UNIVERSITY OF OXFORD

D T C Allcock T P Harty H A Janacek J A Sherman D N Stacey A M Steane D M Lucas

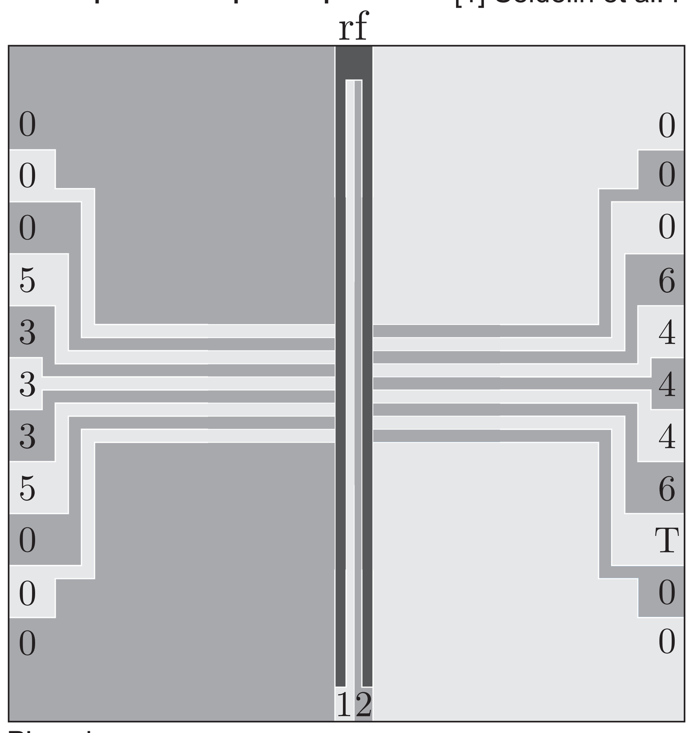
The Oxford planar ion trap project

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

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

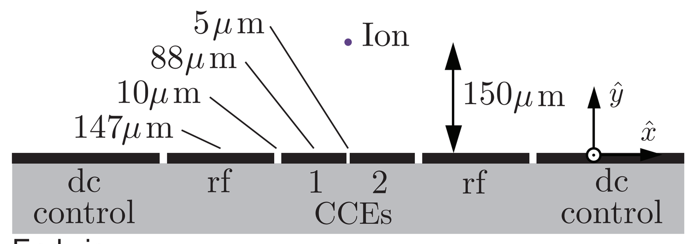
Planar traps based on a simple metal patterned substrate have recently been demonstrated at NIST [1] and MIT [2] with promisingly low heating rates measured. This type of trap is inherently scalable, and manufacturable in-house on short time scales allowing rapid testing and development of electrode 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)

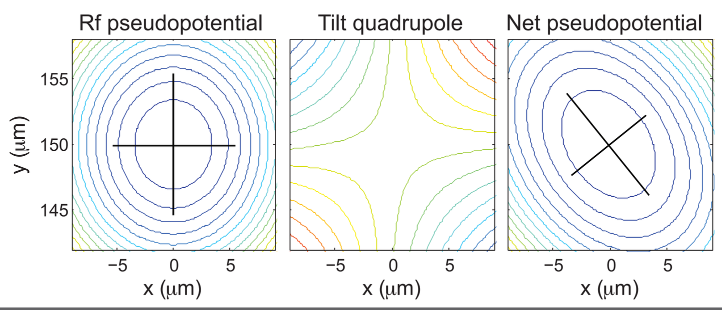


Plan view

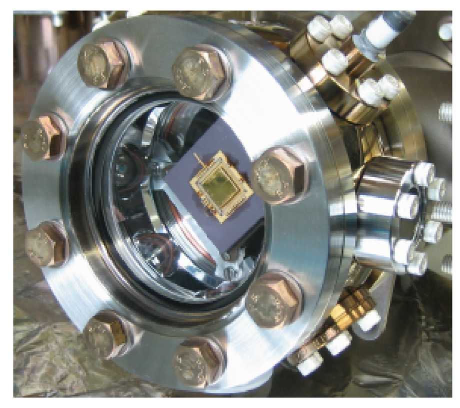
Fabrication Process
Quartz substrate with gold electrodes.
Electrodes electroplated over silver seed layer.
Based on MIT method. See thesis of J. Labaziewicz.

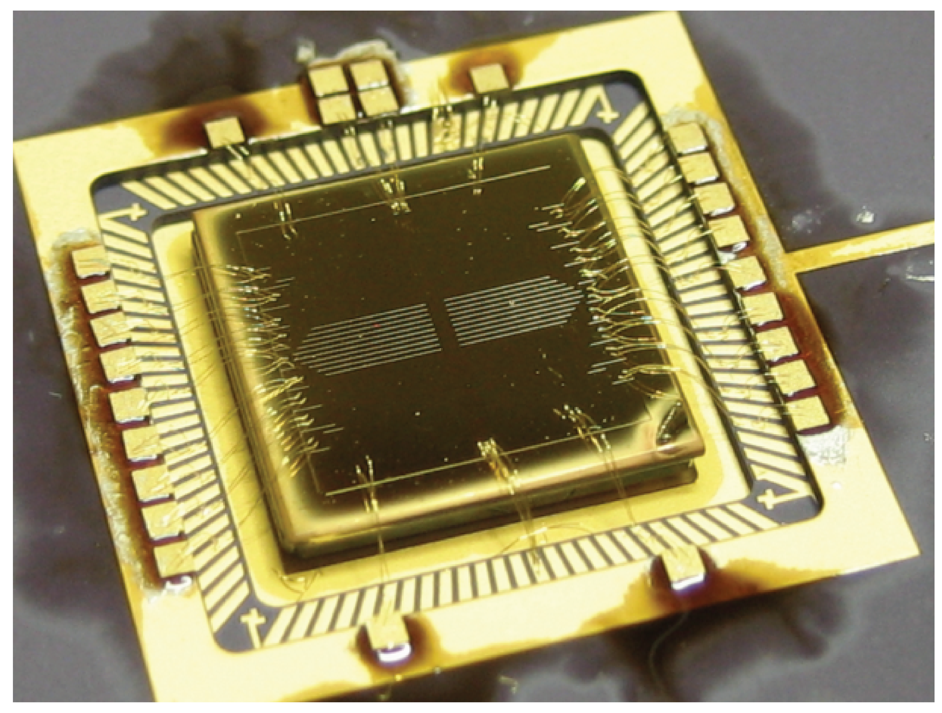


End view



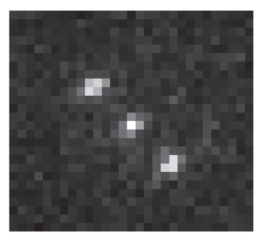
Trap under vacuum (right). Imaging is through the front window which is conductive (ITO coating) to prevent charging. The laser beams pass through the side windows and pass parallel to the trap's surface.

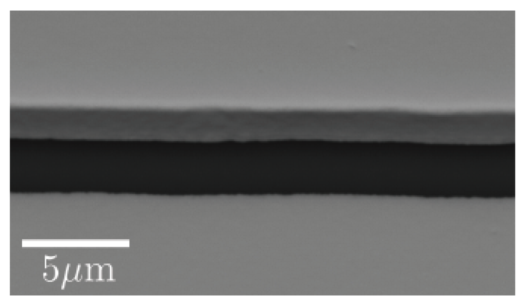




Ion-Surface Distance	150 μm
Rf Frequency	25.8 MHz
Rf Voltage Amplitude	112 to 223 V
Pseudopotential Depth	47 to 188 meV
Radial Secular Frequency	2.0 to 4.0 MHz
Axial Secular Frequency	300 kHz to 1.2 MHz
Ion Lifetime (typical)	5 min

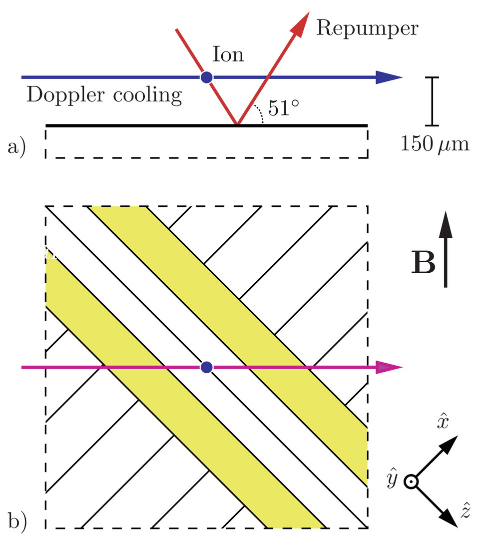
Our trap (far left) is of a '6-wire' design. The split central control electrode (CCE) allows a static quadrupole (above, centre) to be applied at the ion's location with the dc electrodes. This tilts the radial normal modes so that the laser cooling beams couple efficiently to them (left).





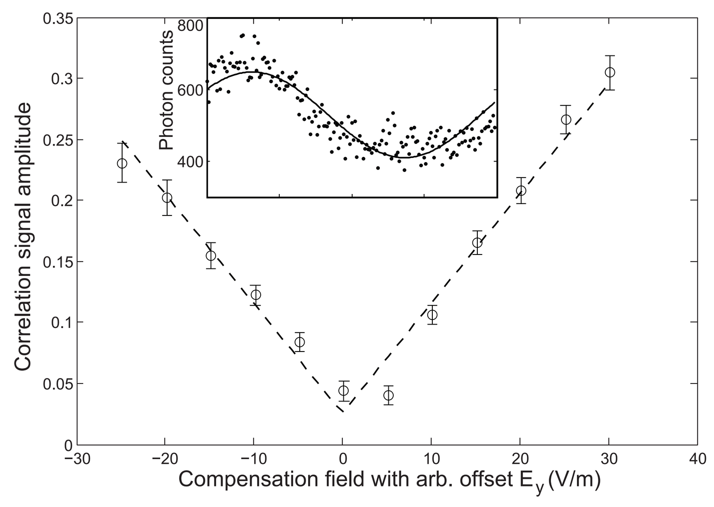
SEM image of an insulating electrode gap, angled to show gold thickness (above left). The trap wire-bonded into a CPGA carrier (top). The carrier also includes single-layer 820pF filter capacitors for the dc electrodes.
Three calcium ions in the trap (above right).

Micromotion Compensation

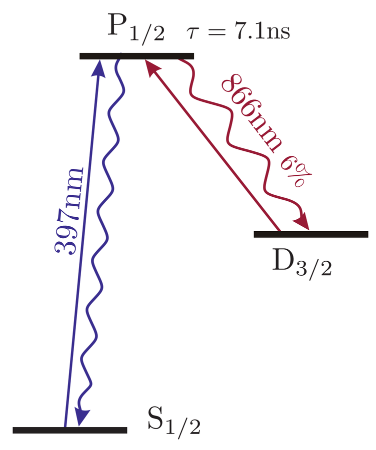


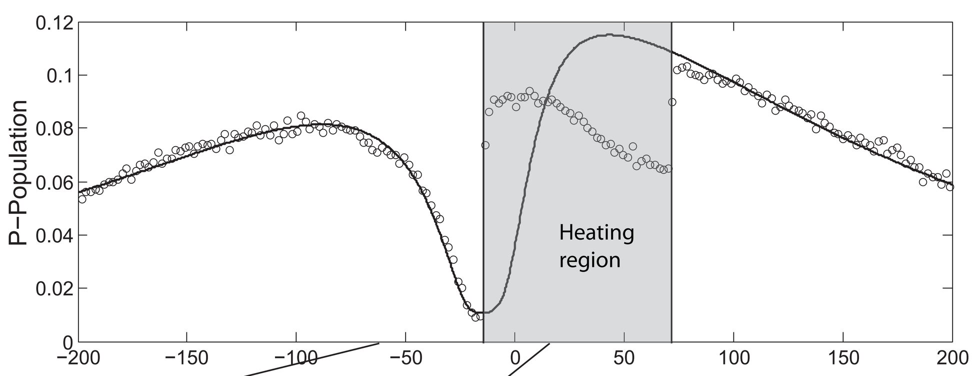
Trap rf drive causes driven micromotion when ion is displaced from rf null by stray fields. Doppler shifts cause correlation between 397nm ion fluorescence and trap rf which can be used for micromotion detection [3]. Beams in plane of trap cannot detect micromotion out-of-plane so we reflect 866nm repumper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

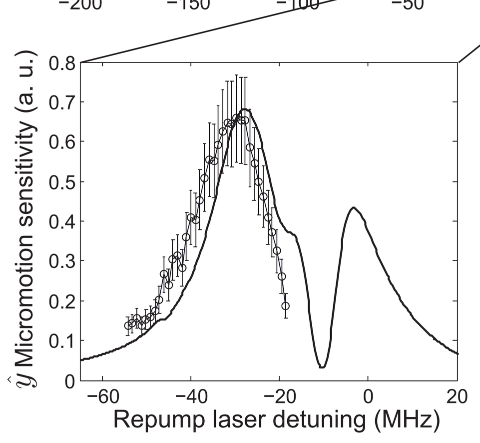
[3] Berkeland et al. J App. Phys. 83, 5025 (1998)

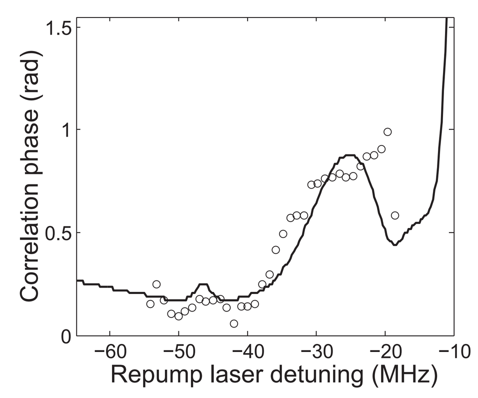


A typical rf correlation scan (inset, left). By applying a compensation field and monitoring the correlation scan we can null any micromotion (left).



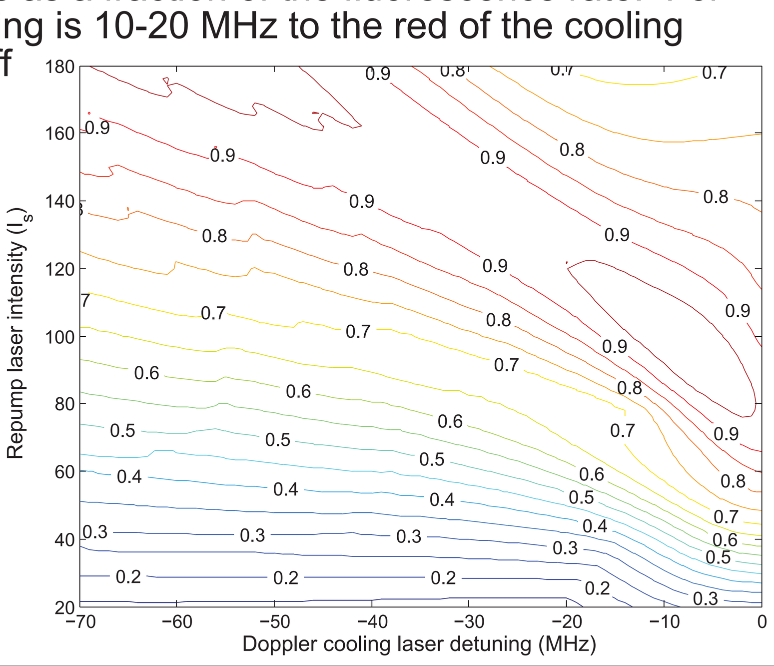






By solving the Bloch equations for the steady state under repump laser modulation we can predict the optimal laser parameters. This contour plot (below right) shows the sensitivity to micromotion for different repumper laser intensities and cooling laser detunings as a fraction of the fluorescence rate. 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.

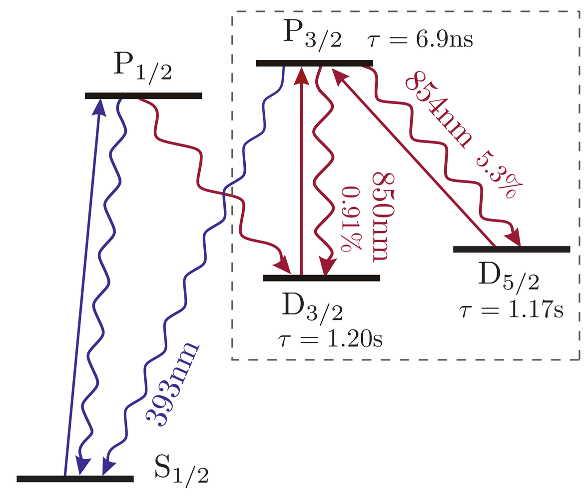
Using this method we are able to compensate stray fields out of the plane to within 3 V/m compared to 1 V/m in the plane (peak ion velocities of 0.3 and 0.1 m/s respectively). We note a drift rate of approximately 10 V/m per hour, but no noticeable change on loading.



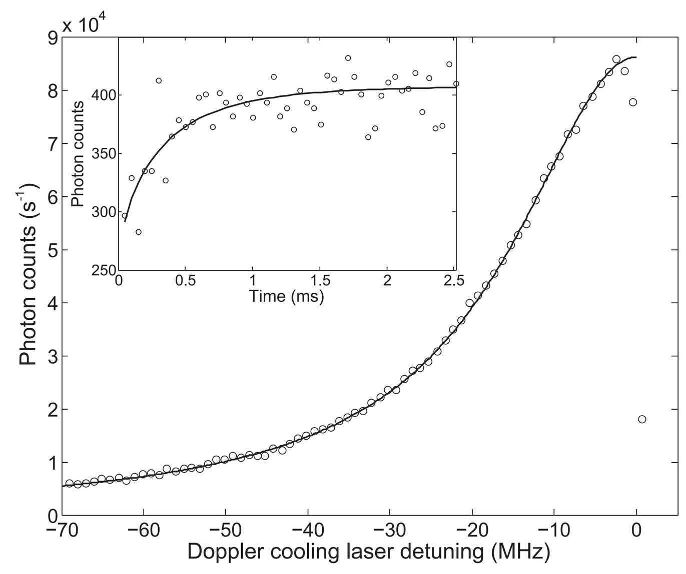
Heating Rates

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)



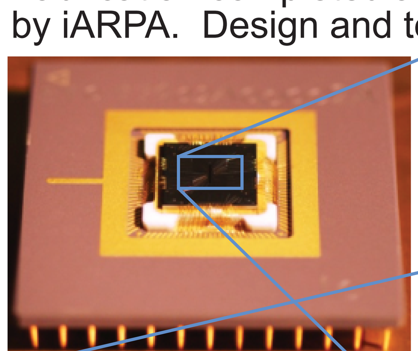
The low-lying D-states in Ca^+ complicate analysis of this experiment if we repump out of them via the $P_{1/2}$ state due to coherent dark resonance effects. Instead we use the modified scheme above. As no laser connects the boxed levels to our fluorescing transition we can treat our system as quasi-two-level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

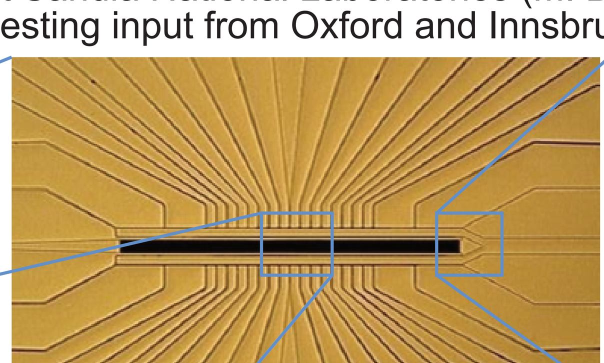


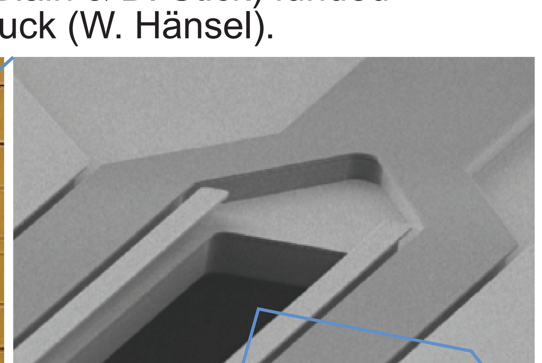
The electric field noise density S_E is comparable to other traps of this size and corresponds to ~50 phonons of heating per ms at 500 kHz axial frequency. Before adequate heating rate data was taken an rf fault caused arcing which damaged the surface quality and lowered the breakdown voltage to around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

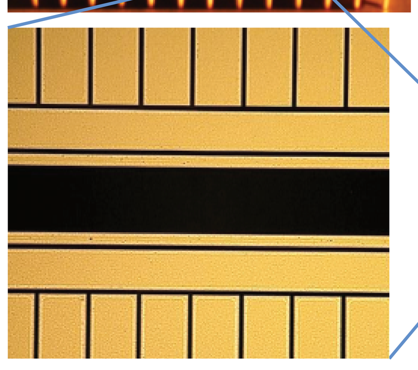
Sandia Fabrication

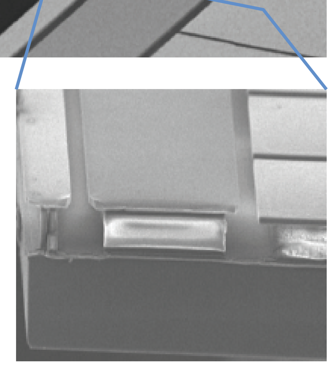
Fabrication completed at Sandia National Laboratories (M. Blain & D. Stick) funded by iARPA. Design and testing input from Oxford and Innsbruck (W. Hänsel).





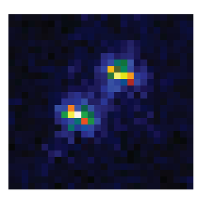




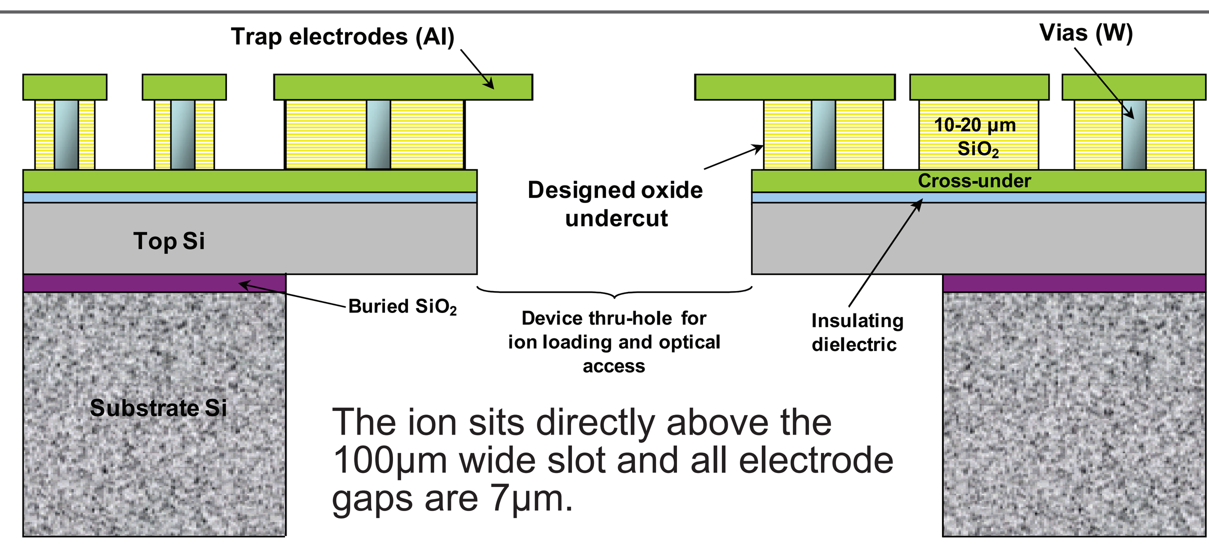


Ion-Electrode Distance	93.9μm
RF Drive	40 MHz, 200V
Trap Depth	190meV
Radial Secular Frequency	5.5 MHz
Axial Secular Frequency	750kHz

Reliable trapping demonstrated at both Sandia (see arXiv:1008.0990) and Oxford. Heating rate measurements awaiting modified trap with better rf grounding on centre control electrodes. This is to reduce rf pickup which is leading to uncompensatable micromotion.



Two ions in the trap



The ion sits directly above the 100μm wide slot and all electrode gaps are 7μm.

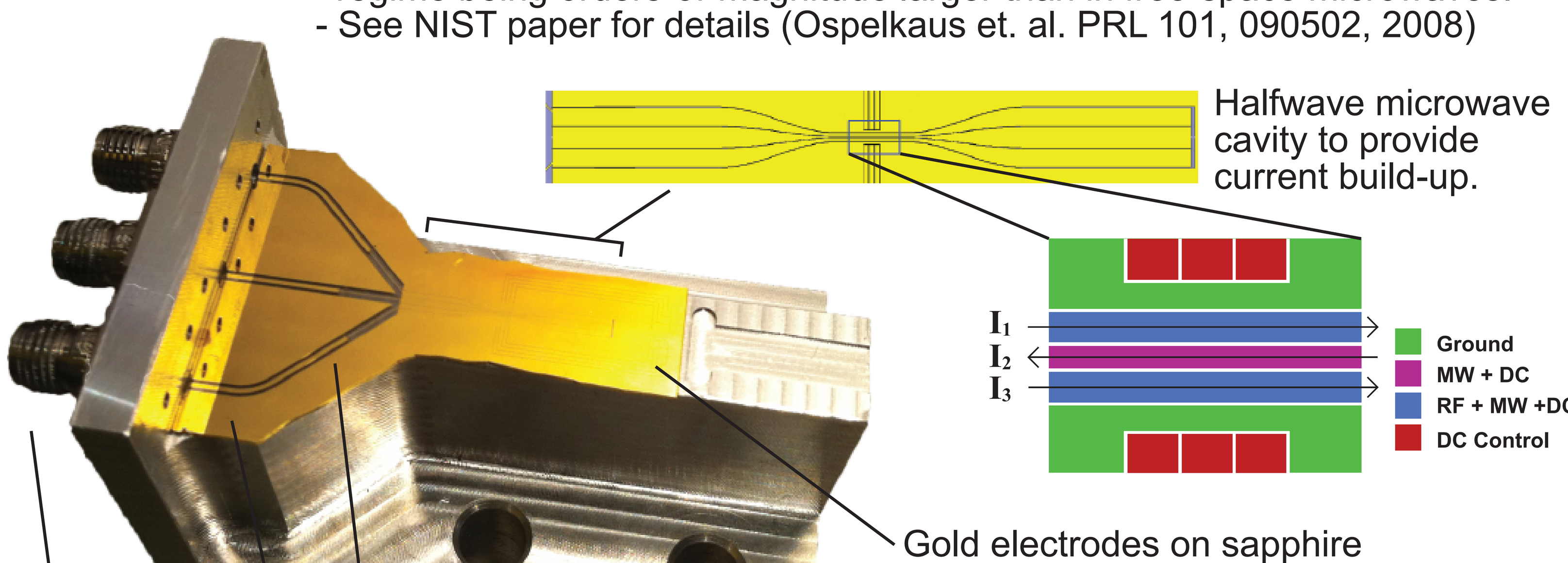
Features
- Ion 'sees' no dielectric or exposed semiconductor.
- Trap can be evaporatively coated with different metals to investigate effects of surface composition on ion heating.
- Split central electrode allows rotation of trap principle axes for efficient laser cooling even in a symmetric design.

Future Developments
- Slot designed to accommodate pre-aligned package of diffractive optics and fibres for laser delivery and fluorescence collection.
- Integration of passive filters into the trap
- Integration of filters into the trap structure is possible with this fabrication technology.

Microwave-Driven Multi-Qubit Entanglement

$^{43}Ca^+$ Qubit - 3.2GHz hyperfine transition between |F=4, m_F=0> and |F=3, m_F=+1>.
- No first order magnetic field dependence at 142G (T_2~1min expected).

Entangling Gate - Multi-ion Molmer-Sorenson gate using radial vibrational modes.
- Magnetic dipole transition driven directly by microwave near-field.
- Motional state coupling possible due to field gradients in the near-field regime being orders-of-magnitude larger than in free-space microwaves.
- See NIST paper for details (Ospelkaus et. al. PRL 101, 090502, 2008)



Halfwave microwave cavity to provide current build-up.

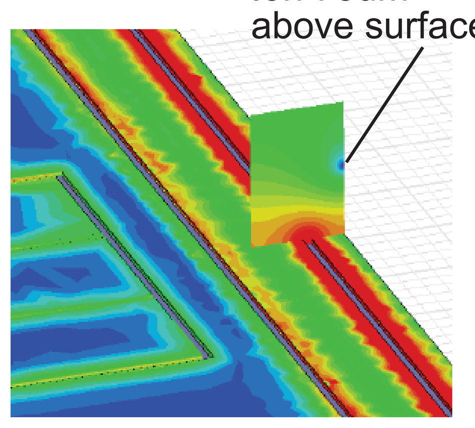
Gold electrodes on sapphire substrate with aluminium base for good heat conductivity.

Transmission line coupling elements. Electrically equivalent to series capacitors at 3.2 GHz but allows RF and DC connection.

SMA connectors

50 Ohm coplanar waveguide

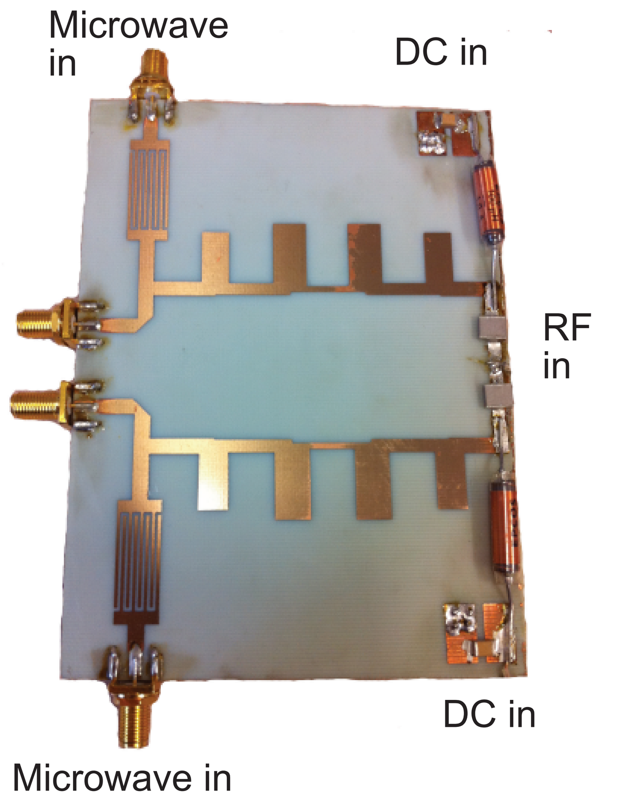
We require zero magnetic field at the ion to avoid single qubit rotations. Modelling the trap using HFSS 12 finite-element analysis software allows us to calculate the required layout of currents. The optimal arrangement combines the microwave and rf drive on the same electrodes.



Advantages - Doppler cooling only. No requirement for sideband cooling and low heating rate trap.
- Complex gate laser systems replaced by electronics.
- Gate operates directly on memory qubit.
- No photon scattering.

Disadvantages - Current densities approach limits imposed by heat dissipation.
- Gate speed will be fairly slow (~500us) for trap this size.
- Crosstalk will be an issue in larger arrays.

Future developments - Single qubit gates with Raman lasers.
- Single ion addressing through ion separation.
- $^{88}Sr^+$ sympathetic cooling.



Prototype multiplexer board (above) for combining microwave gate drive, rf trap drive and dc bias. Board designed in Microwave Office.

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

EPSRC QIPIRC scala THE ROYAL SOCIETY IARPA Microtrap