Physikalisch-Technische Bundesanstalt
National Metrology Institute

Into the Future with Metrology

The Challenges of Quantum Technology

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innovative – technological – visionary

When large amounts of money are invested in the research of small things, it is because our leaders firmly believe that our society and economic future can be shaped this way. These "small things" mean the objects and phenomena of the quantum world. Science is increasingly succeeding in taking control of this world. The range of topics spans from quantum communication with its inherent secure data transmission to quantum computers for unimagined processing power and to quantum simulations of chemical reactions and quantum sensors for medical diagnostics. Great technological promise with enormous economic potential is popping up in these fields. This potential is being raised on a large scale by the European Commission's levied billion euro "Quantum Technologies Flagship" funding program and beyond that, it's being pushed forward in flanking national funding programs. At the same time, not only large companies with long traditions, but also young start-ups are pushing developments which will bring entirely new products to the market which are based on quantum technology (QT).

Just as PTB was once – thanks to its measuring skills – at the beginning of quantum mechanics, PTB is now driving the second quantum revolution's wave of metrological possibilities – with the next generations of atomic clocks, even more precise electrical standards and innovative measurement capabilities in medicine. At the same time, the metrological fundamental research leads to technological applications. To make these applications available for the economic development of QT, the Quantum Technology Competence Center (QTZ) was recently founded.

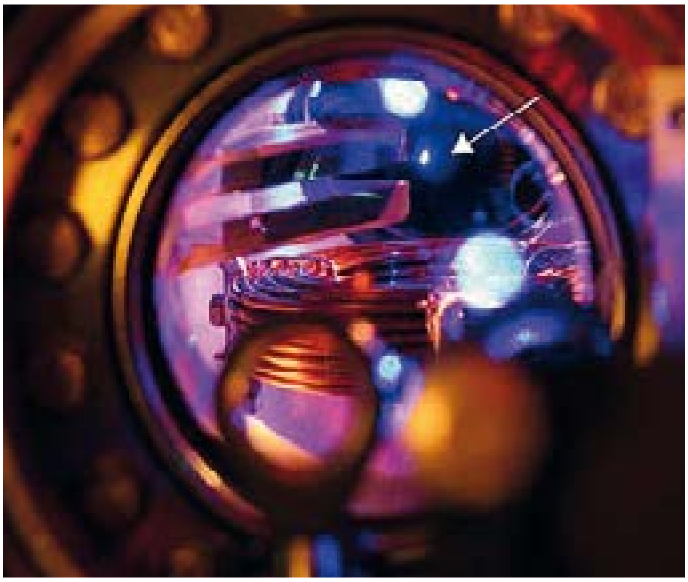
Timekeepers

If you think of passing hours, minutes and seconds when you imagine a clock, you're not wrong, but not completely right, either. When clocks measure time very accurately, scientists can do much more than just state the time:

- Navigation: Atomic clocks are used in satellite navigation. To locate a person or an object, the running times of the exchanged signals are analyzed. The rule of thumb: The more precisely clocks tick, the more precisely things can be successfully located.
- Measuring the Earth's gravitational field: Atomic clocks are highly sensitive to their environment. According to Einstein's theory of relativity, local gravitational forces influence the passage of time and thus the rate of clocks. That is why an atomic clock ticks differently at sea level than on a mountain, for example. Today's best clocks are already able to perceive altitude differences of just a few centimeters.
- The search for "new physics": Our world is the way it is because the natural constants are what they are. If the natural constants changed, our world would change too. That leads to a fundamental question: Are the natural constants *really* constant? As natural constants also play a role in atomic clocks and influence the measure of time, scientists are trying to find out with the help of such clocks whether the natural constants undergo changes.

People who research atomic clocks are aware of the clocks' fields of application: satellite navigation, geodesy, communication technology or in fundamental research.

For decades, PTB has been acquiring expertise on the construction and operation of atomic clocks and is among the world's most famous timekeepers. The fact that PTB provides the national time in Germany is just a small, though important task. The even greater task is developing the clocks of tomorrow. What are known as "optical clocks", which use frequencies in the visible spectral range rather than in the microwave range, are the definitive step toward the next generation of clocks which work, for example, with single or an ensemble of neutral or charged atoms (ions).



Timely: Excited atom (glowing) in an optical clock

With these optical clocks, the measure of time will be raised to a new level of precision from which all the practical applications which can be expected will greatly benefit – from altitude measurement in geodesy to the synchronization of networks with high-precision frequency standards. For such practical applications, however, the highly sensitive technology which tames the underlying quantum states much be transferred from a well-protected and painstakingly stabilized fundamental research laboratory to the rugged environment of practical applications, for example, to the free field in geodesy (PTB's Sr lattice clock is already used there) or for use as a frequency standard in a server room. For this purpose, the first (and still the only) user-friendly, robust and near-commercial optical clock has been realized at PTB in the "opticlock" project in a consortium with partners from industry and academia.

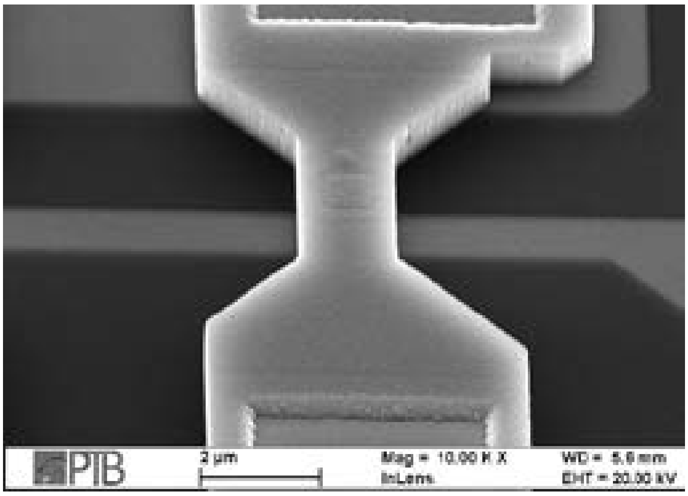
Quantum magnetic-field sensors

While homo sapiens may not be able to detect magnetic fields, as "homo technicus", human beings make use of a wide variety of technical sensors. Quantum effects are increasingly being exploited to collect information unavailable by conventional means – for example, in order to detect magnetic fields in living organisms or to use such fields for medical imaging purposes.

- Medical imaging: In order to peer inside human beings (without having to cut them open), medicine has developed an arsenal of methods. One way to obtain an image from within is to measure the very weak magnetic fields produced by our brain when thinking – or by our beating heart. Sensors that are highly sensitive to such weak magnetic fields exploit quantum effects such as superconductivity.
- Medical biomarkers: In some cases, medicine must send in "spies" to find out what is happening inside. For example, the path of nanoparticles introduced into a patient's body can be followed by means of certain particle properties such as magnetism.
- Quantum communication: Highly sensitive magnetic-field sensors can also be used outside of medicine. For example, single photons can be detected by means of these sensors – an important prerequisite for fundamental research as well as for applications of quantum communication.

To detect very weak magnetic fields, superconducting quantum interference devices (SQUIDs) are especially well suited for use as highly sensitive sensors. This special form of quantum technology, together with its requisite cryotechnology, has enjoyed top-caliber development and manufacturing and been used for measurement at PTB for some time now. For example, SQUID magnetometers have been used for several years to measure the tiny magnetic fields generated by the neural activity of the human brain. PTB is an international leader in both the manufacture of such SQUIDs (via superconductor thin-film technology) and the measurement technology based on them. At PTB, SQUID technology is complemented by so-called optically pumped magnetometers (OPMs) for which nuclear spins are "read out" by means of laser light and which – in contrast to SQUIDs – do not require cooling to low temperatures (approximately that of liquid helium).

Magnetic fields in living organisms are so small that the Earth's magnetic field and the magnetic fields of our electrified world are gigantic by comparison. Therefore, PTB conducts its biomagnetic reference measurements, which are performed before real-life medical applications take place, in a specially shielded room, which is the "magnetically quietest place in the world" (Berlin Magnetically Shielded Room, BMSR). This facility and its associated equipment are also open to external partner institutions from industry and research.



In twos: Pairs of electrons tunnel through a barrier in a SQUID.

Walking into the trap

The discovery that the world is governed by principles of quantum mechanics is over 100 years old. Today, we take many technological applications of quantum physics for granted – from lasers and semiconductor technology to magnetic resonance imaging (MRI). The applications of second-generation quantum technology currently emerging go a step further, allowing individual quantum objects to be controlled and deliberately exploiting basic quantum effects for technological innovations in the near and distant future.

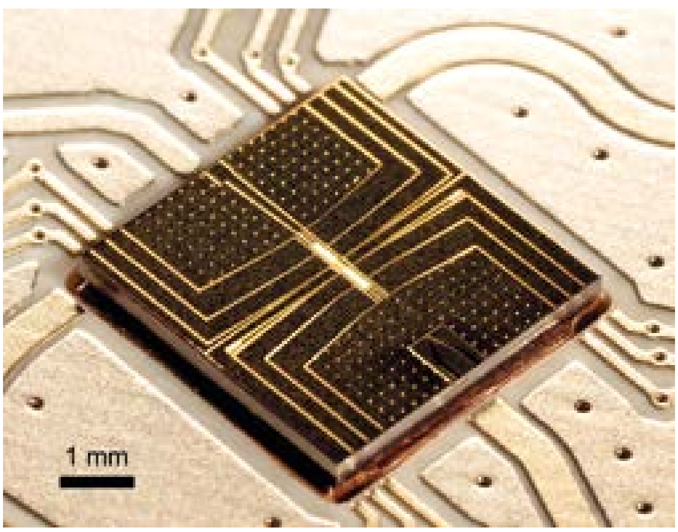
- Quantum computers: A conventional bit has a value of either zero or one. A "quantum bit" (Qubit), on the other hand, does not describe this simple choice but both possibilities simultaneously. While conventional computers, even those with many bits and very fast single steps, can only carry out their computations one after the other, quantum computers are massively parallel systems. However, for such systems to work, the fragile qubits must be isolated extremely well and maintained in exceptionally good condition. With these conditions met, a quantum computer with as few as 50 Qubits can solve special tasks that modern supercomputers cannot handle.
- Quantum simulators: While quantum computers are conceived of as "general-purpose calculating machines", quantum simulators are designed as specialist devices for specific problems in fields such as materials research, quantum chemistry and high-energy physics. Although such simulators must be configured separately for each simulation purpose, they can then tackle problems that cannot be solved by conventional computers.

- Fundamental research: By controlling individual quantum objects, the basic laws of physics can be investigated very closely, allowing greater insight into the principles of the world.

The question of which objects or systems best convey quantum information has not yet been conclusively answered. The two currently most promising candidates are trapped ions in vacuum and tiny superconducting circuits near absolute zero.

PTB is pursuing an approach for a scaleable quantum processor based on patented ion traps developed and manufactured in-house. By means of this technology, so-called quantum gates have been realized that form the core of every quantum computer.

At PTB's Quantum Technology Competence Center, a user facility is currently being built for external partner organizations that will allow ion traps to be characterized quickly and reliably. No facility of this type exists anywhere in the world, yet it is a critical prerequisite for the commercial development of a quantum computer based on ion traps and for additional innovations in high-resolution spectroscopy and metrology (among other things).



Trapped: The chip structure of an ion trap

Electrical Quantum Metrology

Historically speaking, not much time has passed since Nicola Tesla dazzled audiences with his controlled bursts of lightning and ghostly seeming light effects and a certain Thomas Alva Edison electrified the industrialized world with his inventions. The discovery and technical utilization of electricity took off at the end of the 19^{th} century and conquered more and more conventional technical terrain until, in the late 1940s, the transistor was invented at Bell Labs in New Jersey. The transistor gave electricity its first quantum-mechanical form.

- International units: Today, electric currents and voltages and electrical resistances can be best measured by exploiting quantum-mechanical effects. For many years, national metrology institutes have used quantum effects to disseminate these units, which are named after several pioneers of electricity such as André Marie Ampère, Georg Simon Ohm and Alessandro Volta. The fundamental reorganization of the International System of Units (SI) by means of natural constants means that our entire system of units (with the exception of the candela) is now based on quantum-mechanical principles.
- Practical quantum standards: While, for many years, electrical quantum standards were available only in highly specialized metrological laboratories, such standards are being applied to practical situations with increasing success. For example, at PTB, a programmable "quantum voltmeter" has been commercialized, thus making it available to industry. The Josephson Arbitrary Waveform Synthesizer (JAWS) was developed as a universal tool for generating and measuring arbitrary and spectrally pure alternating voltages.

For many decades, PTB has consistently been among the world's top addresses in the world of electrical quantum metrology. At PTB, metrologists develop the scientific foundations for extremely high-precision measurements of the electric quantities, specialists manufacture and characterize the hardware components necessary for this purpose in PTB's own Clean Room Center, and links are forged to industry for practical applications.

For the ohm, the unit of electrical resistance, the freedom of movement of the electrons in a semiconductor is restricted and the resulting abrupt change in the resistance in an applied magnetic field is exploited – this is the so-called quantum Hall effect, for which Klaus von Klitzing received the Nobel Prize in Physics and which was used metrologically at PTB from "the hour of its birth". For voltages, the Josephson effect of superconductivity is used, for which two electrons always group together to form a couple. Finally, for currents, it is possible at PTB to count the individual electrons carrying the electricity while these electrons, being quantum particles, tunnel through barriers that are normally insurmountable.

Less light! The key to quantum cryptography

Information is the most important resource of our time. Enormous amounts of data are collected, processed in computers and exchanged via glass fibers, the air and satellites. We are caught up in information flows that never break and that race around the length and breadth of the globe at the speed of light. Much of this data has to be exchanged between the sender and the receiver in a safe way, as not everything that is communicated is allowed or supposed to be in the public eye. This includes patients' data in the field of medicine as well as financial data that is communicated with and between banks and highly sensitive data from the fields of politics and the economy. Forms of communication that are protected from unauthorized access are necessary for all these data transfers.

In particles: Light as a stream of individual photons

- Quantum communication and quantum cryptography: Data is encrypted so that it can be transported securely. The encryption technology used today is based on mathematical algorithms, in which the prime factorization of large numbers plays a crucial role – a mathematical problem that is time-consuming but can, in principle, be solved by each computer. This means that encryption technology is competing in a never-ending race against unlawfully accessing data. In addition, sensitive stored data might be decoded at a later time when computers with higher performance are available. Transporting data in an inherently secure way, for example with single photons, is however promised by the principles of the quantum world. With quantum cryptography, which is based on the laws of nature rather than mathematical algorithms, it is physically impossible to "listen in" without being detected.
- Quantum radiometry: Ultraweak light signals, which may even be single photons, play a central role in various fields of fundamental research. These fields range from astronomy and experiments about the foundations of quantum physics to the life sciences. Furthermore, the candela (the base unit of luminous intensity) and its derived units in photometry and radiometry can in principle be expressed in the form of a known amount of photons with a known wavelength.

Those of us who want to look at light precisely inevitably turn to PTB. With the smallest measurement uncertainties in the world, PTB is able to create and detect even ultraweak optical signals. To use quantum cryptography in practice, the careful measurement of all the properties of the underlying hardware is absolutely necessary, so that the "quantum secure" properties can in fact be guaranteed. The range of work here encompasses metrological fundamental research and development along with setting up special calibration services. Single-photon sources currently being studied at PTB are based, for instance, on lattice defects (e.g. color centers in diamonds) and on semiconducting quantum dots made of indium gallium arsenide.

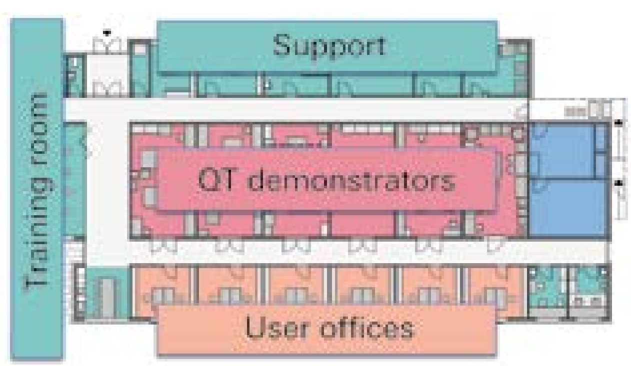
The Quantum Technology Competence Center (QTZ)

Only very few people have so far become accustomed to the phenomena of the quantum world. Yet the technologies that come out of this world are to be used by everyone. PTB is therefore specifically expanding its fundamental research and its highly specialized services to include a Quantum Technology Competence Center (QTZ) that focusses on applications. Work on setting up this center began in 2019, and the QTZ is going to form an important basis for industrial developments of quantum technologies. Special focus will be placed on start-ups as well as on small and medium-sized enterprises (SMEs).

The conditions at PTB are ideal for such a center of competence. For one thing, PTB's technical competence in diverse fields of quantum technology is recognized internationally. For another, supporting Germany's economy in the metrology sector is a primary part of PTB's legal mandate. Apart from the technical competence in its various laboratories, PTB can also rely on its excellent infrastructure. It has, for instance, the Clean Room Center at its Braunschweig site and the Core Facility specializing in the "Metrology of Ultra-Low Magnetic Fields" in Berlin-Charlottenburg.

PTB is going one step further with the QTZ: User facilities with technical equipment, measuring facilities and demonstrators are being set up there to support industry. This is being supplemented with offices for PTB's partners and customers to use on a temporary basis while they are at the QTZ. Robustness and user-friendliness are both of primary importance here. The measuring facilities supported by PTB's staff and its infrastructure are to be available for use by external partners for the development of different quantum technologies. Moreover, the QTZ will offer hands-on training and seminars on quantum technologies. Other important activities are communicating the possibilities and boundaries of quantum technologies to the public as well as developing technical standards.

In Berlin, the QTZ will be located in the newly built Walther Meissner Building from 2021 onwards. At PTB in



Opening early 2023

Architectural sketch of the new QTZ building in Braunschweig

Braunschweig, a new building will be constructed for the QTZ. It is due to be completed in 2023. This new building will be named after two scientists from PTB's predecessor, the Physikalisch-Technische Reichsanstalt (Imperial Physical Technical Institute), whose measurements of the radiation of blackbodies at the end of the 19th century significantly contributed to the discovery of quantum physics: Otto Lummer and Ernst Pringsheim.

The texts of these Info Sheet and further information can be found in the internet: www.ptb.de > Research & Development > Into the Future with Metrology > The Challenges of Quantum Technology

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Photo on the front cover: PTB