Ground state cooling and coherence studies of ions in a Penning trap

R. C. Thompson, J. F. Goodwin, P. Hrmo, V. Jarlaud, M. K. Joshi and G. Stutter

Quantum Optics and Laser Science, Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK

Abstract

- Trapped ions are an ideal platform for quantum simulation and measurement
- Previously we have demonstrated resolved-sideband cooling of the axial motion of a single $^{40}Ca^{+}$ ion in a Penning trap, yielding a ground state occupancy of 98(2)% [1]
- Cooling multiple modes from far beyond the Lamb-Dicke regime ($\eta^2(2n+1) \sim 6$) requires complex, multi-stage sideband cooling sequences
- We have now demonstrated high ground-state occupancy for both axial modes of a two-ion crystal simultaneously
- We have also achieved coherent manipulation of one and two ions in a Penning trap
- Applications include multi-ion qubit quantum operations in a Penning trap

Penning Trap

A Penning trap confines ions using a static quadrupolar electric potential with a strong ($\sim$2 T) axial magnetic field:

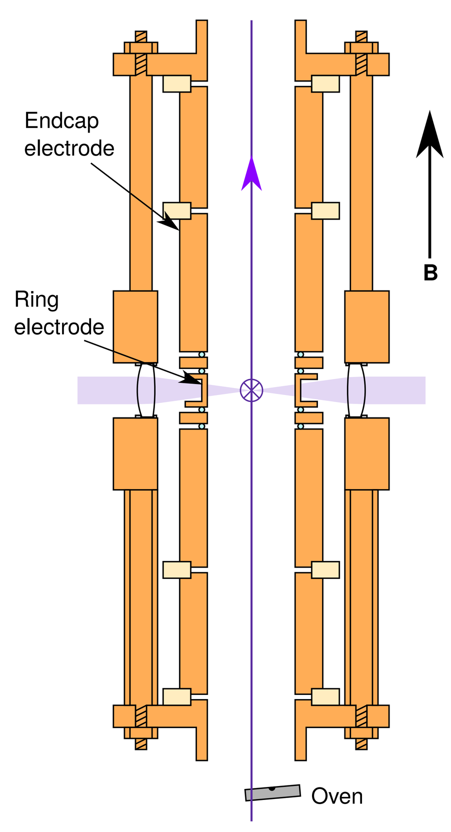
- Axial confinement from the **E**-field
- Radial confinement from the axial **B**-field
- Crystal rotates around the direction of **B**-field
- *Axial motion:* Harmonic motion parallel to magnetic field at ω_z
- *Radial motion:* Superimposed circular magnetron and modified cyclotron motions at ω_m and ω_c'

Schematic of the trap geometry: Ring electrode split into 4 segments for the axialisation field [2]

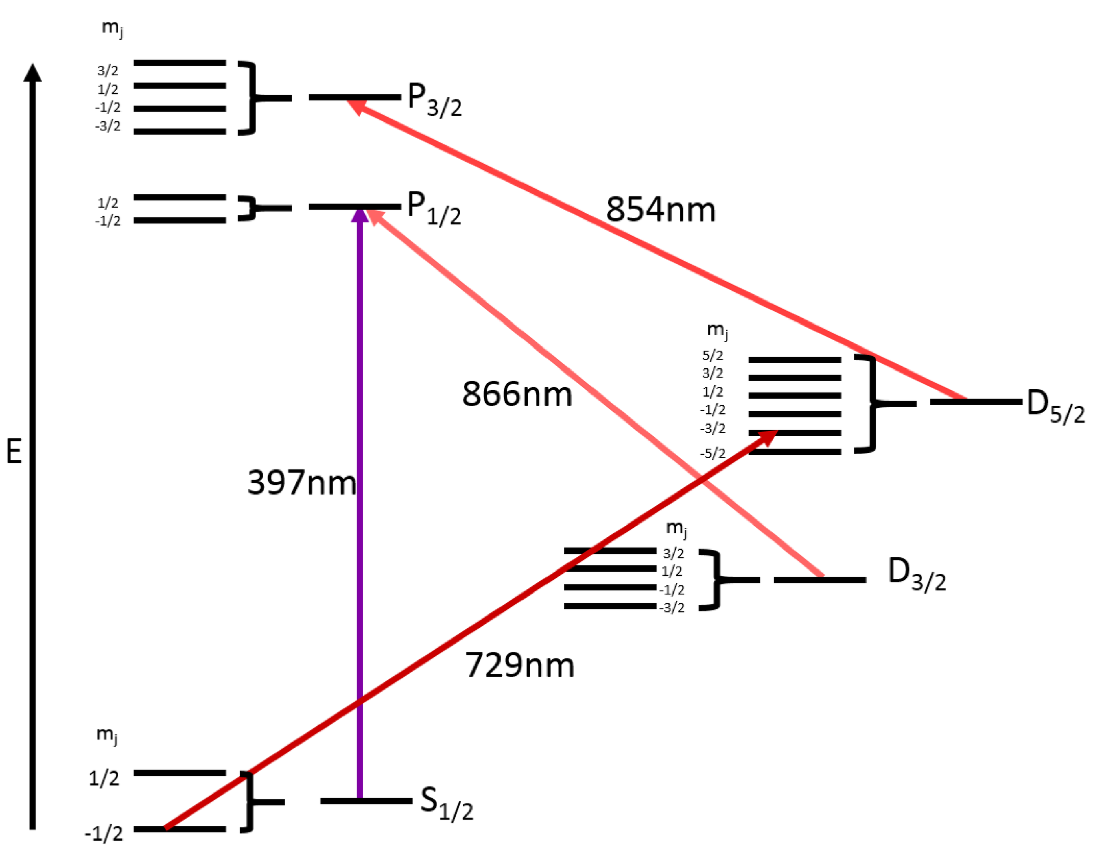
Internal diameter of the trap is 21 mm

No micromotion helps to give low heating rates

Sideband cooling allows us to study quantum dynamics of small Coulomb crystals



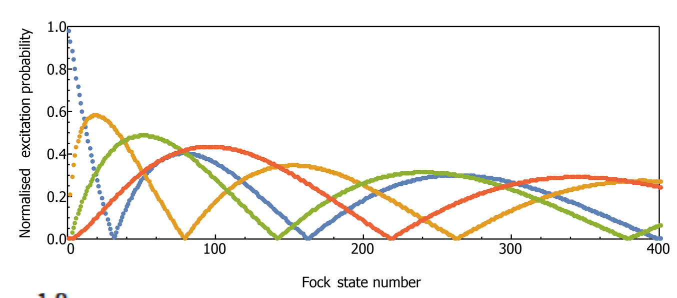
Calcium-40 ions

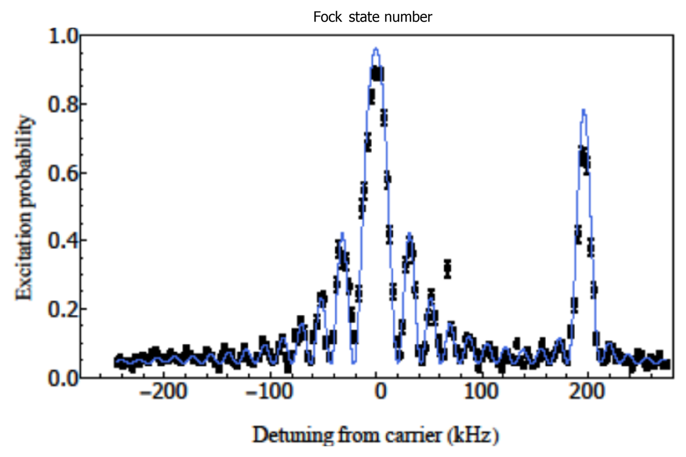


- Doppler cooling and detection are performed on the $S_{1/2} \leftrightarrow P_{1/2}$ transition at 397 nm
- Decay of the ion to the $D_{5/2}$ and $D_{3/2}$ states is avoided by re-pumping with 854 nm and 866 nm lasers, using a fibre EOM to drive all Zeeman components
- Spectroscopy is performed on $S_{1/2} \leftrightarrow D_{5/2}$ transition with a 729 nm laser (linewidth of < 1 kHz) [3]

Sideband Cooling of one ion

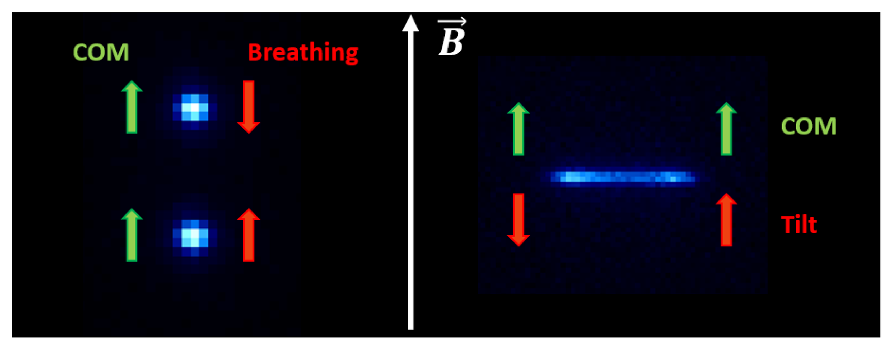
- For sideband cooling, the 729 nm laser is tuned to the red sidebands of the $S_{1/2} \leftrightarrow D_{5/2}$ transition
- Sidebands have minima for particular n values
- Complicated multistage cooling sequence used to cool from: $\bar{n}_{\text{Doppler}} \sim 55$ to $\bar{n}_{\text{SBC}} = 0.02(2)$
- Heating rate is measured to be $\sim$ 2.5 phonons/s

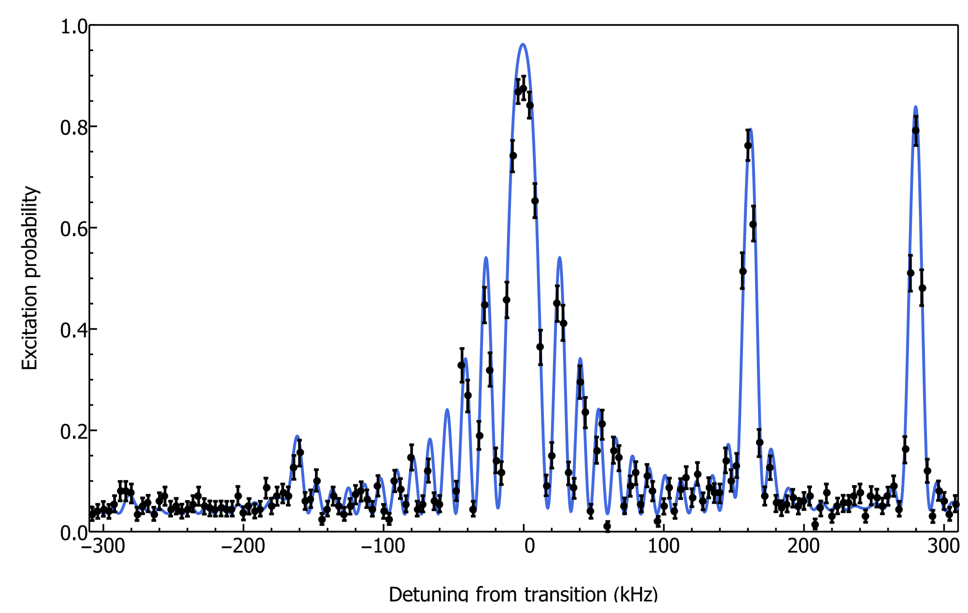




Sideband cooling of a two-ion Coulomb crystal

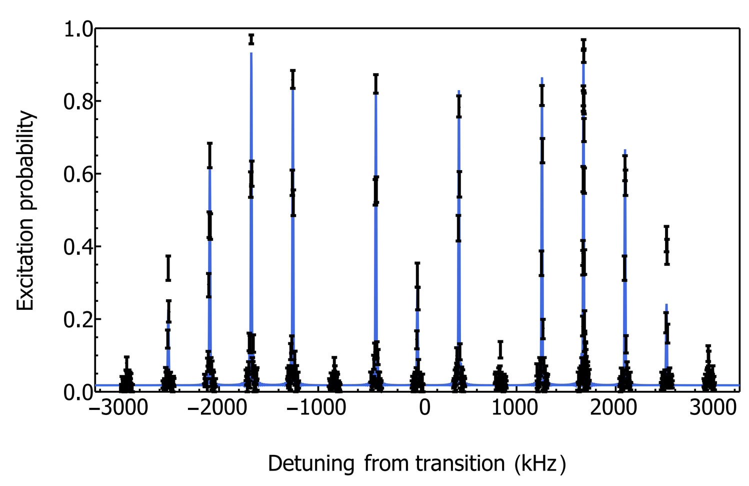
- For two ions: Two orientations are possible
- *String*: Ions align along the magnetic field direction; axial strength < radial strength
- *Planar crystal*: Ions rotate in the radial plane (perpendicular to **B**); axial strength > radial strength
- Both configurations exhibit in-phase (COM) and out-of-phase axial motional modes
- With two modes the Doppler spectrum is much more complicated than a single ion spectrum
- Both motions start well outside the Lamb-Dicke regime
- Simultaneous cooling of both modes requires a complex cooling sequence due to dependence of *every* sideband strength on *both* quantum numbers
- Spectrum of sideband-cooled two-ion string (right) gives $\bar{n}_{\text{COM}}$ = 0.30(4) and $\bar{n}_{\text{B}}$ = 0.07(3)

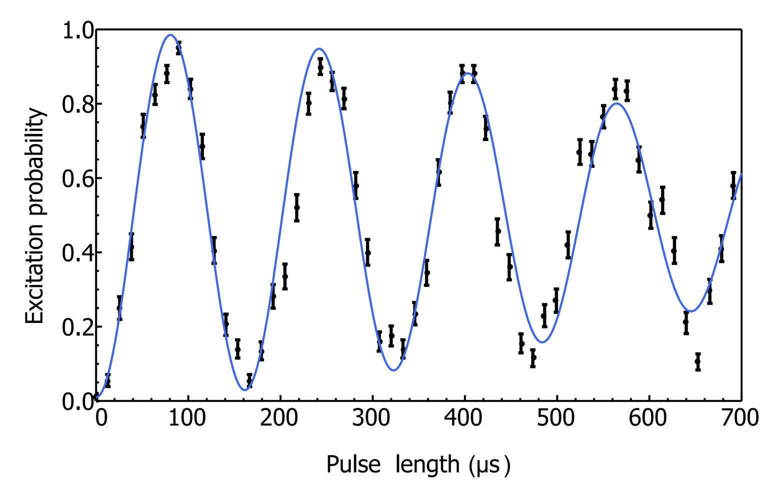




Coherent manipulation of a sideband cooled ion

- Rabi oscillations on the carrier transition after sideband cooling gives optical coherence time $\sim$ 1.4 ms
- Ramsey plot gives a similar coherence time
- Coherence time increased using UDD techniques
- Motional coherence time is $\sim$ 0.3 s
- Ion motion can be 'heated' by driving the first *blue* sideband after sideband cooling
- Final state of the motion is at one of the minima of the sideband strengths (shown in plot above)
- Spectrum (right, upper pane) shows a missing sideband, giving $\bar{n} \sim 288$ with $\Delta n \sim 14$ here
- Rabi oscillations on the 4$^{\text{th}}$ red sideband (right, lower pane) show coherent oscillations even at this high value of n
- Coherent states of motion can be generated using a bichromatic beam





Outlook

Summary

- We have cooled one and two ions to their motional ground states
- Low heating rates for one and two ions, few phonons per second
- We have observed coherent dynamics of the motional and electronic states of the trapped ions.

Future work

- Two-qubit gates with the sideband-cooled ion crystal
- Sideband cooling of the radial motion: Simultaneous cooling of cyclotron and magnetron modes
- Extension of sideband cooling to a bigger crystals including 3D structures

References

[1] J. F. Goodwin et al. Resolved-Sideband Laser Cooling in a Penning Trap, Phys. Rev. Lett. 116, 143002 (2016).

[2] S. Mavadia et al. Control of the conformations of ion Coulomb crystals in a Penning trap, Nature Communications, 4, 2041 (2013).

[3] S. Mavadia et al. Optical sideband spectroscopy of a single ion in a Penning trap. Phys. Rev. A, 89, 3, 032502 (2014).

Contact Information

Web www.imperial.ac.uk/ion-trapping

Email r.thompson@imperial.ac.uk

Phone +44 20 7594 3606

Twitter @iontrapimperial