PTB news
Scientific Newsletter
2
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.



# Boltzmann constant determined

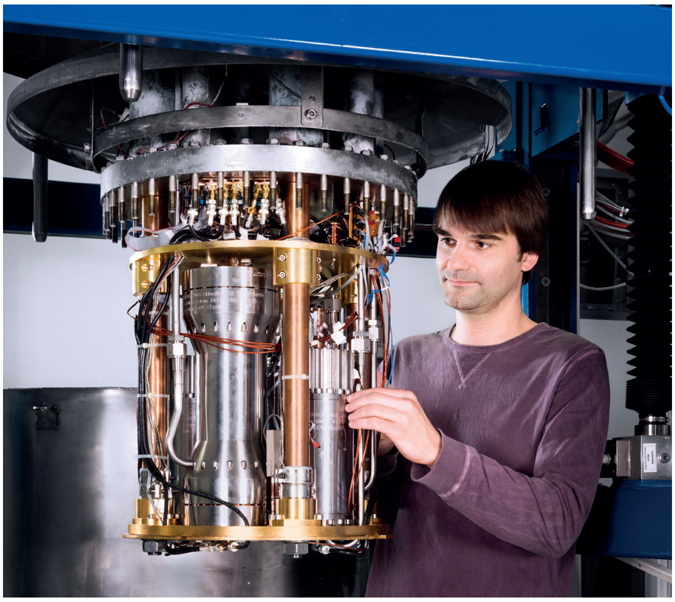
## All obstacles to the redefinition of the unit of temperature, the kelvin, have been removed

**Especially interesting for**
- metrological fundamental research
- redefinitions of the units

**PTB has succeeded in measuring the Boltzmann constant *k* independently. A fundamental condition laid down by the Consultative Committee for Thermometry (CCT) has thereby been met, so that all obstacles to the redefinition of the kelvin have been removed by fixing the value of the Boltzmann constant. The final measurements of *k* with a dielectric-constant gas thermometer were conducted with a relative uncertainty of 1.9 ppm (parts per million). Compared to the uncertainty of 15 ppm obtained at the beginning of the project back in 2007, this represents a reduction by a factor of 8.**

For a unit to be based on a fundamental constant, the latter should, as a matter of principle, be measured by means of two methods which are independent of each other and have a comparable uncertainty. As early as 30 years ago, the Boltzmann constant *k* had already been determined with a relative uncertainty of 1.8 ppm by means of the acoustic gas thermometer. Over the past decade, this method was further refined by various metrology institutes, with the most accurate result exhibiting an uncertainty reduced by a factor of 2. These results allow the first condition of the CCT for the new definition to be met, namely obtaining an averaged value for the Boltzmann constant with an uncertainty of less than 1 ppm.

An independent method of doing this is dielectric-constant gas thermometry, which PTB has been using for many years. This method consists in determining the pressure of the measuring gas, helium, in a gas-filled capacitor. This approach is based on the fact that helium, as a dielectric, changes the capacitance of the capacitor. At pressures up to 7 MPa, the uncertainty of the pressure measurement had to be reduced by a factor of 4. This has now been achieved with a worldwide unequalled relative uncertainty of 1 ppm. In order to measure the capacity changes, relative uncertainties of a few parts per billion may not be exceeded.



PTB scientist Christof Gaiser with the core of the dielectric-constant gas thermometer. The different silver-colored pressure vessels have special capacitors which are filled with helium to carry out the measurement that takes place inside them.

Moreover, the material parameters for the capacitors – at these high pressures – had to be determined at the metrological limit, and a gas purity of better than 99.99999 % had to be ensured. This could only be achieved thanks to various cooperation projects within PTB (with the two working groups "Pressure" and "Geometrical Standards") and thanks to large-scale international cooperation.

Now that the Boltzmann constant has been determined with sufficient precision by means of both methods, CODATA will compute the final value of k in September 2017. This will pave the way for the redefinition of the kelvin based on a fundamental constant. Presumably in the fall of 2018, the whole International System of Units (SI) will rest upon a new basis. ■

**Contact**
*Christof Gaiser*
*Department 7.4*
*Temperature*
*Phone: +49 (0)30 3481-7349*
*christof.gaiser@ptb.de*

**Scientific publication**
*C. Gaiser, B. Fellmuth, N. Haft, A. Kuhn, B. Thiele-Krivoi, T. Zandt, J. Fischer, O. Jusko, W. Sabuga: Final determination of the Boltzmann constant by dielectric-constant gas thermometry. Metrologia 54, 280–289 (2017)*

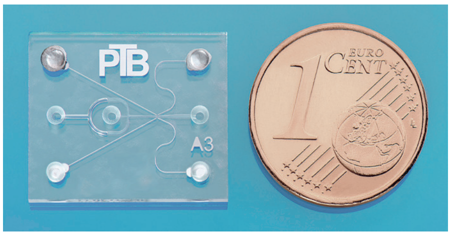
# Label-free cell differentiation

## Novel concentration measurements for the full blood count including 3-part white blood cell differentiation

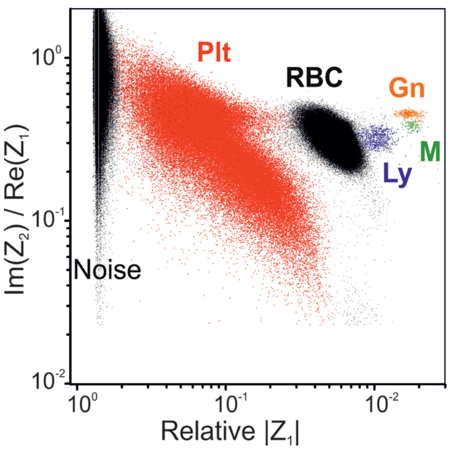
**Especially interesting for**
- manufacturers of flow cytometers
- oncology
- hematology
- laboratory medicine

**In the case of blood samples with pathologically modified blood cells, the hemolysis and staining methods used in routine diagnostics can lead to the wrong identification of certain cell populations or to an inaccurate determination of their concentration. In contrast to this, an AC impedance procedure, which was developed at PTB, allows whole blood samples to be analyzed without disturbing influences due to the pre-processing of the sample.**

The blood count is a compilation of data on the quantity and the shape of cells. From this, the physician can draw conclusions concerning a patient's state of health. The corresponding measurements also include flow cytometric procedures in which optical or impedance counting devices are used. In both cases, the red blood cells are first destroyed by hemolysis to facilitate the measurement of the concentration of white blood cells which, in healthy patients, are less abundant than red blood cells by a factor of approx. 1000. In the case of certain diseases such as leukemia, the white blood cells, however, may either be modified or destroyed by hemolysis procedures. In other blood samples, e.g. from newborns or from anemic patients, hemolysis-resistant erythrocytes may be observed which impede the correct differentiation and concentration measurement of leukocytes. To ensure reliable cell differentiation, such samples require demanding microscopic investigations or staining of the DNA or of the cell membrane.




Microfluidic chip with four integrated electrodes for flow cytometric blood cell measurement.




Label-free cell differentiation in a (diluted) full blood sample by means of AC impedance measurements at two frequencies (Z1 at 2.3 MHz and Z2 at 10 MHz). The clusters correspond to the red blood cells (RBC), the platelets (Plt), and the sub-populations of white blood cells: the granulocytes (Gn), the monocytes (M), and the lymphocytes (Ly).

The procedure developed at PTB allows blood samples, diluted to a suitable concentration, to be analyzed by means of flow cytometry, without modifying them by hemolysis or by using staining procedures. This method is based on measuring the change which occurs in the complex resistance (impedance) when a blood cell passes through the electrode configuration of a microfluidic assembly. In order to identify the cells unequivocally, two alternating voltages are applied with different frequencies and each of the complex AC impedance signals is measured, i.e. the effective resistance, the reactance and the absolute value of the impedance are determined. By choosing suitable frequencies and measurands, it is possible to differentiate in the micro flow cytometer between the cells attributed to the full blood count including the 3-part differential white blood count, i.e. the red blood cells, the platelets, the granulocytes, the monocytes and the lymphocytes.

With this new method, it is possible to facilitate the examination of blood samples from certain groups of patients and, at the same time, to prevent systematic measurement errors. This reduces the number of subsequent microscopic differentiations and/or of cell-specific staining. Moreover, the procedure, which is based on a microfluidic assembly, offers potential for developing a point of care device utilizing a flow cytometric sensor. ■

**Patent application**
*Procedure and measuring equipment for the determination of blood cells, submitted on 5 November 2015.*

**Contact**
*Jörg Neukammer*
*Department 8.3*
*Biomedical Optics*
*Phone: +49 (0)30 3481-7241*
*joerg.neukammer@ptb.de*

**Scientific publication**
*P. Simon. M. Frankowski, N. Bock, J. Neukammer: Label-free whole blood cell differentiation based on multiple frequency AC impedance and light scattering analysis in a micro flow cytometer. Lab Chip 16, 2326–2388 (2016)*

# Core Facility “Metrology of Ultra-Low Magnetic Fields”

## External scientists can use PTB's excellent equipment

**Especially interesting for**
- biomedical research
- nanoparticle research
- fundamental research in physics
- magnetic resonance in very small magnetic fields

**Since the beginning of this year, the DFG has been promoting the establishment and operation of the Core Facility “Metrology of Ultra-Low Magnetic Fields” at PTB. In this way, PTB grants external scientists from universities, international metrology institutes and companies access to its know-how and its equipment for the measurement of extremely small magnetic fields which is unique worldwide.**

PTB has an excellent reputation in the field of biomedical metrology. Besides several magnetically shielded rooms, the Berlin Institute of PTB installed the best walk-in magnetically shielded room (BMSR-2) in 2004. With a shielding factor of more than 10,000,000, a remaining field of less than 500 pT, and a gradient of 1.2 pT/mm, this room offers conditions that are unique worldwide for magnetic field measurements with the highest resolution. This room could only be implemented by means of specially manufactured nonmagnetic structures and by selecting and carefully characterizing suitable materials.

SQUID magnetometers, which were developed by PTB, are used as sensors. They are able to detect magnetic fields down to just a few femtoteslas. With a noise as low as 150 aT/√Hz, they are among the most sensitive SQUID systems in the world.

At PTB, the measurement technology developed is used to carry out research on topics relating to biosignal detection and processing, the nuclear spin precession of hyperpolarized noble gases, the characterization of magnetic nanoparticles and ultra-low-field nuclear magnetic resonance. Due to these versatile activities, the scientists from PTB have been able to gather exhaustive experience in the field of metrology of ultra-low magnetic fields.

For many years, these measuring facilities and capabilities which are unique in the world have not only served PTB's metrological activities, but have also been increasingly used by external scientists from universities and industry. The Core Facility “Metrology of Ultra-Low Magnetic Fields” is a new platform supporting in-house and external users in the best possible way within the scope of their research projects in the field of magnetic metrology. ■

**Contact**
*Martin Burghoff*
*Department 8.2*
*Biosignals*
*Phone: +49 (0)30 3481-7238*
*martin.burghoff@ptb*

External view of the best walk-in magnetically shielded room (BMSR-2) – the heart of the core facility.

Work station for the characterization of magnetic nanoparticles

The logo of the new Core Facility

# Superconducting single-photon detectors

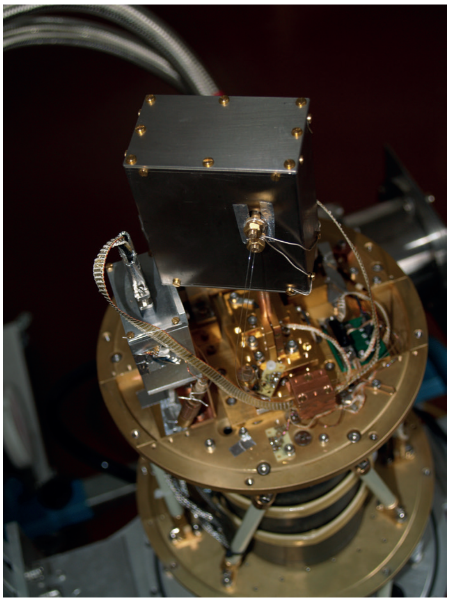
## Characterization of photon sources for quantum communication

**Especially interesting for**
• Quantum optics

**For many years, PTB has been leading in the development of current sensors on the basis of SQUIDs (Superconducting QUantum Interference Devices). Now, PTB's SQUID current sensors are used successfully as essential components of superconducting microcalorimeters to characterize novel single-photon emitters and microlasers for quantum optics.**

Single-photon sources in the optical and the near-infrared wavelength ranges are essential components for procedures of optical quantum communication. A promising method of manufacturing sources for single photons or for few photons is based on quantum dot micro-resonator structures. The better the emission statistics of these sources are known, the more precisely is it possible to understand their behavior.

Within the scope of an ongoing European research project, PTB is collaborating with the Technische Universität Berlin where single-photon emitters and microlasers are being developed on the basis of self-assembled InAs/GaAs quantum dots. At PTB, a measuring system has been set up to characterize sources that emit single photons or few photons with wavelengths in the range from 800 nm to 1000 nm. Superconducting microcalorimeters ("Transition Edge Sensors", TESs, developed by the National Institute of Standards and Technology (NIST) are employed as detectors. But it is only through the combination with PTB's highly sensitive SQUID current sensors for readout that the number of single photons absorbed can be determined exactly.



TES/SQUID detector module (interior view of the cryostat without the radiation shields)

The new system is the enhanced form of a setup which has already been used successfully at the Austrian Academy of Sciences for a loophole-free Bell test experiment with entangled optical photons. Due to the use of TES/SQUID detectors, it is possible to directly determine the photon number distribution of the InAs/GaAs quantum dot sources in a range of up to approx. 20 photons. This enables the characterization of quantum dot microlasers under varying operating conditions. With this measuring system, it has recently even been possible to detect one- and two-photon states of a single-quantum dot emitter directly. ■

**Contact**
*Jörn Beyer*
*Department 7.2*
*Cryophysics and Spectrometry*
*Phone: +49 (0)30 3481-7379*
*joern.beyer@ptb.de*

**Wissenschaftliche Veröffentlichung**
*T. Heindel, A. Thoma, M. von Helversen, M. Schmidt, A. Schlehahn, M. Gschrey, P. Schnauber, J.-H. Schulze, A. Strittmatter, J. Beyer, S. Rodt, A. Carmele, A. Knorr, S. Reitzenstein: A bright triggered twin-photon source in the solid state. Nat. Commun. 8, 14870(2017)*

# PTB's own world record topped!

## Current measurement with single-electron pumps with even smaller uncertainty

**Especially interesting for**
• metrology institutes
• fundamental research

**PTB has topped its own world record established a year ago where electric currents were generated with single-electron pumps and their quantization was verified with the greatest accuracy by means of a special measuring amplifier. The new record (which was made possible by improving the experimental setup) is a relative measurement uncertainty of only 0.16 µA/A. Moreover, this result was achieved within a considerably shorter measuring time.**

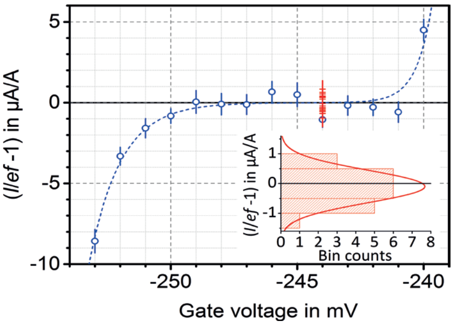
Nanostructured electric circuits which allow the controlled transport of single electrons (so-called "single-electron pumps") can be used to realize a future quantum current standard and are therefore the object of intense investigations at PTB. These circuits generate electric currents on the order of 100 pA that are measured with great accuracy by current/voltage transformers (so-called ULCAs – short for Ultrastable Low-noise Current Amplifiers – see PTB News 1/2015) which were developed at PTB specifically for this purpose. The ULCA's transresistance is calibrated by means of a quantized Hall resistor with a relative measurement uncertainty of less than 0.1 µΩ/Ω.

Thanks to a new experiment, it was possible to further improve the measurement uncertainty and, thus, to break the previous year's world record (see PTB News

1/2016). This was made possible by an enhanced measuring arrangement where the input and output currents of the single-electron pump are transformed into voltages via two ULCA channels; the difference between those voltages was then measured using a quantum standard (a Josephson voltage standard). In this way, the influence of the systematic uncertainty in the voltage measurement was significantly reduced. In addition, the measuring time was exploited more efficiently due to optimizing the computer-aided data acquisition.

The new measurement uncertainty record value of 0.16 µA/A at a current of 96 pA was attained in a measuring time of 21 hours. In comparison, 95 hours were necessary to achieve the previous record value of 0.2 µA/A. In both cases, the current generated by the single-electron pump was in agreement with the expected quantized value $I = e \cdot f$ within the limits of the measurement uncertainty.

PTB has thus successfully demonstrated that the "quantum ampere" can be realized with a smaller measurement uncertainty than the conventional ampere in the current SI, which represents a milestone on the path to the planned revision of the International System of Units. In addition, the experimental improvements allow single-electron pumps to be characterized much faster – a crucial practical advantage for metrological applications. ■




Relative deviation of the current generated by the single-electron pump from the quantized value $I = e \cdot f$. Performing measurements while varying the control voltage (blue symbols) serves to determine the optimal operating point at which the following 21 measurements will be carried out (red symbols). The statistical uncertainty of each of the measurement values (each determined in a measuring time of one hour) corresponds to 0.6 µA/A. The insert shows the histogram of the measuring points, together with the corresponding normal distribution. From this, together with the systematic uncertainty contributions, it is possible to calculate the total measurement result at the operating point by averaging: $(I/e \cdot f) - 1 = (0.10 \pm 0.16)$ µA/A.

**Contact**
*Frank Hohls*
*Department 2.5*
*Semiconductor Physics and Magnetism*
*Phone: +49 (0)531 592-2530*
*frank.hohls@ptb.de*

**Scientific publication**
*F. Stein, H. Scherer, T. Gerster, R. Behr, M. Götz, E. Pesel, C. Leicht, N. Ubbelohde, T. Weimann, K. Pierz, H. W. Schumacher, F. Hohls: Robustness of single-electron pumps at sub-ppm current accuracy level. Metrologia 54, 1–8 (2017)*

# Fast roughness measurements

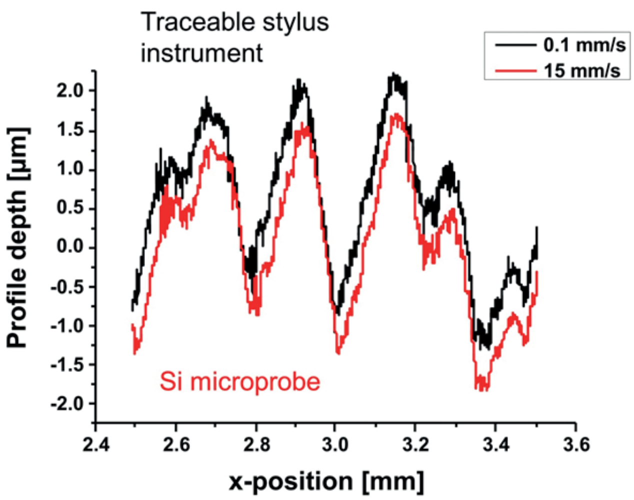
## High-speed microprobes for roughness measurements

**Especially interesting for**
- manufacturers of micronozzles
- manufacturers of metrological equipment

**Within the scope of a BMBF project, high-speed measurements with piezo-resistive microprobes were investigated. Hereby, scanning speeds of up to 15 mm/s were successfully tested. An essential aspect of the investigations was the wear of the tip.**

Piezoresistive silicon microprobes with an integrated stylus tip bridge the gap between scanning force microscopy and tactile profilometry with profilometers. The microprobes enable roughness measurements in structures with a high aspect ratio and depths of up to 5 mm and widths of up to 50 µm (see PTB News 3.2014). Moreover, due to their extremely small inert mass of only 0.1 mg, such microprobes in principle allow high traverse speed and sampling rates. Compared to the probing force of 750 µN recommended for profilometers, the probing force required to prevent the probe from lifting off from the surface due to dynamic forces during a measurement is only 28 µN for the 5 mm long microprobes. Within the scope of a BMBF project, this topic was investigated in more detail. For example, a roughness standard was measured with a silicon microprobe and with a conventional profilometer, and the results were compared. For this purpose, roughness measurements were carried out at high traverse speeds of up to 15 mm/s whilst applying high probing forces of 100 µN on purpose. The profiles obtained show a good agreement between the two methods – even in the details.

In addition, the wear of the tip was investigated. With increasing wear, the tip can no longer measure the grooves with great accuracy. This leads to bias and wrong roughness parameters in the measured profile. Investigations at moderate traverse speeds up to 100 µm/s and very small probing forces of 6 µN which were carried out on a roughness standard have shown that the silicon tip wears out continuously and thus flattens. Even after a measurement length of 54 m, however, the radius of these flattened tips measured less than 1 µm and was thus still smaller than the radius of conventional diamond tips (2 µm). At small probing forces and moderate displacement rates of less than 100 µm/s, a reliable tactile probing and comparability of profiles and parameters with those obtained by means of conventional procedures are ensured. At the maximum possible traverse speed of these microprobes, which amounts to 15 mm/s, wear, however, increases in such a way that after a measurement length as short as 3 m, the radius of the tip reaches more than 2 µm. After 300 m of probing, this radius increases to a value of 3 µm due to wear. At very high probing speeds, stylus tips which are more resistant to wear are therefore required.



Silicon microprobe measurement of a roughness standard with a traverse speed of 15 mm/s compared to a measurement with a conventional profilometer at the usual traverse speed of 0.1 mm/s.

In another BMBF-funded project, it is planned to investigate a tip-testing measurement standard for the exact determination of the tip shape. This is necessary in order to eliminate the influence of the tip's shape from the measured profile by means of morphological filtering. This would, for the first time, enable traceable microform measurements with piezoresistive microprobes. With its three interferometric measuring axes, PTB's "Profilscanner" (see PTB News 1.2012) provides ideal conditions for such measurements. ■


**Contact**
*Uwe Brand*
*Department 5.1*
*Surface Metrology*
*Phone: +49 (0)531 592-5111*
*uwe.brand@ptb.de*



**Scientific publication**
*L. Doering, U. Brand, S. Bütefisch, T. Ahbe, T. Weimann, E. Peiner, T. Frank: High-speed microprobe for roughness measurements in high-aspect-ratio microstructures. Meas. Sci. Technol. 28, 034009 (2017)*


# Most accurate and most stable transportable optical clock

## Flexible applications possible thanks to operation in a car trailer

**Especially interesting for**
- geodesy
- the new system of units
- fundamental research in physics

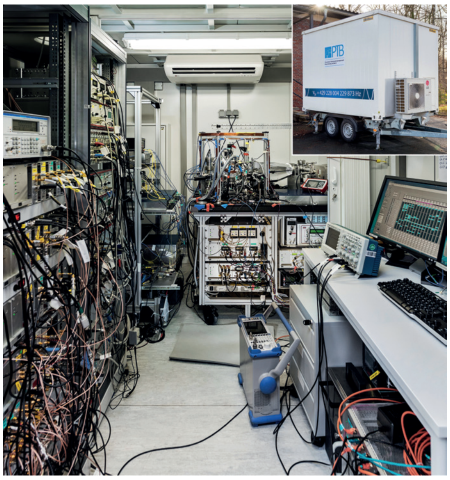
**At PTB, a transportable optical strontium lattice clock was developed and tested for the first time in the world. This clock is suitable for international comparisons, geodesic applications and fundamental investigations in physics.**

The SI base unit of time, the second, might be realized by optical clocks in the future. That the redefinition of the SI, which is planned for the autumn of 2018, is still based on cesium atomic clocks, is due to the fact that several optical clocks are competing with one another; none of them has managed to clearly emerge at the forefront in the long run – neither with regard to accuracy, nor with regard to stability.

PTB's transportable optical strontium lattice clock is more accurate and more stable than any other transportable clock to date. With a relative uncertainty of $7.4 \cdot 10^{-17}$, it has reached a level which is so close to the best stationary optical clocks that they can seriously be compared with each other. This was previously possible only with clocks which are located in the same laboratory or which are connected via a fiberglass link such as the one available between Braunschweig and Paris (see PTB News 3/2016). This has paved the way for a global pooling of optical clocks – which is a precondition for enabling the redefinition of the unit of time, the second.

Due to its high stability, the new clock is interesting for geodesy. Height differences of approx. 10 centimeters can be resolved after as little as an hour – even between two locations that are very far from each other. PTB has therefore been collaborating for several years with geodesists from Leibniz University Hannover within the scope of the DFG's geo-Q Collaborative Research Centre 1128.

During two measurement campaigns outside PTB's site, the clock already turned out to be ten times as precise and a hundred times more stable than the best transportable cesium fountain clocks. Thus, PTB's transportable optical clock is ready for geodetic height measurements, international clock comparisons and precision measurements of fundamental constants – and has taken a step towards future applications in space. ■


An air-conditioned car trailer full of high-tech physics: PTB's transportable optical clock.


**Contact**
*Christian Lisdat*
*Department 4.3*
*Quantum Optics and Unit of Length*
*Phone: +49 (0)531 592-4320,*
*christian.lisdat@ptb.de*



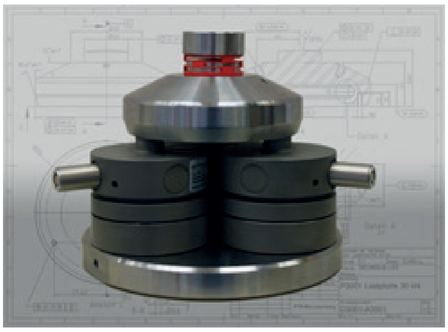
**Scientific publication**
*S. B. Koller, J. Grotti, S. Vogt, A. Al-Masoudi, S. Dörscher, S. Häfner, U. Sterr, C. Lisdat: Transportable optical lattice clock with $7 \cdot 10^{-17}$ uncertainty. Phys. Rev. Lett. 118, 073601 (2017)*

# Bending-neutral loading plate

**Especially interesting for**
- manufacturers of force transducers

To measure medium-sized forces (of approx. 10 kN) up to very high forces (higher than 10 MN), several calibrated force transducers can be connected to obtain a build-up measuring system. Due to increasing requirements, especially in the field of very large force transducers up to 50 MN, reducing the measurement uncertainty of these systems is gaining more and more importance. Due to its special geometry with a bending-neutral loading plate, PTB's new development can dispense with sophisticated compensation mechanisms. Despite deformations at the relevant contact points with the force measuring instrument, deformation angles inducing cross forces to the individual force transducers do not occur. (Technology Offer 0418) ■

**Advantages**
- *no parasitic loads*
- *saves material*
- *no additional loading fittings for compression*

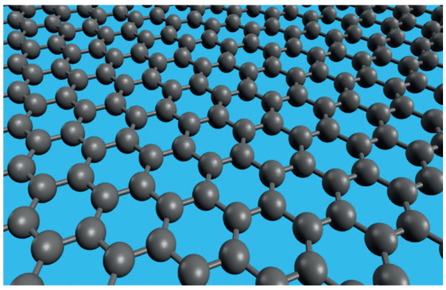


Bending-neutral loading plate for build-up systems

# Manufacturing graphene

**Especially interesting for**
- resistance metrology
- sensors
- semiconductor components

At PTB, a manufacturing procedure for monolayer graphene has been developed to produce a quantum standard for the electric unit of resistance. Thanks to its reliability and simplicity, this enhanced multi-step sublimation method allows the production of large-scale graphene structures. This also paves the way for the mass production of qualitatively high-end monolayer graphene films. The produced samples of 10 mm × 5 mm exhibit no irregularity in their material as may occur due to the formation of multiple layers of graphene or due to high substrate steps. ■



The schematic representation of a monolayer of graphene shows the hexagonal structure of the crystal lattice which consists of carbon atoms.

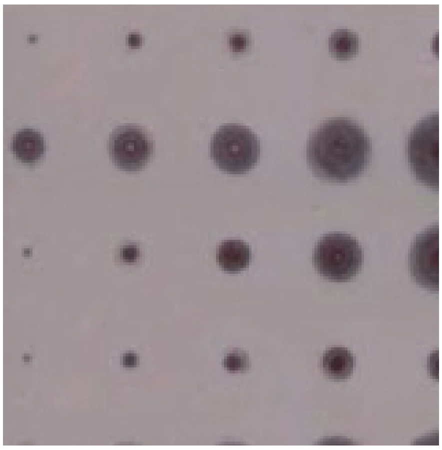
**Advantages**
- *manufacturing of graphene monolayers*
- *size can be scaled*
- *potential for mass production*

# Therapeutic ultrasound

**Especially interesting for**
- medical therapy
- routine check of ultrasonic equipment

Ultrasound is used as a therapeutic modality in medicine for various applications including the removal of kidney stones or tumors. A new procedure developed by PTB now allows a traceable spatial calibration of, e.g., high-intensity therapeutic ultrasonic equipment. Based on thermochromic foils which change color in the event of heating induced by ultrasound, it is possible to determine instrument-specific calibration factors in a multiple-step process, but with little effort. (Technology offer 0426) ■

**Advantages**
- *saves time for calibration/constancy test*
- *precise spatial resolution of the heat input*
- *enables improved quality assurance*



Thermochromic image of a therapeutic ultrasonic field at various intensity levels

**Contact person for questions about technology transfer**
Andreas Barthel, Phone: +49 (0)531 592-8307, andreas.barthel@ptb.de, www.technologietransfer.ptb.de/en

## Awards

Jan Wernecke was awarded the 2016 Ernst Eckhard Koch Prize of the Freundeskreis Helmholtz-Zentrum Berlin at the Technische Universität Berlin for his doctoral thesis entitled "When size does matter: Dimensional metrology of nanostructured layers and surfaces using X-rays". This paper was developed in the X-ray Radiometry Working Group at the BESSY II electron storage ring in Berlin.

## Information website for courts and official experts

For decades, PTB has been carrying out type approval tests for new speed cameras, traffic light cameras and other measuring instruments used in road traffic before they may be put into operation. This ensures, for instance, that no one is suspected of speeding for no good reason due to a wrong measurement. On account of its expertise and neutrality, courts often request PTB's expert opinion in cases where, for example, persons caught speeding dispute the speed indication under the pretext that the measuring instrument used was technically inadequate. To help cope with the flood of several hundreds of enquiries per year, PTB has now set up a special website compiling frequently asked questions: http://www.ptb.de/geschwindigkeit_stellungnahmen. Hundreds of visitors per month demonstrate how successful this measure has been; moreover, the documents provided there have recently been deemed "Expertise from a competent authority" which may be read out in court cases relating to traffic offenses instead of citing a PTB employee before the court for the trial (decision No. 2 Ss-OWi 589/16 of the Higher Regional Court (OLG) Frankfurt dated 26 August 2016). (Robert Wynands, phone: +49 (0)531 592 1300, robert.wynands@ptb.de)

## "Designed Quantum States of Matter"

Within the scope of the Collaborative Research Centre "Designed Quantum States of Matter" (DQ-Mat), with approx. 10 million euros of funding provided by the DFG, researchers from Leibniz University Hannover, from the Center of Applied Space Technology and Microgravity (ZARM) in Bremen and from PTB in Braunschweig have been collaborating to exploit special quantum-mechanical properties of many-particle systems for metrology. It is planned to improve, among other things, the resolution and the accuracy of atom interferometers and clocks, and to use these for fundamental physics tests. (P. O. Schmidt, QUEST, phone: +49 (0)531 592 4700, piet.schmidt@quantummetrology.de)

## PTB as part of Berlin Security Research

PTB's Department 8.5, "Metrological Information Technology", has been accepted as a member of the faculty of the Helmholtz Research School on Security Technologies (HRSST). This is a joint program of the Technische Universität Berlin and the German Aerospace Center (DLR) which was initiated in 2010 and supports, among others, excellent doctoral candidates who deal with research on a secure and reliable system architecture for legal metrology. Through its cooperation, PTB is improving its integration into Berlin's scientific landscape. (F. Thiel, phone: +49 (0)30 3481 7529, florian.thiel@ptb.de)

## Information about the new SI

The International System of Units (SI) is being fundamentally reformed. In the fall of 2018, a large international conference is going to set the historical course for the future of the SI. The new SI will be based on fundamental constants instead of the seven base units as previously. PTB has accompanied this process by means of various large-scale research projects – among others the Avogadro project for the redefinition of the kilogram and of the mole, and the Boltzmann project for the redefinition of the kelvin. Moreover, PTB has played an important role by providing information on these reforms. PTB has recently published an info sheet about the new SI (in German and in English); you are welcome to order one free of charge from the Press and Information Office or to download it from our website. (www.ptb.de > Press & What's new > Brochures > Brochures on the new International System of Units). The website also contains an extra section about the new SI (www.ptb.de > Research & Development > Research on the new SI) with plenty of information about the SI experiments carried out at PTB, scientific papers, articles from journals, news, videos and photos to be downloaded.
If you wish to order a hard copy of the info sheet, please contact Cornelia Land (+49 (0)531 592 9313, cornelia.land@ptb.de)

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phone +49 (0)531 592-3006, fax +49 (0)531 592-3008,
e-mail: ptbnews@ptb.de

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