushing forward into promising photonic applications. One example are particularly small, innovative beam sources that enable the use of X-rays or particle radiation in new areas.

Other examples include the innovative use of photonic sensors in application domains such as mobility, material characterization, environmental monitoring and production technology. It is these new fields that the quantum systems research program is targeting.

In the second focus, the still young field of quantum technologies, the greatest successes and potential still lie in the future. The development through application-oriented research is aimed, for example, at highly precise quantum sensors that could enable people with missing limbs to move prostheses precisely, or on quantum computers, which can be used, for example, to develop tailor-made, personalized therapies against cancer and completely new materials, for example for small , lightweight energy storage devices with high performance could contribute. Such groundbreaking innovations have the potential to significantly improve life in the 21st century.

In order to leverage the potential of quantum systems described above in both areas of focus for the economy and society, ecosystems must be greatly expanded in Germany and Europe. These ecosystems of researchers, technology providers and users from a wide range of disciplines will make it possible to bring technical solutions from the laboratories to market maturity. On the way there, technologies must become more compact, more robust and more energy efficient and their manufacturing processes must become more reliable, more cost-effective and more reproducible. What is also necessary is the targeted further development of so-called enabling technologies (basic technologies), many of which are in the field of photonics. At the same time, it is about investing in talent and supporting young researchers and start-ups at an early stage. All of these challenges are part of the quantum systems research program. The program will thus help Germany to compete internationally

consists.

In order to address the challenges mentioned, the research program builds on experiences and Findings from two areas: On the one hand it uses the lessons and best practices from already used existing programs and activities. Particularly worth mentioning here is the funding program that has existed since 2012. *Photonics Research Germany* program , the framework program *Quantum Technologies - from the basics to the market, which has* existed since 2018 , and the activities that have been running since 2020 as part of the Federal Government's economic stimulus and future package. In particular, the *Photonics Research Germany* funding program has made an important contribution to ensuring that photonics is now one of the most important growth and future sectors in Germany. On the other hand, the BMBF has 2020 initiated an agenda process in which the *quantum systems agenda* was created. Key actors from science and industry, from basic to applied research to application, jointly developed this research agenda, which the BMBF drew on when creating the quantum systems research program .

Overall, the BMBF's aim with the quantum systems research program is to promote the subject area strategically and in the long term with a mission-oriented research policy, to greatly expand ecosystems and to secure Germany a top position in international competition.

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Guidelines of the funding program

Setting goals: In the sense of being mission-oriented Research policy, the research program sets measurable goals. They are intended to serve as a catalyst for ambitious research funding. Due to the fast-moving nature of the research field, the goals are regularly reviewed and adjusted if necessary (see Chapter 1).

Strengthen technology transfer: There is still too little transfer of technologies into applied research and industry, particularly in the young field of quantum technologies. The program therefore involves users at an early stage in the planning of the funding measures.

Daring to do something new: There is also space in the program for daring research ideas for which a proof of concept for technical usability and thus for an economic exploitation perspective still needs to be provided. This should also lower the hurdles for companies to participate in projects with a very high research risk (see Chapter 9). In order to pick up on new ideas at an early stage, experts with disruptive perspectives are regularly involved.

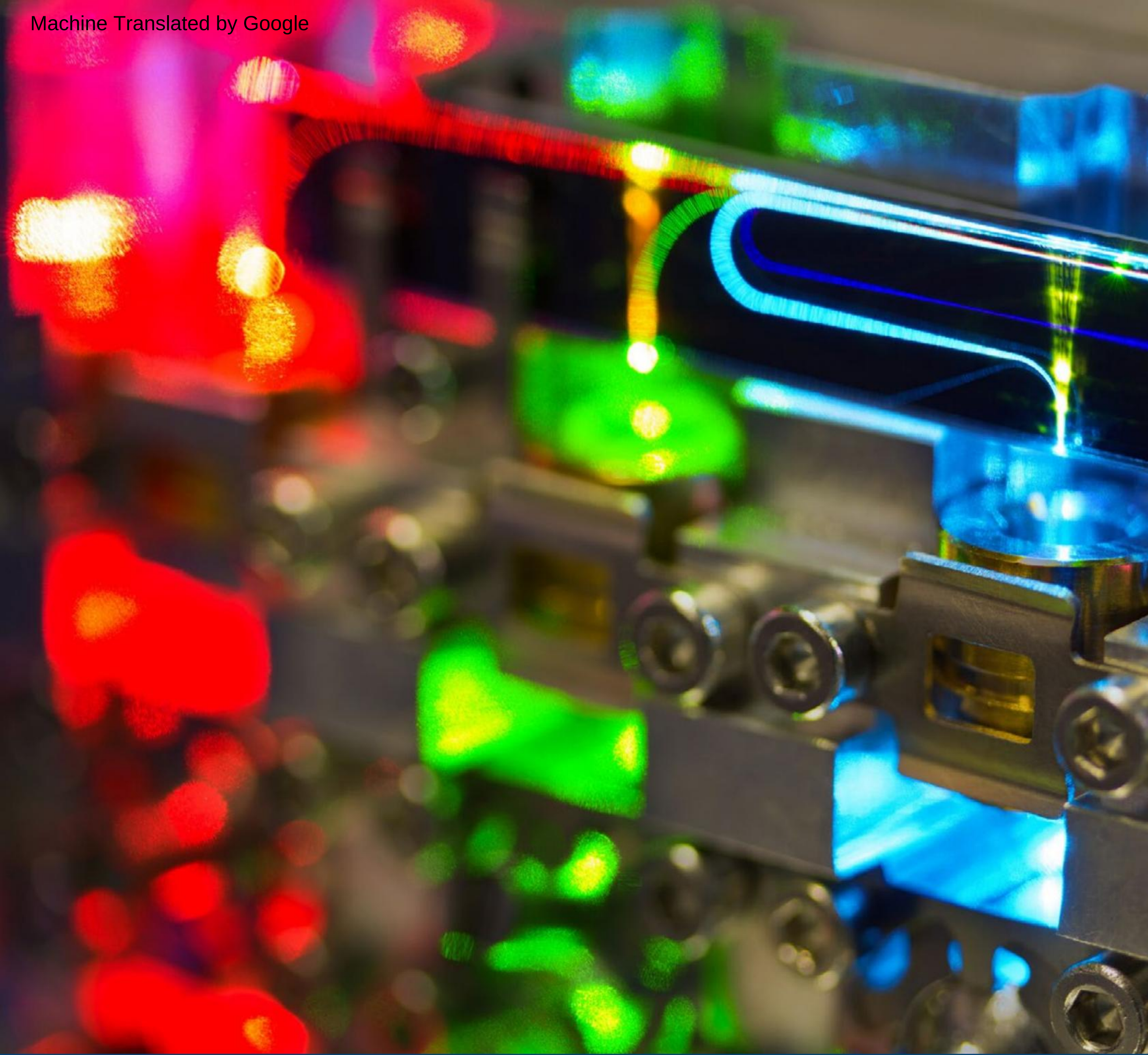
Use strengths: Germany is a world leader in photonics great. An academic specialist community has become an industry here. In quantum technologies, the area of basic research in particular is a world leader. In order to take advantage of this and expand even more effective innovation ecosystems, the program relies on proven success factors (see Chapter 4).

Think long-term: Germany has a strong starting position that needs to be expanded and maintained in the long term. This is also crucial with regard to the technological sovereignty of the country and Europe. This requires perseverance and planning security for the researchers. The program is therefore designed to last ten years.

Rely on networking: In order to be successful in quantum systems, you need actors from business and science alike. The program therefore aims to network quantum technologies and photonics more closely in science and industry, to involve technology providers and users equally and thus to take the entire value chain into account.

Building talent and securing skilled workers: decision-making The key to the successful further development of quantum systems is not least the talent that drives them forward. The program therefore relies on pilot measures for tailor-made, interdisciplinary training and further education offerings in order to secure qualified specialist personnel.

Taking people with you: Quantum systems will improve and noticeably change many areas of society through disruptive new solutions. Its principles must be communicated transparently and understandably in order to support people in dealing with these changes and to promote a positive view of quantum systems. The program therefore attaches great importance to accompanying outreach and communication measures .



4. Initial situation – seize opportunities and expand strengths

Germany is a strong economic and industrial location. The industrial sector contributes a good 30 percent to the gross domestic product (GDP). This puts Germany in third place in an international comparison among the most important industrialized and emerging countries (G20).2 This high proportion of manufacturing companies is an important strength when it comes to successfully implementing new technolog

2 Shares of economic sectors in GDP in industrialized and emerging countries. Statista, accessed on November 10, 2021.

At the same time, in the increasingly fierce competition of the globalized world, technological leadership is fleeting. Germany can only maintain its leading international position if it continues to set the pace for innovative technologies. Germany is coming under increasing pressure: "While in 2010 Germany was one of the three nations with the most world-class patents in 47 of the 58 technologies, in 2019 this share has more than halved to 22 technologies."3 This makes it all the more important that Germany claims by building on its strengths and opportunities – along with its

European partners – used in a targeted manner. In addition to the strong manufacturing economy mentioned above, these strengths include the many outstanding research locations and the trusting cooperation between technology providers and users.
The many strong players in business and science

Science makes it possible for knowledge and needs from different areas of application to be incorporated into the development of new technologies at an early stage. In this way, innovations can be researched and brought to market in a targeted and tailored manner - as a benefit for the economy and to solve social challenges.

Photonics: a prime example of successful technology transfer and great opportunities

Photonics impressively shows how Germany's strengths can be used: Since the 2000s, this technology has quickly developed from a niche topic into an economically strong industry.

With solutions such as lasers, LEDs or fiber optic internet, photonics (or so-called first generation quantum technologies) has long since found its way into everyday life.

Photonics has now become an important economic shaft factor. Around 1,000 German photonics companies

With around 160,000 employees, we serve a global photonics market that will grow to almost 900 billion by 2025.
US dollars should grow (approx. six percent growth per year).4
In addition, these companies have an above-average research and development (FUE) rate of almost eleven percent

3 world-class patents in future technologies. The innovative power of East Asia, North America and Europe. Bertelsmann Foundation, 2020.

4 Trend Report Photonics 2020/2021. Industry Trends and Market Potentials. SPECTARIS, 2021.

Innovation driver for many other industries such as Chemistry, pharmacy and medical diagnostics. Over 500,000 people work in these photonics application sectors in Germany alone.

Despite the successes mentioned above, the need for research in photonics remains high. Many new Technologies with a low level of technological readiness are currently taking their first steps from the laboratory towards technological application. In order to further develop these technologies to market maturity in the future, the following strengths can be used:

1. The close cooperation between science, research companies and users in the Photonics, which already exists in many more mature branches of technology. This can now be expanded to new fields of technology.

2. The international leading position in many areas such as production technology, optical components and systems, image processing and measurement technology, medical technology and the life sciences.5 Due to this, one already exists outstanding expertise in numerous application domains for new photonic technologies.

3. Good networking at European level that enables synergies. The Photonics21 technology platform, with over 3,000 members, brings together the majority of relevant R&D players along the entire value chain in Europe.

With the strengths mentioned above, it is possible to move into new technological areas of photonics in which the need for research and the risk are high. This applies, for example, to photonic microintegration and photonic integrated circuits (PICs), the aim of which - similar to semiconductor technology - to integrate as many photonic components and functions as possible into a single component. New fields of application could be opened up through increases in performance, miniaturization and cost reduction. Digital photonics - the combination of photonic hardware with modern methods of image and data processing - is also due to the rapid developments in electronic technology

5 Industry Report 2014. Statista.

Data processing, machine learning and artificial intelligence have only been possible for a few years. Novel beam sources (so-called secondary beam sources) are another emerging branch of photonic technology that may find their way into widespread use in the future, for example in chip production, battery technology or medical drug development. Overall, the German leadership position in the field of photonics is to be expanded, building on existing strengths and through the targeted promotion and development of new technologies.

Quantum technologies: A new success story begins

Despite their early stage of development, quantum technologies are already considered one of the most important future technologies with great economic and social potential.
According to current market estimates, a global market of 450 to 850 billion US dollars could be created in the field of quantum computing alone in the next 15 to 30 years.6 At the same time, quantum technologies promise far-reaching innovations, for example in medicine, communication, chemistry and logistics.

At the moment the various sub-areas are under-
Differently developed: While quantum sensing and quantum imaging are already taking the first steps towards widespread commercial use, quantum computing, for example, is still in an early testing phase (see Chapter 6).

At the same time, the first users are already recognizing the potential of quantum technologies - especially quantum computing and quantum simulation.
For example, the automotive industry and mechanical engineering are investing in the development of quantum algorithms for process optimization, and the chemical and pharmaceutical industries are relying on significant ones
Advances in the simulation of materials and
complex molecules. Even beyond quantum computing, the targeted use of quantum mechanical effects promises a wide range of possible applications. For example, due to their outstanding performance, quantum sensors and imaging are key drivers for developments such as the navigation of autonomous vehicles

6 What Happens When 'If' Turns to 'When' in Quantum Computing? Boston Consulting Group, July 21, 2021.

for Industry 4.0, in medical diagnostics and molecular biology or in earth observation for the early detection of environmental changes and weather extremes (see Chapter 7).

A race has begun worldwide to exploit the promising potential of quantum technologies. Germany has good prerequisites for being successful in international competition. At the same time, however, there is an urgent need for action. While Germany, for example, is at the top in the world in the academic sector, it is still lagging behind in international comparison when it comes to hardware and system integration in the field of quantum computing. Here US American

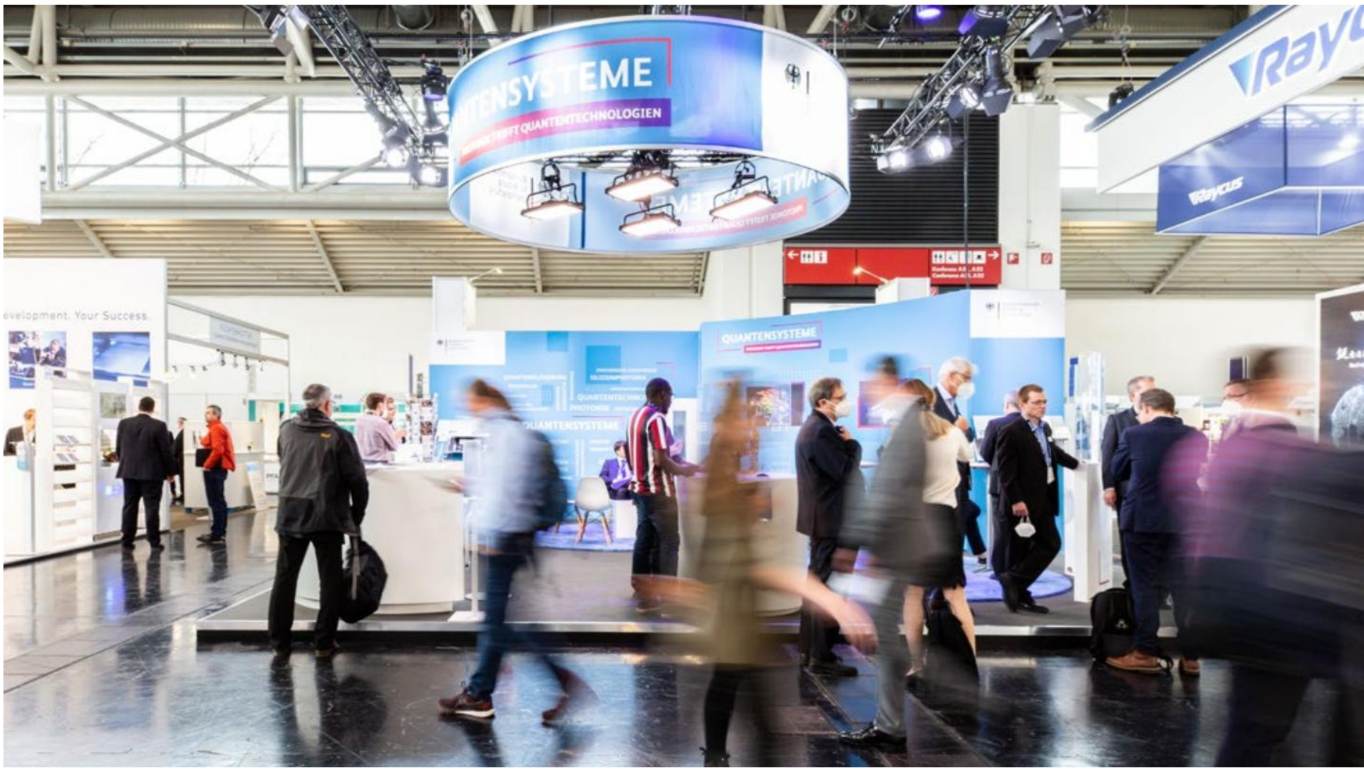
Large corporations monitor the state of the art and set the pace. In the German corporate landscape, which is primarily characterized by medium-sized businesses, there are so far only a few players who are driving forward this highly risky topic with the necessary resources. In Germany and Europe, the best opportunities to catch up are offered by innovative start-ups that have emerged in many places in recent years. They are a central part of the growing ecosystems for quantum technologies. At the same time, however, they are much more dependent on support and cooperation than large US corporations, for example in the areas of basic research and component availability. This example shows that in order to be competitive in the global race for quantum technologies, Germany needs an approach that is specifically tailored to the conditions of German ecosystems.

At the same time, Germany can build on many strengths, in particular:

1. A large number of potential users in sectors such as automobiles, chemicals and pharmaceuticals, which together generate an annual turnover of around 570 billion euros7 and are among the most innovative sectors with R&D rates of between three and 14 percent
count in Germany.8 Quantum technologies promise them important leaps in innovation.

7 Industry focus automotive industry. Federal Ministry of Economics science and climate protection, and industry focus on chemistry and pharmaceuticals, Federal Ministry for Economic Affairs and Climate Protection, both accessed on February 17, 2022.

8 annual reports on research, innovation and technological Germany's performance in 2021.



At the same time, these users are attractive cooperation partners for providers of quantum technologies at home and abroad.9 This offers a great opportunity to map the entire value chain from the basic technologies to the end application in Germany and Europe.

2. A high quality of basic and application-oriented research in quantum technologies in Germany with internationally renowned universities and non-university

ren research institutions. In the field of quantum computing, for example, Germany ranks among the world's most scientific publications.

th comparison among the top 3.10

3. Germany's international strength in photonics

as a central quantum key technology as well as many interfaces between both areas –

both in terms of technologies and actors. The companies in the photonics industry

have already focused their activities on quantum technologies.

4. Close cooperation between basic genetic research, application-oriented research and industry with the participation of a wide range of large companies, small and medium-sized companies and start-ups. This makes it possible to map the most complete innovation chains possible for quantum technologies in Germany and Europe in research projects. This is supported by pre-competitive research funding in collaborative projects, which is not possible in many places internationally.

5. Good networking and collaboration European level. As part of the European Quantum Flagship Initiative, over 3,500 experts from all areas of quantum technologies and the relevant companies and research institutions are already working

together.

Overall, Germany, with its strong players in business and science, its particularly diverse R&D landscape and its experience with technological innovations, has the best prerequisites to make quantum systems with a focus on photonics and quantum technologies a success story.

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9 Innovation potential of second-generation quantum technologies. Acatech, 2020.

10 Together with UK; Quantum Technologies Patents, Publications & Investments, Michel Kurek, Ecole Polytechnique Paris, 2020.

5. Mission, goals and fields of action

The quantum systems research program addresses the need for action in the *Quantum Systems 2030 Agenda* has shown. Over 300 representatives from science and business have compiled the research needs in the field of quantum systems. The program focuses on the research fields most relevant to Germany. What is characteristic of these fields is, on the one hand, a good prospect of implementing the results by companies in Germany and thus important contributions to value creation and prosperity and, on the other hand, important contributions to social and economic challenges. In order to give the quantum systems research program and its funding policy a clear target orientation, the following mission was developed, particularly with regard to competitiveness:

Germany in the next decade in the European network in quantum computing and in the Bringing quantum sensors to the forefront of the world and increasing Germany's competitiveness Expand quantum systems. The mission of the research program was supported by concrete milestones that are regularly reviewed (see Chapter 1).

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Figure 2:

mission

In the next decade, Germany will be one of the world leaders in the European network in quantum computing and quantum sensors and will improve its competitiveness
Expand Germany's quantum systems

ÿ Chapter 1

Additional goals

Securing technological sovereignty in quantum systems

The opportunities of technological Change for the economy and use society

Sustainability in business and Promoting society with quantum systems

ÿ Chapter 5

Fields of action

Pushing technological boundaries – Research and further develop quantum systems

· Quantum computing and develop quantum simulation
· Quantum-based measurement technology and research imaging
· En abling Technologies for Making quantum systems market-ready
· Photonics at its smallest Advance size scales

ÿ Chapter 6

Applying quantum systems – Driving solutions for the economy and society

· Using quantum systems to create new solutions for the connected world
· Production with digital photonics of tomorrow
· Create opportunities for resource efficiency, climate and environmental protection with quantum systems
· Mobility with quantum systems enable the future
· With photonic and quantum based Solutions Recognize, understand and treat diseases

ÿ Chapter 7

Design ecosystems – create new innovation chains, attract the best minds, take people with you

· New innovation chains for create successful technology transfer
· Attract the best minds for quantum systems
· Act European and cooperate internationally
· Take people with you

ÿ Chapter 8

Measures

· Research results bring into application
· Start-ups and support start-ups
· Take up new findings and developments at an early stage

· Bringing together competencies in networks and creating synergies
· Prepare standards
· Cooperate internationally
· Promote young talent

· Enable participation, engage in scientific communication

ÿ Chapter 9

In addition to strengthening competitiveness Contributions to the following goals in the focus of the research program:

ÿ Technological sovereignty in the quantum secure systems

ÿ The opportunities of technological change for benefit the economy and society

ÿ Sustainability in business and society promote with quantum systems

Three handbooks are derived from the mission and goals.
fields. They name the areas in which the most strategically relevant challenges lie for the development of quantum systems in the next few years (see Figure 2):

I. Pushing technological boundaries – researching and further developing quantum systems (see Chapter 6)
In order to use the diverse possibilities of quantum systems for business and society, numerous scientific and technical
nological hurdles can be overcome. It applies, to master both the important basic technologies and new methods for economical
to create practical quantum systems.

II. Applying quantum systems – Advancing solutions for the economy and society (see Chapter 7)
Quantum systems offer completely new opportunities for overcoming economic and social challenges. These range from technologies for the connected world to

Technological sovereignty

Technological sovereignty is the ability to guarantee access at all times to the key technologies that are necessary to implement social priorities and needs. This includes the use and further development of technologies and products, taking into account the available resources and necessary services, as well as the ability to make gaps visible and, if possible, close them and to help determine standards on global markets. Technological sovereignty may also require developing key technologies and technology-based innovations independently in Europe and building up our own production capacities within the value creation networks, if this is to maintain the state's ability to act or to avoid one-sided dependencies - taking into account changing geopolitical conditions. necessary is. This requires the ability to understand and evaluate all relevant technological development and manufacturing processes and requires the ability to work equally with strategically important partners.

Securing prosperity, jobs and social values leads to demands on technologies – for example in terms of security, data protection and sustainability. The EU also speaks of “strategic autonomy”, whereby technological sovereignty and international cooperation are not mutually exclusive. On the contrary: technological sovereignty requires targeted cooperation with European and non-European partners. The aim is to help shape key technologies internationally on an equal footing and taking European standards and values into account and thus strengthen the European community of values.

Due to their economic and social significance, quantum systems are particularly important for the technological sovereignty of Germany and Europe. Quantum computing in particular will lead to major leaps in innovation (see Chapter 7.1) and will be a key technology that Germany and Europe must help shape. In photonics, for example, integrated microphotonic systems are crucial for future data processing and thus also for technological sovereignty. The same applies to the central basic components of these technologies. Single photon sources and infrared detectors, for example, are already subject to strict import and export restrictions. Building up your own know-how and – where necessary – your own production capacities is central to being able to act in the future.

digital photonics for the production of tomorrow or the detection and treatment of diseases through to solutions for the sustainable use of resources and climate protection.

III. Shaping ecosystems – new innovation chains create, attract the best minds, take people with you (see Chapter 8)

Quantum systems need technology landscapes that include all stages of the innovation and value chain in order to be successful. These must be based on the particular strengths

Building Germany. There must be gaps in the Innovation chain is closed and cooperations are initiated along this chain. The best minds from various disciplines must be recruited for quantum systems and the next generation of skilled workers must be secured on a broad basis. And last but not least, a technology that has the potential to have a profound impact on people's lives changed, their consequences understood, publicly discussed and sufficiently accepted.

Within the fields of action of the quantum systems program, the Federal Ministry of Education and Research is guided by the strategic goals mentioned when designing specific funding measures. The guiding principle for project funding is to pave the way for research innovations to be put into application as quickly as possible. Central to this is the close exchange between science and business as well as such as research collaborations between providers and users. Securing the skilled worker base and a high level of acceptance for new quantum technology solutions are further focal points in the implementation of the program. In this way, research policy creates the basis for broad innovation ecosystems supported by science, business and society (see Chapter 9).

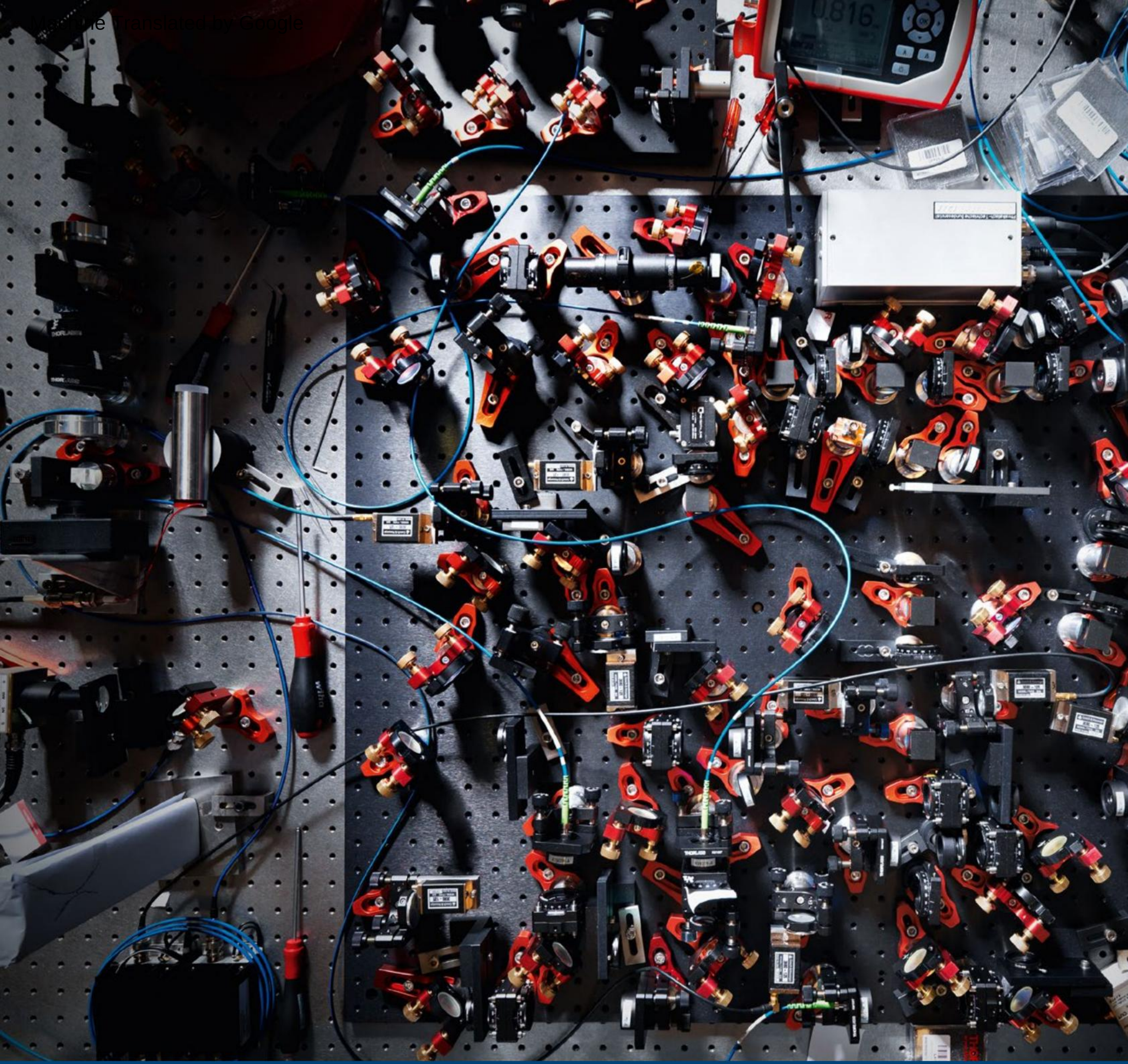
Quantum systems as drivers for sustainability

Germany is committed to implementing the 2030 Agenda for global sustainable development with its 17 Sustainable Development Goals (SDGs) of the United Nations. One of the most important is SDG 13: climate action. Germany wants to be climate neutral by 2045. In order to achieve this, current CO2 emissions must fall massively. The next ten years are crucial to whether this goal is achieved. New technological solutions can make an important contribution to successfully phasing out fossil fuels in industry, switching to green hydrogen, climate-friendly mobility and sustainable forestry and agriculture.

Key technologies such as quantum systems enable breakthroughs in various areas that make societies more sustainable and climate-neutral (see Chapter 7.3). Outstanding examples of this from photonics are photovoltaics and LEDs.

And other solutions may soon follow: Photonic technologies reduce the energy consumption of electronic data processing. Pho-tonic solutions for reversible manufacturing and non-contact identification of materials enable a circular economy with a high recycling rate. New, individualized repair procedures based on laser-based additive processes can extend the life cycles of products.

Second-generation quantum technology solutions will only be available in the medium term, but can then make an enormous contribution to environmental and climate protection. It is foreseeable that quantum computing could, for example, significantly improve climate models and thus enable more targeted measures and evidence-based readjustments. Quantum computers could also help to understand processes such as nitrogen fixation and implement them industrially.



6. Area of action I:
Pushing technological boundaries – Research and further develop quantum systems

In order to be able to use the diverse possibilities of quantum systems for business and society, numerous scientific and technological challenges must be mastered. It is important to master the important basic technologies as well as to create new opportunities for the economic realization of practical quantum systems.

In short

1. Quantum computing is said to be due to its large power potentials for social developments and the Germany as a location for innovation in the coming years have been intensively researched over the years.
ÿ Long-term goal: universal error-corrected Quantum computers
ÿ In the meantime, focus on quantum simulators or gate-based NISQ systems, the first enable applications
ÿ Important: parallel research on algorithms and software

2. Quantum-based measurement technology and imaging include technologies with a wide range of operating principles, technology maturity and possible applications. The most important goals are:
ÿ Increasingly developing applications
ÿ The technologies for real-world use Prepare terms of use
ÿ Involve users and thus align research with actual needs

3. Enabling Technologies are the technological ones Basis for the use of quantum systems. With them you can:
ÿ Quantum computers, simulators and sensors are strong be improved
ÿ Especially SMEs and start-ups as providers on the Research equipment market is already generating sales today

4. Photonics can be used on the smallest size scales bring benefits to a wide range of applications such as measurement technology, materials research or the medical sector. This requires:
ÿ Platform technologies for the scalable implementation of highly integrated electro-optical components and systems
ÿ Practical laser-supported generation of radiation with extremely high spatial and time resolution

6.1 Develop quantum computing and quantum simulation

The major social and economic challenges of our time are becoming increasingly complex. In order to understand and solve them, extensive modeling and calculations often have to be carried out. This applies to the development of new materials and materials, for example with regard to the design of new medicines as well as the resource-efficient optimization of processes and systems, for example in the production and manufacture of green hydrogen, logistics, transport or in energy networks. In many cases, these calculations are so complex that existing computing architectures cannot solve them at all or within acceptable timeframes. Quantum computers and simulators as well as the corresponding software offer a revolutionary new approach.

Quantum computers work differently than conventional computers and thus open up completely new possibilities Possibilities. In contrast to the bits of digital computers, which can only assume the values 0 and 1, their smallest computing units, the quantum bits (qubits), are able to take on any number of superpositions of 0 and 1. The qubits can also connect to each other quantum mechanically and thus assume a highly complex overall state. One then speaks of entanglement. This entanglement of qubits into an overall state is a unique property of quantum computers in terms of computer technologies. There are different computing paradigms to solve problems with them. Universal quantum computers are based on gate operations analogous to classical computers. So-called quantum simulators, on the other hand, imitate the problems to be solved - for example the simulation of a molecule - directly on specially adapted quantum hardware. Although such systems are less flexible and only suitable for certain problems, they could be usable for specific applications much sooner.

Many of the challenges that cannot be solved satisfactorily with conventional computers have one thing in common: numerous conditions have to be calculated, which are also mutually dependent on one another. The complexity of the problem increases exponentially with each additional parameter - be it another atom in the molecule to be simulated or another intermediate destination in the route planning of a parcel service. With classical computers, this means that only smaller model systems can be calculated, but real problems quickly become too complex. Due to its functionality, the quantum computer has an advantage when it comes to solving such complex problems. This creates great opportunities for economic exploitation: a study by the Boston Consulting Group assumes a global market volume of several hundred billion in the long term. dollars for quantum computing. Germany is very well positioned in quantum computing research. Germany is one of the leading nations, particularly when it comes to fundamental questions about various technology platforms for the realization of qubits. In the very capital-intensive area of hardware development and system integration, however, large technology groups, especially from the USA, are much further ahead. There is a lot of catching up to do here in Germany (see Chapter 4).

The long-term goal is to develop a universal error-corrected quantum computer. There are several promising technological approaches that are being researched in parallel. Qubits are much more unstable than classical bits. Likewise, arithmetic operations today are still prone to errors. Around To balance both properties, a universal quantum computer will probably physically need around 1,000,000 qubits. The currently most sophisticated systems are in the physical range of 100 qubits. Decades of research and high investments are therefore still required. It is not yet possible to estimate which of the technological approaches will deliver the universal, error-corrected quantum computer.

As long as universally programmable quantum computers are not yet available, quantum simulators and quantum computers without error correction, so-called Noisy Intermediate Scale Quantum Computers (NISQ), will be used in special applications. You can at one

The moderate number of qubits that can be achieved in the medium term can already achieve a quantum advantage for solving very specific problems - for example in battery research, financial mathematical portfolio optimization or basic chemical and medical research.

Quantum algorithms and quantum software are just as important as more powerful hardware. There are currently only a very limited number of quantum algorithms that offer an advantage over classical algorithms. The identification and operationalization of use cases as well as the research into suitable algorithms also play an important role in the short and medium term, as long as a universal quantum computer is not yet available. Only in this way can the actual utility of a quantum computer be demonstrated and users can benefit from it.

There is a particular need for research in the following fields:

ÿ **Development of a universal error-tolerant quantum computer, in particular:**

ÿ Increasing the maturity and scalability of physical approaches Realization of qubits, including for superconductor-based approaches, ion traps Qubits, neutral atom qubits, spin-based Approaches, photonic systems or topological qubits

ÿ Taking up completely new, disruptive ones Approaches for the realization of qubits

ÿ Further development of process and manufacturing techniques for the realization of Qubits

ÿ Research and implementation of error correction and error prevention

ÿ **Use of gate-based quantum computers without error correction (NISQ systems) as an interim solution, in particular:**

- ÿ System integration based on the most mature technology platforms. The number of usable qubits must be increased from today's approx. 100 to significantly more the error rate can be significantly reduced.
- ÿ Development of hybrid algorithms for Control and optimization of quantum circuits
- ÿ Integration of quantum computers in High-performance computing environments

ÿ **Research into quantum simulators, in particular:**

- ÿ Expanding the range of suitable and relevant use cases
- ÿ Identification of new, robust simulations on methods that reflect the latest state of the art Mapping quantum computing hardware
- ÿ Development of new approaches to reading and for the certification of the quantum simulator
- ÿ Increased controllability and programmability as well as flexible geometries

ÿ **Quantum computing algorithms and -Software, in particular:**

- ÿ Demonstration of practically relevant algorithms with a quantum advantage over classical algorithms - either one Speed advantage (quantum speed-up) or a quality advantage (e.g. better selectivity with fewer parameters in classification algorithms)
- ÿ Adaptation of algorithms and software to the specific properties of hardware systems in order to optimally use the available hardware
- ÿ Development of software and algorithms for the interaction between quantum computing and classical high-Performance computing

6.2 Research quantum-based measurement technology and imaging

Autonomous vehicles, networked production halls, the precise description of climate change and precision medicine - progress in these important topics for high-tech societies depends largely on highly precise measurements and rapid data evaluation (in quasi real time with autonomous vehicles). At the same time, these (measurement) data are becoming an increasingly important part of science as well as products and business models worldwide
in business. Novel quantum sensors and imaging systems offer completely new possibilities for data acquisition and, as a result, for example, better simulation of complex systems.

Quantum sensors enable measurements with accuracies that would otherwise be difficult to achieve. They are based on the targeted use of quantum properties to measure physical quantities such as pressure, temperature, gravity or the strength of electromagnetic fields.
There are different technological approaches to this.
For example, atomic vapor clouds, superconducting circuits, artificially created defects in diamond or the interference of atoms are used
high-precision measurements are used. The approaches differ significantly in terms of their technological maturity and possible areas of application. So-called superconducting quantum interference devices (SQUID) have been on the market for decades and are used, for example, to measure brain waves or observe the earth's magnetic field. There is still a lot of development work to be done with new technologies such as high-precision quantum radar.

In approaches to quantum-based imaging, quantum effects ensure higher sensitivity. On the other hand, they make it possible to examine an object with a low-energy wavelength with little damage and to transmit the measurement signal to a wavelength that is optimized for the actual detector. Areas of application include, for example, quality control in a factory or the examination of biological tissue.

In order for quantum sensors and imaging to deliver the advances mentioned above, the technological boundaries must continue to be pushed. This includes, for example, improved accuracy,

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Robustness and compactness. Usable systems and, if necessary, corresponding business models must be developed together with users.
Aspects such as ease of use by non-specialist personnel or economics play a particularly important role here.
feasibility of new applications plays an important role.

There is a particular need for research in the following fields:

ÿ **Technological improvement of quantum-based measurement systems, in particular:**

ÿ Improvement of technological parameters current measuring systems such as sensitivity, Lifespan, power consumption, duration of Calibration intervals or specificity

ÿ Development of new active principles Use of measurements

ÿ Improved measurement protocols as well as the addition Interaction of different measuring systems in a network

ÿ **Improve the practical suitability of systems, in particular:**

ÿ Size and portability as well (for complex measurement setups) can be integrated into existing overall systems

ÿ Low-threshold operating concepts for use by a wide range of users

ÿ High error tolerance under everyday conditions outside the laboratory

ÿ Increased robustness with low maintenance requirements

ÿ **Increasing the profitability of established companies approaches, in particular:**

ÿ Development of more scalable manufacturing development processes, the use of readily available materials, etc., to ensure the cost-effectiveness of later applications

ÿ Early piloting of economically feasible approaches with direct involvement
retention of users

ÿ **The introduction of quantum-based measurement principles in new (research) and application fields, in particular:**

ÿ Developing the scientific potential of quantum-based measurement techniques for other research fields such as energy and climate research, medicine or geosciences

ÿ Development of best practice examples to raise awareness among potential users of technological possibilities in completely new fields of application

6.3 Making enabling technologies for quantum systems market-ready

Extremely pure materials, highly specialized beam sources, temperatures close to absolute zero – applying quantum systems places high demands on the basic technologies used. The more mature the quantum systems are, the more questions arise about their ability to be integrated into other technologies or about cost- and resource-efficient manufacturing processes. These aspects are addressed by the topic area of enabling technologies (basic technologies).
This refers to technologies that are not necessarily based on quantum effects, but are absolutely necessary for functioning quantum systems. The example of quantum computers shows that this is by no means trivial: arithmetic operations are only possible here if the individual parts of the quantum computer, the enabling technologies, are optimized in such a way that the qubits work for a sufficiently long time, without disruption and with few errors.

The Enabling Technologies area includes a variety of research fields - due, among other things, to the heterogeneous technology platforms for quantum computers and quantum sensors. It's about developing new materials, components and processes. Specially developed beam sources also enable quantum-based imaging, how advances in microwave technology are efficient Enabling arithmetic operations with qubits. With the help of compact cryogenic technology, superconducting sensors can also be used mobile. A highly pure layered Growth is an important prerequisite for solid-state-based quantum computing. Without new developments in all of these enabling technologies, quantum technologies would be unthinkable.

German technology suppliers are already internationally successful in the growing enabling technologies industry, particularly in the research equipment market. This has many advantages: Laboratory structures in research facilities in particular, which largely consist of unique products developed in-house, are becoming simpler, more standardizable and more cost-effective. In addition, professional suppliers are a basic requirement for a successful quantum computer and sensor industry that produces on an industrial scale. Small and medium-sized enterprises (SMEs) and start-ups that position themselves as providers of enabling technologies are important building blocks for comprehensive quantum ecosystems in Germany and Europe (see Chapter 8). Since the research equipment market is also a target segment of this industry, its success does not have to wait for long-term commercial market entry by, for example, quantum computer manufacturers.

There is a particular need for research in the following fields:

ÿ **Development of the most important basic technologies for quantum systems, in particular:**

ÿ Materials, components and adapted Manufacturing technologies as a basis for the Realization of quantum technologies

ÿ Modules and systems for preparation, Detection, control, manipulation and that Reading out quantum states

ÿ System-critical basic technologies for Design, simulation, production and characterization of special components

ÿ **Increase the applicability of quantum systems, in particular:**

ÿ Increasing the compactness and robustness of quantum systems

ÿ Better energy and resource efficiency

6.4 Advancing photonics on the smallest size scales

As a basic technology, photonics can enable innovations in many technological fields - from telecommunications to sensors, consumer electronics, medical and vehicle technology to quantum computing. However, in order to be successful with products and services on the market, in many cases a miniaturization of photonic systems is necessary, which is often accompanied by a reduction in costs. At the same time, photonics offers opportunities to replace existing technical solutions with new, particularly small and practical photonic applications. Both approaches promise application-oriented innovations in the coming years that must be developed to market maturity. This applies in particular to the fields of photonic integrated circuits and laser-based new beam sources.

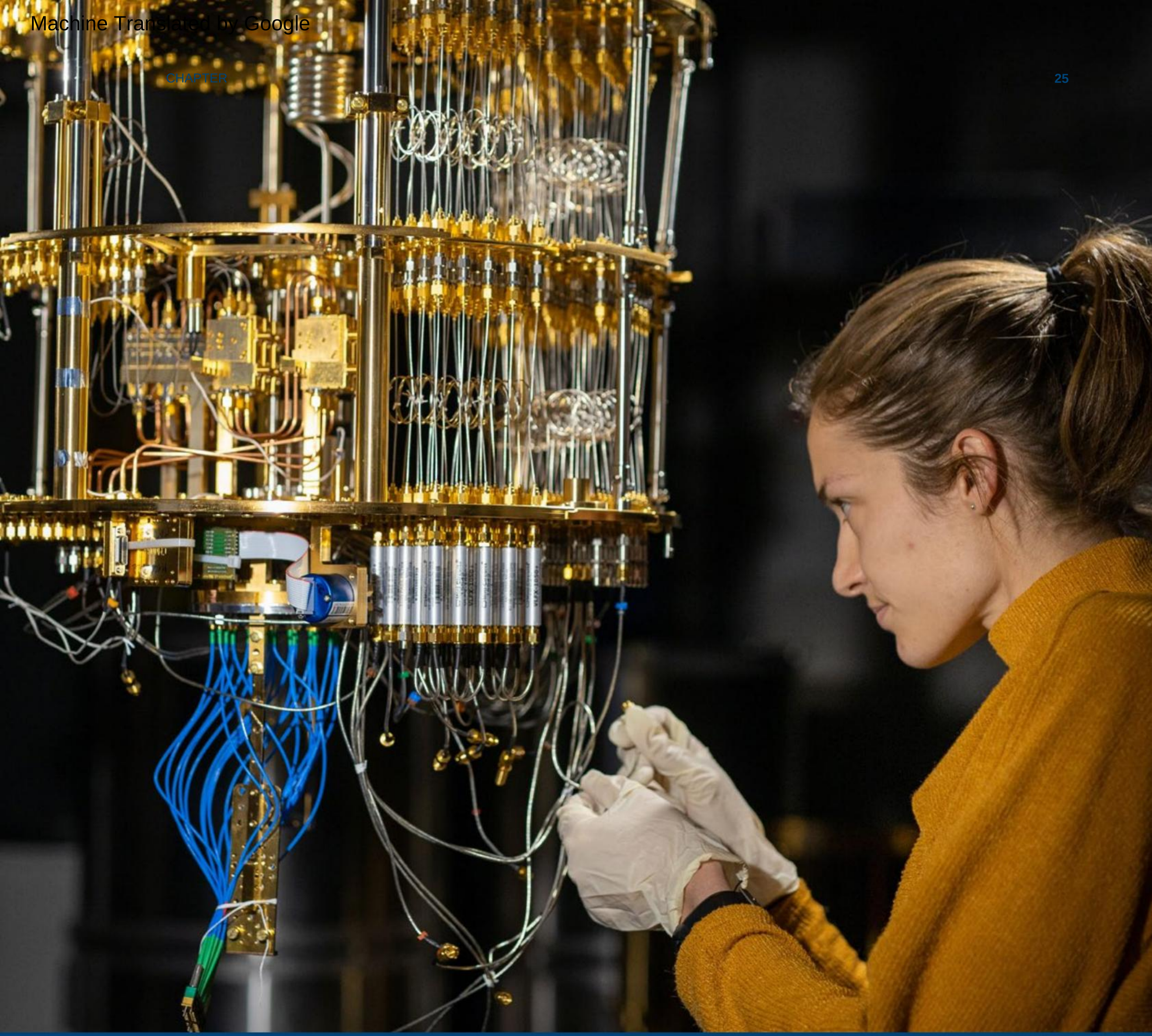
An important field of application for the miniaturization of photonic systems are so-called photonic integrated circuits (PICs). These integrate many optical functions in a single component – analogous to microchips in electronics. Compared to electronic semiconductor chips, which have been standard for decades, PICs are still at the beginning of their development. But they can add crucial functions to the microelectronics and thus lay the foundation for innovative products. For example, highly integrated photonic systems with optical data acquisition and processing in combination with electronic systems promise better performance while saving energy. In order to exploit this potential, both the integrated microphotonic systems themselves and their integration into microelectronic semiconductor chips must be improved.

A second new field of application for photonic technologies, which are particularly relevant to practice and industry due to their compactness, arises from the development of new laser-based high-energy beam sources (so-called secondary beam sources). The interaction of high-intensity laser radiation with certain materials makes it possible to generate radiation in spectral ranges that were previously only accessible with great effort. These new beam sources have a wide range of possible applications. They are due to the price reduction in semiconductor lasers and advances in many others

Laser components have only recently become conceivable. And they massively reduce the technical effort required to generate high-energy (particle) radiation. Their small size and the spectral range they cover will allow them to replace numerous large devices (e.g. synchrotrons) as beam sources for industrial applications. In addition, the practical size and low cost could open up many new industrial applications. Adapted and tailor-made digital imaging methods synergistically build a bridge to industrial applications and markets, for example in medicine, measurement technology, materials research or chip production.

There is a particular need for research in the following fields:

- **Research into highly integrated electrical optical components, in particular:**
  - Optical materials for electro-optical Platform solutions
  - New construction techniques such as hybrid integration or the integration of new material systems in photonic integrated circuits (PICs) on a scalable technology platform
  - Construction and connection technology including the standardization of interfaces for integrated systems from photonics and surrounding technologies
  - Manufacturing technologies and tools, for example structuring technologies including process monitoring
  - Systems engineering – modeling, simulation and holistic design more integrated systems
- **Research into photonic processes for Generation of high-energy radiation, in particular:**
  - Industrial-suitable concepts for radiation generation along the technology chain of laser sources, target materials and detectors
  - Laser-assisted generation of radiation with extremely high spatial and time resolution



7. Area of action II: Applying quantum systems – Driving solutions for the economy and society

Research into quantum systems opens up completely new perspectives for solving economic and social challenges. The spectrum ranges from more powerful components for the connected world to innovative tools for production or the fight against diseases through to solutions for sustainable energy production, sustainable use of resources and climate protection.

In short

1. Quantum systems can create new possibilities for the create a connected world, for example: ÿ Acquisition and use of information for Smart X (Smart City, Smart Factory, Smart Home, etc.) through photonic solutions
ÿ Overcoming the limits of microelectronic systems through micro- and nanophotonics ÿ Decentralized quantum computing structures for secure networking and needs-based expansion of computing capacities
ÿ Effective synchronization of data networks and Data centers through high-precision optical clocks

2. Advances in digital photonics can modernize Enable production processes, for example:
ÿ Automated production systems based on photonic technologies
ÿ Photonic sensor technology and visualization in the Augmented and Mixed Reality for Smart Products

3. Quantum systems can potentially become... Contribute to environmental protection and the saving of resources, possible application examples include:
ÿ Efficient production of chemical products and optimization of complex processes Quantum computers
ÿ Resource-saving manufacturing processes and More efficient use of goods through new photonic tools
ÿ Improved environmental monitoring using new, high-precision quantum sensors
ÿ Production of modern materials for efficient Green hydrogen production

4. Quantum systems contribute to modern mobility, for example through:
ÿ Resource-efficient production of means of transport through photonic tools
ÿ Autonomous means of transport through photonics Sensors and quantum sensors
ÿ Optimized traffic simulations with quantum computers

5. Quantum systems help prevent diseases detect and combat, for example through:
ÿ Detecting and combating pathogens using photonic technologies
ÿ Innovative photonic and quantum based Diagnostic and therapeutic procedures
ÿ Improved prosthetics through innovative procedures Measuring and influencing nerve signals

7.1 Using quantum systems to create new solutions for the connected world

Digitalization is driving the networking of people, machines and infrastructures. By 2023, it is expected that in addition to 5.3 billion people (around 66 percent of the world's population), around 29.3 billion devices will have access to the Internet.11 This brings with it great opportunities, but also means challenges for business and society. Quantum systems help to take advantage of the opportunities of the networked world and to meet the challenges, in particular in the areas of Smart X, networked energy systems, data processing and transmission, and networked computing.

11 Cisco Annual Internet Report (2018-2023) White Paper. Cisco, 2020.

Smart X scenarios such as Smart City, Smart Factory, Smart Home or smart energy systems can increase people's quality of life and safety and make traffic more efficient. Networked sensors can detect emergency situations such as traffic accidents, house fires or heart attacks and provide assistance call. Active traffic control based on simulations and networked sensors can be used for one ensure even utilization of traffic routes. Networked energy systems can help save energy and thus make Germany more independent of energy imports. Requirement

Excursus: quantum communication

Experts expect that powerful quantum computers could be available in ten years that are capable of breaking down common methods used today for encryption, key exchange and secure exchange of information. Before

However, given the backdrop of advancing digitalization, the secure and integrity exchange of data is the backbone of the free democratic society.

Quantum communication makes a decisive contribution to IT security in the quantum age: fundamental physical principles guarantee that the key exchange (quantum key distribution, QKD) cannot be intercepted and every attempt is noticed. Quantum states are exchanged between the sender and receiver, the property of which cannot be intercepted or copied unnoticed and is exploited for IT security.

In addition to QKD, post-quantum cryptography (PQK) methods can be used to protect data transmission from attacks using quantum computers. Both the keys and data are transferred between the sender and

Receivers are exchanged using methods in which - according to the current state of research - even future powerful quantum computers will not provide attackers with a decisive advantage.
PQK procedures can be implemented on classic computers and classic IT security infrastructure.

Quantum communication achieves even more: It represents the basis for a future quantum internet, with which through the exchange of (entangled) Quantum states in a network not only enable tap-proof communication, but also secure and networked computing with quantum computers.

When researching quantum communication, transferring it to applications and combining it with and integrating it into classic communication networks and IT security systems, it is important to actively address a variety of challenges. For example, the transmission rates and distances that can be bridged for quantum states are still too low to be used in broad applications.
The technological foundations for secure and scalable networks with any number of participants must be created, enabling the tap-proof exchange of information between people, authorities or companies as well as devices

quantum computers will also be possible in the future. Quantum communication will play a central role in the research and development of the future 6G mobile communications standard in improving security and resilience. A crucial one

The success factor is the extent to which quantum communication can be integrated into existing communication infrastructu

ren can be integrated and existing networks can be used for quantum communication.
Powerful methods for the simultaneous transmission of quantum states and classical information in optical fibers are needed, as are quantum communication components and systems that can be integrated at the locations where today's network nodes are located. Research is required for the safe use of QKD in combination with PQK processes, with compatibility and integration into classic IT security systems playing a central role.

In all research and development work on quantum communication, a holistic view of all aspects of IT security in all practical applications is the decisive success factor for the future secure networking of the digital society. Quantum communication is therefore a focus of the federal government's research framework program for digital IT security . *Secure. Sovereign.*

Such scenarios require, on the one hand, the collection of a wide range of data and, on the other hand, good networking. Quantum systems contribute to data collection and networking. Optical sensors in particular record data such as images or distances.

Networking is made possible by photonic key components in fiber optic networks and mobile networks. In all of this, data protection and personal rights of citizens must be protected. For this purpose, intelligent photonic solutions can be implemented in the sense of "data protection by design". This means, for example, that only the absolutely necessary data is captured with a deliberately low image resolution.

Concepts for data minimization (data economy) also contribute to keeping the volume of data in the networked world manageable. Despite it

Electronic data processing is increasingly reaching its limits. On the one hand, you reach energy

Energy consumption is a factor that counteracts

climate policy efforts to save energy and CO2.12 On the other hand, there are fundamental

Tale, scientific limits for the reduction of chip structures - and thus purely electronic data processing. A promising approach to overcoming these limitations is disruptive solutions for the convergence of electronics and photonics. Micro- and nanophotonics as well as the intelligent integration of electronics and photonics have great potential here. They could significantly improve parameters such as data rate, range, energy efficiency and compactness. All of this also means new economic opportunities for German companies

economic perspectives.

Quantum systems also open up completely new possibilities for networking decentralized computing structures.
The data of different parties must be included

cannot be brought together or processed centrally at any specific location - and therefore not disclosed . Unlike in conventional computer network

Complete invoices can be carried out decentrally. A quantum physical "overall state" is created that cannot be completely viewed or copied by either party. In this way you can use your own existing ones

Link computing capacities with external systems quickly, as needed and securely.

Faster data transmission in increasingly complex networks places high demands on the low-latency interaction of all network components. A mandatory prerequisite for this is highly accurate time measurement. Ultra-compact and high-precision optical clocks make it possible to synchronize high-speed networks and data centers.

In particular, the structure of the time domain mul-

The tiplexing-based 5G mobile network places high demands on synchronization and will multiply the need for atomic clocks.

There is a particular need for research in the following fields:

ÿ **Development of quantum system-based Solutions for the extraction and use of Information for SmartX, for example Applications, in particular:**

ÿ Systemic solutions that include hardware and Include software to enable efficient and data-efficient information capture

ÿ Fusion of different (quantum) Sensor modalities to make information available that is as accurate as possible

ÿ **Overcoming the limitations of microelectric tronic systems through micro- and nano-photonics as well as convergence of photonics and electronics, in particular:**

ÿ New system-on-chip and system-in Package solutions with previously unknown Integration density

ÿ Photonic-electronic integration with new degrees of freedom in the design of systems

ÿ Holistic approaches for photonic-electronic integration

12 Streaming is one of the biggest CO2 emitters – but there are solutions to the problem. Spiegel Online, December 28, 2019.

- ÿ Solutions for the optical networks of the next generation, which, in addition to high performance, also has a high degree of parallelism make possible
- ÿ Microwave photonics for example Fifth and sixth mobile networks Generation (5G, 6G) or for radar sensors

ÿ **Distributed calculations in quantum networks for more performance and higher data security, in particular:**

- ÿ Photonic systems for quantum computing
- ÿ Information theory for distributed quantum computing
- ÿ Transfer of quantum states between the network node

ÿ **Synchronization of high-speed security data networks and data centers, in particular:**

- ÿ Robust and compact systems for high-precise optical watches

7.2 Developing solutions for the production of tomorrow using digital photonics

German mechanical and plant engineering is one of the main pillars of value creation in Germany. Innovative manufacturing processes and high quality standards are important guarantees of success for German companies. However, increasing digitalization is also leading to significant changes in the value chains. Only with their own innovations can German companies survive in international competition in the long term. Automated

Production processes, individualized products and the connection to additional digital services offer new opportunities to actively shape change.

In digitalized, automated production, 100 percent quality control is becoming indispensable

be part. Photonic sensors are already there Today they are the "sensory organs" of production, as they record production data in a very short time without contact and flexibly. However, processing the immense volume of data and obtaining production-relevant information is increasingly becoming a problem. Photonic sensors are therefore not necessary

will only become smaller, but in the future will also be able to evaluate and reduce data, obtain information from it and make it available to a production network in a compact form. Advances in photonic, machine vision and understanding continue to offer new opportunities for automation.

Photonics is an important enabler for the production of tailor-made, individualized products because it creates flexibility in the production systems.
Laser processing processes are already the most flexible manufacturing processes for industrial production today. These include subtractive methods such as
Cutting and drilling, joining processes such as welding and soldering as well as additive processes such as 3D printing.
Additional flexibility comes from sensor and image processing techniques. This requires adaptation and feedback loops with particularly short reaction times. These can be achieved through innovative
tive solutions for sensor-related processing and evaluation of optical data are made possible.

Smart Products – the combination of hardware with digital solutions and services – promise new and highly customizable services for consumers

cher. Smart products are therefore another important tigious future market for German companies.
Part of this market, for example, includes services in the context of the Industrial Internet of Things, which arises from the high degree of networking of production processes. Here, optical sensor technology could be used in combination with other sensor modalities
In the future, it will allow remote control of production processes anywhere in the world and at the same time ensure access to a huge treasure trove of data. This can enable new business models: system manufacturers no longer necessarily sell a machine, but rather the service of an optimized production process. Augmented reality solutions can support this trend.
An environmental

perception using sensor technology and the context-dependent

In the future, visualization of information can make it possible to use specialist knowledge worldwide and regardless of location.

There is a particular need for research in the following fields:

- **Technologies for new automated production production processes, in particular:**
  - Machine vision and understanding
  - Fusion of different (quantum) sensors Sorting modalities to ensure the most accurate possible fit to make information available
  - Development of 3D cameras and 3D Sensors for the rapid acquisition of geometric and topological data as well as for Object classification
  - Development of evaluation procedures, Algorithms and AI systems for the rapid evaluation of data generated with photonic systems
- **Technologies that enable flexible production with regard to a holistic process chain, in particular:**
  - Systemic approaches from hardware and software for high-performance, low-latency photonic information capture
  - Development of photonic systems for stable and certifiable production additive manufacturing processes
- **Technologies that enable smart products, in particular:**
  - Photonic sensors and quantum sensors for cost-effective data collection most relevant data for a targeted Optimization of production processes
  - Approaches to visualization such as augmented or mixed reality

7.3 Using quantum systems to create new solutions for resource efficiency, climate and environmental protection

Germany has the goal of being climate neutral by 2045[13] and use raw materials more sustainably[14]. This is a major challenge for society and the economy, but also offers opportunities for innovation. Quantum systems could make important contributions to these goals in the future. Quantum computers could, for example, find new solutions for chemical processes and improve simulations. Photonic manufacturing processes have great potential to save resources. Innovative sensors and sensor systems can contribute to improved environmental monitoring.

The particularly good suitability of quantum computers for simulating new classes of materials, chemical compounds, reactions and processes as well as for solving highly complex modeling and optimization tasks opens up numerous possible areas of application for making the economy and society more sustainable. The optimization of chemical processes could, for example, lead to a more effective use of resources in the future. To whom-Examples include electrochemical processes for more powerful batteries and catalysts for the efficient production of green hydrogen. Another possible use case would be to develop a more efficient process for ammonia synthesis, which would make nitrogen fertilizer production more energy efficient. With the current state of the art (Haber-Bosch process), this requires around one percent of global annual energy consumption and is responsible for two percent of annual CO_2 emissions. Another area of application in the future is materials science, particularly in the development of development of complex material combinations. Current research topics include nanostructured surfaces, which are used, for example, in electrodes and catalysts in the field of hydrogen technologies, as well as the simulation of reaction pathways. Quantum computers could also enable resource savings beyond chemical processes. There is potential

13 Climate Protection Act 2021: Generational contract for the climate. The Federal Government, accessed on June 6, 2022.

14 The German Sustainability Strategy. The Federal Government, accessed on June 6, 2022.

For example, in more energy-efficient logistics processes based on optimized planning or in the control of the power grids so that the electricity generated by wind turbines and solar parks is optimally fed into the grids. Quantum computers could also help in dealing with the consequences of the climate changes that have already occurred by improving highly complex and multifactorial climate models.

Photonic tools provide a variety of solutions for the efficient and sustainable use of resources, for example for recycling waste through laser-based detection and sorting processes or targeted dismantling into individual parts, for example by desoldering electronic components. New

In the future, business models could use sensors based on quantum systems to achieve maximum impact with minimal use of resources. This is no longer the case in these business models

Product itself – for example cleaning or plant protection products – but rather its result - for example optimal cleanliness or optimal plant yield - is sold. The incentive to sell as much of a resource as possible is reversed.

Such business models are "resource-saving by design". With Photonic Smart Farming, the high-resolution recording of plant requirements can contribute to the exact local dosage of fertilizers and crop protection products. In some cases, plant protection products can already be used using automated mechanical methods

or replace laser-based weed removal methods. Such approaches can be implemented in the future

More powerful sensors and data processing are playing an increasingly important role in agriculture.

Autonomous and energy-efficient or self-sufficient sensor systems can be used in environmental monitoring in order to detect environmentally harmful events at an early stage. This includes, for example, the detection of methane emissions or the detection of forest fires. In the medium term, high-precision and energy-autonomous quantum sensors also offer new possibilities for earth observation. The melting of ice, changes in sea level or groundwater can be monitored using atomic interfero-

meters and new methods for precise time measurement with previously unattainable precision. Quantum-based gravimeters could, for example, measure the magma distribution and movement in active volcanoes and provide early warning of eruptions.

There is a particular need for research in the following fields:

- **Quantum algorithms for the optimization and modeling of practical problem solutions, in particular:**
  - Simulation of chemical processes, for example for more efficient production of green hydrogen or ammonia
  - More precise understanding of charge carrier distribution in solids, for example for more efficient batteries or solar modules highest efficiency
  - Optimization of complex logistical processes, for example to make them more efficient Path planning
  - Simulation of climate models for one forward planning
- **Photonic tools for resource- and environmentally friendly management, in particular:**
  - Resource-saving additive manufacturing and repair procedures
  - New usage concepts for goods through innovative sensor implementation
  - Optimized sensor and camera data processing, for example for smart farming
- **Sensor systems for environmental monitoring and Earth observation, especially:**
  - Systemic concepts for the energy self-sufficiency of decentralized and mobile sensor systems
  - Robust, compact quantum sensor concepts and structures suitable for long-term operation
  - Optical processes for highly sensitive Environmental analysis

7.4 Using quantum systems to create applications for the mobility of the future

Mobility is a basic need of today's society. The average journey to work for each employed person in Germany in 2018 was just under 17 km.15 Even due to the Covid-19 pandemic, people's mobility is not permanent decreased.16 The automotive industry therefore plays an important economic role with around 800,000 employees. It is also an important driver of innovation:17 Every year, German automobile manufacturers invest mid-double-digit billions in research and development.18 At the same time, alternative mobility concepts are becoming increasingly important, who go beyond the automobile and think of mobility as a system of various means of transport - for environmental and climate protection, but also against the background of the growing desire for flexible mobility that suits individual life situations. In 2020, almost a third of employed people in Germany used means of transport other than cars to get to work.19 Demand-oriented public transport even outside large cities, pedestrian and bicycle-friendly urban planning or control of traffic flows optimized for all transport participants are important topics for the future that also offer scope for countless technological innovations. Mobility is also one of the most important and diverse areas of development and application for quantum systems, for example in the form of photonic production technology, sensor-based autonomous driving and, in the future, quantum computer-based optimization of traffic flows.

15 There are more and more commuters in Germany. Mirror online, February 6, 2020.

16 Changes in mobility during the Corona crisis in Germany. Statista, accessed on November 10, 2021.

17 Industry focus automotive industry. Federal Ministry for Economic Affairs and Climate Protection, accessed on February 17, 2022.

18 Worldwide spending by the German automotive industry on research and development from 2013 to 2018. Statista, accessed on November 10, 2021.

19 employed people by occupation, distance, time spent and means of transport used to get to work in 2020 in %. Federal Statistical Office, January 31, 2022.

On the way to being as resource-efficient as possible Many innovations are based on means of transport photonic technologies. While laser material processing is already established in many places in the area of car body construction, the use of photonics in battery production is currently causing major leaps in development. From the coating of the extremely thin electrode foils to the assembly of the battery packages with the laser, photonics is making progress in this area in many areas.

only possible. The laser-based additive manufacturing of automotive components promises great advantages in terms of material use and lightweight construction is currently taking the step from a rapid prototyping process to series production. In addition to improvements in the additive processes themselves, questions regarding the control and optimization of the entire process chain, including pre- and post-processing, play a crucial role. Photonic sensors in combination with modern methods

Sensor fusion and industrial image processing are a central key to success.

Solutions from the field of quantum systems are of great importance for autonomous locomotion. Solutions from camera technology, photonic sensors, data fusion, image processing and distributed computing promise great progress here. Redundancies are a prerequisite for safe autonomous driving

Sensors and controls. This is particularly challenging for navigation. The aim is to filter out the relevant information from a lot of data quickly and as energy-efficiently as possible. Miniaturized rotation rate sensors (gyroscopes) based on quantum effects could, for example, be alternatives and supplements to GPS navigation.

The constantly increasing need for mobility is already pushing the necessary infrastructure to its limits. Especially in combination with autonomous driving solutions and communicating vehicles (Car2X communication), optimizing traffic flows is crucial for the efficient use of existing infrastructure. This also applies with a view to mobility in general: One thing is to optimally control the interaction of all road users, from pedestrians to cyclists and car drivers to the various means of public transport for everyone involved huge optimization task. What cannot be solved in an acceptable time using classical computers could be solved in the future using quantum computers.

There is a particular need for research in the following fields:

- **Innovative processes for manufacturing and process monitoring in automobile manufacturing, in particular:**
  - New laser-based manufacturing processes and their implementation in pilot lines
  - Process monitoring through highly integrated Sensors
  - Innovative sensor and data fusion for the Process control
- **Innovative technologies for autonomous Locomotion and environmental awareness, in particular:**
  - Camera systems and optics, for example for demanding lighting conditions
  - Highly integrated photonic sensors, for Example LIDAR
  - New sensors for GPS-free navigation gation, for example based on gas cell or diamond-based quantum sensors
- **Technologies for optimizing the Mobility, especially:**
  - Quantum algorithms for optimized infrastructure planning and traffic control
  - Integrated light sources and sensors for the Car2X communication

7.5 Detecting, understanding and treating diseases with photonic and quantum-based solutions

Statistically speaking, a girl who was born in Germany in 2020 will be around 84 years old. Life expectancy has increased by around 15 years since 1950.20 However, this social and medical achievement also brings with it challenges. Age-related diseases such as osteoporosis, macular degeneration and type 2 diabetes are increasing.21 At the same time, innovative procedures mean that increasingly gentle operations can be carried out on increasingly older patients

be performed. New and well-known diseases require improved concepts for prevention, diagnostics and therapy. Due to these social developments, medical technology is one of the sectors with the highest innovation.

ons needs. Research-based medical technology companies currently invest around nine percent of their sales in research and development.22 Health technologies are highly interdisciplinary with a broad scientific base from almost all of them Medical, natural and engineering sciences. Quantum systems can offer solutions in many areas and set trends with new products and services. This includes both different

Facets of infection protection as well as highly specialized diagnostic and therapeutic procedures. In addition, quantum systems create completely new approaches to solutions at the interface between photonics and biology, for example in the areas of prosthetics and optogenetics.

Photonic technologies are important tools for detecting and combating infectious diseases. For example, they enable faster screening of germs or more effective cleaning of water, indoor air and surfaces. Quantum computers also promise enormous advantages for development in the future new drugs and active ingredients. It enables the rapid and precise simulation of molecules and chemical processes and therefore significantly shorter Development times than with pure high-throughput screening.

When it comes to diagnostic and therapeutic procedures, Germany is one of the leading international nations with a comprehensive network of well-equipped clinics. Photonic health technologies were an important pioneer and will continue to drive innovation in the future. The areas of application range from intelligent imaging to optical systems for minimally invasive procedures to combined diagnostic and therapeutic, so-called theragnostic, procedures. In the future, super-resolution microscopy or quantum imaging can make a decisive contribution to better understanding mechanisms of action at the cellular level and to developing tailored therapy concepts derived from them.

The field of prosthetics deals with the possibilities of missing teeth from birth or due to accident or To replace body functions lost due to illness. For example, neuroprosthetics makes it possible to restore disturbed functions of the central nervous system. In this field, quantum magnetometers could be used in the future to measure brain waves - especially where requirements in terms of sensor size, mobility and costs have previously prevented the use of conventional magnetoencephalography. New quantum-based solutions for better control of prostheses therefore appear to be possible in the future.

Further potential for the treatment of nerve diseases lies in optogenetics based on light-based (photonic) approaches. This uses genetic methods to control processes in nerve cells using light-activated proteins

to control. Optogenetics can be used to further develop therapies that were previously based on electrical nerve stimulation. The advantage of light-based Stimulation is that it works more precisely and protects the surrounding tissue. The first possible applications are already being researched: microscopic LEDs in the earpiece (cochlea) for the deaf or fine light networks on the heart muscle as cardiac

pacemaker.

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20 Development of life expectancy at birth in Germany by gender from 1950 to 2060. Statista, accessed on November 10, 2021.

21 Aging healthily: Five chronic diseases that need to be defeated. National Geographic, May 3, 2019.

22 The German medical technology industry. SPECTARIS yearbook 2019/2020.

There is a particular need for research in the following fields:

ÿ **Photonics and quantum technologies Detection and control of pathogens of infections, in particular:**

ÿ Fast, high-resolution microscopy such as fast, automated microscopy for pharmaceutical research, for example high-Content systems

ÿ Optical procedures for rapid on-site diagnostics (including robust, mobile systems)

ÿ Development of compact hyperspectral sensors and hybrid sensors

ÿ Quantum computers for simulating complex biological processes as well as the Drug discovery

ÿ **Photonic and quantum-based innovative vative diagnostic and therapeutic procedures, in particular:**

ÿ Multimodal optical systems, intelligent medical imaging processes and highly sensitive sensors for diagnostics and Therapy control

ÿ Optical systems for minimally invasive therapy

ÿ Theragnostic systems

ÿ Optical imaging with entangled Photons

ÿ **Photonic and quantum-based solutions for improved measurement and influencing of nerve signals, in particular:**

ÿ Highly sensitive sensors for detecting the electromagnetic signals in nerves (and muscles)

ÿ Compact magnetoencephalography, for example, based on diamond-based Quantum sensing

ÿ Improvement of optogenetics, for example through more stable, longer optogenetic Activation and expansion of the absorption spectrum for deeper penetration Tissue and thus targeted stimulation of proteins at the site of action

ÿ Transfer of optogenetics into medical niche areas of application through clinical Evaluation of systems

ÿ Using optogenetics for the better Understanding networks in the brain and Quantum sensor technology for a better understanding of diseases such as depression, addiction, dementia

8. Area of action III: Design ecosystems – create new innovation chains, attract the best minds, take people with you

The potential of quantum systems arises from the transfer of fundamental quantum physics into new industrial or social applications. To achieve this, numerous research fields such as physics, mathematics, computer science, chemistry, medicine and engineering must work together. Companies must also network with universities and research institutions.

In short

1.The successful use of quantum systems needs functioning innovation chains. This are made possible by:

ÿ New collaborations between science and economy and between providers and applications because of new solutions

ÿ A long-term, application-oriented approach Research

ÿ A broad supply industry as well as new ones Technology and system provider

2. Technical innovations require excellent specialists forces essential. In order to secure this in the long term, you need:

ÿ The development of new formats for training, safety securing and recruiting qualified personnel

ÿ Measures to inspire excellent young scientific and technical talent

3.Germany needs international partners to be successful in quantum systems. This is achieved through:

ÿ The establishment and expansion of strategic European and international collaborations

ÿ The targeted promotion of international cooperation to complement the previously missing know-how in Germany

4. In order for a new technology to be successfully implemented, it needs broad social acceptance. The following applies to this:

ÿ Bringing society along in a way that is tailored to the target group and to inform

ÿ Using open innovation approaches to address and involve actors beyond the typical target groups

In order to compete on an equal footing in international competition, Germany and Europe must combine application competence and speed of implementation. Only those who demonstrate scientific excellence on outstanding technology platforms and establish applications and products on the market at high speed can maximize the benefits of quantum systems for their own economy and society.

This requires ecosystems that encompass all stages of the innovation and value chain.
They must build on Germany's special strengths build: excellent universities and research institutions as well as a very wide range of innovative companies that act both as technology providers and users. The development of photonics from a niche technology to one of the most important future industries in Germany is a good example for this.

8.1 Create new innovation chains for successful technology transfer

Cooperations along the innovation chain are central to the effective transfer of new solutions.

gene and new knowledge from the laboratory into broad application. Innovation chains include the area of scientific research as well as the economic implementation by providers and users. The following challenges arise for photonics and quantum technologies:

There are already established innovations in photonics chains of communication that connect science and business well. Above all, functioning ecosystems need to be expanded to include new collaborations and partners. This is intended to include competencies for systemic solution approaches and domain knowledge (e.g. from medicine, production, logistics and mobility) for the development of new applications.

In order to bring the new quantum technologies from the laboratory into widespread use, we must

Research activities go hand in hand with the development of corresponding innovation chains. Since the level of technological maturity is sometimes very low, there is often still a lack of suitable partners. In order to close these gaps, start-ups and small and medium-sized companies in particular play the role of providers

of components and products plays an important role. With photonics as an important basic technology for many quantum applications, an established industry can be built upon.

With its research funding, the Federal Ministry of Education and Research is committed to ensuring that a quantum research and industrial landscape with a critical mass is formed in Germany and Europe, which will continue to develop on its own in the future. In this way the application

The potential for development is becoming increasingly clear, visibility for the new (economic) possibilities of quantum systems is increasing and companies are increasingly being introduced to the topic area.

There is a particular need for action in the following areas:

ÿ **Expansion of the photonics innovation chain, in particular:**

ÿ New collaborations between hardware and software providers and users

from the areas of health, production, Logistics and mobility through to autonomous systems

ÿ Building manufacturing skills and -capacities for highly integrated microphotonic systems such as (quantum) photonics Integrated Circuits (PICs)

ÿ **Creation of quantum technology innovation chains, in particular:**

ÿ Networking of actors from science and business as well as providers and

users through collaborative projects and the targeted expansion of a quantum technology Expert community

ÿ Linking photonics and quantum technology innovation chains to leverage synergies

ÿ Showing possible applications tens and economic potential of the

Quantum technologies, for example Lighthouse projects, publications and trade fairs to motivate people to enter the technology field

ÿ Promoting the expansion of the supply industry for quantum systems with a long-term funding strategy

ÿ Targeted support with regard to critical Dependencies on important components and basic technologies

ÿ Promoting total system providers who can serve as a catalyst for the entire innovation chain by creating a supplier and user industry around them.

8.2 Attracting the best minds for quantum systems

Photonics and quantum technologies are highly interdisciplinary subject areas. Against this background, work in these fields requires know-how from physics, mathematics, chemistry, computer science and engineering. At the same time, the different approaches of science and business are important. The ability to develop products from proof-of-concept through technology demonstrators and prototypes to market readiness must be effectively combined with academic knowledge of quantum physical phenomena and findings from basic research.

There is therefore a need for educational paths that bring both perspectives together: the academic area should

Include application-oriented aspects more in research and maintain an appropriately appreciative attitude towards the user perspective. Companies should create opportunities for the use and commercialization of to build up the basic knowledge necessary for quantum systems. The aim is to create long-term ecosystems of well-trained "quantum natives". This also requires a targeted approach to young talent. To do this, it is necessary to include all target and age groups, from schoolchildren to students

to excellent young scientists and -to inspire scientists with specific measures in the field of quantum systems.

There is a particular need for action in the following areas:

ÿ **Training and further education as well as inter-disciplinarity in support measures, in particular:**

ÿ Special measures for development and Initiation of quantum system modules in natural and engineering sciences Study programs, early involvement of appropriate partners, support for temporary ones Exchange programs between research and industry

ÿ Promotion of cross-measure networking and accompanying research projects that capture and address issues of training and further education. The aim could be, for example, the development of common concepts and standardized content for education and training

ÿ **Arouse interest and highlight Perspectives for the researchers of tomorrow, in particular:**

ÿ A professional and continuous Communication and public relations for quantum systems, which on the one hand increase their scientific and technical attractiveness of the subject area, on the other hand Show career opportunities

ÿ Support measures for children and young people, students and graduates as well Young scientists and -scientists

8.3 Act European and cooperate internationally

Quantum systems are in international focus due to the great opportunities they offer. In almost all leading countries and regions such as the European Union, the United Kingdom, the USA and China, there are corresponding private investments as well as well-equipped national support measures and programs. The race for technological leadership is still open.

Germany is involved and has a good starting position (see Chapter 4).

Make or buy? This question is particularly relevant for quantum systems. On the one hand have developed and commercialized in Germany Applications have great disruptive potential with correspondingly promising future markets. It will therefore be of central importance for Germany as a research and business location to expand the relevant know-how and be at the forefront of the world. In addition, Germany should not become critically dependent on certain technologies and components. On the other hand, it is neither realistic nor sensible to cover all sub-areas completely with your own know-how or even production capacities, because the subject area and the scientific-technical ones

The challenges are simply too big for that. They must therefore be worked on together with European and international partners, in particular the European Commission and the EU member states.

The task will be to continuously monitor markets and science with regard to possible technological opportunities, gaps and dependencies and then make strategic adjustments if necessary. For certain topics it will make sense to build up your own know-how; in other areas it will be more productive to enter into European or international cooperation with value partners in Germany. European and international networking - for example participation in appropriate funding measures - is also a value in itself that should be continuously supported, especially in the context of basic research and the promotion of completely new ideas.

There is a particular need for action in the following areas:

ÿ **Promoting European and international networking in the field of quantum systems, for example participation in European funding measures Commission**

ÿ **Securing and expanding international len and European leading position in the field of quantum systems, in particular through:**

ÿ Cross-project and announcements Accompanying research to identify technological gaps and critical dependencies in know-how and components

ÿ New strategic support measures and Cooperation models for thematically focused development of know-how as well more application-oriented research activities and networking

ÿ The strategic development and promotion of European as well as bilateral and multilateral international cooperation, including through participation in European coordination measures such as the European technology platform Photo-nics21[23] or Coordination and Support Action from the European Quantum Flagship[24]

8.4 Take people with you

New technologies have always fascinated people. Breakthroughs such as the light bulb, the automobile, flying or space travel, the transistor or the Internet have changed people's lives and fundamentally changed their view of the world. At the same time, new technologies can also spark intense public discussions - especially when it comes to assessing their risks. The examples of nuclear energy, artificial intelligence and genetic engineering show this impressively. Well informed

23 photonics21.org

24 qt.eu

Social debates around new technologies are important so that risks are identified before they manifest themselves in practical use.

This is particularly challenging in the area of quantum technologies, because many phenomena such as entanglement or superposition are not very clear and initially appear paradoxical. More in-depth specialist knowledge is missing not only among the general public, but also often in scientific disciplines outside of physics. The aim is therefore to convey understandable information to a wider audience. This means they should

People understand the potential and opportunities of quantum systems and at the same time can objectively discuss possible risks and weigh them up for themselves.

Quantum systems in general and quantum computing in particular are associated with great expectations due to the disruptive possibilities they offer. This helps with communication, but at the same time makes it all the more important to carry out technically sound expectation management and to neutrally classify which hopes and time horizons are realistic.

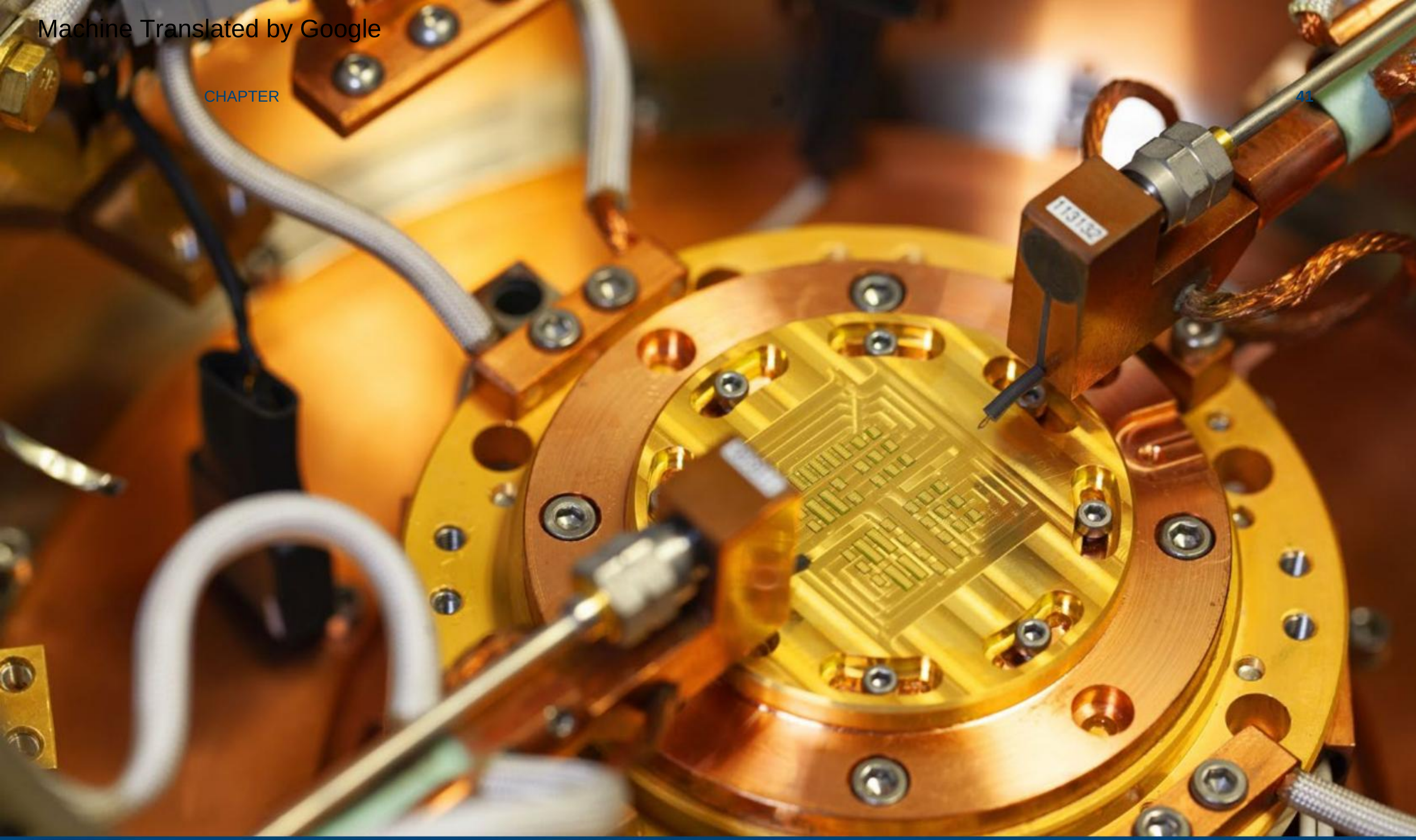
There is a particular need for action in the following areas:

ÿ **In public the information base create, in particular through:**

ÿ Targeted accompanying measures, communication, public relations and events that prepare central topics and content of quantum systems for specific target groups

ÿ Tailored initiatives to promote new outreach concepts and measures for quantum systems

ÿ Promoting open innovation approaches such as open source, open hardware, citizen Science or the integration of, for example, open workshops, fablabs or Makerspaces to create quantum system ecosystems via the classical actors and to expand beyond specialist disciplines



9. Measures: Targeted support for research and use of quantum systems

The most important research questions and approaches that the quantum systems research program addresses were named in the three fields of action. These are implemented through research funding with the following measures:

9.1 Apply research results

The collaboration between research institutions and companies in collaborative projects is central when it comes to transferring research results into application. The aim of project funding from the Federal Ministry of Education and Research (BMBF) is to enable close cooperation by supporting joint projects in the pre-competitive area. To ensure transparent competition for the best ideas, funding guidelines are provided at regular intervals specific content focuses will be announced. The requirements and evaluation criteria vary depending on the topic. For example, the maximum joint funding quota, i.e. the required financial contribution of the participating companies, is based on the technological maturity of the topic. The BMBF sees itself as a pioneer in enabling private investments in a research topic. For this reason, perspective value chains can often be found in the specific composition of the consortia. This path should be continued for innovative technologies in the field of quantum systems.

9.2 Support business start-ups and start-ups

Due to the strong fundamental orientation, the corporate landscape in the area of quantum systems is still young and partially fragmented in many areas. This poses challenges in transferring scientific findings and new technologies into practical applications. In order to close these gaps in technology transfer, start-ups in particular are particularly important. Support measures are needed that relieve the burden on young companies in the start-up phase and create access to project funding.

The BMBF supports the measure

Enabling Start-up – companies already *founded in quantum technologies and photonics* . Start-ups can work closely with a research institution and thus benefit from the scientific expertise as well as from existing laboratory space. The measure is designed for the long term. An important characteristic of the activities is the ability to connect to existing approaches to business start-ups and venture capital investments in young companies, as well as the ability to connect to the federal government's *future strategy for research and innovation* . For example, care is taken to ensure that the funding fits well with simultaneous financing from private investors.

9.3 Take up new findings and developments at an early stage

The program promotes pre-competitive application-oriented research work. In comparison to purely knowledge-oriented basic research, this occurs when scientific phenomena have already been described and result from this

a potential for technical use can be derived. But not every topic is suitable for larger collaborative projects with corporate participation at this stage. The BMBF therefore also supports application-relevant proof-of-concept on a laboratory scale. This enables the first potential assessment of a technology. The continuous measure *scientific preliminary projects*

offers research institutions and universities the opportunity to provide focused proof of functionality

and thus build a bridge to a more comprehensive research and funding topic. If successful, this makes it easier for companies to decide to invest appropriate research and development (R&D) resources in topics with a higher research risk, even after the project has been completed.

9.4 Bringing together competencies in networks and creating synergies

Research topics that are internationally competitive and require a particularly high level of interdisciplinarity or complex structures require networks. Because internationally competitive innovation ecosystems are more than the sum of the individual actors and projects. Scientific discourse across disciplinary boundaries, the broadest possible use of complex infrastructure or the flexible exchange of components – all of this requires functioning networks. The BMBF under-

supports their creation in many ways. Large events and small workshops offer opportunities for networking. There is already a community area on the BMBF's specialist website for quantum technologies, the range of functions of which can be expanded as needed. In addition,

Accompanying projects are supported on an event-related basis, which actively contribute to networking and thus create synergies.

9.5 Prepare standards

Standards are particularly important for the successful transfer of technology into application. The broad acceptance and economical use of a technology require uniform interfaces, protocols and components with one or a few variants. An organic growth of various parallel individual solutions would be a major obstacle to broad technological development and industrial implementation. Common reference values (benchmarks) are also important for better comparability of products and components.

Particularly in the area of enabling technologies, common standards for specifications, interfaces and protocols are of central importance so that system integrators can use the components in their products in a planned and economical manner.

With its funding measures, the program also supports R&D work that serves to prepare standards. Depending on the occasion, cross-measure accompanying research projects are also possible, which identify topics from the field of funded projects that are relevant for standardization, such as standard problems in quantum computing or coordinated interfaces and benchmarks for beam sources.

9.6 Cooperate internationally

The national funding strategy is embedded in a European economic and scientific system. It is important to be a strong and reliable partner, particularly within the *Horizon Europe*25 program. This includes close coordination with the partner countries and the European Commission as well as active participation in European measures.

The aim is also to cooperate beyond Europe's borders in bi- or multinational measures. The prerequisite for this is that on both a scientific and an economic level

Collaboration takes place at eye level, so that all parties benefit from the cooperation.

9.7 Promote young talent

A scientifically and technologically complex field such as quantum systems has a high need for well-trained personnel, both in science and in industry. Not only the

Research, but also the use of new technologies requires specific skills. For this reason, those completing the relevant

Disciplines such as physics, mathematics, computer science and engineering are introduced to quantum systems during their training courses. This applies all the more the less the scientific fundamentals are part of the subject curriculum anyway.

The BMBF funds pilot projects, the formats and Initiate offers that complement existing educational offerings add to. The aim is to create excellent skills for quantum systems in Germany - whenever close cooperation between companies and training institutions creates added value or educational questions arise across national borders. For this purpose, the BMBF launched the *Quantum Future* initiative. It addresses a comprehensive package of measures

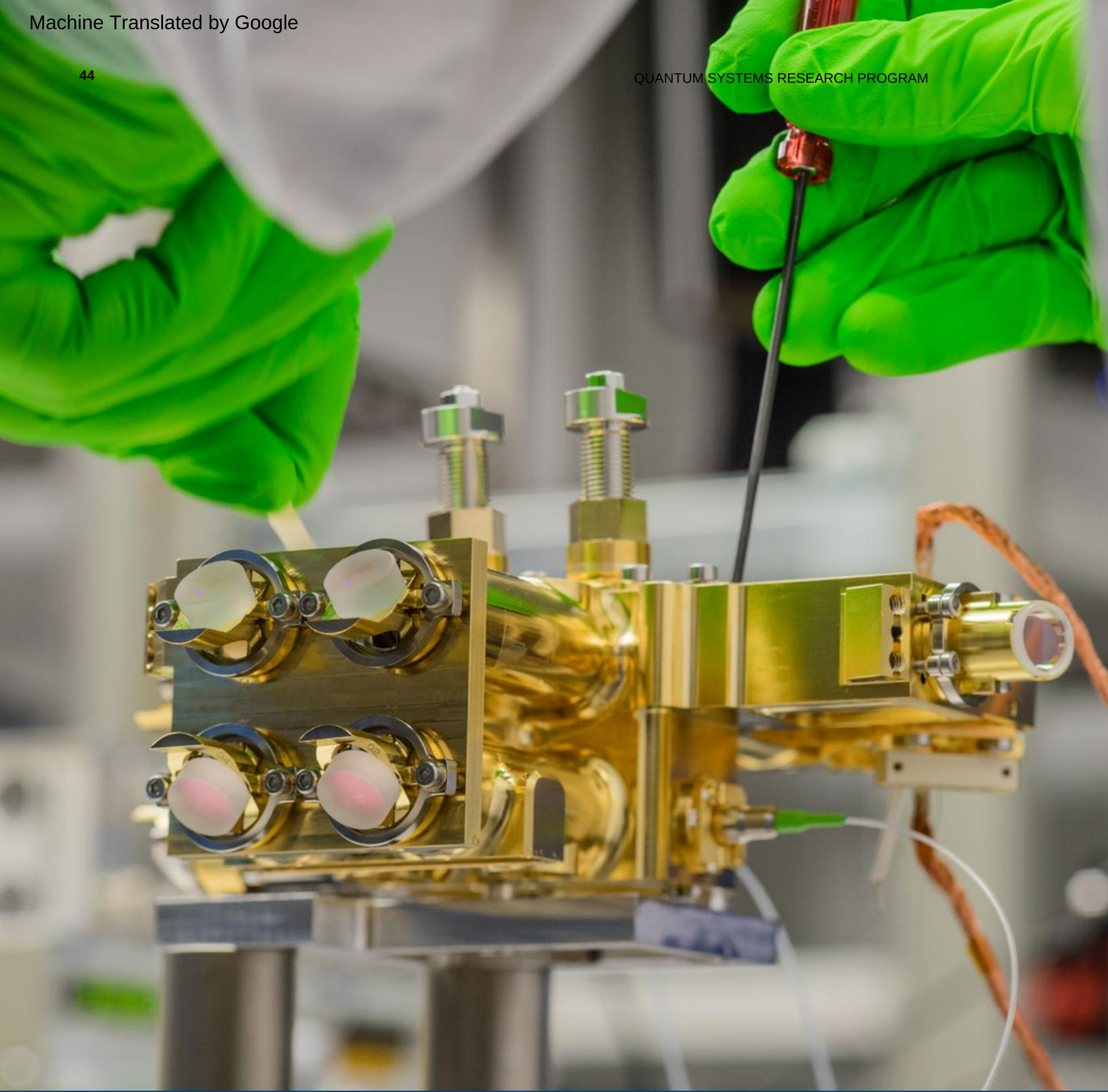
different target groups – from students to junior group leaders. The measures range from funding initiatives with different levels of severity from the annual *Quantum Futur Academy* to the presentation of the *Quantum Futur Award.* The initiative will be continued and flexibly tailored to needs.

9.8 Conduct scientific communication

Quantum systems are a scientifically complex future topic whose generally understandable communication is associated with challenges. Broad participation of the interested public and interest groups promotes the successful implementation and use of this technology in Germany.

Science communication is an integral part of research funding. Informed on topic-specific websites and social media channels the BMBF provides detailed and generally understandable information on current funding topics. Editorial format te like *A Bit of Knowledge* or *Five Questions* convey ··· complex topics clearly. This should be continued and expanded to include innovative formats. For example, exhibitions or exhibits in museums can explain physical backgrounds and technological principles. Dialogue formats with citizens can address the influence of new technologies on our lives and work - especially in the sensitive areas of information and communication. With *Quantum Aktiv,* the BMBF has dedicated its own funding guidelines to the topic of outreach. Such and similar activities will be increasingly taken up as quantum systems become more mature and therefore more tangible.

25 horizont-europa.de



10. Framework conditions of the program

Long-term action is required so that the measures mentioned in Chapter 9 can have the desired effect and achieve their goals. The quantum systems research program is therefore designed as an open, learning framework for action over a period of ten years up to and including 2031.

10.1 Origin

In order to identify the specific need for action in the field of quantum systems, an agenda process was carried out as a strategic audit instead of an ex-ante evaluation. Over 300 participants from science and business have participated in the research

The need for research in the field of quantum systems is summarized in the *Agenda Quantum Systems 2030* . The results of this process were incorporated into the program creation, as were the results of the (interim) evaluation of the *Photonics Research Germany* program published in 2012 by the Federal Ministry of Education and Research (BMBF).

This form of dialogue with the specialist community has existed in photonics for a long time, was intensified with the *Quantum Systems 2030 Agenda* and expanded to include the topic of quantum technologies.
The BMBF will continue it for quality assurance, updating and strategic development of the program in order to be able to respond to technological, economic and social developments in a timely manner and in a coordinated manner. Regular large congresses also serve this purpose, at which the BMBF exchanges ideas with the most important players in the specialist community.

A further agenda process is planned for around the middle of the program term, in which the research needs mentioned in the *Agenda Quantum Systems 2030* will be examined again and, if necessary, updated and supplemented.

10.2 Integration

The political goals of the quantum systems research program are embedded in the federal government's overarching strategies. These are in particular the *future strategy for research and innovation26* and the *German sustainability strategy27.*

The program also has points of contact with numerous other ongoing or planned projects

Strategies and programs of the federal government and its departments. There are particularly strong connections to the *federal government's research framework program for IT security28,* to *the communication systems research program29,* to *the federal government's framework program for research and innovation in the field of microelectronics30* and to the *medical technology specialist program: Improving patient care - strengthening innovative strength31.*

10.3 Learning program, evaluation

The mission of the quantum systems research program (see Chapter 1), the dynamic development of the topic area and expected changes in economic and technical-scientific areas
Framework conditions require constant monitoring and further development of the program.
A regular review of the milestones of the program mission, rapid adaptation to scientific and technical developments and an orientation towards the lead markets take this dynamic into account. If necessary, funding for the research program can be aligned with the achievement of milestones. If the framework conditions change or new technical-scientific dynamics arise, new goals, tasks and priorities are also possible.

In operational research funding, the relevant departments and partners from the economic and scientific environment are consulted before new funding guidelines are announced

included. This happens, for example, in the form of technology analyses, foresight processes and expert discussions. Disruptive opinions and perspectives are also included (via so-called pattern breakers). In this way, the funding measures are adapted to the actual level of development and new ideas are given space at an early stage.

26 bundesregierung.de/breg-de/suche/progress-durch-research-1986628

27 bundesgovernment.de/breg-de/themen/nachhaltigkeitspolitik/a-strategy-accompanies-us

28 forschung-it-sicherheit-kommunikationssysteme.de/digital_safe_sovereign

29 forschung-it-sicherheit-kommunikationssysteme.de/sovereign_digital_networked

30 bmbf.de/bmbf/de/forschung/digitale-wirtschaft-und-gesellschaft/microelectronics/microelectronics.html

31 gesundheitsforschung-bmbf.de/files/BMBF_Fachprogramm-Medizintechnik_2020_sperrfrei.pdf

Table 1: Milestones of the mission of the quantum systems research program.

Technology field	Milestones
Quantum computing	· By 2026: internationally **competitive quantum computer** with at least 100 individually controllable qubits, scalable to 500 qubits · By 2026: **The number of start-ups** in Germany will quadruple to ÿ 20; ÿ 60 end users in Germany, including in business, science and civil society · By 2032: Demonstrate **quantum advantage** in at least two practical applications in Germany · Until 2032: Remain world leader in **publications** (Top 3) and expand in **patents** (in top 5)
Quantum sensing	· By 2026: **5 new products** on the market · By 2032: **ÿ 60 companies** involved, including 10 start-ups · By 2032: Maintain world leadership in **publications** (top 2) and expand in **patents** (in top 5)
Photonics	· By 2026: **ÿ 30 photonics companies** involved in quantum technologies · By 2032: **ÿ 1 a new, research-intensive lead market** developed for the German photonics industry

With a view to achieving the objectives of the research program's mission, the following milestones (see Table 1) were set in the three technology fields of quantum computing, quantum sensors and photonics, which can be checked regularly and updated if necessary. The milestones orientate coincide with 2026 at the end of the 20th legislative period and 2032 at the end of the research period. program.

The stated milestones of the mission of the research program form the research policy level of goal achievement monitoring. At the same time, a ten-year funding program achieves numerous other effects at various levels. With these levels of impact (output, outcome, impact) in mind, the

Mission (competitiveness in quantum systems) and the other objectives of the program (see Chapter 5), first overarching and topic-specific indicators were derived, which represent an approach for the extended monitoring of the success of the program (see Tables 2 and 3). These indicators form the basis for the conception of a professional external evaluation (accompanying after five years and ex post). The expertise of the external evaluators is used for the final definition of the indicators.

be decisive. In total the program should contain **12** valuation a method mix of quantitative and qualitative research methods should be sought, using, for example, econometric approaches, randomized control groups, structured/representative surveys and expert interviews.

Table 2: Additional indicators for evaluating the mission of the program.

mission	**Additional indicators for monitoring success through evaluations** (not exhaustive)
Germany in the next decade in the European network Lead the world in quantum computing and quantum sensing and expand Germany's competitiveness in quantum systems	Number of research collaborations, key figures for specialist training, Number of transfers of new technological solutions and product innovations, performance of German companies worldwide Comparison

Table 3: Additional indicators for evaluating the program.

Additional goals and comprehensive indicators	**Additional indicators for monitoring success through evaluations** (not exhaustive)

	through evaluations (not final)
Germany in the next decade in the European network Quantum computing and quantum sensor technology at the forefront of the world and expand Germany's competitiveness in quantum systems	Number of research collaborations, key figures for specialist training, Number of transfers of new technological solutions and product innovations, performance of German companies worldwide Comparison

Table 3: Additional indicators for evaluating the program.

Additional targets and overarching indicators	**Additional indicators for monitoring success through evaluations** (not exhaustive)
Securing technological sovereignty in quantum systems	Number of companies active in the topic area, degree of coverage Value chains, indicators of the skilled worker base, production volume and export share in the world market
Using the opportunities of technological change for the economy and society (with quantum systems)	Breadth of the spectrum of new solutions, degree of economic/ social use, extent of citizen participation, breadth of the spectrum of applications for which quantum systems offer solutions
Promoting sustainability in business and society with quantum systems	Number of contacts with users of sustainable solutions, number of solutions for SDGs 3, 9, 11, 12 and 13, saving/avoiding climate-damaging emissions, resource savings, effects on health care
Comprehensive impact indicators	Scope of R&D activities and expenses (private/public), Number of successfully implemented R&D projects, degree of use in key sectors, number of new collaborations, volume of private investments

glossary

CCS: Carbon Capture or Carbon Dioxide Capture and Storage
A process for binding and permanently storing carbon dioxide from the atmosphere.

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 research institution with a significant technical risk. In contrast to competitive or experimental development and product development.

Gas cells:
Small-scale device (typically a few cubic centimeters in size) for highly precise measurement of magnetic fields and magnetic field changes. For this purpose, the cell is usually filled with a mixture of noble gases and metal atoms. By applying magnetic fields and laser excitation, the precession of the nuclear spins of the noble gases and their changes can be precisely measured. This also enables, among other things, the realization of a nuclear spin gyroscope.

GPS: Global Positioning System
Global navigation satellite system for position determination. The system has established itself as the world's most important positioning method and is used in navigation systems.

Gyroscope:
Measuring instrument that uses the axially stable position of gyroscopes to determine direction or rotation rate. Previously mainly used in the form of a Gyrocompasses in maritime and aviation. A comparable effect can be observed with atomic nuclear spins. This allows the construction of extremely compact nuclear spin gyroscopes without macroscopic moving parts, which can be used in space travel or autonomous driving.

Haber-Bosch process:
Standard process for producing ammonia from atmospheric components.

Hyperspectral sensors:
Sensors for simultaneously recording spectra in a variety of wavelengths on a sensor chip. In some cases, dozens of wavelengths can be imaged in a typical range from the visible to the near infrared. Application in industry and agriculture (smart farming).

IIoT: Industrial Internet of Things
Networking and (often AI-based) evaluation of production processes, sensor information, product and customer information as well as energy and time management processes in industrial production. Goals can be, for example, energy and cost savings in production or the individualization of products.

IoT: Internet of Things
Networking everyday objects with each other and with the Internet, for example to control heating systems or room lighting via smartphone.

SMEs: small and medium-sized enterprises
According to the EU definition, companies with fewer than 250 employees and an annual turnover of no more than 50 million euros or total assets of a maximum of 43 million euros.

LED: Light-Emitting Diode
Semiconductor component that emits light when electric current flows in the forward direction.

Due to their good light output, LED lamps have replaced many other lamps in everyday life.

LIDAR: Light Detection and Ranging

Distance determination and detection of objects or obstacles using laser light; analogous to radar.

MEG: magnetoencephalography

Magnetic brain wave measurement, analogous to the electrical brain wave measurement Electroencephalography (EEG) a non-invasive method for measuring brain activity. The method is used in brain research It is used for medical purposes and should also be used therapeutically in the future, for example to control prostheses.

NISQ: Noisy Intermediate Scale Quantum Computer

Intermediate 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).

Optogenetics:

Genetic process for light sensitization of living cells. By introducing special proteins into animal or human cells These can cause an electrical reaction Light stimuli are enabled. This also works, for example, in hearing, brain or muscle cells.

PIC: Photonic Integrated Circuit

In analogy to electronic integrated circuits, a monolithically constructed chip (for example based on indium phosphide) with several optical functionalities at the same time. Simple Examples include tunable cavity lasers and Bragg mirrors on the same chip.

PQK: Post-Quantum Cryptography

Term for 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.

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 the breakdown of the communicati conduct communication.

Qubits: Quantum Bits

The smallest logical computing units 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.

Rapid prototyping:

Generic term for the rapid production of prototype components as part of design processes or R&D work in industry, but also in architecture and art. One example is 3D printing of plastic or metal components.

SDGs: Sustainable Development Goals

17 goals of the United Nations for the economic, social and ecological development of the international community. sdgs.un.org/goals.

Secondary radiation sources:

Extremely high power lasers enable the generation of X-rays or the acceleration of particles to almost the speed of light, which in turn can generate radiation or neutrons. This secondary radiation can be used for research purposes, for example in a synchrotron or a spallation source, but with drastically reduced financial outlay and form factor (“table-top synchrotron”).

Sensor fusion:

Linking and intelligent evaluation of several Sensor information and modalities in one Chip or in a system. Can be used, for example, for automation in industry or in the smart home.

SiP: System in Package

In contrast to system-on-a-chip, system functions are implemented on different chips and then connected, stacked or glued in the smallest possible space (the package).

Smart Farming:

Collective term for various technologies for optimization, digitalization and automation in agriculture. The goals are to increase yields, reduce personnel deployment and in particular the reduction of fertilizers and pesticides to protect the soil and fauna. For this purpose, data from satellites, drones and ground sensors or hyperspectral imaging are used.

SmartX:

umbrella term for “smart” products and applications through combination with digitization methods such as machine learning or artificial intelligence, for example smart home, smart city, etc.

SoC: System-on-Chip or System-on-a-Chip

Integrated implementation of multiple system functions on a chip/semiconductor substrate. For example, sensors and evaluation electronics.

SQUID: Superconducting Quantum Interference Device

Measuring device for detecting the smallest changes in the magnetic field, based on a current-carrying, superconducting ring. First described by Brian Josephson in 1962.

Super resolution microscopy:

Generic term for optical microscopy below the actually physically possible optical resolution limit (diffraction limits). Various processes and effects are used for this. Stimulated Emission Depletion (STED) microscopy uses a clever excitation and de-excitation pattern of fluorescence on the sample to reduce the actual imaged area.

Theragnostics:

Interlinking therapy and diagnostics in medicine through novel technological possibilities, for example early detection of diseases through new detection methods and thus possible proactive therapeutic approaches or ongoing diagnoses during therapy to improve and individualize therapeutic approaches.

Time domain multiplexing:

Method for transmitting data streams from different transmitters using a single signal.
To do this, the data is divided into short sequences on the transmitter side by a so-called multiplexer and periodically combined into a signal. A so-called demultiplexer is then required on the receiver side for interpretation.

imprint

editor
Federal Ministry
for Education and Research (BMBF)
Quantum Technologies Unit; Quantum Computing
53170 Bonn

Orders
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Dispatch of publications by the Federal Government
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Email: publikationen@bundesregierung.de
Internet: bmbf.de
or via
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June 2022

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