PTB news
Scientific Newsletter
1
2020

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.

SCIENTIFIC NEWS

Single-particle counter for micro- and nanoparticles
Simultaneous characterization and counting of particles with large dynamic measuring range 2

Simultaneous measurement of ultra-low magnetic fields
Multi-channel readout electronics for novel SQUID sensor systems 3

Thorium-227: Potential for cancer therapy
Accurate determination of the activity and half-life of thorium-227 4

A different way of measuring pressure
New method for top-notch capacitive pressure measurement 4

Wind turbines and air traffic control
Accurate measurements as a basis for the approval of wind turbines 5

Reference surfaces for asphere and freeform measuring instruments
Characterizing measuring instruments for non-spherical optical surfaces 6

TECHNOLOGY TRANSFER

Repairing thin-film sensors, Analytical Jacobian matrices for optics, Energy detector for particle accelerators 7

MISCELLANEOUS

Awards, Millions in funding for clock project, PTB's first caesium clock turns 50 8

Laser spectroscopy of highly charged ions

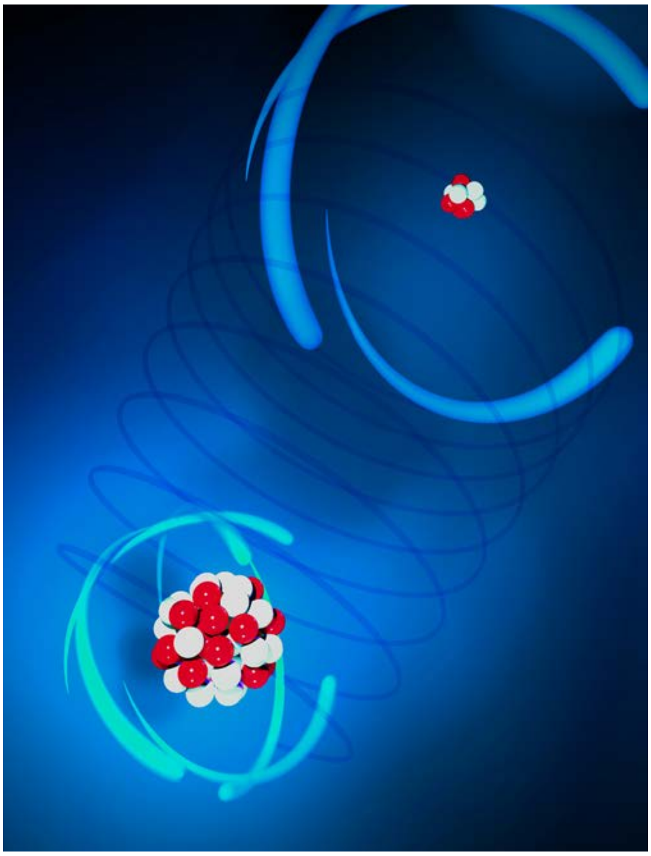
Pioneering experiment in quantum logic enables use of highly charged ions in various fields of research in physics

Especially interesting for
- fundamental research in physics
- astrophysics
- atomic clock development

In cooperation with the Max Planck Institute for Nuclear Physics in Heidelberg, the QUEST Institute at PTB has succeeded for the first time in performing precision spectroscopy on highly charged ions. This pioneering experiment makes the field of highly charged ions accessible for research on novel atomic clocks and tests of fundamental physics.

Highly charged ions are widespread in the cosmos, for example in the form of matter in the sun and all other stars. Due to its high positive charge, the electron shell of an atom is more strongly bound to that atom's nucleus. Thus, disturbances caused by external electromagnetic fields are strongly attenuated, whereas the fundamental effects of the special relativity theory, of quantum electrodynamics and of the nucleus play a more prominent role. This makes them promising candidates for high-precision atomic clocks that can be used to test fundamental physics in particular.

But measurements such as those that have long been established in optical atomic clocks were previously inconceivable on highly charged ions. Generating such ions requires a large amount of energy, and the ions then exist in the form of plasma as hot as the sun itself. However, the most precise experiments require the exact opposite – ultra-low temperatures and easily controllable ambient conditions in order to reduce



Artistic representation of the ion pair: laser cooled Be^{+} (top right) and highly charged Ar^{13+} (bottom left) the shifts and broadening mechanisms of the spectral lines to be measured. Due to their atomic structure, it is virtually not possible for highly charged ions to be cooled with laser light, nor can conventional detection methods be applied.

In an experiment that is unique in the world at the QUEST Institute for Experimental Quantum Metrology in Braunschweig, Germany, in collaboration with the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, the problem was solved using quantum logic spectroscopy. A single highly charged ion was isolated from hot argon plasma and stored in an ion trap together with a singly charged beryllium ion. Using this so-called logic ion, the two-ion crystal was cooled down to the quantum-mechanical ground state of motion. This state is usually assigned a temperature of only a few millionths of a degree above absolute zero. The spectral structure of the highly charged ion was then resolved by means of an ultra-stable laser.

A beryllium ion can be used as a logic ion for most highly charged ions, and the production process and extraction of a highly charged ion are completely unspecific with regard to the atomic species. Thus, the demonstrated experiment grants access to an extremely extensive and previously inaccessible range of atomic systems for use in precision spectroscopy and for future clocks with special properties. A promising approach to fundamental questions thus becomes possible for basic research. It will, for example, be possible to answer the questions as to whether our standard model of particle physics is complete, what dark matter is, or whether fundamental constants are really constant at all. ▪

Contact
Piet O. Schmidt
QUEST Institute at PTB
Phone: +49 531 592-4700
piet.schmidt@ptb.de

Scientific publication
P. Micke, T. Leopold, S. King, E. Benkler, L. Spieß, L. Schmöger, M. Schwarz, J. C. López-Urrutia, P. Schmidt: Coherent laser spectroscopy of highly charged ions using quantum logic. Nature 578, 60–65 (2020)

Single-particle counter for micro- and nanoparticles

Simultaneous characterization and counting of particles with large dynamic measuring range

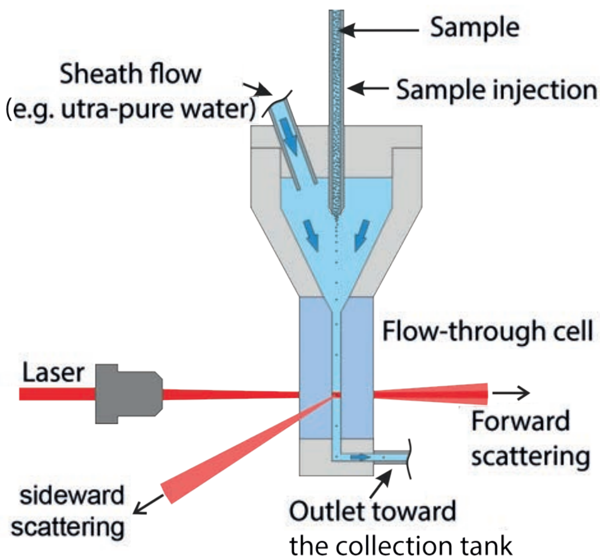
Especially interesting for
- nanoparticle research
- particle analysis
- manufacturers in the pharmaceutical industry
- semiconductor manufacturers

Within the framework of a technology transfer project, an optical single-particle counter has been developed at PTB to detect and determine the size of micro- and nanoparticles in suspension. The resulting prototype covers a dynamic measuring range that allows polystyrene particles from 80 nm to 8 µm in diameter to be detected.

Suspensions and emulsions are used in very different areas of industry and in everyday life. Examples range from abrasives and polishes to skincare products such as sunscreen. To ensure the quality and safe use of products, the particle size, the size distribution and the concentration of the particles must be accurately determined. Conventional measurement methods such as dynamic light scattering applied to characterize particles can be used to determine the particle size distribution, but not to measure the concentration.

Building on the experience gained in flow cytometry, an optical single-particle counter based on light scattering has been designed and set up at PTB. Technically speaking, this counter is a specialized enhanced optical flow cytometer. A flow-through cell with hydrodynamic focusing is used for the stable positioning of the sample flow in the detection focus. The light source used is a diode laser. The stray light is collected in the direction of the laser beam and perpendicular to it by means of aspherical lenses and is detected with two photomultiplier tubes (PMTs) simultaneously.

In addition to improving the detection optics, it was necessary to re-develop



In the single-particle counter, the suspension is injected with a cannula into the conical area of the flow-through cell and then accelerated through the taper and the surrounding sheath flow. In this way, the particles are separated along the direction of flow and mostly pass through the laser focus one by one. For each particle, the stray light is measured in the direction of the laser beam (forward scattering) and perpendicular to it (sideward scattering).

parts of the detection electronics, since due to the physical properties of light scattering, the stray light signals of the particles have a very large dynamic range with regard to their intensity. A difference in the signal intensity of forward scattering by a factor of 10^8 is expected for polystyrene particles with a diameter from 50 nm and 10 µm. To solve this problem, a transimpedance amplifier, for which a patent is pending, was developed in collaboration with an external electronics developer to convert the current signals of the PMTs. This transimpedance amplifier can detect and process input currents within a dynamic range of seven decades. This allows the simultaneous counting and characterization of micro- and nanoparticles within a wide size range.

The project results were transferred to the LUM GmbH company and then used to build a prototype close to series production. ■

Contact
Martin Hussels
Department 8.3
Biomedical Optics
Phone: +49 30 3481-7628
martin.hussels@ptb.de

Simultaneous measurement of ultra-low magnetic fields

Multi-channel readout electronics for novel SQUID sensor systems

Especially interesting for
- biomagnetic diagnostics
- radiometry
- astrophysics
- developers of superconducting sensor systems

Within the scope of an industrial cooperation project, PTB has developed new readout electronics for dc-SQUID multi-channel systems. They are highly scalable and flexible and allow up to several thousand channels to be read out simultaneously.

SQUIDs (superconducting quantum interference devices) are the world's most sensitive and accurate magnetic field detectors. They can be used to detect the extremely small changes in the magnetic fields that occur in the human heart or brain, but also to determine the properties of magnetic nanoparticles. Directly coupled dc-SQUIDs can also be used to read out other highly sensitive superconducting sensors. PTB is the world leader in the development of SQUIDs and readout electronics.

In recent years, there has been an increasing demand for electronics for measuring systems with a high number of superconducting sensors. In response to these market needs, PTB and Magnicon GmbH, in cooperation with the Institute of Applied Photonics e. V. Berlin, have developed readout electronics for dc-SQUID multi-channel systems. To make this system available to a wide range of users, the electronics are designed for a voltage white noise of 0.7 nV/Hz$^{1/2}$, a maximum bandwidth of approx. 5 MHz and a current consumption of approx. 25 mA per channel. With this design, the compromise between the total current requirement of a fully equipped system and the required performance is acceptable for the intended measurements. For highly sensitive experiments, all microcontrollers can be put into sleep mode during measurements to avoid interferences. Up to three different galvanically decoupled signal lines are available to the user for asynchronous hardware control. This functionality is essential, e.g., in applications where the current in the superconducting sensors must be limited in time – as in experiments on LF-NMR (low-field nuclear magnetic resonance), MRI (magnetic resonance imaging) or relaxometry.

The multi-channel electronics will enable new SQUID sensor systems to be operated at PTB and other institutions. The project was supported by Pro FIT, a program of the Investitionsbank Berlin (IBB) for the promotion of research, innovation and technology, and by the European Regional Development Fund. ■

Readout electronics for dc-SQUID multichannel systems. In the foreground: 19'' plug-in card with readout electronics for 9 sensor channels.

Contact
Sylke Bechstein
Department 7.6
Cryogenic Sensors
Phone: +49 30 3481-7426
sylke.bechstein@ptb.de

Scientific publication
S. Bechstein, D. Drung, M. Scheiner, F. Petsche, S. Ali Valiollahi, R. Körber, H. J. Barthelmess: Highly scalable readout electronics for large multi-channel dc-SQUID systems. Accepted for publication in the proceedings of EUCAS 2019 Journal of Physics: Conference Series

Thorium-227: Potential for cancer therapy

Accurate determination of the activity and half-life of thorium-227

Especially interesting for
- nuclear medicine
- radioactivity measurements
- calibration laboratories

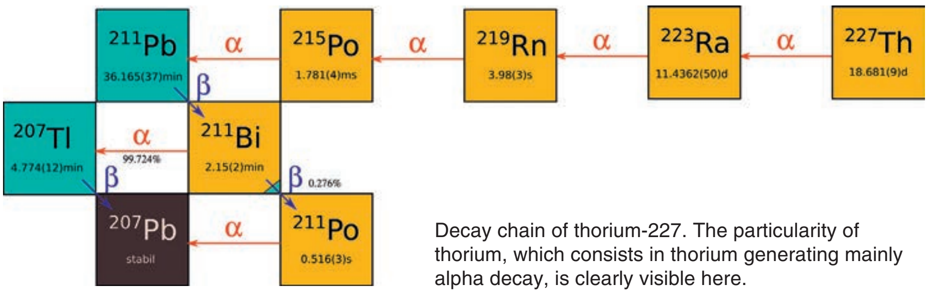
For the first time, PTB has succeeded in determining the specific activity of a thorium-227 solution very accurately by means of liquid scintillation counters. This means that traceable activity measurements of this radionuclide, which is being tested for radioimmunotherapy in nuclear medicine, are now possible. Also, the half-life of thorium-227 was determined by means of two measurement methods.

In nuclear medicine, alpha-emitting radionuclides offer interesting possibilities for cancer therapy. In spite of its relatively high energy, alpha radiation has a short particle range. If an alpha emitter is successfully introduced into the tumor tissue, it essentially destroys tumor cells, whereas strong damage to the healthy surrounding tissue is kept low. It is possible to use radioimmunotherapy to specifically introduce an alpha emitter into the tumor tissue. In radioimmunotherapy, the corresponding radionuclide is coupled with antibodies that will preferably target the diseased tissue. One of the radionuclides investigated for such a therapeutic approach is thorium-227.

At PTB, new methods have been developed to determine the activity of thorium-227 accurately. A particularity of thorium-227 is that it is not in a radioactive equilibrium with its progenies. The activity of its progenies relative to the activity of thorium-227 changes over time. In many measuring devices, the measurement result (counting rate or ionization current) even rises first and only decreases again later. This particularity must be taken into account when determining activity. At PTB, activity has now been measured by means of liquid scintillation counting. In addition, new methods have been developed to calculate the probability of detection as a function of time. For the first time, a time-dependent correction has been applied to decay during the measurement period. For the activity concentration, a relative uncertainty of only 0.25 % has been achieved through these improvements.

The measurement data obtained by means of liquid scintillation counting and additional measurements carried out in an ionization chamber have also been used to determine the half-life of thorium-227. The measurements at PTB took place over a period of almost half a year, which is a significant advantage compared to other experiments with considerably shorter measurement periods. The longer measurement periods reduce the uncertainty of the thorium-227 half-life, since, among other things, dependence on the half-life of radium-223 is reduced.

The results of both procedures are in good agreement, and by combining them, a half-life of 18.681(9) days is obtained. ▪



Decay chain of thorium-227. The particularity of thorium, which consists in thorium generating mainly alpha decay, is clearly visible here.

Contact
Karsten Kossert
Department 6.1
Radioactivity
Phone: +49 531 592-6140
karsten.kossert@ptb.de

Scientific publication
K. Kossert, O. Nähle: Determination of the activity and half-life of ^{227}Th. Appl. Radiat. Isotop. 145, 12–18 (2019)

A different way of measuring pressure

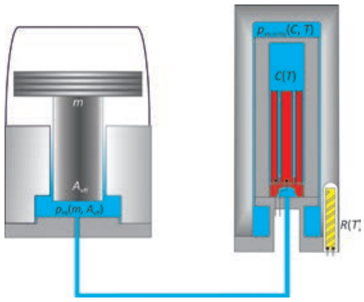
New method for top-notch capacitive pressure measurement

Especially interesting for
- physical-chemical fundamental research
- nuclear physics
- high-precision pressure measurements

Within the scope of the work on the redefinition of the base unit kelvin, PTB developed a new method for pressure measurement based on the capacitance measurement of helium gas. From the first attempt, it was almost as good as the world's best method for pressure measurement with a piston manometer.

Pressure is the result of a force acting vertically onto a surface. Today, the most accurate pressure measurements are still working according to this principle, where the gas pressure under a piston of a certain area is adjusted via the mass stack i.e. via the weight force. At the same time, it has long been endeavored to develop further high-precision methods. As early as 1998, Mike Moldover of the US American metrology institute NIST had voiced his idea of measuring pressure via an electrical (capacitance) measurement using theoretical calculations of the gas properties of helium. In the following years, however, implementing this groundbreaking thought would prove to be a real challenge. Both the precision capacitance measurement and the highly stable capacitors needed for this purpose, as well as the theoretical calculations using solely natural constants (ab initio calculations) were not yet possible with the required accuracy. Moreover, there was no accurate possibility to compare them with conventional pressure balances.

Each of the experimental obstacles has been removed at PTB over the last decade. Due to activities carried out within the scope of the new definition of the base unit kelvin, conventional pressure measurements both with pressure balances and via capacitance measurements were raised to an unprecedented level worldwide. Thanks to the latest theoretical calculations achieved by diverse research groups across the globe, it has now become possible to measure a pressure of 7 million pascals (i.e. 70 times normal pressure) with a relative uncertainty of less than $5 \cdot 10^{-6}$. This uncertainty has been confirmed by comparison with a conventional pressure balance. It was the first comparison on an equal footing between mechanical and electrical pressure measurements.



Left: Conventional pressure measurement with a pressure balance according to $p_{PB} = F_g/A_{eff}$ (PB: pressure balance; g: gravitational force; A_{eff}: effective surface of a piston/cylinder system). Right: The new electrical approach: the relative change in capacitance $C(T)$ caused by the measuring gas at a known temperature T, which is determined by means of a calibrated resistance thermometer $R(T)$, can be directly linked to the gas pressure. The dielectric constant and the interaction of the gas particles enter into the required ab initio calculations: $p_{ab\text{-}initio}(C,T, \mathrm{Gas}_{ab\text{-}initio})$

Thus, a second method is now available to calibrate pressure with high accuracy. The method itself and the direct comparison with the conventional pressure standard offer, for one thing, the possibility to verify theoretical calculations of helium – an important model system in atomic physics. For another, they also allow other gases to be measured and thus, both theory and gas metrology to be further developed. ■

Contact
Christof Gaiser
Department 7.4
Temperature
Phone: +49 30 3481-7349
christof.gaiser@ptb.de

Scientific publication
C. Gaiser, B. Fellmuth, W. Sabuga: Primary gas-pressure standard from electrical measurements and thermophysical ab initio calculations. Nature Physics 16, 177–180 (2019)

Wind turbines and air traffic control

Accurate measurements as a basis for the approval of wind turbines

Especially interesting for
- wind turbine operators
- air navigation and service providers

For the first time worldwide, PTB has succeeded in showing how, to what extent and under which conditions wind turbines influence the signal integrity of air navigation systems. These findings have made a forecasting tool possible that could speed up the decision-making process for hundreds of building applications that are stuck in the "approval backlog".

Deutsche Flugsicherung GmbH, the air navigation and service provider in Germany, operates around 60 air navigation systems (VHF monodirectional radio ranges) on the ground. Similar to lighthouses for ships, they guide aircraft and thus ensure safety in the sky. Wind turbines may scatter and reflect the VHF radio signal emitted by air navigation systems, thereby generating a bearing angle error. Due to this bearing angle error, the signal of the navigation system is slightly distorted when it reaches an aircraft. According to a survey conducted by the Fachagentur Windenergie, German wind energy association in the second quarter of 2019, it was impossible to implement more than 1000 wind turbines with a total output of 4800 megawatts because the planned location would have been too close to a non-directional radio beacon and would have potentially influenced its signal.

In order to realistically assess the interference effect, PTB – in cooperation with Deutsche Flugsicherung GmbH and the Bundesaufsichtsamt für Flugsicherung (German Federal Office for Air Traffic Control) – has both reviewed the scientific basis of the assessment procedure used to date and developed a new forecasting method. DVOR (Doppler Very High Frequency Omnidirectional Radio Range) navigation beacons, of which there are almost 40 in Germany, were focused on. To test the entire electromagnetic field around VORs and wind turbines, drones with precision navigation were developed whose eight rotors enable stationary hovering flight in order to carry out on-site measurements at altitudes of up to several hundred meters. By means of high-frequency measurements and integrated antennas, it was possible to record how the DVOR radio signals propagate, how they are reflected and scattered by wind turbines and how the reflected signals overlap with the direct signals of the DVOR. Presuppositions and real measured data from individual wind turbines were then compared with a comprehensive full-wave simulation carried out on the mainframe computer of Leibniz University Hannover. Here, it was possible to simulate the bearing angle error caused by wind turbines also for large-scale scenarios with numerous wind turbines.

This has provided an easy-to-use method for predicting the angle error, which no longer adds up the individual errors, but superimposes the individual waves and then determines the resulting bearing angle error. The last step still to be taken consists in transferring this state-of-the-art method into practice. The results were obtained within the scope of the WERAN and WERAN plus projects, which were funded by the Federal Ministry for Economic Affairs and Energy. In addition to PTB, Leibniz University Hannover, FCS Flight Calibration Services GmbH, Jade Hochschule Wilhelmshaven, the Institute of Computational Mathematics of TU Braunschweig and steep GmbH were involved in these projects. ▪

Wind turbines and PTB's flying measurement platform

Contact
Thorsten Schrader
Department 2.2
High Frequency & Electromagnetic Fields
Phone: +49 531 592-2200
thorsten.schrader@ptb.de

Scientific publication
T. Schrader, J. Bredemeyer, M. Mihalachi, D. Ulm, T. Kleine-Ostmann, C. Stupperich, S. Sandmann, H. Garbe: High-resolution signal-in-space measurements of VHF omnidirectional ranges using UAS. Adv. Radio Sci. 17, 1–10 (2019)

Reference surfaces for asphere and free-form measuring instruments

Characterizing measuring instruments for non-spherical optical surfaces

Especially interesting for
- manufacturers of asphere and free-form measuring instruments
- optics manufacturers

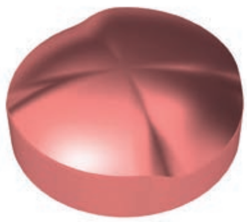
Non-spherical optical surfaces, i.e. aspheres and freeform surfaces, are nowadays essential components of many modern imaging systems in industry and research. To test high-precision measuring instruments for the measurement of aspheres and freeform surfaces, special reference surfaces have been developed which consist of several spherical segments with differing radii. The first prototypes have been manufactured and calibrated at PTB with high accuracy. They were used for the first time to check an asphere measuring device within the scope of the FreeFORM EMPIR project.

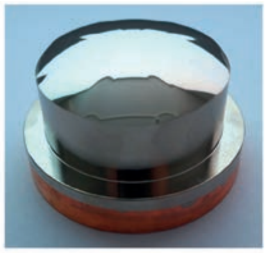
While it is possible to measure and trace back spherical surfaces very accurately, a traceable measurement of non-spherical surfaces with uncertainties in the nanometer range is difficult. In order to check the accuracy of the measuring instruments used for this purpose, special calibration surfaces have been developed. They have well-defined form properties that can be measured using established measuring instruments. These form properties must then also be reflected in the surface shape determined by the measuring device for aspherical/freeform surfaces.

So-called multiradius surfaces, which combine sphere segments of different radii, have proven their worth. The respective radii of the individual spherical sections and the small but unavoidable deviations from the perfect spherical shape (sphericity) can, for example, be measured with Fizeau interferometers.

Thanks to close cooperation between the manufacturing and measuring departments, reference surfaces have been manufactured with great accuracy in PTB's Scientific Instrumentation Department by means of diamond turning. The deviation from the design form was reduced to about 20 nm root-mean-square (rms). A nickel-phosphorus coating also makes the surfaces suitable for tactile measuring systems with low measuring force. The first test consisted in checking an optical asphere measurement system by means of such a multiradius surface. The sphericity measurements deviate from the calibrations by less than 10 nm rms.

Multiradius surfaces are therefore a suitable tool for characterizing measuring instruments for aspherical and freeform surfaces. In order to make this tool accessible to all users, the possibility of manufacturing reference surfaces outside PTB with the necessary accuracy is currently being investigated. ▪





Left: Representation of a multiradius surface. For illustration purposes, the spherical segments of the surface have been raised. Right: Photo of a realization. The diameter is 40 mm.

Contact
Ines Fortmeier
Department 4.2
Imaging and Wave Optics
Phone: +49 531 592-4211
ines.fortmeier@ptb.de

Scientific publication
I. Fortmeier, M. Schulz, R. Meeß, Traceability of form measurements of freeform surfaces: metrological reference surfaces. Optical Engineering 58(9), 092602 (2019)

Repairing thin-film sensors

Especially interesting for
- manufacturers of thin-film sensors

Thin-film sensors enable the high-precision and spatially resolved measurement of various physical states, especially in particularly small places that are difficult to access, and under harsh environmental conditions. In thin-film sensor production, possible defects such as vias caused by pinholes in the insulation are particularly unwelcome as they may make the thin-film sensors applied useless. PTB has developed a procedure in which existing defects are repaired by the electrothermal elimination of the vias between the sensor layer and the substrate. (Technology Offer 327) ▪

Result of the electrothermal removal of a via

Advantages
- removing defects (pinholes)
- securing functionality
- simple post-processing

Analytical Jacobian matrices for optics

Especially interesting for
- optics manufacturers
- manufacturers of asphere and free-form measuring instruments

New challenges are arising for modern optical measuring systems with regard to the simulation and optimization of the measuring systems and assessment procedures. This is particularly true of form measurement systems for aspheres, freeform surfaces and the simulation of optical systems such as those used in modern camera systems, and complex optical measuring systems. Optimizing procedures which require Jacobian matrices are becoming ever more important. Depending on the number of parameters to be optimized, PTB's procedure considerably reduces the number of simulations required to compute the Jacobian matrices, and it allows the computing time to be drastically reduced. PTB's procedure can thus be used in inline systems. (Technology Offer 376) ▪

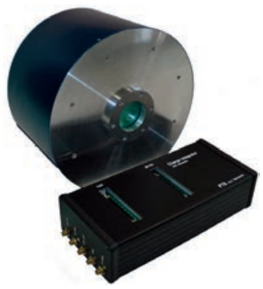
Aspherical lens shape

Advantages
- considerably shorter computing times
- higher numerical accuracies
- versatile application possibilities for various optical systems

Energy detector for particle accelerators

Especially interesting for
- developers and operators of particle accelerators in research
- medical engineering
- materials testing

A detector developed at PTB measures the mean energy and charge of charged particles. These measurements are pulse-resolved and take place in real time. The device, which delivers up to 10 measurements per second, is also suitable for continuous ion radiation and electron radiation. Moreover, its principle allows the energy of particle radiation of very low intensity to be determined. The device consists of a segmented Faraday cup – which is the actual detector – and specifically developed measuring electronics. These electronics are responsible for acquiring the signals and performing important protective functions for the detector. The design is freely scalable to a large extent to suit different energies, power ranges and beam apertures. ▪



Advantages
- real-time beam monitoring
- for electron, carbon-ion and proton accelerators
- also suitable as a temporary beam dump

Contact person for questions about technology transfer
Andreas Barthel, Phone: +49 531 592-8307, andreas.barthel@ptb.de, www.technologietransfer.ptb.de/en

Awards

Rudolf Meeß, Thomas Wiedenhöfer, Frank Härtig and Katharina Lehrmann

The team of PTB scientists was awarded the Technology Transfer Prize of the Chamber of Industry and Commerce of Braunschweig for successfully passing on a masterpiece of metrological and product engineering from research to industry, namely ultra-pure, extremely round silicon spheres which represent the new definition of the kilogram. While the purest spheres with the best-known characteristics will remain at PTB Braunschweig as the highest reference, several other silicon spheres are to go to institutes and laboratories all over the world to serve as the basis of the physical unit of mass. It was possible to entrust the J. Hauser GmbH & Co. KG as well as the Häfner GmbH with the distribution and sale of the mass standards. These companies use the know-how and procedures which were developed at PTB during many years of research for this.

(Photo: IHK Braunschweig)

Christoph Kolbitsch

The head of the 8.13 ”Quantitative MRI“ working group was honoured as a young scientist by the Werner von Siemens Ring Foundation for his work in the field of movement correction for magnetic resonance imaging (MRI). Mr. Kolbitsch's work is focussed on the influence that physiological movements of organs (i.e. due to respiration) has on quantitative MRI procedures. Together with his working group at PTB, he develops procedures which guarantee an accurate and reproducible determination of bio-physical parameters in MRI in patients.

Dieter Hoffmann

The leader of the research project ”The PTR during the Third Reich“ was awarded the ”2020 Abraham Pais Prize for History of Physics“. With this prize, the American Physical Society honours the science historian ”for insightful, determined, often courageous biographical and institutional studies of the history of German physics and technology, from Weimar through the Nazi and East German regimes“.

Millions in funding for clock project

PTB's researchers, together with international colleagues, have secured a prestigious Synergy Grant from the European Research Council (ERC) for the development of an entirely new atomic clock. The aim of the project, which will be funded with a total of 13.8 million euros for six years, is to develop a completely new type of atomic clock: a thorium nuclear clock. It could be significantly more precise than all the previous caesium clocks and – also – than all the previous optical atomic clocks. That promises advantages for precision time and frequency measurement applications and for fundamental physics research.

In addition to PTB, scientists from Vienna, Munich, Delaware (USA), Heidelberg and Aachen are participating in the interdisciplinary and international ”Thorium Nuclear Clock“ project.

The Synergy Programme of the European Research Council (ERC) is the highest endowed research funding of the ERC and is especially focussed on topics with great potential for innovation which require collaboration between different fields such as in this case atomic and nuclear physics, laser physics and theoretical physics.

(Contact: Ekkehard Peik, Department 4.4 ”Time and Frequency“, +49 (0)531 592-4400, ekkehard.peik@ptb.de)

PTB's first caesium clock turns 50

As of now, the CS1 atomic clock – a major quantum standard of PTB – has been ticking for 50 years. The clock was completed in PTB's atomic clock hall in 1969, and the first measurement values were published the same year. The relative uncertainty of CS1 was 4.5 · 10^{-13} in 1970. Today, the uncertainty of the best primary clocks is slightly higher than 1 · 10^{-16}. Until 1992, legal time in Germany was based on CS1's seconds. Then, CS1 was replaced by the CS2 atomic clock, which is more modern, more stable and more precise and which was built using the same principle. CS1, however, still belongs to PTB's ensemble of four primary atomic clocks. ”Primary“ as used here denotes complete uncertainty estimation, whereas for commercial devices, merely summarized information is provided on ”accuracy“ without further explanation.

(Contact: Andreas Bauch, Department 4.4 ”Time and Frequency“, +49 (0)531 592-4420, andreas.bauch@ptb.de)

CS1, PTB's first caesium clock

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Federal Ministry for Economic Affairs and Energy

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.