Title: Cryogenic RF measurements for quantum and semiconductor technologies

Abstract

There is an increasing demand in quantum applications, for radio frequency (RF) components to operate at extreme cryogenic temperatures (4 K and below), to isolate quantum circuits from possible interference and ensure stable qubit detection. However currently, the development of cryogenic devices and systems is limited by a lack of traceable and accurate RF measurements at cryogenic temperatures. Proposals are sought to establish a world-class sustainable and coordinated infrastructure for traceable cryogenic RF metrology at the European level, extending traceability to the SI in order to enable accurate and quality-assured RF (including microwave and millimetre-wave frequency) measurements at cryogenic temperatures. This in turn will support design optimisation, component validation and minimisation of hardware errors, needed for commercialisation of such systems.

Keywords

Radio Frequency, electrical measurements, cryogenic temperature, quantum technologies, semiconductor technologies, metrological traceability, S-parameters, power, noise, quantum sensors, radio astronomy.

Background to the Metrological Challenges

Driven by global quantum technology initiatives to commercialise second-generation quantum technologies, European component manufacturers are developing RF components for operation at extreme cryogenic temperatures. A European supply chain for cryogenic quantum technologies is beginning to be established, including cryogenic photonics, microelectronics and cryo-microsystems to support the low-cost high-volume manufacturing of superconducting and semiconductor-based quantum chips in the EU. Cryogenic temperatures (4 K and below) are required to isolate quantum circuits from environment and interference in order to manipulate and observe quantum behaviour. However, practical quantum computers will require high numbers of qubits to address real-world problems and create value for the global economy and society. Significant quantum and cryogenic high frequency engineering hurdles need to be overcome to realise such large-scale systems. This necessitates a radical shift in design principles at the component and system levels to enable commercialisation. A robust cryogenic RF metrology framework needs to be in place to support such transformation to optimise designs, validate components and minimise hardware errors, leading to efficient and cost-effective product development cycles.

Currently, the development of cryogenic devices and systems is hampered by the lack of traceable and accurate RF measurements at cryogenic temperatures. A major challenge is the need to decouple the effect of auxiliary components, and the measurement system, and thus to measure the electrical performance parameters closer to the device inside cold and isolated cooling platforms. This becomes especially problematic at high frequencies requiring specialised traceable calibration techniques to extract accurate and useful device characteristics. Currently, the capability for accurate in-situ device and signal metrology in cryogenic systems is inadequate, due to insufficient accuracy and poor repeatability. The absence of cryogenic primary standards and SI traceability at temperatures of 4 K and below poses major challenges. There is insufficient understanding of measurement uncertainty limitations especially when performing power and noise characterisation at these high frequencies. There are significant measurement errors introduced, for example, due to the use of non-ideal switches in cryostat-based measurement systems and due to mechanical vibrations present in cryogenic platforms, which need investigating and mitigating.

A number of initiatives are underway across Europe and beyond, to develop and implement roadmaps for quantum computing technologies [1]. Some advances have been made in recent years; for example, the Horizon Europe Q-Test project is supporting the creation of a European trusted supply chain of quantum devices by developing an open testing infrastructure, and an ongoing Metrology Partnership project 23FUN08 MetSuperQ is focused on developing characterisation methods for qubit materials and components to address scalability challenges in superconducting quantum components. The EMPIR project 20FUN07 SuperQuant has contributed to developing cryogenic S-parameter (loss and phase change for transmitted and reflected electrical signals) measurement systems and quantum-based cryogenic power sensors at selected temperatures (4 K and tens of mK) in leading European NMIs. However, despite these advances, there have been no reported demonstrations of interlaboratory measurement comparisons among NMIs in S-parameter, power, or noise measurements at cryogenic temperatures, reducing confidence in providing high quality cryogenic RF measurements. Further work is required to enhance measurement accuracy and establish SI-traceability through a coordinated European NMI network to support end-users effectively. These fundamental measurement challenges need to be addressed to enable reliable characterisation of devices in realistic operating scenarios.

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 and accurate measurement of S-parameters, power and noise at frequencies up to 40 GHz at cryogenic temperatures from 4 K to tens of milli-kelvin (mK).

The specific objectives are

1. To develop S-parameter measurement systems and calibration techniques to enable traceable and accurate characterisation of cryogenic and quantum circuits up to 40 GHz, including the contribution of transmission lines to cryogenic platforms. In addition, to investigate new probing techniques with micrometre resolution and techniques to characterise devices fitted with non-metrology grade coaxial connectors of small footprint.
2. To develop power sensors and techniques using classical and quantum-based approaches to enable traceable and accurate power measurements of signals and devices at cryogenic temperatures (4 K and tens of mK) up to 40 GHz. Performance parameters such as sensitivity, scalability, thermal stability, and thermal hysteresis should be studied to develop robust power sensor solutions and reliable power measurement protocols.
3. To develop methods and approaches to enable traceable and accurate cryogenic noise characterisation, including the development of traceable cryogenic noise sources and verification devices, as well as methods to characterise cryogenic noise parameters (i.e. for non-50 Ω conditions).
4. To conduct an interlaboratory comparison of S-parameter, power and noise measurements at cryogenic temperatures, based on the outputs of objectives 1, 2 and 3.
5. To demonstrate the establishment of an integrated European metrology infrastructure in the field of cryogenic RF measurement and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (device manufacturers, calibration laboratories), standards developing organisations (IEEE, CEN-CENELEC JTC 22 “Quantum Technologies”, IEC/ISO JTC 3 “Quantum Technologies” and its Working Groups, EURAMET TC-EM), EURAMET EMN Quantum Technologies and end users (quantum, semiconductor and electronics industries, researchers in academia and Research Technology Organisations (RTOs)).

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 EMPIR project 20FUN07 SuperQuant and Metrology Partnership projects 23FUN01 PhoQuS-T and 23FUN08 MetSuperQ, and Horizon Europe project QU-TEST, 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 quantum, semiconductor and electronics sectors.

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.

These references have been provided by EURAMET.

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