European Partnership on Metrology
Call 2023 –Fundamental Metrology, Industry, Normative and Research Potential

Selected Research Topic number: **SRT-f07**
Version: 1.0

Title: Metrology for superconducting qubits

Abstract

Superconducting circuits are a leading technology for the realization of practical quantum computers. However, scaling-up towards full-scale, fault-tolerant quantum computers involve addressing many challenges concerning, e.g., qubit coherence, reproducibility, stability, cross-talk, control, and readout. To achieve this, the field needs a new generation of metrological methods and tools for superconducting qubits. Therefore, this project aims to develop such a suite of tools for superconducting qubits and apply them to state-of-the-art one- and two-qubit circuits. These new tools will underpin further engineering advances and allow for accurate characterisation of qubits and materials, as well as manipulation and read-out.

Keywords

Superconducting quantum technologies, qubits, metrology, cryogenic systems, noise and coherence, superconducting circuits, quantum circuits, signal generation and detection.

Background to the Metrological Challenges

Quantum computing in the past few years made a transition from being an academic subject to a field attracting significant interest and investment from both industry and governments. A strength of superconducting qubit circuits, that has now been scaled up to 100’s of qubits, is that it is almost exclusively made from Aluminium on Silicon (or Sapphire) technology. This cohesion in the field has resulted in a technology that is significantly refined where reproducible large-scale circuits can now be made, allowing the community to gradually extend qubit coherence times beyond 100 µs despite the high complexity of quantum processors. A few new materials for auxiliary circuitry, such as Tantalum, has emerged in later years yielding qubits with improved coherence even if yet best quality Josephson junctions for qubits is still exclusively made using Aluminium technology. Currently, there is lack of metrological tools and methods that can be used to directly correlate the materials used and the resulting qubit coherence, meaning there is a huge gap in understanding what is limiting the coherence in superconducting qubits. Why some materials are better is not yet well understood, thus new measurement techniques are needed to understand the material properties at the quantum level and more precise comparisons of qubit performances are required.

The overall qubit fidelity is not only limited by the qubit coherence time, but also by control and read-out electronics. Josephson pulse generators might be able to deliver spectrally pure signals for qubit control and readout. However, additional work is necessary to avoid quasiparticle poisoning of the qubit for such control techniques. The readout-electronics such as superconducting parametric amplifiers are typically characterized using standard high-frequency measurement techniques. Using quantum-accurate techniques to specify microwave power or photon number will raise parametric amplifier characterisation to another level.

Measuring relaxation and dephasing times as well as fidelity of single qubit operations is now a routine task. Recent years from such benchmarking has shown that the measured qubit quantities are not constant (when not limited by measurement-induced infidelities). Therefore, it is not clear to what extent long measurements will give a detailed enough description of device performance. Benchmarking to understand the quality of samples has been used to reveal information of spurious material defects as well as other events such as quasiparticle tunnelling, ionising radiation or cosmic particles impacting the samples. However, so far there is little available in terms of statistical methods or measurement routines to routinely facilitate such accurate qubit benchmarking. Furthermore, Round Robin experiments with superconducting qubits is now emerging, together with other examples of qubits measured at different locations in experiments mainly trying to elucidate sources of decoherence. Establishing this capability within the European ecosystem is key to underpin further advances and establishing a best practice guide for qubit characterisation.

Moreover, advances in design and fabrication are likely to take small steps at a time, as circuit and material quality is gradually improved. There is thus a need to be able to accurately determine the “average” quality of the sample, and contributions to decoherence from external factors (with respect to the qubit chip) to facilitate detailed comparison. Additionally, there is also a need to develop tools that can be used to diagnose issues caused by, e.g., crosstalk and other effects that can then be addressed using improvements in circuit design or compensated by signal processing. These problems can be addressed by improved qubit metrology but also through the development of new ‘materials science’ and measurement techniques as well as standardisation of processing and designs of the qubit chip and the peripheral electronics to facilitate detailed comparisons. For this reason, it is important to develop a full suite of metrology tools able to separate various sources of infidelity, and to quantify qubit properties accurately.

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 JRP shall focus on the development of metrology capability for superconducting qubits.

The specific objectives are

1. To investigate new ways for metrological characterisation of materials used for superconducting qubits, at temperatures below 1 K. This includes exploring different high-coherence materials and processing steps to facilitate comparisons of material measurement techniques. In addition, to develop standardised design and processing procedures for inter-laboratory comparisons and reproducibility tests of material measurement techniques.
2. To develop, fabricate and test peripherical devices, such as parametric amplifiers and quantum-accurate Josephson pulse generators, to perform qubit control and read-out operations. This includes mitigating uncertainties arising from peripherical devices used in the control and read-out chain.
3. To develop harmonised characterisation routines to unpick mechanisms limiting scalability, coherence, and fidelity for single qubit and two qubits gates. In addition, to develop statistical tools for accurate benchmarking with minimised measurement error and overhead.
4. To perform a Round Robin on basic parameters of single qubits. In addition, to develop and validate measurement protocols and recommendations for reproducible characterisation of single qubits, this includes a best practice guide.
5. To facilitate the take up of the technology and measurement methods developed in the project by the industrial stakeholders. To implement a network to enhance collaboration among European NMIs to establish metrological capabilities for superconducting qubits. To engage standardisation bodies (e.g. CEN-CENELEC) to identify standardisation needs for superconducting qubits.

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % 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 JRP 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 Technology 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 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.

Time-scale

The project should be of up to 3 years duration.