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14. ABSTRACT
The main goal of the original MUSIQC proposal was to construct and demonstrate a modular and universally-expandable ion trap quantum computer. This architecture has two separate layers of scalability: the first is to increase the number of ion qubits in a single trap, with full control over the qubits, and the second is to interconnect qubits in different traps using photonic channels. The proof-of-principle demonstrations for single and two-qubit gates in a single ion chain had been carried out (on a 2-ion chain), and a creation of entanglement generation

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Final Report: Modular Universal Scalable Ion-trap Quantum Computer

ABSTRACT

The main goal of the original MUSIQC proposal was to construct and demonstrate a modular and universally-expandable ion trap quantum computer. This architecture has two separate layers of scalability: the first is to increase the number of ion qubits in a single trap, with full control over the qubits, and the second is to interconnect qubits in different traps using photonic channels. The proof-of-principle demonstrations for single and two-qubit gates in a single ion chain had been carried out (on a 2-ion chain), and a creation of entanglement generation through photonic channels was also demonstrated. We had an ambitious goal of integrating all of these components and assemble an 80-qubit quantum processor, consisting of four ion chains with 20 ions in each chain, interconnected by a small photonic network. While it is true that the MUSIQC collaboration has fallen short of constructing and demonstrating our ambitious goal of 80-qubit, networked quantum processor operation, we have accomplished significant progress in the field of ion trap quantum computing that has changed the landscape of the field prior to MUSIQC project. We have developed a deep understanding of fundamental system integration challenges that led to several practical solutions we have been able to partially pursue within the later phases of the MUSIQC project, as well as new research opportunities outside the scope of the MQCO program.

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(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
05/30/2016 73.00	Rachel Noek, Geert Vrijsen, Daniel Gaultney, Emily Mount, Taehyun Kim, Peter Maunz, Jungsang Kim. High speed, high fidelity detection of an atomic hyperfine qubit, Optics Letters, (11 2013): 0. doi: 10.1364/OL.38.004735
05/31/2016 49.00	S. Korenblit, A. Lee, K. W. Lee, T. A. Manning, D. N. Matsukevich, J. Mizrahi, Q. Quraishi, C. Senko, J. Smith, C. Monroe, R. Islam, W. C. Campbell, T. Choi, S. M. Clark, C. W. S. Conover, S. Debnath, E. E. Edwards, B. Fields, D. Hayes, D. Hucul, I. V. Inlek, K. G. Johnson. Beat note stabilization of mode-locked lasers for quantum information processing, Optics Letters, (05 2014): 0. doi: 10.1364/OL.39.003238
05/31/2016 05.00	L.-M. Duan, C. Monroe. : Quantum networks with trapped ions, Reviews of Modern Physics, (4 2010): 0. doi: 10.1103/RevModPhys.82.1209
05/31/2016 04.00	S. OLMSCHENK, D. HAYES, D. N. MATSUKEVICH, P. MAUNZ, D. L. MOEHRING, C. MONROE. QUANTUM LOGIC BETWEEN DISTANT TRAPPED IONS, International Journal of Quantum Information, (02 2010): 0. doi: 10.1142/S0219749910006381
05/31/2016 03.00	J. L. O'Brien, T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe. Quantum computers, Nature, (3 2010): 0. doi: 10.1038/nature08812
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05/31/2016 01.00	M. A. Fogarty, M. Veldhorst, R. Harper, C. H. Yang, S. D. Bartlett, S. T. Flammia, A. S. Dzurak. Nonexponential fidelity decay in randomized benchmarking with low-frequency noise, Physical Review A, (8 2015): 0. doi: 10.1103/PhysRevA.92.022326
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05/31/2016 99.00	Thomas E. deLaubenfels, Karl A. Burkhardt, Grahame Vittorini, J. True Merrill, Kenneth R. Brown, Jason M. Amini. Modulating carrier and sideband coupling strengths in a standing-wave gate beam, Physical Review A, (12 2015): 0. doi: 10.1103/PhysRevA.92.061402
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05/31/2016 96.00	D. Hayes, D. N. Matsukevich, P. Maunz, D. Hucul, Q. Quraishi, S. Olmschenk, W. Campbell, J. Mizrahi, C. Senko, C. Monroe. Entanglement of Atomic Qubits Using an Optical Frequency Comb, Physical Review Letters, (4 2010): 0. doi: 10.1103/PhysRevLett.104.140501
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10/02/2013 42.00 Zi Cai, Lu-Ming Duan, Congjun Wu. Phase-sensitive detection for unconventional Bose-Einstein condensation,
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10/02/2013 38.00 Shi-Liang Zhu, Z.-D. Wang, Y.-H. Chan, L.-M. Duan. Topological Bose-Mott Insulators in a One-Dimensional Optical Superlattice,
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11/06/2015 68.00 Michael W Lee, Marie Claire Jarratt, Christian Marciniak, Michael J Biercuk. Frequency stabilization of a 369 nm diode laser by nonlinear spectroscopy of Ytterbium ions in a discharge,
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TOTAL: **98**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

05/31/2016 76.00 Muhamamd Ahsan, Byung-Soo Choi, Jungsang Kim. Performance simulator based on hardware resources constraints for ion trap quantum computer,
2013 IEEE 31st International Conference on Computer Design (ICCD). 06-OCT-13, Asheville, NC, USA. : ,

05/31/2016 93.00 Dave Bacon, Steven T. Flammia, Aram W. Harrow, Jonathan Shi. Sparse Quantum Codes from Quantum Circuits,
the Forty-Seventh Annual ACM. 14-JUN-15, Portland, Oregon, USA. : ,

TOTAL: 2

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Fault-Tolerant Scalable Modular Quantum Computer Architecture with an Enhanced Control of Multi-mode couplings between trapped ion qubits

Patents Awarded

Awards

Christopher Monroe, National Academy of Sciences (April 2016)
Jungsang Kim, Stansell Family Distinguished Research Award (March 2016)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Rachel Noek	1.00	
Emily Mount	1.00	
Stephen Crain	1.00	
Andre van Rynbach	0.50	
Muhammad Ahsan	0.50	
Daniel Gaultney	1.00	
Robert Spivey	1.00	
FTE Equivalent:	**6.00**	
Total Number:	**7**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
So-Young Baek	1.00
Kai Hudek	0.25
Taehyun Kim	1.00
Geert Vrijsen	1.00
Byeong-Hyeon Ahn	0.50
Byung-Soo Choi	0.10
FTE Equivalent:	**3.85**
Total Number:	**6**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Jungsang Kim	0.40	
Christopher Monroe	0.40	Yes
Kenneth Brown	0.50	
Boris Blinov	0.33	
Luming Duan	0.20	
Robert Raussendorf	0.10	
Michael Biercuk	0.10	
Steven Flammia	0.10	
FTE Equivalent:	**2.13**	
Total Number:	**8**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Michael Feng	0.00	
Michael Adams	0.00	
Cameron GIvler	0.00	
Dennis Lynch	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**4**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 4.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 4.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 4.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Rachel Noek
Emily Mount
Stephen Crain
Andre Van Rynbach
Muhammad Ahsan

Total Number: **5**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

1 a. University of Washington

1 b. Office of Sponsored Programs
4333 Brooklyn Ave NE Box 359472
Seattle WA 981959472

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

---

1 a. University of Washington

1 b. 1100 NE 45th Street, Suite 300
Seattle WA 981054696

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

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1 a. MagiQ Technologies, Inc.

1 b. MagiQ Technologies, Inc.
11 Ward Street
Somerville MA 021434214

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

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1 a. MagiQ Technologies, Inc.

1 b. MagiQ Technologies, Inc.
11 Ward Street
Somerville MA 021434214

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

1 a. Georgia Tech Research Corporation

1 b. 505 Tenth Street NW

Atlanta GA 303320420

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. Georgia Tech Research Corporation

1 b. 505 10th Street, NW

Atlanta GA 303320420

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. Georgia Tech Research Institute

1 b. 410 10th Street

North Buillding

Atlanta GA 303320807

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. Georgia Tech Research Institute

1 b. 410 10th Street

North Buillding

Atlanta GA 303320807

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. University of Michigan - Ann Arbor

1 b. 1058 Wolverine Tower
3003 South State Street
Ann Arbor MI 481091274

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

---

1 a. University of Michigan - Ann Arbor

1 b. 3003 South State Street
Ann Arbor MI 481091274

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

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1 a. University of Sydney

1 b. School of Physics
The University of Sydney
Sydney NSW 2006

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

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1 a. University of Sydney

1 b. Camperdown Campus
Sydney NSW 2006

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
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1 a. University of Sydney

1 b. School Of Physics, A28

Sydney 2006

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

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Sub Contract Est Completion Date(f-2):

---

1 a. University of Sydney

1 b. A28 Physics Road

Sydney 2006

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. University of Sydney

1 b. School Of Physics

The University Of Sydney

Sydney NSW 2006

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. University of Sydney

1 b. School Of Physics

The University Of Sydney

Sydney NSW 2006

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. The University of British Colubmia

1 b. 2329 West Mall

Vancouver BC V6T 1Z4

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

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1 a. University of Maryland - College Park

1 b. Office of Research Administration

3112 Lee Building 7809 Regents Dr

College Park MD 207425141

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2): 1/31/16 12:00AM

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1 a. University of Maryland - College Park

1 b. 3112 Lee Building

College Park MD 207425141

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2): 1/31/16 12:00AM

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1 a. University of Maryland - College Park

1 b. 3112 Lee Building

7809 Regents Drive

College Park MD 207425141

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e):

Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2): 1/31/16 12:00AM

Inventions (DD882)

5 Fault-Tolerant Scalable Modular Quantum Computer Architecture with an Enhanced Control of Multi-mode couplings be

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Jungsang Kim

5f-1a: Duke University

5f-c: 130 Hudson Hall

Durham NC 27708

5a: Robert Raussendorf

5f-1a: University of British Columbia

5f-c: Department of Physics

Vancouver BC V6T 1Z4

5a: Christopher Monroe

5f-1a: University of Maryland

5f-c: Department of Physics

College Park MD 20742

Scientific Progress

See Attachment

Technology Transfer

N/A

Capstone Report for IARPA MQCO Program

Modular Universal Scalable Ion-trap Quantum Computer (MUSIQC)

Summarized by Jungsang Kim

March 14th, 2016

1. Overall Goals for the MQCO Capstone Project

The goal of the MQCO Capstone project were to

(1) Fully characterize the error contribution for our prototype systems and analyze their impact on the performance of the algorithms

(2) Install some upgrades to our existing systems to improve the stability of the system where it makes sense

(3) Explore a range of advanced quantum control techniques to improve the fidelities of qubit manipulation

(4) Improve system control and calibration procedures to enhance the overall error performance of our algorithms

(5) Theoretical activities that enable design and implementation of adequate quantum control techniques and analyze the impact of the fidelity on the algorithm execution.

2. Main Accomplishments in the Capstone Project

a. University of Maryland System

At University of Maryland, we established the experimental capability to individually address a five-ion chain using the multi-channel acousto-optic modulator (MC-AOM). The gates are accomplished by breaking the control Raman pulses into nine segments, which is designed to close phase space loops for all the motional modes. The fidelities of the Molmer-Sorensen gates among arbitrary pair of qubits in the chain were characterized to be in the 96-99% range (where ~2% SPAM errors were subtracted), as shown in Figure 1. The left panel in Figure 2 shows the Rabi oscillations induced on each ion after the chain is Doppler-cooled. Due to the counter-propagating Raman beam geometry, the Rabi oscillations are sensitive to the residual ion motion, limiting the fidelity of the single qubit gates. The right panel in Figure 2 shows the crosstalk of the Raman beams to the neighboring ions. The crosstalk to the nearest neighbors is in the 2-5% range, while that to the next nearest neighbor ions is below 1% range. There are three sources of crosstalk: (1) due to the quality of the optical beam at the ion location, (2) due to RF signal leaking between the AOM channels and (3) due to the acoustic wave leaking between the AOM channels. The crosstalk performance can be improved by improving the design and manufacturing of the MC-AOM device, and by improving the shape of the optical beam incident on the devices.

Upon completion of the MS gates, we proceeded to demonstrate a CNOT gate between the all possible pairs of ions in the chain. This is realized by combining the MS gate with three single-qubit gates applied to either ion, as shown in Figure 3. The average time for the gate is about 283μs, and the achieved gate fidelity is 95.6%. The average detection fidelity is about 98% (SPAM error of about 2%) in the system.

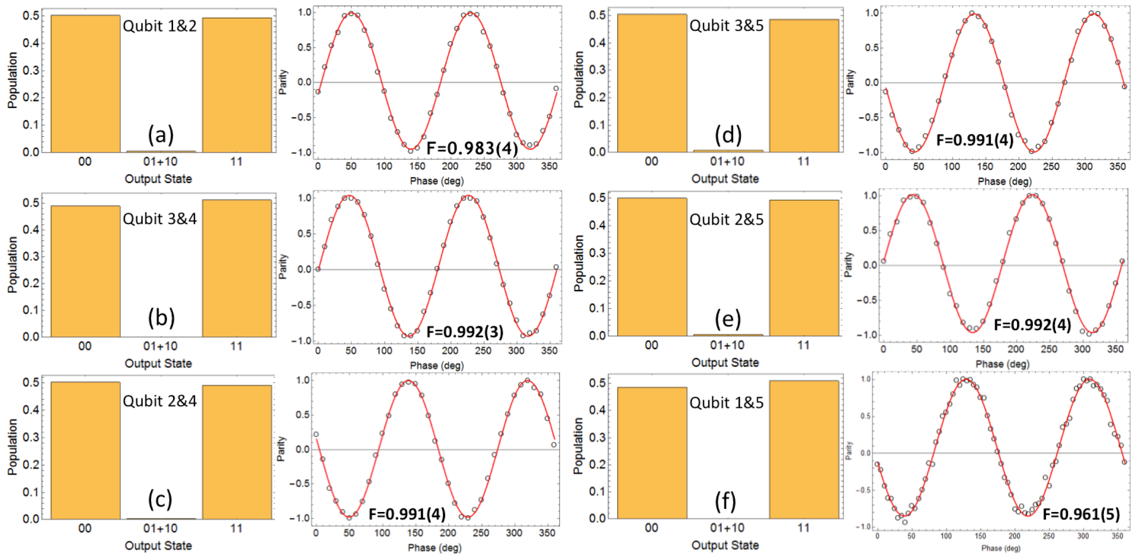

Figure 1: Mølmer-Sørensen gate on all possible ion pairs in a 5-ion chain (less the left-right symmetry). (a-f) denote the two qubit gates between ion pairs 1-2 (similar to 4-5), 3-4 (2-3), 2-4, 3-5 (1-3), 2-5 (1-4) and 1-5, respectively. For each subfigure, the graph on the left shows the population, while the graph on the right shows the parity oscillations. The gate fidelity is measured to be in 96-99% range, when the SPAM error (~2%) is subtracted out.

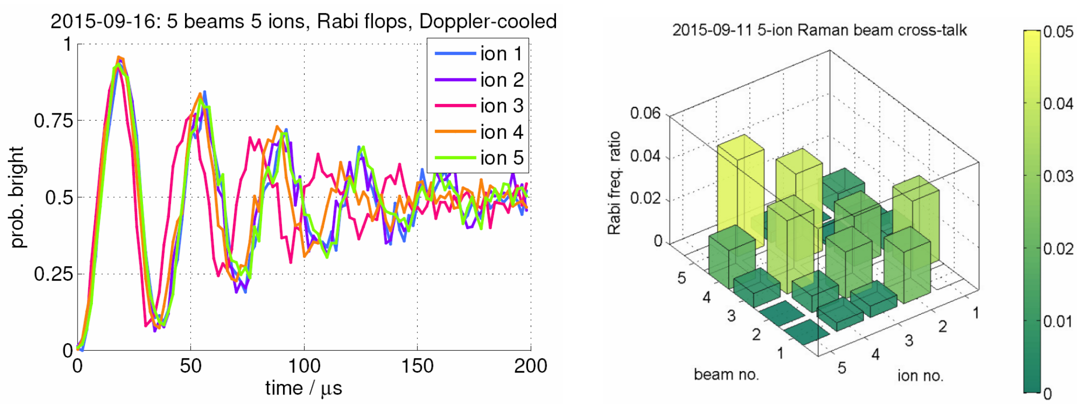

Figure 2: (Left) The Rabi oscillations of each qubit in the chain, when the chain is Doppler-cooled. The counter-propagating gate beams make the Rabi oscillations sensitive to the residual motion of the ion, limiting the fidelity of the single qubit gates. (Right) Characterization of the crosstalk in Raman beams. The crosstalk between the nearest neighbor qubits is in the 2-5% range. While that for the next nearest neighbor is below 1%.

The transverse mode frequencies of trapped ions are determined largely by the rf potential delivered to the trap electrodes through an rf amplifier and a helical resonator. Both amplifier and resonator have mechanical and thermal fluctuations that affect the ion trap frequencies, and are a leading contributions to gate infidelity. We have stabilized the secular frequency of trapped ion motion to less than 20 Hz, at a trap frequency of ~1 MHz. This is accomplished by capacitively picking-off 1% of the rf high voltage, rectifying the signal, comparing to a stable voltage source acting as the set point, with feedback to the rf source. Both pick-off capacitor and diode rectifier circuits (shown in Figure 4) are designed with very low drift and temperature sensitivity.

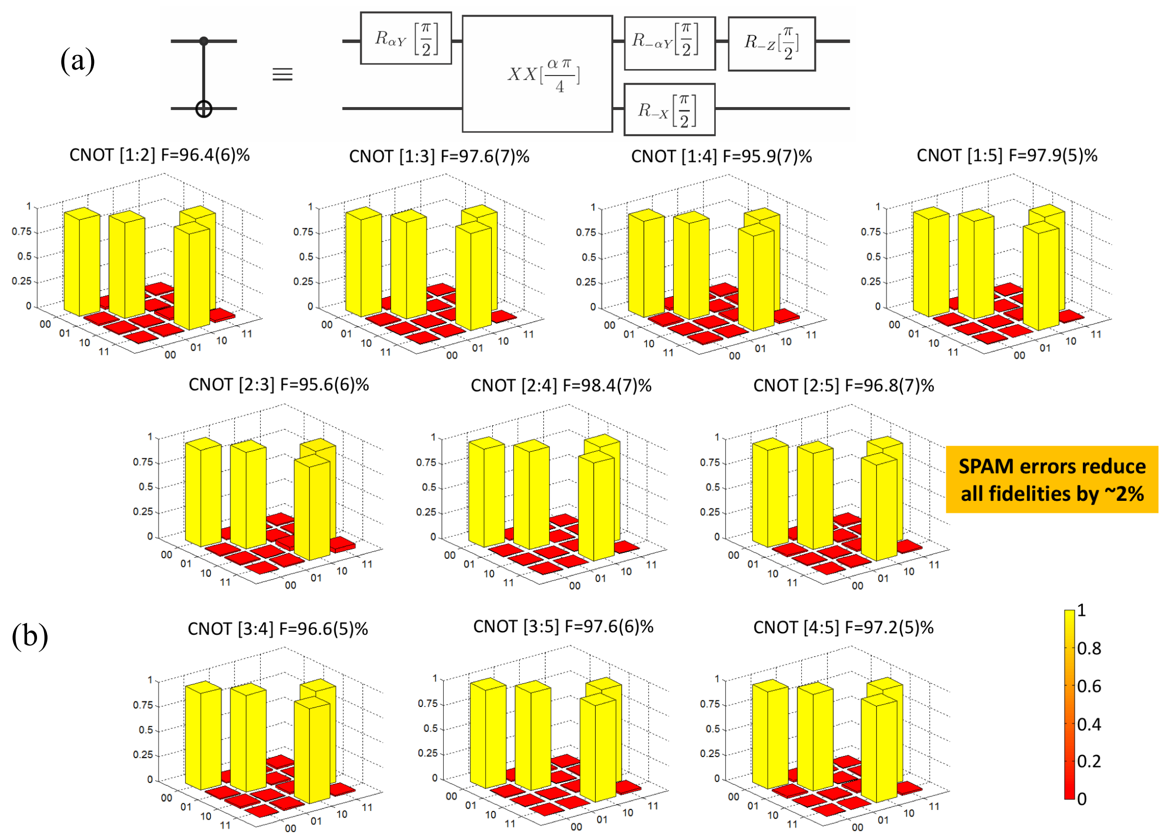

Figure 3: Demonstration of a CNOT gate between the all possible pairs of a 5-ion chain. (a) Schematic of the CNOT gate realized using a MS gate and three single-qubit gates. (b) Histograms representing the population of the input and output states for the CNOT gate. The gate fidelities range from 95-99% range, without the contribution from SPAM errors (~2%).

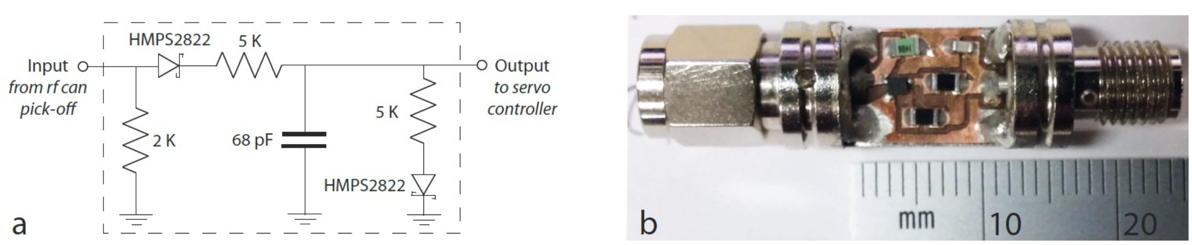

Figure 4: (a) Circuit diagram of the rectifier that processes rf pick-off signal from the helical resonator for feedback and comparison to set point potential, including dual matched diodes for temperature-coefficient compensation. (b) Mounting of rectifier in a closed SMA package.

Using this system, we have implemented the Deutsch-Jozsa algorithm, the Bernstein-Vazirani algorithm, and the quantum Fourier transform algorithm on five physical qubits. Figure 5 shows the results for running both the Deutsch-Jozsa algorithm (for Figure 5a and b) and the Bernstein-Vazirani algorithm (for Figure 5c and d). The average discrimination efficiency is 0.967(2) for constant and 0.932(3) for a balanced functions in the Deutsch-Jozsa algorithm. For the four-qubit Bernstein-Vazirani algorithm, the single-shot detection for the correct estimated sequence is achieved with an experimental average fidelity of 0.903 (2).

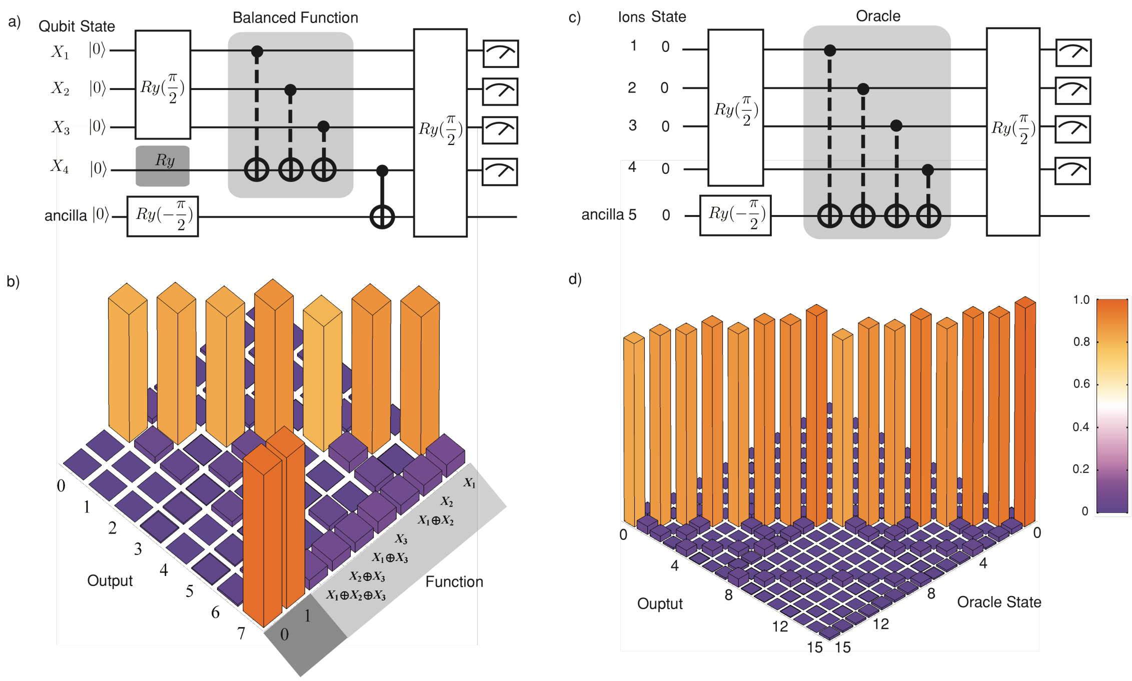

Figure 5: (a) The Deutsch-Jozsa algorithm on 5 ions. Shaded regions show reconfigurable part of the sequence where the light and dark grey sections are executed in separate cases to achieve balanced and constant functions respectively. CNOT gate combinations (light grey) are used to create parity functions of upto three qubits. A rotation on X4 (dark grey) is used to implement constant function f=1. (**b**) Measured population of the output state for various functions post selected on X4 = 1. Binary outcome of the state 111 indicates that the function is constant, while any other outcome indicates that the function is balanced. (**c**) The Bernstein-Vazirani algorithm circuit where shaded region contains reconfigurable CNOT gate combinations used to implement different oracle states. (**d**) Measured output population for various oracle states. The output is the inverted oracle.

We also performed a fully coherent quantum Fourier transform (QFT) on five qubits using techniques that can easily be scaled to larger registers. We examine the performance of QFT as a part of a phase estimation protocol without implementing the Oracle. A state preparation is applied instead in order to mimic a controlled modular exponentiation (Figure 6a). The state preparation involves single qubit rotations on all five qubits which is followed by a QFT protocol. Our version of QFT implementation is different than earlier trapped ion experiments, in the sense that a) we perform a fully coherent QFT that allows us to implement it in a truly reversible way as opposed to a semi-classical scheme, b) we employ two qubit gates for all ${}_5C_2$ = 10 ion pair combinations in the register thereby illustrating a fully connected system capable of performing any arbitrary gate, c) by applying composite conditional phase gates with varying phases for all pairs of ions, we demonstrate the modularity and hence the scalability of this scheme for implementing the QFT, and d) by avoiding intermediate individual detection of qubits or qubit recycling, as required in a semi-classical scheme, our coherent implementation is free of accumulated errors due to imperfect measurement and decoherence induced by the measurement process.

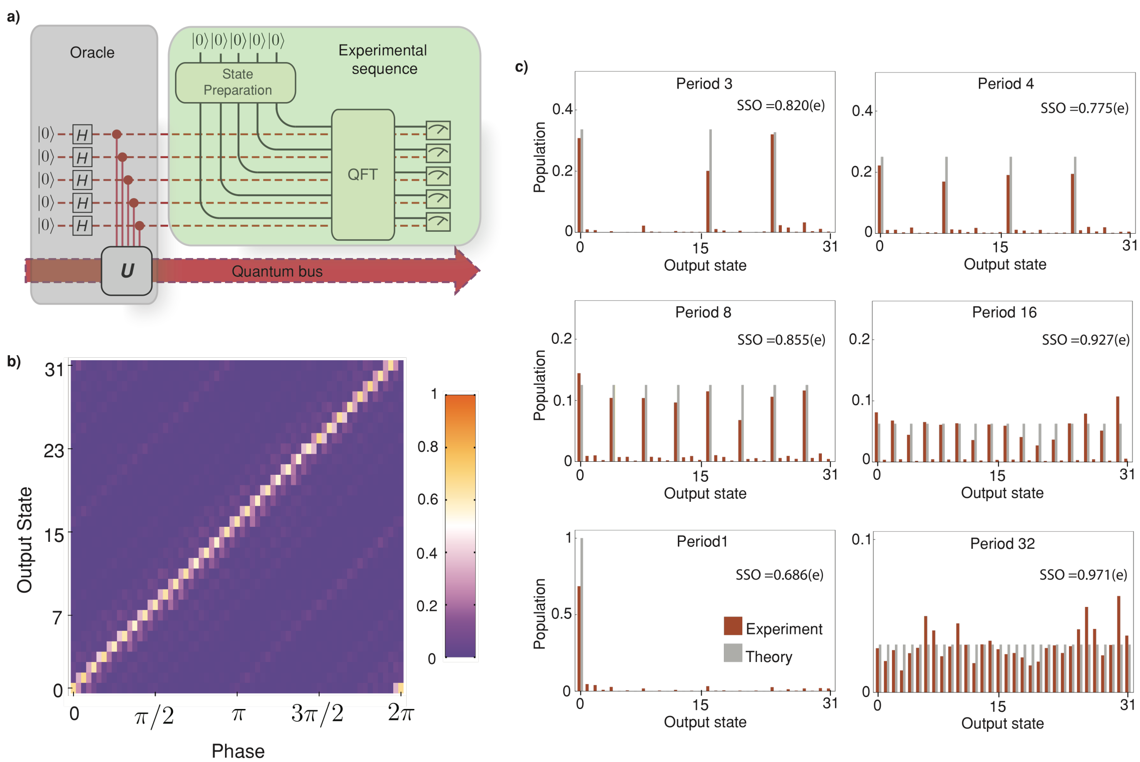

Figure 6: Quantum Fourier transform (QFT) protocol. (**a**) Schematic of a quantum algorithm using QFT. Shaded gray region represents an oracle that starts with a superposition state applying Hadamard (**H**) gates on hypothetical measurement qubits (dashed red wire) followed by controlled unitary (**U**) operations on a computational quantum bus which is then followed by QFT. Shaded green region contains experimental sequence where solid black wires represent trapped ion qubits. 'State preparation' contains single qubit rotations to mimic an initial state given by an oracle corresponding to period finding/quantum phase estimation algorithm. 'QFT' contains a sequence of conditional phase gates and rotations (see supplemental material). (**b**) Quantum phase estimation using five measurement qubits is performed by incrementally setting the input phase in steps of 2π/64. The measured output is a state whose value corresponds to the input phase is detected with a probability > 0.6. (**c**) Quantum period finding using five qubits. Input states are prepared using single qubit rotations to create amplitude modulation for period {1,4,8,16,32} and phase modulation for period 3. The squared statistical overlap(SSO) signifies the fidelity of the protocol where the error is statistical.

One of the performance limitations on the application of multiple gates have been identified. The 4-photon Stark shift, stemming from imperfect polarization of the 355nm Raman beams and driving virtual transitions through the (1,1) or (1,-1) Zeeman levels, is different on all pairs of ions, meaning that gates on particular pairs of ions must account for this factor, especially when qubits are involved in subsequent gates. We have finely optimized the Raman beam polarization to minimize this effect, but it still represents a phase of ~2-5 degrees on each gate, presumably from vacuum window birefringence. In the future this is not a problem as long as the Stark shift does not drift (and it appears to be stable over many hours). However, we currently cannot vary the phase of the individual addressing beams, so this limits the number of gate sequences we can current apply. We have implemented a 5-qubit fully quantum FFT algorithm on a variety of input states, using all 10 possible 2 qubit gates on the 5 qubits. We are currently analyzing the results.

On the photonic link side, the Maryland team continues to press on the establishment of the Ba-Yb dual species system. We have observed (post-selected) entanglement between a single $^{138}Ba^{+}$ ion and the polarization of an emitted photon at 493nm (see Figure 7a). The $^{138}Ba^{+}$ ion is weakly (10%) excited with a 500ns pulse of resonant light at 493nm, and we collect the resulting photon through an NA0.6 objective, orthogonal to the quantization magnetic field. As shown in Figure 7b and Figure 7c, the observed correlation between photonic and atomic qubits in orthogonal bases proves entanglement. Both photonic and atomic state are post-selected (~10% excitation probability, ~2% detection efficiency of photon, and ~2% detection efficiency of $^{138}Ba^{+}$ qubit). The post-selected fidelity is observed to be F=0.86.

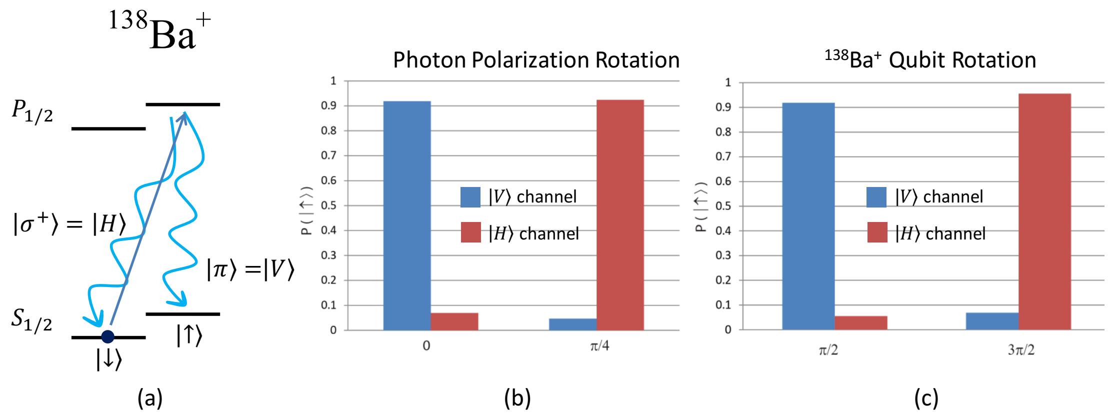

Figure 7: (a) $^{138}Ba^{+}$ energy levels, with atomic qubit stored in the electron spin states in the ground state, and excitation scheme to produce single photons whose polarization (H or V) frequency is correlated with the atomic qubit state. (b) Observed correlation between atomic qubit and photon polarization in two bases of photon measurement, using a waveplate. (c) observed correlation between atomic qubit and photon polarization in two bases of photon measurement, using a waveplate.

b. Duke University System

At Duke University, we pushed on two fronts: the establishment of a two-qubit Molmer-Sorensen (MS) gate on one of our chambers, and improved photon collection into a single mode fiber using the high-NA lens for better ion-photon entanglement experiments.

For the two-qubit gate experiment, we demonstrated initial two-qubit MS gate operation using a single pixel PMT detector, with histogram-fitting to distinguish among the cases where none, single, and two qubits are in the bright state. This measurement method works for the two-ion case, but not in the multi-ion case we are aiming for in our experiments. Since we plan to get to longer chains, we decided to install a multi-channel PMT to detect the qubit state of each ion in the chain independently. For this, we first realized that the alignment of our imaging lens to the ion chain was very far from optimal, leading to significant aberrations of the ion image that spilled photons over to the neighboring PMT channels. While this was not an issue in a single PMT experiment, it accounted for about 9% of photon spillage to the neighboring pixels, and about 3% to the next nearest neighboring pixels (which we used to detect the photons from the adjacent ion). We went through a realignment of the imaging optics to reduce this detection crosstalk. Figure 8 shows the result of an improved alignment: the photon spillage to next nearest neighbor was reduced to below 1%. A careful analysis of the ion image still shows a small halo, leading to the finite spillage to neighboring PMT channels. Since we did not have a fine-tuning capability (of motorized stages, etc., see below), we could not improve the alignment better than this limit. The photon detection crosstalk among the relevant PMT channels will lead to some potential crosstalk error in qubit detection that will depend on the specifics of the qubit detection protocol, but in a standard histogram thresholding approach, we expect the measurement error due to crosstalk to be well below 1% in this case.

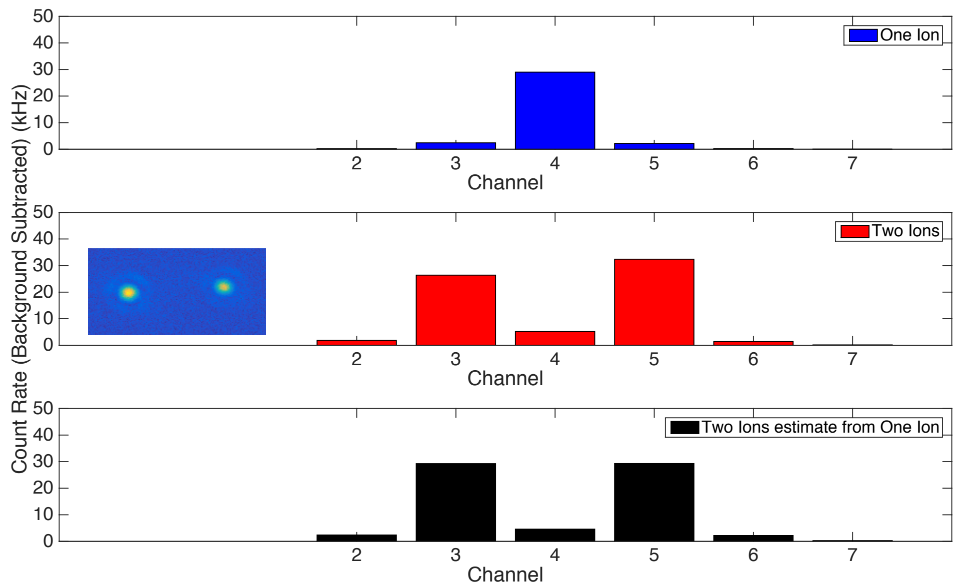

Figure 8: Measurement of pixel crosstalk for the multi-channel PMT. The top panel shows the photon counts from each channel when the photons collected from a single ion is aligned to the fourth pixel in our multi-channel PMT. While there is significant spillage over to the next PMT channel, the spillage to the next nearest channels (pixel 2 and pixel 6) are below 1%. The middle panel shows the case of two ions, where the fluorescence is collected to channels 3 and 5, respectively. The inset shows the image of ions measured by the EMCCD camera, where a small halo around each ion is visible, causing the spillage to neighboring PMT pixels. The bottom panel shows the expected photon count distribution on each pixel, based on the measurement of the single ion case.

Using this setup, we have achieved a two qubit Molmer-Sorensen gate with fidelities in the 97% range, as shown in Figure 9. We have a relatively long and convoluted Raman beam path from the 355nm Paladin laser to the ions, where one of the beams is elevated about 50cm above the optical table, and above our DAC electronics (generating quite a bit of heat). We feel it is difficult to keep the beams stable, and therefore the Raman beam intensities at the ion location is probably fluctuating at a few % level. Our MS gate does include a first-order Walsh correction, but it is not very effective in correcting for intensity errors. We have made efforts to stabilize the trap frequency as the detuning of the Raman beams also drift due to this reason. We plan to implement the Maryland solution on trap frequency stabilization in the future.

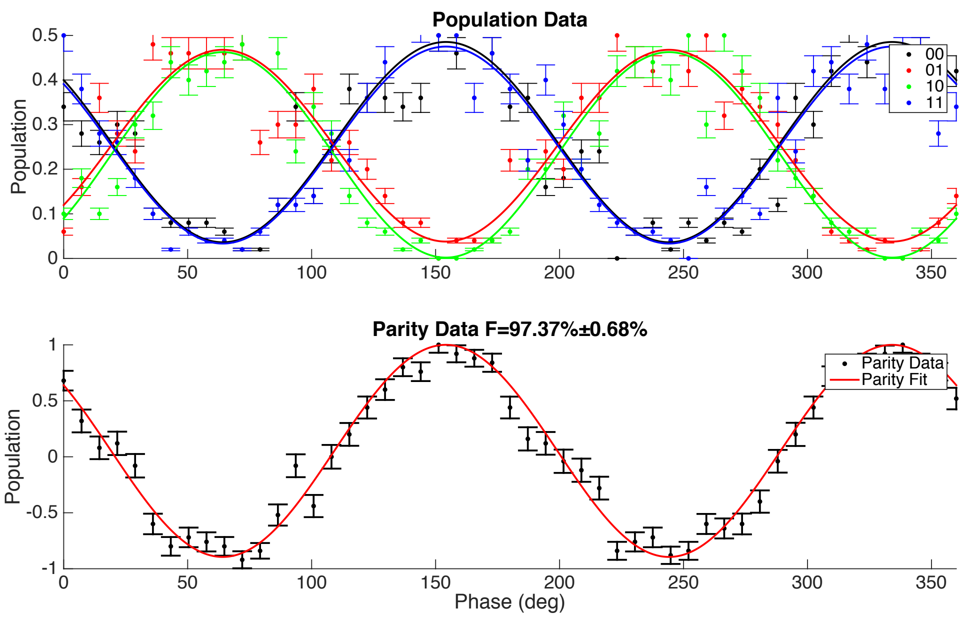

Figure 9: Characterization of a two-qubit Molmer-Sorensen gate at Duke University.

Based on the ray-tracing simulations, optimal fiber coupling of the atomic emission at 370nm using the PhotonGear lens requires critical control of the alignment in three degrees of freedom: the lens position along the optical axis (defined to be the z-axis, to within ~1μm), and x- and y-tilt with respect to the optical z-axis (to within 0.01º). The alignment is completely insensitive to rotation around the z-axis (cylindrical symmetry), and robust against x- and y-shifts (~150μm object space over which the image is diffraction limited). The true z-axis is determined as the normal of the optical window for a single ion case, and for an ion chain, we require that the chain be parallel to the optical window plane to within < 1º for a 20 ion chain. The initial attempts at University of Maryland in controlling the aberrations have been very effective in dramatically improving the coupling efficiency, but it looks like there still is about a factor of 3-4 to be gained. This would correspond to improving the entanglement generation rate by an order of magnitude, so it is definitely worth looking into further improving the fiber coupling efficiency.

The effort at Duke started with an adequate design of motorized translation stage and kinematic mounts that provides sufficient resolution, repeatability and stability to position the PhotonGear lens at the optimal location. The initial alignment process closely followed the procedures developed at Maryland, but with an improved set of alignment optomechanics and diagnostic probes (high resolution imaging and comparison of the aberrated images with ray tracing simulation results). After the final correction, the point spread function (measured as the shape of the image of the ion, which is almost an idea point source) is tightly focused, to within 30% of the diffraction-limited spot size.

With this setup, we have accomplished coupling 50% of the σ-polarized light collected within the NA of the PhotonGear lens into the fiber (see Figure 10). This is a factor of 2.5 improvement over the UMD setup, and approaching the maximum coupling of 80% based on the simulation results (determined by the overlap between the fiber mode and the diffraction-limited collection mode of the PhotonGear lens). This, coupled with an superconducting nanowire single photon detectors (SNSPDs) that have been tested in the Duke lab (this part of the project is being funded by LPS/ARO) which shows 50% system detection efficiency (~68% device efficiency and ~73% fiber transmission), we anticipate achieving the ion-photon entanglement generation rates of about 80 events per second, a factor of 17 improvement from the recent U. Maryland results. The next step is to verify the fast generation rate of ion-photon entanglement generation. In order to facilitate efficient diagnostics, we plan to use the polarization qubit for the photon, which is naturally entangled with the Zeeman qubit in the ion. We need to duplicate this setup for the second chamber before ion-ion entanglement can be verified at higher rates.

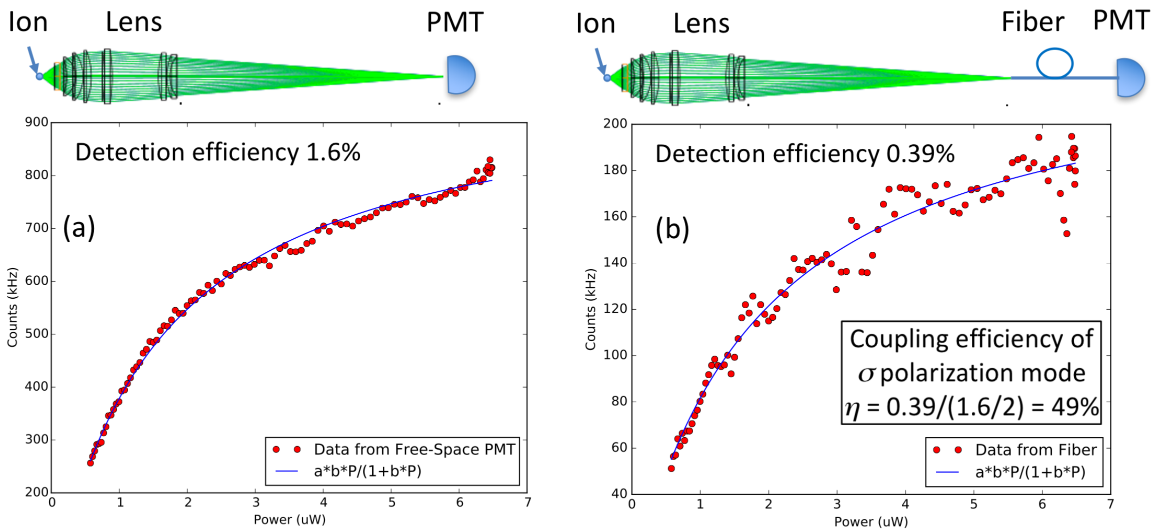

Figure 10: Optimized coupling efficiency of the emitted photons at 370nm into a single mode fiber, measured by atomic emission driven into saturation. (a) The detection efficiency of the photons scattered by $^{174}Yb^{+}$ ions by a photomultiplier tube (PMT), through the PhotonGear lens. The absolute efficiency can be extracted from the saturation curve of the atomic emission. (b) Similar curve when a piece of single mode fiber is inserted between the image of the atomic emission and the PMT. Only σ-polarized photons couple into the single mode fiber in this collection geometry, as π-polarized photons are completely rejected by the mode symmetry.

c. Georgia Tech Research Institute System

The main goal of GTRI's effort in the Capstone project was to push through major hardware upgrades in the system, including: (1) Installation of a 300 mm segment of photonic crystal fiber into one 355 nm Raman gate beam, (2) Reduce the size of that Raman beam into the AOM used to turn the beam on and off, which will decrease the pulse rise time to ~ 50 ns (3x improvement), (3) Redesign path for the other Raman gate beam, such that it is no longer reflecting off a dichroic mirror, (4) Intensity stabilization of both Raman beams with high bandwidth feedback, (5) Study of our feedforward rep-rate lock: by enclosing the entire assembly we were able to remove spurious noise peaks, and (6) Installation of low noise current drivers for magnetic field coils.

Within the first two months, we completed the installation of the fiber segment, reduced the Raman beam into the AOM, fixed the beam paths, and implemented the power stabilization feedback loop for both Raman beams. Upon our initial single qubit Rabi oscillations experiment, we realized that the high power used in the beams have introduced additional qubit frequency shift due to the self-resonant Raman transition 16MHz from the carrier. We modeled this shift and determined that the PB2 pulse sequence removes most of the error (10^{-5}) on targeted ions. However untargeted ions experience a measurable R_z rotation. We've incorporated this knowledge into our gate compiler, such that it applies the appropriate rotations on the whole ion chain. Our simulator also accounts for the unwanted R_z rotations. Having accounted for these errors, we utilized Randomized Benchmarking to characterize single-qubit gate fidelities. The infidelity of a single-qubit gate operation, in a two-ion chain, is still around two percent. To determine what may be causing this error, we utilized the "quantum lock-in" technique with 80 echo π pulses. These scans indicate a large noise source near 45 kHz.

We spent a lot of time tracking down the source of this noise. In the process, we discovered that our repetition rate lock for the 355nm laser had some residual phase noise in ~1ms timescales, which was also observed at Duke and Sandia in the past. We tracked down that and fixed the problem, so that the coherence time measurement (Ramsey spectroscopy) was recovered to expected levels. However, this did not resolve the 45kHz noise issue. We have a pretty good understanding of what this might be: a two-phonon transition in the ion chain, where the ion absorbs (emits) into the rocking mode and emits (absorbs) into the COM mode. As the two radial modes are separated by only 45 kHz, the net transition is 45 kHz detuned from the carrier. While it is a second order coupling, our 62.5 kHz Rabi rate is larger than the detuning. This error can be decoupled by modifying the pulse sequences, or mitigated with better cooling.

Although we have not been able to resolve all of these experimental issues that were uncovered during the Capstone period, we have carried out the 3-qubit Bernstein-Vazirani algorithm at the end of the Capstone period. The average success probability of the algorithm has generally improved greatly over the experiments at the end of the 5-year MQCO program, as shown in Figure 11.

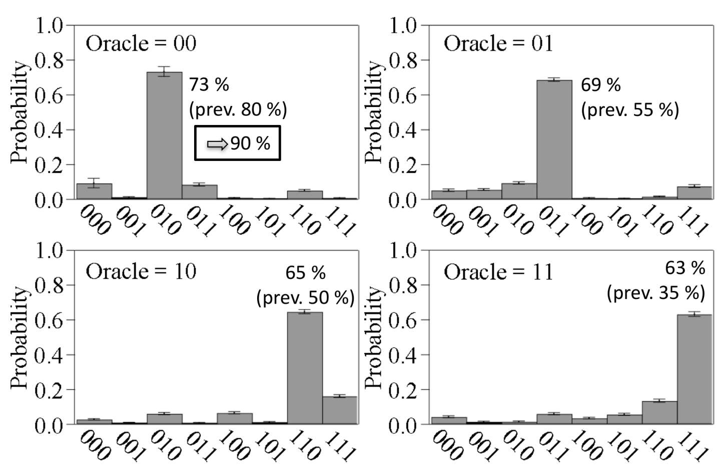

Figure 11:The success probability of 3-qubit Bernstein-Vazirani algorithm in GTRI system. The performance for each oracle state showed significant improvements over previous experiments performed with a setup before the Capstone upgrades.

d. Theory Efforts in Noise Modeling

The challenge of disentangling the spin and motion degree of freedom is crucial in implementing a high performance gate. We developed theoretical model allowing spin-motional disentanglement to be quantified in the presence of phase-modulated MS gates. Theory provides a good prediction of expected MS lineshape as a function of Raman detuning from motional modes. We have experimentally verified that the phase-shifted gate design works well, and started looking at its application to ion-motion entanglement. However, we are seeing that there is residual micromotion that cannot be corrected in our setup, making it difficult to simultaneously cool both the red and the blue sidebands of noise. This could be arising from axial micromotion, potentially due to a slight misalignment of the two end caps in our macroscopic trap, and the lack of in-situ RF filtering (the end cap electrodes picking up a small portion of the RF from the RF electrodes).

We have recently obtained a better estimation of phase noise of the oscillators generating the gate pulses on the qubit gate performance, and conclude that the impact of the phase noise could be much larger than expected, when controllers with wide bandwidths are desired. This is because the phase-noise far from the carrier has a much higher contribution to the qubit noise than previously considered: making the controller narrow-band helps with the noise situation, at the expense of the control bandwidth.

Randomized benchmarking widely used for characterizing the error probabilities of quantum gates lets you estimate the average error rates, while the fault-tolerance threshold theorems require a stricter notion of worst-case error, measured by the diamond distance. The gap between the average error and worst-case error could be very large: in the worst case of unitary (or systematic) errors, this gap could be many orders of magnitude in the low error regime. We have developed a theoretical framework that allows one to clearly distinguish the extent of unitary errors present in the system, with a goal of identifying and eliminating them. In this limit where all coherent errors are eliminated, the average and worst-case errors now coincide, and the error probabilities estimated by randomized benchmarking is directly relevant for the realization of fault-tolerant error correction. At a more concrete level, we studied the effect of modeling errors with extensions to the Pauli error model and how the choice of approximation changes the behavior. For incoherent errors we have found Pauli channels optimized on fidelity are good models even for non-unital errors such as amplitude damping in the context of error correcting codes. A purely coherent error model of unwanted rotation by a fixed angle after each gate is not well captured by either Pauli model. The Pauli channel optimized on fidelity (a Pauli Twirling Model) results in an optimistic threshold while the Pauli channel optimized with the constraint that the distance for pure states must be worse than for the real channel results in a pessimistic threshold. This can be understood by looking at the leading order term in the distance for small distances.

e. Theory Efforts in Algorithms Development and Novel Architectures

We (U. Michigan) carried out more detailed simulation for realization of the boson sampling algorithm with trapped ions. A moderate system size with 20 to 30 ions provides the most interesting physical region for this test to beat the classical computers on this specific problem.

The coherent and dissipative processes (such as photon entanglement or qubit state initialization and detection) that must coexist in a modular architecture like MUSIQC calls for a second ion species, either to support sympathetic cooling or to establish the remote entanglement generation using photons at a different wavelength. We propose a new way for spectral addressing in an ion crystal. In order to avoid resonant photons to scatter and decohere the qubit ions, one approach is to have the ancilla ions represented by a different ion species, and such as a dual-ion species system the MUSIQC team has been focusing on. Apart from the laser complexity to control two species of ions, an issue for this approach is that it is difficult to generate a regular distribution pattern of the ancilla ions around the computational ions, and such a regular pattern is likely required for realization of fault-tolerant quantum computation. We propose a different approach to address this problem, where the ancilla ions are represented by the same species of ions, but on a different metastable state (the shelter D level). We apply laser cooling, repetitive readout measurements, and probabilistic entangling operations all on these D level ions, which leave the laser beams and spontaneous emission photons having no influence on the computational ions. It is easy to get a regular pattern of these ancilla ions through spatially focused laser beams, which bring the ancilla ions to the D level.

We also studied the possibility of constructing robust distributed entanglement between small ELUs similar to those considered in the MUSIQC program, that might be suited for a long-term application to communications, with the following properties:

1. With L the total distance between the communicating parties, the operational cost is of order $L \log^2 (L)$.
2. Under the assumption of fast classical processing (one-way communication + local computation), the rate of secure communication is independent of L.
3. The communication structure can be conveniently built from 5-qubit ELUs, similar to those considered in MUSIQC scalability challenge.

Compared to the recent proposals on QECC-based third-generation quantum repeaters, the present construction provides the compatibility with small ELUs. Traditionally, it is believed that cramming all the necessary components into small repeater stations has a tendency to result in loss of performance: we find that this degradation is not necessary. Similar to the solution of MUSIQC scalability challenge, we can utilize 3D cluster states to get the above 3 characteristics. In this construction, we (1) build a 3D cluster state stretching from one communication party to the other, using 5-qubit ELUs, as shown in Figure 12. Four of the qubits in each ELU are used to establish Bell pairs with neighboring ELUs via photonic links. (2) Locally measure all qubits in the 3D cluster in the eigenbasis of σ_x, except for one at the respective locations of each communicating party. (3) From all the measurement outcomes construct the error-syndrome and correct for the most likely compatible error. This produces an almost pure Bell state between the parties.

The protocol works, of course, only below the fault-tolerance threshold for 3D cluster states, which has numerically been established, for a large range of error models, to be $\langle K_a \rangle \approx 0.72$, where K_a is an elementary cluster state stabilizer operator. From this criterion, we obtain the following bound on the error rates,

$$\varepsilon + \frac{55}{32}\frac{T}{\tau_D} < 2.9\times10^{-3}.$$

Therein, ε is the gate error (all one-and two-qubit gates), T is duration of slowest gate and τ_D is the decoherence time.

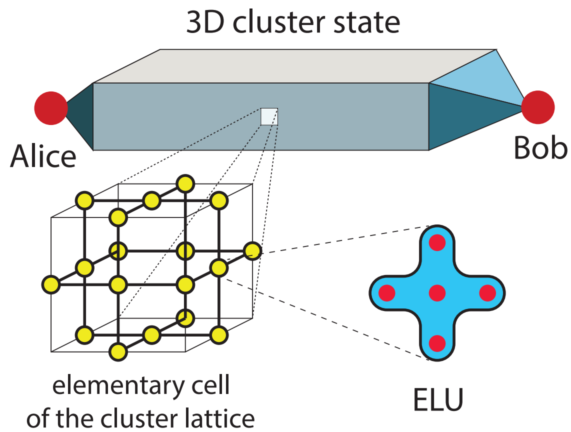

Figure 12: 3D cluster state for fault-tolerant entanglement distribution and quantum communication.