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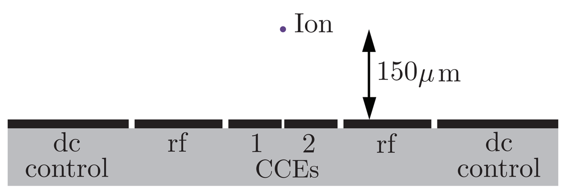
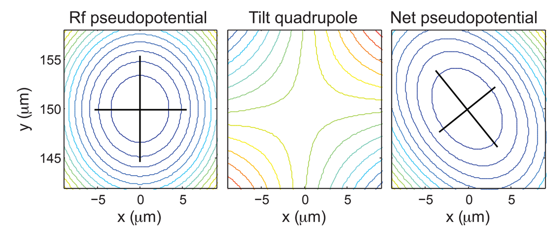
The Oxford planar ion trap project

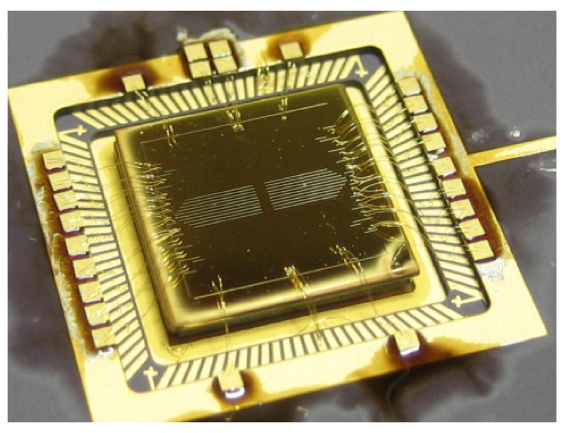
Ion Trap Quantum Computing Group - Department of Physics - University of Oxford

Prototype Trap
- Allcock et. al. - New J. Phys. 12,053026 (2010)

'6-wire' design (below) with split centre dc electrode allows arbitrary orientation of trap principle axes

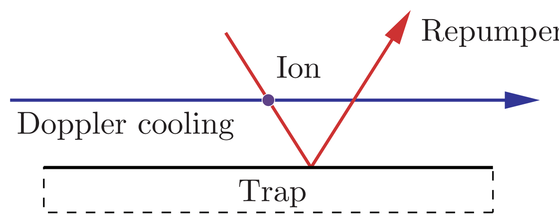


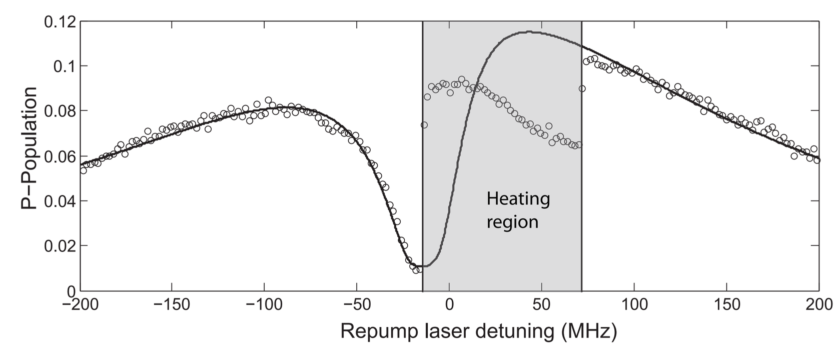




Gold on quartz fabrication at Oxford (left).

Micromotion compensation in all directions is possible by using an out of plane repumper and observing a modulated Raman effect (dip in the scan to the right).

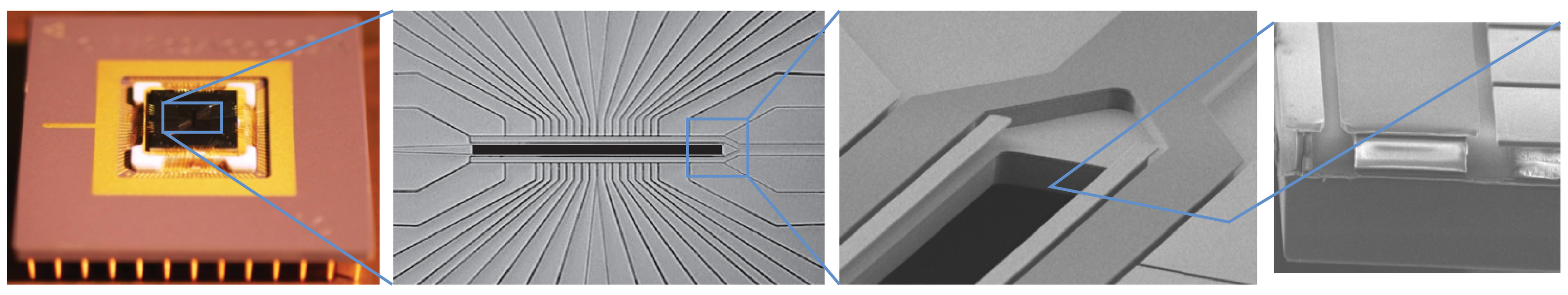




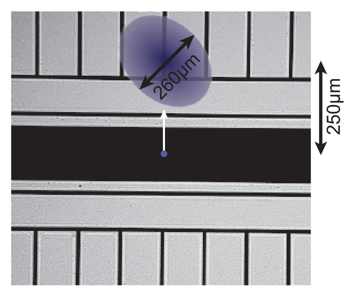
Sandia Trap Testing
- Allcock et. al. - App. Phys. B (2011)

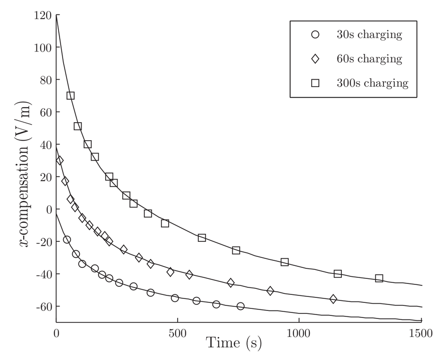
Sandia National Laboratories

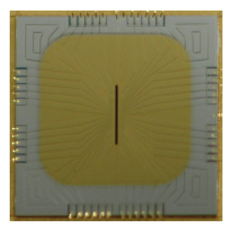
- Similar design to Oxford trap above but with slot for integrated optics.
- Monolithic silicon, glass and aluminium construction.
- Fabrication by Sandia National Laboratories (group of M. Blain) and funded by iARPA.
- See Stick et. al. (arXiv:1008.0990) for fabrication info.
- Three traps tested at Oxford.



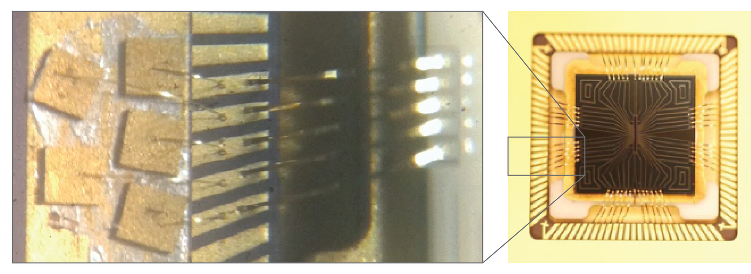
Charging of trap (see graph below) investigated by crashing a 10μW beam into the chip (right). Aluminium itself charges (trap has no exposed dielectrics) due to native oxide.



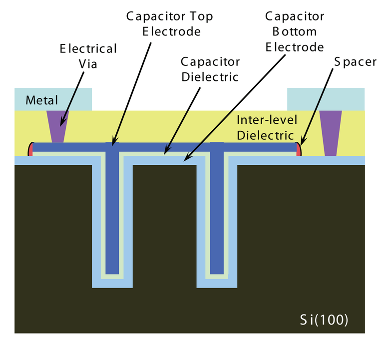




Future traps will be gold coated (above) to reduce charging.



Early versions of trap without on-package capacitors (shown above) had un-compensatable micromotion issues. Future versions will have 'trench' capacitors under the electrodes themselves.



Laser Cleaning
- Allcock et. al. - New J. Phys. 13,123023 (2011)

- 'Anomolous heating' in ion traps thought to be caused by adsorbates on surface.
- Pulsed-laser cleaning of the trap significantly reduces heating rate (by ~50%).
- First reported *in situ* reduction of heating rate by removal of source.

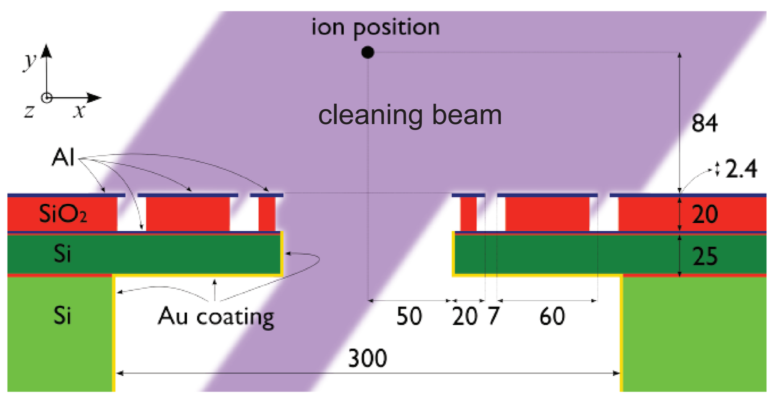
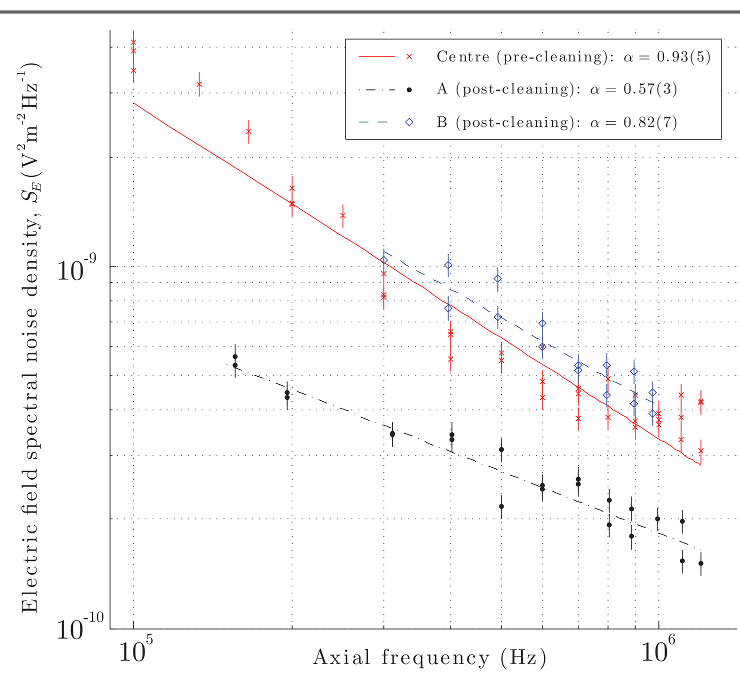


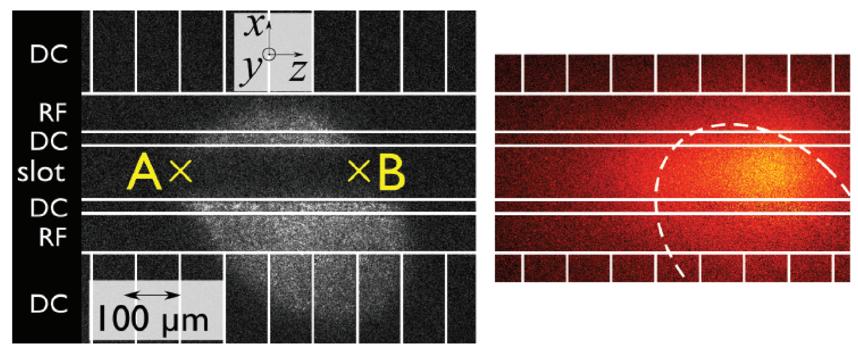
Diagram of laser cleaning geometry. Trap is the Sandia one described above.

Laser is 355nm tripled Nd:YAG
- 2-5ns pulses at 0.2Hz rep rate
- up to 350mJ/cm^2 in 300μm dia. spot



Results (left) showing ~50% reduction in heating rate in cleaned area (A) compared to uncleaned area (B). Note also the change in frequency dependency of S_E ($\omega^{-\alpha}$).

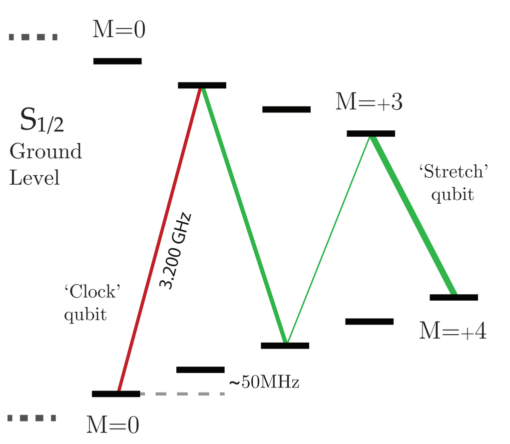
Image of the cleaning spot on the trap (left) and the ablation plume caused when the laser is first applied (right).



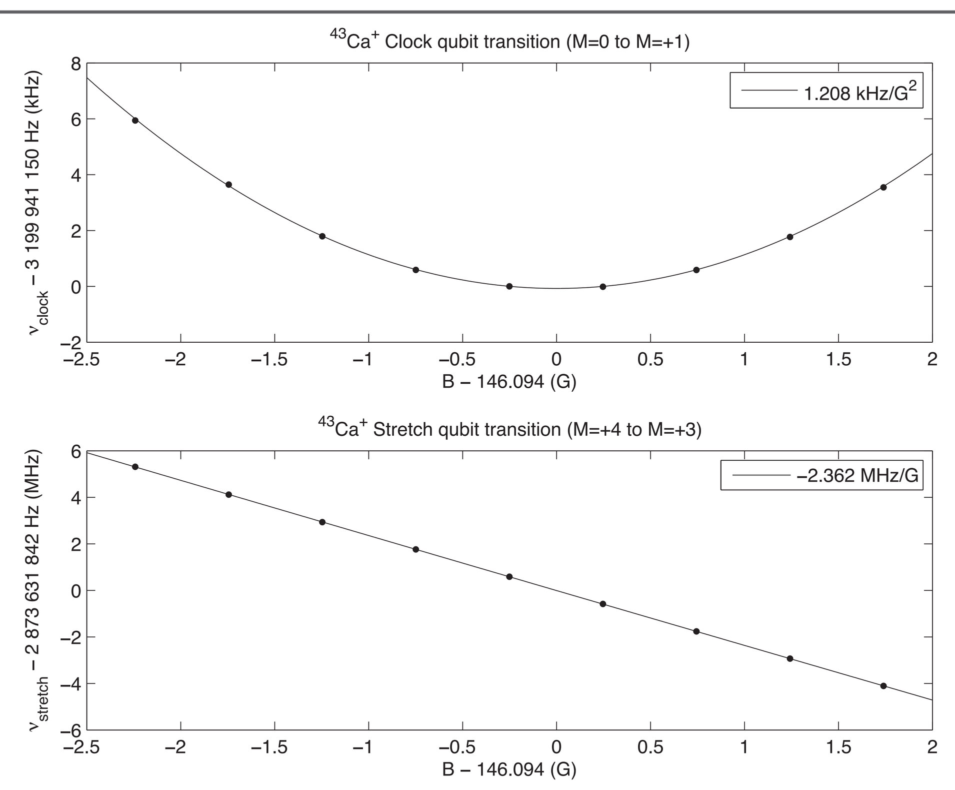
Results backed up by recent Ar$^+$ ion cleaning of trap at NIST (arXiv:1112.5419).
- Two orders of magnitude reported by NIST
- Laser cleaning is experimentally much simpler though so further experiments to optimise the techique should be performed.

$^{43}Ca^+$ Field-Insensitive Qubit

- Intermediate-field clock qubits preferable to zero-field clock qubit as Zeeman shift lifts state degeneracies.
- Until now intermediate-field clock states only demonstrated in $^9Be^+$ and $^{25}Mg^+$ (NIST).
- $^{43}Ca^+$ has the following advantages:
  - No UV lasers which can charge up the trap
  - Laser diodes available at all wavelengths
  - D-states for electron shelving (high readout fidelity)
- However no closed cooling transition...



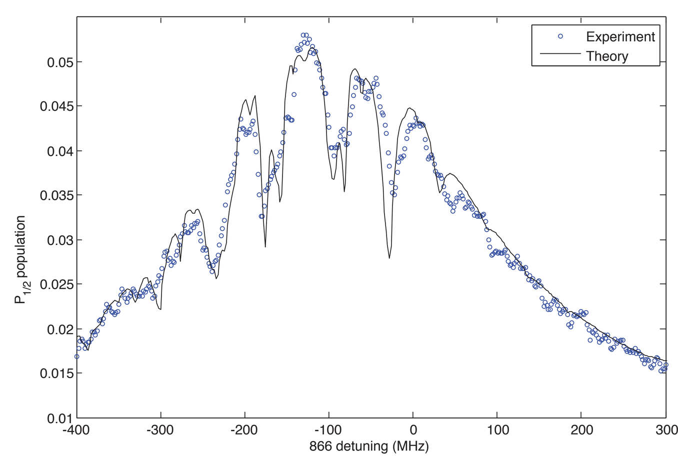
Ion is initialised in M=+4 using optical pumping then 3 microwave pulses (green) are used to prepare the 'clock' qubit.



Measured 'clock' and 'stretch' qubit frequencies using a single $^{43}Ca^+$ ion at 146G.

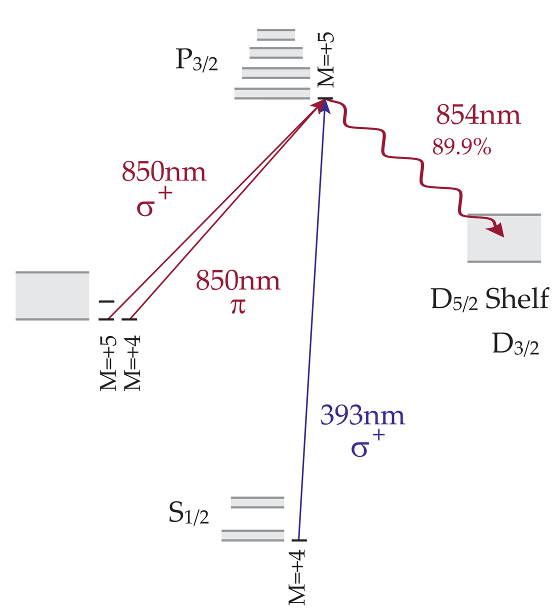
Cooling at 146G

- $S_{1/2}$-$P_{1/2}$-$D_{1/2}$ system has 64 states and no closed transitions.
- Optical Bloch equations used to simulate.
- Straightforward cooling solution found:
  - Polarizations chosen so only a few states populated
  - Needs only one sideband on cooling laser (from EOM)
  - Single frequency 866nm repumping laser
  - $P_{1/2}$ level population of up to 0.16 simulated



Preliminary comparison of experiment and theory for a frequency scan of the 866nm repumping laser.

Readout

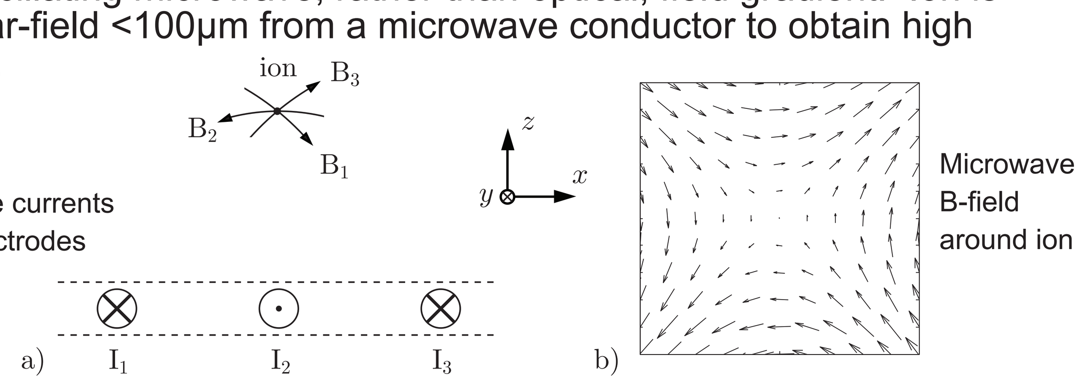


Shelving scheme allows >99.9% readout fidelity without the need for a laser to address the quadrupole transition.

Towards Microwave-driven Entanglement

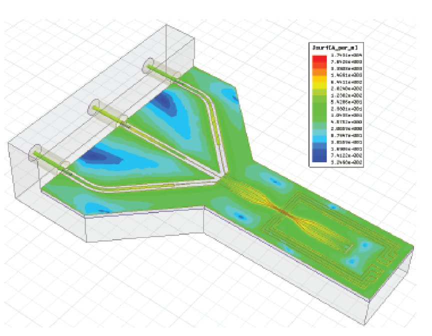
Proposed (2008) and demonstrated (2011) by Ospelkaus and coworkers at NIST.

Gate driven by oscillating microwave, rather than optical, field gradient. Ion is trapped in the near-field <100μm from a microwave conductor to obtain high enough gradients.

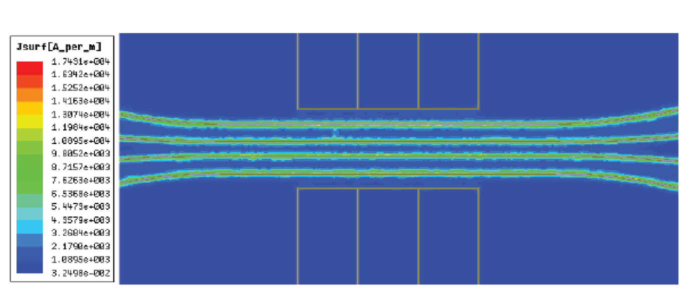


Advantages:
- Microwave electronics more mature and scalable technology than lasers
- No photon scattering as in laser-driven Raman gates
- No requirement for sub-Doppler cooling

Disadvantages:
- Microwave field not as well localised as laser field (crosstalk)
- Careful nulling of microwave field at ion required to suppress AC Zeeman shifts
- Fast gates (~10μs) will require small traps and high microwave current densities



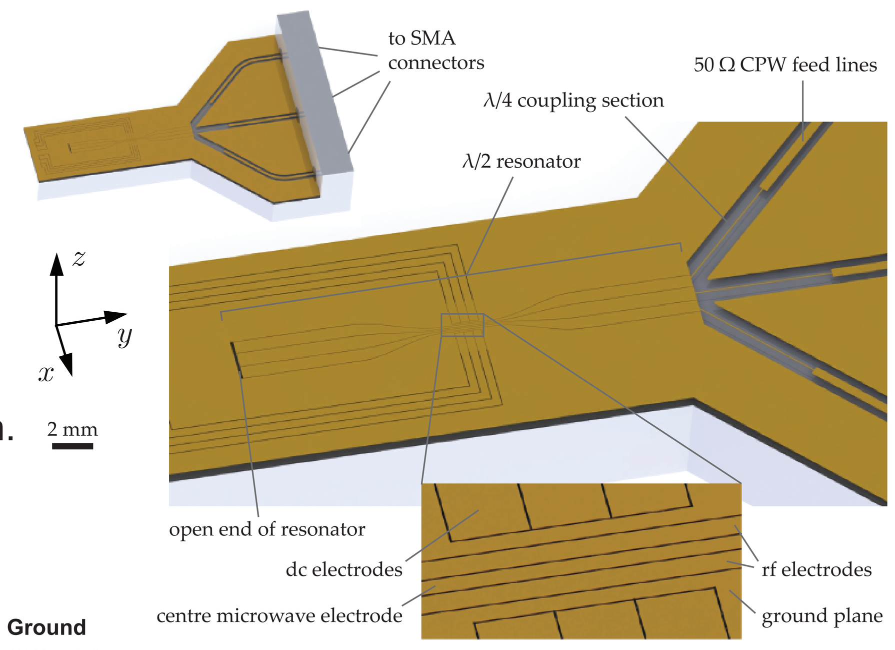
Optimisation of the trap microwave design was carried out using HFSS, finite element microwave simulation software. Figures (left and right) show simulations of current density in the trap.

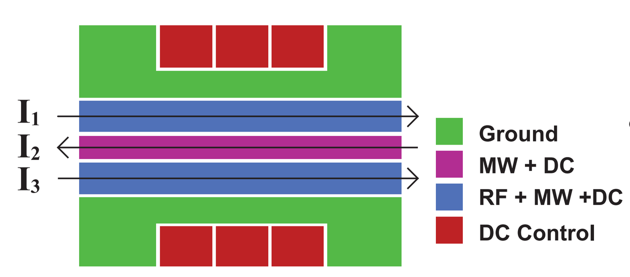


Trap Design

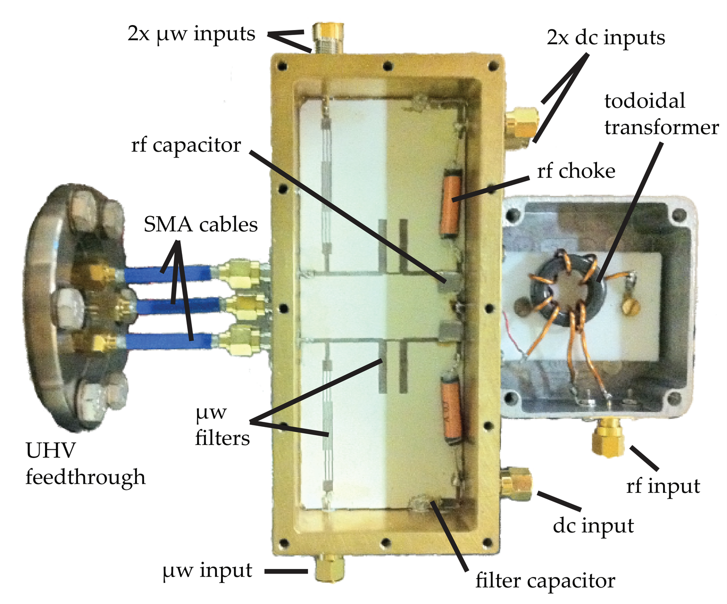
Trap is gold on sapphire for good thermal conductivity.

The trap region is in the centre of a half-wave resonator to increase currents. Quarter-wave coupling sections provide a good 50Ω impedence match.





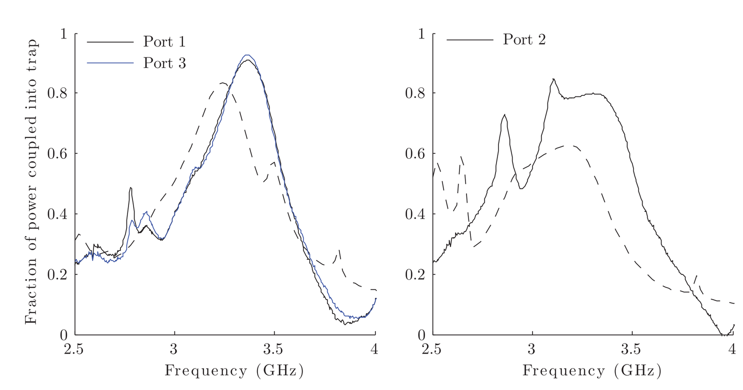
Simulations show that combining the microwave and rf electrodes (above) gives higher microwave gradients than alternative layouts for a given current.



Diplexer (right) is used to combine microwaves, rf voltages and dc offsets. The toroidal transformer steps-up the trap rf supply.

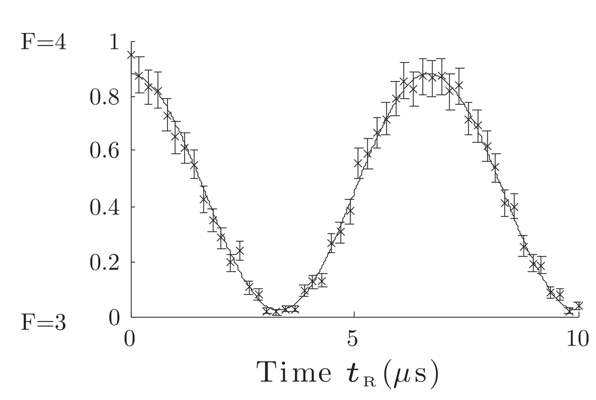
Trap Testing

Network analyser data shows that >75% of input microwave power is coupled into the trap.



Microwave field measured with ion is within 15% of simulation.

π times of ~3μs with <1mW microwave power typical (see below).

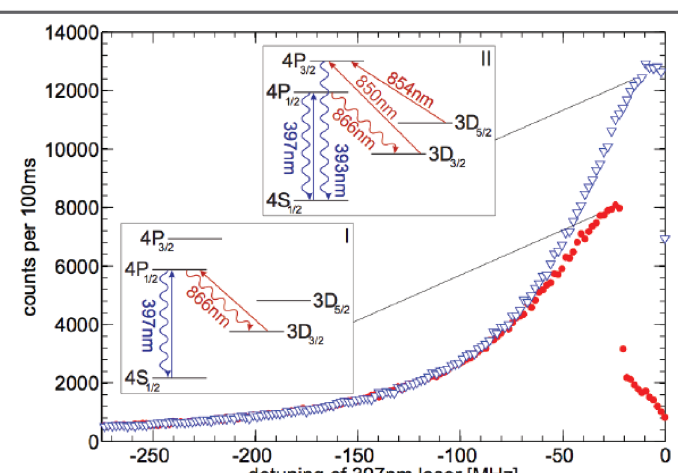


Sideband measurements coming soon...

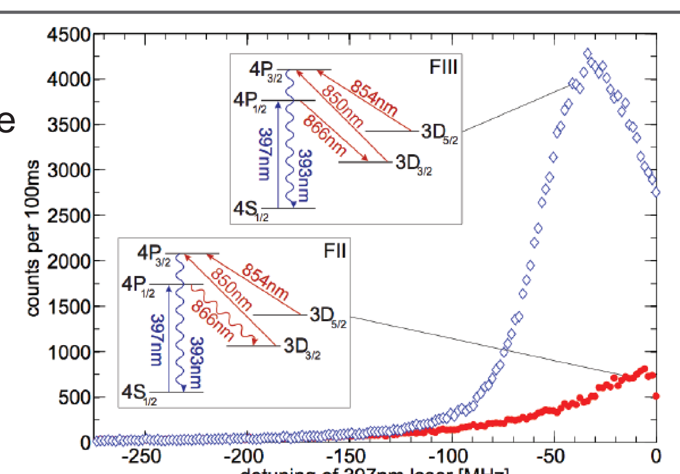
Alternative $^{40}Ca^+$ Repumping Schemes
- Linke et. al. - App. Phys. B (2012)

Standard Doppler cooling re-pumping scheme uses 866nm laser (scheme I). This allows the use of $D_{5/2}$ as a shelve for qubit readout. If qubit readout isn't the goal though better schemes exist.

850nm and 854nm repumpers (scheme II) give higher count and cooling rates and allow easier interpretation of some experiments (eg Doppler recooling heating rate measurements) due to the lack of 2-photon coherent effects, such as dark resonances.



Background free detection can also be achieved (right) by using an interference filter in the detection system to block 397nm light ans detect only 393nm fluorescence. We achieve 29000s^{-1} fluorescence with only 1s^{-1} scattered laser light, at moderate saturation of the cooling transition.



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