Research Spotlight Forum

6.4.19 Quantum Information Sciences

GTRI Quantum System Division Overview

PRESENTED BY:

Craig R. Clark , GTRI, CIPHER Lab, Quantum System Division

Sandia National Laboratories | Georgia Institute of Technology | ILLINOIS | PURDUE UNIVERSITY | THE UNIVERSITY OF TEXAS AT AUSTIN | THE UNIVERSITY OF NEW MEXICO | NM STATE UNIVERSITY | NEW MEXICO TECH SCIENCE • ENGINEERING • RESEARCH UNIVERSITY

SAND2018-14303 O

About GTRI

Georgia Institute of Technology

- Education
- Basic & Applied Research
- Open Environment
  - Unclassified
  - International
- Entrepreneurship & Start-ups

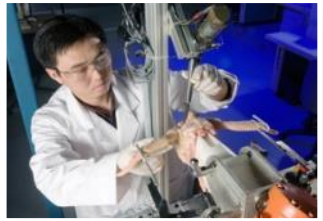
Georgia Tech Research Institute

- Applied Research & Development
- Technology & Systems Prototyping
- Research Space: > 1 million ft^2
  - Field Sites: 18
  - Laboratories: 8
- Department of Defense University Affiliated Research Center (UARC)

GTRI Major Research Areas

Quantum

Aeronautical Systems & Avionics



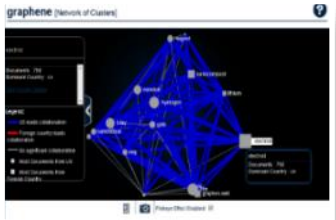
Agricultural & Food Technology

Air & Missile Defense Systems

Autonomous Systems & Robotics

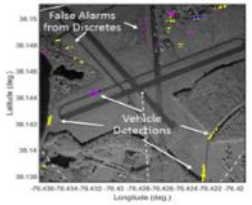
C4 & Decision Support Systems

Cyber Security

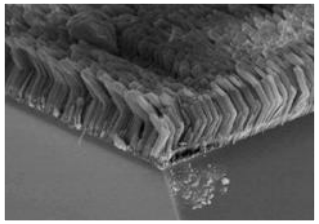


Data and Information Sciences & Systems

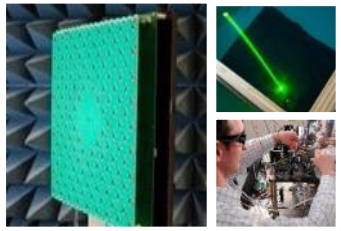
Electronic Warfare



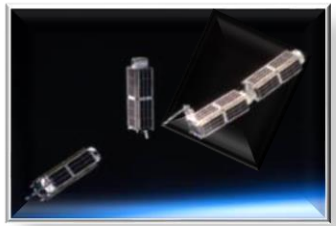
ISR Systems



Materials & Micro-Devices



Sensor Systems



Space Systems

Systems Engineering Research & Applications

Test and Evaluation Systems & Technologies

Threat Systems

Undersea Systems

About QSD

25 Research Scientists

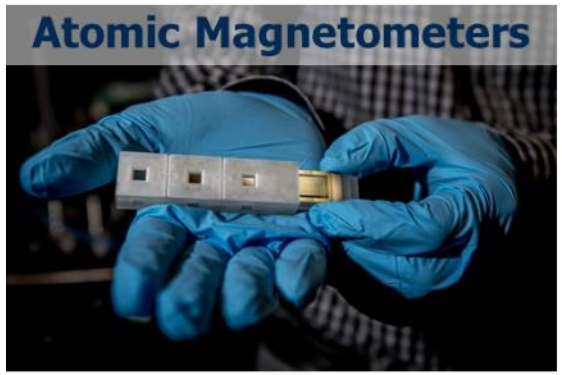
19 PhD's, mostly in AMO physics (also Optics, Mathematics, Chemistry, and Chemical Engineering)

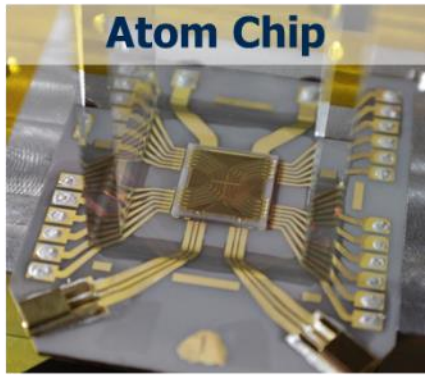
6 other advanced degree (Mechanical Engineering, Electrical Engineering, Mathematics, other physics)

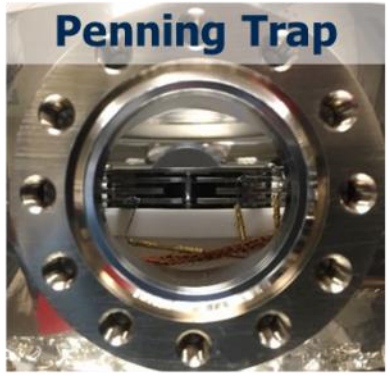
Extensive AMO lab spaces, HPC capability, GT fabrication facilities

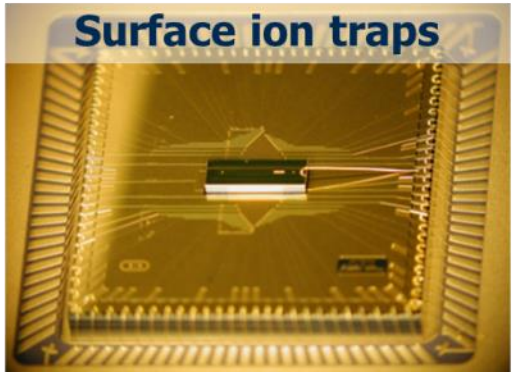
Research programs

- Magnetometers (fabrication, physics techniques, and applications)
- Laser cooled atoms on chip (on-chip microwave waveguides for matter-wave interferometer)
- Permanent magnetic penning trap (atomic clock)
- Surface electrode ion traps (experts in ion-transport, programs in quantum information, atomic clocks, chip-design, microfabrication, modeling, and proof-of-concept designs)
- Mass Spectrometers and devices for chemical sensing









Quantum System Division (QSD) Researchers

Alexa Harter, CIPHER lab director
B.S., Physics and Mathematics, Brown
Ph.D. in Physics, Caltech, 2000

Curtis Volin, QS Division Chief
B.S., Applied and Engineering Physics, Cornell
Ph.D. in Optical Sciences, U. of Arizona, 2000

Robert Wyllie, QS Associate Division Chief
B.S., Physics, Denison University
Ph.D. in Physics, U. of Wisconsin, 2012
Postdoc in Neutral Atom Group, NIST-Gaithersburg

Kenton Brown, QS Chief Scientist
B.S., Physics, Yale
Ph.D. in Physics, U. of Maryland, 2006
Postdoc with David Wineland, NIST-Boulder

Greg Mohler, QS Chief Engineer
B.S. Physics, Purdue University
Ph.D. in Physics, Ohio State, 2001

J. True Merrill, Theory Branch Head

Ph.D. in Physical Chemistry, Georgia Tech, 2013

Brian Sawyer, Experiment Branch Head
B.S., Physics, University of Arkansas
Ph.D. in Physics, U. of Maryland, 2006
Postdoc with David Wineland, NIST-Boulder

Adam Meier, Validation and Verification
B.A., Mathematics, B.S., Physics, Rice University
Ph.D. in Physics, U. Colorado- Boulder, 2013

Nicholas Guise, Ion experiment, communications
B.S, Physics, Cal Tech
Ph.D. in Physics, Harvard, 2010
Postdoc in the Atomic Spectroscopy Group, NIST-Gaithersburg

Harley Hayden, Fabrication

Ph.D. in Chemical Engineering, Georgia Tech, 2008
Postdoc at Georgia Tech, NRC

Creston Herold, Ion and Atom experiment
B.A., Physics and Chemistry, Williams College
Ph.D. in Physics, U. of Maryland, 2014

Jonathan Andreasen, Quantum Noise
Ph.D. in Physics, Northwestern, 2009
Postdoc, University of Arizona
Postdoc, Universite de Nice-Sophia Antipolis

Clayton Kerce, ML, Classical optimization
B.S., Applied Mathematics, Georgia Tech
Ph.D. in Mathematics, Georgia Tech, 2000

Kelly Stevens, Theory

M.S. in Mathematics, Virginia Tech, 2004

Christopher Shappert, Mechanical Analysis & Ion Trap Experiment
M.S. in Mechanical Engineering, U. Illinois-UC, 1997

Wade

Wade Rellergert, Mass spectrometry
B.S. Physics, Mathematics, University of Missouri
Ph.D., Physics, Yale

Craig Clark, Ion trap experiment
B.S., Chemistry, Math, Kennesaw State University
Ph.D., Chemistry, Georgia Tech, 2011
Post-Doc, Sandia National Laboratories

Chris

Christopher Seck, Ion trap experiment
B.S., Physics, California Polytechnic State University
Ph.D., Physics, Northwestern University, 2016

Karl

Karl Burkhardt, Ion trap experiment
B.S., Physics, Georgia Tech
M.S., Chemistry, University of Texas

Brian McMahon, Ion trap experiment
B.S., Physics, Georgia Tech
Ph.D., [in process], Georgia Tech

Yatis Dodia, Electronics and signal processing
B.S., Physics, Georgia Tech
B.S., M.S., Electrical Engineering, Georgia Tech

Abby

Abigail Perry, Magnetometer experiment
B.A., Physics, Wellesley College
Ph.D., Physics, University of Maryland, 2015
Post-Doc, CU-Boulder/NIST-Boulder

Holly Tinkey, ion trap experiment
B.S., Physics, Georgia Tech
M.S., Physics, University of Maryland, 2014

Roger

Roger Brown, Sensors and ions experiment
B.S., Engineering Physics, Colorado School of Mines
Ph.D., Physics, University of Maryland, 2014
Post-Doc, NIST-Boulder

Robert Clark, Ion traps, communications
B.S., Physics, Chemistry, Ohio Northern Univ.
Ph.D., Physics, MIT, 2009
Post-Doc, UT-Austin

Wesl
ey

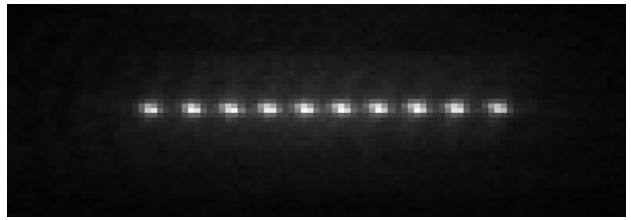
Wesley Robertson, Sensors and ions experiment
B.S., Physics, University of Tennessee
Ph.D., Physics, Emory University, 2010
Post-Doc, Max Planck Institute

Quantum Information: Ion Trap design and fabrication

Advanced design and optimization

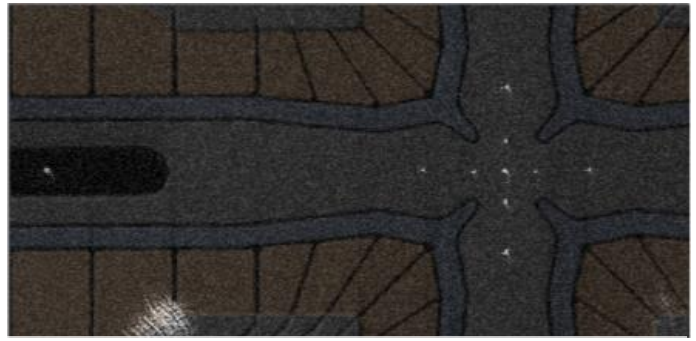
- Trap design uses in-house codes for optimization, allows the design of novel trap features
- Codes also allow dynamic potentials and efficient ion transport

Splitting and merging of four Ca+ ions



Long chains of Ca+ ions

Loading and merging of Ca+ ions

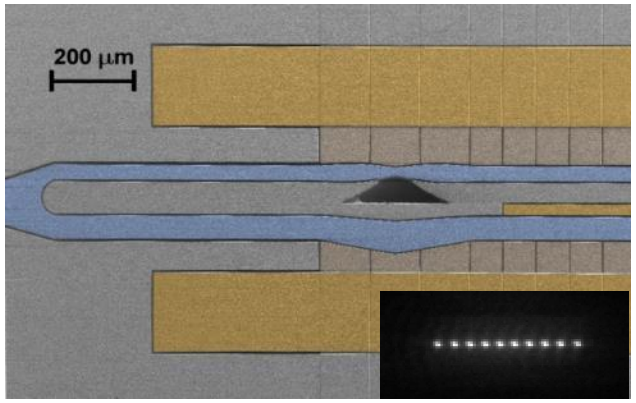


Yb+ ions in a junction trap

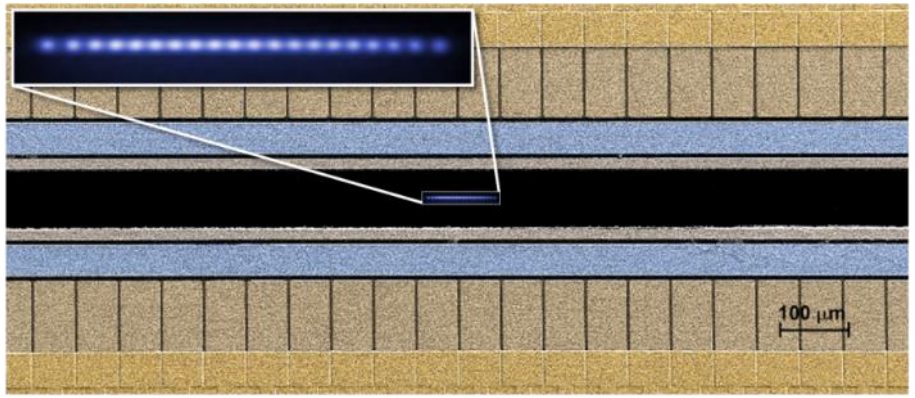
Quantum Information: Ion Trap design and fabrication

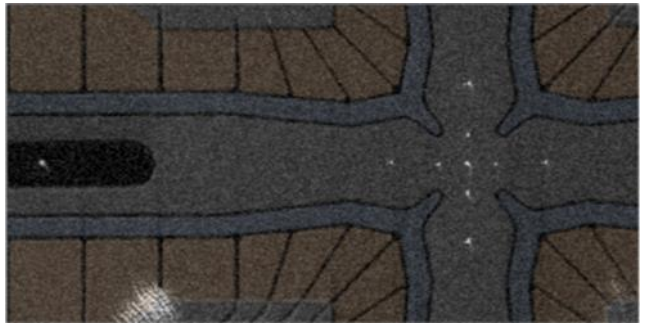
Surface electrode trap design

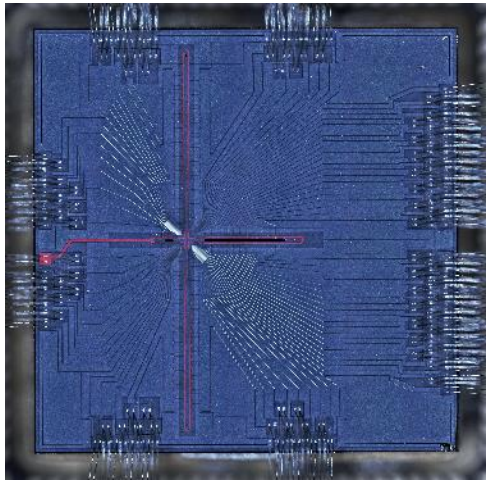
- Designed multiple generations of surface traps, delivered to academic collaborators
- Fabricated at GT and Honeywell
- BGA trap for improved optical access

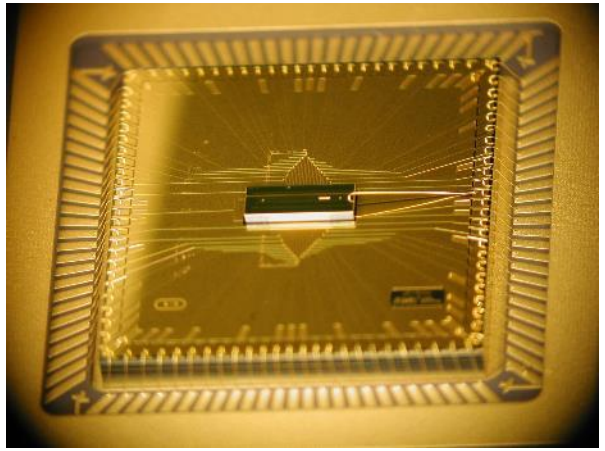


Doret, C. S. *et al.*,Controlling trapping potentials and stray electric fields in a microfabricated ion trap through design and compensations, *New Journal of Physics* **14**, 073012(2012).









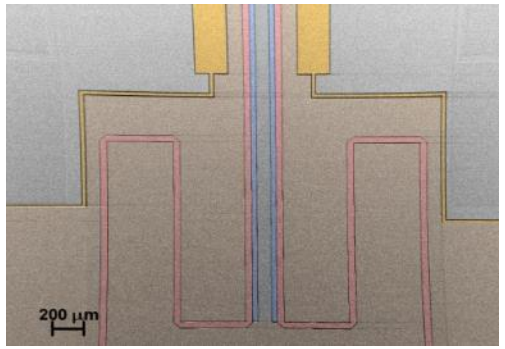
Guise, N. D. *et al.,* Ball-grid array architecture for microfabricated ion traps. *Journal of applied physics* **117**, 174901 (2015).

Quantum Information: Ion Trap design and fabrication

Feature integration

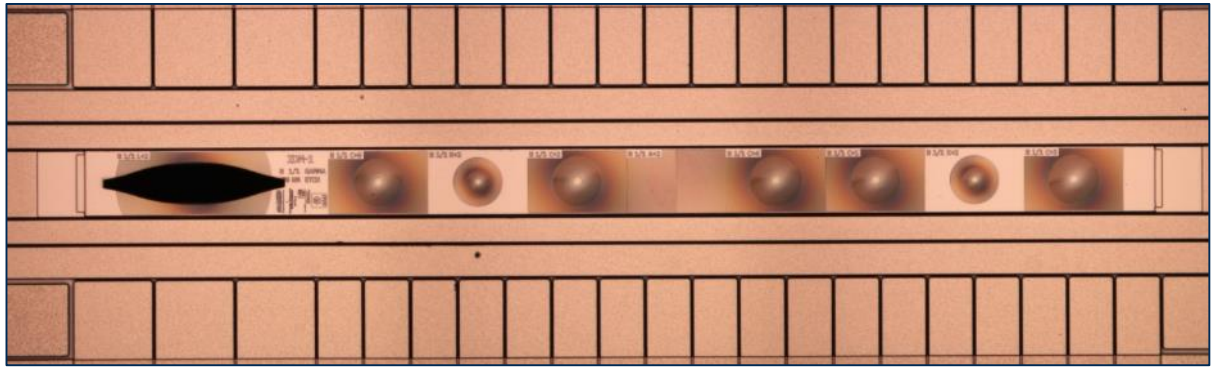
- Integrated optics: bulk and diffractive mirrors for fluorescence detection
- Microwave lines for state manipulation

Microwave lines



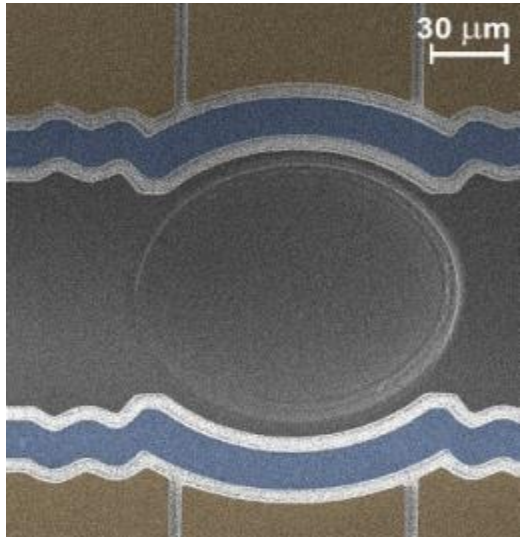
Shappert, C. M. *et al.*, Spatially uniform single qubit gate operations with near field microwaves, *New Journal of Physics* **15**, 083053 (2013).

Diffractive Mirrors



Kielpinski, D. *et al, Integrated optics architecture for trapped-ion quantum information processing, Quantum Information Processing* **15**, 5315 (2016).

Reflective Mirrors

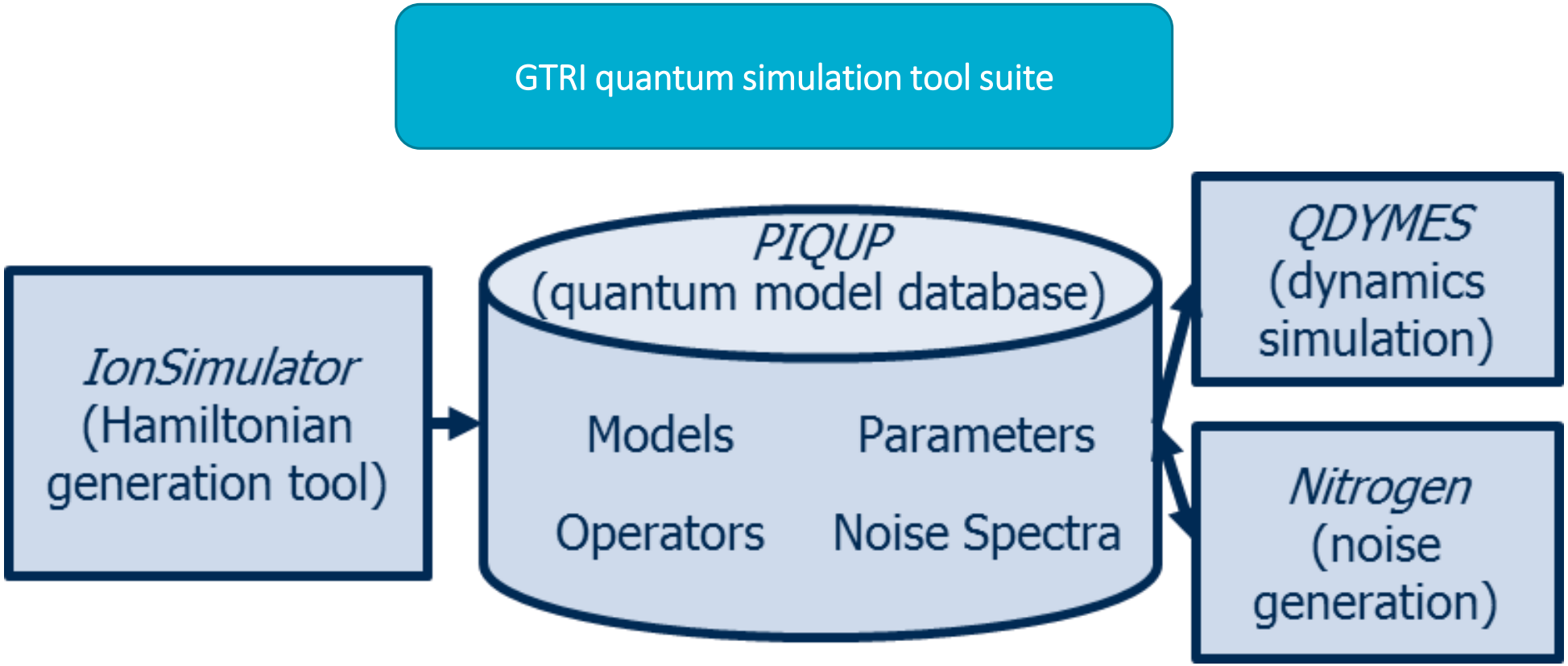


Merrill, J. T, *et al.*, Demonstration of integrated reflective optics in microfabricated ion traps, *New Journal of Physics* **13**, 103005 (2011).

Quantum Information: Previous Verification Results

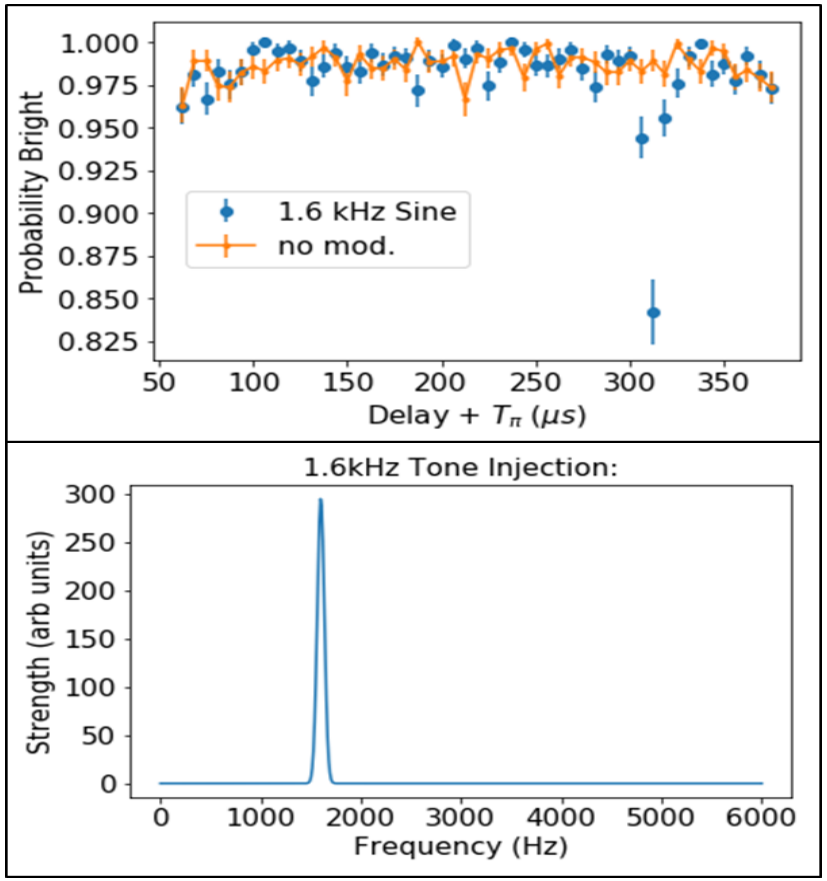
Objectives

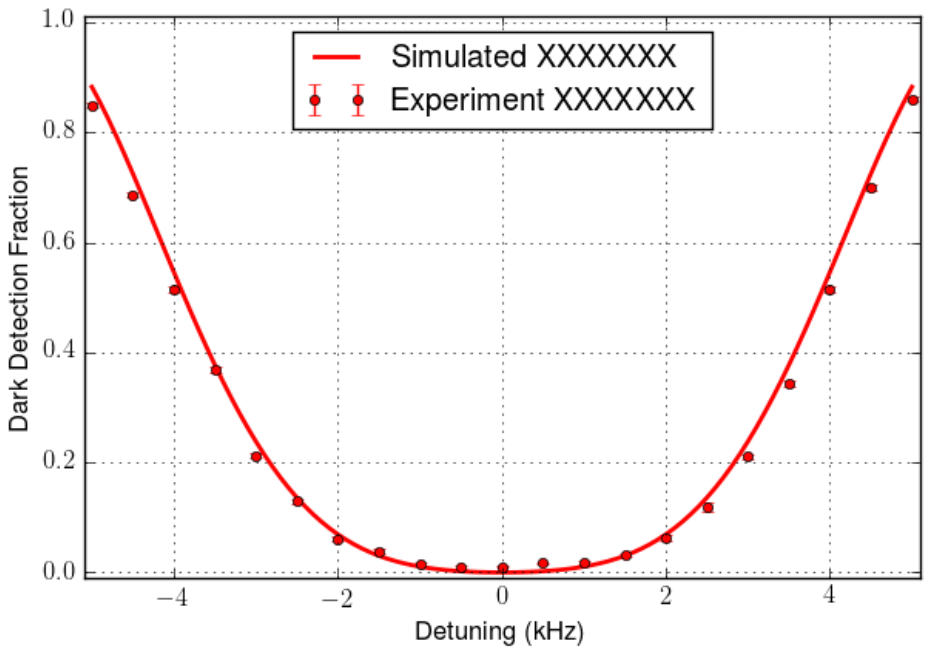
- Assess the quality of quantum operations for computing/sensing
- Simulate and verify the effects of noise and control errors on quantum operations
- Understand the impact of noise and control errors on quantum algorithm



Quantum Information: Previous Verification Results

Error Injections





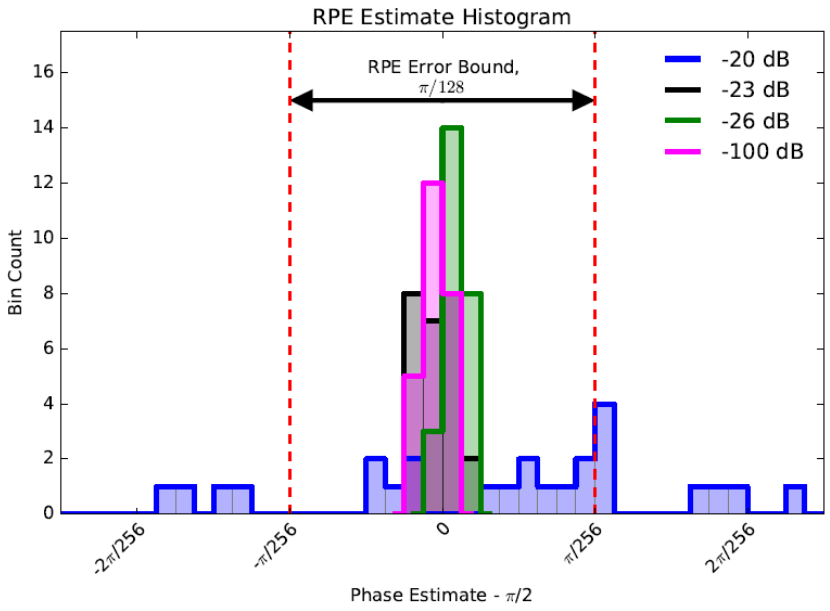
Experiment and simulation with injected frequency detuning error for small algorithm shows great agreement.

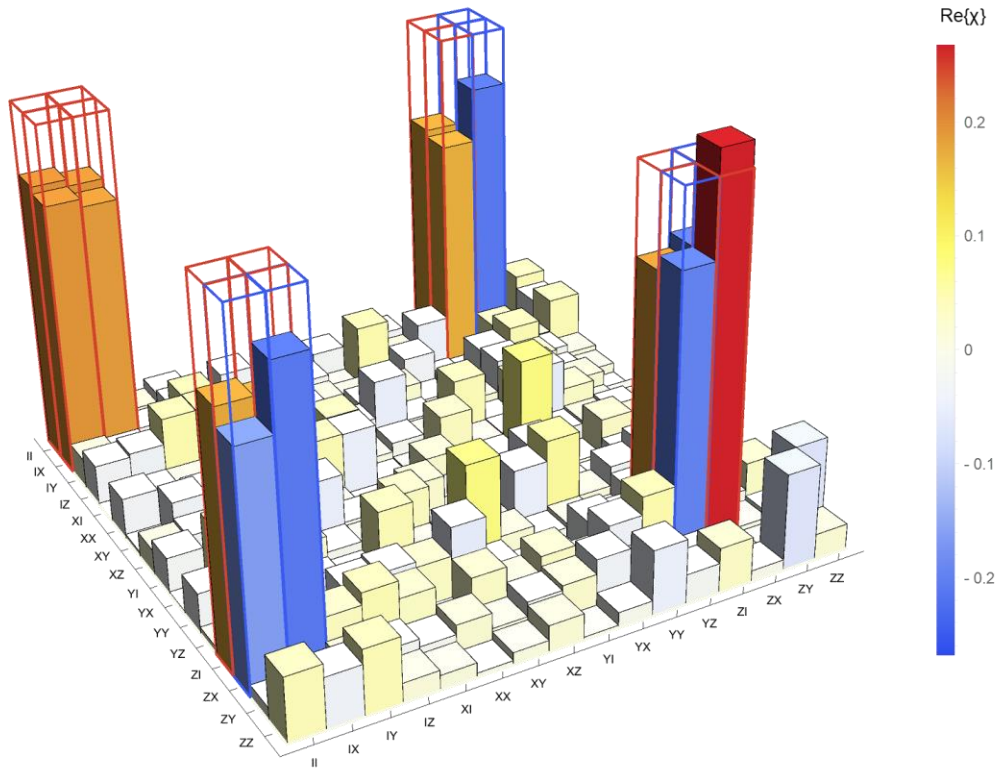
quantum spectroscopy and reconstruction of injected (intentionally introduced) magnetic field noise

Quantum Information: Previous Verification Results

Experiment Verification

Process tomography of CNOT gate

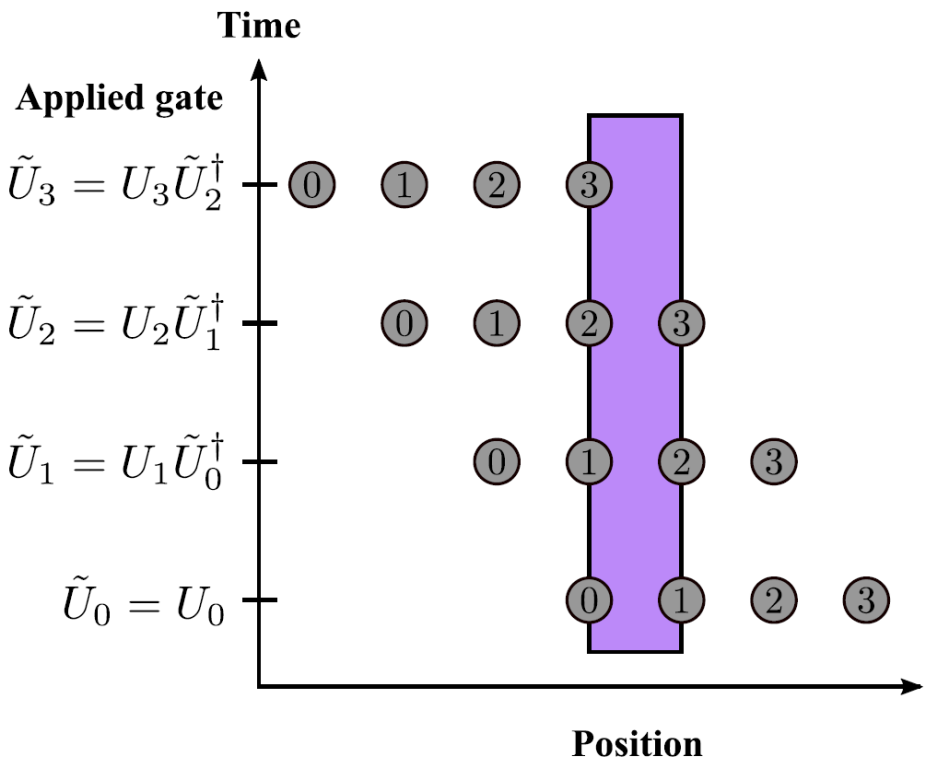




experimental test of Robust Phase Estimation (RPE) (calibration) procedure subject to injected errors

Herold, C. D. *et al.* Universal control of ion qubits in a scalable microfabricated planar trap. *New Journal of Physics* **18**, 023048 (2016).

Quantum Information and Algorithms: Demonstrations



Control & Benchmarking

- Ion chain transport for universal control through pairwise addressing
- Wrote compiler to translate quantum circuits to native operations
- 1Q: > 99%
  2Q: > 96%

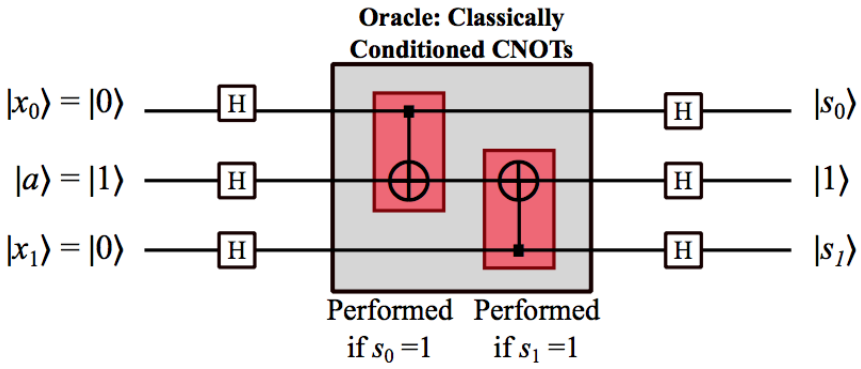
Herold, C. D. *et al.* Universal control of ion qubits in a scalable microfabricated planar trap. *New Journal of Physics* **18**, 023048 (2016).

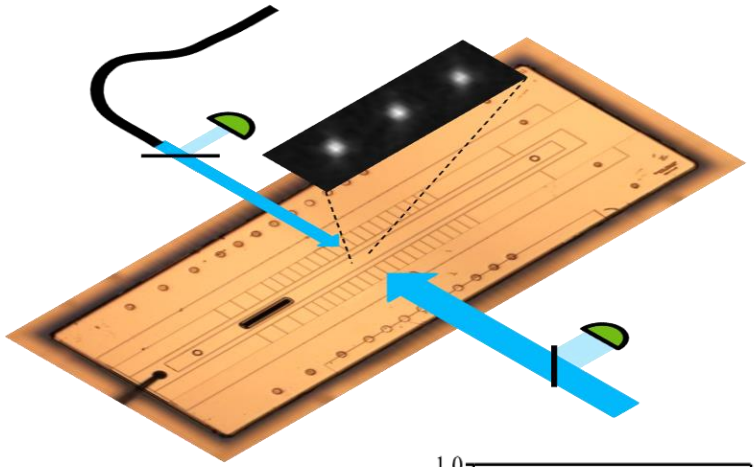
Impact

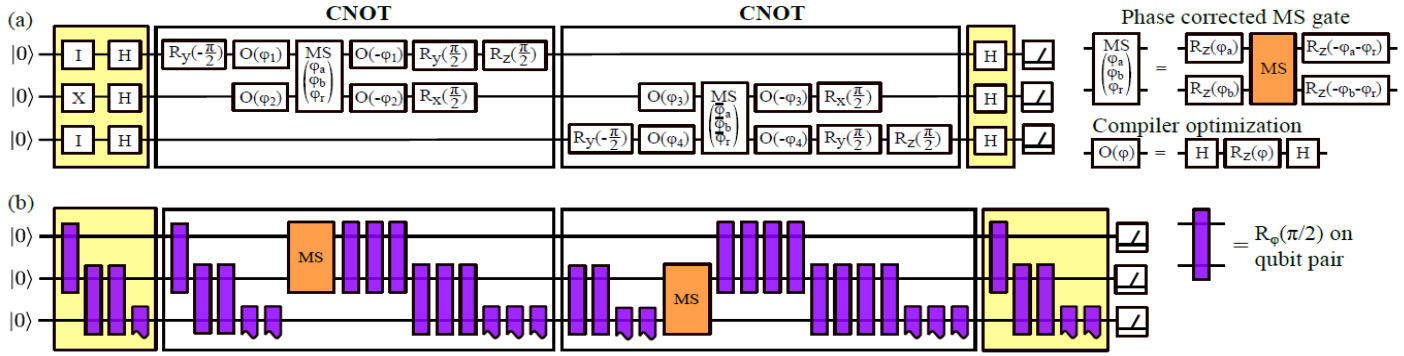
- Showed ion transport in surface-electrode traps compatible with high-fidelity algorithm

Quantum Information and Algorithms: Demonstrations

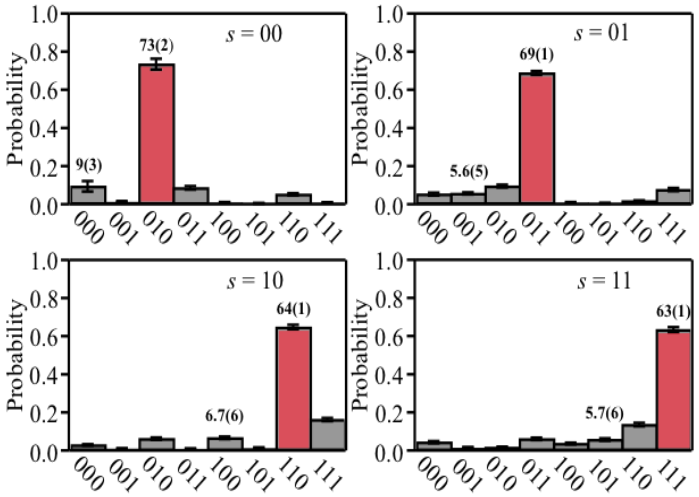
Algorithm: Bernstein-Vazirani (BV)







"Discover hidden bit string with single quantum query"



Fallek, S. *et al.* Transport Implementation of the Bernstein-Vazirani Algorithm with Ion Qubits. *New Journal of Physics* **18**, 083030 (2016).

Impact

- With BV, we obtained 1.10(3) bits of information per query compared to 1 bit classically

QSD Current Research Interest.

Quantum Information Science

- Trap Design and Fabrication
- **Quantum Gates**
- Trap Operation and Hardware
- Simulation and Evaluation

Quantum Sensors

- **Penning Ion Trap Clocks**
- **Atomic Magnetometers**
- Magnetic Anomaly Simulation
- Rydberg Atom Antennas
- Trapped Atom Gyroscopes

Other Research Areas

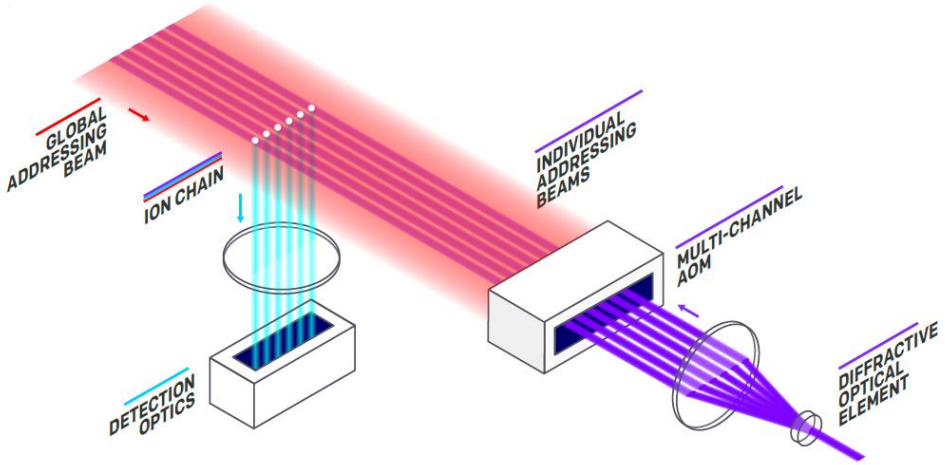
- Quantum Secure Communication (QKD)
- Molecular Data Storage (DNA computing)
- Chip Scale Gas Chromatography/Mass Spectrometry
- Random laser Physical Unclonable Functions

Quantum gates: Ion-trap Potential Modulation as an Optical Phase Control

Objective

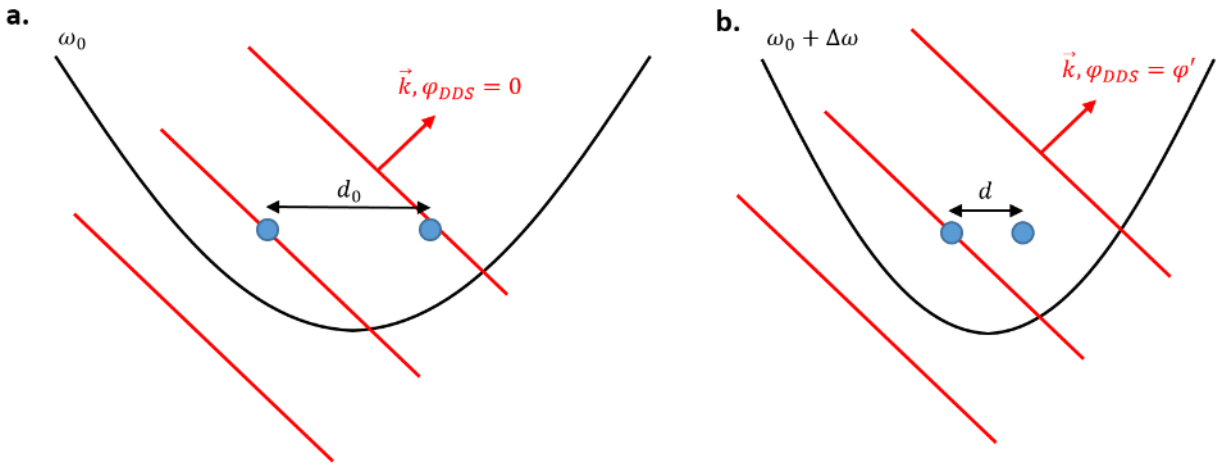
- Individual qubit addressing crucial in quantum systems like quantum process tomography and quantum communications
- Demonstrate ion-selective high fidelity single qubit gates in ~few $^{40}Ca^{+}$
- Eliminates the need for slow split/merge operations and other downsides of spatially dependent Rabi frequency or differential addressing frequency

Beam Addressing of Ions



Wright, K. *et al., Benchmarking an 11 qubit quantum computer*. arXiv:1903.08181[quant-ph]

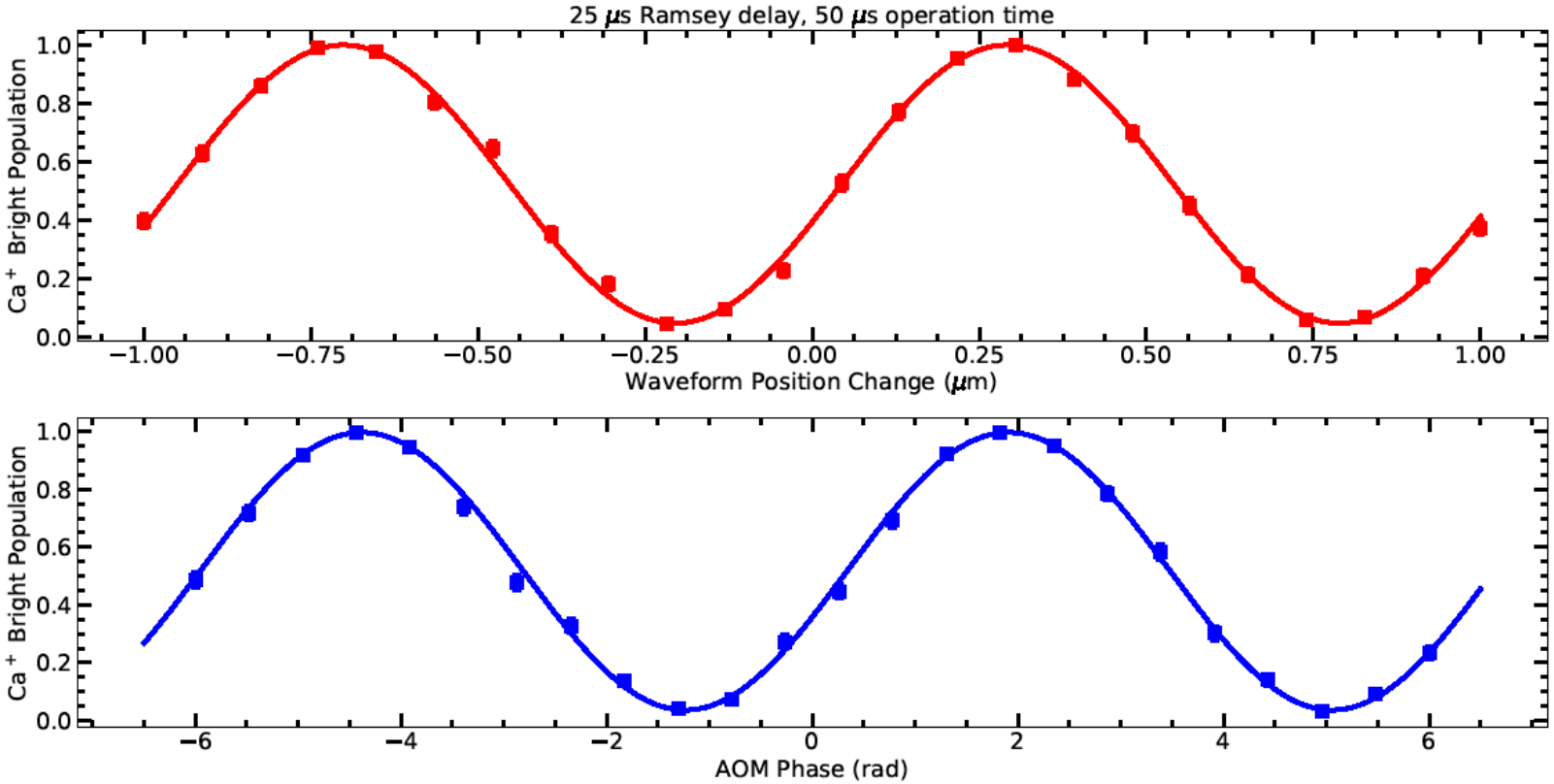
Potential Modulation Addressing of Ions



Individual ion addressing in a global beam using trap potential modulation to impart differential phase shifts between ions

Quantum gates: Ion-trap Potential Modulation as an Optical Phase Control

Single ion shuttling

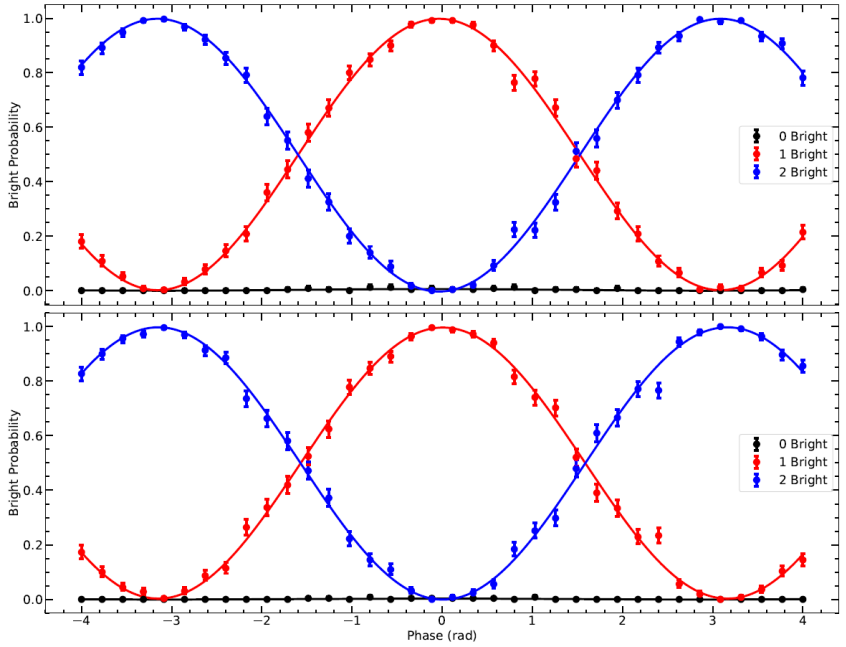


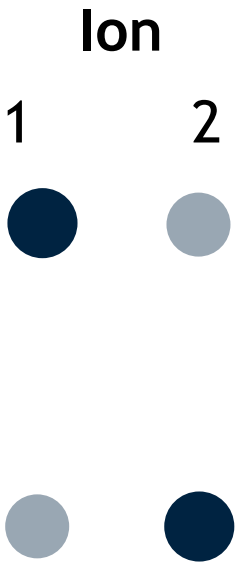
$$\Delta\phi \sim 2\pi\left(\frac{\Delta d}{1\ \mu\mathrm{m}}\right)$$

Quantum gates: Ion-trap Potential Modulation as an Optical Phase Control

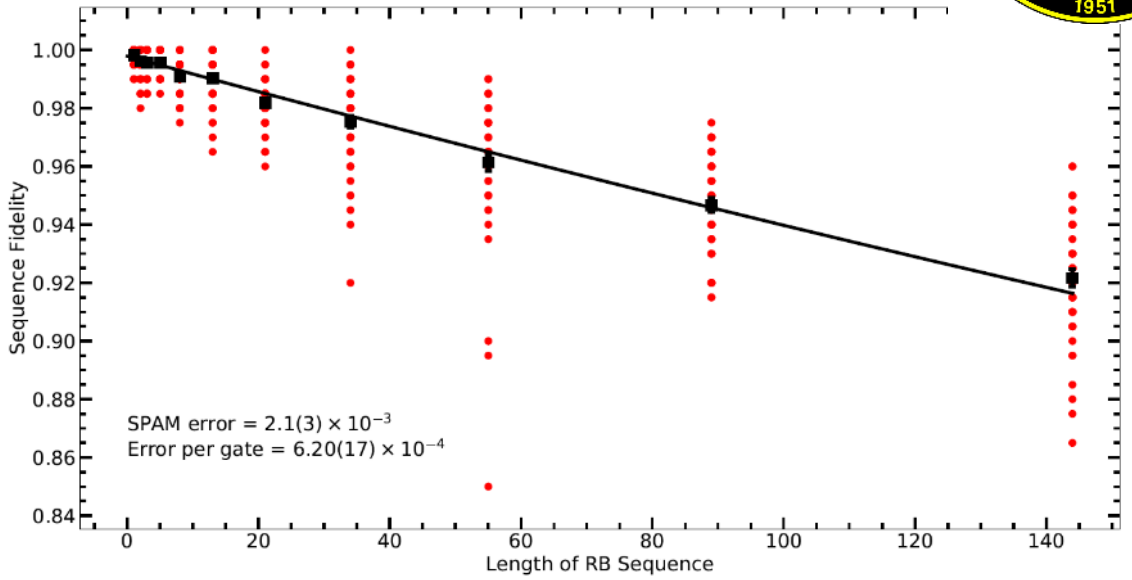
Approach

- Modify trap potential to apply a differential optical phase to ions
- Benefits: high spatial addressability, fast modification of the spatial phase, uses well established control of trap in segmented surface traps, and no global phase for long multi-well chains.





$\epsilon < 10^{-2}$ per gate for each ion

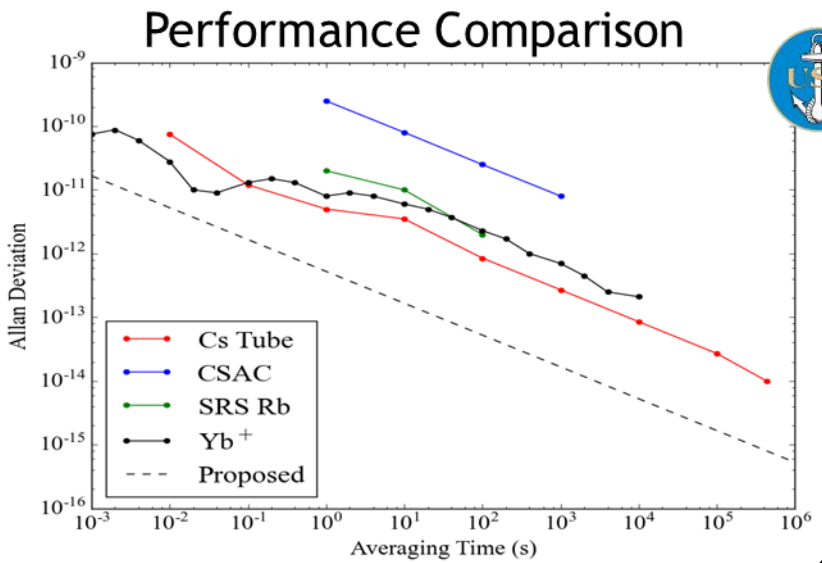


future work

- 1-qubit randomized benchmarking, individually, in the same well
- Quantum process tomography of a 2-qubit Molmer-Sorenson gate
- Implementation of a Toffoli gate and QFT algorithm planned

PERMION: Ion clock

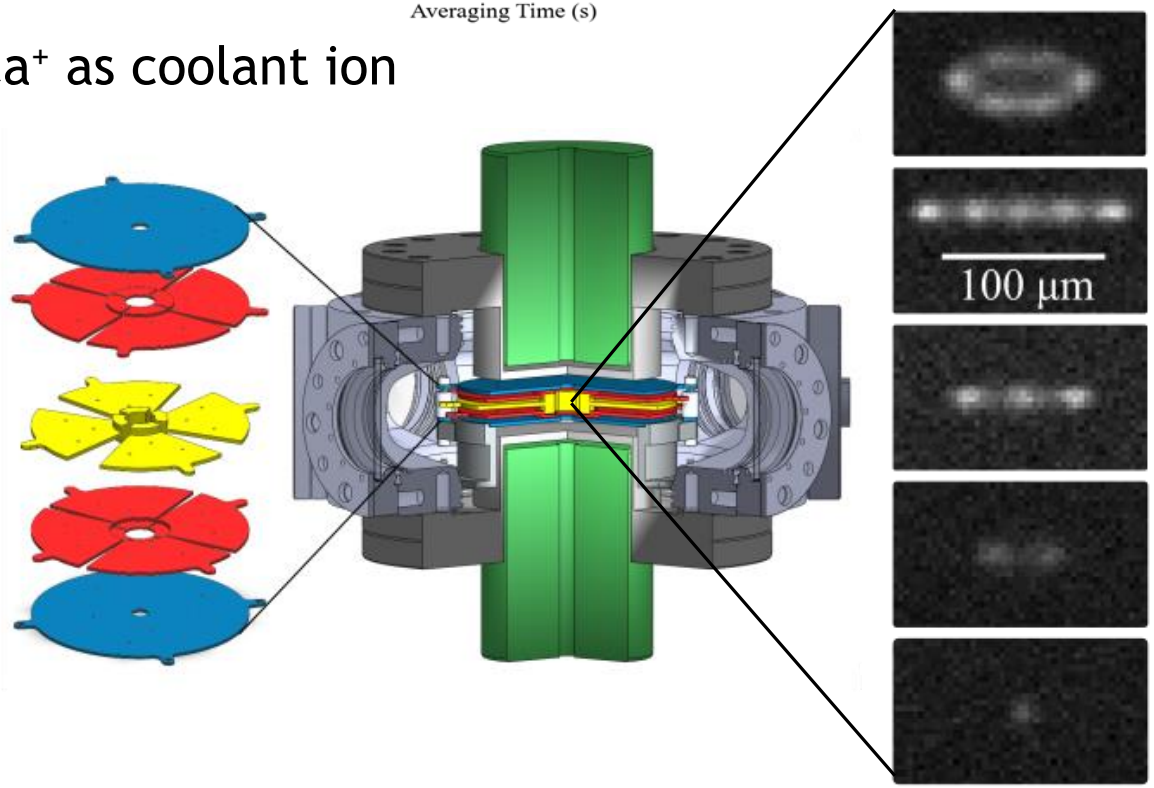
- Goal: Reduce Penning trap clock SWaP



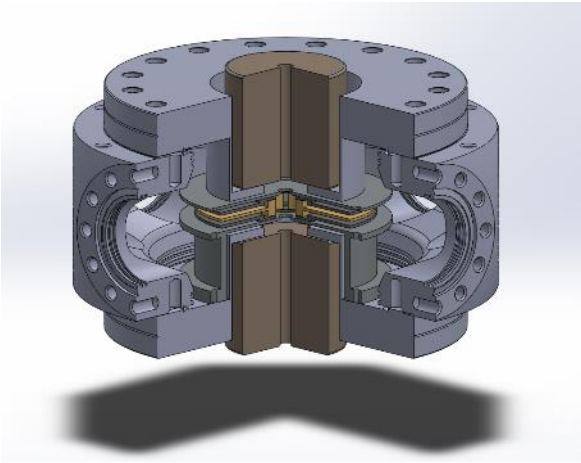
- Demonstrate clock operations with $^{9}Be^{+}$ using $^{40}Ca^{+}$ as coolant ion

  - Low size/weight: NdFeB ring magnets (6500 Gauss at center, 1” magnet spacing)
  - Low power: Passive ion confinement (permanent magnets, static voltages)

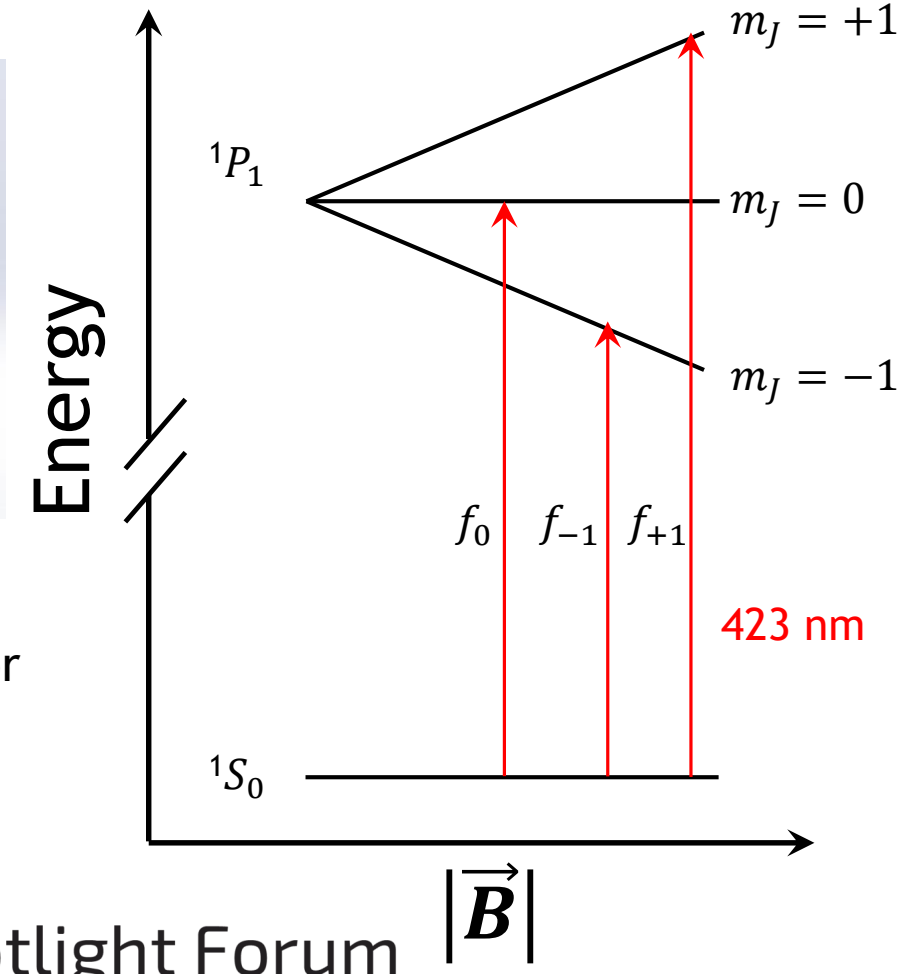
First Doppler laser cooling in a compact Penning trap (~100 mK)

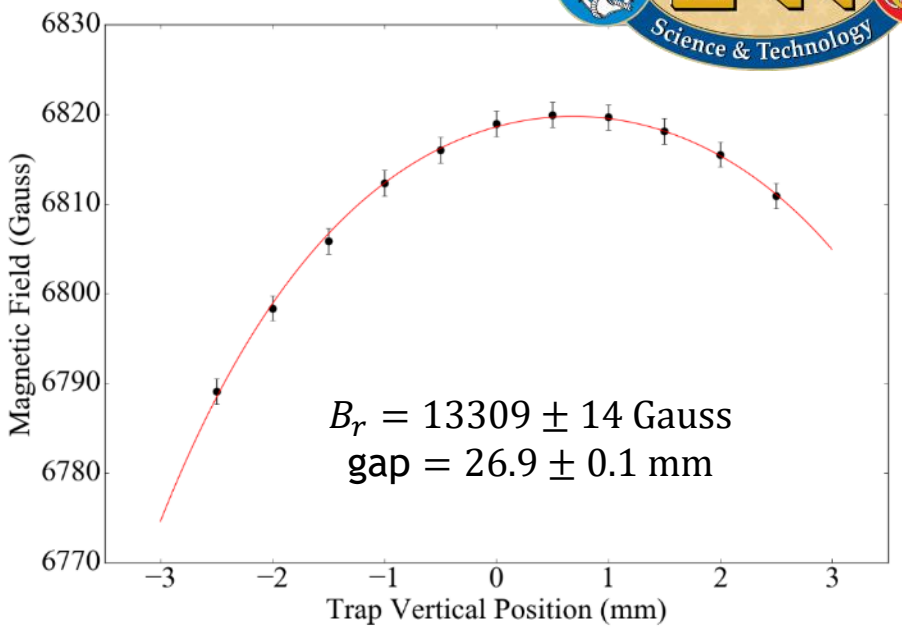


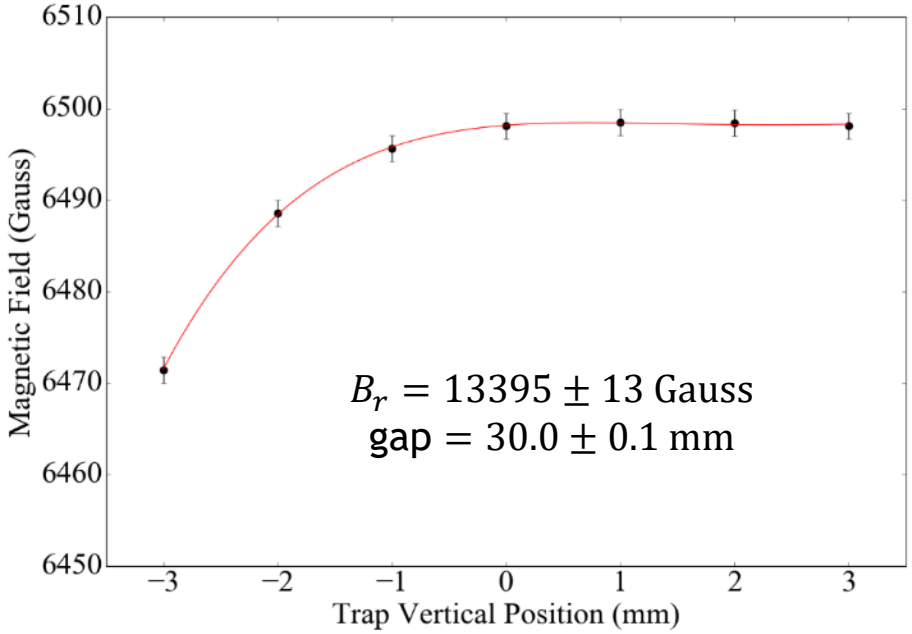
Trap $|\vec{B}|$ Characterization (good magnetometer)



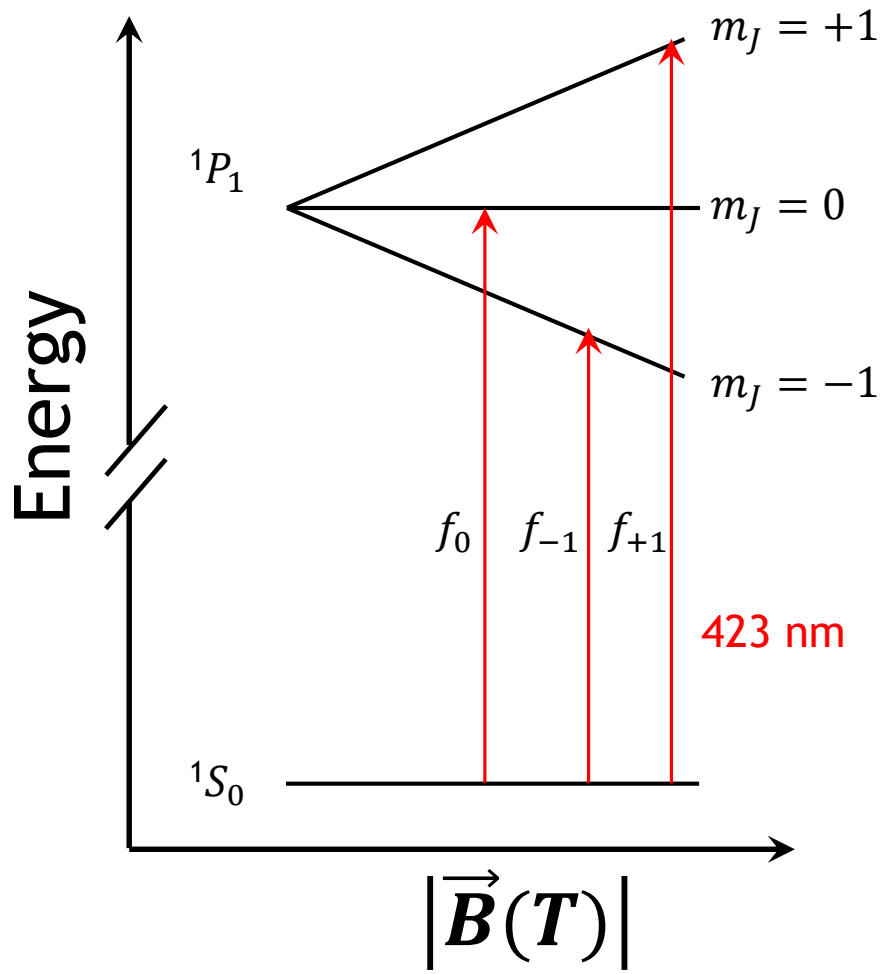
Optimize magnet gap using Ca spectroscopy as magnetic field sensor

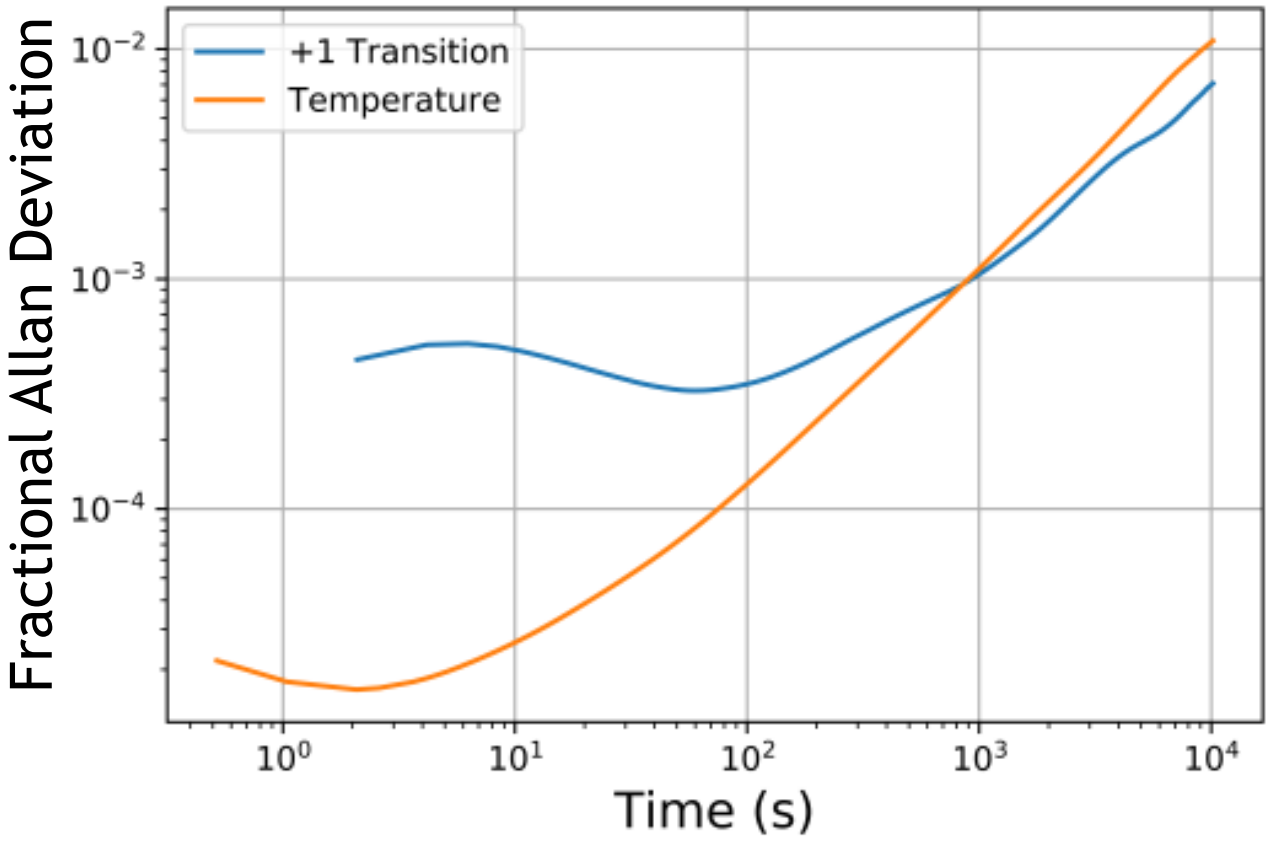






Trap $|\vec{B}(T)|$ Characterization: Good Thermometer?





* Drift of Ca transition frequency correlates with magnet temperature shift at long times (> 20 min). Magnets were slowly heating due to continuous Ca oven operation.

Atomic Magnetometers/Gradiometer (Northrop Grumman, U-Wisc, Freedom Photonics)

Goal: Develop fieldable, combined magnetometer and gradiometer, **with high sensitivity in ambient conditions**, useful for better brain imaging

- Vapor cell (Rb vapor, N2 buffer gas, no UHV)
- Lasers (780 nm and 795 nm, "easy"), unique optical setup and pulsed beams
- Magnetometer at zone 1 ($|B_1|$)
- Gradiometer ($\Delta B_{21} = |B_2| - |B_1|$) suppresses common-mode noise

rubidium
37
Rb
85.468

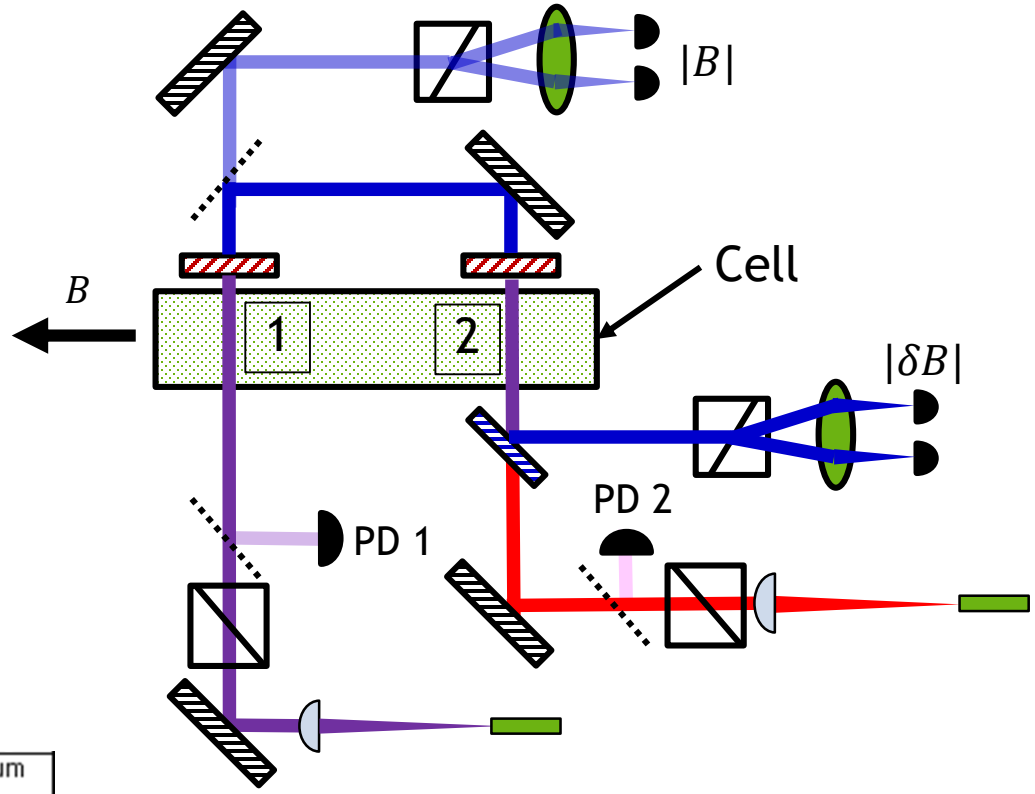
MEG image: E. Boto et al., Nature, vol. 555, no. 7698, pp. 657–661, Mar. 2018.

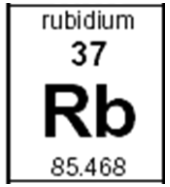
Thermal insulation

Atomic Magnetometers/Gradiometer (Northrop Grumman, U-Wisc, Freedom Photonics)

Goal: Develop fieldable, combined magnetometer and gradiometer, **with high sensitivity in ambient conditions**, useful for better brain imaging

- Vapor cell (Rb vapor, N2 buffer gas, no UHV)
- Lasers (780 nm and 795 nm, "easy"), unique optical setup and pulsed beams
- Magnetometer at zone 1 ($|B_1|$) $\boxed{<1\ \mathrm{pT}/\sqrt{\mathrm{Hz}}}$
- Gradiometer ($\Delta B_{21} = |B_2| - |B_1|$) suppresses common-mode noise $\boxed{<50\ \mathrm{fT}/\mathrm{cm}/\sqrt{\mathrm{Hz}}}$
- fundamental limits (~1 fT/cm/Hz$^{1/2}$ gradient sensitivity)





QSD Current Research Interest.

Quantum Information Science

- Trap Design and Fabrication
- Quantum Gates
- Trap Operation and Hardware
- Simulation and Evaluation

Quantum Sensors

- Penning Ion Trap Clocks
- Atomic Magnetometers
- Magnetic Anomaly Simulation
- Rydberg Atom Antennas
- Trapped Atom Gyroscopes

Questions?

Other Research Areas

- Quantum Secure Communication (QKD)
- Molecular Data Storage (DNA computing)
- Chip Scale Gas Chromatography/Mass Spectrometry
- Random laser Physical Unclonable Functions

Moinuddin Qureshi