Progress Report on Electrical Metrology at the PTB between 2019 and 2021 on the Occasion of the 32nd Meeting of the CCEM

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1. Electrical Quantum Standards

1.1 Josephson Voltage Standards

PTB is working on the development and improvement of pulse-driven Josephson junction series arrays. So far, RMS output voltages of 2.25 V were synthesized with a spurious-free dynamic range of better than 120 dBc using 16 arrays (on 8 chips) containing a total number of 162 000 junctions. Moreover, several pulse-driven Josephson junction series arrays have been delivered to other NMIs and are operated there. To further increase the output voltage and to improve the usability, three different approaches were followed. First, the technology for fabricating fivefold-stacked SNS Josephson junctions with Nb_xSi_{1-x} barriers in an optimized standard window process was further improved increasing the fabrication yield of circuits containing 15 000 junctions. Second, the development of two different kinds of on-chip power dividers has been continued and additional promising results were achieved. Third, the opto-electronics pulse drive has been further investigated together with partners. In addition, special circuits for pulse-drive operation were developed and fabricated for a German technology transfer project (see below) and the development of Johnson noise thermometry at the PTB. (Oliver.Kieler@ptb.de, Johannes.Kohlmann@ptb.de)

PTB is further advancing the technology transfer of pulse-driven Josephson voltage standards. In cooperation with two German companies, all components will be optimized for commercial distribution. Presently, the objective is to develop easy-to-use systems for practical applications by a wide community including industry and research institutes. (Ralf.Behr@ptb.de)

The two-terminal-pair impedance bridge based on pulse-driven Josephson arrays was upgraded for operation in four-terminal-pair configuration. This expands the field of measurable impedances since the bias current is no longer sourced by the Josephson arrays, but by independent current sources. The setup was used to link a 10 nF capacitance standard to a graphene-based quantum Hall resistor. Additionally, a conventional resistance standard of 12.9 kΩ was linked to this quantum Hall resistor. The observed drift of the resistance standard in these measurements was in perfect agreement with the drift measured at DC with a cryogenic current comparator bridge. The usable frequency range of the four-terminal-pair impedance bridge was extended and now covers frequencies between 300 Hz and 50 kHz. Presently, uncertainty contributions are evaluated. (Stephan.Bauer@ptb.de)

A phase generating system (PGS) was set up involving two independent pulse-driven Josephson junction arrays. With the PGS, pure sinewaves with amplitudes up to 100 mV and frequencies between 50 Hz and 100 kHz can be generated, with a well-defined phase angle between both signals. Besides variable frequency operation, also the voltage ratio can be changed in a range between 1:1 and 1000:1. System performance and uncertainty contributions over the whole accessible frequency and voltage ratio ranges are currently under investigation. The PGS allows the realization of precise phase angles also at frequencies much higher than powerline frequencies, which is an essential feature for measuring active and reactive power in modern power grids. (Stephan.Bauer@ptb.de)

In cooperation with PTB's thermometry department, a two-channel pseudo-random Josephson voltage noise source was developed for use in a practical quantum-voltage-based Johnson noise thermometer covering the temperature range between 273 K and 1000 K. Type-B uncertainty contributions were investigated systematically and found to be at the µV/V level for frequencies up to 500 kHz and with 10 mV RMS voltage signal amplitudes. Furthermore, the Josephson voltage noise source was used for linearity measurements of crucial Johnson noise thermometer components by applying low-distortion multitone signals. Presently, the Josephson voltage noise source is transferred to the thermometry department at PTB in Berlin. (Marco.Kraus@ptb.de)

By implementing a new sub-sampling technique, PTB has extended the frequency range of the programmable Josephson voltage standard (PJVS, alias "ac quantum voltmeter") up to 100 kHz. The measurement results for 1 V RMS signal amplitude agree well (within 5 µV/V, $k = 1$) with nominal voltage values for frequencies between 500 Hz and 100 kHz. (Ralf.Behr@ptb.de)

1.2 Single-Electron Transport, Quantum Current Standards, and Quantum-Enhanced Measurements

The integration of single-electron pumps together with charge detectors into single-electron circuits for an in-situ validation of the generated current requires new methodology to assess the deviations from the error-free operation. In collaboration with the University of Latvia, PTB has developed a benchmark for single-electron circuits describing the fidelity of the entire circuit by the accumulation of errors as the circuit executes a sequence of charge-transfer operations. The statistical analysis of this random walk provides a robust measure for rare but unavoidable errors and thereby achieves a rigorous mathematical foundation for validating single-electron quantum standards. This random-walk benchmark allowed to identify fundamental limitations of the single-electron circuit's fidelity induced by external noise and temporal correlations. (Niels.Ubbelohde@ptb.de)

The introduction of on-demand single-electron sources to electron quantum optics, the solid-state analogue to quantum optics, enabled precise time-control of electron emission. This is crucial for applications in quantum tomography and in quantum sensing utilizing ballistically propagating single-electron wave packets. PTB has now developed a fundamental building block that traps and detects single-electron wave packets with high efficiency and thereby offers access to full counting statistics and coincidence correlations. The proposed detection scheme provides insights into energy relaxation mechanisms for the reliable validation of current standards in high magnetic field and is robust against variations of the energy of the injected wave packet and therefore suitable for a variety of collision and interferometer experiments. (Niels.Ubbelohde@ptb.de)

The dissemination of Ultrastable Low-Noise Current Amplifiers (ULCA) was pursued further. Besides being used for measurements and calibrations of small currents and high resistances, different specialised ULCA versions were tested and partly are being established in several application fields of metrology for non-electrical quantities at PTB and beyond, e.g., in ionizing radiation and vacuum metrology, and in photo-/radiometry. In the field of ionizing radiation, PTB experts in radionuclide and electricity metrology are supporting the work towards improved measurements on ionization chambers. Internationally, work in this direction is coordinated by a joint Task Group between the Consultative Committee for Ionizing Radiation (CCRI) and the Consultative Committee for Electricity and Magnetism (CCEM). Comparisons of the ULCA - with its transresistance traced to the quantum Hall effect - and the programmable quantum current generator (PQCG) of LNE – directly involving the Josephson and the quantum Hall effect – are ongoing. Preliminary results are consistent at the level of one part per million. (Martin.Goetz@ptb.de)

PTB has made progress in the development of the Josephson traveling-wave parametric amplifier (JTWPA) within the EMPIR (European Metrology Programme for Innovation and Research) project "ParaWave". Extensive theoretical modelling and circuit simulations were carried out to implement proper dispersion engineering and to find optimum circuit parameters, resulting in high gain, quantum limited noise and a wide bandwidth of several GHz. The fabrication process in niobium technology was optimised and the measurement setup for device characterisation at mK temperature was finalised. Fabrication and characterisation of advanced JTWPA circuits will be continued. (Ralf.Dolata@ptb.de)

1.3 Quantum Hall Effect

Devices for quantum Hall resistance and impedance metrology based on graphene on silicon carbide substrates were further optimized regarding their temporal and operational stability, and regarding contact technology. Control and stability of the carrier density was improved by using different doping methods. The device performance was evaluated in collaboration with several partners in the EMPIR project "GIQS" coordinated by PTB, and the quantisation of the Hall resistance at the parts-per-billion level was verified by device operation under cryocooler conditions at $T = 4$ K, $B = 5$ T. Investigations of the long-term stability of the device properties are ongoing. Additionally, recent studies at PTB have revealed an impact of the underlying SiC facet structure on the doping level of the epitaxial graphene. This might in the future enable new pathways towards lateral modulation doping and towards more homogeneous carrier densities in large quantum Hall devices. (Mattias.Kruskopf@ptb.de, Klaus.Pierz@ptb.de)

In cooperations within European research projects, other novel 2D materials are explored for their potential use for next-generation quantum Hall resistance standards. Such materials are magnetically doped topological insulators, showing Hall resistance quantisation without an external magnetic field due to the quantum anomalous Hall effect (Horizon-2020 project "TOCHA"), and 2D lattices of covalent- and metal-organic frameworks (EMPIR project "COMET"). (Hansjoerg.Scherer@ptb.de)

2. Voltage, Resistance, Current, AC/DC Transfer, and Impedance

A routine calibration facility for small currents below 1 µA with improved CMCs has been established using the ULCA. Also, the scope of CMCs for low current sources has been extended. Furthermore, PTB has extended the range of resistance calibration to 10 MΩ with an uncertainty of 0.2 parts in 10^6 using the cryogenic current comparator. (Bernd.Schumacher@ptb.de)

For bridge standard calibration up to ±100 mV/V a new calibration transformer was developed and integrated into the automated bridge standard calibration setup. The calibration transformer has a two-stage design with a division ratio of D = ¼. The magnetizing winding is sourced by buffer amplifiers to avoid loading of the eight-decade inductive voltage divider in the cascaded measurement configuration. The obtained extended measurement uncertainty at 100 mV/V is U = 140 nV/V at a frequency of 225 Hz. (Florian.Beug@ptb.de)

Synthetic inductance standards made of capacitance standards and gyrators have been realized as prototypes. This concept allows for inductance values up to several kilohenry, a range that was not available so far. The long-term stability has been proven to be comparable to wire wound toroidal inductors, while the noise is higher. However, the thermoregulation and thus transportation issues are simplified significantly due to the physical size reduction by two orders of magnitude compared to conventional toroidal inductance standards. A precision capacitance-to-inductance converter was built and tested. It turned out to be capable of calibrating high-end LCR meters at inductances in the henry and kilohenry ranges. (Torsten.Funck@ptb.de)

For the preparation of the planned CCEM-K3 key comparison of 10 mH inductance, the pilot measurements of the selected travelling standards have been finalized. (Torsten.Funck@ptb.de)

3. Power and Energy

The correct measurement of electrical power and electrical energy is of paramount importance since it is the basis of billing. Several reference measuring systems in the respective state-approved test centers, verification authorities, calibration laboratories, manufacturers or conformity assessment bodies are directly or indirectly connected to the primary power standard of PTB. In the next few years, this standard is to be modernized step by step to enable a wider range of applications with lower measurement uncertainties. In the first step the component with the largest effect on the attainable accuracy, i. e., the current-to-voltage (C-to-V) converter, was investigated. PTB built a new C-to-V converter with rated primary currents from 100 mA to 5 A, a secondary current of 25 mA and a rated output voltage of 3 V using a measuring resistor of 120 Ω. The converter was operated in a fully active state and was investigated as to its suitability as a replacement for the existing one. A total expanded uncertainty of about 0.4 ppm was obtained for the new C-to-V converter including an annual drift of about 0.2 ppm of the thermostated resistor. This result represents a threefold improvement compared to the transducer currently used in the primary power standard. (Enrico.Mohns@ptb.de)

For the approval of devices for use in high and medium voltage grids, reliable high-voltage tests are mandatory to verify that these devices can withstand the operating conditions. For some components, e.g. cables, such "withstand voltage" tests must be performed with combined or composite voltages, where lightning impulse (LI) or switching impulse (SI) voltages are superimposed on AC or DC voltages. To date, there is a lack of comprehensive technical understanding and regulations for the generation and measurement of such composite high voltages. Regulations of international standardization bodies are also inadequate for today's requirements. In May 2020, a normative EMPIR project, coordinated by PTB has been launched. The project partners are involved in various standardization committees, relevant to the revision of associated high voltage standards, such as the IEC series 60060 and 61083. Additionally, new measuring instruments, evaluation software and generators will be developed, build up and commissioned for the combined voltages in this project. Traceability will be established, and calibration services will be developed at the national metrology institutes for these voltage waveforms with an amplitude uncertainty of less than 2%. First tests proved PTB´s capabilities for measuring superimposed HVDC and lightning impulses with amplitudes up to 400 kV. (Johann.Meisner@ptb.de)

4. Magnetic Measurements

PTB participates in a new EMPIR project, named HEFmag, which aims to develop and validate experimental capabilities for traceable power loss measurements in soft magnetic steel sheets commonly used as core material in electric motors, generators, and transformers. The activities are motivated by urgent stakeholder needs for improved normative standards (IEC 60404) that currently do not reflect real operating conditions in modern engines. Supplementary magneto optical characterization techniques in combination with theoretical modelling will enable a qualitative and quantitative understanding of dynamic magnetization processes in steel sheets and their impact on the loss figure. HEFmag directly supports European efforts on energy efficiency and sustainable mobility. (Franziska.Weickert@ptb.de)

As an outcome of the PTB-coordinated EMPIR project NanoMag the first international standard for nanomagnetic measurements has been drafted under PTB lead within IEC TC133 "*Nanotechnology standardisation for electrical and electronic products and systems*". The Technical Specification TS 62607-9-1: *Nanomanufacturing – Key Control Characteristics – Part 9-1: Spatially resolved magnetic field measurements - Magnetic Force Microscopy* is presently in the status of a committee draft and is expected to be published in 2021. This novel standard represents a breakthrough for quantitative research, engineering, and material development in the field of nanomagnetic materials and devices. (Hans.W.Schumacher@ptb.de)

5. High Frequency and Fields

5.1 Electromagnetic Fields and Antenna Measuring Techniques

PTB has made progress in the investigation of antenna calibration techniques in its spherical antenna scanner (1 GHz – 50 GHz). A CMC entry for the calibration of the on-axis gain of horn antennas up to 18 GHz has been accepted in the review by EURAMET. In addition to using phase center determination, multi-path propagation correction techniques and the extrapolation technique, an efficient near-field to far-field transformation algorithm has been implemented based on the Fast Irregular Antenna Field Transformation Algorithm (FIAFTA) that works well with irregular grids. An uncertainty analysis for the near-field to far-field transformation has been completed. (Thomas.Kleine-Ostmann@ptb.de)

PTB has extended its capabilities of precise on-site electromagnetic field measurements employing new unmanned aerial systems (UAS) such as octocopters and vertical take-off and landing vehicles. Further extensive measurement campaigns for signals of terrestrial navigation and radar installations, such as weather radar, were performed to investigate the influence of wind power plants on these services. Work on improving the quantitative prediction of navigation errors of Very High Frequency Omni-Directional Range (VOR) installations caused by wind turbines led to an improved prediction tool for Doppler VOR used by the Germany air traffic control. Ongoing work aims at improved prediction tools for Conventional Very High Frequency Omni-Directional Range (CVOR) installations. (Thomas.Kleine-Ostmann@ptb.de)

5.2 High-Frequency Measuring Techniques

In rectangular waveguides PTB has extended its measurement capabilities of the RF quantities power and scattering parameter up to 170 GHz. In coaxial lines the RF quantity scattering parameter can now be calibrated with the new 1.35 mm connector up to 92 GHz. Ongoing work is aimed at establishing traceability in rectangular waveguides above 170 GHz and traceability for RF mixed frequency scattering parameters, passive intermodulation (PIM), and phase noise. (Karsten.Kuhlmann@ptb.de)

The support for impact (SIP) project "New Waveguide Interfaces for Terahertz Technologies NeWITT" within the European Metrology Programme for Innovation and Research (EMPIR), coordinated by PTB, has been completed successfully in 2020. The objective of this project was to promote the adoption and use of new standards for rectangular waveguide interfaces up to 3.3 THz. This was achieved by hosting an international workshop and publishing a guideline and an open source software program. (Karsten.Kuhlmann@ptb.de)

The EMPIR project "Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies" (TEMMT) has started successfully. One of the major goals of TEMMT is to establish traceability for on-wafer scattering parameter measurements for frequencies beyond 110 GHz. In a previous EMPIR project, coordinated by PTB, traceability was achieved for coplanar waveguide calibrations on fused silica substrates up to 110 GHz. The corresponding CMC entry was approved in the review by EURAMET in 2020. Further activities are concerned with expanding traceability to different substrate materials and probe types. (Uwe.Arz@ptb.de)