Progress Report on Electrical Metrology at the PTB between 2021 and 2023 on the Occasion of the 33rd Meeting of the CCEM

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1. Electrical Quantum Standards

1.1 Josephson Voltage Standards

PTB is working on the further development and improvement of the Josephson Arbitrary Waveform Synthesizer (JAWS) based on pulse-driven Josephson junction series arrays. To increase the output voltage and to improve the usability, the development of on-chip power dividers has been continued. The output voltage synthesized by a single chip was nearly doubled to 600 mV by integration of two Wilkinson power dividers (36,000 Josephson junctions arranged in four series arrays). The fabrication technology for these highly integrated cicuits based on stacked SNS Josephson junctions with Nb_xSi_{1-x} barriers in an optimized standard window process was further improved increasing the fabrication yield. To enable additional applications, the frequency of the synthesized waveforms has been significantly extended to the GHz range. First GHz sine waves have been synthesized by test arrays containing approximately 100 Josephson junctions to implement such an RF JAWS. Several pulse-driven Josephson junction series arrays have been delivered to other NMIs and are operated there. (Oliver.Kieler@ptb.de, Johannes.Kohlmann@ptb.de)

In addition, the opto-electronic pulse drive of JAWS circuits has been further investigated together with partners. Flip-chip technology for mounting photodiodes on carrier chips using gold stud bumps has been established at PTB to further strengthen these developments. A system was developed which consists of two independent optical pulse channels that generate a ternary pulse-bias current at 4 K to drive a single Josephson junction array with 3000 junctions. Quantum-based unipolar and bipolar AC waveforms with an RMS signal amplitude up to 12.5 mV were successfully synthesized. Higher harmonics in the amplitude spectrum were suppressed by more than 95 dBc. The system was used to study the DC linearity of a nanovoltmeter as a first metrological application.
(Oliver.Kieler@ptb.de, Marco.Kraus@ptb.de, Jonas.Herick@ptb.de)

PTB has made further progress in developing a Source-Measuring-Unit based on a JAWS (JAWS-SMU) towards commercialisation in cooperation with two German companies. As a turnkey system for the calibration of common DC and AC voltage standards, the system under development is optimised for the characterization of commercial calibrators and voltage standards widely used by calibration laboratories. Preliminary calibrations of a commercial calibrator with the JAWS-SMU and a calibration performed with an AC quantum voltmeter show agreement at the µV/V-level in the frequency range from 30 Hz to 6.25 kHz. (Jonas.Herick@ptb.de)

Four-terminal-pair Josephson impedance bridges are realized up to now only at two National Metrology Institutes worldwide (METAS and PTB). They show very good potential for impedance metrology, especially when the bridges are combined with quantum Hall devices serving as quantum impedance standard. PTB’s four-terminal-pair Josephson impedance bridge is now able to measure ratios of two impedances and to link an impedance to a graphene quantum Hall resistance (QHR) standard in the AC regime at frequencies between 53 Hz and 50 kHz. The ratio measurement of two 10-nF capacitance standards at 1233.15 Hz was demonstrated with a combined uncertainty of 7 nF/F (k = 1). The use of graphene-based QHR devices as future impedance standards is challenging since AC losses need to be known and/or controlled. To investigate such devices for the use with PTB's pulse-driven Josephson impedance bridge, established methods to investigate contact and longitudinal resistances, magnetocapacitance and the plateau shape of QHR devices are applied and extended. (Stephan.Bauer@ptb.de)

PTB is supporting the update of the BIPM Josephson comparison protocol (BIPM EM-K10) towards AC voltages as a member of a dedicated task group. Pilot studies were performed by joint measurements at BIPM in 2021 and at PTB in 2022, the latter involving experts from BIPM and KRISS. In addition to testing the two different technical implementations for the calibration of AC voltages according to the updated protocol in different environments, two different transfer standards were investigated as well as different configurations of BIPM's calibration setup. (Ralf.Behr@ptb.de)

PTB is collaborating with the German Max-Planck-Institute for Nuclear Physics (MPIK) to develop an ultra-stable and low-noise Josephson voltage source for Penning trap experiments. The Josephson voltage source is based on Programmable Josephson Voltage Standards (PJVS), which are a mature technology used at many National Metrology Institutes to realize the volt, typically at levels up to 10 V. The collaboration triggered the development of a compact 80-V PJVS with a single microwave feed as one of various improvements, aimed at reducing the uncertainties in different precision measurements with Penning traps. The series connection of four 20-V Josephson arrays has been validated by comparing -40 V to 40 V with an agreement better than one part in billion. (Luis.Palafox@ptb.de)

For dielectric-constant gas thermometry (DCGT), a new compact Josephson impedance bridge based on 1-V PJVS is being set up for calibrating 1:1 ratios of 10-pF capacitances at about 1 kHz. With transients below 60 ns and by employing a low-noise pre-amplifier, the 10^{-8} uncertainty level can be achieved. Moreover, the new bridge offers the possibility of performing semi-automated frequency sweeps from 62.5 Hz to 50 kHz in less than two hours. (Ralf.Behr@ptb.de)

1.2 Single-Electron Transport and Quantum Current Standards

Single-electron pumps realized in the GaAs/AlGaAs material platform, for which PTB has established a highly reproducible fabrication of high-quality devices, need to be placed in large quantizing magnetic fields of several Tesla to achieve good quantization of the generated currents when operated by the established single-gate drive scheme. In collaboration with the University of Latvia, PTB has now developed a new scheme to control the dominant single-electron transfer error mechanism responsible for insufficient quantization quality in zero magnetic field. Using a tailored second radio frequency signal applied to a second gate of the single-electron pump, the loss of already captured electrons from the single-electron pump back to the source can be suppressed. In a demonstration experiment, the single-electron tranfer error has been reduced by several orders of magnitude. The improved quantization quality of the generated current in zero magnetic field was verified by traceable high precision current measurements. (Frank.Hohls@ptb.de)

Single-electron pumps have been used to study the correlations by the coincident arrival of individual electrons at an electronic beam splitter. Using high-fidelity single-electron detection, PTB has performed coincidence counting measurements to explore the role of Coulomb interactions between two ballistically propagating electrons. In collaboration with the University of Latvia, general signatures of interaction-induced correlations were identified. An analytic model allowed to quantify time sensitivity and energy selectivity of an electronic beam splitter and provides a figure of merit to assess the interaction strength. These results allow access to the quantum non-linear regime, where the Coulomb interaction between individual ballistic electrons is sufficiently strong to be utilized in applications such as in-flight single-electron detection or quantum logic gates. The techniques are also fundamental for the development of a future tomography of electric currents. (Niels.Ubbelohde@ptb.de)

The development and commercialisation of cost-effective variants of the Ultrastable Low-noise Current Amplifier (ULCA) are pursued within a technology transfer project in collaboration with a German instrumentation manufacturer. The new Advanced Laboratory Current Amplifier (ALCA) is designed for current metrology from the femtoampere up to the microampere range in various applications fields, enabling measurement uncertainties well below 10 µA/A. (Christian.Krause@ptb.de)

1.3 Quantum Hall Effect

Quantum Hall resistors made from chemically doped epitaxial graphene, developed and fabricated by PTB, were investigated extensively in collaboration with several national metrology institutes from Europe and from Asia and with the BIPM in the frame of the EMPIR (European Metrology Programme for Innovation and Research) project "GIQS". By comparison with conventional quantum resistance standards based on semiconductor heterostructures, the excellent properties of the graphene quantum Hall devcies were confirmed, underpinning their suitability as primary DC quantum resistance standards at $T = 4.2$ K and $B = 5$ T. The graphene devices allow resistance quantisation with an accuracy of up to 10^{-9} at currents up to 230 µA. Long-term investigations over 1.5 years confirm the stability of the devices. Further, it has been shown also that the graphene devices can serve as AC impedance standards with an accuracy up to 10^{-8}. The chemical doping method developed by PTB allows the tuning of the electron density in the graphene layer, which shows a characteristic correlation with the onset of the quantum Hall plateau. (Mattias.Kruskopf@ptb.de, Klaus.Pierz@ptb.de)

The quantum anomalous Hall effect in devices made from the vanadium-doped topological insulator material $(BiSb)_2Te_3$ is explored in the frame of a European research project. Focus is on the evaluation of its potential use for next-generation quantum Hall resistance standards which can be operated without external magnetic fields, and on corresponding improvements of the materials and devices. Preliminary results from high-accuracy magneto-transport measurements indicate that the quality of the electrical contacts can affect the device performance significantly. An improved device layout with a novel contact design was implemented to reduce the contact resistances to less than 1 Ω. (Hansjoerg.Scherer@ptb.de)

1.4 Metrology for Quantum Technologies

PTB is a partner in multiple national and European research projects on superconducting quantum circuits. The first pillar of activities addresses parametric amplifers. Based on the results of the EMPIR project 'ParaWave', PTB continues to develop Josephson traveling-wave parametric amplifiers (TWPA) in the nationally funded project 'qBriqs' (Federal Ministry of Education and Research, BMBF). To this end, numerical simulations of TWPA circuits have been performed with the goal to optimize circuit parameters and to investigate circuit parameter spread. Additionally, PTB is a partner in the EU Horizon project 'TruePA', which aims at developing the next generation of TWPAs as well as pushing these devices towards commercial availability. Moreover, owing to the accelerating commercialization of the superconducting quantum computing community, PTB is ramping up efforts towards the standardization of measurements together with European partners in the frame of the EU project 'Qu-Test'. These activities regarding quantum-noise limited amplification of microwave signals are complemented by work on resonant Josephson junction based parametric amplifers in the BMBF project 'QSolid'. PTB envisions that the results of these projects form the basis of mid-term standardization activities. The second pillar of activities addresses full control over the Bloch-sphere for superconducting qubits. This pillar is also part of the BMBF project 'QSolid'. Here, PTB investigates the use of superconducting qubits as sensors for microwave power in the fW power range at temperatures on the order of 20 mK. Furthermore, sources of error for qubit state initialization are going to be quantified with the goal of achieving 97% qubit state initialization fidelity. In the mid-term, this work on qubits will form the basis of a framework to evaluate, characterize, and standardize the measurement of the performance of superconducting qubits and multi-qubit circuits. (Lukas.Gruenhaupt@ptb.de)

Moreover, PTB develops optoelectronic sampling techniques for cryogenic environments with the goal to apply these techniques to superconducting quantum circuits. These activities are supported by the EU projects 'aCryComm' and 'SuperQuant'. Very recently PTB has achieved electro-optic sampling of ultrafast signals containing frequency components above 100 GHz at a temperature of 4 K. To this end, femtosecond optical links from room temperature to cryogenic environments had to be developed, including fibre-chip connections based on flip-chip technology. In the future, this technology will be applied to optoelectronic in-situ measurements of electrical signals in superconducting quantum circuits without the need to use electrical probes. (Mark.Bieler@ptb.de)

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

PTB constantly works on improving the quality and efficiency of its calibration services. To use the cryogenic current comparator (CCC) more effectively for high-precision customer calibrations, a programmable switch box has been developed to overcome the incompatibility of commercially available scanners with respect to the guarding and shielding of CCC bridges. A first switch prototype has been built and tested successfully. It allows to switch two reference standards and up to six resistors to be calibrated. (Bernd.Schumacher@ptb.de)

For capacitance calibrations an automated 2-terminal pair capacitance measuring bridge has been put into operation. The bridge covers the capacitance range from 1 pF to 1 nF at typical frequencies between 1 kHz and 10 kHz. Time-consuming manual calibrations have been replaced by automated measurements with comparable measurement uncertainties. (Florian.Beug@ptb.de)

The measurement capabilities for AC current and AC-DC current transfer have been extended up to 8 A at 1 MHz by the development of calculable shunt resistors. The frequency dependence of the shunts has been simulated and verified by 2-port measurements using a vector network analyzer. (Torsten.Funck@ptb.de)

The supplementary comparison on small current sources EURAMET.EM-S45 (EURAMET Project 1562) was initiated and will be piloted by PTB. In the last decade, significant progress in small current metrology was driven by the rise of the Ultrastable Low-noise Current Amplifier (ULCA). This development motivated an international comparison for DC current sources in the range from 100 fA to 1 nA, in which the ULCA will be used as highly stable transfer standard. Measurements are planned to start in 2023 and to be completed in 2024. (Martin.Goetz@ptb.de)

A state-of-the-art resistance bridge based on a CCC has been used for temperature measurements with a standard platinum resistance thermometer (SPRT) on a triple point of water cell. First measurements gave promising results with respect to the achievable temperature resolution. At current levels corresponding to few tens of nW power dissipation in the SPRT, the noise figure of the CCC bridge allows for reaching a temperature uncertainty of order 10 µK. (Martin.Goetz@ptb.de)

3. Power and Energy

Future electric power grids will require real-time-capable control and monitoring systems to ensure stability under today's increasingly complex and challenging conditions. PTB researchers have developed the metrology needed to close the gap in the traceability chain for energy measurements made in fully digitally operated substations. For this purpose, a self-built sampled value (SV) generator with corresponding software has been developed to calibrate a commercially available digital energy meter. There were no existing standards for digital energy meters based on sampled values, so PTB used the standard IEC 62053-22 for static meters that measure AC electrical active energy (class 0.2 S and 0.5 S). The SV-generator is considered to be a substitute for devices with digital output. It is able to send programmed SV data over ethernet connections using the IEC 61850-9-2 protocol. The corresponding program of the SV-generator box was mainly made up of three main functions: the SV waveform generation, the underlying power/energy calculations, and readout functionalities for the meter. As a result of this research, it has been shown that the calibrated error of the energy meter for the quantity 'Energy' is far below its error class of 0,2S. To optimise measurement time, other tests have been carried out for evaluating different readout methods. The main finding was that all different methods agree within 0.02%, i. e., ten times better than the error class of the meter, while the fastest readout method is 10-30 times faster than the slowest readout method. (Enrico.Mohns@ptb.de)

For millions of public charging stations for electric vehicle foreseen to be installed, conformity assessment ensures correct metering and billing at these charging stations. Before being used for billing, charging stations must first pass a type examination confirming that they are fit for purpose. This is done in the controlled environment of a laboratory. Flawless specimen obtain a certificate allowing them to be placed on the market and to bill energy in kWh. Follow-up tests during regular operation in the field on carparks or at filling stations, however, are a challenge. PTB has developed a precise measuring system specifically for this application. It is inserted into the charging circuit between the charging station and the electric vehicle. It is based on a power analyzer that is traced back to PTB's national standards and can also deliver information on the temporal shape and the frequency components of electric signals. The new measuring system provides the essential technical basis for validating tests of fast charging stations with voltages up to 1000 V and currents of up to 450 A. Depending on the technical implementation of the charging station, the new system could be used for initial verification tests for new charging stations in the field and for market surveillance purposes. (Jannis.Langemann@ptb.de)

4. Magnetic Measurements

IEC TC113 "*Nanotechnology standardisation for electrical and electronic products and systems*" has recently published the world first standard on traceable nanomagnetic measurements. The Technical Specification TS 62607-9-1: *Nanomanufacturing – Key Control Characteristics – Part 9-1: Spatially resolved magnetic field measurements - Magnetic Force Microscopy* was drafted within the EMPIR project NanoMag coordinated by PTB. This novel standard represents a breakthrough for future quantitative research, engineering, and material development in the field of nanomagnetic materials and devices. (Hans.W.Schumacher@ptb.de)

Magnetic force microscope (MFM) calibrations are usually performed by measuring a magnetic thin film reference sample with calculable nano-scale magnetic stray field distribution as described in the IEC standard mentioned above. PTB in collaboration with the University of Ulm has now demonstrated the first quantum-based calibration of an MFM. Here, the magnetic stray field of the MFM tip was measured quantitatively using a single nitrogen vacancy center in diamond that served as an atomic-size quantum sensor for magnetic fields. The quantum-based calibration agreed with the classical calibration within the measurement uncertainty thereby establishing the first independent validation of the classical calibration approach. (Sibylle.Sievers@ptb.de)

5. High Frequency and Fields

5.1 Electromagnetic Fields and Antenna Measuring Techniques

PTB has made further progress in the field of antenna calibration methods based on the near-field far-field transformation algorithm FIAFTA (Fast Irregular Antenna Field Transformation Algorithm) and has extended its calibration capabilities as documented by confirmed CMC entries. The measurement uncertainty for the antenna gain was reduced to 0.2 dB in the frequency range from 1 GHz to 18 GHz. Furthermore, the measurement of antenna patterns can now be offered as a service with also 0.2 dB measurement uncertainty in the same frequency range from 1 GHz to 18 GHz. (Kai.Baaske@ptb.de)

In the field of on-site electromagnetic field measurements, PTB has built up extended capabilities for the investigation of the influence of wind power plants on terrestrial navigation systems for air traffic control as well as on radar systems, such as weather radar or air surveillance radar. Due to precise measurements of the electromagnetic signal in space from a navigation or radar system, e. g. at the location of a wind turbine plant or its surroundings, valuable insight for the improvement of the aviation systems could be derived. The prediction tool for the navigation systems DVOR (Doppler Very High Frequency Omni-Directional Range) and CVOR (conventional VOR) used by the Germany air traffic control was improved. The results of the investigations were published in a report for the German Federal Ministry for Economical Affairs and Climate Action. (Kai.Baaske@ptb.de)

5.2 High-Frequency Measuring Techniques

PTB has extended its measurement capabilities of the RF quantity scattering parameter in rectangular waveguides up to 220 GHz. Corresponding CMC entries will be submitted in the next round. The scattering parameter traceability is essential for calibration of RF power up to 220 GHz and higher, which is currently being worked on. No new coaxial interfaces have been added to the measurement capabilities, though for some coaxial interfaces ongoing work deals with the extension of the frequency range. It is expected that coaxial line standards will increase the useable frequency range for some interfaces. (Karsten.Kuhlmann@ptb.de)

The joint research project “Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies” (TEMMT) within the European Metrology Programme for Innovation and Research (EMPIR), has been completed successfully. PTB took part in RF power calibrations and measurement comparisons up to 170 GHz. (Karsten.Kuhlmann@ptb.de)

In an international on-wafer measurement campaign within TEMMT using HRSi calibration substrates, PTB provided reliable measurement-based uncertainties in two waveguide bands up to 330 GHz. PTB results were in excellent agreement with measurements performed by partners, among them NPL. PTB also participated successfully in the comparison of dielectric material parameter measurements at millimetre-wave and THz frequencies (EURAMET project 1514). Further activities at PTB are concerned with expanding traceability to different commercial calibration substrates and probes. (Uwe.Arz@ptb.de)

In September 2021, the EMPIR project "RF Measurements for future communications applications" (FutureCom) started successfully. For the work package, "Measurement methods for passive inter-modulation in communication systems", which is led by PTB, PTB is developing a traceability method for passive inter-modulation. Among other things, common connector systems in communication technology (4.3-10 and 7/16) are traced back and a vectorial measuring system is characterized. Frequencies of the 3GPP B1 and B3 band are considered. For frequency-converting measurements a software implementation was developed, which enables both measurements and their evaluation. (Friederike.Stein@ptb.de)

Metrological evaluation of broadband signals used in digital modulation at high frequencies demands a stringent calibration of the measurement devices. The parametrical approach for calibrating sampling oscilloscopes provides an acceptable result only for low frequencies. At PTB a traceable full waveform calibration can be achieved using the electrooptical sampling (EOS) system. After correcting the time base of the sampling oscilloscope, the measured waveform can be deconvolved using the impulse response provided by the EOS to deliver a waveform with traceable uncertainties. This enables the calibration of secondary standards like phase references and the traceable derivation of measurement quantities in digital communication systems, such as error vector magnitude and channel capacity. Furthermore, the calibration of real-time oscilloscopes has been investigated, because of its relevance for measuring non-repetitive or long waveforms. Since the calibration depends strongly on the architecture of the measurement instrument, different approaches are currently being explored. (Nora.Meyne@ptb.de, Heiko.Fueser@ptb.de)

6. Digitalization

A new calibration management system (CMS) has been implemented providing a fully digital workflow. It includes the storage of calibration results along with all relevant data for issuing calibration certificates. For selected quantities, a software tool within the CMS allows users to optionally generate digital calibration certificates (DCC). They are intended to promote and harmonize the introduction of the DCC as best practice examples. Currently, processes are implemented in the CMS to digitally sign these certificates, thus providing ISO 17025 compliance.