PTB news
Scientific Newsletter
1
2022

Three times a year, PTB News provides topical information from the varied spectrum of activities of the Physikalisch-Technische Bundesanstalt (PTB) consisting of fundamental research, legal metrology and PTB's various activities in the service of the economy.

Compact accelerators soon to become reality

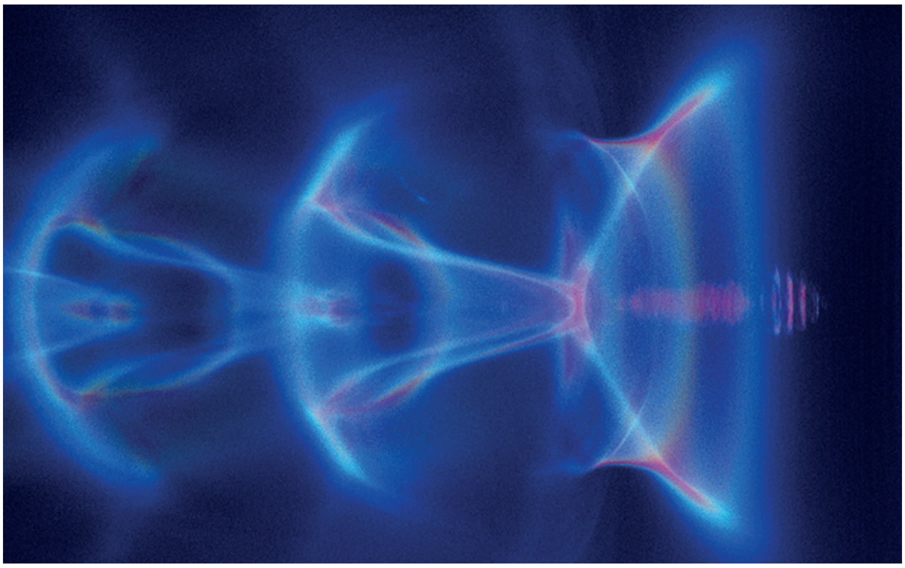
Beam diagnostics method for accurate, non-invasive length measurement of very small electron bunches

Especially interesting for
- electron beam diagnostics
- particle accelerators

Laser excitation in plasmas may enable compact particle accelerators to be realized in the near future. Such accelerators are an alternative to current accelerator facilities that often extend over kilometers. A diagnostic procedure has therefore been developed at the Metrology Light Source. It can be applied to the geometric beam parameters of the electron bunches needed for this purpose.

Particle accelerators have become ever larger over the decades. With circumferences of several kilometers, ring accelerators have now reached their practical limit. Linear accelerators require considerable construction lengths too. And yet, there has been an alternative for several years: compact particle accelerators based on laser wakefield excitation in plasmas. Their design could be a lot more compact than that of other linear accelerators, and compact particle accelerators might be able to supplement linear accelerators both in industry and medicine. However, to be able to utilize the synchrotron radiation generated by this technology, the electron bunches thus formed must have a very well-defined and well-known shape.

At PTB's Metrology Light Source, uniquely flexible setting possibilities are available for the stored electron beam. These settings were used within the scope of a project managed by the Helmholtz-Zentrum Berlin (HZB) to generate particularly small electron bunches that are very similar to those generated by laser wakefield accelerators. By measuring the synchrotron radiation generated by the electrons, it was possible to determine the lateral expansion of individual electron bunches with a resolution of a few micrometers.



Simulation of the electron bunches along the horizontal beam axis in a laser-generated plasma wakefield. The electron bunches having been accelerated to reach a high energy are electrically enclosed in a plasma bubble. The electron density ranges from low (blue) to high (magenta). (Credit: J. Ludwig, cc 4.0 Wikimedia)

This is done by exploiting the fact that the electron bunches generated have a length that is comparable to the wavelength of infrared radiation, which, in this spectral range, leads to coherence effects when the radiation is emitted. The coherent synchrotron radiation generates an interferometric pattern at a double slit. This pattern is detected by a highly sensitive single-photon camera. The pattern is evaluated by means of a special algorithm that reconstructs the lateral expansion of the radiation source – i.e., of the electron bunches themselves.

The results have shown that this procedure has the resolution and sensitivity required to serve as a diagnostic tool for electron bunches generated in the wakefield. In contrast to the procedures realized to date for measuring bunch geometry, this method is non-invasive, i.e., it has no influence on the electron beam, so that continuous measurement in operation is possible. This property is of paramount importance to specifically develop the wakefield technique further. ▪

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Scientific publication
J.-G. Hwang, K. Albrecht, A. Hoehl, B. A. Esuain, T. Kamps: Monitoring the size of low-intensity beams at plasma-wakefield accelerators using high-resolution interferometry. Communications Physics 4, 214 (2021)

Artificial intelligence for heart imaging

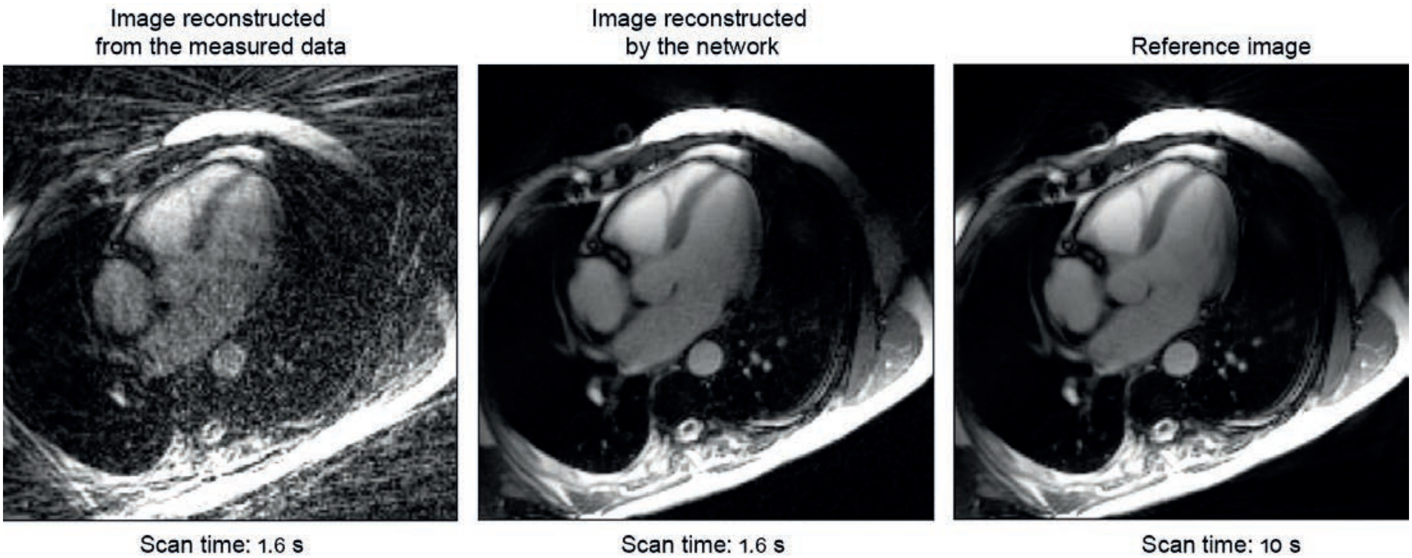
Improved medical image reconstruction by combining a physical model with a neural network

Especially interesting for
- manufacturers of MRI equipment
- image reconstruction
- medical engineering

In patients with a heart condition, magnetic resonance imaging allows parameters such as the pumping capacity of the heart to be determined. This method, however, has a disadvantage: data acquisition is time-consuming. At PTB, a physical model was combined with a neural network to develop a procedure that requires only a small amount of measurement data (and thus only a short measuring time) to obtain high-quality images of the phases of the cardiac cycle.

A magnetic resonance imaging (MRI) scanner excites water molecules in the body cells via high-frequency radiation and then measures the fading magnetization. Due to spatial encoding, the measurement data is acquired in the Fourier space, from which the diagnostic images are then computed. This image reconstruction process requires a physical model which describes the imaging process. Iterative reconstruction procedures are used to obtain as much diagnostic information as possible within as short a measuring time as possible. Based on previous knowledge (e.g., spatial smoothness), it is already possible to compute high-quality images from only a few measuring points. Neural networks can learn this previous knowledge from the data and adapt it for the reconstruction problem.

At PTB, an iterative network has been developed specifically to reconstruct dynamic heart images. During the training phase, this procedure combines the physical model for imaging and the previous knowledge on the structure of the image data learned by the network. MR images



MR image of the heart in one phase of the cardiac cycle. Left: image reconstructed directly from the measured data; center: result of the recently developed method; right: reference image. The reference image required a measurement time that was more than six times longer than that of the new method.

of cardiac function then show the heart during different phases of the cardiac cycle. It was possible to use this temporal component of the data to ensure the best possible efficiency in training.

This method was applied to patients with a heart condition and then assessed. It was also compared to conventional iterative reconstruction procedures as well as to other machine learning methods. The network thus developed yields better results than conventional methods (by up to 6 dB in terms of signal-to-noise ratio and by up to −47 % in terms of relative errors). In addition, this network yielded results similar to those obtained by another method which was also based on neural networks. PTB's procedure was additionally able to do this with only 10 % of the trainable parameters, which proves this new method's robustness and efficiency. ▪

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Scientific publication:
A. Kofler, M. Haltmeier, T. Schäffter, C. Kolbitsch: An end-to-end-trainable iterative network architecture for accelerated radial multi-coil 2D cine MR image reconstruction. Medical Physics 48, 2412–2425 (2021)

Trapped! New cooling method for charged particles

Transmission of cooling power between two Penning traps

Especially interesting for
- fundamental research
- quantum technology

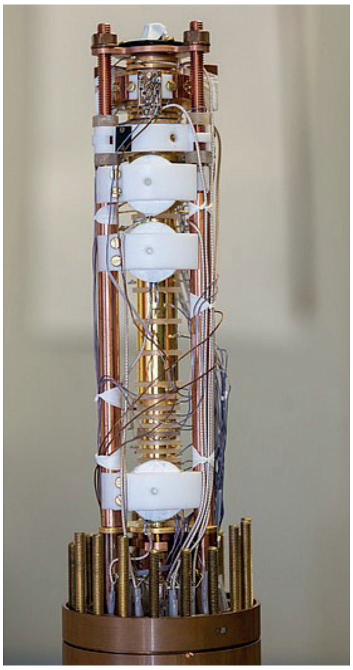
A new method to cool protons by means of laser-cooled ions – in this case, beryllium ions – has been successfully implemented for the first time worldwide. What is new about this method is that the cooling power can now be transmitted via a resonant electric circuit, covering an enhanced distance of 9 cm from one trap to the other. In this way, the proton in one of the traps can be cooled down to much lower temperatures than previously.

To be able to perform precise measurements on single ions, these ions must be enclosed and stored in a trap and must move as little as possible. Energy is removed from the charged particles to reach this state, which leads to their cooling down. Thanks to this indirect laser cooling method, the research team of the BASE collaboration project has been able to lower the temperature by a factor of approx. 10 compared with the results obtained by the previously best method of cooling protons. In this way, they have reached a temperature of a few kelvins − close to absolute zero.

Another advantage of the new double-trap cooling method is that it can also be used on antimatter particles. In a single-trap cooling system, matter and antimatter would mutually destroy each other. This new setup therefore allows a precise comparison between protons and antiprotons − and thus investigations of the fundamental issue as to why there is more matter than antimatter in the universe.

Whereas previous indirect cooling methods required distances of 0.1 mm or less between the particles to be cooled and the beryllium ions, the new method is able to transmit the cooling power over a spatial divide and a distance of 9 cm. This sets the stage for more in-depth research projects and allows the Lamor and cyclotron frequency to be measured precisely and disturbance-free. The BASE collaboration would, moreover, like to perform such measurements in its search for dark matter with the help of antimatter, too.

In the future, it should become possible to cool the particles still more and even getting them closer to absolute zero, where freezing prevents any motion. The particles could then be entirely controlled in all degrees of freedom. For this purpose, it is planned to use quantum logic techniques. Such methods of quantum manipulation are being developed by the Leibniz Universität Hannover and PTB within the BASE collaboration project. ▪



The particles are stored inside the golden structure in the center. The setup is hollow inside and similar to a stack of washers of different sizes. (Picture credits: Stefan F. Sämmer/JGU Mainz)

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Scientific publication
M. Bohman, V. Grunhofer, C. Smorra et al.: Sympathetic cooling of a trapped proton mediated by an LC circuit. Nature 596, 514–518 (2021)

Software for equalizing ultrasound signals

PTB is providing interactive software free of charge for correcting ultrasound signals and determining measurement uncertainties at the same time

Especially interesting for
- manufacturers of ultrasonic devices and ultrasound measuring equipment
- testing laboratories

With its interactive software that can be used to correct measured ultrasound signals, PTB is intending to make its signal deconvolution procedure available to a larger group of users and thus to make a contribution to quality assurance in ultrasound metrology. This open-source software program is available free of charge and can be adapted to individual requirements.

The ultrasound signals generated by medical ultrasound equipment must be characterized before such a device can be placed on the market. For this purpose, it would be ideal if the hydrophones used for these measurements had a large bandwidth and a sensitivity that is, as far as possible, independent of the frequency, so that an ultrasound device's signals can be recorded without distortion. Real hydrophones, however, usually exhibit a clear frequency response, which leads to an unequal weighting of the spectral components measured. This means that the same sound pressure leads to different signal amplitudes at different frequencies. The frequency response of a hydrophone is determined by individual calibration. It is available to users in the form of a data set.

The signal deconvolution method allows such data to be compensated for the distortion arising during a measurement. In this way, the original ultrasound pressure signal can be reconstructed in a frequency range of up to 100 MHz. This method is based on the transfer function of the hydrophone considered (in the form of calibration data) and on the ultrasound signal measured by said hydrophone (in the form of a voltage signal). The final result of the reconstruction can be stated with its associated uncertainty.

The software program developed for this purpose can be used to assess your own measurements and can also be modified after it has been downloaded. If you access it online, it also provides an interactive tutorial explaining how to use the signal deconvolution method based on examples of measurement data. The focus lies on issues arising in ultrasound measurements, for instance, with examples of calibration data from different hydrophones and real measurement data of typical sound emission measurements using these hydrophones. But a transfer to signal deconvolution issues outside ultrasound exposimetry is also possible.

In addition, this software program forms the basis for standardization and will be referenced in the revised IEC 62127-1 Ed. 2 standard. ▪

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The software
https://github.com/Ma-Weber/Tutorial-Deconvolution

Quantum-calibrated magnetic force microscopy

More reliable magnetic field measurements in the nanometer range

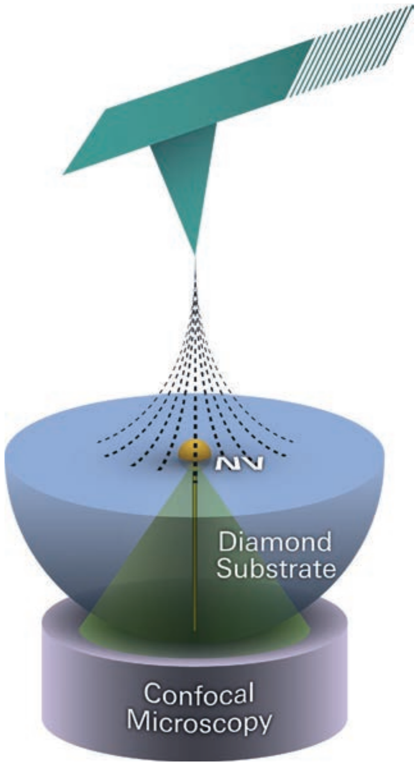
Especially interesting for
- magnetic sensor technology
- magnetic metrology

A classical measurement system for measuring magnetic field distributions, which vary spatially on the nanometer scale, was calibrated by means of an atomic quantum sensor for the first time. This new calibration procedure does not depend on simplifying model assumptions and allows more reliable measurements of magnetic field distributions with high spatial resolution.

To develop future magnetic components such as sensors and data storage devices, industry needs traceable magnetic field measuring systems with the best possible spatial resolution. The most widespread method for measuring magnetic field distributions on the nanometer scale is magnetic force microscopy (MFM). In MFM, a magnetic tip is moved a few nanometers above a sample surface while measuring the force which acts on the tip in the magnetic field of the sample. To be able to calculate the magnetic field strength from this force in SI units, the magnetic properties of the tip must be known very accurately. For this purpose, simplifying models combined with measurements on magnetic reference samples have been used to date.

Within the scope of a cooperation project between PTB and the University of Ulm, the magnetic properties of such a magnetic tip have now been characterized precisely for the first time by means of a quantum sensor. This nitrogen vacancy (NV) center sensor consists of a single atomic lattice defect in a diamond crystal whose optical spectrum depends on the external magnetic field. In the experiments performed, the magnetic tip was scanned in a plane over the NV center, and the optical spectrum was measured at each point. Based on these measurements, a map of the magnetic field emanating from the tip was derived. The tip's magnetic properties that are relevant to magnetic force microscopy were then determined from this map. After this procedure, the tip was quantum calibrated and could be used for precise and reliable magnetic field measurements on the nanoscale.

In further investigations, it is also planned to set up such a measuring system to characterize MFM tips at PTB. In this way, it would be possible to perform MFM measurements using quantum-calibrated tips directly at PTB in the future. ▪



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Scientific publication
B. Sakar, Y. Liu, S. Sievers, V. Neu, J. Lang, C. Osterkamp, M. L. Markham, O. Öztürk, F. Jelezko, H. W. Schumacher: Quantum calibrated magnetic force microscopy. Phys. Rev. B, 104, 214427 (2021)

Schematic representation of the measurement setup used for calibrating an MFM tip by means of a quantum sensor. The MFM tip (turquoise) generates a magnetic stray field which can be measured precisely over a single NV center (yellow) in a diamond substrate (blue). If the tip is scanned over the NV center, its stray field distribution is obtained – and thus quantum-accuracy information on its magnetic imaging properties is also gained.

Measuring system for coronavirus vaccine research

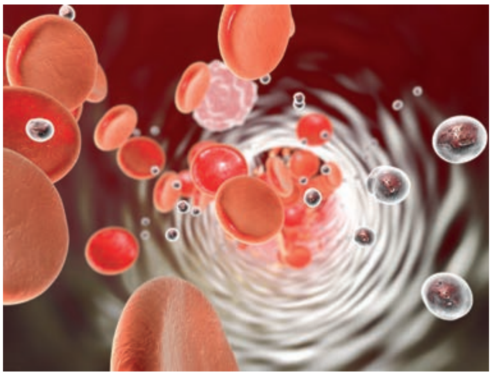
Fast and accurate measurement of the concentration of nanoparticles

Especially interesting for
- vaccine research
- particle analysis

Nanoparticles can be used, for example, to deliver vaccines or drugs deep into the human body to precisely where they are needed. To determine the dose, it is essential to acquire the most accurate information possible on the concentration of these minute particles. A very accurate and fast analytical system measures particle sizes stretching from nanoparticles of approx. 40 nm to microparticles of approx. 10 µm and can be used in applications ranging from drug targeting to coronavirus vaccine research.

In the medical field, nanoparticles represent a source of great hope. They could, for instance, serve as vehicles to help drugs overcome biological obstructions such as the air-blood barrier (in the pulmonary alveoli) and the blood-brain barrier. Researchers are using nanoparticles to try and transport cancer drugs straight to a tumor (drug targeting) or deliver vaccines.

Nanoparticles place great demands on the measuring technology required throughout the chain that stretches from product development to quality control and goes on to product risk assessment. For these tasks, the problem is increasingly not so much measuring the particle size but also measuring the number and concentration of particles.



As nanoparticles are smaller than red blood cells, they can be used as a "vehicle" to transport drugs or vaccines. (Photo credits: Adobe Stock / Kateryna_Kon)

With this in mind, PTB and LUM GmbH collaborated on a technology transfer project supported by the German Ministry for Economic Affairs and Climate Action to develop the measurement principle of a single-particle light-scattering photometer. With this technology, the distribution and concentration of nano- and microparticles in suspensions and emulsions can be determined with high resolution. Besides exhibiting high accuracy, the system can also be used in a very wide range of applications (for particles from 40 nm to 10 µm), and it is extremely fast, with the ability to analyze up to 10,000 particles per second. The fundamental technology at work here is known as single-particle light scattering (SPLS). Here, the intensity of the light scattered in various directions by each individual nano- or microparticle is measured by the instrument. To get the particles to line up so that they move one by one past the measuring device, the technique of hydrodynamic focusing is applied. In this technique, a so-called sheath flow arranges the particles in the desired direction. The particles then pass as it were single file through the center of the measuring cell. This technique has for years been used very successfully for flow cytometry, where things such as body cells can be counted individually and rapidly.

The new measuring system is capable of analyzing particle suspensions of widely varying compositions without the hardware having to be altered. Even in cases where the starting concentration is very high, the system can determine extremely small differences in size down to the nanometer scale. Both the overall system as well as individual components, such as specific amplifiers and the special optical arrangement, are based on techniques developed by the two partners which have now filed patents for these novel procedures. A global pharmaceuticals company was among the first to take delivery of one of these instruments and will use it for developing a coronavirus vaccine. A renowned German research institution has also acquired this new system. ▪

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A material measure for optical surface measurement

Fast characterization of the two-dimensional transfer function of measuring instruments

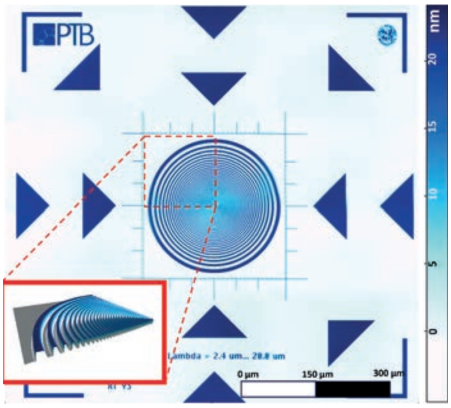
Especially interesting for
- the optical industry
- surface metrology
- microscopy techniques

The measurement responses of optical measuring devices to surface topography can be described by the instrument transfer function (ITF). At PTB, a novel material measure has been developed to characterize two-dimensional instrument transfer functions (2D-ITF) of optical measuring instruments. This material measure is flexible and easy to use. Moreover, it shows high reproducibility and robustness.

Optical areal surface topography metrology tools are often used for noncontact and fast measurements of precision surfaces such as optical mirrors of X-ray or lithography devices. However, using such tools often raises a fundamental question in optical measurements, 'Are we getting the right answer?'

To answer this challenging question, PTB, in collaboration with Zeiss-SMT, has developed a novel material measure to characterize the 2D-ITF of areal surface topography measuring tools within the scope of the 3D-Stack EMPIR project. Among other things, this new standard features circular structural patterns. Such rotationally symmetric patterns are advantageous for characterizing ITFs along different angular directions, i.e., for investigating the angular anisotropy of measuring instruments. Three different kinds of patterns have been implemented in the design: circular step patterns, circular chirp patterns whose spacing continuously changes, and circular discrete grating patterns. They are designed to represent three kinds of spatial signals for ITF characterization in a complementary way. The patterns have radii ranging from 30 µm to 300 µm and wavelengths from 0.1 µm to 150 µm. They may be combined to meet measurement requirements for various instruments that may have very different bandwidth characteristics and fields of view. The design of this material measure is therefore highly flexible and suited to various applications.

Besides the material measure, software has also been developed for the calibration process and the subsequent data evaluation. This combination allows the 2D-ITF of optical surface measuring devices to be characterized conveniently in just a few minutes. The application of the newly developed method at PTB's industrial partners shows the advantages of its high repeatability and robustness, along with its excellent flexibility and ease of use. ▪



Material measure with circular chirp patterns (section: 3D view of the structures)

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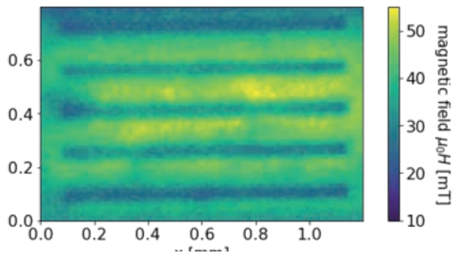
Scientific publication
G. Dai, Z. Jiao, L. Xiang, B. Seeger, T. Weimann, W. Xie, R. Tutsch: A novel material measure for characterising two-dimensional instrument transfer functions of areal surface topography measuring instruments. Surface Topography: Metrology and Properties 8, 045025 (2020)

Laser-structured magnetic scales

Especially interesting for
- dimensional metrology
- production and medical engineering

Magnetic scales are used in various technological areas to measure positions and angles. PTB's invention allows magnetic scales for precision positioning to be manufactured fast and at low cost. This novel procedure mainly consists in patterning the magnetic film defining the scale by means of a laser. Structure sizes in the micrometer range and sharp transitions between the magnetic domains allow high spatial resolution rates for magnetic measuring systems to be attained with low measurement uncertainties. This ensures a clear reduction of the positioning uncertainty and allows the manufacturing of scales that are suited to being used in precision positioning and measurement systems. The manufacturing procedure is low-cost and suited to high-volume manufacturing. (Technology Offer 491) ▪



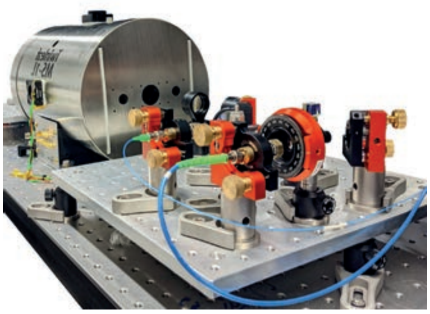
Distribution of the magnetic flux density measured with a magneto-optical viewer and using the new scales

Advantages
- high spatial resolution in the range of a few micrometers
- fast and low-cost manufacturing procedure
- use of conventional materials for the scales

A quantum sensor for velocity

Especially interesting for
- manufacturers of high-precision velocity sensors
- aerospace industry

An innovative concept for improving the sensitivity of a quantum sensor for velocity measurement has made versatile applications in the aerospace industry possible. The new procedure allows high velocities to be recorded quickly with high accuracy and in a large dynamic range. For this purpose, a conventional Doppler measurement is complemented by an additional element of a rubidium cell, and the phase of the laser light is then analyzed. In this way, the resolution of velocity measurements used in conventional applications such as lidar or radar can be improved by several orders of magnitude. This new technology is currently being tested at laboratory scale and can easily be integrated into miniaturized modules. (Technology Offer 528) ▪



Advantages
- simple analytical velocity measurement
- high resolution
- miniaturization

Detecting ultrasonic “noise”

Especially interesting for
- noise measurement technology
- metrology institutes

At many workplaces, the prevailing sound exposure is caused by sound in the high-frequency audible range or even by ultrasound. It has to be possible to detect noise exposure with a small measurement uncertainty even in this frequency range. PTB's concept of a mobile high-frequency personal sound exposure meter is suited to measuring a large number of quantities that are typical of the audible range and can now also be measured in the ultrasound range as noise an individual person is exposed to. This novel concept thus contributes to improved occupational safety. (Technology Offer 7095) ▪

PTB's high-frequency personal sound exposure meter in use

Advantages
- measuring high-frequency audible sound and ultrasound
- determining the sound exposure of a person
- improving occupational safety

Contact person for questions about technology transfer
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Awards

Mathias Richter

Mathias Richter, Head of Division *7 Temperature and Synchrotron Radiation*, was elected to the Council of the German Physical Society (DPG).

Piet Schmidt

Piet Schmidt, *Head of the QUEST Institute at PTB*, was appointed as a "Fellow of the American Physical Society" (APS) in recognition of his achievements in the development of quantum logic spectroscopy techniques and their application in high-precision measurements of optical transitions in atoms, molecules and highly charged ions.

Ekkehard Peik

Ekkehard Peik, *Head of Department 4.4 Time and Frequency*, received the "I. I. Rabi Award 2021" from the Institute of Electrical and Electronics Engineers (IEEE) in recognition of his achievements in the development of optical clocks and in tests of fundamental physics.

Uwe Sterr

Uwe Sterr, a staff member of Department 4.3 *Quantum Optics and Unit of Length*, received the "European Frequency and Time Award" (EFTA Award) in 2020 in the field of ultrastable lasers for optical frequency standards and highest resolution spectroscopy.

Peter Micke

Peter Micke, a post-doc at the *QUEST Institute at PTB*, won the SAMOP dissertation prize of the German Physical Society (DPG) for his doctoral thesis entitled "Quantum Logic Spectroscopy of Highly Charged Ions".

Metrology network for radiation protection

The new European Metrology Network (EMN) for Radiation Protection was launched on 16 September 2021. The expertise of 16 metrology institutes, two national radiation protection institutes and one European radiation protection organization which are now members is gathered here under the umbrella of EURAMET. (Contact: Annette Röttger, +49 531 592-6010, annette.roettger@ptb.de

Metrology network for advanced manufacturing

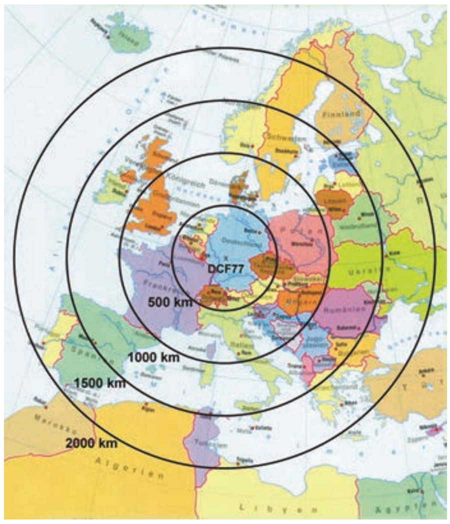
An additional new European Metrology Network (EMN), also under the umbrella of EURAMET, took up work at the beginning of October 2021. Here, 14 metrology organizations which are currently members are working on utilizing the full potential of advanced manufacturing with the aid of improved measuring technologies. (Contact: Harald Bosse, +49 531 592-5010, harald.bosse@ptb.de)

Developing a quantum computer

In the new joint project "ATIQ – *Quantencomputer mit gespeicherten Ionen für Anwendungen*" (quantum computers with stored ions for applications), 25 partners are aiming to develop the first generation of reliable and user-friendly quantum computer demonstrators with around-the-clock availability on the basis of ion trap technology within 30 months. To achieve this, the leading ion trap research groups at the universities of Hannover/Braunschweig, Siegen and Mainz have joined forces with research institutes (including PTB) and partners from industry. The project is being funded with 37.4 million euros by the Federal Ministry of Education and Research. (Contact: Christian Ospelkaus, +49 531 592-4740, christian.ospelkaus@ptb.de)

Time is still being broadcast via longwave

For PTB, the long-wave transmitter DCF77 is still the most important medium for the dissemination of legal time in Germany. Millions of radio-controlled clocks throughout Europe receive the time signals that are broadcast at 77.5 kHz. PTB's contract with the company Media Broadcast GmbH for it to operate the transmitter has just been extended to 2031. Due to continuous modernization of the facility as well as its unbeatable simplicity and reliability, it is still the state of the art to disseminate time via longwave – even decades after it was introduced. (Contact: Andreas Bauch, +49 531 592-4420, andreas.bauch@ptb.de)



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Federal Ministry for Economic Affairs and Climate Action

The Physikalisch-Technische Bundesanstalt, Germany's national metrology institute, is a scientific and technical higher federal authority falling within the competence of the Federal Ministry for Economic Affairs and Climate Action.