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Executive summary

The innovation potential of second-generation quantum technologies

Henning Kagermann, Florian Süssenguth, Jorg Körner, Annka Liepold

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 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 "Germany's current position").

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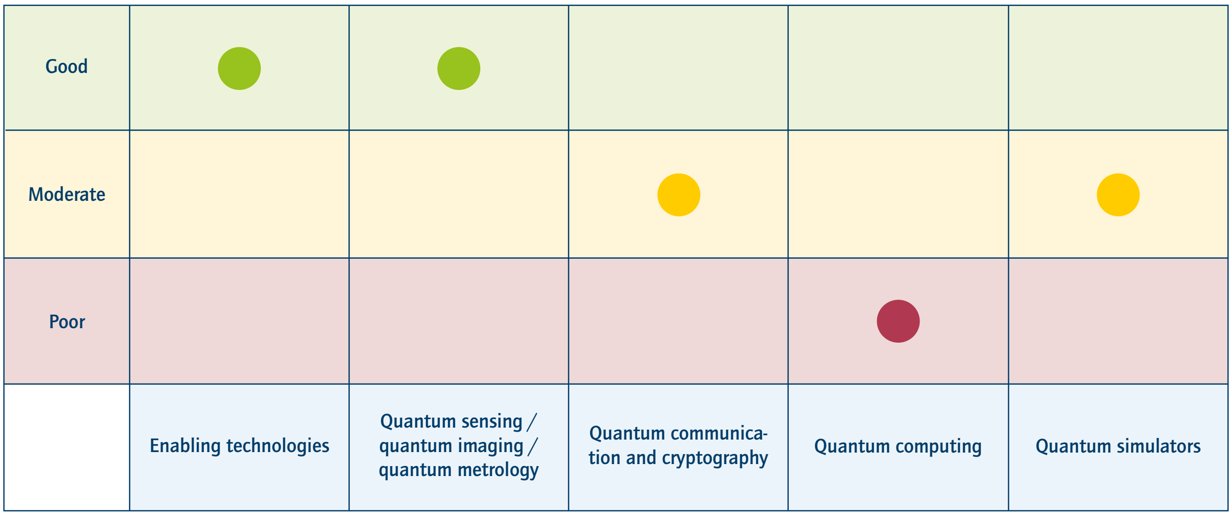

Germany's current position in the commercialisation of quantum technologies compared to other countries (source: own presentation)

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 at many of these sites and could be mobilised to this end.

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 post-doctoral 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 developing 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.

Second-generation quantum technologies

Overall profile of Germany's strengths and weaknesses

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

Enabling technologies

Profile of Germany's strengths and weaknesses

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)

Quantum sensing, quantum imaging and quantum metrology

Profile of Germany's strengths and weaknesses

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

Quantum communication and quantum cryptography

Profile of Germany's strengths and weaknesses

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)

Quantum computing

Profile of Germany's strengths and weaknesses

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

Quantum simulators

Profile of Germany's strengths and weaknesses

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

acatech IMPULSE The innovation potential of second-generation quantum technologies

The acatech IMPULSE paper on the innovation potential of second-generation quantum technologies is based on an evaluation of current specialist literature and interviews with 95 experts from academia and business. The interviews were conducted between June and October 2019. The aim was to obtain a current snapshot of the mood in quantum technologies in both academia and business. Interviewees were firstly asked about the most important trends in significant fields of research and their transformation into practical innovation and secondly about their opinion of the attractiveness of Germany as a location for research and the maturity of its quantum technology ecosystem as well as the status of global developments in individual fields of quantum technology. Finally, interviewees were asked what measures might best release the innovation potential of second-generation quantum technologies.

Overall supervision

- Prof. Dr. Henning Kagermann, Chair of the acatech Board of Trustees

Content collaboration

- Dr. Reinhard Ploss, Infineon Technologies AG
- Prof. Dr. Martin Stratmann, Max Planck Society

Content support and review

- Prof. Dr. Dr. Andreas Barner, Stifterverband für die Deutsche Wissenschaft
- Dr. Martin Brudermüller, BASF SE
- Gabi Grützner, micro resist technology GmbH
- Prof. Dr. Jörg Hacker, German National Academy of Sciences Leopoldina
- Prof. Dietmar Harhoff, Ph. D., Max Planck Institute for Innovation and Competition
- Reiner Hoffmann, German Trade Union Confederation
- Dr. Marion Jung, ChromoTek GmbH
- Prof. Dr. Anke Kaysser-Pyzalla, Technical University of Braunschweig
- Prof. Dr. Renate Köcher, Institut für Demoskopie Allensbach
- Harald Krüger, BMW AG
- Prof. Dr. Reimund Neugebauer, Fraunhofer-Gesellschaft
- Prof. Dr. Günther Schuh, e.GO Mobile AG
- Stefan Vilsmeier, Brainlab AG
- Dr. Anna-Katharina Wittenstein, Wittenstein SE

Editorial collaboration

- Dr. Christoph Ettl, Max Planck Society
- Dr. Tim Gutheit, Infineon Technologies AG

Concept, text and interviews

- Florian Süssenguth, acatech Office
- Dr. Jorg Körner, acatech Office
- Dr. Annka Liepold, acatech Office

Assisted by

- Dr. Patrick Pfister, acatech Office
- Jan Fischer, acatech Office
- Stefan John, acatech Office
- Silke Liebscher, acatech Office
- Elisabeth Paul, acatech Office

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Authors:
Prof. Dr. Henning Kagermann, Chair of the acatech Board of Trustees
Florian Süssenguth, acatech Office
Dr. Jorg Körner, acatech Office
Dr. Annka Liepold, acatech Office

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Munich Office
Karolinenplatz 4
80333 Munich (Germany)
T +49 (0)89/52 03 09-0
F +49 (0)89/52 03 09-900

Berlin Office
Pariser Platz 4a
10117 Berlin (Germany)
T +49 (0)30/2 06 30 96-0
F +49 (0)30/2 06 30 96-11

Brussels Office
Rue d'Egmont/Egmontstraat 13
1000 Brussels (Belgium)
T +32 (0)2/2 13 81-80
F +32 (0)2/2 13 81-89

www.acatech.de
info@acatech.de

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