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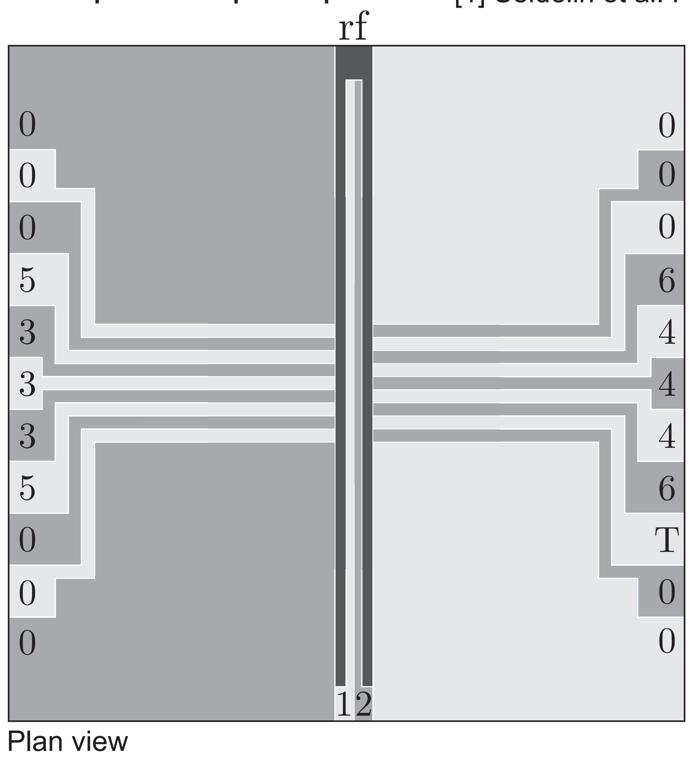
The Oxford planar ion trap project

Ion Trap Quantum Computing Group - Department of Physics - University of Oxford

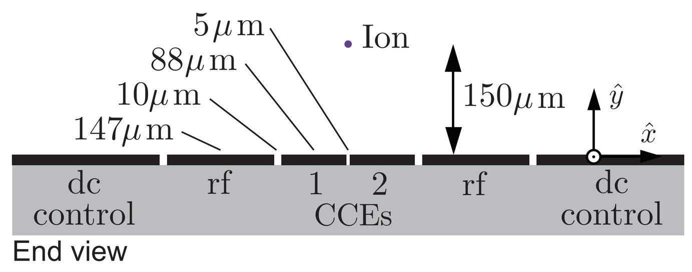
Oxford Fabrication - New J. Phys. Allcock et. al. (2010)

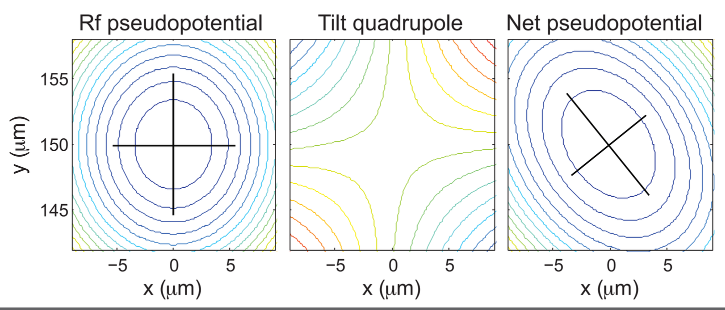
Planar traps based on a simple metal patterned substrate have recently been demonstrated at NIST [1] and MIT [2] with promisingly low heating rates measured. This type of trap is inherently scalable, and manufacturable in-house on short time scales allowing rapid testing and development of electrode geometries. We have fabricated a trap with a geometry similar to the proposed Sandia Mk2 (see below) as a proof of principle.

[1] Seidelin et al. PRL 96, 253003 (2006), [2] Labaziewicz et al. PRL 100, 013001 (2008)

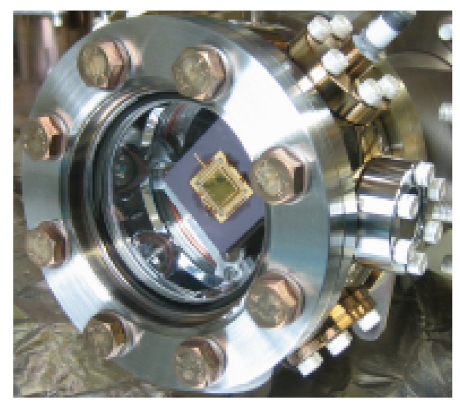


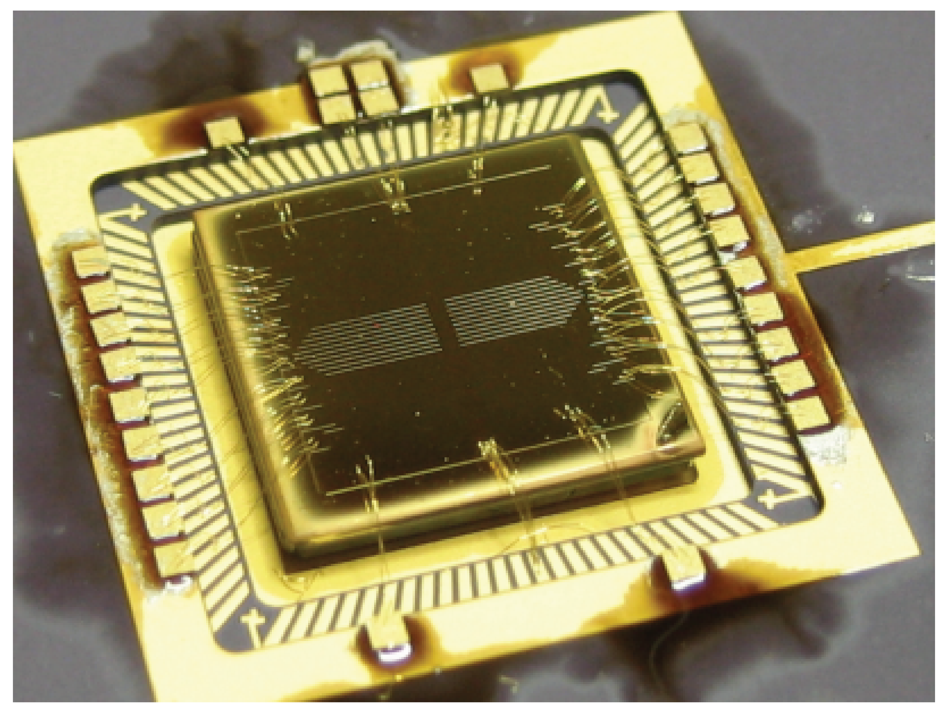
Fabrication Process
Quartz substrate with gold electrodes.
Electrodes electroplated over silver seed layer.
Based on MIT method. See thesis of J. Labaziewicz.





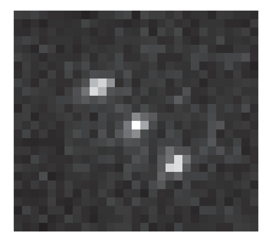
Trap under vacuum (right). Imaging is through the front window which is conductive (ITO coating) to prevent charging. The laser beams pass through the side windows and pass parallel to the trap's surface.

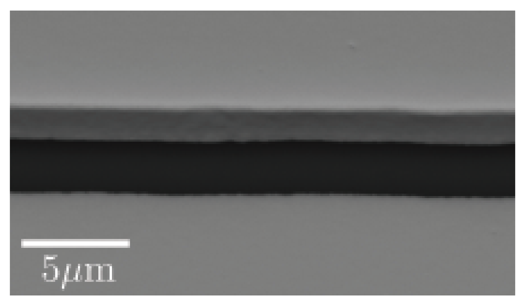




Ion-Surface Distance	150 μm
Rf Frequency	25.8 MHz
Rf Voltage Amplitude	112 to 223 V
Pseudopotential Depth	47 to 188 meV
Radial Secular Frequency	2.0 to 4.0 MHz
Axial Secular Frequency	300 kHz to 1.2 MHz
Ion Lifetime (typical)	5 min

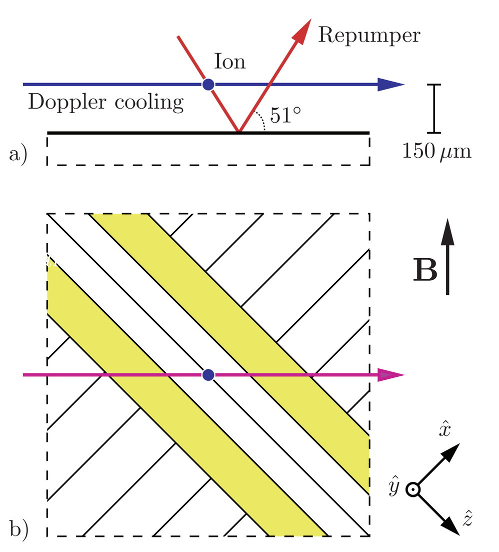
Our trap (far left) is of a '6-wire' design. The split central control electrode (CCE) allows a static quadrupole (above, centre) to be applied at the ion's location with the dc electrodes. This tilts the radial normal modes so that the laser cooling beams couple efficiently to them (left).





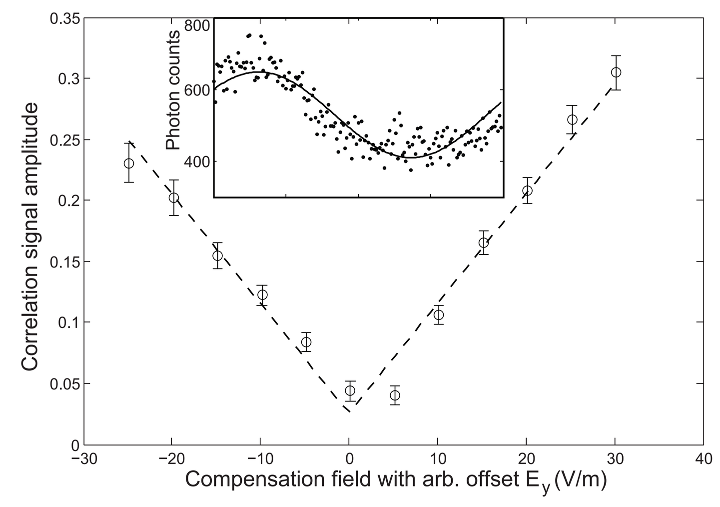
SEM image of an insulating electrode gap, angled to show gold thickness (above left). The trap wire-bonded into a CPGA carrier (top). The carrier also includes single-layer 820pF filter capacitors for the dc electrodes.
Three calcium ions in the trap (above right).

Micromotion Compensation

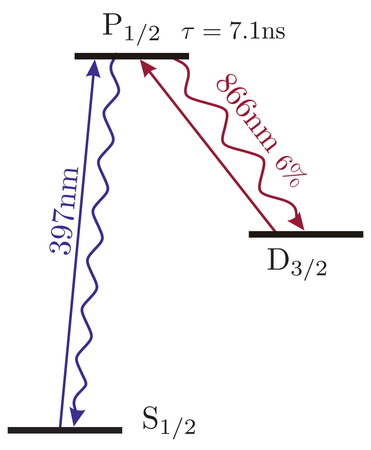


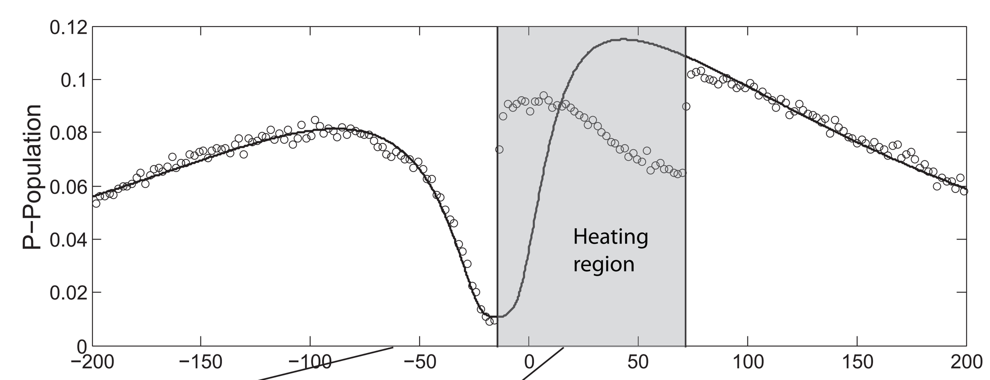
Trap rf drive causes driven micromotion when ion is displaced from rf null by stray fields. Doppler shifts cause correlation between 397nm ion fluorescence and trap rf which can be used for micromotion detection [3]. Beams in plane of trap cannot detect micromotion out-of-plane so we reflect 866nm repumper off trap (left). In regime of high repumper intensity the Doppler shifts of the repumper couple to the P-population and modulate the fluorescence

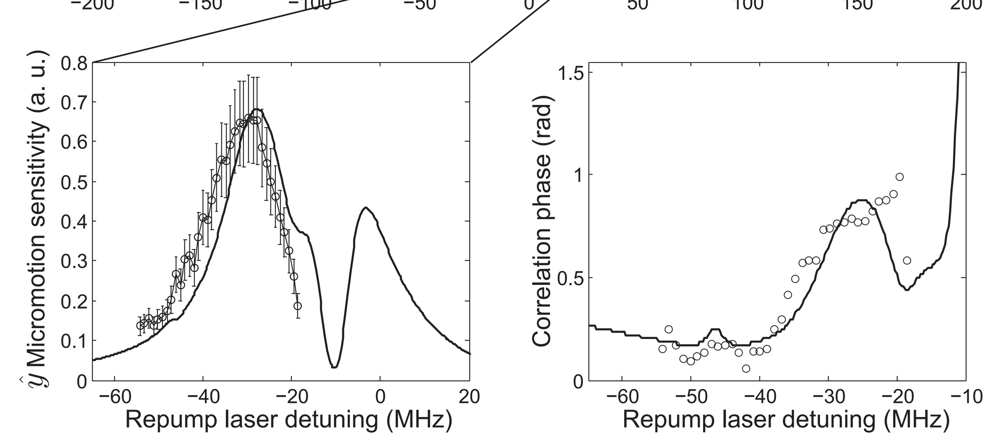
[3] Berkeland et al. J App. Phys. 83, 5025 (1998)



A typical rf correlation scan (inset, left). By applying a compensation field and monitoring the correlation scan we can null any micromotion (left).

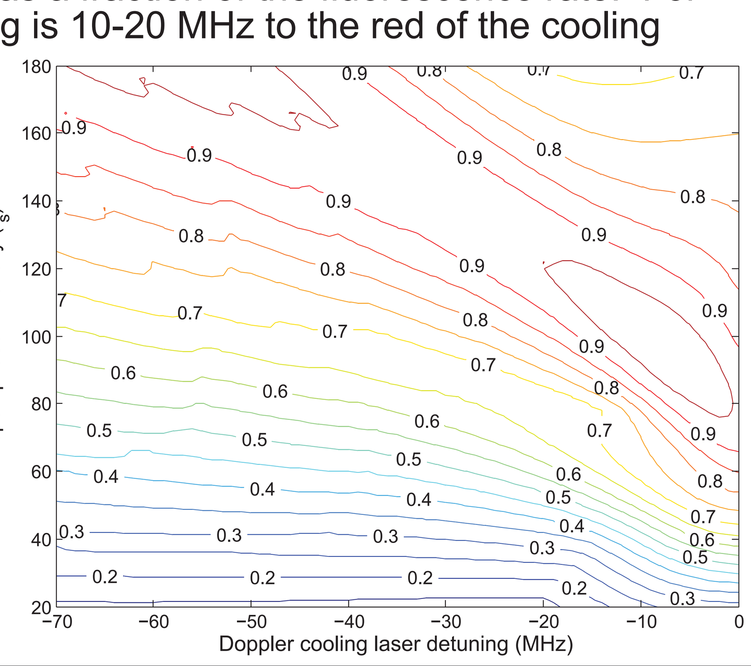






By solving the Bloch equations for the steady state under repump laser modulation we can predict the optimal laser parameters. This contour plot (below right) shows the sensitivity to micromotion for different repumper laser intensities and cooling laser detunings as a fraction of the fluorescence rate. For all points the optimal repumper detuning is 10-20 MHz to the red of the cooling laser. The relative sensitivity drops off linearly with cooling laser intensity I_c but we set I_c to 1.5 saturations to achieve a good absolute sensitivity. The graphs to the left show a good experimental fit to our model.

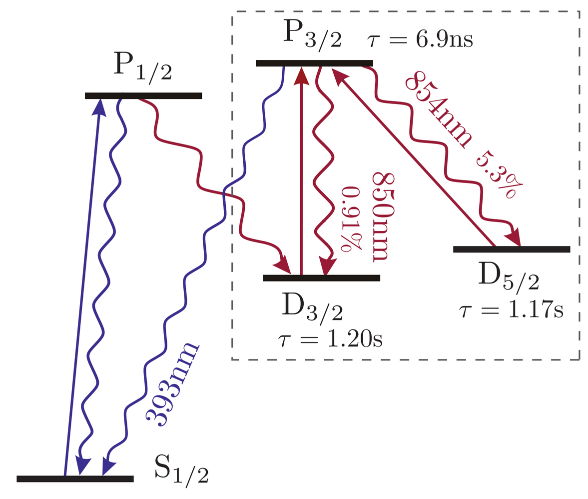
Using this method we are able to compensate stray fields out of the plane to within 3 V/m compared to 1 V/m in the plane (peak ion velocities of 0.3 and 0.1 m/s respectively). We note a drift rate of approximately 10 V/m per hour, but no noticeable change on loading.

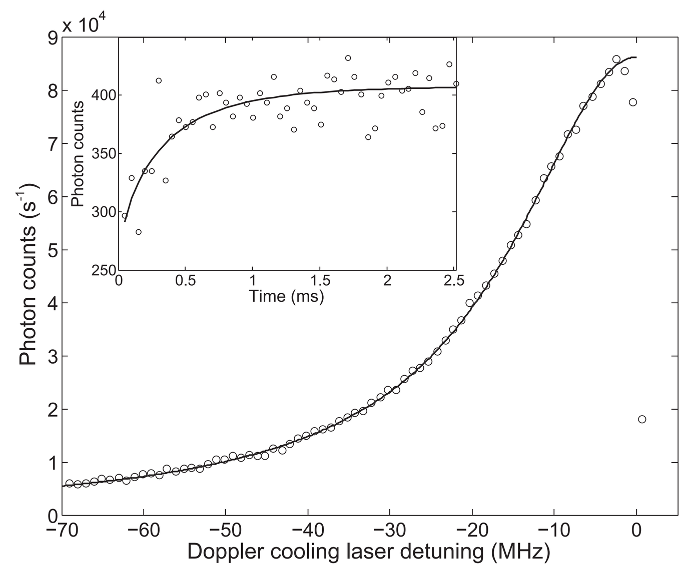


Heating Rates

We measure the motional heating rate of the trap using a Doppler re-cool method [4]. The ion is allowed to heat for 1 second and then the Doppler cooling laser is switched back on. Analysis of the ion's fluorescence as it cools back down allows us to determine its temperature. A typical re-cool curve is shown inset below.

[4] Wesenberg et al. PRA 76, 53416 (1998)



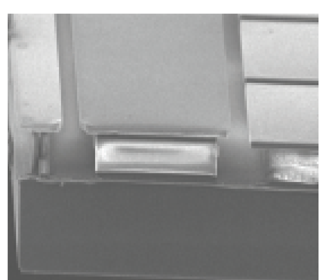


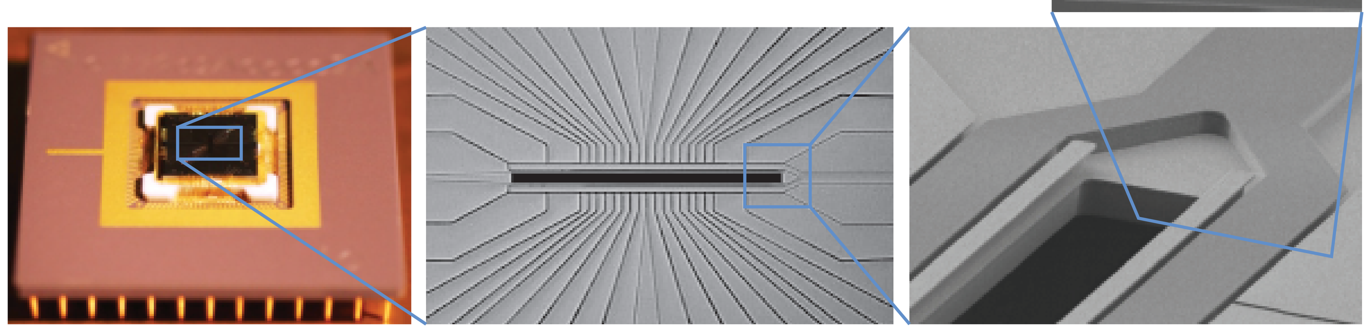
The low-lying D-states in Ca^+ complicate analysis of this experiment if we repump out of them via the $P_{1/2}$ state due to coherent dark resonance effects. Instead we use the modified scheme above. As no laser connects the boxed levels to our fluorescing transition we can treat our system as quasi-two-level (see Lorentzian fit, left).

The electric field noise density S_E is comparable to other traps of this size and corresponds to ~50 phonons of heating per ms at 500 kHz axial frequency. Before adequate heating rate data was taken an rf fault caused arcing which damaged the surface quality and lowered the breakdown voltage to around 150 V. We see clear evidence of electron emission from the increase in background photon counts at higher rf voltages.

Sandia Fabrication

- Similar design to Oxford trap above but with slot for integrated optics.
- Monolithic silicon, glass and aluminium construction.
- Fabrication by Sandia National Laboratories (group of M. Blain) and funded by iARPA.
- See talk by D. Stick (or arXiv:1008.0990) for more info.





Trapping

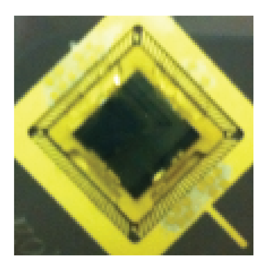
Three traps tested.
Traps similar except for caps on CPGA package.
Trap 1 : No capacitors
Trap 2 : 1nF caps to ground on two centre control electrodes
Trap 3 : 820pF caps to ground on all dc electrodes (below right)

8 ion Ca^+ crystal

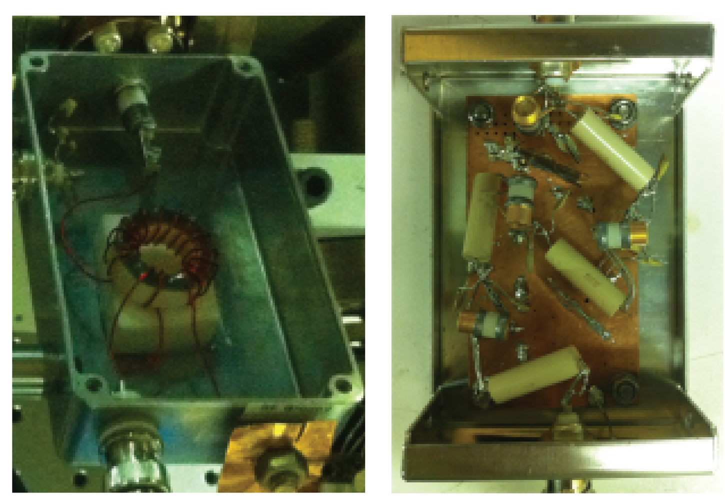
Ion-Electrode Distance	93.9μm
RF Drive	33 MHz, 56 to 138V
Trap Depth	22 to 133 meV
Radial Secular Frequency	1.9 to 4.6 MHz
Stability Parameter (q)	0.16 to 0.39

Tested parameters
(limited at lower end by trap depth and upper end by power available from rf source)

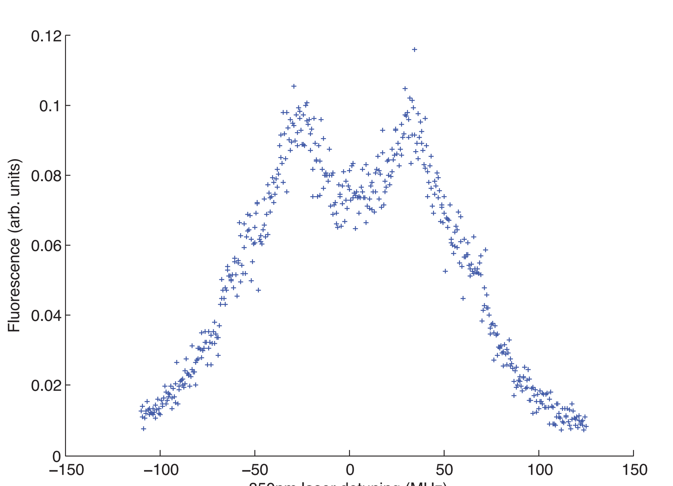
21 ion Ca^+ crystal



Toroidal transformer (below left) is used to match rf source to trap without a bulky helical resonator. Voltage step-up is 21. A -30dBc bandpass filter (below right) is added before toroid to filter noise at $\Omega_{rf} \pm \omega_r$.



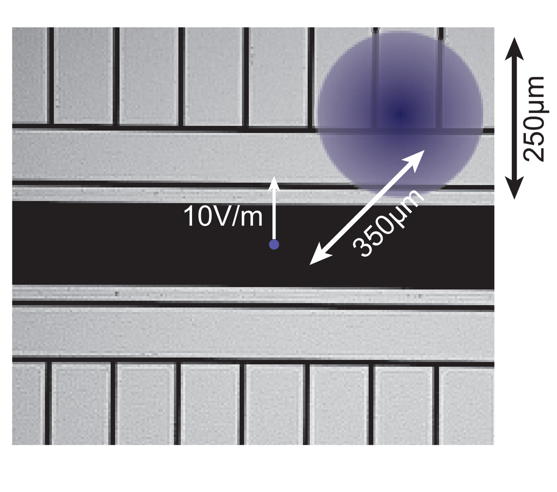
Micromotion



Scan of 850nm repumper that is 45deg out of the plane of trap in Trap 2.

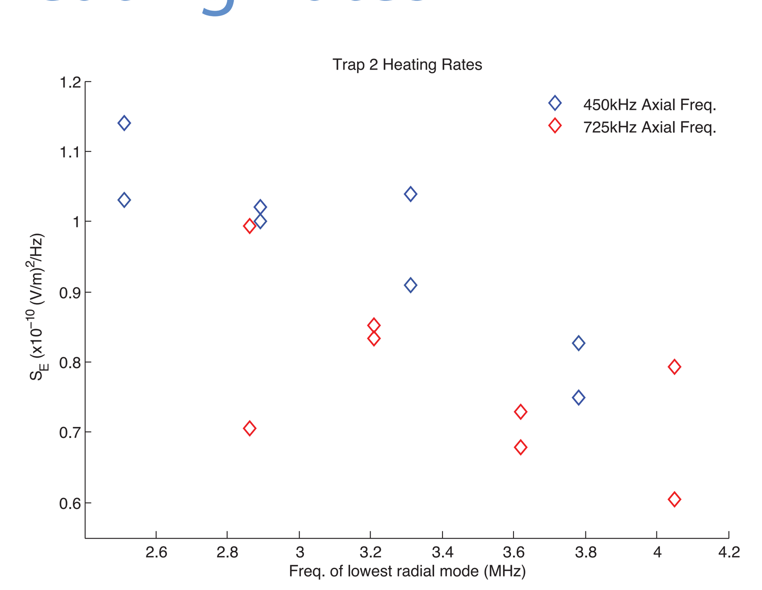
- Without capacitors on all dc electrodes this is as good as out-of-plane micromotion can be compensated.
- Addition of capacitors allows nulling of micromotion to 1V/m in-plane and 10V/m out of plane with residual, uncompensatable, micromotion barely detectable.
- Problem thought to be due to phase shifts in in-vacuum ribbon cable that connects trap to feedthrough.
- Future traps to have capacitors on-chip.

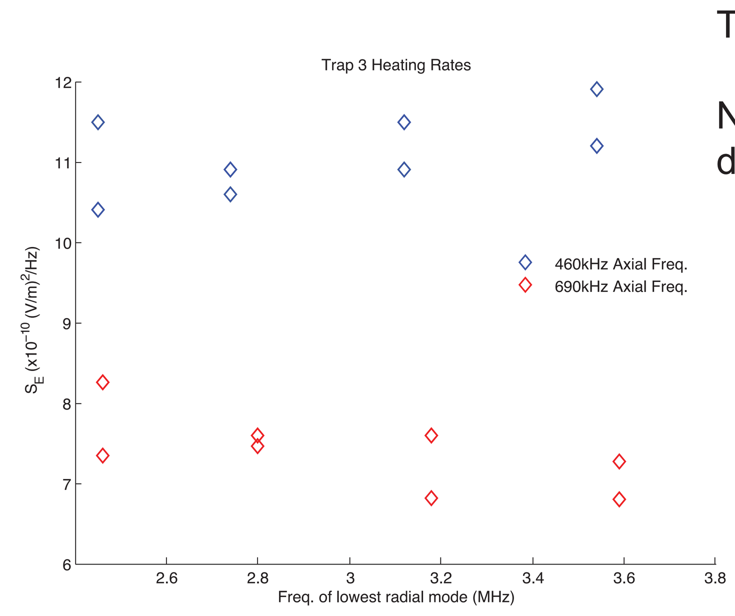
Charging of Trap



Trap appears to be fairly resistant to charging as ion sees no dielectric. 30 seconds of exposure with 10μW of 397nm light in the arrangement shown above produced a 10V/m field in the direction shown. Field returned to initial value after around 10 mins and was measured by looking at the induced micromotion. A more detailed study will follow.

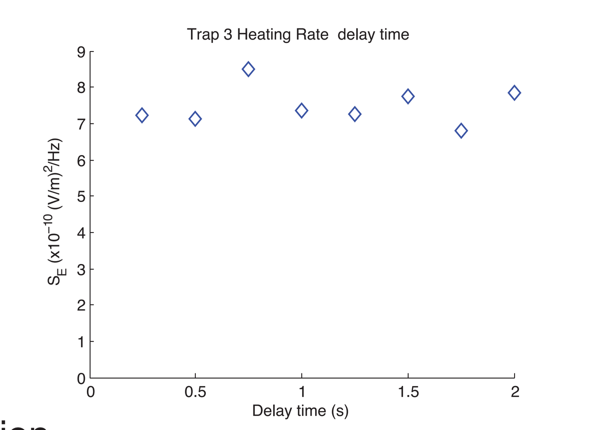
Heating Rates





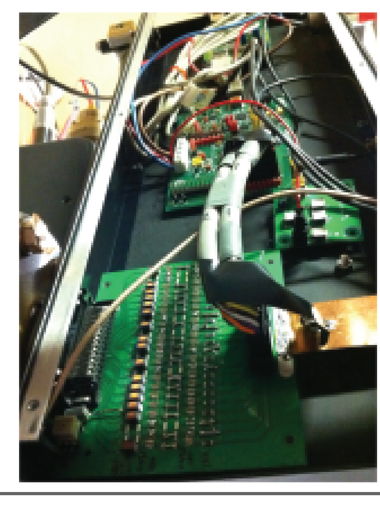
Uncooled lifetime is only ~15s in Trap 3 compared to ~1min in Trap 2.

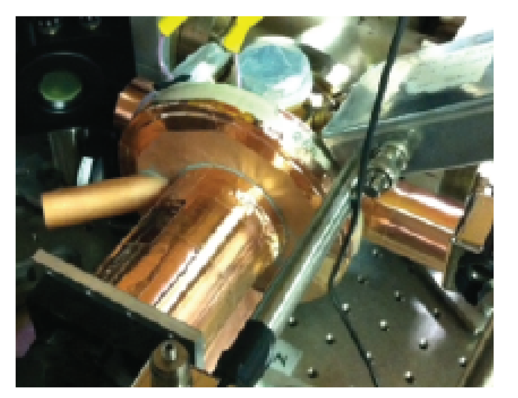
No dependence of heating rate on delay time yet observed (graph below).



The two graphs above show heating rate data for traps 2 and 3. The bad micromotion compensation in trap 2 could well explain the strong dependence on radial rather than axial secular frequency. The reason for the heating rate being almost an order of magnitude worse in Trap 3 is unexplained though. Apart from the added capacitors the experimental arrangement was almost identical.

USB-driven DAC and filter board mounted directly onto UHV flange (right). Noise well below 1nV/rtHz which eliminates need to run trap off batteries when taking heating rate measurements.





In order to eliminate the possibility of electrical noise being picked-up on trap electrodes the vacuum can was electromagnetically shielded (right) after initial measurements in Trap 3. Optical access is via lengths of copper tube which act as waveguide attenuators and give of order -100dB attenuation of incident radiation. Shielding had no effect at these heating rates though.

http://www.physics.ox.ac.uk/users/iontrap/ Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom d.allcock@physics.ox.ac.uk

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