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Quantum logic operations in $^{40}Ca^+$ and $^{43}Ca^+$ using microwaves and lasers

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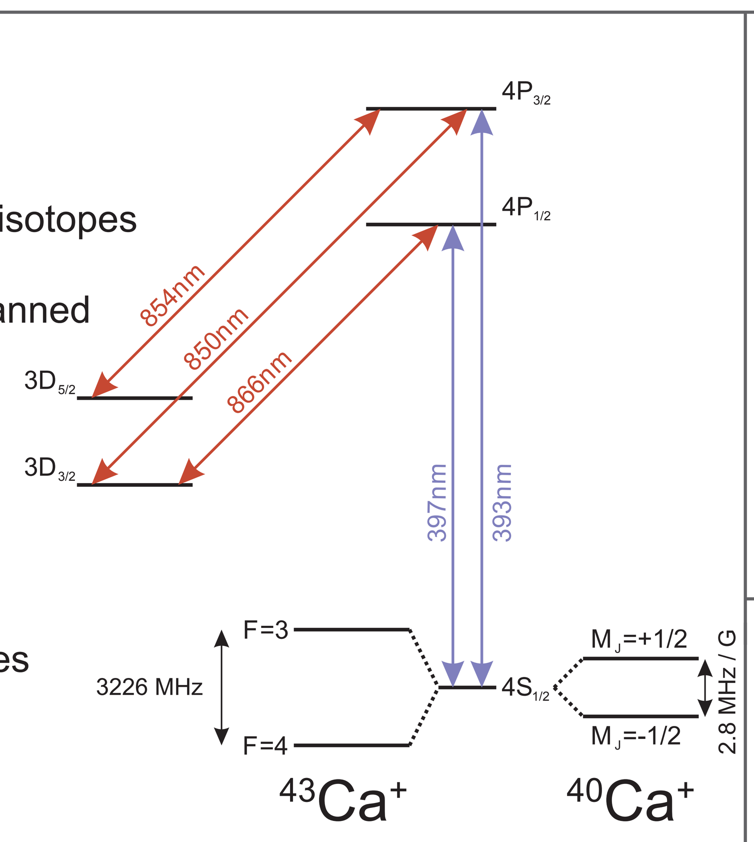
Mixed Species Experiment

- Use mixed isotope crystals of $^{40}Ca^+$ and $^{43}Ca^+$
- Isotope shift of ~ 1 GHz allows addressing of the different isotopes and sympathetic cooling
- Only one set of lasers needed as isotope shifts can be spanned with EOMs
- RF and microwaves used for single-qubit rotations
- Raman lasers used for spin-motion coupling

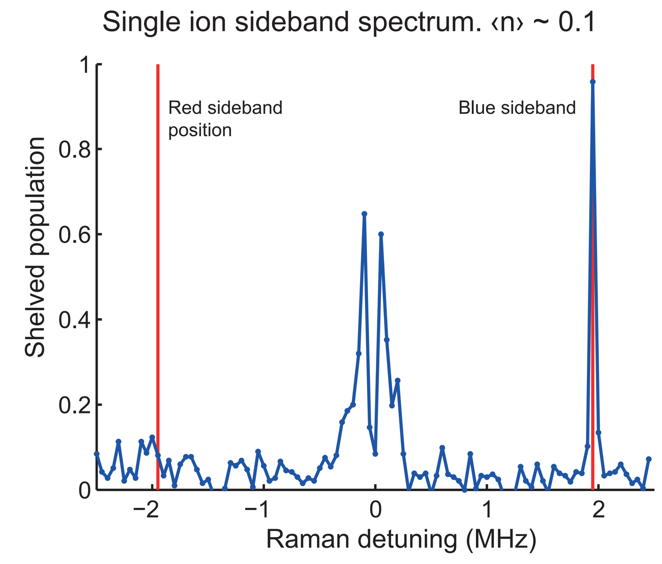


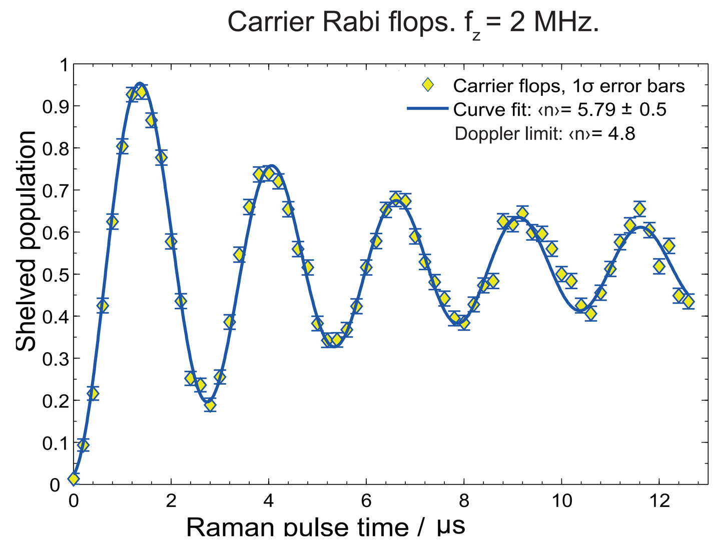
Goals

- Simultaneous manipulation and read-out of a mixed species crystal
- Entanglement by geometric phase gate
- High-fidelity laser gates
- Classical 'AND' gate by controlled relaxation

Cooling Results

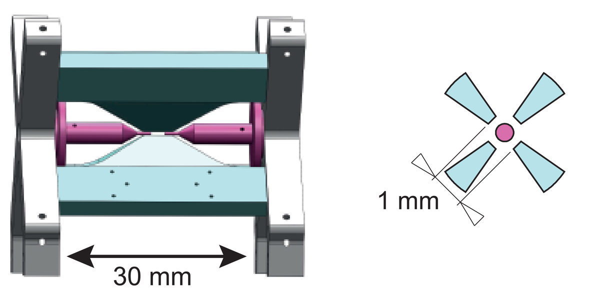
- Doppler cooling to ‹n› < 6
- Pulsed sideband cooling to ‹n› < 0.1
- Heating rate ~5 quanta / s at f_z = 2 MHz
- Mixed crystal sympathetic Doppler cooling





The Trap

- Innsbruck style stainless steel 'blade' trap
- Ion-electrode distance 0.5 mm
- Typical trap parameters:
  - Trap RF drive: 30 MHz
  - Axial secular frequency: 2 MHz
  - Radial secular frequency: 4 MHz



Raman Laser System

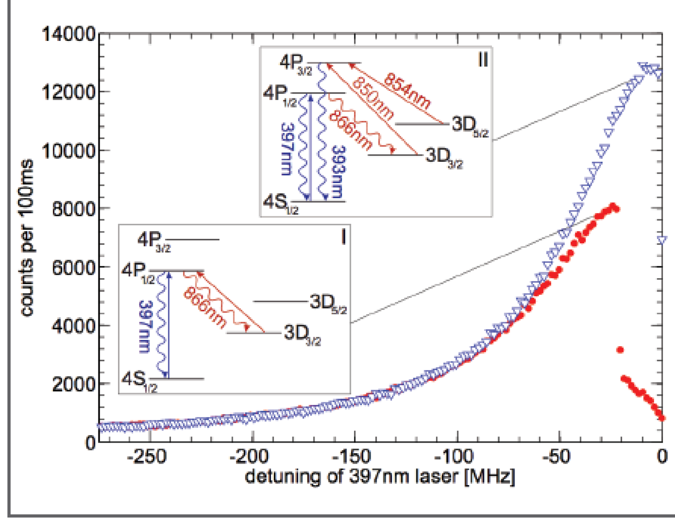
- Pair of injection-locked frequency-doubled amplified diode lasers gives up to 40 mW at 397 nm in each Raman beam at the ions
- Photon scattering error for single qubit rotation predicted to be < 10^{-4} at Ω_{Rabi} = 2π 500 kHz
- System can be switched between addressing $^{40}Ca^+$ and $^{43}Ca^+$ in 100ms by switching injection path
- Intensity stabilised using tapered amplifier current
- Beat-note between Raman beams at ions sub-Hertz width

Alternative $^{40}Ca^+$ Repumping Schemes

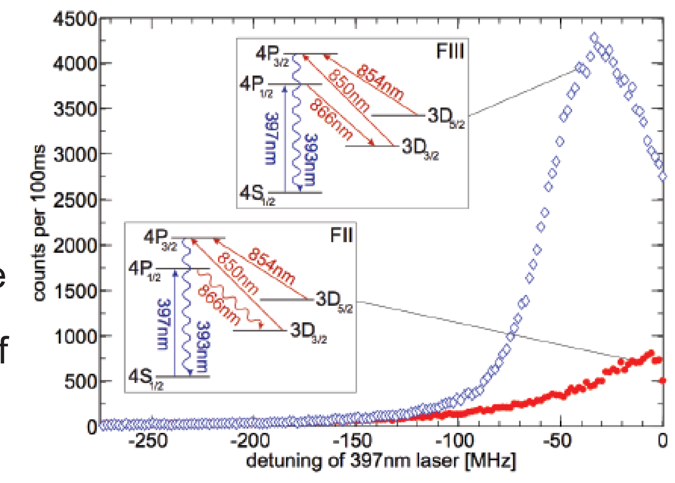
Linke et al. - Appl. Phys. B., 10.1007/s00340-011-4870-z (2012)

Standard Doppler cooling repumping scheme uses 866nm laser (scheme I). This allows the use of $D_{5/2}$ as a shelf for qubit readout. However if qubit readout is not the goal better schemes exist.

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



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



Laser Cleaning

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

- 'Anomalous 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.

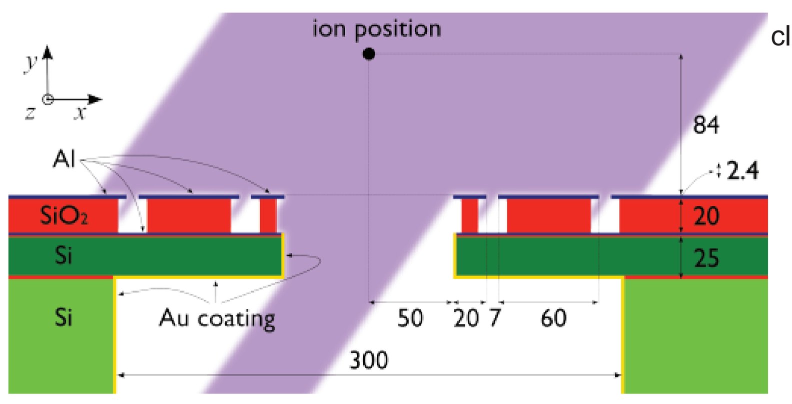
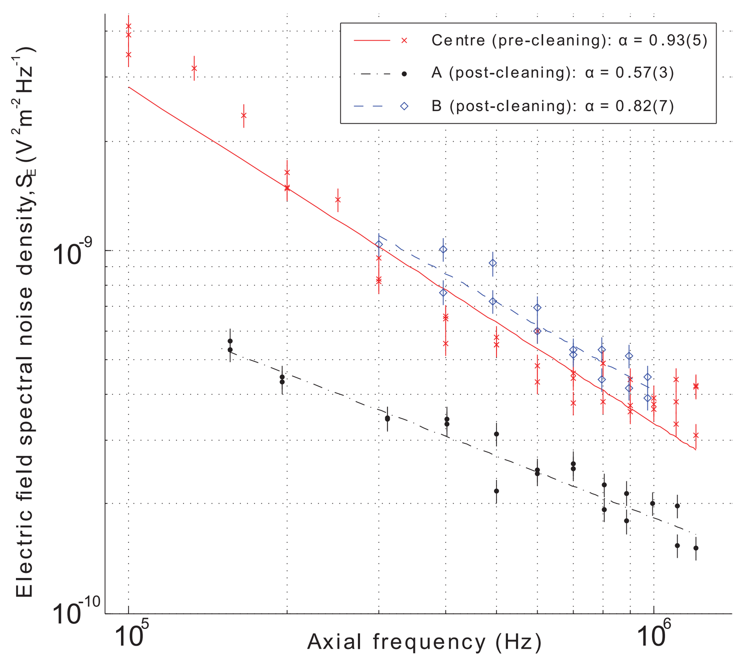


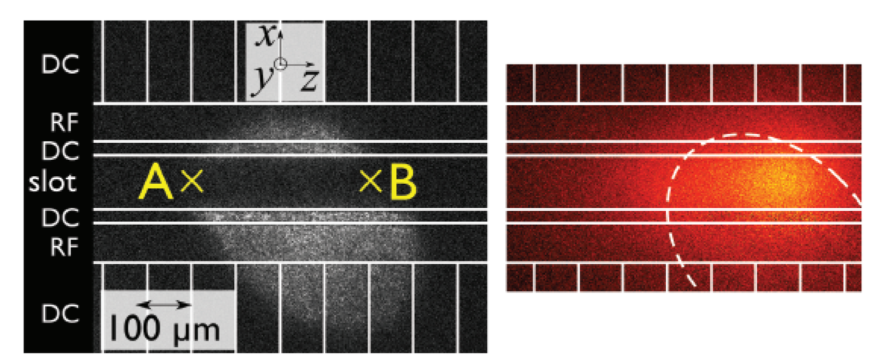
Diagram of laser-cleaning geometry.

Laser is 355nm tripled Nd:YAG
- 2-5ns pulses at 0.2Hz rep rate
- up to 350mJ/cm² 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 dependence (ω^-α) of S_E.

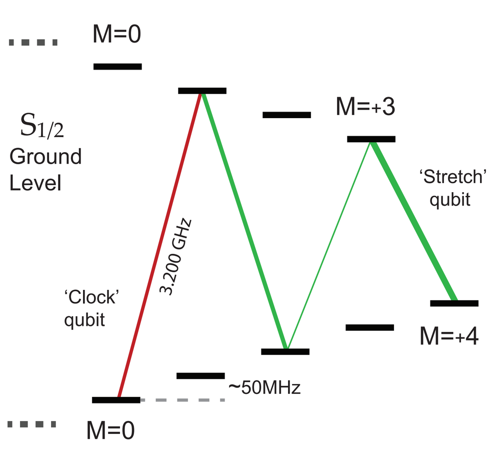
Image of the cleaning spot on the trap (left) and the ablation plume caused when the laser is first applied (right).



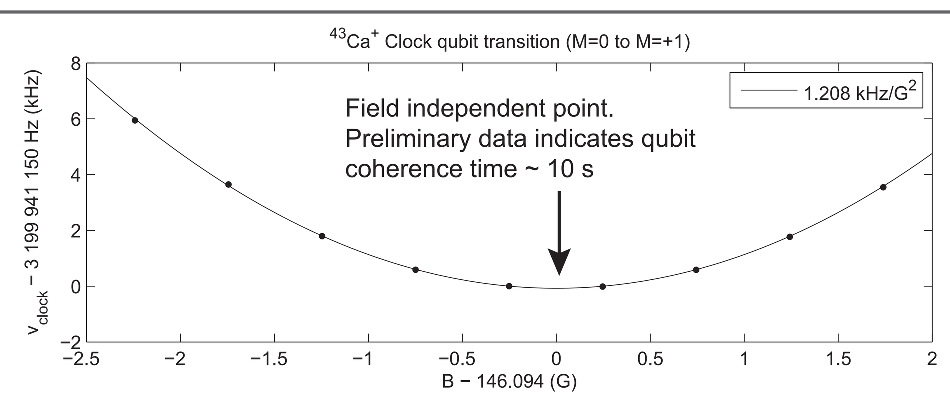
Results backed up by recent Ar⁺ ion cleaning of trap at NIST (arXiv:1112.5419).
- Two orders of magnitude reported by NIST
- Laser cleaning is experimentally simpler however so further experiments to optimise the technique should be performed.

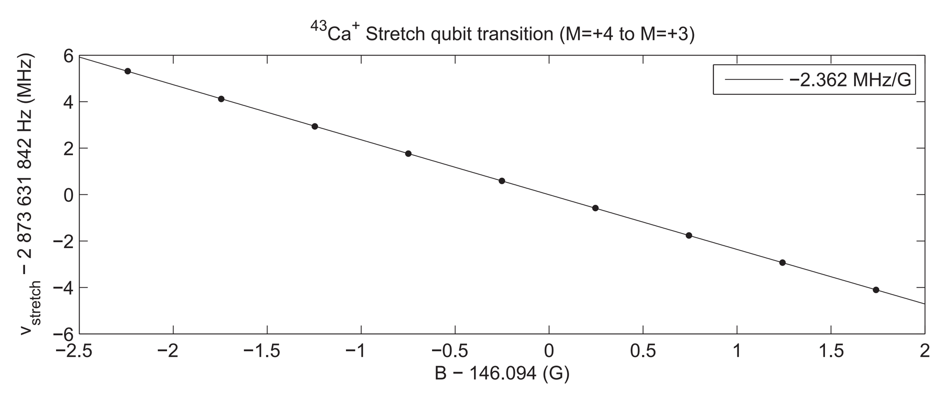
$^{43}Ca^+$ Field-Insensitive Qubit

- 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 (see right)



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

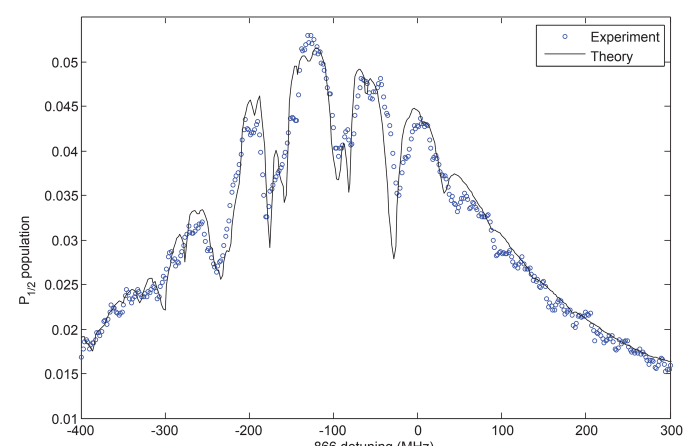




Measured 'clock' and 'stretch' qubit frequencies using a single $^{43}Ca^+$ ion at 146G.

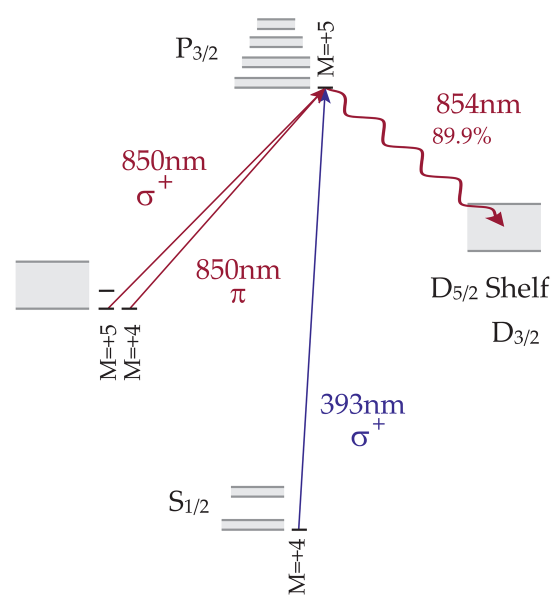
Cooling at 146G

- $S_{1/2}$-$P_{1/2}$-$D_{3/2}$ 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 ~0.15 simulated and achieved (50000 s^{-1} fluorescence)



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

Readout

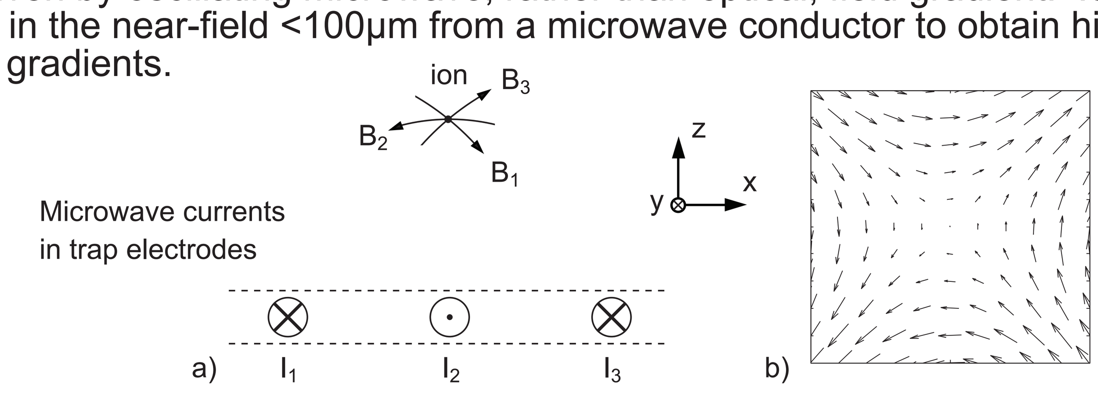


Shelving scheme allows >99.9% readout fidelity without the need for a laser to address the quadrupole transition.

Towards Microwave-driven Entanglement

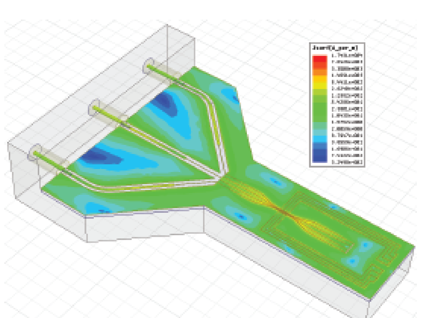
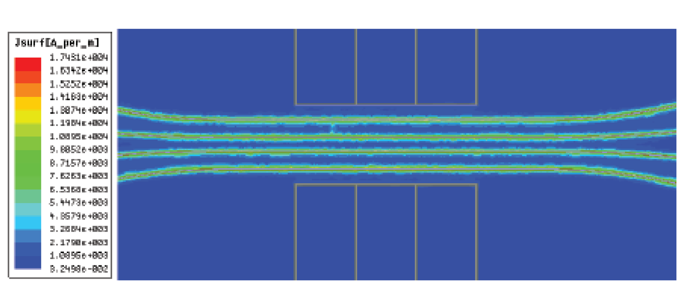
Proposed (2008) and demonstrated (Nature 476 155, 2011) by Ospelkaus and coworkers at NIST.

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

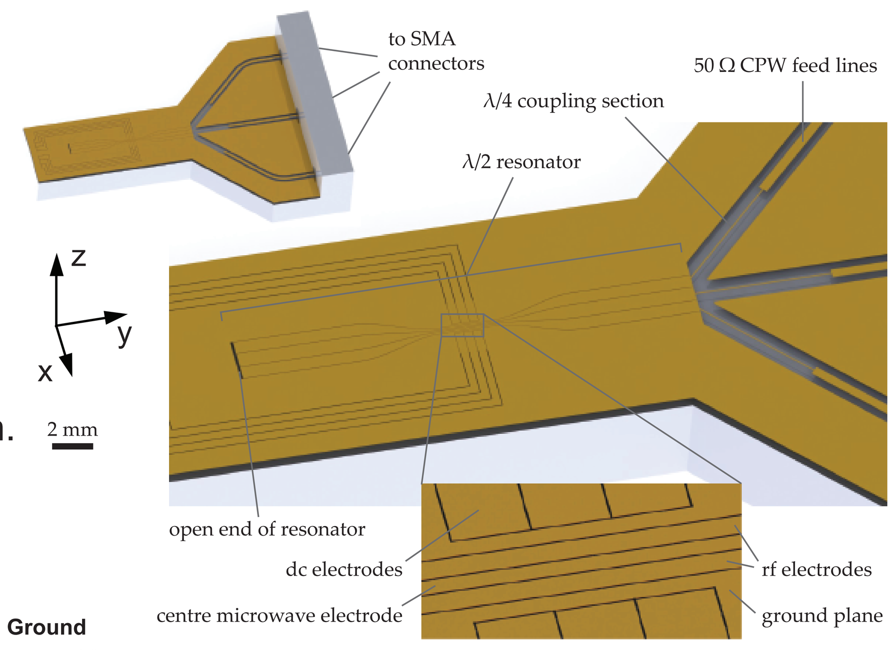



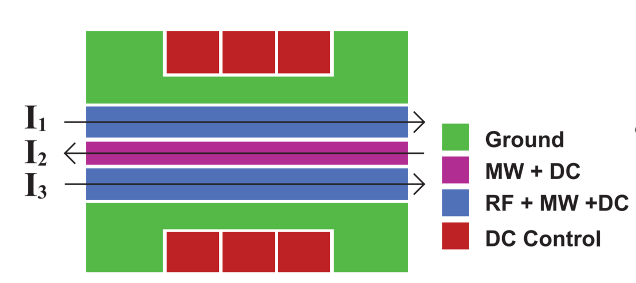
Optimisation of the trap microwave design was carried out using HFSS, finite element microwave simulation software. Figures (left and right) show simulations of current density in the trap.

Trap Design

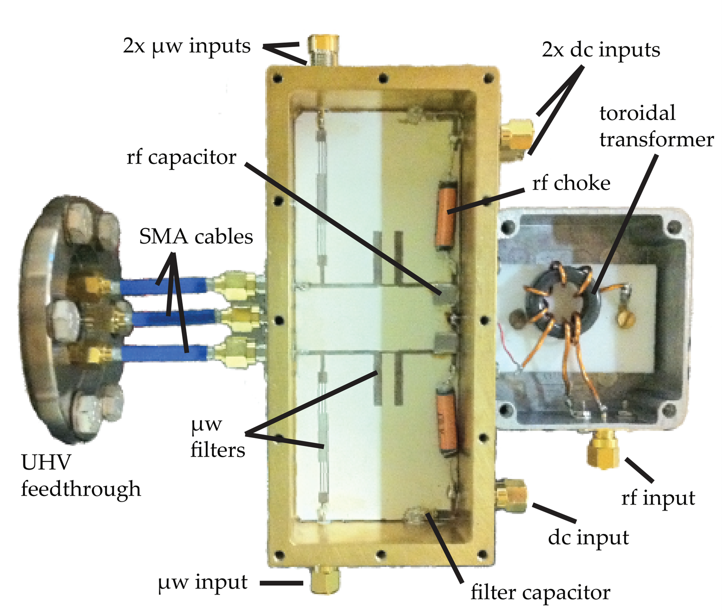
Trap is gold on sapphire for good thermal conductivity.

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





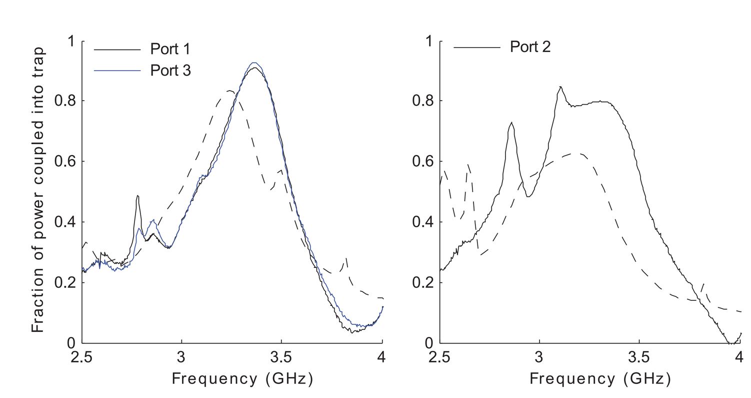
Simulations show that combining the microwave and rf electrodes (above) gives higher microwave gradients than alternative layouts for a given current.



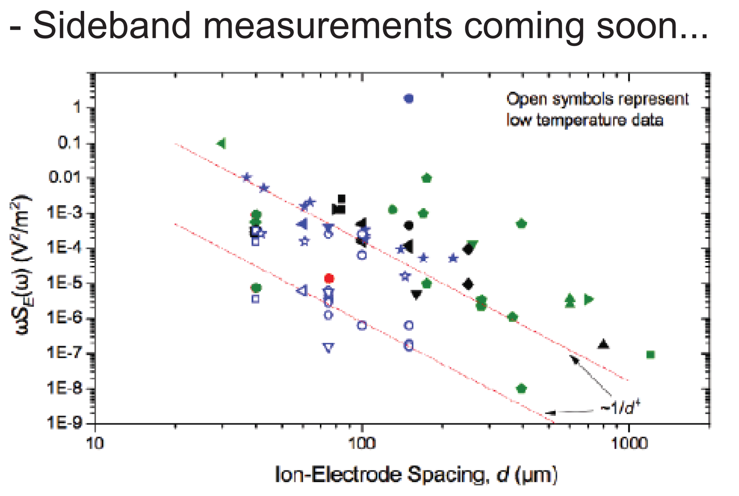
Diplexer (right) is used to combine microwaves, rf voltages and dc offsets. The toroidal transformer steps-up the trap rf supply.

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
- Heating rate is amongst best measured in a room temperature trap (red dot)
- Sideband measurements coming soon...



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