PTB INFO SHEET

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT

DIVISION 7

Temperature and Synchrotron Radiation

Temperature and Synchrotron Radiation

Temperature is not only a base quantity, but actually also one of the most frequently measured physical quantities. In addition to thermometry, metrology with synchrotron radiation in the wide range from terahertz to X-rays is a second central task of Division 7. Moreover, it deals with fundamental and applied questions of radiometry and vacuum metrology as well as with thermal energy measurements.

The Kelvin

Temperature governs the efficiency of heat engines and the emission of thermal radiation, and in statistical thermodynamics, it is a parameter of probability distributions. As practically all other macroscopic physical quantities which are of interest to industry and research are more or less strongly influenced by temperature, they can be easily compared only if they are determined at the same temperature. For these reasons, temperature is one of the most frequently measured physical quantities.

Core piece of PTB's gas thermometer for the redefinition of the kelvin: Four pressure cylinders of stainless steel accommodate the different capacitors for the measurement of the dielectric gas constant.

Among the base quantities of the System of Units, temperature occupies, however, a special position, because – as an intensive thermodynamic parameter of state – it is not "additive": The temperature $2 \cdot T$ cannot be obtained by combining two systems of temperature T. Accordingly, the question of how a complete temperature scale can be realized on the basis of one temperature value plays an important role in thermometry. This task has been assigned to PTB in the Units and Time Act, and it disseminates the current temperature scale with smallest possible uncertainties. The temperature unit kelvin (K) is determined with the aid of the temperature interval between the absolute zero point and a suitable temperature "fixed point". The triple point of water – a rather "accidental" material property – with a temperature value of 273.16 K – was selected as this fixed point. Instead of that, it is envisaged to link the temperature unit up with a fundamental natural constant. In the case of the kelvin, this is the Boltzmann constant k, as in all fundamental physical laws, temperature always occurs in the combination kT as "thermal energy". Before the kelvin can be redefined by the Boltzmann constant, this constant must be determined by different methods with a sufficiently small uncertainty. PTB wants to achieve this objective with the aid of improved dielectric-constant gas thermometry. ■

Temperature Measurement in Extreme Ranges

In accordance with an agreement from the year 1990 (ITS-90), a uniform temperature determination is guaranteed by the specifications and measurement prescriptions in the International Temperature Scale. It reaches from 0.6 K to the highest temperatures which can be practically measured with the aid of Planck's radiation. PTB realizes the temperature scale – unique worldwide – also for low and lowest temperatures with highest accuracy, disseminates them and works on their improvement.

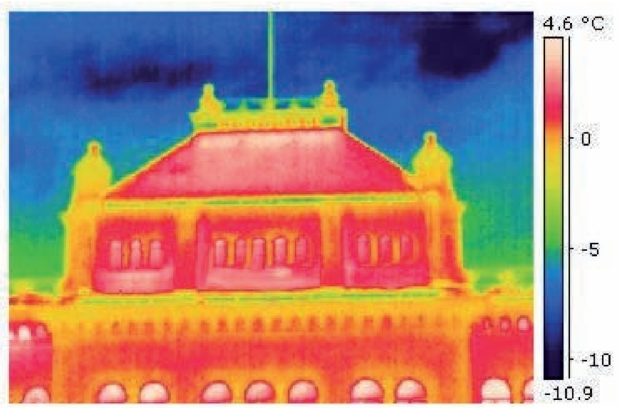
In an international cooperation, measurement techniques were developed for thermometry below 1 K. The result is a new international scale for the temperature range from 1 K down to 0.0009 K – the PLTS-2000. It is based on the relationship between the melting pressure and the melting temperature of the helium isotope ^{3}He.

Within the scope of product safety and for the efficient use of resources, high-temperature measurements with highest reproducibility and accuracy in process control are increasingly gaining in importance. Within the scope of international joint research projects, PTB develops novel temperature fixed points for the exact measurement of temperatures above the highest temperature fixed point of the ITS-90 at 1358 K. It makes high-temperature fixed points, high-temperature thermocouples and thermodynamic measurement procedures available in the range from 1400 K to 3200 K which allow high temperatures to be measured – also in industrial processes – with uncertainties of a few tenths of a degree Celsius.

Tungsten strip lamp as a transfer standard for radiation temperature and spectral radiance.

Radiation Thermometry – Contact-free Temperature Measurement

A great number of temperature measuring procedures are based on contact thermometers which must be brought into direct contact with the body whose temperature is to be determined. With optical radiation measuring devices it is, however, possible to determine the surface temperature of a body contact-free. Radiation thermometry is based on the measurement of the electromagnetic radiation which each body emits with a temperature above the absolute zero point (temperature radiation or thermal radiation). If a body completely absorbs all of the incident radiation, it is called a "black body". Its emitted spectrum is described by Planck's Radiation Law.

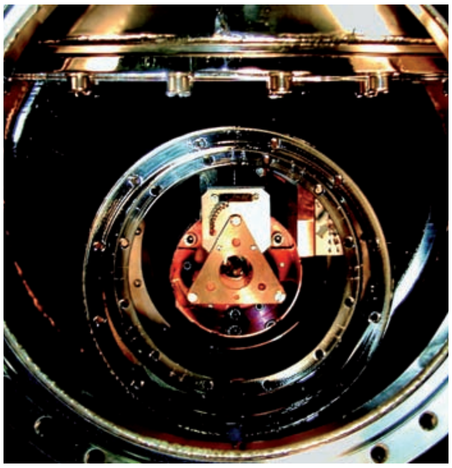


Thermographic image of the dome of the Werner von Siemens Building of PTB Berlin.

Today, radiation thermometry is possible over a temperature range from –100 °C to 3000 °C. Radiation thermometers react very fast, and the measurement is not influenced by thermal conduction. The temperature of objects which are very hot, move very quickly, are energized, experience fast temperature changes or are very far apart, can be measured in this way. Thus, the importance of infrared radiation thermometry is of increasing importance also for remote sensing of the Earth, e.g. in connection with climate observations. The reliable application of radiation thermometry requires an exact calibration of radiation thermometers and the determination of the spectral emissivity of object surfaces. For this purpose, Division 7 operates cavity radiators which emit the radiation of a black body at temperatures from –173 °C to 3000 °C in very good approximation. They allow users and manufacturers of radiation thermometers to trace the contact-free temperature measurement back to the International Temperature Scale.

Heat

The increase in the energy efficiency via the path from the production in power plants and the distribution via district heating networks to the economical use at the user's is an urgent political requirement and a technical challenge of profound economic relevance. PTB already addressed this subject many years ago and is about to develop into a centre for the measurement of thermal energy in Europe. For conformity assessments within the scope of the European Measurements Directive, measurement data are collected for the assessment of heat meters and ambient cooling meters. At present, approximately 80 % of the conformity assessments for heat and ambient cooling meters in Europe are based on PTB measurements. In addition, fundamental questions of thermal energy metrology are investigated in a great number of research projects. In cooperation with eight other metrology institutes and large economic enterprises of the energy branch, PTB is presently heading a European research project to increase the energy efficiency of power plants. An important objective of this project is the improvement of the traceability of the measurands "flow rate" and "temperature" which are of particular relevance and for which extreme conditions prevail in power plants. For this purpose, modern methods of laser-optical flow metrology are, among other things, required which are developed at PTB.



View into the interior of a cryogenic radiometer with the triangular support of the radiation absorber made of copper.

Detectors for Radiant Power Measurements

From the satellite-based remote sensing instrument to the exposure facility of the semi-conductor industry, from colour measurements to radiation thermometry: reliable measurements of the radiant power of light sources require the determination of the spectral responsivity of radiation detectors. This is done with the aid of absolutely measuring primary detector standards. The responsivity of a radiation detector at different wavelengths is obtained by a comparison measurement (calibration) against a primary standard or a reference detector which has already been calibrated. In the spectral ranges from long-wave infrared or terahertz radiation up to short-wave X-rays, PTB uses so-called "cryogenic radiometers" – thermal detectors which are operated at a very low temperature (–269 °C) and whose core piece is a radiation absorber. With these cryogenic radiometers, best relative measurement uncertainties clearly below 0.01 % can be achieved in radiant power measurements. The use of radiation from different sources (laser radiation, thermal radiation, plasma radiation or synchrotron radiation) allows PTB to perform detector calibrations over a wide spectral range and offer manufacturers and users of radiation detectors responsivity determinations of high precision.

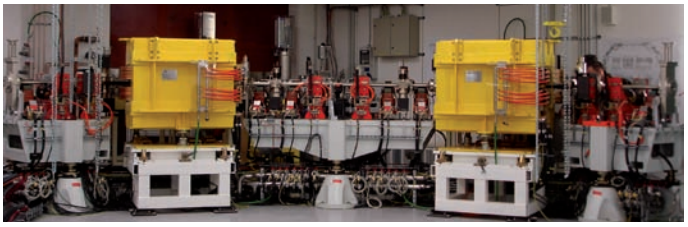
Synchrotron Radiation

Synchrotron radiation from storage rings extends from the infrared spectral range to the range of X-rays and thus offers – compared to thermal radiation – a spectral range for radiometric use which is extended by several decades. Since 1982, PTB has been using electron storage rings as primary source standards: from 1982 to 1999 the Berlin storage ring BESSY I, since 1999, BESSY II and since 2008, the Metrology Light Source (MLS). At their experimental stations, PTB offers a wide spectrum of services – from calibrations and contract research to comprehensive metrological system solutions. Focal points of the work are the realization and dissemination of radiometric units, making use of calculable synchrotron radiation, or using cryogenic radiometers as primary detector standards in the UV, VUV and X-ray range, as well as the characterization and quality control of optical materials, components and sub-assemblies in these spectral ranges. Work is, among other things, focussed on the so-called "extreme UV" (EUV, wavelength approx. 13 nm), a field in which the semiconductor industry is at present developing production procedures for a new generation of high-power processors. The tasks also cover the further and new development of fundamental and applied radiometric procedures, for example for the determination of layer thicknesses and particle diameters in the range of a few nanometers (X-ray reflectometry, small angle X-ray scattering), for the quantification of surface contaminations (X-ray fluorescence analysis) or for satellite-based astronomy.

The EUV reflectometer allows optical components with a mass of up to 50 kg and diameters of up to 65 cm to be characterized.

The Metrology Light Source

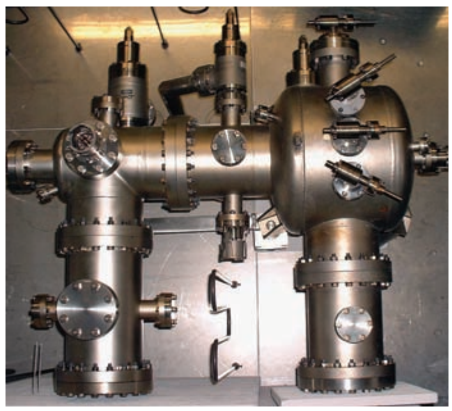
The Metrology Light Source (MLS) installed at the Science and Technology Park Berlin-Adlershof is a low-energy electron storage ring for the generation of synchrotron radiation which has been optimized for metrological use and is unique in Europe. It allows metrology from the far infrared range (FIR) to the extreme ultraviolet (EUV) spectral range to be further developed. The potential created at the MLS supplements the possibilities in the X-ray range used at the electron storage ring BESSY II – with a spectral overlap in the technologically important EUV range. At the MLS, the maximum of the spectral distribution of synchrotron radiation can be adapted over a wide range to the respective application, as well as the intensity, which can be varied over more than 11 orders of magnitude. The new measurement capabilities allow extended tasks for the calibration of radiation sources to be performed. A special operating mode of the MLS allows coherent synchrotron radiation to be generated and creates best measurement possibilities in the spectral range of terahertz radiation. UV/VUV radiometry benefits from the use of intensive and extremely linear-polarized undulator radiation.



MLS storage ring segment.

Vacuum

As a controlled gas atmosphere below the surrounding air pressure, vacuum is an important prerequisite for many physical devices and experiments. Also a great number of industrial production processes require vacuum conditions. Vacuum gauges must cover a bandwidth from 10^{-10} Pa to 10^5 Pa. PTB is the only laboratory worldwide that can cover this whole range for the calibration of vacuum gauges. In Division 7, three different primary standards are operated for the realization of the pressure scale in the vacuum range. A pressure balance measures the force which acts on a piston by a differential pressure down to 30 Pa. In the case of the static expansion system, a known gas quantity is enclosed in a small volume and, after that, expanded into a defined, larger volume. This allows the resulting pressure to be calculated. This procedure has a lower limit of applicability of approx. 10^{-2} Pa. In the case of the continuous expansion system, a known, very small gas flow is generated, the gas is let into a larger vacuum vessel and pumped off in a defined way via diaphragms. Thus, pressures down to 10^{-10} Pa are generated in a defined way. In addition to the calibration of vacuum gauges, also artificial standard leaks, which are calibrated with leak detectors, are measured compared to vacuum and atmosphere.



Vacuum chambers of PTB's primary standard CE3 for the calibration of vacuum gauges for pressure ranges down to 10^{-9} Pa.

SQUID Measuring Techniques

SQUIDs (Superconducting Quantum Interference Devices) are highly sensitive, quantum-electronic sensors for almost all physical quantities which can be converted into magnetic signals. Modern SQUID sensors are complex integrated circuits based on thin layers of superconducting materials. At PTB's Biomagnetic Centre in Berlin, the SQUID sensors of Division 7 are, for example, used as ultra-sensitive SQUID magnetometers to develop new medical diagnosis and therapy methods. At PTB in Braunschweig, SQUID magnetometers in a cryogenic current comparator serve to calibrate resistors with relative uncertainties of only a few 10^{-9}. In addition to SQUID magnetometers, SQUID-based current sensors are used to an ever increasing extent in metrology when smallest currents must be measured at low temperatures. For such measurements, different SQUID-based picoampere meters are developed which are stable against the magnetic interference fields of the environment. The applications in the field of research are versatile and extend from the signal amplification of novel low-temperature radiation detectors for instruments of astrophysics, the use in experiments for quantum communication and the use in NMR spectroscopy, to the measurement of smallest magnetic moments of nanoparticles.

Departments and Contact

Head of Division

Dr. Gerhard Ulm
Phone: +49 (0)30 3481-7312
E-mail: gerhard.ulm@ptb.de

Department 7.1
Radiometry with Synchrotron Radiation

- X-ray Radiometry
- EUV Radiometry
- UV and VUV Radiometry
- Synchrotron Radiation Sources
- Instrumentation Berlin-Adlershof

Prof. Dr. Mathias Richter
Phone: +49 (0)30 3481-7100
E-mail: mathias.richter@ptb.de

Department 7.2
Cryophysics and Spectrometry

- Superconducting Sensors
- Cryogenic Sensors
- Ultra-low Temperatures
- Cryoelectronic Measuring Systems
- X-ray and IR Spectrometry
- Information Technology Berlin-Adlershof

Dr. Thomas Schurig
Phone: +49 (0)30 3481-7290
E-mail: thomas.schurig@ptb.de

Department 7.3
Detector Radiometry and Radiation Thermometry

- High-temperature Scale
- Infrared Radiation Thermometry
- Detector Radiometry
- Terahertz Radiometry

Dr. Jörg Hollandt
Phone: +49 (0)30 3481-7369
E-mail: joerg.hollandt@ptb.de

Department 7.4
Temperature

- High-temperature Technology
- Applied Thermometry
- Fundamentals of Thermometry
- Low-temperature Scale

Dr. Joachim Fischer
Phone: +49 (0)30 3481-7473
E-mail: joachim.fischer@ptb.de

Department 7.5
Heat and Vacuum

- Thermal Energy Measurement
- New Heat Measurement Procedures
- Vacuum Metrology

Dr. Thomas Lederer
Phone: +49 (0)30 3481-7230
E-mail: thomas.lederer@ptb.de

The tasks of Division 7 are focussed on the fields of thermometry at temperatures from 10 µK to more than 3000 K and of radiometry from the THz- into the X-ray range. The measurement of thermal energy, nanometrology, cryo sensor technology, spectrometry and vacuum metrology are additional fields of work. In this connection, manifold use is also made of synchrotron radiation of the storage rings Metrology Light Source (MLS) and BESSY II in Berlin-Adlershof. Many activities are carried out within the scope of national and international cooperations. Due to its special metrological equipment, PTB has here in many cases a worldwide unique position with an outstanding impact on industry and applied research.

Secretariat
Jacqueline Steffen
Phone: +49 (0)30 3481-7444
Fax: +49 (0)30 3481-7503
E-mail: jacqueline.steffen@ptb.de

Physikalisch-Technische Bundesanstalt
Division 7: Temperature und Synchrotron Radiation
Abbestraße 2–12
D-10587 Berlin, Germany
www.ptb.de

As of: March 2012