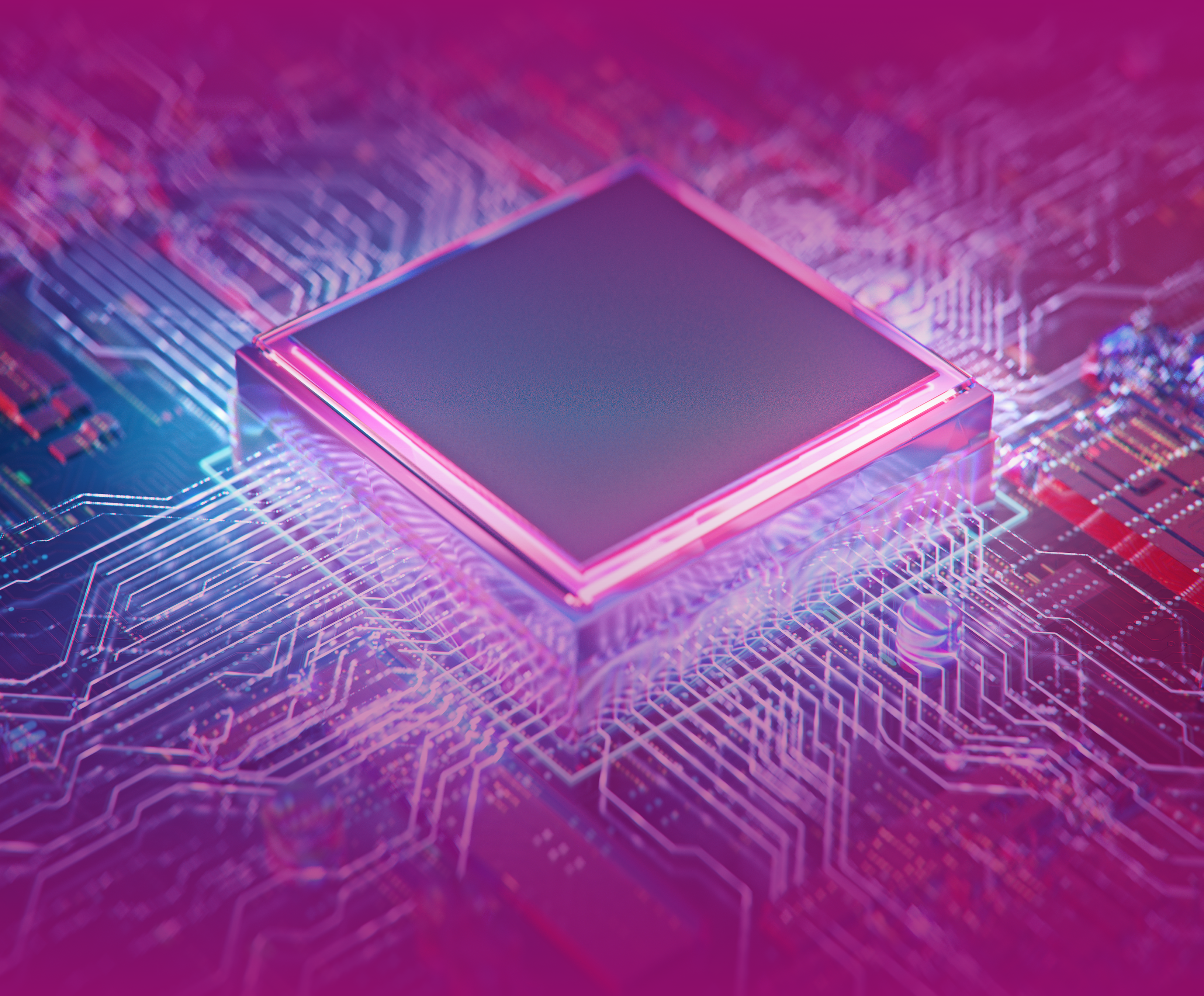
National Quantum Computing Centre

Quantum Computing Scalability Conference
2nd - 4th April 2025



Book of Abstracts

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Talk Abstracts

Trapping atoms in a cryogenic environment: enhancing scalability in quantum systems

Grégoire Pichard
PASQAL SAS

Optical tweezer arrays have proven to be an effective platform for realising analogue and digital quantum simulators. However, as with all quantum hardware, scalability remains a major challenge. In particular, this entails increasing the atom in-tweezer lifetime. In this talk, we will present the advantages of an experimental setup that incorporates tweezer technology in a cryogenic environment. In our first setup operating at 4K, we achieved a vacuum-limited lifetime of over 6000 seconds [1], an improvement of two orders of magnitude over room-temperature setups. However, the optical quality in the transverse field limited the generation of large arrays to a few hundreds of traps. We therefore decided to implement a new cryogenic design with objectives at room-temperature [2]. We will review the performance and limitations of this new design.

[1] Kai-Niklas Schymik et al., Phys. Rev. Applied 16, 034013 (2021)
[2] Gr´egoire Pichard et al., Phys. Rev. Applied 22 024073 (2024).

Architecting a neutral atom quantum computer: the cost of connectivity

Professor Mark Saffman
University of Wisconsin-Madison and Infleqtion, Inc.

Progress in quantum computing with neutral atom qubits has advanced rapidly with the development of large 2D arrays and high fidelity entangling gates. As with all qubit platforms the challenge of establishing rapid connectivity between large numbers of qubits must be overcome for scalable computation. With neutral atoms entanglement can be established at short length scales via Rydberg interactions, at medium length scales with physical transport, and at long scales via photons. I will discuss these options and show how they can be realized in scalable architectures.

Integrated Visible Light to SWIR Lasers and Photonics for Quantum Computing and Qubit Preparation and Control

Professor Daniel Blumenthal
University of California, Santa Barbara

Today's quantum computation experiments require a scaling up in system complexity, improvement in reliability, and reduction in size, weight and cost. Yet the underlying lasers, beamlines, and optical infrastructure inherent to many quantum modalities still occupies laboratory tables and racks. Photonic integration has the potential to realize these laser systems and optical functions needed to prepare light and address qubits at the chip-scale. In this talk we cover efforts using the silicon nitride ultra-low loss platform to integrate quantum atomic visible to SWIR lasers, modulators, reference cavities, beam delivery and other functions for qubit preparation, control, and readout. Technologies include tunable and frequency agile ultra-narrow linewidth lasers, optical reference cavities, low energy stress-optic actuators and modulators, and waveguide to free space beam emitters. We will describe recent results in highly coherent direct laser emission at rubidium and strontium atomic transitions and modulation and other components and functions across this wavelength range. Progress towards integration of a rubidium 3D-MOT with integrated beam delivery and integrated of a coil stabilized Brillouin laser for driving the strontium trapped ion clock transition and performing qubit operations will be described. Future prospects for high level functional circuit integration and beam delivery for neutral atoms will also be discussed.

Integrated optics and Penning traps for scaling trapped-ion quantum computing

Dr Daniel Kienzler
ETH Zürich

Trapped ions are among the leading approaches to realizing quantum computers, having exhibited the highest fidelities and long coherence times. Scaling up will require the adoption of new technologies, and can be facilitated by new approaches to trapping and control. In this talk I will describe recent work from our group across these different aspects. Firstly I will describe the use of integrated optics to deliver light to multiple zones of an ion trap chip in scalable manner [1,2]. I will then introduce a new concept for scaling trapped-ion quantum computers based on microfabricated Penning traps, introducing flexible 3-dimensional ion transport while removing the need for high-voltage radio-frequency fields and thus improving compatibility with standardised chip fabrication [3,4].

[1] K. Mehta et al. Nature 586, 533-537 (2020)
[2] C. Mordini et al. Phys. Rev. X 15, 011040 (2025)
[3] S. Jain et al. Phys. Rev. X 10, 031027 (2021)
[4] S. Jain et al. Nature 627, 8004, pp. 510-514 (2024)

What do Qubits mean for Telecoms?

Professor Peter Smith
Optoelectronics Research Centre, University of Southampton & founder, Covesion Limited

Integrated optics and optical fibre networks are becoming critical technologies for Quantum Technology. This talk will look at how waveguides and fibres have been used in QT research and the requirements for future applications. Looking at fundamental physical properties such as loss, coupling, nonlinearity and on functionality it will help point to directions for future R&D in the optical fibre and integrated optics arena. In conventional telecoms networks the availability of amplifiers, EO/OE conversion, storage in CMOS, signal processing, convergence with data-networks, DSP, etc all means that telecoms has made huge strides in transmission distance, bandwidths, costs, reliability, however, in quantum the physical challenges are different, and will require new components, new materials, and further investment in research.

Towards error-corrected testbeds at the NQCC

Professor Earl Campbell
University of Sheffield

This talk covers selected highlights of Riverlane's quantum error correction research and how it ties into current and potential future work at the NQCC. I will begin with a pedagogical review of the need for quantum error correction with fast decoding performed in real-time and tightly integrated with control systems. This will be followed by insights into the differences between software- and hardware-based approaches and how this impacts the crucial speed metrics of throughput and latency. Next, I dive into one of Riverlane's flagship papers with our partners at Rigetti: we performed the world's first scalable demonstration of low-latency quantum error correction on Rigetti's premises. I'll report progress towards a similar integrated Rigetti-Riverlane system as an NQCC-hosted testbed. For AMO systems, the possibility of using quantum LDPC codes is attractive. I will summarise our research so far on qLDPC decoding, including the ambiguity clustering decoder and its deployment as an NQCC testbed system with Infleqtion. Much work remains to build world-leading error-correction capabilities at the NQCC, and I will conclude with Riverlane's vision for such systems.

Quantum error correction and digital quantum simulation with reconfigurable atom arrays

Simon Evered
Harvard University

Suppressing errors is one of the central challenges for useful quantum computing, requiring quantum error correction for large-scale processing. However, the overhead in the realization of error-corrected "logical" qubits, where information is encoded across many physical qubits for redundancy, poses significant challenges to large-scale quantum computing. Here we will discuss recent advances in quantum information processing using dynamically reconfigurable atom arrays, where physical qubits are encoded in long-lived hyperfine states and entangling operations are realized by coherent excitation to Rydberg states [1]. With this platform we have realized programmable quantum processing with encoded logical qubits, combining the use of 280 physical qubits, high two-qubit gate fidelities, arbitrary connectivity, and mid-circuit readout and feedforward. Using this logical processor with various types of error-correcting codes, we demonstrate that we can improve logical two-qubit gates by increasing code size, outperform physical qubit fidelities, create logical GHZ states, and perform computationally complex scrambling circuits using 48 logical qubits and hundreds of logical gates [2]. Finally, we will discuss recent work realizing gate-based quantum simulations of Kitaev's honeycomb model and fermion dynamics with this architecture [3]. Together, these results chart a path toward future large-scale quantum processors and highlight unique near-term opportunities for gate-based quantum simulation.

[1] S. Evered*, D. Bluvstein*, M. Kalinowski* et al. Nature 622, 268-272 (2023)
[2] D. Bluvstein, S. Evered et al. Nature 626, 58-65 (2024)
[3] S. Evered*, M. Kalinowski* et al. arXiv:2501.18554 (2025)

Quantum computing with metastable 171Yb qubits

Dr Jeff Thompson
Princeton University

Neutral atom quantum computing is a rapidly developing field, but many challenges remain to implementing large-scale computing systems. I will discuss how a particular implementation based on 171Yb atoms, with qubits encoded in the metastable state, can give rise to important advantages to achieve hardware-efficient QEC by converting the dominant errors into erasure errors that can be detected with very low overhead. I will also discuss progress towards mid-circuit loss detection and atom replacement.

Enabling Distributed Quantum Computing with Trapped-Ions

Dr Claire Le Gall
Nu Quantum Ltd

Networking quantum computing cores has the potential to vastly accelerate the path towards utility-scale quantum computing. The network provides remote entanglement links, implemented via entanglement swapping [1], or gates [2] between flying and matter qubits. Optical cavities, as an interface to 'communication' qubits, offer the potential to vastly improve entanglement rates via near-unity collection efficiency [3–6]. Despite these advantages, freespace collection strategies [1,7] have, to date, surpassed those obtained with cavity-based approaches [8]. This disparity is symptomatic of underlying factors, such as fundamental ion-photon interaction [8], loss mechanisms within the cavity or degradation of qubit properties due to nearby mirror surfaces [9]. In this work, we will present Nu Quantum's system-level efforts to develop a performant trapped-ion quantum network demonstrator. Specifically, we will report on optical microcavities operating beyond the confocal regime to achieve small mode-volumes while keeping mirror surfaces distanced from the qubits. Additionally, we will present the progress on a quantum network testbed being built at the NQCC, where Nu Quantum is aiming for entanglement rates of 10 kHz–a 50x improvement over current links. As an outlook, we will discuss integration pathways to trapped-ion quantum computers.

[1] L. J. Stephenson, et al. ”High-rate, high-fidelity entanglement of qubits across an elementary quantum network” PRL 124, 110501 (2020).
[2] C. M. Knaut, et al. ”Entanglement of nanophotonic quantum memory nodes in a telecom network” Nature 629, 573 (2024).
[3] S. Langenfeld, et al. ”A quantum repeater node demonstrating unconditionally secure key distribution” PRL 126, 230506 (2021).
[4] Shankar G. Menon, et al. ”An integrated atom array-nanophotonic chip platform with background-free imaging” Nat. Comm. 15, 6156 (2024).
[5] J. Schupp, et al. ”Interface between Trapped-Ion Qubits and Traveling Photons with Close-to-Optimal Efficiency” PRX Quantum 2, 020331 (2021).
[6] T. Hiroki, et al. ”Strong coupling of a single ion to an optical cavity” PRL 124, 013602 (2020).
[7] S. Saha, et al. ”High-fidelity remote entanglement of trapped atoms mediated by time-bin photons” arXiv:2406.01761 (2024).
[8] V. Krutyanskiy, et al. ”Entanglement of trapped-ion qubits separated by 230 meters” PRL 130, 050803 (2023).
[9] Markus Teller, et al. ”Heating of a trapped ion induced by dielectric materials” PRL 126, 230505 (2021).

NQCC Testbed Showcase

Emma Athawes
National Quantum Computing Center

Beginning in January 2024, the National Quantum Computing Centre (NQCC) initiated the Testbed Project, utilising InnovateUK's Small Business Research Initiative (SBRI) funding mechanism to leverage £30 million in investment. This funding will be distributed among seven quantum computing companies to develop and implement quantum computing testbeds across various modalities. This is a vital part of building the UK's quantum computing capabilities, enabling the technology to be demonstrated and showcased. The objective of the initiative is to deliver operationally ready quantum computing testbeds in an ambitious timescale for the purpose of characterisation, benchmarking, verification, and exploratory applications development. The NQCC Project Manager will introduce the lightning talks, giving an overview of the endeavour and reflections before handing over to the testbed teams to discuss their individual approaches, progress to date and how they have benefitted from involvement in the project.

QubiC: an open-source full-stack scalable real-time Quantum bit Controller

Dr Yilun Xu
Lawrence Berkeley National Lab

QubiC is a field-programmable gate array (FPGA)-based, open-source quantum control system that offers a comprehensive, full-stack solution [1,2]. This system encompasses electronics hardware, FPGA gateware, and engineering software. Leveraging the latest radio frequency system-on-chip (RFSoC) platform, QubiC excels in parametric waveform generation, pulse sequence reuse, and features a distributed architecture for mid-circuit measurement and feed-forward operations [3]. Its clock synchronization and data communication capabilities ensure scalable control [4]. Additionally, QubiC integrates artificial intelligence (AI)-powered quantum state discrimination to facilitate mid-circuit measurement [5].
In this talk, I will provide an overview of QubiC's architecture, functionalities, and capabilities. I will explore the advanced control requirements for superconducting qubits and demonstrate how QubiC meets these needs with features such as real-time decision-making, scalable control, flexible hardware design, and AI-driven measurement and calibration.

[1] Xu, Yilun, et al. "QubiC: An open-source FPGA-based control and measurement system for superconducting quantum information processors." IEEE Transactions on Quantum Engineering 2 (2021): 1-11.
[2] Xu, Yilun, et al. "QubiC 2.0: An extensible open-source qubit control system capable of mid-circuit measurement and feed-forward." arXiv preprint arXiv:2309.10333 (2023).
[3] Fruitwala, Neelay, et al. "Distributed architecture for fpga-based superconducting qubit control." arXiv preprint arXiv:2404.15260 (2024).
[4] Xu, Yilun, et al. "Multi-FPGA Synchronization and Data Communication for Quantum Control and Measurement." In preparation.
[5] Vora, Neel R., et al. "ML-powered FPGA-based real-time quantum state discrimination enabling mid-circuit measurements." arXiv preprint arXiv:2406.18807 (2024).

Mapping the Quantum Control Landscape

Dr Robin Sterling

Unlike classical digital circuits, quantum computing requires control systems that demand precise analog signals, low-latency feedback, and integration with cryogenic environments. This talk explores the current quantum control landscape, mapping the interdependencies and maturity levels across hardware, firmware, and software stacks. Using this foundation, we'll envision the future of these systems, identifying critical bottlenecks, such as cost scaling, and highlighting potential research directions. This talk offers a roadmap to transform quantum control from today's costly setups into a scalable, cost-effective backbone for fault-tolerant quantum computers.

Scaling responsible and ethical quantum computing

Dr Natasha Oughton
National Quantum Computing Center

As quantum computing progresses towards readiness, it becomes increasingly critical to adopt a responsible and ethical approach to its development and use. Building on work done at the NQCC, this talk will explore key considerations for responsible and ethical quantum computing, with a focus on scaling a responsible approach as the technology evolves. Topics will include environmental and sustainability implications, the digital divide, and the societal implications impact of applications. The talk will also highlight initiatives and opportunities to engage further on this topic, along with practical steps to implement responsible innovation.

Accommodating Fabrication Defects on Floquet Codes with Minimal Hardware Requirements

Dr Alexandra E. Moylett
Nu Quantum

Floquet codes are an intriguing generalisation of stabiliser and subsystem codes, which can provide good fault-tolerant characteristics while benefiting from reduced connectivity requirements in hardware. A recent question of interest has been how to run Floquet codes on devices which have defective – and therefore unusable – qubits. This is an under-studied issue of crucial importance for running such codes on realistic hardware. To address this challenge, we introduce a new method of accommodating defective qubits on a wide range of two-dimensional Floquet codes, which requires no additional connectivity in the underlying quantum hardware, no modifications to the original Floquet code's measurement schedule, can accommodate boundaries, and is optimal in terms of the number of qubits and stabilisers removed. We numerically demonstrate that, using this method, the planar honeycomb code is fault tolerant up to a fabrication defect probability of 12%. We find the fault-tolerant performance of this code under defect noise is competitive with that of the surface code, despite its sparser connectivity. We finally propose multiple ways this approach can be adapted to the underlying hardware, through utilising any additional connectivity available, and treating defective auxiliary qubits separately to defective data qubits. Our work therefore serves as a guide for the implementation of Floquet codes in realistic quantum hardware.

Towards Large-Scale Integrated Platform for Solid-State Atoms

Mr. Hao-Cheng Weng
University of Bristol

Nitrogen-vacancy (NV) centers are highly versatile atomic systems, making them ideal for quantum information processing and networking. Their optically active spins enable scalable, nanoscale qubits in solid-state platforms while supporting strong light-matter interactions for distributed quantum computing. However, conventional NV microscopy and spectroscopy setups rely on meter-scale electro-optical control for a single NV center, limiting their practicality for large-scale quantum applications.

Our research addresses this challenge by integrating NV centers with photonic and electronic circuits fabricated using commercial CMOS technology. In my presentation, I will first introduce our approach to heterogeneously integrating NV centers in nanodiamonds with foundry-fabricated silicon nitride photonics. I will then discuss our recent progress in minimizing microwave crosstalk between densely packed spin systems using multi-layer microelectronics. Finally, I will end by discussing how large-scale NV arrays can unlock exciting applications beyond computing, such as in quantum sensing, in the near-term.

[1] Weng, Hao-Cheng, et al. "Heterogeneous integration of solid-state quantum systems with a foundry photonics platform." ACS photonics 10.9 (2023): 3302-3309.
[2] Weng, Hao-Cheng, et al. "Crosstalk-mitigated microelectronic control for optically-active spins." arXiv:2404.04075 (2024).

Poster Abstracts

End-to-End Quantum Error Mitigation for Dynamic Circuits and QEC

Raam Uzdin
Hebrew University of Jerusalem

Despite their success, quantum error mitigation (QEM) protocols often face key limitations. They are typically sensitive to time drift in noise parameters, restricted to Clifford gates, and unable to mitigate mid-circuit measurements—an essential component of quantum error correction codes and efficient dynamic circuit design [1-3]. Additionally, existing QEM methods do not address errors in the preparation of the initial state. We present an end-to-end (E2E) mitigation scheme that simultaneously tackles all these noise sources, including preparation errors, mid-circuit measurement errors, and errors in non-Clifford gates. To achieve this, we introduce a digital parity-based noise amplification scheme for mitigating mid-circuit measurement errors. Our approach also addresses coherent errors [4]. Crucially, the E2E scheme is inherently resilient to noise drifts [5], enabling almost arbitrarily long runtimes without requiring device recalibration. Finally, we emphasize that fault-tolerant quantum error correction—the ultimate goal of quantum computing—is fundamentally a form of dynamic circuit. Thus, even if error correction is not implemented perfectly, the E2E approach can effectively mitigate the remaining errors. This work takes a step toward a future where quantum error correction handles the bulk of error reduction, while quantum error mitigation fills in the gaps with only a mild sampling overhead. Experimental results from IBM quantum computers will be presented.

[1] E. Baumer et al. 'Efficient Long-Range Entanglement Using Dynamic Circuits', PRX Quantum 5, 030339 (2024)
[2] E. Baumer et al. 'Quantum Fourier Transform using Dynamic Circuits' arXiv 2403.09514 (2024)
[3] A. Deshpande, 'Dynamic parameterized quantum circuits: expressive and barren-plateau free', arXiv:2411.05760 (2024)
[4] J.P. Santos B. Bar and R. Uzdin 'Pseudo twirling mitigation of coherent errors in non-Clifford gates', npj quantum information 10, 100 (2024)
[5] I. Henao, J.P. Santon and R. Uzdin 'Adaptive quantum error mitigation using pulse-based inverse evolutions', npj Quantum Information 9, 120 (2023)

QAOA in Quantum Datacenters: Parallelization, Simulation, and Orchestration

Dan Holme
Qoro Quantum

Scaling quantum computing requires networked systems, leveraging HPC for distributed simulation now and quantum networks in the future. Quantum datacenters will be the primary access point for users, but current approaches demand extensive manual decisions and hardware expertise. Tasks like algorithm partitioning, job batching, and resource allocation divert focus from quantum program development. We present a massively parallelized, automated QAOA workflow that integrates problem decomposition, batch job generation, and high-performance simulation. Our framework automates simulator selection, optimizes execution across distributed, heterogeneous resources, and provides a cloud-based infrastructure, enhancing usability and accelerating quantum program development. We find that QAOA partitioning does not significantly degrade optimization performance and often outperforms classical solvers. We introduce our software components-Divi, Composer, and our cloud platform-demonstrating ease of use and superior performance over existing methods.

Time evolution of controlled quantum systems using matrix product operators.

Llorenç Balada Gaggioli
Czech Technical University

We present a method for describing the time evolution of controlled quantum systems using matrix product operators (MPOs). Existing techniques for solving the time-dependent Schrödinger equation (TDSE) with an MPO Hamiltonian often rely on time-independence or time discretization. In contrast, our approach uses the Magnus expansion and Chebyshev polynomials to model the time evolution and the MPO representation to efficiently encode the system's dynamics. This results in a scalable method that can be used efficiently for large controlled quantum systems. We apply this technique to quantum optimal control, specifically for a gate synthesis problem, demonstrating that it can be used for large-scale optimization problems that are otherwise impractical to formulate in a dense matrix format.

[1] - S. Paeckel, T. Köhler, A. Swoboda, S. R. Manmana, U. Schollwöck, and C. Hubig, Time-evolution methods for matrix-product states, Annals of Physics 411, 167998 (2019).
[2] - S. Blanes, F. Casas, J. Oteo, and J. Ros, The Magnus expansion and some of its applications, Physics Reports 470, 151–238 (2009).
[3] - H. Tal-Ezer and R. Kosloff, An accurate and efficient scheme for propagating the time dependent Schrödinger equation, The Journal of Chemical Physics 81, 3967 (1984).

Transversal vs Lattice Surgery CNOT - leveraging long range qubit connectivity

Mark Webber
Universal Quantum

Transversal CNOT (tCX) gates provide an alternative to lattice surgery for logical operations in quantum error correction. While lattice surgery scales with $O(d^3)$ time complexity, tCX can reduce this to $O(d^2)$ using long-range connectivity. However, tCX propagates errors between logical qubits, which standard minimum weight perfect matching (MWPM) decoding fails to handle, leading to degraded logical error rates.
We introduce an iterative decoding method that extends MWPM by tracking propagated errors. Our approach iteratively updates the Pauli frame and syndrome data until convergence. Circuit-level noise simulations up to $d = 11$ show that $O(1)$ quantum error correction (QEC) rounds between alternating tCX operations can achieve logical error rates comparable to memory-equivalent circuits, mitigating correlated errors.
Beyond decoding, we introduce error models for long-range connectivity, incorporating time costs and realistic error rates for physical tCX operations. This enables a concrete space-time volume comparison between tCX and lattice surgery. Our findings show that for architectures with high-fidelity long-range interactions, such as trapped ions, tCX achieves superior performance with significantly lower space-time overhead.
These results establish tCX as a competitive alternative for fault-tolerant quantum computing, contingent on long-range connectivity. Future work will refine these models and optimize implementations for specific hardware platforms.

[1] - Kwok Ho Wan, Mark Webber, Austin G. Fowler, and Winfried K. Hensinger. "An Iterative Transversal CNOT Decoder." arXiv preprint arXiv:2407.20976 (2024). Available at: https://arxiv.org/abs/2407.20976
[2] - Wan, K. H. (2024). "Constant-time magic state distillation." arXiv preprint arXiv:2410.17992. Available at: https://arxiv.org/abs/2410.17992.

Machine learning based characterization of wafer-scale superconducting qubits

Manognya Acharya[1], Juan Carlos Calvo[2], Julian Regan[2], Masum Uddin[1], Deep Lall[1], Marco Caselli[2], Nathan Korda[2], Tobias Lindstrom[1]

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The ability to scale from experiments on small quantum circuits to where large-scale quantum processors can not only be fabricated but also be effectively controlled is a fundamental requirement for a practical quantum computer. As part of the ISCF AutoQT project funded by Innovate UK, National Physical Laboratory and Mind Foundry collaborated to develop an ML-based automated qubit calibration pipeline. The calibration pipeline manager Dioscuri developed by Mind Foundry combines features of Prefect and Kedro allowing an advanced workflow and data management. The pipeline automates the characterization of qubits all the way up to randomized benchmarking. It was tested on hardware at NPL, where we are establishing characterization capabilities for small-scale quantum processors to enable the development of metrology for quantum computing systems. Our approach involves sophisticated measurement methods to allow rapid, accurate characterization of large-scale circuits. Developing and benchmarking automated qubit calibration methods is an integral part of this approach.

Uniting Quantum Processing Nodes of Cavity-coupled Ions with Rare-earth Quantum Repeaters Using Single-photon Pulse Shaping Based on Atomic Frequency Comb

Pierre Cussenot

CEA - IPhT

Connecting quantum processing nodes at a distance is an important challenge in the context of distributed quantum computing. Here[1], we present a new network architecture for remotely connecting cavity-coupled trapped ions processing nodes via a quantum repeater backbone based on rare-earth-doped crystals. The main challenge for its realisation lies in interfacing these two physical platforms, which produce photons with a typical temporal mismatch of one or two orders of magnitude. To address this, we propose an efficient method that enables custom temporal reshaping of single-photon pulses whilst preserving purity. Our approach is to modify a commonly used memory protocol, called cavity-assisted Atomic Frequency Comb[2], for systems (like crystals) exhibiting inhomogeneous broadening. Using a custom sequential readout technique, it is possible in the impedance-matching regime to achieve an arbitrary temporal shaping at the quantum level. In a feasibility study based on recent experiments, it is shown that the photon waveform from a Pr3+:Y2SiO5 memory[3] can be made almost indistinguishable from a pure component of the photon mixed state emitted by a single 40Ca+ ion embedded in a high finesse cavity[4] (99 % overlap instead of 32 %). Addressing the general problem of how to interface two physical platforms that interact with light on very different timescales, we thus offer a viable and tangible solution for uniting quantum processing nodes with a quantum repeater backbone.

[1] Preprint related to this presentation: https://arxiv.org/abs/2501.18704. Collective work with B. Grivet, B.P. Lanyon, T.E. Northup, H. de Riedmatten, A.S. Sørensen, and N. Sangouard.

[2] Afzelius, M. and Simon, C. Impedance-matched cavity quantum memory. Phys. Rev. A 82, 022310 (2010).

[3] Duranti, S. et al. Efficient cavity-assisted storage of photonic qubits in a solid-state quantum memory. Opt. Express 32, 26884 (2024).

[4] Krutyanskiy, V. et al. Entanglement of Trapped-Ion Qubits Separated by 230 Meters. Phys. Rev. Lett. 130, 050803 (2023).

Parametric multi-element coupling architecture for coherent and dissipative control of superconducting qubits

Gerhard B.P. Huber
Walther-Meißner-Institute

As systems for quantum computing keep growing in size and number of qubits, challenges in scaling the control capabilities are becoming increasingly relevant. Efficient schemes to simultaneously mediate coherent interactions between multiple quantum systems and to reduce decoherence errors can minimize the control overhead in next-generation quantum processors. Here, we present a superconducting qubit architecture based on tunable parametric interactions to perform two-qubit gates, reset, leakage recovery and to read out the qubits. In this architecture, parametrically driven multi-element couplers selectively couple qubits to resonators and neighbouring qubits, according to the frequency of the drive. We consider a system with two qubits and one readout resonator interacting via a single coupling circuit and experimentally demonstrate a controlled-Z gate with a fidelity of 98.30 $\pm$ 0.23 %, a reset operation that unconditionally prepares the qubit ground state with a fidelity of 99.80 $\pm$ 0.02 % and a leakage recovery operation with a 98.5 $\pm$ 0.3 % success probability. Furthermore, we implement a parametric readout with a single-shot assignment fidelity of 88.0 $\pm$ 0.4 %. These operations are all realized using a single tunable coupler, demonstrating the experimental feasibility of the proposed architecture and its potential for reducing the system complexity in scalable quantum processors. [1]

[1] - G. B. P. Huber, F. A. Roy, L. Koch, I. Tsitsilin, J. Schirk, N. J. Glaser, N. Bruckmoser, C. Schweizer, J. Romeiro, G. Krylov, et al., Parametric multi-element coupling architecture for coherent and dissipative control of superconducting qubits, arXiv:2403.02203.

Microwave-to-Optics Transduction for Scaling Quantum Processors

Eugenio Cataldo
QphoX

Quantum processors have made great strides in qubit count and computing potential. However, scaling to practical applications requires orders-of-magnitude expansion, often limited by heat dissipation from I/O lines and cryogenic amplifiers [1]. Transferring signals via optical fiber eliminates these heat-loads and offers a promising path toward larger quantum processors [2,3]. QphoX develops technology for large-scale quantum computing by enabling bidirectional signal conversion between microwave and optical domains[4]. In the near term, this addresses the heat-load bottleneck of a single cryostat, replacing coaxial cables with optical fibers and eliminating HEMTs, enabling a 10-100x reduction in heat-load per qubit.At the single photon level, quantum transduction will enable room-temperature links between processors, paving the way for distributed quantum computing.

Our solutions enable both optical qubit control and readout. We extracted the readout signal via an integrated microwave-to-optics transducer, achieving 81% single-shot demolition readout fidelity [5], removing the need for HEMT amplifiers. We also delivered qubit control signals via a cryogenic photodiode-array. The heat-load of our optical link remains well below that of coaxial cabling, without measurably exciting the qubit. Together, these results highlight the feasibility of microwave-over-fiber, enabling quantum processors to scale beyond 1000 qubits in current-generation dilution refrigerators.

[1] Raicu et al. arXiv:2502.01945 (2025)
[2] Lecocq et al. Nature, 591, (2021) 575
[3] Delaney et al. Nature, 606,(2022) 489
[4] Weaver et al. Nat. Nano., 19 (2024) 166
[5] van Thiel et al. Nat. Phys., (2025)

Quantum Error Correction Using Quantum Latin Squares (the quantum combinatorial designs)

Abdul Fatah
Atlantic Technological University Galway Ireland

This study highlights the application of quantum Latin squares (QLS) in the context of quantum error correction (QEC). Inspired by quantum combinatorial designs introduced by Musto and Vicary in 2016, QLS are the quantum variant and generalisation of classical Latin squares (CLS)[1]. QLS offer a novel approach for designing quantum error correction codes[2].
This research elucidates the fundamental principles behind quantum Latin squares, their significance in preserving quantum coherence, and their potential to enhance the robustness of quantum technologies[3]. It establishes the theoretical foundation linking quantum Latin squares to classical Latin squares and emphasises their significance in quantum computing. It provides unique insights into their applications, particularly in quantum error correction. The relationship between quantum Latin squares, mutually unbiased bases, and unitary error bases is examined to underscore their importance in constructing quantum error-correcting codes using mutually orthogonal quantum Latin squares [4]. CLS has a well-established application in classical error correction[5]. We focus on the analogous applications of QLS in quantum error correction
Our study furthers research on the construction of quantum error-correcting codes using quantum Latin squares, which is vital for developing large-scale fault-tolerant quantum computers.

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Modular ion microtrap apparatus at the NQCC

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At the National Physical Laboratory (NPL) we have developed scalable microfabricated ion traps for applications including quantum information processing. Recently we developed a modular platform to accommodate the vacuum-packaged ion microtrap, beam delivery systems for cooling and qubit control lasers, as well as imaging optics for detection. Computer-aided design enables straightforward but accurate assembly of the components; all optical systems and the vacuum chamber are mounted to a compact central platform. The optics delivering all laser beams to the trap are connected to external laser systems via optical fibres. Optical assemblies are mounted in modules that can be easily swapped to alternatives designed for different optical schemes. The complete system fits inside a 3-layer magnetic shield with current-stabilised nulling and bias coils.
Two variants of this modular system have been constructed for 88Sr+ ions. The 1st is specifically focused on coherent control using the optical qubit transition. This apparatus will be used in ongoing development of ion microtrap devices at NPL. The 2nd has additional scope for driving Raman transitions at 422 nm and at 1033 nm to allow the investigation of optical-metastable-ground qubits. The latter system was installed recently at the National Quantum Computing Centre with ion trapping demonstrated; laser cooling, micromotion compensation and ion shuttling along the segmented microtrap array have been shown.

Optimal Scheduling in a Quantum Switch
Sanidhay Bhambay
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With a growing number of quantum networks in operation, there is a pressing need for performance analysis of quantum switching technologies. A quantum switch establishes, distributes, and maintains entanglements across a network. In contrast to a classical switching fabric, a quantum switch is a two-sided queueing network. The switch generates Link-Level Entanglements (LLEs), which are then fused to process the network's entanglement requests. Our proof techniques analyse a two-time scale separation phenomenon at the fluid scale for a general switch topology. This allows us to demonstrate that the optimal fluid dynamics are given by a scheduling algorithm that solves a certain average reward Markov Decision Process.

Optimized flip-chip bonding process for high coherence 3D integrated superconducting quantum circuits
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In order to use quantum computing to tackle classically intractable problems, quantum processors must grow to larger scales. Yet, in current superconducting planar architectures, routing multiple control and readout lines to an increasing number of qubits while minimizing crosstalk remains a significant challenge.
3D-integration techniques, such as flip-chip bonding, play a crucial role in mitigating this problem by enabling more efficient connectivity. However, implementing a novel circuit geometry introduces new challenges, including maintaining high coherence and preserving precise parameter targeting. Flip-chip bonding relies on indium bump bonds to mechanically and galvanically connect two separate chips. The additional fabrication steps needed for this process can lead to new loss channels and degrade overall system performance. Moreover, in superconducting quantum circuits, capacitances and inductances are determined by the design of the electrodes. In a flip-chip assembly, these parameters depend on the gap separating the bonded chips and variations during the bonding process can limit accurate parameter targeting.
To address these challenges, we present the fabrication of high-thickness indium bumps and the development of an optimized flip-chip bonding process for high-coherence quantum circuits. Additionally, we introduce a method for improving interchip spacing control and parameter targeting using polymer spacers.

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In-cryostat qubit control and readout system utilizing cryo-CMOS technology
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Fully realizing cryogenic quantum computing in a scalable format requires fast readout processing and high-density electrical connectivity within the cryogenic environment. We present the operational capabilities and performance of an in-cryostat electronic control and readout system implemented using off-the-shelf CMOS technology for the control and readout of superconducting and semiconductor quantum processors.
We have developed a first-generation control and readout system based on an FPGA processor that operates continuously and effectively within a cryostat from room temperature down to 2.5 Kelvin. The system is fully reconfigurable on the fly and is housed within a 10x10 cm PCB. It is composed of two RF synthesizer channels, two DAC channels and two ADC channels. The RF synthesizer acts as a local oscillator (LO) for up and down conversion, covering a frequency range spanning from 70 MHz to 6.8 GHz. The two 14-bit 275 MSPS DAC channels for I/Q signal generation form the control path, and the two 14-bit 125 MSPS ADC channels for signal digitization form the readout path.

Atomic scale processing for quantum device fabrication

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Current generation quantum devices suffer from losses due to poor interface quality, non-uniform deposition and process induced surface damage. Employing advanced fabrication techniques to minimise (or avoid) these sources of loss could present a route towards higher quality films/interfaces, thus enabling longer coherence times for optical and superconducting quantum devices. In this poster we will discuss the use of atomic layer deposition (ALD) and atomic layer etching (ALE) to deposit high quality films and minimise surface defects. The atomic-scale processing techniques ALD and ALE offer sub-nm thickness control, wafer-scale uniformity & conformality, and low damage processing. Examples of how ALD can be used to fabricate superconducting nanowire single photon detectors (SNSPDs) and superconducting through silicon vias will be given. Both anisotropic and isotropic ALE are highlighted, demonstrating how ALE can accurately control etch depth, while also reducing surface damage. The applicability of ALD and ALE for quantum device fabrication was highlighted at the recent APS March meeting 2025. A 2x improvement in T1 time for Al resonators (300 μs to 600 μs) was demonstrated by first applying ALE to remove the lossy AlOx, and then capping with ALD Al2O3. Utilising advanced deposition and etching techniques with atomic-scale precision may offer a route towards improved performance for next generation quantum devices.

1. https://summit.aps.org/events/MAR-T18/4

Measurement-free, scalable and fault-tolerant universal quantum computing

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Reliable execution of large-scale quantum algorithms requires robust underlying operations, which is addressed by quantum error correction (QEC). Most modern QEC protocols rely on measurements and feed-forward operations, which are experimentally demanding, and often prone to high error rates. Additionally, no single error-correcting code intrinsically supports the full set of logical operations required for universal quantum computing. In this work, we present a complete toolbox for fault-tolerant universal quantum computing without measurements during algorithm execution by combining the strategies of code switching and concatenation. We develop fault-tolerant, measurement-free protocols to transfer encoded information between 2D and 3D color codes, that offer complementary and in combination universal sets of robust logical gates. Moreover, we extend the scheme to higher-distance codes by concatenating the 2D color code and integrating code switching for operations lacking a natively fault-tolerant implementation. Our measurement-free approach thereby provides a practical and scalable pathway for universal quantum computing on state-of-the-art quantum processors.

Quantum Information Processing with Trapped Rydberg Ions

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Combining the strong and long-range interaction of cold Rydberg atoms with the controllability of trapped ions, ultracold trapped Rydberg ions provide a promising platform for scalable quantum computing. We demonstrate how microwave-dressed Rydberg states result in rotating permanent dipole moments causing strong dipole-dipole interaction between ions in highly excited Rydberg states. Due to the large difference in time scales, the fast electronic dynamics of the Rydberg ions decouple from the slower oscillator modes in the linear Coulomb crystal. These properties allow us to realize a submicrosecond two-qubit gate between two Rydberg ions confined in a Paul trap reaching fidelities of $> 99\%$ under consideration of the finite lifetime of the Rydberg states at room temperature.

Wilkinson, J. W. P., Bolsmann, K.,Guedes, T. L. M., Müller, M., & Lesanovsky, I. Two-qubit gate protocols with microwave-dressed Rydberg ions in a linear Paul trap. arXiv:2412.13699 (2024).

Universal Quantum Computation via Scalable Measurement-Free Quantum Error Correction

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A major challenge in quantum error correction (QEC) is implementing fast and reliable measurements and feed-forward. With unconditional resets or a continuous supply of fresh qubits, measurement-free (MF) schemes are possible, where error correction is realized via coherent quantum feedback. Implementations of small MF schemes, fault-tolerant to circuit-level noise, have been designed. Among these, the protocol for the Bacon-Shor code demonstrated the best logical performance [1]. We further show that not only QEC cycles but universal logical quantum computation can be fault-tolerant without intermediate measurements [2]. To this end, we introduce a MF protocol for the logical CCZ gate in the Bacon-Shor code, enabling a universal set of fault-tolerant operations. Independently, we show that certain stabilizer codes can be concatenated in a MF fashion without a universal gate set, via the resource-efficient "disposable Toffoli gadget". For benchmarking, we implement an efficient method to simulate non-Clifford circuits consisting of 80+ qubits and Toffoli-like gates, albeit few Hadamards, available as SparseStates.jl. We show that below-breakeven logical performance is achievable with a depolarizing error rate below 0.1Altogether, the logical-CCZ protocol and the Toffoli gadget provide a blueprint for a universal fully fault-tolerant architecture without feed-forward operations, particularly suited for state-of-the-art neutral-atom platforms.

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Native oxide passivated trilayer junction-based superconducting qubits

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VTT

Superconducting qubits are typically fabricated with angle-evaporated aluminum-aluminum oxide- aluminum Josephson junctions. However, there is an urgent need to overcome the limited reproducibility of this approach when scaling up the number of qubits and junctions. Fabrication methods based on subtractive patterning of superconductor-insulator-superconductor trilayers, used for more classical large-scale Josephson junction circuits, in turn often suffer from lossy dielectrics unsuitable for maintaining high qubit coherence. In this work, we propose and implement a superconducting qubit, utilizing native aluminum oxide as a sidewall passivation layer for an aluminum-aluminum oxide-niobium trilayer. The native oxide serves as an effective insulation for the tunnel junction, whose niobium electrode is electrically connected to a niobium wiring layer with a via. With these components, we design transmon qubits and measure time-averaged coherence times of up to 30 μs at a qubit frequency of 5 GHz, corresponding to a qubit quality factor of one million. Our process uses subtractive patterning and optical lithography on 150 mm wafers, enabling high throughput in patterning. Our approach provides a scalable pathway for the fabrication of superconducting qubits on industry-standard platforms.

Time-resolved noise characterization tool to track fluctuating noise effects in superconducting qubits

Abhishek Agarwal
National Physical Laboratory

We present a framework for the simultaneous and automated characterisation of fluctuating qubit noise sources. Fluctuations in qubit properties and noise present key issues to quantum computing implementations and limit the performance of quantum error mitigation and error correction. Characterising these fluctuations is challenging due to the multitude of fluctuations present concurrently at short and long timescales. Typically, specific experiments are designed to probe the effects of individual sources of fluctuations. Our characterisation framework includes performing averaging over minimal data to detect fluctuations and a tool called the hierarchical discrete fluctuation autosegmentation (HDFA) which we develop to disentangle the different fluctuations present. We apply this framework on a superconducting transmon qubit system and and find that with our autosegmentation tool we can disentangle all frequency fluctuations that occur in timescales ranging from 10s of milliseconds to hours, and map them to compatible physical models by using the computed properties and correlations of different fluctuations.
Thus, with our framework for disentangling fluctuations, overlapping fluctuations with similar amplitudes no longer need to be avoided by characterising different fluctuations independently, but rather can actively be included to allow correlating different fluctuations and gaining insights into their origin.

Agarwal et al. "Modelling non-Markovian noise in driven superconducting qubits" Quantum Sci. Technol. 9 035017 (2024)

Numerical simulation of two-qubit gates for a system of transmons

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While applying gates on specific qubits, the presence of other qubits affect the fidelity of the gates. In this work, we study the crosstalk effects in the two-qubit gate fidelity due to presences of neighbouring qubits and couplers in a system of tuneable transmon qubits which are coupled via tuneable transmon couplers. We compared the fidelity of a CZ gate in the presence and absence of neighbouring transmons. Then we scale up the system to a larger 2-D chip of transmons which are effectively coupled and also study the effect of dissipation on the iSWAP gate.

Lightning Talks

SQALE: Scalable Quantum Atomic Lattice computing testbed

Mathew Hill
Infleqtion

Full stack superconducting testbed with tuneable couplers and scalable control system

Ben Griffiths
Rigetti UK

QUARTET: The QUantum Advantage-Ready Trapped-ion Exploration Testbed

Tom Harty
Oxford Ionics

Asteroidea: a flexible photonic quantum computing testbed for machine learning

Tom Parker
ORCA

Towards an error-corrected neutral-atom quantum computer
Cornelis Ravensbergen
QuEra Computing

Quantum system based on spin qubit technology
David Ibberson
Quantum Motion

ARTEMIS: Advanced Research TEstbed Manipulating PhotonIc States
Scott Dufferwiel
Aegiq