^{22}NACTI^{+}

3rd North American Conference on Trapped Ions

1-4 August 2022

Duke Quantum Center &
Institute for Quantum Computing at the University of Waterloo

Duke University
Durham, NC, USA

Contents

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Timetable

Monday, August 1st

08:15–08:50	Registration
08:50–09:00	Welcome and Opening of the Meeting

1A. Scaling and Architectures + Networking

Chair: N. Linke

09:00–09:30	J. Siverns University of Maryland / Army Research Laboratory *Experiments with trapped ion quantum frequency conversion*
09:30–10:00	B. Nichol Oxford University *Entanglement-enhanced comparison of remote clocks and other quantum networking applications*
10:00–10:30	R. Islam University of Waterloo *Precise and programmable individual optical addressing for Yb^+ and Ba^+ qubits*

10:30–11:15	Break

1B. New qub(d)its and gates

Chair: L. Feng

11:15–11:45	P. McMillin UCLA *Metastable Qubit Operations in* $^{171}Yb^{+}$
11:45–12:15	C. Senko University of Waterloo *High-dimensional qudits in* Ba^{+}

12:15–13:45	Lunch

1C. Precision Measurement and Clocks

Chair: J. Dilling

13:45–14:15	D. Hume NIST *Multi-ion logic spectroscopy*
14:15–14:45	D. A. Craik MIT *Evidence of two-source King nonlinearity in spectroscopic fifth-force search in* Yb^{+}
14:45–15:15	Kia Boon Ng CU Boulder *Probing physics beyond the Standard Model with the JILA eEDM experiments*

15:15–16:45	Poster Session 1 (See page 49)

16:45–17:00	Transit
17:00–18:30	Reception

Tuesday, August 2nd

2A. Beyond Atomic Ions

09:30–10:00 | T. Schaetz

Freiburg University

The onset of controlling atom-ion quantum effects via Feshbach resonances

10:00–10:30 | N. Yadav

UC Berkeley

Towards a Trapped Electron Quantum Computer

10:30–11:15 | Break

2B. New qub(d)its and gates

Chair: C. Senko

11:15–11:45 | C. Clark

Georgia Tech Research Institute

Ion trapping at GTRI: Ion trapping at GTRI: From high-fidelity gates to mass-spectrometry

11:45–12:15 | O. Katz

Duke University

Programmable interactions between spins and bosons in trapped ion systems

12:15–13:45 | Lunch

2C. Quantum Computing and Simulation

Chair: M. Cetina

13:45–14:15	P. Richerme Indiana University *Ion-Trap Quantum Simulations of Hydrogen-Bond Dynamics*
14:15–14:45	C. Ryan-Anderson Quantinuum *Quantum error correction using hybrid compute environment*
14:45–15:15	J. Kim IonQ *Benchmarking IonQ Quantum Computers using Alogorithmic Qubits (#AQ)*

15:15–17:15	Poster Session 2 (See page 49)

17:15–18:00	Transit to Dinner
18:00–20:00	Dinner

Wednesday, August 3rd

3A. Fabrication of New Traps
Increasing accessibility of Ion Trapping

Chair: R. Clark

09:00–09:30	R. McConnell Lincoln Laboratory *Ion Traps with Integrated Components for Quantum Sensing and Computing*
09:30–10:00	S. Clark Sandia National Laboratory *Sandia's Ion Trap Quantum Computing: Increasing Accessibility*
10:00–10:30	A. Bautista Salvador PTB *Fabrication, Integration and Future Standardization of Advanced Surface-Electrode Ion Traps*

10:30–11:15	Break

3B. Hot Topic 1

Chair: S. Clark

11:15–11:35	K. Arnold National Univ. of Singapore *High accuracy assessment of a $^{176}Lu^+$ frequency reference*
11:35–11:55	A. Safavi-Naini Univ. of Amsterdam *Trapped ion quantum computing with tweezers and electric fields*
11:55–12:15	D. Allcock Univ. of Oregon *Geometries and fabrication methods for 3D printing ion traps*

12:15–13:45	Lunch
12:15–13:45	Women in Ions Lunch

3C. Hot Topic 2

Chair: Y. Yu

13:45–14:05	D. Kiesenhofer Innsbruck University *Controlling two-dimensional crystals of up to 91 ions in a novel linear Paul trap*
14:05–14:25	W. Burton Quantinuum *Transport of multispecies ion crystals through a junction in an RF Paul trap*

14:25–15:10	Transit to Garden / Museum
15:10–16:40	Scavanger Hunts (Garden / Museum)
16:40–17:40	Transit to Hotels

20:00–21:30	Industry Session

Thursday, August 4th

4A. Quantum Computing and Simulation

Chair: C. Noel

09:00–09:30	G. Zarantonelo NIST *Coherently coupled mechanical oscillators in the quantum regime*
09:30–10:00	P. Schindler Innsbruck University *Demonstration of fault-tolerant universal quantum gate operations*
10:00–10:30	W. Morong University of Maryland *Analog-digital quantum simulations with trapped ions*

10:30–11:15	Break

4B. Hot Topic 3

11:15–11:35	M. Wójcik M-Labs *The future of ARTIQ ecosystem*
11:35–11:55	L. Riesebos Duke University *Modular software for real-time quantum control systems*

11:55–13:25	Lunch

13:25–14:15	Transit to Chesterfield
14:15–16:15	Chesterfield Lab Tours

16:15–16:45	Walk to One City
16:45–18:15	Happy Hour

Talk abstracts

Mon, Aug. 1st, 1A, 09:00-09:30

Experiments with trapped ions and quantum frequency conversion

J. Siverns

University of Maryland
Army Research Laboratory

Future trapped-ion quantum networks will require the ability to produce ion-photon entanglement at photon frequencies not naturally emitted from the ion. This will allow the creation of a hybrid network architecture, where photons can couple to a wide variety of memory platforms. Additionally, quantum devices such as photonic integrated circuits, useful for multiplexing, routing, and storage, operate at various wavelengths often in the telecom regime. However, most trapped ions emit photons in the ultra-violet and visible wavelength regime. The integration of quantum frequency conversion and photons emitted by trapped ions provides tailor-made photon frequencies. In this talk, I will present our recent demonstration-of-concept of on-demand routing of frequency converted C-band photons emitted from a trapped barium ion using a foundry-fabricated silicon-nitride photonic integrated circuit [**1**]. A critical network task for multiplexing hybrid memory platforms is entanglement of the frequency converted photon with the trapped ion memory. I will also present our recent results demonstrating entanglement between a trapped ion qubit and frequency converted photons at 780 nm [**2**]. This photon wavelength extends the network range and is compatible with neutral atom quantum memory nodes, enabling remote hybrid entanglement-based networking [**3**].

[1] U. Saha, J. D. Siverns, J. Hannegan, M. Prabhu, Q. Quraishi, D. Englund, and E. Waks, arXiv:2203.08048 (2022)

[2] J. Hannegan, J. D. Siverns, and Q. Quraishi, arXiv:2207.13680 (2022)
[3] J. Hannegan, J. D. Siverns, J. Cassell, and Q. Quraishi Phys. Rev. A 103, 052433 (2021)

Mon, Aug. 1st, 1A, 09:30-10:00

Entanglement-enhanced comparison of remote clocks and other quantum networking applications

Bethan C. Nichol

Oxford University

We discuss two recent experiments performed using a state-of-the-art elementary two-node network, which links two separate ion traps via a single-photon optical fibre interface [**1**]. Both experiments rely on the ability to generate high-fidelity entanglement between two remote trapped-ion qubits at high speed. In the first experiment [**2**] we show how remote entanglement could be used to enhance a frequency comparison between two atomic clocks beyond the "standard quantum limit". In the second experiment [**3**] we present a realization of a complete quantum key distribution (QKD) protocol immune to the vulnerabilities of the physical devices used in the implementation. The security of this "device independent" protocol is certified through a Bell test, as first proposed 30 years ago by Ekert.

[1] Stephenson, Nadlinger et al., Phys. Rev. Lett. 124, 110501 (2020)
[2] Nadlinger et al., Nature 607, 682–686 (2022)
[3] Nichol, Srinivas et al., arXiv:2111.10336 (2021)

Mon, Aug. 1st, 1A, 10:00-10:30

Precise and programmable individual optical addressing for Yb^+ and Ba^+ qubits

Rajibul Islam

University of Waterloo

In this talk, I will describe our experimental effort to develop programmable trapped ion quantum simulators based on Ytterbium and Barium ions. Techniques from holographic optical engineering to machine learning can be combined to harness the power of these simulators. I will present our recent experimental results from the Yb system on dissipating and measuring a target ion while retaining the coherence of its neighbor only a few microns away (without shuttling). These capabilities, together with the ability to create programmable coherent spin-spin interactions form the basis of novel quantum simulations, such as new algorithms for cooling into a many-body ground state and observation of measurement driven phase transitions. I will also describe a compact and scalable single-qubit optical addressing system for Ba ions, leveraging laser-written waveguide technology for visible wavelengths.

Mon, Aug. 1st, 1B, 11:15-11:45

Metastable Qubit Operations in ^{171}Yb^{+}

P. McMillin

University of California, Los Angeles

The metastable ("*m*-type") qubit defined on the zero-field hyperfine clock states in the long-lived $^{2}F^{o}_{7/2}$ manifold in ^{171}Yb^{+} gives a promising pathway to low cross-talk, high fidelity multi-qubit operations using the same ion species via the recently proposed "*omg* blueprint" for atomic quantum processing. We describe heralded state preparation, single qubit operations, and state measurement in the *m*-type qubit, achieving a SPAM infidelity of $4^{+3}_{-2} \times 10^{-4}$ and provide empirical, quantitative limits on the effect of direct illumination by ground state ("*g*-type") qubit light. Additionally, we report our progress on spectroscopy, trapping and cooling of ^{173}Yb^{+}, which will have six long-lived *m*-type hyperfine clock states at zero field.

Mon, Aug. 1st, 1B, 11:45-12:15

High-dimensional qudits in Ba^+

C. Senko

University of Waterloo

Multi-level qudits have many potential applications in quantum simulation and quantum computation, and are relatively underexplored compared to the well understood trapped ion qubits. Ba^+ ions, including the rare radioactive isotope $^{133}Ba^+$, are a promising candidate to host qudits. We demonstrate state-measurement protocols for high dimensional qudits encoded in isotopes of Ba^+, and describe progress toward characterizing the scaling of SPAM fidelity with qudit dimension. We also present results in characterizing fabrication processes that are compatible with $^{133}Ba^+$ for producing microgram barium sources.

Mon, Aug. 1st, 1C, 13:45-14:15

Multi-ion Quantum Logic Spectroscopy

David B. Hume

NIST

Quantum logic spectroscopy enables precision measurements on atomic and molecular species that are not amenable to direct fluorescence measurements. Typically, a single "spectroscopy ion" is paired with a single "logic ion", in the same trap and the spectroscopy ion state is transferred to the logic ion via a quantum gate. Scaling up the number of ions in these systems would result in lower projection noise and ultimately higher measurement stability. We have developed a technique for quantum logic spectroscopy that allows for multiple spectroscopy ions and multiple logic ions with the aim of developing a multi-ion optical clock based on $^{27}Al^{+}$. I will discuss these experiments and review recent results from the Al^{+} optical clocks.

Mon, Aug. 1st, 1C, 14:15-14:45

Evidence of two-source King nonlinearity in spectroscopic fifth-force search in Yb^+

Diana Prado Lopes Aude Craik

Massachusetts Institute of Technology

Isotope-shift spectroscopy has recently been put forward as a table-top method for searching for a hypothetical boson that mediates an interaction between the neutron and the electron. The Yukawa potential generated by this boson would lead to neutron-number-dependent shifts in atomic transition frequencies. When measured on at least two transitions, these shifts can be displayed in a "King plot", which will exhibit nonlinearities in the presence of effects beyond the expected first-order standard model shifts.

We have measured isotope shifts on three narrow optical transitions, on five spinless isotopes of Yb^+. Our latest data, on the highly forbidden 467nm octupole transition between $^2S_{1/2}$ and $^2F_{7/2}$, when combined with our previous measurements of quadrupole transitions in Yb^+ and recent measurements in neutral Yb, confirm the presence of a King nonlinearity with up to 240σ confidence. The data also reveal, with 4.3σ sigma confidence, that this nonlinearity emerges from at least two distinct physical effects.

We identify the main source of nonlinearity as differences in the 4^{th} nuclear charge moment between isotopes, a higher-order nuclear effect that had not previously been probed with high precision. From current calculations, we find that the second source of nonlinearity likely cannot be explained by the quadratic field shift, the expected next-largest effect within the standard model. We discuss possible sources for this second nonlinearity and outline how ongoing and future work can elucidate whether it emerges from a new boson.

Mon, Aug. 1st, 1C, 14:45-15:15

Probing physics beyond the Standard Model with the JILA eEDM experiments

Kia Boon Ng, Tanya Roussy, Noah Schlossberger, Sun Yool Park, Trevor Wright, Anzhou Wang, Antonio Vigil, Gustavo Santaella, Luke Caldwell, Jun Ye and Eric Cornell

JILA, University of Colorado, Boulder

The Standard Model of particle physics is one of the most successful models that we use to describe the universe, yet it is known to be incomplete. Substantial efforts on the theoretical front introduce new physics through extensions of the Standard Model, and these new physics models make predictions on the value of the electric dipole moment of the electron (eEDM). Measurements of (or improved limit on) the eEDM places constraints on these new theories. The eEDM experiments at JILA take advantage of the long trapping time of ions to tap the long coherence times of the eEDM-sensitive states in our molecular ions of choice: HfF^+ and ThF^+. The ongoing experiment using HfF^+ is an upgraded version of our 2017 experiment [**1**], using a bigger trap for more ions, amongst other improvements for better statistics. Our current data set places our statistical sensitivity at two times better than the current world record [**2**]. The upcoming experiment using ThF^+ has recently completed spectroscopy of the molecule [**3, 4, 5**], and we are now setting up a prototype experiment to demonstrate much longer coherence times than HfF^+, promised to us by the eEDM-sensitive ground state in ThF^+ [**3, 5**]. Herein, we present updates on our studies on systematics on the upgraded HfF^+ system, and provide a teaser on the demonstration of long coherence times in ThF^+.

[1] W. B. Cairncross, D. N. Gresh, M. Grau, K. C. Cossel, T. S. Roussy, Y. Ni, Y. Zhou, J. Ye, and E. A. Cornell, Precision Measurement of the Electron's Electric Dipole Moment Using Trapped Molecular Ions, Phys. Rev. Lett. 119, 153001 (2017).

[2] The ACME Collaboration: V. Andreev, D. G. Ang, D. DeMille, J. M. Doyle, G. Gabrielse, J. Haefner, N. R. Hutzler, Z. Lasner, C. Meisenhelder, B. R. O'Leary, C. D. Panda, A. D. West, E. P. West, and X. Wu, Improved limit on the electric dipole moment of the electron, Nature 562, 355-360 (2018).

[3] D. N. Gresh, K. C. Cossel, Y. Zhou, J. Ye, and E. A. Cornell, Broadband velocity modulation spectroscopy of ThF^+ for use in a measurement of the electron electric dipole moment, J. Mol. Spectrosc. 319, 1 (2016).

[4] Y. Zhou, K. B. Ng, L. Cheng, D. N. Gresh, R. W. Field, J. Ye, and E. A. Cornell, Visible and ultraviolet laser spectroscopy of ThF, J. Mol. Spectrosc. 358, 1 (2019).

[5] K. B. Ng, Y. Zhou, L. Cheng, N. Schlossberger, S. Y. Park, T. S. Roussy, L. Caldwell, Y. Shagam, A. J. Vigil, E. A. Cornell, and J. Ye, Spectroscopy on the electron-electric-dipole-moment–sensitive states of ThF^+, Phys. Rev. A 105, 022823

Tue, Aug. 2nd, 2A, 09:30-10:00

The onset of controlling atom-ion quantum effects via Feshbach resonances

Tobias Schaetz

Albert Ludwigs University Freiburg, 79104 Freiburg, Germany

Isolating ions and atoms from the environment is essential for experiments, especially if we aim to study quantum effects. For decades, this has been achieved by trapping ions with radiofrequency (rf) fields and neutral particles with optical fields. We are trapping ions by the interaction with light and electrostatic fields, in absence of any rf-fields. We take our results as starting point for studying how to combine the advantages of optical trapping and ions.

In the first part of the talk, we will focus on the basics of optically trapping ions. In the second part we aim to demonstrate the prospects of our approach in the context of interaction and reaction at ultra-low temperatures as a showcase. Following the seminal work in other groups in hybrid traps, we embed optically trapped ions into quantum gases to reach lowest temperatures, circumventing the currently inevitable excess kinetic energy in hybrid traps, where ions are kept but also driven by rf-fields.

We will discuss our recent results on optically trapping $^{138}Ba^{+}$, ^{87}Rb and ^{6}Li atoms in hybrid traps, where we recently observed Feshbach reonances, and bi-chromatic dipole traps, related challenges and perspectives.

Tue, Aug. 2nd, 2A, 10:00-10:30

Towards a Trapped Electron Quantum Computer

Qian Yu, Izze Sacksteder, Alberto Alonso, Neha Yadav and Hartmut Häffner

Department of Physics, University of California, Berkeley, California 94720, USA
Challenge Institute for Quantum Computation, University of California, Berkeley, CA 94720

Due to their light mass and two-level spin system, trapped electrons form a promising platform for realizing a novel quantum computer. The two-level spin system is ideal for storing quantum information, which can be easily manipulated and read out using microwave technology. In this talk, we present the feasibility [**1**] of such a platform and discuss the efforts underway to realize it using Paul trap [**2**], particularly, trap design, cooling, electronic detection, spin readout, and gate operations.

[1] Yu, Qian, Alberto M. Alonso, Jackie Caminiti, Kristin M. Beck, R. Tyler Sutherland, Dietrich Leibfried, Kayla J. Rodriguez, Madhav Dhital, Boerge Hemmerling, and Hartmut Häffner. Feasibility study of quantum computing using trapped electrons. *Physical Review A* 105, no. 2 (2022): 022420.

[2] Matthiesen, Clemens, Qian Yu, Jinen Guo, Alberto M. Alonso, and Hartmut Häffner. Trapping electrons in a room-temperature microwave Paul trap. *Physical Review X*, 11, no. 1 (2021): 011019.

Tue, Aug. 2nd, 2B, 11:15-11:45

Ion trapping at GTRI: From high-fidelity gates to mass-spectrometry

C. Clark

Georgia Tech Research Institute

All of the fundamental elements needed to perform trapped-ion quantum information processing have been demonstrated, but there remains room for improvement in terms of fidelity, speed, reproducibility, and flexibility. GTRI's Quantum Systems Division has been working recently to develop methods for ion transport and gate operations that are more robust, are faster, and require fewer resources than many techniques commonly employed. We have achieved advances in the coherent control of ion motion, demonstrating improvements in high-speed, low-excitation linear transport with the aid of fast commercial DAC/AWG electronics. We have also realized individual addressing and two-qubit process tomography via fast trap potential modulation within a pair of co-trapped ions [**1, 2**]. In the same apparatus we have performed a transport-enabled Mølmer-Sørensen entangling gate on a pair of co-trapped ions by shuttling the pair through a static laser beam [**3**]. In a different apparatus, we have demonstrated high-fidelity generation of an optical-qubit Bell-state using a gate scheme which is less sensitive to laser intensity and magnetic-field variations than the standard Mølmer-Sørensen gate [**4, 5**]. We are currently working to leverage fast electrode waveforms for dynamical exchange cooling, in which a hot ion is cooled via energy exchange with an initially colder ion [**6, 7**]. This could relax the time-consuming sympathetic-cooling requirements of many experiments. We are planning an effort to demonstrate near real-time calibration and stabilization of qubit frequencies via feedback through measurements of a nearby spectator ion [**8**]. GTRI also has experiment and theory efforts directed towards quantum approximate optimization of graph problems (e.g. MaxCut) on NISQ hardware [**9**]. We recently demonstrated MaxCut QAOA on 1D strings of up to 10 $^{171}Yb^+$ ions. We are extending this work to 2D ion arrays in GTRI's compact Penning trap [**10**], leveraging infrared Raman interactions with metastable $D_{5/2}$ qubits in $^{40}Ca^+$ to achieve individual-ion addressing. In work less directly related to quantum information, Georgia Tech has begun an effort to develop a multilayer surface-electrode ion trap incorporating metalens output couplers for complex optical phase-front generation. This will enable flexible beam profiles which could be optimized, for example, to reduce coupling to adjacent ions or to enhance uniformity when addressing multiple ions. GTRI is also developing chip-scale linear ion traps for use as mass analyzers in low size, weight, power, and cost portable mass spectrometers. This system will provide a significant improvement in sensitivity and resolution for substance identification over currently available technology.

[1] Seck, Christopher M. et al., New J. Phys. 22, 053024 (2020)
[2] Tinkey, Holly N. et al., Quantum Sci. Technol. 6, 034013 (2021)
[3] Tinkey, Holly N. et al., Phys. Rev. Lett. 128, 050502 (2022)
[4] Sawyer, Brian C. and Brown, Kenton R., Phys. Rev. A 103, 022427 (2021)
[5] Clark, Craig R. et al., Phys. Rev. Lett. 127, 130505 (2021)
[6] Brown, K. R. et al., Nature 471, 196-199 (2011)
[7] Sägesser, T. et al., New J. Phys. 22., 073069 (2020)
[8] Majumder, Swarnadeep et al., npj Quantum Inf. 6, 19 (2020)
[9] Rajakumar, Joel et al., arXiv:2011.08165 (2020)
[10] McMahon, Brian J. and Sawyer, Brian C., Phys. Rev. Appl. 17, 014005 (2022)

Tue, Aug. 2nd, 2B, 11:45-12:15

Programmable interactions between spins and bosons in trapped ion systems

O. Katz

Duke University

We present new techniques to realize quantum gates and simulations using ion-phonon interactions. We first describe a single-step protocol to generate N-body entangling interactions between trapped atomic ion qubits using spin-dependent squeezing; we analyze the effect of multiple motional modes and present preliminary experimental results. Second, we present a scheme to program a dense graph of couplings between the phonon modes in trapped-ion crystals, with applications to quantum simulations of bosonic systems.

This work is supported by the ARO through the IARPA LogiQ program; the NSF STAQ program; the DOE QSA program; the AFOSR MURIs on Dissipation Engineering in Open Quantum Systems, Quantum Measurement/Verification, and Quantum Interactive Protocols; and the ARO MURI on Modular Quantum Circuits.

Tue, Aug. 2nd, 2C, 13:45-14:15

Ion-Trap Quantum Simulations of Hydrogen-Bond Dynamics

Philip Richerme

Indiana University

Calculating observable properties of quantum chemical systems is a promising application of quantum computers. While most quantum algorithms and experimental demonstrations to date have focused on calculations of electronic structure in molecules, we have recently developed a protocol to study nuclear dynamics processes as well. In this talk, I will describe experiments which use the QSCOUT and IonQ trapped-ion quantum computers to emulate the quantum dynamics and vibrational properties of hydrogen-bonded systems. In our approach, we first treat the proton dynamics as a reduced-dimensional problem on a discretized lattice, then map its Hamiltonian to a sequence of quantum gate operations. Next, we implement these quantum gates on an ion-trap quantum computer to simulate how the proton wavepacket evolves due to the surrounding nuclear framework and electronic potential. Finally, we extract the characteristic vibrational frequencies for the proton motion using the experimentally-simulated dynamics. Our approach offers a new paradigm for simulating quantum dynamics and for computing accurate expectations values, opening the potential to study a range of chemical systems which are otherwise intractable.

Tue, Aug. 2nd, 2C, 14:15-14:45

Quantum error correction using hybrid compute environment

C. Ryan-Anderson,[1*] N. C. Brown,[1†] M. S. Allman,[1] B. Arkin,[1] G. Asa-Attuah,[2] C. Baldwin,[1] J.Berg,[1] J. G. Bohnet,[1] S. Braxton,[1] N. Burdick,[2] J. P. Campora,[1] A. Chernoguzov,[1] J. Esposito,[1] B.Evans,[1] D. Francois,[1] J. P. Gaebler,[1] T. M. Gatterman,[1] J. Gerber,[1] K. Gilmore,[1] D. Gresh,[1] A. Hall,[1] A.Hankin,[1] J. Hostetter,[2] D. Lucchetti,[1] K. Mayer,[1] J. Myers,[2] B. Neyenhuis,[1] J. Santiago,[2] J. Sedlacek,[2] T. Skripka,[1] A. Slattery,[2] R. P. Stutz,[1] J. Tait,[2] R. Tobey,[1] G. Vittorini,[2] J. Walker,[1] and D. Hayes[1]

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We characterize and compare two different implementations of fault-tolerant entangling gates on logical qubits for which we utilize hybrid compute to determine corrections in real-time. In one instance, a twelve-qubit trapped-ion quantum computer is used to implement a non-transversal logical CNOT gate between two logical qubits using the [[5,1,3]] quantum error correction code. The operation is evaluated with varying degrees of fault tolerance, which are provided by including quantum error correction

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circuit primitives known as flagging and pieceable fault tolerance. In the second instance, a twenty-qubit trapped-ion quantum computer isused to implement a transversal logical CNOT gate on two logical qubits using the [[7,1,3]] color code. The two codes were implemented on different but similar devices, and in both instances, all of the quantum error correction primitives, including the determination of corrections via decoding, are implemented during run-time using a classical compute environment that is tightly integrated with the quantum processor. For different combinations of the primitives, logical state fidelity measurements are made after applying the gate to different input states, providing bounds on the process fidelity. We find the highest fidelity operations with the [[7,1,3]] color code, with the fault-tolerant state preparation and measurement (SPAM) operation achieving fidelities of 0.99939(15) and 0.99959(13) when preparing eigenstates of the logical X and Z operators, which is higher than the average physical qubit SPAM fidelities of 0.9968(2) and 0.9970(1) for the physical X and Z bases, respectively. When combined with a logical transversal CNOT gate, we find the [[7,1,3]] color code to perform the sequence – state preparation, CNOT, measure out – with an average fidelity bounded by [0.9957,0.9963] . The logical fidelity bounds are higher than the analogous physical-level fidelity bounds, which we find to be [0.9850,0.9903], reflecting multiple physical noise sources such as SPAM errors for two qubits, several single-qubit gates, a two-qubit gate and some amount of memory error. To help assess the long-term promise of these codes, we also present detailed simulations of the two codes' performance in regimes of lower physical error rates.

Tue, Aug. 2$^{\text{nd}}$, 2C, 14:45-15:15

Benchmarking IonQ Quantum Computers using Alogorithmic Qubits (#AQ)

J. Kim

IonQ Inc.

In this talk I will give an introduction to our proposed volumetric benchmark, based on the recent work of the QEDC, known as algorithmic qubits. Discuss how measurements of this benchmark were performed on our Aria generation hardware including an brief overview of the salient features of this generation of our hardware. Lastly I will describe a newer generation of hardware, Forte, along with the latest results from a system of that generation.

Wed, Aug. 3rd, 3A, 09:00-09:30

Ion Traps with Integrated Components for Quantum Sensing and Computing

Robert McConnell

MIT Lincoln Laboratory

Integrated technologies represent a promising pathway towards increasing the number of qubits in a trapped-ion quantum processor while maintaining high-fidelity operations, and towards miniaturizing trapped-ion systems for future compact optical clocks and other quantum sensors. MIT Lincoln Laboratory has been developing an integrated platform for light delivery and collection in surface-electrode ion array traps. In this talk, I will discuss our recent results on multi-wavelength integrated photonics for light delivery and remote entanglement generation, integrated avalanche photodiodes for ion state detection, and integrated electronics for ion motional control.

Wed, Aug. 3rd, 3A, 09:30-10:00

Sandia's Ion Trap Quantum Computing: Increasing Accessibility

Susan Clark

Sandia National Laboratory

Sandia National Labs has been a leader in ion trap chip fabrication for more than 15 years. In this presentation, I will review Sandia's approach to ion trap chip fabrication and show recent results pertaining to improved trap performance, including mitigations of RF breakdown events, efforts to make traps re-bakable, and heating rate studies with a new gold coating technique. Additionally, I will review results from several ongoing projects to develop technologies for the next-generation scalable ion traps, including the addition of on-chip waveguides, modulators, and detectors.

Finally, I will give an overview of the Quantum Scientific Computing Open User Testbed (QSCOUT) program at Sandia, which is a small quantum computer based on trapped ions available to the research community. This testbed is a unique platform due to its pulse-level access and transparency of implementation, operation, and evaluation of quantum circuits.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Wed, Aug. 3rd, 3A, 10:00-10:30

Fabrication, Integration and Future Standardization of Advanced Surface-Electrode Ion Traps

A. Bautista-Salvador

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In recent years, the development of surface-electrode ion traps has evolved at an incredible pace. On the first part of this talk, I will provide an overview of our past and present results regarding fabrication and operation of scalable surface-electrode ion traps [**1, 2, 3, 4**] at the National Metrology Institute of Germany (PTB). On a second part, I will give you an insight of ongoing projects towards integration of quantum control elements with strong focus on quantum computing applications on next generation of surface-electrode ion traps. On the last part of this talk I will present the ion-trap user facility being built at the Quantum Technology Competence Center at PTB [**5**] and provide an overview of our goals towards standardization of microfabricated ion traps.

[1] A. Bautista-Salvador et al., “Multilayer ion trap technology for scalable quantum computing and quantum simulation,” New J. Phys., vol. 21, no. 4, p. 043011, Apr. 2019, doi: 10.1088/1367-2630/ab0e46.

[2] G. Zarantonello et al., “Robust and Resource-Efficient Microwave Near-Field Entangling 9 Be + Gate,” Phys. Rev. Lett., vol. 123, no. 26, p. 260503, Dec. 2019, doi:10.1103/PhysRevLett.123.260503.
[3] H. Hahn et al., “Multilayer ion trap with three-dimensional microwave circuitry for scalable quantum logic applications,” Appl. Phys. B, vol. 125, no. 8, p. 154, Jul. 2019, doi: 10.1007/s00340-019-7265-1.
[4] M. Duwe et al., “Numerical optimization of amplitude-modulated pulses in microwave-driven entanglement generation,” Quantum Sci. Technol., 2022, doi: 10.1088/2058-9565/ac7b41.
[5] https://www.ptb.de/cms/nc/en/ptb/competence-centers/qtz.html

Wed, Aug. 3rd, 3B, 11:15-11:35

High accuracy assessment of a ^{176}Lu$^+$ frequency reference

K. J. Arnold[‡], M. D. K. Lee, Y. B. Lee, Qin Qichen, W. Y. Tan, Zhao Qi, Zhang Zhao, Zhiqiang Zhang and M. D. Barrett

Centre for Quantum Technologies, National University of Singapore, Singapore

We experimentally demonstrate a frequency comparison between two Lu$^+$ ions operating on the ^{1}S$_0$ − ^{3}D$_1$ transition. The fractional inaccuracy of the comparison is statistically limited to 3×10^{-18} with systematic uncertainty contributing 1.0×10^{-18}. Our results demonstrate the ease at which a ^{176}Lu$^+$ frequency reference can maintain a fractional inaccuracy below 10^{-18}.

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Wed, Aug. 3rd, 3B, 11:35-11:55

Trapped ion quantum computing with tweezers and electric fields

A. Safavi-Naini

University of Amsterdam

Trapped-ions are one of the most mature platforms for quantum computation and quantum simulation. In trapped-ion quantum simulators the spin-spin interactions mediated by the collective motion of the ions in the crystal (phonons) are of the form r^{-a} where $0 < a < 3$. Here, I will show that additional optical tweezer potentials can be used to engineer the phonon spectrum, and thus tune the interactions and connectivity of the ion qubits beyond the power-law interactions accessible in current setups [**1, 2**].

Next, I will show that the combination of optical tweezers delivering qubit state-dependent local potentials with an oscillating electric field allows us to create a new scalable architecture for trapped-ion quantum computing [**2, 4**]. Since the electric field allows for long-range qubit-qubit interactions mediated by the center-of-mass motion of the ion crystal alone, it is inherently scalable to large ion crystals. Furthermore, this scheme does not rely on either ground state cooling or the Lamb-Dicke approximation.

[1] Phys. Rev. A 104, 013302 (2021)
[2] arXiv:2202.13681v1
[3] Phys. Rev. Lett. 127, 260502 (2021)
[4] In preparation

Wed, Aug. 3rd, 3B, 11:55-12:15

Geometries and fabrication methods for 3D printing ion traps

A. Quinn, M. Brown, T.J. Gardner and D.T.C. Allcock

University of Oregon

The majority of microfabricated ion traps in use for quantum information processing are of the 2D 'surface-electrode' type or of the 3D 'wafer' type. Surface-electrode traps greatly simplify fabrication and hold the promise of allowing trapped-ion quantum computers to scale via standard semiconductor industry fabrication techniques. However, their geometry constrains them to having much lower trapping efficiency, depth, and harmonicity compared to 3D geometries. Conversely 3D geometries offer superior trap performance but fabrication is more complex, limiting potential to scale. We describe new 'trench' geometries that exist in the design space between these two paradigms. They still allow for a simple, planar electrode layer but with much more favourable trapping properties. We propose such traps could be 3D-printed over a 2D wafer with microfabricated components already integrated into it, thus retaining all the integration techniques and scaling advantages of surface-electrode traps. As a proof of principle we use 2-photon direct laser writing lithography to print the required electrode structures with the proposed geometry.

[1] A. Quinn, M. Brown, T.J. Gardner and D.T.C. Allcock, Geometries and fabrication methods for 3D printing ion traps, arXiv:2205.15892 (2022)

Wed, Aug. 3rd, 3C, 13:45-14:05

Controlling two-dimensional crystals of up to 91 ions in a novel linear Paul trap

Dominik Kiesenhofer

Universität Innsbruck

Trapped ions in RF traps are a well-established platform for analog and variational quantum simulation of quantum many-body systems. Up to now, ions in linear Paul traps allow for simulations of the 1D Ising model with up to 50 spins. In our project, we aim for extending this approach to the second dimension which will enable studies of 2D spin models with a larger particle number. Our new ion trap apparatus whose centerpiece is a novel monolithic micro-fabricated linear Paul trap allows for trapping planar crystals of up to 91 ions. For these crystals we observe only a small number of distinct crystal configurations by applying a cluster algorithm to an image series recorded over several hours. We also find stable elongated crystal configurations of up to 91 ions by choosing suitable voltage sets inhibiting any configuration changes. Furthermore, we successfully applied electro-magnetically induced transparency cooling to cool the out-of-plane modes of motion of two-dimensional Coulomb crystals to the ground state. Cooling dynamics were analyzed by sideband-resolved spec troscopy on the vibrational modes of motion. Stable crystal configurations as well as fast and simultaneous ground-state cooling of all out-of-plane modes are laying the foundation for high-fidelity interactions in the near future. Effective spin-spin interactions will be induced by laser fields

coupling the ions' electronic levels to excitations of the crystal's out-of-plane modes of motion.

Wed, Aug. 3rd, 3C, 14:05-14:25

Transport of multispecies ion crystals through a junction in an RF Paul trap

William Cody Burton, Brian Estey, Ian M. Hoffman, Abigail R. Perry, Curtis Volin and Gabriel Price

Quantinuum, 303 S. Technology Ct., Broomfield, Colorado 80021, USA

We report on the first demonstration of transport of a multispecies ion crystal through a junction in an RF Paul trap. The trap is a two-dimensional surface-electrode trap with an X junction and segmented control electrodes to which time-varying voltages are applied to control the shape and position of potential wells above the trap surface. We transport either a single $^{171}Yb^{+}$ ion or a crystal composed of a $^{138}Ba^{+}$ ion cotrapped with the $^{171}Yb^{+}$ ion to any port of the junction. We characterize the motional excitation by performing multiple round-trips through the junction and back to the initial well position without cooling. The final excitation is then measured using sideband asymmetry. For a single $^{171}Yb^{+}$ ion, transport with a 4 m/s average speed induces between 0.013 ± 0.001 and 0.014 ± 0.001 quanta of excitation per round trip, depending on the exit port. For a Ba-Yb crystal, transport at the same speed induces between 0.013 ± 0.001 and 0.030 ± 0.002 quanta per round trip of excitation to the axial center of mass mode. Excitation in the axial stretch mode ranges from 0.005 ± 0.001 to 0.021 ± 0.001 quanta per round trip.

Thu, Aug. 4th, 4A, 09:00-09:30

Coherently coupled mechanical oscillators in the quantum regime

Giorgio Zarantonello, Pan-Yu Hou, Jenny J. Wu, Stephen D. Erickson, Dan C. Cole, Adam D. Brandt, Andrew C. Wilson, Daniel H. Slichter and Dietrich Leibfried

NIST

Coherent coupling of quantum harmonic oscillators is a useful operation in many applications. Here we couple spectrally separated pairs of motional modes in multi-ion linear crystals using an electric potential with suitable spatial variation. We demonstrate the coherent exchange of single motional quanta between the coupled modes with control over the coupling strength, timing and phase. We show measurements characterizing the coherent coupling and discuss two potential application. One such application is a projective measurement of the out-of-phase mode in a Be^+-Mg^+-Be^+ crystal that distinguishes $|0\rangle$ and $|1\rangle$ without disturbing the motional state after the first projection to a high degree. Such a measurement can be accommodated for error syndrome readout in bosonic error correction. Another application is cooling inaccessible or weakly coupled motional modes to the cooling radiation for Coulomb-crystals composed of different ion species, including molecular ions and highly charged ions.

Thu, Aug. 4th, 4A, 09:30-10:00

Demonstration of fault-tolerant universal quantum gate operations

Philipp Schindler

Universität Innsbruck

Quantum computers can be protected from noise by encoding the logical quantum information redundantly into multiple qubits using error correcting codes. When manipulating the logical quantum states, it is imperative that errors caused by imperfect operations do not spread uncontrollably through the quantum register. This requires that all operations on the quantum register obey a fault-tolerant circuit design which, in general, increases the complexity of the implementation. Here, we demonstrate a fault-tolerant universal set of gates on two logical qubits in a trapped-ion quantum computer. In particular, we make use of the recently introduced paradigm of flag fault tolerance, where the absence or presence of dangerous errors is heralded by usage of few ancillary 'flag' qubits. Experimental results are accompanied by numerical simulations based on a generic, architecture-agnostic error model.

Thu, Aug. 4th, 4A, 10:00-10:30

Analog-digital quantum simulations with trapped ions

William Morong

University of Maryland, College Park

Quantum simulators combining Hamiltonian evolution with gate operations represent a powerful approach towards probing many-body physics with NISQ devices. We apply a platform based on a linear chain of trapped $^{171}Yb^{+}$ ions to demonstrate some of the uses of this hybrid strategy, such as characterizing slow correlation growth arising from Stark many-body localization, creating and probing a prethermal discrete time crystal, and expanding the simulation toolbox with Floquet Hamiltonian engineering.

Thu, Aug. 4th, 4B, 11:30-11:50

The future of ARTIQ ecosystem

Mateusz Wójcik

M-Labs

ARTIQ is a leading-edge control system for quantum information experiments. It was initiated and developed with the Ion Storage Group at NIST. Nowadays, it's used in many research institutions worldwide. ARTIQ, together with the Sinara hardware, enables scientists to use a language based on Python to program complex experiments in a simplified way, with excellent timing precision and low latency.

The system is in constant development at M-Labs. With the upcoming NAC3 compiler, distributed DMA and other features, we are aiming for higher performance, better user experience and new possibilities.

Thu, Aug. 4th, 4B, 11:50-12:10

Modular software for real-time quantum control systems

L. Riesebos

Duke University

Real-time control software and hardware is essential for operating quantum computers. In particular, the software plays a crucial role in bridging the gap between quantum programs and the quantum system. Unfortunately, current control software is often optimized for a specific system at the cost of flexibility and portability. We propose a systematic design strategy for modular real-time quantum control software and demonstrate that modular control software can reduce the execution time overhead of kernels by 63.3% on average while not increasing the binary size. Our analysis shows that modular control software for two distinctly different systems can share between 49.8% and 91.0% of covered code statements.

List of Posters

Session 1, Monday, August 1st

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1-3	Matthias Bock	Correlation spectroscopy with multi-qubit-enhanced phase estimation in a planar 91-ion crystal
1-4	Sumanta Khan	Test of Causal Non-Linear Quantum Mechanics by Ramsey Interferometry on the Vibrational Mode of a Trapped Ion
1-5	Clinton Cahall	Compact Ion Systems for Scalable and Deployable Quantum Technologies
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1-10	Antonis Kyprianidis	Engineering spin-spin interactions with global beams

1-11	D. Luo	A Monolithic Three-Dimensional Linear Ion Trap
1-12	Abhishek Menon	Towards the Realization of a Dissipative Phase Transition using a Trapped Ion Quantum Simulator
1-13	Lu Qi	Adiabatic control of motional states of calcium oxide ion and calcium ion chain
1-14	Alexander Quinn	Raman scattering errors in metastable $^{40}Ca^{+}$ trapped-ion qubits and implementation of Raman gates
1-15	Alexander Rasmusson	Optimized pulsed sideband cooling and enhanced thermometry of trapped ions
1-16	Roy Ready	Developing 3D-printed micro-traps with a cryogenic ion trapping system
1-17	Evan C. Reed	Optimized pulsed sideband cooling vs continuous sideband cooling on an electric quadrupole transition
1-18	Vikram Sandhu	Ion trapping at GTRI: from high-fidelity gates to mass-spec
1-19	Yotam Shapira	Quantum simulations of interacting systems with broken time-reversal symmetry
1-20	Yotam Shapira	Robust two-qubit trapped ions gates using spin-dependent squeezing
1-21	Samuel Snowden	Design and fabrication of a micro-blade trap with optical cavity for a mixed species quantum network node

1-22	Midhuna Duraisamy Suganthi	Towards a light-shift gate with transverse momentum transfer from spatially modulated light
1-23	Ting Rei Tan	Scalable prediction of molecular vibronic spectra using time-domain analog quantum simulation
1-24	Carl Thomas	Progress on implementation of remote entanglement between Yb^+ and ZnO defect spin
1-25	Qiming Wu	Multi-mode ground state cooling of a trapped ion chain beyond the Lamb-Dicke limit
1-26	Denton Wu	Strontium ions for quantum networking and vortex field experiments
1-27	Ashlyn D. Burch	Quantum Scientific Computing Open User Testbed (QSCOUT) Capabilities
1-28	Christopher Caron	Trapped Ion Quantum Computing Fabrication Testbed at UMass Amherst
1-32	Megan Ivory	Characterization of the AC Zeeman Effect in Microfabricated Surface Traps
1-36	Sungjoo Lim	Profile individual beam by moving ion position
1-39	Billy Robertson	An Yb^+ optical clock for precision metrology and tests of fundamental physics
1-40	George Schwartz	EPICS (Extreme Performance Ion-trap Cavity System)

Session 2, Tuesday, August 2nd		
No.	**Presenters**	**Title**
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2-2	Alejandro Bermudez	Long-range Ising models: Probing the renormalization of sound in non-perturbative QFTs with crystals of trapped ions
2-3	Debopriyo Biswas	Using trapped ions to simulate NMR experiments and observe measurement-induced phase transitions
2-4	Thomas Dellaert	Spectroscopy of metastable trapped $^{173}Yb^{+}$ for quantum information and fundamental science
2-5	Maya Fabrikant	Coherent Deexcitation of Multi-Species Ion Crystals
2-6	Brandon Furey	Quantum state characterization and coherent control of molecular ions
2-7	Lukas Gerster	Experimental Bayesian Calibration of Trapped-Ion Entangling Operations
2-8	Isabella Goetting	Pulsed excitation scheme for barium ion-photon entanglement generation
2-9	Noah Greenberg	Robust optical engineering and atomic source development for a Barium ion-based quantum simulator
2-10	Jane Gunnell	Building a Stylus trap and Deep Parabolic Mirror to Study and Control Quantum Jumps

2-11	H. Mendpara	Towards fault-tolerant quantum computing with an universal set of microwave driven quantum gates with trapped ions
2-12	Zhubing Jia	Angle-robust Two-Qubit Gates in a Linear Ion Crystal
2-13	Mingyu Kang	Mitigating Experimental Imperfections with Frequency-Modulated Pulses for High-Fidelity Two-Qubit Gates in Ion Chains
2-14	Ezra Kassa	Integration of an Optical Cavity with a linear Ion Trap
2-15	Eugene Knyazev	Fifth-force Search with Isotope-Shift Spectroscopy in Yb^+
2-16	Woojun Lee	Qubit control of Yb^+ ions on surface chip with Raman lasers and measurement of electric field from chip silicon-laser collision
2-18	Brian J. McMahon	Optical Addressing of 2D Ion Arrays for Quantum Optimization in a Compact Penning Trap
2-19	Swapnil Patel	Sympathetic Ground State Cooling of CaH^+
2-20	Andrew Risinger	Logical Qubit RF Control System using RFSoC
2-21	Sagnik Saha	Progress towards a three-node quantum network
2-22	Chung-you (Gilbert) Shih	Progress towards building a scalable trapped-ion QIP device with ultralow crosstalk optical control

2-23	Ke Sun	Trapped-Ion Simulators for Molecular Dynamics
2-24	C. H. Valahu	Improving trapped ion camera detection with machine learning
2-25	Samuel Vizvary	Fundamental Limits on Gate-Laser Scattering Errors in Barium-133
2-26	Yuanheng Xie	Building a Mobile Trap setup for severe environment study
2-27	Yichao Yu	A next-generation trapped ion quantum computing system
2-28	Daiwei Zhu	Risk Aggregation by Quantum Generative Modeling of Copulas
2-29	Norbert Linke	Analog and digital quantum simulation of para-particle oscillators
2-30	Brendan Bramman	Metastable state shelving for Barium qudit measurement
2-31	Y. Colombe	Industrially microfabricated ion traps
2-32	Connor Goham	Initial characterization of a direct-telecom single-photon source based on trapped Yb^+
2-33	Brian McFarland	Electric Field Noise in Microfabricated Ion Traps with Varied Capacitor Types and Trap Materials
2-35	Bethan Nichol	An elementary quantum network of optical atomic clocks
2-37	David Reens	Multi-Ion Traps with Integrated Detectors for Portable Clocks
2-38	Lucas Sletten	High-fidelity state preparation and measurement of ion qubits with I¿1/2
2-40	Susanna Todaro	Barium ions for quantum information experiments with metastable qubits

2-41	Joshua M. Wilson	Detecting and Minimizing RF Breakdown on Microfabricated Surface Ion Traps

Poster session 1 abstracts

Mon, Aug. 1st, Session 1, No. 1

Cooling Experiment through Quadrupole Transition in Miniature Room Temperature System

Yuhi Aikyo

Duke University

One of the primary obstacles in the physical realization of quantum computers is the loss of gate fidelity as the number of qubits in the system scales. The advantage of trapped-ion based quantum computing is the negligible loss of coherence of the qubit internal state. This platform, however, also suffers from drawbacks such as an increase in complexity of the hardware requirements and quantum operations with an increase in the length of the ion chain. Another direct consequence of scaling is heating in the ion chain, which is particularly detrimental to the realization of high-fidelity entangled gates. A potential solution to mitigate this is cooling the motional modes via sympathetic cooling of the ion chain, comprising two isotopes whilst minimizing decoherence from resonant scattering. We propose a sympathetic cooling scheme to cool qubit $^{171}\mathrm{Yb}^{+}$ by utilizing different Yb isotopes in the ion chain. The cooling procedure will use the using a $^{2}\mathrm{S}_{1/2} - {}^{2}\mathrm{D}_{3/2}$ quadrupole transition and will be demonstrated on an ion-trapped compact, room-temperature system, potentially improving scalability and system robustness against external noise.

Mon, Aug. 1st, Session 1, No. 2

Controlling trapped-ion motional modes for precision measurement and CVQC

David T.C. Allcock[1], Jeremy Metzner[1], Sean Brudney[1], Alexander Quinn[1], Isam Daniel Moore[1], Gabe Gregory[1], Colin Bruzewicz[2], John Chiaverini[2] and David J. Wineland[1]

[1]University of Oregon
[2]MIT Lincoln Lab

Motional modes of trapped ions have been shown to be a useful tool for quantum sensing as well as a platform for performing continuous variable quantum computing (CVQC). Both applications require the ability to prepare well-defined motional states with high fidelity. Many of these states can be generated from motional ground states without the use of laser fields. We report our progress towards generation of one-mode [**1**] and two-mode squeezed states by means of parametric excitation. These operations comprise part of the tool box to create motional state interferometers (such as SU(1,1) interferometers [**2**]) and can be used to achieve Heisenberg-limited phase sensitivities. We present a preliminary implementation of an SU(1,1) interferometer using two motional modes of a $^{40}Ca^+$ ion in a Paul trap.

In order to characterize motional states, the ions' motion are coupled to internal 'spin' states, which are distinguishable through spin-dependent fluorescence. Photon scattering, giving rise to fluorescence, causes the ion to recoil, which generally decoheres the ions' motional modes. This decoherence prevents mid-algorithm measurements, which are necessary for processes that require classical feedback. To address this issue, we describe progress towards the use of 'protected' [**3**] modes within chains consisting of an odd number of ions, where the center ion has zero displacement ($3(N-1)/2$ protected modes with N ions). The protection offered by these ions is measured by analysis of the heating rates and coherence time of the protected mode during scattering events.

This research was supported by the U.S. Army Research Office through grant W911NF-19-1-0481 as well as support from NSF through the Q-SEnSE Quantum Leap Challenge Institute, Award # 2016244.

[1] S. C. Burd, R. Srinivas, J. J. Bollinger1, A. C. Wilson1, D. J. Wineland,D. Leibfried, D. H. Slichter, D. T. C. Allcock, Quantum Amplification of Mechanical Oscillator Motion, Science 364, 6446 (2019)

[2] B. Yurke, S. L. McCall, J. R. Klauder, SU(2) and SU(1,1) interferometers, Physical Review A 33, 4033 (1986)

[3] P.-Y. Hou, et al. Coherently coupled mechanical oscillators in the quantum regime, arXiv:2205.14841v1 (2022)

Mon, Aug. 1st, Session 1, No. 3

Correlation spectroscopy with multi-qubit-enhanced phase estimation in a planar 91-ion crystal

Matthias Bock[1], Helene Hainzer[2], Dominik Kiesenhofer[2], Tuomas Ollikainen[2], Rainer Blatt[1,2], Tuvia Gefen[3] and Christian F. Roos[1,2]

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[3]Institute for Quantum Information and Matter, Caltech, Pasadena, CA, USA

Trapped ions are a well-established platform for analog or variational quantum simulation of quantum magnetism [**1, 2**]. Up to now, ions in linear Paul traps allow for simulations of the 1D Ising model with up to 50 spins. In our project, we aim for extending this approach to the second dimension by using the platform of planar ion crystals stored in a linear Paul trap, which will enable quantum simulations with larger particle numbers (¿ 50) as well as studies of 2D spin physics. To this end, we construct a new ion trap apparatus whose centerpiece is a monolithic micro-fabricated linear Paul trap, enabling us to create the anisotropic potentials required for trapping 2D ion crystals with simultaneous optical access for imaging and single-ion addressing.
We present details on our apparatus which is currently capable of trapping and cooling stable 2D crystals with up to 100 $^{40}Ca^{+}$-ions. Furthermore, we demonstrate simultaneous ground-state

cooling of all out-of-plane modes of large 2D crystals – the modes we intend to use to engineer spin-spin interactions in quantum simulation experiments – by means of electromagnetically-induced transparency cooling.
As a first application, we perform correlation spectroscopy with multi-qubit-enhanced phase estimation in a 91-ion planar crystal [**3**]. Correlation spectroscopy of multi-qubit systems is a powerful technique, initially developed in the context of precision metrology, to probe phase differences between qubits in the presence of correlated phase noise [**4**]. The quantification of these phase differences, which are caused e.g. by different transition frequencies, is essential if the multi-qubit system is utilized for applications such as quantum computers, simulators or atomic clocks [**5**]. The technique relies on the fact that many decoherence processes, e.g. fluctuations of the ambient magnetic field, affect the qubits in a collective way, i.e. the noise on each qubit is the same due to their spatial proximity in the trap. Thus, correlations of the outcomes of collective Ramsey-type experiments allow for measuring phase differences with probe times that can significantly exceed the coherence time of the individual qubits. Here we utilize correlation spectroscopy to sense a magnetic field gradient which gives rise to transition frequency differences across the planar ion crystal. Furthermore, we demonstrate that the information contained in the 91-particle correlations enhances the phase estimation by reducing its measurement uncertainty as compared to the case where only two-particle correlations are analyzed, and that the advantage of using entangled states for this specific purpose becomes negligible for an infinite amount of qubits.

[1] C. Monroe, W. C. Campbell, L.-M. Duan, Z.-X. Gong, A. V. Gorshkov, P. W. Hess, R. Islam, K. Kim, N. M. Linke, G. Pagano, P. Richerme, C. Senko, and N. Y. Yao, "Programmable quantum simulations of spin systems with trapped ions," Rev. Mod. Phys. **93**, 025001 (2021).
[2] C. Kokail, C. Maier, R. van Bijnen, T. Brydges, M. K. Joshi, P. Jurcevic, C. A. Muschik, P. Silvi, R. Blatt, C. F. Roos, and P. Zoller, "Self-verifying variational quantum simulation of lattice models," Nature **569**, 355-360 (2019).

[3] H. Hainzer, D. Kiesenhofer, T. Ollikainen, M. Bock, F. Kranzl, M. K. Joshi, G. Yoeli, R. Blatt, T. Gefen, and C. F. Roos, "Correlation spectroscopy with multi-qubit-enhanced phase estimation," *arXiv:2203.12656, (2022)*

[4] M. Chwalla, K. Kim, T. Monz, P. Schindler, M. Riebe, C. F. Roos, and R. Blatt, "Precision spectroscopy with two correlated atoms," Appl. Phys. B **89**, 483-488 (2007).

[5] C. W. Chou, D. B. Hume, M. J. Thorpe, D. J. Wineland, and T. Rosenband, "Quantum Coherence between Two Atoms beyond $Q = 10^{15}$," Phys. Rev. Lett. **106**, 160801 (2011).

Mon, Aug. 1st, Session 1, No. 4

Test of Causal Non-Linear Quantum Mechanics by Ramsey Interferometry on the Vibrational Mode of a Trapped Ion [2]

Joseph Broz[1,2], Bingran You[1,2], Sumanta Khan[1,2], Hartmut Häffner[1,2], David E. Kaplan[3] and Surjeet Rajendran[3]

[1]Department of Physics, University of California, Berkeley, California 94720, USA
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[3]Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA

Kaplan and Rajendran have recently demonstrated [**1**] that non-linear and state-dependent terms can be consistently added to quantum field theory to yield causal non-linear time evolution in quantum mechanics. Causal non-linear theories have the unavoidable feature that their quantum effects are dramatically sensitive to the full physical spread of the quantum state of the system. As a result, such theories are not well tested by conventional atomic and nuclear spectroscopy. By using a well-controlled superposition of vibrational modes of a $^{40}Ca^{+}$ ion trapped in a harmonic potential, we set a stringent limit of 5.4×10^{-12} on the magnitude of the unitless scaling factor $\tilde{\epsilon}_\gamma$ for the predicted causal, non-linear perturbation.

[1] David E. Kaplan and Surjeet Rajendran Causal framework for nonlinear quantum mechanics. *Phys. Rev. D*, 105, 055002, Mar 2022.

[2] Joseph Broz, Bingran You, Sumanta Khan, Hartmut Haeffner, David E. Kaplan and Surjeet Rajendran Test of Causal Non-Linear Quantum Mechanics by Ramsey Interferometry on the Vibrational Mode of a Trapped Ion. *arXiv*, 2206.12976, Jun 2022.

Mon, Aug. 1st, Session 1, No. 5

Compact Ion Systems for Scalable and Deployable Quantum Technologies

Clinton Cahall

ColdQuanta

ColdQuanta has developed miniaturized ion trapping systems having performance competitive with traditional vacuum systems to enable the next generation of quantum computing, quantum networking, and precision timekeeping. Quantum research utilizing trapped ions has been developing at a rapid pace in recent years and is conducted in labs all over the world, including virtually every U.S. DoD research lab. Currently, these labs construct one-off laboratory vacuum systems to conduct trapped ion research, as few commercial options exist. These systems are unsuitable for deployment or commercialization of the investigated technologies. ColdQuanta's compact quantum components and turn-key systems facilitate the hand-off between laboratory research and ultimately deployed applications.

Mon, Aug. 1st, Session 1, No. 6

Quantum control of multi-level atoms for quantum signal processing

Kyle DeBry[1], John Chiaverini[2] and Isaac Chuang[1]

[1]Massachusetts Institute of Technology
[2]MIT Lincoln Laboratory

While systems used for quantum computing are often thought of as qubits, real quantum systems are more complex. Rather than working to isolate qubit-like systems, we can instead harness the additional states and operators available to us. We present simulations and preliminary experimental data on the use of optical and radio-frequency pulses in $^{40}Ca^+$ and similar ions with low-lying $D_{5/2}$ levels. By composing RF pulse sequences that act on the metastable $D_{5/2}$ states, we show that it is possible to implement quantum signal processing-inspired decision algorithms, even without arbitrary $SU(6)$ control of the $D_{5/2}$ manifold.

Mon, Aug. 1st, Session 1, No. 7

IonSim: A lightweight Julia package for simulating trapped-ion dynamics

Neil Glikin[1], Joseph Broz[1], Kunal Marwaha[2] and Kristian D. Barajas[3]

[1]UC Berkeley
[2]University of Chicago
[3]UC Los Angeles

We present IonSim.jl, an open-source computational software package in the Julia programming language for simulating the dynamics of trapped ions interacting with laser light. IonSim allows the user to define their system of interest in terms of concrete experimental parameters rather than abstract ones, from which it can efficiently construct the system's Hamiltonian and solve for its time dynamics. User-configurable parameters include motional modes, laser properties and geometry, ion chain length and constituent species, and relevant energy levels and sublevels. The IonSim.jl project is actively expanding its capabilities and robustness, and aims to provide to the trapped-ion community a user-friendly and quantitatively reliable numerical simulation tool.

Mon, Aug. 1st, Session 1, No. 8

Implementation of Two Qubit Gates with Motional Modes in Multiple Directions

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Mølmer–Sørensen gate is a form of two-qubit gate that utilizes the motional states of an ion chain[**1, 2, 3**]. While this type of gate has an advantage that it does not require ground state cooling and individual addressing of ions[**4**], it requires that the phase-space trajectories of all the motional modes excited by the laser should be closed at the end of gate pulse, which becomes more and more difficult as each ion added to the chain increases the number of motional modes by three. One can limit the number of excited motional modes by carefully tuning the directions of the principal axes and laser momentum kick, but it is not always possible due to constraints such as limited optical access and the potential tuning capabilities of the trap used. In this work, we demonstrate that Mølmer–Sørensen gate can be implemented by simultaneously exciting multiple motional modes belonging to two different transverse principal axes. This scheme can be used to generate entanglement between ion qubits in systems with high motional mode degeneracy where the motional modes of different principal axes are separated by only a few kHz.

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Mon, Aug. 1st, Session 1, No. 9

Reproducible optics design for a scalable ion trap

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We present a design workflow for optical systems which provides more reproducible and scalable ways to build large optical system. We studies the essential components for a blueprint of optical systems, which provides complete descriptions of the system for reproduction. We also suggest a workflow for designing optics system based on this 'beam path'-based approach, and introduce our on-going progress for developing automated designing tool for it. We believe this systematic design approach will be greatly advantageous for building a large-scale optics based system, including trapped-ion quantum systems, etc.

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Mon, Aug. 1st, Session 1, No. 10

Engineering spin-spin interactions with global beams

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Trapped-ion quantum simulators typically simulate spin-spin interactions by off-resonantly coupling to the normal modes of the ion crystal motion. The most common choice leads to a scaling of interaction strength with distance like a power law. In this work, we attempt to generalize on the accessible interaction graphs, if only global Raman beams are used, i.e. without individual addressing of each ion. We find that interesting cases other than power laws can be generated under conditions. We explore these conditions and speculate limitations for our 2D ion crystals.

Mon, Aug. 1st, Session 1, No. 11

A Monolithic Three-Dimensional Linear Ion Trap

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Trapped ions are a successful platform for quantum information processing, metrology and many other applications. Compared to microfabricated surface traps, three-dimensional (3D) blade traps benefit from lower heating rate, deeper and more symmetric trapping potential, higher optical access, and better shielding from stray electric fields. However, they are generally assembled from discrete blades and are susceptible to misalignment, which can lead to excess micromotion as well as an inhomogeneous and non-harmonic trapping potential. We present the design and construction of a monolithic 3D blade trap fabricated from a single piece of fused silica, using photo-chemical processes developed by our collaborator Translume Inc. We discuss the optimazation of the trapping potential for a long ion-chain with even spacing. We also present the design of the ceramic structures for mounting the trap, which allow for easy assembly and efficient heat dissipation, while maintaining high optical access.

Mon, Aug. 1st, Session 1, No. 12

Towards the Realization of a Dissipative Phase Transition using a Trapped Ion Quantum Simulator

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Dynamics in open quantum systems is defined by the competition between unitary evolution and non-unitary operations, like measurements and/or interaction with the environment. Recent theoretical studies [**1**] in the field have predicted the existence of a dissipative phase transition (DPT) in a periodically driven, long-range interacting quantum spin chain between a ferromagnetic ordered phase and a paramagnetic disordered phase as a function of resetting measurement probabilities after coherent evolution. We can probe such rich quantum behavior using our trapped ion quantum simulator. We have developed a high optical access vacuum chamber which houses a linear, 3D, RF blade trap to confine a linear quantum spin chain of Yb^+ ions. Using our 0.3 NA and 0.6 NA re-entrant windows, we facilitate global, tunable Ising type interactions (coherent) to couple spins and individual ion addressing for optical pumping (resetting) , respectively. We report on the latest developments to minimize crosstalk between ions with the individual addressing scheme by achieving $< 2\mu$m beam waist per ion, using beam shaping optics and an Acousto-Optic Modulator. We further discuss our plans to decrease the crosstalk through qubit shelving.

[1] Sierant, Piotr et al. Quantum 6 (2022): 638.

Mon, Aug. 1st, Session 1, No. 13

Adiabatic control of motional states of calcium oxide ion and calcium ion chain

Lu Qi, Evan Reed and Ken Brown

Duke University

Control of the external degree of freedom of trapped molecular ions is a prerequisite for their promising applications to spectroscopy, precision measurements of fundamental constants, and quantum information technology. Here, we demonstrate near ground-state cooling of the axial motional modes of a calcium mono-oxide ion via sympathetic cooling with a co-trapped calcium ion. We also show that the phonon state of the axial out-of-phase mode of the ion chain is maintained while the mode frequency is adiabatically ramped up and down. The adiabatic ramping of the motional mode frequency is a prerequisite for searching for the proposed molecular dipole-phonon interaction.

Mon, Aug. 1st, Session 1, No. 14

Raman scattering errors in metastable $^{40}Ca^{+}$ trapped-ion qubits and implementation of Raman gates

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Trapped-ion qubits encoded in metastable states (m qubits) are of interest for their use in the omg qubit scheme, which allows multi-species functionality with a single ion species [**1**]. We present an implementation of m qubits in the $D_{5/2}$ manifold of $^{40}Ca^{+}$. Single-qubit stimulated-Raman gates in m qubits are demonstrated and characterized. We use 976 nm laser beams (detuned 44 THz red of the 854 nm $P_{3/2} \leftrightarrow D_{5/2}$ transition) in order to achieve low spontaneous Raman scattering errors. We compare these observed scattering errors to theory, accounting for effects relevant at large detunings. We also consider these effects in models for scattering in stimulated-Raman driven qubits in the $S_{1/2}$ manifold (g qubits) and predict markedly different scattering behavior in the far-detuned regime than previous models. Finally, we present experimental progress towards implementing a two-qubit light-shift gate on m qubits using far-detuned Raman beams.

This work was supported in part by the US Army Research Office under award W911NF-20-1-0037

[1] D. T. C. Allcock et al., omg Blueprint for trapped ion quantum computing with metastable states, Applied Physics Letters 119, 214002 (2021)

Mon, Aug. 1st, Session 1, No. 15

Optimized pulsed sideband cooling and enhanced thermometry of trapped ions

Alexander Rasmusson, Marissa D'Onofrio, Yuanheng Xie, Jiafeng Cui and Philip Richerme

Indiana University

Resolved sideband cooling is a standard technique for cooling trapped ions below the Doppler limit to near their motional ground state. Yet, the most common methods for sideband cooling implicitly rely on low Doppler-cooled temperatures and tightly confined ions, and they cannot be optimized for different experimental conditions. Here we introduce a framework which calculates the fastest possible pulsed sideband cooling sequence for a given number of pulses and set of experimental parameters, and we verify its improvement compared to traditional methods using a trapped $^{171}Yb^{+}$ ion. After extensive cooling, we find that the ion motional distribution is distinctly non-thermal and thus not amenable to standard thermometry techniques. We therefore develop and experimentally validate an improved method to measure ion temperatures after sideband cooling. These techniques will enable more efficient cooling and thermometry within trapped-ion systems, especially those with high initial temperatures or spatially-extended ion wavepackets.

Mon, Aug. 1st, Session 1, No. 16

Developing 3D-printed micro-traps with a cryogenic ion trapping system

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We are developing 3D-printed ion traps with characteristic dimensions on the order of tens of micrometers. Our traps will be fabricated with sub-micron precision using two-photon polymerization laser writing. We developed and recently assembled a cryogenic ion trapping system for testing these three dimensional traps. We are currently benchmarking our system by working with strontium ions in a 2D chip trap. Our near term goal is to measure heating rates at cryogenic temperatures in this trap.

Mon, Aug. 1st, Session 1, No. 17

Optimized pulsed sideband cooling vs continuous sideband cooling on an electric quadrupole transition

Evan C. Reed

Duke University

Trapped-ion quantum computers rely on two-qubit gates that achieve optimal performance when the ions are near the ground state of motion. Ion cooling, however, takes up a significant amount of the time required to prepare the qubit register, and as the computer scales, cooling the ions in the middle of the algorithm becomes more critical. Therefore, cooling can be a significant source of latency in the algorithm. Recently, a graph theoretic method for determining the optimal set of sideband cooling (SBC) pulses for a given trapped ion system has been proposed and experimentally demonstrated [**1**]. Here, we investigate the difference in efficiency of optimized pulsed SBC versus continuous SBC [**2**] for optical qubits using numerical simulation and experimental confirmation with $^{40}Ca^{+}$ ions.

[1] A. J. Rasmusson, M. D'Onofrio, Y. Xie, J. Cui, & P. Richerme. Optimized pulsed sideband cooling and enhanced thermometry of trapped ions. Phys. Rev. A 104, 043108 (2021).

[2] F. Diedrich, J. C. Bergquist, W. M. Itano, & D. J. Wineland. Laser Cooling to the Zero-Point Energy of Motion. Phys. Rev. Lett. 62, 403 (1989).

Mon, Aug. 1st, Session 1, No. 18

Ion trapping at GTRI: from high-fidelity gates to mass-spec

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The ability to transport ions within a future quantum information processor is expected to play a key role in enabling small subsets of ions to be addressed without crosstalk. This need for transport may necessitate subsequent re-cooling, as it can be difficult to transport ions without heating them up to the detriment of subsequent quantum operations. Furthermore, anomalous heating increases ion temperatures both during transports and in stationary potentials. As the number of transport operations increases, current re-cooling methods impose a bottleneck on the speed of trapped-ion quantum information processors [**1**]. We are currently working towards the experimental implementation of a novel laser-free dynamical cooling scheme [**2**]. We plan to merge a hot ion with a pre-cooled coolant ion (drawn from a cold reservoir) into the same harmonic potential. During and after the merge, a controllable energy exchange takes place [**3**], transferring motional quanta from the hot ion to the coolant. After the exchange, the ions are separated and the coolant ion is returned to the cold reservoir. In this work, we lay out our experimental progress, as well as the challenges ahead.

[1] Pino, J. M., *et al.* Demonstration of the Trapped-Ion Quantum CCD Computer Architecture. Nature 592, 209–213 (2021)

[2] Sägesser, T., *et al.* Robust Dynamical Exchange Cooling with Trapped Ions. New Journal of Physics 22 073069 (2020)

[3] Brown, K. R., *et al.* Coupled Quantized Mechanical Oscillators. Nature 471, 196–199 (2011)

Mon, Aug. 1st, Session 1, No. 19

Quantum simulations of interacting systems with broken time-reversal symmetry

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Quantum many-body systems with broken time-reversal symmetry give rise to rich phenomena and are a research focus in modern physics. However, such systems are typically challenging to explore analytically or probe experimentally. This is mitigated by using quantum simulators, which are analogous systems, that are more easily controlled and probed. Moreover, quantum simulators which are embedded in universal quantum computers are especially advantageous since simulation results can be analyzed using tools such as quantum-classical variational optimization, measurement of topological string operators as well as tomography.

Here [**1**] we employ a method developed in our group [**2**], and experimentally realize quantum simulations of interacting, time-reversal broken and 2d quantum systems in a universal trapped-ion quantum processor [**3**]. Specifically, we realize a quantum ring threaded by magnetic flux. We adiabatically prepare and measure the ring's ground state. We also quench the ring and measure flux dependent chiral currents. Furthermore we realize a triangular spin ladder threaded by a staggered magnetic flux and show that this 2d model exhibits non-trivial interactions between its excitations.

Our method is straightforward to implement on a conventional trapped ion architecture, using only a global driving field and a magnetic field gradient along the ion chain. In addition, it is amenable to scaling up, as adding more sites to the model does not change the driving scheme.

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[2] T. Manovitz *et al.* PRX Quantum 1, 020303 (2020).
[3] T. Manovitz *et al.* PRX Quantum 3, 010347 (2022).

Mon, Aug. 1st, Session 1, No. 20

Robust two-qubit trapped ions gates using spin-dependent squeezing

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Entangling gates are an essential component of quantum computers. However, generating high-fidelity gates, in a scalable manner, remains a major challenge in all quantum information processing platforms. Moreover, fault-tolerant quantum computing requires gates with fidelities above the fault-tolerance threshold. Accordingly, improving the fidelity and robustness of these gates has been a research focus in recent years.

In trapped ions quantum computers, entangling gates are performed by driving the normal modes of motion of the ion chain, generating a spin-dependent force. Even though there has been significant progress in increasing the robustness and modularity of these gates, they are nevertheless sensitive to noise in the driving field's intensity, an inherent noise source in trapped ions systems.

Here [**1**] we supplement the conventional spin-dependent displacement with spin-dependent squeezing, which enables a gate that is robust to deviations in the driving field's amplitude. We solve the general Hamiltonian and engineer its spectrum analytically. We also endow our gate with other, more conventional, robustness properties, making it resilient to many practical sources of noise and inaccuracies.

[1] Y. Shapira, S. Cohen, N. Akerman, A. Stern, R. Ozeri, arXiv:2207.01660 (2022)

Mon, Aug. 1st, Session 1, No. 21

Design and fabrication of a micro-blade trap with optical cavity for a mixed species quantum network node

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A trapped ion coupled to an optical cavity is a natural platform for high efficiency entanglement between an emitted photon and the internal states of the ion [**1**]. Integration of cavities into traps has long been pursued as a key technology for scalability of quantum devices [**2**]. Strong coupling between an ion and a cavity has recently been demonstrated in our group [**3**], however, there are multiple challenges to scalable integration. For example, charging of the mirror dielectrics can disturb the trap potential [**4**], and the physical size of mirror substrates can limit optical access.

We have designed, and are fabricating, a 3D micro trap with an optical cavity to act as a quantum network node, which we report on in this poster. Selective laser-induced etching allowed us to fabricate blades in a two-layer stacked chip design, where short ion-electrode distances help shield ions from a set of cavity mirrors. The trap features multiple zones in a linear QCCD layout where ions can be loaded, stored, and manipulated in high NA areas before being shuttled into the cavity. The symmetric 3D electrode geometry also gives high trap efficiencies at low voltages, which is beneficial for the scaling of trap drive electronics.

We also report on the progress of a novel method of fabricating cavity mirrors. The mirrors are laser machined onto the end of fused silica rods that are rotated at high speed during the ablation process. This yields low-birefringence mirrors and so will reduce polarization oscillations in the cavity that can limit remote entanglement fidelities [**5**]. These mirrors are mounted in a piezo driven flexure mount with high mechanical mode frequencies, avoiding the vibration sensitivity inherent to fibre cavities. Modular design allows for separate cavity assembly and testing before insertion into the trap.

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Mon, Aug. 1st, Session 1, No. 22

Towards a light-shift gate with transverse momentum transfer from spatially modulated light

Midhuna Duraisamy Suganthi, Visal So, Abhishek Menon, Roman Zhuravel and Guido Pagano

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Ions trapped in a chain act as effective two-level systems that can interact with one another using gate operations and can be used to simulate spin quantum systems. Recently, a light shift gate has been demonstrated using the quadrupole transition in $^{171}Yb^{+}$ ions[**1**]. It offers advantages over the Molmer-Sorensen gate as it is insensitive to optical phases and is based on axial normal modes excitations that are more evenly spaced and reduce crosstalk. However, the gate is still sensitive to motional phase and that requires that the ions be placed at even-integer multiples of $\pi/\Delta k$. This becomes a constraint for long ion chains. We plan to use an array of individual beams orthogonal to the trap axis, where each beam has a gradient in its transverse spatial profile that can excite the axial modes of motion[**2, 3**]. We propose to use a spatial light modulator as the beam shaping tool for momentum transfer from the beam and also gain freedom in beam positioning. We illustrate how to realize a light-shift gate using this setup and discuss methods to generate the desired beam shape using the spatial light modulator.

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Mon, Aug. 1st, Session 1, No. 23

Scalable prediction of molecular vibronic spectra using time-domain analog quantum simulation

Ting Rei Tan, Ryan MacDonell, Tomas Navickas, Christophe Valahu, Ivan Kassal and Michael Biercuk

The University of Sydney

The simulation of a quantum chemical system is challenging using conventional computers, particularly in strong vibronic (vibrational + electronic) coupling regimes where the Born-Oppenheimer approximation breaks down. We show that vibronic coupling Hamiltonians representing ultrafast molecular dynamics can be efficiently simulated on quantum systems with coupled internal states and bosonic modes. Furthermore, this "mixed qudit boson" (MQB) approach can be extended to time-domain measurements used to reproduce molecular absorption spectra. We present preliminary experimental results performed with a trapped-ion system.

Mon, Aug. 1st, Session 1, No. 24

Progress on implementation of remote entanglement between Yb^+ and ZnO defect spin

Carl Thomas, A. Kato, C. Zimmermann, V. Niaouris, B. Blinov and K.-M. Fu

University of Washington

Entanglement between a trapped ion and a solid state donor will allow future devices to access the fast gate times demonstrated in semiconductor defects alongside the long coherence times of ionic qubits. To leverage the advantages of such a hybrid architecture, we are constructing a entanglement scheme between photons from a donor bound exciton ensemble in ZnO and the $^2P_{1/2}$ - $^2S_{1/2}$ transition in Yb^+ using their very close optical transition frequencies.

In order to optimize entanglement rate, the Yb ion will be trapped at the focus of a high numerical aperture parabolic mirror and a deformable mirror will be used to improve fiber coupling efficiency, together maximizing single photon detection efficiency. The donor will be embedded in a microfabricated cavity to shift the transition frequency closer to that of the ion. Fine tuning to the target transition will be accomplished via DC stark shift from surface electrodes in the ZnO crystal. Pulse shaping will be applied to maximize temporal waveform overlap between the ionic and solid state photons. Appropriate excitation and phase locking of the two photon sources will be used to generate heralded entanglement.

Mon, Aug. 1st, Session 1, No. 25

Multi-mode ground state cooling of a trapped ion chain beyond the Lamb-Dicke limit

Qiming Wu, Yue Shi and Jiehang Zhang

USTC

Trapped atomic ions are a prime platform for quantum computing and quantum simulations. Based on our last year's efforts to scale up the system size, we present our experimental progress toward quantum simulation with long ion strings. First, we report a new method to prepare qubits in their motional ground state beyond the Lamb Dicke limit, providing a necessary condition for quantum information processing with a long ion chain in the strong spin-motion coupling regime. By driving multiple red sideband transitons in parallel and applying weak optical pumping to continuously reset the spin-state, we can prepare a single ion with $\eta = 0.78$ in the ground state in 200μs. We also show effective parallel cooling for the axial modes of 24 ions to the near-ground state with η up to 1.3, limited by the center-of-mass mode heating. We expect this cooling scheme to cool 100+ ions in a much faster time than the traditional resolved sideband cooling, paving the way for future quantum simulations with more ions.

We then show the first demonstration of Hamiltonian engineering in a trapped ion chain using the axial modes, in which the mode spectrum is sparse and has near equal mode spacings. By applying an optical dipole force on the ions with tunable couplings, the Coulomb forces can induce different Ising-type interactions via spin-motion coupling of motional modes. We engineer the couplings wisely to encode different connectivity configurations of qubits and apply a digital-analog model to implement the spin interactions on a square-lattice, a sphere, and a four-dimensional hyper-sphere, with 4,6,8 qubits respectively.

Mon, Aug. 1st, Session 1, No. 26

Strontium ions for quantum networking and vortex field experiments

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The strontium ion is an ideal candidate for medium-distance quantum networking due to an atomic transition at 1.1 μm, a wavelength compatible with existing fiber optic infrastructure. This transition eliminates the need for lossy photon conversion processes, allowing for direct remote entanglement on the kilometer scale. We discuss the design and assembly of a strontium trapped-ion system and report on current progress towards remote entanglement. The final qubit states in our photon-generation scheme lie in the D3/2 level and differ by $\Delta m_j = 2$. We propose a scheme for driving this dipole-forbidden transition using a microwave vortex field, which carries a unit of orbital angular momentum in addition to the unit of photon spin. It will also allow us to make a first measurement of the ratio of E2 and M1 multipoles in this transition.

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Mon, Aug. 1st, Session 1, No. 27

Quantum Scientific Computing Open User Testbed (QSCOUT) Capabilities

Ashlyn D. Burch, Matthew N. H. Chow, Craig W. Hogle, Megan K. Ivory, Daniel S. Lobser, Theala L. Redhouse, Melissa C. Revelle, Joshua M. Wilson, Christopher G. Yale and Susan M. Clark

Sandia National Laboratory

At Sandia National Laboratories, we are developing and operating an open user testbed for quantum information protocols based on trapped ions, known as the Quantum Scientific Computing Open User Testbed, or QSCOUT. This testbed provides not only the opportunity to perform quantum algorithms and study noisy-intermediate-scale quantum (NISQ) systems, but unlike many commercial testbeds, it also allows users control of the system both at the quantum-circuit level and at the more fundamental pulse-control level to study alternate methods of gate construction and optimization. Here, we present our progress thus far in developing the testbed and running algorithms with two to three ions for our first group of users, as well as some of the experimental challenges encountered in developing such a system. We also discuss the current and anticipated capabilities of QSCOUT, including future testbed developments such as longer ion chains, a cryogenic system, and measuring subsets of qubits mid-circuit. In addition, we will look at QSCOUT's own intuitive quantum programming language, Just Another Quantum Assembly Language (Jaqal), as well as the

ability for users to specify their own gate pulses via Jaqal Pulses and Waveforms (JaqalPaw). As such, QSCOUT provides the scientific community a unique opportunity for low-level access to a NISQ trapped-ion system.

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Mon, Aug. 1st, Session 1, No. 28

Trapped Ion Quantum Computing Fabrication Testbed at UMass Amherst

Christopher Caron

University of Massachusetts Amherst

Here we present our progress towards assembling our first room-temperature ion trap system. Our research aims to improve the performance and design scalability of trapped ion quantum computing hardware using $^{88}Sr^{+}$ as a qubit platform. The design features a custom niobium surface Paul trap fabricated on a fused silica substrate in-house at UMass. The die is then mounted to a hybrid Rogers/aluminum nitride interposer PCB within a vacuum chamber which is now ready for assembly. We also present our next layout which will act as a testbed for ion traps with integrated photonic waveguides and diffraction grating couplers for individual ion addressing in collaboration with MIT Lincoln Labs.

Mon, Aug. 1st, Session 1, No. 32

Characterization of the AC Zeeman Effect in Microfabricated Surface Traps

Megan Ivory

Sandia National Laboratory

Microfabricated surface traps have enabled precise control over trapped ions in a compact device with lower power requirements than traditional traps, but have also presented unique challenges due to the small ion-surface distance. One such challenge is AC Zeeman effect which leads to frequency shift due to the oscillating magnetic field associated with the RF drive. Here, we characterize the frequency shift of the ground state microwave transition of a $^{171}Yb^{+}$ ion confined by microfabricated surface traps driven by an RF field. We compare AC Zeeman effect due to the drive RF and induced RF current in the trap ground planes for various traps fabricated at Sandia National Laboratories.

Mon, Aug. 1st, Session 1, No. 39

An Yb^+ optical clock for precision metrology and tests of fundamental physics

Billy Robertson

National Physical Laboratory (UK)

Mon, Aug. 1st, Session 1, No. 40

EPICS (Extreme Performance Ion-trap Cavity System)

George Schwartz

Duke University

In collaboration with Sandia National Labs (SNL), NIST and JPL, the purpose of the Extreme Performance Ion-trap Cavity System (EPICS) is to improve the signal-to-background ratio for qubit state detection. EPICS addresses this issue by trapping an ion within a hemispherical optical cavity. In the case of $^{171}Yb^{+}$, a Fabry-Perot interferometer around the ion increases the photon collection efficiency by an order of magnitude. Duke's team is also pursuing a second approach utilizing $^{137}Ba^{+}$ and incorporating the ion with a novel flexure design.

Poster session 2 abstracts

Tue, Aug. 2nd, Session 2, No. 1

Towards scalable quantum networks using fiber cavities and surface ion traps

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Trapped ions coupled to an optical cavity have proven to be good candidates for atom – photon interface, which is basis for quantum network applications [**1**]. One of the main challenges remains scalability of the systems. Promising approach would be the usage of surface ion traps with integrated fiber cavities and microelectromechanical system-based (MEMS) microactuator for the mirror position [**2**]. In this poster an existing experimental setup will be presented, which consists of linear Paul trap with integrated fiber cavity along the trap axis. Additionally, the design of a new surface ion trap and MEMS based microactuators will be presented, with the experimental apparatus that has been designed to test these systems.

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Tue, Aug. 2nd, Session 2, No. 2

Long-range Ising models: Probing the renormalization of sound in non-perturbative QFTs with crystals of trapped ions

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In this poster, I will present our recent results on different strategies to probe non-perturbative aspects of the relativistic $\lambda\phi^4$ quantum field theory (QFT), which arises in the vicinity of the linear-to-zigzag transition in trapped-ion chains. I will discuss interferometric techniques to infer the generating functional of this QFT, and simpler protocols where the distance-decay of the spin-spin couplings in the Ising quantum simulators gives information about Feynman diagrams and the renormalization of this QFT.

[1] G. Martín-Vázquez, G. Aarts, M. Müller, and A. Bermudez PRX Quantum 3, 020352 (2022)

[2] A. Bermudez, G. Aarts, and M. Müller Phys. Rev. X 7, 041012 (2017)

Tue, Aug. 2nd, Session 2, No. 3

Using trapped ions to simulate NMR experiments and observe measurement-induced phase transitions

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Nuclear magnetic resonance (NMR) spectroscopy is a useful tool in understanding molecular composition and dynamics, but simulating NMR spectra of large molecules becomes intractable on classical computers as the spin correlations in these systems can grow exponentially with molecule size. In contrast, quantum computers are well suited to simulate NMR spectra of molecules, particularly zero- to ultralow field (ZULF) NMR where the spin-spin interactions in the molecules dominate. In this work, we demonstrate the first quantum simulation of an NMR spectrum, specifically that of the methyl group of acetonitrile in ZULF, using a trapped ion quantum computer. The simulation involves state-of-the-art "QFAST" circuit synthesis algorithm that produces short circuits, with the circuit sampling rate considerably reduced by employing a compressed sensing technique. This work lays the foundation for simulation of NMR experiments on near-term quantum hardware.

Many-body open quantum systems balance internal dynamics against decoherence from interactions with an environment.

Here, we explore this balance via random quantum circuits implemented on a trapped-ion quantum computer, where the system evolution is represented by unitary gates with interspersed projective measurements. As the measurement rate is varied, a purification phase transition is predicted to emerge at a critical point akin to a fault-tolerent threshold. We probe the “pure” phase, where the system is rapidly projected to a deterministic state conditioned on the measurement outcomes, and the “mixed” or “coding” phase, where the initial state becomes partially encoded into a quantum error correcting codespace. We find evidence of the two phases and show numerically that, with modest system scaling, critical properties of the transition emerge.

Tue, Aug. 2nd, Session 2, No. 4

Spectroscopy of metastable trapped $^{173}\mathrm{Yb}^{+}$ for quantum information and fundamental science

Thomas Dellaert, Patrick McMillin, Hassan Farhat and Wesley Campbell

University of California, Los Angeles

The metastable $^{2}\mathrm{F}^{o}_{7/2}$ state in $^{171}\mathrm{Yb}^{+}$ is increasingly being utilized as a resource for quantum information processing, but the more complex (and potentially more useful) hyperfine structure of this state for the deformed-nucleus ytterbium-173 isotope is experimentally unexplored. Predictions, however, point to unique aspects of the hyperfine interaction in this case, including hyperfine quenching of the metastable state lifetime to a technologically attractive level [**1**] and the potential to resolve a 4 orders of magnitude discrepancy in the nuclear magnetic octupole moment of ytterbium-173 [**2**][**3**][**4**].

[1] V. A. Dzuba and V. V. Flambaum, *Hyperfine-induced electric dipole contributions to the electric octupole and magnetic quadrupole atomic clock transitions*, Phys. Rev. A 93, 052517 (2016)

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[3] R. P. de Groote, S. Kujanpää, Á. Koszorús, J. G. Li, and I. D. Moore, *Magnetic octupole moment of* $^{173}\mathrm{Yb}$ *using collinear laser spectroscopy*, Phys. Rev. A 103, 032826 (2021)

[4] A. K. Singh, D. Angom, and V. Natarajan, *Observation of the nuclear magnetic octupole moment of* ^{173}Yb *from precise measurements of the hyperfine structure in the* $^3P_2$ *state*, Phys. Rev. A 87, 012512 (2013)

Tue, Aug. 2nd, Session 2, No. 5

Coherent Deexcitation of Multi-Species Ion Crystals

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In a recent demonstration of the quantum charge coupled device (QCCD) trapped ion architecture [**1**], circuit time is dominated by transport and cooling operations. Cooling time can be improved by reducing the excitation imparted to the ion by transport. It has been shown that the coherent part of this motion can be displaced back to near the motional ground state, either when stationary or during the transport operation [**2, 3**]. We extend these techniques to transporting multiple mixed-species ion crystals in a linear ion trap, while deexciting the acquired coherent excitation en route. We have developed a calibration procedure for finding the ideal deexcitation parameters that will deexcite coherent states with $n_{coh} = |\alpha|^2 < 1000$ quanta. With this technique, we achieve 10X faster speed that could potentially reduce our circuit time by as much as 15%. We demonstrate a successful deexcitation of 6 wells to near the ground state, both for a $^{171}Yb^+$ ion and $^{138}Ba^+$ – $^{171}Yb^+$ crystals. Future work will include extending this technique to larger numbers of ions and larger ion crystals.

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[3] R. Bowler et al, PRL 109, 080502 (2012)

Tue, Aug. 2nd, Session 2, No. 6

Quantum state characterization and coherent control of molecular ions

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Universität Innsbruck

Precision characterization and high-fidelity coherent control of quantum degrees of freedom in molecular systems is challenging due to their complexity. Recently, quantum logic techniques have been developed that transfer the exquisite control over atomic ions onto co-trapped molecular ions. We are implementing three approaches towards characterization and coherent control of molecular ion vibrational and rotational states which utilize these quantum logic techniques. The first method is the detection of single-photon absorption events by mapping the recoil of a molecule to the electronic state of a co-trapped atomic ion. This enables a pump-probe experiment to investigate ultrafast molecular dynamics such as intramolecular vibrational redistribution. The second method is state-dependent force spectroscopy which uses optical tweezers to exert a state-dependent force on a molecule which shifts the common motional mode frequency of the trapped molecular and atomic ions. Such a shift can be measured by observing the atomic ions, thus realizing a quantum non-demolition measurement of the molecular state. The third method involves heralded state preparation and coherent control over molecular external degrees of freedom using stimulated Raman transitions and frequency comb spectroscopy techniques. This could enable the

creation of rotational or vibrational cat states which could enable an experimentally-feasible, resource-efficient quantum error correction scheme. This method can also be used for precision experiments searching for new physics and serve as the basis to control state-selective chemical reactions with applications in chemistry and biology.

Tue, Aug. 2nd, Session 2, No. 7

Experimental Bayesian Calibration of Trapped-Ion Entangling Operations

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The performance of quantum gate operations is experimentally determined by how correctly operational parameters can be determined and set, and how stable these parameters can

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be maintained. In addition, gates acting on different sets of qubits require unique sets of control parameters. Thus, an efficient multi-dimensional parameter estimation procedure is crucial to calibrate even medium sized quantum processors. Here, we develop and characterize an efficient calibration protocol to automatically estimate and adjust experimental parameters of the widely used two-qubit MS entangling gate operation in a trapped ion quantum information processor. The protocol exploits Bayesian parameter estimation methods which includes a stopping criterion based on a desired gate infidelity. We experimentally demonstrate a tune-up procedure that leads to a residual median gate infidelity due to miscalibration of $1.3(1) \cdot 10^{-3}$, requiring 1200 ± 500 experimental cycles, while completing the entire gate calibration procedure in less than one minute, which provides a significant speedup over commonly used manual tune-up routines. This approach is applicable to other quantum information processor architectures with known or sufficiently characterized theoretical models.

Tue, Aug. 2nd, Session 2, No. 8

Pulsed excitation scheme for barium ion-photon entanglement generation

Isabella Goetting, Mikhail Shalaev, Jameson O'Reilly, George Toh, Sagnik Saha and Tingguang Li

Duke University

Larger chains of trapped ions have greater spectral crowding, are more susceptible to background gas collisions, and require more complicated optical set-ups for individual addressing. To avoid this problem, we envision connecting smaller trapped-ion quantum computers through optical links of single photons, allowing for quantum entanglement of separated ion chains. We use ^{138}Ba as our communication ion because it has the reddest S to P wavelength and is therefore the most amenable to integrated photonic technologies. The main limitation in this solution is the entanglement generation rate, which is restricted by optical pumping to the D3/2 state, so our goal is to increase this rate by exciting directly from the S state. We present details about a new single-photon generation scheme using a pulsed laser source at 493 nm for the S to P transition in ^{138}Ba, and a shelving scheme using the narrow 1762 nm transition from S to D5/2 in ^{138}Ba.

Tue, Aug. 2nd, Session 2, No. 9

Robust optical engineering and atomic source development for a Barium ion-based quantum simulator

Noah Greenberg, Ali Binai-Motlagh, Xinghe Tan, Collin Epstein, Rajibul Islam and Crystal Senko

University of Waterloo

Trapped ions for quantum information processing has been an area of intense study the past twenty years due to the extraordinary high fidelity operations that have been achieved experimentally and the recent microfabricated ion traps that offer a potential path to scaling the technology. Specifically, barium trapped ions have shown to have exceptional state-preparation and measurement (SPAM) fidelities. However, a major pitfall with the leading isotope, 133Ba, is that it is radioactive and can only be used in microgram quantities. We describe two methods for creating microgram barium chloride (BaCl2) ablation targets for use in trapped ion experiments. We characterize these targets using energy dispersive x-ray spectroscopy (EDS) and search for neutral fluorescence from these targets to gauge their viability for use in trapped ion experiments. In addition to characterizing barium atomic sources for trapping, we present optical designs for fiber coupling, monitoring, and focusing light at the ions that are robust against drifts due to thermal fluctuations and optomechanical failure. Harnessing the full potential

of trapped ion as a platform requires building increasingly complex machines capable of driving many different atomic transitions and addressing long chains of ions.

Tue, Aug. 2nd, Session 2, No. 10

Building a Stylus trap and Deep Parabolic Mirror to Study and Control Quantum Jumps

Jane Gunnell, C. Thomas, D. Tchaikovski, J. Liteanu and B. Blinov

University of Washington

In this poster we present a method for studying quantum jumps in trapped barium ions using a novel "stylus" trap design that minimizes the solid angle blocked by the trap, and a deep parabolic mirror with solid angle coverage of ¿95%. The trapped ion will sit at the focus of the mirror resulting in a total single photon detection efficiency of about 65% using high-efficiency avalanche photodiodes.

Part of the motivation for this research comes from work of Minev et al whose group found they could predict a quantum jump from ground state to first excited state of a superconducting artificial three-level atom. Once our trap is complete we plan to try and replicate these results with the goal of predicting quantum jumps and ultimately reserving them before they occur.

Tue, Aug. 2^{nd}, Session 2, No. 11

Towards fault-tolerant quantum computing with an universal set of microwave driven quantum gates with trapped ions

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A certain set of mathematical problems could potentially be solved more efficiently by quantum computers than their classical counterparts. To realize a quantum advantage with quantum computers, the prerequisite condition is to coherently control a large number of qubits while maintaining an error rate per gate below the fault-tolerant threshold [**1**]. Furtheremore single-qubit rotation operations and two-qubit entangling gates form a universal set of quantum operations capable of performing any quantum algorithm. Here, we consider the implementation of single-qubit rotations and two-qubit gates using microwaves as a scalable alternative to the more widely used laser-based addressing techniques, which have fidelities that are typically limited by photon scattering [**2**]. The control fields are generated by microwave conductors embedded directly into the trap structure. Using this fully integrated microwave approach, we obtain single-qubit gate infidelity with the randomized benchmarking protocol of 10^{-4} and using the cycle benchmarking protocol we extract the preliminary composite process fidelity of 96.6% [**3, 4, 5, 6**].

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Tue, Aug. 2nd, Session 2, No. 12

Angle-robust Two-Qubit Gates in a Linear Ion Crystal

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In an ion trap quantum computer, collective spin-motion entanglement are used to achieve high-fidelity two-qubit gates. By using modulated pulses the residual spin-motion entanglement can be first-order insensitive to mode frequency drifting or miscalibration, but the rotation angle is usually sensitive to mode frequency error. Here we propose a gate scheme that concatenates two modulated pulses (Angle-robust or A-robust), which eliminates the first-order sensitivity of both residual entanglement and rotation angle to mode frequency error in a linear ion crystal. We experimentally implemented A-robust gate sequence using robust frequency-modulated (FM) pulses in a 2-ion chain, and verified that with mode frequency error A-robust gates outperform FM gates with more robust rotation angle.

Tue, Aug. 2nd, Session 2, No. 13

Mitigating Experimental Imperfections with Frequency-Modulated Pulses for High-Fidelity Two-Qubit Gates in Ion Chains

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High-fidelity two-qubit gates are essential in many quantum information processing tasks. In a trapped-ion quantum computer, collective motional modes of the ion chain are used to entangle the internal states of two ions. The quality of the gates suffers when the experimental parameters such as trap frequency and laser intensity differ from the ideal case or fluctuate over time. Here we present two methods of improving the fidelity of frequency-modulated Mølmer-Sørensen gates under experimental imperfections. First, we achieve robustness to motional mode frequency offsets by optimizing average performance over

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a range of systematic errors using batch optimization. Next, we mitigate dephasing of the motional modes under a known noise spectrum by designing the filter function of the pulse. We present theoretical methods and experimental results.

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[2] **MK**, Y. Wang, C. Fang, B. Zhang, O. Khosravani, J. Kim, and K.R. Brown, Designing Filter Functions of Frequency-Modulated Pulses for High-Fidelity Two-Qubit Gates in Ion Chains, arXiv:2206.10850 (2022)

Tue, Aug. 2nd, Session 2, No. 14

Integration of an Optical Cavity with a linear Ion Trap

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Trapped ions have been shown to be excellent qubit candidates for quantum information processing. However, due to scaling constraints, the number of qubits that can be reliably controlled has been limited to a few tens, whereas thousands more are required for harnessing the potential of quantum processors. To this end, optical cavity mediated photonic interconnects have been pursued as promising candidates. We review the challenges faced with combining optical cavities and linear ion trap systems. By numerical simulations, we have found that the conventional integration of optical cavities with linear ion traps can lead to significant distortion of the trapping field, converting the rf-null line to a deep potential well. We present configurations of cavity designs and rf-drives that are compatible for integration. The small cavity mode volumes that are required for efficient interfaces necessitate miniature ion traps. We have developed blade-type ion traps with low defects using selective laser etching. Another challenge that has limited the efficiency of ion-cavity interfaces is the degradation of high finesse ultraviolet band cavities designed to couple to the stronger dipole transitions in ions such as Ca^{+} and Yb^{+}. We consider Ba^{+} ions as alternatives which offer a strong dipole transition outside the

UV band at 493 nm. We have measured a stable finesse of a high finesse cavity at this wavelength at a pressure of $\sim 10^{-8}$ mbar. This offers a route for cavity-QED with trapped ions in the strong coupling regime with much less stringent geometric limitations. This work was supported by JST Moonshot R&D Grant No. JPMJMS2063 and MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant No. JP-MXS0118067477.

Tue, Aug. 2nd, Session 2, No. 15

Fifth-force Search with Isotope-Shift Spectroscopy in Yb^+

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Isotope shift spectroscopy is one of the promising new avenues for the New Physics search. By measuring optical clock

transitions in isotopes of Yb^+, one can probe the coupling induced by the hypothetical bosonic force carrier. Calculation of the first-order nuclear effects within the Standard Model is much less accurate than precision isotope shift measurement, and can be avoided using the King plot method [**1**]. Contributions from New Physics may manifest as deviations from the King plot linearity, alongside higher-order Standard Model effects. Patterns of these deviations serve as a tool to distinguish possible sources of King plot nonlinearity. Our results show that nuclear density functional theory calculations explain the dominant source of the observed nonlinearity [**2**]. Combining recently reported data and our new measurement results we observe a distinct second source with 4.3 sigma significance. We outline possible directions to improve precision and pinpoint the second nonlinearity source.

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Tue, Aug. 2nd, Session 2, No. 16

Qubit control of Yb^+ ions on surface chip with Raman lasers and measurement of electric field from chip silicon-laser collision

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Quantum gates in trapped-ion quantum computers are realized by applying laser beams to individual ions for Raman transition between their qubit states. Two-qubit gates of ion qubits additionally exploit the common oscillation modes of the trapped ion chain, so Raman beams having enough amount of momentum difference, or angle between them are used [**1**]. We trapped $^{171}Yb^+$ ions on a microfabricated chip, which was designed to suppress the dielectric charging by metallization of sidewalls of the electrode pillar structure [**2**]. Then, 355 nm pulse laser Raman beams were applied in counter-propagating configuration to achieve the fidelity of 97% for 1-qubit gate. During this operation, we observed stray electric field generated

from chip-laser collision in gate time scale, which is suspected to happen through photovoltaic effect. We also estimated the magnitude of the stray electric field by measuring the compensation voltage necessary to suppress the micromotion.

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Tue, Aug. 2$^{\text{nd}}$, Session 2, No. 18

Optical Addressing of 2D Ion Arrays for Quantum Optimization in a Compact Penning Trap

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Trapped ions form the basis of many state-of-the-art quantum technologies. Penning traps confine charged particles within static electric and magnetic fields, allowing for coherent manipulation of large numbers of trapped-ion qubits with reduced heating as compared with radiofrequency ion traps. We have recently demonstrated ion confinement, Doppler laser cooling [**1**], and global radiofrequency and microwave spectroscopy [**2**] of $^{40}Ca^{+}$ and $^{9}Be^{+}$ Coulomb crystals in compact, room-temperature Penning ion traps based on permanent magnets. We discuss recent preparation, measurement, and individual optical addressing of $^{40}Ca^{+}$ metastable ($D_{5/2}$) qubits within rotating two-dimensional crystals with applications for quantum simulation (e.g. quantum approximate optimization algorithm). We also present experimental progress towards combining an in-vacuum, intermediate-finesse (~ 3000) optical cavity with our compact Penning traps for efficient cavity-assisted Doppler laser cooling of Ca^{+} using the narrow $S_{1/2} \leftrightarrow D_{5/2}$ electric quadrupole transition near 729 nm.

This work is supported by ONR (N00014-17-1-2408, N00014-20-1-2427) and the DARPA ONISQ program (HR0011-20-C-0046).

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Tue, Aug. 2nd, Session 2, No. 19

Sympathetic Ground State Cooling of CaH^+

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The complex internal structure of molecular ions poses challenges with employing direct laser cooling [**1**]. An alternative and more general approach is to sympathetically cool the external and internal degrees of freedom of the molecular ions using laser-cooled atomic ions and neutral atoms, respectively [**2**]. Our hybrid ion-atom trap is ideally suited for this method of ground-state cooling of a molecular ion [**3**], and our goal is to demonstrate this with calcium mono-hydride ions (CaH^+) using co-trapped calcium ($^{40}Ca^+$) ions and potassium (^{39}K) atoms for sympathetic cooling. Moreover, the ability to simultaneously trap the three species, $^{40}Ca^+$, ^{39}K, and CaH^+, allows for the study of various possible chemical reactions. We have observed photon-mediated charge exchange between $^{40}Ca^+$ ions and ^{39}K atoms and plan to study the interaction between CaH^+ ions and ^{39}K atoms [**4**]. Finally, our lab in the past has established vibronic and rovibronic spectroscopy of CaH^+ [**5**], and next, we plan to pursue rotational spectroscopy of CaH^+ using a narrow bandwidth TiS laser.

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Tue, Aug. 2nd, Session 2, No. 20

Logical Qubit RF Control System using RFSoC

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Logical qubits require more complex control than an unconditional circuit, necessitating low latency between measurement and correcting the logical qubit. In an ion trap system, this requires synchronizing many different pieces of hardware, including RF waveforms, ion shuttling, PMT measurement, and readout lasers. Here, we discuss progress on upgrading our RF control using an RFSoC FPGA, accompanying software from Sandia National Laboratories, and our own custom software. This allows us to realize simultaneous & realtime waveform control, as well as reduces typical gate sequence compile times from over a minute to less than a second. We also discuss control layers that we have developed on top of this hardware, which allow us to easily write and use new gates, calibrate the gates, and then visualize gate sequences at the pulse level.

Tue, Aug. 2nd, Session 2, No. 21

Progress towards a three-node quantum network

Sagnik Saha, Jameson O'Reilly, George Toh, Isabella Goetting, Mikhail Shalaev and Christopher Monroe

Duke University

Scaling up the trapped ion quantum computing platform to a larger number of qubits will likely require photonic interconnects to establish entanglement between ions in different traps. In this work, we discuss our progress towards demonstrating a three-node network. Each of these nodes will contain a $^{171}Yb^{+}$ and a $^{138}Ba^{+}$ as the memory and the communication ions, respectively. Two of our nodes have 0.6 NA light- collecting objectives while our latest and third node has two 0.8 NA in-vacuum aspheric lenses. Our preliminary measurements include heating rates of our traps in all three nodes. We also discuss plans to create GHZ states distributed across three traps and demonstrate quantum repeater protocols.

Tue, Aug. 2nd, Session 2, No. 22

Progress towards building a scalable trapped-ion QIP device with ultralow crosstalk optical control

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We report on our recent results with holographic optical addressing of individual ions. We experimentally and numerically explore the limits of individual spin reset (optical pumping) and subsystem measurement while maintaining coherence of neighboring ions. With in-situ aberration characterization using a single trapped ion, we demonstrate extremely low intensity crosstalk ($\approx 10^{-4}$), which translates to $\approx 99.8\%$ coherence (Ramsey fringe contrast) at the neighboring ion while the target ion is optically pumped. When coupled with state-of-the-art state detection efficiency, this low intensity crosstalk error can retain $\approx 99\%$ coherence at the neighboring ion, thus enabling subsystem measurements without ion-shuttling. We also report on our progress in building a trapped-ion quantum information processor that is optimized for a long chain of Yb ion qubits (> 50). We optimize the vacuum and the trap (a segmented blade trap) design for long lifetime, high optical access from four

sides, and low heating rate. Our holographic optical addressing system will be integrated to this large scale processor.

Tue, Aug. 2nd, Session 2, No. 23

Trapped-Ion Simulators for Molecular Dynamics

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The quantum dynamics of a molecular system are complicated to simulate due to the coupling between the system and the surrounding environment. The environment is often treated as harmonic oscillators coupled to the electronic states of the system. The trapped-ion simulators provide the opportunity of studying the effects of a quantum environment, as their native operations consist of controlling the coupling between spins and their quantized motional degrees of freedom. In this poster, we present the computational efficiency comparison between classical simulators and trapped ion simulators based on a general electron transfer open system, showing the winning regions for different simulators. On the other hand, the multiple energy levels (d-levels, $d > 2$) in molecules generally need d qubits to fully simulate. The interaction between levels requires multi-qubit transition to achieve. However, the qudit system has inherent advantages in simulating such d-level systems. Only one ion and single qubit gate are needed for mapping the energy level transitions, which improves the simplicity and fidelity by a large a

mount. In this poster, we present some preliminary data of simulating the electron transfer in molecules under polarized light by qutrits.

Tue, Aug. 2nd, Session 2, No. 24

Improving trapped ion camera detection with machine learning

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Measuring the quantum state of trapped ions typically involves collecting photons from state-dependent fluorescence. EMCCD cameras are an attractive solution as they provide spatial resolution enabling individual measurement of ions confined in multi-ion crystals. However, measurement fidelities and acquisition speeds of EMCCD cameras are often lower than single-photon detectors (e.g. avalanche photodiodes and photomultiplier tubes). Here, we leverage machine learning techniques to benefit camera detections for ions trapped in Paul and Penning traps.

In Paul traps, measuring the quantum state of a one-dimensional ion chain with a camera typically involves defining regions of interest around each individual ion. The total number of fluorescent photons in each sub-region can then be used to infer the quantum states through thresholding. Instead, one can leverage the information in each pixel and apply machine learning aided image classification to the full image. In a previous demonstration with a qubit encoded in the $^2S_{1/2}$ ground state of $^{171}Yb^+$, we improved the state measurement infidelity from $4.3(3)\times10^{-2}$

to $3.3(2) \times 10^{-2}$ with a random forest classifier [**1**]. Here, we investigate the performance of a convolutional neural network for the state classification of multiple ions in a chain. Using simulated camera images modelled after experimental data, the infidelity averaged over all possible states of a three-ion chain is improved from $11(5) \times 10^{-2}$ to $5(2) \times 10^{-2}$. This suggests that machine learning can be particularly useful for larger ion chains by correcting for spatial photon leakage.

Imaging large ion crystals in a Penning trap is complicated by the ions' cyclotron rotation. Common solutions involve stroboscopic camera triggering, in which fast images are captured at a rate matching that of the cyclotron frequency. This method, however, suffers from poor detection times. Here, we leverage a high-speed XYT camera (TPX3 from ASI, bandwidth of 80 Mhits/s) to reconstruct the ions' position using the fluorescence photons' time of arrival [**2**]. This method requires the precise knowledge of each ion's position, which is complicated by the uncertainty in the crystal's size, potential "dark" ions, and other abnormalities. To overcome this, we train a physics-based object detection model which reliably locates ions with an accuracy greater than 99.5%.

[1] C. L. Edmunds *et al.*, Phys. Rev. A 104, 012606 (2021)
[2] M. T. Robinson, *"A high data-rate time-correlated single-photon counter for site-resolved imaging of large trapped-ion crystals."*, Honour's thesis, The University of Sydney (2021)

Tue, Aug. 2nd, Session 2, No. 25

Fundamental Limits on Gate-Laser Scattering Errors in Barium-133

Samuel Vizvary[1], Matthew Boguslawski[1], Zachary Wall[1], Isam Daniel Moore[2], Eric Hudson[1] and Wesley Campbell[1]

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Barium-133 is a promising trapped-ion qubit for large scale quantum computing with easily accessible laser frequencies, robust state preparation, and high fidelity readout. Past theoretical calculations placed a lower limit on Ba^+ stimulated Raman Gate errors due to off resonant photon scattering from the qubit hyperfine ground state to auxiliary electron states that limited two-qubit gate fidelities to around 0.999. However, examining the scattering errors with an expanded model for the Raman gate and scattering processes reveals that the error rates can be orders of magnitude lower at readily available gate laser wavelengths. We present a study of measured scattering errors and relate these errors to the ultimate fidelity limits of laser-driven gates in the $^{133}Ba^+$ qubit. We additionally report progress in our next generation blade trap.

Tue, Aug. 2nd, Session 2, No. 26

Building a Mobile Trap setup for severe environment study

Yuanheng Xie

Indiana University

We currently build a developing a portable ion trap system for studying the real-time susceptibility of trapped ions to ionizing radiation. This unit integrates the laser system, Artiq control system which all compactly fitting a 23.6in. x 33.5in. x 35.5in. wheeled rack. In the coming month, the trapped ion will be exposed to a variety of α, β, and γ radiation sources, and we will measure the resulting changes in ion lifetimes, coherence times, gate fidelities, and motional heating rates. The low-dose radiation results show that trapped ion-based quantum systems may be robust in extreme environments, indicating that much larger doses may be required to induce errors in trapped-ion quantum processors, and the high-does radiation will be implemented on this portable trap system.

Tue, Aug. 2nd, Session 2, No. 27

A next-generation trapped ion quantum computing system

Yichao Yu[1], Liudmila Zhukas[1], Lei Feng[2,1], Marko Cetina[2,1], Crystal Noel[2,1], Debopriyo Biswas[2,1], Andrew Risinger[2], Alexander Kozhanov[1] and Christopher Monroe[2,1,3]

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The first generation of a universal trapped ion integrated quantum processor, constructed in a collaboration between universities and industrial partners, was used to perform quantum algorithms with high-fidelity on 12 qubits, and high-fidelity quantum gates with up to 23 qubits. We present progress on the second-generation system, which has several design improvements, such as a capacity of 32 qubits, parallel addressing capability using an RF-System-On-Chip, a next-generation microfabricated surface ion trap from Sandia National Laboratories, and the integration with the upgraded Raman and CW laser systems built by L3Harris.

Tue, Aug. 2nd, Session 2, No. 28

Risk Aggregation by Quantum Generative Modeling of Copulas

Daiwei Zhu[1], Weiwei Shen[2], Annarita Giani[2], Saikat Ray-Majumder[2], Bogdan Neculaes[2] and Sonika Johri[1]

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Copulas are mathematical tools for modeling joint probability distributions. Since copulas enable one to conveniently treat the marginal distribution of each variable and the interdependencies among variables separately, in the past 60 years they have become an essential analysis tool on classical computers in various fields ranging from quantitative finance and civil engineering to signal processing and medicine. The recent finding that copulas can be expressed as maximally entangled quantum states [**1**] has revealed a promising approach to practical quantum advantages: performing tasks faster, requiring less memory, or, as we show, yielding better predictions. Studying the scalability of this quantum approach as both the precision and the number of modeled variables increase is crucial for its adoption in real-world applications. In this work, we successfully apply a Quantum Circuit Born Machine (QCBM) based approach to modeling 3- and 4-variable copulas on trapped ion quantum computers. We study the training of QCBMs with different levels of precision and circuit design on a simulator and a state-of-the-art trapped ion quantum computer. We observe decreased training efficacy due to the increased complexity in parameter optimization as the models scale up. To address this challenge, we introduce an annealing-inspired strategy that dramatically improves the training results. In our end-to-end tests, various configurations of the quantum models make a comparable or better prediction in risk aggregation tasks than the standard classical models. Our detailed study of the copula paradigm using quantum computing opens opportunities for its deployment in various industries.

[1] E. Zhu *et al.* arXiv:2109.06315 (2021)

Tue, Aug. 2nd, Session 2, No. 29

Analog and digital quantum simulation of para-particle oscillators

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A para-oscillator is a parity-deformed harmonic oscillator characterized by an order parameter. This generalizes the standard Fermi-Dirac and Bose-Einstein statistics associated with fermions and bosons to para-particles. In this work, we realize a method for simulating and characterizing these alternative particles using a trapped ion simulator/computer. On the one hand, we report the analog quantum simulation of para-particle oscillators with a single trapped ion by tailoring the native couplings to two orthogonal motional modes in the trap. Our system reproduces the well-defined statistics for para-bosons and para-fermions of even order. On the other hand, we report the digital quantum simulation of para-particle oscillators by mapping para-particle states to the state of a qubit register, which allow us to identify the para-particle oscillator Hamiltonian as an XY model, and further digitize it onto a universal set of gates. These results represent the first experimental realization of a quantum simulation of the para-particle dynamics in any physical system and demonstrate the full controllability of para-particle oscillators using a trapped-ion experiment.

Tue, Aug. 2nd, Session 2, No. 30

Metastable state shelving for Barium qudit measurement

Brendan Bramman

University of Waterloo

We present on results of trapped-ion qudit shelving measurements and sideband cooling using the quadrupole transition in barium ions. We describe shelving sequences which allow for optimal measurement of high-level ($d > 10$) qudits. We present the results of a 6-level qudit measurement in ^{138}Ba with fidelity over 90%. This work is a first-step towards fully implementing the qudit framework of quantum-information processing in trapped-ion systems. We also observed useful four-level dynamics which allowed us to coarsely tune the 1 Hz laser to the quadrupole transition before fine-tuning by Rabi oscillations. We present progress on spectroscopy of the quadrupole transition for ^{137}Ba and other experimental steps towards full qudit manipulation.

This research was supported in part by the Natural Sciences and Eng ineering Research Council of Canada (NSERC) and the Canada First Research Excellence Fund (CFREF).

Tue, Aug. 2nd, Session 2, No. 31

Industrially microfabricated ion traps

S. Auchter[1,2], M. Valentini[1], C. Axline[3], P. Holz[1,4], C. Decaroli[3], K. Lakhmanskiy[1], R. Oswald[3], R. Matt[3], G. Stocker[2], L. Purwin[2], P. Stampfer[2], S. Sgouridis[2], E. Aschauer[2], Y. Colombe[2], C. Rössler[2], P. Schindler[1], T. Monz[1,4], J. Home[3] and R. Blatt[1,4,5]

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An outstanding challenge in ion-based quantum information processing is the scaling to a large number of qubits. This poster presents two ion traps fabricated in an industrial semiconductor fab, which is an important step toward the production of large-scale, reliable ion traps.

The first trap is a 2D surface-electrode trap that confines ions in individual wells of two contiguous segmented linear traps, forming the building block for a 2D lattice of ions [**1**]. Each string of ions can be moved independently along the direction of the linear traps. The design of the trap aims to enable interaction between ions in separate wells, both between neighboring wells in one of the linear traps and, by adjusting the amplitude of an RF voltage, between linear traps.

The second trap has a 3D geometry formed by a stack of three wafers that are anodically bonded. The bottom wafer holds RF and DC electrodes forming a linear trap, and the top wafer has DC electrodes that can be used to increase the trap depth to $\simeq 1$ eV [**2**]. The spacer wafer has openings that give laser access from a wide range of directions; the top wafer allows light collection from the ions with a numerical aperture N.A. = 0.75.

We present experimental results for both of these traps operated in cryogenic setups, and we report on the development of a PCB socket that allows a convenient swapping between ion traps.

[1] P.C. Holz et al., Two-dimensional linear trap array for quantum information processing, Adv. Quantum Technol. 3, 2000031 (2020)
[2] S. Auchter, C. Axline et al., Industrially microfabricated ion trap with 1 eV trap depth, Quantum Sci. Technol. 7, 035015 (2022)

Tue, Aug. 2nd, Session 2, No. 32

Initial characterization of a direct-telecom single-photon source based on trapped Yb^+

Connor Goham

University of Maryland, College Park

Trapped ions are an interesting platform for quantum networking because ion-qubit coherence is long, high-fidelity quantum logic gates are routine and high-fidelity ion-photon entanglement has been demonstrated in several labs. For fiber-based networks with node-node spacing > 10 km it is imperative to use telecom-fiber compatible wavelengths. Our lab is exploring generation of ion-entangled 1650 nm photons in $^{171}Yb^+$ without dependence on quantum frequency conversion.

The Yb+ ion emits 1650 nm photons on the $^2P_{3/2} \leftrightarrow {}^2D_{5/2}$ dipole transition. We aim to populate the $^2P_{3/2}$ level using a two-photon process from the $^2S_{1/2}$ level mediated by the $^2D_{3/2}$ manifold, circumventing the need for UV lasers. This also avoids laser light at the collection wavelength or the possibility of multiple excitations, in principle guaranteeing high purity spontaneously emitted single photons. We are starting with $^{172}Yb^+$ ions to avoid the complexity of hyperfine structure. We have characterized an in-air 0.77 NA refractive photon collection system to route photons to an SMF28e+ optical fiber and begun scattering of background-free 1650 nm photons, progressing towards a direct-telecom single photon source with a well-established qubit candidate.

Tue, Aug. 2nd, Session 2, No. 33

Electric Field Noise in Microfabricated Ion Traps with Varied Capacitor Types and Trap Materials

Brian McFarland

Sandia National Laboratory

Electric field noise emanating from microfabricated ion traps has multiple sources which are not well understood and result in increased motional heating leading to reduced entangling gate fidelity. We show current results from a series of heating rate measurements that characterize the electric field noise on a set of geometrically identical ion traps with different filtering electrode capacitors, silicon substrate resistivities, and passivation layers above the substrate. Additionally, we highlight two other experiments in our lab. We have demonstrated Rabi flopping using a CMOS compatible Mach-Zehnder interferometer to amplitude modulate the driving laser. An array of such interferometers could allow control of multiple ions from a single fiber input. Finally, we show recent results demonstrating fast shuttling of an ion using a closed-loop optimization procedure which achieved sub-quanta heating at speeds up to 35 m/s.

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Tue, Aug. 2nd, Session 2, No. 37

Multi-Ion Traps with Integrated Detectors for Portable Clocks

David Reens

MIT Lincoln Lab

Integrated technologies enhance the prospects for practical quantum information processing and sensing devices based on trapped ions. High-speed and high-fidelity ion state readout is important for these applications. Integrated detectors offer significant advantages for system portability and can also greatly facilitate parallel operations if a separate detector is incorporated at each ion-trapping location. Here, we demonstrate ion quantum state detection at room temperature utilizing single-photon avalanche diodes (SPADs) integrated directly into the substrate of silicon ion trapping chips. We detect the state of a trapped $^{88}Sr^{+}$ ion via fluorescence collection with the SPAD, achieving 99.92(1)% average fidelity in 450 μs, opening the door to the application of integrated state detection to quantum computing and sensing with arrays of trapped ions.

Tue, Aug. 2nd, Session 2, No. 38

High-fidelity state preparation and measurement of ion qubits with I¿1/2

Lucas Sletten

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We present a method of state preparation and measurement (SPAM) that is amenable to trapped ion hyperfine qubits with nuclear spins higher than I = 1/2. The ground states of these higher nuclear spin isotopes do not afford a simple frequency selective preparation scheme on a strong transition, this limitation is circumvented by stroboscopically driving strong and weak transitions. We demonstrate this method achieving a SPAM infidelity of ¡ 1e-4,allowing future systems to leverage naturally occurring isotopes with favorable wavelengths and masses such as the $^{137}Ba^{+}$ qubit used in this work. State preparation is performed by blending standard, fast optical pumping using E1 transitions and narrow microwave or optical E2 transitions addressing the extra states in the I=3/2 isotope of $^{137}Ba^{+}$. Measurement is performed with repeated coherent shelving to multiple metastable states.

Tue, Aug. 2nd, Session 2, No. 40

Barium ions for quantum information experiments with metastable qubits

Susanna Todaro

Massachusetts Institute of Technology

Trapped-ion quantum information experiments have generally encoded the qubit either between sublevels of the ground electronic state or between the ground state and a long-lived metastable state. I will present work investigating another category of qubits: the metastable qubit, in which the qubit is encoded in sublevels of a long-lived metastable state. Qubits in this metastable manifold would be largely insensitive to scattered laser light addressing a neighboring qubit in the ground state manifold and vice versa. This could enable quasi-dual species operation, in which many of the applications of dual-species ion trapping, such as for sympathetic cooling or ancilla qubits in quantum error correcting codes, could be implemented in a chain of identical ions. This would improve the vibrational mode structure and potentially reduce experimental complexity. I will present experimental progress towards metastable qubit operations using sublevels of the $^2D_{5/2}$ state of alkaline earth ions, which have accessible visible and infrared transition wavelengths and an appropriate atomic structure for encoding quantum information in a metastable qubit. Barium-133 ions have accessible visible and infrared transition wavelengths, hyperfine sublevels, and a metastable state with a 26 second lifetime, making them particularly appealing for this application. However,

this isotope is radioactive, with a 10.5-year half-life. Photoionization of neutral barium atoms produced by laser ablation of a barium compound could enable isotope-selective loading of a small volume source, improving the ease and safety of eventually working with radioactive material. I will discuss progress loading, cooling, and coherently controlling barium ions produced by laser ablation such a method in a cryogenic surface electrode ion trap.

Tue, Aug. 2nd, Session 2, No. 41

Detecting and Minimizing RF Breakdown on Microfabricated Surface Ion Traps

Joshua M. Wilson, Julia N. Tilles, Raymond A. Haltli, Eric Ou, Matthew G. Blain, Susan M. Clark and Melissa C. Revelle

Sandia National Laboratory

RF breakdown is a major limiting factor in the maximum RF voltage microfabricated surface ion traps can sustain. The complicated physics involved in breakdown makes it difficult to predict a priori how susceptible new trap designs will be to this destructive process. We have developed two techniques for detecting RF breakdown events in situ, one using free-space RF field detectors, and the other monitoring the back-reflected RF signal from the trap itself. Here we describe these techniques and share the results of an extended study of RF breakdown on many different traps. Our results highlight the danger of ramping up the RF voltage too quickly for the initial use of a new trap. We present a procedure for safely turning on new traps, by increasing the voltage slowly and monitoring for breakdown. Also, we briefly describe our most recent fabrication efforts to mitigate breakdown in future traps.

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