PTB news
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Technology
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09.3

PTB produces first Bose-Einstein condensate with calcium atoms

Since 1995, it has been possible to produce Bose-Einstein condensates, by cooling mainly alkali elements close to absolute zero. Completely new possibilities for precision measurements are offered by alkaline earth atoms, as they exhibit very narrow transitions in the optical spectral range. At PTB, it was possible for the first time worldwide to produce a Bose-Einstein condensate from the alkaline earth element calcium.

If a strongly diluted gas is cooled close to absolute zero, then the quantum-mechanical properties of the gas particles come to the fore. The particles must then be described as waves. If the so-called de Broglie wavelength of the particles is equivalent to the mean particle distance, a special state with new properties emerges: In the case of bosons, i.e. particles with integer spin, a phase transition occurs, in which more and more particles are in the same state. This is called a Bose-Einstein condensate. Since their first generation, Bose-Einstein condensates have been used for manifold investigations into the fundamentals of quantum mechanics, as a model system for solids, or in quantum information technology.

At PTB, it has been possible for the first time worldwide to produce a Bose-Einstein condensate from an alkaline earth element. To this end, $2 \cdot 10^6$ calcium atoms, precooled in magneto-optical traps to a temperature of 20 µK, were loaded in an optical dipole trap. By weakening the holding force, hot atoms evaporate, whereby the remaining atoms are cooled. At a temperature of typically 200 nK, the critical temperature is reached with 10^5 atoms. Of these, approx. $2 \cdot 10^4$ atoms can be cooled to form a pure condensate.

In contrast to the hitherto customary Bose-Einstein condensates made of alkali elements, alkaline earth elements, such as calcium or also strontium, which are both being investigated at PTB for their suitability as optical clocks, offer with their super narrow spectral lines novel possibilities for precision investigations. Thus, for example, the wave properties could be exploited to construct highly sensitive interferometric sensors for gravitational fields. This goal is now to be further pursued at PTB – among others, as a focus of research of the excellence cluster QUEST (Centre for Quantum Engineering and Space-Time Research) at PTB.

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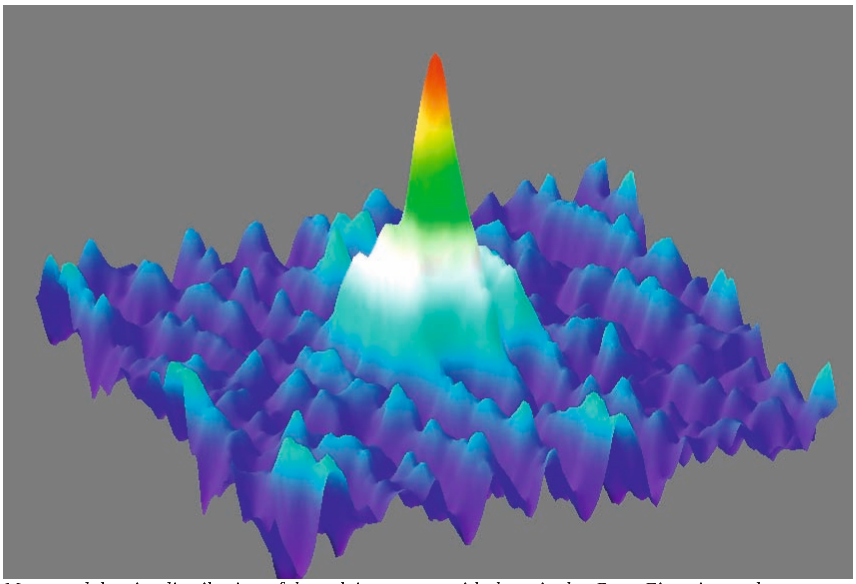

Measured density distribution of the calcium atoms with the spicular Bose-Einstein condensate

Bosonic cluster effect with helium

PTB measurements with the dielectric-constant gas thermometer as preparation for the Boltzmann Project have confirmed ab-initio theories for the interaction between two helium atoms for the range from 3.7 K to 26 K. At lower temperatures, however, deviations from this are exhibited, which could be explained by a novel bosonic cluster effect.

The principle of dielectric-constant gas thermometry (DCGT) used for the redetermination of the Boltzmann constant is based on the in-situ density determination of helium gas. For that purpose, the relative capacity change of a capacitor filled with helium gas is measured. With a constant temperature and different pressures in the measuring capacitor, the temperature can be determined by means of fundamental relations. A key role in this method is exhibited by the atomic dipole polarizability of the measuring gas helium. For some years now, its value has been known with the necessary relative uncertainty of less than 1 ppm, which makes the DCGT one of the most precise primary thermometers. With it, the Boltzmann constant is to be determined at the triple point of water, in order to enable linking the future definition of the temperature unit to the previous one. In addition to this, the measuring gas is of interest to fundamental research, which concerns the particle in-

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Bosonic cluster effect with helium *(Continued from page 1)*

teractions, above all, at lower temperatures. Below a certain temperature, helium exhibits particular properties, as, for example, superfluidity (vanishing viscosity, among other things), which cannot be described by the laws of classical physics.

The latest PTB measurements in the range between 3.7 K and 26 K display a nearly perfect agreement of the experimentally determined two-particle interaction with the latest quantum mechanical calculations. In the range from 2.4 K – the lowest temperature open to the experiment – to 3.7 K, the DCGT measurements with the helium-4 isotope show, however, a clear deviation from the temperature and interaction values. This unexpected result can be explained by the formation of bosonic helium-4 clusters in the gas phase, which leads to an increase in the molar polarizability and a change in the particle interaction. In cooperation with theorists of the University of Rostock, an attempt is now being made to obtain a founded theoretical description of the cluster effect and to confirm the assumption that the driving force of this effect is the same as that of superfluidity in the liquid phase.

Cryostatic insert with a dielectric-constant gas thermometer, the core piece of the low temperature experiment for the determination of the gas properties of helium

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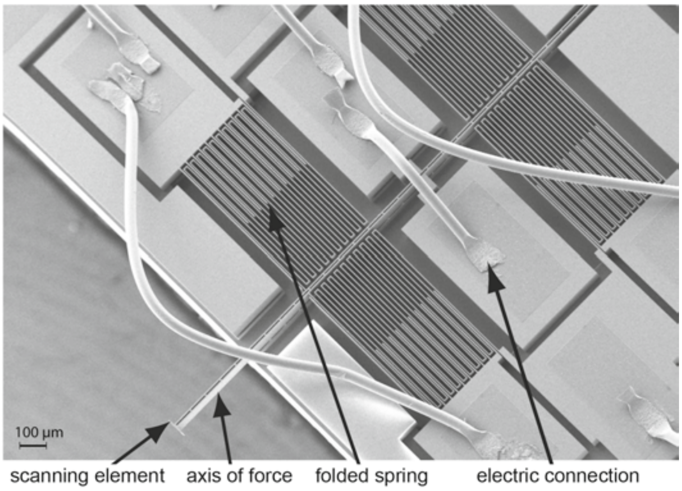
Transducer detects und produces picoforces

It is only 2.0 mm long, 1.8 mm wide and 50 µm thick – the prototype of a high-resolution transducer for small forces, which was developed at PTB and produced at the Center for Microtechnologies of the Technical University of Chemnitz.

The production and scanning of smallest forces into the pico Newton range is required in various fields of fundamental and applied research. For these requirements, a transducer based on a microelectromechanical system (MEMS) was developed. With the aid of multiple-folded Si springs, its stiffness in the scanning direction is reduced. For the force scanning and feedback of the transducer, the in-plane displacement of the springs is capacitively measured with high resolution. The force transducer is characterized by a simple structure, a reliable feedback strategy as well as an integrated electrostatic force generator. The latter delivers the desired balanced force in order to eliminate the potential nonlinearity in force scanning.

A prototype of the picoforce transducer was produced in Si microtechnology using deep reactive ion etching and bond contacting. It exhibits a very low stiffness in the scanning direction of 0.254 N/m and a resolution in force feedback of 50.8 pN (1 σ). With a pair of electrostatic comb actuators, the prototype can produce a maximum electrostatic force of 1.23 µN.

Due to the special form of its scanning element, the picoforce transducer can find various applications, among other things as pico/nano force transfer standard, in the calibration of sensors for small forces, in the determination of the mechanical properties of micro/nano materials und in the investigation of the lateral force of scanning force microscopes.



Scanning force microscope image of the high-resolution force transducer

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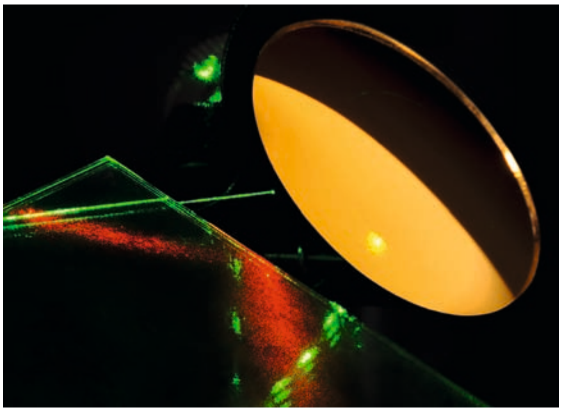
Highly sensitive measurement of optical nonlinearity

In the „century of the photon", integrated optical components play an increasingly important role. Some applications, such as optical communication or high power pulse delivery systems, require photonic components with linear characteristics, whereas nonlinearities as high as possible are desired in cases like optical switches or optical memory elements. At PTB, a novel method has been developed to measure weak nonlinearities using only moderate laser intensities.

Measurements of optical nonlinearities are usually afflicted with large uncertainties, due to dependence on the excitation parameters. Therefore, methods independent of the laser and waveguide parameters are desirable. The method developed at PTB (within the framework of the German Research Foundation Collaborative Research Centre 407) performs the measurements of optical nonlinearities by comparison with well-known reference samples, thus ruling out the dependence on excitation parameters (for instance, laser pulse properties such as duration or chirp) and of the mode area of the waveguide.

To this end, the light from a mode-locked erbium fibre laser ($\lambda \cong 1.55$ µm) at the exit face of the measurement object is 1:1 imaged into a thin fused silica plate acting as reference. The nonlinear signal generated in both samples is superimposed onto a coherent frequency-shifted auxiliary field and the resulting beat note is detected with an InGaAs photodiode. The contribution from the reference plate can be switched on and off by movement of the plate in propagation direction without changing the beam geometry or other excitation parameters.

Owing to the high sensitivity of this heterodyne scheme, it was possible to measure the nonlinearity of a hollow-core photonic-crystal fibre only 21 mm long, which was found to be more than 1000 times weaker than that of standard telecommunication fibre. This is due to the fact that the dominant part of the light propagates in the air or vacuum core of this novel type of fibre. In addition to the nonlinear refractive index, the method allows the measurement of nonlinear absorption. It is not limited to waveguides but can be extended to measure optical nonlinearities in solids (e.g., polymers), in liquids (e.g., nanoparticle suspensions), of surfaces (e.g. due to plasmonic resonances), and in gas samples.



Photonic fibre and part of the parabolic broadband imaging system

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New magnetic field measurement technique for medical research

The measurement of magnetic fields in living organisms is of increasing importance in biomedical diagnostics. In order to detect the very low fields, they have to be extensively shielded against external perturbations. A novel magnetic field measuring device enables the shielding to be improved with reduced effort. Furthermore, the device is transportable and thus applicable in a clinical environment.

The most sensitive sensors for magnetic fields are currently superconducting quantum interferometers, so-called SQUIDs. They are used in biomedical engineering, among other things, to detect the magnetic fields of living organisms. The high sensitivity of a SQUID measurement requires extensive shielding to reduce the Earth's magnetic field and further perturbations, for example from electrical cables or mobile radio. Up to now, this shielding has been achieved by the use of special cabins made of highly magnetically permeable metal, which is associated with high costs of material and resources.

With the completion of the measuring device, PTB has broken new ground. In the process, the fact was exploited that some metals (such as niobium or lead) are, at very low temperatures, completely impermeable for magnetic fields (Meissner-Ochsenfeld effect). The new measuring device consists of a niobium cylinder with a horizontal bore, externally accessible. Small samples or also small test animals can be placed here. Via a vertical access, 18 SQUIDs are inserted on a flexible chain into the interior of the niobium cylinder, so that they enclose the sample annularly. The niobium cylinder, together with the SQUIDs, is kept in liquid helium at a temperature of 4 K. External interfering magnetic fields, which can enter the niobium shielding cylinder and reach the SQUIDs only through the open ends of the cylinder, are reduced

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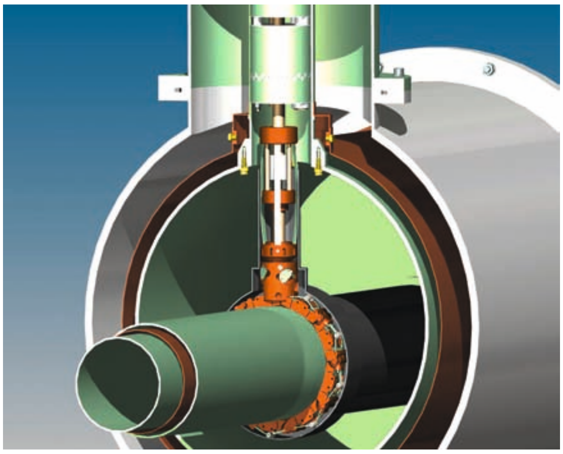
New magnetic field measurement technique for medical research *(Continued from page 3)*

by up to eight orders of magnitude at the site of the sensors. This by far exceeds the shielding obtained by conventional methods.

With the new measuring device, non-contact observation is possible, for example, of the electrical activity in the heart of a mouse via magnetic field measurement. Due to its compact construction, it is transportable. Thus, in future it will enable highly accurate magnetic field measurements in clinical laboratories.



The structure of the new measuring device

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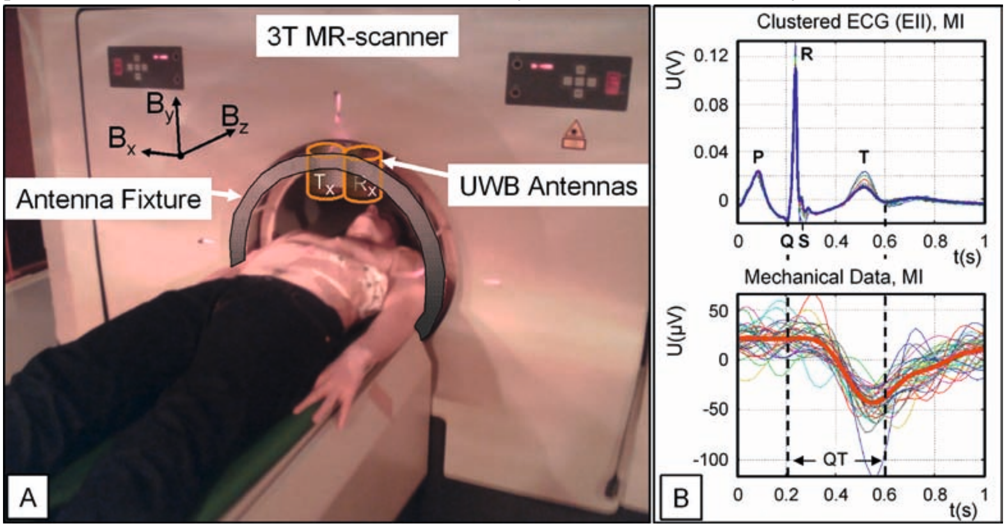
Radar technology produces sharper MRT images

PTB scientists have, together with colleagues from TU Ilmenau, developed a method to increase the image quality of magnetic resonance tomographs (MRT) which work with high field strength (3 Tesla to 9.4 Tesla). They use, thereby, ultra-wideband (UWB) radar signals, which can depict the physiological movement of the heart. With it, it is possible to identify those time intervals which correspond to certain cycles of movement of the heart. Thus, the MRT images can be synchronised with the heart beat and image artefacts can be avoided.

In order to produce images of the moving heart, an MRT requires more detailed information about the various positions of the heart. In the case of clinical standard MRT devices (with a field strength of 1.5 Tesla), they are provided by an electrocardiogram, which is not suitable for high field systems, however. Here, ultra-wideband techniques (up to 10 GHz) are suitable. They do not interfere with narrow band systems, such as the MRT, and penetrate the materials to be examined with only a small emission performance of less than one milliwatt. A further advantage of such sensors is their high temporal and spatial resolution. With them, it is possible to detect body or organ movement, whose perturbing influence can then be eliminated in a subsequent statistical analysis of the MRT data.

At PTB, a combined MRT/UWB radar technique was developed in cooperation with TU Ilmenau and tested on phantoms as well as on volunteers. Results of the analytical and model-based tests document that the new method is principally suitable as navigator technique. Comparisons with an ECG/UWB method on patients have shown that the UWB radar displays the movement of those parts of the heart which are also detected by the MRT.

These results confirm the suitability of the UWB radar to follow physiological processes directly to their place of origin inside the body and to identify in these signals characteristic points with which an MR scanner can be controlled. In a next step, the data acquisition is further optimized with focused UWB antenna arrays.



Left: Arrangement of a combined MRT/UWB measurement on the opening of the 3-T-MR scanner of PTB. Right: Result of a combined ECG/UWB radar experiment. (top: superposed ECG epochs, bottom: superposed corresponding myocardial deformation, reconstructed from the signals of the UWB radar. The red line indicates the mean value of the signals.)

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