acatech IMPULSE

The Innovation Potential of Second-generation Quantum Technologies

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Contents

Foreword

The quantum computer is at the centre of public and political interest in the debate around the next generation of quantum technologies. Even if the debate tends to overestimate the practical implementability and performance of today's quantum computing approaches, the latest breakthroughs have shown that, from a longer-term perspective, the disruptive potential of this new type of computer is indeed very likely to become a reality.

In addition to the quantum computer, there are also other new quantum technologies which, whilst not widely publicly known, may have a major impact on our lives. Practically usable quantum simulators might be more quickly achievable than quantum computers, so they could be put to use sooner in materials research, for example for developing more efficient and thus carbon-saving catalysts for fixing nitrogen. Tap-proof quantum communication could become a central pillar of our IT architecture. Last but by no means least, quantum-mechanical effects could be used in novel sensors to make diagnostic methods not only more accurate but also pleasanter for patients.

This acatech IMPULSE paper therefore provides a comprehensive analysis of current scientific and economic trends in individual second-generation quantum technologies. In addition to their associated value creation potential, their implications for the technological sovereignty of the European internal market are also discussed.

The intention is to create an awareness that converting the insights of quantum physics into real-world applications is extremely challenging. It requires a quantum technology ecosystem with the expertise and endurance to complete the long road from initial proof of concept in the laboratory to an innovation fit for practical use. Germany has all the necessary building blocks, in particular an excellent research landscape. Putting them together, however, will require long-term, concerted effort by academia, business and politics.

The National Academy of Science and Engineering trusts that this investigation will contribute to a substantive and foresighted debate about second-generation quantum technologies. The acatech Office conducted numerous background interviews with experts in preparation for this IMPULSE paper. The resultant insights were brought together to provide a clear picture of the factors which, in the coming years, will determine the international competition around the next generation of quantum technologies.

The present study is a revised version of a paper which was discussed with members of the Federal Government.

acatech would like to thank everyone involved for their committed input to writing the study.

Prof. Dr. Dr.-Ing. E. h. Henning Kagermann
Chair of the acatech Board of Trustees

Executive Summary

Quantum physics came into being almost 120 years ago thanks to the efforts of physicists including Max Planck and Albert Einstein. Their insights enabled a distinctly more accurate description of the behaviour of light and matter on (sub)atomic scales and created the **theoretical basis** for much of **modern physics**.

Lasers, magnetic resonance tomography and semiconductors are three technologies based on quantum physics which have already been having a major impact on our lives for over half a century. The advent of **second-generation quantum technologies** means there is an upcoming **wave of novel applications** which precisely control quantum-mechanical effects on individual or small numbers of particles.

Currently, the **quantum computer** is the most discussed new application and is considered to have the greatest disruptive potential. It is anticipated that it will be able to solve many problems which are beyond the capabilities of today's supercomputers. Examples include route optimisation for autonomous vehicle fleets to cut emissions and journey times or decryption of encrypted data. However, most of the experts surveyed predict that it will **probably take another five to 15 years** before a practically usable quantum computer is available.

Quantum simulators, a kind of analogue quantum computer, might possibly be in use sooner for solving specific user problems. They may, for example, be used for modelling the chemical **behaviour of candidate drug molecules** and for designing **novel materials** for more efficient batteries or energy-saving catalysts for chemical processes.

Quantum effects can be exploited for designing physically tap-proof communication links. Such **quantum communication** may therefore be a building block for future IT security architectures. In addition, **new forms of encryption,** which cannot be broken even by a quantum computer, are currently being developed and tested.

Not least, the progress made in research is enabling the development of more effective **sensors, imaging methods and measuring instruments**. These could, for example, be used for more accurately detecting brain waves, extending the spectrum of microscopy or also for surveying underground structures on the basis of fluctuations in the gravitational field.

All second-generation quantum technologies are based on specialised components such as light sources, cooling technology or semiconductors. The **practical usability** of new quantum technologies outside the laboratory crucially depends on whether it is possible to make these **enabling technologies less costly, more robust and smaller** so that they can be integrated into systems which are attractive to users.

The described fields of quantum technology have reached differing levels of maturity, but overall they are all still at an **early stage**. So far, the technologies are not yet profitable and **no mature value chains** have yet developed. At present, researchers and business are primarily working on demonstrating that laboratory findings can in principle be implemented into practical

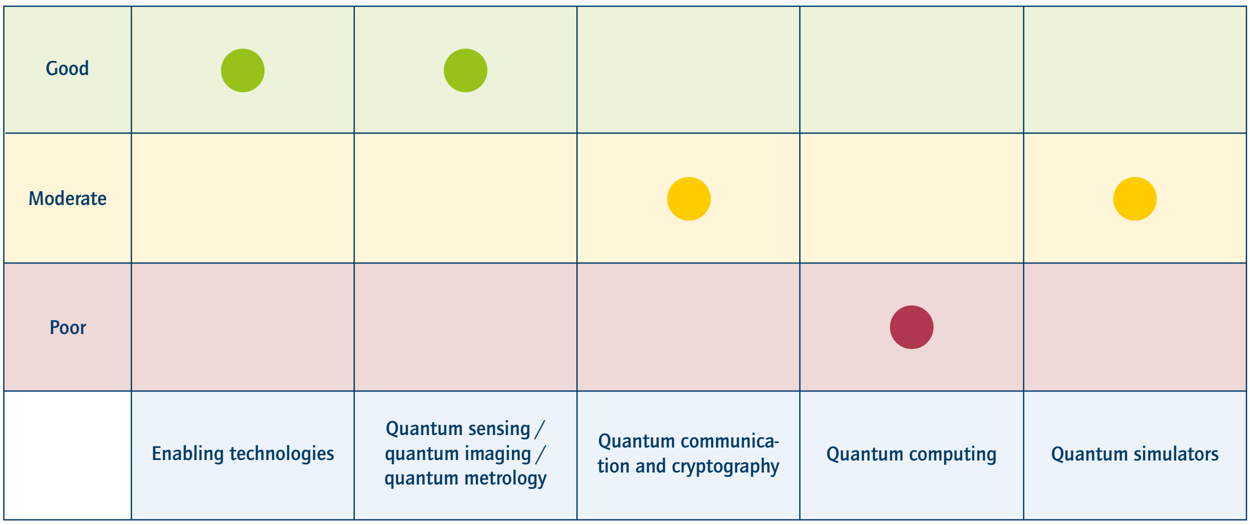

Figure 1: Germany's current position in the commercialisation of quantum technologies compared to other countries (source: own presentation)

applications. Using **experiments, competitions and small-series production,** they are investigating the application scenarios in which the anticipated advantages of quantum technologies can materialise.

Businesses as well as governments are therefore **not seeking to make short-term profits from their early investments**. Instead, they are attempting to develop **in the long run a major lead** in key technologies in many economic sectors and industries which are of great significance to Germany and Europe. The analyses and expert interviews carried out for this IMPULSE paper reveal a mixed picture of **Germany's** current position in this international competition (see Figure 1).

The following **ten key messages** summarise the central findings of the analysis which has been carried out and the assessment of the possible development pathways and outline **Germany's potential future position**:

1. **Germany's** universities and non-university research institutions have a long tradition of **quantum research which is held in high international esteem**. This strength can be purposefully developed by perpetuating **strategic alliances** with leading research institutions within the **EU** and **worldwide.** Germans are already working in research and development in many of these institutions and could be encouraged to advocate such cooperation.

2. It is vital to make **experienced specialists** "quantum-ready" by **further training**. The **next generation** not only of students but also of technical trainees, for example in precision optics, must be made **"quantum natives"** by adapting existing provision and offering new courses of study. **International researchers** need better **career prospects and more attractive options for remaining in Germany**, in particular at postdoctoral level.

3. **Commercialising** quantum technologies requires **perseverance** in order to avoid a "quantum winter" similar to earlier AI winters. Long-term continuation and **further development** of German and European funding initiatives and strategic processes are not only vital for research institutions but can also maintain the **commitment of German businesses** during a phase of weak economic performance.

4. **Basic and applied research** must work together **more closely than usual in what is still a young field**. Not only does this require physics, engineering sciences and other disciplines to be open to each other's cultures but it also entails **business involvement from an early stage**. Achieving this will require appropriate support for the development of expertise and experience.

5. Germany has a **large number of potential users** in many different sectors for all second-generation quantum technologies, for whom quantum technologies may be a logical next step in quality and who are **at the same time attractive cooperation partners for domestic and foreign manufacturers** of such applications.

6. A **network** of excellent researchers, first-moving companies as well as potential users, which will build the foundation of an **effective German ecosystem** for second-generation quantum technologies, **is only just getting off the ground**. As a result, there is often a **lack** of **coordination**, **speed** and **critical mass** in comparison with other countries.

7. Germany is in a **very good starting position,** in particular in **enabling technologies** and quantum-based **sensing, imaging and metrology**. The provision of **production, test and validation environments** may lower the entry threshold for SMEs and start-ups in particular for enabling components and in quantum sensing. When it comes to quantum communication, the **government can act as a trailblazer** to establish trust in the technology and work towards the creation of certification options and standards.

8. Most surveyed experts expect the greatest potential for value creation in quantum computing to be **not in hardware production but instead in the next wave of digitalisation it will enable in various applications.** In order to develop the necessary **algorithms and software applications**, German businesses and researchers need the greatest possible ongoing **access to quantum computing platforms**, ideally right down to the hardware level.

9. **If Germany is to achieve technological sovereignty** in quantum computing, it is vital for there to be a **German or at least European manufacturer of quantum computers.** The same applies to the development of its own domestic quantum communication technologies and infrastructure.

10. The process of moving towards the **development of European quantum computing hardware capacity according to many surveyed experts** would entail rapid strategic **coordination** of existing expertise and infrastructure and speedily **joining forces with other leading EU member states**, in particular France, the Netherlands and Austria.

Interviewees

Thanks

For this IMPULSE paper, members of staff of the acatech Office have not only evaluated specialist literature and other studies but also carried out exploratory interviews with 95 representatives from academia, business, politics and society. In doing this, the aim was to obtain a current snapshot of the mood in relation to the development status and potential of second-generation quantum technologies.

The discussions took place by telephone or in person in the period from June to October 2019 and lasted an hour on average. The interviews were unstructured in order to emphasise their exploratory nature and to capture any nuances. This study takes the form of an overview of the main opinions and positions expressed in the interviews, but the intention is not to rule out the possibility of individual interviewees holding different viewpoints on certain questions.

The interviewee roles cited are those they occupied at the time of the relevant conversation. To illustrate certain selected central ideas held by the respondents, every now and again quotes taken from the interviews are included in anonymised form.

On behalf of the acatech President's Office, the acatech Office would like to express their heartfelt thanks to all parties concerned for their readiness to take part in the interviews.

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1 Towards a quantum ecosystem in Germany

Quantum physics came into being almost 120 years ago thanks to the efforts of physicists including Max Planck and Albert Einstein. Their insights enabled a distinctly more accurate description of the behaviour of light and matter on (sub)atomic scales and created the **theoretical basis** for much of **modern physics**. These revolutionary changes to the science and the basic research based on it also subsequently led to practical technological applications such as lasers, semiconductor technology and magnetic resonance tomography. For more than half a century these technologies have shaped our lives and given birth to **many new industries**.

The advent of **second-generation quantum technologies** means there is an upcoming **wave of novel applications** which precisely control quantum-mechanical effects on individual or small numbers of particles. These innovations are conventionally divided into four **technological fields**: **quantum-based sensing, imaging and metrology; quantum communication and cryptography; quantum computing** and **quantum simulators**. All of these are also dependent on **enabling technologies** for the necessary components.

The basic research carried out by Germany and **Europe in general** in all the stated technological fields has been of excellent quality. At the same time, the experts surveyed for this IMPULSE paper expressed concern that the **"European Paradox"**, Europe's comparatively **weak performance in transferring** excellent scientific achievements **into concrete innovation**, may also strike in the field of quantum technologies unless sufficient counter-measures are taken.[1] These same experts rank Germany's **current** relative position in the international competition to convert research results into concrete, marketable applications as shown in Figure 1.

Germany and Europe have introduced initiatives to address this initial situation and a series of identified weak points, for instance the German Federal Government's **Framework Programme "Quantum Technologies – from basic research to market"** and the **EU Quantum Flagship.** These initiatives provide not only funding for those researchers who are already active, but are also aimed at making quantum technologies more visible and attractive in Germany and the EU and at sending important signals to industry (manufacturers and also potential users) to encourage early consideration of this future market.[2] Interested companies are being actively involved in the project.

Several German research institutions have also entered into **collaborative projects with Google or IBM**, to give people working in research and development **access to these American**

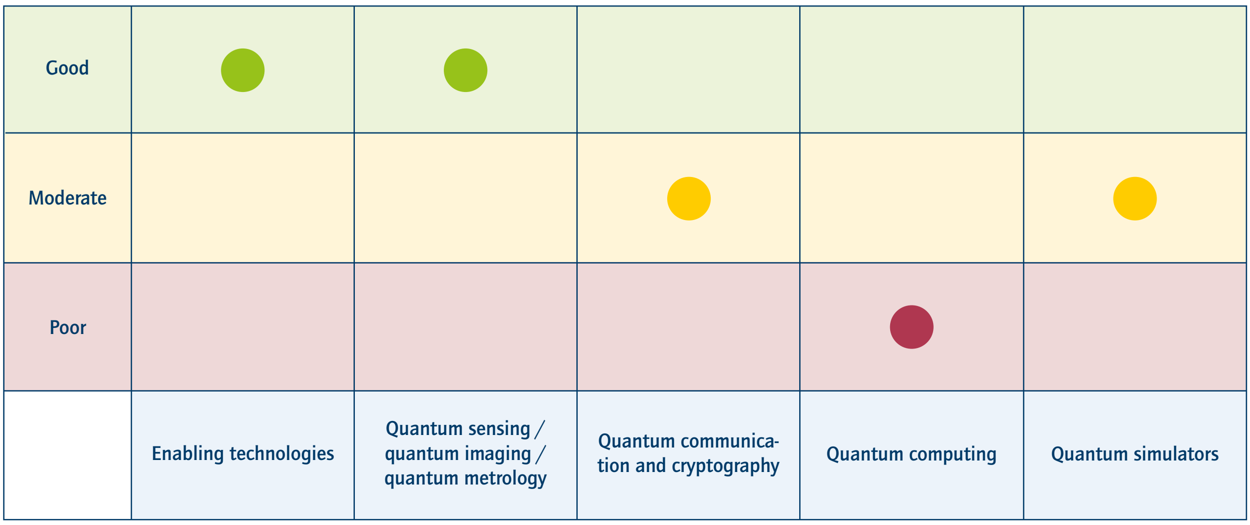


Figure 1: Germany's current position in the commercialisation of quantum technologies compared to other countries (source: own presentation)

1 | See EU COM 1995.
2 | See BMBF 2018; High-Level Steering Committee 2017.

companies' quantum computing platforms, a move which will be crucial to **algorithm and software development** and thus to quantum computer-based value creation. In the respondents' view, this constitutes an important first step in improving Germany's position in this technological field. However, there is still **no European supplier of quantum computing hardware**.

Successfully commercialising second-generation quantum technologies has **major potential for value creation** for Germany's high-tech industries, although at this early point in time it is very **difficult** to make precise **market estimates** for second-generation quantum technologies.[3] In addition to optimising existing products and services, the experts surveyed also expect **completely new potential applications** to spring up, together with the associated **new markets**. The general assumption is that markets will grow slowly, with **highly specialised users**, such as research institutions and development labs, constituting the **first customers** who will then further develop the applications to make them accessible to broader user groups.

Although an initial few products are already commercially available, experts stress that quantum technologies in general require **researchers and developers to display considerable perseverance**. This is true both of further basic research and of transfer into everyday products suitable for use outside specialist laboratories. The **products currently available** are moreover produced **by hand**, with **full-series production** of large numbers still lying **far in the future**.

An **agile quantum technology ecosystem** will be absolutely crucial for **Germany** to achieve high value creation potential. However, most of the respondents consider that there is still **a marked need for development**, and they therefore feel that policymakers could make a significant contribution by creating a **platform for exchanges and coordination between stakeholders**. In addition to **research institutions** and **companies active in R&D**, stakeholders such as potential and actual **users**, **investors** and the **general public** could also be included.

1.1 Structure of the paper

The following section is a brief introduction to the **physical principles** of quantum technologies, with section 3 then shedding light on **Germany** as a centre for quantum technologies. Section 4 gives an **international picture**, taking the UK National Quantum Technologies Programme as an example of what can be achieved by agile networking and the development of a quantum technology ecosystem. Sections 5 to 9 provide deeper insights into the following technological fields:

- **Enabling technologies for quantum technologies** (section 5)
- **Quantum sensing/quantum imaging/quantum metrology** (section 6)
- **Quantum communication and quantum cryptography** (section 7)
- **Quantum computing** (section 8)
- **Quantum simulators** (section 9)

A general introduction and depiction of likely **use scenarios** are in each case followed by a summary of the current **status of research and the development** of commercial applications. Appraisals of **market potential** are then provided, along with assessments of anticipated effects on **value chains** and the **technological sovereignty** of Germany and Europe. Each section then concludes with an overview of Germany's **strengths and weaknesses** in the particular field and the opportunities and threats it faces as a consequence.

3 | See BCG 2019.

2 Basic physical principles of quantum technologies

The **quantum-mechanical effects** which form the basis for quantum technologies and occur in the atomic and sub-atomic range **differ markedly from conventional physics** (Newtonian mechanics, electrodynamics, thermodynamics). Consequently, even Einstein had difficulty accepting the implications of quantum mechanics. In the meantime, however, quantum mechanics has become the **main pillar of modern physics**, forming the basis for the description of phenomena in atomic physics, solid state physics and nuclear and elementary particle physics.

The **differences** between **first-** and **second-generation** quantum technologies together with **fundamental effects** are explained below. Further central terminology is defined in the quantum glossary (see Appendix A).

2.1 Differences from first-generation quantum technologies

While **quantum effects were put to only passive use in first-generation** quantum technologies, on the basis of **multiple particles** (e.g. in superconductivity), **second-generation** quantum technologies **involve the active generation of quantum states** on the basis of **small numbers of or individual particles**. In second-generation quantum technologies, the controlled quantum state of individual or coupled systems is the focus of applications, i.e. targeted generation, coherent control and subsequent interrogation.[5]

The term **second-generation quantum technologies**, as **distinguished** from first-generation quantum technologies, is used in this paper in line with use by policy-makers in the various Framework Programmes.[6] The term "generation" does not define very clear boundaries in quantum technologies and the **transition between first and second generation is often fluid**, meaning that clear classifications are not always possible. This

First-generation quantum technologies[4]

Lasers: Lasers have been in use since the 1960s in industrial manufacturing, research and daily life, for example in applications ranging from distance measurement, cutting and welding tools, reading optical storage media (CDs, DVDs etc.) to laser scalpels in surgery. The physical effect underlying laser technology (**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation) is known as stimulated emission.

Semiconductor technologies: Electronic semiconductor components are the most important active components of the electronic circuits used for example in communication technology, power electronics and computer systems. A quantum dot is a nanoscopic material structure produced on semiconductor material. Because its shape, its size, and the number of electrons it contains can be influenced (unlike in the case of atoms), the electronic and optical properties of quantum dots can be tailored.

Satellite navigation: The timing pulse in atomic clocks is derived from the characteristic frequency of the radiative transitions of the electrons of free atoms, such as caesium. The resultant precision of atomic clocks is less than one second's inaccuracy over a period of 130 million years. Location finding by Galileo or GPS is based on satellites equipped with atomic clocks which continuously transmit their position and a time signal. A receiver can calculate its own location to within a few metres on the basis of an analysis of at least four satellite datasets.

Magnetic Resonance Tomography (MRT): MRT is an imaging method primarily used in medical diagnostics for elucidating the structure and function of tissues and organs within the body. In physical terms, MRT is based on the principles of nuclear spin resonance and exploits the fact that the atomic nuclei of hydrogen (protons) have an intrinsic angular momentum (spin) and associated magnetic properties. The atomic nuclei in the investigated tissue are first excited and then, once the magnetic field has been switched off, the realignment of the spins, which varies in speed depending on the tissue, is measured and provides the basis for three-dimensional imaging.

4 | Brief descriptions based on detailed Wikipedia articles.
5 | See VDI Technologiezentrum GmbH 2017.
6 | See BMBF 2018; High-Level Steering Committee 2017.

IMPULSE paper also includes important applications which fall within the transitional region.

First-generation quantum technologies are used in many everyday applications in our **modern knowledge-based industrial society**, although many users are not aware of the fact that quantum-mechanical effects lie behind the technologies. "First-generation quantum technologies" offers an overview of selected examples of first-generation quantum technologies.

2.2 Historical development of quantum research

Quantum physics came into being at the **start of the 20th century** thanks to the efforts of physicists including Max Planck. The German-speaking scientific world, in the form of researchers such as Albert Einstein, Werner Heisenberg and Erwin Schrödinger, was heavily involved in further developments, making major contributions to theoretical (and later also applied) physics.

One of the reasons why it was so difficult in practice to prove quantum-mechanical phenomena is the **remarkable feature** that **quantum systems behave differently** when observed in the context of experiments. **"Observation"** is here a **technical procedure** performed using appropriate measuring instruments which influences the experiment, sometimes making it difficult to distinguish clearly between observer and experimental subject.

Research has been being carried out for around 20 years into the "new" quantum technologies, which are based on the idea that quantum systems and individual quanta can increasingly be completely controlled and desired quantum effects actively generated. In this way, **effects described theoretically** (see "Overview of the most important quantum-mechanical effects"), such as "entangled" quanta, which remain connected together over arbitrary distances due to "spooky action at a distance" (Einstein), and systems which can simultaneously assume multiple states, like "Schrödinger's cat" which, in this thought experiment is simultaneously both alive and dead (if no observation is carried out), **can be put to practical use**.

In-depth explanations of the fundamental principles of quantum mechanics and the basics of quantum technologies can be found, inter alia, in the **following Publications**:

- Bruß, D.: *Quanteninformation: Turingmaschine, Komplexität, Superposition, Verschränkung, No-cloning-Prinzip, Bell'sche Ungleichung, Quantenteleportation, Quantenkryptographie, Quantencomputer, Quantenalgorithmen, Quantenspiele*, Frankfurt am Main: Fischer Verlag, 2003.
- Dürr, D. und Lazarovici, D.: *Verständliche Quantenmechanik: Drei mögliche Weltbilder der Quantenphysik*, Berlin: Springer Spektrum, 2018.
- Feynman, R.: *The Feynman Lectures on Physics*, Boston: Addison Wesley, 1989.
- Susskind, L. and Friedman, A.: *Quantum Mechanics: The Theoretical Minimum*, London: Penguin, 2015.

Overview of the most important quantum-mechanical effects

Superposition: Classically, states are unambiguously defined, for example switches are on or off. Computer science refers to such a binary state as a bit (0 and 1). Quantum technology, in contrast, has what are known as qubits which may also assume any superposition of the states 0 and 1, with the precise value only being obtained in the course of measurement.[7] The "Schrödinger's cat" thought experiment has become well known in this context.[8] The possibility of processing linear superpositions forms the basis of quantum-mechanical applications. **Qubits** thus form the basis for **quantum computing**. According to the surveyed experts, superposition states are already being put to use today.

Uncertainty relations: This phenomenon of quantum mechanics described by Heisenberg states that there are quantities which are not simultaneously measurable to arbitrary accuracy; for instance, the location and velocity of a particle cannot simultaneously be accurately determined.[9] If a particle's location is measured, this measurement leads to uncertainty with regard to its velocity and vice versa. The complementary quantities also need not together correspond to a deterministic value (Copenhagen interpretation). In other words, measuring one value more accurately does not make it possible to determine the other more precisely. This effect is exploited in **quantum cryptography** for secure data transmission.

Entanglement: The possibility of also superposing states in systems comprising a number of particles is the prerequisite for the entanglement of objects,[10] according to which there may be a specific connection between two or more particles, even over large distances. The probability of their states is then no longer mutually independent but is instead described by a common wave or probability function.[11] Putting entangled states to targeted use is a central focus of second-generation quantum technologies, for instance not only in the development of **quantum computers** but also in certain **quantum cryptography** methods. Entangled states will be substantially more important in future.

Many-body effects: Identical quantum systems are indistinguishable and cannot be individually marked. With spin, quantum particles have a distinctive internal property which has no correspondence in the macroscopic world. Particles with "half-integer" spin are known as fermions (e.g. protons, neutrons or electrons) and those with integer spin as bosons (e.g. photons).[12] In particular at very low temperatures, fermion particle systems behave fundamentally differently from boson particle systems. The many-body effects which then occur are responsible for many magnetic properties and the superconductivity of materials and may therefore be used for **simulations** and the **design of new materials**. Many-body effects will also be more important in future.

7 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
8 | See Schrödinger 1935.
9 | See Heisenberg 1927.
10 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
11 | See Spektrum der Wissenschaft 2017.
12 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.

3 Germany as a centre for quantum technologies

Germany is in a good starting position, having a well established research landscape and companies with experience in developing and integrating cutting-edge components. Industry has also shown interest in making use of quantum technologies. It is also important to have sufficient numbers of well trained specialists and for the population at large to be aware of the benefits of quantum technologies.

Germany is in a **very good starting position** when it comes to shaping and benefiting from the coming **quantum revolution**. This good starting position is explained by:

- research which is excellent in both depth and breadth
- strong enabling technologies (e.g. manufacture of specialised lasers)
- large numbers of major corporations and SMEs with a need for quantum technologies
- strategic visibility through EU Quantum Flagship and the Federal Government's Framework Programme
- highly qualified specialists

3.1 Features of Germany's quantum landscape

Germany's universities and non-university research institutions carry out excellent research from the point of view of both depth and breadth. The German Federal Government's Quantum Technology Framework Programme has contributed to a marked improvement in the visibility of this field, but there is still room for improvement in terms of transfer activities becoming actual commercial applications.

Second-generation quantum technologies and academia

A number of universities and also of non-university research institutions (Max Planck Society, Helmholtz Association including the German Aerospace Center (DLR), Leibniz Association, Fraunhofer Gesellschaft) are undertaking **top-quality research** into second-generation quantum technologies. **Research priority initiatives each involving several institutions** have been set up for instance in the following regions: Ulm/Stuttgart/Freiburg, Munich/Nürnberg/Erlangen, Braunschweig/Hanover, Jena and North Rhine-Westphalia.

Experts say there is still some **room for improvement** when it comes to **linking up German research institutions**. Major consortia, such as Q.Link.X (see section 7.1) or QUILT, a consortium headed up by Fraunhofer Gesellschaft for research into quantum-based imaging methods, are so far rather the exception.

Germany's **Physikalisch-Technische Bundesanstalt** (PTB) is a metrological institute of international renown, where a **Quantum Technology Competence Centre** (QTZ) is set to be established in the coming years (see section 6.1).[13]

The important role of quantum technologies in the **university research landscape** is also reflected in the fact that **seven out of 57 excellence clusters selected in 2018** are working on quantum technologies in the broader sense of the term (see Figure 2). The first five on the list have additionally decided to join together to form a "Quantum Alliance".[14] University quantum technology research projects have also produced their first spin-offs.

The high quality of German research in quantum technologies is also apparent from the fact that Germany is the country with the largest number of projects and the highest funding total awarded under the EU's 7th Framework Programme and Horizon 2020 (see Figure 3).

Second-generation quantum technologies and business

Germany is traditionally **well placed** in the field of **laser technology**, with **German SMEs** already occupying a **strong position internationally** in regard to **highly specialised laser and photon sources**, which are important **enabling technologies** for many quantum technologies (e.g. TOPTICA or Menlo Systems). German companies are also well placed in **microelectronics and materials**

13 | See BMBF 2019a.
14 | See Quantum Alliance 2019.

Name	Applicant/Participating institutions
Matter and Light for Quantum Information (ML4Q)	University of Cologne, RWTH Aachen University, University of Bonn, Forschungszentrum Jülich, Heinrich Heine University Düsseldorf
Munich Center for Quantum Science and Technology (MCQST)	Ludwig Maximilian University of Munich, Technical University of Munich, Max Planck Institute of Quantum Optics (MPQ), Deutsches Museum, Bavarian Academy of Sciences and Humanities Walther-Meißner-Institute for Low Temperature Research
QuantumFrontiers – Light and Matter at the Quantum Frontier	University of Hanover, Technical University of Braunschweig, Laser Zentrum Hannover e.V. (LZH), Physikalisch-Technische Bundesanstalt (PTB), Max Planck Institute for Gravitational Physics (Albert Einstein Institute) Hanover site, University of Bremen Fluid Dynamics Department Center of Applied Space Technology and Microgravity (ZARM)
Complexity and Topology in Quantum Materials (CT.QMAT)	University of Würzburg, TU Dresden, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Leibniz Institute for Solid State and Materials Research Dresden (IFW) e.V., Max Planck Institute for Chemical Physics of Solids, Max Planck Institute for Physics of Complex Systems, Bayerisches Zentrum für Angewandte Energieforschung e.V. (ZAE Bayern)
CUI: Advanced Imaging of Matter	University of Hamburg, Helmholtz-Zentrum Deutsches Elektronen-Synchrotron (DESY), Max Planck Institute for the Structure and Dynamics of Matter, European XFEL GmbH
STRUKTUREN: Emergenz in Natur, Mathematik und komplexen Daten	Heidelberg University, Heidelberg Institute for Theoretical Studies (HITS), Max Planck Institute for Astronomy (MPIA), Central Institute of Mental Health, Max Planck Institute for Nuclear Physics
Cyber Security in the Age of Large-scale Adversaries (CASA)	Ruhr-University Bochum, Technical University of Munich Department of Electrical and Computer Engineering Chair of Theoretical Information Technology, Fraunhofer Institute for Material Flow and Logistics, Technical University of Braunschweig, University of Duisburg-Essen

Figure 2: Excellence clusters relating to second-generation quantum technologies in the latest round of the German Excellence Strategy (source: own presentation based on DFG 2019)

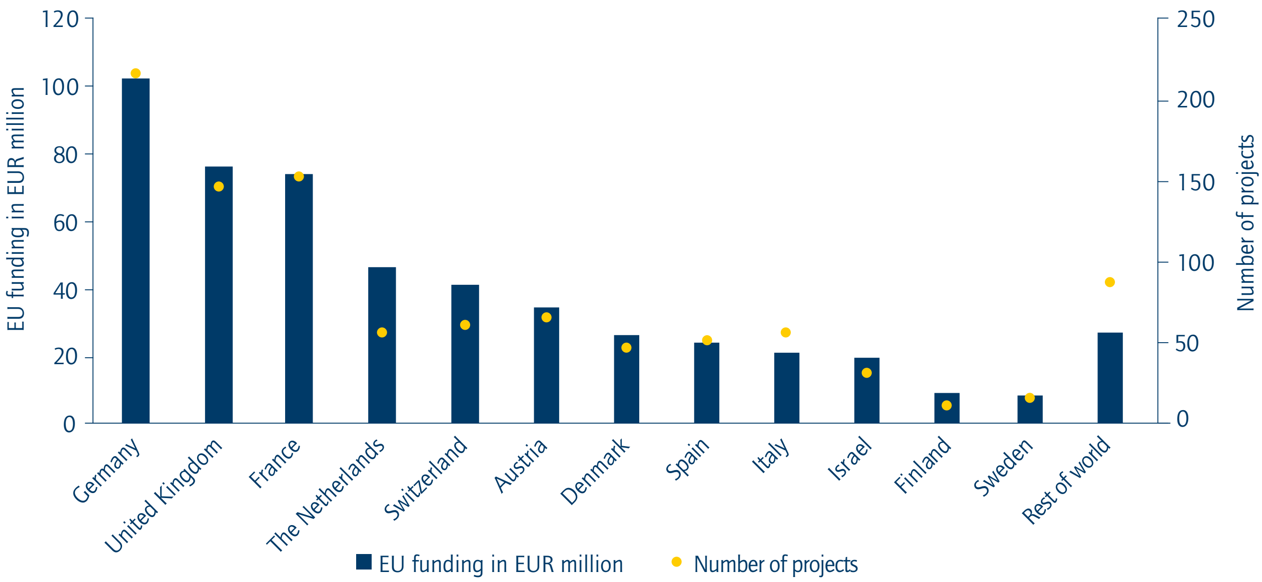


Figure 3: EU quantum technology funding in the 7th Framework Programme and Horizon 2020 by country (source: Birch 2018)

science and in the laboratory and equipment engineering essential to quantum technologies. This position needs to be supported and developed further.

"Quantum technologies are a good fit for Germany's corporate culture."

Major German corporations, such as BASF, Bayer, BMW, Bosch, Daimler and VW, are some of the pioneers in **trialling quantum simulations and quantum computers** for solving materials research or optimisation problems.[15] In the long term, this experience in dealing with the still developing technologies could give them a market edge. German companies, such as Bosch, Siemens or Zeiss and also specialist SMEs, are also in a good position with regard to **sensor technology and imaging** to play a major role on world markets when it comes to quantum-based products.

Expert opinion is that the **biggest gap** in German activities at present is **in quantum computing**, development currently being dominated primarily by North American technology corporations and start-ups. **Significant efforts** will be required to close the existing development gap. The projects already up and running and the planned collaborative efforts with US manufacturers are a significant first step, but they are nowhere near sufficient (see also section 8).

Despite BMBF funding initiatives, such as "Enabling Start-up – Unternehmensgründungen in den Quantentechnologien und der Photonik", experts still consider the current **start-up landscape** in Germany as a whole to be **underdeveloped** and report a lack of **venture capital and especially growth capital**. They also explain that the subsidies and durations of many government-run programmes are **not tailored to the needs of "deep tech" start-ups**, as these entail high infrastructure costs and long development cycles. Instead of or in addition to financial help, **access to research and development infrastructure and to IP** at universities or other research institutions can be an important factor in start-up success. One possible point of contact in the field of quantum optics is the BMBF-funded Quantum Photonics Labs (QPL) at the Fraunhofer Institute for Applied Optics and Precision Engineering in Jena.

An appraisal of the overall innovation system suggests that one of **Germany's weaknesses** is the **transfer** of research results to application. Expert opinion is that this is attributable to Germany's existing **academic incentive systems** which do not provide sufficient academic recognition for the development of laboratory products into robust, scalable products which means that such work is often not pursued. One possible way **for spin-offs to bridge this "valley of death"** is to carry on the further development of research results in **practical competitions** which bring scientists and businesses together (see "Faster from lab to application thanks to quantum challenges").

15 | See Atos 2018; BMW 2019; Daimler 2018; Kühn et al. 2019; QuSoft 2019.

Faster from lab to application thanks to quantum challenges

Various companies are using **competitions** to encourage researchers to identify approaches to solving problems in their business sector. These competitions are also intended to **create networked communities** and above all to **align industry's needs** with the **technology on offer from academia**.

The companies set the terms of reference, so enabling an **agile and targeted** design of the challenges, tailored to the companies' specific development aims. This can create a **win-win situation**: companies find out about **talent** with an interest in their own research priorities, while challenges can offer scientists a way to bridge the "valley of death" by working together with experienced development engineers **to move a concept from the laboratory to commercialisation**.

- **Zeiss** announced a **"Quantum Sensing & Imaging Challenge"** in late September 2019. In each of three fields – **medical technology, microscopy and industrial metrology** – Zeiss describes two central problems in which quantum-based solutions are sought for qualitative improvements. For instance, new approaches are sought for better tissue differentiation, for detecting and visualising neuronal signals and for developing high precision industrial localisation methods. Individuals and teams from anywhere in the world can submit entries by 31.03.2020 and the prizes for the best ideas will be awarded in Spring 2020. The **winners** will firstly receive a **monetary prize** and will secondly have the opportunity to **develop their idea in a workshop at the Zeiss Innovation Hub**. Zeiss sees itself as a mediator between academia and practical application and hopes to extend its ongoing in-house quantum research still further.[16]
- **Back in January 2019, Airbus** flagged up **five problems** facing aviation and flight physics in the global **"Airbus Quantum Computing Challenge"**. The stated problems involve **differing levels of complexity,** ranging from simple aircraft climb optimisation to the more complex task of optimising wingbox design. Researchers are invited to propose and develop solutions for complex **optimisation and modelling of the full lifetime of an aircraft** using the newly available capabilities of quantum-based computing.[17] The challenge is open to students, PhD candidates, researchers, start-ups and professionals in the quantum computing field. The **winners** will receive **hardware access** and an opportunity to develop their ideas to market maturity in **collaboration with Airbus' industry experts.**[18]
- **In 2018, US company Rigetti Computing** announced the Quantum Advantage Prize of USD 1 million for the first demonstration of quantum advantage on a cloud quantum computer (see also section 8).[19]
- In 2017, the **National Institute of Standards and Technology (NIST)** launched the **"Post-Quantum Cryptography Challenge"**. The aim is to identify **uniform post-quantum cryptography standards** which offer robust security and are also supported by the broader community. The challenge is a two-stage process: the first round is already complete, while the remaining 26 algorithms are at present being tested in the second round with public comment being accepted until November 2019. The winning algorithms are set to be announced in 2020. The international competition called for entries from individuals and teams.[20]

16 | See Zeiss 2019.
17 | See Airbus 2019b.
18 | See Airbus 2019a.
19 | See Rigetti Computing 2018.
20 | See NIST 2017.

German Federal Government's Quantum Technology Framework Programme

In 2018, **the German Federal Government** introduced a **Framework Programme** for second-generation quantum technologies, with the aim of pooling, strengthening and broadening existing activities and ensuring faster **transfer from basic research to market maturity**. This will run to 2022 and has total funding to the tune of EUR 650 million.[21]

The QuNET consortium is one example of a major initiative (funding: EUR 165 million) which has grown up from this and has the aim of developing an infrastructure for secure quantum communication (see section 6.1).

In addition, **three new DLR institutions have been established for quantum technologies**: the Institute for Satellite Geodesy and Inertial Sensing in Hanover and Bremen, the DLR Institute of Quantum Technologies in Ulm and the DLR Galileo Competence Center in Oberpfaffenhofen. The focus of these institutes is on **supporting businesses in transferring research results** to application. Funding of around EUR 210 million will be provided for the next four years, meaning that the **total funding** made available for quantum technologies by the Federal Government over the period of the Framework Programme amounts to **EUR 860 million**.

> *"Better networks are a prerequisite for success."*

Expert opinion differs about the scope of the Quantum Technology Framework Programme and the start that has been made. Overall, however, experts welcome the **increased visibility given to the topic** by publication of the Framework Programme and have noticed **greater interest from industry** in entering the world of second-generation quantum technologies. Nevertheless, they would like **still closer links between academia and business to be encouraged**. Some experts consider that the transfer activity criteria for funding applications are not yet sufficiently transparent.

A strategic process is needed in the near future **for the development of a follow-up programme**. While the focus of the current Quantum Technology Framework Programme is on aligning science with applications and markets, expert opinion is that, in the context of a follow-up programme, **specific application projects need to be identified and structured**. To achieve this, research institutions and businesses need to be actively integrated into the strategic process. A central question requiring clarification is, in the respondents' opinion, how to structure future project support so that users can also be involved as effectively as possible.

3.2 Quantum expertise

At present, the availability of specialists in Germany is generally good, but there is still room for improvement at interfaces between disciplines. University and non-university courses in quantum technologies must therefore be expanded. At the moment, the population is generally open to but also ignorant about quantum technologies. The benefits of quantum technologies should be communicated clearly in order to build on this basically positive attitude.

Germany is currently for the most part in a good situation with regard to availability of specialists. First and foremost, outstanding scientists are being trained who are also in great demand abroad. This migration, in particular to companies with deep pockets in the USA, could pose a problem in the medium term. Also in the medium term, an **increase in demand for specialists** with knowledge in quantum technologies is to be expected and this issue must be dealt with in good time. Demand will be not only for pure physicists but also for engineers. Experts from companies in particular are already reporting some **difficulties in recruiting the necessary interdisciplinary experts such as quantum engineers or quantum information scientists** to take the development of applications forward to market maturity.

New master's programmes such as "Quantum Engineering" are important approaches to meeting this future demand for specialist expertise. Such programmes are already in place at Saarland University and at Technical University of Munich and are planned for example at the Technical University of Braunschweig/Leibniz University Hanover. In addition, in the respondents' opinion **a basic understanding of quantum physics**, for instance as a **subsidiary subject**, should be a **greater part** of a wide range of courses. If companies are to **access the best minds** internationally, procedures **for recruiting international specialists should be simplified**. In addition, it should be made easier, especially for **foreign students** who have successfully completed their studies or been awarded a doctorate, to transition to employment in Germany.

21 | See BMBF 2018.

"Scientists who go abroad are difficult to get back."

Members of the **EU Quantum Flagship** have recognised the need to **strengthen training in quantum technologies** and, in a strategy paper, have called for an expansion of study opportunities and teaching provision, professional development for industrial specialists and greater inclusion of quantum physics in school curricula.[22]

Germany plays a leading role at the European level in the development of "quantum education" programmes. At **school level,** the most important **educational task** according to experts is making pupils aware quite how much **quantum physics has changed our worldview**.

"Quantum 2.0 also entails quantum teaching 2.0."

There are only **very few female graduates** in the field of quantum technologies. Decisive and long-term action must be taken to counter this massive gender imbalance, which affects many STEM subjects. The **"leaky pipe" phenomenon** can also be observed; in other words, only a very small percentage of those women who choose a course of study with a focus on quantum technologies **reach senior academic positions**.

The **EU Quantum Flagship and Swiss activities** in quantum technologies therefore include concrete steps to increase the **visibility of women in this field and to support them better**. For instance, networking events are organised specifically for women, attention is paid to quotas of women on conference panels and opportunities are provided for schoolgirls to arouse their interest in STEM subjects in general and quantum technologies in particular.[23]

However, it is not only the training of future specialists that is important, but also the **continuing further training and development of those already in employment**. Appropriate training must be provided to make experienced staff **"quantum-ready"** for new working processes at their places of employment, where they will also act as **multipliers** to propagate this knowledge. PTB's Quantum Technology Competence Centre is one possible point of contact for appropriate further training and development provision (see also section 6.1).

Societal impact of quantum technologies

A UK **study** has revealed that the population is generally **open to and has little anxiety or scepticism about quantum technologies**. The greatest **hopes** are for those quantum technologies which offer direct **benefits to society**, for example in new medical diagnostic methods. The population's greatest **concern**, in contrast, is that the new **technologies** will be **privatised** in the course of development and will then **no longer be accessible or only at high cost**. UK citizens expect military use but are not additionally concerned about it.[24] The experts surveyed consider that the results from this study are also largely applicable to Germany, with the exception of **military use**, where they consider that the German population might well be rather more critical (than in the United Kingdom).

The **impact of quantum computing** might stoke anxieties, although fascination predominates at present. One threat that may firstly be mentioned is that quantum computers will potentially **render today's encryption methods obsolete**, allowing communications to be decrypted with little effort (see also "Post-quantum cryptography" on page 55). Secondly, quantum computers have the potential to give **another major boost to the performance of artificial intelligence and machine learning** (see section 8), which may in turn **further reinforce existing anxieties** about these approaches, for instance in terms of potential job losses.

In the absence of proper explanation, the population may come to **distrust quantum technologies in general** because the **characteristics underlying quantum mechanics** are so strange and **difficult to reconcile with our daily experience**.[25] This explains some experts' insistence on the importance of "quantum education" for the entire population.

Another danger mentioned by some respondents is that quantum technologies might fall into disrepute thanks to the **sale of esoteric products with alleged quantum effects** (e.g. "quantum water" or "quantum crystals") so **undermining the population's trust and acceptance**, for instance in the use of quantum sensors in medical technology.

Anxieties should be countered by **an open and factual line of argument** which takes **citizens' fears seriously**. For example, with regard to communication security, it can be shown that encryption methods which are secure from attack by quantum computers are

22 | See Quantum Flagship 2019.
23 | See NCCR-QSIT 2018; Quantum Flagship 2019.
24 | See EPSRC 2019.
25 | See Vermaas 2017.

available right now. In any event, communication should above all **emphasise the benefits** offered by quantum technologies, such as **improved emergency management**, **communication security** or a **better understanding of diseases**. The possibility **of completely novel materials being developed** is a gain for consumers.

The surveyed experts consider that in recent years the average **availability and quality of popular scientific communication** about "quantum physics" and "quantum technologies" has already **distinctly improved** and resulted overall in **better visibility and greater understanding of the topic** in the population. It is important to build on these foundations to ensure that the debates around these issues continue to be conducted on an objective basis.

In terms of the **labour market**, experts **do not anticipate any major impact** in the immediate future. Quantum technologies are **not a threat to jobs**, instead there will initially be some **new job creation, especially for highly skilled personnel**.

3.3 Profile of Germany's strengths and weaknesses

The table below provides a general overview of Germany's strengths and weaknesses as well as the opportunities and threats it faces across the various areas of quantum technology. A specific overview of the strengths and weaknesses and resultant opportunities and threats in the individual areas of technology is provided at the end of each section.

Strengths

- Outstanding university and non-university research institutions with good technical facilities and infrastructure
- Current sufficient availability of well-trained specialists
- Many potential users from various sectors in the immediate vicinity of research and development institutions and potential start-ups
- High levels of interest from politics and business

Weaknesses

- Inadequate networking between individual scientific communities
- Only occasional prioritisation aimed at achieving a critical mass of stakeholders and expertise for successful transfer
- Frequent absence of strategies for exploiting/putting research results to industrial use
- Academia's transfer-inhibiting incentive system
- Few major companies significantly investing in new quantum technologies
- Little start-up activity, in part due to shortage of venture capital and inadequate subsidies for "deep tech" start-ups
- Small number of patent applications

Opportunities

- Linking up previously scattered expertise in science and business to create a quantum technology ecosystem
- Continuation of ongoing, long-term research funding to support growth of initial markets
- Ensuring a broad skills base by quickly established initial and further training provision
- Government as trailblazer, for example by innovative procurement
- Early alignment of German industry's needs with the performance profiles of new quantum technologies
- Leading development of software and services thanks to vicinity to and close cooperation with potential users

Threats

- Missing out on an internationally leading position and jeopardising technological sovereignty due to inadequate pooling of significant stakeholders for transfer to market maturity
- Excessively short time horizons or premature abandonment of funding initiatives (e.g. "quantum winter" as a result of over-hyped expectations not being met)
- Barriers to European suppliers due to strong patents and (de facto) norms and standards from China and the USA
- Migration of value creation and specialists to foreign countries with more quickly maturing ecosystems

4 International activities in quantum technologies

Germany produces a large number of high-quality specialist publications, but only very few patents for quantum technologies. International efforts to develop quantum technologies have increased significantly in recent years, and many countries have established or are currently developing national strategies. Germany is in a good position in terms of basic research and the level of funding applied. The differing approaches taken by various countries to bring quantum technologies to market maturity by prioritisation and pooling expertise can be instructive for Germany.

Recent years have seen a **distinct increase in the levels of international investment** made in the development of quantum technologies. This relates not only to **government research-funding programmes** (see section 4.2) but also to **company formations**. Figure 4 shows this increase and the global distribution of successful funding rounds between 2012 and 2018. Not only have the volume and number of investments increased, but they are also increasingly spread across the **various fields of quantum technology**. One critical point to note here is that **not a single German company** has raised capital in a sufficient order of magnitude over this period to be included in these figures.[26]

4.1 Publications and patents

The number and quality of relevant German research publications compare very well internationally. However, Germany and other EU countries are filing only a small number of quantum technology patents, whereas the USA and China are pursuing aggressive patent strategies. This may lead to strategic obstacles and inequalities in market access.

Germany's good position in quantum technology research is apparent from the **quantity and quality** of **scientific publications** and the country is in a **leading international position** (see Figure 5).

In terms of the **absolute number of publications** between 2012 and 2016, **Germany ranked third** behind China and the USA. If the publications of the 28 EU member states are combined, **the EU** still has a clear lead **over China and the USA** in total numbers.

In terms of the share of publications which are among the ten per cent most frequently cited (as a **measure of quality**), **Germany is ranked fifth** behind Austria, Switzerland, the Netherlands and the United Kingdom, but **well above the worldwide average**. Chinese publications, in contrast, are of only moderate quality. The proportion of US publications which are among the ten per cent most cited is above the EU average, but somewhat below the proportion in Germany.[27]

An analysis of the co-authorship of the publications also reveals that **German science is very well embedded in the international community** and that publications with German involvement often achieve particularly high citation rates.[28]

Patents

Compared with their strength in scientific publications, **Germany and Europe** are clearly trailing in terms of **patent filings** in the field of second-generation quantum technologies.

The **USA and China in particular are filing distinctly larger numbers of patents**. According to experts, these **aggressive patenting strategies** are driven either by state funding (China) or private enterprise (USA). These jurisdictions do, however, also grant patents for developments involving little creativity but this should not be taken to mean that these patents will not constitute a strategic obstacle for European competitors.

The USA is the leader in patents on quantum computing, while China is the leader in quantum key distribution (QKD) (quantum cryptography methods, see section 7) and cold atom interferometry (whose applications include quantum sensing and metrology) (see Figure 6). **Europe trails significantly behind** the leaders in every area. **Germany** is **ranked only eighth in quantum computing** and **only sixth in QKD**. Within the EU, more

26 | See Gibney 2019.
27 | See Bornmann et al. 2019.
28 | See ibid.

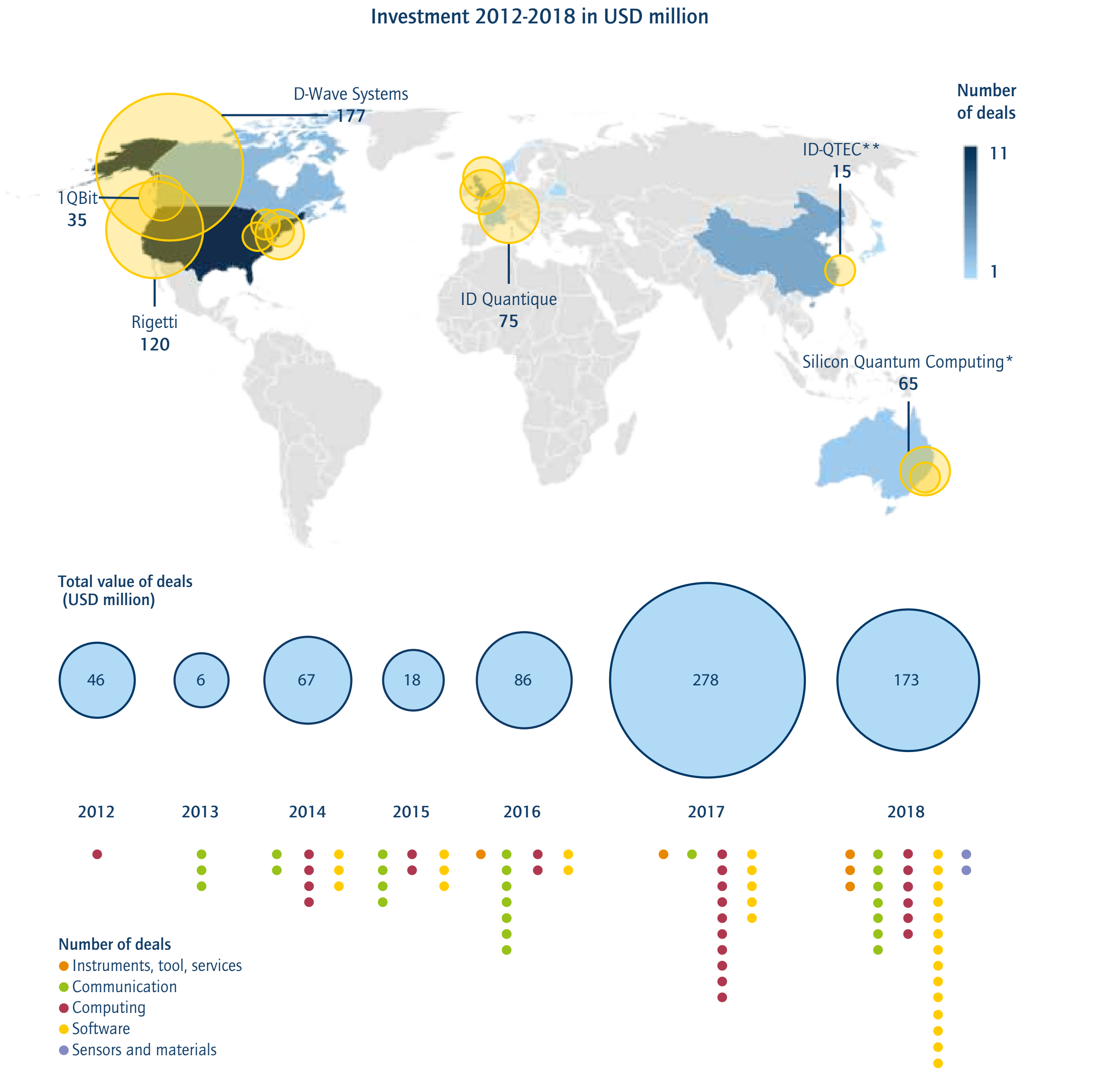


Figure 4: Investment in quantum technology companies (2012–2018) (*) Includes an Australian government contribution of an unknown amount plus private investment. (**) China invests large sums in the commercialisation of quantum technologies, in particular in quantum communication. However, there is little information regarding the specific levels of investment and the amounts for individual companies. (source: Gibney 2019)

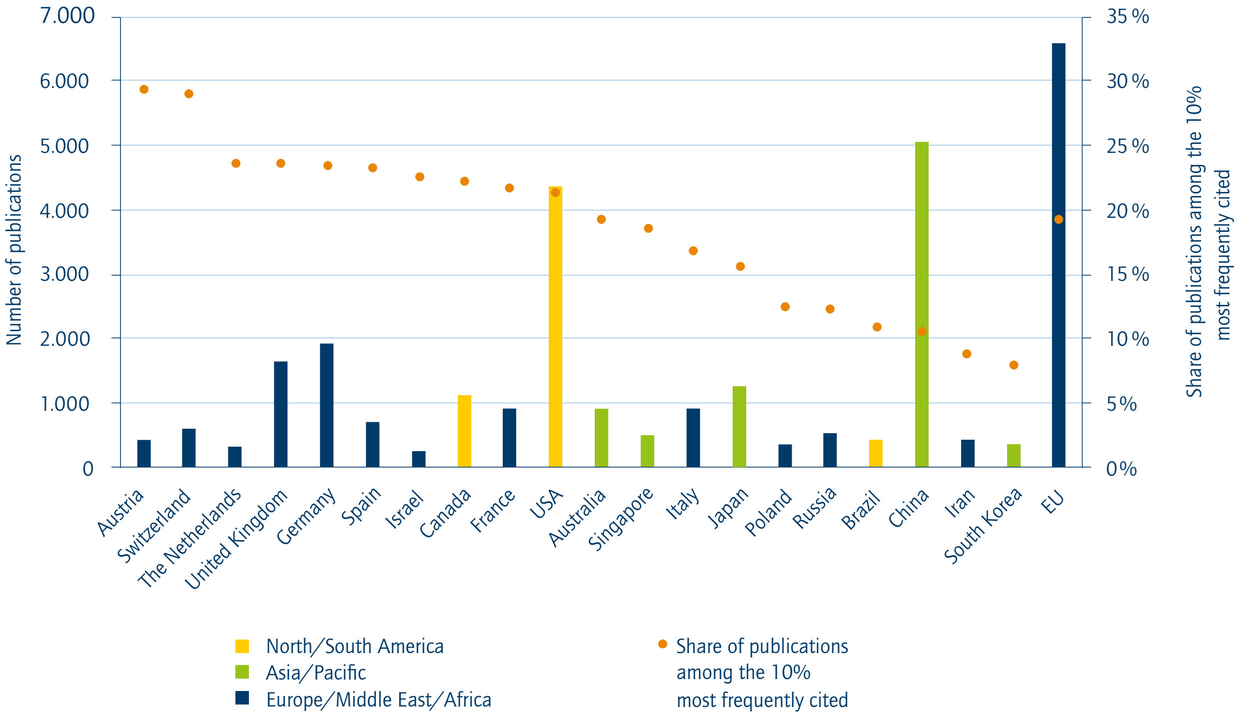


Figure 5: Total number of publications and share of frequently cited publications in quantum technologies by country (2012–2016) (source: Bornmann et al. 2019)

patents are filed in the United Kingdom (quantum computing and communication) and France (cold atom interferometry).[29]

An analysis of the top 35 institutions and companies to file patents in quantum computing and QKD also reveals that there are **no German institutions or companies** among their number.[30]

The **incentive system in academia** partly explains low patent filing rates in Europe and Germany because, unlike publications, patent applications carry only little weight in appointment and evaluation procedures. **Adjustments to the appointment and selection criteria** and to the **funding instruments** to take better account of the importance of patents as a significant **contribution to knowledge and technology transfer** by scientists may help to change the situation.

Some voices also emphasise that **excessive patenting may hinder innovation**. Nevertheless, in the light of **international dynamics**, a large proportion of experts are calling for **patenting activities to be stepped up** in Germany and Europe so as not to run the risk of being exposed to major strategic disadvantages.

Some respondents also report that **access to intellectual property** arising from joint research projects is sometimes **made very restrictive** for participating companies or subsequent spin-offs from universities and other research institutions. Depending on the institution, **there are clear differences with regard to terms and costs** which make planning more difficult for businesses.

4.2 International initiatives for promoting quantum technologies

Many countries have now launched targeted programmes for promoting quantum technologies. It is striking that some smaller European countries are very successful in this area. Germany should learn from the factors enabling their success, such as prioritisation or central coordination, and enter into targeted alliances.

Increasing levels of international interest in the development of second-generation quantum technologies is reflected in **numerous**

29 | See Max-Planck-Institut für Innovation und Wettbewerb 2019.
30 | See EU COM 2019c.

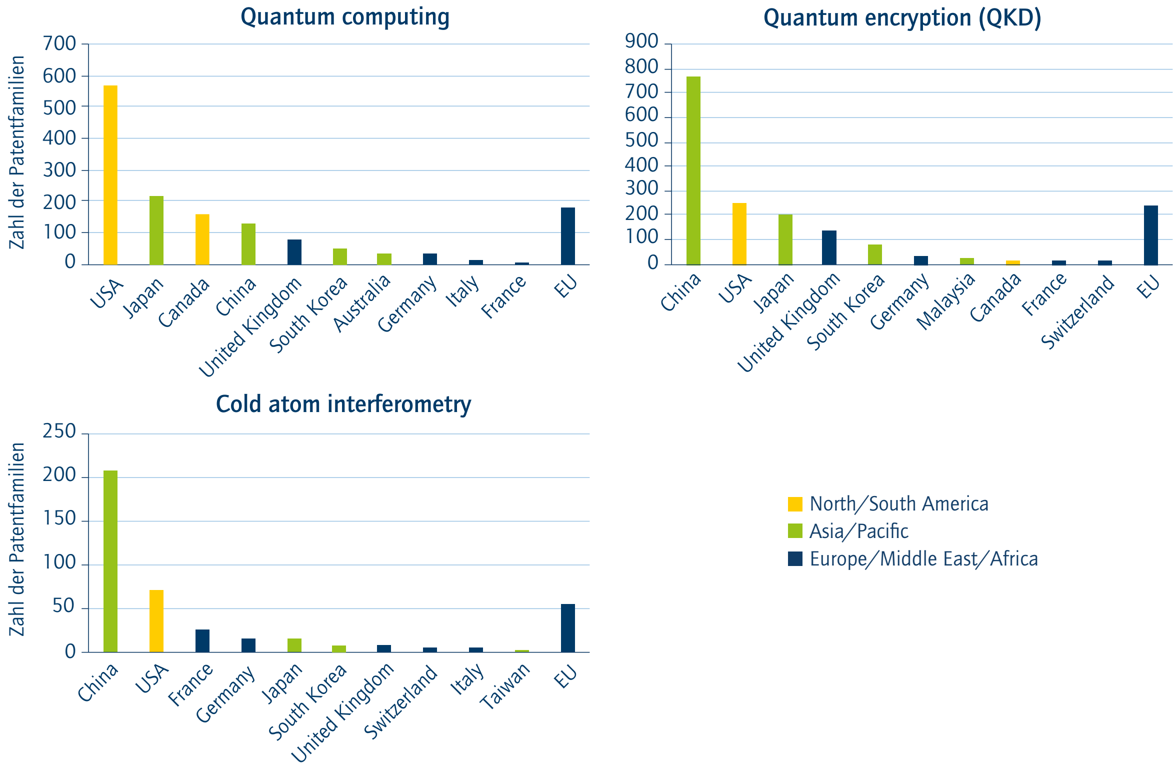


Figure 6: Number of patent families filed in the areas of quantum computing, quantum encryption (QKD) and cold atom interferometry (applied in quantum-based sensing/metrology) by applicant's country of origin; data as of August 2019 (source: Max-Planck-Institut für Innovation und Wettbewerb 2019)

national and regional programmes and initiatives. Some of these differ significantly in terms of focus and funding.

Figure 7 provides an overview of the initiatives in selected countries.

Smaller nations in particular are **successful** in quantum technologies, not least as evidenced by the good positions of the Netherlands, Switzerland and Austria in attracting European funding and in their share of highly cited publications (see Figure 3 and Figure 5). Germany may find it worthwhile to take a closer **look at these countries' success factors**.

QuTech in Delft (the Netherlands)

The **Netherlands** with its quantum technologies hotspot **QuTech in Delft** occupies a **leading position** in **quantum computing and communication** in Europe.

QuTech is funded by Delft University of Technology and TNO, the Netherlands organisation for applied scientific research, and conducts **mission-led research** into the development of a **quantum computer and the quantum internet**. The clear goal for the scientists is to follow a **roadmap and work towards specific applications**.

Between 2015 and 2025, the government funding alone for QuTech will amount to EUR 135 million.[31] On top of that, **there are collaborative projects with two major US tech groups** (Intel and Microsoft) in the field of quantum computing. This **pooling of expertise, resources and activities** around QuTech has already created a **network, which is a hive of research and development, of SMEs and spin-offs** which are specifically promoted through incubator programs.[32]

31 | See QuTech 2015.
32 | See Birch 2018.

	EU	USA
Start	2017	2018
Funding volume	EUR 1 billion / 10 years	USD 1.2 billion / 5 years
Priorities/ Special features	All four areas covered, but greater emphasis on basic research, quantum sensing and imaging as well as quantum communication Pan-European dimension and networking of relevant stakeholders from academia and business in the foreground Supplemented by further European and national funding lines	Focus: quantum computing and quantum information technology Coordination office in the White House
	China	**United Kingdom**
Start	–	2014
Funding volume	Approx. EUR 10 billion (exact amount unclear)	Approx. GBP 600 million / 10 years
Priorities/ Special features	Broad programme with a particular emphasis on quantum communication and cryptography and quantum computing Establishment of National Laboratory for Quantum Information Science Close links between military and civil research	Four Quantum Hubs as consortia of universities and companies with a thematic focus (see section 4.3) Close involvement of industry to ensure targeted development and rapid market launch
	Australia	**Japan**
Start	–	2018
Funding volume	> EUR 80 million (only from federal funds)	EUR 180 million / 10 years
Priorities/ Special features	Four Centres of Excellence: Engineered Quantum Science (EQUS), Exciton Science, Future Low-Energy Electronics Technologies (FLEET), Quantum Computation and Communication Technology (CQC2T) Additional Department of Defence funding (Next Generation Technologies Fund) Dedicated, wide-ranging quantum strategy at the planning stage	QLEAP as a combination of quantum technology and photonics research with four main focuses: Superconductive quantum computers and accompanying basic research, solid-state quantum sensors, laser research and attosecond laser technologies and their application
	Canada	**The Netherlands**
Start	–	2015 (only QuTech Delft, National Agenda Quantum Technologies in 2019)
Funding volume	> EUR 680 million (CAD 1 billion) for the 2006–2016 period	> EUR 250 million / 10 years for QuTech Delft (including contributions from industry)
Priorities/ Special features	Thematic conferences to demonstrate the benefits of quantum technologies for individual industrial sectors (e.g. for the raw materials sector) Strong military interest (cybersecurity, quantum sensing and computing) Training and recruitment of Highly Qualified Personnel (HQP) as a key priority	QuTech Delft: collaborative project between Delft University of Technology and TNO, the Netherlands organisation for applied scientific research Focus: quantum computing and quantum internet Joint know-how centre with industrial partners (Intel and Microsoft in quantum computing)

	Switzerland	Austria
Start	2011	2016
Funding volume	approx. EUR 52 million (CHF 57 million) / 10 years (only for NCCR QSIT – Quantum Science and Technology, no national strategy)	EUR 32.7 million / 5 years (ramp-up phase of the national R&D funding programme for quantum research and technology)
Priorities/ Special features	High level of basic equipment for researchers National Centre of Competence in Research (NCCR) QSIT – Quantum Science and Technology in Zurich Focus: quantum sensing, quantum simulation, quantum information and communication, engineered quantum states	Establishment of collaborative projects between Austrian scientists in European and international initiatives Transfer of R&D results into value creation and development of demonstrators Further development of R&D infrastructure in quantum technologies

Figure 7: Overview of funding programmes for second-generation quantum technologies (source: own presentation based on Australian Government Department of Defence 2018, Australian Research Council 2019, BCG 2017, 2018c, Canada NRC 2017, Executive Office of the President of the United States 2018, Foreign Affairs 2018, High-Level Steering Committee 2017, Knight/Walmsley 2019, ÖBMWFW 2017, Quantum Delta Nederland 2019, QuTech 2015, Raymer/Monroe 2019, Riedel et al. 2018, Riedel et al. 2019, Roberson/White 2019, Sussman et al. 2019, FNSNF 2019, Yamamoto et al. 2019, Zhang et al. 2019)

Innsbruck (Austria)

Austria, with its two **centres of gravity in Vienna and Innsbruck**, has also become a centre of **world-leading research** into quantum technologies. According to experts, one crucial factor has been the Austrian government's **early recognition of the significance** of quantum technologies. **Leading scientists** have accordingly been attracted to or retained in Austria, around whom successful working groups have developed. In particular, research into building a **quantum computer based on ion traps** (see also "Different approaches to the implementation of a quantum computer" on page 62) is at the highest international level and has led to the formation of a **start-up to commercialise** the technology (Alpine Quantum Technologies).[33]

The **regulatory framework governing company formations** in Austria is, however, described as similarly difficult to that in Germany and the **level of government research funding** also provides **no location advantage**.

Zurich (Switzerland)

Zurich is another hotspot for quantum technology research and development. **Since 2011, ETH Zurich,** as a leading research university at the federal level, has been hosting a National Centre of Competence in Research into quantum technologies which has encouraged the development of **a network of local research groups** and increased **visibility to potential industrial partners**.

A greater **degree of freedom** in selecting research priorities and **generous basic funding** are cited by experts as decisive factors in the attractiveness of Switzerland as a research location. In addition, a good general environment including **plannable career paths, clear residence conditions** and a **high quality of life** are attracting outstanding researchers from all over the world.[34]

IBM moreover operates a large research centre in Zurich, at which research into quantum technologies, specifically into quantum computing, is conducted. This centre has evolved over time, having been in existence since 1956. **Start-ups** have been established in Switzerland outside Zurich too, for example ID Quantique (quantum communication) and Qunami (quantum sensing), the former now majority held by South Korea's SK Telecom.

EU – quantum technologies as a Flagship Initiative

At the European level, quantum technologies were in 2017 designated the **third Flagship Initiative**, as part of Horizon 2020 and with total funding of **more than EUR 1 billion** over ten years. Some respondents, however, expressed concerns that the funding of the Flagship has not yet been fully secured in the future EU financial framework.

33 | See Alpine Quantum Technologies 2019.
34 | See NCCR-QSIT 2018; Swiss National Science Foundation 2019; FNSNF 2019.

By **pooling European** expertise in science and industry, the aim is to safeguard **Europe's leading research position**, to build up a **European quantum industry** and to foster **market development**.

Projects from all areas of second-generation quantum technologies are taken into account and **milestones for individual areas of technology** are targeted. For instance, the aim in quantum communication is to develop inexpensive and powerful QKD devices and to establish the basics of a quantum repeater in three years. The long-term target (ten years) is to create the conditions for a European quantum internet.[35]

"Germany is a major pillar and partner in the European Quantum Flagship."

German institutions and companies are playing a central role in the EU Quantum Flagship. **German partners are accordingly involved in 19 out of the 20 projects which have so far been launched**. Four of the projects are led by one of the German participants.

One important positive aspect which goes beyond the funding of excellent individual projects and is highlighted by experts is the **formation of a close-knit quantum technology community**. Both the consultation and identification process before the start of the flagship and the **governance structures** are praised by some experts. It has proved possible to get leading **scientists fully on board, and to involve industry representatives** while simultaneously remaining slim enough to enable **agility and flexibility**. Other experts, however, accuse the flagship of **a lack of transparency** in decision-making and **unclear criteria** for the specific applications of individual projects.

Other criticisms are **inadequate funding** in view of the duration of funding and number of projects involved, as well as the fact that too little attention was paid to potential investors, for example from the venture capital sector. It would appear that the latter were not able to contribute their expertise for stimulating start-ups and growing young companies.

In addition to the flagship, the **European Research Council** is also to a great extent funding **excellent basic research** in quantum technology.[36]

Quantum initiatives in other countries

China's research strategy has long focused on quantum technologies and the current five-year plan also designates them as one of the **ten most important technology sectors**. In particular in **quantum communication**, China has achieved significant breakthroughs by making the first successful transfer of a quantum key via satellite and establishing a QKD-based communication network. According to Chinese sources, around USD 987 million have been invested by the state over the last 20 years.[37]

Exact figures for current government funding for quantum technologies in China are rarely publicly available, but over the coming years, some experts assume that China **will invest almost EUR 10 billion in quantum technologies**, with EUR 3 billion being devoted solely to catching up in quantum computing.[38] These figures are disputed, however.

EUR 1 billion are set to be spent solely on setting up the **National Laboratory for Quantum Information Science**. Alibaba has also announced plans to invest some of its USD 15 billion R&D spending in quantum computing. One particular focus of Chinese activities is also on quantum technologies which can be put to military use.[39]

Experts view China's **clearer definition of goals and more stringent implementation** as a comparative strength of the country. In addition, the "1,000 talents" programme was directed towards **recruiting top foreign talent**, while Chinese scientists who have **received excellent training abroad** have been returning.

The **USA**, quite probably in part in response to the increased activities in the EU and China, established a **National Quantum Initiative** in 2018. This is intended to focus and strengthen state funding for quantum technologies and is funded to the tune of USD 1.2 billion over a period of five years.[40] A **National Quantum Coordination Office in the White House** is responsible for coordinating activities. The military and intelligence sectors in the form of DARPA and IARPA are also very active.[41]

In addition, the USA is also seeing very **large investment in quantum computing by technology corporations** such as Google, IBM, Intel or Microsoft as well as a large number of powerful start-ups. A Quantum Economic Development Consortium

35 | See High-Level Steering Committee 2017; Quantum Flagship 2019; Riedel et al. 2019.
36 | See ERC 2019.
37 | See EU COM 2019a; Foreign Affairs 2018; Zhang et al. 2019.
38 | See BCG 2018c.
39 | See Center for New American Security 2018.
40 | See Raymer/Monroe 2019.
41 | See DARPA 2013; DARPA 2019; IARPA 2019.

led by the National Institute of Standards and Technology (NIST) has also been set up to improve the management of commercialisation activities.[42]

Australia has also long been investing significant sums in quantum technologies, in particular **in quantum computing**. Efforts are being made to develop a comprehensive quantum strategy.[43] In **France** too, a committee of experts presented proposals for a national strategy in early 2020.[44]

With the adoption of the Framework Programme program in 2018, Germany is certainly playing a pioneering role in international comparison.

International alliances in research projects

Germany could benefit as a location for quantum technologies from **closer collaboration** and possibly stronger alliances, including **with non-European partners**, especially where strengths are complementary.

In this context, some experts express a hope that both German ministries and the EU should clarify the conditions under which **companies and institutions from non-EU states** may participate in funding programs.

4.3 United Kingdom – with agility and networks to a leadership role in quantum technologies

The United Kingdom's National Quantum Technologies Programme was one of the first of its kind. It aims to develop concrete applications and products by involving partners from the business world at an early stage. Consequently, an ecosystem of research institutions, new and established providers and potential users has grown up, whose strength lies so far only in numbers of patents, however, and not as yet in market-mature applications.

The **United Kingdom** was one of the first countries to set out, as early as 2013, a **dedicated national strategy** for quantum technologies ("UK National Quantum Technologies Programme (NQTP)").[45]

It is interesting to compare this with developments in Germany: in the United Kingdom it took **only two to three years** to get from the **first targeted discussions** about a quantum technologies programme **within the scientific community** to parliamentary **approval of the programme**. The initiative clearly lay with the scientists.

In Germany, the **discussion processes** within **the scientific community took significantly longer**, with more than three years passing between the initial decision to tackle the subject and publication of a position paper by the Union of the German Academies of Sciences and Humanities.[46] This was followed by the Federal Government-initiated QUTEGA process, before the government's Framework Programme was adopted in 2018.[47]

The NQTP, the **first phase of which ran from 2014 to 2019** and which is now entering the **second phase to 2024**, rests on **two pillars**: firstly, four **"Quantum Hubs"** with core themes situated at the **interface between university-based and application research**, and secondly the provision of funding via **Innovate UK for near-industrial development**.

"The United Kingdom had the courage to forge ahead."

In its **first phase, the NQTP was allocated around GBP 270 million**, while for the **second phase a further GBP 235 million** are being provided for the programme in general and **GBP 94 million for the Quantum Hubs**. The total amount provided by the government is thus around **GBP 600 million over a ten year period**.[48]

The NQTP **does not cover basic research**, the funding for which comes from other pots, the focus clearly intended to be on the **development of applications and market-mature products**.

42 | See NIST 2018.
43 | See Roberson/White 2019.
44 | See Forteza et al. 2020.
45 | See Knight/Walmsley 2019.
46 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
47 | See BMBF 2018.
48 | See Innovate UK and the Engineering and Physical Science Research Council 2015; UK Research and Innovation 2018; 2019a.

A **competitive process** was used to select the four Quantum Hubs, which have the following **thematic priorities**:

- Quantum Sensors and Metrology (lead institution: University of Birmingham)
- Quantum Enhanced Imaging (lead institution: University of Glasgow)
- Networked Quantum Information Technologies (lead institution: University of Oxford)
- Quantum Communications Technologies (lead institution: University of York)

The second phase of the NQTP also involves establishing a **National Quantum Computing Centre**. Experts have, however, pointed out that the funds so far budgeted for this centre will not be enough to construct a several hundred qubit quantum computer.

Each hub is **led by a university** and also involves **other universities and industry partners,** including, among others, the Fraunhofer Centre for Applied Photonics in Glasgow and the German telecommunications vendor ADVA Optical Networking.

The Quantum Hubs have a relatively high degree of **autonomy and flexibility** in how they use the funds available to them, but all are pinning their hopes on a **re-focusing of activities** within the field and the establishment of **flagship projects** to increase visibility above all for industrial sectors which might be interested. Some experts stress that this approach, though associated with **opportunity costs**, will make a major contribution to establishing shared core brand values and increasing **community identification**.

Dividing the **four hubs** along thematic lines **prevents them from being in competition with one another** and ensures that they work together to establish the United Kingdom as a centre for quantum technologies.

The **transfer** of research to industrial application **will take place in three waves**, with the first wave involving the development of **initial prototypes in parallel with scientific research**. In the second wave, the Industry Strategy Challenge Fund will fund **further development and trialling of prototypes** and analyse possible **application and market potential**. One example of this is a quantum-based gravitation sensor for underground investigations in building projects.[49] The final wave will involve **transfer to industrial application**, at which point the UK government will expect business to make a significant financial investment, in the form of matched funding.[50] The hubs also assist transfer by providing simple **access to infrastructure and intellectual property** for participating businesses.

Experts consider a key factor to be the **early involvement of all relevant stakeholders**, in particular businesses. Stakeholders include not only **manufacturers of enabling technologies** and potential **manufacturers of products** which make use of second-generation quantum technologies, but also possible **users** of such products and services, whose **feedback can be used directly in development processes** for concrete applications. To encourage participation by such businesses, **regular showcase events** are held, which are attended by large parts of the relevant communities, present flagship projects and promote exchange with interested industry representatives.

> *"The idea is not that scientists simply collect their funding and then disappear into their laboratories."*

These **ongoing activities**, which were planned into **project budgets** from the outset, are turning initially reluctant potential industrial partners into a **critical mass** of collaborative partners and users. In addition, Quantum Hubs have already seen some **start-ups** grow up around them, **universities in the United Kingdom** traditionally being more supportive of such initiatives than those in Germany.

Expert opinion suggests that, despite the United Kingdom's poorer starting position than Germany's, this **close cooperation** between the parties involved and some clever **incentivisation** has resulted in the country's **quantum community being livelier and above all more closely linked**. This makes the process of taking quantum technologies from the laboratory onto the market **agile and flexible**.

Despite having established an **efficient quantum ecosystem**, the United Kingdom has nonetheless suffered the **departure of some leading figures**, for example in the field of quantum computing, who have gone to launch start-ups in Silicon Valley.[51] Expert opinion also suggests that, despite the UK's industrial focus, **only few developments will have actually reached market maturity by the end of the second phase in 2024**. Moreover, **patenting activity** so far compares **poorly** internationally, despite the United Kingdom occupying **a leading position within the EU** in two out of three fields (see Figure 6).

49 | See UK Research and Innovation 2019b.
50 | See UK Research and Innovation 2018.
51 | See Financial Times 2019.

5 Enabling technologies for applying second-generation quantum technologies

German companies, in particular SMEs, hold leading market positions in some quantum enabling technologies. The market is currently mainly limited to laboratory equipment and small-series production, but will continue to grow. At present, demand for some specific components cannot be met from Germany or Europe. Miniaturisation and reducing susceptibility to interference are the greatest challenges. The creation of test environments and real-world laboratories can drive development forward to practical usability.

Despite the four areas of second-generation quantum technologies having completely different applications, all are based on **exploiting and controlling individual quantum states**. This explains the existence of **quantum enabling technologies (QET)** comprising components such as specialised lasers and photon sources, speciality semi- or superconducting materials or also specialised cooling technologies for achieving temperatures of a few millikelvin, i.e. just above absolute zero, which are used in various areas (see selected examples in "Scenarios for the use of enabling technologies").

The major advances in quantum technologies in recent decades have been made possible precisely by breakthroughs in QET. Nevertheless, **further development of QET is vitally important** to quantum technologies achieving market maturity.

Germany has already seen the formation of **some specialised manufacturers**, including **spin-offs** from universities and research institutes, which **are assuming a leading role, including on international markets**, in particular in specialised lasers and light sources. One established company active in this field is TRUMPF, while up and coming SMEs include TOPTICA and Menlo Systems in specialised laser manufacture, PicoQuant in single-photon detectors or Kiutra and attocube in cooling technology.

5.1 Status of research and commercial application

Currently, the greatest challenges involve making the components ready for use in broader markets and outside laboratory environments by miniaturisation, reducing susceptibility to interference and reducing costs. Lighthouse projects which bring research and development expertise to bear on specific application and user requirements may be of assistance here.

In QET, many of the **fundamentals for application** in second-generation quantum technologies are **already in place**. They enable **targeted exploitation of quantum effects** together with **control and readability** of the respective processes. Some of these components are already available from commercial suppliers.

In simplified terms, QET can be divided into three fields:[52]

- **Quantum-compatible data acquisition, high-speed electronics and cryogenics:** data processing electronics – high time resolution, short dead times, optimised for data throughput, parallelised etc. – including software, compact and magnetic cryocoolers etc.
- **Lasers, detectors, sources and interfaces**: single photons, entangled photons, highly coherent, highly incoherent, new spectral ranges, especially for efficient interaction with atoms etc.
- **Materials, components and quantum technology devices:** topological materials for quantum computing, efficient systems and methods for immobilising, positioning and implanting individual atoms, ions or molecules, vacuum technology, optical precision assembly and connection technology, hybrid microstructures, integrated solutions and modular techniques, processing of superconductive layers, compound semiconductors or diamonds for quantum technology applications etc.

Challenges

For many enabling technologies, **only a laboratory proof of concept** has so far been provided and they are as yet **unsuitable for use outside** such protected conditions. Decisive factors for moving second-generation quantum technologies out of the laboratory into general use include **component miniaturisation** and in many cases a **reduction in susceptibility to interference**.

52 | See QUTEGA 2017.

However, these improvements must **by no means be achieved at the expense of functionality and sensitivity**. Instead, in this area too **further advances** need to be made while **costs must also be reduced**.

The aim is to produce **"turnkey" products and components** which quantum technology suppliers can simply purchase and use in their products without any major need for customisation.

It is, however, not only in engineering and materials science that further advances are necessary in order to bring quantum technologies to market maturity. Further key development areas in particular for quantum computing are **algorithms and software components for control elements**.[53]

One **possible lighthouse project** which has been proposed by experts involves making concerted efforts in **integrated micro-optics**, potentially miniaturising optical elements for quantum technologies to chip size, in a similar way to what the UNIQORN collaborative research project is currently attempting to do in quantum communication. **Major demand** for this technology is also predicted especially in quantum sensing and imaging

Further **engineering development pathways for QET** are already mapped out in many areas. Nevertheless, the innovations and major advances which might still emerge from **theoretical and experimental basic research** (e.g. materials with room-temperature superconductive properties) should not be underestimated.

Norms and standards

Since QET are already in use in research and development and will also be used in future commercially available products, setting **norms and standards** for them is also on the agenda. It is important to take action early in this area to ensure that **German and European interests** (such as drawing up the standards close to existing German product specifications) are taken into account in international standardisation processes.

Some experts point out, however, that it is precisely by focusing on **product specifications tailored to specific customer requirements** combined with high product quality that many German companies are securing market share. Setting excessively **rigid** norms and standards could be **something of a hindrance** in this market segment. **Involving the German quantum community** at an early stage of the discussion processes at **DIN**, which is already doing initial scouting in quantum technologies, may help to identify a sensible, incremental approach here.

5.2 Market potential and value chains

The significance of quantum enabling technologies as critical components at the beginning of value chains for the various fields of second-generation quantum technologies should not be underestimated. In particular, German SMEs should make use of their good starting position in this field to fill crucial positions in the international value chains. To do this, they must be empowered to complete the final necessary development steps to make their products ready for the market and series production.

At the moment, QET are still primarily in use **as laboratory equipment**. The manufacturers are therefore usually **specialised manufacturers** who primarily operate in **a craft and small series manufacturing context**. The order of magnitude of investment in such laboratory equipment has been estimated for **Germany** at **some EUR 100 to 150 million** annually.[54] Due to increasing levels of activity, including as a result of the Federal Government's Quantum Technology Framework Programme, this **market segment is likely to see steady growth** and **new customer segments** are likely to be added.[55]

In relation to **photon sources as QET** (specialised lasers as well as single-photon and photon pair sources), a study of the **UK quantum programme** forecasts growth in market volume from **GBP 10 million in 2017** to over **GBP 60 million in 2022**.[56] If major German corporations active in sensor technology and microscopy/imaging, such as Bosch, Siemens or Zeiss were to focus to a greater extent on quantum technologies, the **corresponding market in Germany might well turn out to be larger**.

Even if the market for QET were **to see major growth compared to the above figures in the medium term**, QET will always only be a **small part of total value creation** in quantum technologies.

53 | See VDI Technologiezentrum GmbH 2017.
54 | See VDI Technologiezentrum GmbH 2017.
55 | See BMBF 2018.
56 | See Gooch & Housego *et al.* 2018.

"German companies have much to gain from quantum enabling technologies not only in market potential but also in useful developments for other sectors."

Experts anticipate further market potential because the development of QET will also give rise to products, such as specialised lasers or single-photon detectors, which can be used **outside the field of quantum technologies as narrowly defined**. Such detectors may, for instance, be used in biomedical research for DNA sequencing and in microscopy, for tomography methods in medicine or in surveying, without second-generation quantum technologies being used in the process.

The resultant market potential is not easy to quantify. It may, however, be assumed that it may be an **important mainstay** for some suppliers, in particular while the market for quantum technologies is still relatively small.

Scenarios for the use of enabling technologies

Nitrogen-vacancy (NV) centres in diamonds – greater accuracy through minute defects: Nitrogen-vacancy centres are **point defects in a diamond** where a nitrogen atom (N) replaces the lattice site of a carbon atom with an adjacent vacancy (V). This reliably gives rise at this point to a quantum state which is **very sensitive** to the minutest changes in the surrounding **magnetic or electrical field**, to **microwave radiation** or to **light**. One central advantage of **NV centres in diamonds** is that these quantum characteristics are also **usable at room temperature**.

A sensor based on such NV centres in diamonds is capable of measuring changes in magnetic fields, for instance in a **nuclear spin resonance measurement** of the kind used **in medicine,** with a **distinctly higher spatial resolution** than would be possible with conventional sensors. However, it is not only in sensing that NV centres can be used. They can also play a role in **quantum cryptography** or as a central building block of a **qubit for a quantum computer**. They are moreover suitable as **single-photon sources.**

Photon sources – quanta at the push of a button: Second-generation quantum technologies are based on the targeted use and control of **quantum states in individual or small numbers of particles**. In many cases, the particles involved are **photons**. Conventional light sources and lasers always emit a number of photons at time intervals which are not precisely quantifiable. A conventional light bulb accordingly emits approximately 10^{20} photons per second.

Single-photon sources in contrast are capable of emitting **individual photons** with **defined quantum states** and at **defined time intervals**. Single-photon sources are therefore true **masters of versatility** in quantum technologies. They can be put to use in all fields ranging from **sensing/imaging/metrology** via **quantum communication**, where they can be used for **quantum key exchange (QKD)**, to **quantum computing and simulation**.

Sources which reliably produce **entangled photon pairs** (see "Overview of the most important quantum-mechanical effects" on page 20, for the phenomenon of entanglement) likewise perform important tasks in various areas of quantum technology. They can be used for microscopic imaging without interacting with the investigated object (**"ghost imaging"**), in **quantum communication** and likewise in **quantum key exchange**.

Cryoelements – quantum technologies in the deep freezer: Many quantum technologies exploit the circumstance that, at **extremely low temperatures** (very close to absolute zero at -273.15 °C), materials exhibit other special properties. Different approaches to building **quantum computers and quantum simulators** as well as experimental approaches to a **quantum repeater** are accordingly based on the phenomenon of **superconductivity** which only occurs in certain materials once such low temperatures are reached.

Achieving these temperatures entails using **"cryostats"** which mainly use liquid helium as coolant. The **particular difficulty** associated with using cryostats in quantum technologies is that they must have **no influence on the quantum states** on which the technologies are based and which are highly susceptible to interference.

Value chains

QET are by definition often **at the beginning of value chains** in their respective areas of second-generation quantum technologies. Specialised quantum technology components are at present mainly manufactured by **specialised suppliers in SMEs or start-ups** which are frequently **located in Germany** and serve the global market.

Experts are reporting, however, that many manufacturers from sectors which are of peripheral relevance to quantum technologies, such as electrical engineering, have **not yet recognised quantum technologies as a potential market**. As a result, some components currently have to be adapted by quantum device manufacturers themselves, since they are not commercially available with the required specifications.

Since there is currently only a small market for quantum technologies, it is **not certain** that the developing **ecosystem of specialised manufacturers will be able to be self-supporting** until the necessary development work is done in QET. If they are to be able to invest in **further developing QET to market maturity**, suppliers need **ongoing sales**, as might for example be generated by demand from the research sector thanks to **continuous investment and long-term funding programmes**. This might make it possible to **bridge the "valley of death"** between the development of prototypes in the course of research funding and the final steps to a marketable product. At the same time, this will in future enable German companies to participate **in these links of the value chain**.

> *"Businesses depend on constant demand in order to be able to continue investing in the development of enabling technologies. This is where continuous government investment can give a helping hand to build bridges."*

Activities at **universities and non-university research institutions**, such as the Digital Innovation Hub Photonics transfer centre at the Fraunhofer Institute for Applied Optics and Precision Engineering in Jena, can make an important contribution here. The **BMBF funding line** for the development of key components is already providing appropriate incentives with the aim of ensuring cooperation between **excellent quantum technology research institutions** and **manufacturers of key components**.[57]

5.3 Technological sovereignty

Quantum enabling technologies are an important part of maintaining technological sovereignty. Germany's good position in this area should be maintained and developed. At present, there is only a slight risk of dependencies on raw materials and individual components.

QET will be **critical components for value creation** in the individual areas of quantum technologies. **Germany** is in a good position to occupy this **key position in international value chains** with **strong businesses**.

> *"A quantum computer can in principle be built solely using components from Germany."*

However, most **highly developed industrialised nations** should themselves be capable of developing a **significant industry** even in this area and this is what is already happening in places, as is apparent for example from the companies emerging or growing in the UK around the National Quantum Technology Programme.

Experts indicate that in **individual areas value creation and expertise** formerly present in Germany **have migrated away from the country**. This even applies to academia, for instance due to scrapping or non-reappointment of chairs in the field of cooling technology.

Accordingly, **ultravacuum technology** is today often purchased from China while UK and Finnish companies are leading the market for the **latest** cooling systems of the kind used in quantum computing. Should **demand for high quality, high value products** strengthen, it might be attractive **to re-establish capacity in Germany.** This also applies to components whose availability is limited by export controls.

There are some reports of **supply bottlenecks** for select quantum computer hardware components since suppliers do not yet have the industrial manufacturing capacity for these products due to the limited market for them.[58]

Experts do not consider that there is **any great risk of strategic dependencies and raw material shortages for the base**

57 | See BMBF 2017c.
58 | See MIT Technology Review 2019b.

components for QET. While **simple components** such as standard lenses, adhesives or housings are often **purchased from foreign (Asian) countries**, this is primarily for cost reasons and not because German manufacturers would not be able to produce them themselves. In contrast, for **specialised products** (speciality lenses or adhesives etc.) the **high quality of German or European manufacturers** is preferred. Only for **individual components** such as nonlinear crystals for constructing specialised light sources do some experts regret that they can **no longer turn to German manufacturers**. But even here, the necessary production know-how would still be available in Germany.

5.4 Profile of Germany's strengths and weaknesses and current opportunities and threats

The following is a specific overview of Germany's strengths and weaknesses as well as the opportunities and threats it faces in **enabling technologies** for the application of second-generation quantum technologies. See section 3.3 for a general overview across the various technological fields of quantum technologies.

Strengths

- SME base with focus on enabling technologies (in photonics, microelectronics and microscopy)
- Good availability of the specialised laboratory equipment and components from Germany/Europe which are required in cutting-edge research
- Proven experience of German industry and research institutions in processes such as component miniaturisation and systems integration which are vital to commercialisation

Weaknesses

- Demand still highly dependent on the academic market
- Poor availability of components which already meet all requirements for use outside the laboratory without further development effort
- Small company sizes and funding structures as barriers to in-house development activities

Opportunities

- Good starting position for occupying key links in international value chains
- Provision of production and test environments for SMEs and start-ups
- Retention of technological sovereignty in key components
- Spill-over effects from component development into adjacent areas of technology

Threats

- Dependency on imports for individual components (e.g. at present from China for nonlinear crystals)
- Unresolved chicken and egg problem in market development: without components no producers of new quantum technologies, without producers no demand for components or component development
- Loss of academic knowledge base due to inadequate embedding in research institutions (e.g. cooling technology or crystal growing)

6 Quantum sensing, quantum imaging and quantum metrology

Germany's starting position in quantum-based sensing, imaging and metrology is strong. Quantum effects can enable new levels of sensitivity and accuracy as well as completely new measurement methods. Initial products are already commercially available, while others will be on the market shortly. High secondary value creation potential in many sectors is also to be expected in this field.

The area of second-generation quantum technology **which is at the most advanced stage of development** covers the areas of quantum sensing, quantum imaging and quantum metrology. Some **initial products are already** on the market, and expert opinion suggests that the immediate future will see further applications in the fields in particular of sensing and metrology reaching a marketable stage, with imaging following on in five to 15 years (see "Scenarios for the use of quantum-based sensing/imaging/metrology").

By exploiting quantum effects, **quantum sensing** can achieve **hitherto unimaginable levels of sensitivity and accuracy**, so for example significantly improving the measurement of masses and currents.[59]

The aim of **quantum imaging** is to achieve **improved imaging methods**, above all in living cells, through the use of single-photon sources. Furthermore, completely **novel observation methods** are becoming possible, such as **Ghost Imaging**, in which indirect imaging may proceed in hitherto inaccessible wavelength ranges. It may moreover be integrated on a chip and offers highly promising potential applications in the fields of communication, remote sensing and ultrafast spectroscopy.[60]

Redefinition of the International System of Units

A uniform system for defining weights and measures has been in place since 1790. Over the centuries, the **International System of Units (SI)** has been constantly refined but has remained dependent on physical reference objects such as the prototype kilo or the prototype metre. In **May 2019**, the SI **was redefined on the basis of quantum metrology** and completely decoupled from the physical reference objects. Quantum physics played a major role here because the system was redefined on the basis of constants including the **Planck constant**.[61] The four units kilogram, mole, ampere and kelvin are now defined on the basis of values of physical constants.

The **Physikalisch-Technische Bundesanstalt (PTB)**, the national metrology institute in Braunschweig, is responsible for implementing the SI in Germany. It made a **significant contribution** to the redefinition of the SI, among other things by carrying out preliminary experimental testing.

The redefinition of SI units and therefore of metrology is of great economic significance because, by substantially **simplifying the calibration process**, it promises additional **value creation potential** for Germany's **machinery and plant engineering sector**.

In **quantum metrology**, many of the expected practical applications are based on **more precise time measurement**. This forms the basis for ICT technologies and locating systems, which will become even more accurate as a result of the higher measuring accuracy of quantum-based time measurement.[62]

Not just time but also other quantities can be measured more accurately using quantum approaches. This characteristic was used to redefine the International System of Units (see "Redefinition of the International System of Units"). Quantum electronic effects often form the basis for measuring many different quantities.

59 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
60 | See PhotonicsViews 2016.
61 | See PTB 2019; Siegner/Göbel 2019.
62 | See EU COM 2017.

Quantum electronics is a field of technology at the interface between first- and second-generation quantum technologies. However, since these technologies are being constantly driven forward, for example **miniaturisation of individual systems** or **simplified operability**, quantum electronics will also play an important role in future, making a major contribution to quality infrastructure at the nexus between all constituents of standardisation, standards and metrology, certification and testing services. **Uniform, high-precision measurements** can in the meantime **for the most past be carried out electronically,** for instance the accurate measurement of very small or very large masses by voltage.[63]

All in all, it is hoped that the use of quantum technologies in sensing, imaging and metrology will bring about **improvements in several performance dimensions,** and in the medium term will also reduce costs, making them comparable with current mass-produced products, specifically

- more accurate resolution,
- higher measuring accuracy,
- better diagnostic possibilities,
- imaging methods based on sources with relatively low light levels and
- overall more compact products.

Scenarios for the use of quantum-based sensing/imaging/metrology

Avoidance of construction delays: Nearly 40 per cent of all construction projects suffer delays and/or additional costs due to a **lack of clarity about what will be found under the ground's surface**. Measurements can be made using conventional sensors, but this is only infrequently done because they are very time-consuming and the results obtained are of limited utility. **Quantum sensors** for underground surveying are **ten to 100 times faster** and **twice as accurate** as non-quantum sensors.[64] Better advance knowledge of the underground situation may, for example, **reduce the duration of roadworks** and so **prevent unnecessary traffic jams**.

Less intrusive and more accurate diagnoses: Diseases are often diagnosed by measuring magnetic fields originating from waves/currents in the human body, for example brain waves by magnetoencephalography (MEG) or cardiac currents by magnetocardiography (MCG). Undergoing investigations in today's large and often cramped equipment is an additional burden for patients. This is set to change with the use **of sensors based on optically pumped magnetometers (OPMs).**[65] These permit the development of **small, mobile diodes** which can be applied directly to patients and will limit their freedom of movement distinctly less. Since, unlike measuring instruments based on "Superconducting Quantum Interference Devices (SQUIDs)", OPMs operate at room temperature, there is no need for large cryostats, and the technology can be implemented in miniaturised form in "MEG helmets" and applied directly to patients. Direct contact means the sensors provide more accurate measurement results, especially for patient groups such as newborns whose physique differs greatly from that of an average adult. In addition to diagnostic use, application in research is also hoped to provide a **better understanding of neurological diseases**, such as Alzheimer's, and so advance patient care.[66] Further development of this technology will be pursued in the macQsimal project which is part of the EU Quantum Flagship.[67]

Easy-to-use, high-precision clocks: Ultra-high-precision clocks are required for measuring height differences in geodesy or for synchronising networks with high-accuracy frequency standards (satellite navigation, such as GPS and Galileo, computer systems, radiotelescopes). They are accordingly vital to the **smooth functioning of our infrastructure** but are often complex to operate and fault-prone. A demonstrator of a **compact optical clock rated for continuous duty** is therefore being developed as part of the BMBF "Optical single-ion clock for users" (opticlock) project whose funding runs until 2020. This latest generation of ultra-high-precision clocks is based on optical transitions in neutral atoms or charged ions. Prototypes are now achieving accuracies corresponding to rate deviations of around one second over the age of the universe. The clock developed by "opticlock" is also intended to function outside specialised laboratories and to be **easy to operate** by non-scientists.[68]

63 | See Chaste et al. 2012.
64 | See UK National Quantum Technology Hub Sensors and Metrology 2018.
65 | See Boto et al. 2018.
66 | See BMBF 2017b; FieldLine Inc. 2019.
67 | See macQsimal 2019.
68 | See opticlock 2019.

6.1 Status of research and commercial application

Germany has a strong university and non-university research landscape in this field of technology. In addition, comparatively significant interest has been shown in quantum sensing, quantum imaging and quantum metrology, with industry displaying commitment to research and development. The geographical proximity of research groups to potential users from a very wide range of sectors is of definite benefit.

Internationally, Germany is one of the leading locations for research and development in quantum-based sensing, imaging and metrology. There are **close links** between the **basic research carried out at universities** and **non-university research institutions** such as the **PTB**, the **DLR** and the **Fraunhofer** and **Max Planck Institutes**, for instance in the form of the Quantum Frontiers – Light and Matter at the Quantum Frontier excellence cluster in Braunschweig and Hanover. There has been considerable growth in the number of publications in quantum sensing and quantum metrology between 2010 and 2016.[69]

Germany's Hightech-Strategie 2025 sets out plans to establish **a Quantum Technology Competence Centre (QTZ)**, provided enough funding is ensured for the requisite personnel. The Centre's most important objective will be to support business in implementing quantum technology research results.[70] One objective is to **offer further training and development**. A further intention is to support quantum technology **start-ups** in prototype testing or the further development of prototypes. Given the PTB's core skills, the QTZ will focus primarily on quantum-based metrology, but will also go further, for example, **various types of equipment**, both from quantum technologies and from enabling technologies, for instance single-photon sources and detectors or specialised lasers, will in future **be measured and characterised** at the PTB.

Initial sensing applications are also being developed as part of the **Fraunhofer Q-Mag lighthouse project**. Freiburg-based Fraunhofer institutes are working together with the University of Stuttgart and industry representatives (e.g Intel and Siemens Healthineers) on NV diamond technologies for high-resolution measurement of minuscule currents and magnetic fields, for instance for detecting brainwaves in medical technology or for measuring the earth's magnetic field in geodesy.

Industry's comparatively enthusiastic commitment to this field of quantum technologies is generally positive (see also "Faster from lab to application thanks to quantum challenges" on page 24). Companies stress the **importance of early involvement** in **R&D** if they are to **maintain their position as market leaders** and even **generate IP**. Of the major German R&D-intensive companies, **Bosch, Siemens, TRUMPF and Zeiss are most actively** involved, focusing on their respective fields of business. Zeiss, for example, is focusing on quantum imaging, with a view to microscopy as a possible application. Germany is also home to **some smaller companies**, such as Q.ANT and NVISION IMAGING Technologies, whose primary focus is quantum-based applications. The general expert opinion is that early involvement of industry in publicly funded projects, for example via project-related industry committees, can improve the **fit** between the **direction taken by development efforts** and **industry's needs**.

Experts feel that **test and validation structures should be developed for quantum sensors in Germany,** so that they can be tested in direct comparison with currently available sensors. In this way, potential users could apply **specific use scenarios** to test whether quantum-based sensing and imaging applications do actually meet the requirements better than conventional approaches. Given the right financial and personnel resources, the QTZ at PTB could probably fill this gap.

> *"In quantum sensing there is a relatively straight path from the current development status to a product; the roadmap is very well defined and technical problems are clearly identified."*

When transitioning from basic to application-oriented research, it is important to ensure, at an early stage, that the **necessary components are affordable and mass-producible** and function reliably under real-life conditions.[71] The quantum state achieved in the lab must also be reliably controllable and stable in everyday use. It must also be ensured that **sensors can be simply integrated into larger systems**.[72] Since NV centres in diamonds,

69 | See Bornmann et al. 2019.
70 | See BMBF 2019a.
71 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
72 | See Zeiss 2018.

unlike other approaches, are capable of functioning at room temperature, this approach is particularly attractive, because there is no need for cooling.

Selected applications

Various applications which experts expect to make the most successful use of quantum-based methods are listed below. In some fields, there are applications which have already reached market maturity, but most of the possible applications listed are still only realistic aspirations.

Quantum sensors:

- **Mineral resources:** improved exploration of underground raw material deposits
- **Construction:** imaging of underground structures before excavation is begun
- **Early warning systems for natural disasters:** gravitational measurement of magma movement in active volcanoes
- **(Micro)electronics:** through-surface inspection, for example to identify errors in circuits

Quantum imaging:

- **Medical technology:** tissue differentiation, of importance, for example, in cancer diagnosis
- **Research:** NV centre microscopy for low-light imaging, of importance above all in living cells
- **Ghost Imaging:** possibility of imaging objects in hitherto inaccessible wavelength ranges, for example for microscopy applications or in satellite/GPS applications
- **Detection of neurological signals:** improved understanding of neurological diseases (such as Alzheimer's) through better detection methods and more accurate resolution of signals

Quantum metrology:

- **Navigation**: high-precision inertial locating and navigation systems, independent of satellite-based navigation; clocks for navigation satellites such as GPS or Galileo
- **IT technology:** improvement of signal processing and thus faster information transmission using new, high-sensitivity optical atomic clocks

6.2 Market potential and value chains

The greatest value creation potential does not reside in the markets for quantum sensors or atomic clocks themselves, but instead in the various sectors wishing to use them, such as the construction or ICT industries. Initial applications are anticipated above all in the high-quality sensor and imaging market, i.e. in market segments which are of great significance to Germany.

It is not expected that quantum sensors will generate completely new markets but **sensors will find applications in many macroeconomically significant markets**. The market for sensing and metrology is seeing meteoric growth. Sales rose a (forecast) 240 per cent between 2009 and 2019 which mean sensing and metrology are growing distinctly above Germany's nationwide growth trend.[73] **Quantum sensors** count among **high-grade sensors**. This is **a market segment of particular significance to Germany**, since many German manufacturers specialise in producing state-of-the-art, high-performance sensors which have to stand out from the competition by their performance rather than the lowest possible unit price.

Initial estimates of the **market for quantum sensors amount to USD 1.3 billion in 2023** and assume **growth to USD 2.2 billion by 2028**.[74] The UK Quantum Technology Hub Sensors and Metrology even anticipates a market of **GBP 4 billion GBP** (around EUR 4.5 billion) annually for quantum sensors.[75]

The **hype cycle** shown in Figure 8 gives an overview of the expected time to market maturity for quantum sensing and quantum metrology.

The greatest value creation potential is **not in the respective markets** themselves, **but instead in the sectors** in which **value creation can be increased through the use of these technologies**. The UK Quantum Technology Hub Sensors and Metrology has attempted to identify the potential share of quantum sensing/imaging/metrology in different economic sectors (see Figure 9). However, many experts are of the opinion that **secondary value creation** cannot at present be reliably quantified.

73 | See AMA 2019.
74 | See Inside Quantum Technology 2018.
75 | See UK National Quantum Technology Hub Sensors and Metrology 2018.

Quantum-based medical technology, such as magnetic resonance imaging, has become an integral part of hospital and medical practice (see also "First-generation quantum technologies" on page 18). Experts anticipate that **the most disruptive breakthroughs in medical technology will be in quantum-based sensing/imaging/metrology**. **Breakthroughs in quality terms, such as new microscopy and diagnostic methods** may also be expected. For example, the **miniaturised MEG methods** described above **may be assumed to have the potential to take a share of the magnetic resonance imaging market, currently valued at USD 5.8 billion**.[76] The introduction of more compact equipment will mean that they can also be made available to patients in more settings.

Experts view the possibility of using quantum sensors **to see underground without having to dig or drill** to be particularly economically significant. The consequent economic benefits (e.g. by avoiding delays during excavation on construction sites) far exceeds the market potential of the quantum sensors themselves. **Pioneering products, such as the first gravity meters for construction companies, are already commercially available.**[77] According to experts, the cost point for such sensors is currently around EUR 100,000. However, once sensor production has been scaled up, prices can be expected to fall substantially and so enable more versatile applications in fields which are not yet financially profitable.

"Quick wins in sensing are possible in niche markets, but the mass market is still a long way off."

Quantum electronics can make a major contribution to ICT and mechanical engineering. For instance, it will in future be possible to use **low maintenance**, quantum-based voltage measurement devices in electrical grids. These **devices can be operated continuously** and have the advantage over today's devices that they do not have to be recalibrated or readjusted at regular intervals, so permitting **time savings** for operators. In addition, computable SI values provide certainty that the correct value is always directly calibrated in the system and incorrect values due to calibration errors can be ruled out.

"Calibration and measurement methods will change completely thanks to computable quantum-based SI standards."

Estimates by experts indicate that **5 to 8 per cent of gross domestic product depends directly and indirectly on navigation**. More accurate satellite-based and satellite-independent location finding methods are therefore important applications in an economic sector which is of great significance to Germany. In **quantum metrology**,

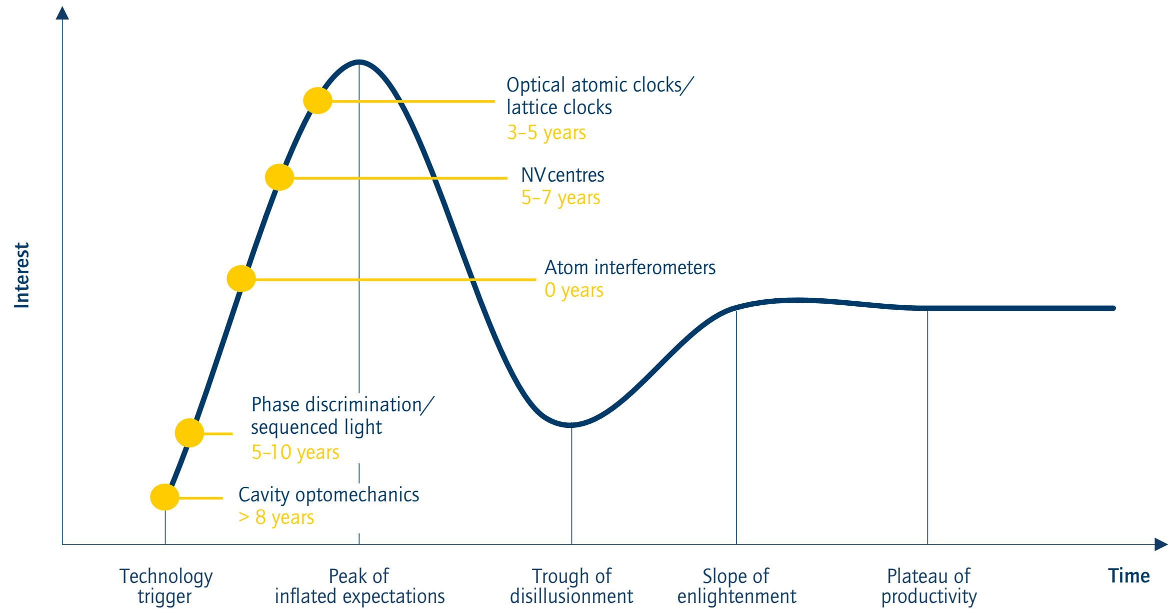


Figure 8: Quantum metrology and quantum sensing hype cycle (source: Zeiss 2018)

76 | See UK National Quantum Technology Hub Sensors and Metrology 2018.
77 | See Muquans 2019.

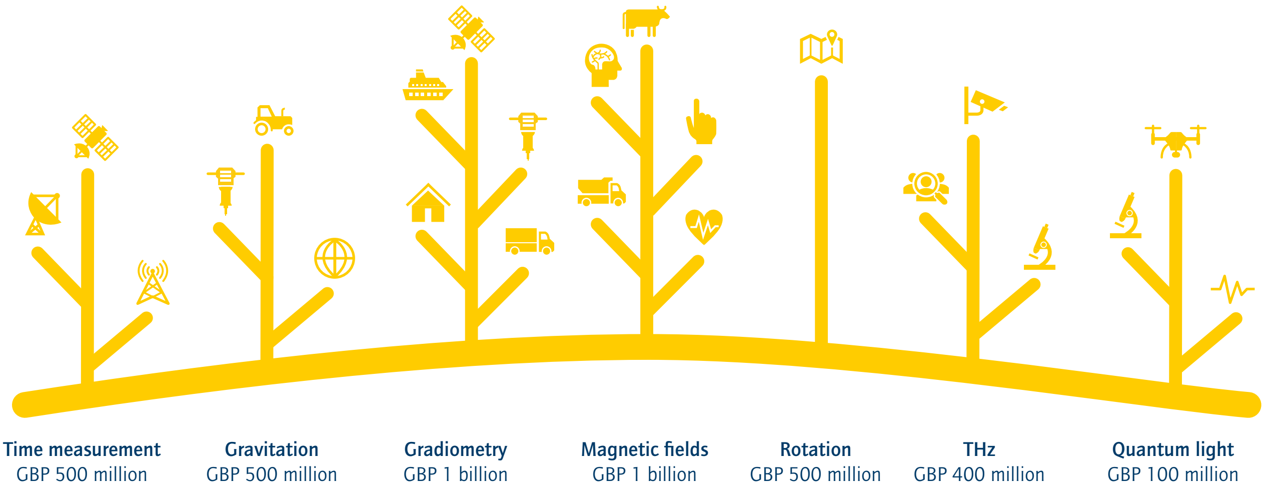


Figure 9: Potential value creation volume for various applications in quantum-based sensing/imaging/metrology (source: own presentation based on UK National Quantum Technology Hub Sensors and Metrology 2018)

quantum-based **ultra-precise time determination will still further optimise location finding**. It is expected that **quantum-based** navigation aids will primarily be used in the **high-end segment**.

This offers huge **value creation potential for automated driving** where the most accurate possible location finding and knowledge about the environment in which the vehicle is moving will play a major role in the success of the technology.[78]

"Rule of thumb: the new technology must be an order of magnitude better than the established one."

The business models of start-ups reflect the still early stage of the markets. For instance, one German start-up is offering customers a taste of the benefits offered by quantum sensors via **leasing models**: customers receive quantum sensors which they can put to the test in their specific use contexts. If the product is developed further, the leased sensors **are automatically replaced with the new generation of sensors**. This allows customers to test the new technology without great risk, while the start-up can **build a customer base** and feed customer experience into the further development of its technology.

Experts believe that similar business models are also conceivable for specific **quantum-based imaging methods**, such as NV centre microscopes. The first users will probably be leading research institutions who will **provide input as the supplier develops the products and makes them suitable for a broader market** .

Experts emphasise that it is vital **not to underestimate the engineering work which is still required**. Moving from proof of principle to commercial application means that **robustness and reliability** under everyday use scenarios must be ensured, **components integrated and miniaturised** and prices reduced thanks to **scalable production**. However, there is a long way to go to commercial mass production, and even those products which are currently ready for the market are usually still custom products made by craft manufacturers.

6.3 Technological sovereignty

There is a very low risk of dependence on producers outside Europe for individual components.

Expert opinion is that there is only a **slight risk to Germany's technological sovereignty** in quantum-based sensing, imaging and metrology since it is not to be expected that there will be critical dependencies on producers outside Europe for enabling or key components.

78 | See UK National Quantum Technology Hub Sensors and Metrology 2018.

6.4 Profile of Germany's strengths and weaknesses and current opportunities and threats

The following is a specific overview of Germany's strengths and weaknesses as well as the opportunities and threats it faces in **quantum sensing, quantum imaging and quantum metrology**. See section 3.3 for a general overview across the various technological fields of quantum technologies.

Strengths

- Initial exploration of potential for use/commercialisation by industrial suppliers (including spin-offs, internal teams or competitions)
- Strong corporate base in photonics, microelectronics, microscopy, medical technology and sensing
- High level of expertise in metrology and sensing in aerospace

Weaknesses

- Reticent demand from German industry for first-to-market products
- Research and development often focuses on basic feasibility and less on users' required performance profiles

Opportunities

- Retention of lead supplier status in high-performance, high-priced market segments thanks to rapid transfer (e.g. via collaborative research projects, practically oriented test facilities or competitions)
- Exploitation of secondary value creation potential by early use in sectors of importance to Germany (e.g. construction, medical technology and ICT)
- Prompt demonstration of the practical benefit of new quantum technologies to people, for instance in medicine

Threats

- Failure to target development funding at potential users' actual needs
- Migration of value creation and specialists due to risk aversion of German businesses in trialling early applications
- Underestimation of the commercial significance of quantum technology in sensing, imaging and metrology due to excessive focus on quantum computing

7 Quantum communication and quantum cryptography

Quantum communication enables tap-proof communication via fibre optics, air and satellite. Quantum cryptography provides methods for generating and exchanging cryptographic keys to secure communication traffic. Germany and Europe are currently planning and building their first quantum communication infrastructure, the main users of which will be governments and companies with highly sensitive data. One key component which is still missing is the quantum repeater.

Quantum communication is a **tap-proof form of communication** which uses entangled pairs of photons or single photons since these can be generated and transmitted with comparatively little effort. The fact that **quantum information** cannot simply be amplified in the same manner as conventional information **complicates transmission** over very long distances, but does make it physically **impossible to listen in undetected**.[79]

Communication security is of central importance to consumers, businesses and politicians alike.[80] In contrast with ordinary cryptographic methods, however, quantum **security is based** on our understanding **of the physical laws of nature and not on mathematical calculations**, such as the factorisation of the products of large prime numbers.[81]

In cryptology, a key is an item of information which provides a cryptographic algorithm with a parameter and so controls it. On this basis, **quantum cryptography** provides provably **secure methods for generating and distributing such keys**. Quantum Key Distribution (QKD) is one possible application.[82]

The **"no-cloning theorem"** states that an unknown quantum state cannot be perfectly copied and provides the basis for **quantum cryptography being fundamentally more secure than conventional cryptography**.[83] As a result, quantum information processing differs fundamentally from conventional information processing. This has far-reaching consequences, for example it is not possible to create **a "quantum backup"**.

Since **quantum encryption is based on natural laws**, it is physically impossible to "listen in" undetected. Any external interaction disrupts the fragile quantum state, **so revealing an attempted attack**. Whichever method an "eavesdropper" may use, even a quantum computer, the method remains secure.[84]

Post-quantum cryptography denotes conventional encryption methods which are already in existence and are capable of protecting **data from being accessed in the future using quantum computers**. The encryption methods used for this purpose are, however, not quantum-based, but instead involve the development of complex new tasks, the structure of which cannot (yet) be solved by quantum computers. This is necessary because quantum computers might in future be able to break the currently most widely used encryption system which is based on prime factors (RSA standard). In the light of recent advances in quantum computer development, the results of a survey now indicate that **half of the experts consider that there is a probability of 50 per cent or higher that this will be the case** within the next 15 years.[85]

Although post-quantum cryptography is not a quantum-based form of communication, it is a cryptographic method which protects data from possible decryption by quantum computers and is therefore addressed in this section under "Post-quantum cryptography" on page 55.

79 | See MPG 2019.
80 | See High-Level Steering Committee 2017.
81 | See BMBF 2018.
82 | See ETSI 2018.
83 | See MIT Technology Review 2019a; MPG 2019.
84 | See Bruß 2003; Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
85 | See Global Risk Institute 2019.

Scenarios for the use of quantum communication

The most important benefit of quantum-based communication and cryptography is **increased security during data exchange**. **Sensitive data**, for example relating to banking, insurance, healthcare and critical infrastructure, **will be even better protected in the future**. There are various channels which can be used for quantum-secured data exchange.

- **Fibre optics:** Quantum-encrypted data, like conventional data, can be transmitted by fibre optics. This is the current practice in QKD networks. Since photons "get lost" after a certain distance, data can only be transmitted via fibre optics up to **a maximum of approximately 100 kilometres** or at present have to be appropriately decrypted and re-encrypted **at regular distances at trusted nodes**, which provides a further point of attack.
- **In a straight line through air:** A fixed link is not necessarily required for transmission. In 2015, DLR demonstrated that it is possible to **transmit quantum-encrypted data** between a **stationary ground station** and a **flying object.** The laser-generated photons carrying the data to be transmitted were sent through the atmosphere.[86]
- **Satellite:** In a similar manner to transmission to a flying object, the encrypted **information is transmitted by laser to a satellite** where it is decrypted and re-encrypted in order to be forwarded to another ground station or another satellite. The necessary infrastructure and technology is being developed in Germany in part within the CUBE collaborative research project (see "Quantum communication infrastructure" section).

7.1 Status of research and commercial application

Initial quantum communication products are already commercially available, for example QKD applications, but significant further efforts are required for large-scale implementation. Government-funded projects, such as QuNET, Q.Link.X and EuroQCI, are driving the expansion of quantum communication infrastructure in Germany and Europe with the participation of research institutions and industry representatives.

Initial commercial applications for communication secured by quantum key exchange are available **in quantum cryptography** (see "Quantum Key Distribution (QKD)" for more information). There are also post-quantum cryptography methods which are capable of securing existing data against potential future access by a quantum computer (see "Post-quantum cryptography" on page 55).

The **use of integrated optics**, for example waveguide chips, fibre optic cables or optically coupled networks has **enhanced the efficiency of generating quantum states and improved their quality**. At the same time, the miniaturisation of the components required for building more complex quantum networks has been pushed ahead.[87]

Overall, however, some aspects of **quantum communication** are still at the **basic research stage**. The principle of information exchange via **quantum teleportation** (instead of via an optical signal) has so far only been described theoretically. Such exchange is based on the entanglement effect and would enable direct, tap-proof transmission of information over long distances.[88]

Targeted research into quantum technologies in **aerospace applications** is set to be carried out at a dedicated institute of the German Aerospace Center (DLR) in Ulm.[89] The **DLR** is moreover one of the world's leading research institutions in the field of laser-based quantum communication through space. The advantage of this method is the high transmission data rate. A number of initiatives for **developing satellite-based quantum key distribution** are currently under way.[90] These also include the "Quantum Key Distribution with Cube-Sat (QUBE)" collaborative research project with BMBF funding to 2020 which aims to develop hardware for global, tap-proof communication using satellites. The technological platform is provided by inexpensive, compact satellites known as Cube-Sats which are equipped with miniaturised, space-qualified quantum communication components (BMBF 2017c).

86 | See DLR 2015.
87 | See Nationale Akademie der Wissenschaften Leopoldina et al. 2015.
88 | See Bruß 2003.
89 | See Braxmeier et al. 2018.
90 | See DLR 2019.

The **number of publications** in quantum communication and quantum cryptography has **risen sharply**[91] (see Figure 10). **In Europe**, apart from **Germany**, the leaders in quantum communication research are in particular the **Netherlands**, especially Delft University of Technology, and **Austria**, especially the Austrian Institute of Technology and the University of Vienna. Viewed globally, **China is particularly strong** in quantum communication research and implementation.

Major German corporations which are actively researching and developing applications for quantum communication, cryptography and/or post-quantum cryptography include **Deutsche Telekom**, **Infineon** and **SAP**. In October 2018, **Deutsche Telekom announced its investment in the Swiss quantum cryptography company ID Quantique** as part of a strategic cross-investment agreement with SK Telecom (South Korea).[92] **Infineon** has implemented **post-quantum cryptography** on a **contactless security chip**. In this way, sensitive identity documents, for example, can be protected against future access by a quantum computer.[93]

Germany also has its first **start-ups**, such as **InfiniQuant** (Erlangen), which specialises in quantum cryptography or **QuantiCor Security** (Darmstadt), whose focus is on post-quantum cryptography.[94] ID Quantique (Switzerland) is currently the leader in quantum cryptography in Europe.

Quantum repeater – a significant missing piece of the jigsaw puzzle

Since the entangled quantum state of photons is fragile, the **maximum transmission range is currently some 300 to 400 kilometres** through air and 100 kilometres in fibre optics. Carrying information greater distances will entail teleportation of the signal.

The goal is therefore to develop a **quantum repeater** capable of teleporting the signals in tap-proof manner. The technical approaches which might lead to this goal are currently still under discussion at the basic research level, which is why in Germany the

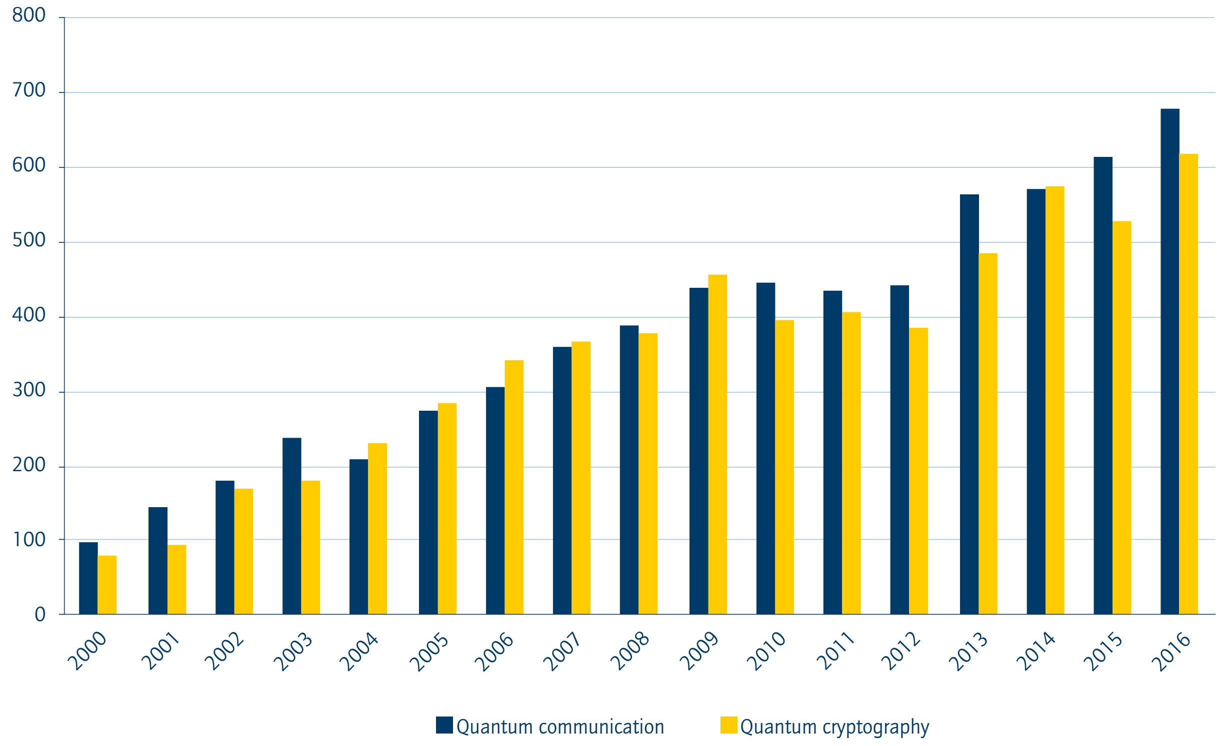


Figure 10: Total number of publications in quantum communication/cryptography (2000–2016) (source: Bornmann et al. 2019)

91 | See Bornmann et al. 2019.
92 | See Deutsche Telekom AG 2018.
93 | See Infineon Technologies AG 2017.
94 | See InfiniQuant 2019; QuantiCor Security 2019.

BMBF initiated among other things the **Q.Link.X collaborative research project** in 2018. With its funding of some EUR 15 million, it is intended to accelerate research into and implementation of a quantum repeater.[95]

According to experts, a quantum repeater can be compared to a quantum computer based on just a few qubits. The biggest **problem** is **storing the photons** on which the information is transported. Unlike key exchange by QKD via trusted nodes where information is decrypted and re-encrypted, a quantum repeater is intended to forward the **information without decryption**. This is intended to ensure that the information remains encrypted from start to finish and so better protected from attempted tapping.

"Photon storage is an important basic research problem that remains to be solved."

There is disagreement in the quantum community as to how close the **quantum repeater is to maturity**. Some experts assume that a proof of concept can be provided in the laboratory in one to two years and subsequent commercialisation will then be a matter of a few years of engineering. Other experts are more sceptical as they are not yet clear exactly how quantum teleportation is intended to work and they regard the EU Quantum Flagship roadmap, which assumes proof of feasibility of a quantum repeater in three to five years, as much too optimistic.

Quantum communication infrastructure

Appropriate technical infrastructure is required as the basis for quantum communication. Since quantum communication can **only in part build upon conventional communication infrastructure** (for instance, the existing fibre optic network can only be used to a limited extent due to the absence of quantum relay stations, such as trusted nodes or, in future, quantum repeaters, at most 100 kilometres apart), **additional quantum communication infrastructure components** will have to be installed.

The **QuNET consortium** was founded in 2019 under the leadership of the Fraunhofer-Gesellschaft. It brings together further partners from academia and industry, including the Max Planck Society, DLR, Deutsche Telekom, Rohde & Schwarz, 1&1 and ADVA. Its initial aim is to **establish quantum infrastructure** so that data can be exchanged securely between federal institutions. The partners in the initiative are to define the **physical and technical requirements** which can then serve as a model for Germany's quantum communication infrastructure. This is also intended to point the way forward to the long-term goal of building a quantum internet. Total funding is **EUR 165 million** in three phases.[96]

At a European level, the seven EU Member States Belgium, Germany, Italy, Luxembourg, Malta, the Netherlands and Spain signed a declaration in June 2019 on the deployment of European quantum communication infrastructure as part of the **EuroQCI** project (QCI = Quantum Communication Infrastructure).[97] Hungary, Portugal and Poland also joined the project in July 2019. The aim is to create a roadmap by the end of 2020 which, together with the OPENQKD test bed, will be the cornerstone for the **deployment of secure European quantum communication infrastructure** over the following decade. In the light of China's huge efforts and high levels of American investment, experts consider that developing a European response is an important step for securing Europe's technological sovereignty.

The "**UNIQORN** – Affordable Quantum Communication for Everyone: Revolutionizing the Quantum Ecosystem from Fabrication to Application" project with its 16 international partners which is funded by the EU Quantum Flagship is also pursuing the goal of developing **key components for future quantum communication systems**. UNIQORN has set itself the goal of **miniaturising** quantum technologies using photonic integration and making them available to users as **system-on-chip solutions**.[98]

Quantum internet

The long-term **vision** of a number of scientists, the QuNET consortium and the EU Quantum Flagship is to establish a **quantum internet or "Web Q.0"** for the secure global transmission of quantum-encrypted information.[99] Further applications, such as clock synchronisation and the interconnection of individual quantum computers to boost total computing power or a digital quantum signature, are also conceivable.[100]

95 | See BMBF 2019b; Q.Link.X 2019; Universität Bonn 2019.
96 | See Fraunhofer-Gesellschaft 2019a; MPG 2019.
97 | See Digital Assembly 2019; EU COM 2019.
98 | See Fraunhofer HHI 2018.
99 | See MPG 2019; Quantum Flagship 2019; Wehner et al. 2018.
100 | See Birch 2018; TU Delft Quantum Vision Team 2019.

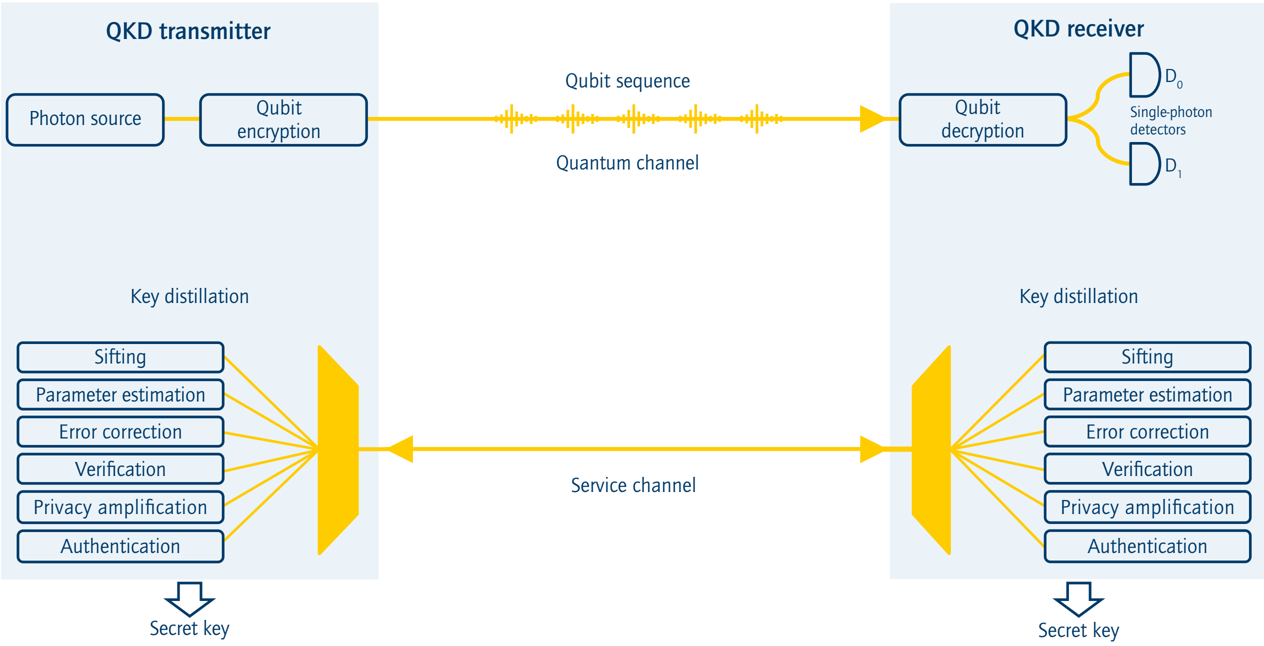


Figure 11: Schematic diagram of QKD-secured communication (source: own presentation based on ETSI 2015)

In autumn 2019, an international research group in Munich managed **to establish** a tap-proof **quantum communication link via a superconductive cable** in a local network. The researchers regard this **in itself as an important step towards a quantum internet**. The distance spanned in the experimental setup is 35 centimetres.[101]

> *"In the short-term future, the quantum internet will merely be an ‚add-on' and not a complete replacement for the conventional internet."*

Experts are of the opinion, however, that the quantum internet **will for the foreseeable future only act as an add-on to the conventional internet** for specific applications (sensitive communications, high-performance computing) and will not completely replace it.

It should be noted that the term **"quantum internet" is controversial** in the quantum community. Though the EU Quantum Flagship and some scientists name it as the long-term goal of quantum communication, other experts question what is meant by it and see it as nothing more than empty hype.

Quantum Key Distribution (QKD)

QKD is a **quantum-based way of generating and distributing random, secret keys** in which the keys are exchanged via quantum communication infrastructure. The content encrypted with the keys is, however, still transmitted via a second, conventional channel, for instance in the normal data stream of a fibre optic cable or satellite, and additionally "conventionally" encrypted (see Figure 11). QKD communication is thus a **hybrid form of communication** with key exchange proceeding on a quantum basis and other content continuing to be conventionally transmitted. This procedure leads to a very high level of communication security.

> *"China's QKD network is an organisational triumph but conceptually nothing new."*

The first terrestrial **QKD networks** were established in Suffolk (UK), Boston (USA) and Vienna (Austria) but they are currently **most widespread in China**,[102] where a QKD network over 2,000 kilometres in length has been put in place between the metropolitan regions of Beijing and Shanghai passing via Jinan and Hefei. Due to the maximum transmission distance of the quantum states of around 100 kilometres in the fibre optics, they have to

101 | See Bayerische Akademie der Wissenschaften 2019; Schmidt et al. 2018.
102 | See Zhang et al. 2018.

be decrypted and re-encrypted at **trusted nodes** so they can be transmitted onwards. There are 32 trusted nodes between Beijing and Shanghai.[103] These points are potential points of attack for external "eavesdroppers".

In **August 2016**, China started up the quantum-based **"Micius" satellite**. Scientists managed to carry out a successful key exchange between China and Austria by satellite and so establish a secure communication channel. The satellite here acted as a trusted node. Encrypted in this way via QKD, the video conference was then conducted over a normal internet connection.[104]

In Europe, a **QKD test environment is being deployed** for three years from September 2019 as part of the **OPENQKD** project with its EU funding of EUR 17 million. **Researchers and industrial partners from 13 Member States,** who will jointly test specific use cases and build regional QKD infrastructure, are participating in the project.[105] The project is expected to offer insights which will improve the functionality of QKD networks and assist a QKD infrastructure ecosystem to develop to maturity in Europe. German partners in the project are Deutsche Telekom, DLR, Rohde & Schwarz and ADVA Optical Networking.

In addition, again as part of the EU Quantum Flagship, the **CiViQ** project's remit is to develop flexible and affordable solutions for **QKD networks** with the aim of **integration into existing communication networks**.[106]

Post-quantum cryptography

One disruptive consequence of introducing second-generation quantum technologies is considered to be the risk that **quantum computers** will be capable of **breaking current encryption protocols extremely rapidly**. As a result, data which are at present encrypted would no longer be secure and this would apply to all currently used variants of public key cryptography (RSA, Diffie-Hellman, ElGamal, ECIES, DSA, ECC).

However, experts call for calm for two reasons: firstly, hacker attacks will in future still be limited by the costs and effort involved, for which reason it will certainly not result **in an "internet doomsday"** when all currently encrypted data are disclosed all at once by hackers.

Secondly, **possibilities for safeguarding databases** against this anticipated future event **are already available**: using **post-quantum cryptography**, data are encrypted with protocols which will remain undecryptable (for the foreseeable future) even by quantum computers.[107] These make use of a new, more complex class of problems as the encryption technology.

Initial solutions have already been tested and products are commercially available. For instance, factorisation problems are replaced by other methods, such as mathematical lattices, hash-based or code-based algorithms.[108] In an open, competitive call for proposals, **NIST** is currently attempting to develop **internationally uniform and secure standards** for post-quantum cryptography algorithms (see also "Faster from lab to application thanks to quantum challenges" on page 24).

At present, it is primarily **government agencies** and companies, such as **banks** which handle highly sensitive data, which are showing interest in post-quantum cryptography.[109] In the absence of certification processes, however, general demand from companies remains negligible.

The aim of the three-year **QuantumRISC** project, which was launched in 2019 with funding of EUR 2.9 million, is to advance **embedded system security using PQC methods**. Consideration must already be given to protecting systems from possible future attacks by quantum computers because the components which are currently being fitted in equipment will often be in service for decades. One focus of this project is **securing the vehicles of the future**.[110]

103 | See MIT Technology Review 2019a.
104 | See FAZ 2017.
105 | See EU COM 2019b.
106 | See CiViQ 2019.
107 | See Buchmann et al. 2017.
108 | See BMBF 2017a; Stebila/Mosca 2017.
109 | See Inside Quantum Technology 2019a.
110 | See BMBF 2019c; Fraunhofer SIT 2019.

"Quantum key exchange is a cornerstone technology because it offers sustainable security."

Although many initiatives are being promoted in QKD communication, experts are pointing out that there is a need to **manage expectations**. It must be clarified that, in the short term, **QKD** will not be securing all future communications but instead **will initially only be used in the most significant areas**. Since the data rate transmissible via QKD is limited, it will only be possible to implement certain potential applications.

7.2 Market potential and value chains

Major investment is being made in building quantum communication infrastructure and the market for components is growing. However, experts are not in agreement about the anticipated size of the quantum communication network, whether it will be for niche applications or will become the standard way of securing communications. The deployment of government-funded infrastructure is intended to create a "pull" effect for industrial users.

Estimates of the market potential for secure quantum-based communication vary widely due to experts' differing assessments of how widespread quantum communication will be in the future. At the lower end of the scale, Deloitte accordingly estimates the market for quantum communication from 2020 to be some **several million US dollars annually**.[111] Estimates by the EU Commission, in contrast, assume a market of over **EUR 1 billion annually from 2020** with annual growth of 20 per cent.[112] The Markets and Markets report "Quantum Cryptography Market by Component – Global Forecast to 2023" values the global **quantum cryptography market in 2018 at USD 101 million** and expects the market to grow **to USD 506 million by 2023**.[113]

As digitalisation proceeds apace, **cybersecurity** will become still more important in the future. This is true not only in relation to the necessary protection of communication between individuals, but also **communication security between systems** and for applications in the **internet of things**. Quantum-based data security will **make industrial espionage considerably more difficult** for hackers, and make it possible to provide better protection for sensitive **business and customer data**. It will also be possible to protect Industry 4.0 production processes more effectively from external access.

QKD applications have been commercially **available for specific niche markets** for some time now. Typical customers currently include banks and governments.[114] The **upcoming expansion** of quantum communication infrastructure in Germany will enable transmission over **greater distances**, which will open up the market for quantum-based data exchange to additional applications.

If a **quantum repeater** is successfully developed, experts estimate the consequent **sales** at **in excess of USD 800 million by 2026**.[115] This presents Germany with an opportunity to occupy a key technology in the quantum communication infrastructure value chain.

The **deployment of government quantum communication infrastructure** and **political guidance** in favour of security regulation make it **possible to promote the development of components and products in Germany and Europe** at an early stage and so lower the entry threshold for local commercial users. Funded consortia and projects which involve industrial partners from the outset, such as OPENQKD or QuNET, can lay vital foundation stones here.

The DLR is **awarding contracts on a qualification basis** in satellite-related quantum technologies in order to vigorously promote the growth of an industrial base and to include innovative SMEs in the value chain.[116]

111 | See Deloitte 2018.
112 | See EU COM 2016.
113 | See Markets and Markets 2019.
114 | See Deutscher Bundestag 2018.
115 | See Inside Quantum Technology 2019b.
116 | See BMBF 2018

7.3 Technological sovereignty

For reasons of technological sovereignty, it is desirable to ensure the availability of a European quantum satellite network and quantum repeater. Clear norms and standards for applications are important for establishing trust among users and thus markets.

Tap-proof satellite communication is essential. The plans of the EU Quantum Flagship mention the prospect of a **European quantum satellite network** being deployed (possibly jointly with the USA) (Quantum Flagship 2019). This would be a major contribution to **European technological sovereignty**, as would a **quantum repeater** manufactured in Europe.

Experts point out that **certification** must play a fundamental role in quantum communication and cryptography so that **uniform standards apply internationally** and interoperability is ensured. This also creates trust for users. It is for this reason that the relevant German stakeholders, such as the PTB, the Federal Office for Information Security (BSI) and DIN, participate in standardisation and certification committees not only nationally, for instance in the QuNET project, but also internationally, for example in the European Metrology Network for Quantum Technologies (EMN-Q).[117]

7.4 Profile of Germany's strengths and weaknesses and current opportunities and threats

The following is a specific overview of Germany's strengths and weaknesses as well as the opportunities and threats it faces in **quantum communication and quantum cryptography**. See section 3.3 for a general overview across the various technological fields of quantum technologies.

Strengths

- Well equipped consortia for establishing quantum communication infrastructure
- Commitment of German stakeholders to the current development of international norms and standards for post-quantum cryptography

Weaknesses

- Hesitant use of initial applications, in part due to the absence of established standards and certification options
- Trailing position in ambitious infrastructure projects (especially in comparison with China)

Opportunities

- Development of a commercially mature quantum repeater as a key component in the value chain
- Government acting as trailblazer, for example in procurement, in order to work towards higher security standards for citizens and businesses

Threats

- Loss of technological sovereignty in the event of dependency on non-European equipment suppliers
- Inadequate or disproportionately high investment due to lack of clarity about anticipated size and significance of the quantum communication market
- Establishment of diverse national standards (especially in China) instead of internationally uniform standards
- Patenting of central post-quantum cryptography methods (at present: freely usable methods)

117 | See EURAMET 2019.

8 Quantum computing

While quantum computing offers huge disruptive potential and general market potential for many areas of application, its development horizon extends far into the future. North American technology companies and start-ups are currently driving development. European stakeholders are playing an only subordinate role, often limited to basic research or software and component development. The availability of quantum computing hardware is a question of European and German technological sovereignty.

Quantum computing is one of the most complex quantum technologies and, in the opinion of many experts, **involves the greatest disruptive innovation potential**.

The quantum computer is based on **quantum bits (qubits)** and is consequently theoretically **superior to conventional, digital computers** in computing power. Quantum bits exploit the quantum-mechanical phenomena of superposition and entanglement (see also "Overview of the most important quantum-mechanical effects" on page 20). As a result, it is theoretically possible to achieve a **high degree of parallelisation** of computing operations **which is impossible for classic computers**. Since many experts expect that the physical limits for what has previously been a continuous increase in the computing power of conventional computers (Moore's law) will be reached, **high hopes are attached to the quantum computer**.

"Second-generation quantum technologies will primarily have an evolutionary effect. Only the quantum computer might conceivably lead to a small revolution."

Unlike a quantum simulator (see section 9), a quantum computer is theoretically universally applicable which means it can be programmed **for different classes of problem** (e.g optimisation, factorisation or unstructured searching). For **factorisation problems** in particular, an **exponential increase in speed** over a conventional computer is possible.[118] When it comes to **molecular simulation**, quantum computers can likewise advance into new dimensions. For instance, modelling the chemical interactions of a relatively simple molecule such as **caffeine** requires **10^{48} bits** in a conventional computer, a number which corresponds to 10 per cent of the total number of atoms on earth. In contrast, a quantum computer could possibly carry out the same simulation with **just 160 qubits**.[119]

Significant **applications** are to be expected for example in the industrial sectors **chemistry, materials production, pharmaceuticals, energy, metals, logistics, aviation, mobility and finance**.[120] See selected applications in "Scenarios for the use of quantum computers" on page 59.

Quantum computers are also believed to be capable of providing a further significant boost in performance for emerging key technologies such as **artificial intelligence and machine learning**. Quantum computers are also able to recognise patterns and connections in **large, complex and unstructured volumes of data** and will consequently enable some applications for example the recognition of objects in the environment in **autonomous driving** or identifying medically significant **interrelationships in patients' genomic data**.[121]

"It is wrong to think of the quantum computer as a supercomputer than can do everything better. Its advantages will mainly be apparent in some specific problem areas."

In principle, however, experts also anticipate that in the medium and long term **further applications for quantum computers** will develop which are simply **not yet foreseeable**. Some more sceptical voices, however, think that even in the long run **quantum computers will only be used for specialised problems** in a similar way to today's supercomputers.

There is also the risk in quantum computing that the current hype will arouse **inflated expectations** with regard to performance and, above all, the time horizons by which quantum computers will bring real benefits. Experts are calling for **realistic management of expectations** in order to prevent disenchantment from setting in if rapid success is not achieved, so resulting in a **quantum winter**, i.e. a disproportionate decline in development and funding activities.

118 | See BCG 2018b; BSI 2019.
119 | See Financial Times 2018.
120 | See BCG 2018b; BCG 2018c; 2019.
121 | See BCG 2018c; Marr 2017; Mohseni et al. 2017; Quantum Flagship 2019.

Scenarios for the use of quantum computers

Materials science – higher performance batteries thanks to new materials: The challenges of **climate change** are driving demands for a **changeover** to a larger proportion of electric vehicles. **Better batteries** combining higher power with shorter charging times and a longer service life are essential to the further development of electric vehicles.

Simulating complex new materials which might be used in batteries and their reaction characteristics **is beyond the capabilities of conventional supercomputers**. Quantum computers, on the other hand, can potentially predict the properties of new materials, which explains why German automotive manufacturers are increasingly also experimenting with quantum computing.

Transport and logistics – avoiding jams and shortening routes: Variants of the **"travelling salesman" problem** are encountered not only in the **management of traffic flows** on rail and road but also in many areas of **logistics**: when an attempt is made to calculate an optimum route with a number of intermediate stops, the number of possibilities increases combinatorially, rapidly reaching orders of magnitude at which even a **supercomputer would take decades to find a solution.**

A quantum computer capable of calculating large numbers of possible routes in parallel makes this problem solvable. As a result, traffic flows could be managed more efficiently, so **avoiding jams**, and **optimum routes calculated with maximum efficiency**, for example for couriers or warehouse operatives.

Medicine – predicting interactions between diseases: A major challenge in medicine is handling often **unpredictable complications** when a patient is suffering from more than one disease (multimorbidity). On the one hand, the interactions complicate **diagnosis of the individual diseases** and, on the other hand, therapeutic approaches become more complex since for example different **drugs interact adversely**.

In-depth analysis of existing patient data might in principle elucidate such possible interactions. The complex clinical data records of patients with their numerous different parameters cannot, however, **be analysed using machine learning approaches on conventional computers**. **Quantum computing-assisted machine learning**, which exploits the advantages of quantum computers in unstructured searching, can overcome this problem and so contribute to **better diagnostic and therapeutic outcomes**.

Financial markets – rapidly optimising portfolios and minimising risk: A strong and reliable financial industry is an important building block for a competitive business location. When developing **structured financial products**, the challenge arises of selecting individual **claims from an overall portfolio**. A number of criteria, such as the sum total of the selected claims or remaining terms, have to be taken into account. This results in a **combinatorial problem** which requires optimisation.

The research and development unit of the Commerzbank group has addressed this problem with a **quantum annealer** (see "Different approaches to the implementation of a quantum computer" on page 62) and achieved a **significant performance advantage**.

However, quantum computing is capable not only of optimising financial products more quickly but also of **better analysing the associated risks**. This can help to ensure **safer and more stable financial products**.

Quantum computers may in principle also be used for any **scenarios for the use of quantum simulations** (see "Scenarios for the use of quantum simulators" on page 71).

8.1 Status of research and commercial application

Despite major progress, quantum computers cannot yet be used to solve commercially significant problems. However, this might become possible for certain optimisation tasks or simulations in the next few years. The greatest challenges are further scaling and improving the quality of the computing units. There is still a need for development in algorithms and software too.

In recent years, **significant progress** has been made in the **development of quantum computers**. One indicator here is the trend in **publication numbers**: after a merely minimal increase between 2003 and 2013, numbers have since **risen significantly** (see Figure 12). Globally, Germany ranks third behind the USA and China in terms of number of publications from 2012 to 2016,[122] which is thanks to the numerous **excellent researchers** who work in German universities and non-university research institutions.

In addition, **new records with regard to the number and quality of qubits** provided by experimental platforms are continuously coming in from abroad.[123]

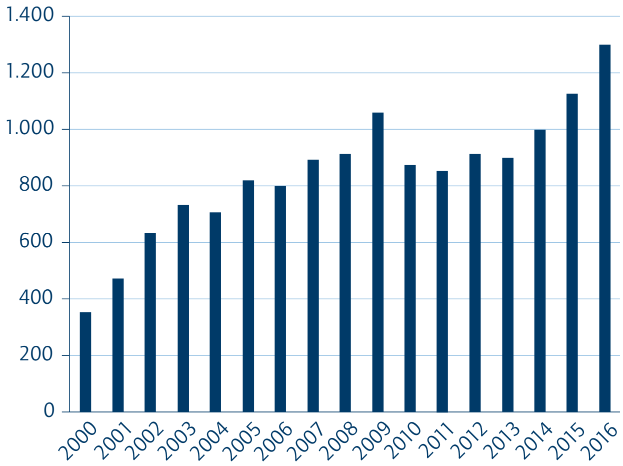
Such successes should not, however, obscure the fact that the technology is still **at an early stage**, only just beyond proof of concept. The next technical goal was to demonstrate a **"quantum advantage" or "quantum supremacy"** by using a quantum computer to solve a problem which a **conventional computer cannot solve at all or only much more slowly**.

In a paper published in October 2019, a **team from Google** has for the first time demonstrated such a **quantum advantage**. Google's quantum computer calculated a **problem specifically tailored to its abilities** in **3 minutes and 20 seconds**, whereas the currently most powerful **conventional supercomputer** would, according to Google's calculations, have taken **10,000 years**.[124] However, IBM has stated that calculating the problem using its Summit supercomputer would only take two and a half days instead of 10,000 years and thus quantum supremacy has not, strictly speaking, been achieved.[125]

While the respondents do indeed regard this quantum advantage to be a significant **technological milestone**, it is however **only a first step** towards a multipurpose quantum computer which can be used for a variety of relevant applications.

There are **various platforms** for implementing a quantum computer and for producing qubits (see "Different approaches to the

Total number of publications in quantum computing



Publications in quantum computing by country (2012-2016)

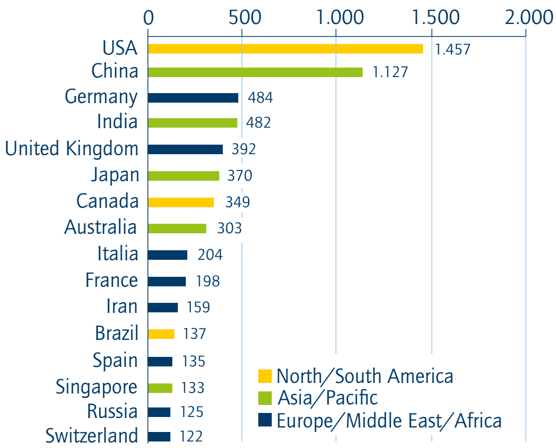


Figure 12: Number of publications in quantum computing; overview by country only taking account of publications in the 2012–2016 period (source: Bornmann et al. 2019)

122 | See Bornmann et al. 2019.
123 | See BCG 2018b; BCG 2018a; BSI 2019; MIT Technology Review 2018a; 2018b.
124 | See Arute et al. 2019.
125 | See IBM 2019a.

implementation of a quantum computer" on page 62, and Appendix C).[126]

The approaches in which the **greatest progress** has been made are currently those using **superconductive circuits or ion traps**. However, these two platforms also face the greatest technical barriers if they are to be scaled to a larger number of qubits and **the sensitive quantum systems are still highly susceptible to interference**. A **substantial proportion of the computing power** therefore has to be used for **error correction**. Depending on the quality of the qubits, several hundred qubits might be required for correcting a single "computing" qubit. **Comprehensive error correction** is therefore not yet possible **with current numbers of qubits**. This is why these platforms are also known as **Noisy Intermediate-Scale Quantum Devices (NISQ)**.[127]

"Nobody yet knows which platform will prevail for building the quantum computer."

Experts are nevertheless working on the assumption that it will be possible to implement **significant applications even with these NISQ systems**, in particular in quantum simulations for example of molecules or chemical processes and in basic research in physics.[128]

Experts disagree about whether **one platform** will in the medium term prove to be superior or whether in future **different platforms** will be used for different areas of application.[129]

Driven by the major commercial potential seen in the technology (see section 8.2), the development of the quantum computer has now left a purely academic environment. The **main drivers** here are primarily North America's major technology corporations such as **IBM, Microsoft, Google, Intel and Amazon**. However, there is a large and **growing number of start-ups** in this field which are active in software and services but some of which, such as Rigetti and D-Wave, also develop their own hardware (see Figure 16 and Appendix B).

In Europe, the quantum computing landscape is in contrast still **somewhat more academic**. There are hotspots in other European countries, such as in the **Netherlands (Delft), Switzerland (Zurich), Austria (Innsbruck), Sweden (Chalmers) and Finland (Espoo)** (see also section 4.2). With the exception of Alpine Quantum Technologies (Austria) and IQM (Finland), the **few existing European start-ups** focus exclusively on software and service development as well as component manufacture. **Major European corporations** have **not yet been active** in hardware development.

According to experts, the precise **development status of Chinese approaches**, whether by government or companies such

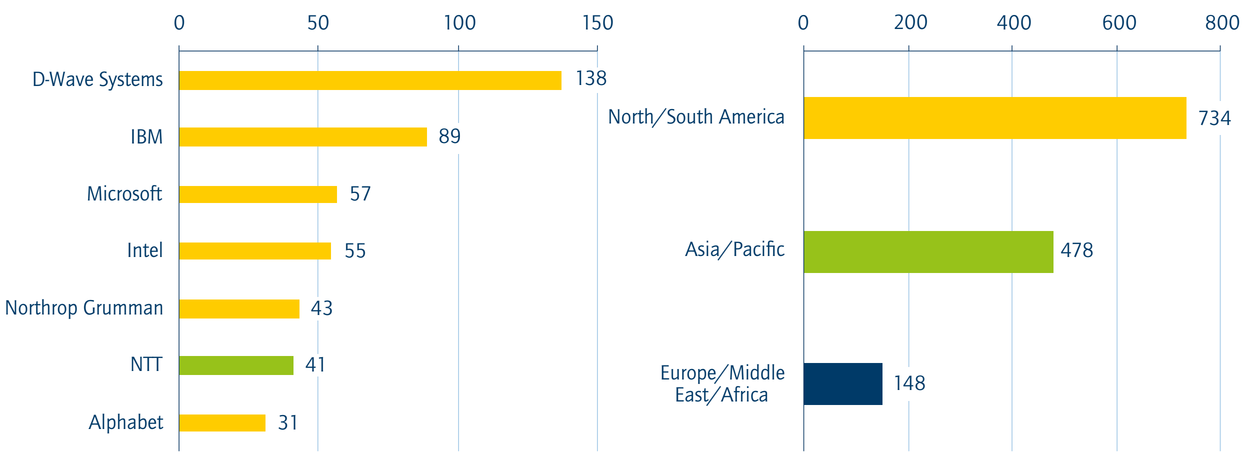


Figure 13: Number of patent families filed in quantum computing by applicant (as of 2017) (source: BCG 2018c)

126 | A more in-depth analysis of the state of development in the various approaches to the implementation of a quantum computer may be found in a study by the Federal Office for Information Security and the publication of the US National Academies of Sciences, Engineering, and Medicine (see BSI 2019; Grumbling/Horowitz 2019).
127 | See BCG 2018b; BCG 2018c; Preskill 2018; QUTEGA 2017; Quantum Flagship 2019.
128 | See Brooks 2019; Kühn et al. 2019; Preskill 2018.
129 | See Global Risk Institute 2019.

Different approaches to the implementation of a quantum computer

- **Superconductive circuits:** Superconductive materials conduct current without resistance and, given suitable circuit design, can form a quantum state, but ultra-low temperatures are necessary. This approach is the one where most progress has been made and is used by most commercial suppliers. They have at present reached an order of magnitude of approximately 50 qubits.
- **Ion traps:** This less widespread approach is based on ionised atoms in a vacuum. The qubits are longer-lasting than in superconductive circuits, however response times in control processes are distinctly slower. The best devices currently have around 20 qubits.
- **Photonics:** This approach is based on entangled photons from single-photon sources and has the advantages of functioning at room temperature and having a modular structure. However, the development of this system is still in its infancy.
- **Semiconductors or quantum dots:** These approaches promise to be easily scalable and are based on well-established semiconductor technology design principles. However, they likewise require ultra-low temperatures and there are still fundamental barriers to overcome in the fabrication and configuration processes on the necessary nanoscale.
- **Topological quantum computers:** This approach is based on exotic particles such as Majorana fermions or anyons and is the furthest away from implementation. However, the approach is highly promising thanks to its theoretically distinctly lower error susceptibility and easier scalability in comparison with other quantum systems.

Other approaches

Quantum annealers (adiabatic quantum computers): This approach, pursued by D-Wave among others, is not strictly speaking a quantum computer since it is only suitable for specific kinds of problem (optimisation problems). As a result, it does not require the same extent of error correction as other approaches and can already be put to commercial use. It is, however, disputed whether and for which kinds of problem a quantum annealer can achieve a "quantum advantage".

Quantum computer emulators: Approaches in which qubits and their behaviour are simulated on a conventional computer are also being pursued to develop quantum algorithms and software. Atos is one well-known supplier in this area. Fujitsu also offers a "digital annealer" which again is an emulation of a quantum annealer.

as Alibaba and Huawei, is **difficult to assess**. They do, however, assume that the major investment made will **lead to significant breakthroughs in the coming years** there as well.

The strong position of North American players is also reflected in the **number of patents** filed in the field of quantum computing (see Figure 13).

Experts report that parts of the quantum computing community are still characterised by a **sense of community and a spirit of academic exchange**. One reason for this is certainly that the companies working on the development of the quantum computer have a **strong common interest** in bringing it to market maturity. In this case they would then have an **almost unassailable lead** in technology and expertise over competitors who have not participated in research and development.

"At the moment, everyone still benefits from cooperation in quantum computing. The tide lifts all boats."

However, things will change as **market maturity approaches**, and a spirit of competition will come more strongly to the fore. In addition, some players are already very **restrictive in collaborative projects and their handling of intellectual property**.

Quantum computing in Germany

In Germany, the focus has long been primarily on **basic research**, which has led to the formation of strong research groups in the **various quantum computing platforms** at universities and non-university research institutions (see Appendix C).

Initiatives have now been put in place to accelerate **application development by the provision of quantum computing hardware platforms.** For instance, Forschungszentrum Jülich and Saarland University are heavily involved in the EU Quantum Flagship **OpenSuperQ** project, which has the goal of developing a **European quantum computer** with up to 100 superconductive qubits.[130] Collaborative projects have furthermore been established between **Forschungszentrum Jülich and both Google and D-Wave** and between the **Universität der Bundeswehr in Munich and IBM**.[131]

"German industry is extremely hesitant about quantum computing."

The collaboration announced in September 2019 between the **Fraunhofer-Gesellschaft and IBM**, which has Federal Government support, marks a new, deeper level of cooperation and will for the first time see a physical **quantum computer installed in Germany** at an IBM data centre at Ehningen near Stuttgart. Under the leadership of the Fraunhofer-Gesellschaft, a new national competence centre in quantum computing is being established which will provide interested users **from academia and business** with access to the quantum computer. The focus is set to be on the development of **practical applications and quantum algorithms**. Another particular feature of the project is that the conditions of use are planned to be in accordance with **German and European data protection legislation**, so offering users legal certainty with regard to intellectual property and the use of sensitive corporate data.[132]

German industry is as yet showing **no sign** of getting involved or taking a lead in the development of a quantum computer.

Challenges

While some researchers have long been extremely sceptical about whether it is even possible to implement a quantum computer with error correction and significant computing power, the **large majority** are now convinced that there will be **fully functional, error-corrected quantum computers**.

When this will come to pass, however, is a matter for speculation. A **time frame of 20 to 30 years** is, however, considered **distinctly more realistic** than 10 years. Experts concur that it will be necessary **to take major risks** and **to persevere** if breakthroughs are to be made in quantum computing.

However, **some research and development challenges** remain to be overcome before that happens and it is possible for quantum computers to solve a range of practical problems. For instance, **efficient error correction methods** must be identified so that the computing power of the qubits can actually be put to use. In parallel, the **error rate of quantum computers must be reduced**, which can be achieved on the one hand by means of **more stable qubits** and on the other by **better methods of shielding** from environmental influences.

"Simply scaling today's machines up to the one million qubits required for error correction would mean that the computer will occupy an entire building."

Scaling up hardware and control systems (increasing the number of qubits, simplifying system components) and at the same time **miniaturising components** result in further technical challenges to be managed. **Progress in cooling technology or the temperature tolerance of the qubits** may also be of importance for individual platforms.[133]

Experts also consider the development **of reliable and easily configurable interfaces to conventional computers** to be an important factor. Some specialists believe that this is also the first area which should be considered when it comes to **setting norms and standards**. Other experts, in contrast, think that it is still much too early to set norms and standards in general for quantum computers or that de facto standards will in all likelihood be established by the earliest suppliers.

In general, the development of the quantum computer requires close **coordination between theoretical and experimental approaches** and benefits from **advances in the underlying enabling technologies** (see section 5). All platform technologies still have not only **basic research questions to answer** but also **engineering problems to solve**, with there being **substantial differences in the level of maturity** between the various approaches.[134]

130 | See OpenSuperQ 2018.
131 | See Forschungszentrum Jülich 2019; Forschungszentrum Jülich 2019; IBM 2018.
132 | See Fraunhofer-Gesellschaft 2019b.
133 | See Cao et al. 2019; Kühn et al. 2019; Peruzzo et al. 2014.
134 | See BCG 2018c; BCG 2018b; Quantum Flagship 2019.

When it comes to development towards the **commercial production** of quantum computers **Europe and Germany** currently also lack a stakeholder who might be able to assume the role of **system integrator** in order to amalgamate existing research expertise with industrial know-how.

Algorithms

The **first quantum algorithms** which were developed and which promise the **greatest speed advantage**, such as Shor's algorithm[135] are reliant on an **error-corrected quantum computer**. They **do not work on currently available NISQ platforms**.

Quantum algorithms have now also become available which are **more error-tolerant** while still promising progress over conventional systems, for example in the simulation of quantum-chemical systems.[136] Nonetheless, the **development of further algorithms** is crucial if it is to be possible **in the near future** to use quantum computers with just a few qubits to solve significant problems.[137] These also include algorithms which themselves assist with error correction.[138]

Algorithm and service development may in principle also be accelerated using currently available **cloud offerings**, for instance from Rigetti, Google and IBM, or by using **quantum computing emulators** (see "Different approaches to the implementation of a quantum computer" on page 62). Experts nevertheless believe that **faster progress** can be achieved, in particular at what is still an early stage of development, by **more direct access to the hardware component**. In addition, consideration must also be given to the **protection of intellectual property rights** and the **security of sensitive user data** when using these offerings.

Research into quantum algorithms has also led to algorithms which can be used on conventional supercomputers which are referred to as **quantum-inspired algorithms** and offer efficient solutions **for comparing molecules or for optimisation tasks**.[139]

The development of the quantum computer and corresponding algorithms also creates challenges in terms of **communication security**. For instance, Shor's algorithm is capable of **quickly breaking current encryption** based on prime factors (**RSA standard**).[140] The effects of this on the protection and confidentiality of data are potentially huge, since not only might it be possible to attack future communications in this way, but **existing data could also be subsequently decrypted**.[141] Leading experts estimate the **probability** of a quantum computer being capable of achieving this **within the next ten to 20 years to be over 50 per cent** (see also "Post-quantum cryptography" on page 55).[142]

8.2 Market potential and value chains

In the medium to long term, the projected market potential for quantum computers is up to the three-digit billion range. The many and varied potential applications along the value chain mean there is also very large secondary value creation potential. At present, an ecosystem of hardware, software and mixed providers is emerging worldwide. However, German and European companies are absent from the hardware area in particular.

Of all second-generation quantum technologies, quantum computers have by far the **greatest theoretical market potential**. At the same time, however, huge barriers to use still remain, which means **reliable market estimates are almost impossible**. The following figures should accordingly be viewed with some scepticism.

The **optimistic scenario** in one study assumes that a significant market will develop from 2030 which will experience spectacular growth to **USD 57 billion in 2035** and **USD 295 billion in 2050** (see Figure 14). The **more conservative scenario** assumes that the breakthroughs which lead to major market growth will not occur until later (2040). Nonetheless, rapid growth **from USD 6 billion to USD 263 billion within ten years** is then predicted.[143]

135 | See Shor 1997.
136 | See Cao et al. 2019; Kühn et al. 2019; Peruzzo et al. 2014.
137 | See BCG 2018c; Quantum Flagship 2019.
138 | See QUTEGA 2017.
139 | See Accenture 2018.
140 | See Shor 1997.
141 | See Richter 2018.
142 | See Global Risk Institute 2019.
143 | See BCG 2018b.

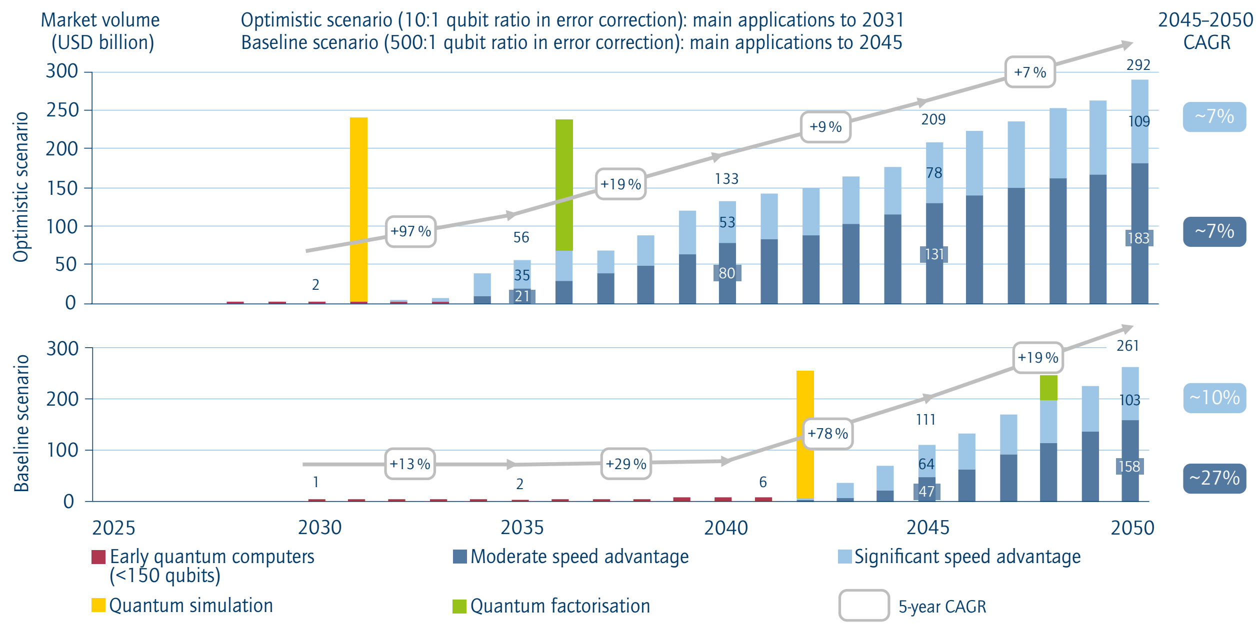


Figure 14: Projected trend in market potential for quantum computers (2025–2050) with baseline and optimistic scenarios (source: BCG 2018b)

In other studies, estimates for **short- to medium-term market development range** from **USD 0.5 billion in 2023** via **USD 5 to 10 billion** in the 2020 to 2025 period up to **USD 23 billion in 2025**.[144]

More conservative estimates assume that the long-term market potential for **quantum computing hardware will not exceed the current size of the market for supercomputers (USD 50 billion)** and that in the **foreseeable future** (the 2020s) the market for **NISQ quantum computers will amount to several hundred million US dollars**.[145] Another relevant benchmark could also be the global server market which was valued at USD 86 billion in 2018.[146]

The **possible increases in value creation** accruing to **users** by the use of quantum computers on the one hand thanks to **cost savings** and on the other hand due to **increased sales** are put at **USD 2 to 5 billion** in the next **3 to 5 years**, **USD 25 to 50 billion** in the next 10 years and **USD 450 to 850 billion** in the event of a completely error-corrected quantum computer being developed **(more than 20 years)**. Since the progress which can be achieved with quantum computers, for example in materials development, will take the form **not of gradual improvements but of leaps forward in quality**, **early adopters** will be able to secure a **market advantage**.[147]

One speculative study for the **pharmaceutical industry in the USA** considers that quantum simulations, quantum computer-assisted machine learning approaches and optimisation solutions will bring about improvements in the **selection of candidates** for drug development and in the **design of clinical studies**. As a result, it will be possible to develop **better medicines with a higher market share**. The anticipated **time savings** in development amount to **20 per cent** and it is assumed that **the approvals rate for the resultant medicines will double**. The calculated **total value creation from these improvements is stated to be USD 150 to 300 billion**. On the assumption that pharmaceutical companies are willing to invest 10 per cent of this total in the underlying quantum computing, the **market for this sector alone would be USD 15 to 30 billion**.[148]

144 | See Homeland Security Research 2017; Markets and Markets 2017; Market Media Research 2019; Persistence Market Research 2017.
145 | See Deloitte 2018.
146 | See Counterpoint Research.
147 | See BCG 2019.
148 | See BCG 2018b.

Value creation	Chemical development	Product development	Supply chain	Production	Marketing
Time horizon to implementation	Early killer application	Early killer application	Mature quantum computing	Potential early application	Mature quantum computing
Quantum computing approach used	▪ Quantum simulation ▪ Optimisation ▪ Quantum AI	▪ Quantum simulation ▪ Optimisation ▪ Quantum AI	▪ Optimisation	▪ Quantum simulation ▪ Optimisation ▪ Quantum AI	▪ Optimisation ▪ Quantum AI
Examples of future applications	▪ Development of molecules and solid materials having specific properties with reduced laboratory effort ▪ Use of computers to define the shape of proteins and produce improved active ingredients	▪ Discovery of improved formulations by modelling the effect of ingredients on processes or the behaviour of complex mixtures	▪ Use of quantum computers for cost-saving optimisation of supply chains and logistics	▪ Improvement of yield while reducing waste products through a better understanding of the reactions and discovery of novel catalysts ▪ Use of quantum algorithms to optimise complex processes in heat and mass transfer	▪ Use of quantum AI for improving B2B and B2C customer relations

Figure 15: Potential applications for quantum computers along the value chain in the chemicals industry (source: McKinsey & Company 2019)

Figure 15 shows how quantum computers might be used in **various links in the value chain in the chemicals industry**.[149]

Value chain

The **value chain** in quantum computing has **a number of levels** and extends from **hardware and control systems** via **software** to **services** (see Figure 16). The major technology companies are trying to cover the whole spectrum for consumers. Start-ups (with some exceptions such as Rigetti or D-Wave) tend to focus on individual links in the value chain or speciality applications.[150]

Experts assume that **quantum computing as a service**, as is for example already implemented by IBM, will predominate within the foreseeable future and only the tiniest minority of users will consider acquiring their own quantum computer.[151]

Some manufacturers are pursuing a **two-pronged approach**, firstly offering the highest performance variants of the quantum computer in **exclusive development agreements** in which the results and developments can be put to proprietary use. Secondly, they are also providing quantum computers in an **"open source" environment** which means that any developments benefit the whole community.

This will create user networks which will contribute significantly to the development of small **quantum computing ecosystems** which will firstly assist manufacturers with the **further development of quantum computers**, the system environment and the software and application layer and secondly, in the long term, be the **founder members of the customer base**.

In addition, many experts primarily see quantum computers acting as **co-processors in hybrid systems with conventional computers**. Their computing power will only be used for certain problems in which the quantum computer provides advantages.

Hardware production will therefore **remain more of a niche market in the medium term** and the **majority of the value creation** will occur in **software and services**.

The very high and continuously rising **levels of investment in international start-ups** covering not only software and services but also hardware reveal the high hopes being placed on the market potential of quantum computing (see Figure 16 and Appendix B).[152]

"When the technology arrives, you'll need quantum computing to be competitive."

149 | See McKinsey & Company 2019.
150 | See BCG 2018c.
151 | See IBM 2019b; IBM 2019.
152 | See BCG 2018c; Gibney 2019.

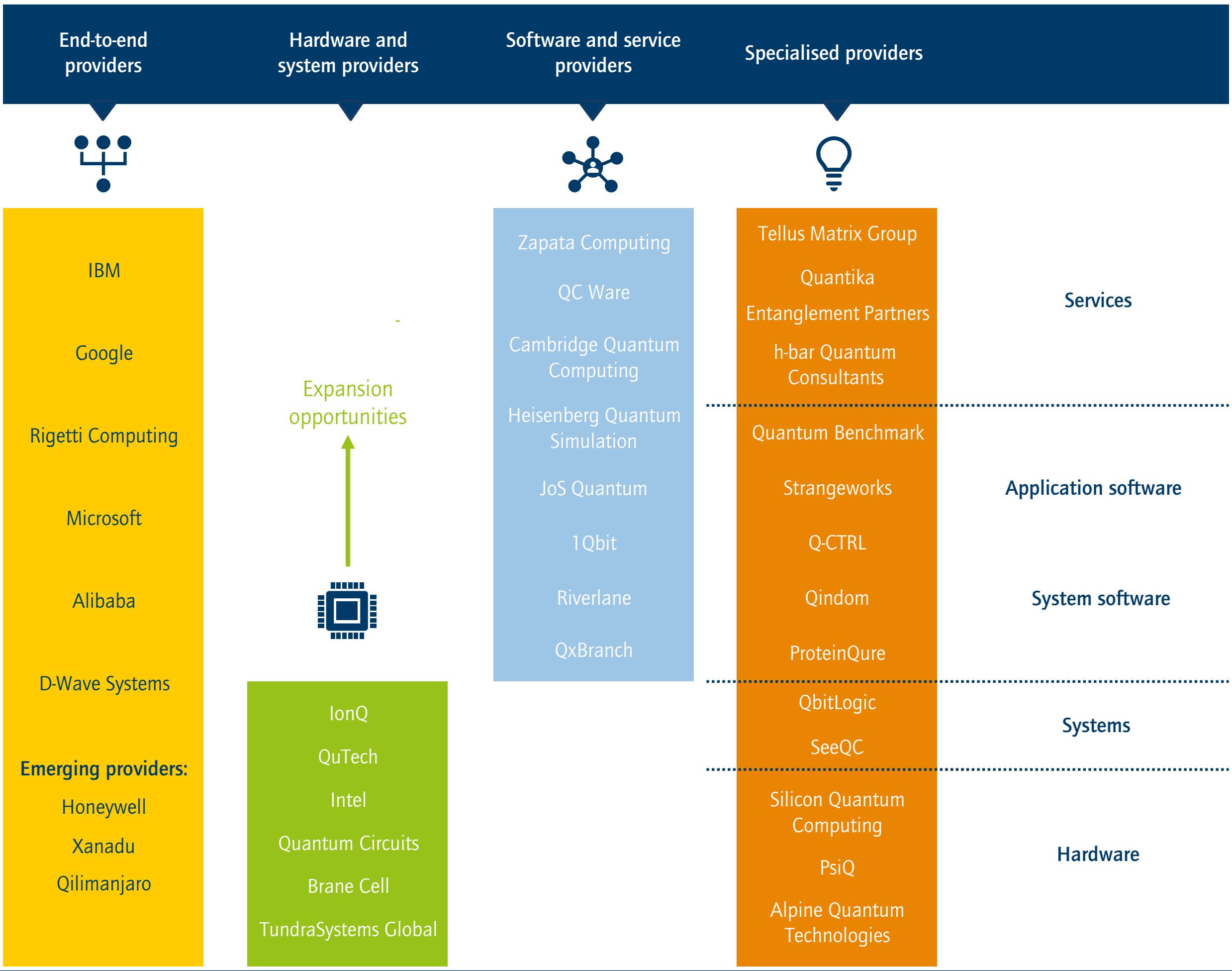


Figure 16: Value creation segments in the quantum computing ecosystem (source: own presentation based on BCG 2018c)

Germany so far only has a **small start-up community** (e.g. Heisenberg Quantum Simulations in Karlsruhe or JoS Quantum in Frankfurt). On the one hand, this is due to the generally **difficult conditions for start-ups** (shortage of capital, lack of entrepreneurial spirit) and, on the other, to the **absence of substantial activities to promote the development of quantum computing hardware** in Germany. If they are potentially to secure a share of the attractive software and service segment, German companies are therefore currently dependent on **collaborative efforts with foreign hardware manufacturers**.

On the user side, in Germany **major industrial corporations in various sectors** (e.g. BASF, Bayer, BMW, Bosch, Daimler, Merck, Volkswagen) have in recent years entered into **collaborative arrangements with technology companies** which are developing quantum computers or software applications.[153] While, due to the still limited performance of quantum computers, these collaborative projects are currently **providing little in the way of directly commercially usable results**, they are providing an important platform for gaining early **experience with this new technology**. In this way, the companies can **build up expertise** and so be ready for when the use of quantum computers will provide commercially usable benefits.

So far, **German companies remain in a poor position** to participate in **value creation in quantum computing**. If the challenges in the development of the quantum computer and corresponding applications are to be overcome and the **full potential** of the technology is to be achieved, **expertise must be developed in three areas**:

- hardware
- software and algorithms
- methodology for addressing problems and utilising results

153 | See BASF 2019; BMW 2019; Daimler 2018; Merck 2019; QuSoft 2019; Volkswagen AG 2017.

The **intensified efforts** in quantum computing in Germany, such as the quantum computing platform planned by the Fraunhofer-Gesellschaft and IBM, can make a contribution at least to the latter two points by providing **low-threshold, unbureaucratic access** for users and developers.

However, developing expertise in **quantum computing hardware** will require efforts which go above and beyond current and planned projects.

8.3 Technological sovereignty

Access to quantum computers will in future be central to Germany's and Europe's technological sovereignty. At present, Germany and Europe do not yet have the capacity to produce their own hardware.

Given quantum computing's potential for **significant competitive advantages** in **key German industries,** it is essential for Germany to obtain **as unrestricted access to this key technology as is possible**.

The current **dependency on foreign partners** due to the **absence of domestic hardware capacity** may therefore be a potential problem for German and European businesses. In times of **volatile trading relationships,** it is no longer possible to be categorically certain that European and thus also German companies will not be locked out from importing certain products and components. In the absence of its own capacity in quantum computing hardware, this would **jeopardise Europe's technological sovereignty** and its ability to participate in all of the value creation based on it, including in software and services.

Access to quantum computing applications via **cloud services**, most of which are run on **non-European servers**, is viewed as a **critical issue** by some experts since such access might possibly jeopardise the **protection** of the **intellectual property** of quantum computing software developers, of **commercial secrets** or of **personal data**.

The designs for a **European cloud service** ("Gaia-X") presented by the Federal Ministry for Economic Affairs and Energy and the Federal Ministry of Education and Research, which already include quantum computing as a possible application, might offer a solution here.[154] The planned reliance on compliance with European data protection directives in the collaborative project between IBM and the Fraunhofer-Gesellschaft also takes these concerns into account.[155]

154 | See BMWi/BMBF 2019.
155 | See Fraunhofer-Gesellschaft 2019b.

8.4 Profile of Germany's strengths and weaknesses and current opportunities and threats

The following is a specific overview of Germany's strengths and weaknesses as well as the opportunities and threats it faces in **quantum computing**. See section 3.3 for a general overview across the various technological fields of quantum technologies.

Strengths

- Many internationally leading researchers who are German/trained in Germany
- Internationally competitive basic research in all currently trialled technological platforms for quantum computing and in quantum information theory
- Interest in potential applications from leading German corporations (e.g. from the automotive, chemicals or pharmaceuticals industries and the financial sector)

Weaknesses

- No quantum computing hardware development in Germany
- No unhindered hardware access in alliances with foreign quantum computer manufacturers
- No investment by German businesses comparable with that by Google, IBM or Microsoft

Opportunities

- Pooling of existing expertise to create a German/European hardware basis
- Provision of a quantum computing platform publicly accessible to academia and business
- Development of expertise by alliances between German stakeholders and international trailblazers at institutions within Germany
- Lasting competitive advantages for first mover users
- Leading development of software and services thanks to vicinity to and close cooperation with potential users

Threats

- Loss of technological sovereignty in the absence of a German/European quantum computer
- Vulnerability of future quantum computing-based value chains due to jeopardised access to hardware basis, for example in the financial sector and in the chemicals, pharmaceuticals, logistics or automotive industries
- Disadvantages in software development in the absence of direct access to hardware
- Establishment of de facto standards in particular by major US corporations
- Migration of top talent

9 Quantum simulators

As "analogue quantum computers", quantum simulators can offer advantages similar to those provided by quantum computers for some problems, for instance in materials research, high-energy physics or chemistry and the development timeframe to commercially significant applications is thought to be distinctly shorter. German researchers are world leaders in this field. So far, no companies are dedicated to the development of commercial quantum simulators. This is a gap that German or European providers could fill.

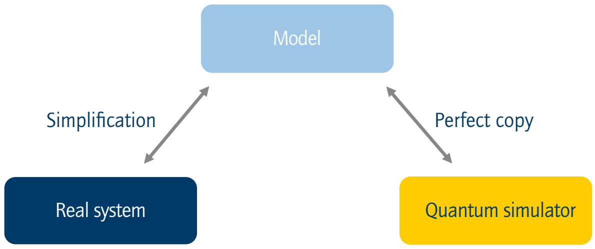


Figure 17: Schematic diagram of the principle of quantum simulation (source: own presentation based on DFG 2014)

Quantum simulators[156] **exploit quantum effects** to represent the behaviour of a quantum system which it is desired to predict using another quantum system which is easier to control and read out (see Figure 17). They may therefore be considered **"analogue" versions of quantum computers** (see section 8 for explanations regarding quantum computers), which however need to be specifically calibrated for each simulation task.[157] One **advantage over universal quantum computers** is that they are substantially **easier to produce** because a lower level of fine control is required over each individual component.

Another **approach in addition to quantum simulators and quantum computers** is what is known as a **quantum annealer**, which is offered for sale by suppliers including D-Wave from Canada. It has so far only been possible to put quantum annealers to practical use for one class of problems, **optimisation problems**. Within this class, however, they can be programmed for various questions, which distinguishes them from a pure quantum simulator (see also "Different approaches to the implementation of a quantum computer" on page 62). Experts **differ in their optimism** about the short- and medium-term **prospects for success** of this approach having any benefits in tackling economically significant questions.

In particular in **materials research and high-energy physics** (for instance in complex equations, synthesis of materials, superconductivity), there are a number of areas in which even supercomputers have weaknesses because computing the underlying quantum systems is too complex. Since, however, **quantum simulators** are subject to the **same laws** as the **systems to be investigated**, they can be used to address these specific physical and chemical questions.[158]

In the medium and long term, experts hope to use quantum simulations to make **breakthroughs** in **energy storage and distribution, drug and battery research** or **the development of new energy-saving catalysts** (see examples of application "Scenarios for the use of quantum simulators").

156 | The terms quantum simulation and quantum simulators are not used uniformly. The simulation of quantum computers or the qubits on which it is based with a conventional computer may also be used to develop algorithms and software applications for quantum computing. This is sometimes referred to as quantum simulation and the corresponding platforms as quantum simulators. Experts, however, prefer the term quantum computer emulator (see "Different approaches to the implementation of a quantum computer", page 67). In this section, the terms quantum simulation and quantum simulator are only used to refer to the simulation of quantum system by another quantum system (namely by an analogue quantum simulator or a quantum computer).

157 | See Feynman 1982; High-Level Steering Committee 2017.

158 | See Eisert et al., 2017; Bloch 2018.

Scenarios for the use of quantum simulators

CO_2 savings in fertiliser production: Due to the high energy inputs required, the manufacture of synthetic fertilisers is responsible for **two to three per cent of global CO_2 emissions**. The main reason for this is that the highly **energy-intensive Haber-Bosch process** has to be used for fixing the nitrogen for the fertilisers. It has so far not proven possible to develop **efficient catalysts** for this process using supercomputers due to the complexity of the underlying quantum characteristics of the materials. Quantum simulators promise **breakthroughs by accurately simulating the reaction characteristics** of potential candidate molecules such as ferredoxin. If results from quantum simulations could reduce the energy intensity of nitrogen fixation, this would be a major contribution to **reconciling food security with climate protection**.

Faster drug development: Developing new drugs is **time-consuming and costly** with development costs often running to several billion euro. At present, the **interactions of potential medicines with the target molecules** in the body can only be predicted to a limited extent using conventional supercomputers. From several thousand investigated molecules, only a few are ultimately actually considered as drugs. Quantum simulators can potentially better model the significant quantum-mechanical characteristics of the molecules, so **accelerating the selection of good candidate molecules** for clinical development. Any gain in efficiency in drug development will help to ensure that **more new drugs** can be developed, in particular also for previously untreatable or difficult to treat diseases, and delivered **to patients more quickly**.

It should, however, be borne in mind that these example applications can also be achieved with **quantum computers**.

9.1 Status of research and commercial application

The field of quantum simulations has seen spectacular developments in recent years with German research groups occupying a leading position internationally. Nevertheless, economically significant questions cannot yet be answered using today's quantum simulators. The key challenges facing further development are scaling up to larger quantum systems and, at the same time, simplifying operation.

Research in the quantum simulation field has developed rapidly over the last ten years and achieved **major progress**. This is also reflected by the huge **increase in scientific publications** in this area (see Figure 18).[159]

A **number of quantum simulator platforms** are currently in development which in part overlap with the basic concepts of various approaches to quantum computers:

- ultracold trapped ions
- ultracold atomic or molecular quantum gas in optical lattices
- systems of superconductive elements and resonators in the microwave range
- polaritons and photon condensates, for example in semiconductor nanostructures
- quantum dot networks
- photonic platforms of discrete optical elements or also photonic lattices and crystals

The various platforms have their **individual strengths and weaknesses** and differ for example with regard to size of the quantum systems they can simulate or the problem for which they are best suited.[160] Experts assume that, in the medium and long term, this **wide variety of platforms will endure due to their different application profiles** and that no single system will prevail.

Experiments with what are still very small-scale quantum simulators have **already demonstrated their fundamental applicability** to problems from the areas of **quantum magnetism** or **quantum chemistry**.[161]

159 | See Bornmann et al. 2019.
160 | See QUTEGA 2017.
161 | See Argüello-Luengo et al. 2018; Spektrum der Wissenschaft 2018.

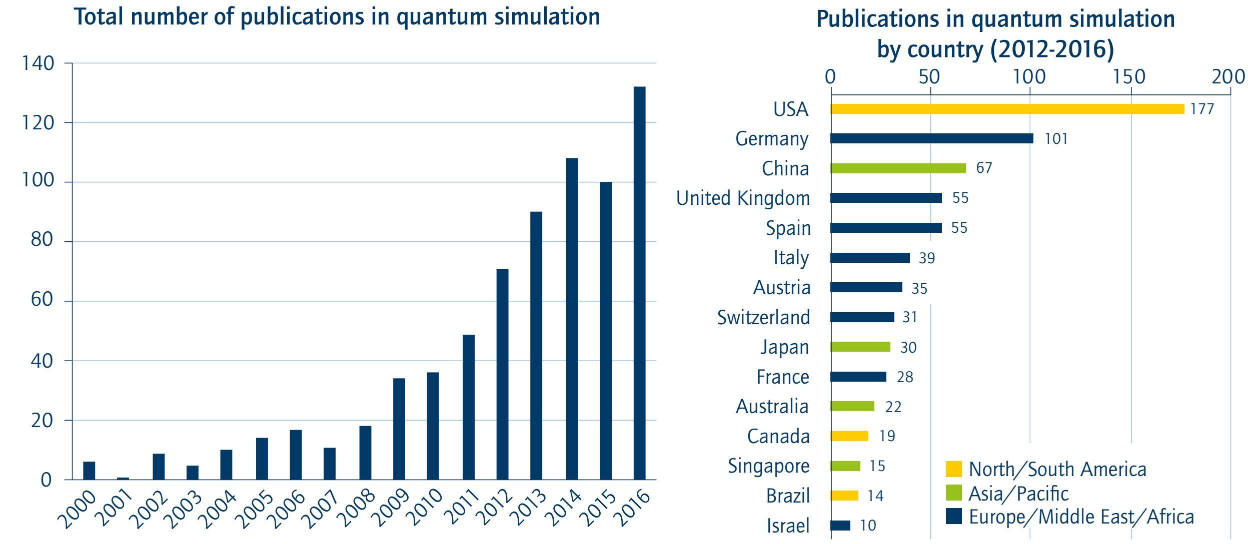


Figure 18: Number of publications in quantum simulation; overview by country only taking account of publications in the 2012–2016 period (source: Bornmann et al. 2019)

Germany's researchers are among the world's leaders in quantum simulations (see second position in publication ranking, Figure 18). **German institutes are accordingly also playing a leading role in EU Flagship projects** in quantum simulation. One example is PASQuanS (Programmable Atomic Large-Scale Quantum Simulation) which is led by the Max Planck Institute of Quantum Optics. Its aim is to increase the performance of currently existing quantum simulation platforms by a factor of ten to 50 and so achieve a "quantum advantage" (see section 8.1) in relevant questions.[162]

> *"Many of the questions which are central to the use of a quantum computer can also be answered with a quantum simulator. And much sooner too."*

Challenges

Quantum simulators are so far **still purely laboratory experiments** which are primarily used to address questions from basic research in physics. Before quantum simulations can actually be used to solve significant problems, **fine control and readability must be improved** and the **computing capacity** of quantum systems must also be expanded.

The **greatest engineering challenge** facing commercialisation is **simplifying usability**. At present, quantum simulators have to be **recalibrated** after every single simulation, a task which requires **considerable expertise**. In particular, using the quantum simulator to address **different questions** entails **complex hardware reconfiguration**. In addition, there is a need for work on **miniaturising** the necessary components if they are not only to be used in research laboratories.

Projects which are already under way, such as PASQuanS, can help to build these **bridges from proof of concept to proof of value** and engage potential users to identify appropriate use cases.[163]

A further challenge facing the use of quantum simulators is **verification** of whether a quantum simulation is providing **trustworthy results** when it is used for calculations beyond the capabilities of conventional supercomputers. Possible approaches to quantum mathematical verification and ultimately certification of a quantum simulator may for example be identified by **further developments in quantum theory**.[164]

There is also still a great need for further development in **suitable algorithms** for quantum simulation and **dovetailing with conventional computer systems**.[165]

162 | See MPQ 2018.
163 | See ibid.
164 | See QUTEGA 2017.
165 | See VDI Technologiezentrum GmbH 2017.

The EU Flagship's High Level Steering Committee estimates that within the **next three years** quantum simulators will, under laboratory conditions, be capable of solving **individual questions from physics** more effectively than supercomputers. Developing **quantum simulation prototypes in materials research**, on the other hand, is expected to take around **ten years**.[166] However, there is some divergence between the opinions of the surveyed experts. For instance, **some** of them expect **applications** in chemistry and materials research to materialise **distinctly sooner** but are sceptical when it comes to high-energy physics.

9.2 Market potential and value chains

Quantum simulators are thought to have major market potential because they promise breakthroughs in lucrative economic sectors which are of great significance to Germany. Quantum simulators might be commercially mature before quantum computers but will be in competition with them in the long term. There are as yet no manufacturers and no value chain for quantum simulators. German companies, including start-ups yet to be launched, could fill key positions here, for example offering quantum simulation as a service.

Since the quantum simulation field is still at an **early stage of development** and is a long way from commercial use, it is **difficult to make reliable statements about its market potential**.

Experts consider that **commercial applications are most likely in materials research**, for instance in chemicals, pharmaceuticals or automotive companies. This area is also thought to be a scenario for the use of quantum computers (see section 8). In relation to quantum computers, the estimates for the **economic value creation** possibly arising from **use in materials science and pharmaceutical research**, **range in an initial phase** (the next three to five years) between **USD 0.6 and 1.1 billion** annually.[167] Potential users might accordingly be willing to pay significant sums for the corresponding services and capabilities. Experts assume that **quantum simulators will be able to secure some of this market**, especially if they reach market maturity before quantum computers.

However, when **commercial quantum computers do become available**, there is a risk that the **market for quantum simulators** will relatively **quickly dry up**. Quantum computers are more highly versatile and can also address most problems which are processed by quantum simulators.[168]

Although quantum simulators have more limited fields of use than quantum computers, they still promise a **significant competitive advantage for industries** which are of **great importance in particular in Germany**. There are therefore considerable opportunities associated with the further development of quantum simulators and Germany possibly being established as a **leading market and supplier**.

Value chains

The potential value chain for quantum simulators looks very **similar to value chains for quantum computers** (see section 8.2). It requires the provision of **components**, often identical to those for quantum computers, as well as the **production and utilisation of the actual hardware**. A quantum simulator also requires a system and control element layer, albeit less complex than for quantum computers.

Furthermore, there is a need for **software applications,** such as algorithms and custom mathematical models, which also enable **coordination with conventional supercomputers**. This might be an opportunity for **start-ups**, which are already developing such services for quantum computers, to secure market share, as well as for specialised users focusing on quantum simulators to be established.

In a similar way to quantum computers, given the difficulty of operating quantum simulators, the first **business models** to be established might be **"as a service" models**.

The surveyed experts have not yet seen **any industrial activity** for the commercialisation of quantum simulators. **Filling these gaps** is an **attractive option for German companies and potential entrepreneurs** since Germany has both the relevant scientific know-how and a large number of significant potential users. Possible German suppliers are, however, exposed to competition from companies which are already working on the development of quantum computers and, thanks to their similar basic principles, could also relatively quickly develop their own quantum simulators.

166 | See High-Level Steering Committee 2017.
167 | See BCG 2019.
168 | See Preskill 2018.

"Germany combines the ideal conditions, namely the right minds and potential major industrial users, for quickly putting quantum simulators to use. So why is nobody doing it?"

The potential and applications of quantum simulators are still **a matter of debate within the academic community**. This is another reason why potential users are often **not yet aware** of the possibilities and are primarily focusing on quantum computers. Events, such as showcases or competitions, might be a way of bringing **developers and users closer together**. The respondents also assume that it is precisely **major chemicals and pharmaceuticals corporations** with their ongoing need for quantum simulations which will increasingly **develop internal capabilities** once they understand the associated potential.

9.3 Technological sovereignty

Since there are not yet any commercial suppliers of quantum simulator hardware, potential German or European suppliers are in a position to prevent strategic dependencies from occurring in the first place.

Unlike for quantum computers, there are not yet **any established companies** for quantum simulators who have already gained **a head start in development** by major spending. There is therefore a possibility that **German or European suppliers** will be able to drive the development and commercialisation of quantum simulators. In such a case, **possible problems of hardware access**, as are conceivable for quantum computers, would not develop.

Closer cooperation between European stakeholders, including beyond the EU Quantum Flagship PASQuanS project, with a clear aim of developing commercial applications may be a first step towards this.

9.4 Profile of Germany's strengths and weaknesses and current opportunities and threats

The following is a specific overview of Germany's strengths and weaknesses as well as the opportunities and threats it faces in **quantum simulators**. See section 3.3 for a general overview across the various technological fields of quantum technologies.

Strengths

- Numerous top researchers from Germany
- Extremely significant potential applications for leading German corporations (e.g. in the automotive, chemicals or pharmaceuticals industries)

Weaknesses

- No spin-offs or offerings from existing German businesses
- Little knowledge about potential applications among potential users

Opportunities

- No commercialisation activities even internationally: first mover advantage still achievable for German businesses and start-ups
- Competitive advantage from early use in many sectors which are important to Germany

Threats

- Possible obsolescence on implementation of quantum computing; time horizon unclear
- Quantum advantage not yet demonstrated for economically significant issues, time horizon likewise unclear
- Displacement of small specialised suppliers due to major corporate players in quantum computing jumping on the bandwagon as soon as quantum simulators become commercially worthwhile

Appendix

The following **glossary** is intended to explain **central technological terms in the current debate around first- and second-generation quantum technologies**. The glossary is based on definitions from a number of specialist literature sources and from official bodies.[169] Further information about quantum computing follows.

Appendix A: Quantum glossary

Ion trap: In ion traps, electrical and magnetic fields ensure that ions, i.e. electrically charged atoms or molecules, are confined. It is alternatively also possible to hold all the ions in storage in a trap and carry out mass-separated scanning of the stored ions by modifying the fields. Ion traps are one of the possible foundations for quantum computers.

Coherence: In physics, coherence refers to the wave property that, with the exception of a phase shift, wave deflection varies identically over time. One consequence of coherence is that stationary interference may be visible when waves are superimposed. In this context, the absence of a desired form of coherence is referred to as incoherence. The phenomenon which leads to incomplete or complete suppression of the coherence properties of quantum-mechanical states is known as decoherence.

NISQ: Expands to "**N**oisy **I**ntermediate-**S**cale **Q**uantum" and describes quantum computer-like devices of the current era which are still highly susceptible to interference and on which algorithms can only be used to a limited extent. A large proportion of their computing power therefore has to be used for error correction. They have applications in quantum simulation.

No-cloning theorem: This states that an unknown quantum state, thus including a qubit, cannot be perfectly copied or deleted. As a result, quantum information processing differs fundamentally from conventional information processing.

NV centre: Expands to "**N**itrogen-**V**acancy centre in diamond". This is one of the leading candidates for use as a nanoscale magnetic field sensor in medicine or as an emitter in a single-photon source at room temperature. Possible applications are, for example, in quantum computer systems and quantum cryptography.

Quantum: The smallest amount by which certain quantities (such as energy) in a quantum system can change. Max Planck and Albert Einstein, for example, showed that light only occurs in packets known as photons.

Qubit: The usual abbreviation for quantum bit, the fundamental unit of information of a quantum computer. Conventional computers are based on the bit which can adopt exactly two states (0 or 1). However, a qubit, for example produced from an atom or photon, can adopt a not only a state of 0 and 1 but simultaneously any state which is a vector of the amount 1, i.e. a superposition.

Spin: This describes the intrinsic angular momentum of particles. Like mass, spin is an immutable internal property of fundamental particles. Measurement of the change in spin states forms the basis for quantum sensor and quantum metrology applications.

SQUID: Expands to **S**uperconducting **QU**antum **I**nterference **D**evice. A SQUID is a sensor, for example used in medicine, with which very precise measurements of extremely small magnetic field variations can be measured.

Superconductor: Superconductors are materials whose electrical resistance (abruptly) drops to zero when they reach a specific, very low temperature known as the transition temperature. Superconductivity, a macroscopic quantum state, was discovered in 1911 by Heike Kamerlingh Onnes. Superconductivity is used for generating strong magnetic fields, for example for particle accelerators, nuclear fusion reactors, magnetic resonance imaging, as well as for metrology and energy technology. Superconductors are also one of the possible foundations for quantum computers. Research projects are currently under way into room-temperature superconductors which would allow them to be used without cooling.

Wave-particle duality: Depending on the question asked, in quantum physics entities may equally have the fundamental characteristics of classical waves and of classical particles. Light is one example of this. On the one hand, it appears to consist of individual particles (photons) whose energy can be determined. On the other hand, the double-slit experiment demonstrates that two beams of light can amplify or quench one another. This phenomenon can only be explained by the wave character of light.

169 See Bruß 2003; Grumbling/Horowitz 2019; Krupansky 2018; Nationale Akademie der Wissenschaften Leopoldina et al. 2015.

Appendix B: Investment in quantum computing start-ups

Figure 19 is a summary table of successfully completed financing rounds for quantum computing start-ups up to and including mid-2018.[170] This means that the most recently completed funding rounds, for example of IQM (a Finnish hardware start-up) and Heisenberg Quantum Simulations (German quantum algorithm developer) have not been taken into account.[171]

Start-up	Country	Amount (USD million)	Latest funding	
D-Wave Systems	Canada	205	1 June 2018	USD 10.15 million by the Canadian government
Rigetti Computing	USA	119	28 March 2017	USD 40 million in Series B funding round
PsiQ	USA	65	–	–
Silicon Quantum Computing	Australia	60	August 2017	AUD 83 million venture capital by: Government of New South Wales (AUD 9 million), University of New South Wales (AUD 25 million), Commonwealth Bank of Australia (AUD 14 million), Telstra (AUD 10 million over two years), Government of Australia (AUD 25 million over five years)
Cambridge Quantum Computing	United Kingdom	50	26 August 2015	USD 50 million USD development capital
1QBit	Canada	35	28 November 2017	CAD 45 million development capital in Series B funding
IonQ	USA	22	24 February 2017	USD 20 million in Series B funding
Quantum Circuits	USA	18	13 November 2017	USD 18 million in Series A funding
Alpine Quantum Computing	Austria	12	8 February 2018	EUR 10 million funding
QC Ware	USA	8	5 July 2018	USD 7 million in Series A funding
Optalysys	United Kingdom	8	21 September 2017	GBP 3 million seed funding
Nextremer	Japan	5	8 August 2017	JPY 500 million venture capital
Oxford Quantum Circuits	United Kingdom	3	8 September 2017	GBP 2 million venture capital

Figure 19: Investment in quantum computing start-ups (source: BCG 2018c)

170 | See BCG 2018c.
171 | See High-Tech Gründerfonds 2019; IQM 2019.

Appendix C: Approaches to the implementation of a quantum computer

Figure 20 provides an overview of the options for implementing a quantum computer and summarises the mode of operation, current situation, existing barriers, main international players and research groups active in Germany.

	Superconductive qubits	Ion trap qubits	Topological qubits	Semiconductor spin qubits
Basic principle	Microwave circuits which embed a Josephson junction	Electromagnetic field which entraps ions	Specialised topological space for qubits using e.g. Majorana particles	Nanoscale devices which capture electrons and use spin as a qubit
Current status	Most mature and the basis of commercially usable systems	Medium-sized systems have been implemented	Particles observed, major investment, but first qubit yet to be built	Two qubit algorithms implemented
Barriers	Scalability due to susceptibility to interference	Manufacturing technology for qubits	Proof of concept for functioning qubits	Uniformity of qubits
Main international players*	Research institutes, IBM, Intel, Google, QuTech, Rigetti, QDev	Research institutes, IonQ, Alpine QT, Quantum Factory	Research institutes, Microsoft, QuTech, Nokia, Bell Labs	Research institutes, Intel, QuTech
German research groups*	Karlsruhe Institute of Technology, Walther-Meißner-Institute (Munich), Institute for Photonic Technologies (Jena)	University of Mainz, University of Siegen	University of Cologne	Forschungszentrum Jülich/RWTH Aachen, Technical University of Munich, Karlsruhe Institute of Technology

*Lists not exhaustive

Figure 20: Overview of different approaches to the implementation of a quantum computer (source: own presentation based on Birch 2018)

Appendix D: List of figures

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The quantum computer is merely the best known example of a whole series of conceivable innovative applications for putting quantum-mechanical effects to controlled use. Apart from permitting the design of tap-proof communication channels or novel simulation methods which might be used in materials development, insights from quantum physics could enable quantum sensors which, embedded in medical devices, would allow patients to benefit from more accurate and simultaneously less intrusive investigations. Successfully developing this and further second-generation quantum technologies will require close, long-term collaboration between researchers and businesses. If such an effective quantum technology ecosystem were to be successfully developed in Germany, it would make a major contribution to securing the country's technological sovereignty.

This acatech IMPULSE paper summarises the most important scientific and economic trends in relation to second-generation quantum technologies and provides an overview of the associated innovation potential and challenges for Germany and elsewhere.