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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.

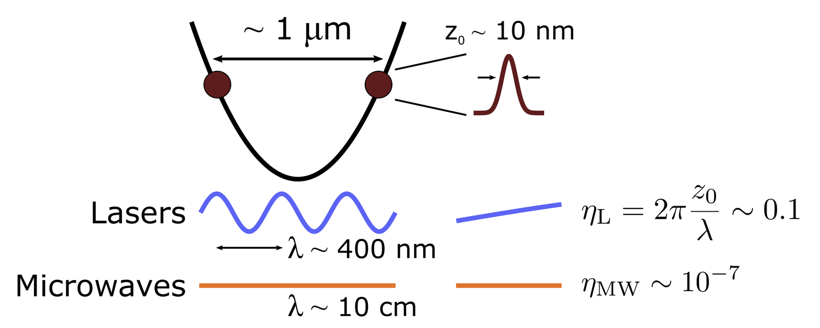
Microwaves for quantum logic

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

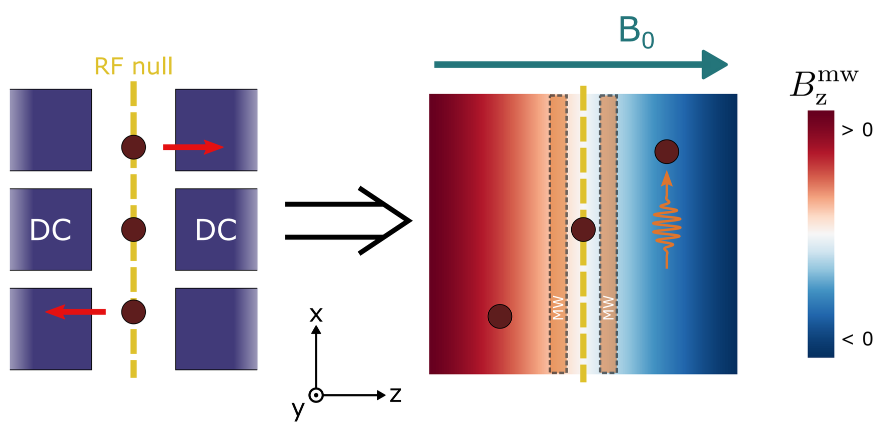
Two-qubit gates: use indirect coupling between internal states of two qubits mediated by normal modes of motion in trap using a spin-dependent force

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



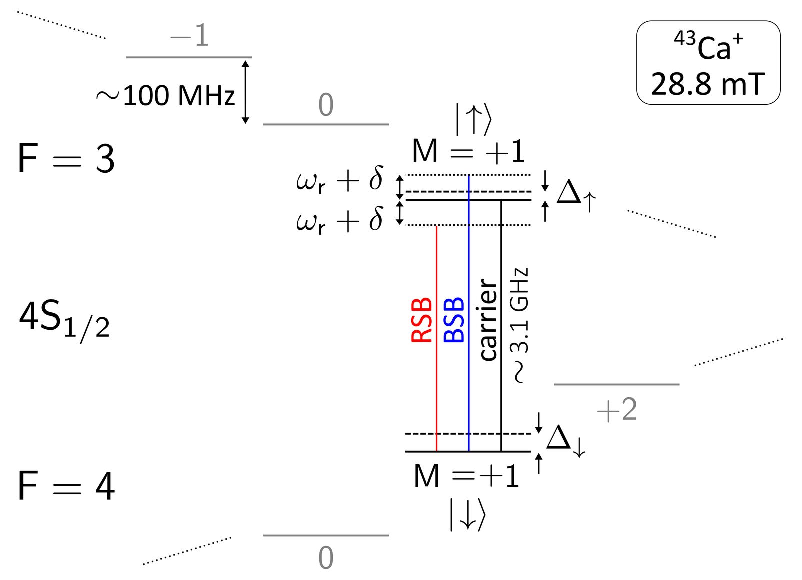
- But a significantly higher microwave field gradient can be achieved in the near field of a current-carrying waveguide

Single-qubit gates with addressing

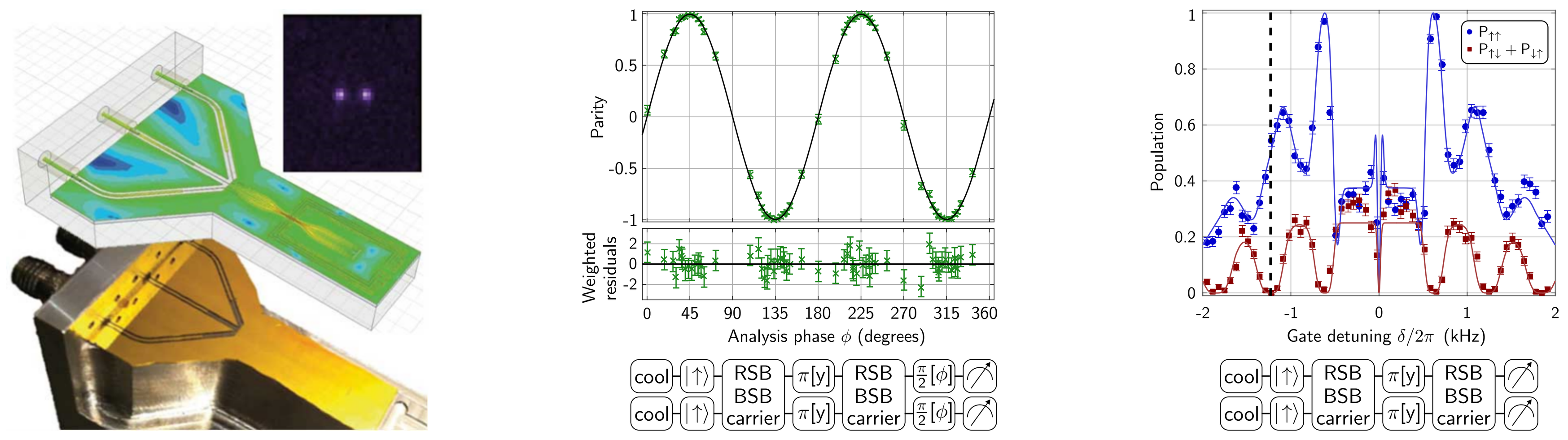


Ions first displaced from RF null via DC field, microwave pulses are then resonant only with desired ion [8]; see also [9] for a different method of addressing

Two-qubit gates



Previous results

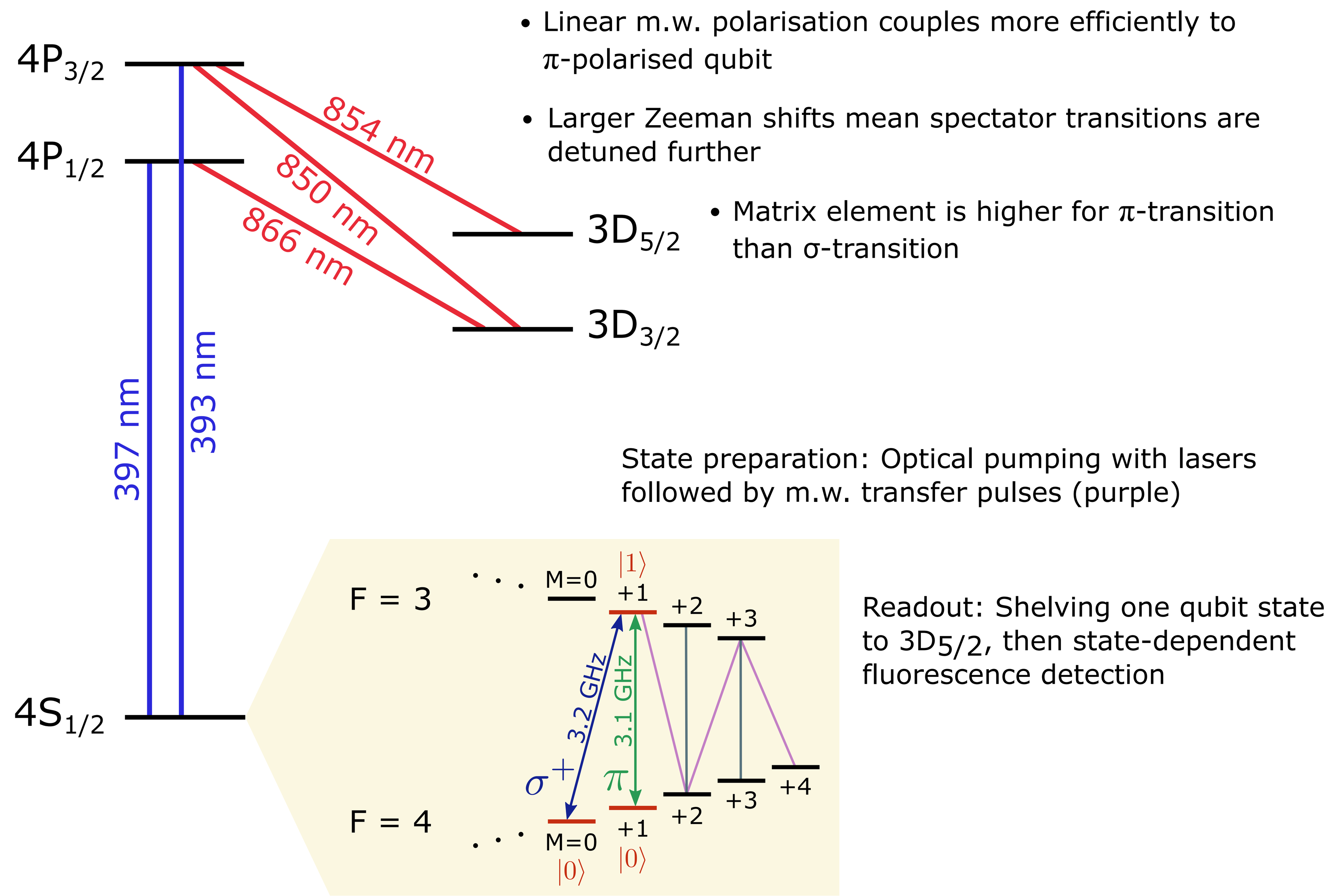


Measurement	Method	Result
Coherence time	Ramsey	$T_2^* \approx 50$ s
State preparation error	Lasers + microwaves	2×10^{-4}
Single-shot readout error	Microwaves + lasers	5×10^{-4}
Single-qubit gate error	Microwaves (benchmarked)	1×10^{-6}
Two-qubit "DDMS" gate error	Microwaves (tomography)	3×10^{-3}
Single-qubit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

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



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

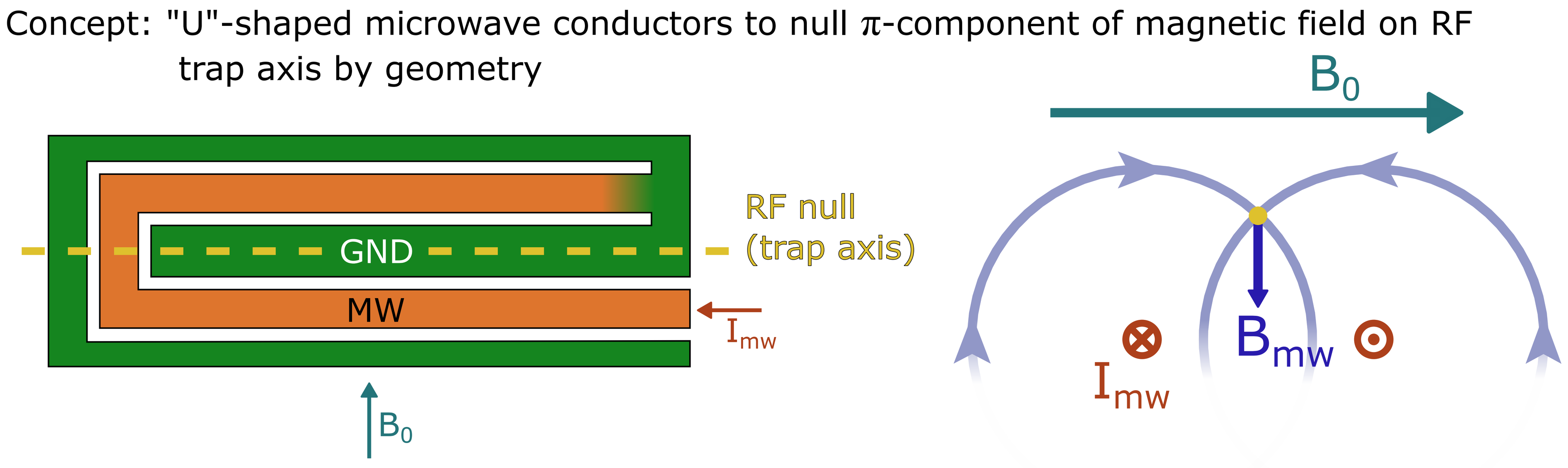
Readout: Shelving one qubit state to $3D_{5/2}$, then state-dependent fluorescence detection

Trap design

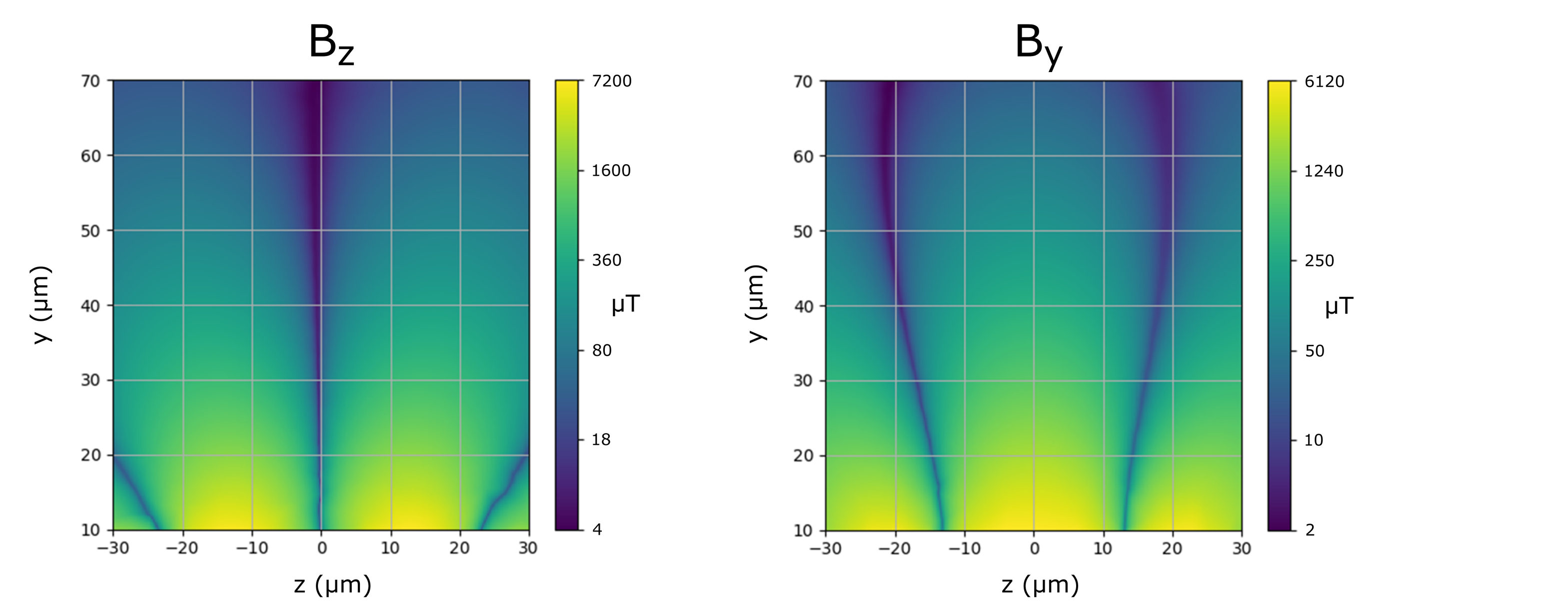
High-fidelity, fast two-qubit gates driven by microwaves require the component of the magnetic field along the qubit polarisation at the position of the ion to be zero and to have a strong gradient

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



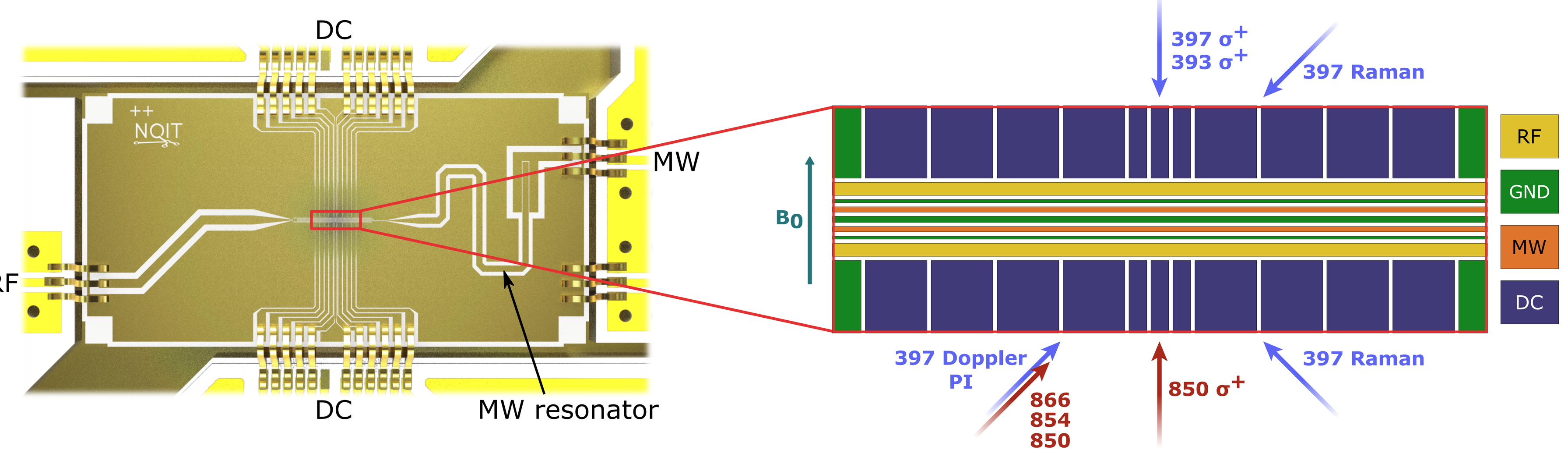
Fields have been simulated numerically with ANSYS HFSS software:



Estimates for field and gradient on RF trap axis for 1 W of microwave power: $\frac{\partial B_z}{\partial z} = 28\ \mathrm{T\,m^{-1}}$

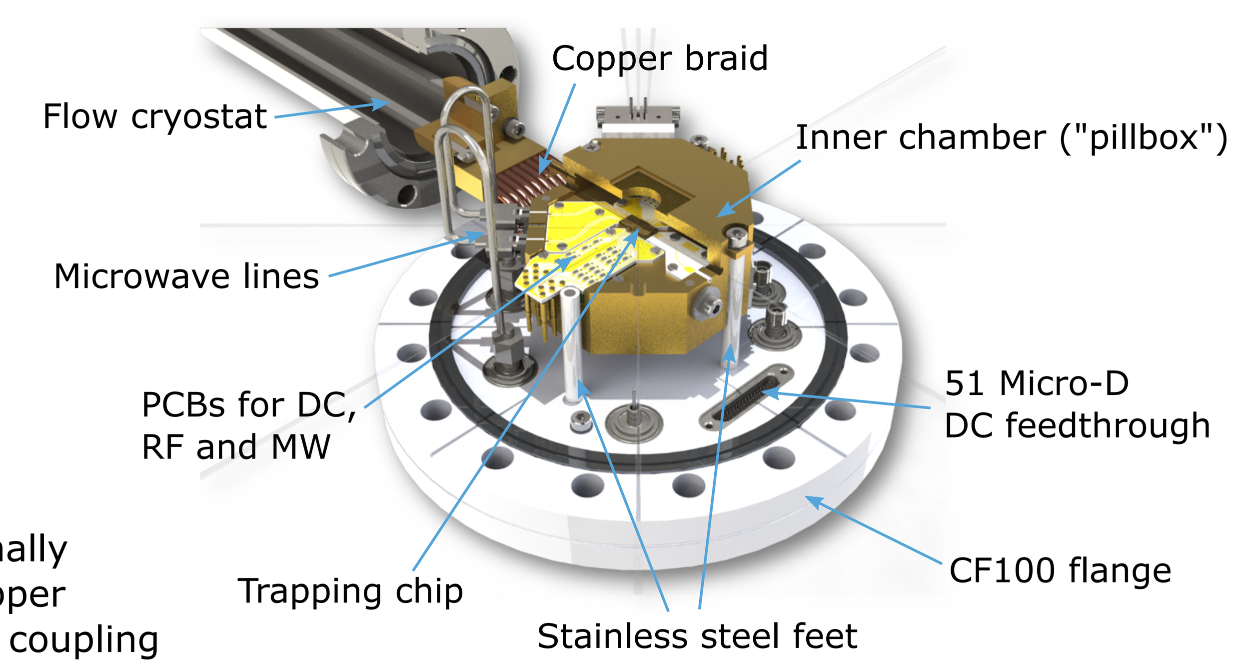
$B_y = 300\ \mu\mathrm{T} \quad B_z = 6\ \mu\mathrm{T}$

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



Cryogenic vacuum system

- Trap chip consists of gold electrodes on sapphire substrate
- Cryogenic cooling to <20 K to reduce anomalous heating
- Extended lifetime of ions in trap as freeze-out lowers residual gas pressure
- Cold finger of cryostat thermally connected to pillbox with copper braid to minimise vibrational coupling



Status and future directions

- Trapped $^{43}Ca^{+}$ at room temperature
- 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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[4] S. Weidt et al., Phys. Rev. Lett. 117, 220501 (2016)
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