QI 16: Quantum Software

Time: Thursday 9:30–12:45 Location: BEY/0245

Invited Talk QI 16.1 Thu 9:30 BEY/0245

Measurement-free universal fault-tolerant quantum computation — •Friederike Butt[1,2], Ivan Pogorelov[3], Alex Steiner[3], Marcel Meyer[3], Thomas Monz[3,4], Markus Müller[1,2], and Robert Freund[3] — [1]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich — [2]Institute for Quantum Information, RWTH Aachen University — [3]Universität Innsbruck, Institut für Experimentalphysik, Innsbruck — [4]Alpine Quantum Technologies GmbH, Innsbruck

The ability to perform quantum error correction (QEC) and robust gate operations on encoded qubits opens the door to demonstrations of quantum algorithms. Contemporary QEC schemes typically require mid-circuit measurements with feed-forward control, which are challenging for qubit control, often slow, and susceptible to relatively high error rates. I will present protocols and the experimental realization of a universal toolbox of fault-tolerant logical operations without mid-circuit measurements on a trapped-ion quantum processor. This includes modular logical state teleportation between two four-qubit error-detecting codes without measurements during algorithm execution, as well as a fault-tolerant universal gate set on an eight-qubit error-detecting code hosting three logical qubits, based on state injection, which can be executed by coherent gate operations only. This toolbox can then be used to realize Grover's quantum search algorithm fault-tolerantly on three logical qubits encoded in eight physical qubits, with the implementation displaying clear identification of the desired solution states.

QI 16.2 Thu 10:00 BEY/0245

A Framework for Spectator Error Mitigation in Surface-Code Hamiltonian Modeling — •Xuexin Xu[1], Mohammad H. Ansari[1], and John M. Martinis[2] — [1]PGI-2, Forschungszentrum Juelich, Juelich, 52428, Germany — [2]Qolab, Madison, Wisconsin, 53706, USA

Realistic surface-code architectures rely on precisely engineered single and two-qubit gates across large-scale quantum lattices. Yet subtle whispers from spectator qubits those surrounding but not directly involved in a target operation can disturb intended surface-code Hamiltonian and degrade logical fidelity. We analyze the origin and effects of spectator-induced errors in lattices and propose a mitigation scheme based on the inherent symmetry of spectator qubits. Through numerical simulations and perturbative analysis, we show that our method gently suppresses parasitic effects while boosting the performance of intended two-qubit gates. This approach offers a scalable and systematic path to enhance gate fidelity and tame crosstalk, bringing surface-code quantum processors closer to practical, reliable operation.

QI 16.3 Thu 10:15 BEY/0245

Handling Quantum Errors under Realistic Noise Models of Trapped Ion Quantum Devices — •Niko Trittschanke[1,2], Daniel Borcherding[2], and Robert Raussendorf[1,3] — [1]Institut für Theoretische Physik, Leibniz Universität Hannover — [2]QUDORA Technologies GmbH — [3]Stewart Blusson Quantum Matter Institute, University of British Columbia

Quantum computers are poised to grant an advantage over classical computers for some specific problems. These applications will require fully fault-tolerant quantum computers in order to produce significant results. However, due to the overhead of gates and qubits required by quantum error correction, fault-tolerant computation is out of scope for current devices. This necessitates the development of lightweight yet effective strategies to handle errors in noisy quantum devices. We investigate a $[[2m, 2m-2, 2]]$ error-detection code based on the 'Iceberg code' by applying it to realistic quantum simulations of the Schwinger model. Using an accurate noise model for the two-qubit entangling gate based on the upcoming trapped ion architecture of QUDORA, we simulate the dynamics of the particle number density on a noisy emulator. We demonstrate that the Iceberg code is able to substantially reduce the errors in this simulation, if correctly tuned. To that end, we propose a workflow to optimize the Iceberg code by selecting an optimal number of stabilizer measurements for a given problem. These results show that noisy intermediate-scale quantum computing can extensively be improved by carefully choosing low-overhead error-handling methods.

QI 16.4 Thu 10:30 BEY/0245

Probabilistic error cancellation for single-mode Gottesman-Kitaev-Preskillev-Preskill codes — Alessandro Ciani[1] and •Victoria Wadewitz[1,2] — [1]Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Theoretical Physics, Universität des Saarlandes, 66123 Saarbrücken, Germany

To solve practical problems on a quantum computer, fault-tolerant quantum error correction schemes are necessary to overcome noise from imperfections in physical components. The Gottesman-Kitaev-Preskill (GKP) code achieves this by encoding finite-dimensional logical space within the continuous variables of bosonic modes, offering a pathway to scalable, fault-tolerant quantum computing. However, it is not feasible to eliminate errors entirely, so they must be mitigated. In this work, we study a quantum error mitigation method known as probabilistic error cancellation (PEC) in the context of GKP codes. We compare Steane-type and teleportation-based GKP error correction, and calculate sampling overheads for square and hexagonal GKP codes. The PEC sampling probabilities are derived using a stabilizer subsystem decomposition for GKP codes. Considering noise from finite squeezing of the data and the two ancilla modes, as well as other contributions like pure loss and Gaussian random displacement, we examine the relationship between the overhead and the noise. Our results cover single- and two-GKP-qubit Clifford gates. Preliminary analysis suggests that, when combined with error mitigation techniques, teleportation-based GKP error correction outperforms Steane-type GKP error correction.

QI 16.5 Thu 10:45 BEY/0245

Real-time adaptive quantum error correction by model-free multi-agent learning — •Manuel Guatto[1,2], Francesco Preti[1], Michael Schilling[1,2], Tommaso Calarco[1,2,3], Francisco Cardenas-Lopez[1], and Felix Motzoi[1,2] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, D-50937 Cologne, Germany — [3]Dipartimento di Fisica e Astronomia, Università di Bologna, 40127 Bologna, Italy

Can Quantum Error Correction (QEC) adapt in real time to changing noise? We show that it can. We introduce a two-level reinforcement-learning framework that learns QEC from scratch and adapts it on the fly. At the first level, a model-free multi-agent RL system automatically discovers full QEC cycles*encoding, stabilizer measurements, and recovery*using only orthogonality constraints and no prior knowledge of the device. Using the stabilizer formalism, we demonstrate that it can generate new QEC codes tailored to multi-level quantum architectures. At the second level, we present BRAVE (Bandit Retraining for Adaptive Variational Error correction), an efficient algorithm that continuously retunes the variational layer to track time-dependent noise with minimal retraining. Combined, these methods yield more than an order-of-magnitude improvement in logical fidelity under time-varying bit- and phase-flip noise compared to standard QEC schemes.

30min. break

QI 16.6 Thu 11:30 BEY/0245

Continuous vs. Pauli Noise: Impact on Small-Scale Quantum Codes — •Yunos El Kaderi[1,2], Andreas Honecker[1], and Iryna Andriyanova[2] — [1]LPTM CNRS UMR 8089, CY Cergy Paris University, France — [2]ETIS CNRS UMR 8051, CY Cergy Paris University, France

Noise remains the main limit to reliable quantum computation. Standard Pauli models treat faults as discrete events, but real devices exhibit small, coherent shifts in gate rotations that accumulate over time [1,2]. These shifts follow directional patterns linked to axis and angle drift, which are well described by von Mises–Fisher statistics [3].

We study a continuous coherent-noise model built from these rotational laws and apply it to memory circuits based on the $[[5, 1, 3]]$ and $[[7, 1, 3]]$ stabilizer codes. We compare its logical performance with that of a matched-entropy Pauli channel, so both models share the same binary-symmetric uncertainty at readout. This isolates how the *shape* of noise, not only its strength, affects logical error rates.

We also introduce an approximate method that propagates small coherent errors through Clifford circuits without full Monte Carlo.

[1] S. Sheldon *et al.*, Phys. Rev. A 93, 012301 (2016)
[2] E. Huang *et al.*, Phys. Rev. A 99, 022313 (2019)
[3] G. Ragazzi *et al.*, Phys. Rev. A 110, 052425 (2024)

QI 16.7 Thu 11:45 BEY/0245

Encoding Numerical Data for Generative Quantum Machine Learning — •Michael Krebsbach[1], Hagen-Henrik Kowalski[2], Florentin Reiter[1], Ali Abedi[2], and Thomas Wellens[1] — [1]Fraunhofer IAF, Tullastraße 72, 79108 Freiburg — [2]Bundesdruckerei GmbH, Kommandantenstraße 18, 10969 Berlin

Generative quantum machine learning has the potential to model probability distributions that are out of reach for their classical counterparts. Due to the binary nature of samples drawn from a quantum computer, many of the generative models described in the literature focus on binary data. The transition from binary to real-world data, which is typically numerical, necessitates an additional encoding step that can obscure structure in the data and hinder effective learning.

In this talk, we present our investigation into binary encodings and their effect on the training process of generative quantum machine learning algorithms. We identify situations in which the conventional approach is limited, and propose strategies that circumvent these limitations at essentially no additional cost. We test these strategies on a range of datasets and provide numerical evidence that they provide an average-case improvement over the conventional approach.

QI 16.8 Thu 12:00 BEY/0245

Machine Learning methods for Entanglement Detection in High Dimensional Systems — •Yasmin Bougammoura[1], Martin Plávala[1], Fabio Anselmi[2], and Fabio Benatti[2] — [1]Institute of Theoretical Physics - Leibniz University Hannover, Germany — [2]University of Trieste, Italy

A universal approach to entanglement detection can be cast as a semidefinite program (SDP), but this formulation becomes computationally inefficient as the dimension of the system grows. Since entanglement detection for systems of dimension $d \geq 6$ is already an NP-hard task, this motivates the search for practical numerical strategies. Although current machine learning models reach high accuracy values, they do not provide robust and verifiable separability criteria. We propose two simple approaches: i. using automatic differentiation to approximate a given quantum state, and ii. training an artificial neural network to construct a certifiable entanglement witness W for a given entangled quantum state. The former efficiently approximates separable states; the latter achieves an improvement of two orders of magnitude in the dimension of the optimisation problem, which increases exponentially with the number of qubits. In terms of computational resources, the neural network model runs on a local machine with 16 GB RAM for a system of 8 qubits, whereas the SDP formulation is limited to a system of only 4 qubits.

QI 16.9 Thu 12:15 BEY/0245

Reducing the cost of gate-set tomography of superconducting quantum processors — •Martin Koppenhöfer, Michael Krebsbach, and Thomas Wellens — Fraunhofer-Institut für Angewandte Festkörperphysik IAF, Tullastraße 72, 79108 Freiburg, Deutschland

Gate errors remain one of the biggest obstacles on the road towards scalable quantum processors. Obtaining a precise understanding of these errors and of their origin is a necessary step for hardware improvements and error mitigation. In principle, gate-set tomography protocols allow one to obtain a detailed, self-consistent picture of quantum processors including state-preparation and measurement steps. However, a drawback of these protocols is that they become computationally very costly when multi-qubit gates are analyzed, leading to a very large set of germ circuits as well as an exponential growth of the initial states that need to be prepared and measurements that need to be performed.

In this talk, we present a modified approach to gate-set tomography that exploits different gate fidelities for single- and two-qubit gates to reduce the number of germ circuits and fiducial states. For two-qubit gate-set tomography, this approach reduces the number of required experiments by more than an order of magnitude and thus speeds up gate-set tomography protocols. We demonstrate this new technique on a superconducting quantum processor.

QI 16.10 Thu 12:30 BEY/0245

Detecting genuine multipartite entanglement in multi-qubit devices with restricted measurements — •Nicky Kai Hong Li[1,2], Xi Dai[3,4], Manuel Muñoz-Arias[5], Kevin Reuer[3,4], Marcus Huber[1,2], and Nicolai Friis[1] — [1]Atominstitut, Technische Universität Wien, Stadionallee 2, 1020 Vienna, Austria — [2]Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria — [3]Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland — [4]Quantum Center, ETH Zurich, CH-8093 Zurich, Switzerland — [5]Institut Quantique and Département de Physique, Université de Sherbrooke, Sherbrooke J1K 2R1 QC, Canada

Detecting genuine multipartite entanglement (GME) is a state-characterization task that benchmarks coherence and experimental control in quantum systems. Existing GME tests often require joint measurements on many qubits, posing experimental challenges for systems like time-bin qubits and microwave photons from superconducting circuits. Here we introduce GME and k-inseparability criteria applicable to any state, which only require measuring $O(n^2)$ out of 2^n $\leqslant m$-body stabilizers of n-qubit target graph states, with m at most twice the graph's maximum degree. For cluster or ring-graph states, only constant-weight stabilizers are needed. Using SDP, we further reduce both the number and weight of required stabilizers. Analytical and numerical results show that our criteria are noise-robust and can infer state infidelity from certified k-inseparability in microwave photonic graph states generated under realistic conditions.