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Quantum logic operations in $^{40}Ca^+$ and $^{43}Ca^+$ trapped-ion qubits

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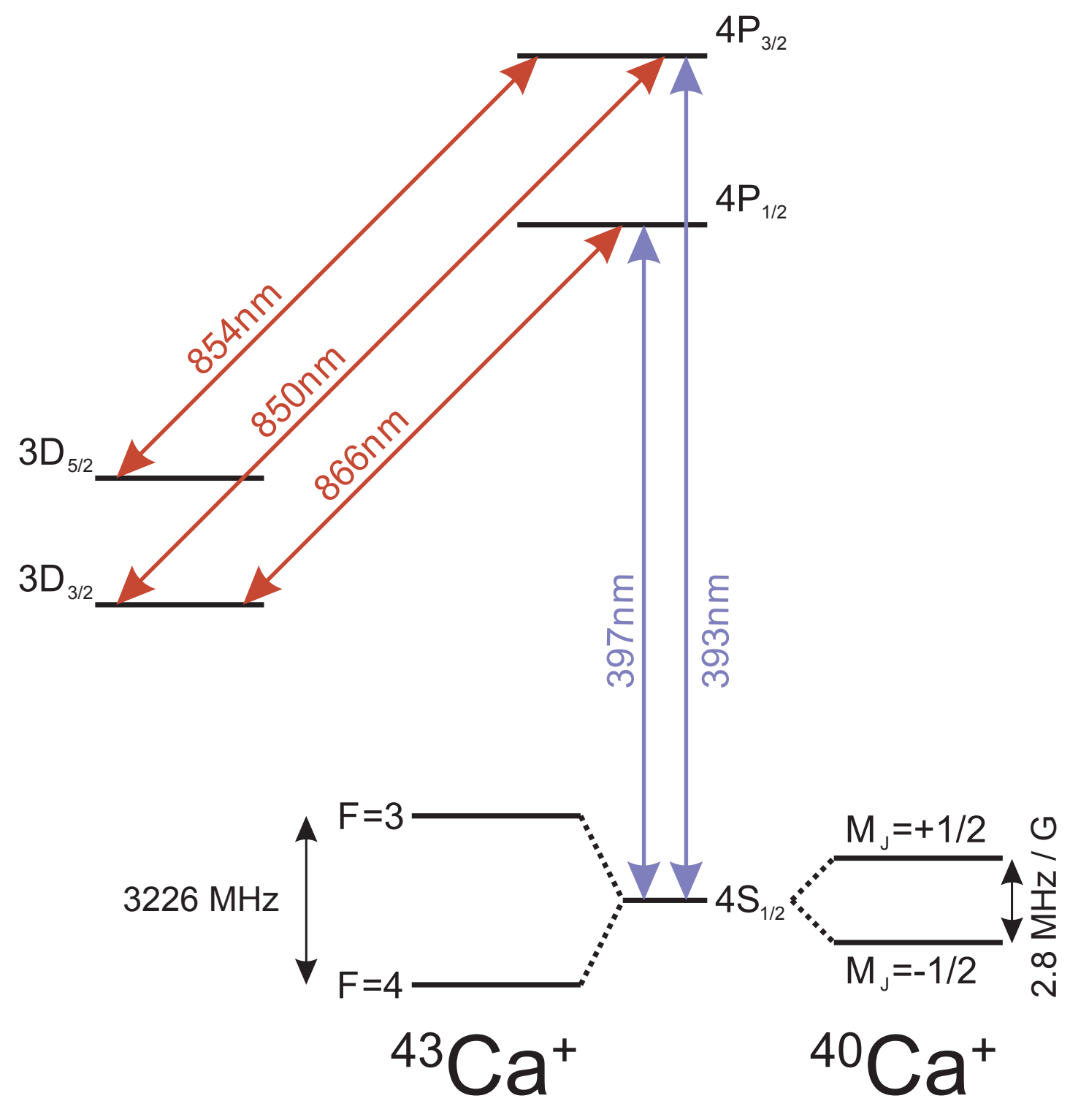
Mixed Species Experiment

Goals

- Two ion entanglement using a geometric phase gate
- High-fidelity laser gates
- Classical 'AND' gate by controlled relaxation (useful for practical error correction schemes)

Details

- Qubit stored in ground state manifold (T_2 very large)
- Only one set of lasers needed as isotope shifts can be spanned with EOMs
- RF ($^{40}Ca^+$) and microwaves ($^{43}Ca^+$) used for single-qubit rotations
- Raman lasers used for spin-motion coupling and single-qubit rotations
- Isotope shift of ~ 1 GHz allows individual addressing of the different isotopes and sympathetic cooling
- Simultaneous readout of both isotopes implemented

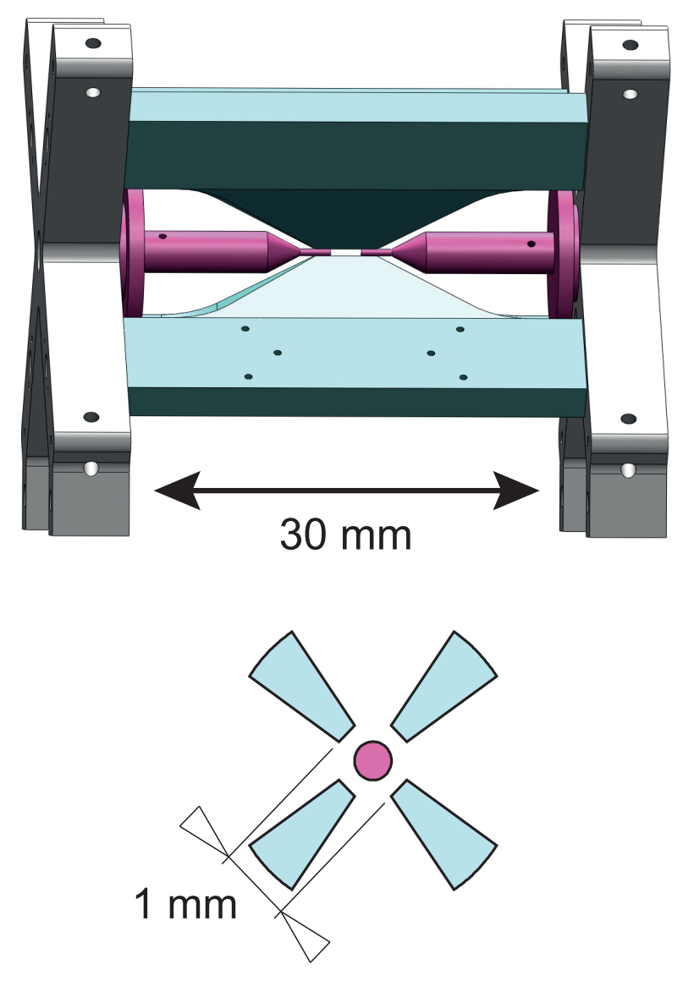


Raman Laser System

- 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 $\Omega_{Rabi} = 2\pi$ 500 kHz
- System can be switched between addressing $^{40}Ca^+$ and $^{43}Ca^+$ in 100ms by switching injection path
- Beat-note between Raman beams at ions sub-Hertz width

The Ion Trap

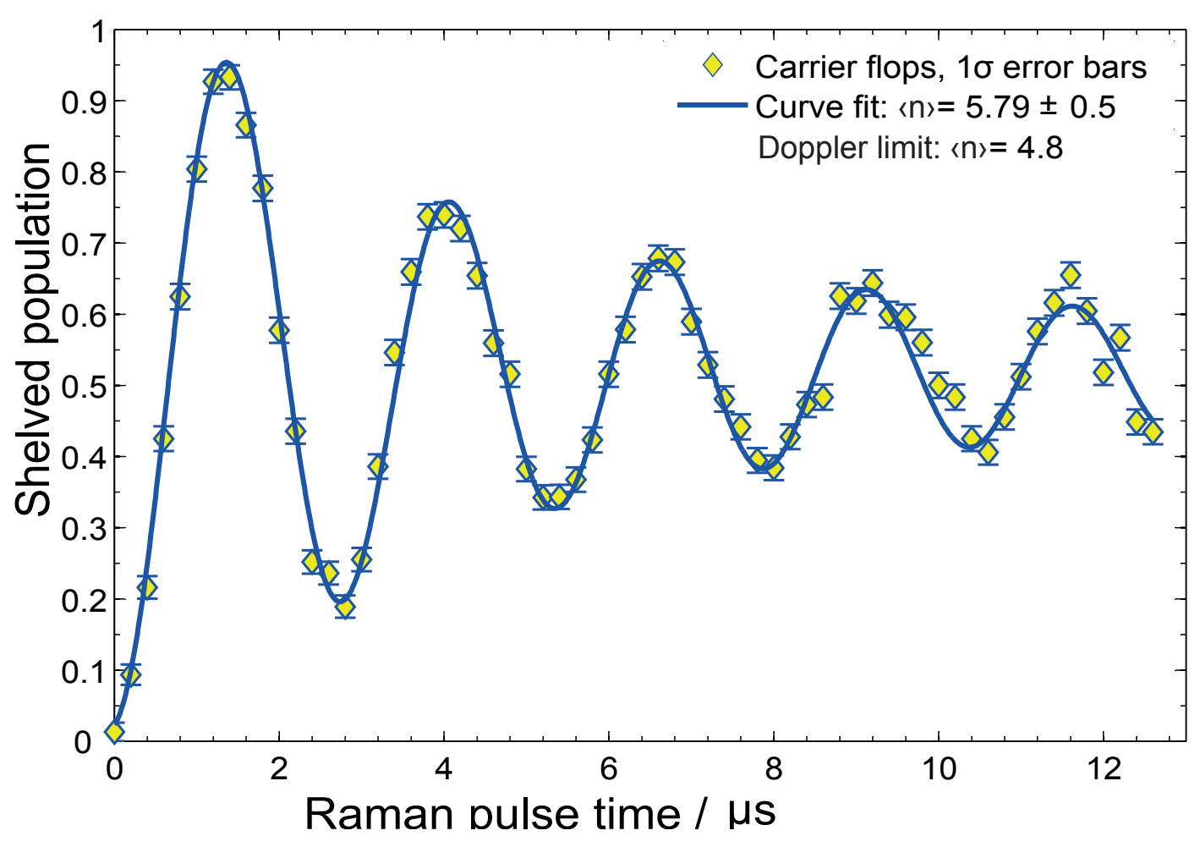
- Macroscopic linear Paul trap (RF applied to 'blades' (blue) for radial confinement, DC applied to 'end-caps' (red) for axial confinement)
- 'Innsbruck style' stainless steel 'blade' type
- Ion-electrode distance 0.5 mm
- Typical trap parameters:
  - Trap RF drive: 30 MHz
  - Axial secular frequency: 2 MHz
  - Radial secular frequency: 4 MHz



Cooling Results

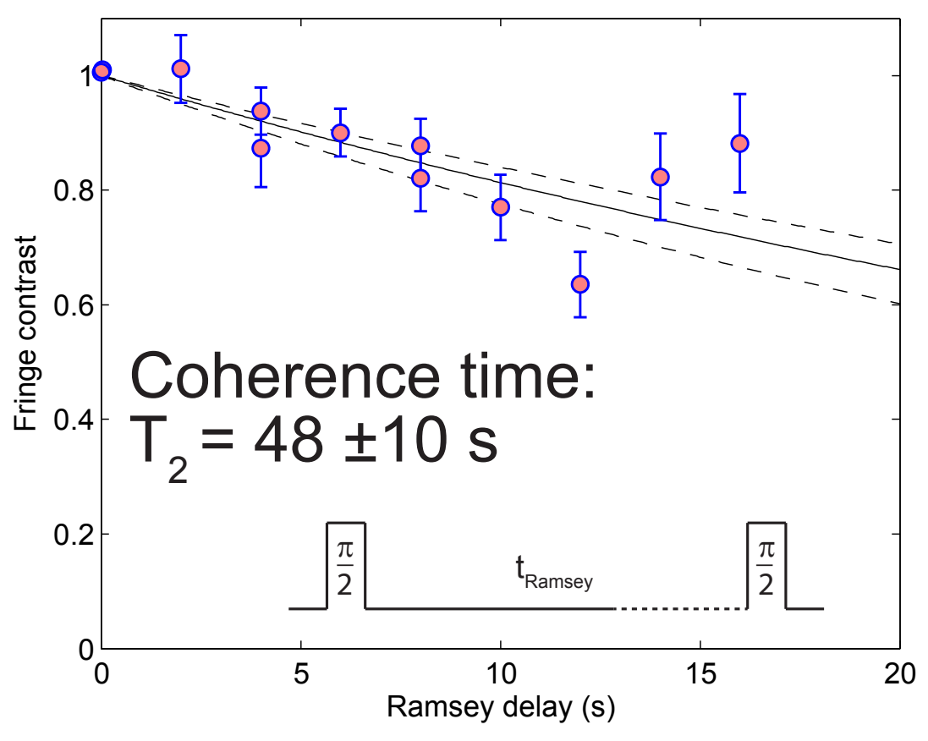
- Doppler cooling to ‹n› < 6
- Pulsed sideband cooling of crystal's two axial modes to ‹n› < 0.1
- Heating rate ~5 quanta / s at f_z = 2 MHz
- Mixed crystal sympathetic Doppler cooling

Carrier Rabi flops. f_z = 2 MHz.



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

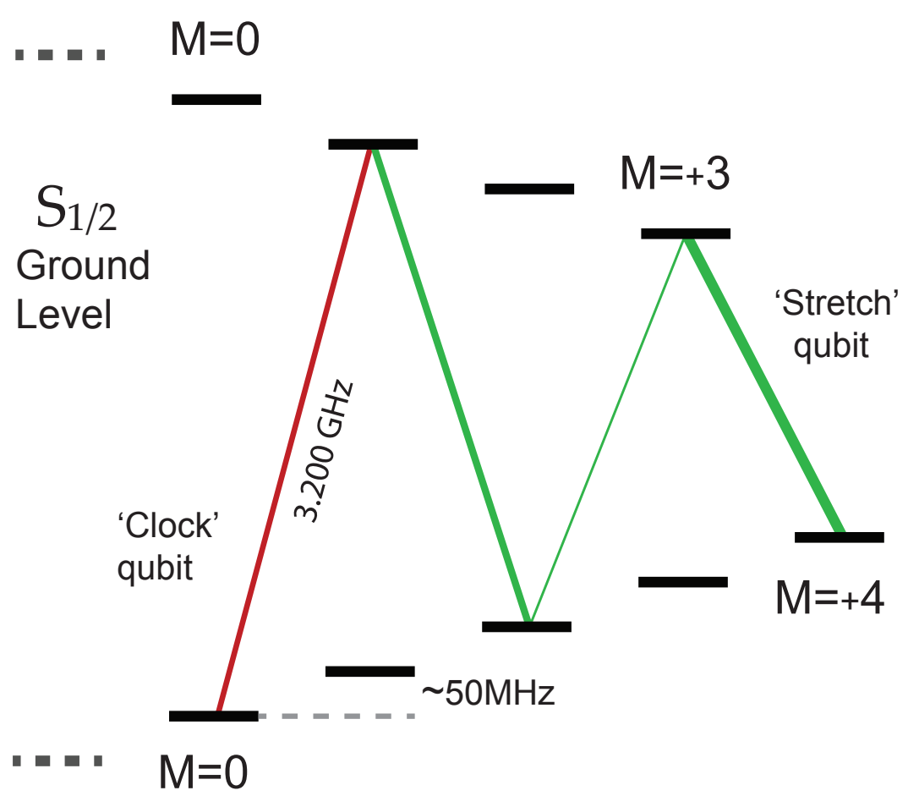
- Intermediate-field clock qubits preferable to zero-field clock qubit as Zeeman shift lifts state degeneracies.
- Until now intermediate-field clock states only demonstrated in $^9Be^+$ and $^{25}Mg^+$ (NIST).
- $^{43}Ca^+$ has the following advantages:
  - No UV lasers which can charge up the trap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

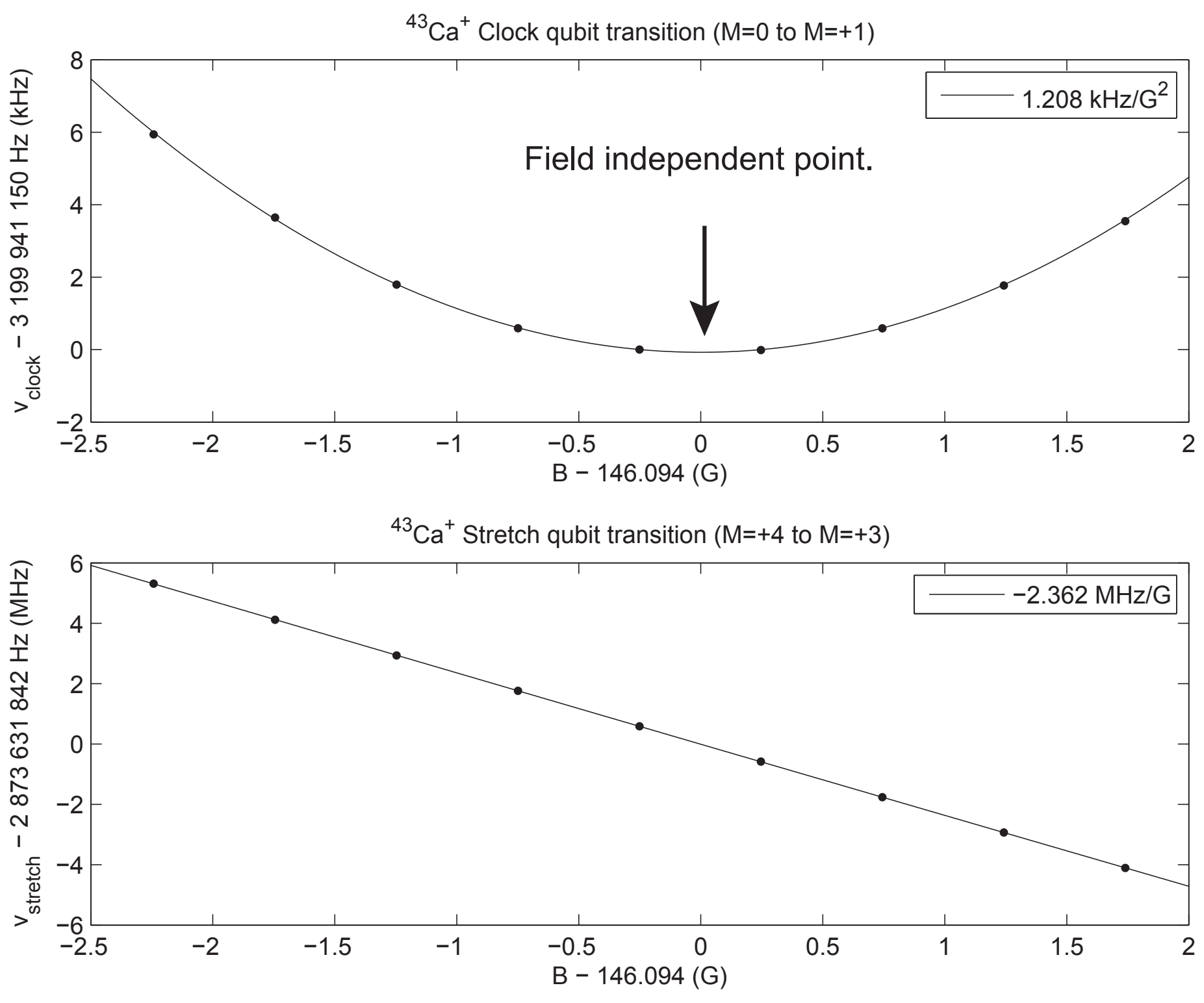


Coherence time: T_2 = 48 ±10 s

State preparation

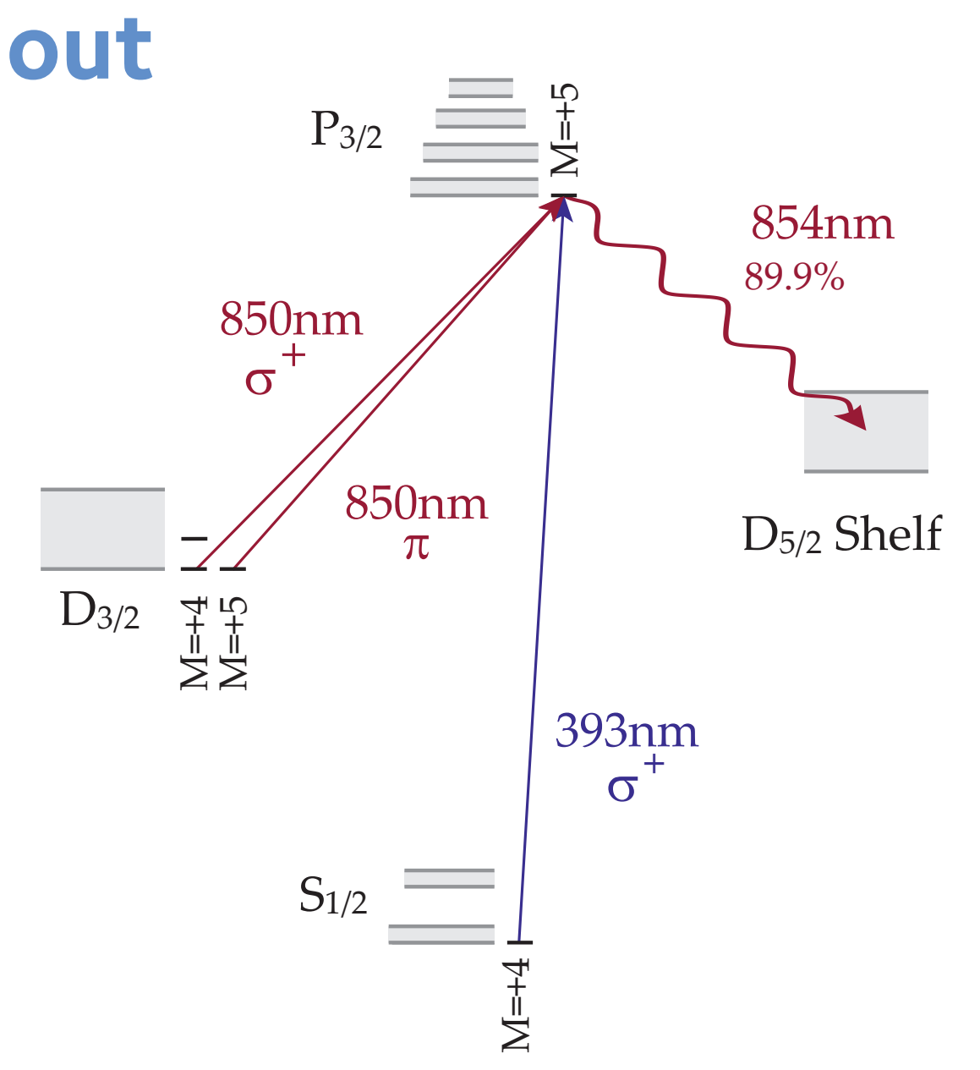
The ion is initialised in F=4,M=+4 by several cycles of optical pumping and microwave 'reclaiming' pulses, giving good state preparation with impure optical polarisation. 3 microwave pulses (green) are then used to prepare the 'clock' qubit (red)





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

Readout

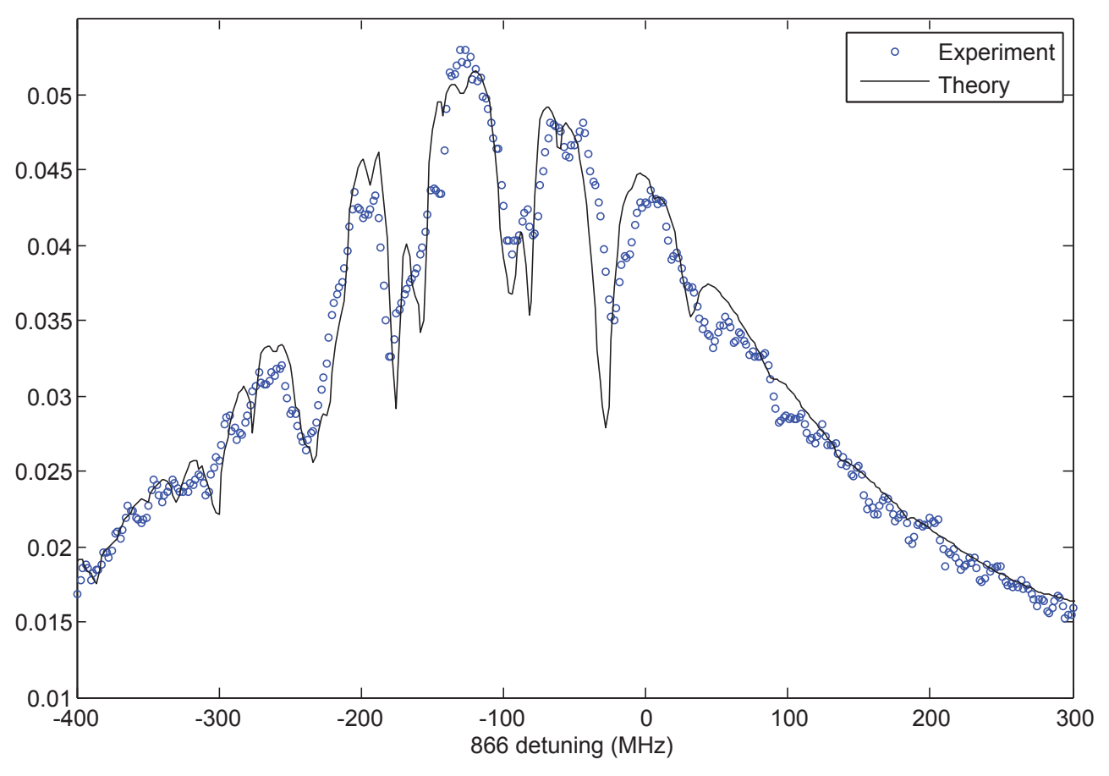


Shelving scheme simulated to give ~99.98% shelving fidelity without the need for a laser to address the quadrupole transition ($S_{1/2}$ - $D_{5/2}$);

preliminary experimental data: combined state-preparation and readout fidelity of **~99.94%** is achieved

Doppler 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 the system.
- 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)

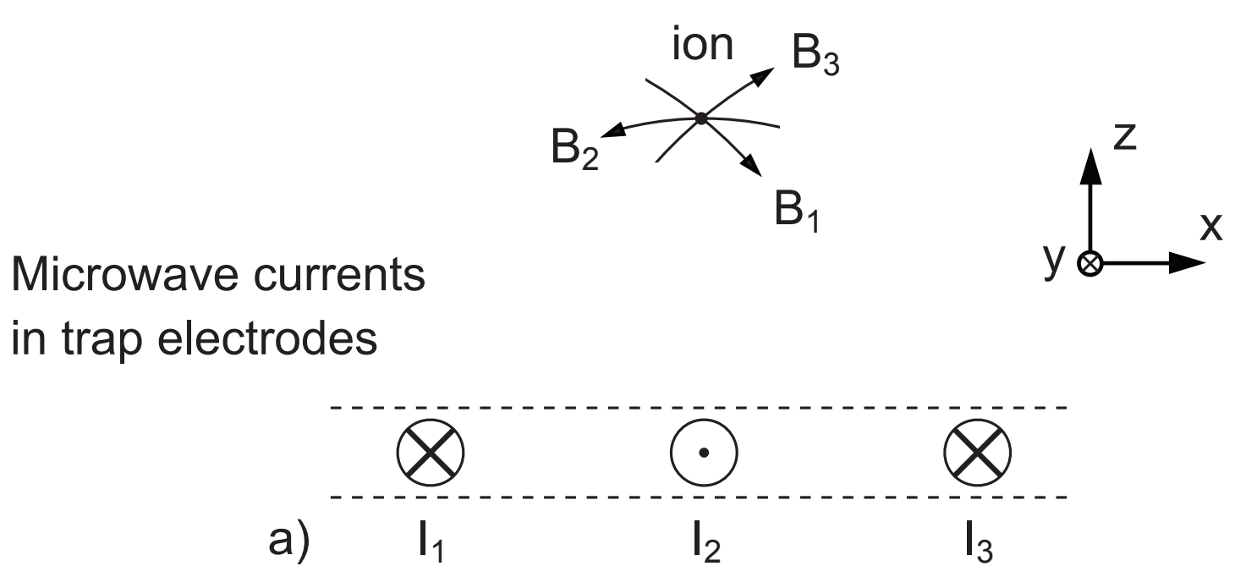


Comparison of experiment and theory for a frequency scan of the 866nm repumping laser.

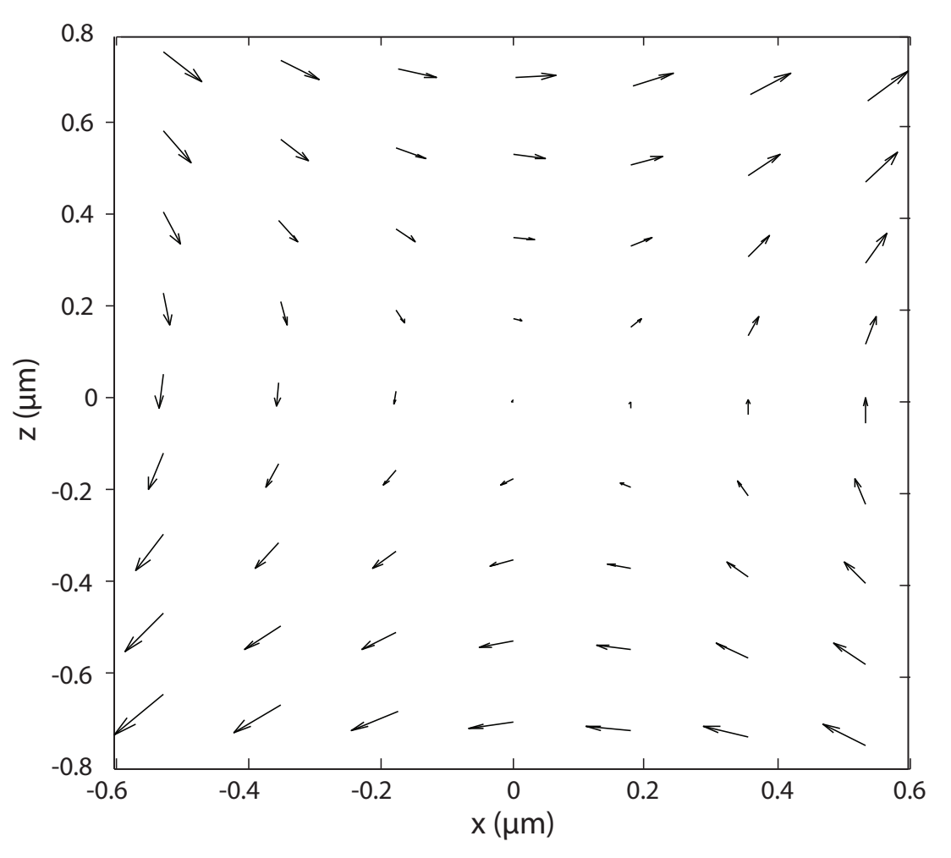
Towards Microwave-driven Entanglement

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.



Measured microwave B-field around ion



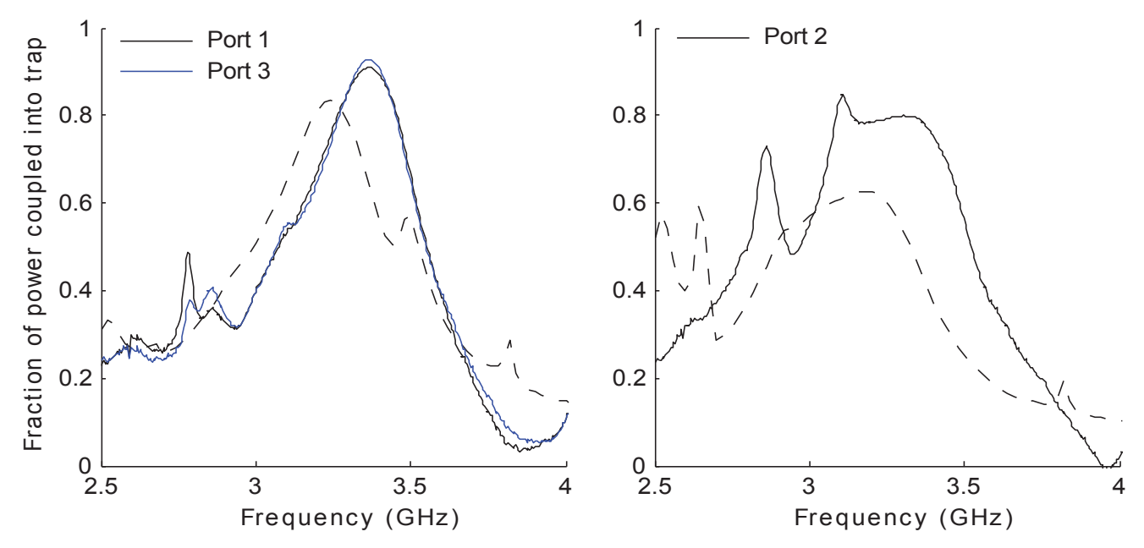
dB_x/dz = 0.30T/m; dB_z/dx =0.29T/m

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

Trap Testing

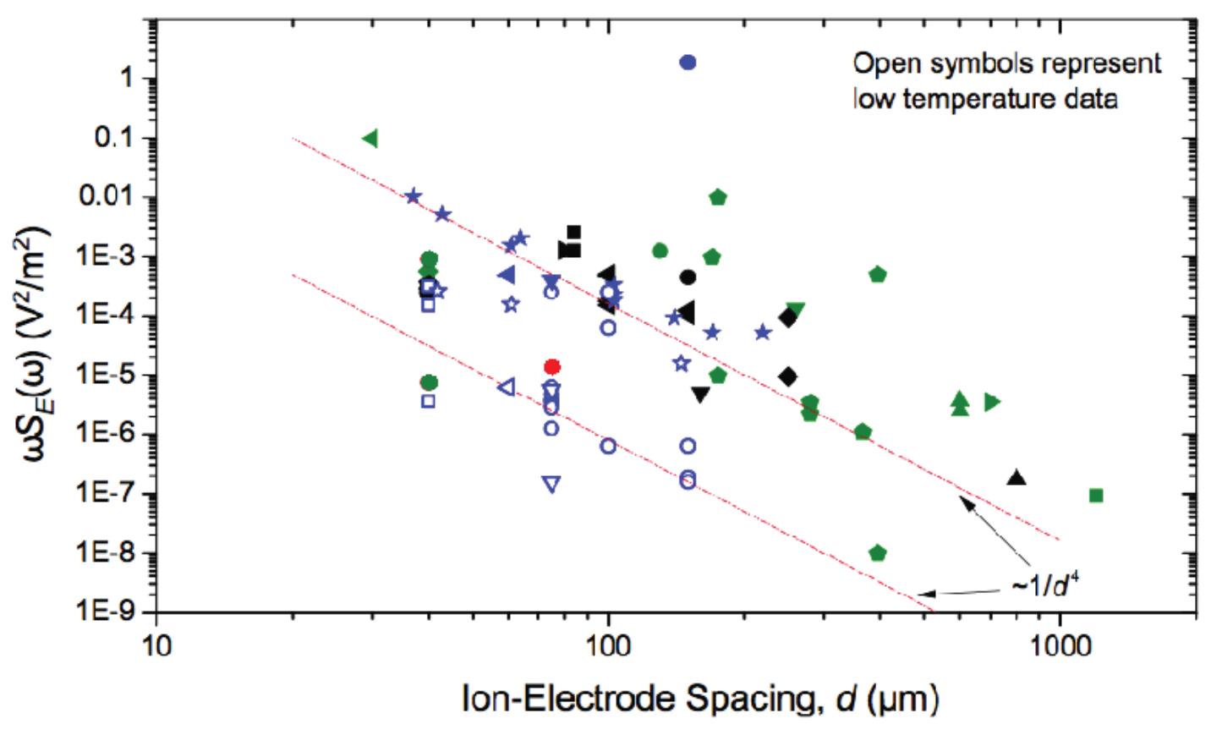
Network analyser data shows that >75% of input microwave power is coupled into the trap.



- we find agreement between simulated and measured gradients at the 5% level (see measured field on the left)

- Sidebands observed

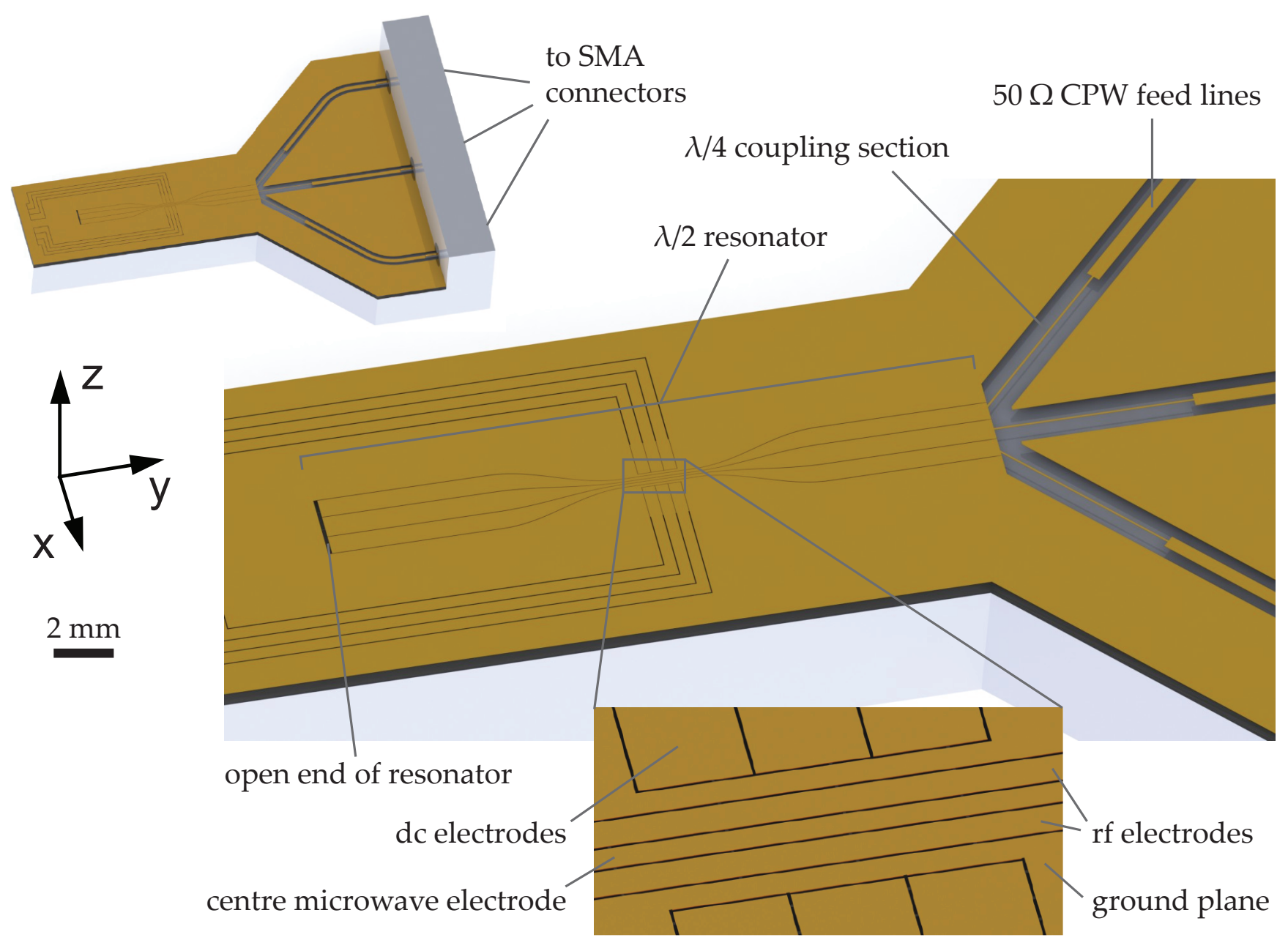
- Heating rate is amongst best measured in a room temperature trap (red dot)

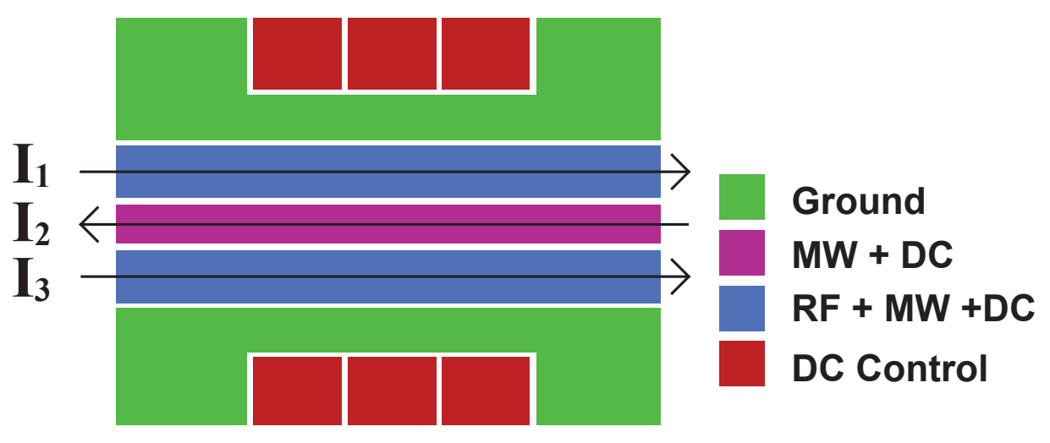


Trap Design

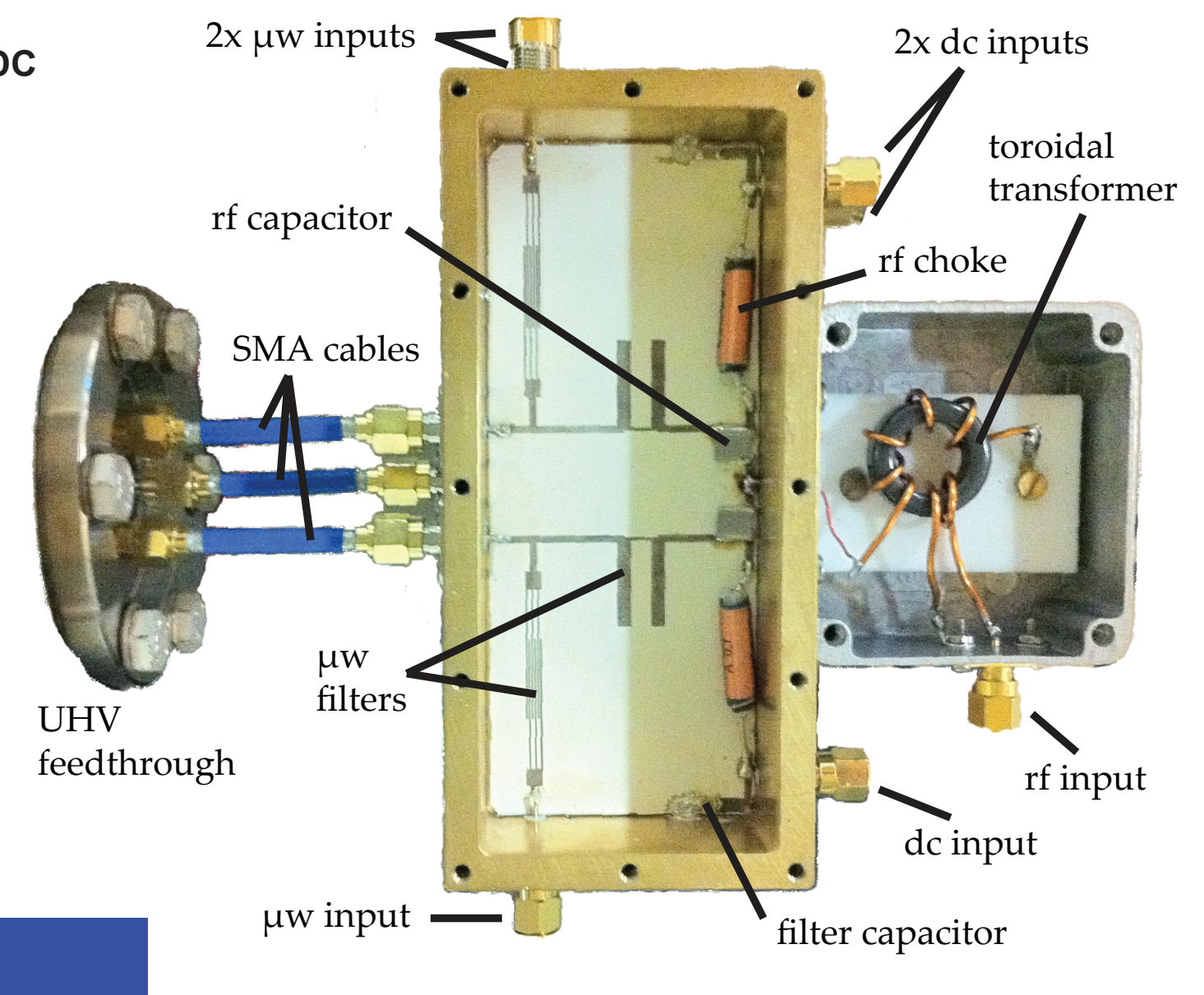
Trap is gold on sapphire for good thermal conductivity.

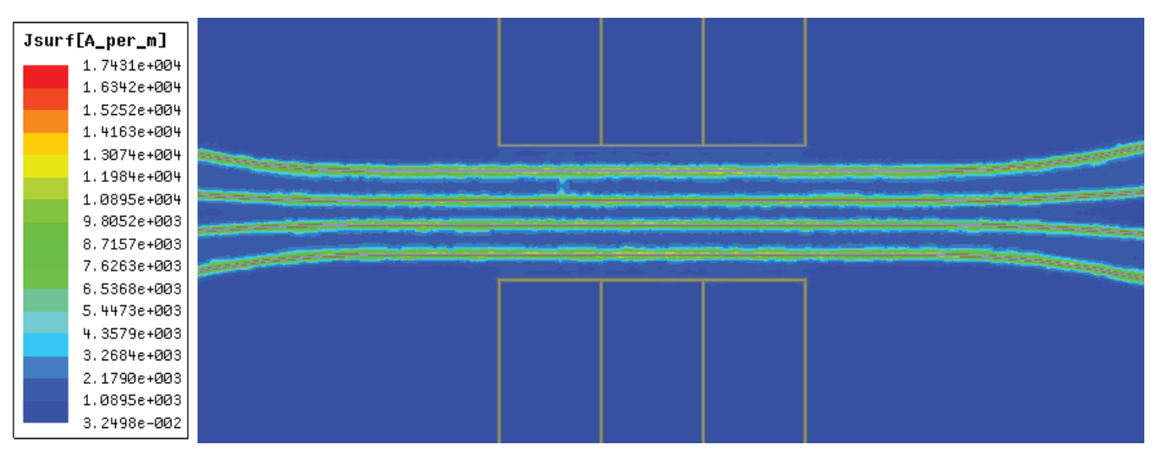
The trap region is in the centre of a half-wave microwave resonator to increase currents. Quarter-wave coupling sections provide a good 50Ω impedance match.





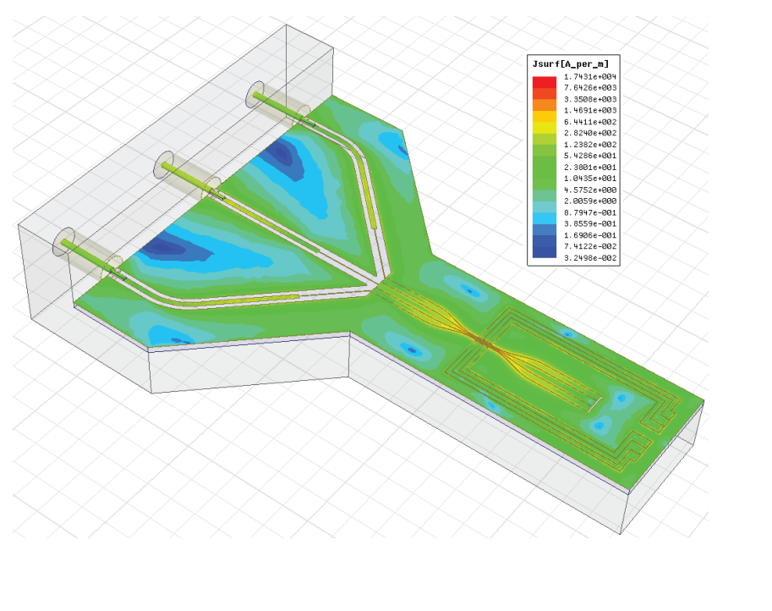
Simulations show that combining the microwave and rf electrodes (above) gives higher microwave gradients than alternative layouts for a given current.





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

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



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