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Two-qubit near-field microwave gates on $^{43}Ca^+$

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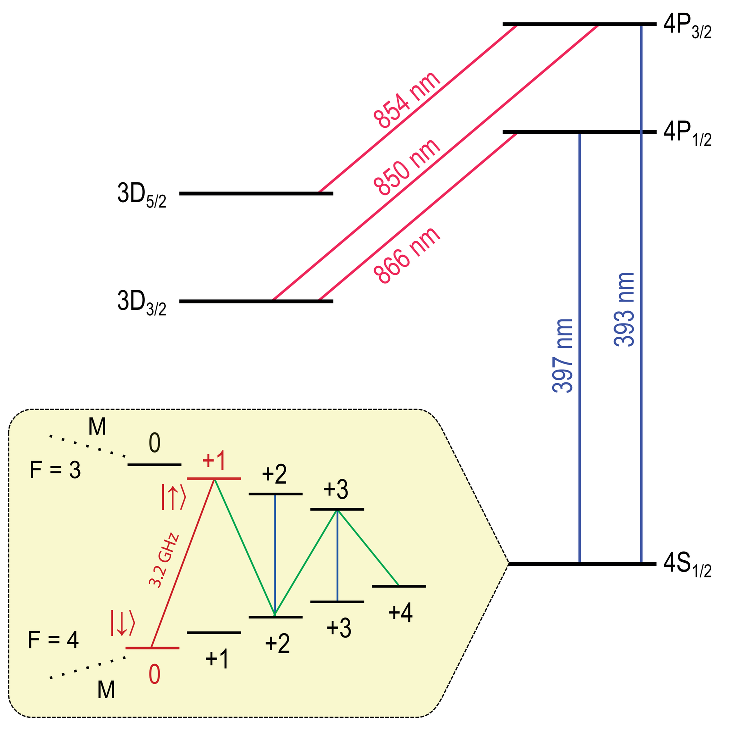
Introduction

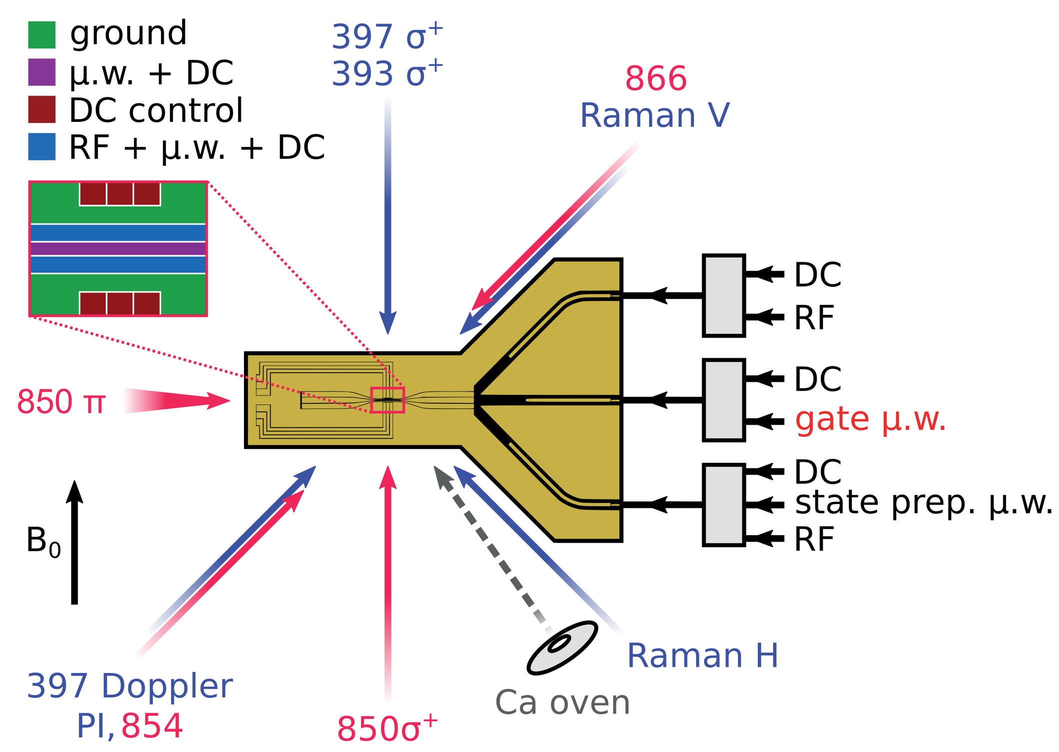
In order to build a scalable quantum computer, accurate qubit state preparation and single-shot readout, long coherence times, and high-fidelity single- and two-qubit gates must all be possible. We present results that fulfil these requirements using $^{43}Ca^+$ trapped-ion qubits. We use near-field microwave control in a surface-electrode ion trap to achieve a single-qubit gate fidelity of 99.9999%. Using a novel dynamically-decoupled gate method, we achieve a two-qubit gate fidelity of 99.7%. We also achieve a coherence time of $T_2^* \approx 50$s and a state preparation and measurement (SPAM) fidelity of 99.93%. In addition to these results, we present preliminary designs for a next-generation experimental system. Technical improvements include cryogenic cooling, ex-situ argon ion surface cleaning, passive microwave field nulling, ion shuttling and ion chain splitting.

Intermediate-field "atomic clock" hyperfine qubit



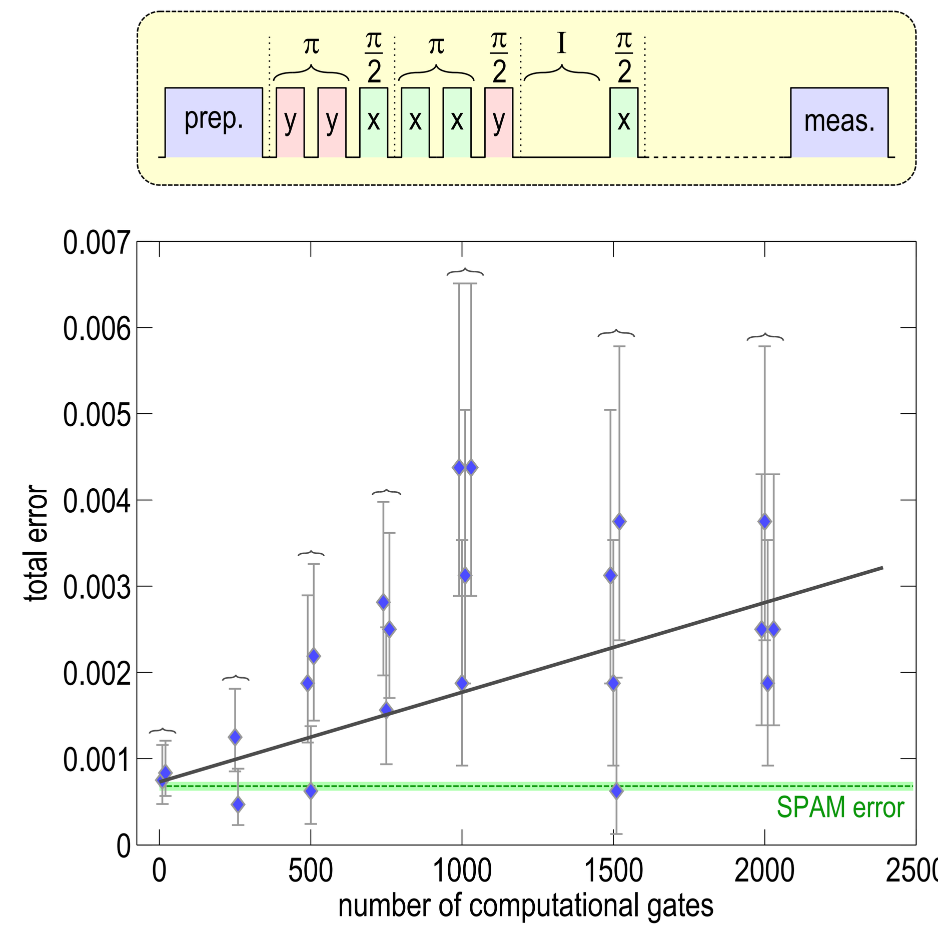
- Qubit transition frequency independent of magnetic field at 146G
- We obtain a coherence time of $T_2^* = 50(10)$s
- Initialised in $4S_{1/2}$ (F = 4, M = +4) by several cycles of 397σ⁺ optical pumping and microwave "reclaiming" π-pulses (shown in blue)
- Qubit prepared using microwave π-pulses (shown in green)
- Readout achieved by "shelving" one qubit state in $3D_{5/2}$
- State preparation and measurement (SPAM) error of $6.8(5)\times10^{-4}$ achieved
- See [Harty et al. PRL (2014)]

Current trap design



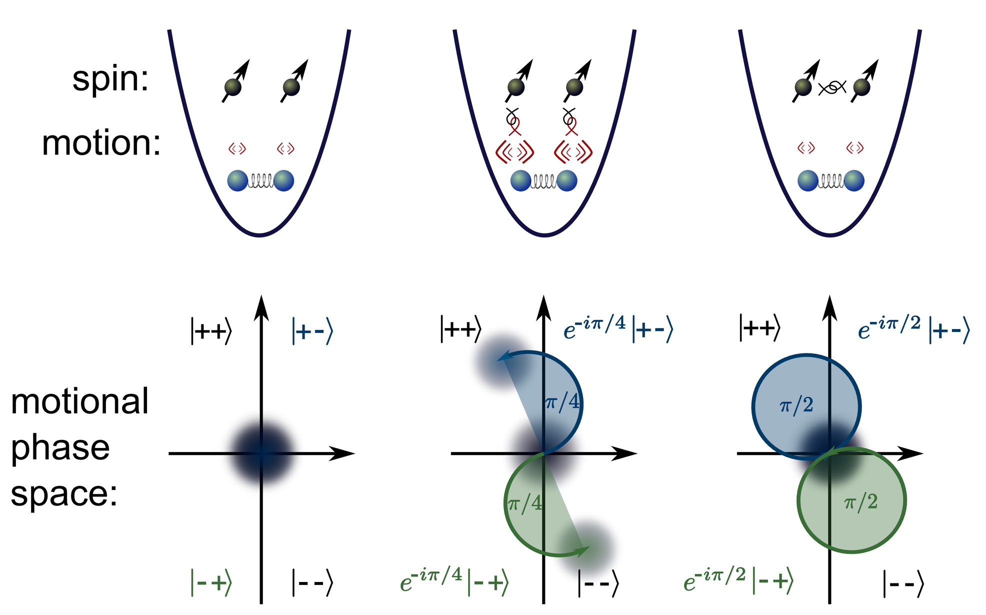
- Uses oscillating currents in an rf surface trap to apply near-field microwaves to ions
- Features integrated microwave circuitry [Allcock et al. APL (2013)]
- Capable of performing both single- and two-qubit gates

Single-qubit gates



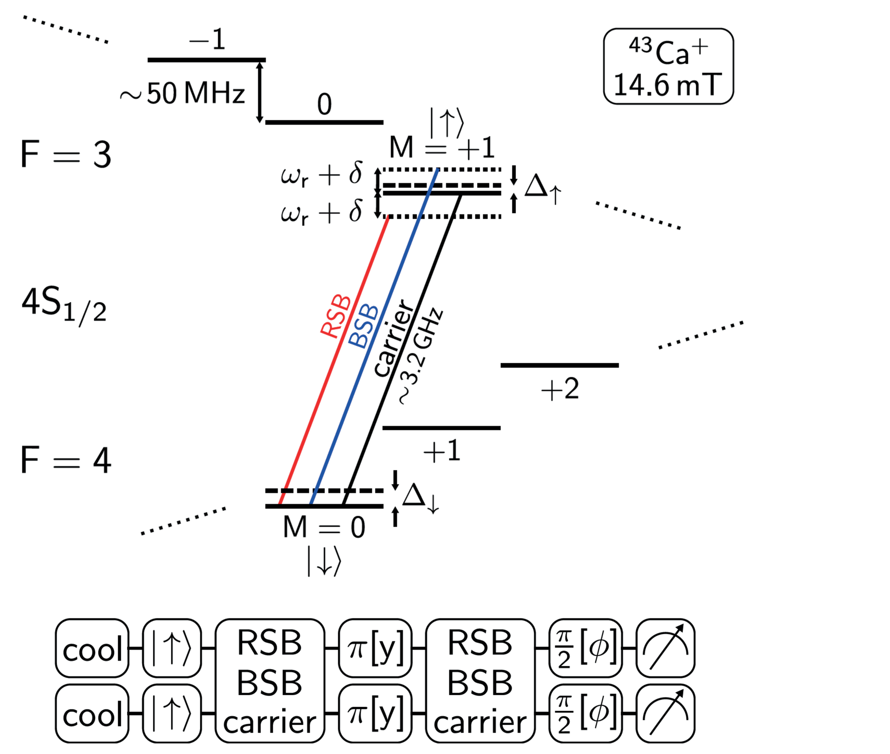
- Randomised benchmarking used to measure average single-qubit gate error
- Average gate error of $1.0(3)\times10^{-6}$ [Harty et al. PRL (2014)]

Entanglement generation



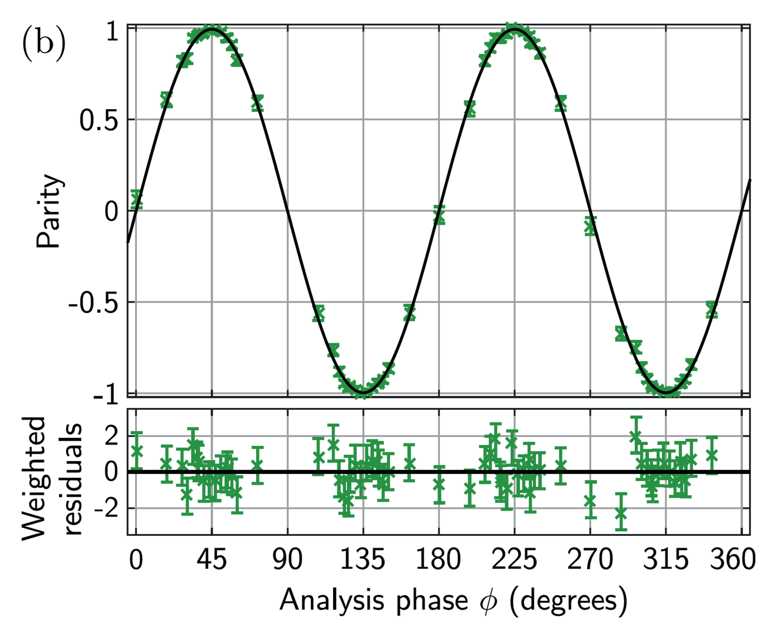
- We generate entanglement by inducing different geometric phases on different parts of the wavefunction ($|\pm\rangle \equiv (|\downarrow\rangle \pm |\uparrow\rangle)/\sqrt{2}$)
- Operation achieved using near-field microwave scheme proposed in [Ospelkaus et al. PRL (2008)]
- Scheme first demonstrated at NIST [Ospelkaus et al. Nature (2011)]

Two-qubit gate scheme



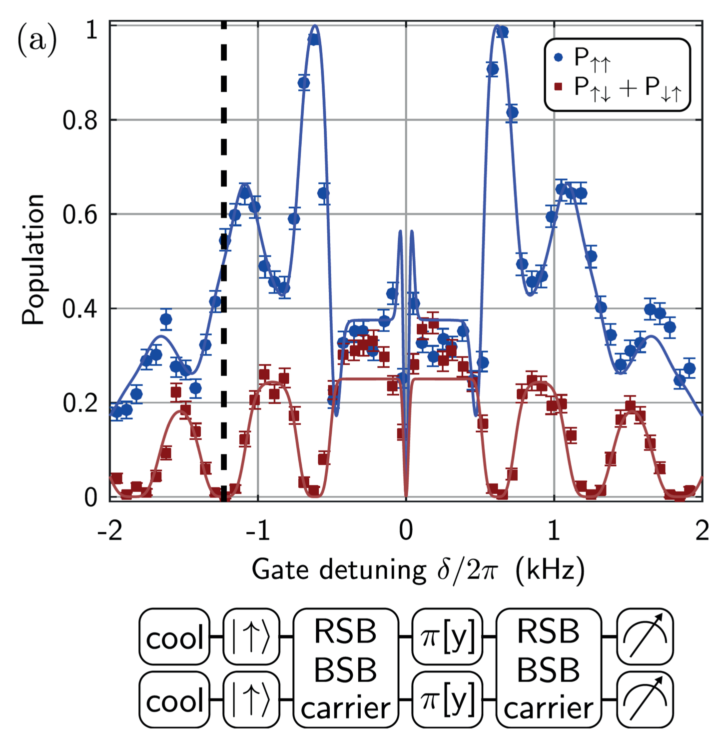
- Bichromatic field with frequencies near first red and blue sidebands as for Mølmer-Sørensen gates
- Dynamical decoupling with a σ_x carrier drive protects against fluctuations in AC Zeeman shift ($\Delta_\uparrow - \Delta_\downarrow$)
- Carrier drive Rabi frequency of 4kHz compared with 436Hz for single-ion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

Two-qubit gate results



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

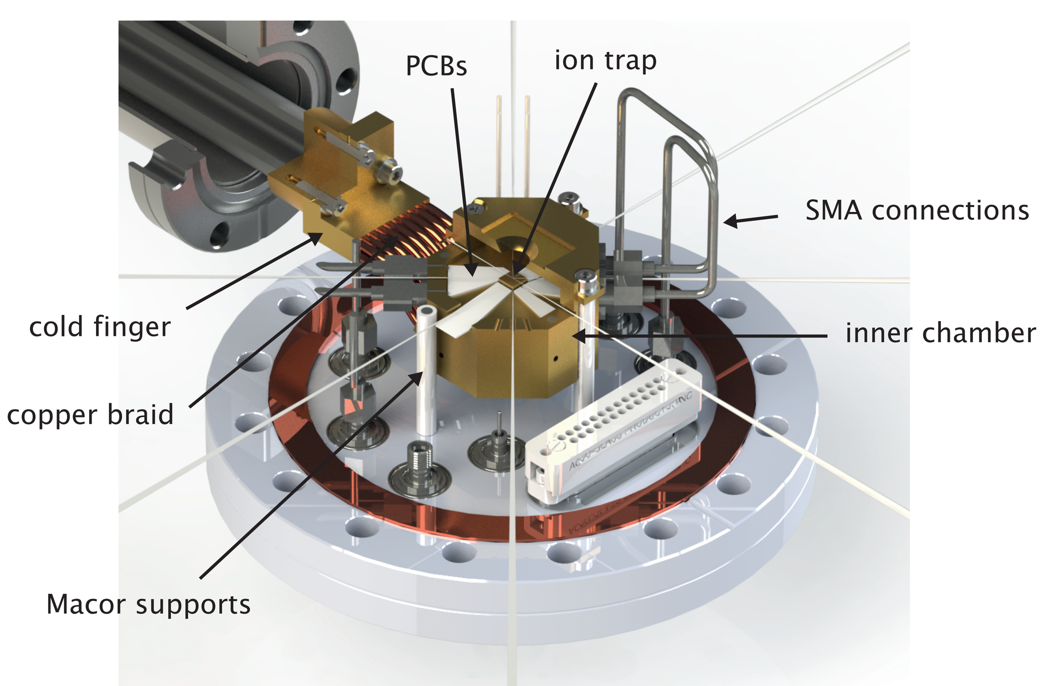
Detuning scans



- 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

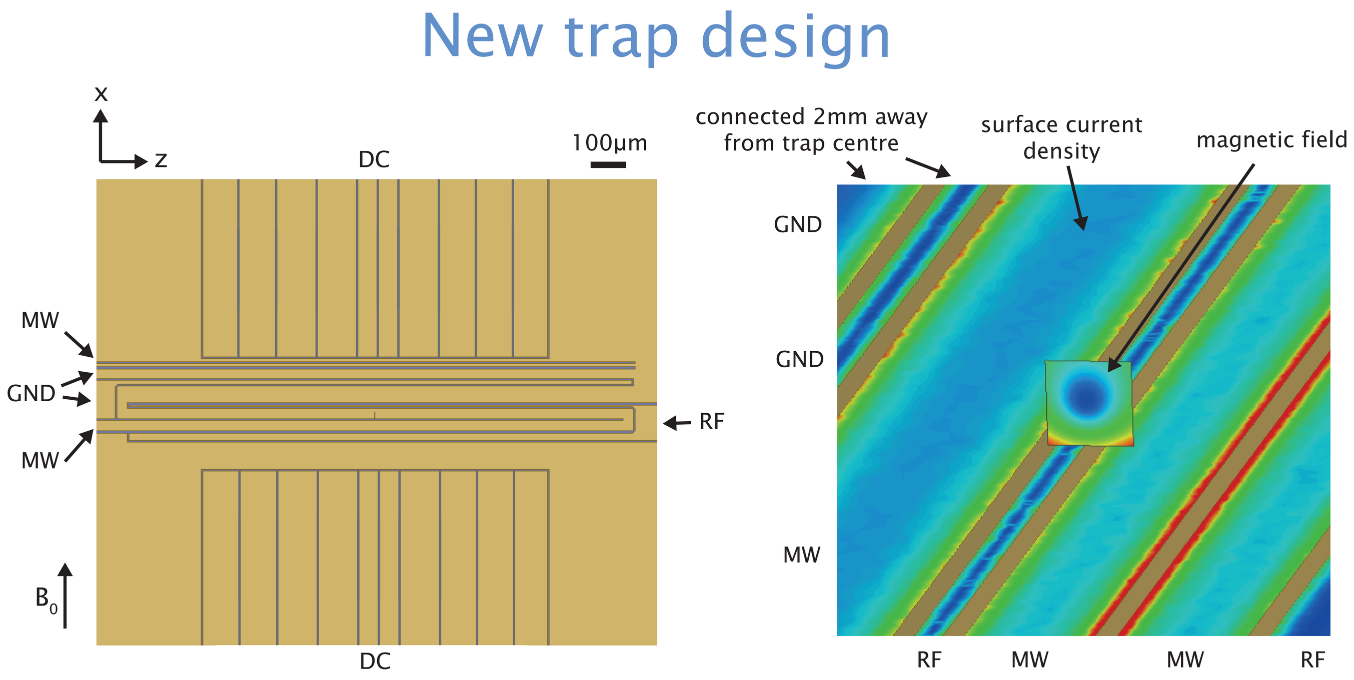
Next-generation system

Cryogenic vacuum system design



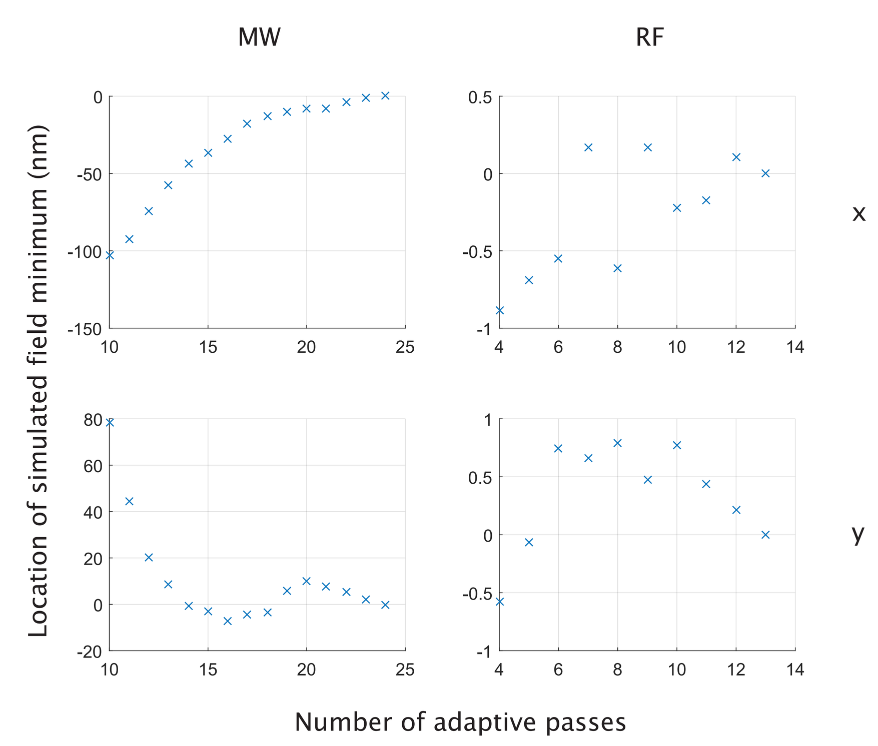
- Cryogenic cooling with Janis ST-400 cryostat
- Cold finger thermally connected to inner chamber with copper braid to minimise vibrational coupling
- Inner chamber attached to base of vacuum chamber with Macor supports to minimise thermal load
- Ex-situ argon ion surface cleaning

New trap design



- Single meander-shaped electrode for entangling microwave signals (see [Carsjens et al. App. Phys. B (2014)] and [Wahnschaffe et al. arXiv (2016)] for previous work on this idea)
- Second meander electrode for single-qubit gates and small adjustments to two-qubit gate field
- DC electrodes for transporting between three trapping zones and separating ions in the central zone
- Asymmetric RF electrode geometry
- Includes a cut in the ground plane (the two parts are connected 2mm away from the trap centre, to the left of region shown above) to manipulate the microwave return currents

Simulation results



- RF electric and microwave magnetic field minima fixed by trap geometry, so need to ensure alignment during design process
- HFSS simulations give precision error of <100nm (see plots)
- Trap fabrication tolerances expected to give misalignment of <1µm
- Corresponding ratio B′/B of ~1×10^5 m⁻¹ for ion at RF null, compared to 9×10^3 m⁻¹ for current trap

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