Distribution of entanglement in an ion trap array

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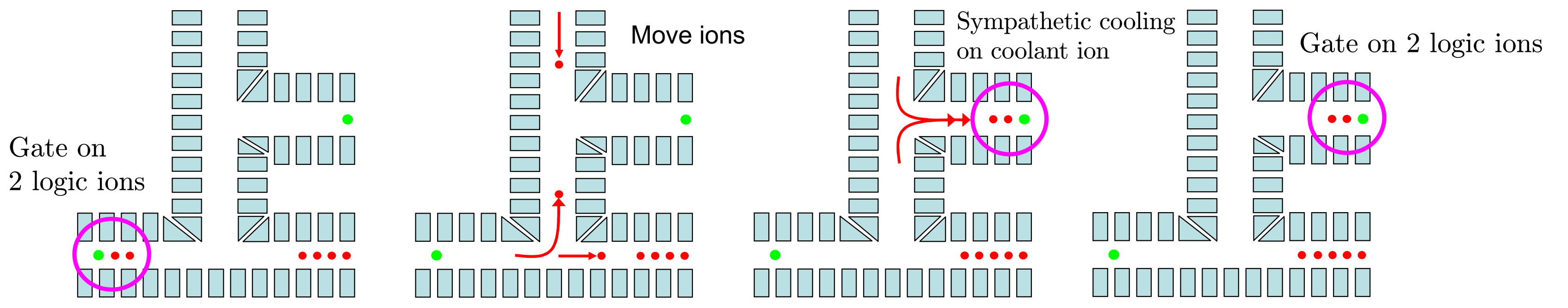
Experimental investigation of scalable ion trap QIP

Two main requirements for scaling up an ion trap quantum information processor:

1) The ability to move information between locations in the processor.
2) High fidelity logic gates.

For 1), move the ions themselves: negligible perturbation of the internal states.

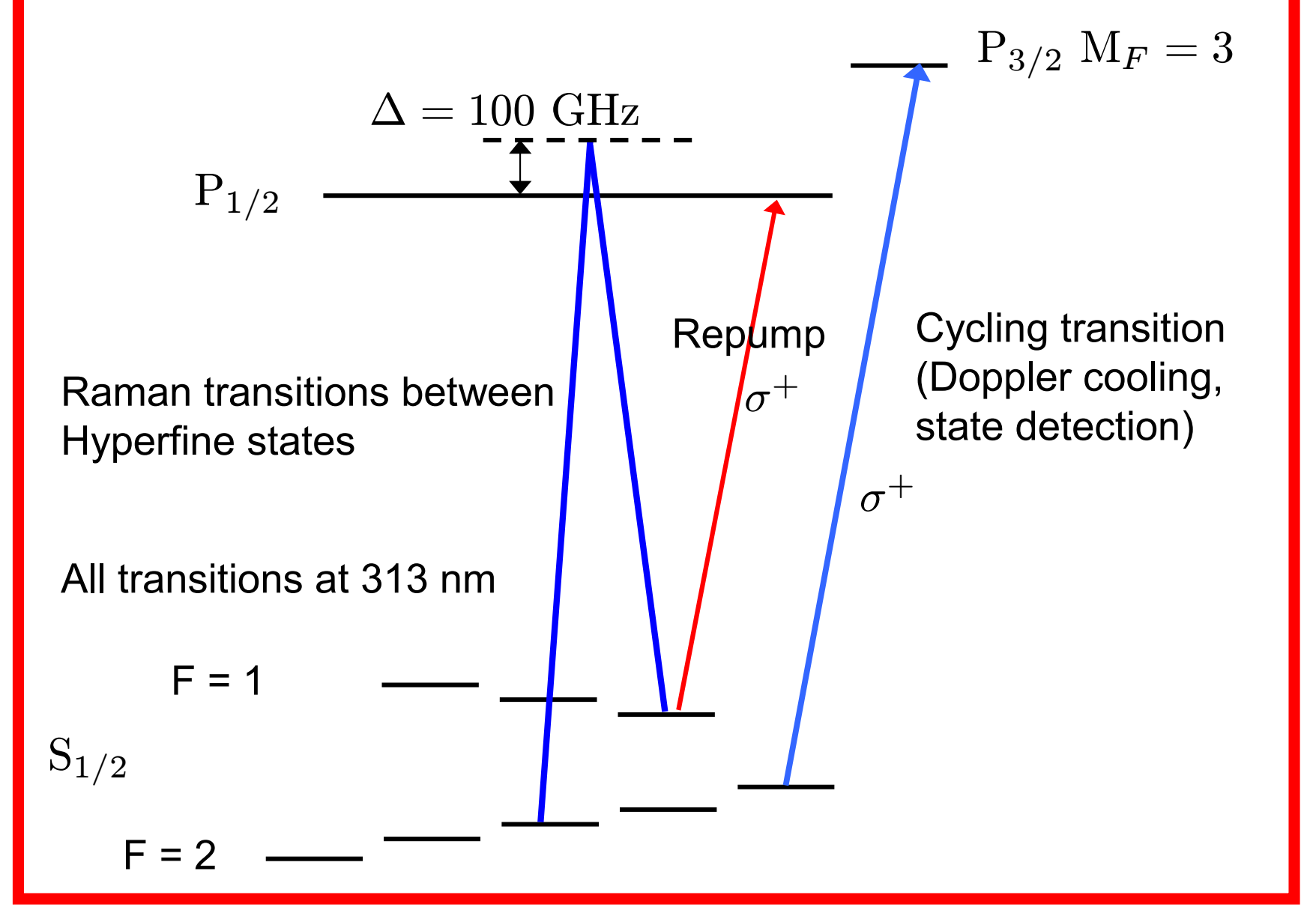
Moving ions heats them up, which decreases the fidelity of 2-qubit gates using a motional mode, therefore we recool the motion while preserving quantum information.



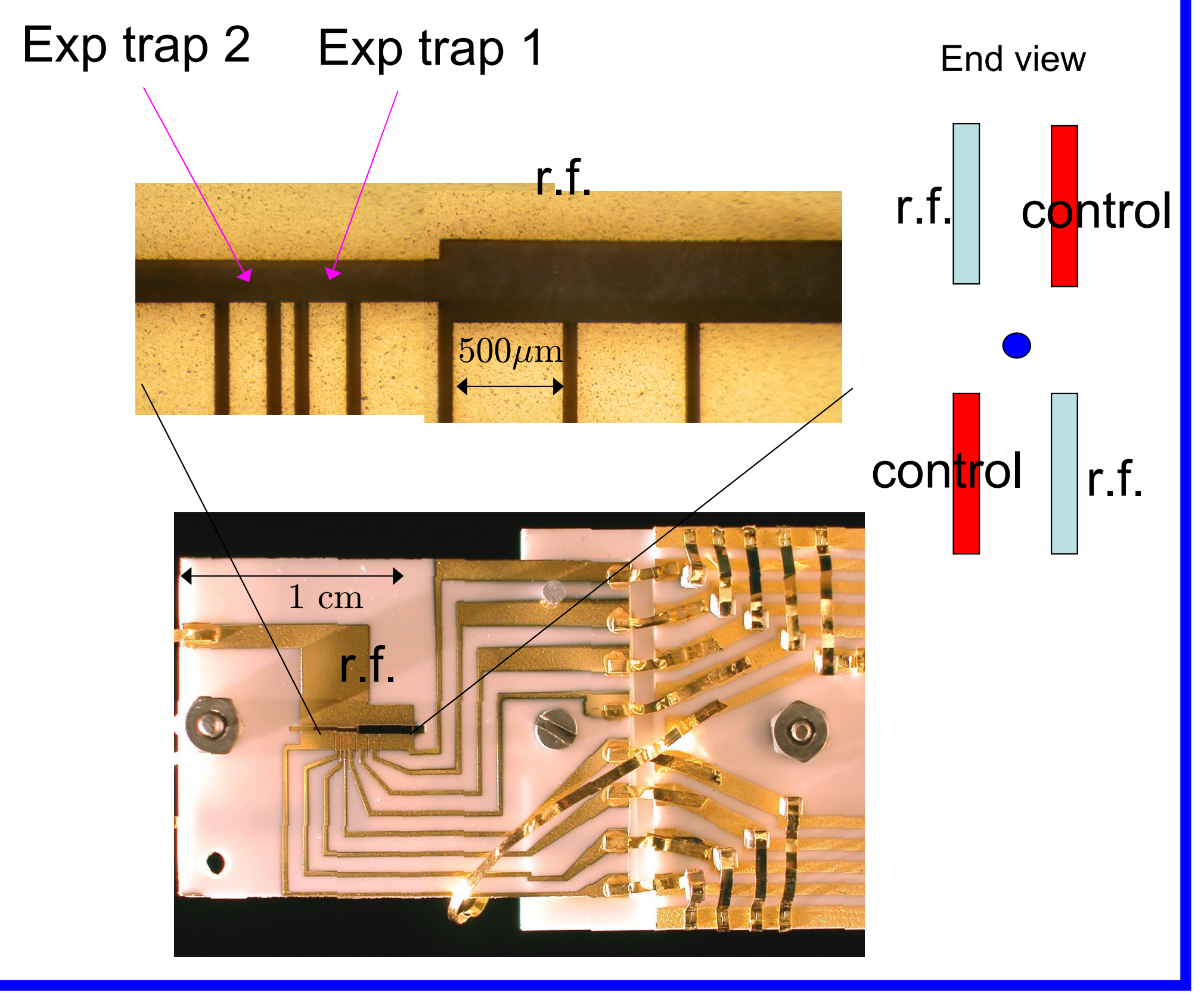
Experiments: multiple high-fidelity single and two-ion gates after transporting ions.

$^9\mathrm{Be}^+$ logic ion

Magnetic field of 119.4 Gauss gives a qubit which is B-field insensitive due to an extremum in the energy difference with respect to magnetic field



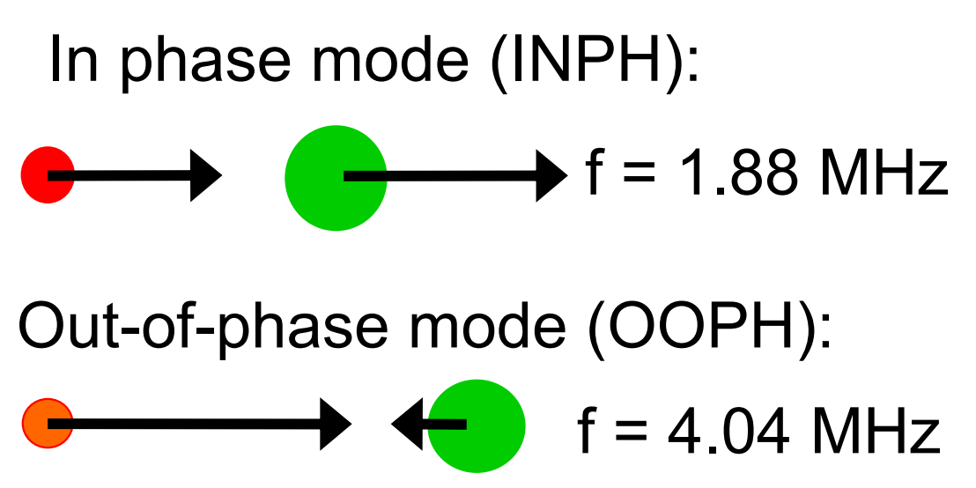
Segmented linear Paul trap



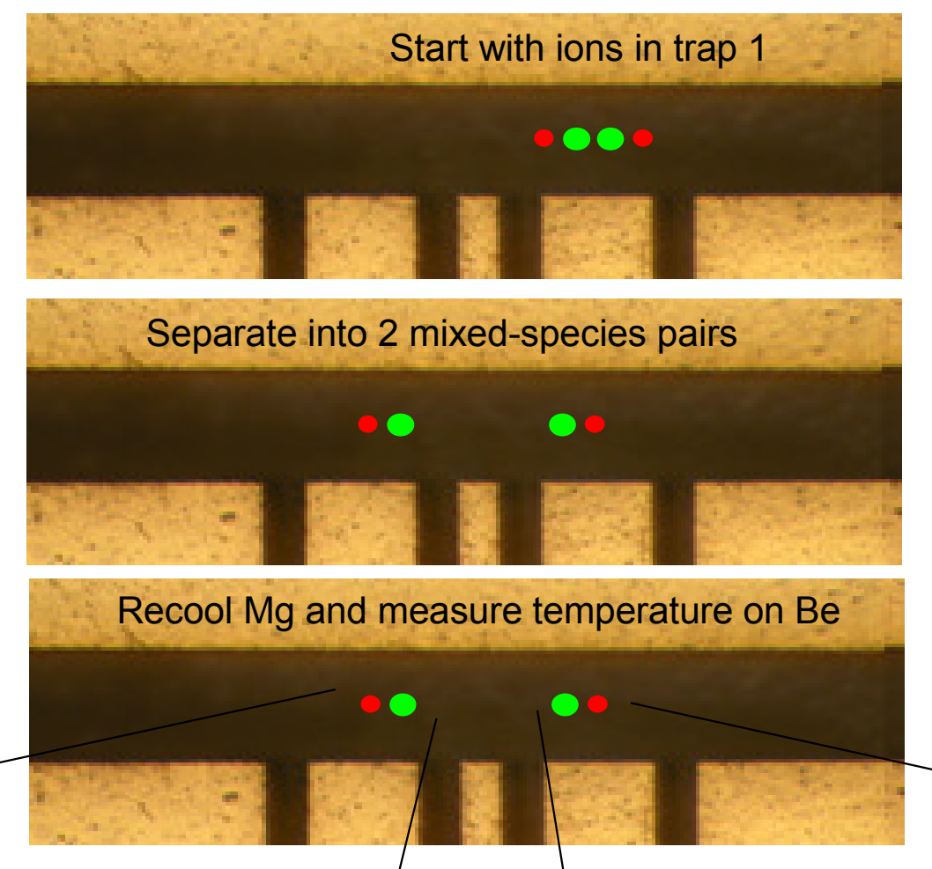
Sympathetic cooling of two-species ion crystals

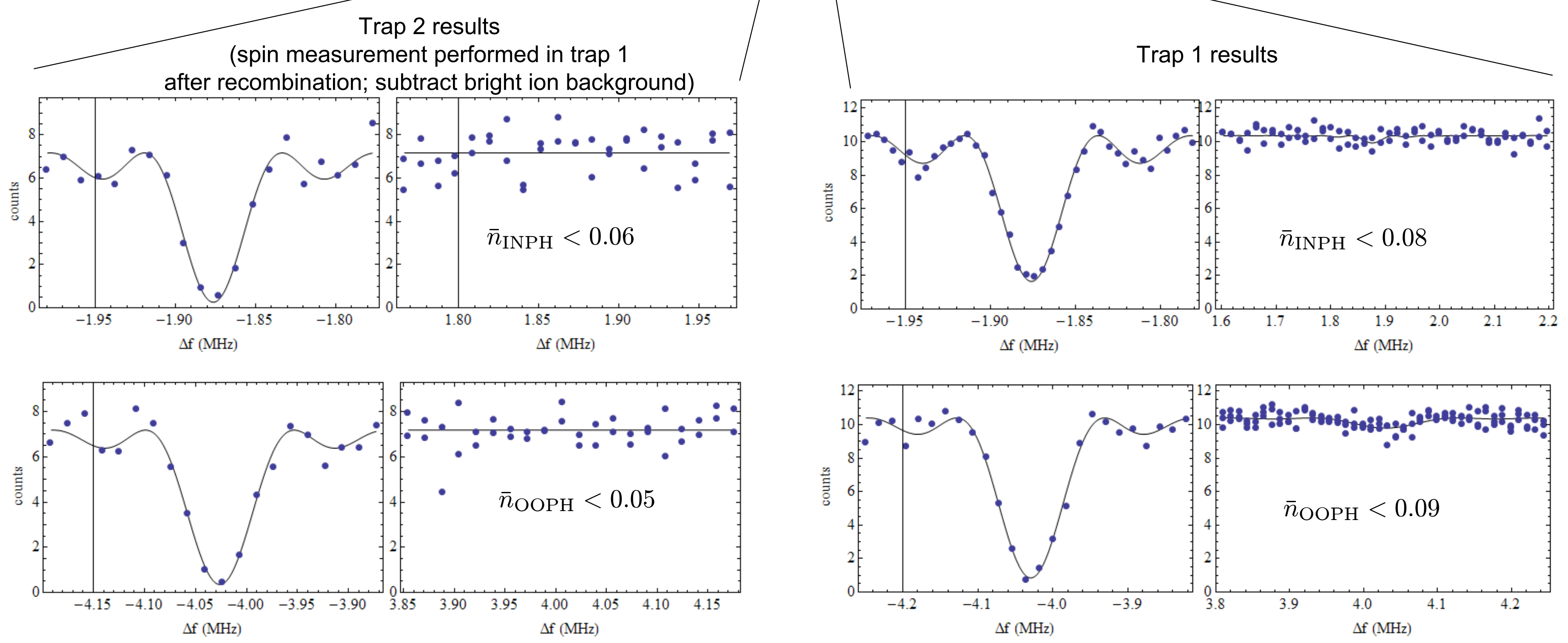
- Spectral addressing of ions – Magnesium transitions at 280 nm are 33 nm detuned from the nearest Beryllium transition (313nm).
- Laser cooling Magnesium doesn't affect the coherence of Be⁺ qubits.
- The Coulomb interaction means vibrational modes are shared among ions.

- We demonstrate Magnesium recooling after separating the Be-Mg-Mg-Be chain.
- Magnesium recooling involves Doppler cooling and resolved sideband cooling on the 1st and 2nd sidebands in each trap.

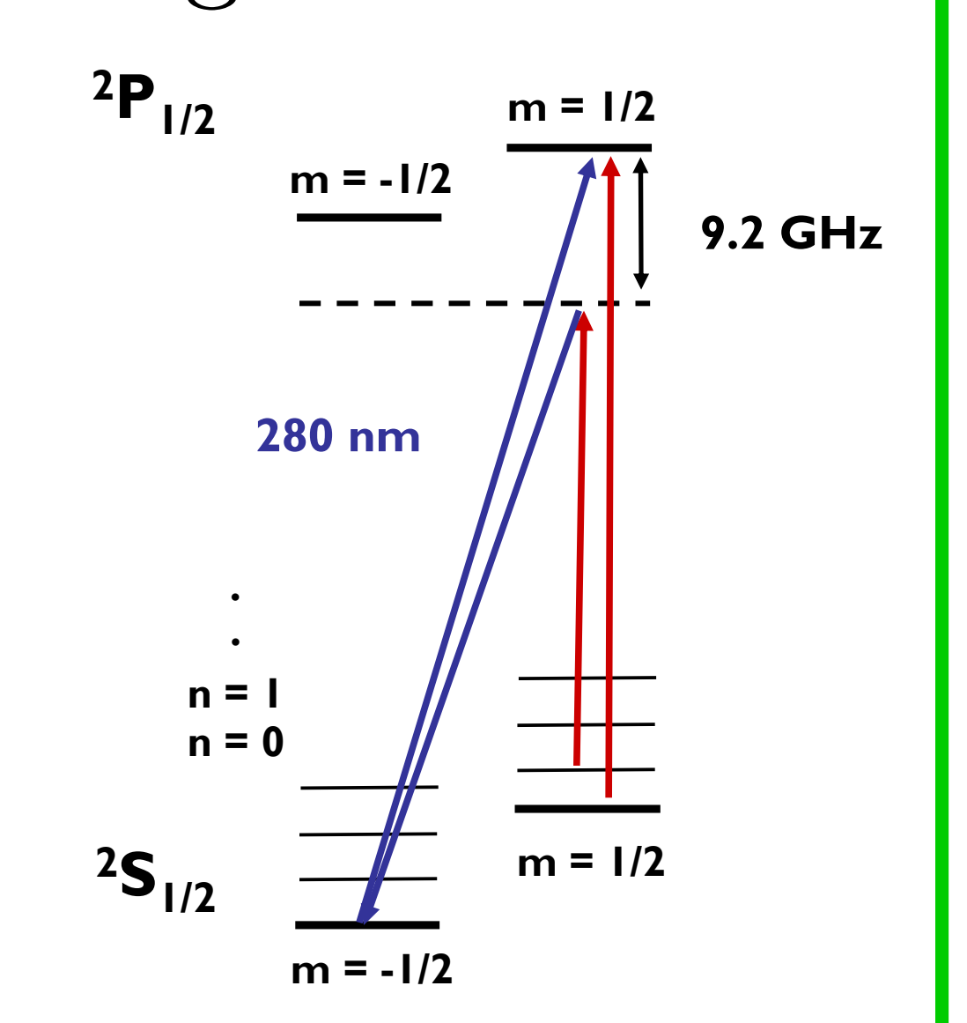


Ions not drawn to scale





$^{24}\mathrm{Mg}^+$ coolant ion



Same beams used for Raman and Doppler cooling.

Creation and separation of DFS states

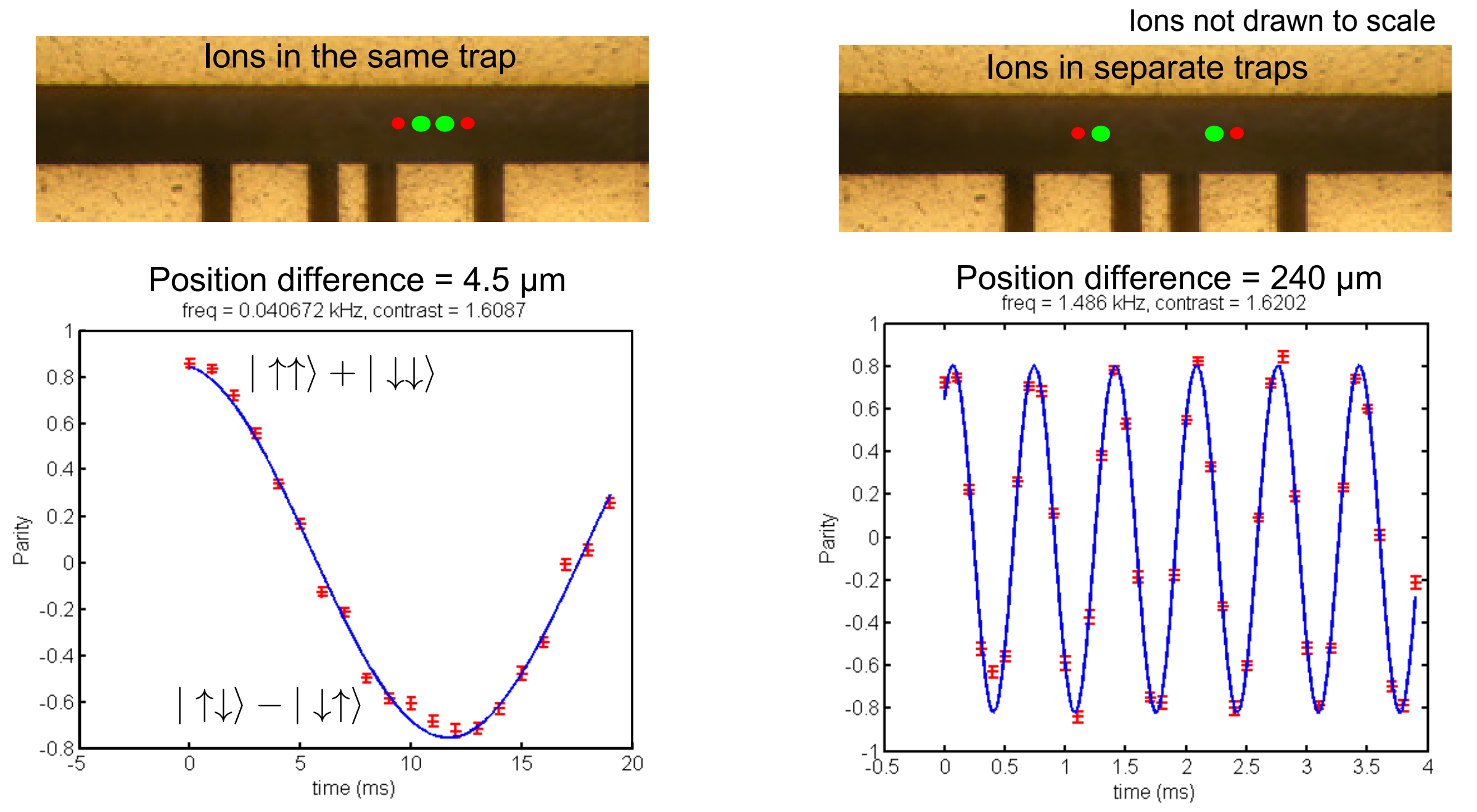
Entangled states of the form $|\uparrow\downarrow\rangle + e^{i\phi}|\downarrow\uparrow\rangle$ are insensitive to correlated phase noise. In an ion trap, this makes them robust against fluctuations in the magnetic field strength, one of the principal mechanisms for spin decoherence.

Magnetic field differences between the two qubits leads to precession of the state of one ion relative to the other. This leads to precession between the singlet and triplet states. We observe this precession for two ions in the same trap, and for two ions separated by 240 microns.

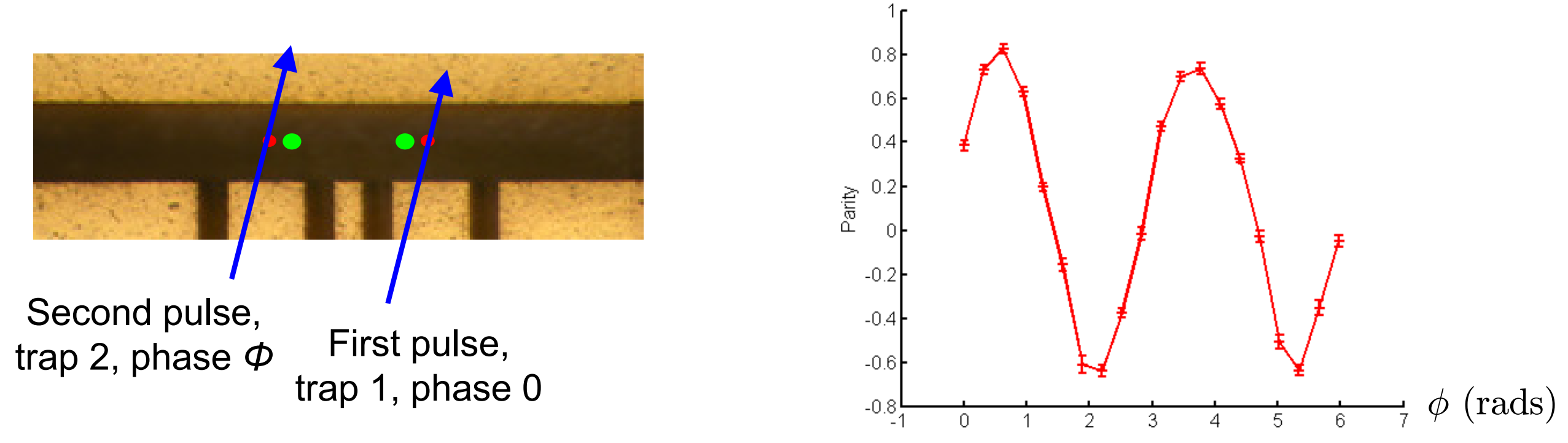
Sequence:

- Create DFS state
- Allow to precess for time *t*
- Use a map pulse: $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \rightarrow |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$; $|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle$
- Measure parity

Ions not drawn to scale



Individual addressing of the ions can compensate for this phase evolution. We address sequentially by switching beams between traps.

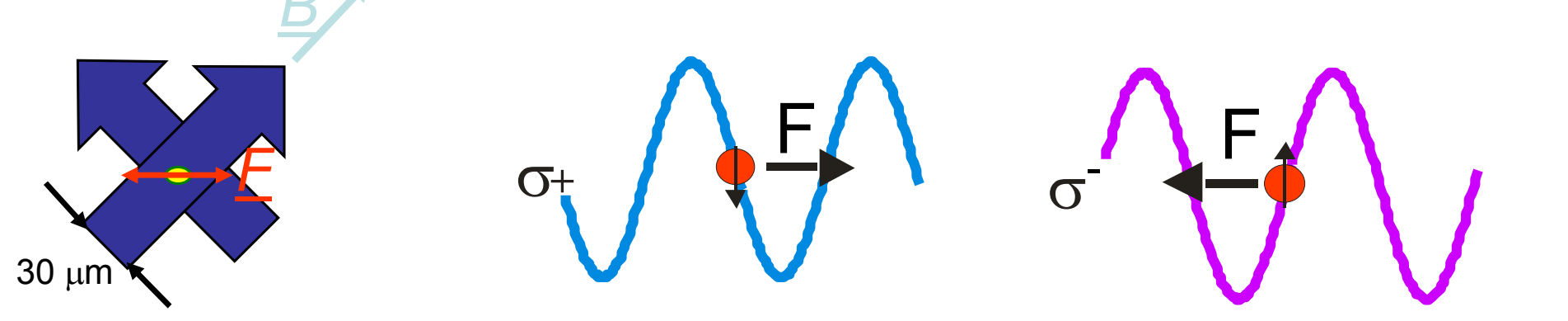


Quantum logic gates with mixed species ion chains

We demonstrate a quantum logic gate between the two Beryllium internal state qubits in our four-ion, mixed-species array. The gate is a geometric phase gate where state-dependent forces are applied to the Beryllium ions (see details of these gates in inset). We produce Bell states with fidelities up to 89%.

How the gate works – the simplest case, a spin half system

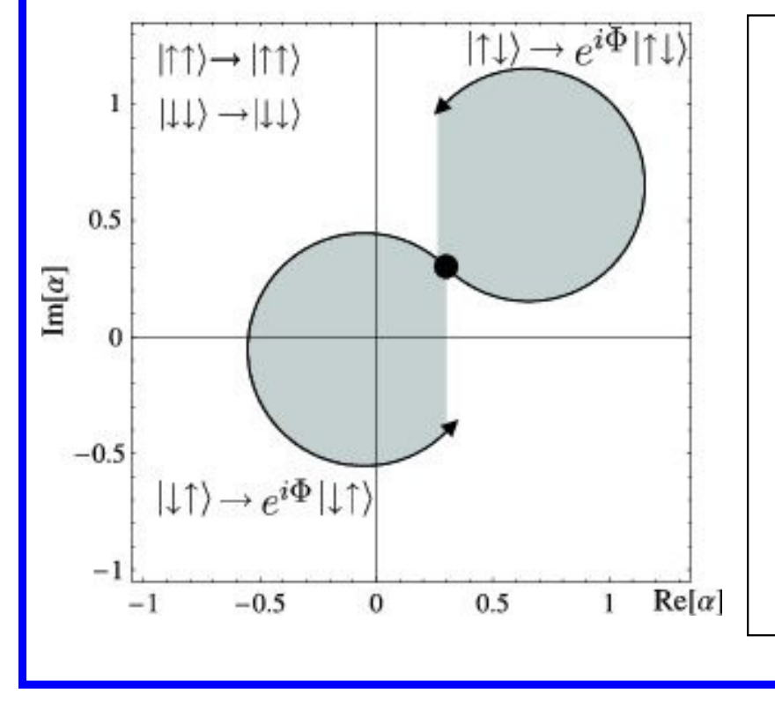
Raman beams set up a “travelling” standing wave, σ^+ and σ^- polarisations out of phase.



Set the ion **separation** to be an **integer number** of effective wavelengths.

Now tune the **frequency** close to one mode **(out of phase mode)**, **resonantly enhancing** excitation of this mode.

A force detuned from resonance displaces the motional state around a circle in *x-p* phase space. States acquire a phase proportional to the area enclosed.



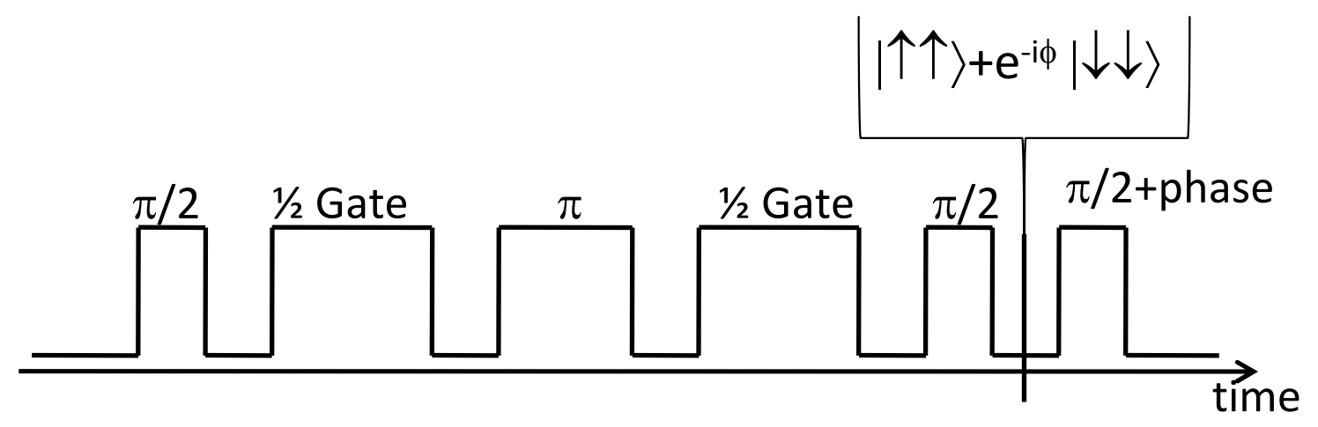
Motional state returns to original position after t = 2π/δ

For $F_S(\uparrow\downarrow)/\delta = 1, \Phi = \pi/2$

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

Proposed and demonstrated
Leibfried et. al. Nature **422** 412 (2003)

Pulse sequence (after re-ordering and cooling)

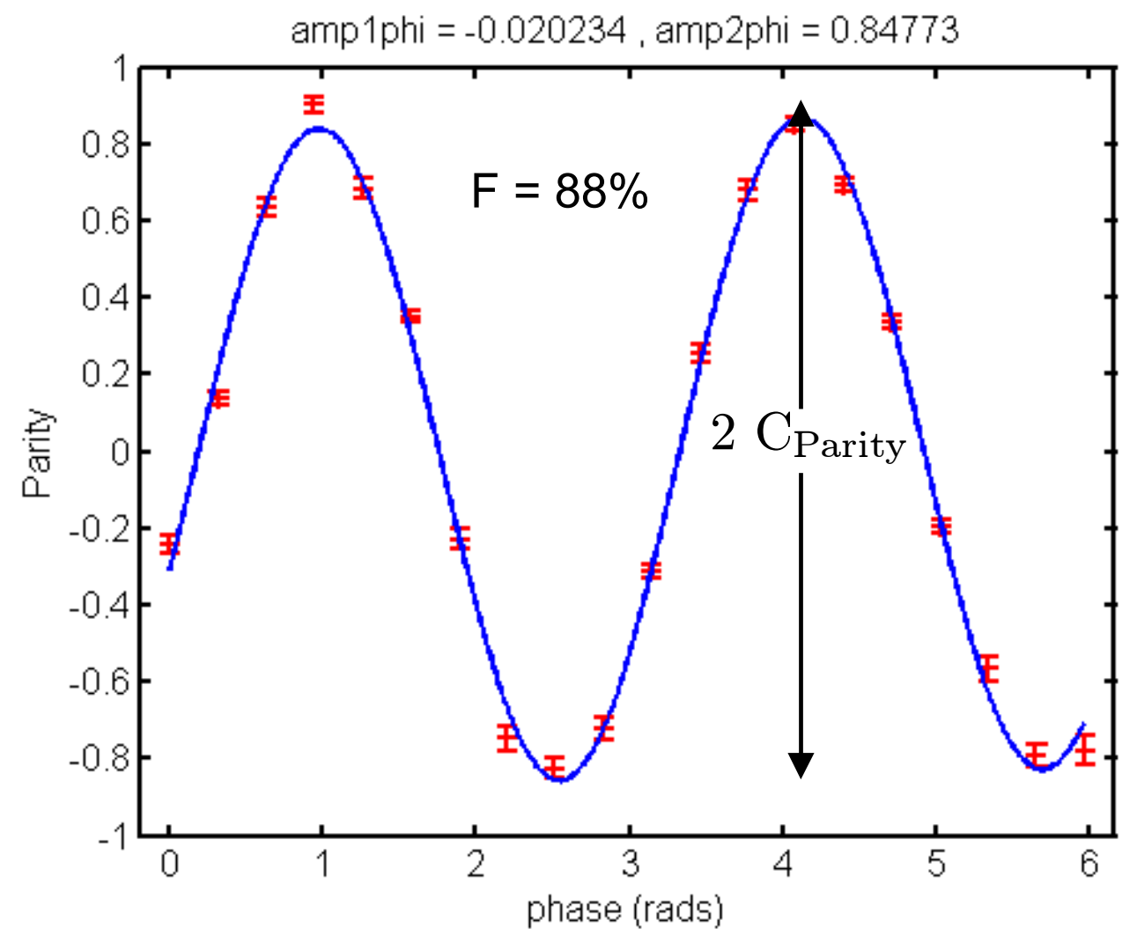


½ gates are performed in each half of the spin-echo sequence, which increases photon scattering but is more robust against single qubit rotations induced by Stark shifts from the gate light.

Fidelity of production of a known Bell state is given by populations at the end of the spin echo sequence and the contrast of the 2φ oscillation in the "parity signal" produced as the phase of the final pulse is scanned. This contrast is an entanglement "witness."

$$\mathrm{Parity} = P(\uparrow\uparrow) + P(\downarrow\downarrow) - (P(\uparrow\downarrow) + P(\downarrow\uparrow))$$

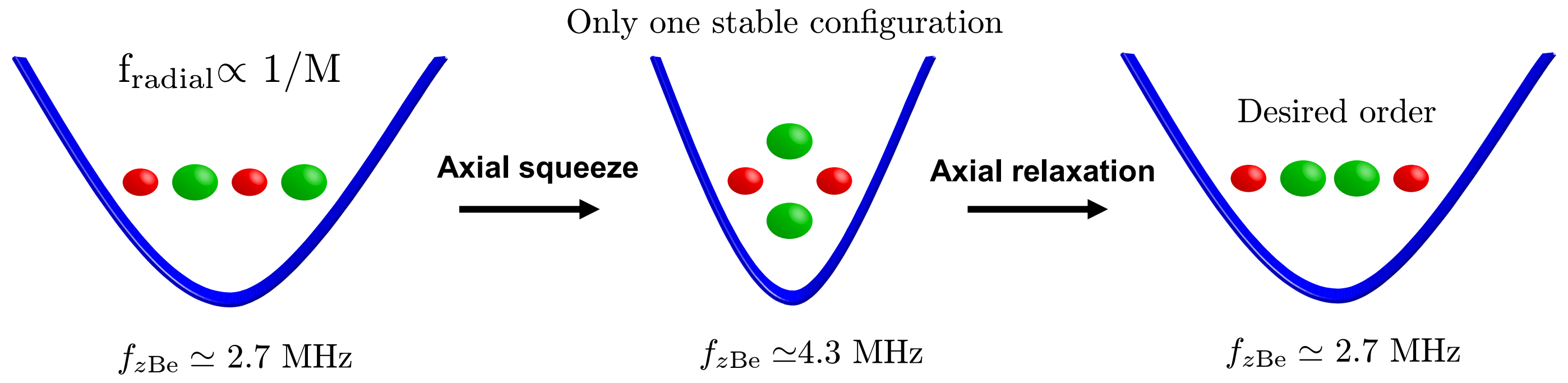
$$F = \tfrac{1}{2}(P(\uparrow\uparrow) + P(\downarrow\downarrow) + C_{\mathrm{Parity}})$$



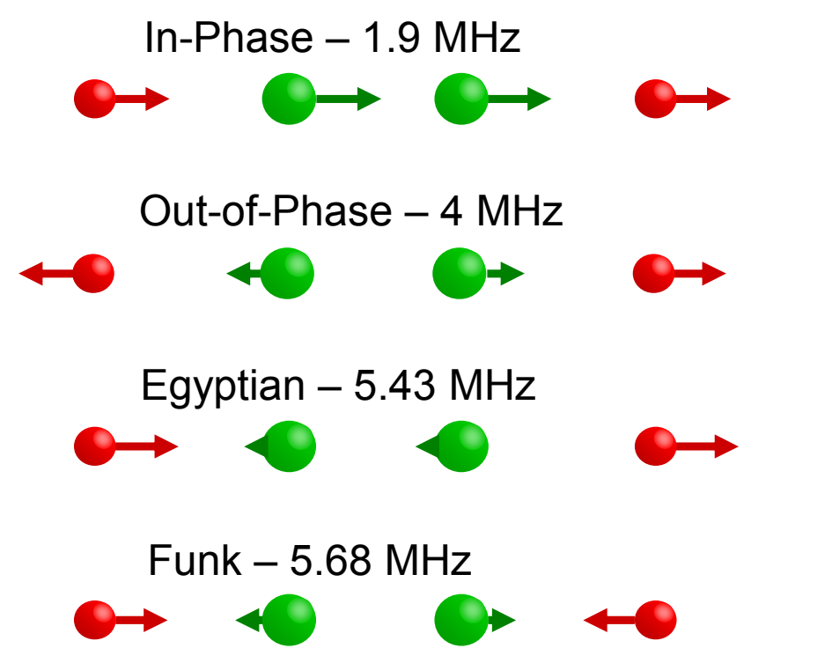
Re-ordering and cooling a two-species, 4 ion array

For sideband cooling and quantum logic gates, a prerequisite is knowing the frequencies of the normal modes.
For a four-ion, mixed-species array, this depends on ion order. Therefore it is crucial to be able to re-order the crystal.

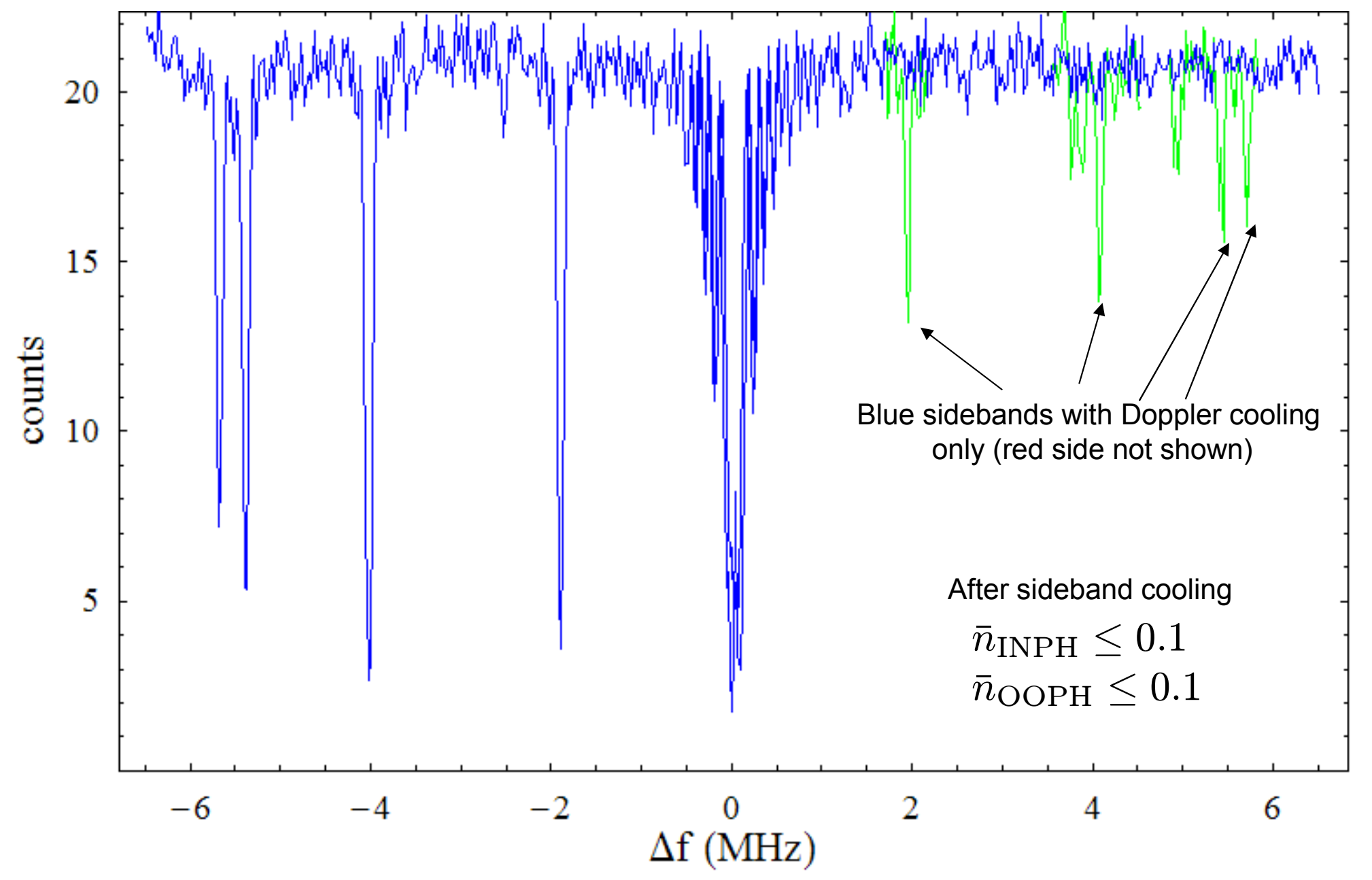
The radial pseudopotential strength is mass-dependent, whereas the static axial potential is not.
As axial confinement increases, heavier ions “pop out” radially.



Axial modes of an ordered array



Full scan over red and blue sidebands: sideband cool then apply a fixed-length Raman probe pulse at the carrier frequency + Δf.



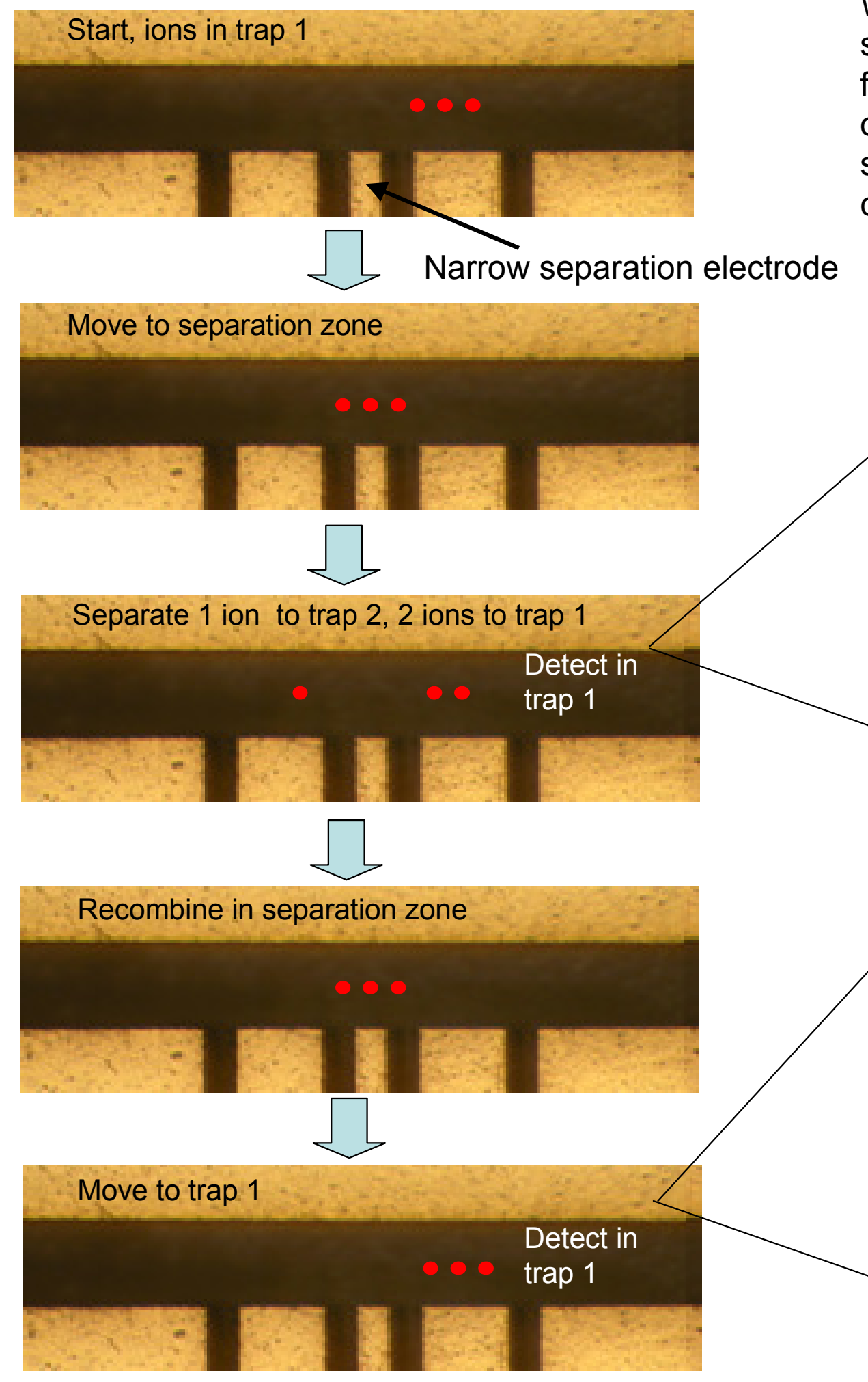
Separating large ion crystals

Voltage waveforms applied to the control electrodes separate string of ions into smaller groups. The voltage waveforms consist of three parts:

1) Move the ions over the separation electrode while maintaining the trap frequency.
2) Split the single well potential into a double well while maintaining the highest possible trap frequency to protect against heating.
3) Move the two wells to the separate trap positions.

Experimental sequence. Pictured example: 3 ions

Ions not drawn to scale



We observe the loss in fluorescence in one trap after separating, then recombine the ions and observe the fluorescence level again. We then change the voltage on one of the end electrodes to a new value and repeat the sequence. The control voltage determines where the ion crystal is split.

Experimental results: 9 ions