PTB news
Scientific Newsletter
3
2017

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.

Carbon ions against cancer

Radiation measurements in cooperation with PTB create a basis for more precise dosage

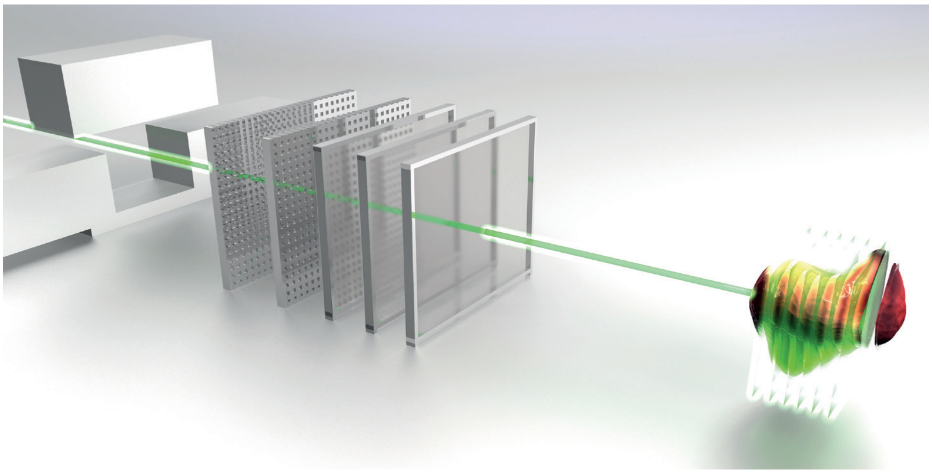
Especially interesting for
- radiation therapy
- dosimetry

Tumor irradiation by carbon ions is clearly becoming more precise. With the help of investigations carried out by the Physikalisch-Technische Bundesanstalt (PTB), the accuracy of the absorbed dose measurement could be improved by a factor of three. The German Cancer Research Center (DKFZ) and the Heidelberg Ion Beam Therapy Center (HIT) were also involved in this research collaboration.

Tumor radiation with carbon ions can offer an additional healing effect compared to conventional irradiation methods, since together with the raster scan method used in this case, the radiation dose can be positioned very precisely and the surrounding tissue is best preserved. This therapy is particularly interesting in the case of deep-seated tumors as well as of those which are surrounded by particularly radiation-sensitive tissue. To date, however, the dosimetry of such ion beams has not been as precise as the dosimetry of conventional, high-energy X-rays.

In order to measure the absorbed dose of the radiation used, calibrated detectors, usually so-called ionization chambers, are used in clinical dosimetry. However, ionization chambers respond differently to different types of radiation. Therefore, a correction factor must be taken into account depending on the type of radiation. This factor previously had an uncertainty of approximately 3 % when using carbon ions, which is approximately three times higher than in x-radiation. The goal of the cooperation project was to reduce the uncertainty to 1 %.

To date, only a theoretically determined correction factor has been used in everyday clinical practice, as there is no reliable experimental data. This project has now shown for the first time that this factor can indeed be measured with much less uncertainty. This was achieved by means



Schematic representation of the raster-scan method used at the HIT. The ion beam (green) is scanned by means of magnets using a predefined raster, while the number of particles is determined at each position. By varying the energy, the penetration depth of the ions into the tumor (on the right of the figure) is also varied. This enables very precise irradiation of the tumor as a whole. (Fig.: HIT) of a portable water calorimeter, which was used at the HIT facility to exactly measure the absorbed dose to water and to experimentally determine the correction factor for different ionization chambers.

The next step will be to carry out investigations also with other ion beams, e. g. with helium or oxygen ions. ▪

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Scientific publication
J.-M. Osinga-Blättermann, S. Brons, S. Greilich, O. Jäkel, A. Krauss: Direct determination of k_Q for Farmer-type ionization chambers in a clinical scanned carbon ion beam using water calorimetry. Phys. Med. Biol. 62, 2033–2054 (2017)

Highly sensitive SQUID system

Modular, field-tolerant multi-channel magnetometer with so far unequalled sensitivity

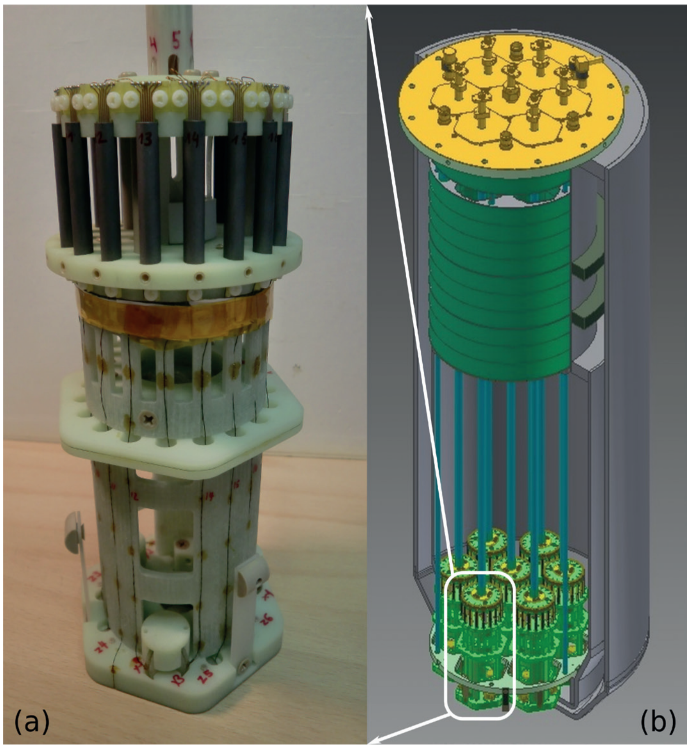
Especially interesting for
- biomedical research
- fundamental research in physics

In order to develop the highly sensitive magnetic measurement technology for biomedical research further and to deal with fundamental questions of physics, a new multichannel vector magnetometer module has been developed at PTB. This 18-channel device forms the basis of a measuring system using a modular design.

At PTB, SQUID (Superconducting QUantum Interference Device) magnetometers have long been used to determine extremely small changes in magnetic flux. The previously used multichannel SQUID systems were mainly applied in medical metrology to detect magnetic heart signals (magnetocardiography) and to measure and localize ion currents in the human brain (magnetoencephalography). For new applications in ultralow-field magnetic resonance or for magnetic relaxometry, samples must be pre-polarized with a magnetic field in the mT range shortly before the actual measurement is performed. This required the development of new SQUID magnetometers that are robust against the fields of the pre-polarization phase (which are higher by a factor of 10^{12}) without losing sensitivity during the measuring phase.

To achieve these requirements, a SQUID current sensor, which had already been developed at PTB, was combined with a separate field coil. The highly sensitive SQUIDs are located within a superconducting shielding to protect them from the high fields occurring during the pre-polarization phase. One sensor module consists of an array of 18 of those SQUID magnetometers. Each module is equipped with sensors in two measurement planes with individual field coils that are sensitive to all three spatial directions, and with coils of two different diameters. The larger coil improves the detection of sources that are located further away. The individual field coils are arranged in such a way that several sensor modules can be combined with each other.

It has been demonstrated that the new system is robust against pre-polarization fields into the mT range. The new SQUID measuring systems with the 17 mm and 75 mm field coils attain a minimum white noise of the magnetic flux density of 540 aT/√Hz and 61 aT/√Hz, respectively. The sensitivity of the sensors compared to the previous system has thus been more than doubled, and the application possibilities have considerably increased. ▪



Prototype of the new 18-channel SQUID module. (a) Multichannel module. (b) Measuring system with seven multichannel modules.

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Scientific publication
J.-H. Storm, D. Drung, M. Burghoff, R. Körber: A modular, extendible and field-tolerant multichannel vector magnetometer based on current sensor SQUIDs. Supercond. Sci. Technol. 29, 094001 (2016)

3D-Lasermeter with refractive index compensation

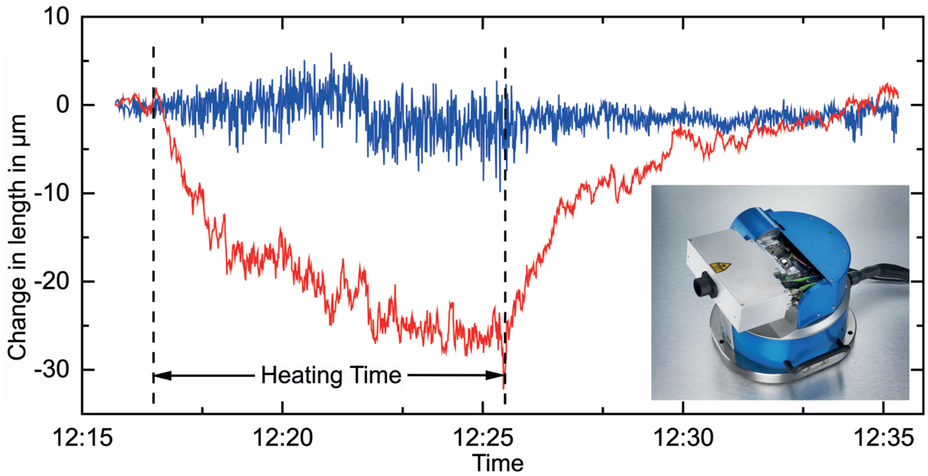
Interferometric length measurement under difficult ambient conditions

Especially interesting for
- the aviation industry and other manufacturers of large-scale components (wind power industry, etc.)
- manufacturers and operators of coordinate measuring machines
- providers of calibration services

Within the scope of an international project, PTB has developed the prototype of a 3D-capable interferometer that compensates for the optical refractive index of air intrinsically. This so-called 3D-Lasermeter has been successfully tested in two series of tests under difficult industrial ambient conditions.

The requirements placed on the dimensional accuracy of large-scale components (with dimensions of several meters) are becoming more and more demanding in industry and fundamental research. In the aviation industry, for instance, drill holes in wing segments must be positioned with an accuracy on the order of a few tens of micrometers. Such accuracies can be attained with various optical measurement procedures – in particular interferometry-based ones. For correct measurements, the refractive index of the ambient air must, however, be known with sufficient precision. This, in turn, requires the correct detection of the following ambient parameters: pressure, temperature, relative humidity and CO_2 concentration. If a length is to be determined with micrometer accuracy over a length of 10 m, for example, then the temperature inside the beam must be known with 0.1 K accuracy. For measurements performed outside well-air-conditioned laboratories, this can only be achieved approximatively by means of a very dense and elaborate network of sensors to pick up the ambient parameters.

Within the scope of the international LUMINAR (Large Volume Metrology in Industry) project, an alternative approach has been pursued: the refractive index is determined parallel to the actual length measurement by dispersive refraction compensation. Hereby, the geometrical length is measured by means of two interferometers with optical frequencies (or wavelengths) that are different from each other but very accurately known. By combining the information gained about the path length in this way, it is possible to determine the refractive index – and thus the exact geometrical length – without additional information and with an accuracy of up to $1 \cdot 10^{-7}$.



Verification of the 3D-Lasermeter during measurements at the Polish metrology institute (GUM). A constant distance of 19 m was measured with the wavelengths 532 nm and 1064 nm of the 3D-Lasermeter manufactured by SIOS GmbH (small picture). When using a network of temperature sensors to compensate for the refractive index, the distance is allegedly reduced by up to 30 µm (red curve) during the warm-up phase. Contrary to this, the distance from the intrinsically determined correction of the refractive index (blue curve) remains stable (apart from the slightly higher noise).

Within the scope of the LUMINAR project, PTB, together with SIOS Meßtechnik GmbH, has developed the prototype of an auto-tracking interferometer which intrinsically compensates for the refractive index. The probe can automatically follow a measuring reflector in space. To this end, two wavelengths of two NdYAG lasers, which are stabilized against each other, are used.

The 3D-Lasermeter was tested within the scope of the same project at the 50 m comparator section of the Polish metrology institute (GUM) under difficult controlled ambient conditions. Moreover, it was also successfully tested under real industrial conditions in an Airbus test hangar in Filton, UK. Thereby, it was possible to demonstrate that the measurement uncertainty of the intrinsically optical refractive index compensation is in the micrometer range.

Two patents have been granted with regard to the procedure. By means of established multilateration procedures, the system can be used to determine the position of points in space – i.e. in the future, it could be used to calibrate large-scale coordinate measuring machines (such as those used to measure the components of wind turbines). ■

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Scientific publication
K. Meiners-Hagen, T. Meyer, G. Prellinger, W. Pöschel, D. Dontsov, F. Pollinger: Overcoming the refractivity limit in manufacturing environment, Opt. Express 24, 25092 (2016)

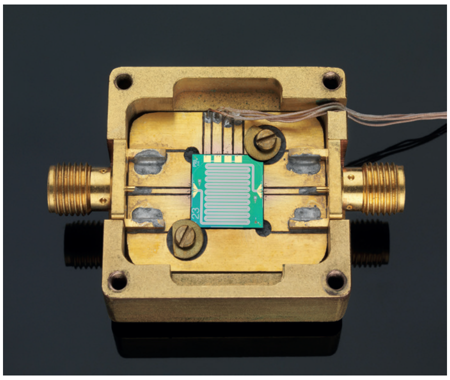
Microwave amplifier for quantum electronics

Superconducting tunnel junction circuit allows broadband parametric amplification of very weak microwave signals

Especially interesting for
- fundamental research
- electrical quantum technologies
- quantum information processing

Quantum information technology requires low-noise and extreme broadband amplifiers for weak microwave signals. A novel parametric amplifier with Josephson junctions that was developed at PTB distinguishes itself through high gain, broad bandwidth and low noise.

A parametric amplifier is a low-noise high-frequency amplifier which converts energy from a pump into a signal wave by means of nonlinear, reactive components. Modern parametric amplifiers with Josephson junctions (Josephson parametric amplifiers – JPAs) exhibit almost quantum-limited noise behavior, but due to their resonance architecture, they cannot attain sufficiently broad bandwidths. These are, however, urgently required for ultrasensitive microwave sensors (for the detection of microwave signals on the order of single photons) or for the development of quantum computers. In contrast, JPAs based on so-called traveling waves can achieve broad bandwidths. To date, these traveling-wave JPAs have been realized by Josephson junctions that were embedded in high-frequency lines, whereby the relation between the Josephson current and its phase (the so-called Josephson nonlinearity) is given by a cubic relation.



Chip with series-connected superconducting SQUIDs of the traveling-wave amplifier in the sample holder with microwave connectors. The series circuit contains 2296 SQUIDs in a meander-shaped high-frequency line of 11.5 cm in length.

A new concept for a simple set-up of a traveling-wave JPA based on an advantageous quadratic Josephson nonlinearity has now been suggested at PTB. This approach is based on single-junction SQUIDs connected in series; it allows the Josephson nonlinearity to be controlled by means of an external magnetic field. In contrast to JPAs with a cubic nonlinearity, it is possible to efficiently adjust the phases of the traveling pump wave and of the signal wave to be amplified by suitably selecting the operating point. This leads to a larger gain of the amplifier in a broad frequency range. Moreover, the useful signal can easily be separated, since it is much better distinguished from the pump signal in the frequency range.

An initial test circuit was manufactured using the niobium technology with Nb/AlOx/Nb Josephson junctions; it was then characterized in liquid helium at a temperature of 4.2 K. The measurements show a power gain of more than 10 dB in a frequency range of approx. 3 GHz. Further investigations of the JPA circuit will show whether the minimum amplifier noise aimed for can be achieved at the quantum-mechanical limit. For a possible later use in quantum electronics, however, gain and bandwidth need to be further increased. ▪

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Scientific publication
A. B. Zorin: Josephson traveling-wave parametric amplifier with three-wave mixing. Phys. Rev. Applied 6, 034006 (2016)

Phantoms coming out of a 3D printer

Manufacturing of novel test pieces with magnetic nanoparticles

Especially interesting for
- biomedical research
- magnetic particle imaging

A procedure further developed by PTB allows plastic test pieces (phantoms) containing well-defined additions of magnetic nanoparticles to be manufactured for the first time. This procedure opens up the possibility of making nanoparticle distributions that are precise and have long-term stability available to biomedicine in any arbitrary geometries for the testing of magnetic imaging modalities.

3D printing is a manufacturing process in which a component is built up by adding layer after layer of material. Within the scope of a joint project with PTB's Biosignals Department, the Scientific Instrumentation Department is operating a digital light processing facility in which the components are manufactured by adding layer after layer of liquid and photocurable resin. This procedure allows components made from the most various acrylic polymers to be manufactured with great precision and attention to detail.

It had not been possible to date to produce test pieces with defined magnetic properties. These are, however, highly relevant for activities of medical metrology at PTB such as calibration artefacts with long-term stability or phantoms in biomedical imaging. PTB has now succeeded in developing a procedure that allows components with defined concentrations of homogeneously distributed magnetic nanoparticles to be manufactured with great attention to detail of the geometries produced. For this purpose, it was necessary to develop special characterization procedures to control the quality of the magnetic components.

The 3D printing of phantoms containing magnetic nanoparticles provides components with well-defined magnetic functions and geometries, and allows new procedures of biomedical imaging to be assessed and improved. This is supported by research activities on components with defined optical properties for fluorescence imaging which can also be manufactured by means of 3D printing. ■

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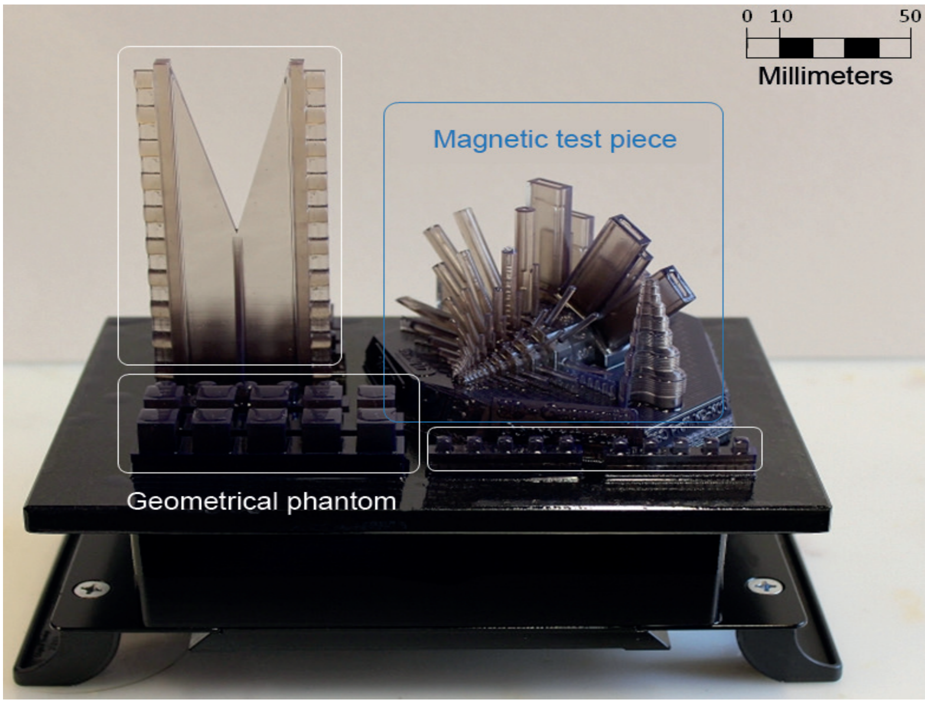

Geometrical phantom (framed in blue) for the assessment of the level of detail, and magnetic test pieces of different dimensions (framed in white) with defined combinations of nanoparticles and resins from generative manufacturing. Size of the assembly space: 230 mm × 160 mm × 125 mm.

How fit is the battery of my electric car?

Reference measurement set-up for Li ion battery cells

Especially interesting for
• electromobility

For the practical use of battery-operated electric vehicles, measurement methods are required which provide fast and reliable information as to whether and to what extent the maximum charging capacity of a Li ion battery has already decreased. This is referred to as the "state of health". To measure a battery's state of health, PTB has installed a reference measuring set-up that uses electrochemical impedance spectroscopy as well as a model designed to simulate aging.

A promising measurement method to quickly measure the health of a Li ion battery is electrochemical impedance spectroscopy. If the electrochemical processes in a battery cell change due to battery aging, then the impedances measured at different frequencies (AC resistances) – the so-called impedance spectrum – also change. As a result, these changes can be used as a measure of a battery cell's state of health.

Reference measuring set-up for the state of health of Li ion battery cells for electric vehicles. Due to the large amount of electrochemically stored energy, aging and impedance measurements must be performed in air-conditioned safety cabinets.

The aging that to date has been quantified merely empirically by impedance spectroscopy is now additionally simulated with a battery model. It is based on charge and mass transport equations which describe the processes in the battery cell mathematically. If – in addition – equations are implemented for the description of the aging processes, the degradation process can also be simulated. The modeling, unlike the experiment, offers the possibility to vary all parameters independently of one another, for example diffusion coefficients, layer thicknesses or reaction rates, in order to analyze their influence on the impedance spectrum.

The simulations implemented by PTB together with the Institute of Energy and Process Systems Engineering of the Technical University (TU) Braunschweig can be used to describe the change of measured impedance spectra during aging by means of parameter variations. Meanwhile, initial model calculations have been carried out successfully. The aging model is now applied to identify parameters derived from the impedance spectra that change with the state of health of a battery cell.

After the measuring set-up has been validated by means of further lifetime tests, it will be included in PTB's range of services. This will provide industry with type-specific reference spectra for the measurement of the health of Li ion battery cells using electrochemical impedance spectroscopy. ■

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Solar wind and space weather

ESA spacecraft Solar Orbiter's instruments calibrated

Especially interesting for
- solar and atmospheric research
- developers of space telescopes

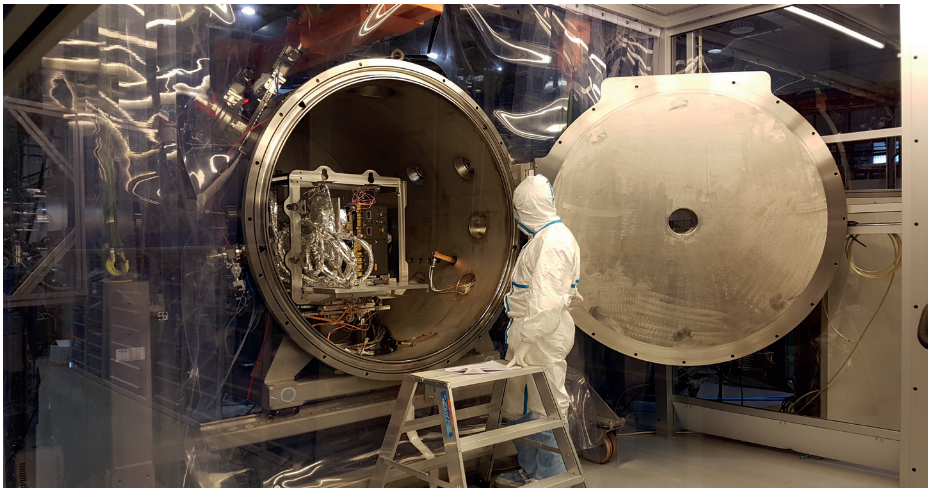
Solar Orbiter is a spacecraft of the European Space Agency (ESA) which is intended to orbit and investigate the Sun scientifically for seven years. This mission is currently scheduled to start in October 2018. Three of the Solar Orbiter's instruments will measure the Sun in the vacuum UV or extreme ultraviolet radiation spectral range with radiation at wavelengths shorter than 130 nm. The concluding characterization at these wavelengths was recently carried out using synchrotron radiation at the Metrology Light Source (MLS) of PTB.

The main objective of the Solar Orbiter mission is to observe the so-called space weather, i.e. processes taking place in the solar corona which, due to particle radiation (the "solar wind"), directly influence the Earth's atmosphere. They are responsible for polar lights, but can also massively interfere with satellite communications and air travel, as examples.

Solar Orbiter will have a total of ten instruments on board, six of which serve the purpose of remote sensing – three of those in the VUV and EUV spectral range: the Extreme Ultraviolet Imager (EUI) and the SPICE instrument (Spectral Imaging of the Coronal Environment) as well as an observatory channel of the METIS (Multi Element Telescope for Imaging and Spectroscopy). PTB was already involved early on in the development phase of all three instruments by characterizing individual optical components.

In the final phase of instrument characterization, the EUI's flight model has now been calibrated directly radiometrically using the large vacuum tank that was conceived specially for such purposes at the MLS and by tracing it to cryogenic electrical substitution radiometers as primary detector standards. The final calibration of SPICE, however, was carried out externally by means of source-based radiometry using a hollow-cathode discharge source whose calibration had, in turn, been traced to the MLS as a primary radiation standard.

These activities were undertaken in close cooperation especially with the following scientific institutions responsible for the construction and the operation of the instruments: the Centre Spatial de Liège (CSL, Liège, Belgium), the Max Planck Institute for Solar System Research (MPS, Göttingen, Germany) and the Rutherford Appleton Laboratory (RAL, Harwell, UK). The calibrated instruments are currently receiving final assembly on the spacecraft platform and are being prepared for launch. ■


The EUI instrument for Solar Orbiter during installation in a large vacuum tank at the MLS

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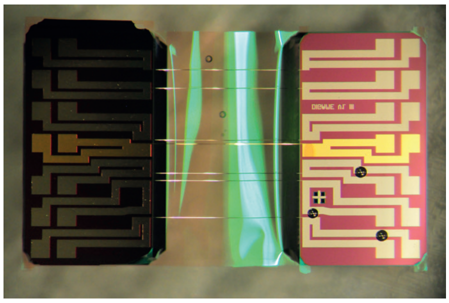
Miniature gas sensor

Especially interesting for
- manufacturers of flow sensors
- manufacturers of household gas meters

A new miniature gas sensor developed by PTB not only precisely determines the volumetric flow of a gas but also identifies the composition, for example, of several energy gases. For this purpose, it measures the thermal conductivity, temperature conductivity and specific heat of gas volumes of a few milliliters within one tenth of a second. The thermal conductivity is determined by the hot strip method. The temperature conductivity follows from a long-term measurement; the specific heat is measured calorimetrically. (Technology Offer 0344) ■

Advantages
- *simultaneous measurement of flow and gas composition*
- *cost-effective production*
- *miniaturized sensor*



Arrangement of the sensor elements in the gas sensor system

Improved strip electrode

Especially interesting for
- testing laboratories
- explosion protection

Surface resistance is considered an important parameter in explosion protection to assess the electrostatic charge of building elements which might lead to electrostatic discharge and, in the worst case, to an ignition of an explosive atmosphere. A strip electrode constructed by PTB serves to measure surface resistance according to the relevant standard IEC 60079-32-2. It combines the advantages of various marketable concepts and aims at a safe, user-friendly solution that provides precise and reproducible results. (Technology Offer 7062) ■

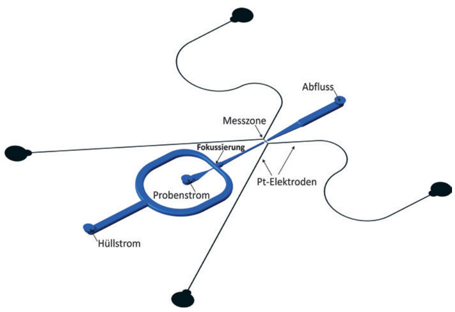
Strip electrode

Advantages
- *safe and user-friendly handling*
- *guaranteed contact pressure force of 20 N*
- *in accordance with the standard*

Counting different blood cell types simultaneously

Especially interesting for
- medical engineering
- oncology
- immunology

The quantitative investigation of cells in blood by means of flow cytometry is a routine procedure in medical diagnostics. Thanks to the development of this novel procedure by PTB, it has become possible to determine the concentrations of erythrocytes, thrombocytes and leukocytes in blood samples simultaneously and reliably by means of AC impedance. Due to



Microfluidic component with flow channel (center) and sensor electrodes

this, hemolysis, which might destroy target cells in patients with diseases, can be avoided. Via a micro-channel system with hydrodynamic focusing, the blood sample is led to a sensor which measures the electric impedance (typically in a range from 1 MHz to 10 MHz). It is thus possible for the first time to determine concentrations easily and reliably by impedance measurements without staining or hemolysis in patients with diseases such as leukemia. (Technology Offer 0422) ■

Advantages
- *no hemolysis*
- *no (fluorescence) staining required*
- *improved diagnosis of leukemia and anemia*
- *low cost*

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Awards

PTB

The German Council of Science and Humanities has evaluated PTB and awarded it an excellent rating. The results go above and beyond the previous outstanding rating from the first evaluation in 2008. In the report which was published on 2 May, the Council praised PTB's performance of legal core tasks, research activities and services as well as strategy and planning processes that are necessary for the two aspects. The report can be reviewed as a pdf at: http://t1p.de/gfsv

Joachim Ullrich

The PTB President was awarded with the Federal Cross of Merit, Class 1. Thereby, the Federal Republic of Germany honored Ullrich's substantial activities as a world renowned researcher and scientific manager. Braunschweig's Mayor Ulrich Markuth presented the award at a ceremony in the city's Old Town Hall.

Roman Schwartz

PTB's Vice President (left in the photo) was named honorary professor of the Leibniz Universität Hannover (LUH). By awarding the honorary title, the university recognizes the internationally renowned physicist's long-term commitment to teaching "Introduction to metrology – measuring mechanical quantities" at the LUH's Faculty of Mechanical Engineering.

Manfred Kochsiek

The former PTB Vice President (left in the photo) received the great Mendeleyev Medal for 50 years of excellent work in teaching, research and international cooperation. The Russian Academy of Metrology has only awarded this distinction four times and presented it during a ceremony at the VNIIM Mendeleyev Institute's 175th anniversary celebration in St. Petersburg.

Harald Bosse

The Head of Division 5, "Precision Engineering", was named President of euspen (European Society for Precision Engineering and Nanotechnology).

Fritz Riehle

The former Head of Division 4, "Optics", received the EFTF award. With it, the European Frequency and Time Forum (EFTF) honored Riehle's longtime and enduring achievements in the development of highly precise optical atomic clocks and their influence on the future new definition of the second.

Andreas Steiger, Ralf Müller

In cooperation with the company SLT Sensor- und Lasertechnik GmbH in Wildau, Andreas Steiger (Department 7.3) und Ralf Müller (formerly Department 7.3) received the special "Junges Unternehmen" award from the AMA Verband für Sensorik und Messtechnik e.V. The team developed detectors for the absolute radiant power measurement in the terahertz spectral range.

Application-oriented quantum technology

As the first of three pilot projects within the national initiative "Quantum technology – basics and applications" (QUTEGA), which was created by the Federal Ministry of Education and Research, the joint project "Optical single ion clocks for users" (optIclock) was started on 1 May. Under the special guidance of TOPTICA Photonics AG and PTB, it is intended to realize a demonstrator for optical single ion clocks within three years. The clock should go well beyond being a solution in the lab and therefore be attractive for different applications. Further information: QUTEGA concept paper: http://www.qutega.de

Call for Entries: Helmholtz Prize 2018

The Helmholtz Prize, awarded every two to three years by the Helmholtz-Fonds e.V. (Helmholtz Foundation) and the Stifterverband für die Deutsche Wissenschaft (Donors' Association for the Promotion of Science and Humanities in Germany), is a token of the highest esteem to scientists for precision measurements in physics, chemistry and medicine. The work to be submitted must be a recent research achievement, either contributing to fundamental research or aiming at concrete applications. The work should have been carried out in Europe or in cooperation with German scientists. Manuscripts may be written in German or English. The awards ceremony will be held on 17 May 2018 in the context of the 670th WE Heraeus Seminar titled "Fundamental Constants: Basic Physics and Units" in the Physikzentrum in Bad Honnef. Applications may be submitted electronically by 18 December 2017 to: Prof. Dr. Joachim Ullrich, Chair of the Board of Administration of the Helmholtz-Fonds e.V., c/o PTB, using the application web page: www.helmholtz-fonds.de/helmholtz-preis

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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 Energy.