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Closed-loop optimization of ion shuttling

QSA science talk

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QCCD architecture

- First proposed in 2002
- Utilizes ion transport for connectivity
- Strengths: all primitives demonstrated
- Weaknesses: transport speed, motional heating during transport

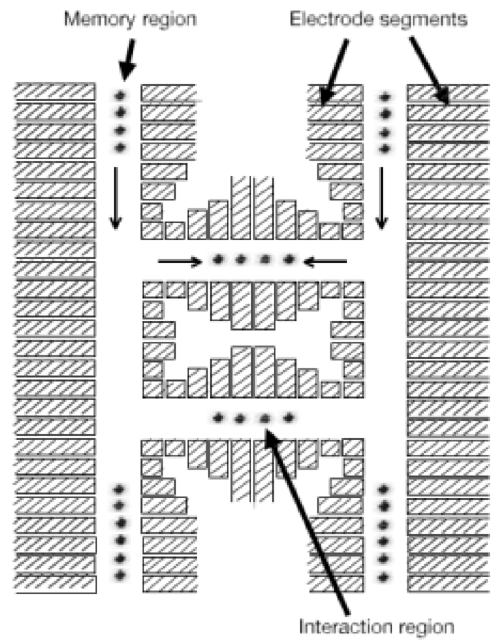
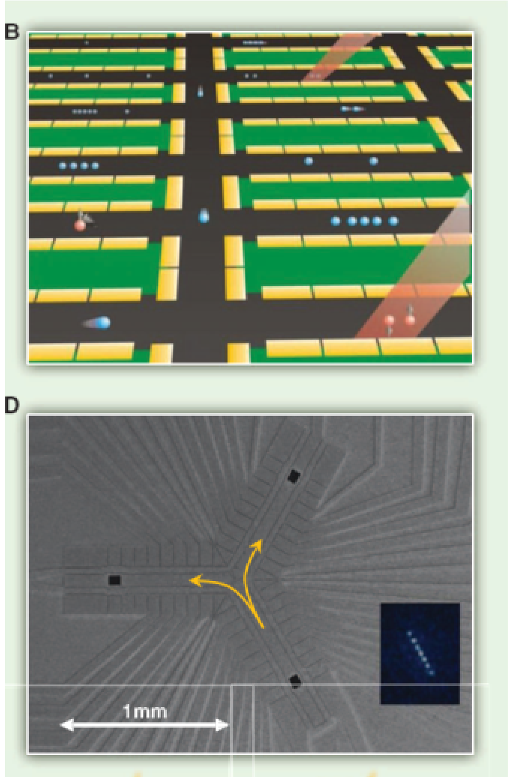
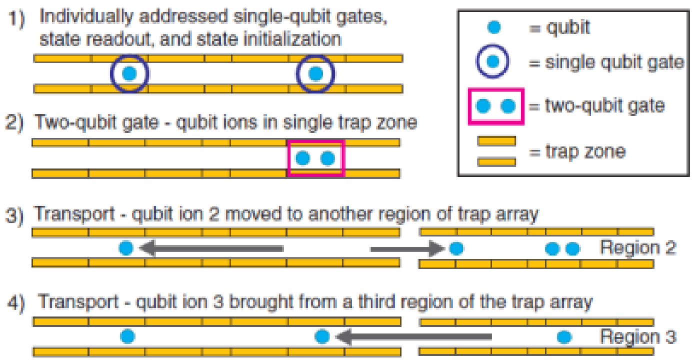


Figure 1 Diagram of the quantum charge-coupled device (QCCD). Ions are stored in the memory region and moved to the interaction region for logic operations. Thin arrows show transport and confinement along the local trap axis.



“Architecture for a large-scale ion-trap quantum computer,” D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002).

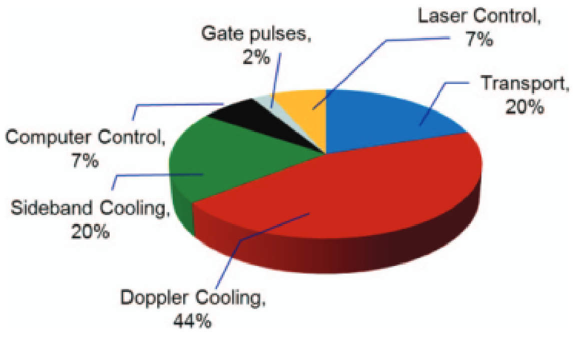
Fig. 1. Schematic of the sequence of operations implemented in a single processing region for building up a computation in the architecture of (*5*, *9*). A large-scale device would involve many of these processing regions performing operations in parallel along with additional regions for memory. Generalized operations would use this block structure repeatedly, with perhaps some of the steps omitted.



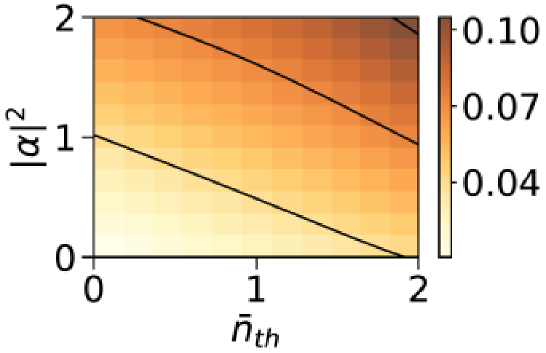
“Complete Methods Set for Scalable Ion Trap Quantum Information Processing, ” J. Home, *et al.* Science **325**, 1277 (2009).

Fast transport

- Reduce overhead in shuttling
  - Can take a large chunk of operation time
- Imperfect controls lead to coherent excitation
  - Impacts fidelity of 2-qubit gates



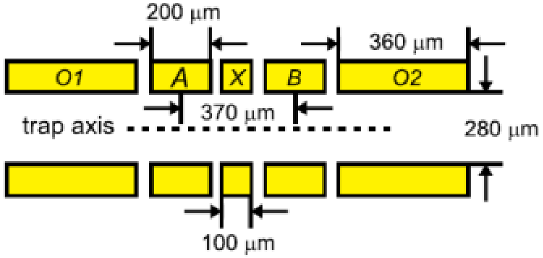
Bowler, *et al.* Rev. Sci. Inst **84,** 033108 (2013)



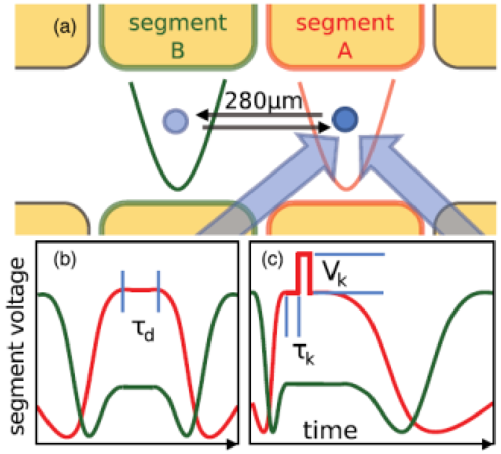
Ruzic, *et al.* (in preparation)

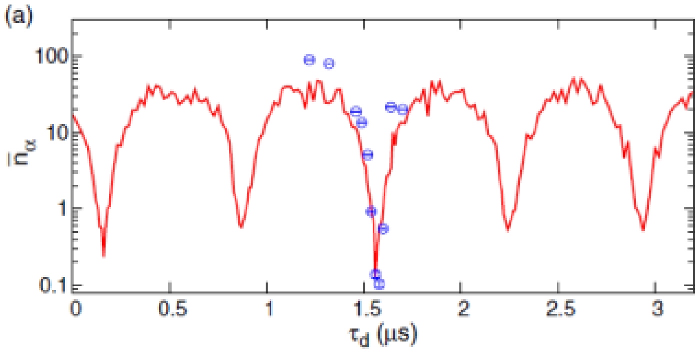
We want:
- Fast transport (electrodes/s)
- Low excitation (coherent and incoherent)
- Insensitive to timing

Prior Demonstrations



- Large electrodes
- Speeds of only 0.2-0.3 electrodes/us
- Sensitive to timing of return/application of kicks





Bowler, *et al.*, PRL **109**, 080502 (2012)
Walther, *et al.*, PRL **109**, 080501 (2012)

Main results

We want:

- Fast transport (electrode/s)
- Low heating (coherent and incoherent)
- Insensitive to timing

Challenges:

- Background electric fields
- Imperfect simulation of transport solution
- Pseudopotential curvature
- Imperfect DAC voltages
- Variation of individual filter parameters (~5% variability in resistance and capacitance)

Demonstrated:

- Fast transport of a single ion (35m/s = 0.5 electrode/μs) over three electrodes
- with sub-quanta heating,
- regardless of hold time

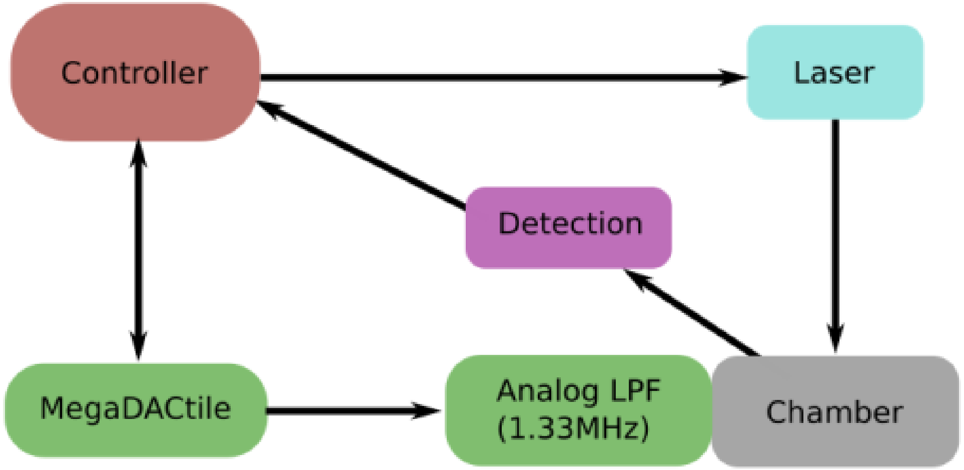
Method:

Closed-loop derivative free optimization procedure utilized to transform waveform to correct the trajectory and axial frequency

Hardware

MegaDACtile (MDT)

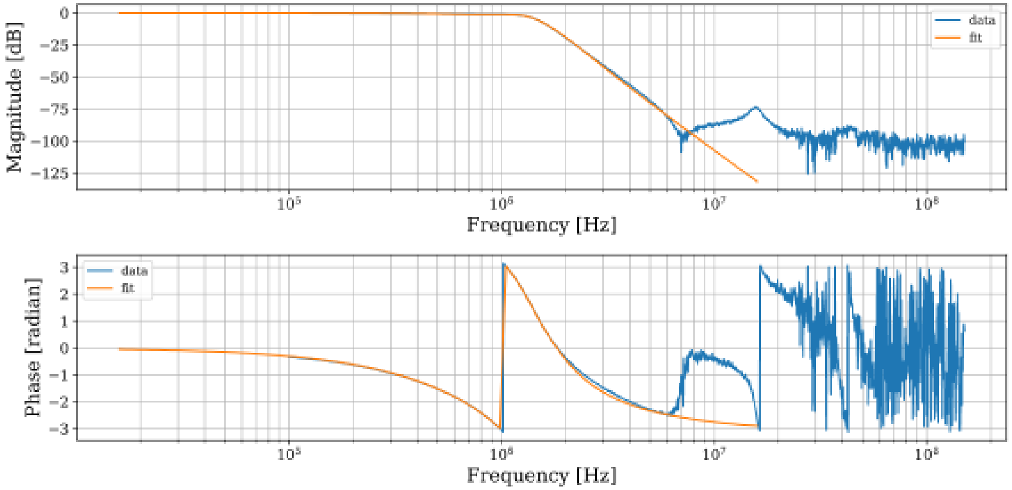
- A 96-channel arbitrary waveform generator
- Designed for 14-bit high-precision voltage steps (<1.5mV) across a wide voltage range (+/- 10V)
- Capable of 12MHz of analog output bandwidth
- Able to store and playback up to 1.7s of samples per channel
- Controlled via Python running on Windows 7/8/10
- Waveforms are specified at a rate of 33Megasamples/sec

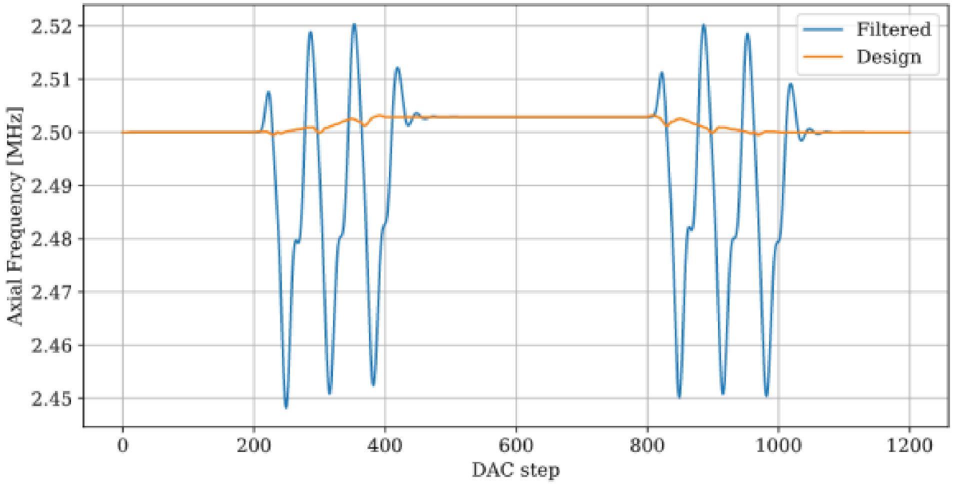


Additional 1.33MHz analog low pass filter right at entrance to the vacuum chamber to remove noise at axial frequency (chosen to be 2.5MHz)

Controller computer synchronizes waveform output with pulse sequences

Distortion of trapping potential



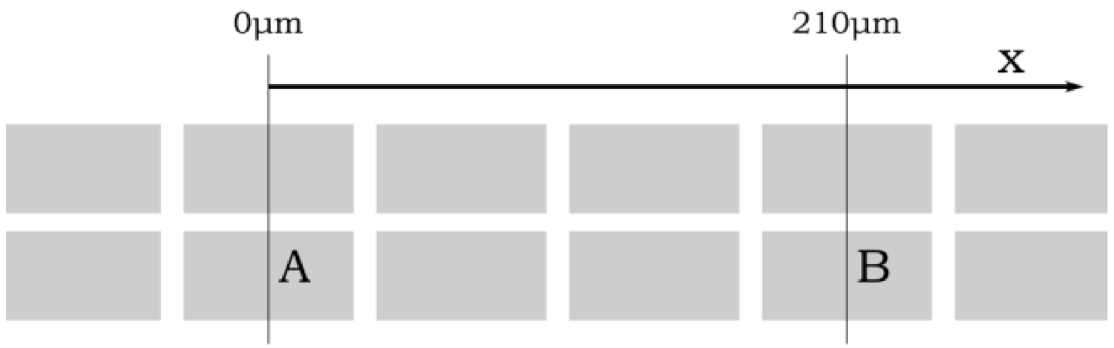


- Model of low pass filter shows small changes in axial frequency can be amplified
  - Voltages on trap cannot change as fast as design, distorting the potential
- Can give rise to other motional excitations (squeezing)
- Optimization: set the axial frequency at various points along the trajectory

Trajectories

Ion position $x(t) = x_f\, s(t/t_f)$

- Boundary conditions: $s(0) = 0$ and $s(1) = 1$
- Zero starting and ending velocity: $\dot{s}(0) = \dot{s}(1) = 0$
- Symmetry: $s(1-\tau) = 1 - s(\tau)$

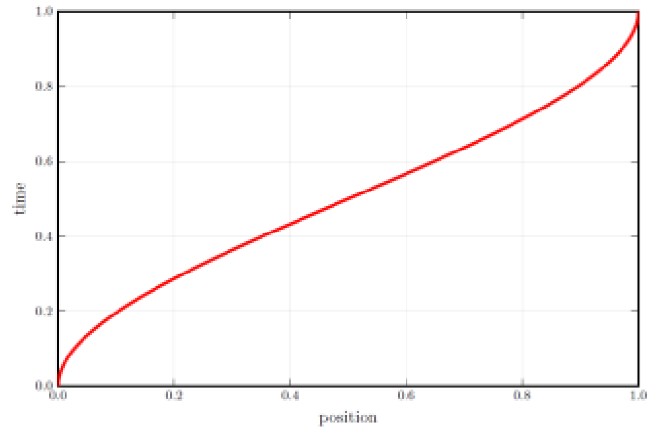


Parameterize trajectory as a Bezier curve:

$$s(\tau) = \sum_{j=0}^{N} \binom{N}{j} b_j\, \tau^j\, (1-\tau)^{N-j}$$

Constraints transform to:

- $b_0 = 0$, $b_N = 1$
- $b_1 = b_0$, $b_{N-1} = b_N$
- $b_k + b_{N-k} = 1$



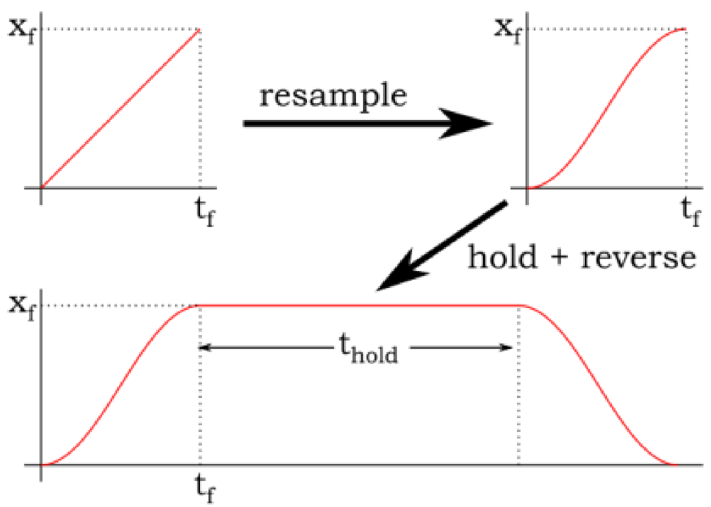
Spacetime diagram of an example Bezier curve (no free parameters)

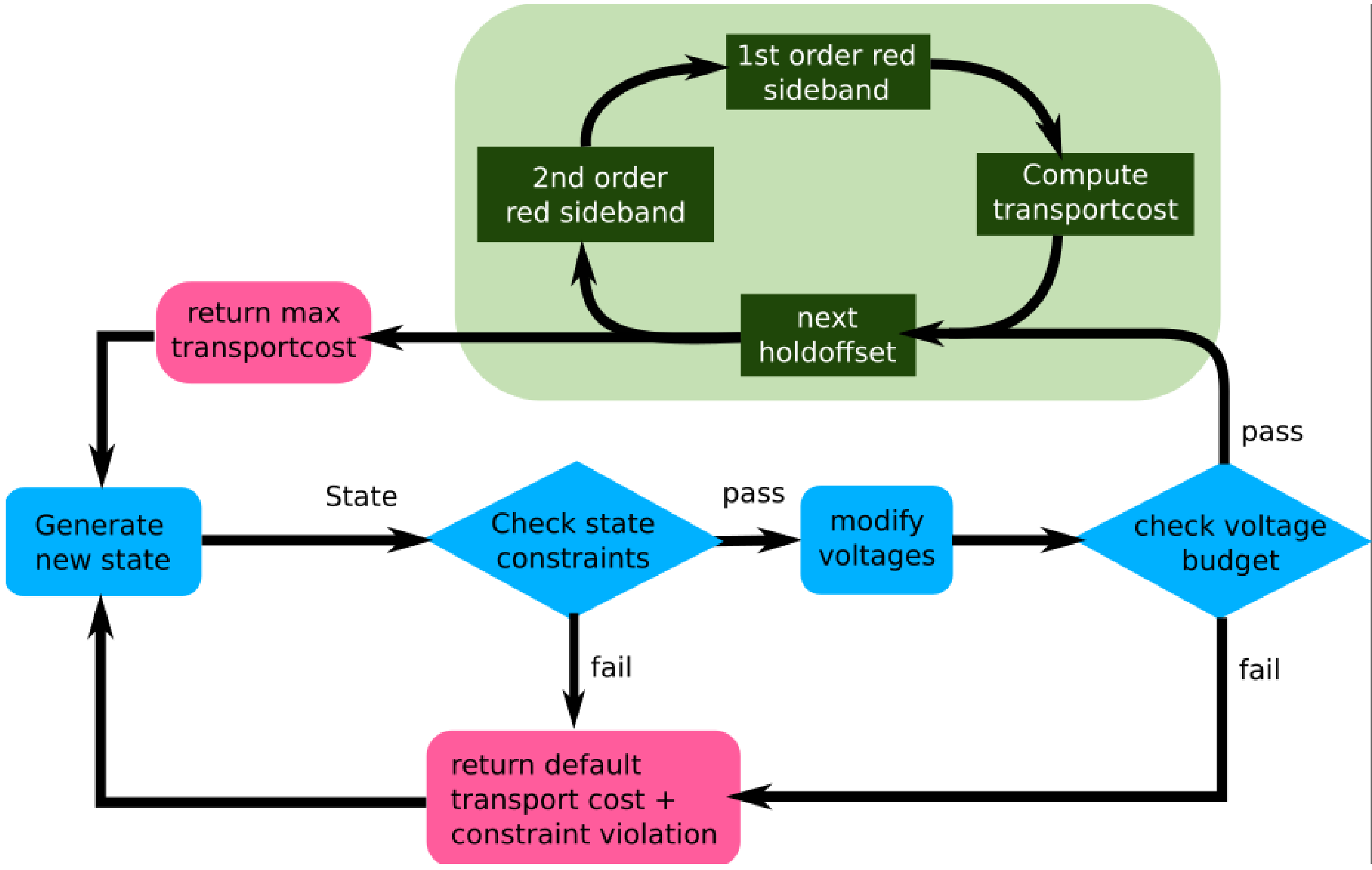
Procedure

Degrees of freedom:
- 3 Bezier coefficients
- 6 axial frequency points

Transport cost: $\int rsb(f)df + \left(\int rsb_2(f)df\right)^2$

Voltage modification:
- Update frequency corrections
- Resample to Bezier trajectory
- Generate full waveform of forward + hold + reverse





Optimization results

Using Nelder-Mead optimization

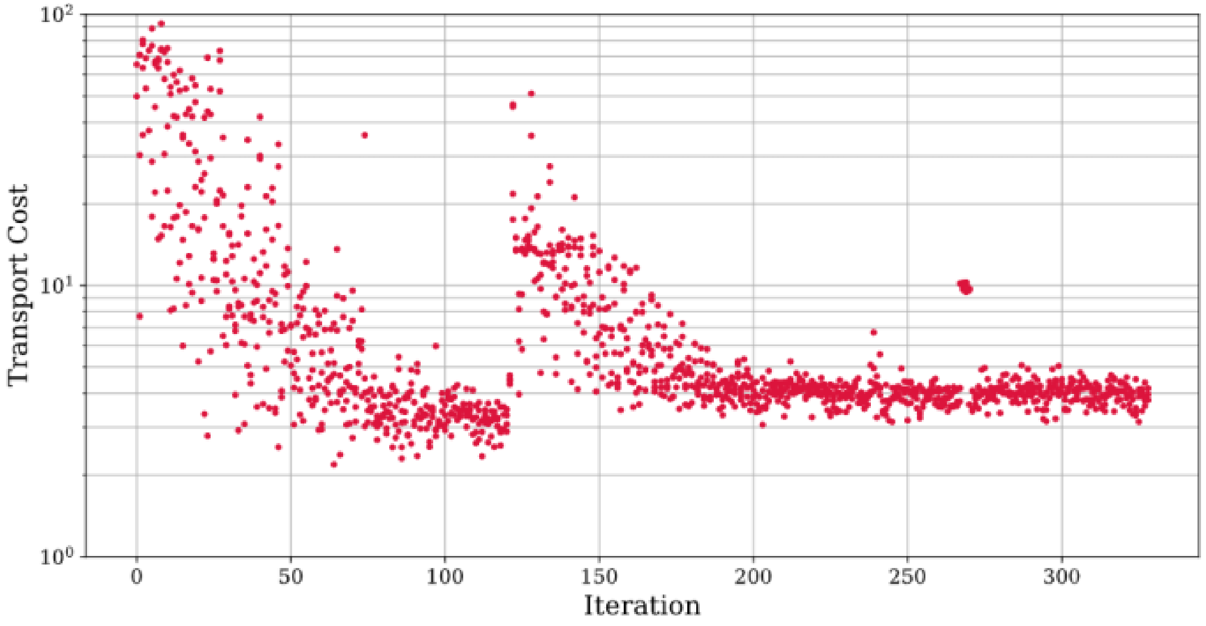
- 120 iterations with short probe
- Followed by 200 iterations at a longer probe time

Transport:

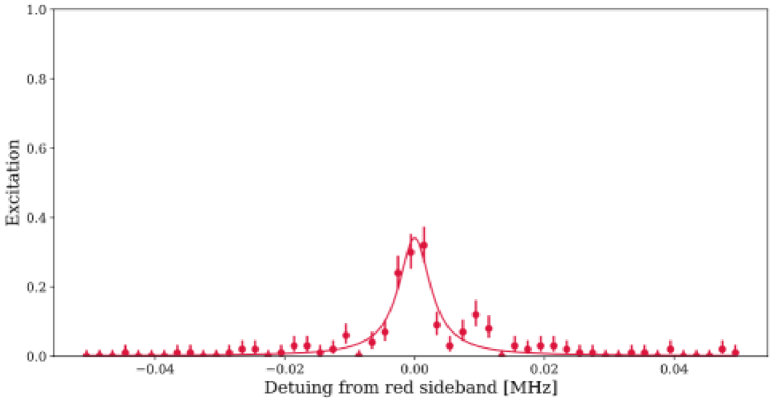
- 0.5electrode/μs. (6 μs to go 210 μm)
- Hold time: 12 μs + n*30ns for n=0, 3, 6, 9
  - Approx 13.3 DAC steps / period

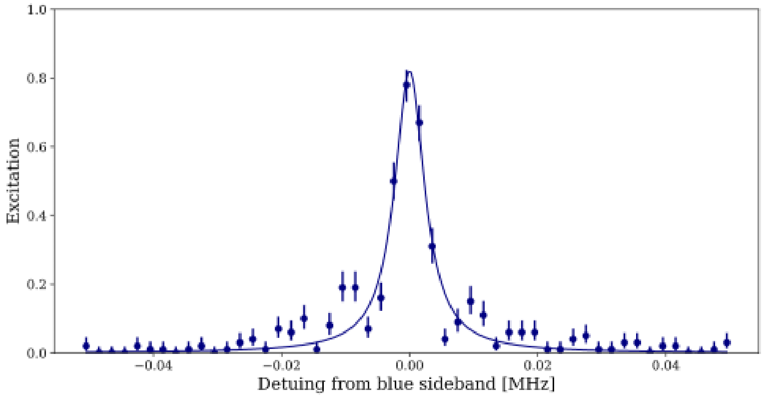
Measured motional quanta via sideband thermometry after transport

- Observed $\bar{n}$ at best :

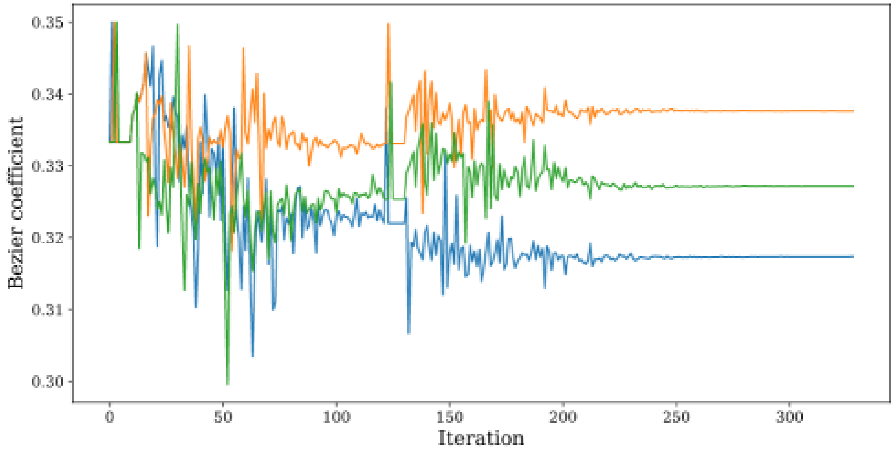


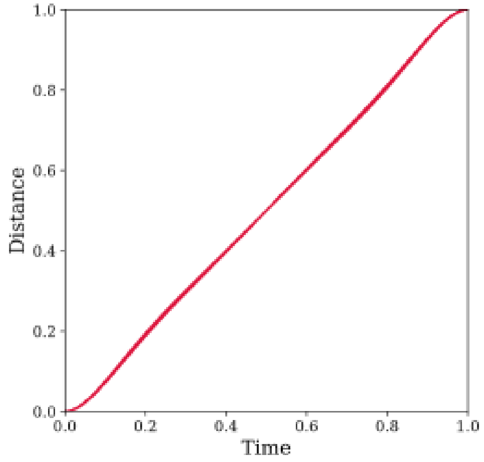
offset	$\bar{n}$
0 steps	0.38 ± 0.04
3 steps	0.71 ± 0.10
6 steps	0.58 ± 0.07
9 steps	0.26 ± 0.03

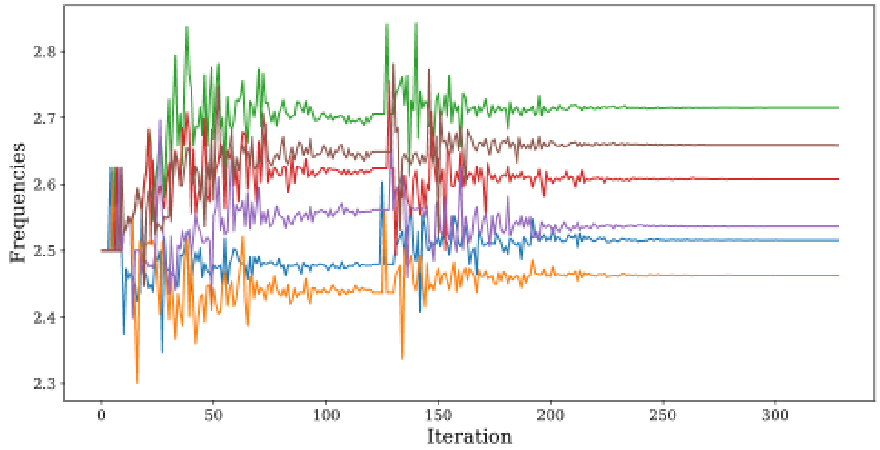


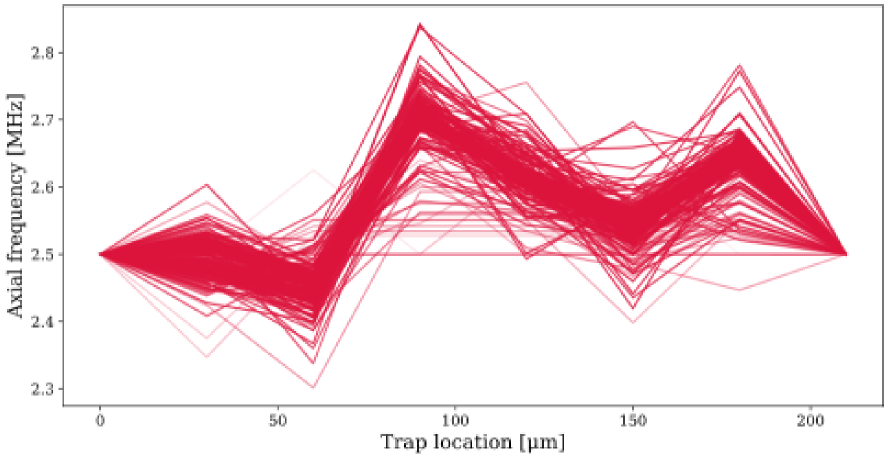


Optimization Results II



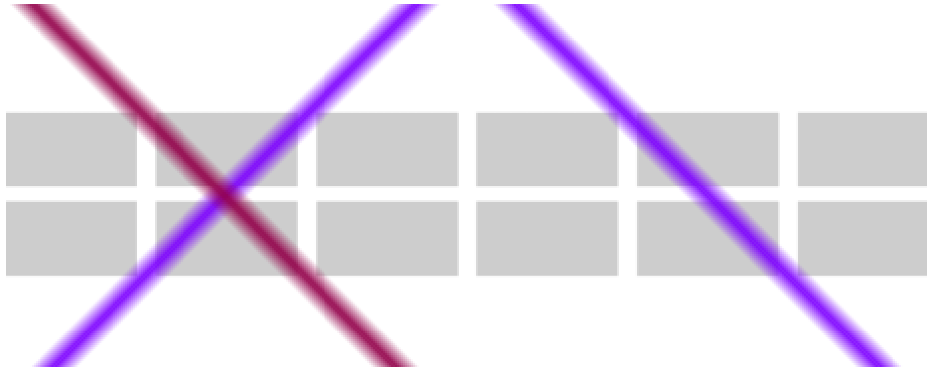






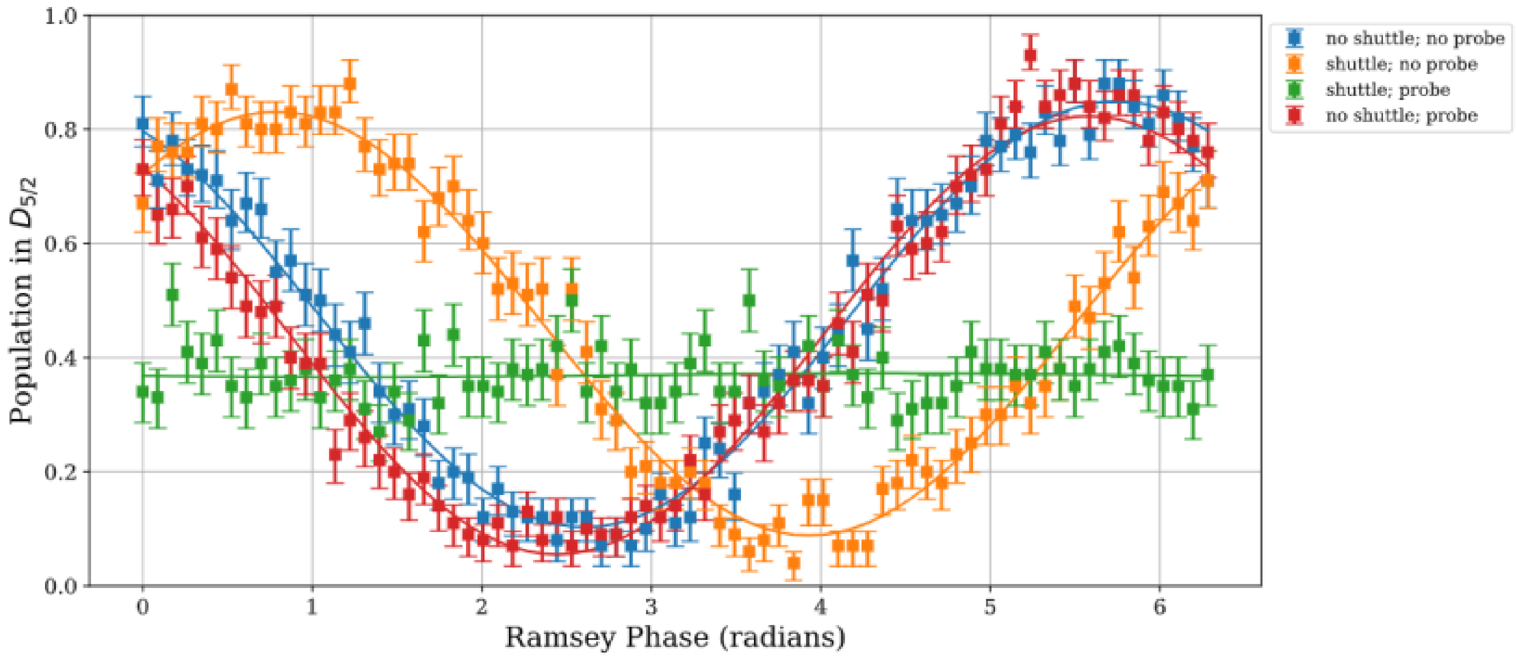
- Bezier wasn't well explored.
- Axial frequency correction was more important

Verification of transport



Ramsey measurements of ion for various configurations

- Stationary/transported
- With / Without probe (secondary doppler)



	No Probe	Probe
Stationary	0.7468	0.7681
Transport	0.7428	0.0065

Future Directions

- High-speed transport optimizations
  - Would optimization on a generic digital filter yield similar results?
  - Is the transport insensitive to the Bezier coefficients?
- How fast can we shuttle?
- Add split-join, quantum gates

High speed transport need a large voltage budget

Acknowledgments

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