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STEM Degrees: 1 **STEM Participants:** 12

Major Goals: Most quantum computing research to date has focused on the qubit paradigm, where two-level quantum systems are prepared, manipulated, and measured in order to implement quantum operations that are part of algorithmic realizations. While this approach has been used to demonstrate many incipient quantum information processing (QIP) systems, there are drawbacks to limiting QIP to two-level systems. Utilizing multiple-level systems may provide some efficiency of resources, such that limitations of the current era of few-qubit, shallow depth circuits can be surpassed in order to attack larger problems and lay the foundation for future quantum computers.

Toward this end, quantum systems with an infinite set of levels, such as the quantum harmonic oscillator which appears naturally in many bosonic quantum systems, have the potential to provide a basis for a new quantum computing paradigm. Such so-called continuous-variable quantum computing (CVQC) provides a much larger Hilbert space per quantum element, therefore encompassing a more efficiently powerful substrate for quantum operations.

One of the most promising physical implementations of QIP, trapped atomic ions, enables the control and coupling of two separate quantum systems, one a system of qubits (pairs of internal electronic states) and the other a set of quantum harmonic oscillator based infinite-level systems (the modes of the ions' harmonic motion in the trapping potential). In fact, the qubits, or "spin" degrees of freedom, can be exquisitely controlled, and via coupling through a Jaynes-Cummings-like interaction, this control can be extended to the continuous-variable states of the harmonic modes (and there are 3N vibrational modes for N ions in the trap). The great success of ion-spin-state control may be leveraged for CVQC; our overarching goal is to lay the groundwork for trapped-ion CVQC experiments and to begin to determine the feasibility of this approach.

Beyond the prospect of employing a larger computational space per element (or per ion in this case), additional motivation includes possibly faster quantum operations on the ion motional states, when compared to those addressing the spin states. The latter require a dipole coupling, typically to a laser field or magnetic-field-based gradient, and this be slow for attainable field intensities. On the other hand, operations on the ion motion can be brought about through direct excitation via electric field interaction with the ions' charge, and hence can be significantly stronger for comparable field strength. Additionally, use of the continuous-variable space of harmonic oscillator modes may provide for algorithmic encoding efficiency of another kind when {?} computing the behavior of quantum systems of interest with similar potentials. For instance, molecular potentials are non-linear quantum oscillators, with the associated rotational and vibrational modes governing the interaction of these systems with external fields. Spin-controlled operations on motional state spaces may have promise for directly simulating such systems, in order to probe quantum chemistry, for example. Computational methods using trapped ions for CVQC may hence be of wide interest.

In particular, the goals of this program were to set up trapped-ion experimental systems that have the capability to enact CVQC operations using the vibrational states of trapped ions, and to evaluate, theoretically and computationally, potential CVQC gate operations that can form a universal set of quantum logic operations in such infinite-level systems. Cryogenic and room-temperature vacuum systems were to be constructed, and ion traps tailored for CVQC operation based on electric-field excitation were to be designed. The ultimate goal was to prepare the team for future collaborative work in answering fundamental questions about the utility of CVQC logic in collections of trapped ions.

Accomplishments: A. Ion trapping and laser systems
At MIT, we have completed the setup of a cryogenic UHV system based in part on a design developed at Lincoln Laboratory over the past several years (see Figure 1). Sr+ ions are loaded, from a remote, pre-cooled source based on magneto-optically cooled atoms, into a linear surface-electrode trap held at approximately 6 K. We have also set up all the required laser beam paths for the 6 wavelengths needed for creation and control of Sr+ ion qubits; this included the development of chamber-registered optical clamps for delivering multiple wavelengths of light to the trap with reduced relative vibration between the final beam-delivery lens and the chamber. We also designed and built reproducible optical-component baseplates to increase beam stability for commonly used subsystems, such as double-pass acousto-optic modulator switching systems and laser diode injection locking. We have demonstrated 88Sr+ optical-qubit state preparation and readout and single qubit operations using the 674nm quadrupole transition (see Figure 2 in uploaded PDF).

At UO we moved the optical subsystems constructed during year 1 to our refurbished lab space. These included our rack mounted lasers, wavelength locking system, ion imaging, AOM control boards, and associated electronics. Furthermore, these systems were integrated, tested, and the beam delivery optics for the trap were assembled on the optical table. The vacuum pumps were assembled on the chamber and tested. The trap, feedthrough flange, and viewports are all cleaned and ready for final system assembly (see Figure).

B. Electronics for potential stabilization and CVQC operation generation

Trap frequency stability is of paramount importance for control of motional states, as uncontrolled frequency variation can result in apparent decoherence if the fluctuations remain untracked over many experimental iterations. We have developed an ultra-low noise amplifier for trap RF stabilization based on custom upgrades to ARTIQ related hardware for trap RF potential generation (see Figure 4). The amplitude of a stable RF signal can be digitally controlled, with selectable filtering. This should result in less variability in the radial curvature of the trap potential, steadying radial mode frequencies. We have also implemented selectable filtering for DC voltages applied to (non-RF) control electrodes to enable tailored implementation of CVQC operations using variation of the trap potential near multiples of, and differences between, mode frequencies (i.e. to produce resonant, parametric, or mode-difference drives).

C. Novel trap designs (see Figure 5)
The UO part of the team explored a surface-electrode trap design that could simultaneously trap ions using a quadrupole field and produce a field with a hexapole component for application of a potential suitable for tri-

squeezing, a non-Gaussian operation suitable for general CVQC. There was not time to fabricate such a trap in this seedling, but we are working on a manuscript describing the approach as we believe it would be a good avenue to explore in a potential follow-on grant.

At MIT and Lincoln, we designed a surface-electrode trap with small center-segmented electrodes that was optimized for ion crystal splitting and generating quartic potentials that could produce a different non-Gaussian operation on the ion motional state. This trap was simulated and fabricated using a multi-level metal process. At Lincoln, ions have been trapped in this device, and basic potential variation was shown via demonstration of ion shuttling, but CVQC operations will need to wait for follow-on work.

D. Simulations of CVQC operations

We have written a codebase to help simulate CVQC operations on ion motional modes. The code, utilizing the QuTiP package, is based on open-system quantum dynamics (numerically integrating the master equation) including the spin and motional states, and it allows for the determination of system behavior using realistic system parameters as inputs; this includes noise based on amplitude and phase damping channels (implemented via Lindblad operators), and can be used to simulate an ion heating rate that thermalizes the ion motional modes. Various CVQC operations (e.g. displacement, squeezing, two-mode beamsplitter) can be applied serially in the presence of such noise, and the final motional state can be determined (see Figure 6).

E. Protocols for high-fidelity motional-state-space manipulation

The manipulation of ion harmonic-oscillator motional states necessary for CVQC accomplished using the Jaynes-Cummings interaction between the spin qubit and the motional mode implies concerted control of these two quantum systems. This control can be utilized for additional computational primitives; we have explored some of these analytically and computationally. For instance, we have determined methods for the “closing” or high-fidelity truncation of the coupled qubit-oscillator state space at a chosen level of the harmonic oscillator excitation, n, such that an effective 2*(n+1) level system can be isolated from the infinite dimensional state space of general CVQC. Red-sideband and carrier pulses used in conjunction to form bespoke pulse sequences allow coherent and precise control of this truncated space, such that qudit-relevant protocols can be implemented using a trapped ion’s motional state. Moreover, the ability to perform arbitrary unitaries in this space naturally implies readout of any Fock state less than or equal to n, a potentially useful element of CVQC algorithms. Initial estimates of the scaling of pulse length with n suggest it to be exponential, but a polynomial scaling is potentially attainable.
Additionally, we have explored the embedding of arbitrary molecular vibration potentials into combinations of multiple harmonic modes. An algebraic encoding can be determined such that beamsplitter and phase-difference type operators utilizing the harmonic modes can be used to bring about tunable anharmonic potentials relevant to molecular potentials (e.g. the Morse potential). These kind of potentials may be brought about in trapped-ion systems using parametric driving near (but detuned from) mode difference frequencies. This technique has promise for calculating Franck-Condon factors for molecular systems of interest using a trapped-ion quantum information processor.

F. Investigation of protected vibrational modes (see Figure 7)

We have also explored opportunities for utilizing the vibrational mode structure of multi-ion chains to enable more complex algorithmic control in CVQC operation sequences. As motivation, fault-tolerant quantum computation is generally seen to require measurement of error syndromes during a calculation. While fault-tolerance under the CVQC paradigm is currently unsettled theoretically, one can assume that such measurements and feedback without negatively affecting the coherence of unmeasured modes will be a necessary part of complex CVQC algorithms. A challenge with an approach based on coupling of the mode of interest to the internal ion spin state for readout during algorithmic processing is that high-fidelity ion qubit measurement is based on scattering photons from an ion (or ions). Recoil of the ion due to this scattering can in general lead to decoherence of the motional modes the ion participates in, negating the ability to continue a calculation beyond intermediate measurements.

A potential way around this issue is non-destructive readout of a particular motional mode while storing in-process quantum information in “protected” modes, modes that are minimally impacted by photon scattering from a subset of ions. A concrete example is the axial breathing mode of a chain consisting of an odd number of ions: the central ion in the chain does not participate in this mode. See uploaded PDF.

Training Opportunities: The program involved 10 graduate and 3 undergraduate students, as well as 2 postdoctoral scholars. These students and early-career scientists worked with MIT and UO professors and with Lincoln Laboratory staff, and so there were ample training opportunities in the fields of quantum computing, ion trapping and coherent control, vacuum system and electronics design, and the theory of control of continuous-variable quantum systems and atoms interacting with light.

See participants list for details.

Results Dissemination: Presentations of this work were made as several conferences; one manuscript suggesting a method for motional state use and manipulation was posted to the arXiv preprint server, and additional manuscripts are under preparation for publication.
Conference and workshop presentations:
1) “Continuous Variable Quantum Computing with Trapped Ions,” poster presented at APS DAMOP Meeting, June 2021.
2) “Towards a robust system for cryogenic multi-species ion trapping,” poster presented at APS DAMOP Meeting, June 2021.
3) “Using protected modes in trapped ions to enable mid-algorithm measurements for CVQC,” contributed presentation at APS DAMOP Meeting, June 2021.
4) “A novel surface-electrode trap design enabling electrically-driven non-Gaussian operations for trapped-ion CVQC,” contributed presentation at APS DAMOP Meeting, June 2021.
5) “A Dual-species Trapped-ion System for Quantum Information Processing with Sr+ and Ba+,” poster presented at APS DAMOP Meeting, June 2020.
6) “Realizing Quantum Computation Using Continuous Variables in Trapped Ions,” contributed presentation at APS DAMOP Meeting, June 2020.
Preprints submitted for publication:
1) Y. Liu, J. Sinanan-Singh, M.T. Kearney, G. Mintzer, and I.L. Chuang, “Constructing Qudits from Infinite Dimensional Oscillators by Coupling to Qubits,” arXiv:2105.02896 (2021).

Honors and Awards: 1) Intelligence Community Postdoctoral Fellowship, Susanna Todaro, MIT, October 2020.

Protocol Activity Status:

Technology Transfer: This program was a collaboration between MIT, the University of Oregon (UO), and MIT Lincoln Laboratory. Staff from Lincoln Laboratory worked on MIT campus to transfer cryogenic UHV system technology and best practices. Students from MIT worked with staff at Lincoln Laboratory on novel trap design and testing. Students from UO worked with staff at Lincoln Laboratory on computational analysis and experimental demonstration of CVQC protocols using multi-species ion crystals. Pulse sequences and multi-ion control techniques developed at MIT and UO were implemented in systems at Lincoln Laboratory.

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Project Contribution:
National Academy Member: N

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Article Title: Constructing Qudits from Infinite Dimensional Oscillators by Coupling to Qubits
Authors: 1) Y. Liu, J. Sinanan-Singh, M.T. Kearney, G. Mintzer, and I.L. Chuang
Keywords: continuous variable quantum computing
Abstract: An infinite dimensional system such as a quantum harmonic oscillator offers a potentially unbounded Hilbert space for computation, but accessing and manipulating the entire state space requires a physically unrealistic amount of energy. When such a quantum harmonic oscillator is coupled to a qubit, for example via a Jaynes-Cummings interaction, it is well known that the total Hilbert space can be separated into independently accessible subspaces of constant energy, but the number of subspaces is still infinite. Nevertheless, a closed four-dimensional Hilbert space can be analytically constructed from the lowest energy states of the qubit-oscillator system. We extend this idea and show how a d-dimensional Hilbert space can be analytically constructed, which is closed under a finite set of unitary operations resulting solely from manipulating standard Jaynes-Cummings Hamiltonian terms. Moreover, we prove that the first-order sideband pulses and carrier pulses comprise a universal set f
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Development of methods for continuous variable quantum computing with trapped ions

(W911NF-19-1-0481)

David Allcock, John Chiaverini, Isaac Chuang, and David Wineland

1. Major Goals

A description of the major goals of the project.

Most quantum computing research to date has focused on the qubit paradigm, where two-level quantum systems are prepared, manipulated, and measured in order to implement quantum operations that are part of algorithmic realizations. While this approach has been used to demonstrate many incipient quantum information processing (QIP) systems, there are drawbacks to limiting QIP to two-level systems. Utilizing multiple-level systems may provide some efficiency of resources, such that limitations of the current era of few-qubit, shallow depth circuits can be surpassed in order to attack larger problems and lay the foundation for future quantum computers.

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Beyond the prospect of employing a larger computational space per element (or per ion in this case), additional motivation includes possibly faster quantum operations on the ion motional states, when compared to those addressing the spin states. The latter require a dipole coupling, typically to a laser field or magnetic-field-based gradient, and this be slow for attainable field intensities. On the other hand, operations on the ion motion can be brought about through direct excitation via electric field interaction with the ions' charge, and hence can be significantly stronger for comparable field strength. Additionally, use of the continuous-variable space of harmonic oscillator modes may provide for algorithmic encoding efficiency of another kind when {?} computing the behavior of quantum systems of interest with similar potentials. For instance, molecular potentials are non-linear quantum oscillators, with the associated rotational and vibrational modes governing the interaction of these systems with external fields. Spin-controlled operations on motional state spaces may have promise for directly simulating such systems, in order to probe quantum chemistry, for example. Computational methods using trapped ions for CVQC may hence be of wide interest.

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2. Accomplished under Goals

A description of what was accomplished under the goals during the reporting period.

A. Ion trapping and laser systems

At MIT, we have completed the setup of a cryogenic UHV system based in part on a design developed at Lincoln Laboratory over the past several years (see Figure 1). Sr+ ions are loaded, from a remote, pre-cooled source based on magneto-optically cooled atoms, into a linear surface-electrode trap held at approximately 6 K. We have also set up all the required laser beam paths for the 6 wavelengths needed for creation and control of Sr+ ion qubits; this included the development of chamber-registered optical clamps for delivering multiple wavelengths of light to the trap with reduced relative vibration between the final beam-delivery lens and the chamber. We also designed and built reproducible optical-component baseplates to increase beam stability for commonly used subsystems, such as double-pass acousto-optic modulator switching systems and laser diode injection locking. We have demonstrated ^{88}Sr+ optical-qubit state preparation and readout and single qubit operations using the 674nm quadrupole transition (see Figure 2).

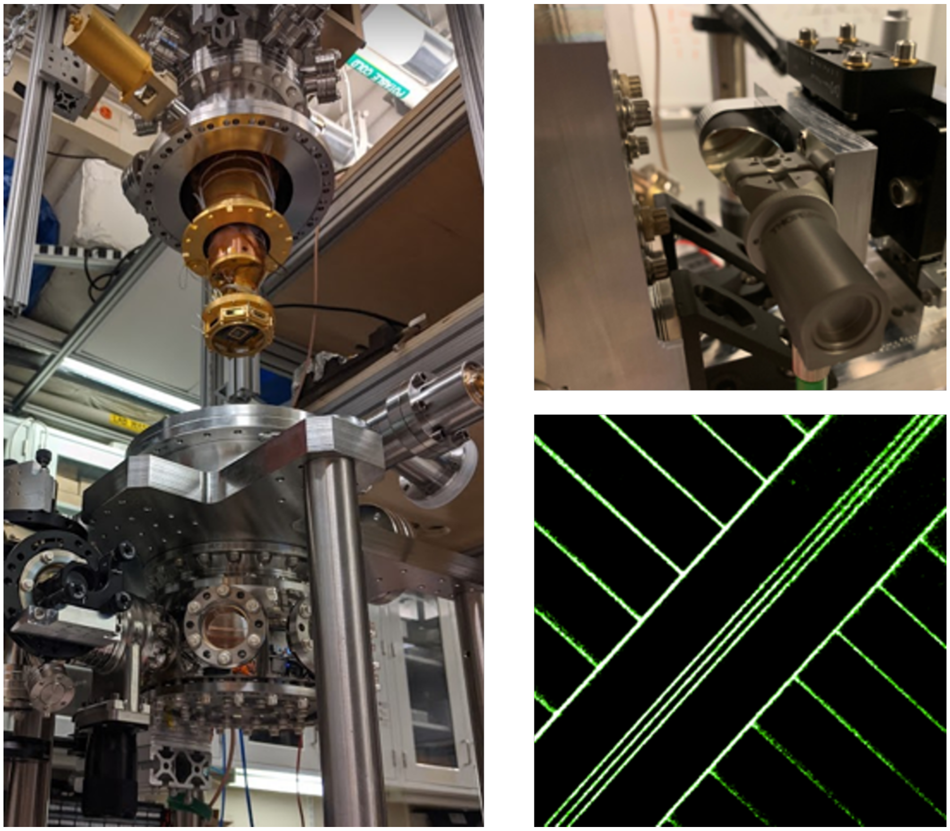

Figure 1: Ion-trapping system at MIT. Left: Cryogenic vacuum system with insert extracted and ion trap chip visible at its tip {you might add an arrow pointing to this}; main chamber is at bottom with MOT loading chamber to the left. Upper right: Parabolic mirror mount for multi-wavelength focusing into chamber. Lower right: Image of linear surface electrode trap in situ (gaps between electrodes are illuminated).

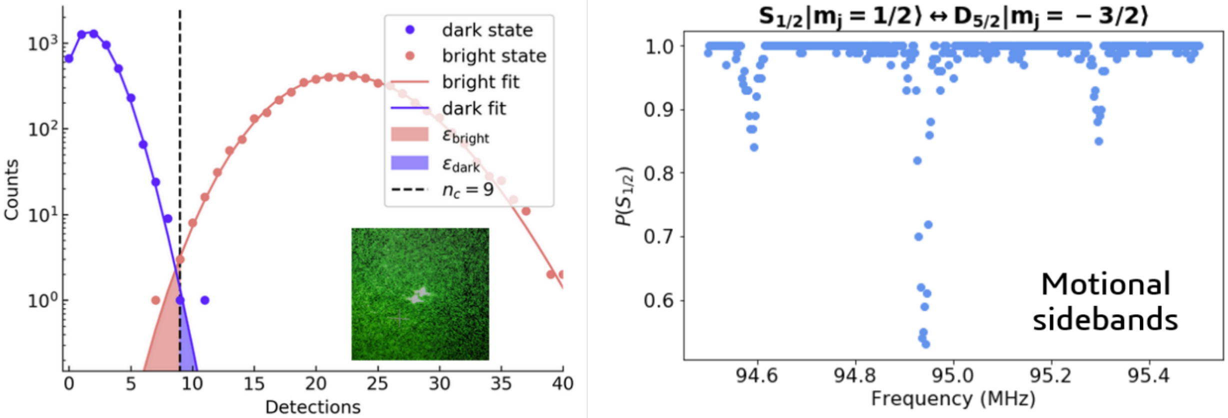

Figure 2: Ion qubit operations. Left: Internal state detection histograms for ions in bright and dark states. Inset: Image of two ions in the trap taken using electron-multiplying CCD. Right: Spectroscopy of quadrupole transition with motional sidebands (the probability to remain in the S state, after a spectroscopy pulse, is plotted as a function of the frequency shift (relative to the transition near 445 THz) of the light in the pulse applied via an acousto-optic modulator.

At UO we moved the optical subsystems constructed during year 1 to our refurbished lab space. These included our rack mounted lasers, wavelength locking system, ion imaging, AOM control boards, and associated electronics. Furthermore, these systems were integrated, tested, and the beam delivery optics for the trap were assembled on the optical table. The vacuum pumps were assembled on the chamber and tested. The trap, feedthrough flange, and viewports are all cleaned and ready for final system assembly (see Figure 3).

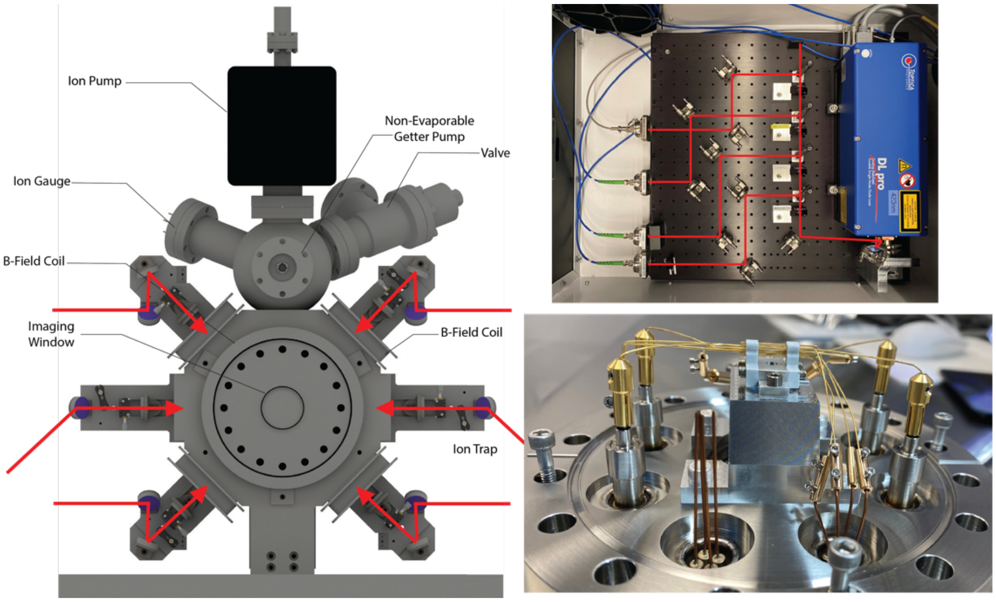

Figure 3: Ion trapping system at UO. Left: Diagram of vacuum chamber assembly. Upper right: Rack-drawer mounted diode laser and associated optics for fiber coupling and delivery to the chamber. Lower right: Ion trap on feedthrough flange ready for assembly.

B. Electronics for potential stabilization and CVQC operation generation

Trap frequency stability is of paramount importance for control of motional states, as uncontrolled frequency variation can result in apparent decoherence if the fluctuations remain untracked over many experimental iterations. We have developed an ultra-low noise amplifier for trap RF stabilization based on custom upgrades to ARTIQ related hardware for trap RF potential generation (see Figure 4). The amplitude of a stable RF signal can be digitally controlled, with selectable filtering. This should result in less variability in the radial curvature of the trap potential, steadying radial mode frequencies. We have also implemented selectable filtering for DC voltages applied to (non-RF) control electrodes to enable tailored implementation of CVQC operations using variation of the trap potential near multiples of, and differences between, mode frequencies (i.e. to produce resonant, parametric, or mode-difference drives).

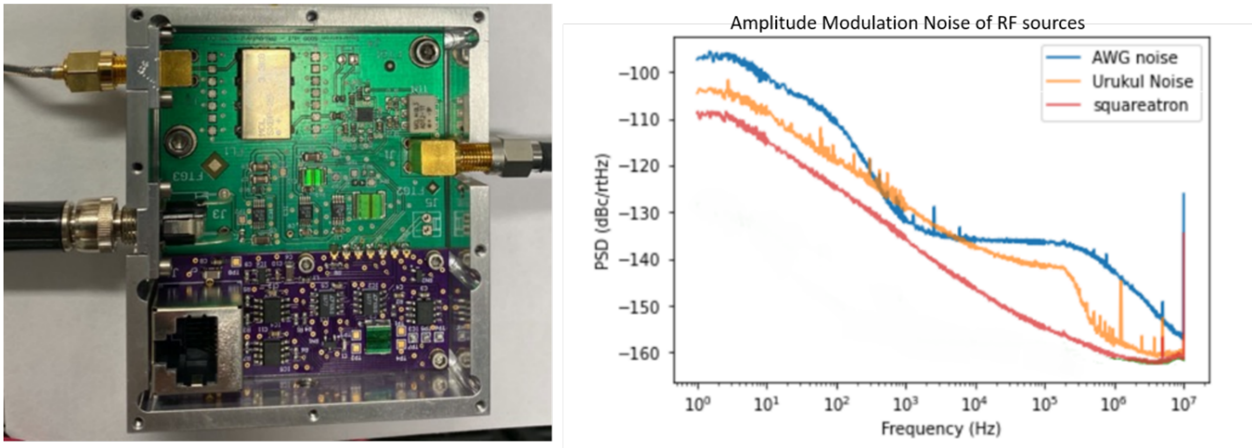

Figure 4: Ultra-low noise amplifier for trap radio-frequency (RF) potential. Left: picture of "Squaretron" with tailorable filtering and digital control of amplitude. Right: Comparison of phase noise frequency response for a standrad arbitray-waveform generator (AWG, ***Rigol DG1062Z****), a direct-digital synthesizer (Urukul, M-Labs), and the Squaretron.*

C. Novel trap designs (see Figure 5)

The UO part of the team explored a surface-electrode trap design that could simultaneously trap ions using a quadrupole field and produce a field with a hexapole component for application of a potential suitable for tri-squeezing, a non-Gaussian operation suitable for general CVQC. There was not time to fabricate such a trap in this seedling, but we are working on a manuscript describing the approach as we believe it would be a good avenue to explore in a potential follow-on grant.

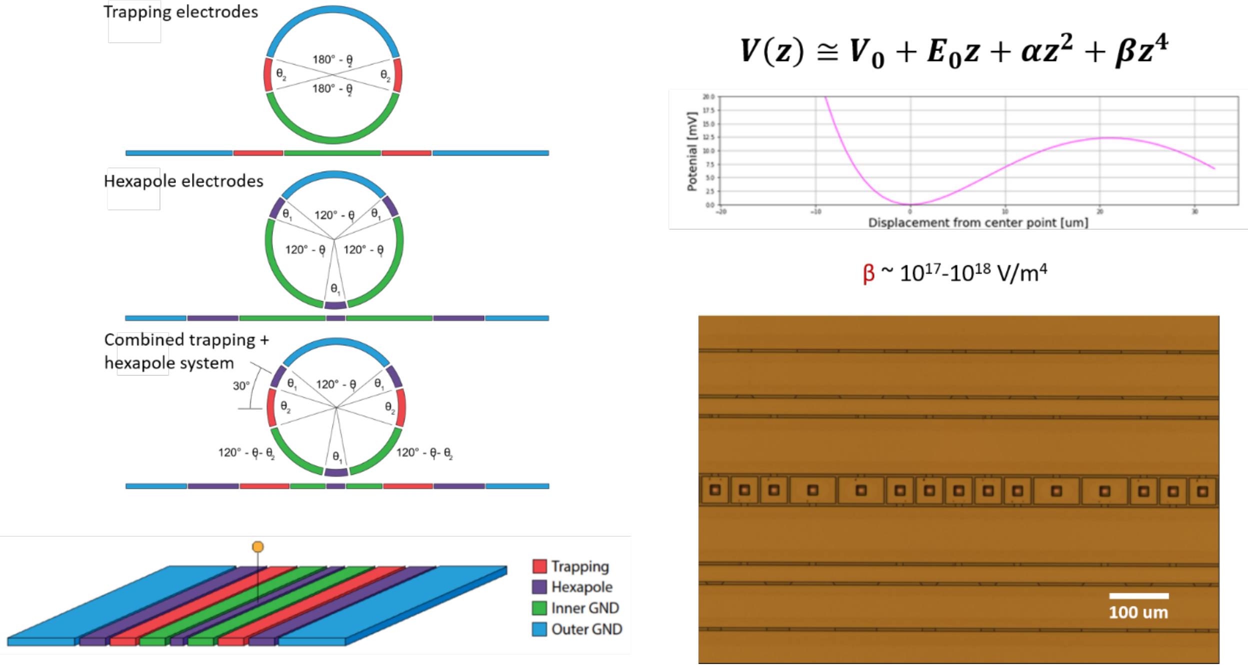

Figure 5: Surface-electrode trap designs for potential modulation to bring about non-Gaussian operations. Left: Combination of quadrupole and hexapole electrode layout enabling simultaneous trapping and motional-mode tri-squeezing; bottom shows trap electrode geometry in perspective view. Right: Trap designed to produce a large quartic term in the potential (β); bottom shows micrograph of center of trap with center-segmented electrodes (small squares in segments are VIA connections).

At MIT and Lincoln, we designed a surface-electrode trap with small center-segmented electrodes that was optimized for ion crystal splitting and generating quartic potentials that could produce a different non-Gaussian operation on the ion motional state. This trap was simulated and fabricated using a multi-level metal process. At Lincoln, ions have been trapped in this device, and basic potential variation was shown via demonstration of ion shuttling, but CVQC operations will need to wait for follow-on work.

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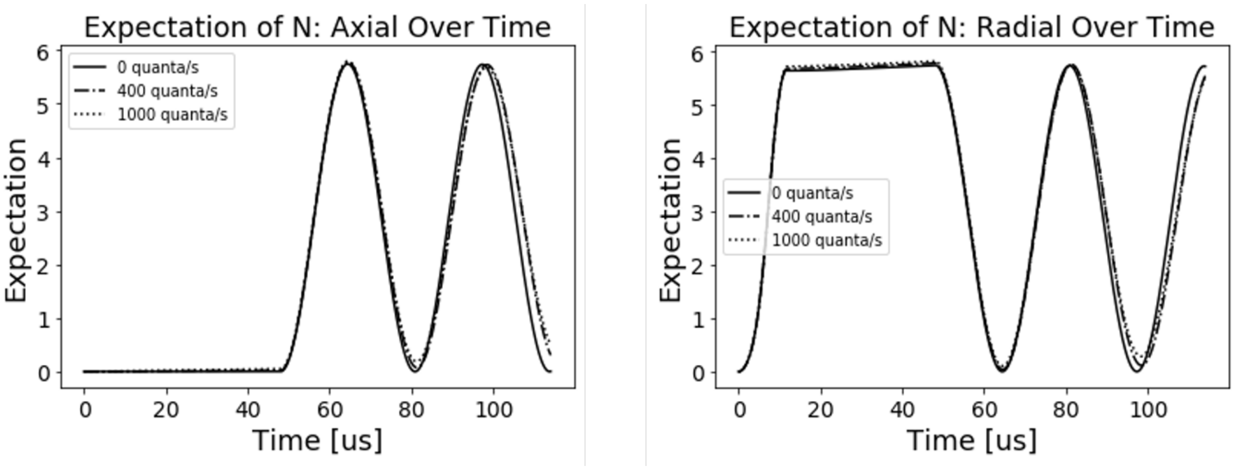

Figure 6: Output of simulation for example CVQC operation sequence. Left (right): Expectation of the motional-state excitation of the axial (radial) vibrational mode of a single trapped ion as a function of time during a sequence that consists of radial-mode squeezing, a small coherent displacement, and a beam splitter operation between the two modes. The expectation is shown for several motional-mode heating rates. {N needs to be defined}

E. Protocols for high-fidelity motional-state-space manipulation

The manipulation of ion harmonic-oscillator motional states necessary for CVQC accomplished using the Jaynes-Cummings interaction between the spin qubit and the motional mode implies concerted control of these two quantum systems. This control can be utilized for additional computational primitives; we have explored some of these analytically and computationally. For instance, we have determined methods for the “closing” or high-fidelity truncation of the coupled qubit-oscillator state space at a chosen level of the harmonic oscillator excitation, n, such that an effective 2*(n+1) level system can be isolated from the infinite dimensional state space of general CVQC. Red-sideband and carrier pulses used in conjunction to form bespoke pulse sequences allow coherent and precise control of this truncated space, such that qudit-relevant protocols can be implemented using a trapped ion's motional state. Moreover, the ability to perform arbitrary unitaries in this space naturally implies readout of any Fock state less than or equal to n, a potentially useful element of CVQC algorithms. Initial estimates of the scaling of pulse length with n suggest it to be exponential, but a polynomial scaling is potentially attainable.

Additionally, we have explored the embedding of arbitrary molecular vibration potentials into combinations of multiple harmonic modes. An algebraic encoding can be determined such that beamsplitter and phase-difference type operators utilizing the harmonic modes can be used to bring about tunable anharmonic potentials relevant to molecular potentials (e.g. the Morse potential). These kind of potentials may be brought about in trapped-ion systems using parametric driving near (but detuned from) mode difference frequencies. This technique has promise for calculating Franck-Condon factors for molecular systems of interest using a trapped-ion quantum information processor.

F. Investigation of protected vibrational modes (see Figure 7)

We have also explored opportunities for utilizing the vibrational mode structure of multi-ion chains to enable more complex algorithmic control in CVQC operation sequences. As motivation, fault-tolerant quantum computation is generally seen to require measurement of error syndromes during a calculation. While fault-tolerance under the CVQC paradigm is currently unsettled theoretically, one can assume that such measurements and feedback without negatively affecting the coherence of unmeasured modes will be a necessary part of complex CVQC algorithms. A challenge with an approach based on coupling of the mode of interest to the internal ion spin state for readout during algorithmic processing is that high-fidelity ion qubit measurement is based on scattering photons from an ion (or ions). Recoil of the ion due to this scattering can in general lead to decoherence of the motional modes the ion participates in, negating the ability to continue a calculation beyond intermediate measurements.

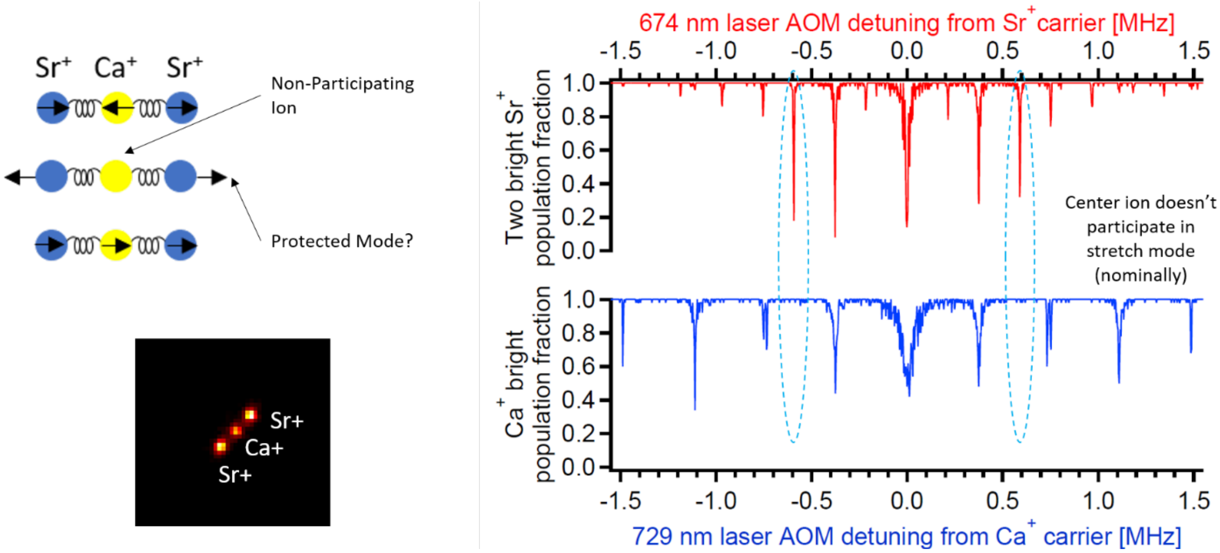

Figure 1: Scheme for protection of one mode from decoherence while reading out another mode via the spin state of the center ion. Upper left: Axial modes of a three-ion, dual-species chain. Lower left: A realization of this chain at Lincoln. Right: spectroscopy of this chain of ions via excitation of the Sr+ (Ca+) as shown on the top (bottom). The dotted ovals highlight the presence (absence) of the "stretch" or breathing mode when observing the Sr+ (Ca+) ions. {I'd remove the "?" in the "Protected Mode?" label in the diagram}

A potential way around this issue is non-destructive readout of a particular motional mode while storing in-process quantum information in "protected" modes, modes that are minimally impacted by photon scattering from a subset of ions. A concrete example is the axial breathing mode of a chain consisting of an odd number of ions: the central ion in the chain does not participate in this mode (it has zero amplitude during the excitation of this normal mode), and therefore the quantum state of this mode should be unaffected by scattering of light from the central ion during a measurement.

As part of this project, we have devised experiments to test this hypothesis (namely a three-ion mode coherence experiment with a center ion of a different species, such that individual addressing is simplified), and we have made calculations of processes which can limit the isolation of protected modes, such as distortion of the crystal (and hence normal mode participation) due to the optical radiation pressure force imparted by the measurement beam; and nonlinear coupling between modes due to frequency shifts based on occupation of unaddressed modes. We have determined basic parameters for exploring this technique using the Ca+/Sr+ crystals attainable at Lincoln, and UO has performed calculations of the scale of non-idealites we should expect. Measurements built on this preliminary work are beyond the scope of this program, but we hope to attempt them in the near term.

3. Training Opportunities

A description of Opportunities for training during the reporting period.

The program involved 10 graduate and 3 undergraduate students, as well as 2 postdoctoral scholars. These students and early-career scientists worked with MIT and UO professors and with Lincoln Laboratory staff, and so there were ample training opportunities in the fields of quantum computing, ion trapping and coherent control, vacuum system and electronics design, and the theory of control of continuous-variable quantum systems and atoms interacting with light.   See participants list, below.

4.Results Dissemination

A description of dissemination during the reporting period.

Presentations of this work were made as several conferences; one manuscript suggesting a method for motional state use and manipulation was posted to the arXiv preprint server, and additional manuscripts are under preparation for publication.

Conference and workshop presentations:

1) "Continuous Variable Quantum Computing with Trapped Ions," poster presented at APS DAMOP Meeting, June 2021.
2) "Towards a robust system for cryogenic multi-species ion trapping," poster presented at APS DAMOP Meeting, June 2021.
3) "Using protected modes in trapped ions to enable mid-algorithm measurements for CVQC," contributed presentation at APS DAMOP Meeting, June 2021.
4) "A novel surface-electrode trap design enabling electrically-driven non-Gaussian operations for trapped-ion CVQC," contributed presentation at APS DAMOP Meeting, June 2021.
5) "A Dual-species Trapped-ion System for Quantum Information Processing with Sr+ and Ba+," poster presented at APS DAMOP Meeting, June 2020.
6) "Realizing Quantum Computation Using Continuous Variables in Trapped Ions," contributed presentation at APS DAMOP Meeting, June 2020.

Preprints submitted for publication:

1) Y. Liu, J. Sinanan-Singh, M.T. Kearney, G. Mintzer, and I.L. Chuang, "Constructing Qudits from Infinite Dimensional Oscillators by Coupling to Qubits," arXiv:2105.02896 (2021).

5.Honors and Awards

Honors and Awards received during the reporting period

1) Intelligence Community Postdoctoral Fellowship, Susanna Todaro, MIT, October 2020.

6. Technology Transfer (patent applications, inventions, licenses, interaction with DoD laboratories)

This program was a collaboration between MIT, the University of Oregon (UO), and MIT Lincoln Laboratory. Staff from Lincoln Laboratory worked on MIT campus to transfer cryogenic UHV system technology and best practices. Students from MIT worked with staff at Lincoln Laboratory on novel trap design and testing. Students from UO worked with staff at Lincoln Laboratory on computational analysis and experimental demonstration of CVQC protocols using multi-species ion crystals. Pulse sequences and multi-ion control techniques developed at MIT and UO were implemented in systems at Lincoln Laboratory.

7. Participants

Please be sure to list all supported participants including: Undergraduate Student, Graduate Student (research assistant), PD/PI, Co PD/PI, Co-Investigator, Faculty, Community College Faculty, Technical School Faculty, K-12 Teacher, Postdoctoral (scholar, fellow or other postdoctoral position), Other Professional, Technician, Staff Scientist (doctoral level), Statistician, Non-Student Research Assistant, Technical School Student, High School Student, Consultant, Research Experience for Undergraduates (REU) Participant, Other (specify)

Matt Kearney, undergrad, MIT
Gabriel Mintzer, undergrad and graduate student, MIT
Jasmine Sinanan-Singh, graduate student, MIT
Jules Stuart, graduate student, MIT
Xiaoyang Shi, graduate student, MIT
Felix Knollmann, graduate student, MIT
Kyle DeBry, graduate student, MIT
Vikram Sandhu, undergraduate student, UO
Jeremy Metzner, graduate student, UO
Alexander Quinn, graduate student, UO
Isam Moore, graduate student, UO
Sean Brudney, graduate student, UO
Yuan Liu, postdoctoral scholar, MIT
Susanna Todaro, postdoctoral fellow, MIT
Colin Bruzewicz, technical staff, MIT Lincoln Laboratory
Jeremy Sage, senior technical staff, MIT Lincoln Laboratory and PI, MIT
John Chiaverini, senior technical staff, MIT Lincoln Laboratory and PI, MIT
Isaac Chuang, professor, MIT and PI
David Allcock, professor, UO

David Wineland, professor, UO

8.Upload Report Attachment

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9.Students

Number of students receiving STEM degrees during the reporting period: [**1**]

Number of undergraduate and graduate STEM participants during the reporting period : **12**

10. Products (publications)

See number 4 above.