Quantum^BW

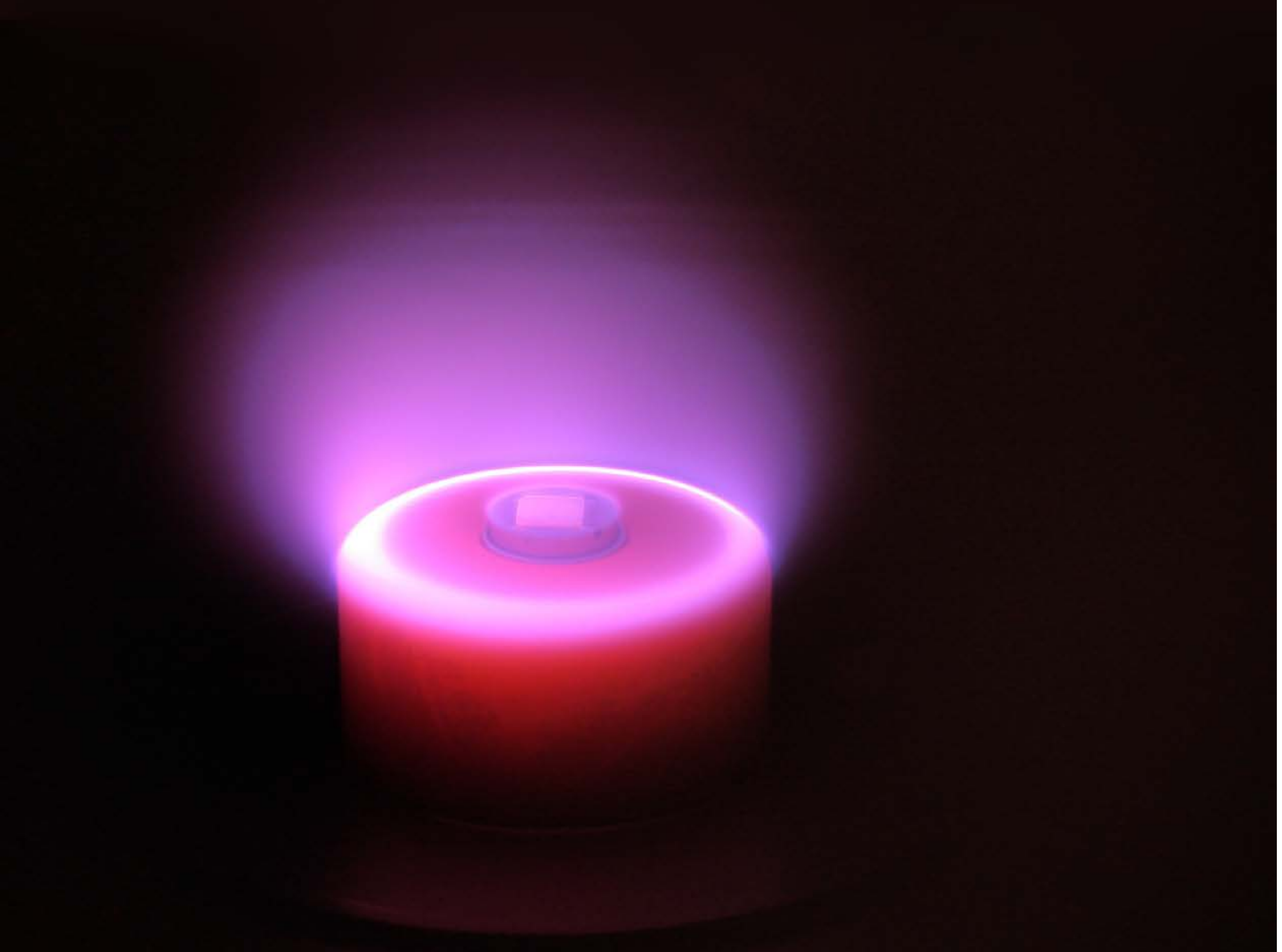
WHERE POSSIBILITY becomes reality

Quantum Strategy Baden-Württemberg

Part of THE LÄND

Quantum[BW]

THE LÄND of quantum technology



To help shape the quantum revolution, Quantum[BW] is pooling the unique scientific and economic expertise available in Europe's no. 1 region for innovation – THE LÄND.

Together we are promoting the transfer of the insights gained in quantum technology research to actual applications in order to improve various areas of life and have a disruptive impact on markets.

The Quantum Technology Alliance Baden-Württemberg is an initiative that has been set up to promote quantum technology in THE LÄND – Germany's federal state of Baden-Württemberg.
Quantum[BW] comprises leading research institutions and business enterprises at various locations around the state that are combining forces to drive forward research and development work in the fields of quantum sensor technology and quantum computing, areas of crucial importance for the future.

The Quantum[BW] Office, which coordinates the activities of this innovation initiative and is the first port of call, is managed by the Center for Integrated Quantum Science and Technology (IQST) of the universities of Stuttgart and Ulm, together with the institutes Fraunhofer IAF and Fraunhofer IAO. It is jointly funded by Baden-Württemberg's Ministry of Science, Research and Arts and its Ministry of Economic Affairs, Labour and Tourism.

Baden-Württemberg
MINISTRY OF SCIENCE, RESEARCH AND ARTS

Baden-Württemberg
MINISTRY OF ECONOMIC AFFAIRS, LABOUR AND TOURISM

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01 EXECUTIVE SUMMARY

Quantum technologies are among the key technologies of the 21st century. The transfer of the compelling properties and influences of the quantum world to technological applications will improve our lives in many areas and disruptively change numerous markets.

Baden-Württemberg is in an excellent position to help shape and benefit from the upcoming quantum revolution. Thanks to networks of excellence in quantum science already established at universities and non-university research institutions, as well as high-tech companies and start-ups, our state is predestined to play crucial roles in national and European initiatives in quantum technologies, to develop successful and profitable products and services, and to conquer the emerging markets for quantum technologies.

At the same time, bold, decisive and coordinated action is necessary to expand this prime position in research and especially in new business fields. Only if science, business and politics all pull together will we be successful in the tough international competition for ideas, minds, markets and investments and in leveraging the great innovation and value-creation potentials of quantum technologies in Baden-Württemberg.

Quantum^{BW} is an initiative in which leading research institutions and enterprises in our state are joining forces to strategically develop Baden-Württemberg as a science and business hub for quantum technologies and to grow its international visibility as a quantum centre. As a long-term and innovative framework, Quantum^{BW} will promote even closer networking and pooling of expertise among the players along the entire innovation and value chain.

Within this framework, we will build on coherent, results-oriented technology roadmaps and prioritize measures that

→ strengthen and accelerate innovations in the field of quantum technologies through application-oriented, collaborative research and development projects;
→ create and expand productive infrastructures for collaboration between science, business and investors;
→ promote the training and qualification of specialists, junior staff and trainees in science and business and create local conditions that will attract top talent;
→ support a vibrant entrepreneurial environment that encourages start-ups from within the scientific and business communities and promotes investment.

Particularly in the areas of quantum sensor technology, quantum computing and quantum networks, and the necessary enabling technologies in which our state already has a strong presence, these measures will enable us to achieve a critical mass that will pave the way for new ideas and lay the foundation for the evolution of a powerful ecosystem — an ecosystem that offers researchers, established companies and start-ups the necessary conditions and freedom to conduct research in cooperation with other disciplines and players, develop strategies and solutions, and create new markets with innovative products and services.

02

QUANTUM TECHNOLOGY

in Baden-Württemberg

Potentials, status quo and key challenges

Quantum technologies — which are based on the ability to generate and control quantum mechanical effects in a targeted manner — facilitate innovations and applications that can make our lives faster, easier or safer in a wide variety of areas.

Since quanta react extremely sensitively to environmental influences, quantum sensors are capable of achieving unprecedented levels of sensitivity and accuracy or even of capturing new measurement parameters. In the field of medical diagnostics, for example, this opens up new possibilities for early and more precise detection of numerous metabolic diseases. Other applications include positioning/tracking and navigation systems, the measurement of gravitational or magnetic fields and the development of new types of temperature and pressure sensor.

Quantum computers — in combination with supercomputers, too — have the potential to solve certain tasks and complex optimization problems at enormous speed. For example, they possess the ability to take the modelling and development of new materials or active medical ingredients to a new level. Like quantum sensor technology, they contribute to important developments and innovation leaps in the key future fields of health, mobility, climate protection and sustainability.

Even though the quantum technologies described are still at an early stage on their journey from research to the market, they are gaining enormous relevance as disruptive technologies that can change markets from the ground up. Around the globe, initiatives and ecosystems are emerging from research projects and applications in which manufacturers, component suppliers and service providers are collaborating along the value chain.

The quantum computing segment in particular is predicted to have huge market and value-creation potential. Market assessments can be relied on to only a limited degree due to the early stage of development, but they forecast the emergence of a global market worth USD450 to 850 billion within the next 15 to 30 years[1].

In contrast to quantum computing, the availability of robust sensors for widespread industrial use is already on the horizon, potentially within the next three to five years. Initial estimates for the quantum sensor market amount to USD1.3 billion in 2023 and anticipate it will grow to USD2.2 billion by 2028[2].

[1] Source: Federal Ministry of Education and Research (BMBF) “Forschungsprogramm Quantensysteme” (German only)
[2] Source: acatech - “The Innovation Potential of Second-generation Quantum Technologies”

2.1 Quantum Technology Ecosystem Baden-Württemberg

As a leading centre of science, business and innovation in Germany and Europe, Baden-Württemberg offers ideal conditions for leveraging the potentials of quantum technologies with the emergence of a powerful quantum industry. Our state has a diverse and excellent research landscape at universities and non-university research institutions, as well as numerous industrial champions and highly innovative high-tech start-ups. The already successful combination of outstanding basic research with practical experience and successes in the development, integration, commercialisation and application of quantum systems is a great strength of Baden-Württemberg.

Alliance partners

Corporations

Balluff GmbH
Carl Zeiss AG
HQS Quantum Simulations GmbH
IBM Deutschland GmbH
Kipu Quantum GmbH
Mercedes-Benz Group AG
NVision Imaging Technologies GmbH
Q.ANT GmbH
Quantum Brilliance GmbH
Robert Bosch GmbH
Tesat-Spacecom GmbH & Co.KG
TRUMPF SE + Co. KG

Universities and Institutions

Baden-Württemberg Cooperative State University (DHBW)
Baden-Württemberg International
Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
German Aerospace Center (DLR)
Heidelberg University
Karlsruhe Institute of Technology (KIT)
Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V.
Technoseum Mannheim
Ulm University
University of Freiburg
University of Konstanz
University of Stuttgart
University of Tübingen

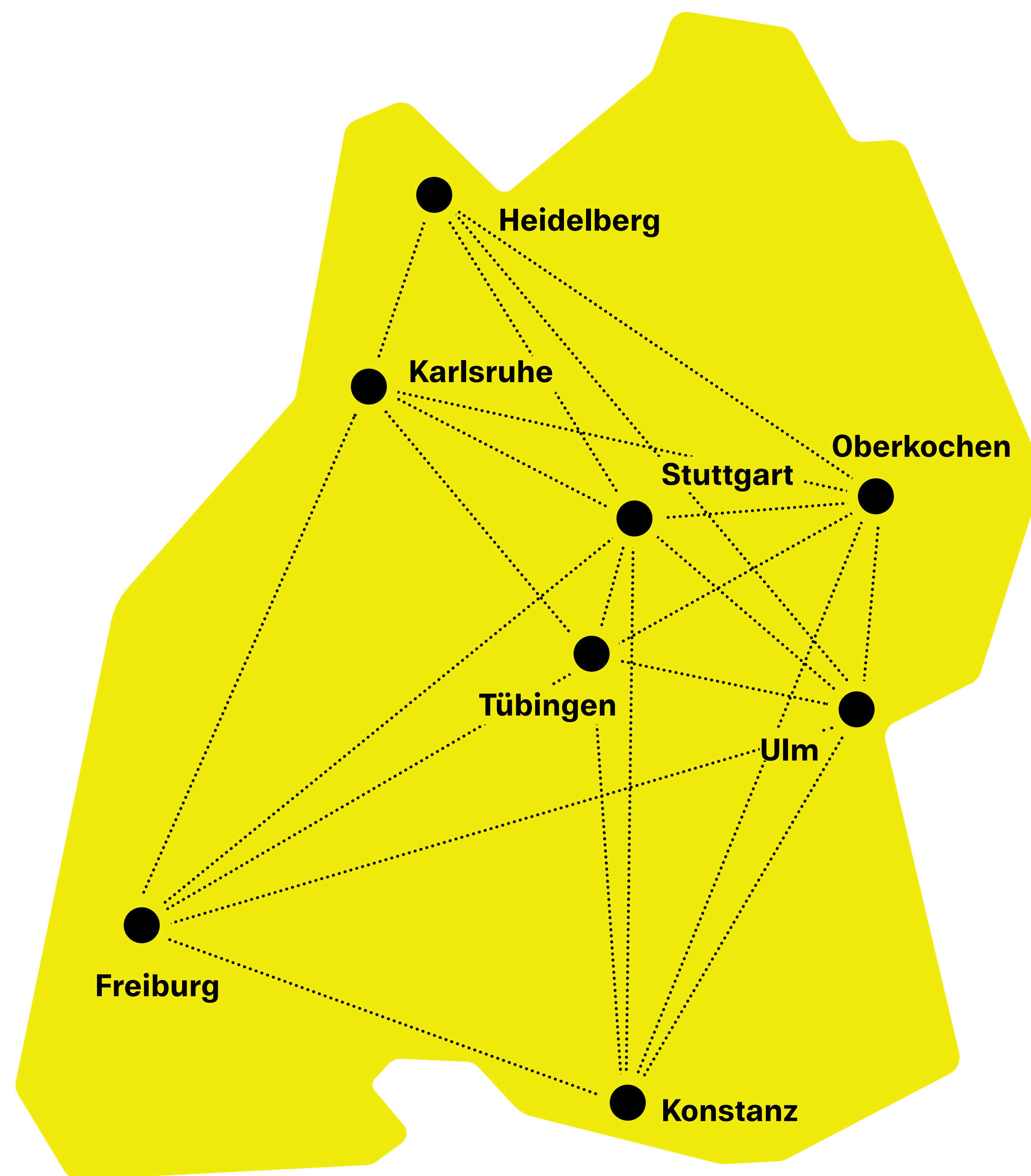


Figure 1:
Alliance partners in the Quantum[BW] network

2.1 Quantum Technology Ecosystem Baden-Württemberg

Among the flagship initiatives with a supra-regional lighthouse character that have already been or are being funded by the state — in many cases together with the federal government — are, for example, the Center for Integrated Quantum Science and Technology (IQST) based in Ulm and Stuttgart, the Competence Center Quantum Computing Baden-Württemberg (KQCBW) and the future cluster “QSens — Quantum Sensors of the Future” (part of the Clusters4Future initiative). These joint research projects meld basic and applied research in the field of quantum technology across the various locations and foster the exchange of knowledge with high-tech companies in THE LÄND. Since 2019, the state has invested over EUR115 million in projects and infrastructure measures that support the development and expansion of this unique excellence.

At the same time, the scientists and network partners involved in Baden-Württemberg play an extremely successful role in many nationally and EU-funded joint projects thanks to their outstanding international expertise. In addition to funding from the state, over EUR480 million in third-party funding from the federal government and the EU has been raised over the past ten years for university and non-university quantum science research in Baden-Württemberg.

Besides its strength in basic and application-oriented research in the fields of quantum sensor technology and quantum computing, Baden-Württemberg finds itself in an excellent starting position regarding the development of the underlying quantum enabling technologies. All fields of application of quantum technologies are based on these basic technology components, such as specialized laser and photon sources or semi- and superconducting special materials. They are a key prerequisite to enable quantum technology innovations to find their way out of laboratories and clean rooms into real-life products and applications. Fields that are particularly relevant in this context are microelectronics, photonics and packaging technology, in which Baden-Württemberg’s high-tech ecosystem is strongly positioned. In respect of quantum computing, the development of algorithms, software and associated services also plays a crucial role in the widespread implementation of quantum technology applications. For most companies, the focus, at least in the long term, will not be on building a quantum computer, but on developing quantum-based company-specific software solutions and algorithms that can then run on external quantum computing capacities. Here, too, Baden-Württemberg can profit from extensive expertise in the field of academic research as well as from global players in this area. Furthermore, major synergies are expected between quantum computing, classic high-performance computing (HPC) and machine learning that can be optimally developed by an excellent network of supercomputing centres in THE LÄND and Cyber Valley — as an international hotspot for artificial intelligence — and then exploited.

These regional strengths must be resolutely reinforced, so that Baden-Württemberg continues to be a driving force in shaping dynamic developments in quantum technologies.

2.2 Strategic Objectives and Fields of Action of Quantum^{BW}

The intensity with which the various quantum technologies are being researched and implemented in Baden-Württemberg varies. Particular strengths lie in quantum sensor technology and in the development of hardware for quantum computing. THE LÄND is superbly positioned as regards basic research and is a global leader in many areas. A key challenge is to transfer this broad expertise to applied science and concrete technological innovations for industry. While this is still in its infancy in the field of quantum computing, the prospects for quantum sensor technology in the state successfully embracing the entire value chain, from potential users to manufacturers of key enabling technologies, and translating research results into concrete applications and products are already good.

Innovative companies and start-ups in Baden-Württemberg are already actively pioneering the industrialization and commercialization of quantum sensors on a huge scale. Our companies and institutions are leaders in this area, a position we want to expand further. Quantum computing will have a considerable impact on the business models of many of our global companies and hidden champions. And science and industry have a decisive role to play in successfully launching the commercial use of quantum computers and adapted software solutions.

As part of the Quantum^{BW} innovation initiative, we want to ensure that Baden-Württemberg continues to play a leading role in value creation with new quantum solutions. Building on the strengths of our universities and research institutions as important drivers of new technological innovations, companies and start-ups from THE LÄND are to operate as key providers and users in the global market for quantum solutions.

Representatives of leading quantum research institutions and enterprises have come together behind this common goal and, in a broad-based exchange and coordination process, have identified key spheres of action for a strategy to further develop Baden-Württemberg as a quantum technology hub. At the heart of this is the alignment of research and development work with quantum technology roadmaps that are based on existing strengths, as well as a clear focus on the transfer of research findings to applications and R&D projects conducted jointly by science and industry. The roadmaps take up the fields of action and concretize them. The resulting intertwined network of scientific institutions and businesses forms the nucleus for the long-term development of a new innovation campus for quantum technologies, in which innovative collaborative frameworks and spaces in which science and industry can interact as mutual drivers are sustainably anchored.

2.2.1 Field of Action No. 1: Networking and visibility

The development of quantum technologies is a highly competitive field of research that requires strong cross-institutional and interdisciplinary networks in order to be competitive in the global market. The pooling of expertise, the scientific discourse across disciplines and the broadest possible utilization of complex infrastructures promise great value added for Baden-Württemberg and are to be purposefully promoted within the framework of Quantum^{BW}.

At the heart of these activities will be the Quantum^{BW} Office that will serve as the central point of contact, pool and process information about the quantum ecosystem in Baden-Württemberg, coordinate the implementation measures of the quantum strategy as well as for continuing development of the roadmaps, and proactively promote networking between the various locations.

The Qunatum^{BW} Office will also represent Baden-Württemberg to the outside world as a quantum technology hub and help to make Baden-Württemberg's quantum ecosystem and existing expertise more visible under the Quantum^{BW} umbrella.

It will act as a node working in close cooperation with existing organisational structures in order to maximize synergies while avoiding the creation of duplicate structures.

2.2 Strategic Objectives and Fields of Action of Quantum^BW

2.2.2 Field of Action No. 2: Collaboration projects

Collaboration between research institutions and businesses in dealing with specific application-relevant scientific issues is crucial when it comes to translating research results into concrete applications and establishing sustainable innovation-driven partnerships. To facilitate this, Quantum^BW will create a framework designed to provide flexible support for pre-competition, application-oriented research projects and application-relevant proofs of concept for initial assessment of a technology's potential. In contrast to purely knowledge-oriented basic research, these begin at the point where fundamental findings have already been described and from which potential for a technical application can be derived. The defining characteristic of such projects must be that the partners from university, non-university and industry research departments work hand in hand and their activities are aligned with Baden-Württemberg's technology roadmaps. The focus on our current strengths in quantum sensor technology as well as hardware and software development in quantum computing is to be sharpened. These strengths are to be developed further with regard to specific issues and problem solutions with a view to fulfilling the needs of industry and the markets.

2.2.3 Field of Action No. 3: Infrastructure

The research, development and validation of quantum technologies requires complex and capital-intensive infrastructures, such as clean- and grey-room capacities or specialized research laboratories. For start-ups and smaller companies in particular, this is a major obstacle to the rapid transfer of ideas. Consequently, low-threshold and uncomplicated access to research equipment, production, testing and validation environments represents significant value added for academic and industrial players, especially with respect to basic components and quantum sensor technology. Within the framework of Quantum^BW, models for shared, more efficient utilization of the existing building and equipment infrastructures available in the state are to be established on the basis of a comprehensive appraisal, and these infrastructures are to be specifically supplemented and expanded based on the technology roadmaps.
One focus is on the infrastructure for quantum enabling technologies, which currently represent a significant bottleneck when it comes to high-volume industrial use of quantum systems. The technology roadmaps distinguish between the R&D infrastructure required and an infrastructure necessary for manufacturing both small and high-volume series of quantum components and systems.

2.2.4 Field of Action No. 4: Education, training, CPD and spin-offs

A field as scientifically and technologically complex as that of quantum technologies requires well-trained personnel with specific skills, both in science and industry. Quantum^BW will therefore also establish itself as a platform for the coordinated development, promotion and retention of specialists for science and industry and develop concepts for the sustainable promotion of talent by interlinking excellent university teaching and business practice.

An excellent and at the same time standardized education, training and CPD landscape in Baden-Württemberg in the field of quantum technologies is an essential building block to achieve a sustainable quantum ecosystem and the first link in a successful value chain in quantum technologies.

In particular, the creation of uniform, state-wide standards for university education at bachelor's and master's level, and for doctorates, too, offers the opportunity to train highly qualified quantum specialists as a sustainable resource for the local economy. This can be further supported by deliberately addressing young talent, from school pupils and students to outstanding up-and-coming scientists. Existing curricula and graduate programs at Baden-Württemberg's universities can serve as a starting point for establishing a state-wide education and training network.
The corresponding standardization and networking activities will be backed within the framework of Quantum^{BW}.

Likewise, the set up of new professorships or junior research groups specializing in quantum technology engineering and possibly, in the future, in computer science, too, holds the potential to build bridges between the various disciplines.

With regard to continuing professional development, the future cluster QSens and the Competence Center Quantum Computing Baden-Württemberg already have relevant programs in place. The aim must therefore be to bundle these activities in order to gain maximum benefit. Here too, the Quantum^{BW} Office will play an important role as a central point of contact for interested parties.

Through integration and possible targeted expansion of existing support formats and incubators, these initiatives aim to promote science-driven spin-off activities and to inspire young talent to implement innovative ideas in entrepreneurial independence.

Guided by the framework of these four fields of action for the promotion of quantum technologies in Baden-Württemberg and the targets formulated in the technology roadmaps, the committees within the governing body of Quantum^{BW} — the Executive Board, supported by the Advisory Board and the Office — will prioritize and shape concrete implementation steps and measures in a timely manner.

Pooling activities for maximum benefit

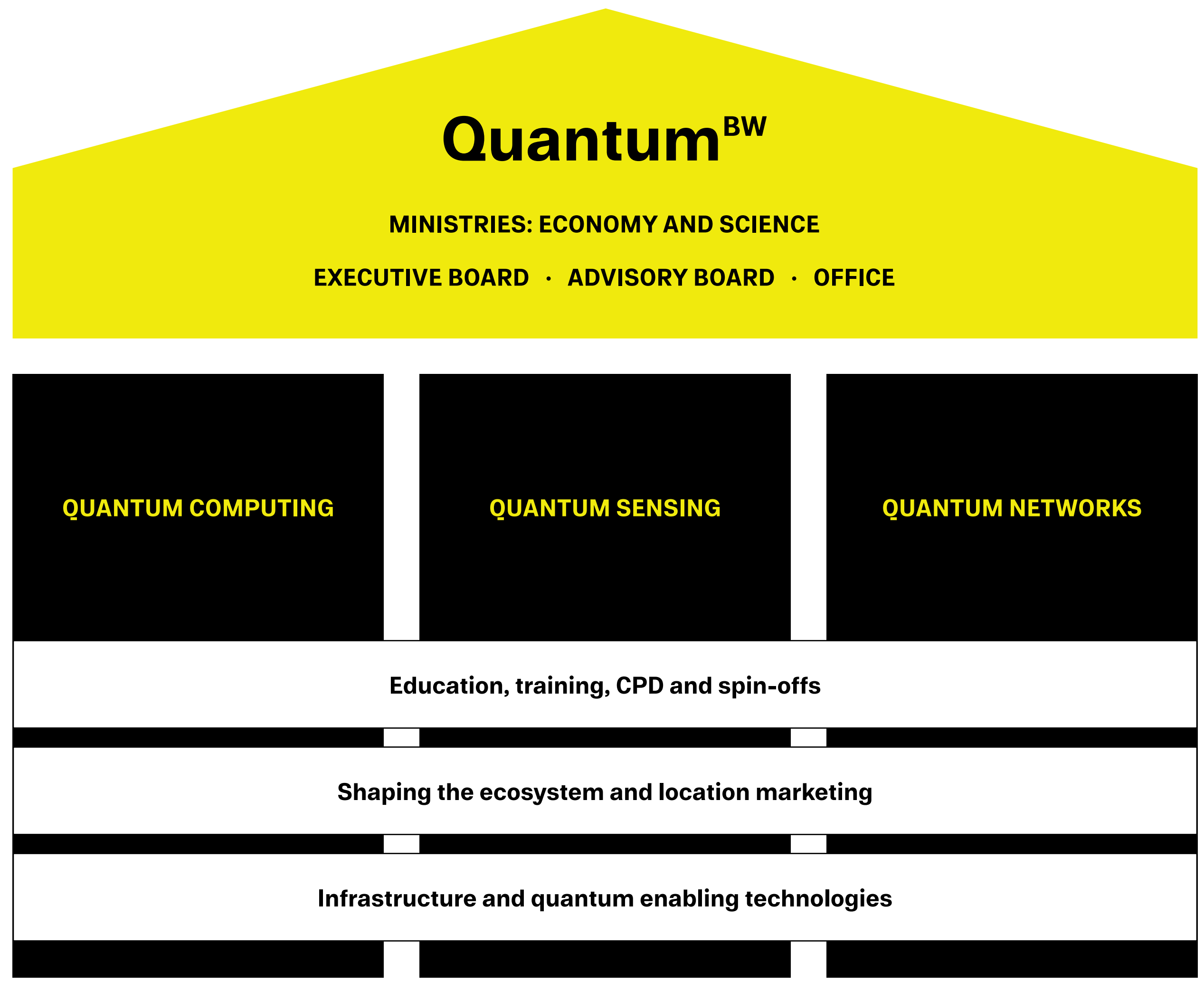
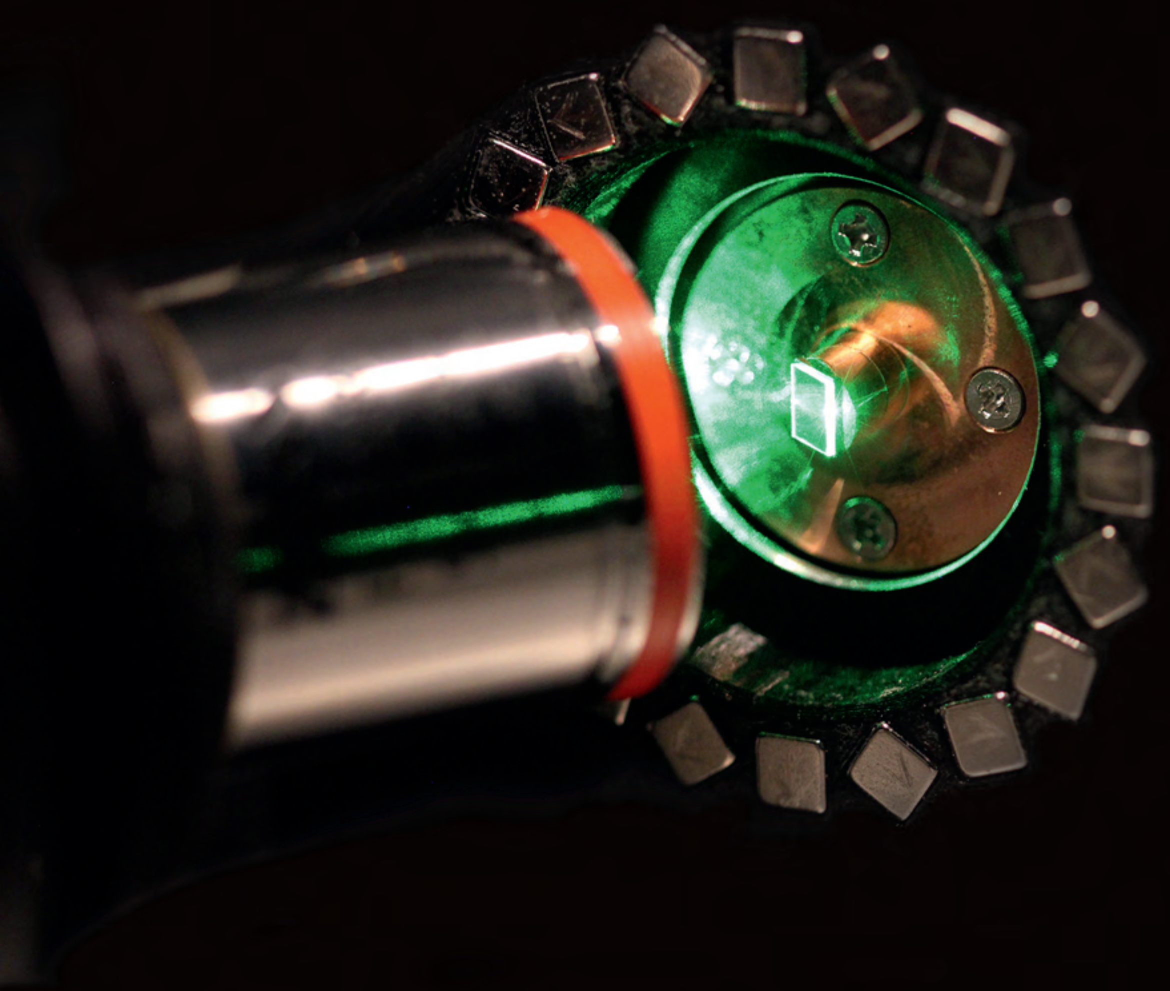


Figure 2:
Overview of the governance structure and fields of action of Quantum^{BW}

03 TECHNOLOGY ROADMAPS



In order to underpin the four central fields of action of Quantum[BW] with concrete measures and milestones, a roadmap process has been initiated in the fields of quantum sensor technology and quantum computing, as well as the associated field of quantum networks. This is intended to provide the players in the governing body of Quantum[BW] with a coherent and binding schedule for the next implementation steps, based on input from foremost experts.

The roadmaps aim to establish Baden-Württemberg as a leading technology and business hub in the national and international competition around quantum technology. Quantum[BW] focuses on translating outstanding research findings achieved by the state's universities and non-university research institutions into concrete applications and regional value chains.

The task of the roadmap process is to

→ establish transparent, issue-specific roadmaps to be followed by the state over the next ten years, i.e. through to 2033 (in time scales of three, five and ten years) and to continue these on an ongoing basis
→ synchronize the state's activities with the relevant national and international roadmaps
→ continuously review and compare the progress made against the roadmaps and, if necessary, to formulate changes to the measures or adjustments to the roadmaps.

Overarching objectives of the roadmaps

1. To take a leading industrial position in quantum technologies over the next ten years.

2. To take a leading position in the field of quantum sensor technology and those applications that become widely available in Baden-Württemberg over the next ten years.

3. To become an international leader in industrial applications of quantum computing and its algorithms that become widely available in Baden-Württemberg over the next ten years.

In order to achieve these overarching objectives, the roadmaps are divided into separate themes, the content of which is based on the central fields of action of the concept paper and the corresponding framework conditions of the respective fields of quantum technology. Technology-specific challenges, objectives and recommendations for quantum sensor technology and quantum computing are set out in separate roadmaps. Within the organisational structure of Quantum^{BW}, these roadmaps will be regularly reviewed and updated by the Executive Board, supported by the Advisory Board and the Head Office.

Overarching themes and associated objectives

	QUANTUM SENSING	QUANTUM COMPUTING AND ALGORITHMS
01 Joint projects "Applications"	Support of pre-competition research and knowledge transfer in the field of quantum sensor technology with a view to future key applications	Support of pre-competition research and knowledge transfer in quantum computing with a view to applications for relevant and confirmed use cases and algorithms
02 Joint projects "Enabling technologies"	Research into the necessary integration technologies for quantum sensor technology (enabling technologies)	Setting-up of technological basics for quantum computing hardware with access options for network partners
03 Basics, infrastructure	Creation of a scientific and economic ecosystem for the sustainable industrial use of quantum technologies	Support of a broad scientific basis for the quantum computing stack through the fundamental creation and coordination of infrastructure
04 Promoting young talent and training	Training and further qualification of a sufficient number of academic and non-academic specialists in the fields of quantum sensor technology and quantum computing using existing regional structures	
05 Spin-offs	Utilization and, if necessary, broadening of the spin-off and incubation activities of the state to include quantum technologies	

Table 1:
Overarching themes and associated objectives

3.1 Quantum Sensing Roadmap

In order to achieve the overarching objectives, the roadmap will address the following key questions:

→ What will be the fundamental socio-economic implications of quantum sensor technology?
→ What impact will the availability of this new type of sensor technology have on industry in Baden-Württemberg?
→ What are the first important use cases for quantum sensor technology? And how can these be addressed on an industrial scale?
→ Which markets will benefit from quantum sensor technology first? And which markets will follow over time?
→ How can quantum sensor technology be put to use in mass markets?
→ What synergies are there for industry in the area of enabling technologies?
→ How can synergies with Cyber Valley and other AI activities be exploited in THE LÄND?

3.1.1 Starting point 2023

Quantum sensor technology, quantum imaging and quantum metrology are among the most advanced quantum technologies. In particular, quantum sensors that are based on defects in solids are close to being market-ready and the first products suitable for mass production are expected in the next three to five years.

Work underway in Baden-Württemberg in this area is focusing primarily on such defects in solids, as well as atomic systems in the gas phase and photons. Further focal points in THE LÄND are to be found in the areas of materials research — with a key focus on 2D materials — for sensor technology, enabling technologies such as microelectronics, photonics and microhybrid assembly and connection technology, as well as in combining these quantum sensors with conventional sensor technology (hybrid sensors) and AI.

New applications and markets can be successfully developed in two steps:

1. Identifying suitable niche applications and gradually expanding production capacities in the state. These can be products for selected niche applications that are launched on the relevant markets in small volumes and that enable the companies involved to achieve a return on investment (ROI) very quickly.

2. Identifying larger-volume target markets with the aid of suitable applications and developing them from a technological perspective.
To bring this about, quantum sensors must be drastically miniaturized and further progress be made with respect to the scalability of their production. Appropriate research and development work in the field of integration technologies is also imperative. Suitable applications under this second step can include quantum measurement standards and calibration services for the certification of these novel quantum devices and systems.
Due to the wide variety of potential applications and their specificity, a broad range of physical platforms needs to be considered, including (but not limited to) trapped ions, ultracold atoms, warm and hot atomic vapours, nano- and micromechanical oscillators and optomechanical systems, superconducting and semiconducting nanocircuits, artificial systems such as quantum dots and spin defects in solids, as well as purely optical systems involving non-classical states of light.

3.1.2 Key challenges in bringing quantum sensor technology to market

Commercial applications require the development of miniaturized, integrated, cost-effective and user-friendly quantum sensors. To achieve this, the following technological challenges must be met:

→ Successful integration of sensor qubits by means of classical microelectronics and photonics to make size, cost, robustness and reproducibility sufficiently scalable and compatible with the mass market
→ Improved solutions for production, integration and packaging, as well as for quantum materials, as the basis for many applications in quantum sensor technology (and in quantum computing)
→ Improved access to foundries, e.g. integrated photonics and electronics Integration of electronics and optics in sensor platforms
→ Integration of electronics and optics in sensor platforms
→ Miniaturized laser and vacuum systems
→ Use of nano- and micro-electromechanical systems (NEMS and MEMS), optomechanical systems and microsystems technology
→ Definitions for standard interfaces between components
→ Development of measures for quality assurance and definition of standards and certifications

3.1.3
Short-, medium- and long-term objectives in the five thematic areas

General: Establishing compatibility with tenders made at state, federal and EU level to maximize synergies and close funding gaps. Current research and development projects as well as industrial R&D are expected to deliver initial small-volume products by 2026.

	GOALS AFTER 3 YEARS (2023-2026)	GOALS AFTER 5 YEARS (2023-2028)	GOALS AFTER 10 YEARS (2023-2033)
01 **Joint projects "Applications"**	If quantum sensor technology is to have a sustainable, long-term future in industrial applications, it is crucial to develop the first target markets. Here, projects are being funded that have been designed specifically from a market perspective and that aim to promote research into the utilization of technologically advanced (>TRL 4) quantum technologies for specific markets/applications that may have been previously identified by means of suitable processes.	Placing of a significant number of quantum sensor products in small and medium volumes in relevant markets that may have been previously identified by means of suitable processes	Quantum sensor technology available in mass markets
02 **Joint projects "Enabling technologies"**	Research into enabling technologies such as microelectronics and photonics will play a key role in bringing about future scalability in the production of quantum sensors. For this reason, research projects are needed that specifically investigate integration technologies for certain quantum systems.	→ Availability of the first laboratory demonstrators for highly scalable quantum sensors → Availability of scalable and parameterized simulation models for designing and optimizing monolithic and hybrid integrated quantum sensors	First laboratory demonstrators for monolithically integrated (SoC) quantum sensors or quantum sensors implemented as “system-in-package” (SiP) modules.
03 **Basics, infrastructure**	A broad scientific basis is being established through the long-term development of new research structures. The key goal is to create low-threshold access to new methods and technologies (see 02). → Low-threshold access to relevant measurement and laboratory equipment will be created for all partners at the locations and across regions; the equipment will be managed by the local universities and institutes of the Innovation Alliance Baden-Württemberg (innBW). The same applies to access to structures from other major national projects, such as the Fraunhofer Research Fab Microelectronics Germany (FMD), the DLR Quantum Computing Initiative or the IQST. Concrete access will be demonstrated by measurable key performance indicators and organized in a pragmatic process that involves very little bureaucracy → In addition to coordination, the availability of scientific and technical personnel is of key importance as regards access to technology	→ Continuation of basic research on the basis of locally developed excellence and new professorships → Access to technology is adapted and, if necessary, expanded in line with the necessities of progress	→ Further filling of the quantum sensor technology “pipeline” through basic research → Availability of sensor qubits with further improved properties at room temperature → Access to technology at the state universities and innBW institutes for partners in Baden-Württemberg
04 **Promoting young talent and training**	The successful university training activities will be intensified and driven forward. → Creation of junior professorships, particularly in the field of enabling technologies and at the interfaces between physics and other disciplines (engineering, medicine, material sciences) → Expansion of advanced training opportunities for existing employees in the academic and non-academic sectors. As the technology advances, the importance of non-academic training will grow	→ Junior professorships have been established → Existing advanced training activities are being expanded and diversified regionally, especially for non-academic users	Maximum diversification of education, training and CPD activities
05 **Spin-offs**	Creation or support of a significant number of spin-offs from the universities and research institutions; supported by standard performance indicators in line with methods applied in the start-up scene and networking with venture capital	Transition of a significant number of start-ups to successful companies	Successful quantum companies as market leaders

3.1.4
Short-, medium- and long-term measures derived in the five thematic areas

Measures derived for 2023: To establish compatibility with tenders made at state, federal and EU level to maximize synergies and close funding gaps. Current research and development projects as well as industrial R&D are expected to deliver initial small-volume products by 2026.

	MEASURES BY 2026	MEASURES BY 2028	MEASURES BY 2033
01 **Joint projects "Applications"**	→ Creation of suitable collaboration and innovation formats in order to identify particularly promising applications for interaction between industrial users and researchers and commitment on the part of industry → Funding for three-year research projects (2024-2027) focusing on future applications of quantum sensor technology (market-oriented projects) → This involves creating a link to conventional sensor technology (hybrid sensors) and artificial intelligence → Workshops to determine suitable applications and target markets	More market-oriented projects, taking into account technological developments in thematic area 2, i.e. a look at initial applications with higher volumes	Application-oriented (market-oriented) research projects for successive transitioning of quantum sensors to continuously growing target markets
02 **Joint projects "Enabling technologies"**	→ Development of customized quantum materials for quantum technology → Standardization of quantum materials for reproducible quantum sensor technology → Systematic qualification of materials, simulation models and technologies for the design and production of quantum sensor prototypes, classification of materials and technologies according to their suitability for different accuracy classes of quantum sensor → Funding for three-year research projects (2024-2027) focusing on the enabling technologies for scalable production of quantum sensors → Coordination, creation and synchronisation of opportunities for technology access	→ Further research projects on the scalable integration of quantum sensors taking into account new developments in sensor qubits → Research projects on the monolithic integration of quantum sensors → Research projects to ensure the reliability of monolithically integrated and hybrid quantum sensors	Technology-oriented research projects to boost the scalability of quantum sensors with the aim of being able to manufacture highly scalable quantum sensors in Baden-Württemberg's quantum ecosystem
03 **Basics, infrastructure**	→ Integration of relevant partners into the overall structure of the cluster → Establishing of posts (coordination posts and tool operator posts) for technology access and the creation of new technology infrastructure/supplementing of the existing technology infrastructure	Complementary new technology infrastructures have been created. Where applicable, additions taking into account new developments in sensor qubits	→ Targeted support for basic research to fill the "pipeline" with new sensor qubits (e.g. through financial backing for third-party funding applications) → Creation of a functional system for accessing technology from various sources (universities, innBW, industry)
04 **Promoting young talent and training**	→ Establishment of junior professorships or junior research groups → General training program of existing associations (e.g. QSens) continued and expanded	→ Junior professorships and junior research groups are successfully set up → Transition to regional facilities and to the non-academic training sector	Creation of a wide-ranging and sustainable training system for both existing specialists and beginners in the academic and non-academic sectors
05 **Spin-offs**	→ Integration of quantum sensor technology into the start-up scene and networking with venture capitalists (equipping a quantum incubator as part of the venture capital activities) → Link-up with the QSens quantum incubator and, for specific applications, with incubators such as the start-up Autobahn or AIXpress	Review of start-up numbers If necessary, adjustment of the above measures	Sufficient number of venture capital offers and measures along the development chain

3.2 Quantum Computing Roadmap

In order to achieve the overarching objectives, the roadmap will address the following key questions:

- → How fundamental is the change in the industrial landscape brought about by quantum computing?
- → What is the impact of this industrialization of new information technology on all the technologies that make up the state of Baden-Württemberg today and in the future?
- → What is the impact on implementation across the entire scope of Baden-Württemberg's high-tech industry?
- → How can the entire quantum computing stack be industrialized?
- → How can a link-up with Cyber Valley and AI activities in THE LÄND be exploited?

3.2.1 Starting point 2023

The aim of the roadmap is to establish Baden-Württemberg as a national and international industrial hub at the forefront of quantum technology and quantum-based business, based on the disruptive impacts of new findings in quantum physics. This success will be founded on wide-ranging and successful basic research underway in Baden-Württemberg. Technologies with a focus on optical and photonic processes will be opened up.
In addition, a broad training and CPD program, comprising both academic and non-academic measures, will be put in place to secure the availability of the specialists required.

Work underway in Baden-Württemberg in this area is focused primarily on defects in solids, such as diamond, and on utilising photons. Other focal points include materials research, enabling technologies such as cryogenics and microelectronics, photonics and microhybrid assembly and connection technology for quantum computing.

3.2.2 State of the art

The state of the art in hardware technologies lies in the industrial availability of physical qubit systems in various processor architectures (e.g. superconducting qubits, ion traps, neutral atoms, spin or photonic qubits). The various technology platforms, with all their pros and cons, can then be connected to, controlled and activated individually to good effect.

Today's quantum computers are custom-built one-offs with a highly specific hardware component. At present, the control and programming of quantum processors of different types is not standardized. There are some attempts to create a standardized format such as IBM's Qiskit software development kit, but this has not yet found broad acceptance.

3.2.3 Key challenges of quantum computing

If quantum computers are to be deployed in future market-oriented applications, they will have to incorporate high-quality qubits. This demands relevant research and development into the hardware for these novel quantum systems — specifically into materials, process, cooling and integration technologies. At the same time, the development of quantum algorithms and advances in quantum computing and standardization also have a key role to play in software development.

In contrast to the concepts being pursued at other locations in Germany with respect to building German quantum computers, research underway in Baden-Württemberg is focusing on approaches founded chiefly on photons, spin qubits in diamond and Rydberg atoms.

Photonic quantum processors are characterized by incredibly stable states and particularly seamless integration into quantum communication networks.

3.2 Quantum Computing Roadmap

Their operating principle is based on the generation of individual photons, processing in optical networks and efficient quantum measurement. The hardware consists of photonic components that manipulate light at quantum level; for example, photonic silicon chips are used. One of the main challenges is the need to integrate a large number of photonic quantum components — a basic requirement for a scalable photonic quantum processor. It is crucial that we grow and develop synergies with the traditional photonics industry, which has a strong presence in Baden-Württemberg.

Electron spins, which are located in colour centres of semiconductor crystals and can interact with nuclear spins in their immediate atomic neighbourhood, enable qubit topologies with very high levels of connectivity and scalable qubit architectures that offer great application potential for quantum information processing and quantum networks. Baden-Württemberg has a large number of university and non-university research institutions that enjoy an exceptional international reputation in the field of diamond-based quantum systems (nitrogen-vacancy (NV) centres in diamond). They are supported by spin-offs and SMEs that have extensive expertise in the production and processing of synthetic diamond coatings.

Digital quantum computing using Rydberg atoms is a relatively new and highly dynamic platform compared to traditional systems that use ionic or superconducting qubits. In recent years, control, entanglement and competitive qualities have been demonstrated in qubit gate operations. The platform also has enormous innovation potential that has not yet been fully exploited. This includes the realization of dynamic connectivity in two or even three dimensions as well as the realization of many-body gates. These two elements open up new algorithmic possibilities and potential applications in materials design and quantum chemistry.

To fulfil the promise of a quantum computer, various layers of hardware and software must be developed, which together are referred to as a quantum computing stack. The basis of the stack is the quantum processor, with the qubits being the smallest computing and information units of a quantum computer. Every quantum computer requires an abstraction layer (quantum firmware layer), which provides an interface between the hardware/control electronics and the application logic to be realized. This is currently implemented for each individual quantum computer architecture on a technology-specific basis. A major challenge is the fact that qubits are extremely sensitive to noise and are disturbed by the slightest fluctuations in their environment. The resulting errors then have to be corrected. Approaches for fault-tolerant quantum computing are based on various quantum error correction techniques, which are also part of the stack.

The stack of a future fault-tolerant quantum computer will therefore consist of layers that correspond to the abstraction levels of the software. At the top of the stack is Quantum-as-a-Service (QaaS), which provides functions for data-based value creation and with which users can interact via a cloud service, for example. Below this are quantum algorithms and applications that are coded with the aid of developer tools and enable high-level abstraction. The algorithms and applications are compiled on the third level in order to realize circuits on coded blocks. In fault-tolerant computing, this is implemented on logical qubits that are coded with quantum error correction (QEC), although realization of the QEC code and other associated tasks is performed on a separate level. The physical connectivity between the devices and the compensation of any stray couplings are taken into account in a hardware-aware compiler. The quantum firmware layer, which is responsible for minimizing hardware errors, is located between this layer and the physical hardware. It performs all the tasks required for hardware calibration, adjustment, characterization, stabilization and automation.

One of Baden-Württemberg’s strengths in quantum computing are the activities of leading companies that play a key role in the industrialization, application and commercialization of quantum technologies. In photonic quantum computing in particular, as well as in algorithms for quantum computing, players from research and industry play a leading role in Baden-Württemberg.

By focusing on these areas, the State's technological strengths can be elevated and further developed with the broad involvement of the various players in its research landscape. Such focusing also facilitates further differentiation from other initiatives, but should not limit the scope of research into diverse technological platforms in the field of quantum computing.

Besides photonics, Baden-Württemberg also currently boasts additional strengths and specialties in quantum computing; in solid-state technologies and materials research, in particular, quantum materials.

What’s more, Baden-Württemberg possesses extensive expertise in the development,

3.2 Quantum Computing Roadmap

implementation and delivery of quantum software as well as its standardization and regulation. Moreover, the goal in the research and industry sectors is to ascertain and explore high-performance, automated and controllable solutions for industrial applications by means of holistic quantum software engineering throughout the entire quantum software development process and to deliver best practices. Crucial contributions are being made in THE LÄND to quantum computing stack development, such as through application-oriented solutions for error correction. Based on industrial use cases, benchmarks are also being developed that quantify the state of progress of quantum computing for various industrial issues and establish transparency.

Enormous potential for quantum computing in Baden-Württemberg is seen in the combination with artificial intelligence (quantum machine learning) and classical high-performance computing (hybrid quantum computing). Excellent structures in science and industry are already in place, which should be further built upon.

Furthermore, there are links here to quantum communication, first and foremost quantum networks, which are particularly necessary with regard to the entanglement of subsystems in the quantum computer, e.g. in order to connect quantum memory and quantum processors quantum mechanically.

This critical aspect of quantum computer hardware is also considered in the roadmap developed by Quantum^{BW}, without demanding the development of quantum communication be a part of Baden-Württemberg's remit. Such networks and the study of their properties are an inherent part of research into the hardware and system approach of quantum computing, as this progress supports scaling of the various architectures. The intensity with which they are studied depends on how significant they are expected to be.

3.2.4
Short-, medium- and long-term objectives in the five thematic areas

General: To establish compatibility with tenders made at state, federal and EU level to maximize synergies and close funding gaps.

	GOALS AFTER 3 YEARS (2023-2026)	GOALS AFTER 5 YEARS (2023-2028)	GOALS AFTER 10 YEARS (2023-2033)
01 **Joint projects "Applications"**	Setting-up of pre-competition research into quantum computing algorithms → The broad-based focus on applications for relevant and confirmed use cases is strengthened and implemented through significant projects. The first transfer and potential-analysis projects with industry are launched in parallel (quick checks/exploring projects) → Quantum computing's AI links with Cyber Valley and IPAI as well as quantum computing applications in materials research will be strengthened → The use of hybrid approaches to quantum computing is being pursued centrally. State-of-the-art quantum computer hardware will be provided, with parallel demonstrators and further access to other quantum computing technologies for low-threshold access to quantum computing for SMEs	→ Some of the algorithm research projects will be led by industry → Setting-up of a demonstration centre with training for SMEs and quick checks/exploring projects (3-5 months)	Availability of quantum computing as a standard IT technology with low-threshold offers and resources available
02 **Joint projects "Enabling technologies"**	Making technology available while avoiding duplicate structures → Establishing low-threshold access for all partners to relevant measurement and laboratory equipment, which will be managed by the local universities and institutes → Access to parallel structures from other major national projects, such as the Fraunhofer Research Fab Microelectronics Germany (FMD), the DLR Quantum Computing Initiative or the IQST. Concrete access will be demonstrated by measurable KPIs and organized in a pragmatic process that involves very little bureaucracy → Quantum computing technologies will continue to be compared in an open race. In addition to coordination, the establishment of permanent positions is of key importance to universities with regard to access to technology → Photonic systems are the focus of attention in Baden-Württemberg, with corresponding materials research and R&D work on their integration	Access to the technology will be adapted and expanded according to what's required to make progress	Access to the technology at the universities and making it available to the participating universities and spin-offs
03 **Basics, infrastructure**	A broad scientific basis is being established through the research structures. The key goal is to create low-threshold access to new methods and technologies (see thematic area 2).	Continuation of basic research on the basis of locally developed excellence and new professorships	Further refilling of the quantum computing "pipeline" through basic research; opening up for new topics in the post-quantum era
04 **Promoting young talent and training**	→ The successful university training activities will be intensified and driven forward → To this end, junior professorships and mid-level academic positions for technology access are being created → These will be supplemented by advanced training opportunities for existing employees in both academic and non-academic fields. As the technology advances, the importance of non-academic training will also grow	→ Junior professorships/junior research groups are established → Advanced training activities (Fraunhofer, IQST, etc.) will be expanded and diversified regionally, especially for non-academic users	Maximum diversification of education, training and CPD activities
05 **Spin-offs**	Creation or support of a significant number of spin-offs from the universities and research institutions; supported by standard performance indicators in line with methods applied in the start-up scene and networking with venture capital	Transition of a significant number of start-ups to successful companies	Successful quantum companies as market leaders

3.2.5
Short-, medium- and long-term measures derived in the five thematic areas

Measures derived for 2023: Technical exploitation of IP: cooperation agreements ensure that the intellectual property (IP) of the project partners must initially be licensed to the partners (right of first use); this is to promote regional exploitation in Baden-Württemberg. Cyber Valley or the future cluster QSens can serve as a model.

	MEASURES BY 2026	MEASURES BY 2028	MEASURES BY 2033
01 **Joint projects "Applications"**	→ For Q2/2024, continuation of the scientific projects scheduled for 2024-2027, with a focus on the software use cases established through research → First quick checks/exploring projects where it already makes sense to promote SMEs → In the process, establish a link to hybrid quantum computing in particular and, where technically feasible, quantum machine learning → For Q2/2024, delivery of a new generation of centralized quantum computer hardware and parallel access to comparable technologies	Transition to industry-led projects in software and exploring projects, demonstrator rooms	Development of a research and development ecosystem for quantum algorithms
02 **Joint projects "Enabling technologies"**	→ Coordination, creation and synchronization of opportunities for technology access	Review of technology offerings and support for spin-offs	Creation of a functional system for accessing technology from various sources (universities, Fraunhofer-Gesellschaft, IQST, industry, if desired) as a model for basic access to technology
03 **Basics, infrastructure**	→ Integration of relevant partners into the overall structure of the cluster; for the universities: establishment of permanent positions for access, support of the network infrastructure through known activities at the universities, but also at the research institutions (Fraunhofer-Gesellschaft, IQST), and the establishment/ addition of new infrastructure, e.g. technology	→ Complementary new infrastructures/technology are created	Sufficient basic research to fill the downstream technologies
04 **Promoting young talent and training**	→ Establishment of junior professorships or junior research groups → General advanced training program (e.g. Fraunhofer Academy) continued and expanded	→ Junior professorships have been established; transition to regional academic educational institutions and to the non-academic advanced training sector	→ Creation of a wide-ranging and sustainable training system for both existing specialists and beginners in the academic and non-aca demic sectors
05 **Spin-offs**	Integration of quantum computing into the start-up scene and networking with venture capitalists (equipping a quantum incubator as part of the venture capital activities)	→ Review of start-up numbers If necessary, adjustment of the above measures	Sufficient number of venture capital offers and measures along the development chain

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