SQA CONFERENCE

25-28 August 2022

Helsinki, Finland

SUPERCONDUCTING QUBITS AND ALGORITHMS CONFERENCE

CONFERENCE GUIDE

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ABOUT THE CONFERENCE

Superconducting Qubits and Algorithms (SQA) is a not-for-profit scientific conference with a focus on science, technology, and algorithms relevant for superconducting quantum computers. It is organized by IQM Quantum Computers in cooperation with the scientific community. Our goal is to make this an annual event and establish SQA as the leading scientific conference in this field.

SQA is an official satellite conference of **LT29**.

Contents

Preface

Welcome to the first **Superconducting Qubits and Algorithms (SQA) Conference** in Helsinki, Finland. This not-for-profit scientific conference focuses on science, technology, and algorithms relevant for superconducting qubits. This two-and-a-half-day conference is packed with interesting talks, great posters, an exhibition, and will offer plenty of networking opportunities.

The conference is organized by IQM Quantum Computers, a European company building superconducting quantum computers, in cooperation with the scientific community. We are happy to welcome over 270 participants on-site and even more online, and we hope you will have a stimulating and technically rewarding experience.

However, this event would not have been possible without the great support of our scientific community around superconducting quantum computing. Therefore, we would like to thank you, whether you contributed by sponsoring the event, participating in the scientific committee or advisory board, submitting an abstract, presenting your work, or attending as a guest. We would also like to thank the members of the organizing committee and volunteers for their valuable support.

It feels great to be part of this incredible community and we wish you all an enjoyable scientific gathering in Helsinki. Do not miss the opportunity to explore this beautiful city through the tours we have planned.

We look forward to seeing all of you at this unique conference.

Mikko Möttönen (Conference Chair)
Stefan Seegerer (Member of the Organizing Committee)

IMAGE: SUPERCONDUCTING QUANTUM COMPUTER FROM IQM QUANTUM LAB IN ESPOO, FINLAND.

Details

The conference is held from **25–28 August 2022** in Helsinki, Finland. We are excited to welcome over 270 researchers and experts from the field of superconducting qubits and algorithms to Helsinki.

The conference themes include the following:

- Quantum error correction and mitigation
- High-fidelity elementary operations: gates, readout, reset
- Non-computing applications of superconducting qubits
- Unconventional qubits
- Algorithms and applications
- Benchmarking and enabling software
- Design and modeling
- Millikelvin electronics and other supporting technologies
- Fabrication and materials

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Conference Program

The event is a scientific conference structured around scientific talks and poster sessions. The conference program is outlined as follows (all times in EEST):

THURSDAY, 25 AUGUST

16:00	Registration opens
17:00	Opening and Keynote by **Pedram Roushan**
18:00	Welcome reception

FRIDAY, 26 AUGUST

09:00	Opening Day 2 and Keynote by **Andreas Wallraff**
09:40	Scientific session: *Quantum error correction and mitigation*
10:40	Coffee break
11:00	Scientific session: *Non-computing applications of superconducting qubits*
12:30	Lunch break - 1
13:15	Lunch break - 2
14:00	Scientific session (posters)
15:30	Coffee break
16:00	Keynote by **Vladimir Manucharyan**
16:40	Scientific session: *Unconventional qubits*
17:20	Scientific session: *IQM Quantum Computers*
18:10	Excursions (Helsinki Tour, Bluefors Facility Tour, or IQM Visit)

SATURDAY, 27 AUGUST

09:00	Opening Day 3 and Keynote by **Will Oliver**
09:40	Scientific session: *Fabrication and materials*
10:40	Coffee break
11:00	Scientific session: *High-fidelity elementary operations: gates, readout, reset*
12:30	Lunch break - 1
13:15	Lunch break - 2
14:00	Scientific session (posters)
15:30	Coffee break
16:00	Scientific session: *Algorithms and applications*
17:10	Scientific session: *Millikelvin electronics and other supporting technologies*
19:00	Conference aperitivo and dinner

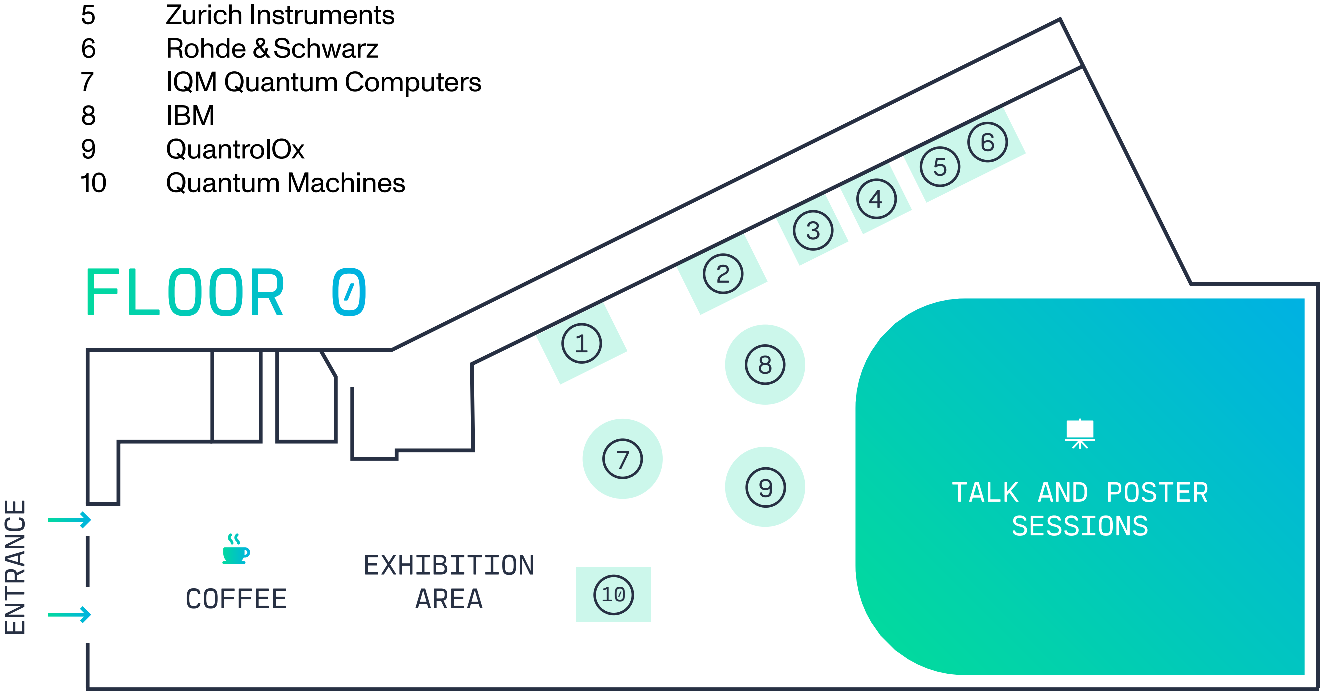
SUNDAY, 28 AUGUST

09:00	Scientific session: *Benchmarking and enabling software*
10:00	Coffee break
10:30	Scientific Session: *Design and modeling*
11:30	Closing
12:00	Lunch and Farewell

Exhibition

EXHIBITORS

1	Qblox
2	Bluefors
3	Intermodulation Products
4	QpiAI
5	Zurich Instruments
6	Rohde & Schwarz
7	IQM Quantum Computers
8	IBM
9	QuantrolOx
10	Quantum Machines



BLUEFORS

We are dedicated to build easy to operate one push button cool-down cryogen-free dilution refrigerator measurement systems. Our dedication and expertise will make sure that each final product is trouble free with a guaranteed long lifetime. We offer a variety of models of dilution refrigerator measurement systems and these models can be further equipped with a wide range of options, for example, experimental wiring, optical access, and magnet integration. Our systems can be customized to meet the requirements of each intended use by allowing the customer to get in direct contact with the scientists and engineers that design their system.

Bluefors – Cool for Progress.

QBLOX

With a dedicated team of scientists, engineers, and developers, we are pushing quantum technology to support scientists worldwide with our scalable qubit control and readout equipment from ultrastable DC to 18.5 GHz for academic and industrial quantum labs. The Qblox control stack combines unlevelled noise performance, low-latency arbitrary control flows and can be scaled up to 100s of qubits. Our company is based in the Netherlands as a spinoff of QuTech, which enables us to implement the latest scientific insights and take a position upfront in the worldwide race towards quantum advantage. Using the technology developed at QuTech as a springboard, the Qblox team has fundamentally reimagined the architecture of quantum control to create a single integrated control stack that provides all the functionality needed to manipulate and measure quantum computers. The Qblox team is interested in meeting experimental quantum physicists to learn about their applications and how Qblox could support their scaling needs.

QUANTUM MACHINES

Quantum Machines is a provider of full-stack control systems for quantum processors, end-to-end hardware, and software, made by physicists for physicists. QM's Quantum Orchestration Platform (QOP) redefines the limits of quantum control with a sleek single-box solution that replaces multiple general-purpose tools and offers unparalleled integration of quantum and classical resources. This new paradigm offers every component of the stack dedicated and optimized for real-time quantum control procedures. The QOP can run even the most complex sequences, from multi-qubit calibrations to quantum error correction, right out of the box. Quantum teams can now code sequences as easily as writing pseudo code and run them with the industry's lowest feedback latencies while scaling seamlessly into the 1000s of qubits.

QuantrolOx

QuantrolOx is a spinout from the University of Oxford's Ares Lab. QuantrolOx is building automated control software for quantum technologies based on machine learning to tune, stabilise, and optimise qubits. QuantrolOx's software is technology agnostic and applicable to all types of quantum technologies, however initially, the company is targeting solid-state qubits where the team has already demonstrated substantial practical benefits.

IBM **Quantum**

IBM Quantum is an industry-first initiative to build quantum systems for business and science applications.

ROHDE&SCHWARZ

Make ideas real

The Rohde & Schwarz technology group is among the trailblazers when it comes to paving the way for a safer and connected world with its leading solutions in test & measurement, technology systems, and networks & cybersecurity. Founded more than 85 years ago, the group is a reliable partner for industry and government customers around the globe.

Since Zurich Instruments joined Rohde & Schwarz, the range of solutions for Quantum Technology has extended from general purpose to system level.

Zurich Instruments

Zurich Instruments makes cutting-edge instrumentation for scientists and technologists in advanced laboratories who are passionate about phenomena that are notoriously difficult to measure. The company's hardware offering includes lock-in amplifiers, quantum computing control systems, impedance analyzers, and arbitrary waveform generators.

Zurich Instruments brings innovation to quantum control systems in the form of efficient workflows, tailored specifications and feature sets, and a high degree of reliability. The company's goal is to support quantum researchers and engineers by allowing them to focus on developing and scaling up quantum processors and other elements of the quantum stack while benefiting from the most advanced classical control electronics and software.

Google

Google's mission is to organize the world's information and make it universally accessible and useful, and we advance that mission every day in incredible new ways. Research across Google provides new ways of looking at old problems and helps transform how we all work and live, and we think the biggest impact comes when everyone in the world can access it. To that end, we use state-of-the-art computer science techniques to solve problems for our users, our customers and the world, making it easier for you to do things every day, whether it's searching for photos of people you love, breaking down language barriers, or helping you get things done with your own personal digital assistant.

Thursday, August 25

KEYNOTE

TOWARD DISCOVERING NOVEL PHYSICS WITH A NISQ PROCESSOR

Keynote by **Pedram Roushan** (pedramr@google.com), Google

In 2019, it was experimentally demonstrated that a quantum processor could perform certain computational tasks exponentially faster than a classical computer [1]. Going beyond this milestone, we seek to utilize these Noisy Intermediate Scale Quantum (NISQ) processors to study computationally intractable physics problems. The class of problems that seems near to us in this regard are quantum dynamics in interacting spin systems far away from equilibrium. I will provide an overview of our progress by describing several of our recent works [2-6]. The talk hopefully will provide a sense of what NISQ discoveries to anticipate and a time scale for them.

[1] Nature 574, 505–510 (2019)
[2] Science 374, 6574 (2021)
[3] Nature 601, 531–536 (2022)
[4] Science 374, 6572 (2021)
[5] arXiv: 2206.05254
[6] arXiv: 2204.11372

Quantum AI

Google Quantum AI is advancing the state of the art of quantum computing and developing the tools for researchers to operate beyond classical capabilities.

Our research efforts aim to build an error-corrected quantum computer and to develop novel quantum algorithms while providing researchers open-source software like Cirq and qsim to develop and simulate novel quantum algorithms.

To learn more about Google Quantum AI, please visit quantumai.google.

Friday, August 26

KEYNOTE I

REALIZING QUANTUM ERROR CORRECTION IN THE SURFACE CODE*

Keynote by **Andreas Wallraff**
Department of Physics, ETH Zurich, Switzerland
www.qudev.ethz.ch

Superconducting electronic circuits are ideally suited for studying quantum physics and its applications. Since complex circuits containing hundreds or thousands of elements can be designed, fabricated, and operated with relative ease, they are one of the prime contenders for realizing quantum computers. Currently, both academic and industrial labs vigorously pursue the realization of universal fault-tolerant quantum computers. However, building systems which can address commercially relevant computational problems continues to require significant conceptual and technological progress. For fault-tolerant operation quantum computers must correct errors occurring due to unavoidable decoherence and limited control accuracy. Here, we demonstrate quantum error correction using the surface code, which is known for its exceptionally high tolerance to errors. Using 17 physical qubits in a superconducting circuit we encode quantum information in a distance-three logical qubit building up on our recent distance-two error detection experiments [1]. In an error correction cycle taking only 1.1 μs, we demonstrate the preservation of four cardinal states of the logical qubit. Repeatedly executing the cycle, we measure and decode both bit- and phase-flip error syndromes using a minimum-weight perfect-matching algorithm in an error-model-free approach and apply corrections in postprocessing. We find a low logical error probability of 3% per cycle [2]. The measured characteristics of our device agree well with a numerical model. Our demonstration of repeated, fast, and high-performance quantum error correction cycles, together with recent advances in ion traps, support our understanding that fault-tolerant quantum computation will be practically realizable.

[1] C. Kraglund Andersen et al., Nature Physics **16**, 875–880 (2020)
[2] S. Krinner, N. Lacroix et al., Nature **605**, 669–674 (2022)

*Work done in collaboration with Sebastian Krinner, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux, Christoph Hellings, Stefania Lazar, Francois Swiadek, Johannes Herrmann, Graham J. Norris, Christian Kraglund Andersen, Markus Müller, Alexandre Blais, Christopher Eichler, and Andreas Wallraff

Scientific session: Quantum error correction and mitigation

COHERENT ERROR MITIGATION AND DENSITY MATRIX EXPONENTIATION USING EMULATED QUANTUM MEASUREMENTS

Ami Greene (greenea@mit.edu), Massachusetts Institute of Technology

Density matrix exponentiation (DME) is a technique for using a control state $\hat{\rho}$ to enact the quantum operation $e^{i\hat{\rho}\theta}$ on a target system. It was first proposed in the context of quantum machine learning, but has since been shown to have broad applications in quantum metrology and computation. In this presentation, we describe our implementation of DME using two transmon superconducting qubits. Error mitigation is critical for running deep circuits such as DME, and reducing coherent errors is particularly important since infidelity grows linearly with incoherent errors but can grow quadratically with coherent errors. The first part of this talk describes an error mitigation technique for coherent errors called Quantum Measurement Emulation (QME) which was key for demonstrating DME. In the second part of the talk, we introduce the DME algorithm and benchmark our implementation.

Eli Levenson-Falk, elevenso@usc.edu, University of Southern California, USA Evangelos Vlachos, evlachos@usc.edu, University of Southern California, USA Haimeng Zhang, haimeng@usc.edu, University of Southern California, USA Darian Hartsell, dhartsel@usc.edu, University of Southern California, USA Sacha Greenfield, sgreenf@usc.edu, University of Southern California, USA Leigh Martin, culeigh@gmail.com, Harvard University, USA James Farmer, jtfarmer@usc.edu, University of Southern California, USA Tameem Albash, talbash@usc.edu, University of New Mexico, USA Jeffrey Marshall, jmarshall@usra.edu, NASA Quantum Artificial Intelligence Lab, USA	Engineering and harnessing noisy environments to preserve quantum process fidelity in superconducting qubits	Environmental noise is typically thought of as a limiting source of infidelity in quantum processes. However, carefully engineered noise can be used to preserve quantum process fidelity. Theoretical results have shown that an environment that implements so-called generalized Markovian noise can counteract Markovian decoherence processes [1]. We show simulations and experimental data using classical drives to emulate a generalized Markovian quantum environment, preserving coherence of a single qubit. We demonstrate correspondence between the classically-engineered and quantum environments, and quantify improvements in qubit coherence. In another approach, we demonstrate the suppression of photon shot noise dephasing through engineered dissipation. And we discuss a weak-measurement-feedback based approach to achieve high-fidelity entangled state preparation. Our results demonstrate a toolkit of flexible experimental techniques that may be used to preserve process fidelity and study open quantum systems effects in superconducting qubits. [1] Marshall et al., PRA 96 052113 (2017)

Petr Zapletal, petr.zapletal@fau.de, University of Erlangen-Nuremberg, Germany Nathan A. McMahon, nathan.mcmahon@fau.de, University of Erlangen-Nuremberg, Germany Michael J. Hartmann, michael.j.hartmann@fau.de, University of Erlangen-Nuremberg, Germany	Error-tolerant quantum convolutional neural networks for the recognition of symmetry-protected topological phases on noisy quantum computers	The development and application of quantum computers requires tools to evaluate noisy quantum data produced by quantum hardware. With increasing system size, standard characterization techniques using direct measurements and classical post-processing become prohibitively demanding because of large measurement counts and computational efforts. Quantum neural networks based on parametrized quantum circuits, measurements and feedforward can process large quantum data, to detect non-local quantum correlations with reduced measurement and computational efforts. Quantum convolutional neural networks (QCNNs) have been shown to efficiently measure characteristic signatures of symmetry-protected topological (SPT) order and to recognize SPT phases of exact (noise-free) ground states with a reduced sample complexity [1]. Here we construct QCNNs based on the multiscale entanglement renormalization ansatz that can recognize different SPT phases of generalized cluster-Ising Hamiltonians in the presence of incoherent errors, simulating the effects of decoherence under NISQ conditions. Using matrix product state simulations, we show that the QCNN output is robust against symmetry-preserving errors if the error channel is invertible. Moreover, the QCNNs tolerate symmetry-breaking errors below a threshold error probability in contrast to the QCNN designed in [1] and string order parameters (SOPs), which are significantly suppressed for any non-vanishing error probability. Even though the error tolerance is limited close to phase boundaries due to a diverging correlation length, the QCNNs can precisely determine critical values of Hamiltonian parameters. The exploitation of QCNNs as a characterization tool for NISQ devices crucially benefits from the error tolerance. In a complementary work [2], we have demonstrated that, due to the error tolerance, a QCNN realized on a 7-qubit superconducting quantum processor detects an SPT phase with a higher fidelity than the measurement of SOPs. To facilitate the implementation of QCNNs, we show how to shorten a class of logarithmic-depth QCNNs to a constant-depth quantum circuit and classical post-processing. The constant-depth quantum circuit reduces sample complexity exponentially with system size in comparison to the direct sampling of the QCNN output using local Pauli measurements. [1] I. Cong, S. Choi, and M. D. Lukin, Nat. Phys. 15, 1273 (2019) [2] J. Herrmann, S. M. Llima, A. Remm, P. Zapletal, et al., arXiv:2109.05909 (2021)

Scientific session: Non-computing applications of superconducting qubits

This session is supported by Zurich Instruments/Rohde & Schwarz.

DETECTION OF HIGH-FREQUENCY DEFECTS IN SUPERCONDUCTING QUBITS

L. V. Abdurakhimov[1], I. Mahboob[1], H. Toida[1], K. Kakuyanagi[1], Y. Matsuzaki[2], and S. Saito[1]

[1] NTT Basic Research Laboratories, NTT Corporation, Kanagawa 243-0198, Japan
[2] Research Center for Emerging Computing Technologies, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

Superconducting circuits are a well-established platforms to perform various quantum computing and quantum sensing applications. In both cases, improvement of the qubits coherence is one of the most important issues. It is well known that two level system (TLS) defects around a qubit are a big obstacle limiting the qubits coherence. Although TLS defects have been observed in various ways, it is difficult to identify the type of TLS defects. Here we have succeeded in identifying different types of coupling between a qubit and a TLS defect, that is coupling due to critical current fluctuations and coupling due to charge fluctuations. To observe this, we first prepared a capacitively shunted flux qubit [1] and successfully detected off-resonant high-frequency TLS defects using a spin-locking method [2]. We then distinguished the two types of coupling by measuring the spectrum of the TLS defects as a function of magnetic field applying to the qubit [3]. These results provide a new analytical method for TLS defects and contributes to improving the coherence of qubits.

This work was partially supported by JST CREST (JPMJCR1774) and JST Moonshot R&D (JPMJMS2067).

[1] L. V. Abdurakhimov, et al., Appl. Phys. Lett. 115, 262601 (2019).
[2] L. V. Abdurakhimov, et al., Phys. Rev. B 102, 100502(R) (2020).
[3] L. V. Abdurakhimov, et al., arXiv:2112.05391.

Shabir Barzanjeh, Shabir.barzanjeh@ucalgary.ca, University of Calgary Canada	Microwave entanglement generation and its application in quantum sensing	The recent interest in mechanical quantum systems is driven not only by fundamental tests of quantum gravity but also by developing a new generation of hybrid quantum technologies. Here I confirm the long-standing prediction that a parametrically driven mechanical oscillator can entangle electromagnetic fields. We observe stationary emission of path-entangled microwave radiation from a micro-machined silicon nanostring oscillator, squeezing the joint field operators of two thermal modes by 3.40 (37) ~ dB below the vacuum level. This entanglement can be used to implement Quantum Illumination. Quantum illumination is a powerful sensing technique that employs entangled photons to boost the detection of low-reflectivity objects in environments with bright thermal noise. The promised advantage over classical strategies is particularly evident at low signal photon flux. This feature makes the protocol an ideal prototype for non-invasive biomedical scanning or

		low-power short-range radar detection. We experimentally demonstrated quantum illumination at microwave frequencies. We generate entangled fields using a Josephson parametric converter at millikelvin temperatures to illuminate at room-temperature an object at a distance of one meter. These results are experimental proof-of-principle of bistatic radar setup.
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Scientific Session (Posters)

APPLICATIONS AND ALGORITHMS

Abhishek Agarwal National Physical Laboratory abhishek.agarwal@npl.co.uk Ivan Rungger National Physical Laboratory ivan.rungger@npl.co.uk	Quantum subspace expansion algorithm for Green's functions	Quantum embedding approaches for materials simulations, such as the dynamical mean-field theory (DMFT), provide corrections to first-principles calculations for strongly correlated electrons, which are poorly described at lower levels of theory. These embedding methods are computationally demanding on classical computing architectures and hence remain restricted to small systems, limiting the scope of their applicability. Quantum computers have the potential to overcome this limitation. We present a method to compute the Green's function in a continued fraction representation using a Krylov basis. We consider two methods to construct the Krylov basis. The first is based on the Krylov variational quantum algorithm (KVQA, arXiv:2105.13298), while the second method uses the quantum subspace Expansion for the Green's function (QSE-G) (submitted on Arxiv on May 2nd).
Luciano Pereira luciano.ivan@iff.csic.es Instituto de Física Fundamental IFF-CSIC, Spain Juan José Gracia Ripoll juanjose.garcia.ripoll@csic.es Instituto de Física Fundamental IFF-CSIC, Spain Tomás Ramos del Ríom t.ramos@csic.es Instituto de Física Fundamental IFF-CSIC, Spain	Parallel QND measurement tomography of multi-qubit quantum devices	Efficient characterization of QND measurements is an important ingredient towards certifying and improving the performance and scalability of quantum processors. We introduce the QND measurement tomography (QND-MT) [1] as a self-consistent reconstruction of the Choi operators for a general QND detector, describing the measurement process, its dynamics, relevant quantifiers —fidelity, QND-ness, destructiveness—, and sources of error. We study by numerical simulation the characterization and calibration of a dispersive measurement of a single superconducting qubit. We recently extended the QND-MT to a multiqubit quantum processor by a parallelized tomography that addresses single- and two-qubit measurements [2]. We demonstrate the efficient scaling of this protocol experimentally, fully characterizing a 7-qubit IBM-Q quantum processor for direct measurements and measurement-and-reset schemes. We also introduce quantification schemes that reveal the influence of cross-talk on the measurement outcomes. Our protocol identifies sources of errors that limit the performance of the device for repeated QND measurements and enables the systematic study of largely unexplored effects in superconducting qubit readout such as the strong driving regime for fast measurement, the leakage to higher qubit levels, and cross-talk. [1] Complete physical characterization of QND measurements via tomography, L. Pereira, J.J. García-Ripoll, T. Ramos, arXiv:2109.06616 [2] Parallel QND measurement tomography of multi-qubit quantum devices, L. Pereira, J.J. García-Ripoll, T. Ramos, arXiv:2204.10336
Albert Solana, albert.solana@ qilimanjaro.tech, Qilimanjaro, Spain	Qibo: the open source quantum OS	We are currently facing a continuous evolution of the technology involved in the quantum computing industry, and specially inside a lab, which makes it very challenging to co-design algorithms that take advantage and test at the same time the latest devices and quantum chips manufactured. For solving it, Qilimanjaro is presenting Qibo: the open source operating system for quantum hardware (quantum programming, simulation, control and remote access), as a joint collaboration

		from Technology Innovation Institute from Abu Dhabi, the Centre of Quantum Technologies from Singapore, Barcelona Supercomputing Centre from Barcelona, and Qilimanjaro Quantum Tech, also from Barcelona. We will present the four layers of Qibo that make it completely scalable, hardware agnostic and ready to use for the end users (business users, researchers and for the experimentalists): - Qibo language: the definition of a quantum computing language for the construction of and execution of quantum algorithms based on either gate-based circuits or annealing models - Qibo laboratory: Set of libraries to control and calibrate the qubits, operate with the hardware lab devices and set the backends to execute the experiments on different quantum hardware technologies. - Qibo Quantum-as-a-Service: Qilimanjaro set of backend services to provide access to the Qilimanjaro Quantum Global Service platform. - Qibo Applications: Qilimanjaro web service for users to access their profile and code algorithms using Qilimanjaro algorithm portfolio and launch experiments to several backends: - Simulation: numpy backend, qibojit backend using just-in-time (JIT) custom kernel with numba, cupy, cuQuantum, and a connector to HPCs. - Qubit Simulation backend: Transmon and Flux-qubit simulator - Quantum Hardware backend References: - Efthymiou, S., Ramos-Calderer, S., Bravo-Prieto, C., Pérez-Salinas, A., García-Martín, D., Garcia-Saez, A., ... & Carrazza, S. (2021). Qibo: a framework for quantum simulation with hardware acceleration. Quantum Science and Technology, 7(1), 015018 - Efthymiou, S., Lazzarin, M., Pasquale, A., & Carrazza, S. (2022). Quantum simulation with just-in-time compilation. arXiv preprint arXiv:2203.08826. - Canivell, V., Forn-Díaz, P., Garcia-Saez, A. et al. Startup Qilimanjaro—towards a European full-stack coherent quantum annealer platform. EPJ Quantum Technol. 8, 6 (2021). https://doi.org/10.1140/epjqt/s40507-021-00094-y
Amit Devra, amit.devra@tum.de, Technical University of Munich, Germany Niklas J Glaser, niklas.glaser@tum.de, Walther-Meißner-Institut, Munich, Germany Dennis Huber, dennis.huber@tum.de, Technical University of Munich, Germany	Wigner State and Process Tomography on Near-Term Quantum Devices	With the growing interest and rapid development in near-term quantum devices, the migration of theoretical and experimental approaches from existing devices to near-term quantum devices is imperative. We present an experimental scanning-based tomography approach in the context of finite-dimensional Wigner representations. These representations characterize and visualize quantum operators such as density matrices, processes, etc. using shapes assembled from linear combinations of spherical harmonics [1]. The shapes can be recovered experimentally by measuring the expectation values of rotated axial tensor operators [2]. Here, we reformulate the theory

Steffen J Glaser, glaser@tum.de, Technical University of Munich, Germany		of Wigner state and process tomography for the case of a general-purpose pure state quantum computer. We, therefore, present the experimental approach for implementing this scanning-based tomography technique on the IBM quantum experience and showcase the results. We also show the methodology for estimating the density and process matrices from the experimentally created droplet functions. References: [1] A. Garon, R. Zeier, and S.J.Glaser, Phys. Rev. A 91, 042122 (2015). [2] D. Leiner, R. Zeier, and S. J. Glaser, Phys. Rev. A 96, 063413 (2017). [3] A. Devra, N. J. Glaser, D. Huber, S. J. Glaser, Wigner State and Process Tomography on Near-Term Quantum Device (in preparation).
Ljubomir Budinski, ljubomir.budinski@quanscient.com, Quanscient, Finland Ossi Niemimäki, ossi.niemimaki@quanscient.com, Quanscient, Finland Valtteri Lahtinen, valtteri.lahtinen@quanscient.com, Quanscient, Finland	Quantum algorithms for the lattice Boltzmann method in computational physics: Towards NISQ era implementations	One of the major challenges in computational physics today is to reduce the simulation time on one hand and to provide more detailed models in terms of grid resolution and number of unknown variables on the other. In this talk, we present novel quantum algorithms for the numerical solution of computational problems in physics. Particularly, we propose quantum algorithms for solving transport processes [1] and the Navier-Stokes equations [2], based on the lattice Boltzmann method (LBM), and discuss the possibilities to extend the algorithms to other fields. To implement the algorithms, we utilize IBM's quantum computing software development framework Qiskit. We compare the results with an analytical solution and with results obtained utilizing a corresponding classical code, obtaining excellent agreement. The computational complexity for both algorithms and the full preservation of the computational structure of the classical LBM demonstrate a high potential for gaining a quantum speedup with quantum LBM. Finally, we consider the possibilities and guidelines for implementing our algorithms on superconducting noisy intermediate-scale quantum (NISQ) devices. [1] Budinski, Lj. Quantum algorithm for the advection–diffusion equation simulated with the lattice Boltzmann method. Quantum Inf Process 20, 57 (2021). [2] Budinski, Lj. Quantum algorithm for the Navier–Stokes equations by using the streamfunction-vorticity formulation and the lattice Boltzmann method. Int. J. Quantum Inf. 20, 2 (2022).
Teiko Heinosaari, teiko.heinosaari@vtt.fi, VTT Technical Research Centre of Finland Ltd, Finland Daniel Reitzner, daniel.reitzner@vtt.fi, VTT Technical Research Centre of Finland Ltd, Finland Alessandro Toigo, alessandro.	Anticipative measurements in hybrid quantum-classical computation	We are considering a class of tasks where one is required to compute the value of a function $f : X \to Y$ on any given input from X. We don't concentrate on any specific problem, but rather on a method applicable to a variety of such task. We focus on a scheme where the computation has two parts: classical part and quantum part. The essential assumption in our investigation is that these computations are run in parallel, meaning that they take an input at the same time and they are carried out simultaneously. The final inference happens only after both parts have been completed. The motivation for this parallel computing

toigo@polimi.it, Politecnico di Milano, Italy		assumption is that the overall goal is to minimize the total computing time and the available quantum computer may be less efficient as required, hence a classical computer may provide a useful aid. The quantum computer operates with a d-level quantum system and this size limits its power. We assume that the quantum computing part is giving a probabilistic guess of the correct value $f(x)$. The classical part is able to rule out one or more wrong values. The final step is to combine the results from the two parts and make the final guess. The success of the full computation is characterized by the expectation value of having $y = f(x)$ when the input x is sampled uniformly from X. If the two parts are optimized independently, then the classical computation cannot help too much. An alternative method is based on the idea that we can optimize the quantum and classical steps together instead of treating them separately, even if they are run independently in parallel.This means that we adjust the measurement performed in the end of the quantum computation. The crux is take into account that there will be information in the form of wrong answers before we have to make the final decision, although we cannot know the specific wrong answers before we have to perform the measurement. We will call the measurement anticipative if it is optimized with respect to this later arriving additional information. Our main goal is to show that the anticipative method can be better than the standard method and is therefore a valuable tool in hybrid quantum-classical computation. We also elucidate the quantum nature of the anticipative method by demonstrating the required quantum resources for the achieved benefit and we explain how the anticipative method works in practice. This presentation is based on work in progress research.
Pablo Díez Valle, pablo.diez@csic.es, Institute of Fundamental Physics IFF-CSIC, Spain	Quantum Approximate Optimization Algorithm pseudo-Boltzmann states	In this poster we present the main results of [1]. The Quantum Approximate Optimization Algorithm (QAOA) was originally proposed as a hybrid variational algorithm suitable for solving combinatorial optimization problems on NISQ devices [2]. Even though it has been shown, from reasonable theoretic assumptions, that the shallowest version of the algorithm already engineers a quantum probability distribution that is classically hard to sample [3], this formal sampling advantage may or may not translate into a practical advantage in the optimization scenario. In our work [1], we study a simple, single-layer generalization of the QAOA ansatz, and we analyse its performance both from the optimization point of view - i.e. the probability to find the ground state - and also by understanding the types of states it prepares - i.e. the probability distributions that are hard to sample. With a new theoretical approach, our study reveals that the shallowest QAOA on universal Ising spin models creates pure, but thermal-like states with Gaussian perturbations. We find that these states resemble Boltzmann distributions with a temperature lower than can be efficiently simulated classically according to state-of-art

		techniques, such as Markov Chain Monte Carlo (MCMC) algorithms. Moreover, we connect the sampling advantage and the optimization properties, presenting that this low temperature also implies an advantage with respect to optimization as compared to classical stochastic algorithms, with an algebraic (Grover-like) enhancement of the ground state probability. References: [1] P. Díez-Valle et al., arxiv: 2201.03358 (2022). [2] E. Farhi et al., arxiv:1411.4028 (2014). [3] E. Farhi et al., arxiv:1602:07674 (2019).
Santosh Kumar Radha, santosh@agnostiq.ai, Agnostiq, Canada Casey Jao, casey@agnostiq.ai, Agnostiq, Canada	Generalized quantum similarity learning	The similarity between objects is significant in a broad range of areas. While similarity can be measured using off-the-shelf distance functions, they may fail to capture the inherent meaning of similarity, which tends to depend on the underlying data and task. Moreover, conventional distance functions limit the space of similarity measures to be symmetric and do not directly allow comparing objects from different spaces. In this talk, we will go over the recent proposal [1] of using quantum networks (named, GQSim) for learning task-dependent (a)symmetric similarity between data that need not have the same dimensionality. We will analyze the properties of such similarity function analytically (for a simple case) and numerically (for a complex case) and show that these similarity measures can extract salient features of the data. Finally, we will conclude by applying this technique for three relevant applications - Classification, Graph Completion, Generative modeling. arXiv preprint arXiv:2201.02310 (2022).
Alexander Geng, alexander.geng@itwm.fraunhofer.de, Fraunhofer Institute for Industrial Mathematics ITWM, Germany; Ali Moghiseh, ali.moghiseh@itwm.fraunhofer.de, Fraunhofer Institute for Industrial Mathematics ITWM, Germany; Claudia Redenbach, redenbach@mathematik.uni-kl.de, University of Kaiserslautern, Germany; Katja Schladitz, katja.schladitz@itwm.fraunhofer.de, Fraunhofer Institute for Industrial Mathematics ITWM, Germany	A hybrid quantum image edge detector for the NISQ era	Edges are image locations where the gray value intensity changes suddenly. They are among the most important features to understand and segment an image. Edge detection is a standard task in digital image processing, solved for example using filtering techniques. However, the amount of data to be processed grows rapidly and pushes even supercomputers to their limits. Quantum computing promises exponentially lower memory usage in terms of the number of qubits compared to the number of classical bits. In this paper, we propose a hybrid method for quantum edge detection. It is motivated by classical filtering and makes use of a quantum artificial neuron algorithm. We use three filter masks highlighting horizontal, vertical, and diagonal edges. For each of the three directions, we build a quantum circuit, measure them, and classically reassemble the partial results. We evaluate our method on superconducting quantum computers of the current noisy intermediate-scale quantum era. For that, we compare six variants of the method to reduce the number of circuits and thus the time required for the quantum edge detection. We process the three directions and several pixels in one circuit. Taking advantage of the scalability of our method, we can practically detect edges in images considerably larger than reached before. We report on a paper published on arxiv [1] and submitted to the Journal of Quantum Machine Intelligence.

		[1] Geng, Alexander, et al. "A hybrid quantum image edge detector for the NISQ era." arXiv preprint arXiv:2203.12072 (2022).
Jiří Tomčala, jiri.tomcala@vsb.cz, IT4Innovations, VSB - Technical University of Ostrava, 17. listopadu 2172/15, 708 33 Ostrava, Czech Republic	A Key Component of the Shor's Algorithm and Its Possible Quantum Implementations	A fundamental problem in factorization by Shor's algorithm [1] is the implementation of the modular exponentiation function. The period of this function is important for determining the individual factors, so its accurate implementation is for successful factorization critical. The imprecision of current quantum computers requires that any quantum circuits should be as simple as possible. Both in terms of the number of qubits used, the number of quantum gates and the depth of the quantum circuit. Therefore, it is necessary to search for an optimal variant for the implementation of the above-mentioned modular exponentiation function. The standard method is to implement individual arithmetic functions [2] which can be combined to achieve the desired modular exponentiation function. This process, however, creates a very complex quantum circuit, so that its measured result (probability distribution) will be so skewed that it will not be possible to reliably obtain the period of sought. Another way is to create a special quantum circuit for one particular modular exponentiation function [3]. Such a circuit is of course simpler than the circuit created by the above universal implementation, but in practice it only makes sense for testing the functionality of the surrounding quantum circuit for period detection. A very interesting possibility for the implementation of arithmetic functions is to use the direct and inverse quantum Fourier transform [4]. For a quantum computer, these transformations are very easy operations, and this interesting feature can then be used to advantage in these various implementations. This contribution will explore these possible approaches and show their advantages and disadvantages through concrete examples. References: [1] Shor, P.W. Algorithms for quantum computation: discrete logarithms and factoring, Proceedings 35th Annual Symposium on Foundations of Computer Science, IEEE Comput. Soc. Press: 124–134 (1994). [2] Pavlidis, A. and Gizopoulos, D. Fast Quantum Modular Exponentiation Architecture for Shor's Factorization Algorithm, https://arxiv.org/abs/1207.0511 (2012). [3] Nielsen M.A. and Chuang I.L. Quantum Computation and Quantum Information: 10th Anniversary Edition, Cambridge University Press (2010). [4] Zalka, C. Fast versions of Shor's quantum factoring algorithm, https://arxiv.org/abs/quant-ph/9806084v1 (1998).

Haim Horowitz, haim@agnostiq.ai, Agnostiq, Canada Pooja Rao, pooja@agnostiq.ai, Agnostiq, Canada Santosh Kumar Radha, santosh@agnostiq.ai, Agnostiq, Canada	A quantum generating network for multi-dimensional time series	Synthetic data generation has proven to be a promising solution for addressing data availability issues in various domains. Even more challenging is the generation of synthetic time series data, where one has to preserve temporal dynamics, i.e., the generated time series must respect the original relationships between variables across time. Recently proposed techniques such as generative adversarial networks (GANs) and quantum-GANs lack the ability to attend to the time series specific temporal correlations adequately. In this talk (based on [1]), we will introduce a technique which exploits the ability of quantum computers to explore hard-to-classically simulate process space, to learn and model a given classical time series. We start by assuming that a given time series can be generated by a quantum process, after which we proceed to learn that quantum process using an uniquely defined parameterized ansatz. We then use the learned model to generate out-of-sample time series and show that it captures unique and complex features of the learned time series. arXiv preprint arXiv:2201.02310 (2022)
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Hermanni Heimonen, hermanni@meetiqm.com, IQM Quantum Computers, Finland	Co-Design quantum simulation of nanoscale NMR	Quantum computers have the potential to efficiently simulate the dynamics of nanoscale NMR systems. In this work we demonstrate that a noisy intermediate-scale quantum computer can be used to simulate and predict nanoscale NMR resonances. In order to minimize the required gate fidelities, we propose a superconducting application-specific Co-Design quantum processor that reduces the number of SWAP gates by over 90% for chips with more than 20 qubits. The processor consists of transmon qubits capacitively coupled via tunable couplers to a central co-planar waveguide resonator with a quantum circuit refrigerator (QCR) for fast resonator reset. The QCR implements the non-unitary quantum operations required to simulate nuclear hyperpolarization scenarios.
Arun Sehrawat arun.s@qpiai.tech QpiAI India Pvt Ltd, India Manjunath R. Venkatesh manjunath.r@qpiai.tech QpiAI India Pvt Ltd, India Nawaf Alampara nawaf.a@qpivolta.tech QpiVolta India Pvt Ltd, India Aswanth Krishnan ashwanth.krishnan@qpiai.tech	A variational quantum algorithm for sensor positions optimization for autonomous vehicles	Sensors form an integral part in the development of an autonomous vehicle. The main types of sensors used by automotive manufacturers include cameras, radars, ultrasound, and lidars. Each sensor type is mainly categorized by the coverage provided by the sensor at a particular position, orientation and cost[1]. The reliable data that needs to be collected in the vicinity of the car requires a combined (fusion) data from such sensors and an onboard computer that enables decision-making based on the sensor fusion dataset. Furthermore, the specific positioning of these sensors plays an important role in accurately determining and avoiding blind spots, and preventing collisions with oncoming obstacles. Thus, there is a need for developing an optimized solution for positioning the sensors in the autonomous vehicle formulated as sensor position optimization problem (SPOP), in order to obtain a sensor configuration for maximum possible coverage at minimum cost[1]. Variational quantum algorithms (VQA) have many real-world applications [2]. Our VQAs are based on finding the minimum energy eigenstate (that represents an optimal solution of the

QpiAI India Pvt Ltd, India Lakshya Priyadarshi, lakshya.priyadarshi@qpiai.tech, QpiAI India Pvt Ltd, India Amlan Mukherjee, amlan.m@qpiai.tech, QpiAI India Pvt Ltd, India Nagendra Nagaraja, nagendra.nagaraja@qpiai.tech, QpiAI India Pvt Ltd, India		SPOP) of a Hamiltonian associated with the SPOP. After each iteration, we get a better variational state that provides lower energy, and thus gives a better sensor configuration. In the present work, we provide a mathematical formulation, quantum and quantum-inspired variational algorithms for optimizing the positions of sensors in an autonomous vehicle. We present the performance of our VQA for an instance having 3 sensor types placed at 4 positions on the body of the vehicle using 12 qubits to obtain a sensor configuration providing maximum coverage within the region of interest at minimum cost. The global minimum obtained with our VQA overlap with the global minimum acquired from the exact diagonalization of the Hamiltonian thus providing optimal sensor configuration solution for the SPOP. Furthermore, we investigate the average performance of our algorithms with respect to increasing the number of sensor positions on the body of the car and computed with up to 50 qubits (and 40000 binary variables with our quantum-inspired algorithm). References: [1] Sensor position optimisation, BMW Quantum Computing Challenge. http://crowd-innovation.bmwgroup.com/ [2] J. R. McClean, J. Romero, R. Babbush, and A. AspuruGuzik, The theory of variational hybrid quantum-classical algorithms, New J. Phys. 18, 023023 (2016).
Matti Raasakka matti.raasakka@aalto.fi Aalto University, Finland	Generating approximate state preparation circuits for a noisy quantum computer with a genetic algorithm	Genetic algorithms have recently been shown to provide a versatile method for automated quantum circuit design, useful for many applications (see, e.g., [1]). We apply automated quantum circuit design via genetic algorithms for the task of state preparation on a noisy quantum computer. State preparation on a noisy machine must balance between the circuit length and accuracy: Too long a circuit introduces too many errors, but too short a circuit cannot approximate the target state well enough. We show that multi-objective genetic algorithms are capable of finding near-optimal trade-offs between circuit length / CNOT count and noise-free fidelity for state preparation, improving on the state-of-the-art method by Araujo et al. [2]. Our results show that genetic algorithms provide a useful way to generate quantum circuits for noisy state preparation. The method may be useful for applications, such as quantum error correction, where the same state must be prepared on a quantum computer many times over. References: [1] U. Las Heras, U. Alvarez-Rodriguez, E. Solano, and M. Sanz, Phys. Rev. Lett. 116, 230504 (2016), arXiv:1512.00674 [2] I.F. Araujo, C. Blanck, A.J. da Silva, arXiv:2111.03132
Dor Israeli, dor@quantum-machines.co, Quantum Machines	Fullstack Quantum Compilation and Control Architecture: Mind the Pulse Gap	The quantum computing ecosystem has grown substantially in terms of accessible cloud solutions, quantum programming languages, and different open source and proprietary tools. The physics and engineering effort is also rapidly advancing with new technologies and ideas being put forth on a daily basis, from error correction algorithms to qRAM, and many more. Hence, it becomes increasingly important to bridge the gap between the various end-user interfaces and the many different types of QPUs, while aligning algorithms and SW/HW constraints.

		In this poster, we discuss quantum compilation, the process in which the high-level quantum programming language is optimized and transformed into low-level instructions, focusing on compilation from logic gate level (e.g. OpenQASM) into QUA, our pulse programming language. Additionally, we dive into the software and hardware architectures, with their advantages and bottlenecks, NISQ variational algorithms and considerations about the communication between classical and quantum resources. We conclude by discussing a unified framework for controlling quantum processors and how the compilation and control architecture support the hybrid quantum-classical operations required to realize its full potential, in NISQ algorithms like VQE and QAOA.

FABRICATION

Jian Ma, jian.ma@aalto.fi, Aalto University, Finland Timm Mörstedt, timm.morstedt@aalto.fi, Aalto University, Finland Sah Aashish, aashish.sah@aalto.fi, Aalto University, Finland Mikko Möttönen, mikko.mottonen@aalto.fi, IQM Quantum Computers; Aalto University, Finland	Remove argon milling damage by simplified bandage technique	Argon milling damage on silicon substrate is an important decoherence source of superconducting qubits. Bandage technique is a good solution to this problem, the original bandage technique uses two-steps electron beam lithography (EBL) to make josephson junction and bandage layer separately [1]. Recently there are some ideas to use 1-step EBL to simultaneously pattern Josephson junctions and bandage layers to simplify the fabrication of superconducting qubits [2,3 Here, we present a new method for fabricating josephson junction and bandage layers using one-step EBL. Unlike the one-step Dolan bridge bandage technique, our junction size is not affected by the roughness of the bridge edge, so we can have better control over junction size. Unlike one step Manhattan bandage technique, we only use vertical argon milling in our method. To validate our idea, we fabricate the device, measure the qubit lifetime and junction resistance distribution. References: [1] Dunsworth, A., et al. "Characterization and reduction of capacitive loss induced by sub-micron Josephson junction fabrication in superconducting qubits." Applied Physics Letters 111.2 (2017): 022601. [2] Osman, A., et al. "Simplified Josephson-junction fabrication process for reproducibly high-performance superconducting qubits." Applied Physics Letters 118.6 (2021): 064002. [3] Bilmes, Alexander, et al. "In-situ bandaged Josephson junctions for superconducting quantum processors." Superconductor Science and Technology 34.12 (2021): 125011.

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QUANTUM MACHINES

HIGH-FIDELITY ELEMENTARY OPERATIONS: GATES, READOUT, RESET

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Gerwin Koolstra, gkoolstra@lbl.gov, Lawrence Berkeley National Lab Karthik Siva, karthik_siva@berkeley.edu, University of California Berkeley William Livingston, wlivingston@berkeley.edu, University of California Berkeley John Steinmetz, jsteinm3@ur.rochester.edu, University of Rochester Debmalya Das, ddas7@ur.rochester.edu, University of Rochester Larry Chen, larrychen@	Diagnosing quantum gates in a superconducting quantum processor using continuous measurements	High-fidelity quantum gates are essential for successful execution of quantum algorithms. Typically, single and two qubit gates are characterized with techniques such as randomized benchmarking or gate set tomography [1], which treat gates as discrete operations acting on a quantum state. Such methods have been widely adopted, but give little insight in the qubit dynamics during the gate, which may differ from the expected evolution due to crosstalk or leakage. In this talk, we use two parametrically coupled transmon qubits to demonstrate a new gate diagnosis technique based on continuous measurements [2]. Using only knowledge of the quantum state before the gate and continuous measurement strength, our method fits the averaged continuous measurement signal to a Hamiltonian model to diagnose arbitrary pulse shapes with nano-second time resolution. First, we use calibrated single qubit gates to benchmark the method, and show that we can reconstruct the expected pulse amplitude and phase with high fidelity. We show reconstruction for various imperfect pulse shapes, and characterize the breakdown of the method for very short pulses, which is related to entangling dynamics of the qubit-resonator system [3]. Finally, we apply our method to iSWAP-like entangling gates, and visualize two-qubit Pauli operators with high time resolution. These results give a unique insight into the qubit dynamics during gates and can be used to extract transfer functions

berkeley.edu, University of California Berkeley Christian Juenger, cjuenger@lbl.gov, Lawrence Berkeley National Lab Noah Stevenson, noah.stevenson@berkeley.edu, University of California Berkeley David I. Santiago, david.i.santiago@lbl.gov, Lawrence Berkeley National Lab Andrew N. Jordan, jordan@chapman.edu, Chapman University Irfan Siddiqi, irfan_siddiqi@berkeley.edu, University of California Berkeley		of the microwave control lines and improve qubit gate dynamics. References: [1] K. Rudinger et al., PRX Quantum 2, 040338 (2021) [2] S. Hacohen-Gourgy & L. S. Martin, Advances in Physics: X Vol. 5 (2020) [3] G. Koolstra, et al., arXiv:2108.12023 (2021)
Yoshiki Sunada, sunada@qipe.t.u-tokyo.ac.jp, The University of Tokyo, Japan Shingo Kono, shingo.kono@epfl.ch, RIKEN Center for Quantum Computing, Japan Jesper Ilves, jesper.ilves@qipe.t.u-tokyo.ac.jp, The University of Tokyo, Japan Shuhei Tamate, shuhei.tamate@riken.jp, RIKEN Center for Quantum Computing, Japan Takanori Sugiyama, sugiyama-taka@fujitsu.com, The University of Tokyo, Japan Yutaka Tabuchi, yutaka.tabuchi@riken.jp, RIKEN Center for Quantum Computing, Japan Yasunobu Nakamura, yasunobu@ap.t.u-tokyo.ac.jp, The University of Tokyo & RIKEN Center for Quantum Computing, Japan	Fast Readout and Reset of a Superconducting Qubit Coupled to a Resonator with an Intrinsic Purcell Filter	Coupling a resonator to a superconducting qubit enables various operations on the qubit, including dispersive readout and unconditional reset [1]. The speed of these operations is limited by the external decay rate of the resonator. However, increasing the decay rate also increases the rate of qubit decay via the resonator, limiting the qubit lifetime. Here, we demonstrate that the resonator-mediated qubit decay can be suppressed by utilizing the distributed-element, multimode nature of the resonator [2]. We design this “intrinsic Purcell filter” by simulating how the resonator field deforms when it dresses the qubit. We measure the resonator-mediated qubit decay and show that it is suppressed by 2 orders of magnitude over a bandwidth of 600 MHz. We use this device to demonstrate a 40-ns readout with 99.1% fidelity and a 100-ns reset with residual excitation of less than 1.7%. We also present circuit-based design methods and preliminary measurements of filters with improved suppression and bandwidth. References: [1] P. Magnard et al., Phys. Rev. Lett. 121, 060502 (2018). [2] Y. Sunada et al., Phys. Rev. Applied 17, 044016 (2022).

Elisha Svetitsky, elisha@ quantum-machines-co, Quantum Machines Nir Halay, nir@quantum-machines-co, Quantum Machines Niv Drucker, niv@quantum-machines-co, Quantum Machines Yoav Romach, yoav@quantum-machines-co, Quantum Machines Daniel Louzon, daniel@quantum-machines-co, Quantum Machines Nissim Ofek, nissim@quantum-machines-co, Quantum Machines	High-Fidelity Qubit Initialization With Real-Time Control	Quantum computing requires the initialization of a many-qubit processor in its ground state with high fidelity between experiment repetitions. One approach for qubit reset involves measuring a qubit and applying a pi-pulse if it is measured in the excited state. The main drawback of this method is that the measurement fidelity limits the reset fidelity. Using a transmon qubit and the low-latency, real-time decision-making capabilities of a real-time control platform, we overcome this limitation with two novel protocols. We present a double-threshold, repeat-until-success method that is not limited by measurement fidelity or pi-pulse fidelity. While extremely effective on a few-qubit level, this method requires verification of every qubit initialization by a central processor and is therefore not suitable for a many-qubit system. We show how this problem is overcome with a dynamically adaptive discrimination threshold, implemented on our control platform for a high-fidelity qubit initialization method scalable to many-qubit systems.
Timm Fabian Mörstedt, timm. morstedt@aalto.fi, QCD Labs, QTF Centre of Excellence and InstituteQ, Department of Applied Physics, Aalto University, Finland Arto Viitanen, arto.viitanen@ aalto.fi, QCD Labs, QTF Centre of Excellence and InstituteQ, Department of Applied Physics, Aalto University, Finland Vasilii Vadimov, vasilii.vadimov@ aalto.fi, QCD Labs, QTF Centre of Excellence and InstituteQ, Department of Applied Physics, Aalto University, Finland Vasillii Sevriuk, vasilii@meetiqm. com, IQM Quantum Computers, Finland Matti Partanen, matti@meetiqm. com, IQM Quantum Computers, Finland Wei Liu, wei@meetiqm.com, IQM Quantum Computers, Finland	Fast Qubit Reset with a Quantum-Circuit Refrigerator	Superconducting qubits have emerged as powerful building blocks for a potential quantum computer. However, controlling superconducting qubits remains a challenge, particularly resetting the qubit into the ground state. Although the qubit naturally relaxes to its lowest-energy state, this process can take a significant amount of time and eventually inhibit fast computing. A promising solution is the voltage-tunable quantum-circuit refrigerator (QCR), a microcooler based on photon-assisted electron tunneling in a pair of NIS-junctions [1,2]. We now present the experimental realization of a QCR coupled to a transmon qubit as well as it's optimization for fast on-demand qubit reset. Since the lifetime of a quantum state is a key parameter of any qubit, we evaluate the influence of a QCR on characteristic qubit lifetimes T1 and T2 and present a coupling design that allows for both long qubit lifetime and effective cooling. Furthermore, we discuss the effects of pulsed or radio frequency operation of the QCR, which enables fast resetting of the qubit state in the nanosecond range [3]. We further compare this initialization protocol to a system of a QCR coupled to the qubit via a coplanar waveguide resonator, which, when off-resonant to the qubit, protects the qubit state from dissipation in the QCR off-state [4]. This circuit also allows for a reset protocol based on a parametric qubit drive pulse, which rapidly transfers the qubit excitation into the resonator [5], which is subsequently depleted through the QCR.

Mikko Möttönen, mikko.möttönen@aalto.fi, QCD Labs, QTF Centre of Excellence and InstituteQ, Department of Applied Physics, Aalto University, Finland		Altogether, this device not only improves qubit performance, but offers a versatile platform for studies on open quantum systems [6]. References: [1] K. Tan, M. Partanen, R. Lake et al. Nat Commun 8, 15189 (2017) [2] M. Silveri, H. Grabert, S. Masuda et al. Phys. Rev. B 96, 094524 (2017) [3] H. Hsu, M. Silveri, A. Gunyhó et al. Phys. Rev. B 101, 235422 (2020) [4] T. Yoshioka and J. S. Tsai. Appl. Phys. Lett. 119, 124003 (2021) [5] Y. Zhou, Z. Zhang, Z. Yin et al. Nat Commun 12, 5924 (2021) [6] T. Mörstedt, A. Viitanen, V. Vadimov et al. Ann Phys (in press)
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Weixi Zhang, weixi.zhang@npl.co.uk, National Physical Laboratory, UK Shuxiang Cao, shuxiang.cao@physics.ox.ac.uk, University of Oxford, UK	High-quality superconducting qutrits for quantum machine learning	Qutrits are three-level quantum systems that can be used for quantum computation. Compared to qubits, the advantage of increasing the dimension beyond two is that equivalent quantum circuits can potentially be built using fewer qutrits and gates, which can be of advantage for quantum machine learning (QML). We have built and benchmarked a qutrit based on a superconducting coaxmon, and find high fidelities and long

Deep Lall, deep.lall@npl.co.uk, National Physical Laboratory, UK Peter Leek, peter.leek@physics.ox.ac.uk, University of Oxford, UK Ivan Rungger, ivan.rungger@npl.co.uk, National Physical Laboratory, UK		coherence times. We use gate-set tomography (GST) to characterize the performance of quantum logical gates on the superconducting qutrits. In comparison to the process tomography protocol, GST can eliminate the measurement and state preparation (SPAM) error. We propose an efficient measurement basis to implement qutrit tomography with only 4 measurement axes. We compare the GST data with the qutrit Clifford randomized benchmarking results and find good agreement. We propose a practical application of the high-fidelity superconducting qutrit with newly developed parameterized qutrit circuits to perform QML classification. Our quantum machine learning approach is a special case of a general variational quantum algorithm (VQA). We first apply the quantum circuits on an emulator to perform classification on the Iris dataset and the palmer-penguins dataset. We show that the additional dimensions provided by qutrits allow to encode more data into qutrits than qubits. This allows qutrit classifiers to reach similar classification accuracy compared to qubit classifiers, but with fewer qutrits and fewer gates. If the number of used qutrits is equal to the number of qubits, the classification accuracy is significantly higher. Our runs on a superconducting qutrit achieve similar classification accuracies as predicted by the noiseless emulators. This firstly confirms the high quality of the superconducting qutrits, and secondly provides a proof of concept that the proposed QML algorithm can run on existing hardware. Our results show that using more than two states in the superconducting coaxmons may improve performance of quantum algorithms.
Vladimir Milchakov, vladimir_ph@protonmail.com, CNRS, France Olivier Buisson, olivier.buisson@neel.cnrs.fr, CNRS, France Cyril Mori, cyril.mori@neel.cnrs.fr, CNRS, France Luca Planat, luca.planat@neel.cnrs.fr, CNRS, France	A non-perturbative cross-Kerr coupling to achieve high fidelity quantum non-demolition superconducting qubit measurement	The most common technique of qubit readout in cQED relies on the transverse coupling between a qubit and a microwave cavity, leading to the Jaynes-Cummings Hamiltonian description and dispersive readout. However, despite important progresses, implementing fast high fidelity and Quantum Non Demolition (QND) measurement remains a major challenge. Indeed, inferring the qubit state is limited by the trade-off between speed and accuracy due to Purcell effect and unwanted transitions induced by readout photons in the cavity. To overcome this, we propose and experimentally demonstrate a new measurement scheme based on a transmon molecule inserted inside a 3D-cavity_[1,2]. The full system presents a transmon qubit mode coupled to a readout mode through an original non-perturbative cross-Kerr coupling, which is definitely different from Jaynes-Cummings Hamiltonian. This novel coupling is a key point of our readout scheme which imprint new properties in our qubit such as a protection from Purcell effect and a robust QNDness. A first generation of transmon molecule had presented

		promising results [2]. A novel circuit with optimized parameters such as the circuit geometry, the electric circuit parameters, the nanofabrication process leading to relaxation time of about 20us has recently developed. We will present the readout performance based on the cross-Kerr coupling of this second generation of transmon circuit with readout fidelity higher than 99%, QND estimation near 99%. We will also discuss the effect of readout photon number on the measurement and its QNDness. This work is supported by the French Agence Nationale de la Recherche (ANR-CE24-REQUIEM). References: [1] I. Diniz et al, Phys. Rev. A 87 033837 (2013). [2] R. Dassonneville et al, Phys. Rev. X 10, 011045 (2020).
Figen Yilmaz, f.yilmaz@tudelft.nl, QuTech, Delft University of Technology, Netherlands. Taryn Stefanski, t.v.stefanski@tudelft.nl, Quantum Engineering Centre for Doctoral Training, University of Bristol, England. Research carried out at TU Delft, Netherlands and supported by EPSRC CDT grant EP/SO23607/1.	Towards Optimized Fluxonium Qubit Operation	As the interest in fluxonium qubits as a promising contender for quantum computation continues to grow, we are looking to optimize readout times and measurement fidelity of these devices using a combination of flux and gate pulses. Through numerical simulations, we examine the dispersive shift landscape as a function of energy parameters and resulting fidelities at flux bias points detuned away from the sweet spot. We report a notable improvement in fidelity and readout time by exploiting a large dispersive shift. We also examine the simultaneous optimization of the fidelity and gate speed of a Pauli-X gate on a fluxonium qubit (1,2). These results will motivate our future experiments to be performed on a six qubit chip with independent charge, flux, and readout lines, designed in IBM Qiskit Metal (3). We developed our own library for design and EPR analysis of the fluxonium qubit with the inductive element (4). Bibliography: 1. Rol, M. A., Battistel, F., Malinowski, F. K., Bultink, C. C., Tarasinski, B. M., Vollmer, R., ... & DiCarlo, L. (2019). Fast, high-fidelity conditional-phase gate exploiting leakage interference in weakly anharmonic superconducting qubits. Physical review letters, 123(12), 120502. 2. Nguyen, L. B., Koolstra, G., Kim, Y., Morvan, A., Chistolini, T., Singh, S., ... & Singh, I. S. (2022). Scalable High-Performance Fluxonium Quantum Processor. arXiv preprint arXiv:2201.09374. 3. Zlatko K Minev, Thomas G McConkey, Jeremy Drysdale, Priti Shah, Dennis Wang, Marco Facchini, Grace Harper, John Blair, Helena Zhang, Nick Lanzillo, Sagarika Mukesh, Will Shanks, Chris Warren, and Jay M Gambetta. Qiskit Metal: An Open-Source Framework for Quantum Device Design & Analysis, 2021. 4. Zlatko K. Minev, Zaki Leghtas, Shantanu O. Mundhada, Lysander Christakis, Ioan M. Pop, and Michel H. Devoret. Energy-participation quantization of josephson circuits, 2021.

Gerhard Huber, gerhard.huber@wmi.badw.de, Walther-Meissner-Institut, Germany Federico Roy, federico.roy@wmi.badw.de, Walther-Meissner-Institut, Germany Stefan Filipp, stefan.filipp@wmi.badw.de, Walther-Meissner-Institut, Germany	Coupler-mediated unconditional reset of fixed-frequency superconducting qubits	Advances in superconducting qubit fabrication procedures have led to energy relaxation times regularly exceeding 100 μs [1]. Therefore, passive reset via relaxation has become unpractical, and an active reset protocol is required to achieve high repetition rate of quantum algorithms. Previous unconditional qubit reset schemes have relied on flux tunable qubits [2] or multiple transitions over higher qubit states [3],[4]. We extend the reset scheme proposed in [2] to fixed frequency transmon qubits with tunable couplers. The reset pulse consists of a single parametric flux pulse on the coupler to transfer qubit excitations to a quickly decaying resonator. Our protocol does not rely on additional control lines and can be implemented on current multi-qubit architectures. Further, it can be extended to architectures where a single coupler allows for reset of multiple qubits. We present preliminary numerical and experimental results for this reset protocol demonstrating its potential usefulness. [1] Alexander P. M. Place, New material platform for superconducting transmon qubits with coherence times exceeding 0.3 milliseconds, Nature Communications 1779 (2021) [2] Yu Zhou, Rapid and Unconditional Parametric Reset Protocol for Tunable Superconducting Qubits, Nature Communications 5924 (2021) [3] D.J. Egger, Pulsed Reset Protocol for Fixed-Frequency Superconducting Qubits, PhysRevApplied.10.044030 (2018) [4] P. Magnard, Fast and Unconditional All-Microwave Reset of a Superconducting Qubit, PRL 060502 (2018)
Max Werninghaus, max.werninghaus@wmi.badw.de, Walther-Meissner-Institute, Germany Stefan Filipp, stefan.filipp@wmi.badw.de, Walther-Meissner-Institute, Germany.	Efficient control of superconducting qubit processors	In the NISQ era of quantum computing, many quantum algorithms follow a hybrid approach to perform computations, in which a classical optimization algorithm performs iterative quantum measurements. The success of such algorithms is severely limited by the ability of the control hardware to initialize and execute the measurement sequences as fast as possible, to not exceed the runtime limits. Here, we present several improvements to the conventional programming of quantum control hardware, and demonstrate the benefits on a pulse optimization protocol of complex control pulses. The results of this demonstration have been published in [1], and the methods have since been further improved. [1] Werninghaus et al. npj Quantum Inf. 7 14 (2021)

MILLIKELVIN ELECTRONICS AND OTHER SUPPORTING TECHNOLOGIES

Heorhii Bohuslavskyi, heorhii.bohuslavskyi@vtt.fi , VTT, Finland Alberto Ronzani, alberto.ronzani@vtt.fi , VTT, Finland Arto Rantala, arto.rantala@vtt.fi , VTT, Finland Mika Prunnila, mika.prunnila@vtt.fi, VTT, Finland Janne Lehtinen, janne.lehtinen@vtt.fi, VTT, Finland	64-channel millikelvin-operational cryoCMOS multiplexer based on custom silicon-on-insulator technology	Tremendous progress in scaling up solid-state qubits and, in particular, superconducting qubits has been witnessed over the last few years [1]. However, in addition to developing a practically scalable qubit architecture, the optimization in terms of design, materials, and fabrication process at the scale of single or two-qubit systems yet remains one of the most important challenges. Thus, quick and parallelized cryogenic characterization of qubits is highly desirable. In this respect, cryogenic signal multiplexing is particularly useful not only to increase cryogenic characterization throughput but also to alleviate the wiring problem related to each qubit requiring at least one control line in large-scale quantum processors. To date, most of the cryoCMOS multiplexer (MUX) realizations for controlling quantum devices and qubits were designed using standard, commercial Si-bulk technologies [2,3,4] which typically have inferior cryogenic performance in terms of speed and power dissipation [5] as compared to silicon-on-insulator (SOI) technologies [6]. Here, we report on cryogenic operation down to 300mK of a 64-channel cryoCMOS MUX designed for DC operation with ultra-low power dissipation. To validate our custom SOI platform, suitable for quick prototyping of silicon qubits and cryoCMOS circuits using semi-industrial processing on 150mm wafers [7], we individually characterized 64 different test devices ranging from small nanowires to single and double quantum dots using the cryo-MUX in a single cooldown. Finally, using the same Si platform, we show preliminary results on a cryoCMOS microwave MUX based on RF switches. Due to flexibility in the design of Si circuits, fast prototyping, and excellent cryogenic performance at both single transistor and complex circuit levels, we expect our cryogenic cryoCMOS multiplexers to enable scalable characterization of silicon spin qubits, superconducting qubits and resonators, and other quantum devices. We would like to acknowledge funding from EU Horizon 2020 (grant no. 688539) and Business Finland through QuTI project (grant no. 40562) [1] F. Arute et al., Nature 574, 505–510 (2019) [2] S.J. Pauka et al., Phys. Rev. Applied 13, 054072 (2020) [3] A. Potonik et al., Quantum Sci. Technol. 7, 015004 (2022) [4] A. Ruffino et al., Nat. Electron. 5, 53–59 (2022) [5] J.C. Bardin et al., IEEE JSSC 54, 11 (2019) [6] H. Bohuslavskyi et al., IEEE TED 65, 9, (2018) [7] J. Duan et al., Appl. Phys. Lett. 118, 164002 (2021)
Joel Hätinen, joel.hatinen@vtt.fi, VTT Oy, Finland Lassi Lehtisyrjä, lassi.lehtisyrja@vtt.fi, VTT Oy, Finland	Superconducting multi-stage thermionic cooler for quantum technology	Cooling of quantum devices to their operating temperatures in mK range is traditionally achieved by bulky and expensive $^3He/^4He$ dilution refrigerators. Unlike our target device, these need to cool down an impractical amount of thermal mass and take a few days to reach their base temperature. We propose the concept of cascaded phonon-engineered thermionic coolers to cool from ^4He pulse tube compatible temperature level of 1.5 K to sub-100 mK range. This

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Hampus Renberg Nilsson, Hampus.Renberg.Nilsson@chalmers.se, Chalmers University of Technology, Sweden	Enabling high gain based on three-wave mixing for a Josephson travelling-wave parametric amplifier	The continuous three-mode model by Tien [1] predicts large gain for propagating waves in a nonlinear medium. We extend this model for a Josephson travelling-wave parametric amplifier (TWPA) operating in the three-wave mixing (3WM) regime in two ways, both with a multimode model capturing the complex behaviour for the TWPA in the small frequency limit, as well as with a discrete model describing a discrete chain of Josephson junctions at frequencies close to the spectral cutoff. We demonstrate that in both cases the gain is significantly reduced compared to the prediction of the continuous three-mode model, either due to a large amount of up-converted modes or too large phase mismatch. The multimode model is in quantitative agreement with experimental observations. To recover the large gain of the continuous three-mode model, we propose two solutions that both eliminate both up-conversion and the phase mismatch. This results in a high gain which grows exponentially with the length of the TWPA. [1] P. K. Tien, Parametric amplification and frequency mixing in propagating circuits, J. Appl. Phys. 29, 1347 (1958).
Robert Rehammar, robert@scalinq.com, SCALINQ, Sweden	A scalable packaging solution for quantum processors	Building superconducting quantum computers with a large number of qubits poses several challenges. One of them is how to reliably scale the microwave package to support a large number of microwave transmission lines.

Giovanna Tancredi, tancredi@chalmers.se, SCALINQ, Sweden Sandoko Kosen, sandoko@chalmers.se, SCALINQ, Sweden Lars Jonsson, larjons@chalmers.se, SCALINQ, Sweden		In this work, we present a newly-developed package for a superconductor-based quantum processing unit (QPU). To be able to efficiently connect up to some hundreds of microwave lines, a spring-loaded connector is used. High signal integrity is guaranteed by careful mechanical and electrical engineering of all structures.We discuss design choices of a microwave package prototype with 80 microwave lines and initial characterisation of basic performance metrics.
Jorden Senior, jorden.senior@ist.ac.at, IST Austria, Austria Soham Mukhopadhyay, soham.mukhopadhyay@ist.ac.at, IST Austria, Austria Diego A. Lancheros Naranjo diegoalejandro.lancherosnaranjo@ist.ac.at, IST Austria, Austria Andrew P. Higginbotham, andrew.higginbotham@ist.ac.at, IST Austria, Austria	Thermally activated superconductivity in a 1D Josephson Junction Array	Josephson-junction chains are important circuit elements for quantum-limited amplifiers, qubits, and other hybrid systems. They are also increasingly-explored as a model system for the quantum breakdown of superconductivity, as a way of understanding how superconductivity works in more complex and many-body systems. Recently, motivated by connections to quantum circuits that operate at microwave frequencies, the high- frequency response of Josephson-junction chains has been measured deep into the insulating phase, with the surprising observation that the high-frequency plasma modes are essentially unaffected by the superconductor- insulator quantum phase transition. Here I will present observations from our recent experiments probing the superconducting physics in such Josephson Junction chains, using a combination of both the microwave and quantum transport response measured across the superconductor-insulator transition. We map out the response of both the plasma modes and the differential resistance of the chain as a function of magnetic field, and temperature, observing the onset of thermally activated superconductivity, and the eventual breakdown of superconductivity in this system. Using these techniques, we also demonstrate a protocol to extract the energy scales corresponding to the (tunable) Josephson energy and the charging energies from the microwave and transport response.
Debopam Datta, ddatta201318@gmail.com, VTT Technical Research Centre of Finland, FI Visa Vesterinen, Visa.Vesterinen@vtt.fi, VTT Technical Research Centre of Finland, FI Nils Tiencken, Nils.Tiencken@	SNAIL based Josephson traveling wave parametric amplifier for cQED frequency range.	We present our latest experimental results on Josephson traveling wave parametric amplifiers (TWPAs) consisting of SNAIL elements, fabricated with Nb/Al-AlOx/Nb trilayer junction process [1]. A typical amplifier has demonstrated broadband gain in excess of 14 dB and maximum added noise of 2 photon [2] between 4 to 8 GHz. As a use case, we present measurements of superconducting resonators utilizing this TWPA in the RF chain to significantly reduce the measurement time without retuning the TWPA for different samples in multiple cooldown cycles.

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Friday, August 26

KEYNOTE II

RECENT PROGRESS WITH FLUXONIUMS

Keynote by **Vladimir Manucharyan**
School of Basic Science,
École Polytechnique Fédérale de Lausanne

In the first part of my talk I will introduce the classification of elemental superconducting qubits based on the nature of their macroscopic quantum variables, focusing on "fluxonium" and the more recently demonstrated "blochnium" qubits. In the second part I will overview the progress made by our group over the last few years with respect to fluxoniums, with the focus on the implementation of high-fidelity two-qubit gates.

Scientific session: Unconventional qubits

Eric Hyyppä, eric@meetiqm.com, IQM Quantum Computers, Finland (Presenter) Suman Kundu, suman.kundu@aalto.fi, Aalto University, Finland Chun Fai Chan, jeffrey@meetiqm.com, IQM Quantum Computers, Finland András Gunyhó, andras.gunyho@aalto.fi, Aalto University, Finland Juho Hotari, juho@meetiqm.com, IQM Quantum Computers, Finland David Janzso, david@meetiqm.com, IQM Quantum Computers, Finland Kristinn Juliusson, kristinn@meetiqm.com, IQM Quantum Computers, Finland Olavi Kiuru, olavi.kiuru00@gmail.com, Aalto University, Finland Janne Kotilahti, Janne@meetiqm.com, IQM Quantum Computers, Finland Alessandro Landra, alessandro@meetiqm.com, IQM Quantum Computers, Finland Wei Liu, wei@meetiqm.com, IQM Quantum Computers, Finland Fabian Marxer, Fabian@meetiqm.com, IQM Quantum Computers, Finland Akseli Mäkinen, akseli@meetiqm.com, IQM Quantum Computers, Finland Jean-Luc Orgiazzi, jean-luc@meetiqm.com, IQM Quantum Computers, Finland Mario Palma, mario.palma@meetiqm.com, IQM Quantum Computers, Finland Mykhailo Savytskyi, mykhailo@meetiqm.com, IQM Quantum Computers, Finland	Unimon qubit	The currently wide-spread superconducting qubit designs [1-5] have shown tremendous progress over the past two decades but they do not yet provide high enough performance to enable practical applications or efficient scaling of logical qubits owing to one or several of the following issues: sensitivity to charge or flux noise leading to decoherence, too weak non-linearity preventing fast operations, undesirably dense excitation spectrum, or complicated design vulnerable to parasitic capacitance. To this end, we present a novel superconducting qubit type, the unimon, which we proposed and demonstrated in our recent arxiv preprint [6]. The unimon qubit combines the desired properties of high anharmonicity, full insensitivity to dc charge noise, a flux-insensitive sweet spot, and a simple structure consisting of a single flux-biased Josephson junction in a gradiometric resonator. In this talk, we present a theoretical treatment of the unimon circuit as well as our first experimental results. Our experimental results demonstrate that the anharmonicity of the unimon qubit is greatly enhanced at the sweet-spot operation point in agreement with our theoretical models, which enables the implementation of 13-ns single-qubit gates with fidelities of 99.9% and 99.8% on two qubits with sweet-spot anharmonicities of 434 MHz and 744 MHz, respectively. Future improvements to the design, materials, and gate time may promote the unimon to break the 99.99% fidelity target for efficient quantum error correction and possible quantum advantage with noisy systems. References: [1] Koch, J. et al. Charge-insensitive qubit design derived from the Cooper pair box. Physical Review A 76, 042319 (2007). [2] Nguyen, L. B. et al. High-Coherence Fluxonium Qubit. Physical Review X 9, 041041 (2019). [3] Pechenezhskiy, I. V., Mencia, R. A., Nguyen, L. B., Lin, Y.-H. & Manucharyan, V. E. The superconducting quasicharge qubit. Nature 585, 368–371 (2020). [4] Gyenis, A. et al. Experimental Realization of a Protected Superconducting Circuit Derived from the $0-\pi$ Qubit. PRX Quantum 2, 010339 (2021). [5] Yan, F. et al. Engineering Framework for Optimizing Superconducting Qubit Designs. arXiv:2006.04130 [quant-ph] (2020). [6] Hyyppä, E., Kundu, S., Chan, C. F., Gunyhó, A., Hotari, J., Kiuru, O., ... & Möttönen, M. (2022). Unimon qubit. arXiv preprint arXiv:2203.05896. (Main paper)

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Dennis Rieger, dennis.rieger@kit.edu, Karlsruhe Institute of Technology, Germany Simon Günzler, simon.guenzler@kit.edu, Karlsruhe Institute of Technology, Germany Martin Spiecker, martin.spiecker@kit.edu, Karlsruhe Institute of Technology, Germany Patrick Paluch, patrick.paluch@kit.edu, Karlsruhe Institute of Technology, Germany Patrick Winkel, patrick.winkel@yale.edu, Yale University, United States Lothar Hahn, lothar.hahn@kit.edu, Karlsruhe Institute of Technology, Germany Judith K. Hohmann, judith.hohmann@ kit.edu, Karlsruhe Institute of Technology, Germany Andreas Bacher, andreas.bacher@kit.edu, Karlsruhe Institute of Technology, Germany Wolfgang Wernsdorfer, wolfgang.wernsdorfer@kit.edu, Karlsruhe Institute of Technology, Germany Ioan M. Pop, ioan.pop@kit.edu, Karlsruhe Institute of Technology, Germany	Gralmonium: Granular Aluminum Nano-Junction Fluxonium Qubit	Mesoscopic Josephson junctions (JJs), consisting of overlapping superconducting electrodes separated by a nanometer thin oxide layer, provide a precious source of nonlinearity for superconducting quantum circuits and are at the heart of state-of-the-art qubits, such as the transmon and fluxonium. Here, we show that in a fluxonium qubit the role of the JJ can also be played by a lithographically defined, self-structured granular aluminum (grAl) nano-junction: a superconductor-insulator-superconductor (SIS) JJ obtained in a single layer, zero-angle evaporation. The measured spectrum of the resulting qubit, which we nickname gralmonium, is indistinguishable from the one of a standard fluxonium qubit. Remarkably, the lack of a mesoscopic parallel plate capacitor gives rise to an intrinsically large grAl nano-junction charging energy in the range of $10-100\,\mathrm{GHz}$, comparable to its Josephson energy E_J. We measure average energy relaxation times of $T_1 = 10\,\mu\mathrm{s}$ and Hahn echo coherence times of $T_2^\mathrm{echo} = 9\,\mu\mathrm{s}$. The exponential sensitivity of the gralmonium to the E_J of the grAl nano-junction provides a highly susceptible detector. Indeed, we observe spontaneous jumps of the value of E_J on timescales from milliseconds to days, which offer a powerful diagnostics tool for microscopic defects in superconducting materials. Reference: arxiv:2202.01776

Scientific session: IQM Quantum Computers

PREPARATION OF MAXIMALLY ENTANGLED STATES WITH DIGITAL-ANALOG QUANTUM COMPUTING (DAQC)

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Digital-Analog Quantum Computing (DAQC) is a novel approach, which combines digital single qubit gates with analog multi-qubit blocks. The DAQC concept distinguishes between two variants, stepwise and banged DAQC, where the single qubit gates are placed in between analog blocks or applied simultaneously with the analog (entangling) evolution, respectively.

We have implemented the preparation protocol of a maximally entangled two-qubit state (Bell state) on IQM's 5-qubit QPU using both the stepwise and banged DAQC approach. The entangling evolution is induced by a flux-tunable coupler element, which allows for the accumulation of adiabatic conditional phase. We have identified the relevant sources of error for both DAQC protocols, and we reach similar fidelities as in the purely digital case when preparing a Bell state using either stepwise DAQC or banged DAQC.

The multi-qubit version of the implemented circuit allows us to create GHZ states by parallelizing several two-qubit interactions. For the minimum example, the case of three qubits, we have investigated infidelities arising due to the multi-qubit nature of the interaction, including parasitic and higher order couplings.

Johannes Heinsoo, johannes@meetiqm.com, IQM Quantum Computers, Finland	State of the art qubit readout and two-qubit gates at IQM	We present recent advances in readout and two-qubit gate operations of small quantum processors design and fabricated at IQM. The experimental data is obtained from 2- and 5-qubit devices designed to be compatible with large qubit lattices.

Saturday, August 27

KEYNOTE I

GIANT ARTIFICIAL ATOMS AND WAVEGUIDE QED

Keynote by **William D. Oliver**

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Models of light-matter interaction with natural atoms typically invoke the dipole approximation, wherein atoms are treated as point-like objects compared with the wavelength of their resonant driving fields. In this talk, we present a demonstration of "giant artificial atoms" realized with superconducting qubits in a waveguide QED architecture. The superconducting qubits couple to the waveguide at multiple, well-separated locations. In this configuration, the dipole approximation no longer holds, and the giant atom may quantum mechanically self-interfere. This system enables tunable qubit-waveguide couplings with large on-off ratios and a coupling spectrum that can be engineered by design. Multiple, interleaved qubits in this architecture can be switched between protected and emissive configurations, while retaining qubit-qubit interactions mediated by the waveguide. Using this architecture, we generate a Bell state with 94% fidelity, despite both qubits being strongly coupled to the waveguide. Time permitting, we also discuss recent advances in 3D integration of superconducting quantum circuits.

Scientific session: Fabrication and materials

QUBIT-COMPATIBLE 3D-INTEGRATION METHODS FOR LARGE QUANTUM PROCESSORS

Joonas Govenius, VTT Technical Research Centre of Finland

We fabricate and characterize superconducting through-silicon vias and electrodes suitable for superconducting quantum processors. We measure internal quality factors of a million for test resonators excited at single-photon levels, on chips with superconducting vias used to stitch ground planes on the front and back sides of the chips. This resonator performance is on par with the state of the art for silicon-based planar solutions, despite the presence of vias. Via stitching of ground planes is an important enabling technology for increasing the physical size of quantum processor chips, and is a first step toward more complex quantum devices with three-dimensional integration.

Mario Palma, mario.palma@meetiqm.com, IQM Quantum Computers, Finland Hasnain Ahmad, hasnain.ahmad@meetiqm.com, IQM Quantum Computers, Finland Manjunath Ramachandrappa, manjunath.rv2@gmail.com, IQM Quantum Computers, Finland Grégoire Coiffard, gregoire@meetiqm.com, IQM Quantum Computers, Finland Wei Liu, wei@meetiqm.com, IQM Quantum Computers, Finland Lily Yang, lily@meetiqm.com, IQM Quantum Computers, Finland Tianyi Li, tianyili@meetiqm.com, IQM Quantum Computers, Finland Jean-Luc Orgiazzi, jean-luc@meetiqm.com, IQM Quantum Computers, Finland Alessandro Landra, alessandro@meetiqm.com, IQM Quantum Computers, Finland	Electroplated indium bumps for scalable 3D integration of superconducting qubits.	Quantum computing to be fault tolerant, it is necessary to reach the number of qubits to at least thousands. To this end, is important to develop low-loss interconnects between the different components of the quantum processor. We report high qubit coherence made with flip-chip bonded electroplated indium bumps. The employed metal stack, bump and seed layer, exhibits electrically and cryogenically as good as the thermally evaporated indium bumps. In addition, the fabrication process is compatible with Josephson junction manufacturing process , keeping the average coherence time T1 ~ 45 µs. Electroplating technology allows growing bumps as tall as 20 µm, which reduces crosstalk and increases freedom in design choices, allowing for example stronger coupling between elements by reducing stray coupling to the ground plane.

Anton Komlev, anton@meetiqm.com IQM Quantum Computers, Finland Kunal Mitra, kunal@meetiqm.com IQM Quantum Computers, Finland Caspar Ockeloen-Korppi, caspar@meetiqm.com, IQM Quantum Computers, Finland Máté Jenei, mate@meetiqm.com IQM Quantum Computers, Finland	Electroplated indium bumps for scalable 3D integration of superconducting qubits.	
Anton Potocnik anton.potocnik@imec.be, imec, Belgium Jeroen Verjauw jeroen.verjauw@imec.be, imec, Belgium Rohith Acharya rohith.acharja@imec.be, imec, Belgium Jacques Van Damme jacques.vandamme@imec.be, imec, Belgium Tsvetan Ivanov tsvetan.ivanov@imec.be, imec, Belgium Daniel Perez Lozano daniel.perezlozano@imec.be, imec, Belgium Fahad A. Mohiyaddin, Fahd.Ayyalil.Mohiyaddin@imec.be, imec, Belgium Danny Wan, danny.wan@imec.be, imec, Belgium Julien Jussot ulien.jussot@imec.be, imec, Belgium Vadiraj A. Rao vadirajrao@imec.be, imec, Belgium Massimo Mongillo massimo.mongillo@imec.be, imec, Belgium Marc Heyns marc.heyns@imec.be, imec, Belgium Iuliana Radu iuliana.radu@imec.be, imec, Belgium Bogdan Govoreanu bogdan.govoreanu@imec.be, imec, Belgium	High-coherence foundry-compatible superconducting qubit platform	State-of-the-art superconducting qubits are almost exclusively fabricated using shadow evaporation and lift-off techniques. These techniques yield impurity-free Josephson junctions and capacitor structures with relatively clean surface interfaces. However, due to poor process control shadow evaporation and lift-off are not compatible with advanced lithographic process flows developed for scalable fabrication of integrated circuits. In this talk I will present IMEC's platform for scalable superconducting qubit fabrication based on foundry compatible thin film processing [1,2] and overlay Josephson junction fabrication [3]. Superconducting Transmon qubits with overlay junctions have energy relaxation times up to 100 us with a mean of T1 = 60-70 us. Based on the geometry and surface participation ratio scaling we can infer that the overlay junction does not limit qubit performance up to T1 ~ 100 us at 3 GHz. The presented work paves the way for scalable high-coherence superconducting qubit fabrication in both existing research institutions as well as advanced microelectronics foundry facilities. References: [1] Verjauw, et al., Phys. Rev. Applied. 16, 014018 (2021). [2] Mongillo, et al., IEDM (2022). [3] Verjauw, et al., arXiv 2202.10303 (2022).

Scientific session: High-fidelity elementary operations: gates, readout, reset

This session is supported by QBlox and Quantum Machines.

REDUCING ERRORS VIA DEVICE AND ALGORITHMIC IMPROVEMENTS

David McKay, IBM

In the quest to build large quantum devices, reducing noise is one of the major challenges since effective applications in quantum computing require noise-free outcomes. Therefore, to attack this challenge requires a dual pronged hardware and algorithmic approach. At the hardware level, we can develop better gates with lower errors. I will discuss one such gate – "Sizzle" – which is based on the use of microwave tones to tune the ZZ interaction between qubits [1]. At the algorithmic level, I will discuss our recent work on probabilistic error correction (PEC) [2,3]. By applying and averaging the results of multiple circuits we can mitigate the noise in observables. Therefore, there is a fundamental tradeoff between errors and the runtime of the circuit, i.e., more averaging leads to lower errors. Our approaches are linked; the scaling of PEC is a strong function of gate error, which we can make clear with our tunable ZZ interaction. With low enough errors there is a very favorable scaling of PEC, I will comment on where that error threshold lies and how it compares to our current devices.

[1] https://arxiv.org/abs/2106.00675
[2] Phys. Rev. Lett. 119, 180509 (2017)
[3] https://arxiv.org/abs/2201.09866

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		[1] Kokkoniemi, R., Govenius, J., Vesterinen, V. et al. Nanobolometer with ultralow noise equivalent power. Commun Phys 2, 124 (2019). https://doi.org/10.1038/s42005-019-0225-6 [2] Kokkoniemi, R., Girard, J.P., Hazra, D. et al. Bolometer operating at the threshold for circuit quantum electrodynamics. Nature 586, 47–51 (2020). https://doi.org/10.1038/s41586-020-2753-3
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Javier Cerrillo, javier.cerrillo@upct.es Universidad Politécnica de Cartagena, Spain	Andreev Spin Coherent Manipulation in Josephson Weak Links	As shown in our recent contribution to the demonstration of Andreev spin qubits [1], reliable control of auxiliary levels in quantum systems can be crucial to the development of new technologies. Andreev quasiparticles, hosted in Josephson weak links, feature high localization and built-in protection against charge noise. Nevertheless, lack of direct coupling between spin states prevented their establishment as a realistic alternative for solid-state quantum-computer architectures. Thorough analysis of their level structure and the implementation of techniques stemming from quantum optics introduced high-lying Andreev modes as intermediaries for the coherent control of spin [2]. The involvement of a third level in control protocols can break ground into the exploitation of previously inaccessible regimes in analogous platforms. NV-centers in nanodiamonds, which have been proposed as highly accurate nanoscale NMR devices, fail to respond to microwave control pulses at low local magnetic fields. With the design of an effective Raman coupling (ERC) [3], it is possible to circumvent this limitation. The ERC can be achieved by adjustment of the microwave frequency to that of the zero-field line and judicious timing of the pulses, such that the full potential of its spin-1 ground state is put to work. The technique has been recently implemented experimentally [4], paving the way for low-field detection of biomolecules. The ERC technique has a direct application in Andreev quasiparticles. In this context, the possibility of using single-tone instead of two-tone microwave pulses will further reduce the detrimental effect of the fourth level to the Raman triplet, thus increasing their gate fidelity. References: [1] Coherent manipulation of an Andreev spin qubit. M. Hays, V. Fatemi, D. Bouman, J. Cerrillo, et.al., Science 373, 430 (2021). [2] Spin Coherent Manipulation in Josephson Weak Links. J. Cerrillo, M. Hays, V. Fatemi, A. L. Yeyati, Phys. Rev. Res. 3, L022012 (2021). (Editor's Suggestion) [3] Low field nano-NMR via three-level system control. J. Cerrillo, S. Oviedo Casado, J. Prior, Phys. Rev. Lett. 126, 220402 (2021). [4] Zero- and low-field sensing with nitrogen-vacancy centers, P. J. Vetter, A. Marshall, G. T. Genov, T. F. Weiss, N. Striegler, E. F. Großmann, S. Oviedo-Casado, J. Cerrillo, J. Prior, P. Neumann, and F. Jelezko, Phys. Rev. Applied 17, 044028 (2022).

Scientific Session (Posters)

BENCHMARKING AND ENABLING SOFTWARE

Yuriy Makhlin, makhlin@itp.ac.ru, HSE Physics & Landau Institute	Partial randomized benchmarking of quantum operations	In randomized benchmarking of quantum logical gates, partial twirling can be used for simpler implementation, better scaling, and higher accuracy and reliability. For instance, for two-qubit gates, single-qubit twirling is easier to realize than full averaging [1,2]. We analyze such simplified, partial twirling and demonstrate that, unlike for the standard randomized benchmarking, the measured decay of fidelity is a linear combination of exponentials with different decay rates (3 for two qubits and single-bit twirling). The evolution with the sequence length is governed by an iteration matrix, whose spectrum gives the decay rates. For generic two-qubit gates one slowest exponential dominates and characterizes gate errors in three channels. Its decay rate is close, but different from that in the standard randomized benchmarking, and we find the leading correction. Using relations to the local invariants of two-qubit gates we identify all exceptional gates with several slow exponentials and analyze possibilities to extract their decay rates from the measured curves. Based on K.Dubovitskii, Yu.Makhlin; arxiv:2111.04192 [1] Chen, Y. et al. Qubit architecture with high coherence and fast tunable coupling. Phys. Rev. Lett. 113, 220502 (2014); [2] Casparis, L. et al. Gatemon benchmarking and two-qubit operations. Phys. Rev. Lett. 116, 150505 (2016)

NON-COMPUTING APPLICATIONS OF SUPERCONDUCTING QUBITS

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Bayan Karimi, bayan.karimi@aalto.fi, Aalto University and University of Helsinki, Finland Jukka Pekola, jukka.pekola@aalto.fi, Aalto University, School of Science, Finland	Calorimetric detection of microwave photons emitted by a superconducting qubit	We describe a qubit linearly coupled to a heat bath, either directly or via a cavity [1]. The main focus of the work is on calorimetric detection in a realistic circuit, specifically a superconducting qubit coupled to a resistor as an absorber. The bath in the theoretical model is formed of oscillators initially in the ground state with a distribution of energies and coupling strengths.

		We address quantitatively the question of separation of the qubit and bath by adding a cavity in between which by detuning allows one to adjust the decay rate into a convenient regime for detection purposes. We propose splitting a quantum to two uncoupled baths and performing a cross-correlation measurement of their temperatures to enhance the signal-to-noise ratio of the calorimeter. To justify our model, we present experimental results in our group on temperature noise of a corresponding nano-calorimeter and qubit-mediated heat transport [2-4]. [1] Jukka P. Pekola and Bayan Karimi, Ultrasensitive Calorimetric Detection of Single Photons from Qubit Decay, Phys. Rev. X 12, 011026 (2022). [2] Bayan Karimi, Fredrik Brange, Peter Samuelsson, and Jukka P. Pekola, Reaching the ultimate energy resolution of a quantum detector, Nat. Commun. 11, 367 (2020). [3] Alberto Ronzani, Bayan Karimi, Jorden Senior, Yu-Cheng Chang, Joonas T. Peltonen, ChiiDong Chen, and Jukka P. Pekola, Tunable photonic heat transport in a quantum heat valve, Nat. Phys. 14, 991 (2018). [4] Jukka P. Pekola and Bayan Karimi, Colloquium: Quantum heat transport in condensed matter systems, Rev. Mod. Phys. 93, 041001 (2021).
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Gianluca Aiello, gianluca.aiello@npl.co.uk, Université Paris-Saclay, France (Current affiliation: National Physical Laboratory, UK)	Quantum bath engineering of a high impedance microwave mode through quasiparticle tunneling	Quantum bath engineering is considered a promising route to perform certain tasks in quantum information processing, such as state stabilization, passive error correction, or fast qubit initialization. In the context of circuit QED, bath engineering usually results from the

		interplay between coherent evolution and dissipation in the form of single photon loss. In this talk, I will discuss a different approach [1], where engineered dissipation comes from the non-linear coupling of a microwave mode to a tunnel junction. Because the mode is sustained by a high kinetic inductance resonator made of granular Aluminum [2], its characteristic impedance is sufficiently large such that high order photon loss processes are allowed. As an example of engineered dissipation, I will focus on the regime where two photons loss processes dominate over single photon loss. The dynamics is then restricted by the quantum Zeno effect [3] to the subspace spanned by the zero and one photon Fock states turning the harmonic oscillator mode into a two-level system. Because of causality, the junction induces a shift in the energy levels of the resonator [4]. I will show that these Lamb shifts are Fock state dependent and in good agreement with the predictions of the Kramers-Kronig relations for single quantum states in a regime of highly non-linear bath coupling. References: [1] G. Aiello et al. "Quantum bath engineering of a high impedance microwave mode through quasiparticle tunneling". 2022. DOI: 10.48550/ARXIV.2204.08701. [2] N. Maleeva et al. "Circuit quantum electrodynamics of granular aluminum resonators". In: Nature Communications 9.1 (2018). DOI: 10.1038/s41467-018-06386-9. [3] P. Facchi and S. Pascazio. "Quantum Zeno dynamics: mathematical and physical aspects". In: J. Phys. A: Math. Theor. 41.49 (2008). DOI: 10 . 1088 / 1751 - 8113/41/49/493001. [4] M. Silveri et al. "Broadband Lamb shift in an engineered quantum system". In: Nature Physics 15.6 (2019). DOI: 10.1038/s41567-019-0449-0.
Amir Karamlou, karamlou@mit.edu, Massachusetts Institute of Technology, USA	Many-body quantum simulation using a superconducting quantum processor	Quantum processors hold great potential for simulating many-body quantum systems. However, experimental studies of such systems are challenging due to stringent coherence requirements and limitations in experimental control. We experimentally simulate quantum transport in the presence of varying degrees of localization in one-dimensional (1d) and two-dimensional (2d) tight-binding lattices using an array of superconducting qubits. We use this platform to study the time-reversibility of the quantum dynamics by performing a Loschmidt echo, and measure out-of-time-ordered correlators (OTOCs) to observe the propagation of quantum information. We observe that information localization can partially be overcome with the addition of more interacting particles, demonstrating that our techniques can be utilized to study analytically challenging problems such as many-body localization in 2d systems.

Olli Mansikkamäki, olli.mansikkamaki@oulu.fi, University of Oulu	Beyond hard-core bosons in transmon arrays	Bosonic many-body systems are notoriously difficult to simulate classically due to the exponential growth of the Hilbert space dimension with the size of the system. If we discard the usual two-level approximation, an array of capacitively coupled trans-mons realises the attractive Bose-Hubbard model. We pre-sent here two significant as-pects of the model: the ground state phase diagram[1] and an effective framework for de-scribing the dynamics in the phase most relevant to trans-mon arrays. We construct the phase dia-grams for fixed numbers of bosons with respect to disor-der and the ratio of the hop-ping frequency and the on-site interaction, or the cou-pling strength and the trans-mon anhamonicity, respec-tively. In the diagram, we find three ground state phases. When the hopping domi-nates, the ground state is su-perfluid. With strong disor-der, the ground state is spa-tially localised, i.e all the bos-ons are stacked onto a single site. Finally, when the an-harmonicity dominates, we find the W phase where the ground state is a superposition of localised states. This is the usual case with experimental realisations using transmons. Unitary dynamics in the W phase is characterised by the approximate conservation of the interaction energy. This results in the appearance of various kinds of many-body effects. For example, bosons initially stacked onto the same site behave as a single quasiparticle moving at a slower effective hopping fre-quency. The quasiparticles also experience effective off-site interactions with other quasiparticles, individual bos-ons, and the edges of the ar-rays. Using high-order degen-erate perturbation theory, we can effectively describe the dynamics within the subspac-es of approximately conserved interaction energy. The approximation signifi-cantly reduces dimensionality of the Hilbert space and is accurate within timescales relevant to a given subspace and the decoherence times of modern transmons. This al-lows us to explore the largely ignored Hilbert space of transmon arrays beyond the two-level model. [1] O. Mansikkamäki, S. Laine, and M. Silveri, Phases of the Disordered Bose-Hubbard Model with Attractive Inter-actions, Phys. Rev. B 103, L220202 (2021).
Pradeepkumar Nandakumar, uqpnanda@uq.edu.au, University of Queensland	Directional control of macroscopic photonic wavefunction for quantum state transfer in waveguide QED platform	Controlling the directionality of single-photons that can mediate interaction between quantum emitters is one of the key resource for quantum information processing tasks. In this work, we propose a 1D waveguide QED system that is engineered to support photonic states that decay unidirectionally either to the left or the right. Furthermore, the directionality can be controlled in-situ by tuning the frequency of the transmon qubit coupled to the waveguide. Such directional photonic states, dubbed as chiral edge states arises in 1D topological insulators. We will show that our model of the waveguide essentially resembles the so-called Rice-Mele model with a defect at the central site, that hosts both unidirectional and bidirectional edge states which can be independently excited by simply tuning the frequency of the

		qubit. We will also discuss the experimental progress towards realizing such a waveguide composed of an array of coupled cavities that can be built using conventional nano-fabrication techniques. The macroscopic nature of the photonic wavefunction and the in-situ directional control can be utilized for routing quantum information between distant qubits coupled to the waveguide and thereby enabling a deterministic directional quantum state transfer.
Vishal Ranjan, vishal.ranjan@npl.co.uk, NPL London, UK	Demonstration of spin echo silencing towards a quantum random access memory for superconducting processors	The ability to control microwave emission from a spin ensemble is a requirement of several quantum memory protocols. Here, we demonstrate such ability by using a superconducting resonator whose frequency can be rapidly tuned with a bias current. We store excitations in an ensemble of rare-earth-ion and suppress on-demand the echo emission (`echo silencing') by two methods: 1) detuning the resonator during the spin rephasing, and 2) subjecting spins to magnetic field gradients due to the bias current itself. We also show that spin coherence is preserved during silencing.
Sourav Majumder, sourav@iisc.ac.in, Indian Institute of Science (IISc) Bengaluru, India	Prospects of sideband cooling of a mechanical resonator using a transmon qubit in c-QED setup	Hybrid devices based on superconducting qubits have emerged as a promising platform for controlling the quantum state of macroscopic resonators. The nonlinearity added by qubit mode can be a valuable resource in this direction. Here we analyze mechanical mode coupled to a flux-tunable transmon in c-QED setup. The coupling between mechanical resonator and transmon qubit can be implemented by modulation of SQUID inductance, as demonstrated in the recent experiments. The qubit state readout can be performed in a traditional c-QED setup. In such a tri-partite system, we analyze the steady-state occupation of the mechanical mode when all three modes are dispersively coupled. We can achieve a large coupling between mechanical and qubit modes with a flux bias in the dispersive regime of cavity and qubit. We use quantum noise and Lindblad formalism to show that cooling mechanical mode to the ground state is possible. To address the issue of mechanical readout in the dispersive regime, we introduce a pump signal in cavity frequency. Due to cross-Kerr interaction, it allows recording of thermal motion. Our initial experimental results show the prospects of measurements of thermomechanical motion while maintaining a large coupling between qubit and mechanics. Our theoretical modeling suggests that such a cross-Kerr interaction can be a valuable resource for the quantum control of the mechanical resonator.
Ana Laura Gramajo, agramajo@ictp.it, International Centre for Theoretical Physics, Italy Daniel Domínguez, domingd@cab.cnea.gov.ar , Centro Atómico Bariloche and Instituto Balseiro, Argentina Maria José Sánchez, majo@cab.cnea.gov.ar , Centro Atómico Bariloche and Instituto Balseiro, Argentina	Non-equilibrium dynamics and efficient steady-state-entanglement generation in strongly driven coupled-qubits	We investigate the non-equilibrium dynamics of two-coupled qubits driven by strong harmonic external fields by employing the Flo-quet-Born-Markov master equation. We report an off-resonance three-level mecha-nism to optimize the genera-tion of steady-state entangle-ment [1]. The entanglement mechanism essentially con-sists of the excitation to a higher level through a non-resonant process based on Landau-Zener transitions, with the addition of the tun-ing of a fast-relaxation chan-nel to the desired final state. The mechanism does not re-quire the fine-tuning of spe-cific photon resonances [2]. We also find that by a proper design of the system parame-ters and the driving protocol, the two-qubit steady-state concurrence can attain values close to 1 in a wide range of driving amplitudes. Circuits of coupled small-gap supercon-ducting qubits, with control of the system-bath coupling, are possible candidates for the implementation of the entan-glement generation mecha-nism proposed here. References: [1] Phys. Rev. A 104, 032410 (2021). [2] Phys. Rev. A 98, 042337 (2018).

QUANTUM ERROR CORRECTION AND MITIGATION

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Tobias Haug, thaug@ic.ac.uk, Imperial College London, UK	Scalable measures of magic for quantum computers	Magic characterizes the degree of non-stabilizerness of quantum states. It is a crucial resource for realizing fault-tolerant quantum computers. Further, magic is a necessary condition to achieve quantum advantage. However, quantifying the magic of quantum computers beyond a few qubits has been a major challenge. Here, we introduce Bell magic to efficiently measure magic for any number of qubits [1]. Our method can be easily implemented in experiments together with a cost-free error mitigation scheme. We experimentally demonstrate the transition of classically simulable

		stabilizer states into intractable quantum states on the IonQ quantum computer. For applications, Bell magic distinguishes stabilizer and magical states with a low measurement cost. Further, variational quantum algorithms can maximize the magic of quantum states via the shift-rule. Our results pave the way to understand the non-classical power of quantum computers, quantum simulators and quantum many-body systems. [1] T. Haug, M.S. Kim, arXiv:2204.10061 (2022), https://doi.org/10.48550/arXiv.2204.10061
Konstantin Tiurev, konstantin.tiurev@gmail.com, HQS Quantum Simulations, Germany Joschka Roffe, Freie Universität Berlin, Germany Peter-Jan H. S. Derks, Freie Universität Berlin, Germany Jan-Michael Reiner, HQS Quantum Simulations, Germany	Correcting non-independent, non-identically distributed errors with surface codes	A common approach to studying the performance of quantum error correcting codes is to assume independent and identically distributed single-qubit errors. However, errors in experimental multiqubit devices are typically neither independent, nor identical across qubits. Here we develop and investigate the properties of topological surface codes adapted to a known noise structure. We show that the surface code locally tailored to single-qubit noise by Clifford deformations yields exponentially suppressed subthreshold failure rates. Furthermore, we study the behaviour of the tailored surface code under local two-qubit noise and show the importance of code degeneracy for correcting such noise. The proposed methods do not require additional overhead in terms of the number of qubit and use a standard matching decoder, hence come at no extra cost compared to the standard surface-code error correction.
Pranav S. Mundada, pranav.mundada@q-ctrl.com, Q-CTRL Inc, USA	Deterministic error-suppression enhanced execution of quantum circuit	Excitement about the promise of quantum computers is tempered by the reality that the hardware remains exceptionally fragile and error-prone, forming a bottleneck in the development of novel applications. In this talk, we will describe a pre-processing pipeline consisting of compilation, crosstalk mitigation, optimized gate replacement on any given quantum circuit along with a novel measurement error mitigation protocol in post-processing after the execution on the quantum device. We present autonomous two-qubit gate calibration using closed-loop calibration techniques and provide a protocol for simultaneous tune-up across the full device. We show a deterministic dynamical decoupling motif that mitigates ZZ crosstalk and qubit dephasing which is ubiquitous in superconducting devices. We also present a novel scalable measurement error mitigation scheme by combining the tensored mitigation and neural network techniques and validate its performance on a 16-qubit superconducting device. We demonstrate that combining all the above improvements lead to dramatic improvements on current NISQ devices. We observe over 1000X improvement in the success probability of both deterministic algorithms, such as QFT and BV, and hybrid algorithms such as QAOA and VQE.

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UNCONVENTIONAL QUBITS

Ilya Antonov, ilya.antonov.2013@live.rhul.ac.uk, Royal Holloway University of London, United Kingdom	Symmetric qubit designs	We propose devices that extend the CQPS qubit [1] and flux qubits [2] utilising the Josephson junction (JJ) and quantum phase slip junctions (QPSJ) respectively, which are dual non-linear elements operating on the transfer of Cooper pairs and flux quanta respectively. With the additional of symmetrical superconducting loops "mirroring" the devices about the central axis, we attempt to make the systems robust to global magnetic field fluctuations. The 'twin' flux qubit consists of a symmetrical pair of superconducting loops, with two Josephson junctions in each, joined by a common Josephson junction [3]. A change in global flux should result in opposing circulating currents on the peripheral branches, making it more robust to magnetic noise than a standard flux qubit. We perform a detailed analytical analysis of the double-loop system, revealing its properties and compare experimental results with numerical simulations. At half-flux quantum bias of both loops, the qubit is protected against global and local magnetic field fluctuations with much less sensitivity to the global field in the second order. The system selection rules allow even-odd transitions and prohibit transitions between even-even or odd-odd levels due to the symmetry of the device. The 'twin' CQPS qubit extends the qubit operating on the coherent transfer of flux quanta across a narrow constriction in a superconducting loop. QPSJ based qubits are beginning to see wider implementation as: hybrid structures [4], CQPS-based transistor [5], interference devices [6]. In these systems, Cooper pairs are not localised on islands, but flux quanta are localised to loops and tunnelling across this flux-matrix serves for interesting analysis. We fabricate and analyse the peculiar flux-tunneling matrix system of a symmetrical CQPS qubit and make attempts at capturing the essential dynamics to match experimental spectra. References: [1] "Superconducting nanowires as quantum phase-slip junctions", Nature Physics 2.3 (Feb. 2006) [2] "Coherent Quantum Dynamics of a Superconducting Flux Qubit", Science 299.5614 (Feb. 2003), [3] "Superconducting "twin" qubit", Physical Review B 102.11 (Sept. 2020) [4] "Hybrid rf SQUID qubit based on high kinetic inductance", Scientific Reports 8.1 (July 2018). [5] "Coulomb blockade due to quantum phase slips illustrated with devices", Physical Review B 83.17 (May 2011) [6] "Charge quantum interference device", Nature Physics 14.6 (Apr. 2018)

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		superimposed, phase-locked Bloch oscillations are predicted to show as current plateaus in the IV charac-teristic, the so called dual-Shapiro steps. In rf-SQUID qubits, the inductive shunt makes the device insensitive to charge noise, while flux-noise sup-pression can be reached for large values of the superinductance: larger impedance delocalizes the phase variable from the flux-qubit and fluxonium regimes all the way to the quasicharge regime [2]. More gener-ally, superinductors are also a key ingredient for novel and intrinsically protected superconducting qubits [3][4]. We present our progress in studying the physics of single ultra-small JJs in an ultra-high impedance envi-ronment. We rely on two different type of devices, i.e. current-biased JJs and loop-based superconducting qubits [5]. The high-impedance environments are realized using a diverse set of technologies ranging from resistive elements to tunable SQUIDs arrays and geometric superinductors [6]. [1] M. Watanabe et al., Phys. Rev. Lett. 86, 5120 (2001) [2] I. Pechenezhskiy et al., Nature 585 368 (2020) [3] A. Gyenis et al., PRX Quantum 2, 010339 (2021) [4] F. Hassani et al., arXiv:2202.13917v1 (2022) [5] M. Peruzzo et al., PRX Quantum 2, 040341(2021) [6] M. Peruzzo, A. Trioni et al., Phys. Rev. Applied 14, 044055 (2020)
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Lassi Lehtisyrjä, lassi.lehtisyrja@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Joel Hätinen, joel.hatinen@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Alberto Ronzani, alberto.ronzani@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Emma Mykkänen, emma.mykkanen@vtt.fi, VTT Technical	High transparency superconductor-insulator-semiconductor tunnel junctions for thermionic cooling of quantum devices	For superconducting tunnel junction based thermionic coolers, control of electric and thermal transport through material interfaces is crucial for efficient operation [1, 2]. We have fabricated high transparency superconductor-insulator-semiconductor (S-Sm) tunnel junctions (Fig. 1(a)), that enable very high cooling power per unit area and are of high quality, i.e., have low sub-gap leakage. These aspects are important for operation of practical phonon-blocked thermionic coolers [2]. We have fabricated junctions with two superconducting materials, aluminum and vanadium (Fig. 1(b)). The process can potentially be expanded to use a number of superconducting materials, such as niobium and titanium. The use of materials with different superconducting gaps can enable effective cooling even from higher bath temperatures, with the ultimate goal of fabricating a platform applicable for cooling of practical quantum devices.

Research Centre of Finland Ltd., Espoo, Finland Janne S. Lehtinen, janne.lehtinen@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Mika Prunnila, mika.prunnila@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland		In this communication, we will report on electronic and thermal properties of these S-Sm tunnel junctions. References: [1] A. Kemppinen et al. Cascaded superconducting junction refrigerators: Optimization and performance limits. Applied Physics Letters, 119(5):052603, 2021. [2] E. Mykkänen et al. Thermionic junction devices utilizing phonon blocking. Science Advances, 6(15):eaax9191, 2020.
Ville Iso-Kouvola, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Joel Hätinen, joel.hatinen@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Alberto Ronzani, alberto.ronzani@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Janne Lehtinen, janne.lehtinen@vtt.fi,VTT Technical Research Centre of Finland Ltd., Espoo, Finland Sophie Chevalliez, sophie.chevalliez@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland Mika Prunnila, mika.prunnila@vtt.fi, VTT Technical Research Centre of Finland Ltd., Espoo, Finland	Superconducting silicon patterned by focused gallium-ion beam	Superconducting silicon via localized gallium overdoping (Si:Ga) has been fabricated through implantation [1] and mask-less patterning by means of focused gallium-ion beam [2]. Direct patterning by FIB allows low effort, on demand fabrication of superconducting two-dimensional elements directly on a silicon layer, without the need of an additional lithography step and without the requirement of annealing after deep implant [3]. Previous work [2] has found out superconducting transition temperature of 7 K for gallium overdoped silicon with optimal ion beam dose. Our findings are in line with this result, and we supplement as well as advance the work. We present low temperature electrical characteristics of FIB patterned gallium overdoped silicon nanowires and thin films. Superconductor transition temperature and critical current values are measured on different geometries. References: [1] R. Skrotzki et al., Appl. Phys. Lett. 97, 192505 (2010). [2] R. Matsumoto et al., ACS Appl. Electron. Mater. 2, 677-682 (2020). [3] K. Sardashti et al., Appl. Phys. Lett. 118, 0783102 (2021).

DESIGN AND MODELLING

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Mikhail Perelshtein, michael.perelshtein@aalto.fi, Aalto University, Finland Kirill Petrovnin, kirill.petrovnin@aalto.fi, Aalto University, Finland Ilari Lilja, ilari.lilja@aalto.fi, Aalto University, Finland Visa Vesterinen, visa.vesterinen@vtt.fi, VTT, Finland Joonas Govenius, Joonas.Govenius@vtt.fi, VTT, Finland G. S. Paraoanu, sorin.paraoanu@aalto.fi, Aalto University, Finland Pertti Hakonen, pertti.hakonen@aalto.fi, Aalto University, Finland	Multipartite continuous-variable entanglement generation using Josephson metamaterials	Generation of quantum resources, most notably quantum entanglement, is an essential task for the new emerging industry employing quantum technologies. While entanglement in discrete variables represents the standard approach for quantum computing, continuous variable entanglement between microwave photons is a cornerstone for more robust quantum computing, sensing and communication schemes. We have developed a low-loss Josephson metamaterial comprising superconducting, non-linear, asymmetric inductive elements to generate frequency-entangled photons from vacuum fluctuations at a rate of 2 Giga entangled bits per second spanning over 4 GHz bandwidth. The device is operated as a travelling wave parametric amplifier under Kerr-relieving biasing conditions that allow us to generate microwave entanglement over previously inaccessible bandwidth. Furthermore, for the first time to our knowledge, we realize a single-mode squeezing in such devices: -3.1 dB below the zero-point level at half of the modulation frequency. As we demonstrated, the broadband features of the TWPA allow operation over a few gigahertz bandwidth, and in combination with multiple pumps, pave the way toward the generation of "frequency-

		-based" multimode entanglement. We propose a method for high-quality generation and control of entanglement between microwaves in multiple frequency ranges. Using the developed scheme, we generate on-demand tunable entangled 3-partite and 4-partite states in a lumped-element Josephson parametric amplifier [1]. Multimode schemes can be employed for various quantum applications, such as CV computing with cluster states, secure and robust communications, distributed quantum-limited sensing, and search for dark matter [2]. We envision that generated quantum resources offer enhanced prospects for quantum data processing using parametric microwave cavities [3]. References: [1] K. Petrovnin et al., arXiv:2203.09247 (2022) [2] M. Perelshtein, et al., arXiv:2111.06145 (2021) [3] T. Elo et al., Appl. Phys. Lett. 114, 152601 (2019)
Jared Cole, jared.cole@rmit.edu.au, RMIT University, Melbourne, Australia	Qubit materials: the challenges of computer modelling for quantum technology	Large-scale quantum computing requires extremely high precision qubits. This includes qubits that have long coherence times, can be accurately calibrated and are free from uncontrolled parameter drift. While superconducting qubits are one of the leading quantum computing technologies, they are still significant challenges in addressing these requirements for large-scale devices. Equivalent constraints have been addressed in conventional semiconductor electronics, often with the help of advanced computer simulation tools. Yet for quantum technology, we are facing entirely new difficulties in terms of the scale and precision required for design and simulation. Significant progress has been made in terms of automated circuit design and qubit control. However the underlying materials science is proving to be relatively difficult to simulate with the precision required for quantum computing applications. I will discuss what are some of the fundamental challenges in simulating materials for quantum technology, specifically those relevant to superconducting qubits. These include the difficulties of modelling defects in amorphous materials[1,2,3], the fabrication process for superconducting qubits[4] and the electric response of Josephson junctions[5]. In doing so I will also discuss our recent efforts in this area to develop proof-of-principle simulation methods for superconducting qubits. References: [1] C. Müller, J.H. Cole & J. Lisenfeld, Rep. Prog. Phys. 82 (12), 124501 (2019) [2] T. DuBois et al. Physical Review Letters 110 (7), 077002 (2013) [3] T. DuBois et al. New Journal of Physics 17 (2), 023017 (2015) [4] M. Cyster et al. npj Quantum Information 7 (1), 1-12 (2021) [5] M. Cyster et al. Physical Review Research 2 (1), 013110 (2020)

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Boxi Li, bli@fz-juelich.de, Forschungszentrum Juelich, Germany	Modelling and engineering cQED devices via effective Hamiltonians	Deriving effective Hamiltonian models plays an essential role in quantum theory, with particular emphasis in recent years on control and engineering problems. To develop fast, high-fidelity operations on cQED devices, there are also increasing demands on modelling tools that go beyond the strong perturbative regime and accurately capture the time-dependent dynamics. To this goal, we present two symbolic methods for computing effective Hamiltonian models [1]. The first method makes use of the Jacobi iteration and works without the assumptions of perturbation theory while retaining convergence. In the perturbation regime, it reduces to a variant of the ubiquitous Schrieffer-Wolff method, which takes advantage of a recursive structure and exponentially decreasing the number of terms in high-order expansion. Both methods consist of algebraic expressions and can be easily automated for symbolic computation. Based on these methods, we perform analytical calculations and develop semi-classical tools that can compute the time-dependent effective Hamiltonian to arbitrary accuracy [2]. We investigate both the ZZ interaction and the cross-resonance (CR) interaction in the quasi-dispersive regimes and develop strategies both to suppress and engineer different interaction terms. By defining leakage in the adiabatic (block-diagonalized) frame, our method provides a deterministic way to compute the optimal DRAG coefficient without numerical optimization. In addition, we show that the residual noise such as the dynamical ZZ coupling in CR operation can be suppressed by exploring additional flexibility in the two-qubit subspace via time-dependent frame transformation. We expect our method to have significant application in quantum technologies, where the elimination of auxiliary or unwanted spaces needs to be done to significant precision to enable practically useful models. [1] Li B, Calarco T, Motzoi F. arXiv preprint arXiv:2112.00039, 2021. [2] Li B, Calarco T, Motzoi F. in preparation, 2022.

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Pol Forn-Díaz, pforndiaz@ifae.es, Institut de Física d'Altes Energies, Spain</td><td>Coherent flux qubits for quantum annealing</td><td>In this work, we present a capacitively shunted flux qubit made out of four Josephson junctions in a superconducting loop. As part of the European FET Open project AVaQus [1], we designed and characterized a first prototype of low-impedance persistent current qubits [2] suitable for coherent quantum annealing.

Here, we consider a circuit topology with four Josephson junctions in a loop to avoid undesired stray junctions by design. Based on progress made in the field [3], we shunt the smaller α junction with a capacitor Csh = 8 to 13 fF, making the charging energy Ec more reproducible and thus the qubit gap Ω01 more controllable, which is targeted to be between 1 to 2 GHz. Aiming at application in quantum annealing, the persistent current is designed to be small enough (Ip around ~ 100 nA) to remain high coherence while allowing for an inductive coupling between qubits in future designs [4]. Besides the single-qubit Hamiltonian, the qubit-resonator coupling is numerically calculated and the expected dispersive shift extracted.

The first generation device contains 8 individual and uncoupled flux qubits in order to test and verify various design choices. Allowing for dispersive readout, each qubit is capacitively coupled to a $\lambda/4$ readout resonator, which in turn is inductively coupled to a common transmission line. In order to investigate the influence of grounding, half the qubits are floating while the other half is connected to ground. Furthermore, each qubit can be manipulated by an on-chip flux bias line. Within the framework of the AVaQus project, this first generation device was fabricated by our collaborators at the University of Glasgow using a subtractive junction fabrication process [5] while the characterization of the device is carried out at IFAE.

References:
[1] https://www.avaqus.eu
[2] J. E. Mooij et al., Science 284, 5930 (1999).
[3] F. Yan et al., Nat Commun. 7, 12964 (2016).
[4] S. J. Weber et al., Phys. Rev. Applied 8, 014004 (2017).
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Stefan Filipp, stefan.filipp@wmi.badw.de, Walther-Meissner-Institut, Germany</td><td>Tunable multi-qubit couplers with low residual ZZ interactions</td><td>Maintaining high gate fidelities when scaling quantum processors to a large number of qubits is key to practically useful quantum computing. Two-qubit gates based on tunable couplers now reach fidelities above 99.5% in superconducting qubit quantum processors, in which the qubits are typically arranged on a square grid with pair-wise qubit-qubit couplers. However, involving multi-qubit couplers that provide higher connectivity may lead to more efficient algorithms. In this work, we specifically discuss the challenges imposed by residual ZZ interactions in such multi-qubit tunable-coupler architectures. We analyze possibilities to suppress these off-resonant interactions by connecting qubits to the coupler with different polarities of the coupling. Moreover, we investigate the use of additional two-qubit couplers as a way to mitigate ZZ interactions.</td></tr>
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Verena Feulner, verena.vf.feulner@fau.de, Friedrich-Alexander Universität Erlangen-Nürnberg Michael J. Hartmann, michael.j.hartmann@fau.de, Universität Erlangen-Nürnberg	Multi-qubit coupler for multi-qubit gates	An important part of research in the field of quantum computing is the implementation of multi-qubit gates whose execution time is significantly faster than the decoherence time of the qubits used. At the same time, a precision should also be achieved that is high enough to be able to use the gates for meaningful purposes. It is very difficult to represent interactions between more than two qubits, these have so far been split into two-body interactions, which also costs the process time and is therefore much more susceptible to the decoherence of the qubits.

		So far, it is also very difficult to simulate qubits interacting diagonally with quantum computer architectures on a rectangular grid. This is associated with high gate consumption and thus inaccuracy, since one needs several gates for a diagonal interaction. This project is related to the idea of finding a way to achieve diagonal coupling of qubits and possibly use the circuit for multi-qubit gates. We are investigating whether a particular quantum circuit with four transmon qubits and a SNAIL coupler can achieve this goal.
Graham J. Norris, graham.norris@phys.ethz.ch, ETH Zurich, Switzerland Michael Kerschbaum, michael.kerschbaum@phys.ethz.ch, ETH Zurich, Switzerland Jean-Claude Besse, jean-claude.besse@phys.ethz.ch, ETH Zurich, Switzerland Christopher Eichler, christopher.eichler@phys.ethz.ch, ETH Zurich, Switzerland Andreas Wallraff, andreas.wallraff@phys.ethz.ch, ETH Zurich, Switzerland	A polymer spacer process for improved parameter targeting in 3D-integrated superconducting circuits	Creating devices with hundreds of superconducting qubits is difficult on single-layer devices due to the large number of intra-die connections and impractical with multi-layer wiring processes due to their use of potentially lossy dielectrics. Instead, indium flip-chip bonding, a type of 3D-integration, can be used to join several single-layer superconducting dies, providing extra signal routing planes while avoiding deposited dielectrics. Although indium bump bonding of superconducting circuits has been successfully demonstrated [1, 2], precisely controlling the vertical chip spacing, which strongly affects circuit parameters such as resonator frequencies and qubit anharmonicities, without degrading the substrate surface remains a challenge [2]. Here we present a polymer hard-stop spacer fabrication process that provides deterministic inter-chip separation and benchmark the frequency reproducibility and internal loss rates of coplanar waveguide resonators. Since the flip-chip bonded die can significantly alter the electrical properties of circuit elements, we also characterize resonators with varying dimensions and discuss the implications of our results for large-scale devices. References: [1] Rosenberg et al., IEEE Microw. Mag. 21, 72 (2020) [2] Gold et al., npj Quantum Inf. 7, 142 (2021)
Abhishek Agarwal, abhishek.agarwal@npl.co.uk, National Physical Laboratory, United Kingdom Deep Lall, deep.lall@npl.co.uk, National Physical Laboratory, United Kingdom Ivan Rungger, ivan.rungger@npl.co.uk, National Physical Laboratory, United Kingdom	Amplification and modelling of single-qubit gate operations in superconducting qubits	Achieving fast, high-fidelity gate operations is necessary for useful quantum computation. Although reducing gate durations can speed up computations and reduce the effects of certain decoherent errors, it often comes at the expense of increasing the systematic or coherent errors in the operations. A detailed understanding of the sources of noise in quantum gates can help in developing methods to mitigate the effects of noise and improve gate calibrations. By repeatedly applying various error amplifying gate sequences on the IBMQ superconducting qubit platforms, we detect and amplify the effects of different kinds of noise sources in the single-qubit gate operations. Using this method, we are also able to detect and analyse certain kinds of non-Markovian noise in the devices. By comparing the performance of various noise models in predicting the results of computations, we are able to find the dominant sources of noise in single-qubit gate operations on superconducting qubits.

Scientific session: Algorithms and applications

This session is supported by IBM Quantum.

A QUANTUM SZILARD ENGINE FOR TWO-LEVEL SYSTEMS COUPLED TO A QUBIT

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The innate complexity of solid state physics exposes superconducting quantum circuits to interactions with uncontrolled degrees of freedom degrading their coherence. By using a simple stabilization sequence we show that a superconducting fluxonium qubit is coupled to a two-level system (TLS) environment of unknown origin, with a relatively long energy relaxation time exceeding 50ms.

Implementing a quantum Szilard engine with an active feedback control loop allows us to decide whether the qubit heats or cools its TLS environment. The TLSs can be cooled down resulting in a four times lower qubit population, or they can be heated to manifest themselves as a negative temperature environment corresponding to a qubit population of 80%. We show that the TLSs and the qubit are each other's dominant loss mechanism and that the qubit relaxation is independent of the TLS populations. Understanding and mitigating TLS environments is therefore not only crucial to improve qubit lifetimes but also to avoid non-Markovian qubit dynamics.

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Pascal Stadler, pascal.stadler@quantumsimulations.de, HQS Quantum Quantum Simulations GmbH	Simulating system-bath type problems on a quantum computer	Quantum computers offer the possibility for large scale simulations of quantum mechanical systems. Today the simulation are limited by noise and imperfection of the quantum devices. In recent years a variety of different approaches have been discussed to reduce the error in noisy quantum devices. We introduce a new and different approach to simulate quantum mechanical systems on a quantum computer. The idea is that we simulate systems that are themselves noisy enabling the simulation of open quantum systems such as system-bath models. In this approach the noise of the quantum device is part of the algorithm itself. We will outline how we generate algorithms for quantum simulations of system-bath type models and extract effective models from an open quantum systems which can be used to run simulations on a quantum computer. Finally we compare the results of effective models with a full simulation of the quantum circuit and discuss future application of our method.

Scientific session: Millikelvin electronics and other supporting technologies

This session is supported by Bluefors.

HARDWARE FOR EFFICIENT MEASUREMENTS AND SCALABLE SIGNAL DELIVERY IN SUPERCONDUCTING QUANTUM PROCESSORS

Florent Lecocq, National Institute of Standards and Technology

There are many challenges to scaling the size of superconducting quantum computers. First and foremost, building processors with increasing numbers of qubits and longer coherence remains a daunting task. However, the success of superconducting quantum computing will also hinge on the development of many supporting technologies such as cryogenics, signal delivery, and microwave readout. Here I will discuss approaches to two of these bottlenecks, lying at the interface between quantum physics and engineering. First, I will discuss the challenges of wiring a million-qubit processor with coaxial lines, and how using photonic links can enable the use of optical fibers instead. Second, I will discuss why superconducting quantum processors need nonreciprocal components, what are the limitations of the conventional microwave circulators, and how we intend to replace them with integrable nonreciprocal devices based on multimode parametric interactions.

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		The original scheme does not have a sufficient number of tuning knobs to satisfy impedance matching conditions in the presence of random deviation of circuit parameters from the design. Here we propose a modified circuit configuration reducing the number of relevant modes and enabling impedance matching for a finite range of circuit parameters with a single tuning knob of the flux bias. We fabricated a modified Josephson ring circulator circuit with the sufficiently high three-fold symmetry necessary for the circulator circuit. The device shows microwave nonreciprocity in the transmission spectra. The circulation direction can be reversed by changing the sign of the flux bias or the gate-charge operation point as predicted in the theory. The results indicate the potential of a Josephson ring circulator for scalable superconducting-qubit readout. References: [1] B. Chapman et al., Phys. Rev. X 7, 041043 (2017). [2] F. Lecocq et al., Phys. Rev. Applied 7, 024028 (2017). [3] J. Koch et al., Phys. Rev. A 82, 043811 (2010)
Rohith Acharya, rohith.acharya@student.kuleuven.be, KU Lueven/ Imec Leuven, Belgium Steven Brebels, steven.brebels@imec.be, Imec Leuven, Belgium Alexander Grill, alexander.grill@imec.be, Imec Lueven, Belgium Jeroen Verjauw, jeroen.verjauw@student.kuleuven.be, KU Leuven/ Imec Leuven, Belgium Tsvetan Ivanov, tsvetan.ivanov@imec.be, Imec Leuven, Belgium Daniel Perez Lozano, Daniel.PerezLozano@imec.be, Imec Leuven, Belgium Danny Wan, danny.wan@imec.be, Imec Leuven, Belgium Fahd A. Mohiyaddin, Fahd.Ayyalil.Mohiyaddin@imec.be, Imec Leuven, Belgium Jacques Van Damme, jacques.vandamme@student.kuleuven.be,	Interfacing superconducting qubits with ultra-low power cryo-CMOS multiplexer at 11mK	A large-scale superconducting quantum computing system will require the control and readout of a large number of high-fidelity qubits operating at millikelvin temperatures [1]. CMOS based cryo-electronics offer a scalable solution to overcome the input-output bottleneck present in these systems. The high throughput required for quantum processors can be achieved using a network of multiplexers and de-multiplexers at the base temperature stage of a dilution refrigerator [2]. As the multiplexers are intended to operate in close proximity to the qubits, the electronic and thermal noise generated during their operation could be detrimental to the qubit performance. In this work, we present the electrical characterization results obtained for a custom-designed RF multiplexer operating at 11 mK with an ultra-low static power consumption of ~0.7 μW. We observe that the qubit's T_1 times are unaffected and maintain a mean value of ~47 μs, while the T_2^e times decrease to ~40 μs from ~65 μs due to finite thermal population in the readout resonator. Nevertheless, we show that high coherence qubit measurements with single qubit gate fidelities above 99.9% can still be achieved using signals routed through the multiplexer by using additional thermalization attenuators. Our results pave the way for the integration of cryo-CMOS based multiplexers at the base temperature of the dilution refrigerator for addressing multiple quantum devices and enabling large-scale device characterization. References: [1] S. J. Pauka, et al. "A Cryogenic CMOS Chip for Generating Control Signals for Multiple Qubits." Nature Electronics 4, no. 1 (January 2021): 64–70.

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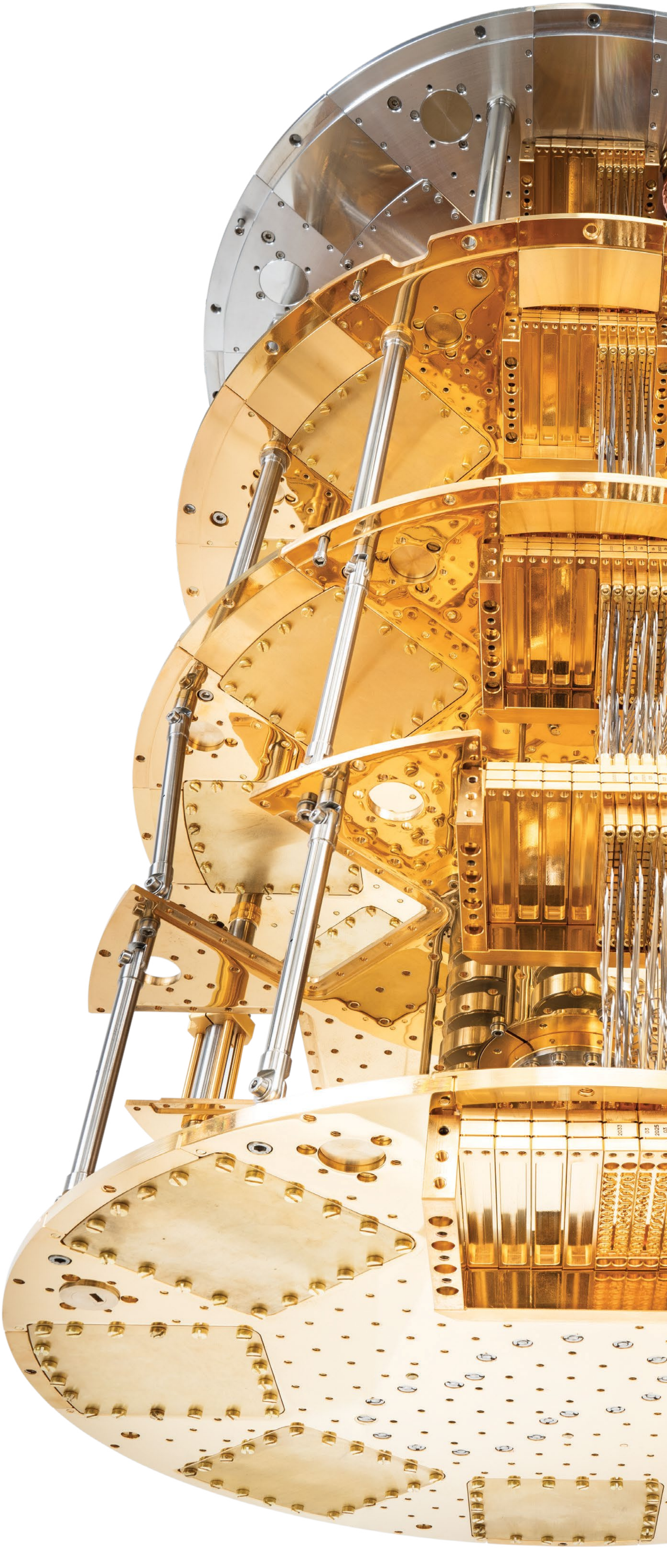

Sunday, August 28

Scientific session: Benchmarking and enabling software

This session is supported by Quantrolox.

IMPROVING SUPERCONDUCTING QC PERFORMANCE >1000X WITH DETERMINISTIC ERROR SUPPRESSION

Michael Biercuk (michael.biercuk@q-ctrl.com) , Q-CTRL

In this talk, we introduce quantum control infrastructure software for hardware performance augmentation, focusing on how deterministic error suppression strategies at the gate and circuit level can dramatically reduce correlated errors in superconducting devices without the need for additional sampling overhead. We present experiments on superconducting quantum computers illustrating these concepts and demonstrating how they may be deployed in situ to augment various system-level performance metrics.

We begin by describing the application of open-loop robust control techniques to the design of single-qubit operations, yielding improved gate errors, reduced qubit-to-qubit variability, and extended calibration windows by up to 10X. We then demonstrate how deep reinforcement learning (and other closed-loop optimization strategies) executed in runtime can be used to autonomously design multiqubit cross-resonance gates outperforming the best human-defined gates by ~2.5X, and saturating T1 error bounds. We discuss how the training process "learns" robustness in gate design in order to produce gates which do not require recalibration for up to 25 days, while also accounting for uncharacterized system nonlinearities and signal distortions. Owing to the use of parallelizable agents, we extend closed-loop gate optimization to all interacting pairs on a 16-qubit device and combine these gate-level error-suppression strategies with a new form of context-aware crosstalk cancellation at the circuit level, based on interleaved dynamic decoupling. Benchmarking results on a 16 qubit device reveal up to 9000X enhancements in the Bernstein Vazirani algorithm and show binary transformation of the outputs of deeper circuits such as Grover's search. Similarly, we show how these techniques can be combined with quantum error correction encoding to improve the success of syndrome extraction using a five-qubit CSS code by ~70%.

Anurag Saha Roy, anurag@qruise.eu, Qruise GmbH/Forschungszentrum Jülich, Germany Desi R Ivanona, University of Oxford, United Kingdom Nicolas Wittler, Forschungszentrum Jülich, Germany Kevin Pack, Forschungszentrum Jülich, Germany Daniel J Weigand, Forschungszentrum Jülich, Germany Matthias Müller, Forschungszentrum Jülich, Germany Shai Machnes, Qruise GmbH/ Forschungszentrum Jülich, Germany	Bayesian Experiment Design for Adaptive Characterization of Superconducting Qubits	Modern superconducting quantum computers are severely limited not by the number of qubits but by the high error and noise characteristics. The detailed system characterization required to understand the underlying error sources is an arduous process and impractical with increasing chip size. Typical textbook characterisation routines do not scale efficiently to large multi-qubit chips, requiring the development of advanced techniques based on statistical and information theoretic foundations. We present a Bayesian Experiment Design process that adaptively recommends the most optimal experiments at every step to maximise the expected information gain about the system. The cost of calculating expensive Bayesian posteriors is amortised by the use of Reinforcement Learning assisted Deep Adaptive Design techniques. A high-fidelity differentiable digital twin that models the open quantum dynamics, complete electronic control stack and noise & transfer functions for various superconducting quantum devices lies at the heart of this closed loop adaptive calibration and characterisation process. The practical usability of this Bayesian Experiment Design method is demonstrated on a multi-qubit superconducting transmon chip at the Forschungszentrum Jülich in Germany. References: 1. N. Wittler, F. Roy et al., "Integrated tool set for control, calibration, and characterization of quantum devices applied to superconducting qubits," Physical Review Applied, vol. 15, no. 3, p. 034080, 2021. 2. A. Foster, D. R. Ivanova et al, "Deep adaptive design: Amortizing sequential bayesian experimental design,", International Conference on Machine Learning, 2021.
M. Adriaan Rol - Orange Quantum Systems, adriaan@orangeqs.com	Tackling the quantum device characterization bottleneck	In traditional semiconductor development processes, fabrication of new devices takes several months while characterization takes a few days. With quantum computing devices this situation is reversed, fabricating a device takes on the order of two weeks for a state-of-the art superconducting transmon device while characterizing such a device up to the level where one can determine its performance in a quantum algorithm takes on the order of 3 to 6 months. Consequently, the calibration and characterization of quantum devices is one of the largest bottlenecks in quantum device development. In this talk we discuss what makes calibrating and characterizing quantum devices so difficult, what can be done to eliminate this bottleneck, and show initial results from the ImpaQT project. A project in which different companies collaborate to build a full-stack demonstration platform and execute a variational quantum algorithm on it.

Scientific session: Design and modeling

READOUT PROBLEM IN CIRCUIT QED

Alexandru Petrescu (tudor-alexandru.petrescu@inria.fr) , École des Mines

In typical circuit quantum electrodynamics experiments, the quantum state of a superconducting qubit is measured by monitoring a readout resonator weakly and off-resonantly coupled to the qubit. As drive power is increased to achieve a higher-fidelity and faster measurement, unwanted transitions occur, which, for example, decrease the qubit's energy relaxation time T1. In this talk, focusing on transmon qubits, we introduce a perturbative approach to catalog nonlinear relaxation processes, and identify stimulated emission as one possible mechanism for spurious qubit relaxation during readout [1]. We further address the related phenomenon of escape into unconfined states [2,3], and discuss a second mechanism for rate enhancement during measurement: by interactions between the low-lying states defining the qubit subspace and high-energy chaotic states. This analysis can help impose parameter constraints in current experiments.

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Ahmed Kenawy, a.kenawy@fz-juelich.de, Peter Grünberg Institut, Forschungszentrum Jülich, Germany Fabian Hassler, Institute for Quantum Information, RWTH Aachen University, Germany David P. DiVincenzo, Peter Grünberg Institut, Forschungszentrum Jülich Roman-Pascal Riwar, Peter Grünberg Institut, Forschungszentrum Jülich	How to correctly account for time-varying fluxes in superconducting circuits	Time-varying fluxes are a ubiquitous tool to control superconducting hardware. Surprisingly, however, the existing literature has never fully accounted for the electromotive force induced by the magnetic field. Here, we propose a general recipe to construct a low-energy Hamiltonian, taking as input only the circuit geometry and the solution of the external magnetic fields. We apply this recipe to the example of a dc SQUID and show that the assignment of individual capacitances to each Josephson junction is possible only if we permit those capacitances to be negative, time-dependent, or even momentarily singular. Such anomalous capacitances lead, among others, to a strong enhancement of qubit relaxation rates. Then, we tackle the problem of driven topological quantum circuits, focusing on two weakly coupled Kitaev chains and study how the electromotive force modifies the time-dependent fractional Josephson effect.
T. Ramos, t.ramos.delrio@gmail.com, Institute for Fundamental Physics, IFF-CSIC, Spain A. Gómez-León, Institute for Fundamental Physics, IFF-CSIC, Spain	Directional broadband amplification via a topological Josephson junction array	Microwave signals coming from superconducting quantum devices are typically very weak and therefore one requires efficient and near quantum-limited amplifiers to detect them. The most advanced amplifiers currently available are Josephson traveling-wave parametric amplifiers (JTWPA) which are built of a carefully engineered array of Josephson junctions [1]. Using four-wave-mixing, these amplifiers have shown excellent performance, especially regarding the large bandwidths, which are required for multiplexed readout in large-scale quantum information devices. The main drawback is that JTWPAs are

J. J. García-Ripoll, Institute for Fundamental Physics, IFF-CSIC, Spain A. González-Tudela, Institute for Fundamental Physics, IFF-CSIC, Spain D. Porras, Institute for Fundamental Physics, IFF-CSIC, Spain		not truly directional, meaning that parasitic signals and vacuum fluctuations can be back-amplified and contaminate the quantum source. In practice, this is avoided by equipping the JTWPAs with isolators, but these are bulky and lossy external elements that strongly limit the efficiency and scalability of superconducting quantum devices. Here, we show how to build truly directional and large bandwidth JTWPA by identifying the conditions under which it enters a topological amplifying phase [2,3]. As a consequence, microwave photons are unidirectionally amplified along the JTWPA with all back-reflections and backward noise exponentially suppressed. Moreover, due to the topological origin of the directional amplification, the device achieves perfect phase-matching without dispersion engineering, and it is robust to large amounts of disorder. Another topological property is that the gain of the amplifier grows exponentially with system size, implying that only 8 sites are enough to surpass 20 dB of near quantum-limited amplification and -20 dB of isolation over a bandwidth of GHz [5]. This topological JTWPA can be immediately implemented with state-of-the-art superconducting technology, opening the door for the integration of the quantum processors with compact broadband pre-amplifiers on the same chip. References; [1] M. Esposito et al., APL 119 (2021) 120501. [2] V. Peano et al., PRX 6(2016) 041026. [3] T. Ramos, J.J. García-Ripoll, D. Porras, PRA 103 (2021) 033513. [4] T. Ramos, A. Gómez-León, J.J. García-Ripoll, A. González-Tudela, D. Porras, to be submitted

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