

Title: Advancing Impedance Metrology in an Extended Frequency range

Abstract

Recent developments in impedance metrology across Europe highlight the need for automated, reliable and precise measurements. There is growing demand in different fields to extend traceability in a broader range of frequency. Proposals addressing this topic should leverage world-leading expertise of European NMIs and universities to harmonise capabilities and expand the frequency and measurand ranges in impedance metrology. Optimising existing standards and measurement systems, guided by theory and simulations, should address challenges at frequencies from 100 mHz to 2 MHz, further enhancing EU metrology leadership and impact scientific and industrial applications spanning materials science, energy distribution, acoustics, biotechnology and quantum technologies.

Keywords

Impedance measurements, electrochemical impedance spectroscopy, impedance bridges, Josephson impedance bridges, quantum Hall effect, impedance standards, biosensors, electricity grids.

Background to the Metrological Challenges

The European Metrology Network on Quantum Technologies (EMN-Q) has identified “robust and stable graphene-based quantum Hall devices as primary standards in the DC and AC regime” [1], which will be covered in this topic by the investigation of quantum Hall devices at frequencies of up to 2 MHz. The quantum Hall effect is expected to perform equally well at DC and AC, potentially until the breakdown frequency (in the THz range). This still needs to be proven with metrological uncertainties. The same document states that “Quantum-enhanced measurement bridges are essential for electrical DC and AC measurement applications” and identifies digitally improved or assisted, fully digital and electronic bridges for impedance metrology up to several MHz. Integrating these advanced bridge technologies with state-of-the-art impedance standards, such as the quantum Hall resistance (QHR), would position European metrology as a global leader in the emerging field of broadband precision impedance metrology. By addressing the needs of calibration service providers and industry, the project builds on the successful outcomes of previous projects such as: EMRP Aim QuTE, EMPIR GIQS and the Partnership QuAHMET for classical, quantum-enhanced and quantum impedance metrology. The current state-of-the-art are high precision measurements of GaAs QHR devices around 1 kHz. First attempts during the GIQS project increased the frequency to slightly more than 10 kHz using graphene devices with higher uncertainties.

Attempts have been made to increase the operation frequency of the state of-the-art coaxial impedance bridges from audio frequency up to MHz range. Such work enables the investigation of measurement techniques based on miniaturised but manually controlled bridges leading to achieve uncertainties for selected impedance measurements of few parts in 10^5 . Implementation of digital based principles developed later within EMRP Aim QuTE over a considerably wider frequency range is missing and resulting in a lack of MHz bridges deployment at NMIs. The extension of digital sampling methods up to 1 MHz was partially implemented in the scope of EMPIR TracePQM for mid and low impedances only with uncertainties of few parts in 10^5 . Schurr and Awan recently presented the possibility of reducing by at least a factor of ten the measurement uncertainties of a commercial inductance capacitance, and resistance (LCR) meter for frequencies up to 2 MHz.

Four terminal-pair impedance standards with predicted frequency dependency up to 100 MHz were recently developed. The validity of the calculated frequency dependence has been confirmed using Vector network analyser (VNA) instruments for frequencies above 100 MHz. Below this frequency, VNA measurements have an accuracy of roughly 0.3 %. Full digital bridges can be used to validate the frequency dependence up to 100 kHz; above this, new measuring instruments are required. For one- and two-port coaxial devices at RF and microwave frequencies traceability of impedance is obtained through calculable measurement standards such as air-dielectric lines, offset shorts, flush shorts, etc., generally characterised at RF and DC, with interpolation required for low frequencies, leading to relatively high uncertainty at audio frequencies (AF). Recent research shows that calculable standards can be used for AF range. Work should be aimed to characterise these standards up to 2 MHz and use LCR meters for traceable impedance characterization.

With the introduction of commercial LCR meters and analysers, their calibration to primary standards has become essential. Accurate calibration could benefit areas from electrochemical impedance spectroscopy, quantum Hall resistance and 2D quantum materials to biotechnology for early disease diagnosis (such as Alzheimer's, cancer and cardiovascular). Although some efforts have been made to provide such calibration for LCR meters and network analysers, they cover only a narrow range. Intellectual property rights protect operational methods, complicating comprehensive uncertainty budgets. Electrical Impedance Spectroscopy (EIS) requires extended frequency ranges, and international standards guide accuracy. The 23IND04 MetSuperCap project funded by the European Partnership on Metrology advances traceability for EIS, but NMIs and calibration centres still lack capability to calibrate artifact impedance standards or meters.

On-site power grid measurements face largest uncertainties above 9 kHz. Standardisation is missing, especially in defining reference impedances and Line Impedance Standardization Network (LISN) updates. These issues should be addressed from 9 kHz up to 500 kHz. The expanding EU electrical equipment market supports the need for metrology across these areas.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The proposal shall focus on the traceable measurement and characterisation of impedance standards over an extended frequency range.

The specific objectives are

1. To enable efficient and robust optimisation of new and existing impedance bridge methods and topologies by deepening the understanding of existing impedance standards. This will be achieved through rigorous validation of uncertainty budgets across a wide range of frequencies and measurands (100 mHz to 2 MHz), using developed practical models and advanced simulations.
2. To enable accurate calibration of commercial LCR meters, analysers, and electrochemical impedance spectroscopy systems over an extended frequency range (100 mHz to 2 MHz) by optimising calculable impedance standards and coaxial bridges. Calibrations will use LCR impedance transfer standards traceable to calculable standards, with target uncertainties ($k=1$) at 2 MHz of 10 $\mu\text{F}/\text{F}$ for 10 pF capacitance standards, 10 $\mu\Omega/\Omega$ for 1 k Ω resistance standards, and 30 ps for time constant standards.
3. To investigate and develop GaAs- and graphene-based quantum Hall devices and associated cryomagnetic setups over an extended frequency range (100 mHz to 2 MHz), with target measurement uncertainty of 20 $\mu\Omega/\Omega$ ($k=1$) at 2 MHz. Additionally, to outline a pathway towards a universal quantum standard for impedance.
4. To strengthen and expand the European measurement infrastructure for advanced impedance techniques over the extended frequency range (100 mHz to 2 MHz), supporting the development of new Calibration and Measurement Capability entries. This will involve the development of methods for uncertainty evaluation and calibration approaches aligned with practical service requirements and user needs, enabling the adoption of new calibration methods and robust traceability chains.
5. To demonstrate the establishment of an integrated European metrology infrastructure in the field of impedance metrology and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (calibration laboratories, instrument manufacturers), standards developing organisations (IEC/ISO, CEN-CENELEC, IEEE) and end users.

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources both within and outside Europe, plus engagement with existing European research infrastructures and European Partnerships is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry and end users. Where relevant, proposals are encouraged to build on, or seek collaboration with, existing projects and develop synergies with other relevant European, national or regional initiatives and funding programmes. In particular, links are encouraged with (i) the projects funded under earlier relevant topics of the Horizon Europe programme; or (ii) other relevant European Partnerships.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMRP SIB53 Aim QuTE, EMPIR 18SIB07 GIQS, EMPIR 15RPT04 TracePQM and Metrology Partnership 23FUN07 QuAHMET projects and how their proposal will build on those.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.1 M€ and has defined an upper limit of 2.6 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 25 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your proposal's results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability, or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the instrument manufacturer sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Metrology Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Timescale

The project should be of up to 3 years duration.

Additional information

The links provided in this section are only correct at the time of publication up until the end of the Call year.

The references below were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] EMN Quantum Strategic Research Agenda, <https://www.euramet.org/research-innovation/metrology-partnership/strategic-research-and-innovation-agendas>