PTB news
Scientific Newsletter
2
2016

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.

World record for two optical clocks

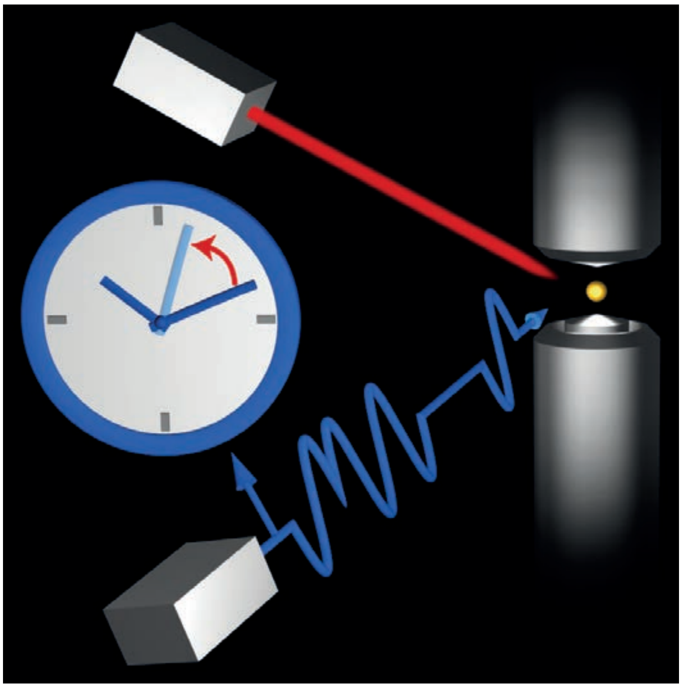
PTB's ytterbium single-ion clock is the most accurate clock of its kind worldwide; the strontium clock is the most stable optical clock ever

Especially interesting for
- developers of optical atomic clocks
- geodesy
- fundamental research

With two clocks that are currently the best worldwide in terms of accuracy and stability, respectively, PTB is well-prepared for future tasks in fields such as fundamental physics where such clocks are necessary to detect possible changes in fundamental constants.

Optical clocks are deemed the clocks of the future. In optical clocks, the atoms, which act as a "pendulum", are resonantly excited by means of optical radiation. Compared to cesium atomic clocks (10^{10} Hz) – on which the SI base unit, the second, is currently based – their excitation frequency (10^{14} Hz to 10^{15} Hz) is much higher. Therefore, the resonance quality is much better, which implies considerably increased clock accuracy (i.e. lower deviation from the true frequency) and higher stability (i.e. the required averaging period for one measurement is reduced). In both fields, PTB's optical atomic clocks are currently one step ahead.

PTB's ytterbium clock is approximately a hundred times more accurate than the best cesium clocks and is currently the world's most accurate single-ion clock. To develop this clock, the researchers from PTB exploited particular physical properties of Yb^+: this ion has two reference transitions with which an optical clock can be realized. The clock is actually based on the excitation into the so-called "$F_{7/2}$ state" which, due to its extremely long natural lifetime (approx. 6 years), provides exceptionally narrow resonance. Due to the particular electro-



Schematic representation: Measuring the influence of thermal ambient radiation on the frequency of the trapped ion in the ytterbium clock. The "clock laser" (blue beam) excites the trapped ion (yellow) with a special pulse sequence. The resonance frequency of the ion is shifted by infrared radiation (here by an infrared laser, red beam). This can be measured by means of the clock laser.

nic structure of the $F_{7/2}$ state, the shifts of the resonance frequency caused by electric and magnetic fields are exceptionally small. The other reference transition (into the $D_{3/2}$ state) exhibits higher frequency shifts and is therefore used as a sensitive "sensor" to optimize and control the operating conditions.

The decisive factor for the last leap in accuracy was the combination of two measures: firstly, a special procedure was developed for the excitation of the reference transition. With this procedure, the "light shift" of the resonance frequency caused by the exciting laser is measured separately. This information is then used to immunize the excitation of the reference transition against the light shift and its possible variation. Secondly, the frequency shift induced by the thermal infrared radiation of the environment (which is relatively small for the F state of Yb^+ anyway) was determined with an uncertainty of only 3 %.

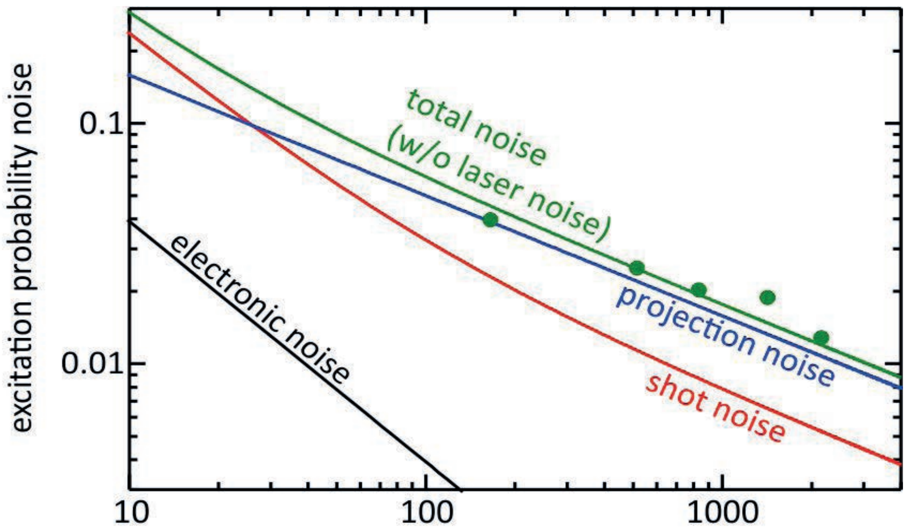
Another particular property of the F state of Yb^+ is the strong dependence of the state energy on the value of the fine-structure constant (the elementary fundamental constant of electromagnetic interaction) and on violations of the Lorentz invariance for photons or electrons, as expected in some presently discussed theories on the unification of the fundamental interactions. Comparisons between Yb^+ clocks and other highly accurate optical clocks (such as the strontium clock) are currently probably the most promising way of verifying theories from this area of "New Physics" in the lab.

Contrary to ion clocks, a strontium clock uses laser cooling to slow a gas of neutral atoms down to temperatures near absolute zero. Then, an extremely narrow transition between long-lived eigenstates of the atoms is excited in order to stabilize the frequency of the excitation laser to that of the atoms. The simultaneous interrogation of numerous atoms leads to a particularly high signal-to-noise ratio and, thus, to higher stability. However, since an atomic cloud must be prepared after each comparison between the laser and the atomic frequency, interruptions in the observation of the laser frequency occur. The laser itself hence serves as a "flywheel" and is commonly pre-stabilized to a resonance frequency of an optical resonator which keeps the laser frequency stable over short periods of time.

For PTB's strontium clock, a resonator was developed whose frequency is among the most stable worldwide. Due to its length of 48 cm and ingenious thermal and mechanical isolation from its environment, it reaches a fractional frequency instability of only $8 \cdot 10^{-17}$. When analyzing the individual contributions to noise of the detected excitation probability, it turned out that the clock reaches the physically determined fundamental quantum projection noise limit as soon as with 130 atoms.

A model based on the data obtained for the noise was supplemented by the known influence of the laser frequency noise, and its prediction was experimentally verified by a self-comparison of the clock. From this, a fractional instability in normal operation amounting to $1.6 \cdot 10^{-16}/\tau^{1/2}$ was ·derived as a function of the averaging time τ in seconds. This is the best published value for an atomic clock so far. This is expected to considerably facilitate the further reduction of the total measurement uncertainty of the strontium clock down to a few parts in 10^{18}.

Apart from testing the "big issues" of fundamental physics, possible applications of highest-precision clocks arise in geodesy where they enable direct and accurate measurement of the gravitational potential of the Earth. ■



Noise contributions of the strontium lattice clock as a function of the number of atoms. The predicted total noise without the contribution of the interrogation laser (green line) is confirmed by experimental data (green circles). The quantum projection noise (blue line) already dominates with few atoms.

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Scientific publication
N. Huntemann, C. Sanner, B. Lipphardt, C. Tamm, E. Peik: Single ion atomic clock with 3 · 10⁻¹⁸ uncertainty
Phys. Rev. Lett. 116, 063001 (2016)

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Scientific publication
A. Al-Masoudi, S. Dörscher, S. Häfner, U. Sterr, C. Lisdat: Noise and instability of an optical lattice clock
Phys. Rev. A 92, 063814 (2015)

Ultrastable materials investigated in depth

Thermal expansion measured at low temperatures for future space missions

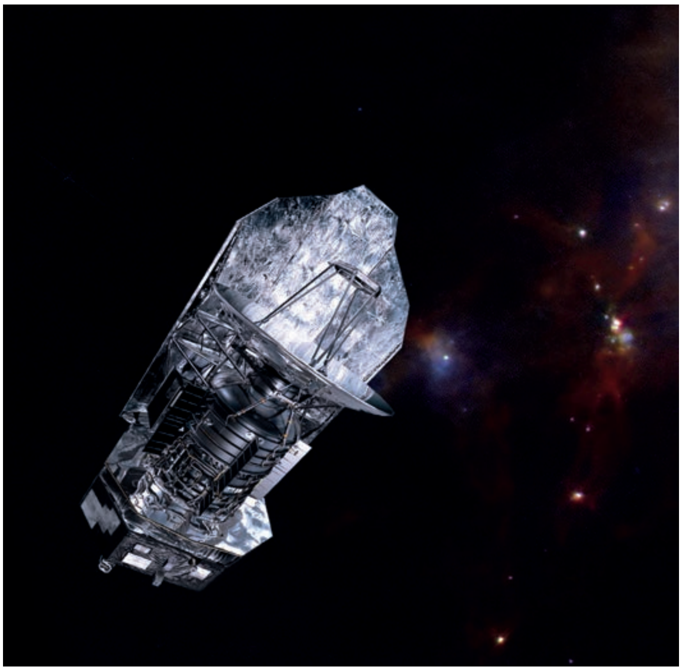
Especially interesting for
- space research
- semiconductor physics
- materials research

Space telescopes such as the infrared observatory Herschel of the European Space Agency (ESA) observe radiation in the far infrared. In this context, it is of vital importance that the instruments are cooled so that they do not emit disturbing infrared radiation. The mirrors of these telescopes, which are used at temperatures below –190 °C, are made of special, ultrastable ceramics. In a cooperation project with ESA, PTB measured the thermal expansion of the materials used and of single-crystal silicon very precisely. The investigations will be useful for future space missions, but have also shown that the values used to date for single-crystal silicon as a reference material must be corrected.

From outer space, space telescopes can investigate spectral ranges that are not accessible from the Earth. How critical it is to know the exact thermal expansion of the materials used when setting up such telescopes was clearly demonstrated during the Herschel mission, as it was revealed that the simulations performed previously were not in agreement with the manufactured mirrors. The discrepancies were fortunately not discovered in space, but still led to unnecessary delays. To prevent such unpleasant surprises from recurring, in-depth investigations of the materials used were required. Within the scope of the ESA project, the scientists from PTB investigated the thermal expansion of the special, ultrastable ceramics (such as silicon carbide) in a temperature range from –266 °C to +20 °C with nanometer accuracy. In vast parts of this temperature range, the accuracy attained corresponds to a relative change in length of approx. one billionth per degree Celsius.

PTB's Ultra Precision Interferometer, which was used for this purpose, is deemed the most accurate worldwide. To allow measurements to be taken with similar accuracy but with less effort, even at other institutes, reference materials whose exact thermal expansion is known are usually used for comparison. One such reference material, single-crystal silicon, has also been investigated within the scope of the project. Across a vast temperature range, the values obtained turned out to deviate significantly from the reference values used to date for single-crystal silicon.

The results are of importance for further space missions that have already been planned. A clever procedure can prevent any radiation heat from occurring, so that the James Webb space telescope will be used at temperatures below –220 °C. In the case of the Space Infrared Telescope for Cosmology and Astrophysics (SPICA), the temperatures may be even lower. ■



Space telescope Herschel (2009-2013) allowed fascinating insights into the birth of stars. (Photo: ESA)

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Scientific publication
T. Middelmann, A. Walkov, G. Bartl, R. Schödel: Thermal expansion coefficient of single-crystal silicon from 7 K to 293 K. Phys. Rev. B 92, 174113 (2015)

Breakthrough: quantum-precise 1-volt alternating current obtained for the first time

Pulse-driven AC Josephson voltage standard with effective output voltages of up to 1 volt for generation of arbitrary waveforms of the highest quality

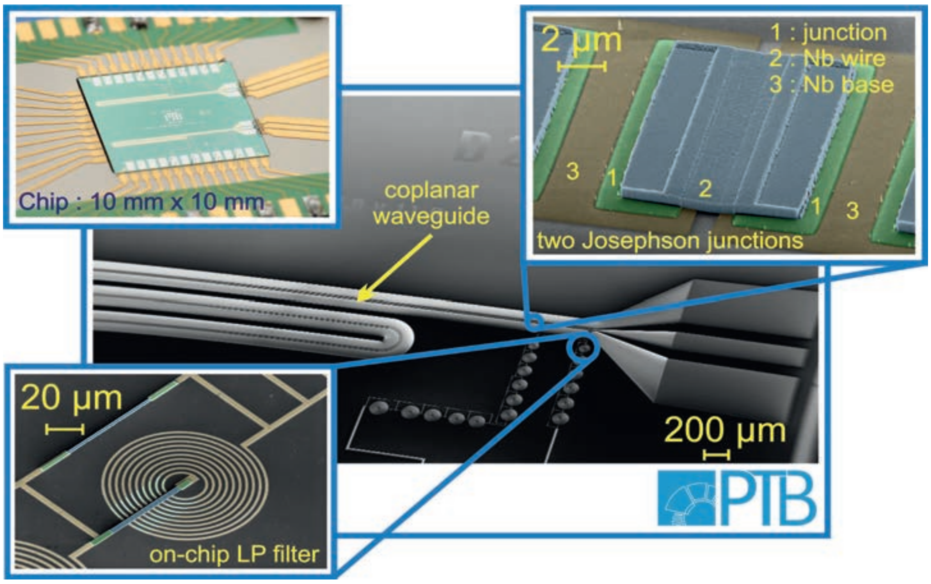
Especially interesting for
- metrology institutes
- calibration laboratories
- manufacturers of electrical precision measuring instruments

At PTB, the output voltage of a pulse-driven AC Josephson voltage standard has been significantly increased by using triple-stacked Josephson junctions, and by series connection of eight circuits with a total of 63 000 junctions; where previously obtained maximum output voltages were around an effective value of 300 mV, a standard value of 1 volt (important for metrological applications) has now been achieved for the first time. A precision comparison with an AC quantum voltmeter, at a frequency of 250 Hz, demonstrated an excellent agreement of (3.5 ± 11.7) nV/V. The increase obtained in the effective voltage opens up a range of new application possibilities.

Pulse-driven AC Josephson voltage standards make it possible to generate spectrally pure, arbitrary waveforms; for this reason, they are also referred to as Josephson Arbitrary Waveform Synthesizers (JAWS). They are based on series arrays of superconducting Josephson junctions of the kind manufactured in the Clean Room Center of PTB. In a complex multilayer thin-film process enhanced by PTB, a sequence of three layers (superconductor – normal conductor – superconductor) is used, of which the middle, very thin normal conductor layer of Nb_xSi_{1-x} weakly connects the two superconductor Nb layers. The extremely stable and reproducible deposition conditions allow layers of well-defined thickness to be manufactured. In this way, stacks of three Josephson junctions each – i.e., four Nb layers and three Nb_xSi_{1-x} layers in sequence – were manufactured with a high fabrication yield. On a single chip (10 mm · 10 mm), two circuits are integrated with a total of around 18 000 Josephson junctions (see image). The combination of eight JAWS circuits (i.e., four chips) resulted in a series connection of 63 000 Josephson junctions in total. By irradiating these JAWS circuits with a pulse signal in the GHz frequency range, sine waves are generated. The output voltage achieved was 1 volt and demonstrated outstanding spectral purity (signal-to-noise ratio better than 120 dB).

An AC quantum voltmeter, also developed at PTB (see PTB News 2013/2), was used to check the accuracy of the sine waves generated in this way. This enabled a direct comparison of two different Josephson voltage standards, performed at 1 volt across the frequency range of 30 Hz to 1.5 kHz – the first such comparison in the world. The "quantum accuracy" of the new, pulse-driven 1-volt JAWS system was proven with an excellent agreement of (3.5 ± 11.7) nV/V at a frequency of 250 Hz.

The fact that an effective voltage of 1 volt can be generated opens up a wide range of new possibilities for applying JAWS in the field of electrical AC voltage metrology such as calibrating measuring instruments, analog-to-digital and digital-to-analog converters, AC/DC standards, voltage dividers and impedance standards. ▪



Top left: chip with two JAWS circuits (with a total of around 18 000 integrated Josephson contacts). Center: scanning electron microscope image of a JAWS circuit. Top right and bottom left: detailed enlargement of the circuit.

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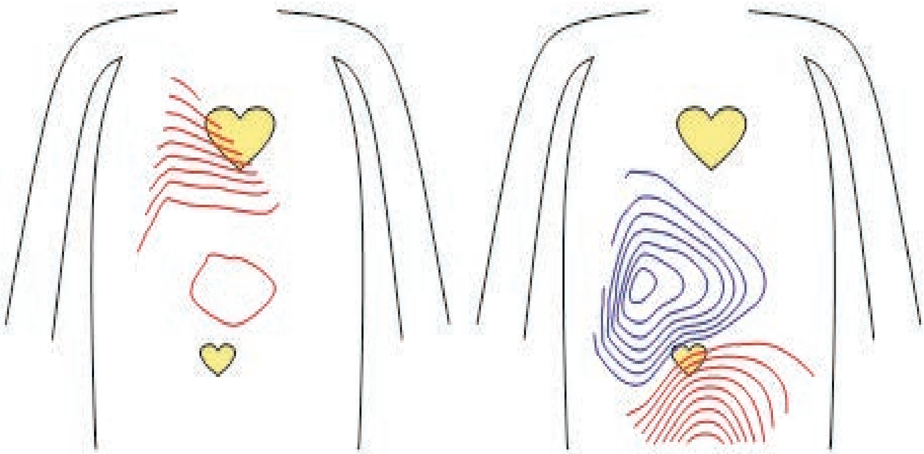
Scientific publication
R. Behr, O. Kieler, J. Lee, S. Bauer, L. Palafox, J. Kohlmann: Direct comparison of a 1 V Josephson arbitrary waveform synthesizer and an ac quantum voltmeter.
Metrologia 52(4), 528–537 (2015)

Magnetic field sensor measures fetal heartbeat

Contactless heartbeat monitoring during pregnancy

Especially interesting for
- cardiologists
- prenatal diagnostics



The measured field distribution of the maternal heart (left) and the fetal heart (right). The red iso-field lines denote the areas with a positive sign of the magnetic field; the blue lines denote those with a negative sign. The position of each heart in this diagram is only approximate, as the exact positions were not determined precisely in this test measurement. Both heartbeat signals were measured simultaneously and then separated by means of a mathematical algorithm.

PTB researchers have measured the magnetic signals generated by the heart activity of the unborn child of a pregnant woman by using optical magnetic field sensors on her abdomen. They have demonstrated that the technology developed by the US National Institute of Standards and Technology (NIST) measures as reliably as other methods, and that it can even provide additional information. This might permit fetal heart defects to be diagnosed at an early stage.

To detect cardiac arrhythmias in unborn babies, their heartbeats are monitored with the aid of an electrocardiogram (ECG), among other techniques. During such monitoring, electrodes are placed on the mother's skin. However, the baby's electrical signals are muffled by the surrounding protective layer (vernix) during certain parts of pregnancy and can be masked by the mother's own signals. By contrast, magnetic sensors are advantageous because they can pick up heart signals in a form which is less influenced by insulating layers. Furthermore, they do not require electrical contact with the skin.

For this reason, the German-American team of scientists tested µOPMs (microfabricated optically pumped magnetometers). Optical magnetometers are based on the notion that the electron spin of atoms will precess in magnetic fields at a precisely known frequency. In the case of Alkali atoms such as rubidium used in µOPMs, macroscopic polarization of the electron spin can be achieved in the gas phase by means of optical pumping. In this state, the atomic vapor is optically transparent. When a magnetic field is applied, the transparency is lost due to the precession of the electron spin; the measured change in absorption is a measure of the applied field strength.

The prototype which the researchers have developed is composed of three belts placed around the pregnant woman's torso. The belts have a flexible array of 25 µOPM sensors. At a distance of approx. 4.5 mm from the skin, these sensors measure the magnetic signals generated by the heartbeats of the mother and the child without direct skin contact. The belt below the mother's chest is used to detect her heartbeat separately. It is subtracted from the overall measurement in order to extract the signal of the child's heart (the weaker of the two signals).

The measurements are a step towards a user-friendly and informative fetal heartbeat measurement device which can be applied at any time during pregnancy directly to the mother's body. ■

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Scientific publication
O. Alem, T. H. Sander, R. Mhaskar, J. LeBlanc, H. Eswaran, U. Steinhoff, Y. Okada, J. Kitching, L. Trahms, S. Knappe: Fetal magnetocardiography measurements with an array of microfabricated optically pumped magnetometers. Phys. Med. Biol. 60, 4797–4811 (2015)

PTB's new service offer for activity standards

Alpha spectrometry under a defined solid angle

Especially interesting for
- radiation protection
- semiconductor industry
- radionuclide industry
- metrology institutes

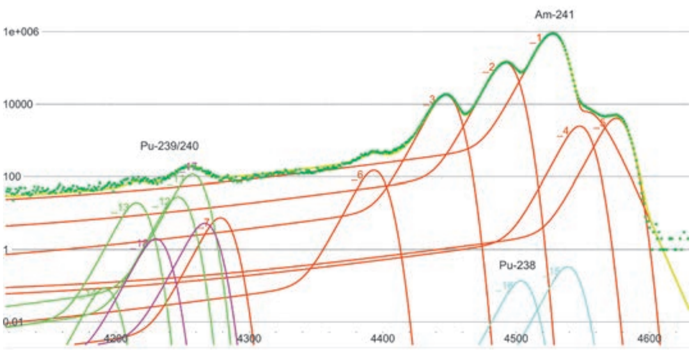
So far, the metrological characterization of alpha emitters has only been offered by a small number of national metrology institutes, as the manufacturing of the sources and characterizing measurement technology are very laborious. The determination of the activity of open alpha particle emitting sources has now been included in PTB's range of services. As of now, such activity standards can be transferred to customers with an improved characterization. To characterize the sources, an alpha spectrometry under a defined solid angle – an absolute method – is used. Currently, relative standard measurement uncertainties of 0.3 % are achieved.

The emission rates and the activities of the radioactive sources of alpha-emitting nuclides are determined by measuring the alpha particles which impact per time on a detector with a known solid angle. This kind of activity determination is an absolute method in the sense that – for the determination of all required calibration factors – only measurements are necessary which are based on the base units of our system of units. In this case, these are time and length measurements.

The measurement uncertainty which can be achieved for an activity determination with the aid of this measurement procedure, is, thus, essentially determined by the accuracy with which the geometry factor of the spectrometer used can be calculated. The calculation of this factor also requires quantitative knowledge of the relative activity distribution as a function of the position on the source surface. This distribution is measured by means of a digital radiography system. The geometry factor is then calculated using a Monte Carlo simulation, into which the dimensions of the diaphragm system used and of the activity distribution measured enter. The measuring device contains energy-dispersive detector systems. From the measured pulse height distributions, information can then be gained, with the aid of suitable computer programs, on the quality of the source as regards the energy loss of the alpha particles in the source, as well as on the radionuclide composition.

Present and future of alpha spectrometry under a defined solid angle: On the right, the current set-up including source holder, diaphragm system and detector. In measuring operation, the detector is flush at the outlet of the diaphragm system. On the left, the future detector can be seen. The appurtenant diaphragm system along with the source holder and the vacuum chamber are still under construction.

Currently, the existing equipment can be further developed and the energy-resolving power of the detector systems can be optimized. Work will be focused on the reduction of the measurement uncertainty. This measurement uncertainty is mainly determined by the uncertainty of length measurements. By enlarging the equipment, the relative uncertainty of these length measurements can be clearly reduced. Due to the design, this procedure is limited by the maximum size of the detector. In contrast to the previous systems having a maximum detector size of 450 mm², the new equipment will comprise a detector with an active surface of 5000 mm² and will thus allow the measurement uncertainty to be reduced. In addition, the new equipment will comprise measures for the reduction of the so-called zero effect and make a rapid exchange of sources possible. This opens up the possibility to determine – besides the activity – also the half-lives in the field of short-lived nuclides. Here, the general aim is not only to be able to disseminate the becquerel for alpha-emitting nuclides with smallest possible uncertainties, but at the same time also to be able to detect radioactive impurities and to analyze isotopic mixtures. This requires an improved spectrometric resolution and complex analytical algorithms. ■



Pulse height spectrum (counts over channels) in logarithmic scale of an Americium-241 source. The attribution of the individual transitions of the alpha decay of americium (Peak 1 to Peak 7) is to be seen, but also the impurities by Pu-238, Pu-239 and Pu-240 (Peak 11 to Peak 18).

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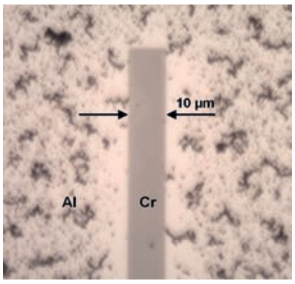
Zero-topography resolution standards

Especially interesting for
- manufacturers of X-ray photoelectron spectrometers
- chemical analysis

To determine the chemical nature of surfaces, different analytical procedures are used which allow element-specific statements to be made. In order to calibrate their lateral resolution, appropriate two-dimensional artifacts are required which



Artifact with zero-topography material contrast (aluminum and chromium)

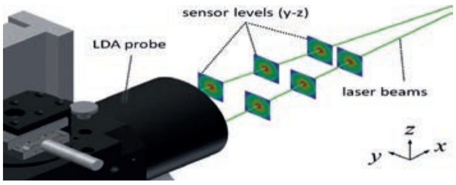
are made of adapted 2D structures composed of several materials that are specially defined for applications in measurements. For this purpose, PTB has developed a novel fabrication procedure which allows these zero-topography artifacts to be manufactured in several steps. (Technology Offer 0385) ■

Advantages
- Calibration of the lateral resolution in chemical analytical methods
- optimized investigation of material properties

Enhanced laser Doppler anemometry

Especially interesting for
- manufacturers of laser Doppler anemometers
- power plant operators

To measure volume flow accurately by means of laser Doppler anemometry (LDA) (e.g. in CHP plants), the velocity profile must be determined inside the piping. For this purpose, the fluid velocities are calibrated at several measurement



Schematic representation of the procedure used to calibrate the laser beams

positions inside the pipe. The velocity information obtained is traceable to the interference fringe interval of a velocity measurement standard. Thanks to a new invention by PTB, the measurement uncertainty of the position determination has been considerably reduced, since now, even information on the geometry and on the refraction index of the optical access are measured directly on site. (Technology Offer 0411) ■

Advantages
- LDA with greater accuracy
- optimized ray-tracing

Characterization of magnetic nanoparticles

Especially interesting for
- manufacturers of analytical measuring instruments
- laboratory measuring instruments for medicine and pharmacy

Magnetic particle spectroscopy (MPS) is a highly sensitive and fast magnetic measurement procedure for the quantification and characterization of magnetic nanoparticles (MNPs). Thanks to a flow cell which was developed at PTB, MPS can now be combined with a chromatographic separation procedure in a


Fixture (black) of the flow capillaries in a spiral set-up when they are introduced into the MPS

flow system. This clever combination of sensitive magnetic measuring instruments and established quantity determination procedures makes the relationship between the size of the particles and the magnetic behavior rapidly and effectively detectable. The flow cell is easily interchangeable, which prevents dead spaces from occurring in the flow geometry. (Technology Offer 0408) ■

Advantages
- high-resolution magnetic characterization of flowing nanoparticle suspensions
- laminar flow conditions
- easy integration into multidetector platforms

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Awards

Frank Härtig

In January, the head of Division 1 (Mechanics and Acoustics) was made an honorary professor by the Institute of Ultra-precision Optoelectronic Instrument Engineering of the Harbin Institute of Technology (HIT), a university in Harbin, China, based on his work in the field of metrology and his pioneering developments in the field of traceability of metrological algorithms.

Harald Schnatz

The head of Department 4.3 (Quantum Optics and Unit of Length), was presented with the European Frequency and Time Award 2016 at the European Frequency and Time Forum (EFTF), which took place from 4-7 April 2016 in York.

Nils Huntemann,

a staff member of Department 4.4 (Time and Frequency), was presented with the European Frequency and Time Forum (EFTF) Young Scientist Award at the EFTF 2016.

Ingo Kröger

In December, the staff member of Department 4.1 (Photometry and Applied Radiometry) was named a Young Scientist of the Werner-von-Siemens-Ring Foundation.

New theory professorship

Since 1 April 2016, Andrey Surzhykov has held the position of W3 Professor for Fundamental Physics of Metrology. This was preceded by a joint professorial appointment by PTB together with TU Braunschweig. One focus of Surzhykov's work is the relativistic theory of atomic systems in order to find new approaches to testing fundamental constants and new approaches to inspecting the standard model of fundamental particles and interactions.

Wind Energy Competence Center

As the first national metrology institute in the world to do so, PTB is planning to provide reliable and comprehensive quality assurance to the wind energy industry. To this end, a new building is being built on the premises of PTB in Braunschweig: The Wind Energy Competence Center. This building will house a large coordinate measuring machine which can be used to measure very large components of wind turbines. The building will also contain measurement and calibration facilities for very large torques, as well as wind speed measurement instruments by means of which the yield forecasts of high wind turbines can be improved.

At the first groundbreaking (from left to right): Dr. Harald Müller (PTB), Dr. Rolf Kumme (PTB), Dr. Karin Kniel (PTB), Dr. Frank Härtig (PTB, project coordinator), Prof. Dr. Joachim Ullrich (PTB, President), Renate Müller-Steinweg (public building construction management), Juliane and Peter von Klitzing (architects), Hendrik Welp (architect), Dr. Christian Schlegel (PTB)

New harmonies: NAGA

By founding the "Niedersächsische Arbeitsgemeinschaft Akustik" (Acoustics Study Group of Lower Saxony – NAGA), five institutions from the region of south-east Lower Saxony have agreed to enhance cooperation in research and teaching. The Technische Universität Braunschweig (TUBS), the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the Technische Universität Clausthal (TUC), the Leibniz Universität Hannover and PTB expect that this will bring about a more efficient utilization of their excellent test and measurement facilities as well as improved visibility of the region's competence in the field of acoustics. They also aim to establish a joint master's degree program in acoustics.

NAGA
Niedersächsische Arbeitsgemeinschaft Akustik

EMRP and EMPIR

For a few years, metrology institutes, researchers and companies have linked up with the support of the EU, to pool their resources and to make available the measurement technology that a modern society needs. This is also reflected in the fact that a coordinated European metrology research program was launched with the support of the European Union – first within the scope of the 7th EU Framework Programme for Research and Technological Development, subsequently as a measure under Article 185 of the Treaty on the Functioning of the European Union. At the moment, two programs are running: EMRP and EMPIR. All meetings of the "European Metrology Research Programme" (EMRP) and the "European Metrology Programme for Innovation and Research" (EMPIR) are to be found on the PTB website.

Contact person for all EMRP and EMPIR projects in the PTB

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Bundesministerium
für Wirtschaft
und Energie

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.