Publishable Summary for 23FUN08 MetSuperQ
Metrology for superconducting qubits

Overview

Superconducting circuits are a leading technology for the realisation of practical quantum computers. However, scaling-up towards full-scale, fault-tolerant quantum computers will involve addressing many challenges concerning, e.g., qubit coherence, reproducibility, stability, cross-talk, control, and readout. In order to achieve this, a new generation of metrological methods and tools will be needed. This project will 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.

Need

A qubit is regarded as the basic unit of information in quantum computing and a counterpart to the bit (binary digit) in classical computing. In recent years quantum computing has become one of the hottest research topics worldwide. Yet, despite many advancements, qubits are still too faulty to be used for practical quantum computers and this situation is referred to as the Noisy Intermediate Scale Quantum (NISQ) era. Many obstacles remain towards a practical fault-tolerant, i.e., error-corrected, quantum computer (FTQC) capable of solving computational problems far beyond today's classical capabilities, impacting a broad range of sectors.

To reach beyond today's NISQ computers measurement methodology and accuracy need to be improved - this is a key objective of MetSuperQ. With improved measurements for superconducting qubits and peripherical devices comes the ability to distinguish, and accurately quantify the contributions of the plethora of different decoherence mechanisms arising from the materials, circuits, and devices, that degrade the performance of quantum computers. This will directly trigger advances in engineering, hardware, and materials aimed towards improved coherence and scalability. National (NMI-level) capabilities are required that can support commercial efforts, accelerate commercialisation in the field and bring European capabilities reaching beyond the present NISQ-era.

More specifically, there is discrepancy regarding how superconducting qubit metrics are reported in the literature and by companies, which makes comparison of parameters and performance difficult. Current performance metrics potentially mask key decoherence-limiting physical mechanisms, and in order for these to be addressed significant improvements to materials, readout and control electronics, and circuit design are required. Both measurement methodologies and analysis routines need harmonisation. Such harmonisation requires a large number of institutions to work together to develop techniques that are applicable to a wide range of conditions, and to conduct laboratory Round Robin comparisons using different hardware setups that subject superconducting circuits to a wide range of conditions.

Objectives

The main goal of this project is to develop novel metrology tools for superconducting qubits, to support the development of superconducting quantum computers. The specific objectives are:

1. Qubit materials: To investigate new ways of characterising materials of superconducting qubits, to be used for qubit metrology, at temperatures below 1 K. To explore different high-coherence materials and processing steps to facilitate comparisons of material measurement techniques. To

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develop standardised design and processing procedures for interlaboratory comparisons and reproducibility tests of material measurement techniques.

2. Qubit periphery: 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. To mitigate uncertainties arising from peripherical devices used in the control and read-out chain.
3. Metrology for single and two-qubit gates: To develop harmonised qubit characterisation routines to unpick mechanisms limiting scalability, coherence, and fidelity. To develop statistical tools for accurate benchmarking with minimised measurement error and overhead.
4. Round Robin: To perform a first Europe-wide Round Robin on basic parameters of single qubits. To develop and validate measurement protocols and recommendations for reproducible characterisation of single qubits, including a best practice guide.
5. Impact: To facilitate the take up of the technology and measurement methods developed in the project by the industrial stakeholders and others, and to engage with industrial stakeholders to understand how to support their future needs for superconducting qubit metrology. To implement a research network to enhance collaboration and to create characterisation abilities for superconducting qubits among European NMIs. To engage standardisation bodies (e.g. CEN-CENELEC) to identify standardisation needs for superconducting qubits and to initiate corresponding standardisation activities.

Progress beyond the state of the art and results

So far, no superconducting qubit metrology exists worldwide, and MetSuperQ will enter this new metrology area. By the end of the project understanding of decoherence mechanisms in devices and materials that limit scalability of superconducting quantum computers will have been advanced. The project will specifically target results advancing state of the art and gaining new fundamental insights in the following areas:

Qubit materials (Objective 1)

All state-of-the-art superconducting qubits are made using Aluminium/Aluminium-Oxide/Aluminium Josephson junctions with the rest of the circuitry being made either from Aluminium, Niobium or Niobium-Nitride. Qubit devices fabricated from a variety of materials, including Aluminium, Niobium, Tantalum and other, higher-Tc superconductors, will be evaluated aimed at better understanding the advantages of individual materials. A range of new characterisation techniques, including low temperature scanning probe microscopy and analysis techniques for in-situ material and device characterisation, will be specifically designed and implemented. Knowledge will be improved of the factors limiting the coherence of state-of-the-art superconducting qubit chips (including two-level systems, flux noise, quasiparticles, infrared radiation, control and readout) and how to mitigate them. Standardised device designs will be produced for comparisons and studies on the effects of materials, design parameters, and processing steps on qubit coherence. In addition, new fabrication techniques and materials for qubits with increased coherence and characterisation of their dominant residual decoherence mechanisms will be developed.

Qubit periphery (Objective 2)

The overall superconducting quantum computing system capability is not only limited by the qubit coherence time, but also by the control and read-out electronics, and interconnections. In the project, quantum-limited parametric amplifiers and quantum-accurate cryogenic waveform generators will be developed, benchmarked, and integrated with qubit readout/control. Moreover, component-based and full system characterisation will be compared to each other. Josephson pulse generators and optimised pulse patterns will be utilised to reduce qubit gate times towards greater circuit depth execution and scalability.

Metrology for single and two-qubit gates (Objective 3)

A range of different sample devices designed to be limited by different decoherence mechanisms (TLS, quasiparticles, etc.) will be investigated. Harmonised measurement and analysis routines (including public, modular and futureproof framework) for fast and accurate benchmarking of superconducting qubits will be developed, as well as methods to speed up qubit benchmarking. The benchmarking and analysis routines developed will go beyond the current state of the art in accuracy of deducing the ‘decoherence budget’ of qubits and determining factors limiting scalability.

Europe-wide Round Robin on basic parameters of single qubits (Objective 4)

Utilising developments earlier in the project, a Round Robin comparison will be performed demonstrating qubit benchmarking at multiple NMIs and laboratory settings capable of disentangling intrinsic (package level) from external (laboratory, electronics) sources of decoherence. This European comparison will bring several NMIs and other institutes into alignment to be able to deliver state of the art measurement capabilities for superconducting circuits and will form a European counterpart to US activities.

Progress beyond 20FUN07 SuperQuant

To obtain these insights and successfully reach the objectives, input from 20FUN07 SuperQuant will be required with respect to Josephson pulse generators working at GHz frequencies and microwave metrology in cryogenic environments. Yet, it is important to emphasize that SuperQuant does not address metrology of superconducting qubits and, thus, MetSuperQ will significantly go beyond SuperQuant.

It is expected that the project’s results will lead to a large number of high impact journal publications with joint authors from different countries across this whole range of activities, in addition to new tools, measurement protocols and circuits with enhanced performance compared to today’s state of art. In the addition to the scientific and metrological results, the NMI participants will investigate the possibility for new measurement services or capabilities for qubit materials, parametric amplifiers, and qubits.

Outcomes and impact

<u>Outcomes for industrial and other user communities</u>

American enterprises are currently industry leaders in the development of superconducting quantum computers, but there are a number of important and growing European SMEs focusing on both hardware- and software development. Additionally, there is also a growing European supply chain with companies producing, for example, instrumentation, parametric amplifiers, RF-components, and cryogenic systems needed to build superconducting quantum computers.

The outputs from the project, e.g., improved fabrication techniques to reduce decoherence and other defects in materials, optimised drives for superconducting qubits to reduce qubit gate times, processes for fast and accurate benchmarking of qubit parameters and state preparation, tools for improved statistical analysis of qubit temporal data, and a best practice guide, will further underpin development of the industry in Europe. Access to accurate information about the parameters of qubits, as well as good metrics that enable comparison of parameters, devices, and performance is increasingly important not only for quantum computing hardware manufacturers, but also to the wider supply chain as well as end-users and potential investors in quantum computing. The capability created in MetSuperQ among European NMIs for accurate measurement of superconducting qubits and the novel methods and best practises established will help to meet the metrology challenges in this emerging field. The tools developed in this project will also be relevant to other areas using related superconducting- and cryogenic technologies, such as test and measurement, telecommunications, microwave components, space and military communications systems, cryogenic systems, and medical imaging. The generated IP will be offered for exploitation to European stakeholders to increase the competitiveness of the European quantum industry.

The project will help create awareness in the community about the importance of metrology, best-practice and comparisons for achieving precise, trusted measurements, for example through the publication of peer-reviewed papers, the good practice guide, a workshop, and liaison with relevant networks and consortia such as the European Metrology Network for quantum technology (EMN-Q)[1], the European Quantum Industry Consortium (QuIC)[2], and the Quantum Economic Development Consortium (QED-C)[3].

<u>Outcomes for the metrology and scientific communities</u>

[1] https://www.euramet.org/european-metrology-networks/quantum-technologies/
[2] https://www.euroquic.org/
[3] https://quantumconsortium.org/

The project will enable the participating NMIs to enhance their ability to support leading European quantum technology and computing hardware- and software companies as well as the supply chain with enhanced measurements and future standards. No NMI currently has the capabilities required to carry out all aspects of establishing this capability alone, so the collaborative effort among several NMIs and leading research groups in MetSuperQ will help fully exploit and disseminate the outcomes of this opportunity. The results and outputs of MetSuperQ will lead the way to the worldwide first calibration services for parametric amplifiers and superconducting qubits.

International comparisons, i.e., Round Robins, are essential prerequisites for obtaining confidence in measurements. The first Round Robin on qubits in Europe performed in MetSuperQ will establish a European counterpart to a US initiative[4] and can be considered to be a very important milestone for qubit measurements in Europe. The protocol for the Round Robin will be converted into a Best Practice Guide, which will be disseminated to international stakeholders.

In addition to metrology aspects MetSuperQ also addresses cutting-edge quantum technology projects in Europe within the EU quantum flagship, Horizon Europe and Horizon 2020 programmes. MetSuperQ participants also participating in these projects will profit from mutual synergy effects and contribute to the growing together of the European science community on superconducting quantum technology.

Outcomes for relevant standards

Several standardisation development organisations (SDOs) have already initiated activities in the area addressed by this project, including, for example, IEC and CEN/CENELEC (via the new JTC22). European NMIs are already actively participating in these standardisation activities. Based on the roadmaps already created within CEN/CENELEC (via JTC 22) with participation from participants of MetSuperQ, it is expected that standards for basic metrics for qubits and quantum processors will be an early area of interest for standards development. Standardised benchmarks and metrics for the current generation of quantum processors are also under discussion within other organisations such as IEEE, QED-C and QuIC. All these efforts will require the relevant metrology and best practices to be developed.

Longer-term economic, social and environmental impacts

The quantum computing market is projected to grow rapidly within the next decades. Significant economic impact will occur through the development of new products. The value-added growth due to the use of quantum computers could be between $600 billion and $1300 billion in 2035[5]. Europe urgently needs to invest in quantum technology to be able to keep pace with the US and China. Metrology developed within the MetSuperQ project will support the European quantum technology and quantum computing industries, since metrology tools are needed to realise and scale up practical quantum computers.

Computing with significantly more than 10^{18} floating point operations per second will require new computational schemes offering improvement in flops per watt over the technology available today. Superconducting quantum computing is one of the technologies, which might be able to reach this goal. This also has significant economic impact, as data centres are foreseen to have an energy consumption of up to 8000 TWh in 2030[6], thus a 10 % energy saving of such devices, i.e., 800 TWh per year, would directly result in about €240 billion financial savings.

In the long-term society needs technologies based on innovative products and concepts. Quantum computing has the potential to disruptively improve our daily life through the realisation of orders-of-magnitude-improved computational speed. Superconducting circuits are a leading technology for the realisation of such quantum computers. As quantum computers continue to be scaled up, the need for associated metrology will continue to grow.

The MetSuperQ project may also have environmental impact if it helps to contribute to solving the unsustainable growth of energy consumption of ICT equipment. The European Green Deal aims to create the first climate-neutral continent. The above-mentioned energy saving of data centres could be used to shut down more than 90 medium-sized coal-fired power plants and, thus, considerably decarbonising the energy sector.

[4] https://sqmscenter.fnal.gov/
[5] https://www.mckinsey.com/de/news/presse/quantum-technology-monitor-2023-marktanalyse-quantencomputer-quantenkommunikation-quantensensorik
[6] https://doi.org/10.3390/challe6010117

List of publications

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 June 2024
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