

Report on the activities in Electricity and Magnetism within the LNE between 2023 and 2025

34th CCEM Meeting, March 6-7 2025

In this report, we provide a brief outline of the main research and development activities in the field of Electricity and Magnetism since March 2023 at the Laboratoire national de métrologie et d'essais (LNE).

1 Fundamental mass metrology

Kibble balance

LNE continues the developments on the Kibble balance to realize the kilogram with an aimed uncertainty of a few parts in 10^{-8} in vacuum.

In 2023, efforts focused on mechanical implementation, system interfacing, and optimizing the PID controller. These controller drive a contactless DC motor that controls the trajectories during the dynamic phase. The noise associated with determining the field profile in the dynamic phase was thus reduced by a factor of 2 compared to the measurements carried out for the key comparison in 2021.

Building on this improvement, in 2024, metrological measurement campaigns were conducted to determine the mass of two 500 g standards (W1 in platinum-iridium and DB1 in iridium). These campaigns demonstrated a Type A relative uncertainty of $2 \cdot 10^{-8}$, achieved in less than four days (evaluated using overlapping Allan deviation). Measurements on the W1 standard took place between September and November 2024 and should contribute to the key comparison CCM.M-K8.2024, with a standard uncertainty below $4 \cdot 10^{-8}$.

Electrostatic balance

LNE has begun the conception and machining of an electrostatic force balance, aiming at realizing the mass unit at the milligram level in the SI.

The key components have been designed, machined, and assembled: a mass balance mechanism and two circular capacitance actuators, one for force balancing and the other for vertical position control. The balance mechanism is a fully monolithic parallelogram with 40 μm -thick flexure hinges. The two actuators are fixed on the same side of balance mechanism, with their own monolithic adjustment system.

Without directly measuring the capacitance gradient, artifacts ranging from 1 mg to 20 mg were weighed in air: given the repeatability (standard deviation of ABA of measured masses) of these measurements (5 μg for this experimental set up), there is no deviation to the linearity. Vacuum weighings were thereafter conducted over several days, consistently achieving repeatabilities around 0.2 μg .

The capacitance gradient was determined by measuring capacitance (with an Andeen-Hagerling capacitance bridge) at different known vertical positions of the mass balance mechanism (position controlled from an interferometer).

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2 Fundamental capacitance metrology

Thompson-Lampard calculable capacitance standard

A finite element simulation focusing on the mechanical imperfections inherent in the calculable Thompson-Lampard capacitor (TLCC) developed at LNE, and their influence on the combined uncertainty of the practical realization of the farad was carried out. In particular, this study made it possible to assess the acceptable tolerances on deviations from a perfect geometric arrangement of the TLCC electrodes required to achieve the target relative uncertainty of $1 \cdot 10^{-8}$. Simulation predictions were compared with the corresponding experimental observations, which were carried out using sub-micrometer control of the standard electrode geometry. This study demonstrated that the contribution of mechanical imperfections to uncertainty has been reduced by at least a factor of 4 compared with the previous LNE's TLCC. Combined with other improvements, the overall uncertainty of the standard reaches the target level of $1 \cdot 10^{-8}$.

A fully automated coaxial impedance bridge with two pairs of terminals has been developed. It was specifically designed to compare low-value capacitances, such as those measured in the TLCC. The bridge was validated by comparing a 2 pF capacitance standard with the TLCC standard in a 3:8 ratio. The new system has excellent long-term stability and repeatability of the order of $3 \cdot 10^{-8}$. This bridge is very useful for characterizing the TLCC, in particular for estimating the type A uncertainty, and for detecting a possible problem with the wavelength control of the laser used in the interferometer.

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3 Quantum electrical metrology

Quantum ampère

LNE has developed the next-generation of the programmable quantum current generator (PQCG) which is a quantum current standard realizing the new ampere definition from the elementary charge e based on applying Ohm's law to the Josephson voltage and quantum Hall resistance (QHR) standards. Compared to the implementation of 2016 [1], the PQCG, installed in the new Ampère Laboratory, is capable of generating currents, at quantized values, $\pm(n/p)ef_J$, where n and p are integer control parameters and f_J is the Josephson frequency, without the need for any cable correction [2].

This performance results from the implementation of the three-terminal connection of the quantum Hall resistance standard (QHRS) to the 1V-SNS programmable Josephson voltage standard (PJVS) through winding triplets of same number of turns of a specially developed cryogenic current comparator (CCC). This allows a highly-accurate application of the Josephson voltage to the quantized resistance and the scaling of the current over a wide range.

Accuracy tests in the microampere range have been performed by implementing a fully quantum instrumentation comprising five quantum systems. It resumes to applying the output current of the PQCG to a second QHRS and measuring the voltage drop with a quantum voltmeter composed of a second PJVS

and a null detector. This implementation removed the need of any calibration and allowed us increasing the signal-to-noise ratio and applying new measurement protocols based on the adjustment of Josephson array frequencies. All these improvements have allowed demonstrating quantified values of the current in the microampere range with a record relative uncertainty of 10^{-8} . Hence, now, we have demonstrated the realization of the ampere with relative uncertainties below 10^{-8} for different current levels, filling the gap between the milliamperere range and the microampere range. The level of uncertainties achieved are two orders magnitude lower than those of the best current measurement capabilities (CMCs). Finally, the accuracy tests can be viewed as a demonstration of the capability to calibrate resistance standards, for instance 100 Ω and 13 k Ω , with the quantum instrumentation that has been implemented in our laboratory and it should be extended to higher values. The complete setup opens the way to the realization of several electrical units in a single experiment.

[1] J. Brun-Picard et al, Phys.Rev. X, 6, 041051 (2016)

[2] S. Djordjevic, R. Behr, W. Poirier, Nat. Commun., 16, 1447 (2025)

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Quantum ohm

The efforts of LNE on the resistance metrology have been concentrated on two aspects: the validation of a cryogen-free cryomagnetic system and the fabrication of graphene-based quantum Hall resistance standards (QHRS).

After the validation of the cryomagnetic system regarding the thermal and metrological performances, extensive characterizations have been performed to optimize and to consolidate the high-precision and high-accuracy measurements, such as the addition of a second TO-8 holder (also AC-compatible), the mapping of the stray field (as high as few mT around the cables), the quantification of the vibrations of the cryostat and its probe, and the electrical noise spectrum related to resistance measurements. It has been evidenced that the electromagnetic perturbations are minimum without magnetic field (in the same level as the previous liquid helium-based cryostat), but drastically increase when the magnetic field is applied, the level being relatively insensitive to its amplitude. These perturbations most likely originate from the cold head and its pulse-tube technology, generating vibrations. At high magnetic field (typically in the order of 10 T or more), this electromagnetic noise can render the DC-SQUID of the cryogenic current comparator (CCC) unstable. It is possible to mitigate this issue by changing the SQUID feedback gain (to adjust its sensitivity) or by connecting a resonant damping circuit (to damp high frequency perturbations) to a winding of the CCC. It is also worth noting that the RF-SQUID of another CCC is less sensitive to these perturbations, evidencing that the problem might simply be caused by the higher sensitivity of the DC-SQUID, or its working frequency close to the one of the perturbations. This is under investigation. Overall, the measurement accuracy and its statistical uncertainty remain at the same level (a few ppb) to the ones of the previously used helium-liquid-based cryostat.

LNE is working on the development of graphene-based resistance standard for the realization of the QHRS in relaxed conditions ($T \geq 4$ K, $B \leq 5$ T and $I \geq 100$ μ A) with the collaboration of C2N at CNRS/Université Paris-Saclay and CRHEA at CNRS. The technology relies on graphene grown by chemical vapor deposition on silicon carbide (G/SiC) with the control of the charge carrier density using molecular doping. The whole process has been proven to be efficient and reliable, several graphene samples (5 devices, number in progress) with the targeted carrier density (in the order of 10^{11} carrier/cm²) and mobility (> 10000 cm²/Vs) have been obtained, operating QHR devices as QHRS at best at temperature up to 8 K, magnetic field below 4 T and current up to 300 μ A with an accuracy of the Hall resistance quantization within a few 10^{-9} in relative value. The study of these QHR devices is still under progress.

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Metrology for quantum technologies

As part of the French National Strategy on Quantum Technologies, LNE is coordinating the MetriQs-France program, dedicated to reference measurements, evaluation and standardization of quantum technologies. Notably LNE is involved in characterization of solid-state qubits (superconducting- and semiconductor spin-based) and their associated enabling technologies (RF and DC (cryo-)electronics, cabling, cryogenics, etc.), through metrology R&D projects with research organizations as well as startups, and deployment of a dedicated open experimental platform. The objectives are to develop and exploit measurements capabilities for reliable and harmonized characterization and performance assessment of quantum technologies to support their industrial development. The laboratory dedicated to this new activity is currently being developed with new equipment (dilution fridges, electronics for control and readout of qubits) and will be fully operational by the second half of 2025.

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4 Nanometrology

Exploration of radiative heat exchanges by measuring STHM thermometer resistance

Radiative heat exchanges in many-body systems play a major role in the field of nano/micro thermal management of complex engineered systems and could impact the development of numerous technologies (microelectronics, energy conversion systems, remote sensing, heat assisted data recording ...). In vacuum, two solid bodies at different temperatures exchange heat in the form of thermal photons. This exchange is limited in the far-field by Stefan-Boltzmann's law. On the other hand in the near field, (when the separation distance is smaller than the thermal wavelength) the flux can overcome this limit by several orders of magnitude due to tunneling of photons making this transfer prominent at nanoscale. These heat exchanges between objects can be studied by heating and measuring small temperature variations. One particular route consists in using resistance thermometers patterned on cantilever of scanning thermal heat microscope (STHM) to both heat objects and measure their temperature. Radiative heat exchanges (in the nanowatt range) being far smaller than those through cantilevers, it must be possible to detect temperature variations with sub-mK precision and reasonable accuracy. Achieving this goal requires the development of specific resistance bridges.

A measuring instrument prototype based on a Wheatstone bridge has been developed at LNE. It was used to measure the evolution of the temperature with sub-mK precision of a glass micro-sphere, heated with an alternating current, and moving towards a cold planar substrate made of different materials (SiO₂, SiC, Gold). These measurements unveiled a non-monotonic radiative heat transfer in the transition from far field to near field [1]. This effect results from a competition between near-field heat exchanges boosted by surface phonon-polaritons and a decreasing effective far-field sphere emissivity due to the presence of the substrate. Two improved and lower-noise measuring instruments were recently developed. They will be used to study many-body heat exchange transfers

[1] V. Guillemot *et al*, Non-monotonic radiative heat transfer in the transition from far field to near field, <https://arxiv.org/pdf/2410.20394>

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Electrical metrology at the nanoscale

This activity is focused on the development of metrological instrumentation (reference calibration samples, probes, and electronics) and calibration methods for measuring electrical quantities at the nanoscale using electrical Scanning Probe Microscope (eSPM). Reducing the total standard uncertainty down to a few percent in relative value under optimal conditions forms one of the main challenges in eSPM. In addition to improving the accuracy of electrical quantities' measured in eSPM, this enables the determination of the materials' inherent electrical properties (e.g., permittivity, doping concentration, mobility) at the nanoscale.

To improve the calibration of Scanning Microwave Microscope (SMM) for capacitance measurements at nanoscale, we have investigated a new generation of calibration kit fabricated by MC2 Technologies based on our specifications and covering the capacitance range from 0.3 fF to 40 fF. Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM) measurements have highlighted a marked improvement in topography but cleaning process was found necessary to get good electrical contrasts on SMM images. To validate the new design, complete measurement campaign was carried out on one cleaned structure. Results have shown a small dispersion between the measured capacitance values and the values calculated by finite element method (FEM), contained within a $\pm 5\%$ over the full capacitance range. In addition, the uncertainty budget for calculating the capacitance values in this new kit leads to a combined relative uncertainty close to 1% over a capacitance range from 0.3 fF to 40 fF, a reduction of a factor of 2 compared to the uncertainty obtained for the old version of the MC2 kit.

Many experimental parameters affect the accuracy of impedance measurements by SMM. Studying their effects on the measured values is particularly difficult. We have developed a fully numerical simulation of SMM measurements using FEM. We demonstrate the application of a self-calibration procedure for simulated SMM measurements with a maximum deviation of $\pm 0.8\%$ from reference capacitances calculated from an electrostatic model. In addition, we highlight the possibility of evaluating the effects induced by the water meniscus on the simulated SMM measurements. In general, the water meniscus has an impact of 0.4% on the calibration, only for very small capacitance values (≤ 300 aF), which is in line with previously reported empirical data.

In collaboration with University of Picardie Jules Verne, we investigated the use of a graphene-coated tip to reduce much more the influence of relative humidity (RH) on SMM measurements. First measurements have shown a lower dispersion on the relative differences between the measured capacitances and the calculated capacitances obtained with at RH = 1% for a graphene-coated tip in contrast with representative conductive tips. These measurements were complemented by adhesion force measurements at different RH values, ranging from 1% to 30%, for each type of tip. The results show a net adhesion force transition at RH = 24% for the non-graphene coated tips and no significant change in adhesion force up to 30% RH. These results demonstrated a low impact of the RH effect with the graphene-coated tip, which could be explained by the hydrophobic properties of graphene.

Moreover, in collaboration with CNRS, we developed novel reference standards enabling a Conductive probe AFM (C-AFM) to be calibrated in terms of both resistance and current measurands. These calibration samples were designed to facilitate access to highly accurate calibrated C-AFM measurements over wide resistance and current ranges from 1 k Ω to 1 T Ω and from 10 fA to 10 μ A, respectively. To this end, the influence of the AFM tip (material, wear) was extensively studied. Detailed measurement protocols have been drawn up with simplified uncertainty budgets, showing that the combined uncertainties do not exceed a few per cent over all the resistance and current ranges.

We took part in drawing up two good practice guides, the first for calibrated resistance and current measurements using C-AFM and the second for calibrated admittance measurements using SMM. On the basis of these two guides, which are available on request from the ELENA project website, we have

contributed to the preparation of two standards related to C-AFM and SMM which are currently being examined by IEC TC113.

The final highlight of this period 2023-2025 is the organization of the Summer school “ELENAM” in collaboration with CETHIL and INSA-Lyon, dedicated to Metrology at the nanoscale. The school was held in Fréjus (France), from June 3rd to June 7th, 2024 and gathered 50 attendees including 15 lecturers.

Part of this work has been developed in the frame of the project Elena (20IND12), which received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme. In particular, the project Elena (1st Sept 2021 – 31 Aug 2024).

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5 Low Frequency metrology

DC Measurements

Over the last two years, 2023 and 2024, the LNE has tackled a number of challenges concerning measurement methods and traceable setups, challenges risen by applications involving DC power supply.

Active partner in the consortium of the European project JRP 20NRM03 DC Grids (“Standardisation of measurements for DC electricity grids”), LNE focused on the ripple present on DC voltage. Among the several phenomena affecting the quality of DC power grid that has been identified in the JRP DC grids project: voltage dip/swell, overvoltage, supply interruption, voltage/current ripple, the LNE dealt with the ripple as a steady-state phenomenon. Generated by the power electronic converters, the instability of DC power sources and/or the connection of various loads to the network and their operating modes, the ripple might affect the exposed equipment and the safe operation of electrical grids. Quantify the ripple and its frequency content is important to estimate the risk and to launch the necessary operations.

The LNE setup allows determining voltage ripple of few tens of millivolts with frequencies up to 500 kHz. Some metrological aspects were outlined: to filter the DC component of the studied signal in order to take benefit of the full performances of the acquisition system, to characterize the signal-to-noise features of the measurement system since it affects the ripple determination.

The quality of the DC energy is an important topic not only for electrical grid operators but also for rail infrastructure operators. Light urban transport systems (metro/tram/trolleybus) are generally powered by AC/DC substations of a few megawatts which are connected to the medium-voltage AC network. New power electronic devices that allow excess energy to be switched from DC to AC (reversible substations) and/or stationary storage systems have been proposed and are currently being installed. Effective energy efficiency can be achieved by combining infrastructure improvements with optimum management of the energy flows exchanged within the DC system and between it and the upstream AC distribution network. Accurate knowledge of the efficiency of power system components under actual operating conditions is important information for managing electrical energy. Since June 2023, the JRP 22NRM04 e-TRENY project (“Metrology support for enhanced energy efficiency in DC transportation systems”) has started. Partner of this project, LNE contributes at developing calibrations for voltage and current transducers under dynamic conditions with typical time scales ranging from a few hundred milliseconds to a few seconds.

LNE is also involved in the development of calibration electrical DC meters and their integration into vehicle charging stations, as well as associated metrology. LNE is taking part in the JRP Metrology for charging station MET4EVCS, particularly in the measurement of superharmonics and the calibration of charging stations with the best uncertainties. The Electrical Vehicle (EV) is the core of the European Commission's transition plan for the transport sector towards electromobility. The successful integration of EVs requires the deployment of an extensive EV Charging Stations (EVCSs) infrastructure covering

the overall charging needs of the consumers. This project will tackle the challenges of power quality effects on and as a result of EVCS, and evaluate the associated losses and reliability of metering under actual on-site conditions. The project aims to cover several charging modes, such as direct DC charging at low and high power, smart charging, and specialised bi-directional charging. The project will support the industry needs by the development of a metrology infrastructure for traceable testing of EV charging systems which remains a major bottleneck at the moment. The project will also provide input to OIML TC 12, WELMEC WG 11, and the European Commission (EC) Working group WgMI E01349 for uptake in their guidelines and regulations which will, in turn, support the EV charging industry through standardisation.

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Storage metrology

Batteries and supercapacitors are currently the most commonly used energy storage solutions. They convert chemical energy into electrical energy. Several parameters must be considered when using these electrochemical systems. The first category of parameters refers to those used to design the system for its future use. The second category of parameters refers to the main phenomena that need to be considered when using the system. For example, capacitance, internal resistance and state indicators (state of charge SoC, state of health SoH and state of function SoF) are the main characteristic parameters of the second category. Optimal determination of these characteristic parameters from the manufacturing process ensures safe and reliable operation. Unfortunately, the measurement quality of the characteristics of these electrochemical elements is still insufficient.

As part of two projects: an internal French metrology project and the European JRP MetSuperCap project, the LNE is working to develop a metrology infrastructure for the characterisation of electrochemical cells, mainly supercapacitors and lithium-ion batteries. A PhD student is working on this project and started her thesis in September 2024. The uncertainty budget to be established in this study will take into account the influence of the metrological configuration of the measured impedance and also the influence of the different interferences of the different characterisation methods (measurement bias), such as: The influence of temperature, the influence of hysteresis in electrochemical impedance spectroscopy (EIS) measurements, the change of direction of the current or voltage, especially for sinusoidal waves, the influence of the delay effects of the responses of the electrochemical elements for sinusoidal excitations, the influence of the stabilisation method and the recovery times in each characterisation method. A statistical analysis of the measurement results will be carried out and compared with the results obtained from calculations using thermoelectric identification models. The results of this study will be validated by interlaboratory comparison measurements with collaborators from the JRP MetSuperCap project using the same measurement protocol.

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19NRM07 HV-com² - Support for standardisation of high voltage testing with composite and combined wave shapes

LNE worked closely with other NMIs to develop traceable measurement systems and calibration services for composite and combined wave shapes. Input was provided to IEC TC 42 “High voltage and high current test techniques,” which revises relevant standards, in particular the IEC 60060 series. Most of the recommendations developed in this project were adopted by the standardization committee and used as a basis for the currently published 42/414/CDV and 42/416/CDV.

As a partner in this project, LNE was also involved in technical tasks. It developed new software and a reference generator for measuring devices. This calibrator is based on a high-speed linear amplifier and allows the generation of all types of wave shapes up to 900 V for the calibration of digital recorders used to measure these complex wave shapes. The calibrator's traceability has demonstrated the ability to calibrate digital recorders used for combined and composite waveform measurements with very good uncertainty. In addition, where there was previously no traceability, it is now assured up to 900 V with a measurement uncertainty of 0.2% for amplitude and 1% for time parameters.

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19NRM05 IT4PQ - Measurement methods and test procedures for assessing accuracy of Instrument Transformers for Power Quality Measurements

The LNE has developed a platform for characterizing voltage transformers under the combined influence of temperature, vibrations, and harmonics. The characterization is mainly performed for voltages up to 35 kV for the fundamental component (50 Hz) and superimposed harmonics in the range up to 9 kHz with an amplitude of 1 kV. The traceable calibration is carried out by comparison with a standard high voltage divider and accurate synchronized digitizers. The calibration uncertainty is a function of frequency f (in Hz) and is equal to $(0.13 \times f + 20) \mu\text{V/V}$ for the ratio error and $(0.13 \times f + 20) \mu\text{rad}$ for the phase displacement. The temperature range extends from -25 °C to 55 °C. An electrodynamic shaker has been incorporated into the system, capable of vibrating at frequencies ranging from 3 Hz to 2 kHz, generating peak-to-peak displacements from 25 mm to 75 mm, and exerting forces from 27 kN to 80 kN. It can deliver vibrations along different directional axes, including the X, Y, and Z axes.

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19ENG02 FutureEnergy - Metrology for future energy transmission

LNE collaborated with the French company VETTINER to design a voltage capacitor with improved voltage linearity, targeting a capacitance variation below 10 $\mu\text{F/F}$ up to 800 kV. A method was conducted to determine the voltage coefficient of gas insulated capacitors through mechanical oscillations. A mechanical shock induces electrode oscillation, generating an alternating current used to measure oscillation frequency, initial eccentricity, and voltage coefficient. Tests on one of the reference capacitor showed excellent results, with initial eccentricity at 0.07 mm and a voltage deviation of 0.45 $\mu\text{F/F}$ at 100 kV.

LNE developed a 185 kV HVDC universal modules for DC, AC, and impulse voltages measurements achieving a 35 MHz bandwidth. A 555 kV divider was formed by stacking three 185 kV modules, with appropriate low voltage arm maintaining consistent scale factor variation on voltage and frequency for accurate impulse measurement. DC characterization up to 555 kV showed a voltage coefficient of $-0.65 \cdot 10^{-6}/\text{kV}$ and negligible self-heating remaining below 3 $\mu\text{V/V/min}$. Correcting voltage coefficient and self-heating allows achieving uncertainties below 0.01 % at 555 kV.

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22NRM06 ADMIT - Characterisation of AC and DC MV instrument transformers in extended frequency range up to 150 kHz.

LNE collaborates with NMIs to develop AC and DC voltage generators designed to simulate grid disturbances focuses on generating fundamental voltage components with amplitudes up to 36 kV for AC and 50 kV for DC. These generators will also superimpose frequency components in the 9 kHz to 150 kHz range, with amplitudes ranging from 5 V to 500 V. In this purpose LNE has developed a generator based

on the use two grounded parallel sources to combine voltages through appropriate blocking elements and filters. This generator operates correctly with voltage stability at 50 Hz better than 0.01% and better than 0.1% for harmonics up to 150 kHz.

LNE collaborates also to establish reference measurement systems to provide traceability for high voltage in the 9 kHz–150 kHz frequency range. This will enable the calibration of voltage measuring systems with a 0.1% accuracy class. The target uncertainties are 0.01% for the fundamental component and between 0.2% (0.2 crad for phase) and 1% (1 crad for phase), depending on the voltage level, for the 9 kHz–150 kHz components. For this purpose LNE is developing a new measuring systems for such application. The main challenge lies in measuring a 50 kVp (DC or AC/50 Hz) voltage superimposed with harmonics that can reach amplitudes as low as 5 V. Measuring such signal presents significant technical challenges due to the extreme dynamic range requirement. To achieve an accurate measurement of the 5 V harmonic up to 150 kHz with an uncertainty of 1%, a system sensitivity of at least 120 dB is required. To overcome these technical constraints two solutions are proposed, the first one is to use a filtering and amplifying techniques. The second is to use a HV system with a very high sensitivity with a dynamic range of at least 120 dB.

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6 RF and MW metrology

High frequency power calibration: traceability and extension towards terahertz frequencies

This project aims to consolidate and extend the traceability of average power to terahertz frequencies (170 GHz). Given the scarcity of bolometric power probes and the difficulty in sourcing thermoelectric power probes compatible with our primary reference (microcalorimeter), this large-scale project aims to ensure the sustainability of our CMCs by developing and producing HF power probes based on thermoelectric technology. These probes will be integrated into new primary (microcalorimeter) and secondary (HF power transfer benches) level benches, which will also be developed and operational by the end of the project. Therefore LNE is developing power transfer standards as well as primary power standards (microcalorimeter) for 2.4 mm connector and waveguide transfer standards (R620, R900 and R400).

The development of a 2.4 mm coaxial power standard for the [DC - 50 GHz] frequency bandwidth started in 2023. The main components of the power standard are a 2.4 mm connector, a CPW transmission line, and an RF detecting unit. The design and optimization of electromagnetic performance were completed in 2024. The input reflection coefficient is less than 20 dB, and the efficiency is higher than 0.8 across the entire frequency range. The RF detecting unit is composed of two parts: two parallel 100 Ω resistors terminating the CPW transmission line and a thermopile located close to the resistors for temperature sensing. Regarding the power sensor sensitivity, thermal simulations were carried out to find the optimal distance between the two resistors and the thermopile to achieve high output voltage. At 50 GHz, a sensitivity of 0.247 mV/mW was achieved. The sensitivity of the power sensor depends on the distance between the thermopile and the two resistors. The first prototype will be built in 2025. Special emphasis was placed on the design of the housing geometry and the integration of the detecting unit.

During the 2024 the design concept and development of the rectangular power standard in the frequency range of [110 GHz – 170 GHz] was finalized. The PhD candidate who carried out the design and performance optimization successfully defended her thesis regarding the new concept of the design with promising performance based on electromagnetics (return loss is less than 15 dB) and thermal simulations (output voltage around 1mV for an injected power of 10 mW) results across the entire frequency range. We received the power sensor components (RF detecting unit, housing, DC connector...) in the second half of 2024 from our supplier. In the next step we will proceed with the prototype fabrication by assembling all the components. Based on the design of this power standard, the development and RF

performances optimization of a rectangular power standard in the frequency band [50 GHz – 75 GHz] also started in 2024.

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JRP RF 4 6G (RF key quantities for 6G development)

This European project, starting in May 2024, aims to extend metrology for RF key quantities in line-based connectorized systems in both frequency and time domains to optimally support 6G wireless developments. Since 6G development efforts are leading to operating frequencies above 200 GHz to enable the anticipated high data rate, specific measurement needs include the development of primary standards for RF power measurement up to 220 GHz, the expansion of coaxial connector frequency limits up to at least 220 GHz, the establishment of traceable calibration procedures for electrical waveform parameters above 110 GHz, and the creation of new methods to measure linearity and, based on that, novel attenuation standards. These capabilities are crucial for ensuring the reliability and performance of future 6G systems, reducing development costs, and enabling European industries to compete effectively on a global scale.

The specific technical and scientific objectives of this project regarding LNE involvement are: RF power measurement up to 220 GHz, extending the frequency range of broadband existing coaxial connectors, and enhancing VNA methods for determining their linearity.

The last results concern the first objective, with the development of WR5 waveguide microcalorimeters for the calibration of power transfer standards in the frequency range from 140 to 220 GHz, which started in the second half of 2024. The microcalorimeter head, including the thermopile and thermal isolation section, has been designed and drawings have been made. Components like the thermopile and calorimeter head have already been received from our supplier. We also purchased a frequency multiplier to cover the frequency range from 140 GHz to 220 GHz. The development of the LNE WR5 waveguide microcalorimeter is expected to be completed by the end of the first half of 2025, and the validation of the microcalorimeter will start shortly after with the support of the project's partners (PTB, NPL, TUBITAK, R&S, BHAM) for the development of the WR5 waveguide power sensor.

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Nanoscale extreme impedance S parameter measurement

This project, in collaboration with IEMN and the University of Lille, aims to establish traceability for S-parameter measurements at the nanoscale and in the extreme impedance domain. It addresses the challenges of accurate high-frequency measurements at these scales, where conventional calibration kits are inadequate due to impedance mismatches and dimensional constraints.

To facilitate measurements, coplanar waveguide (CPW) structures were designed with a microscale section for probe contact and a nanoscale section implementing a transmission line interconnect with a signal strip width of 500 nm. A tapered transition ensures impedance continuity between these sections, with optimization performed using 3D electromagnetic simulations.

Nanoscale calibration standards and DUTs were fabricated on a high-resistivity silicon (HR Si) substrate using gold as the conductor and titanium as an adhesion layer. Electron beam lithography (EBL) was used and the process had to be optimised to obtain the high resolution needed to accurately define the nanoscale structures. Two fabrication runs were performed, with the second yielding significantly improved results.

On-wafer S-parameter measurements were carried out up to 110 GHz, using an LRRM calibration with an off-wafer microscale commercial calibration kit and a TRL calibration with the developed nanoscale calibration kit. The TRL calibration establishes the reference plane at the nanoscale DUT input. The TRL

standards comprised a 200 μm line (thru standard), a set of lines of varying lengths (line standard), and short circuits (reflect standard).

Extracted effective permittivity and propagation constant of the nanoscale CPW structures were compared with those of microscale structures, also fabricated on the same substrate. The nanoscale lines exhibited higher, frequency-dependent effective permittivity and significantly greater losses, attributed to increased conductor losses at reduced dimensions. Measurements of a 300 μm CPW transmission line DUT demonstrated that TRL calibration provided a more accurate DUT response than LRRM, effectively isolating the DUT characteristics and referencing the calibration plane within the nanoscale CPW transmission line.

These initial results confirm the feasibility of nanoscale on-wafer calibration. Ongoing work focuses on preparing a third fabrication run with the aim to be able to measure and differentiate high-impedance DUTs, identifying factors influencing performance, and conducting a comprehensive uncertainty analysis.

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Calibration of vector electric field probe and reference antennas for SAR measurements

This project aims to consolidate and extend the traceability of vector field probe sensors with applicability to specific absorption rate traceability, therefore including calibration of probes in tissue simulant liquids. A first realization has led to the deposit of CMCs for the calibration of vector field probes inside a WR187 waveguide [3940 MHz-5990 MHz] filled with a calibrated tissue simulant liquid, the scope of the new project is to extend the frequency

S-parameter measurements of the calibration system have been performed from 5100 MHz to 5500 MHz as the waveguide matching level is guaranteed in this frequency range. The correction factor derived from S-parameters of the calibration bench and the waveguide cell then filtered by polynomial regression gives coherent results with the dispersion value less than 2% for three positions of the probe in the liquid. Moreover, the good agreement between the magnitude of probe correction factor obtained from vector-based and scalar calibration methods allows validating the proposed calibration method.

Several uncertainty contributors in the probe calibration such as dielectric constant measurements of the liquid, waveguide dimensions, uncertainty of network analyser, repeatability of measurements and probe positioning have been evaluated. Knowing the uncertainties of the input quantities of the probe calibration model, the Monte Carlo numerical method allows propagating the input uncertainties to the probe correction factor. The relative expanded uncertainty of this factor has been estimated in the order of 10% at the target frequency of 5200 MHz.

LNE continues working on the development and improvement of the vector E-field probe calibration method and system to cover different frequency bands from 400 MHz to 4 GHz. This proposed probe calibration method will be further used in reference antenna calibration.

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