Multi-Qubit Operations using Scalable Techniques

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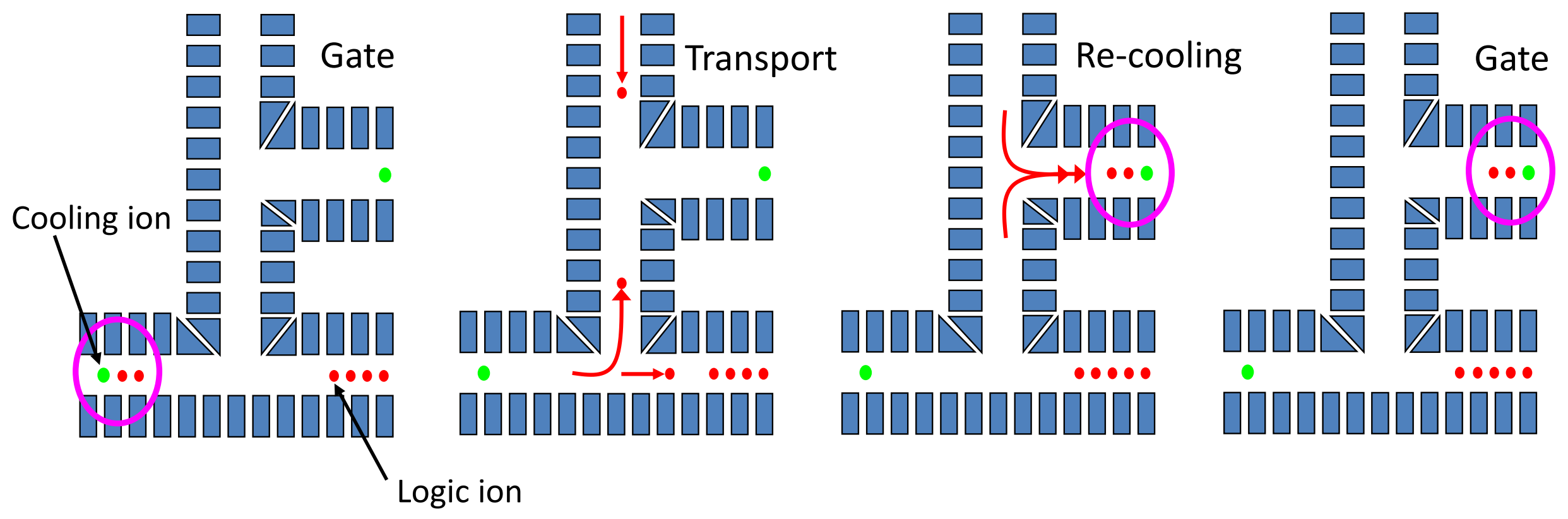
Scalable quantum registers

- A scalable quantum register must implement all the operations required for QIP
- Must use scalable methods – operations should be combined with information transport.
- Must implement operations in a manner which is consistent with a large-scale device
- Should be versatile – no hardware changes required for different tasks.

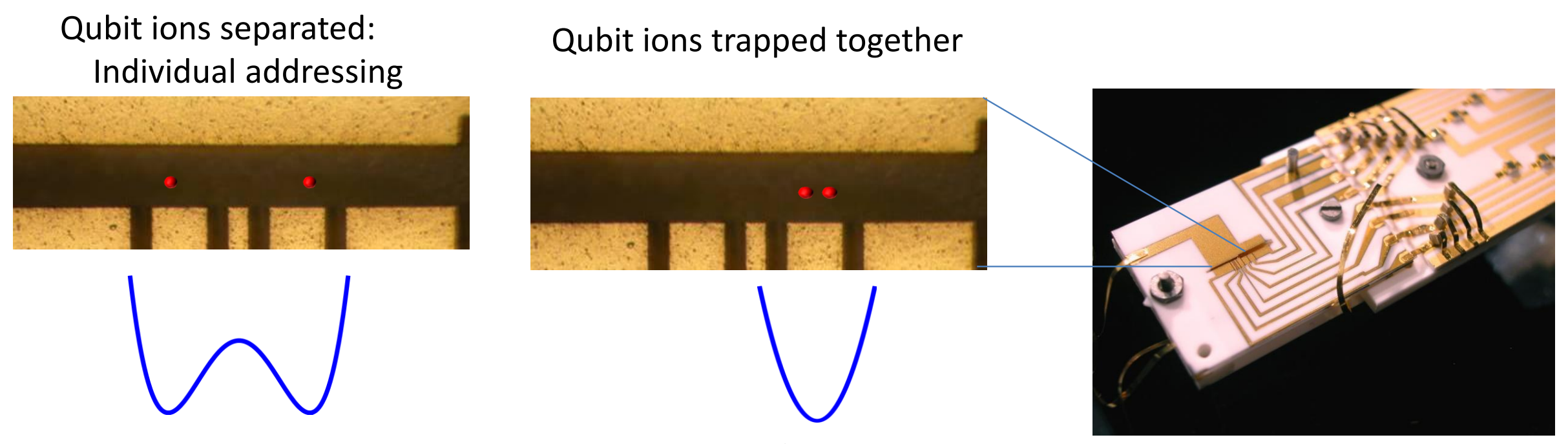
With trapped ions, one scalable architecture uses multi-zone traps
– transport of qubits involves moving the qubit ions themselves



- Requires qubit states robust against environmental perturbations
- Requires recooling prior to two-qubit gates due to imperfect control of transport and ambient heating (two-qubit gates only work for cold ions)

Multi-zone trap

Time varying voltages applied to electrodes of a segmented trap allow us to move and separate chains of ions



- Two-qubit gates

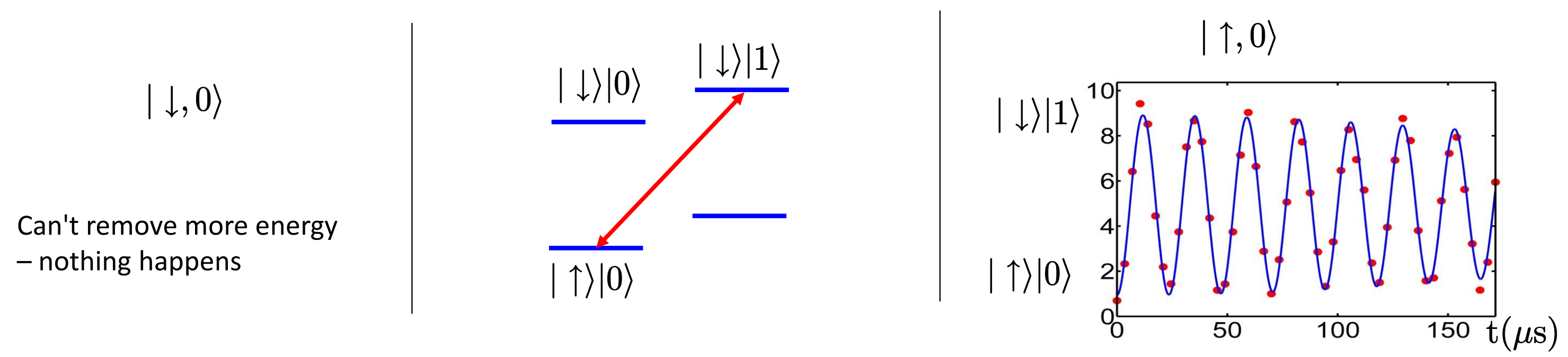
- Qubit readout
- Single-qubit gates

Entangled Mechanical Oscillators

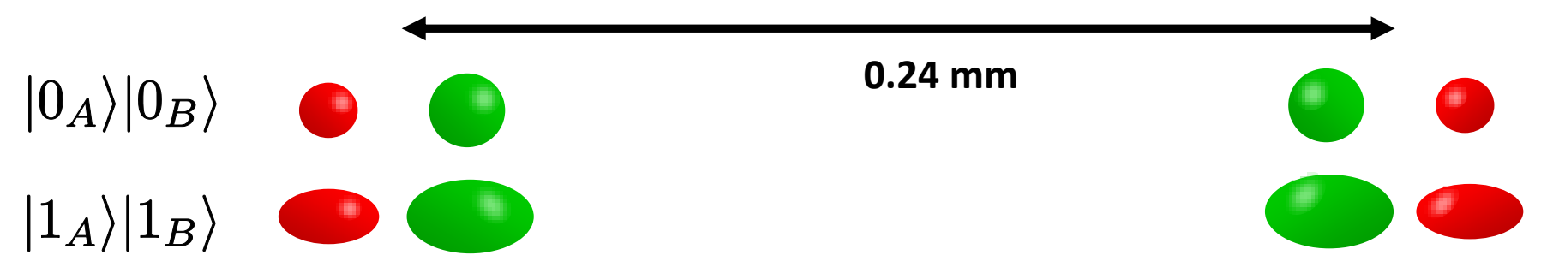
J.D.Jost et. al. Nature **459** 683-685 (2009)

- After entangling the internal states of two Beryllium ions, we can separate them, and use **sympathetic cooling** (see right) with Magnesium to initilise the ground state of motion in each trap

- We can then drive Rabi flopping on the motional sideband in each trap.

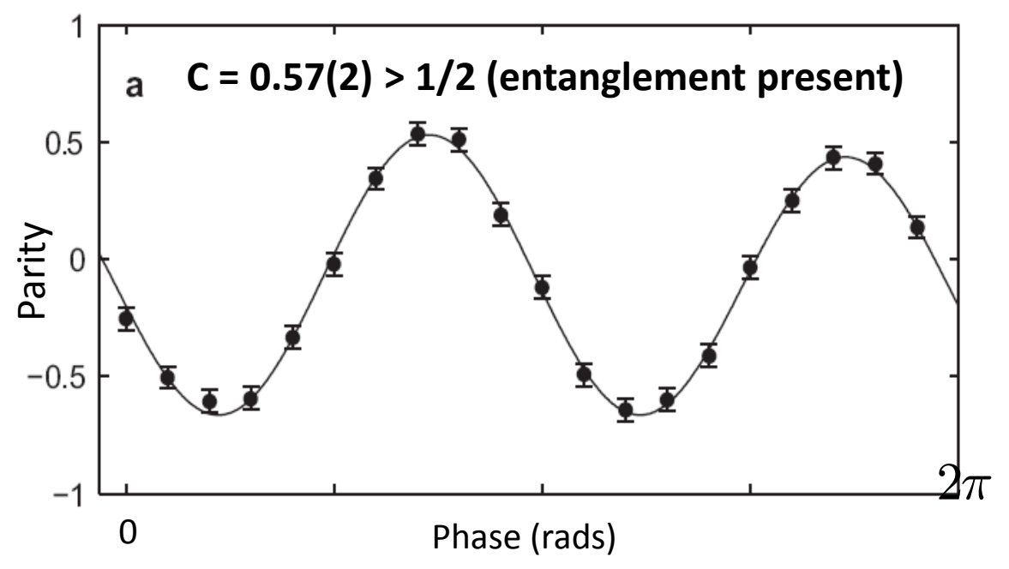


- By performing a "pi" pulse in each trap, we can map the internal state entanglement into the motional state.



$$\frac{1}{\sqrt{2}}\left[|0_A\rangle|0_B\rangle + |1_A\rangle|1_B\rangle\right]$$

- We verify by reversing the mapping, and verifying the coherence element of the resulting spin density matrix.

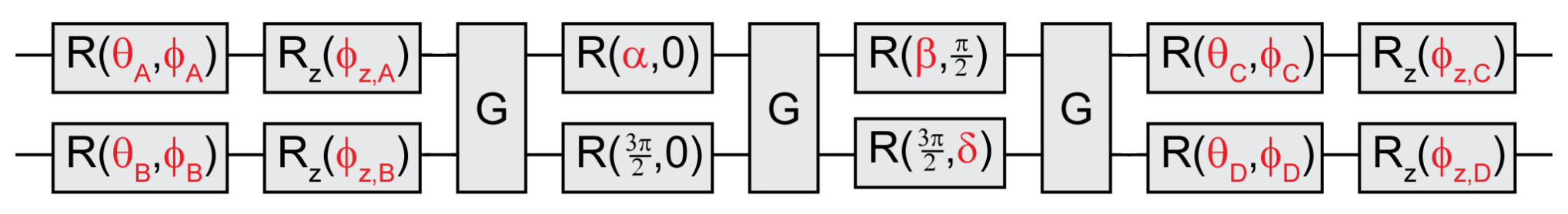


Mapping in and out can be misleading – what if some population got left behind in the spin? We ensure that this doesn't contribute to C, by "shelving" this population in a state which doesn't interact with the phase-scanned analysis pulse

Arbitrary Control of 2-qubits (universal 2-qubit QIP)

D. Hanneke, *et al*, *Nature Phys.* **6** 13-16 (2010)

We implement an arbitrary unitary operation in SU(4) using two-qubits
- 15 free parameters are inputs to single qubit gates.
- 3 two-qubit gates required to reach all local equivalence classes

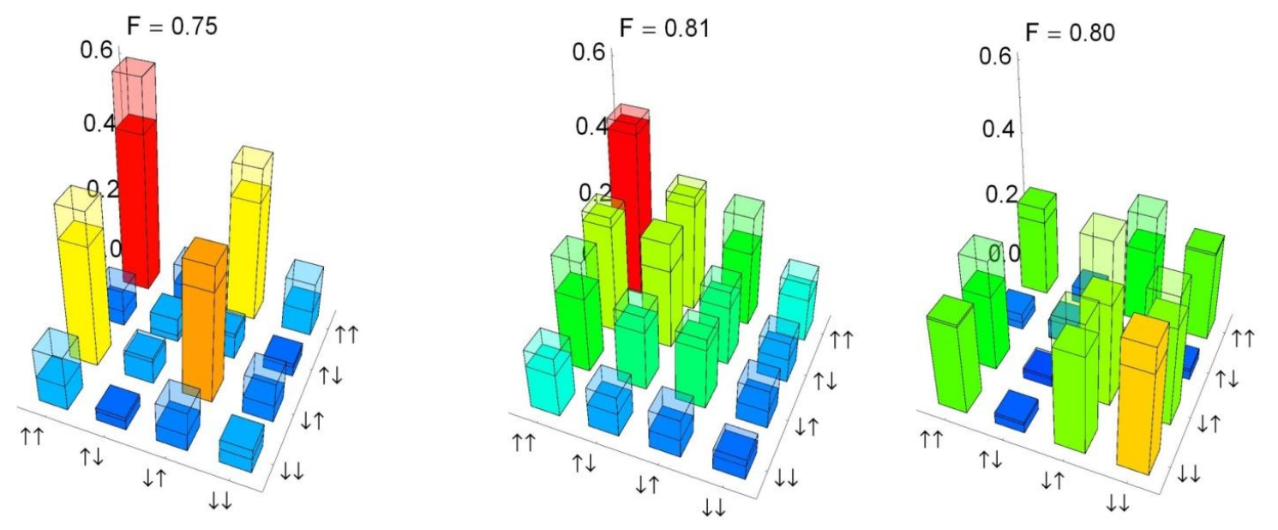


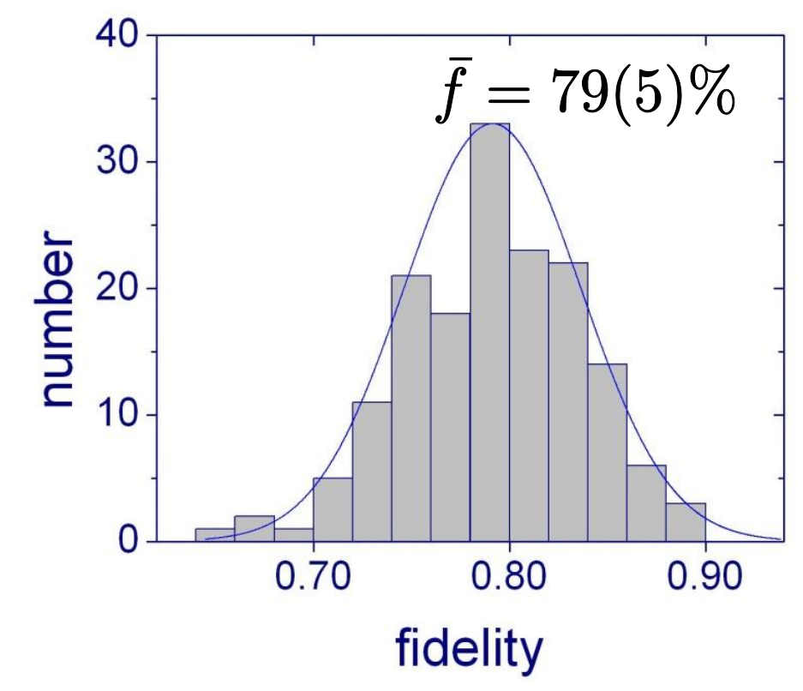
G is a two-qubit phase gate

$$\hat{G} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

We demonstrate arbitrary control by choosing at random a unitary operator and one of 16 input states. We perform state-tomography on the output, and compare this to the ideal state

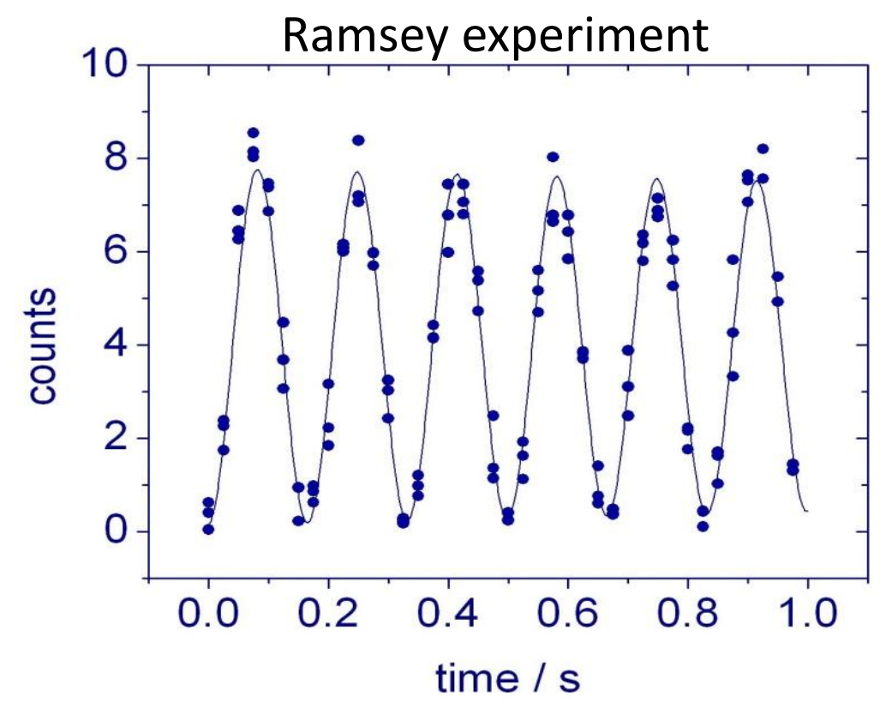
Absolute value of density matrix obtained from state tomography for 3 example unitaries. Solid: data, Translucent: theory





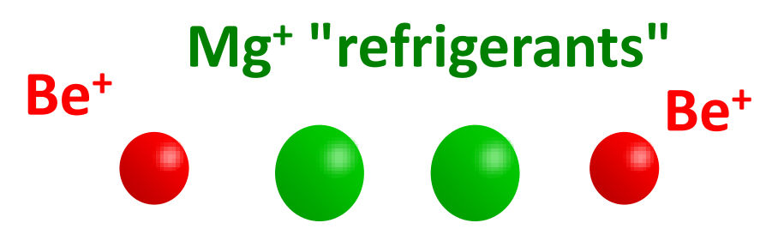
Scalable trapped ion quantum register

Long-lived qubits



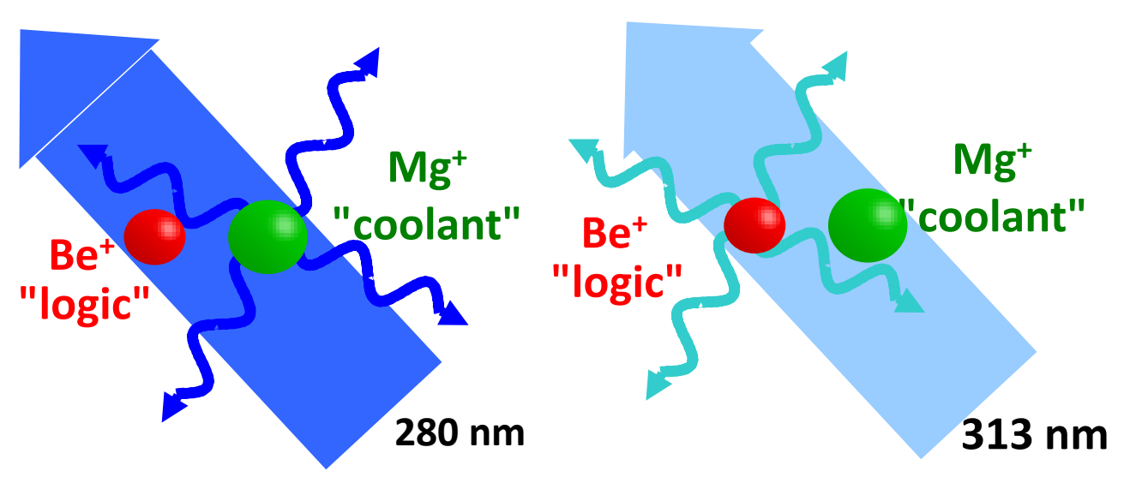
Coherence time ~ 15 s
C. Langer, *et al*, *Phys. Rev. Lett.* **95** 060502 (2005)

To control 2 qubits, we use a four ion crystal



Sympathetic cooling

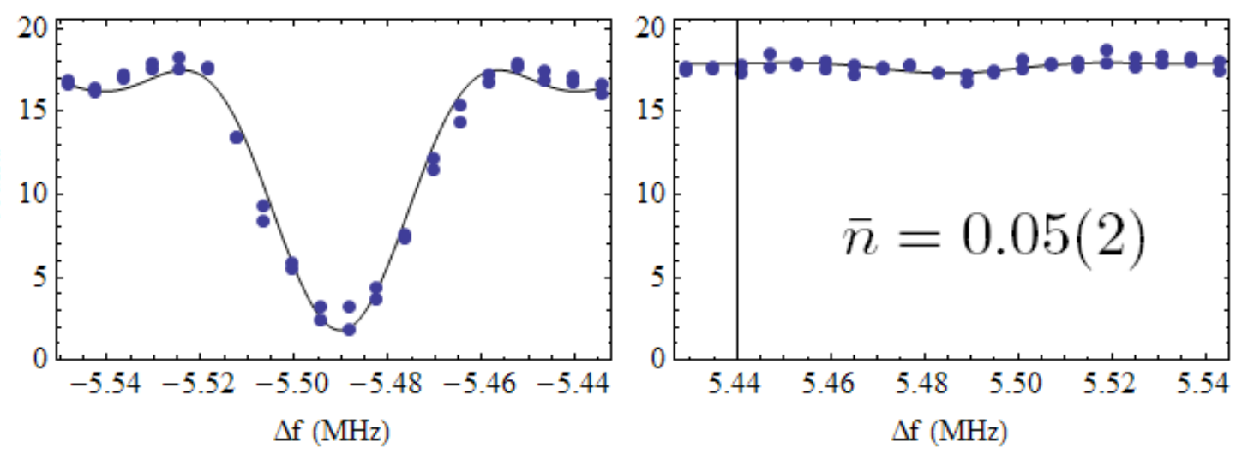
Cannot directly laser cool qubit ion - destroy qubit coherence
Instead - trap two species of ion



Mg light doesn't couple to **internal** Be (qubit) states

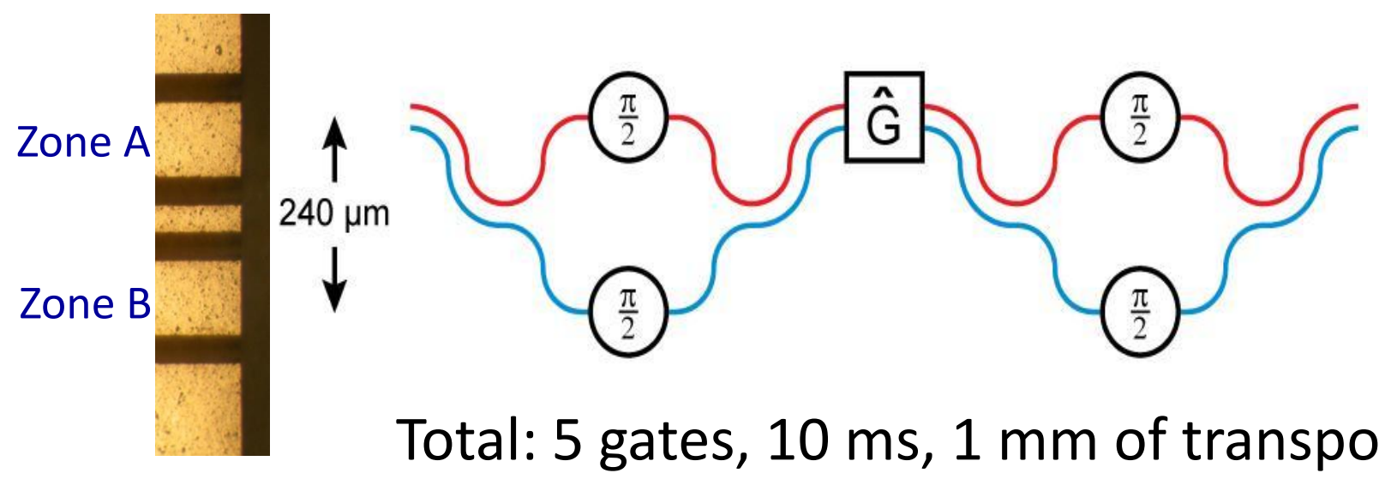
It can cool the **motion** of Be, due to the Coulomb interaction

Example of sympathetic cooling - motion-subtracting beryllium sideband can't be driven (cooling all done using magnesium)



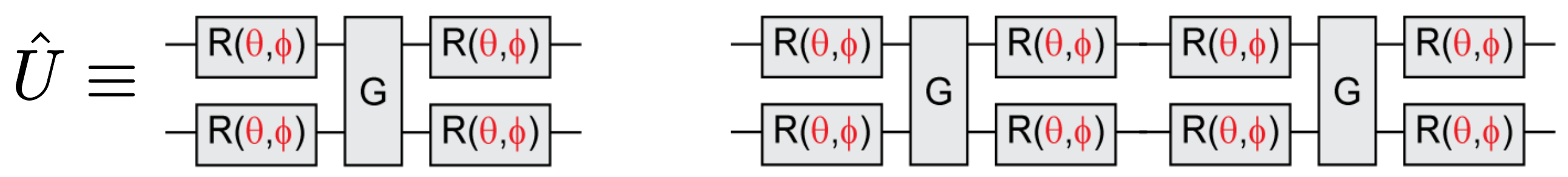
Putting the pieces together

J. P. Home et al. Science **325**, 1227 (2009)



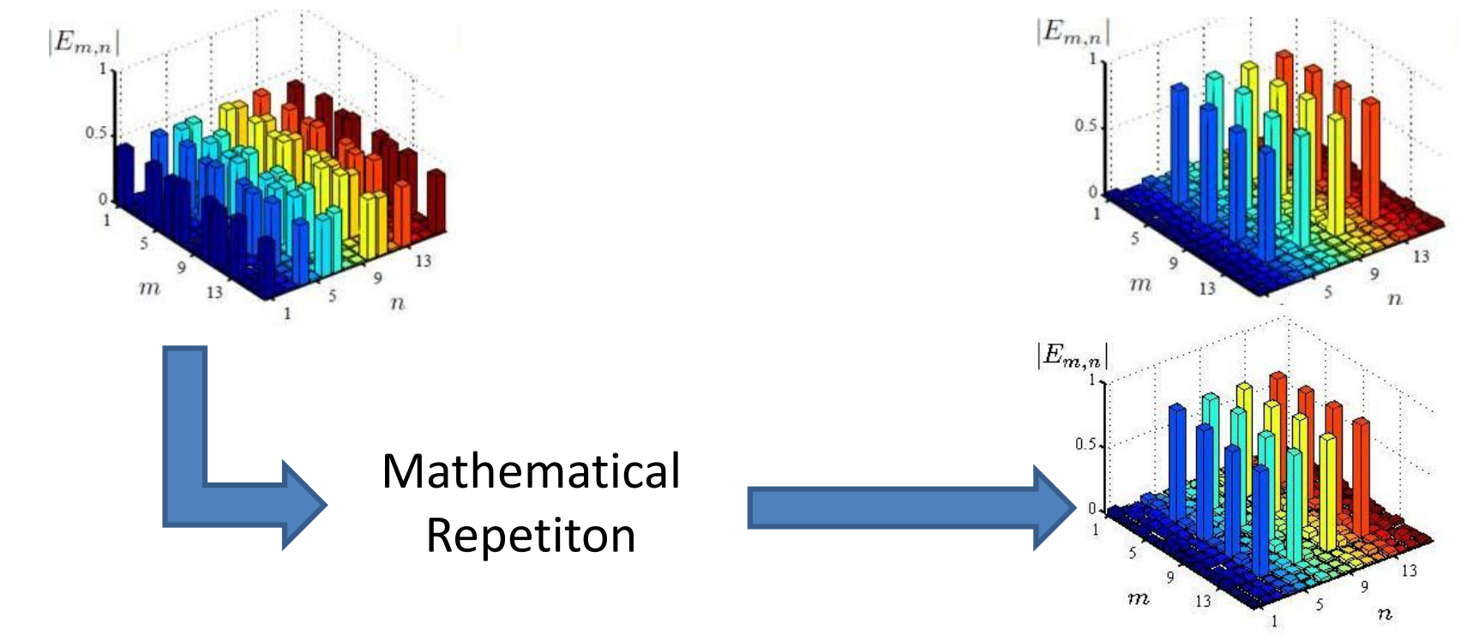
Total: 5 gates, 10 ms, 1 mm of transport

Characterization of repeatability of operation U, which involves a combination of tasks



Individual addressing for readout and gates allows us to perform quantum process tomography

Absolute value of reconstructed process matrices



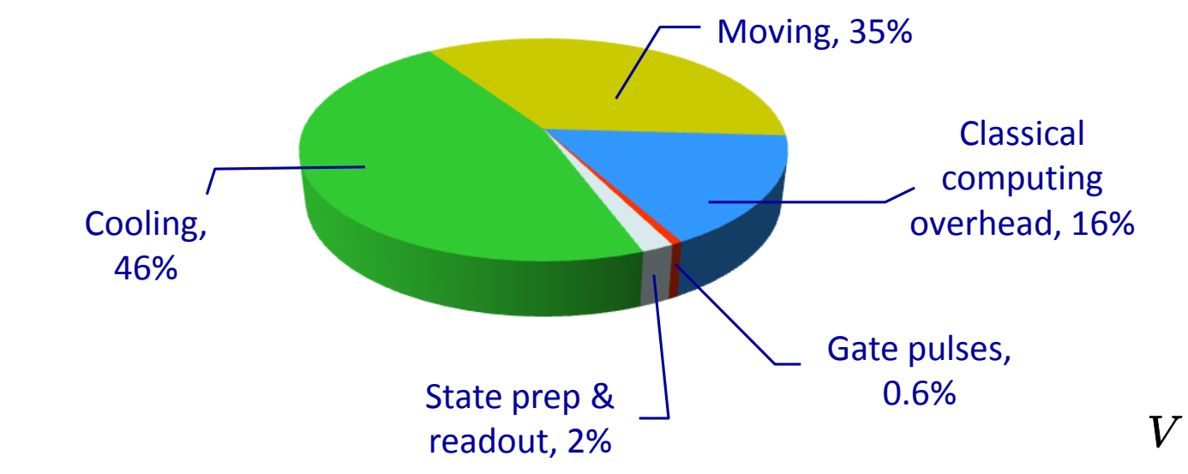
$$\frac{f(\hat{U}.\hat{U},\hat{U}^2)}{f(\mathrm{MaxLike})} = 0.998(4)$$

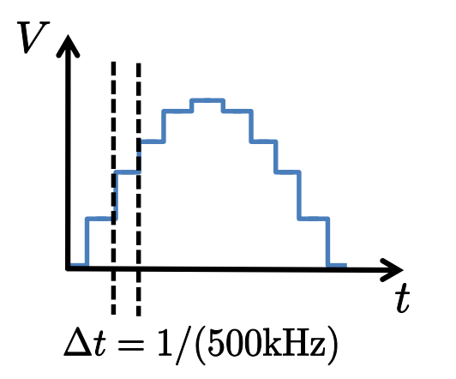
All operations are repeatable and can be interspersed

($f(\mathrm{MaxLike})$ accounts for bias in Maximum Likelihood Estimation - problem for tomography methods)

Smooth voltage supplies for fast transport of ions

Operation time limited by transport and cooling.

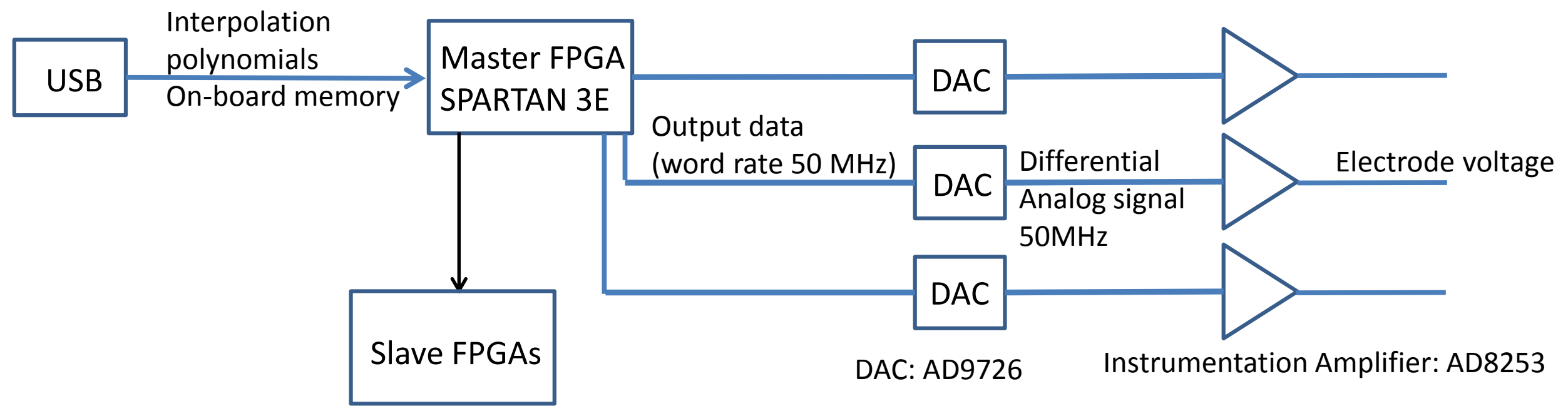




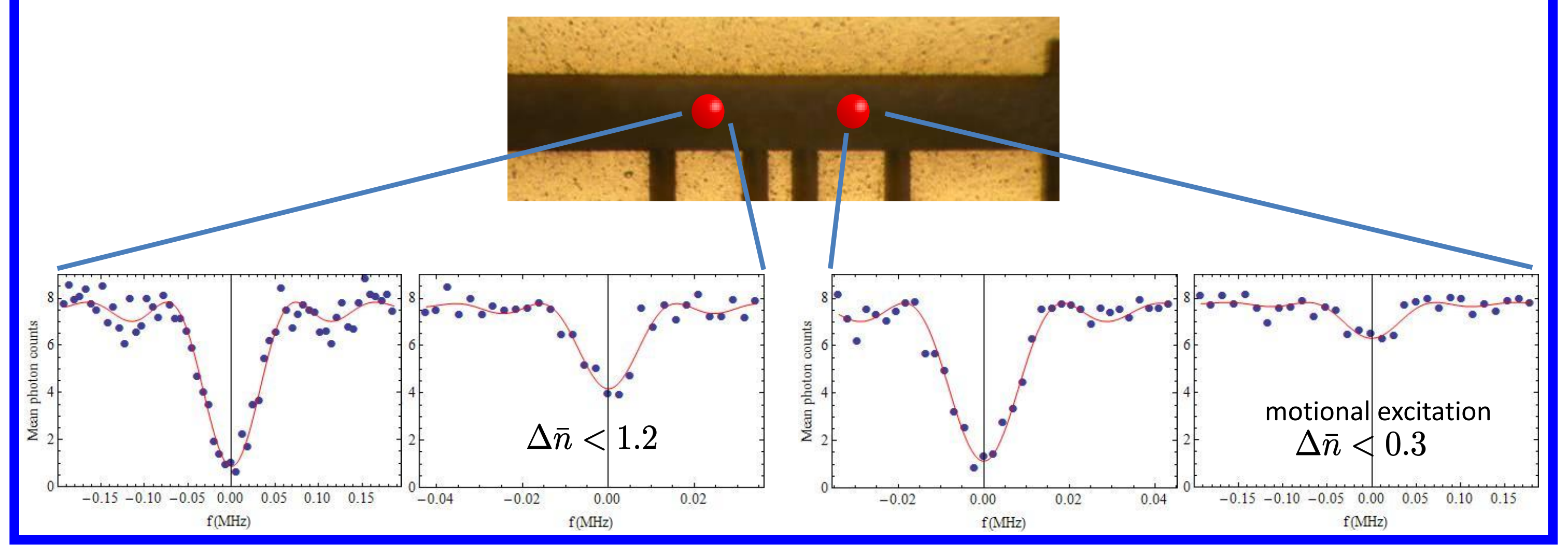
Currently: NI PCI-6733 voltage supplies update at 500 kHz:
- Ion separation requires trap frequency to be lowered through 500 kHz,
- steps result in resonant motional excitation (even with filtering)!

Currently overcome this with lots of sympathetic cooling - takes time.

New home built supply with update rate of 50 MHz >> all ion secular frequencies



Tested two channels by attaching to separation electrode only
- separation of two beryllium ions - record low amounts of heating!



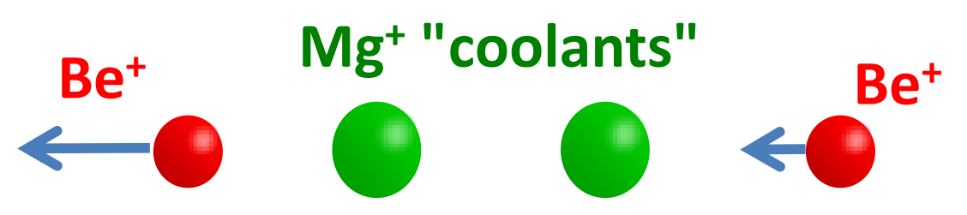
Anharmonic trap potentials

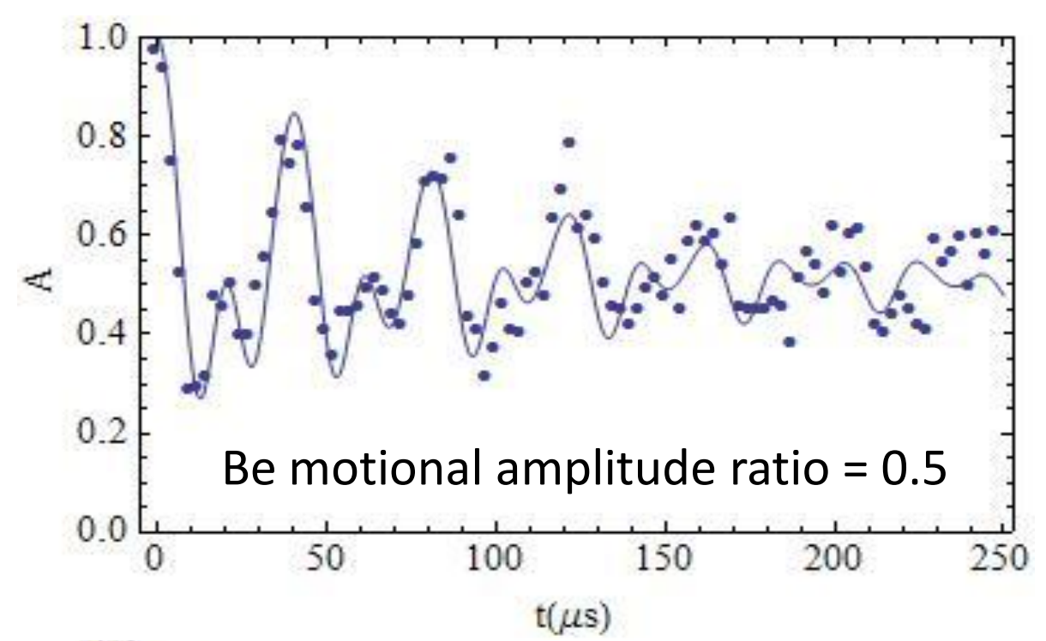
Most work up until now assumes a harmonic potential well. This is generally a good approximation when the electrode size and ion-electrode distance ρ is large compared to the extent of the ion crystal
We observe effects on the motional modes due to higher order terms in the trapping potential, which will become more important with larger crystals and smaller traps.

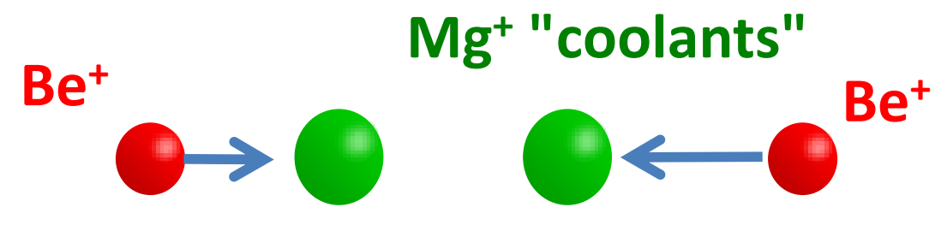
$$V = \alpha_2 z^2 + \alpha_3 z^3 + \alpha_4 z^4$$

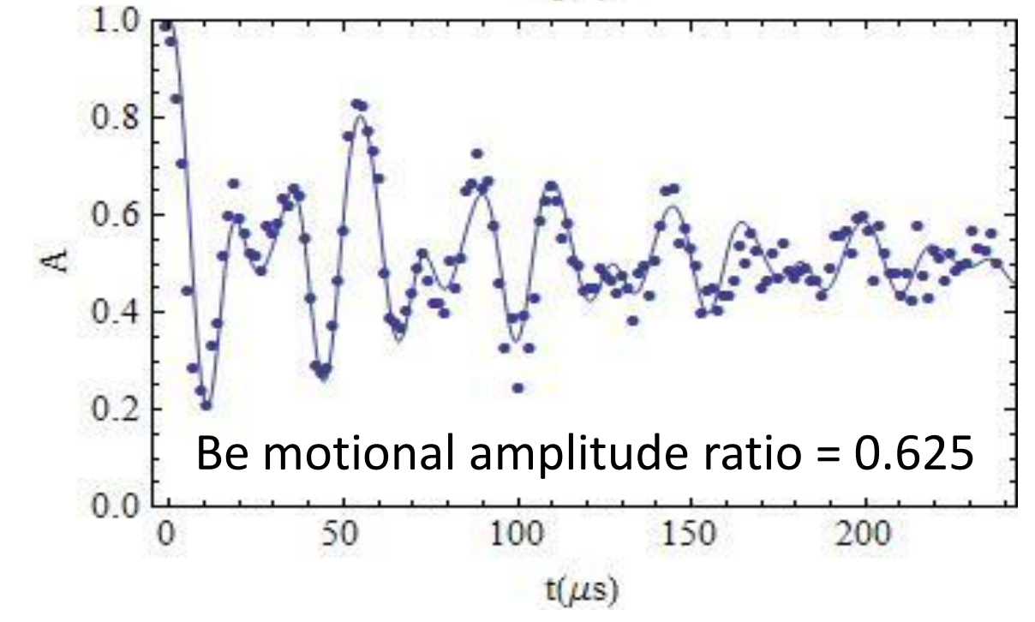
The curvature of the potential is now different at each ion

Odd-order anharmonicity - asymmetry results in different amplitudes for the beryllium ions for our four ion crystal
We observe beating when Rabi flopping on motional sidebands









In an asymmetric ion crystal there is now a mode frequency shift which depends on the ion order