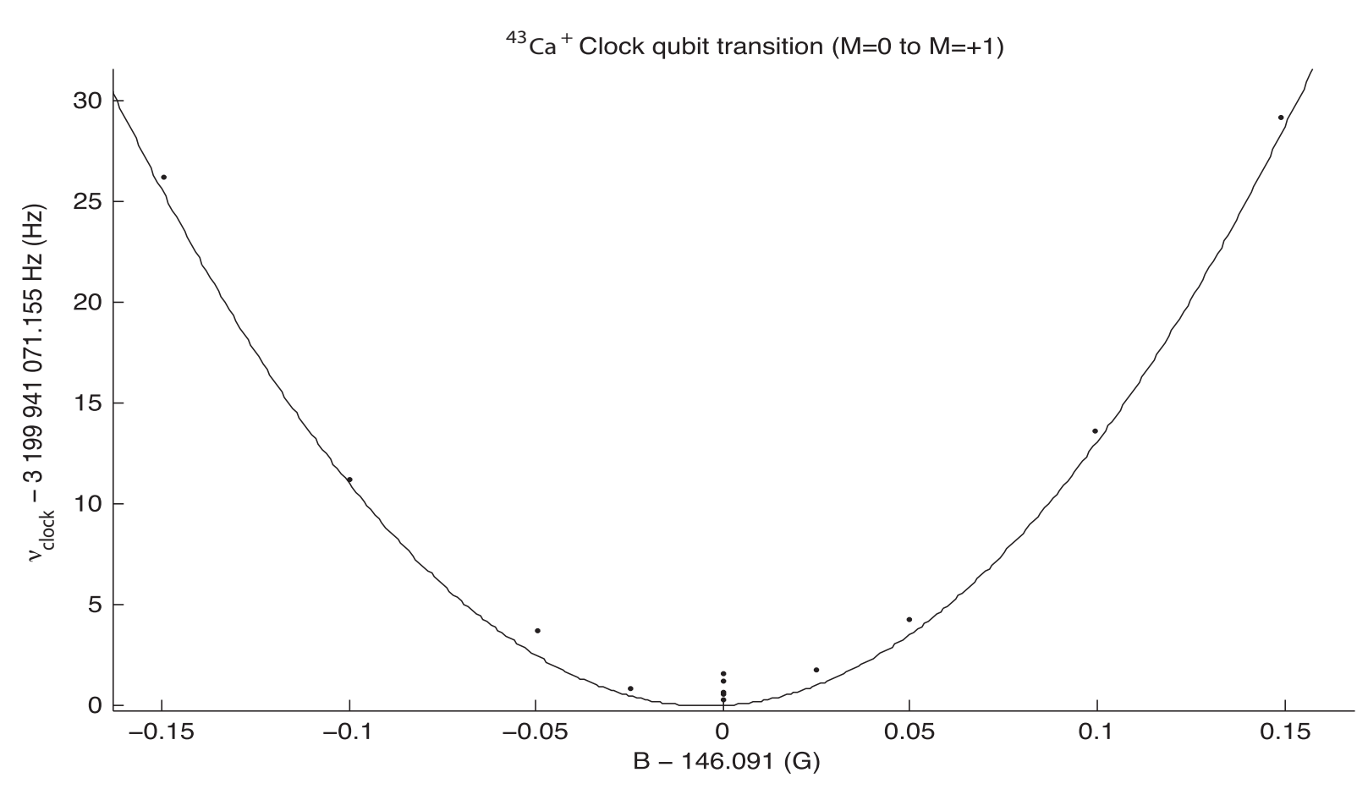
T P Harty D T C Allcock N M Linke C J Ballance H A Janacek L Guidoni D N Stacey D P L Aude Craik A M Steane D M Lucas

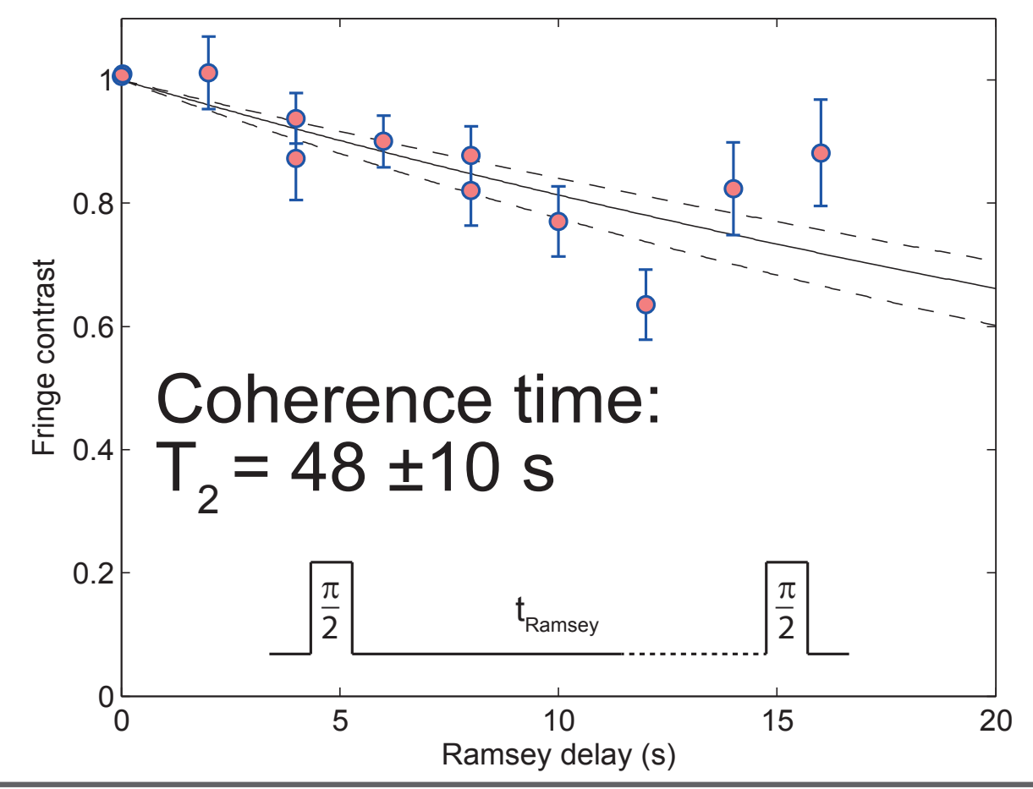
Ion trap quantum information processing using Ca^+ at Oxford

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

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

- Magnetic field independent "clock" qubits allow long coherence times
- Intermediate-field clock qubits are preferable to zero-field clock qubits, as the Zeeman shifts required to break state degeneracy induce first-order field dependances
- Until now, intermediate-field clock states have only been demonstrated in $^9Be^+$ and $^{25}Mg^+$ (NIST)
- $^{43}Ca^+$ has the following advantages:
    - No UV lasers, which can charge the trap
    - Laser diodes, fibres and other optics readily available at all required wavelengths
    - Low-lying D-states allow high fidelity readout via electron shelving
- The main disadvantage is the lack of a closed cooling transition

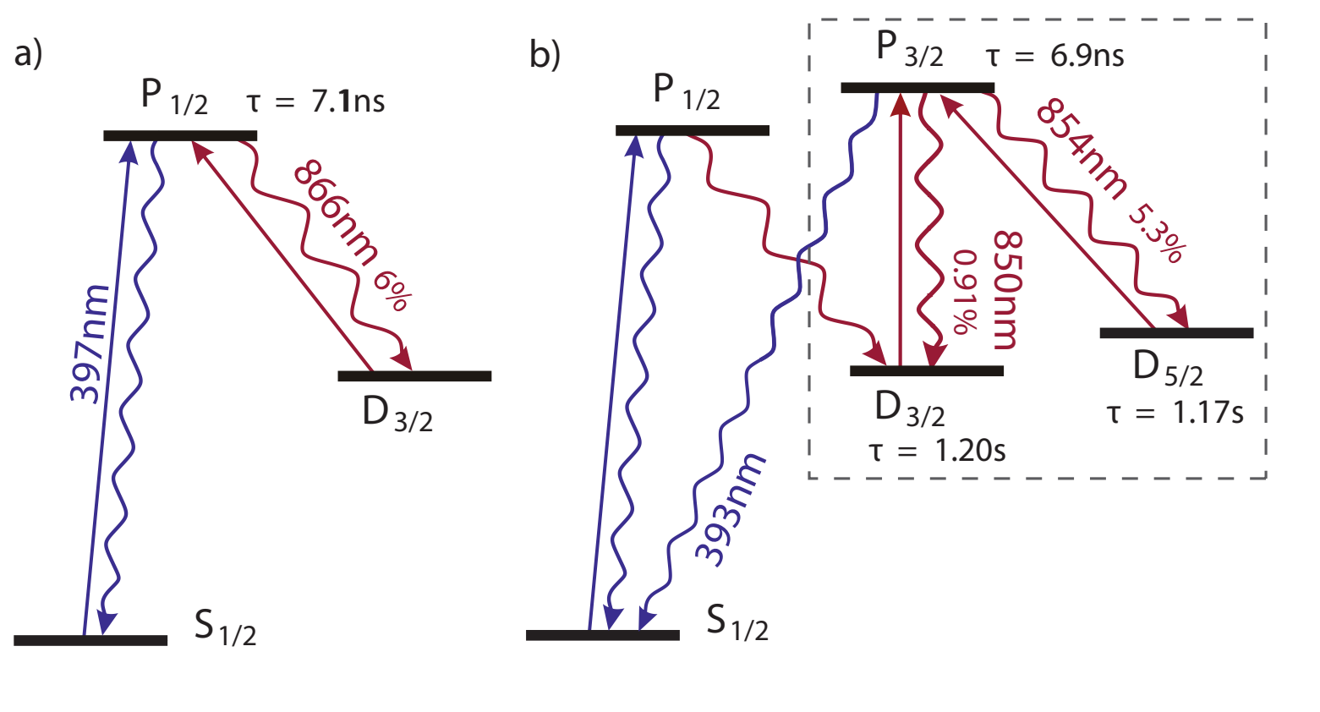




Coherence time:
T_2 = 48 ±10 s

Doppler Cooling at 146G

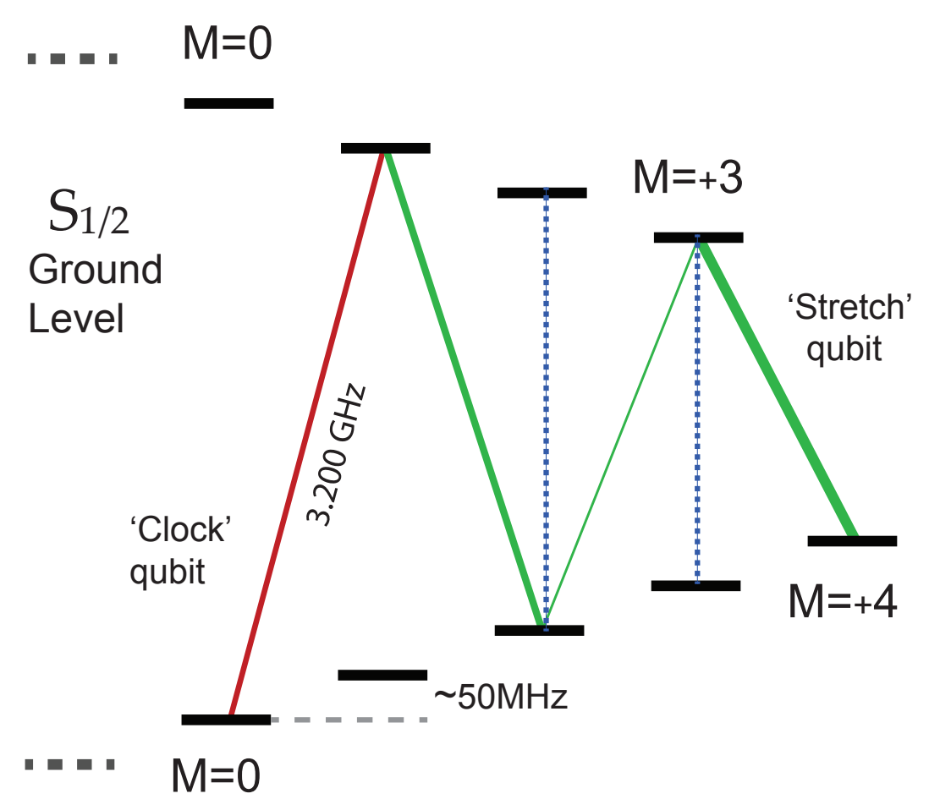
- $S_{1/2}$-$P_{1/2}$-$D_{3/2}$ system has 64 states and no closed transitions for cooling
- Optical Bloch equations used to simulate internal dynamics of the system
- Straightforward cooling solution found using 397nm laser + 866nm repumper (figure a):
    - 397nm polarization chosen so that only a few states are populated (2:1 ratio of σ^+:π)
    - Needs only single sideband on 397nm cooling laser (from 3.2GHz EOM)
    - Single frequency 866nm repumping laser
    - $P_{1/2}$ level population of up to ~0.15 simulated and achieved (50000 s^{-1} fluorescence)



- Cooling also possible using 850nm + 854nm repumpers (figure b):
    - Involves $D_{5/2}$ "shelf" level, so cannot be used for qubit readout
    - Simpler system since no dark resonances between cooling and repumper lasers

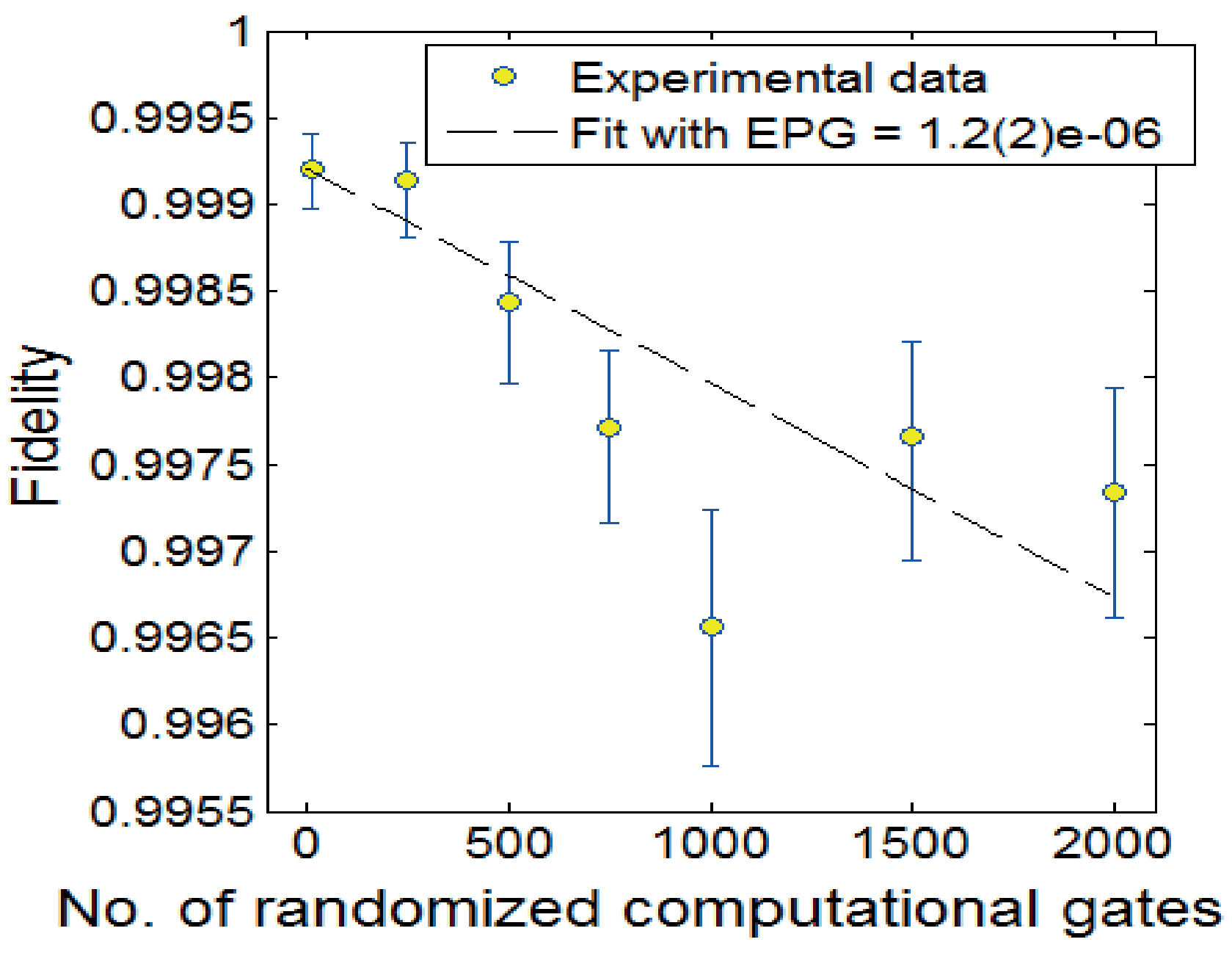
State preparation

The ion is initialised in the "stretch" state $4S_{1/2}$ (F=4,M_F=+4) by several cycles of 397σ^+ optical pumping and microwave "reclaiming" π-pulses (blue), giving good state preparation (>~99.99%) even with imperfect optical polarisation. Three microwave π-pulses (green) are then used to prepare the 'clock' qubit (red)

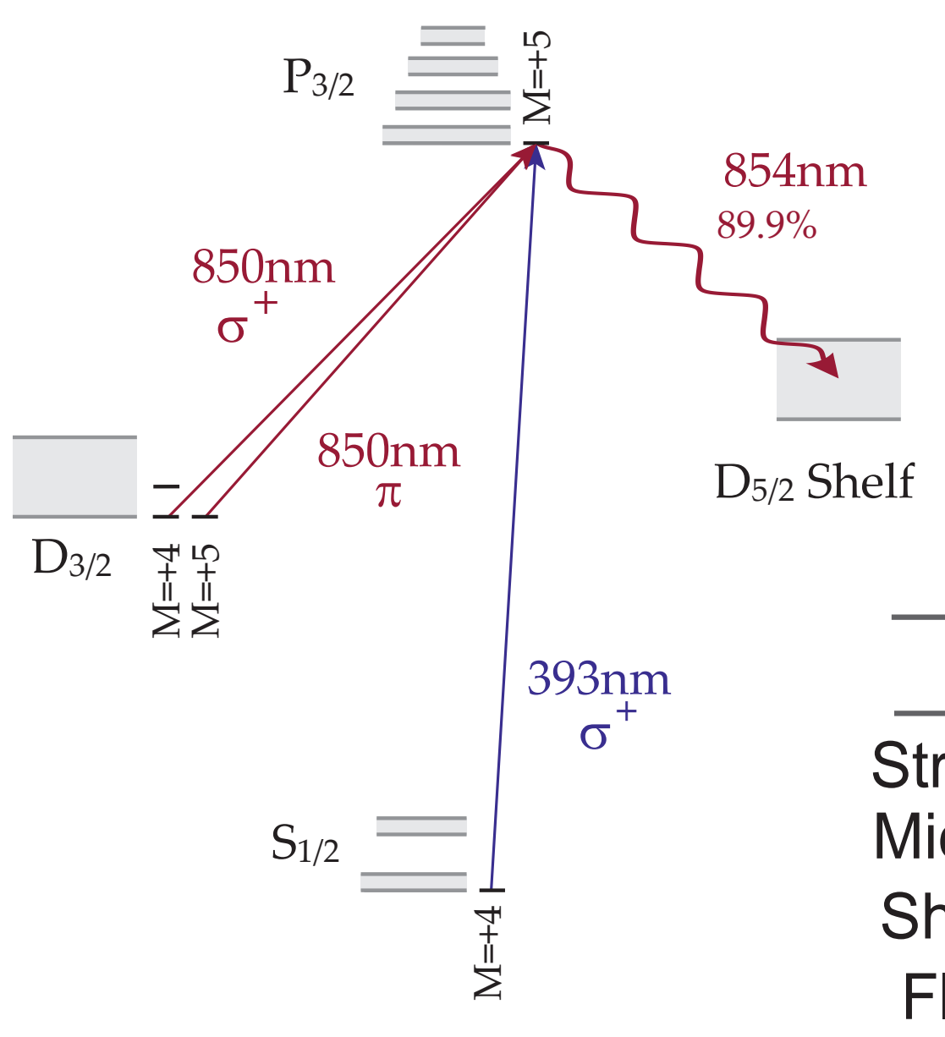


Single-qubit gate error at the 1ppm level

We measured the single-qubit gate error by randomized benchmarking. After 2000 computational gates (each composed of a 12μs Clifford π/2 gate, randomized by a Pauli π gate), we measure an error of 0.2%, indicating an error-per-gate (EPG) at the part-per-million level.



Readout



- The qubit is transferred to the $D_{5/2}$ "shelf" level, using a 393nm laser as well as one or more 850nm beams to repump population that decays to the $D_{3/2}$ level
- Once shelved, unshelved population is detected by looking for fluorescence using Doppler cooling lasers
- The shelving scheme is simulated to give fidelities of up to 99.985%
- Although two lasers are required, these can be standard diode lasers, which are much less demanding than a 729nm ($S_{1/2}$-$D_{5/2}$) quadrupole laser

Experimental results

Source of error	Error from stretch-qubit	Error from clock-qubit
Total error	6.5 (5) x 10^{-4}	6.8 (5) x 10^{-4}
Stretch-state preparation	< 10^{-4}	< 10^{-4}
Microwave transfer pulses	2.3 x 10^{-4}	3.8 x 10^{-4}
Shelving transfer to $D_{5/2}$	2.7 x 10^{-4}	1.5 x 10^{-4}
Fluorescence detection	1.5 x 10^{-4}	1.5 x 10^{-4}

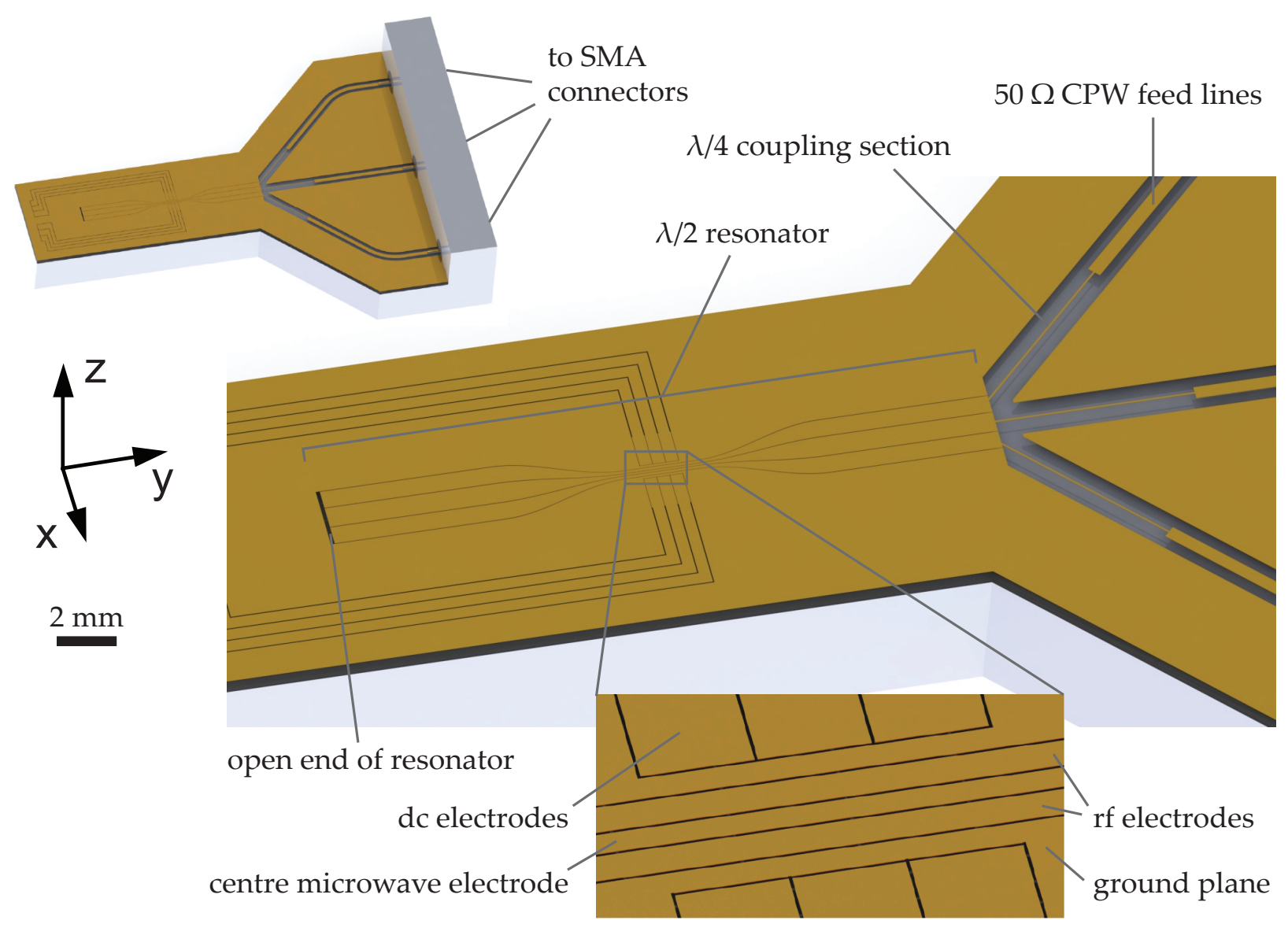
Towards Microwave-driven Entanglement

Aim is to drive two-qubit entanglement using oscillating microwave, rather than optical, field gradients. This is achieved by trapping the ion in the near-field (<100μm) of a microwave conductor to obtain high enough gradients.

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

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 and unwanted single-qubit rotations
- Fast gates (~10μs) will require small traps and high microwave current densities

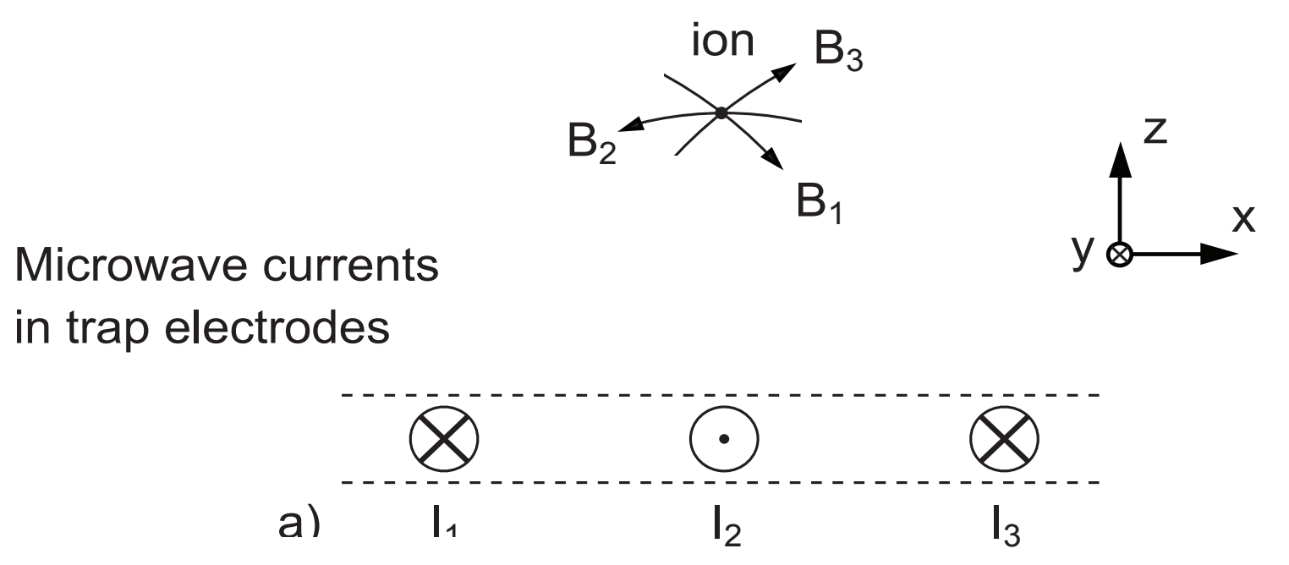


Trap design showing microwave resonators and coupling elements

Below: Fields produced by microwave currents

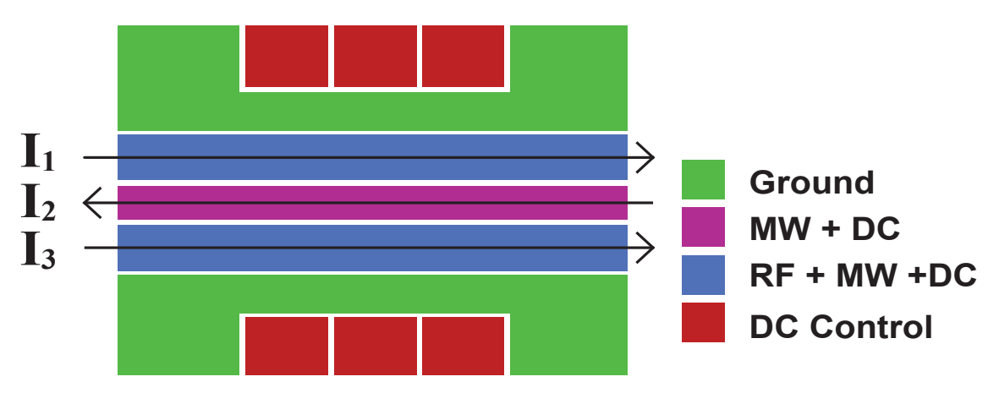
Top right: HFSS simulations of trap, showing microwave currents in each electrode

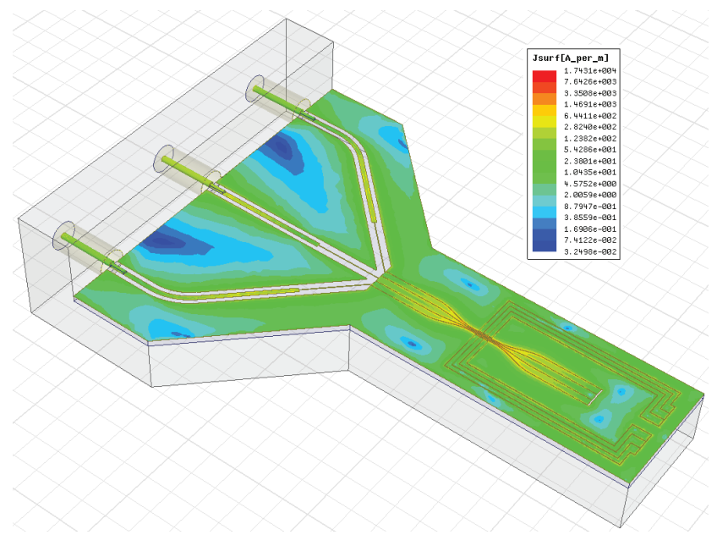
Bottom right: Multiplexer used to combine microwaves, RF and DC

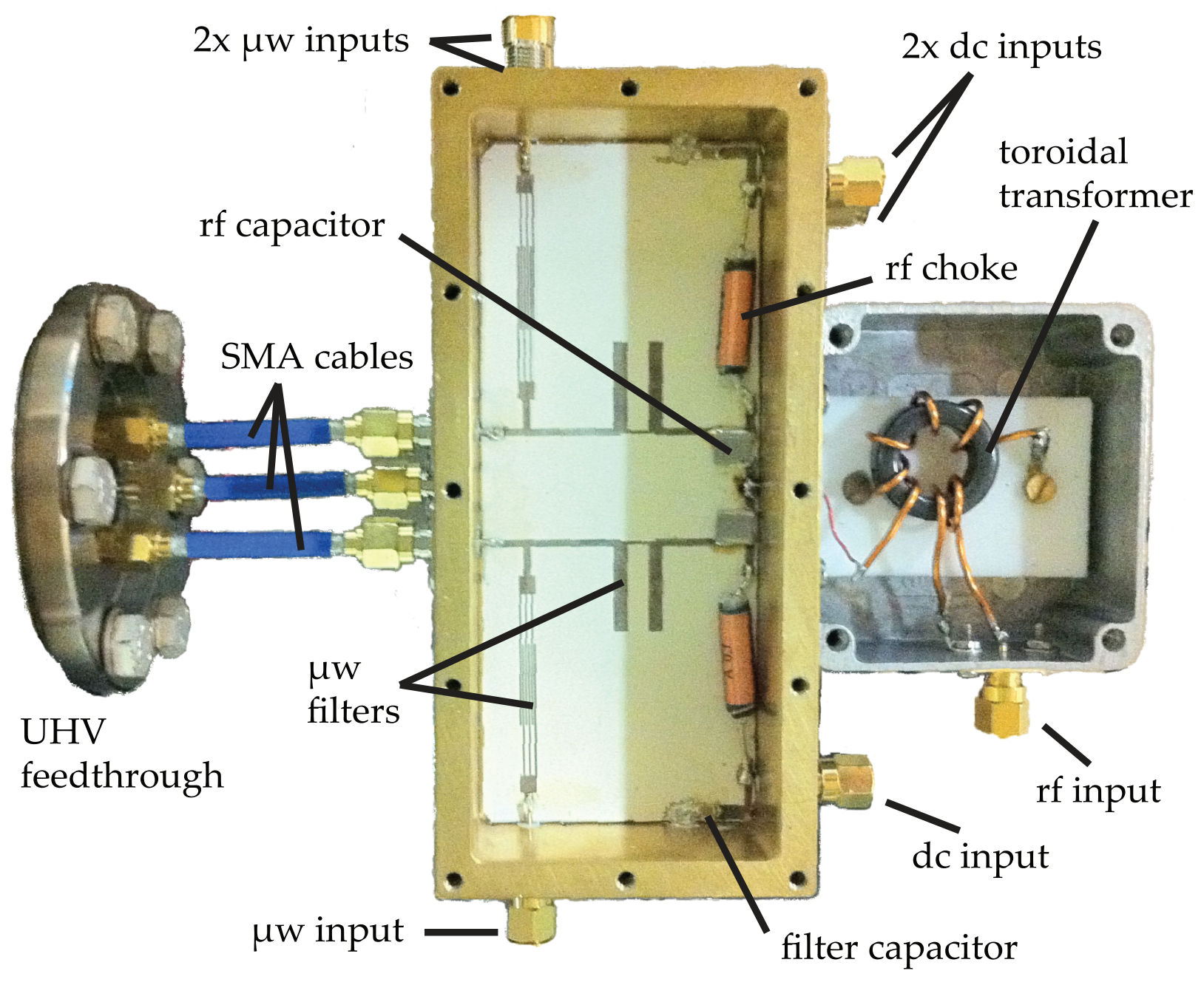


Trap Design

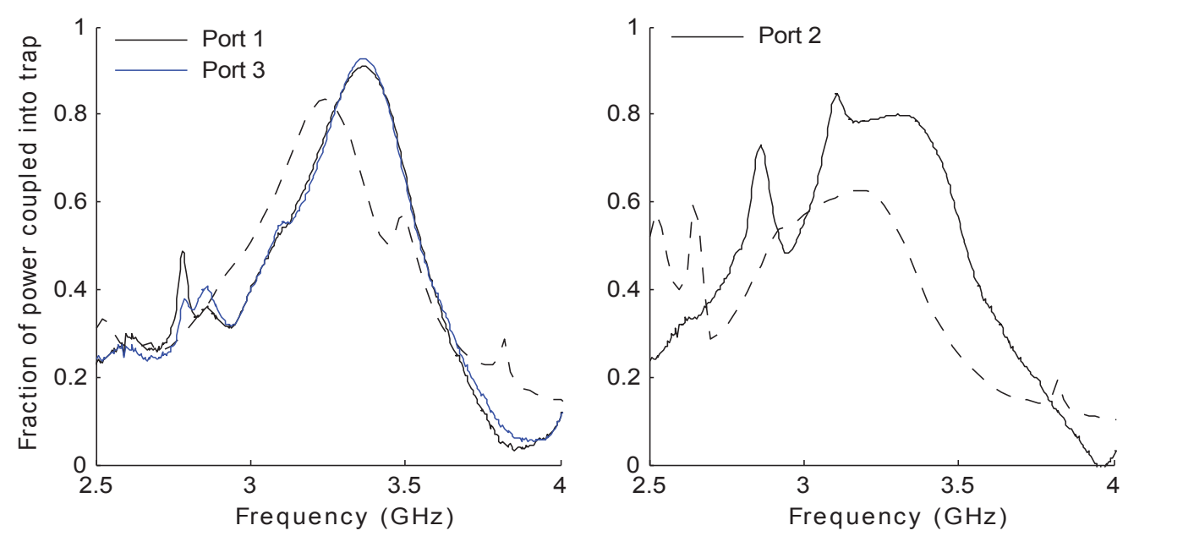
- Producing a strong gradient while nulling the field requires three wires
- For optimal coupling to the ion, microwaves should be combined onto the same electrodes as the RF trapping currents and DC control voltages
- Low-Q (~5) half-wave resonators allow impedance matching to 50Ω system and provide current build up
- Resonators are coupled to 50Ω system using quarter-wave coupling elements
- Design and simulation done using HFSS finite element microwave simulation software
- Trap constructed from gold electroplated onto a sapphire substrate for good thermal conductivity





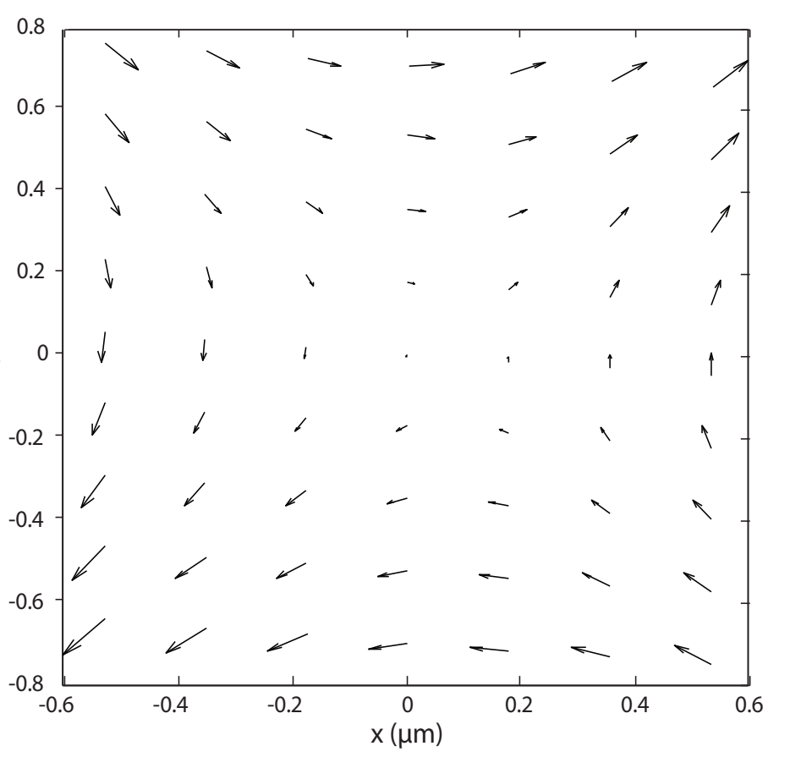


Results



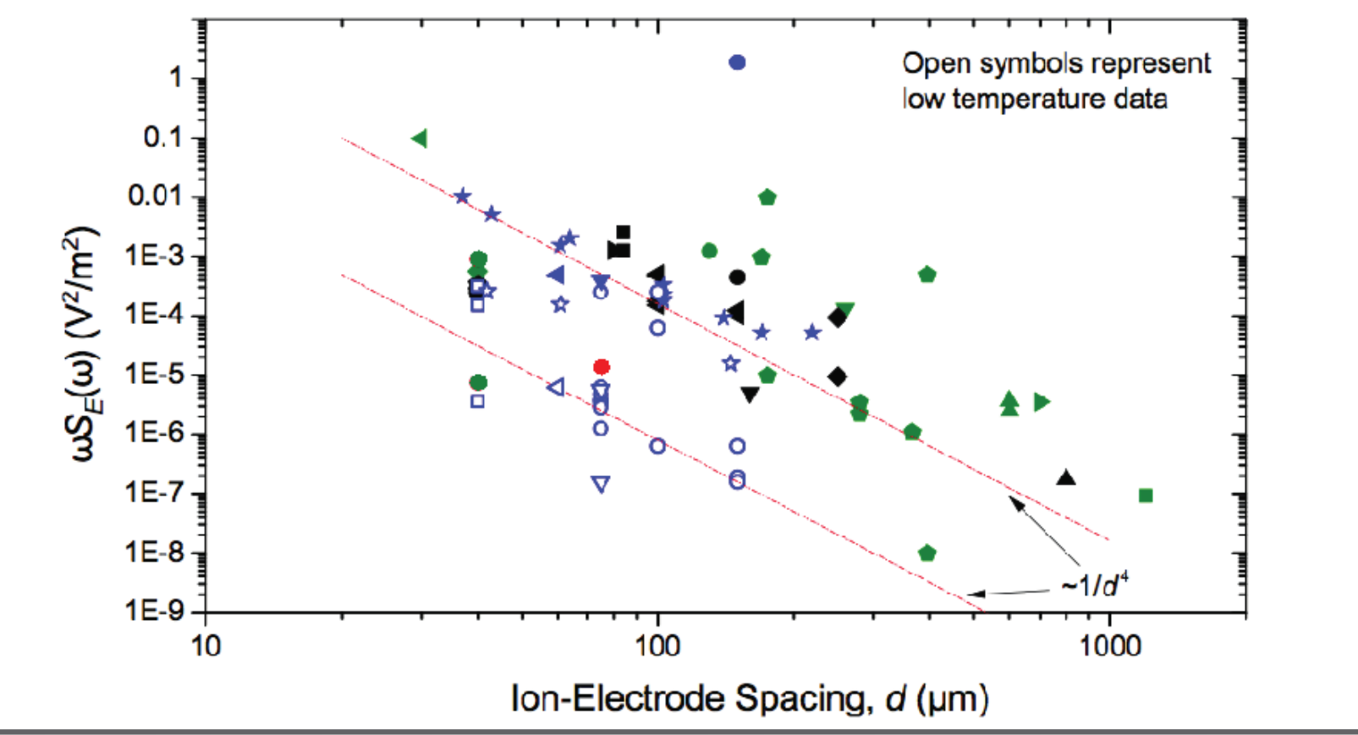
- Network analyser data (above) shows that >75% of input microwave power is coupled into the trap.

Measured microwave B-field around ion



- Measured field gradients (right) agree with simulations to 5%
- Sidebands observed
- Heating rate is among best measured in a room temperature trap (red dot on figure below)

$\partial B_x/\partial z$ = 0.30T/m; $\partial B_z/\partial x$ =0.29T/m



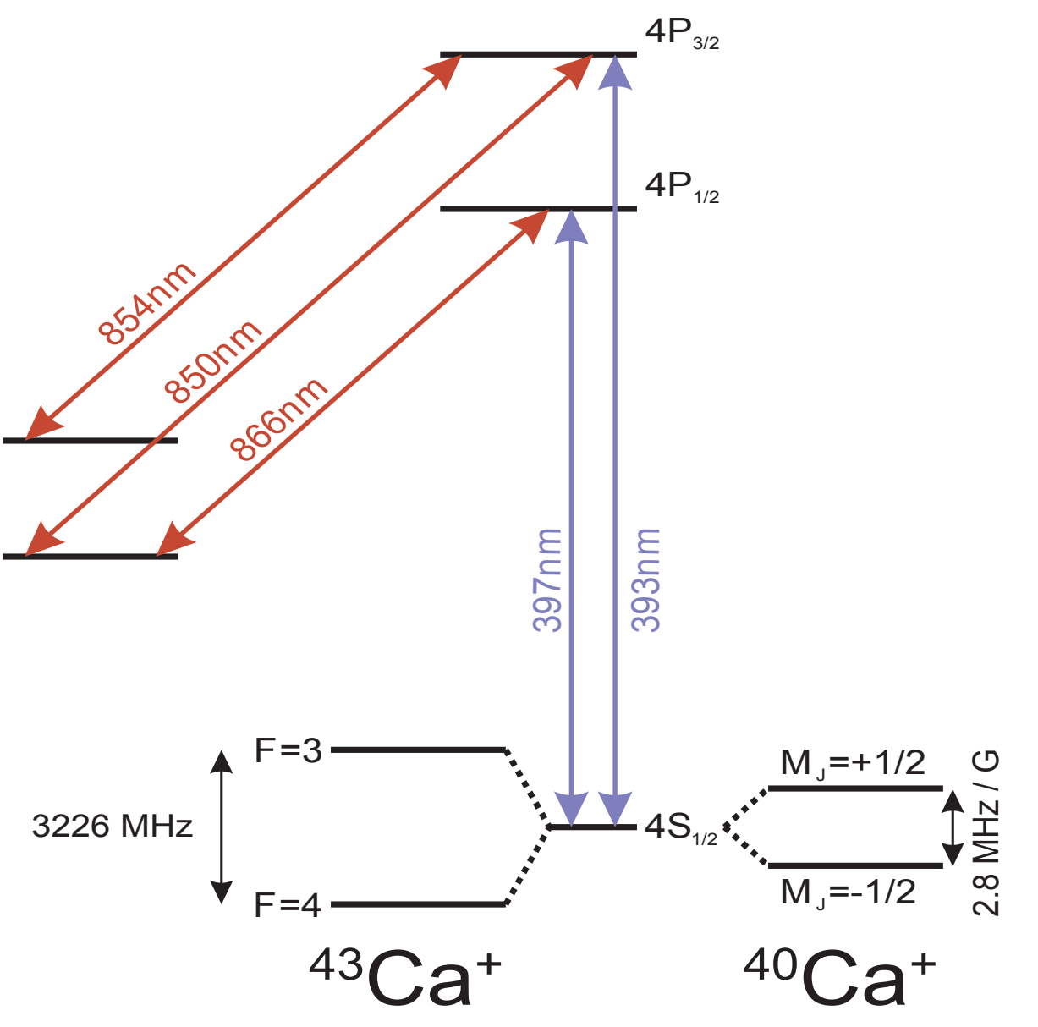
Mixed Species ($^{40}Ca/^{43}Ca$) Experiment

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)

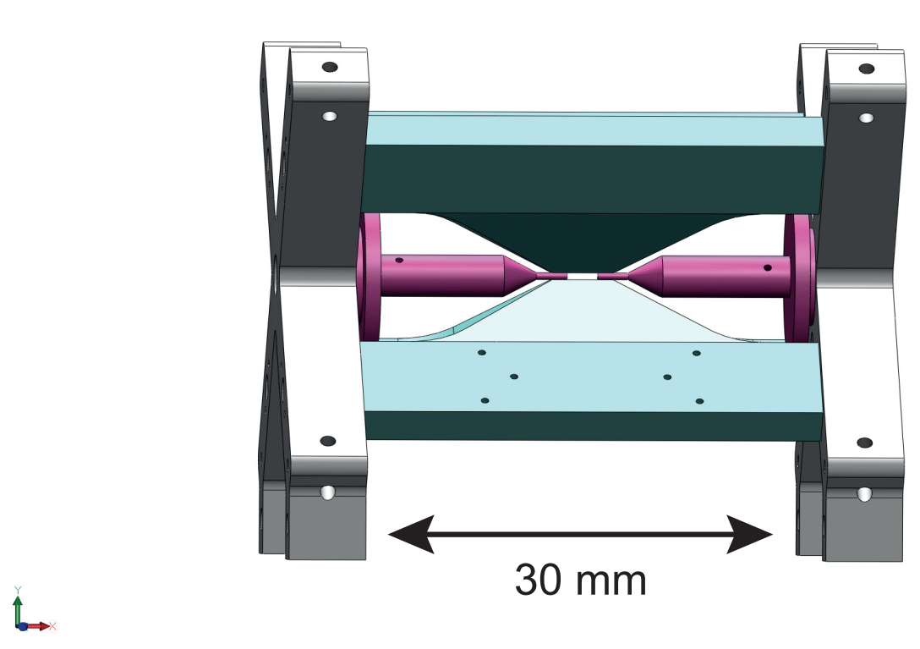
Details

- Qubit stored in ground state manifold (T_2 very large)
- Only one set of lasers needed as isotope shifts can be spanned using 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



The Ion Trap

- '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

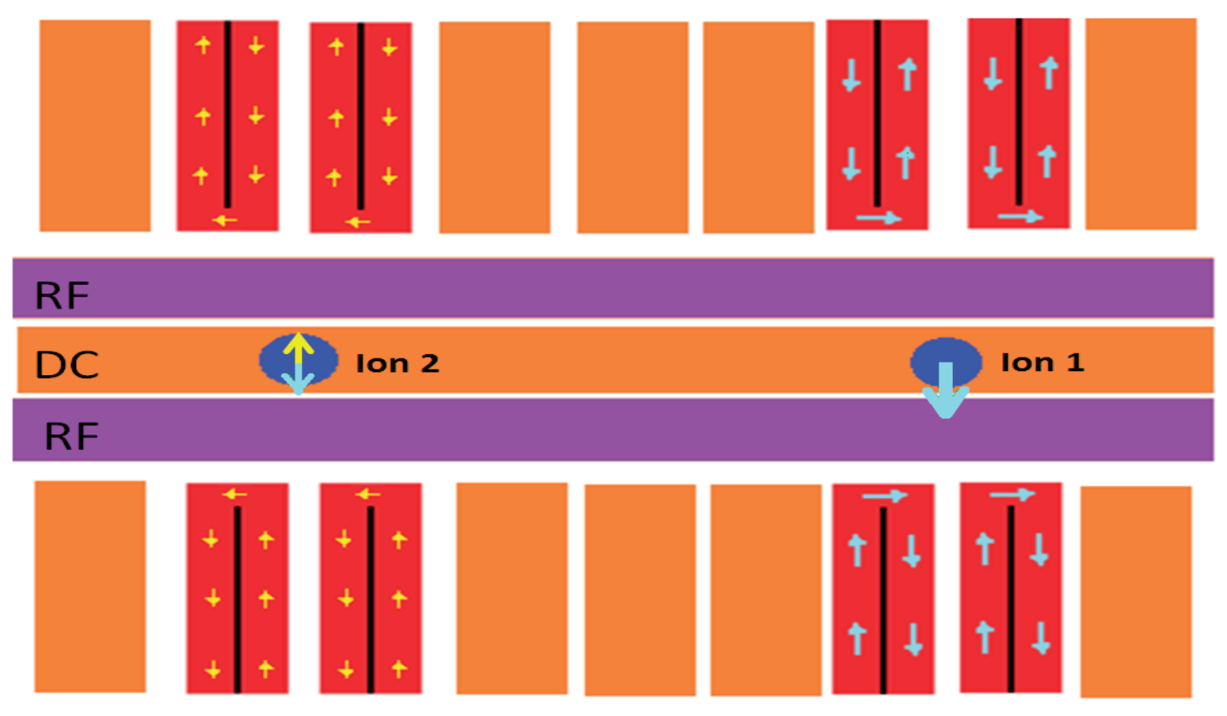


Raman Laser System

- 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 x 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

Single-qubit addressing with microwaves

- Microwaves are a more mature and simple technology than lasers. Driving gates with microwaves offer many advantages in terms of stability, scalability, noise and cost (see above).
- However, the longer wavelength of microwave radiation makes it hard to localise, giving large cross-talk between qubits.
- Our goal is to overcome this problem by designing and building a trap with integrated microwave electrodes to enable single-qubit addressing
- Addressing is accomplished by two techniques:
    - Each ion is addressed by four microwave electrodes, whose geometry produces a high-order multipole field, which dies off rapidly. Simulations suggest that this may reduce cross-talk to ~5%
    - The microwave electrodes for the second ion are used to produce a cancellation field, nulling the effect of the first ion's electrodes. Simulations suggest that if these currents have phase and amiplitude stability of 0.1° and 0.1% then cross-talk may be reduced to 10^{-4} level
- The trap has been designed and simulated using Ansoft HFSS software



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

EPSRC Pioneering research and skills
IOTA