Trapped Ion Quantum Computing at GTRI

Jan. 31, 2020

Dr. Craig R. Clark

Quantum Systems Division
CIPHER LAB

About GTRI

Georgia Institute of Technology

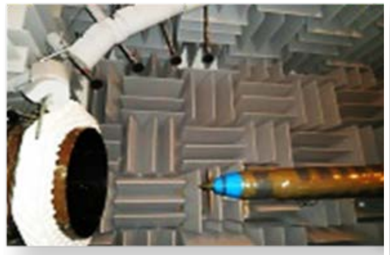
- Education
- Basic & Applied Research
- Open Environment
  - Unclassified
  - International
- Entrepreneurship & Start-ups

Georgia Tech Research Institute

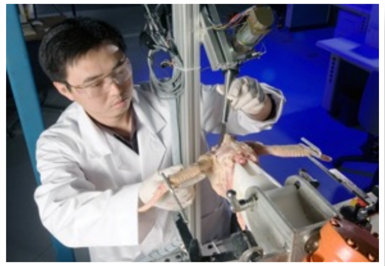
- Applied Research & Development
- Technology & Systems Prototyping
- Research Space: > 1 million ft^2
  - Field Sites: 18
  - Laboratories: 8
- Department of Defense University Affiliated Research Center (UARC)

GTRI Major Research Areas

QSD



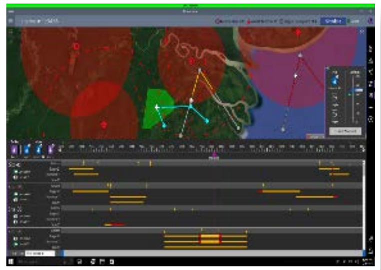
Aeronautical Systems & Avionics



Agricultural & Food Technology

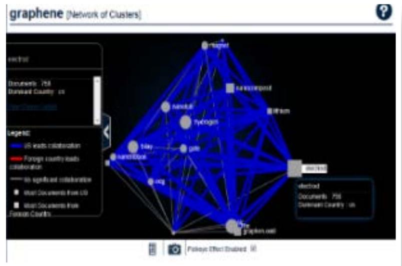
Air & Missile Defense Systems

Autonomous Systems & Robotics



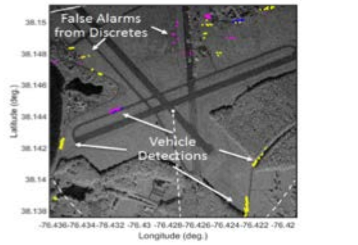
C4 & Decision Support Systems

Cyber Security

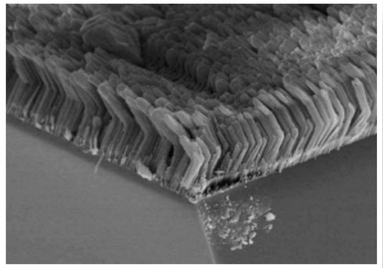


Data and Information Sciences & Systems

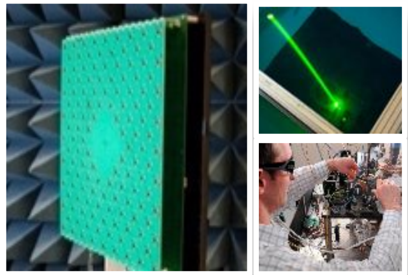
Electronic Warfare



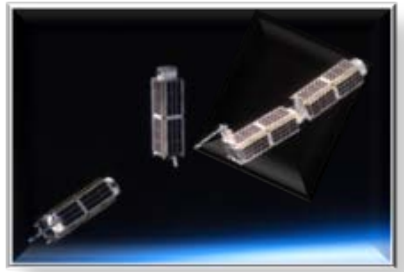
ISR Systems



Materials & Micro-Devices



Sensor Systems



Space Systems

Systems Engineering Research & Applications

Test and Evaluation Systems & Technologies

Threat Systems

Undersea Systems

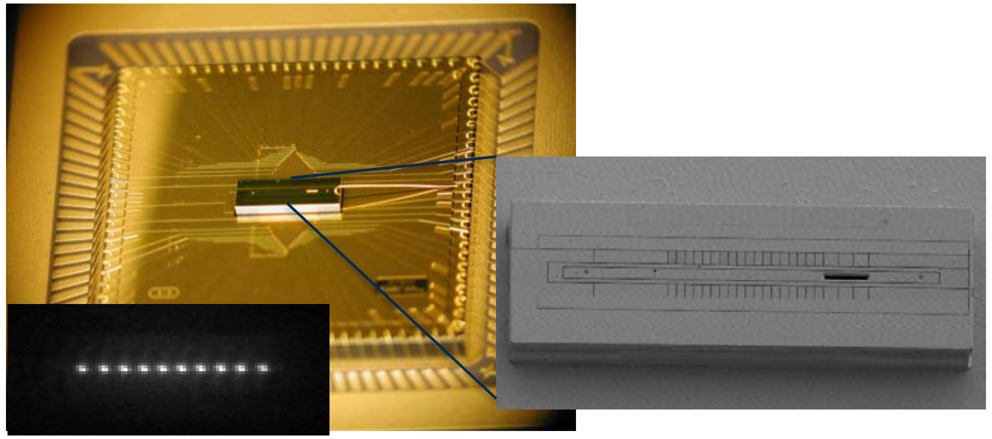
QSD-25 Research Scientists

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

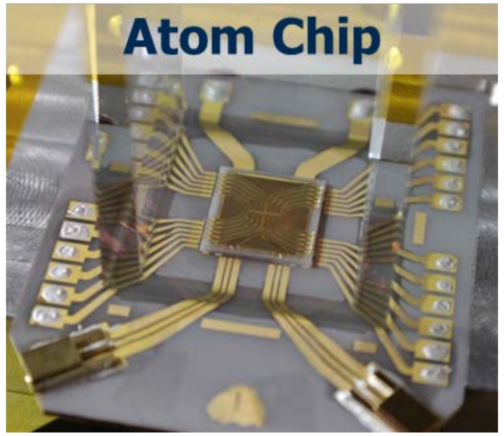
6 other advanced degree (Mechanical Engineering, Electrical Engineering, Mathematics, other physics)

QSD Research Areas

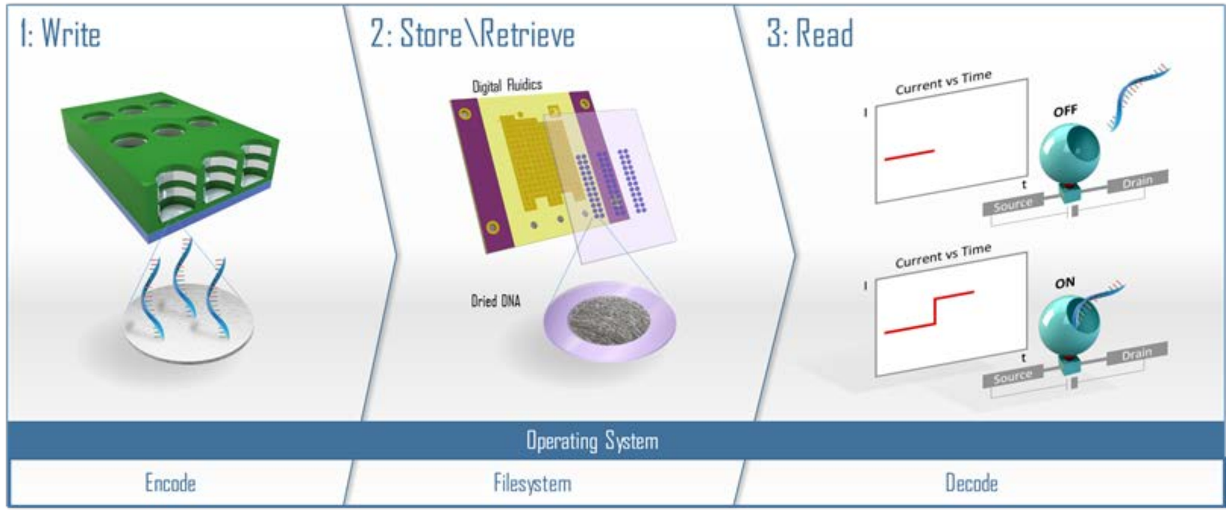
Ion Trap Quantum Information



Neutral Atom Chips

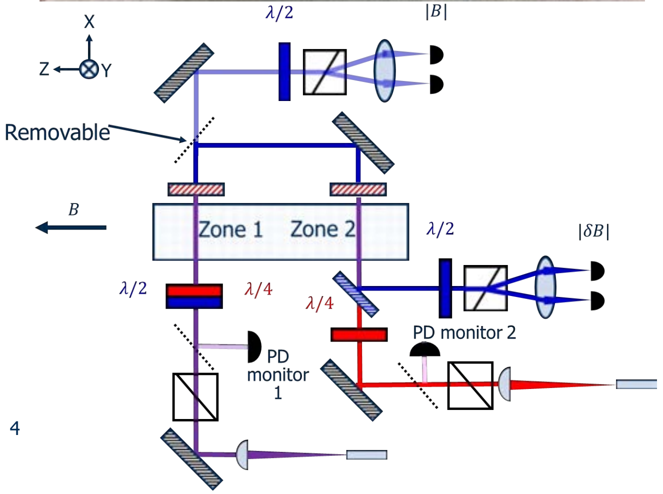


Molecular DNA Data Storage



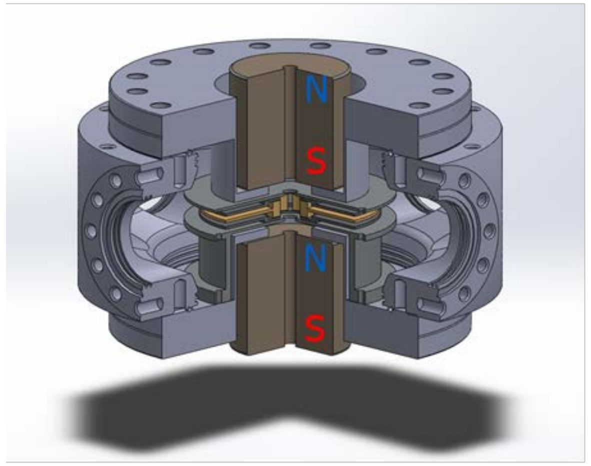
Atomic Magnetometers

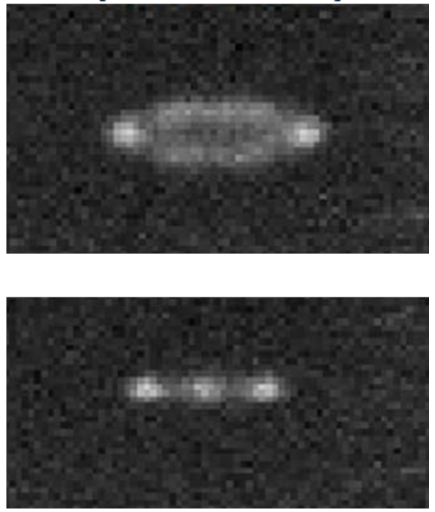
4 cm



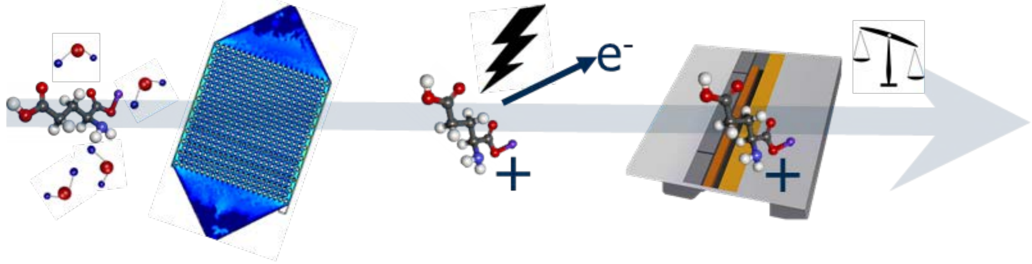
Permanent Magnet Penning Trap Atomic Clocks

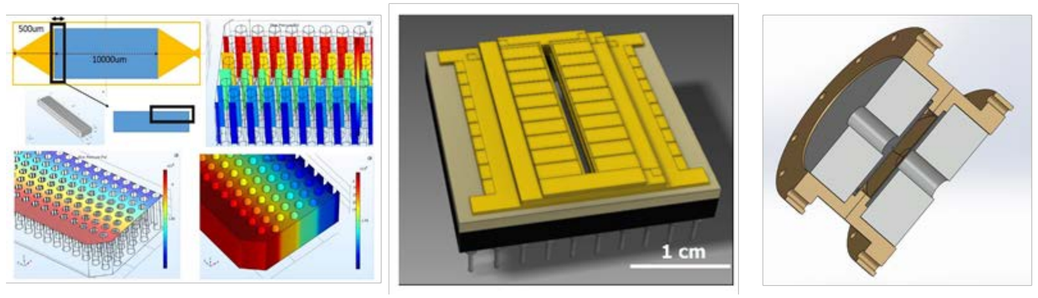
(10-20 ions)





Chip-Scale Gas Chromatograph Mass Spectrometer





Ion Qubits at GTRI

1 H																	2 He
3 Li	**4 Be**											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	**20 Ca**	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	**38 Sr**	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
		*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	**70 Yb**	71 Lu
		**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

$\boxed{\text{Ions at GTRI}}$

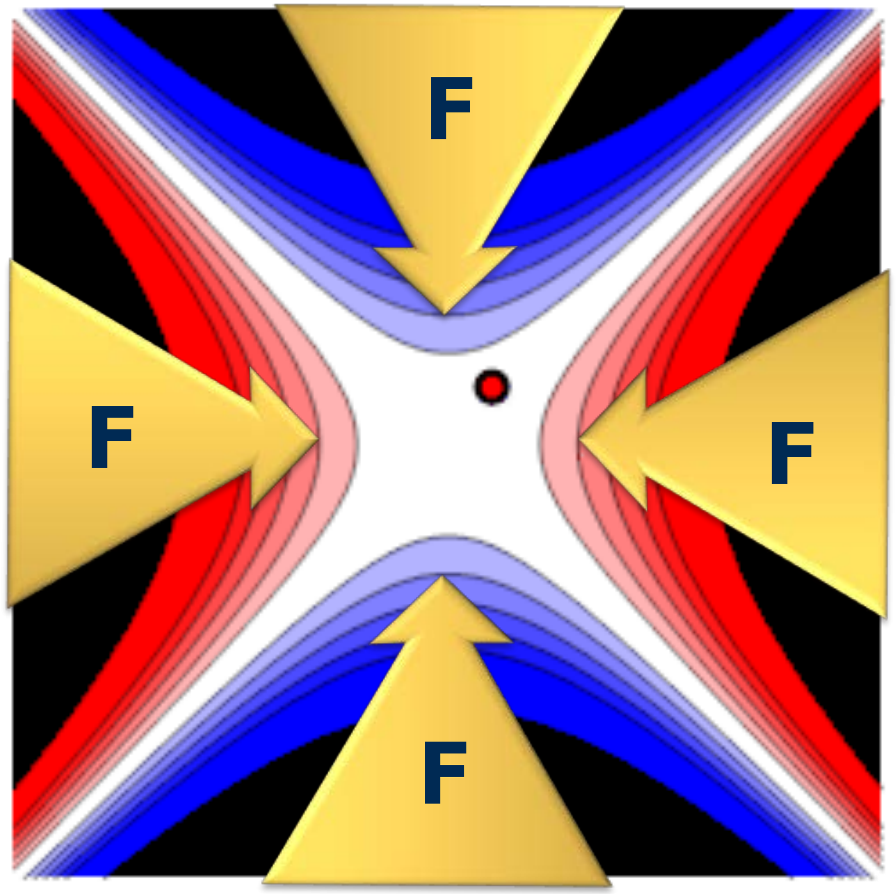
Ion = remove an electron from the neutral atom

What It Takes to Work with Ion Qubits

Lasers

- Photo-ionization
- Cooling
- Repump
- Quantum Gates

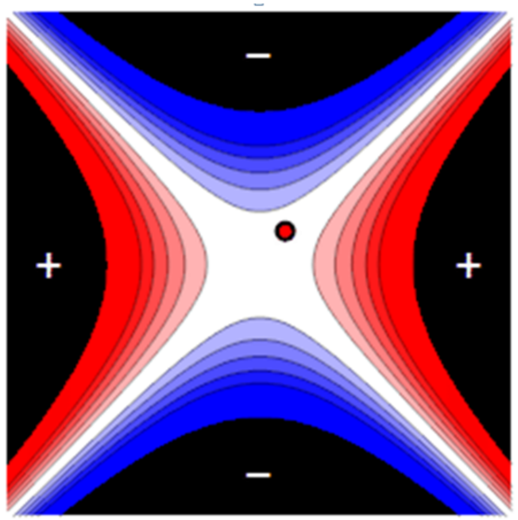
Ion traps

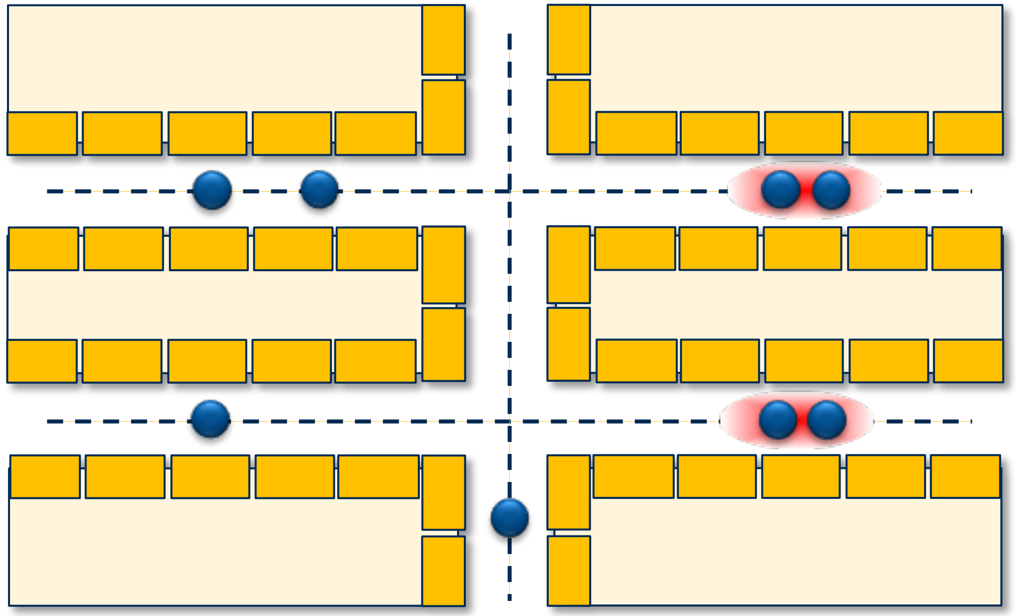


Imaging/detection

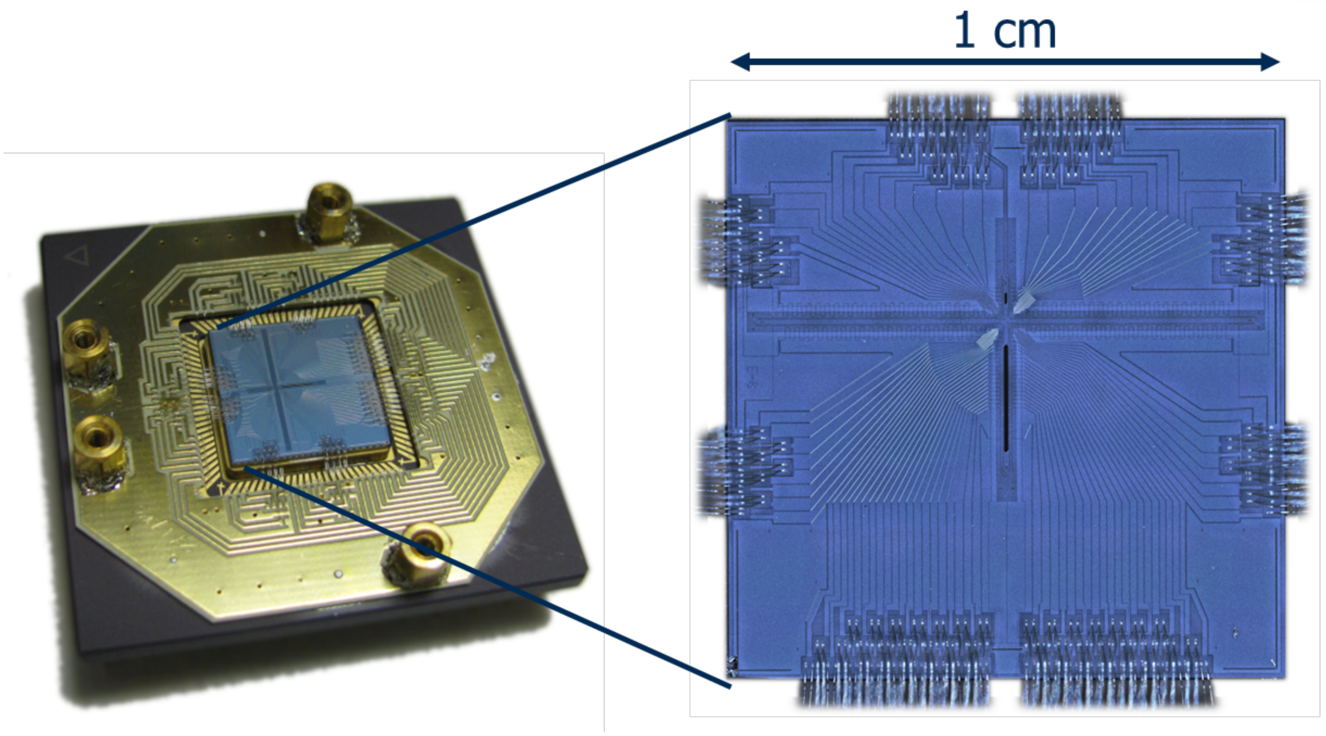
Electronics

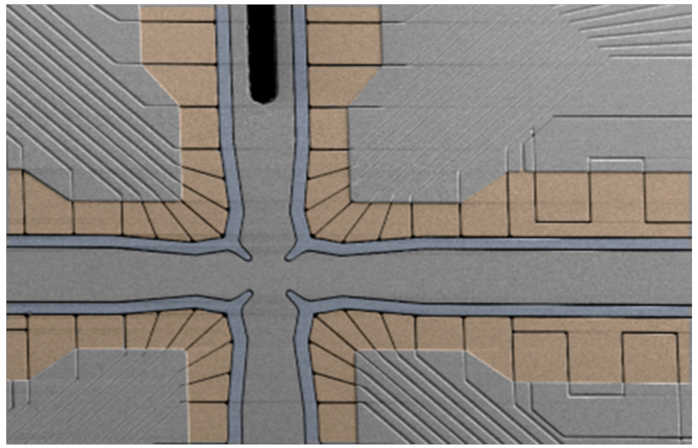
Architecture approach for Ion Trap Quantum Computing at GTRI



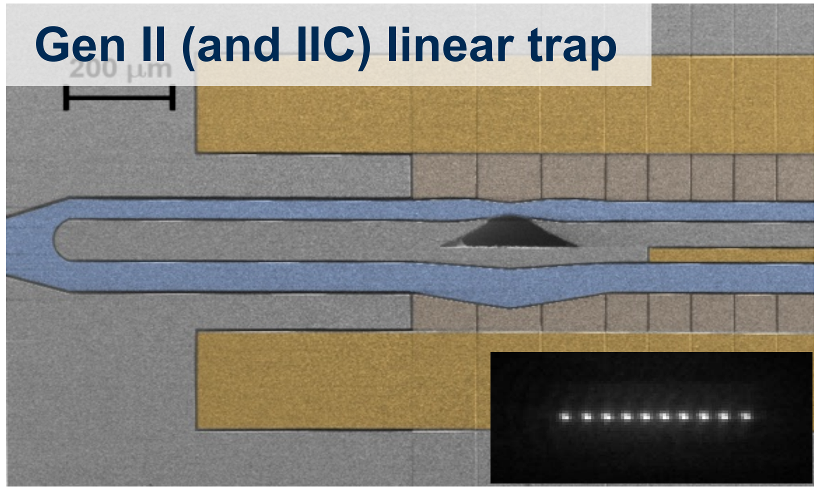


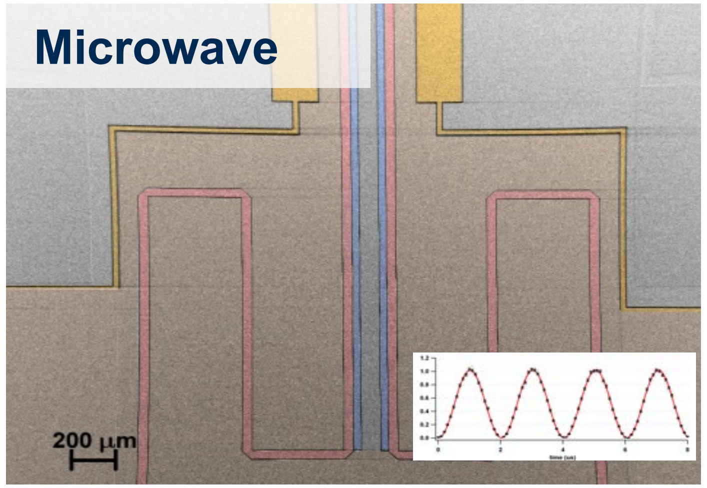
2D Transport Architecture

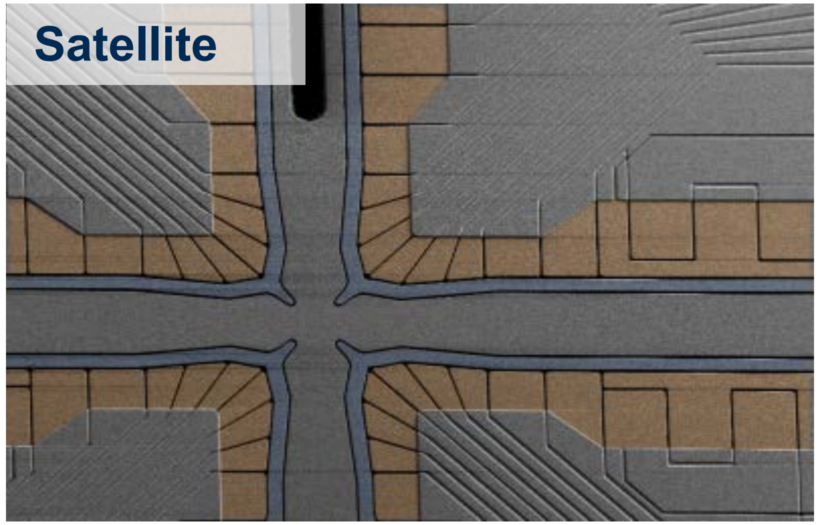


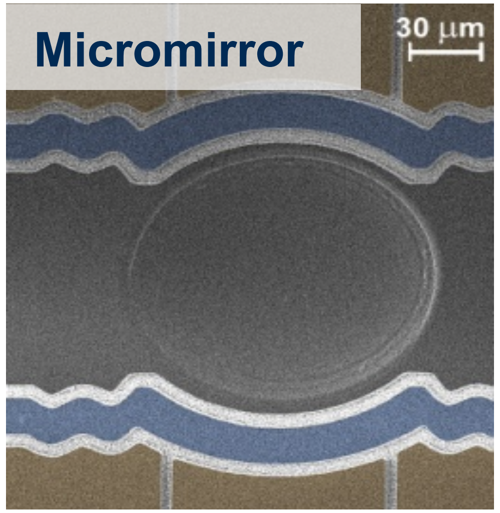


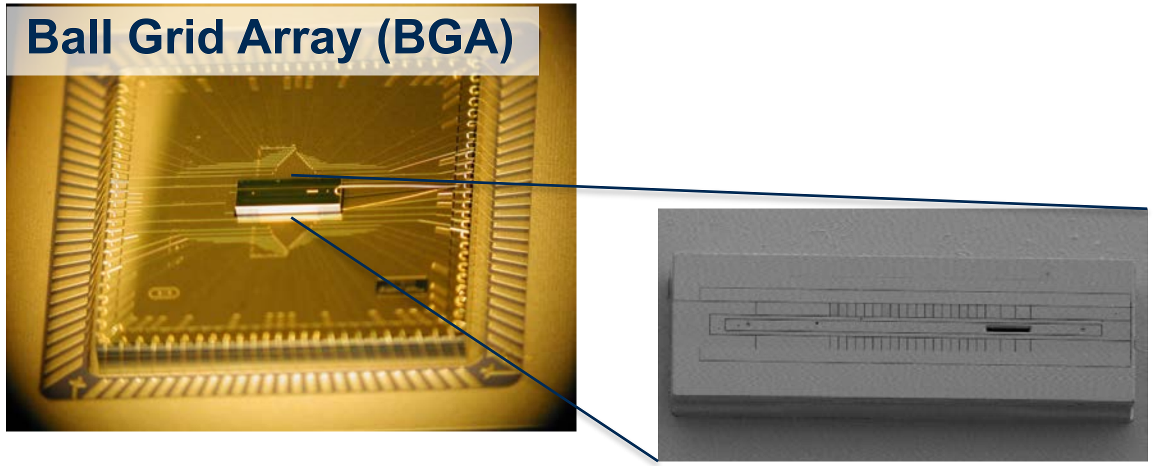
Trap Examples



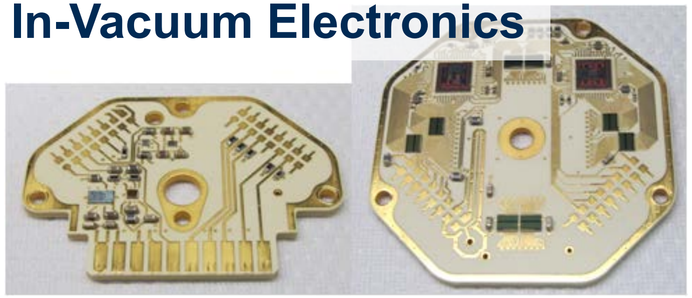


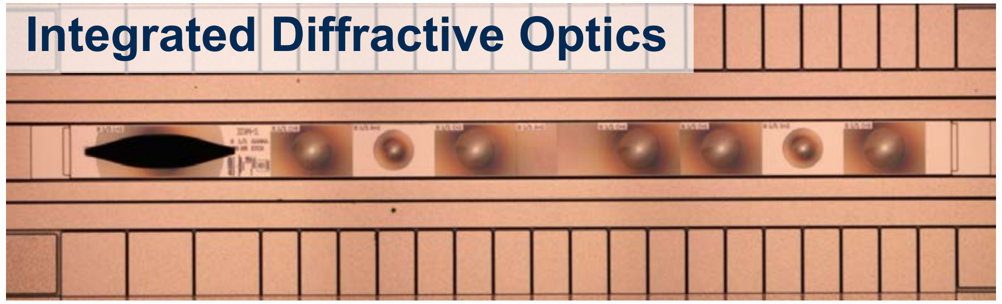






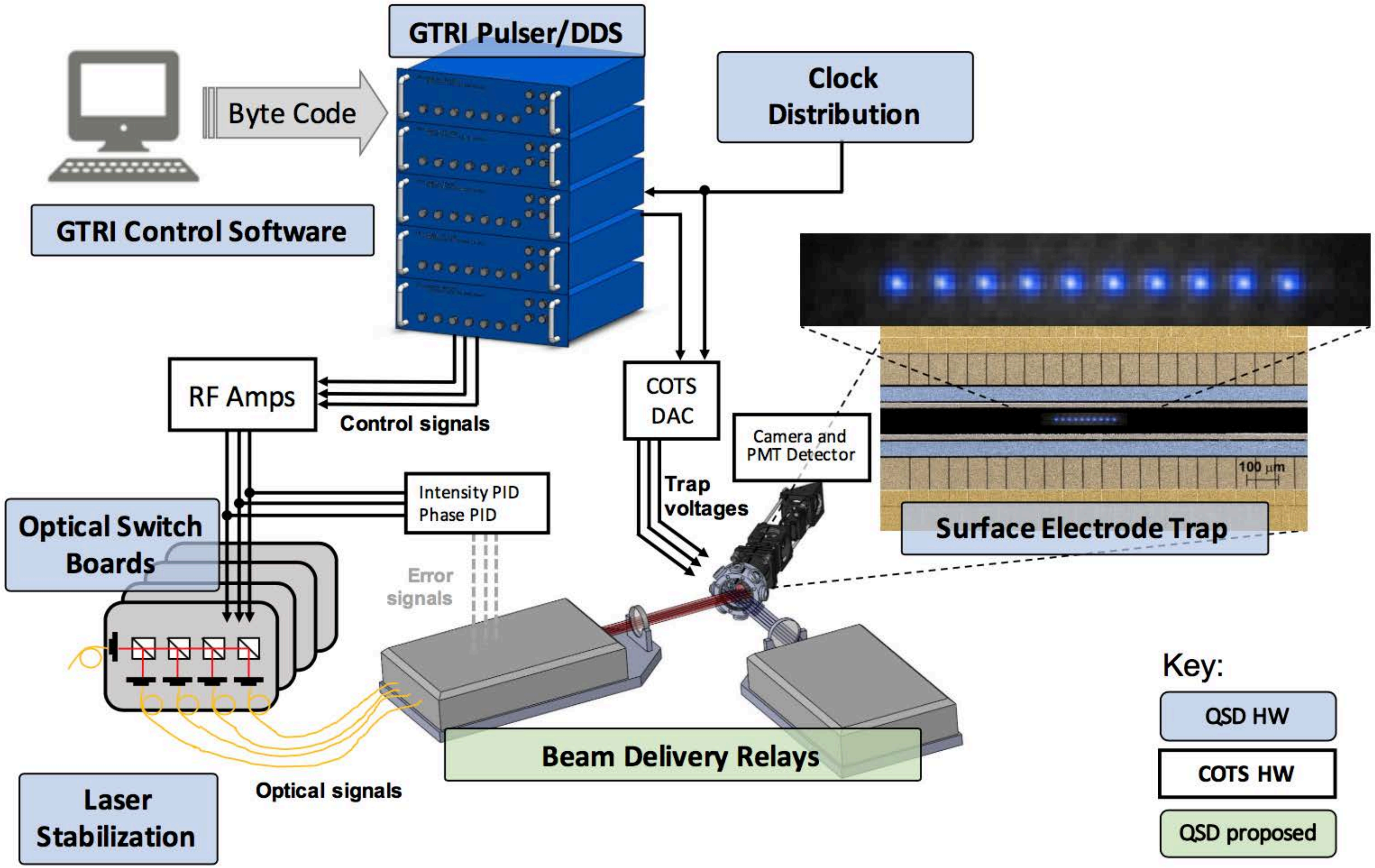
In-Vacuum Electronics



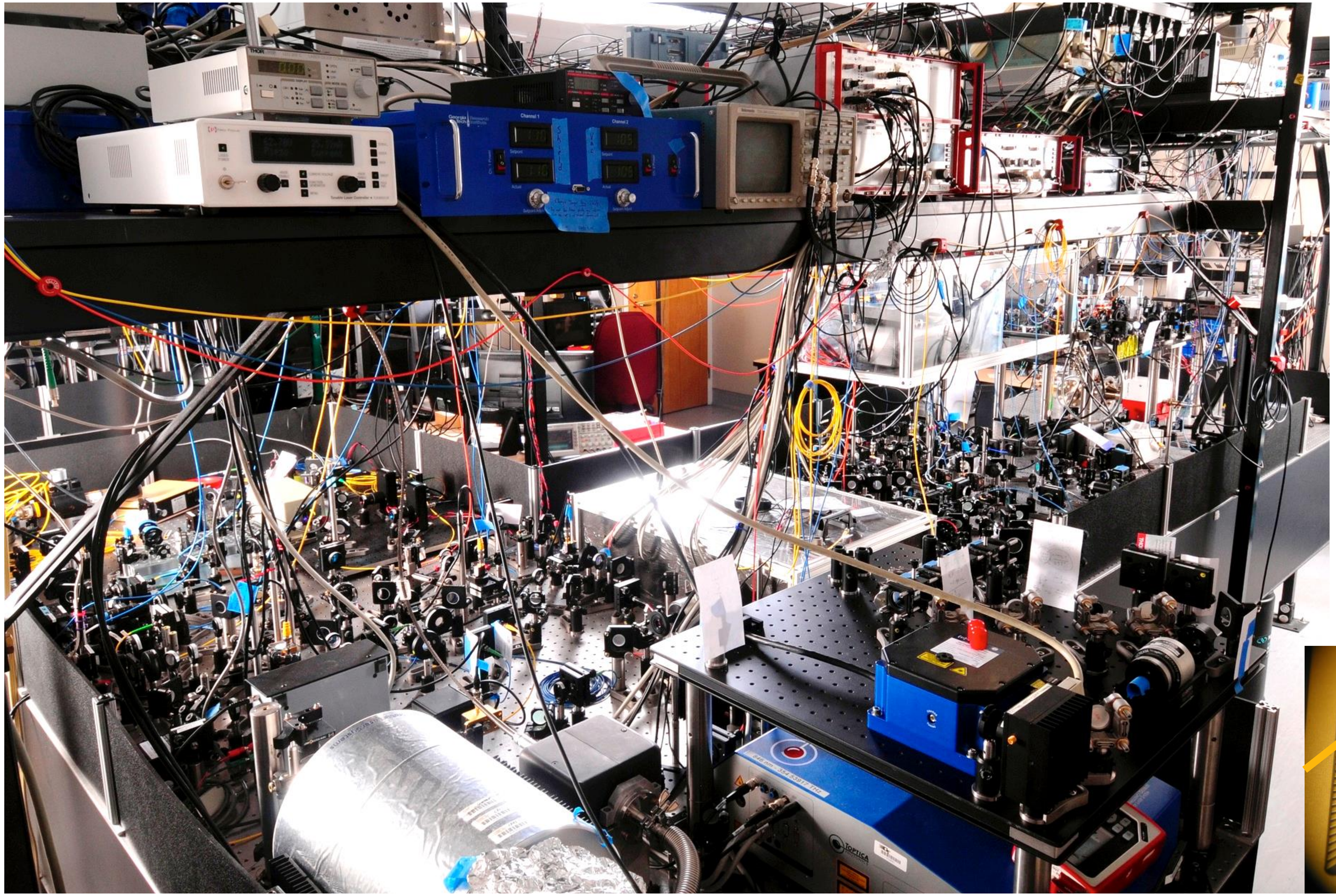


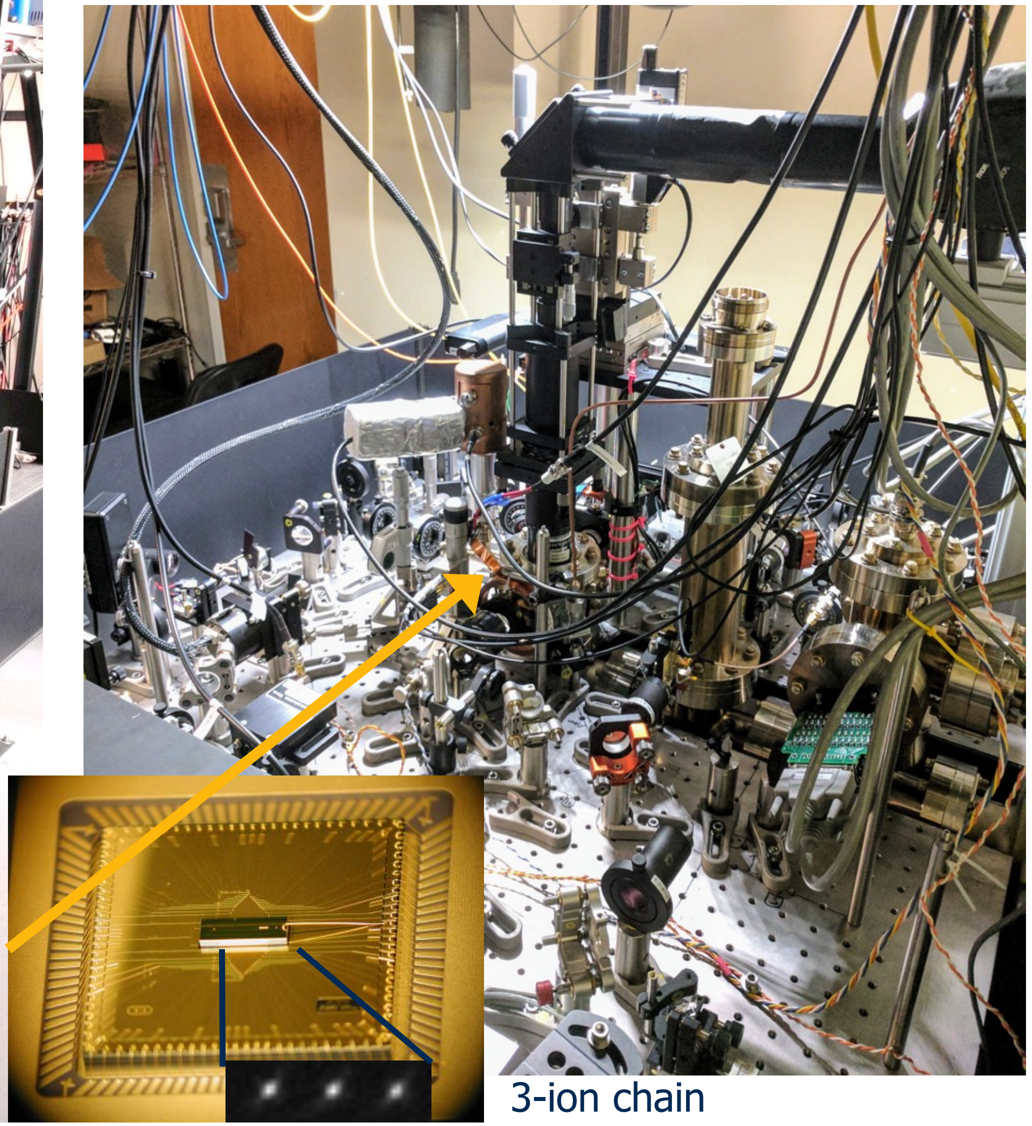
IARPA = Intelligence Advanced Research Projects Activity

QSD Quantum Information Efforts



Quantum System Division Laboratory Space (CRB)





3-ion chain

5 µm

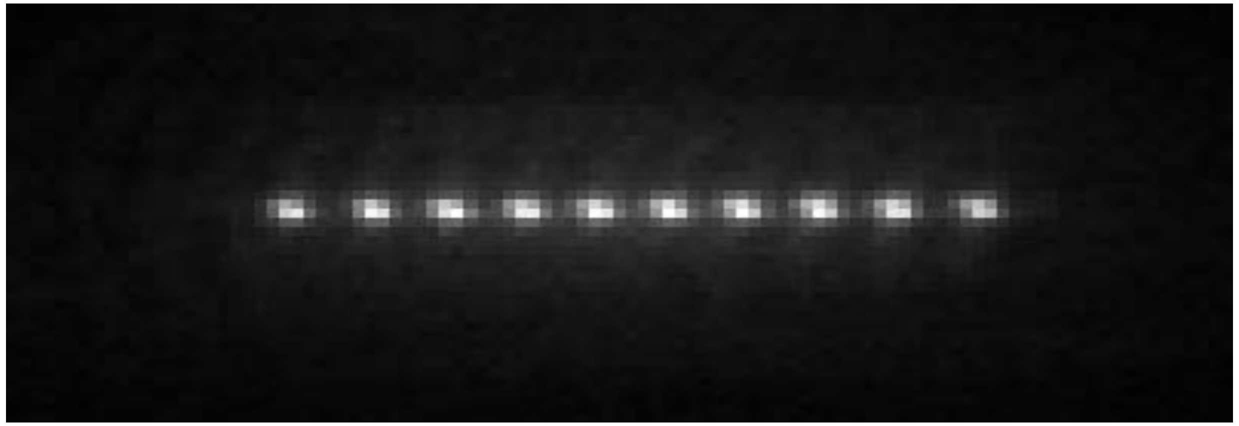
Ion Control Building blocks

- Moving an ion = moving information
- Precise position control of the ions
- Unparalleled in-house EM modeling capabilities
- Microfabricated traps have evolved from experimental devices to tools for quantum computing

Simple String of Ion Architecture

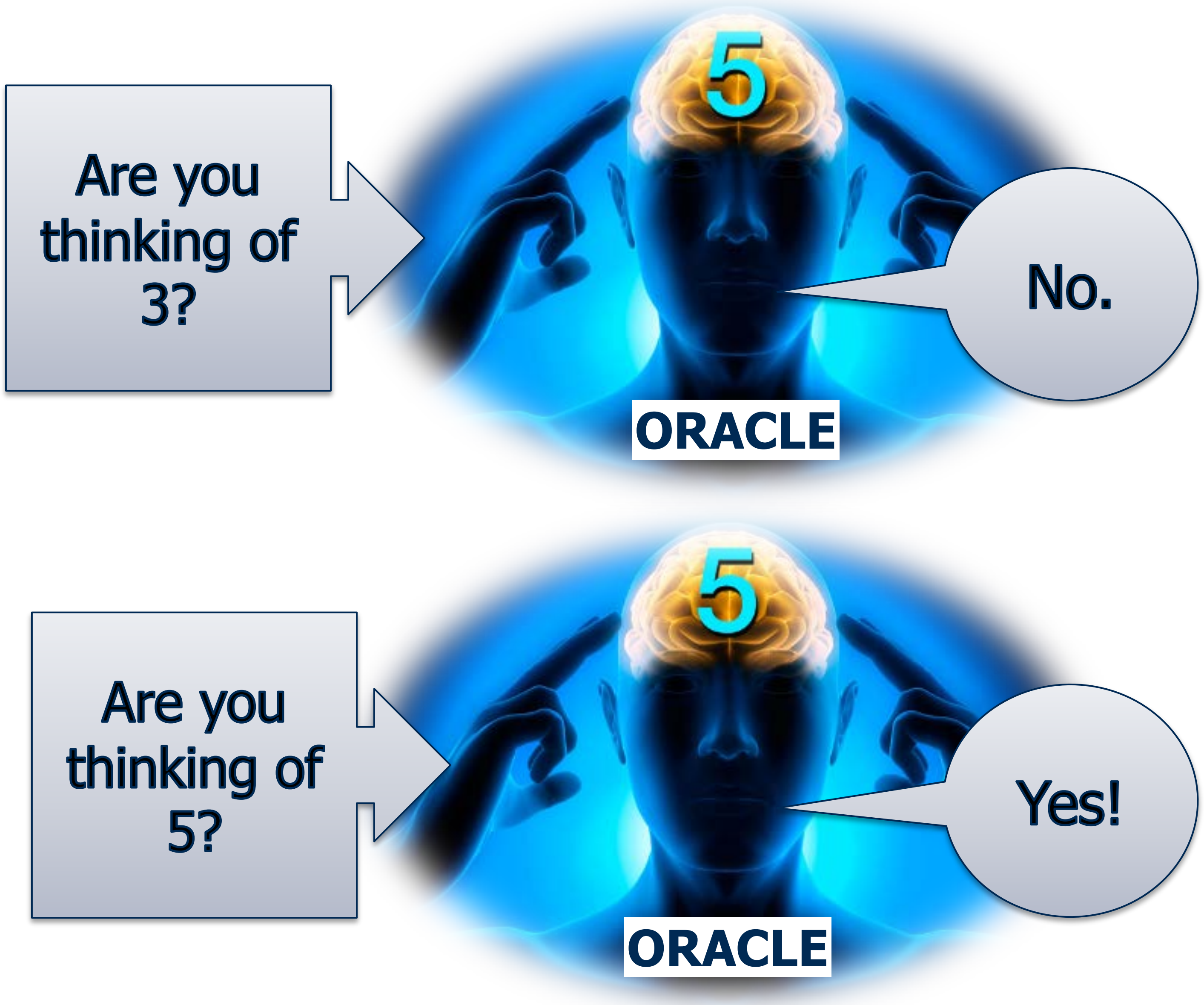
Splitting and merging of four Ca^+ ions

Loading and merging of Ca^+ ions


Long chains of Ca^+ ions

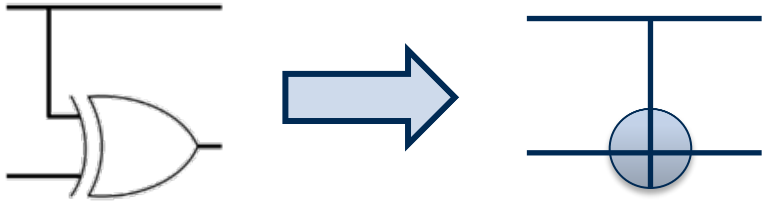
Bernstein-Vazirani: "Guess what number I am thinking of"

- In the classic guessing game, we guess a number and get the response
  - "No, guess again," or
  - "Yes, that is the right number"
- Bernstein-Vazirani algorithm provides a solution to a variant of this game
- A black box, the "ORACLE", returns more information about how "close" our guess is
- This algorithm scales smoothly from two qubits on up

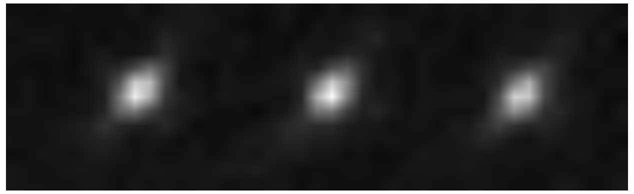


Bernstein-Vazirani Algorithm

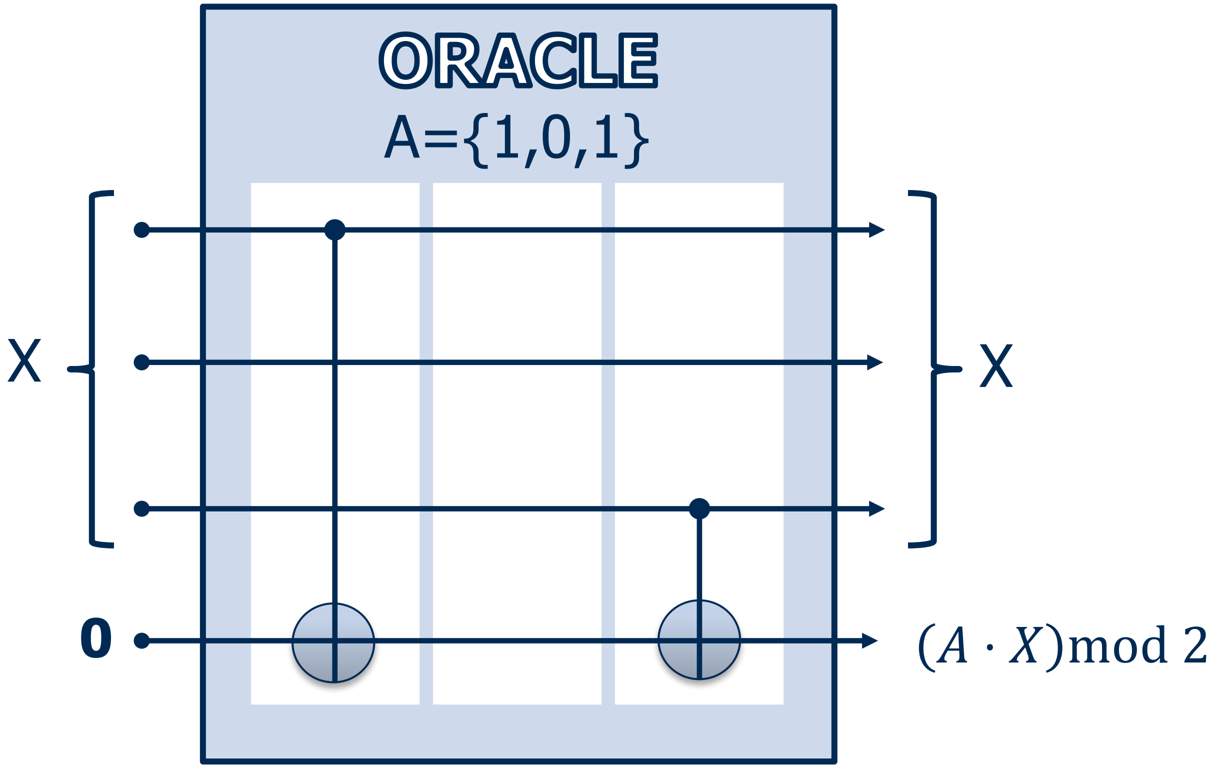
- Quantum version of the XOR is the CNOT



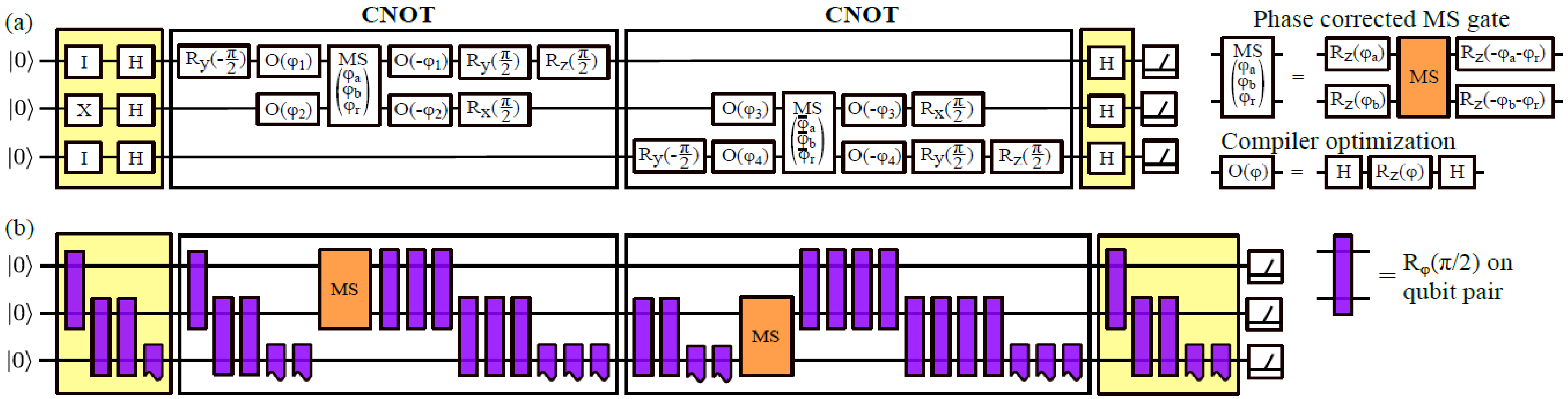
- Acts like classical circuit for single inputs
- Classical version requires one query for each bit in the number
- Quantum version requires one, and only one, query for all the bits



Quantum BV ORACLE



Quantum Information and Algorithms: Bernstein-Vazirani Algorithm



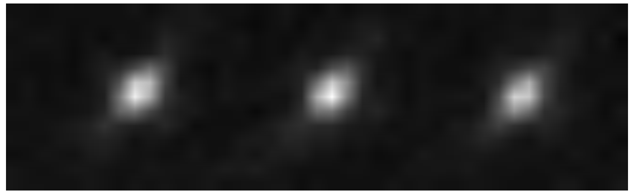
"Discover hidden bit string with single quantum query"

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

Algorithm Architecture

- Algorithm takes ~10 ms
  - 12 passes
  - 400 gate-laser pulses

- At the end, ions glow, or don't glow, indicating 1 and 0

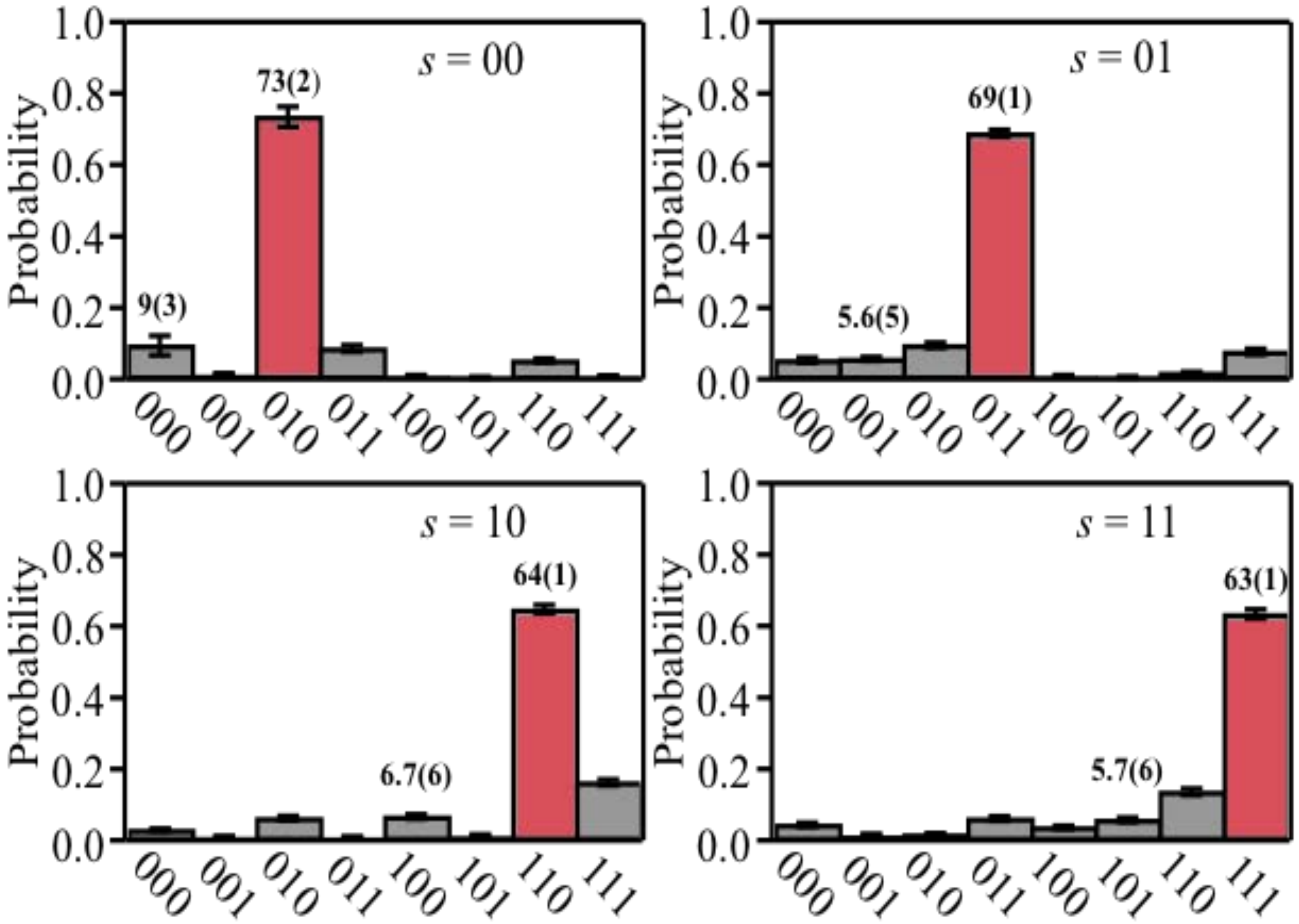


- Ideally, the middle ion will be 1. Control errors and noise will cause other results

Ideal Measurement Result

ORACLE	X	1	Y
A={0,0}	0	1	0
A={1,0}	1	1	0
A={0,1}	0	1	1
A={1,1}	1	1	1

Bernstein-Vazirani Algorithm Results

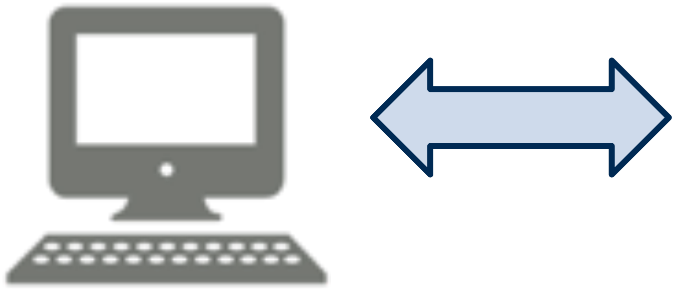


With Bernstein-Vazirani algorithm, we obtained 1.10(3) bits of information per query compared to 1 bit classically

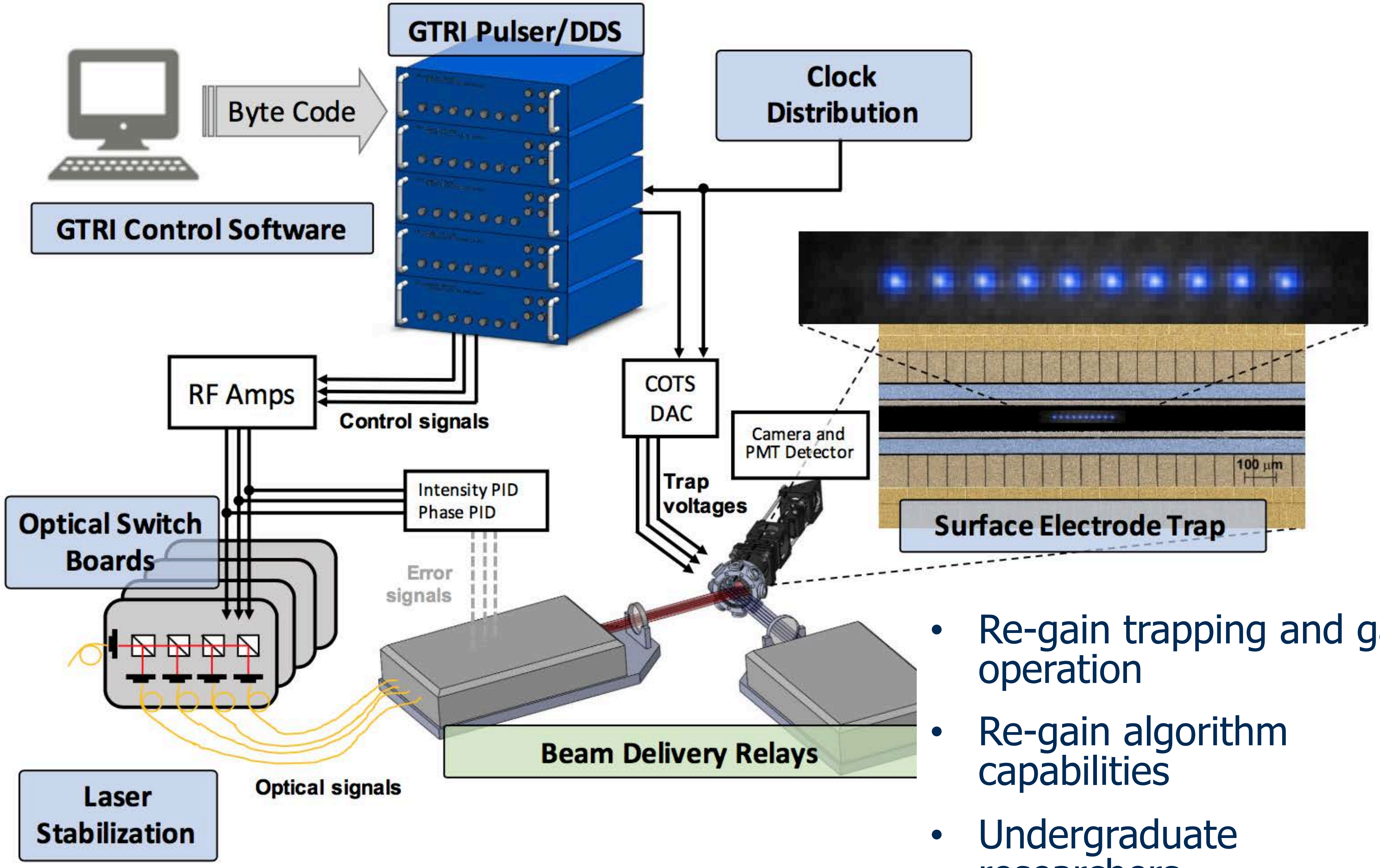
Fallek, S. *et al.* Transport Implementation of the Bernstein-Vazirani Algorithm with Ion Qubits. *New Journal of Physics* **18**, 083030 (2016).

Quantum System Division- Quantum Testbed Revival

Email

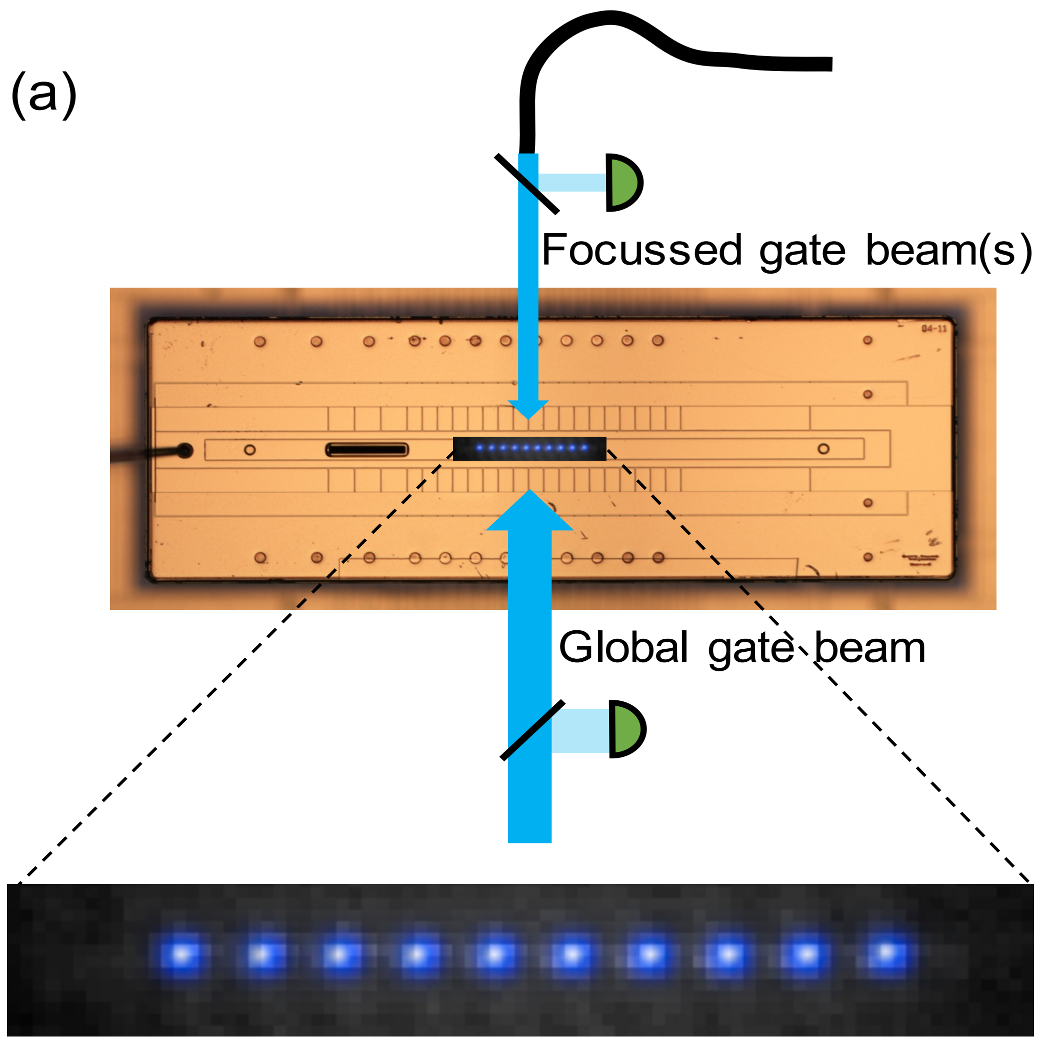


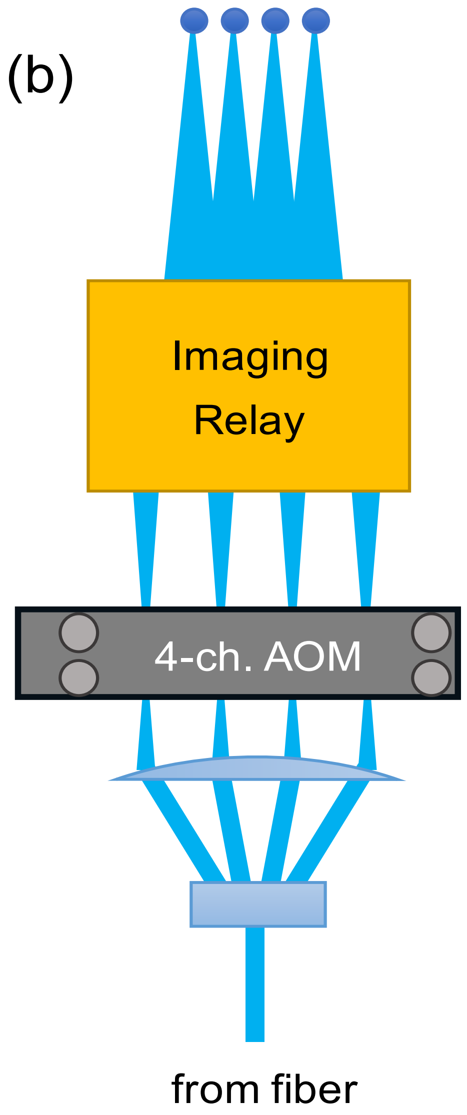
- Connect experiment to a internet facing computer.
- Python-based e-mail interpreter.
- Multi-qubit algorithm via e-mail submission.
- Written by undergraduate researcher.



- Re-gain trapping and gate operation
- Re-gain algorithm capabilities
- Undergraduate researchers

Quantum System Division- Future Quantum Testbed





- Full build up of a GT/GTRI User Facility for a Ion Trap Quantum testbed.
- Full Student involvement from build up to operation.
- Improved ion addressing though more advance optical set-ups
- Expand number of qubits

We are looking for research partners/users of the future testbed.

NISQ computation

- We're entering the era of "Noisy Intermediate-Scale Quantum" (NISQ) computation [Preskill, Quantum **2**, 79 (2018)]

- Hope to demonstrate useful computation with quantum hardware prior to realization of full quantum error correction

- A few general types of computation:
  - VQE – Variational Quantum Eigensolver, e.g.
    - **$H_2$0** – Nam et al., arXiv:1902.10171, **Deuteron EFT** – Shehab et al., arXiv:1904.04338,
    - **Schwinger lattice model** – Kokail et al., Nature **569**, 355 (2019)
  - QAOA – for Quantum Approximate Optimization Algorithm [Farhi (2014)] or perhaps Quantum Alternating Operator Ansatz [Hadfield (2019)]
  - Quantum simulation: both direct implementation of Hamiltonian (analog) and circuit-based (digital)

Physical implementation of QAOA: Challenges

OPTI

Maximum-Cut optimization kernel

DARPA ONISQ program:
Optimization with Trapped Ion Qubits
GTRI, GT ISyE, ORNL, NIST

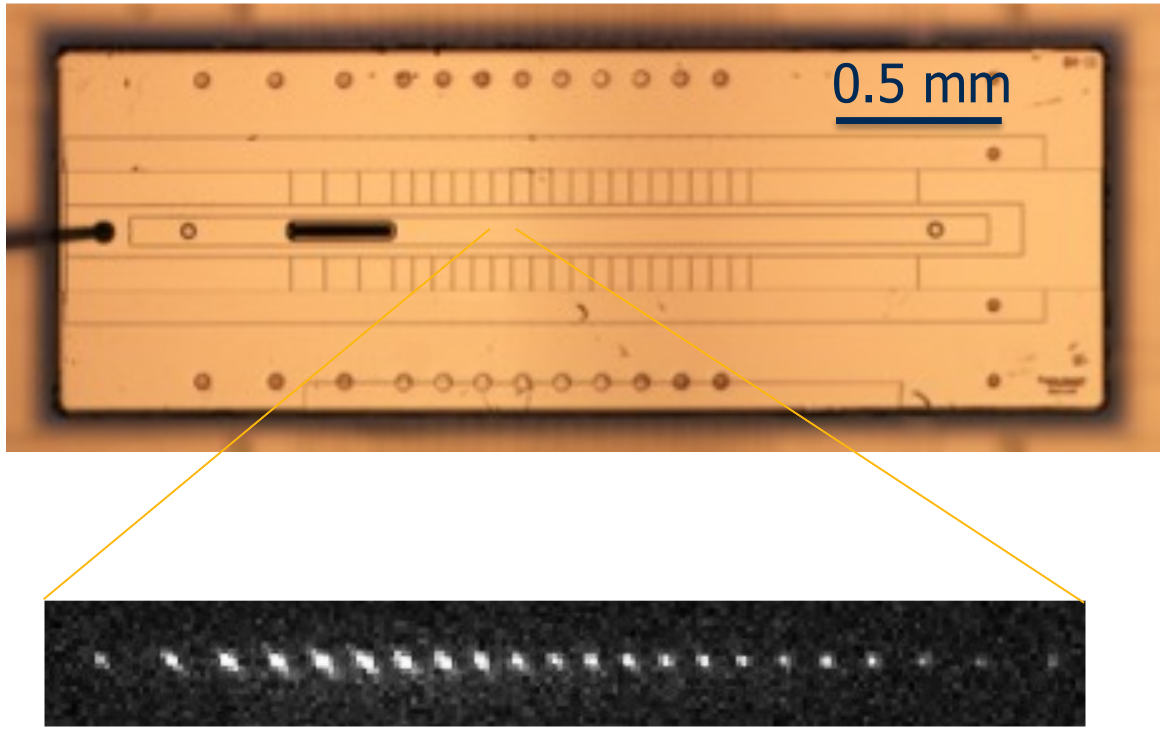
- Need lots of ions ($\mathrm{N} > 100$) to hope to beat classical algorithm
- This will push the limits of a linear chain, but readily trap hundreds in Penning trap
- Must then implement selective 1Q operations for rotating 2D crystal in Penning trap

QAOA – for Quantum Approximate Optimization Algorithm [Farhi (2014)] or perhaps Quantum Alternating Operator Ansatz [Hadfield (2019)]

Physical hardware: crystals of trapped ions

1D chain, surface-electrode rf Paul trap

GTRI-Honeywell BGA trap

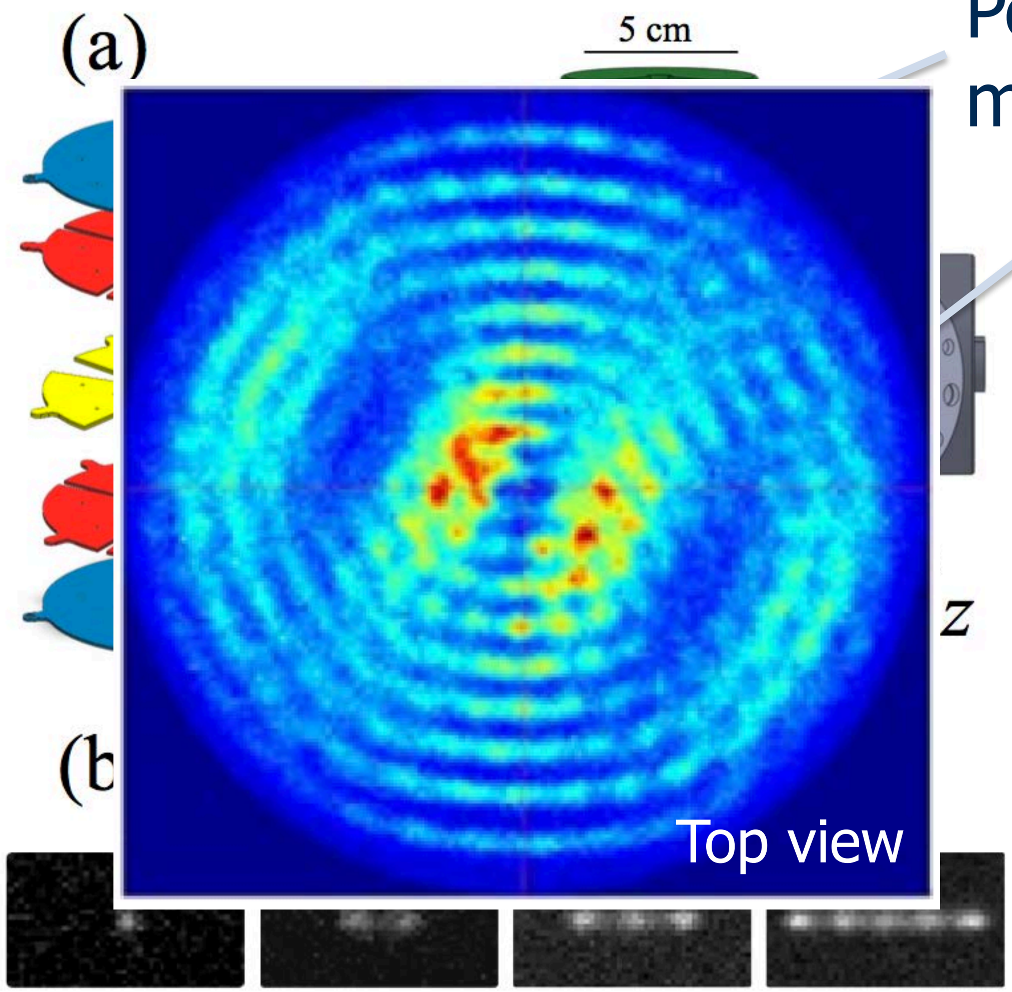


Ion spacing 2-8 μm

N. Guise, et al. *Journal of Applied Physics* **117**, 174901 (2015).

2D array, (compact) Penning trap

Permanent magnets



Side view

B. McMahon, et al. *Phys. Rev. A* **101**, 013408 (2020)

GTRI's Quantum Systems Division

Georgia Tech Research Institute

CREATING THE NEXT®

<u>We are looking to hire</u> (US Citizenship required):

- **Bachelor's degree level** (tuition assistance => full-time pay for PhD research at Georgia Tech!)
- **Postdoc opportunity** on OPTIQ