SAND2023-08377D

Sandia National Laboratories

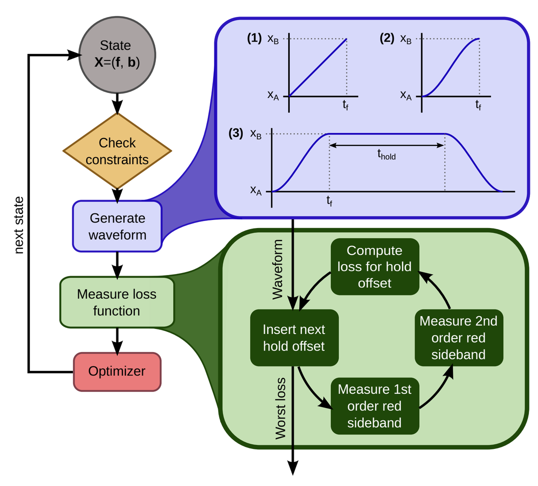
Advanced Technologies for Ion Trap Systems

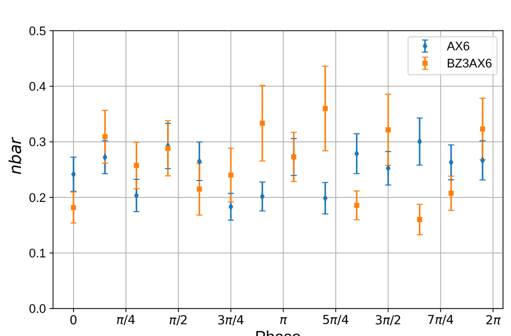
Jonathan D. Sterk, Craig Hogle, Jeffrey Hunker, Hayden McGuinness, Brian McFarland, William Setzer, Daniel L. Stick
Sandia National Laboratories, Albuquerque NM 87106

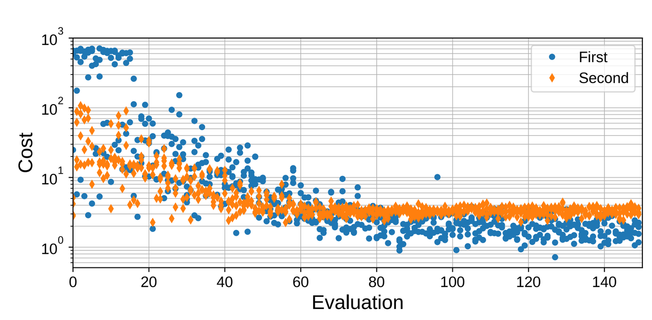
Fast shuttling of ions

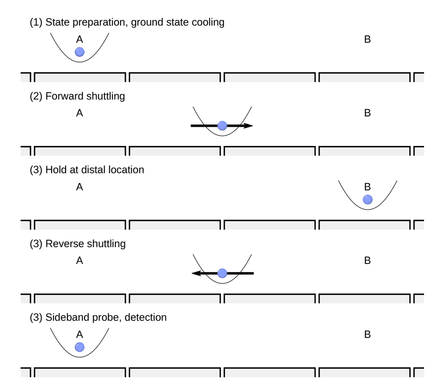
Recent work [1]:

- Demonstrated a closed-loop optimization of ion shuttling to achieve sub-quanta excitation at average speeds of 35m/s
  - Controlling axial frequency and well trajectory
  - Varying hold offset allows for soutions independent of dwell-time
- Used custom electronics that output arbitrary waveforms with 12 MHz analog bandwidth for 96 channels.
- Obvserved ~0.3quanta gain indpendent of phase in the distal location



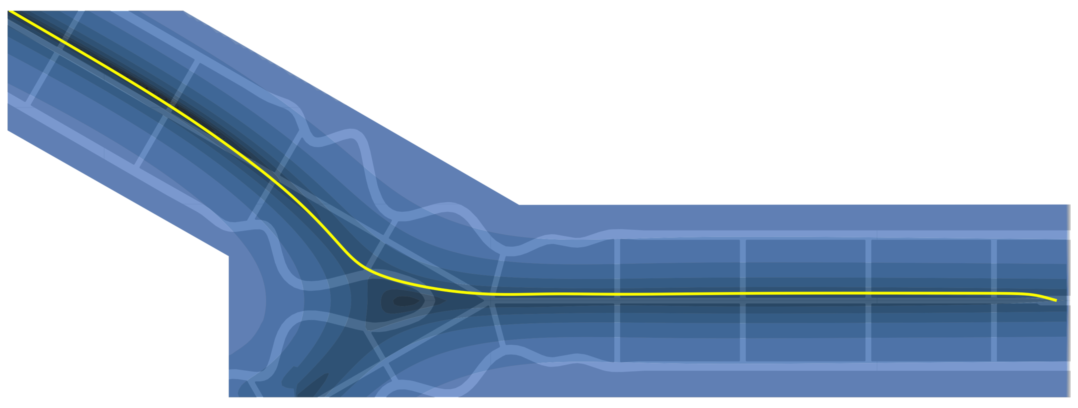


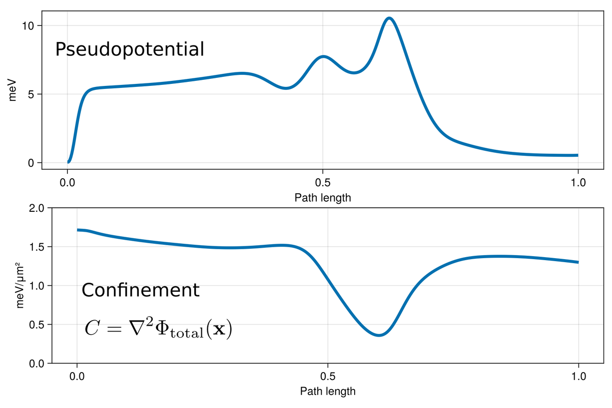




Current Work

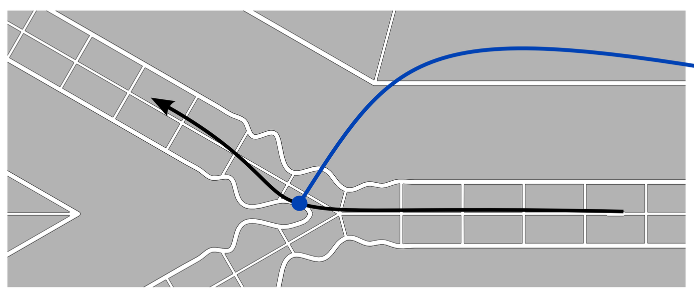
- Designing trajectories to shuttle ions through a junction
- Lack of trap symmetry makes path generation more complex
- Have been able to successfully shuttle 50m/s through a junction
- Getting optimization to work is more challenging
- Developing both closed and open loop approaches

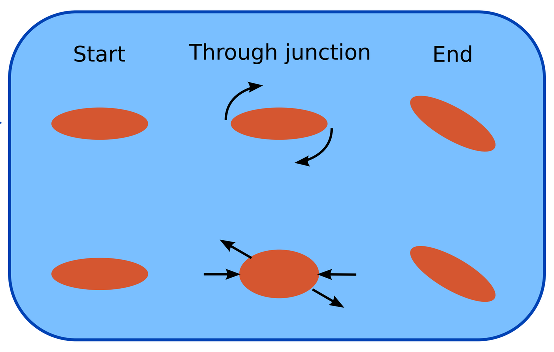




Junction behavior

- Confinement [2] drops in the junction
- Trap becomes isotropic,leading to mixing of radial and axial modes
- What is a good loss function?





Rotation of weak axis vs. compression/expansion

[1] Sterk, *et al.* "Closed-loop optimization of fast trapped-ion shuttling with sub-quanta excitation" *npj Quantum Inf* **8**, 68 (2022)
[2] Burton *et al.* "Transport of Multispecies Ion Crystals through a Junction in a Radio-Frequency Paul Trap" *Phys. Rev. Lett.* **130**, 173202 (2023).

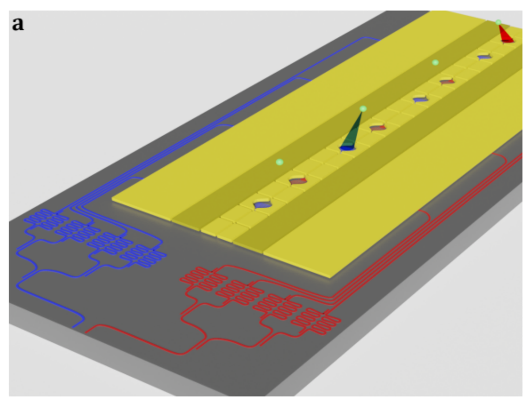
Integrated Modulators

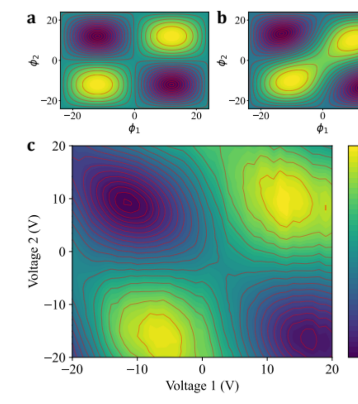
Why Modulators?

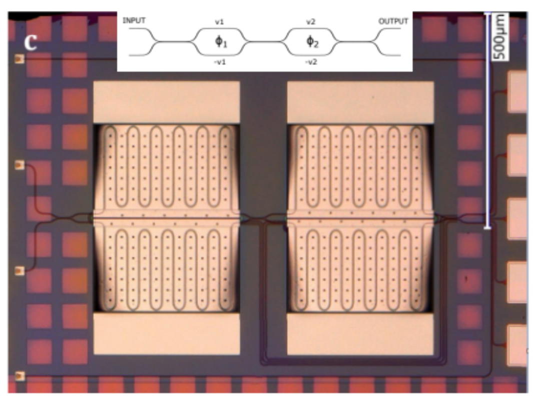
- Reduce alignment issues
- Reduce the optical phase drift
- Reduce number of optical input couplers while maintaining addressability
- Requires on-chip modulators for switching.

Requirements

- Fast switching (≪ 1 µs)
- Support optical powers (1 to 10 mW)
- High extinction ratio (gate laser >60 dB, higher for resonant detection beam)
- Support high fidelity quantum gates
- CMOS compatible
- Cryogenic operation (desired)

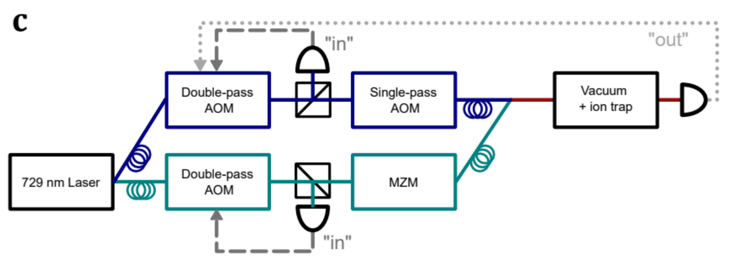


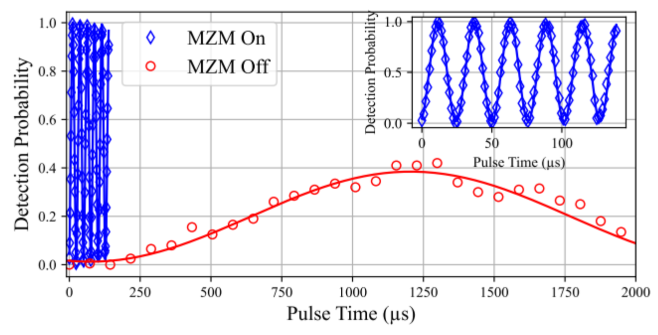




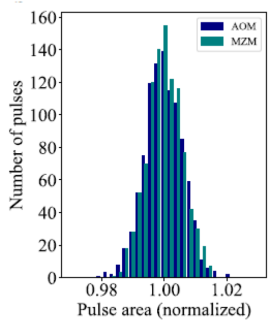
Experiment [3]

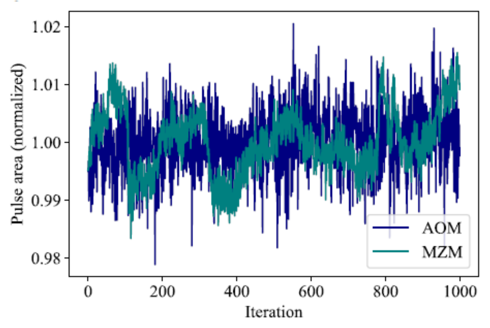
- External modulator chip (double MZI) delivered to ion via free space
- Driving 729nm optical qubit transition in calcium
- Compare performance of modulators with AOM setup





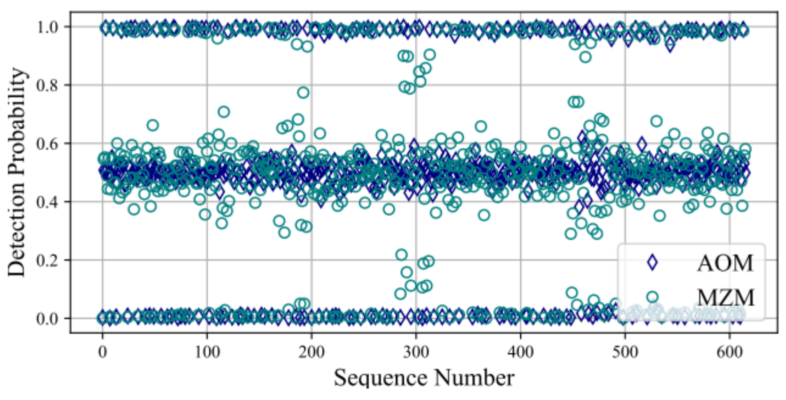
- Measurement of Rabi flopping with MZM on and off, indicating a 38.7dB extinction.





- Pulse areas from AOM and MZM exhibit similar variance in pulse area, but different noise/drift

Modulator (GST, stabilization)	Process infidelity ($\times 10^{-3}$) $\sqrt{X}$ / $\sqrt{Y}$ / I
MZM (standard, in)	2.64±0.06 / 2.42±0.05 / 2.64±0.06
MZM (physical, in)	0.23 ± 0.01 // 1.62 ± 0.02
AOM (standard, in)	1.6 ± 0.1 / 1.5 ± 0.1 / 0.7 ± 0.1
AOM (standard, out)	0.73 ± 0.07 / 1.05 ± 0.08 / 0.1 ± 0.1
Modulator (GST, stabilization)	**Diamond error** ($\times 10^{-2}$) $\sqrt{X}$ / $\sqrt{Y}$ / I
MZM (standard, in)	1.90±0.04 / 2.15±0.03 / 4.78±0.03
MZM (physical, in)	1.52 ± 0.02 // 4.03 ± 0.02
AOM (standard, in)	2.83±0.07 / 2.34±0.06 / 0.30±0.04
AOM (standard, out)	0.53±0.06 / 0.73±0.06 / 0.69±0.04

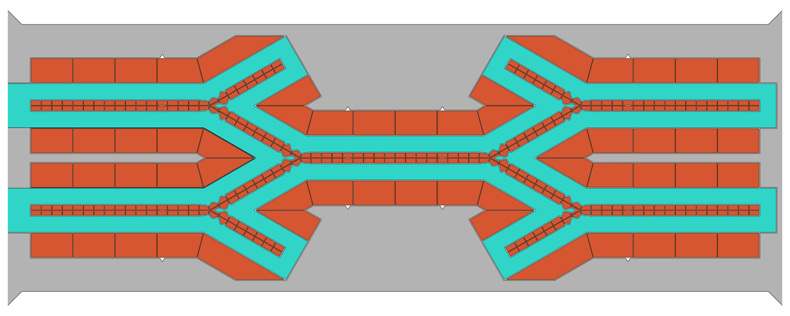


[3] Hogle, *et al.* "High-fidelity trapped-ion qubit operations with scalable photonic modulators" arXiv:2210.14368v1 (2022)

Complex ion trap design (Enchilada trap)

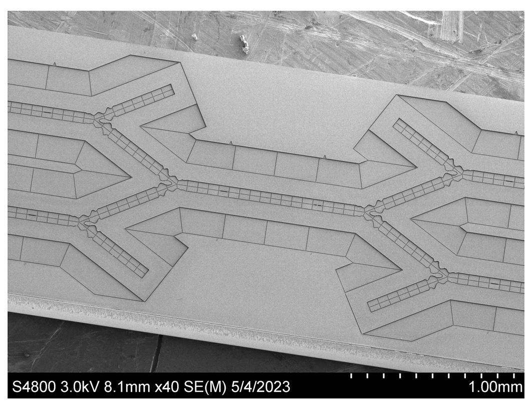
Purpose and Capabilities

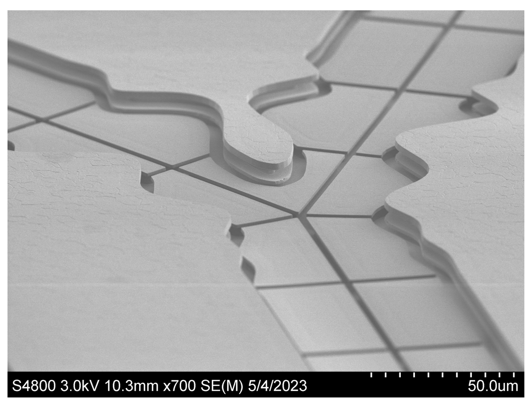
- To perform operations on many more ionic qubits than previous traps.
- Able to store up to 200 ions using 4 outer storage regions connected by a central interaction region.
- Contains 6 junctions for transporting ions and 5 linear sections for manipulation/storage (Earlier traps had 1 or 2 junctions, and 1 linear section)



Status

- Fabrication completed spring 2023
- Installation, test, delivery: Summer 2023
- Experiments: Utilize and extend previous optimization and junction transport efforts





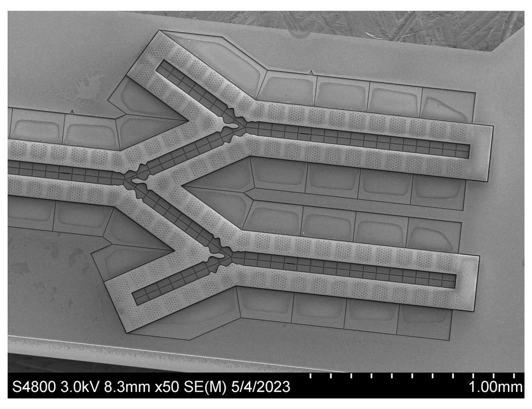
Scaling Challenges

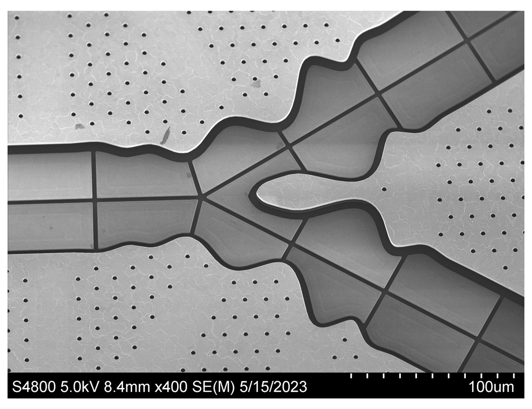
Challenge 1: RF Capacitance and power dissipation

- 4x reduction of rf capacitance by raising the RF electrodes above the control layer and perforating the dielectric

Challenge 2: I/O and routing density

- Enchilada contains 316 control electrodes, which can be independent or tied together.
- Full version requires a new package.
- Multiple metal levels needed to connect islanded electrodes.





U.S. DEPARTMENT OF ENERGY
National Nuclear Security Administration
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.