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Quantum logic gates driven by near-field microwaves

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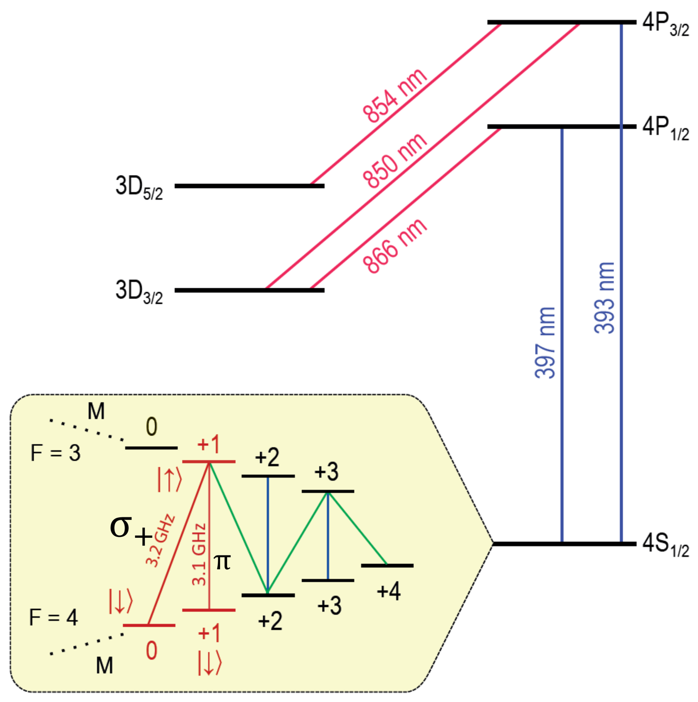
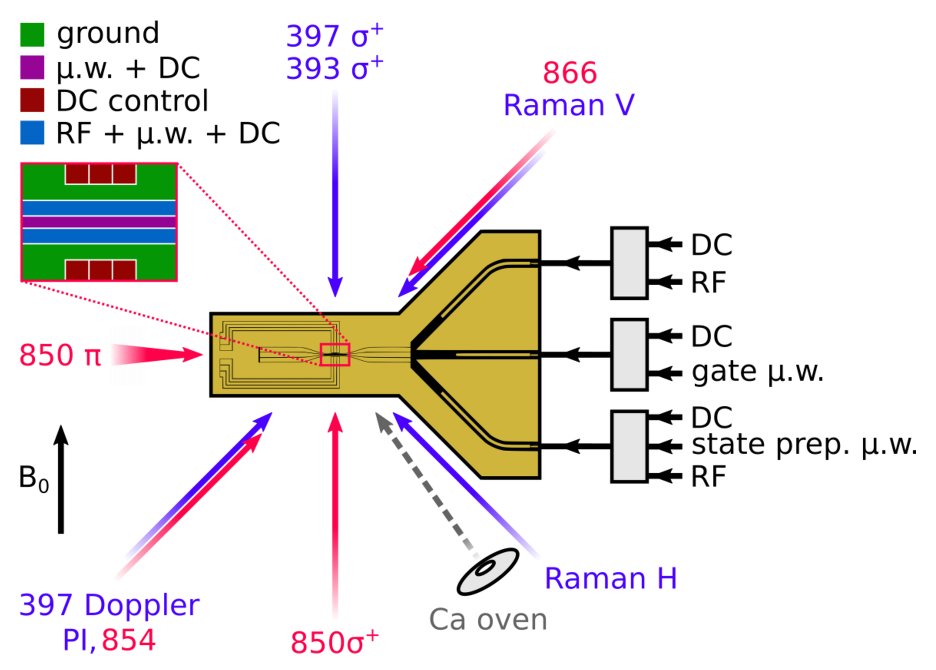
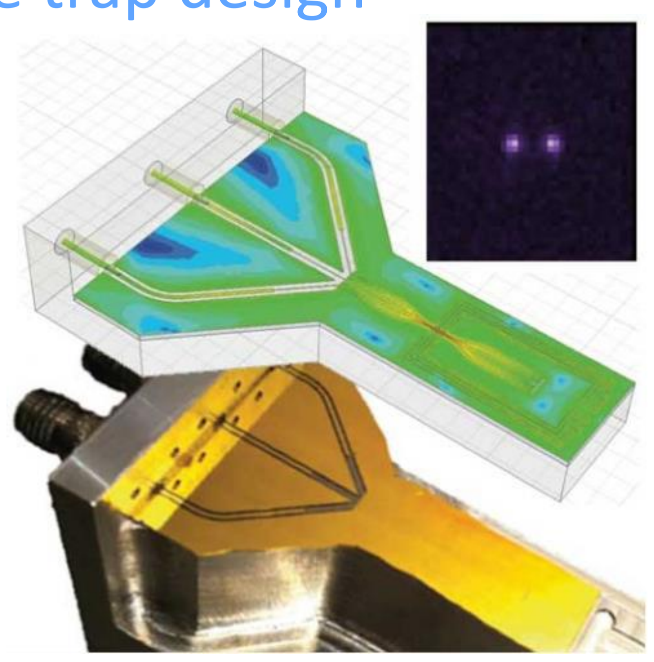
Intermediate-field "atomic clock" hyperfine qubit



	Current qubit	New qubit
Magnetic field for field independent qubit frequency	14.6 mT	28.8 mT
Qubit polarisation	σ_+	π
Initialisation	$4S_{1/2}$(F=4, M_F=+4) via multiple 397σ_+ & m.w. (shown in blue) Then $4S_{1/2}$(F=3, M_F=+1) Via m.w. pulses (shown in green)	
Readout	"shelving" one qubit state to $3D_{5/2}$	
Advantages	Lower magnetic field	Faster gate Less off-resonant excitation

Current room temperature trap design



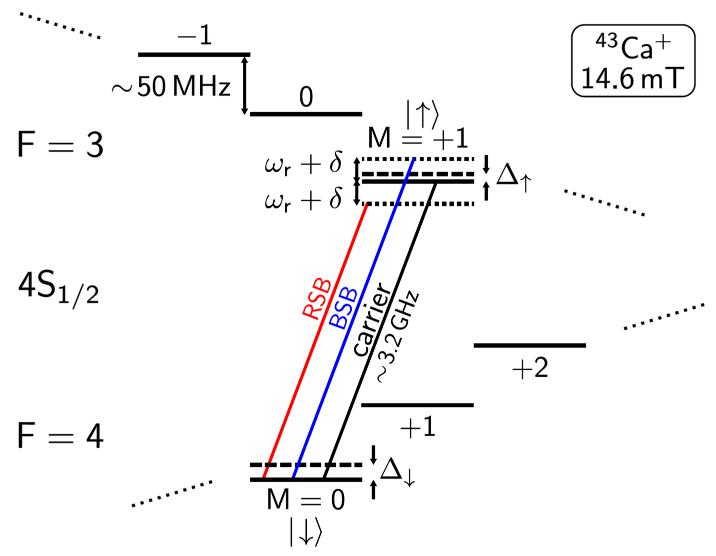


Summary of performance achieved for calcium-43 hyperfine "clock" qubits in this trap

coherence time	Ramsey	$T_2^* \approx 50$ sec
qubit state preparation	m.w.+laser	99.98%
single-shot qubit readout	m.w.+laser	99.95%
global single-qubit gates	m.w. (benchmarked)	99.9999%
two-qubit "DDMS" gate	m.w. (tomography)	99.7%v

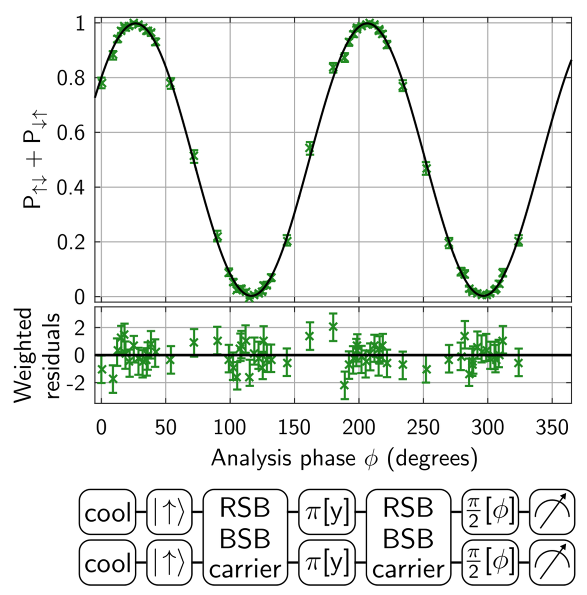
- Uses oscillating currents in an surface trap to apply near-field microwaves to ions
- Features integrated microwave circuitry [Allcock et al. APL (2013)]

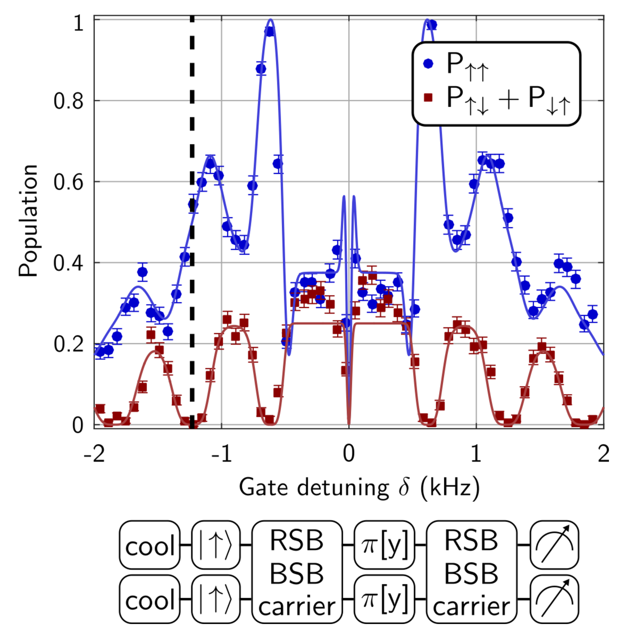
Current two-qubit gate scheme



- Bichromatic field with frequencies near first red and blue sidebands as for Mølmer-Sørensen gates
- Dynamical decoupling with a σx carrier drive protects against fluctuations in AC Zeeman shift (Δ↑-Δ↓)
- Carrier drive Rabi frequency of 4kHz compared with 436Hz for single-ion sideband
- π[y] pulse at midpoint to refocus qubit populations

Current two-qubit gate results

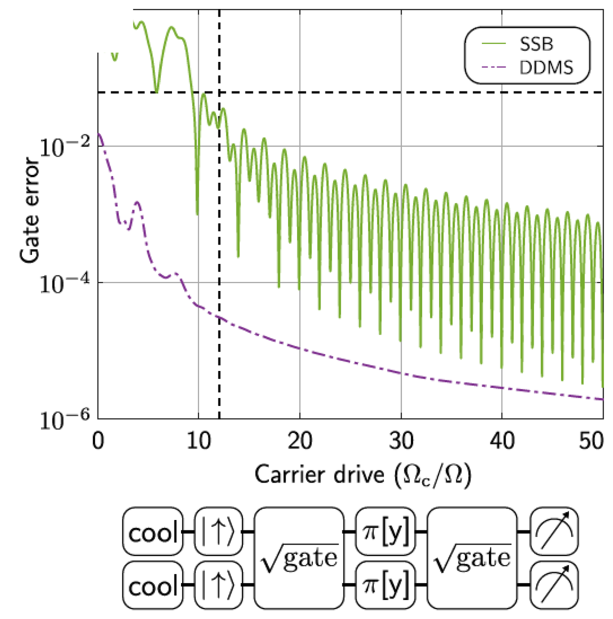




- Two-qubit gate fidelity of 99.7(1)% [Harty et al. Phys. Rev. Lett. 117, 140501 (2016)]
- See also work done with far-field microwaves at Siegen [Khromova et al. PRL (2012)] and Sussex [Weidt et al. Phys. Rev. Lett. 117, 220501 (2016)]

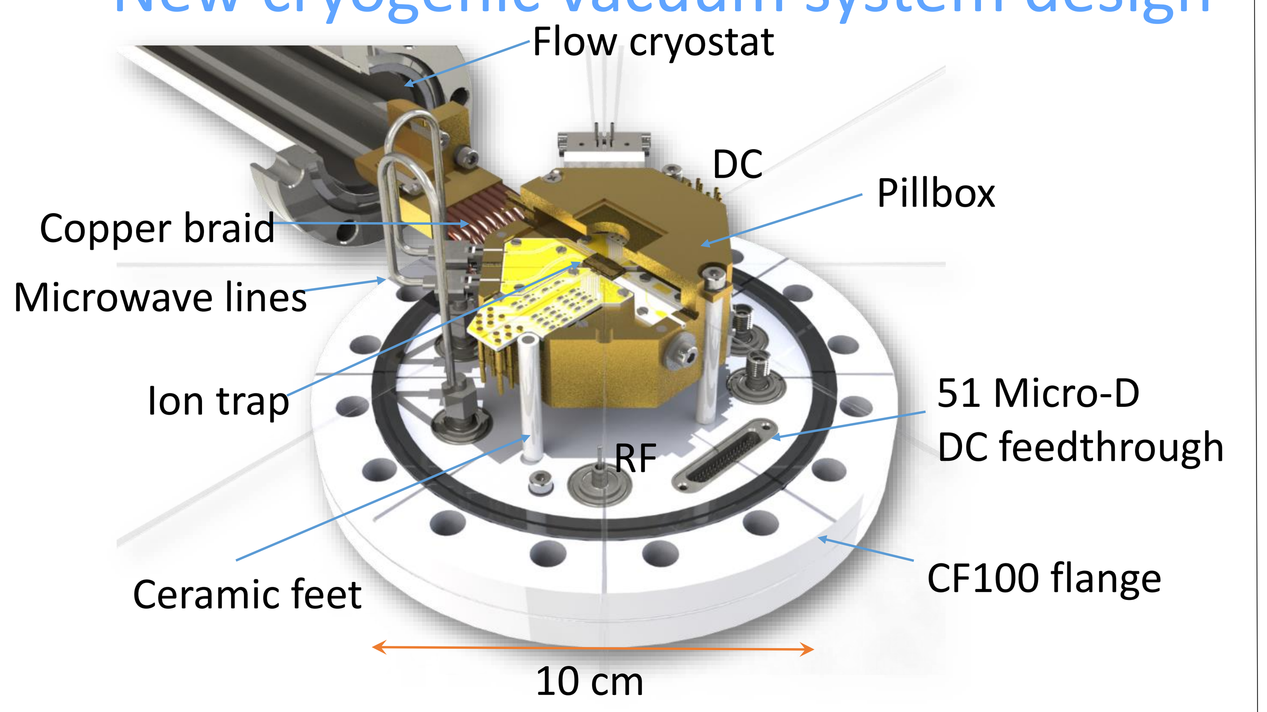
- Plot shows the different two-qubit populations
- as a function of microwave detuning from sidebands
- Dashed line indicates detuning used for gate
- Compared with simulations to calibrate gate parameters

Current DDMS gate: numerical simulations



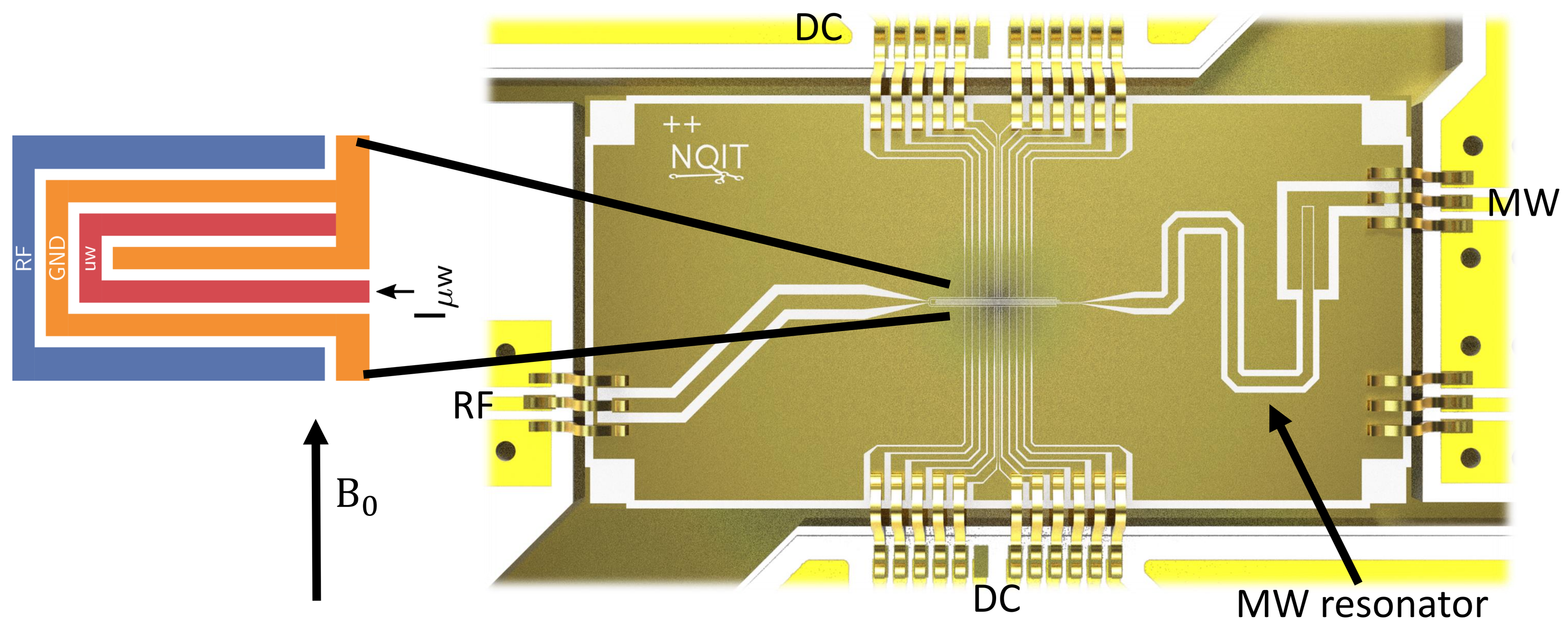
- comparison between dynamically-decoupled Molmer-Sorensen (DDMS) gate and single-sideband Bermudez (SSB) gate
- simulation assumes 4-loop gate with sideband Rabi frequency $\Omega/2\pi$ = 308 Hz, and uncompensated a.c. Zeeman shift of 20 Hz
- vertical dashed line indicates the carrier Rabi frequency used in our experiment ($\Omega_c/2\pi$ = 3.69 kHz)

New cryogenic vacuum system design



- Cryogenic cooling with Janis ST-400 cryostat
- Cold finger thermally connected to inner chamber with copper braid to minimise vibrational coupling
- Inner chamber attached to base of vacuum chamber with Macor supports to minimise thermal load
- Option for ex-situ argon ion surface cleaning

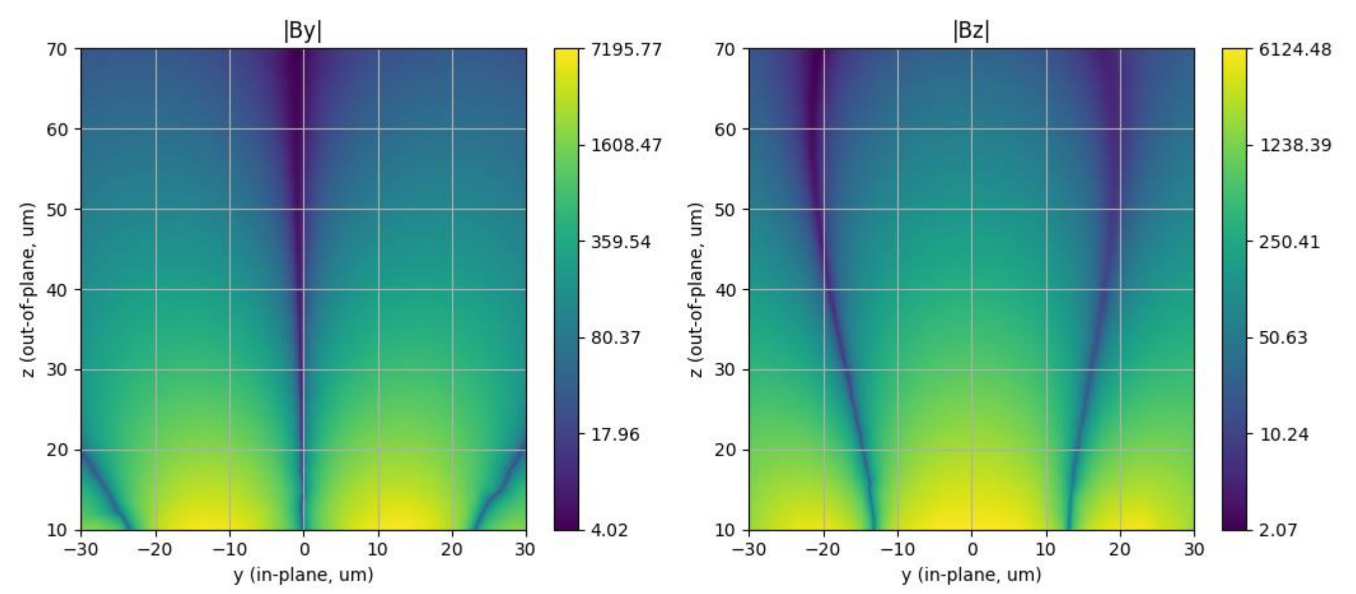
New cryogenic trap design



Designed for 288gauss clock qubit: $S_{1/2}$ (4,+1)↔(3,+1)

- Concept: "U-shaped" microwave drive electrode to null π-field along quantisation axis (B_0) direction by geometry [see Carjens et al. App. Phys. B (2014) for alternative geometry]
- Not necessary to null σ-field for high-fidelity DDMS gate
- On-chip microwave resonator to increase field strength

New simulation results



- Microwave fields simulated using HFSS
- Design goal: microwave π-field gradient of > 30 T/m, with π-field nulled to < 30 µT
- Should allow DDMS gate with up to an order of magnitude improvement in speed and error over previous trap

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