PTB news
Scientific Newsletter
1
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.

SCIENTIFIC NEWS

TECHNOLOGY TRANSFER

MISCELLANEOUS

Spectroscopy of single trapped molecules

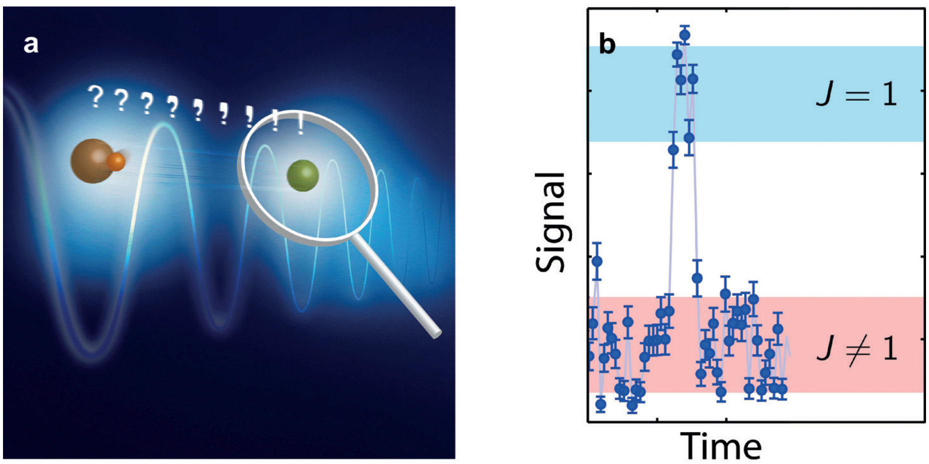
New method for state detection in molecular ions

Especially interesting for
- the development of molecular optical clocks
- fundamental research in physics
- quantum chemistry
- astronomy

The QUEST Institute at PTB has, for the first time, succeeded in proving the quantum state of trapped and indirectly laser-cooled molecular ions without destroying the molecule itself or its internal state. In this way, quantum jumps which were induced by thermal environmental radiation could be observed directly in a single molecule, and a new form of spectroscopy could be demonstrated. The new method enables precision spectroscopy of molecular ions with applications ranging from chemistry to tests in fundamental physics.

For the development of optical frequency standards and clocks, several preparation and detection techniques were successfully demonstrated in atomic systems. Prominent examples are laser cooling – to control motion – and the detection of quantum states based on state-dependent fluorescence. However, the resonant laser manipulation techniques successfully demonstrated with atoms cannot in general be transferred to molecules. Molecules have additional degrees of freedom in the form of rotation and vibration resulting in a large number of possible transitions from the excited state.

PTB researchers have now succeeded in reading out a selected quantum state of a trapped molecular ion (MgH^+) non-destructively via the strong electrostatic interaction with a simultaneously trapped atomic ion (Mg^+). To this end, the motion of the two ions along a direction is cooled down to the ground state via the atomic ion by means of lasers. Another laser is tuned in such a way that it exerts an oscillating optical force (similar to that of



(a) Conceptual set-up of the experiment with MgH^+(orange) and Mg^+ (green) in a linear ion trap. The ionic crystal is cooled to the ground state via Mg^+. An oscillating dipole force changes the motion state, depending on the rotation state of MgH^+. This excitation is read out via Mg^+. (b) Typical detection signal in which a quantum jump into the (J = 1) rotation state (transition from the red to the blue area) of the molecule and out of it (from blue to red) can be seen.

optical tweezers) onto the molecular ion only if the latter is in a selected state of rotation. The oscillation frequency of the force is adjusted to the period of a joint oscillation of the two ions in the trap which is thus resonantly enhanced. It is only when the molecular ion is in the selected state that the joint motional state of the two ions is excited. This motional excitation can be read out via the atomic ion. The thermal radiation of the environment interacts with the rotational states of the molecular ion and induces transitions between these states. These quantum jumps between the rotational states of the molecule were observed "live".

Moreover, it was demonstrated that the dependence of the optical force on the detuning of the laser with respect to a resonance in the molecular ion can be used for a new form of spectroscopy. Combined with efficient state preparation procedures, the state detection method presented here allows precision spectroscopy on narrow-band transitions for molecular optical clocks and tests in fundamental physics such as a possible change of fundamental constants. Furthermore, the method could be applied in quantum chemistry and to interpret spectra of cold molecular ions in space. ▪

Contact
Piet O. Schmidt
QUEST Institute at PTB
Phone: +49 (0)531 592-4700
E-mail:
piet.schmidt@quantummetrology.de

Scientific publication
F. Wolf, Y. Wan, J. C. Heip, F. Gebert, C. Shi, P. O. Schmidt: Non-destructive state detection for quantum logic spectroscopy of molecular ions. Nature (2016), Doi: 10.1038/nature16513

World record set with single-electron pump

Demonstration of the quantum ampere with previously unattained accuracy

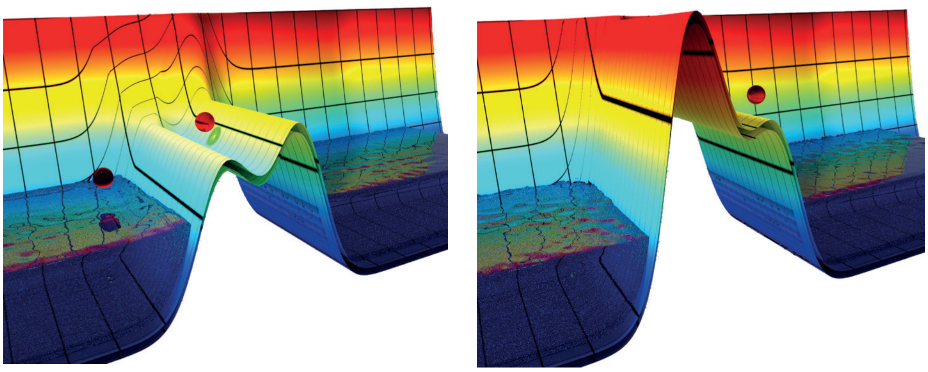
Especially interesting for
- metrology institutes
- fundamental research

Single-electron pumps are promising candidates for the realization of a future quantum current standard, and are the subject of intensive metrological research. By means of a novel, high-precision current amplifier, PTB researchers have succeeded in proving the quantization of a current of 100 pA supplied by a single-electron pump with an accuracy which had previously been unattained: within the relative uncertainty of only $2 \cdot 10^{-7}$, the electric current agreed with the expected quantized value. This means a measurement uncertainty which is smaller than all results previously attained by around a factor of five and is thus for the first time better than the best possible ampere realization in the currently valid International System of Units (SI).

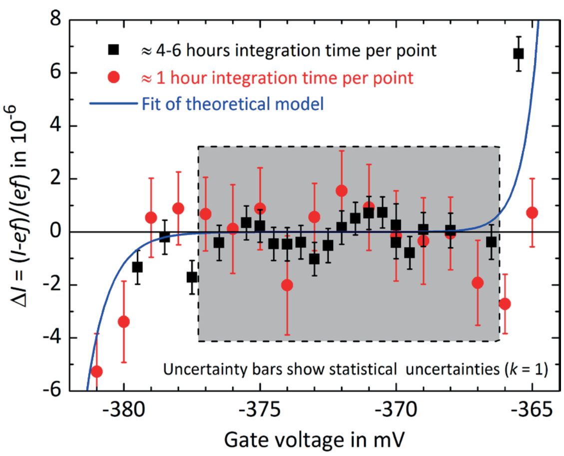
Single-electron pumps are nanostructured electrical circuits which allow the clocked transport of individual charge quanta (electrons with elementary charge e). At PTB, such circuits are manufactured on the basis of semiconductor heterostructures and investigated with a view to future metrological applications. For clock rates f which extend into the gigahertz range, quantized electric currents I of more than one hundred picoamperes can be generated in accordance with $I = e \cdot f$. This makes single-electron pumps promising candidates for quantum current sources, by means of which the unit of current could be realized in future after the envisaged redefinition of the ampere (see also PTB News 2.2014).

PTB researchers used a high-precision current amplifier developed by PTB itself (ultrastable low-noise current amplifier, see also PTB News 1.2015) which is calibrated in a traceable way. This amplifier is around one hundred times more accurate than the picoamperemeters which have been available to date. The current generated by a single-electron pump operated at f = 545 MHz was measured with this new instrument as a function of external control parameters. The relative systematic measurement uncertainty in these current measurements was only $1.3 \cdot 10^{-7}$.

The figure on the left shows the measurement results obtained while varying the current at the gate electrode, which controls the right-hand barrier of the "quantum well" of the electron pump. Depending on the measurement duration per point, statistical standard measurement uncertainties of down to $6 \cdot 10^{-7}$ are reached. Within a relatively large range of around 11 mV, the measurement values deviated from the value of the inflection point by less than two standard deviations. Averaging the measurement values of this plateau region (plotted in



Operating principle of the single-electron pump investigated: single electrons, depicted as red spheres, are captured while moving from one side of a conductor (in the figure, from the left-hand side) by a "dynamic quantum well" (between the "hills" of the potential landscape depicted here), and released toward the other side. The entire procedure is repeated at the clock frequency of the AC voltage, which raises and lowers the left-hand barrier of the quantum well.



Precision current measurement at a single-electron pump (f = 545 MHz, corresponding to $I = e \cdot f \approx$ 87 pA) as a function of the voltage at a control gate, depicted as a relative deviation from the nominal value. The error bars at the points (which were measured with different integration times) correspond to statistical standard measurement uncertainties. Also shown is the progression of a fitted theory line.

the figure as the dashed frame) ultimately provided the final result: the relative difference between the generated current and the quantized nominal value – i.e., $(I - e \cdot f)/(e \cdot f)$ – was $-0.94 \pm 1.94 \cdot 10^{-7}$. This proved that the generated current agrees, within a total measurement uncertainty of around $2 \cdot 10^{-7}$, with the expected quantized value $e \cdot f$. At 545 million electrons transferred per second, this corresponds to an uncertainty of only around 100 electrons. This means that – when compared to measurement results obtained previously – the measurement uncertainty is reduced by a factor of around five.

Furthermore, for the first time, the accuracy achieved during this “quantum ampere” demonstration surpasses the best possible experimental realization of the ampere, which uses “traditional” experiments in the currently valid International System of Units (SI); this realization achieves a total measurement uncertainty of $2.7 \cdot 10^{-7}$. ■

Contact
Hansjörg Scherer
Department 2.6 Electrical Quantum Metrology
Phone: +49 (0)531 592 2610
E-mail: hansjoerg.scherer@ptb.de

Scientific publication
F. Stein, D. Drung, L. Fricke, H. Scherer, F. Hohls, C. Leicht, M. Götz, C. Krause, R. Behr, E. Pesel, K. Pierz, U. Siegner, F.-J. Ahlers, H. W. Schumacher: Validation of a quantized-current source with 0.2 ppm uncertainty, Applied Physics Letters 107, 103501 (2015)

Protection against X-rays: lead-reduced but safe

Updated standard improves protection of medical staff and patients

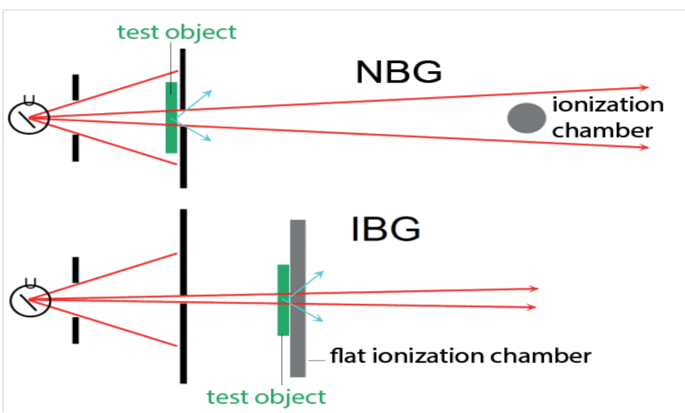
Especially interesting for
- manufacturers of protective devices against x-radiation
- staff and patients in radiology and nuclear medicine

A new measurement method developed at PTB has been included in the updated version of the international series of standards IEC 61331. For the staff and the patients in medical X-ray diagnosis and nuclear medicine, the application of this standard, which has been elaborated under the leadership of PTB, represents a considerable improvement in radiation protection.

Personal protective equipment and shielding (such as protective aprons, gloves and goggles as well as gonadal, testicle and ovary protection or even translucent protective plates such as lead glass plates) must comply with the series of standards IEC 61331 which lays down the requirements, testing procedures and markings.

For a long time, the protective effect of such equipment was solely based on lead (e.g. lead rubber or lead glass plates). This is why the designation “lead equivalent” has become common. It refers to the thickness of a layer of pure lead which would provide the same degree of attenuation as the material actually used (in a beam of a defined radiation quality and under specified geometric conditions).

In addition to lead rubber, materials which contain reduced lead or no lead at all have, for many years, been used for the manufacture of X-ray aprons. They offer the same protective effect but are up to 20 % lighter and also easier to dispose of. The determination of the lead equivalent value used so far was no longer suitable to describe the protective effect of these new materials appropriately. The new measurement method developed at PTB – inverse broad-beam geometry – consists of a flat ionization chamber



Old (top) and new (bottom) method compared: The intensity of the X-rays is measured by means of ionization chambers. The measured ratio of the radiation intensity with and without the test object shows how much a layer of material (test object) attenuates the X-rays (red). With the conventional narrow-beam geometry (NBG), the scattered radiation (blue) is not detected by the ionization chamber; with the new inverse broad-beam geometry (IBG), the flat ionization chamber can detect it.

which not only detects the primary radiation which is attenuated by the material sample, but also the scattered and fluorescence radiation on the side of the sample where the radiation is released. Since protective aprons are worn close to the body, this modified geometry is a good approximation of the real situation.

In the latest (2nd) edition of the IEC 61331 standard, this new procedure has now been made compulsory. Further improvements of the standard consist in the extension of the scope of application to photon-emitting radionuclides, in the definition of better suited radiation qualities for the tests, in the inclusion of all kinds of transparent radiation protection plates (not only lead glass), and in the inclusion of further protective equipment such as protective collars for the thyroid glands, protective goggles and masks for the eyes, and protective aprons for the dental X-ray region. For the staff and the patients in medical X-ray diagnosis and nuclear medicine, the consistent application of these second editions of the standard series IEC 61331 represents a considerable improvement in radiation protection. ■

Contact
Ludwig Büermann
6.2 Dosimetry for Radiation Therapy and Diagnostic Radiology
Phone: +49 (0)531 592-6250
E-mail: ludwig.bueermann@ptb.de

The standard
IEC 61331:2014, Protective devices against diagnostic medical X-radiation. Part 1: Determination of attenuation properties of materials. Part 2: Translucent protective plates. Part 3: Protective clothing, eyewear and protective patient shields

High-precision measurement of the Boltzmann constant

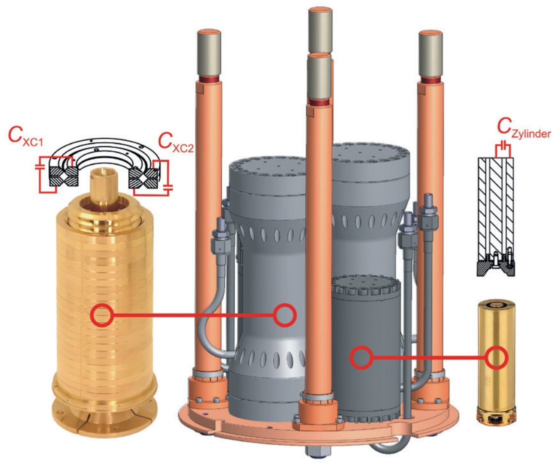
Considerable reduction of the measurement uncertainty by means of an alternative primary-thermometry method

Especially interesting for
- fundamentals of metrology

New measurements performed with PTB's dielectric-constant gas thermometer have yielded a value of 1.3806509 · 10⁻²³ J/K for the Boltzmann constant *k*. The measurement uncertainty was thereby reduced to 4 parts per million (4 ppm). The new value is within 1.5 ppm in agreement with the current CODATA value (CODATA – Committee on Data for Science and Technology). Reaching the final step towards the aimed-for uncertainty of 2 ppm in the coming year is envisaged. In this way, it will be possible to redefine the base unit "kelvin" via the fixing of the *k* value.

Ludwig Boltzmann probably never dreamed that the constant named after him would attract so much attention one day. Within the scope of the redefinition of the base units of the International System of Units via the fixing of fundamental constants, however, research groups from all over the world have been engaged in determining the value of *k* with the smallest possible uncertainty in order to enable the redefinition of the unit "kelvin".

For the determination of the Boltzmann constant, numerous research groups are using acoustic gas thermometry, as this method has provided the most accurate values so far. PTB, in contrast, wants to rule out systematic error sources by means of an alternative and completely independent primary-thermometry method and thus to provide the new definition with a sound footing. This alternative method is dielectric-constant gas thermometry (DCGT). DGCT is based on determining the density of the measuring gas, helium, via the dielectric constant. In practice, the PTB researchers measure to what degree the gas changes the capacitance of a special, highly stable measuring capacitor. From experiments at the triple point of water at exactly 0.01 °C and at various gas pressures (measurement of isotherms), *k* can be determined by means of fundamental relations. In this way, it has been possible to reduce the relative uncertainty down to 4 ppm.



Capacitor systems (cross capacitor with partial capacitances C_{XC1} and C_{XC2}, and cylindrical capacitor with capacitance $C_{Zylinder}$) with corresponding pressure vessels to measure the dielectric constant of helium.

The measurements were extremely demanding with regard to capacitance, pressure, temperature and dimensional measurements. They could only be carried out successfully thanks to close cooperation between different PTB working groups and industry. Pressure, for example, had to be measured up to 7 MPa with a relative uncertainty of 1 ppm applying pressure balances; relative capacitance changes even had to be measured with 0.001 ppm uncertainty. Exhaustive comparisons between pressure balances of different effective cross-sectional areas, combined with dimensional data, have now led to pressure measurements with the worldwide lowest measurement uncertainty. The required temperature stability was provided by a large bath thermostat which was manufactured and optimized in cooperation with the Italian national metrology institute (INRIM).

Recently, a cooperation project between the Chinese (NIM) and the American metrology institute (NIST) allowed the relative uncertainty of the measurement of k to be reduced to a few parts per million thanks to yet another primary-thermometry procedure, known as noise thermometry. Acoustic gas thermometry, dielectric-constant gas thermometry and noise thermometry – as complementary methods – thus constitute the basis for the determination of the Boltzmann constant with an aimed-for relative standard measurement uncertainty of 1 ppm. ■

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

Scientific publication
C. Gaiser, T. Zandt, B. Fellmuth:
Dielectric-constant gas thermometry.
Metrologia 52, 217–226 (2015)

Neutron monitors for Wendelstein 7-X

Fusion experiment with PTB measuring equipment launched

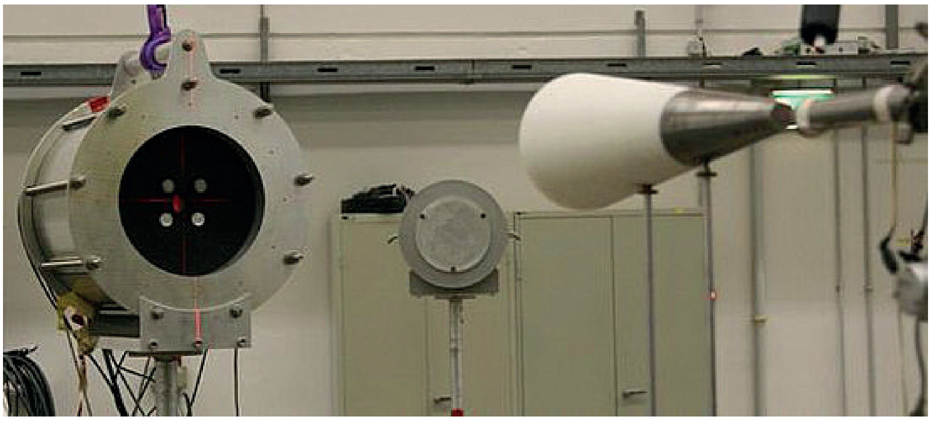
Especially interesting for
- energy generation

The Wendelstein 7-X fusion experiment, which recently went into operation at the Max-Planck-Institut für Plasmaphysik (IPP) in Greifswald, is intended to demonstrate the suitability of stellerator-type fusion facilities for the production of energy. At the end of 2015, a helium plasma was generated for the first time. Producing plasmas with deuterium, in which neutrons are generated by nuclear reactions, is planned for a later date. Within the scope of a cooperation agreement, PTB together with IPP developed a monitoring system which measures the total neutron radiation generated by the machine during operation.

The neutron monitors are used to measure neutron radiation during the operation of Wendelstein 7-X (W7-X), in particular to establish that the annual limit of neutron production permitted by the operation authorization will not be exceeded. In addition, important information about physical processes taking place in the fusion plasma will be obtained by measuring the time-resolved neutron fluence rate. When the neutron monitors are correctly calibrated, they enable the measurement of the fusion rate and of the energy generated by the fusion plasma. They also allow conclusions to be drawn, e.g. on the ion temperature of the plasma.

Essential criteria for the design of the three monitors installed at the facility include the lowest possible energy dependence of the monitor response and a directional dependence adapted to the main angle of incidence of the neutrons. These requirements ensure that the influence of scattered neutrons is kept low. A further design criterion is the ability to measure the neutron production rate over a dynamic range of at least five orders of magnitude. These requirements have been accounted for by means of a set-up which conforms to the principle of the "precision long counter" from 1966: the monitor design consists of a moderator made of polyethylene, which surrounds several detectors with different sensitivities to thermal neutrons. The design was optimized by means of neutron transport calculations.

The three monitors were calibrated in the reference radiation fields of PTB. In addition, the behavior of the various detectors in the monitors was examined at very high count rates using the high-intensity neutron field of PTB. It could be demonstrated that the proportional counters used (types ^{3}He and BF_3) can each be operated with count rates of up to $2 \cdot 10^5\ s^{-1}$, and the ionization chambers with cathodes made of ^{235}U with count rates of up to $1 \cdot 10^6\ s^{-1}$. These counters make it possible to measure the neutron production rate of W7-X in a range from 10^{11} to 10^{16} neutrons per second with a time resolution of 5 ms and a relative statistical accuracy that is better than 15 %.



Neutron monitor (left) during calibration with monoenergetic neutrons in the reference radiation fields of PTB.

Before W7-X went into operation, the neutron monitors were calibrated on site – as specified in the operation authorisation which had been applied for. For this purpose, a $^{241}AmBe$ radionuclide neutron source was used. The source strength had previously been determined at PTB and is traceable to primary standards. The source was placed on a rail system installed inside the plasma vessel and moved along a path which corresponds to the average location of the plasma in the vessel. The calibration factor was obtained from the time-dependent count rates of all detectors; for the most sensitive proportional counters, this factor was determined with a relative statistical measurement uncertainty of better than 1 %. To determine the total measurement uncertainty of the calibration factors during plasma operation, it is in addition necessary to take systematic effects into account such as the complex plasma volume and the neutron energy distribution from the plasma which differs from the one of the calibration source used. To better understand these interdependences, further investigations based on detailed neutron transport calculations will be carried out. ■

Contact
Andreas Zimbal
Department 6.4
Ion and Neutron Radiation
Phone: +49 (0)531 592-6530
E-mail: andreas.zimbal@ptb.de

Scientific publication
B. Wiegel, W. Schneider, F. Grünauer, R. Burhenn, H. Schuhmacher, A. Zimbal: Monitoring of the neutron production at the Wendelstein 7-X stellarator. Radiat. Prot. Dosim. 161, 326–330 (2014)

Measurement instruments secure even with standard operating systems

Use of microkernels for encapsulating software modules

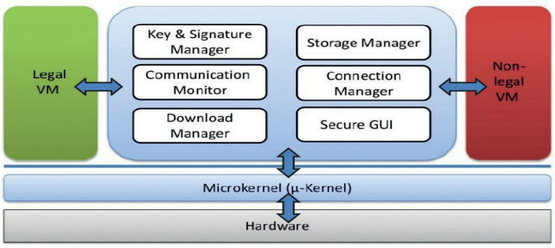
Especially interesting for
- legal metrology
- industry 4.0
- IT security

Measuring instruments often use large standard operating systems as their underlying software. This often makes software testing difficult as such systems contain a large number of bugs. A new system architecture developed at PTB makes use of the advantages of standard operating systems – such as a higher degree of functionality, an established user interface and executable drivers – yet still guarantees security due to the system being encapsulated and modularized.

The core element of any operating system is its kernel, which holds the greatest number of privileges in the system and provides applications with the mechanisms they need to run correctly. Modern operating systems offer a very wide range of functions, most of which are located in the kernel. A kernel which offers only the most necessary mechanisms in order to ensure that the individual applications are encapsulated, and that communication between them is secure, is called a microkernel. It is several orders of magnitude smaller than the kernels of established operating systems, and is thus more resistant to errors. Microkernels can provide software security in the form of manipulation detection and system stability. The algorithms necessary to ensure correct measurement and calculation thus run in a secure environment, but still have to be checked for correctness.

At PTB, a configurable software system architecture has been developed which is based on a microkernel. The microkernel encapsulates the actual operating systems in modules (known as virtual machines – VMs), and serves as an additional layer of protection. The operating systems can continue to load their usual programs and drivers, but can communicate with each other and access hardware only via the microkernel. The system architecture is based on a modular design. In this design, the individual virtual machines comply with the requirements of the Measuring Instruments Directive of the European Union (MID) as well as those of WELMEC 7.2 Software Guide. These modules can be seen in the image on the right: Secure GUI; Key & Signature Manager; Storage Manager; Download Manager; Connection Manager; and Communication Monitor. This ensures a legally compliant architecture which executes all functions which are relevant to legal metrology in such a way that these functions are secure and can be monitored. In addition, software which is not legally relevant (N) is separated from software which is legally relevant (L). All computations which are subject to legal control are executed in the L-VM, all others in the N-VM. This strict separation ensures that legally relevant software programs are not influenced by legally non-relevant software.

This project will be continued in cooperation with the Technische Universität Berlin, which is developing a novel microkernel that will be, at least in parts, mathematically formally verified to prevent typical operating system errors from arising. This is important for measuring instruments which are required to prove their correctness for legal purposes (such as for those used in road transportation). The system architecture proposed was implemented on an evaluation board using this microkernel. ■



Communication of individual modules within the system architecture

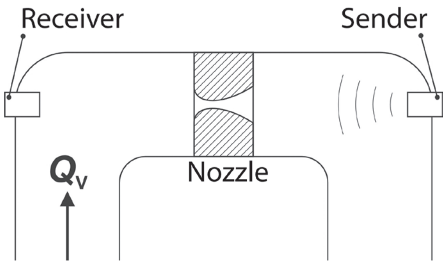
Contact
Daniel Peters
Department 8.5
Metrological Information Technology
Phone: +49 (0)30 3481-7916
E-mail: daniel.peters@ptb.de

Scientific publication
D. Peters, M. Peter, J.-P. Seifert, F. Thiel: A secure system architecture for measuring instruments in legal metrology. Computers – Open Access Journal 4(2), 61 to 86 (2015)

Procedure for detecting the critical flowrate state

Especially interesting for
- flow measurement
- testing laboratories

In the field of gas flow measurement, nozzles and diaphragms are used. When a suitable pressure ratio between the inlet pressure and the outlet pressure at the nozzle is exceeded, a critical state results in which the volume flow is independent of the pressure behind the nozzle. A new form of sensor technology developed at PTB makes it possible to detect this critical state in order to significantly



minimize the energy needed to create the differential pressure. Here, sound or light signals are fed through the nozzle to a detector. The signal which changes upon reaching the critical state is analyzed. (Technology Offer 0387) ■

Advantages
- *optimized flow measurement*
- *low operating costs*
- *precise analysis of the critical state*

Interface for incremental encoders

Especially interesting for
- measurement, control and regulation technology

Today, analog rotary controls can still be found in power plant control stations, system control units and many control rooms. In order to make digital conversion of such controls possible while retaining the advantages of sensitive rotary controls, PTB has developed a conversion set which is compatible with many digital controls. Operation by means of these

Using the PTB conversion set, the potentiometers of old switch rooms can be converted easily to digital operation (image: Fotolia)

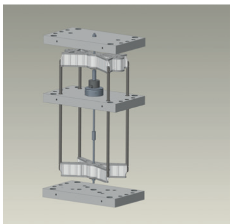
digital controls is markedly more ergonomic than by means of a commercially available monitor, and is a better option especially when very small parameters have to be continuously re-adjusted. Software programs, parts lists and documentation of the global approach are available for technology transfer. (Technology Offer 0392) ■

Advantages
- *suitable for all types of switch rooms*
- *USB interface*
- *SPS compatible*

Force measuring machine for tensile and compressive forces

Especially interesting for
- manufacturers of force measuring devices

Force measuring machines measure either tensile or compressive forces; they have to be converted when switching between these two operating modes. A new diversion device developed by PTB makes it possible to avoid these conversion times. As a result, novel and faster calibrations are possible, even over the full range of tensile and compressive forces with zero crossing. An additional advantage is that only one air-conditioned testing chamber is required for both tensile and compressive measurements. The diversion principle can be used for force measuring machines with a direct deadweight effect, with a lever transmission or a hydraulic transmission, with reference transducers and with other principles, but can also be used for material testing machines. (Technology Offer 0349) ■

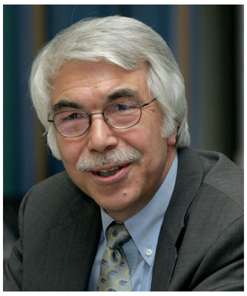


Advantages
- *measurement of tensile and compressive forces in one set-up*
- *no conversion necessary*
- *measurement scenarios with zero crossing*

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

Manfred Peters



The former Vice President of PTB has been awarded the 2015 Ludwig Finkelstein Medal. With this distinction, the Institute of Measurement and Control, an internationally active organization of engineers which is headquartered in the United Kingdom, has honored his many years of substantial contributions to international metrology. The Institute further noted that Dr. Peters, whose accomplishments include his term as president of the IMEKO (International Measurement Confederation) from 2000 to 2003, played an active, prominent role in international metrology for over 40 years.

Rolf Behrens

a staff member of Department 6.3, Radiation Protection Dosimetry, has been awarded the IEC 1906 Award. With this award, the International Electrotechnical Commission (IEC) has honored him for his expertise and dedication to international standardization.

Office of Chinese explosion protection center at PTB

Since 1 October 2015, PTB has been host to an office of the Chinese National Supervision and Inspection Center for Explosion Protection and Safety of Instrumentation (NEPSI), based in Shanghai. The partnership between PTB and NEPSI has existed since 1997; in July of 2015, the cooperation agreement between the two institutions was renewed. This office makes it easier for German industry, in particular small and medium-sized enterprises, to access the Chinese market for explosion-proof devices. The wide range of tasks performed by this office include consultation and certification in the field of explosion protection, as well as type examinations of measurement instruments.

Contact at PTB: Ulrich Johannsmeyer (+49 (0)531 592-3600, ulrich.johannsmeyer@ptb.de), Martin Thedens (+49 (0)531 592-3730, martin.thedens@ptb.de)

PTB at trade shows

10–12 May 2016
Sensor & Test
Metrology trade fair, Nuremberg.

7–9 June 2016
Optatec
International trade fair for optical technologies, components and systems, Messezentrum Frankfurt.

Contact person for all trade fairs:
Christine Werner, (+49 (0)531 592-3007, christine.werner@ptb.de)

International conferences

26. June–1. July 2016
TEMPMEKO
XIII Internat. Symposium on Temperature and Thermal Measurements in Industry and Science. Zakopane, Polen.
Contact person: Ramona Peper (+49 (0)30 3481-7474, ramona.peper@ptb.de)

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: http://t1p.de/8hak

Contact person for all EMRP and EMPIR projects in the PTB
Corinna Kroner, Presidential Staff, (+49 (0)531-592-3090, corinna.kroner@ptb.de)

Imprint
PTB News 1/2016, English edition, Issue April 2016, ISSN 1611-163X
The PTB News is published three times each year in a German as well as in an English edition and can be subscribed to free of charge.
Subscription form: www.ptb.de > English Version > Publications > PTB News > Subscribe the PTB News
Publisher: Physikalisch-Technische Bundesanstalt (PTB), Braunschweig and Berlin
Editors: Andreas Barthel, Ludger Koenders, Christian Lisdat, Dirk Ratschko, Mathias Richter, Hansjörg Scherer, Erika Schow, Florian Schubert, Jens Simon (responsible)
Layout: Volker Großmann, Alberto Parra del Riego (concept)
Translation: PTB Translation Office (Cécile Charvieux, Charles Minnick)
Editorial Office: Press and Information Office, PTB, Bundesallee 100, D-38116 Braunschweig, phone +49 (0)531 592-3006, fax +49 (0)531 592-3008, e-mail: ptbnews@ptb.de

Federal Ministry for Economic Affairs and Energy

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