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Microwave-driven high-fidelity quantum logic in $^{43}Ca^+$

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The ability to induce controlled transitions between atomic states through time-varying electromagnetic fields is crucial if one is to use trapped ions for quantum information processing. While lasers have successfully been used before to implement high-fidelity single- and two-qubit gates, other methods are available that have advantages over laser-driven gates [1, 2, 3, 4]. We make use of the magnetic field generated in the proximity of conductors carrying microwave currents. Our group has previously demonstrated high-fidelity microwave-driven quantum logic [5, 6] and here we present the main features of our next-generation microwave trap with which we plan to increase two-qubit microwave gate fidelities above the fault-tolerant threshold.

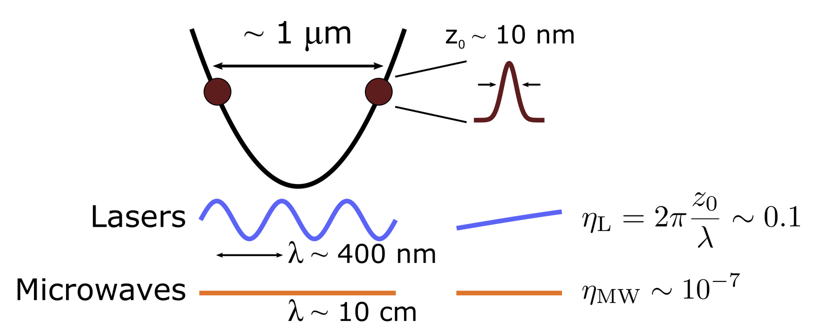
Microwaves for quantum logic

Advantages compared to lasers: no errors due to spontaneous photon scattering; accurate control over frequency, phase and amplitude easily achieved; better scalability through integration of waveguides into trap; lower cost

Single-qubit gates: global gates easily implemented for ground-level qubits by direct interaction of electron spin with magnetic field; schemes exist for addressing of individual qubits

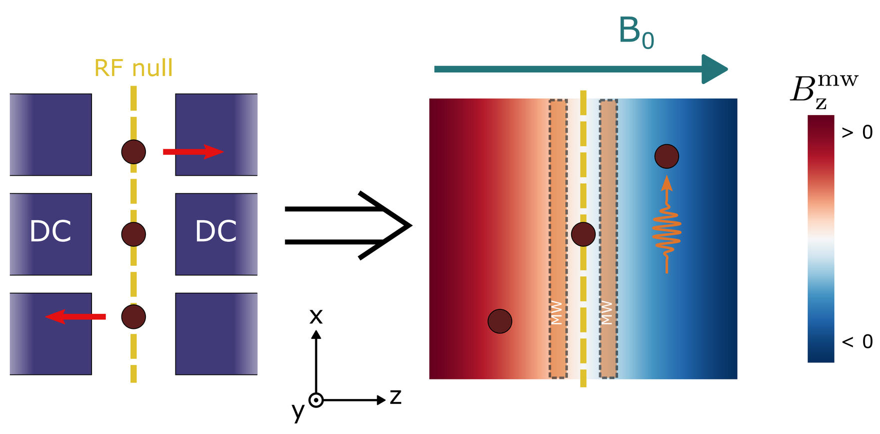
Two-qubit gates: use indirect coupling between internal states of two qubits mediated by normal modes of motion in trap using a spin-dependent force

- Free-space microwave radiation not feasible for this due to negligible Lamb-Dicke parameter:



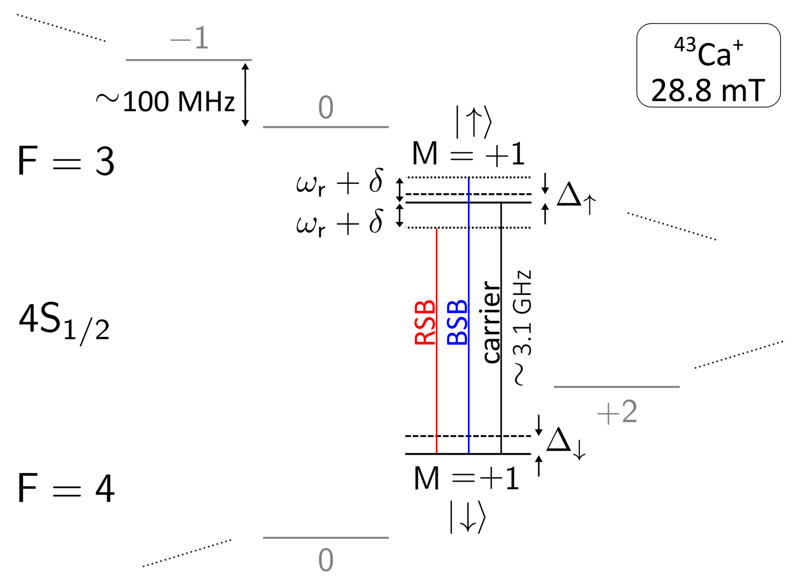
- But a significantly higher microwave field gradient can be achieved in the near field of a current-carrying waveguide

Single-qubit gates with addressing



Ions first displaced from RF null via DC field, microwave pulses are then resonant only with desired ion [8]; see also [9] for a different method of addressing

Two-qubit gates



Previous results

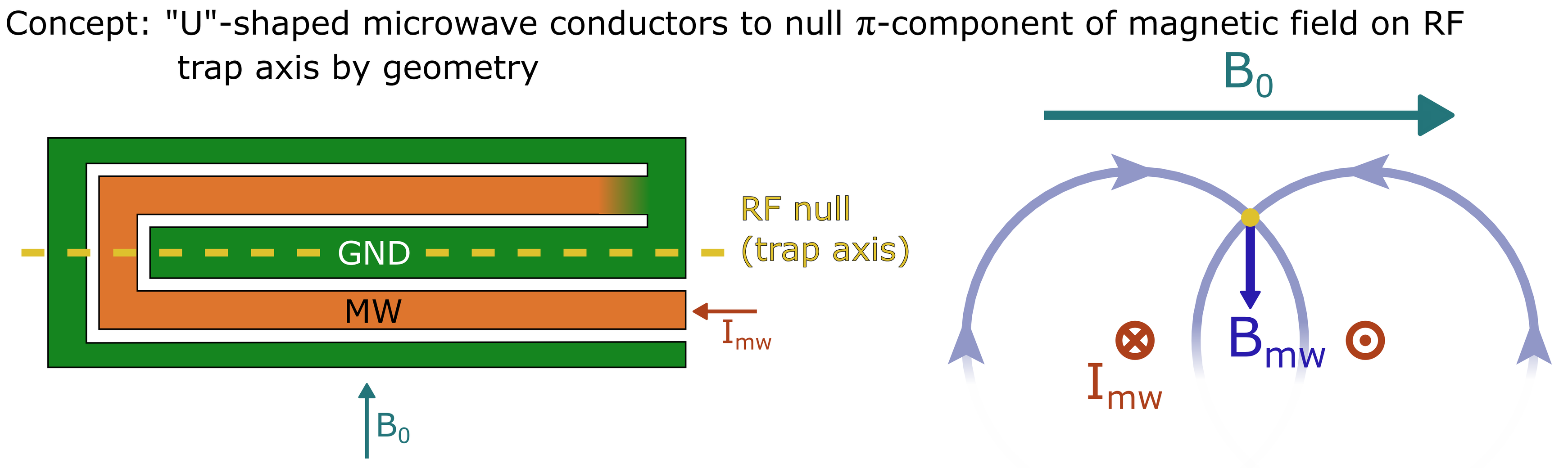
Measurement	Method	Result
Coherence time	Ramsey	$T_2^* \approx 50$ s
State preparation error	Lasers + microwaves	2×10^{-4}
Single-shot readout error	Microwaves + lasers	5×10^{-4}
Single-qubit gate error	Microwaves (benchmarked)	1×10^{-6}
Two-qubit "DDMS" gate error	Microwaves (tomography)	3×10^{-3}
Single-qubit gate time	Microwaves	12 µs (π/2-pulse)
Two-qubit "DDMS" gate time	Microwaves	3.25 ms

Trap design

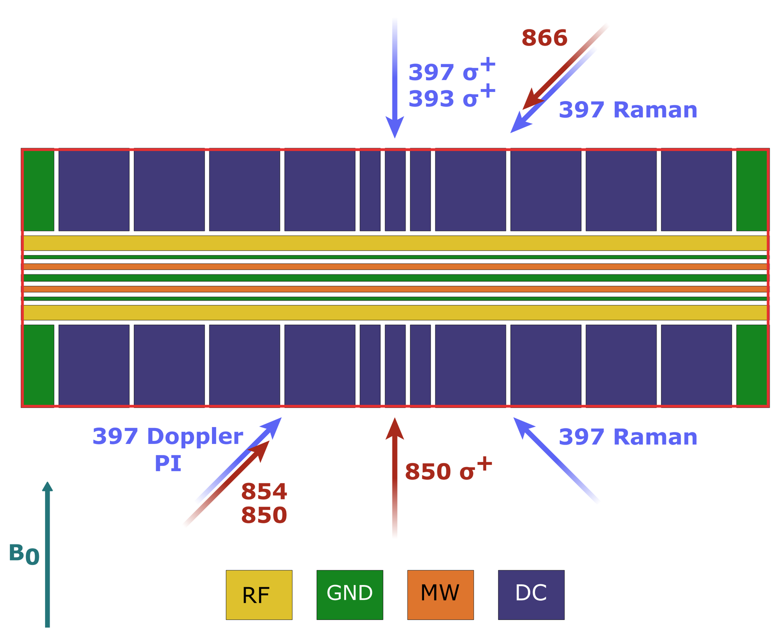
High-fidelity, fast two-qubit gates driven by microwaves require the component of the magnetic field along the qubit polarisation at the position of the ion to be zero and to have a strong gradient

Trap chip designed for π-polarised clock qubit at 28.8 mT: (F=4, M=+1) ↔ (3, +1)

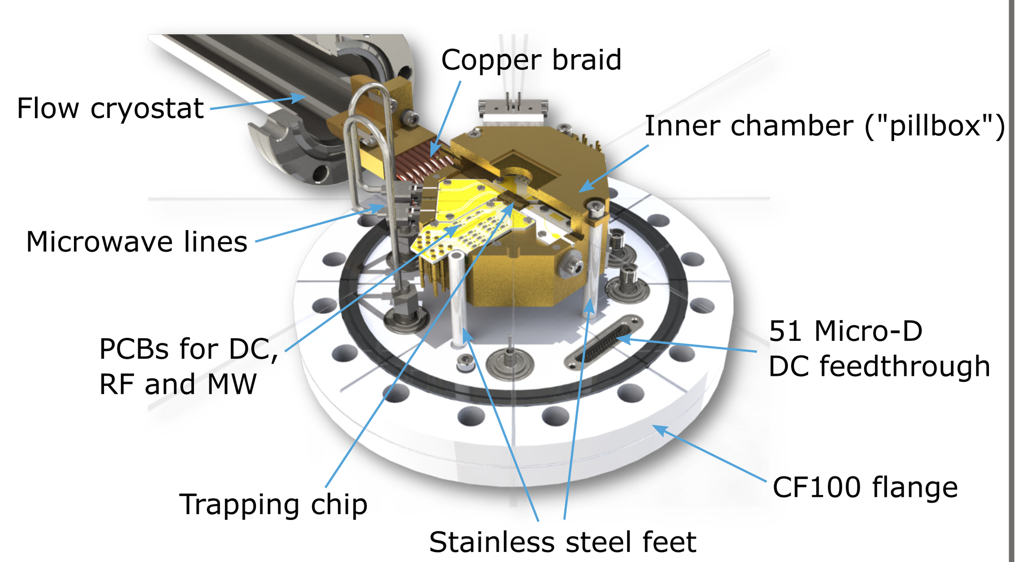
Concept: "U"-shaped microwave conductors to null π-component of magnetic field on RF trap axis by geometry



Segmented electrode design to allow shuttling of ions between different zones:



Cryogenic cooling to <20 K to reduce anomalous heating:



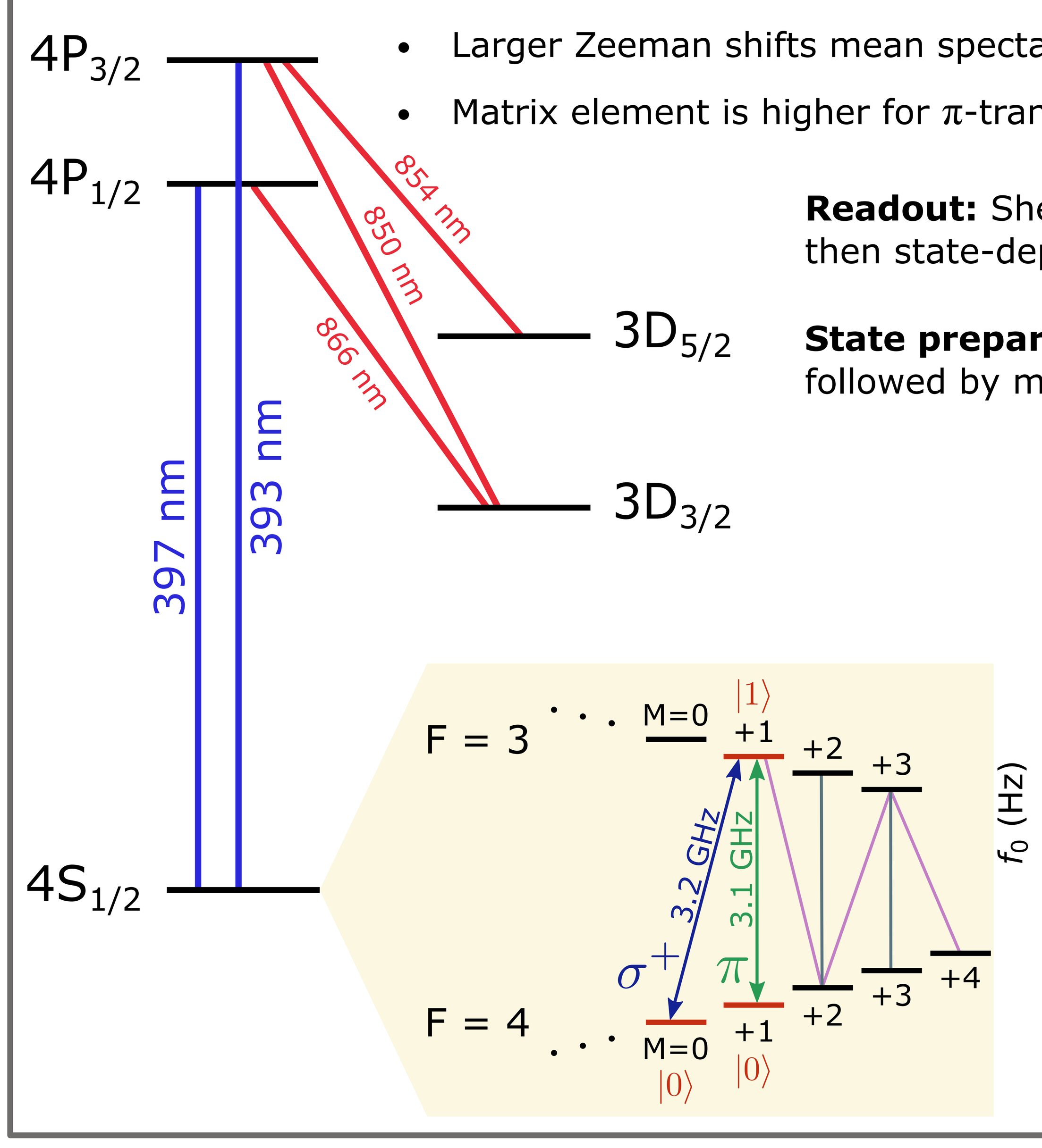
Hyperfine $^{43}Ca^+$ "clock" qubit

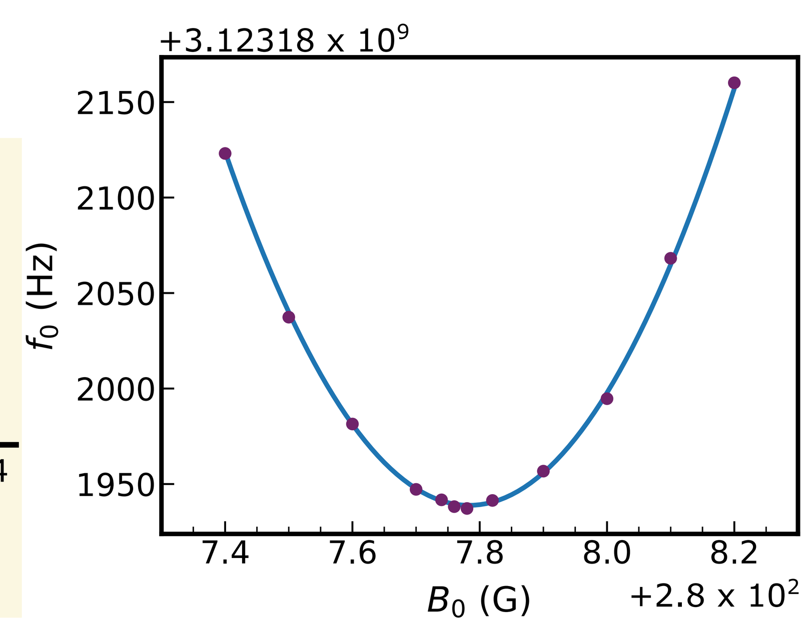
We use a clock qubit [7] at 28.8 mT (green) in our new trap.
Advantages for gate speed and fidelity compared to qubit used previously (blue) in this group:

- Linear m.w. polarisation couples more efficiently to π-polarised qubit
- Larger Zeeman shifts mean spectator transitions are detuned further
- Matrix element is higher for π-transition than σ-transition

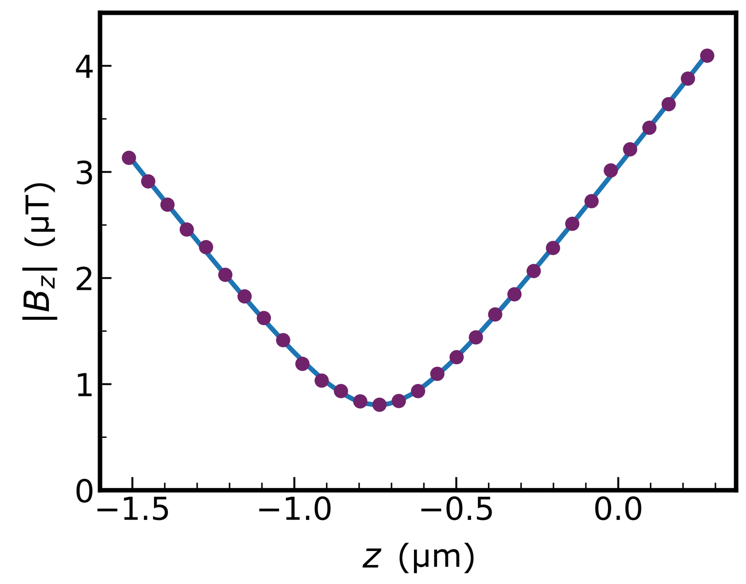
Readout: Shelving one qubit state to $3D_{5/2}$, then state-dependent fluorescence detection

State preparation: Optical pumping with lasers followed by m.w. transfer pulses (purple)





Mapping microwave field gradient



Trapped $^{43}Ca^+$ at low magnetic field

Moved ion position using DC electrodes and measured π-component Rabi frequency

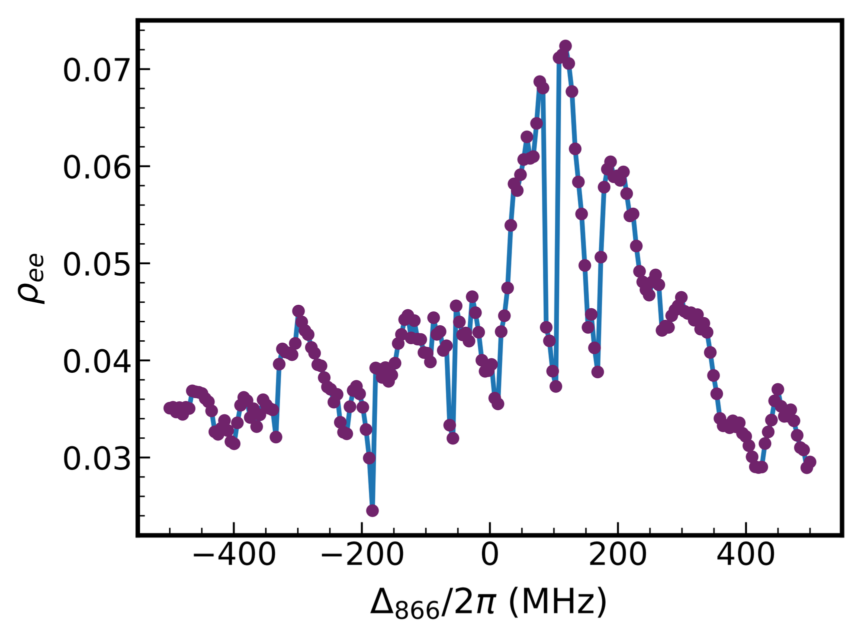
Measurements lower than simulations, but this is expected given the increased gold resistance at room temperature and off-resonance with the microwave resonator

Field gradient and null should facilitate a two-qubit gate which is both an order of magnitude faster and higher fidelity than the previous generation

Parameter	Measured	Simulation
dB_z/dz	12 T/m	28 T/m
B_z	2.5 µT	6 µT
B_y	125 µT	300 µT

Measurements and simulation scaled to nominal 1W m.w. power

Cooling $^{43}Ca^+$ at 288G



Laser cooling at 288G is not trivial due to the large Zeeman splitting of all states

Address each hyperfine manifold using a 3.2 GHz EOM

Polarisation of 397nm and 866nm chosen to drive only π and σ+ transitions

Observe multiple dark resonances due to coherent interference

Use dark resonances for sub-Doppler cooling [10]

Status and future directions

- Trapped $^{43}Ca^+$ at room temperature, and have operational clock qubit
- Operate trap at cryogenic temperatures
- Multi-species operation
- Two-qubit randomised benchmarking
- Scaling up will require significantly reduced power dissipation and complex multi-layer fabrication
- Superconducting electrodes will likely have to be used, but critical current too low in most superconductors at microwave frequencies
- Lower qubit frequency can be obtained by using spin-1/2 Zeeman qubits ($^{40}Ca^+$)
- Superconducting magnets give excellent coherence even without clock qubit

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