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

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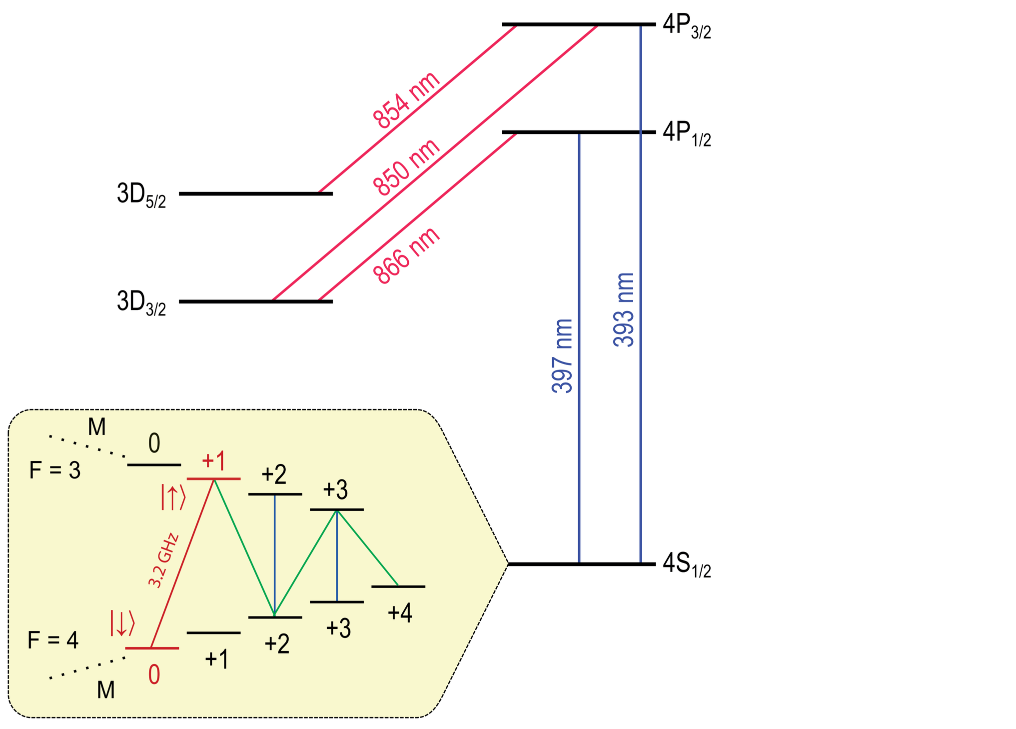
Introduction

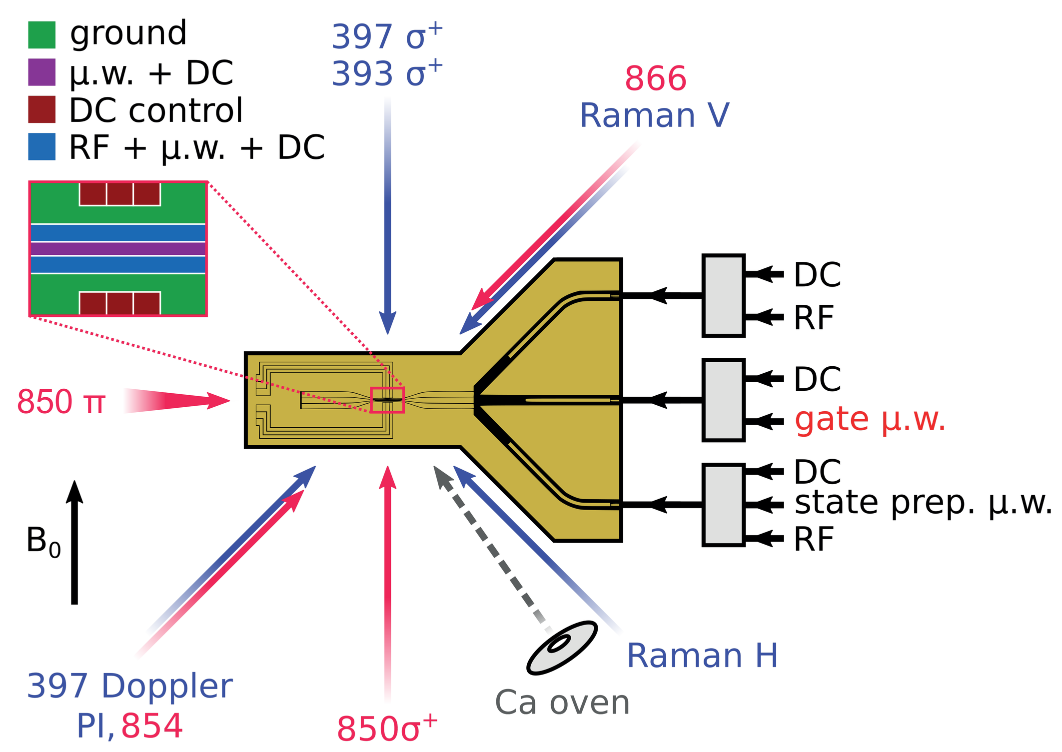
In order to build a scalable quantum computer, accurate qubit state preparation and single-shot readout, long coherence times, and high-fidelity single- and two-qubit gates must all be possible. We present results that fulfil these requirements using $^{43}Ca^+$ trapped-ion qubits. We use near-field 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, surface cleaning, passive microwave field nulling, and ion shuttling.

Intermediate-field "atomic clock" hyperfine qubit



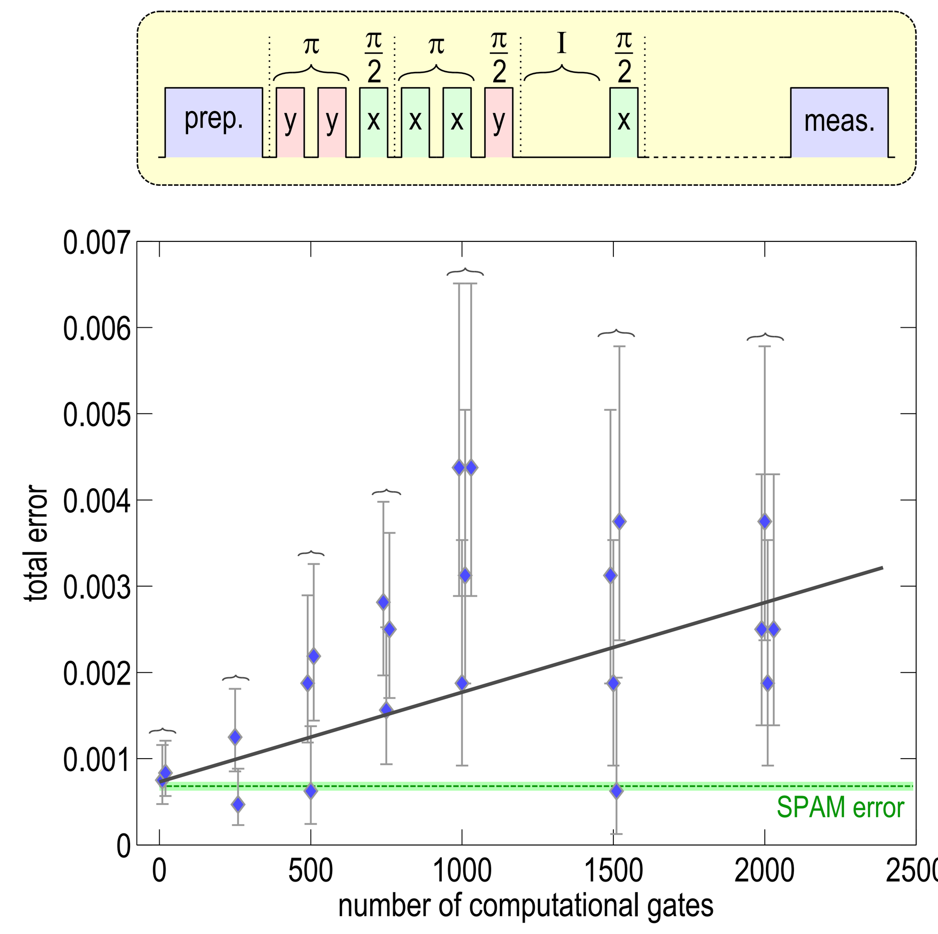
- Qubit transition frequency independent of magnetic field at 146G
- We obtain a coherence time of $T_2^* = 50(10)$s
- Initialised in $4S_{1/2}$ (F = 4, M = +4) by several cycles of 397σ^+ optical pumping and microwave "reclaiming" π-pulses (shown in blue)
- Qubit prepared using microwave π-pulses (shown 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



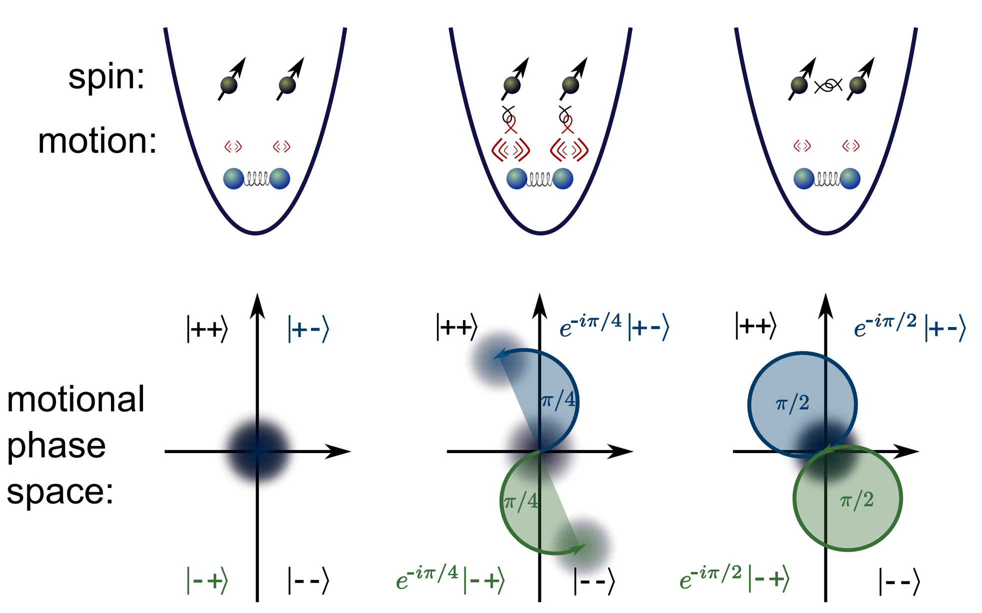
- Uses oscillating currents in an rf surface trap to apply near-field microwaves to ions
- Features integrated microwave circuitry [Allcock et al. APL (2013)]
- Capable of performing both single- and two-qubit gates

Single-qubit gates



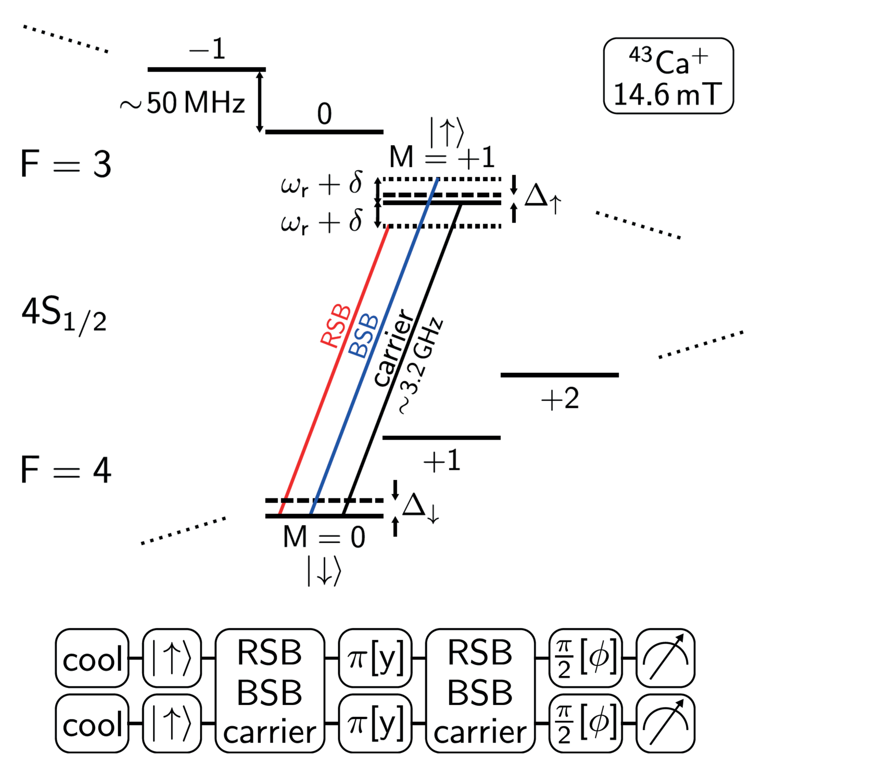
- Randomised benchmarking used to measure average single-qubit gate error
- Average gate error of $1.0(3)\times10^{-6}$ [Harty et al. PRL (2014)]

Entanglement generation



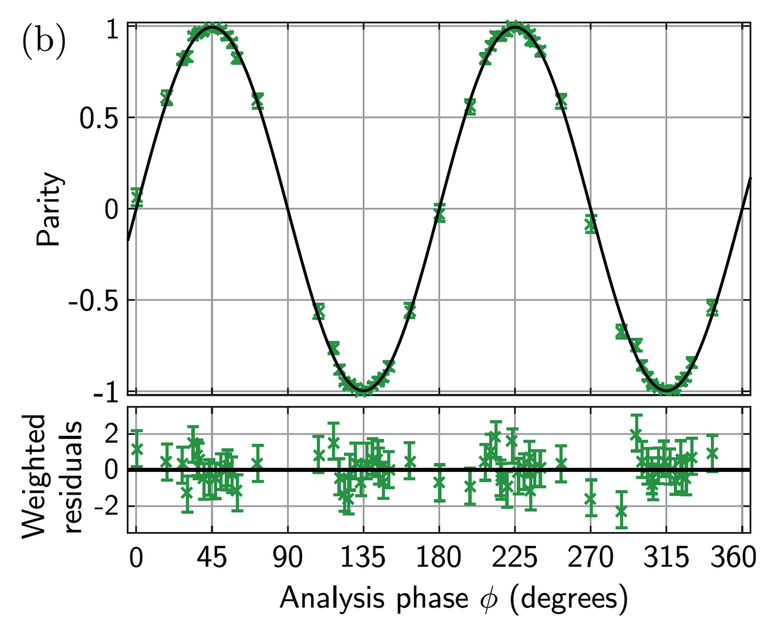
- We generate entanglement by inducing different geometric phases on different parts of the wavefunction ($|\pm\rangle \equiv (|\downarrow\rangle \pm |\uparrow\rangle)/\sqrt{2}$)
- Operation achieved using near-field microwave scheme proposed in [Ospelkaus et al. PRL (2008)]
- Scheme first demonstrated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

Two-qubit gate scheme



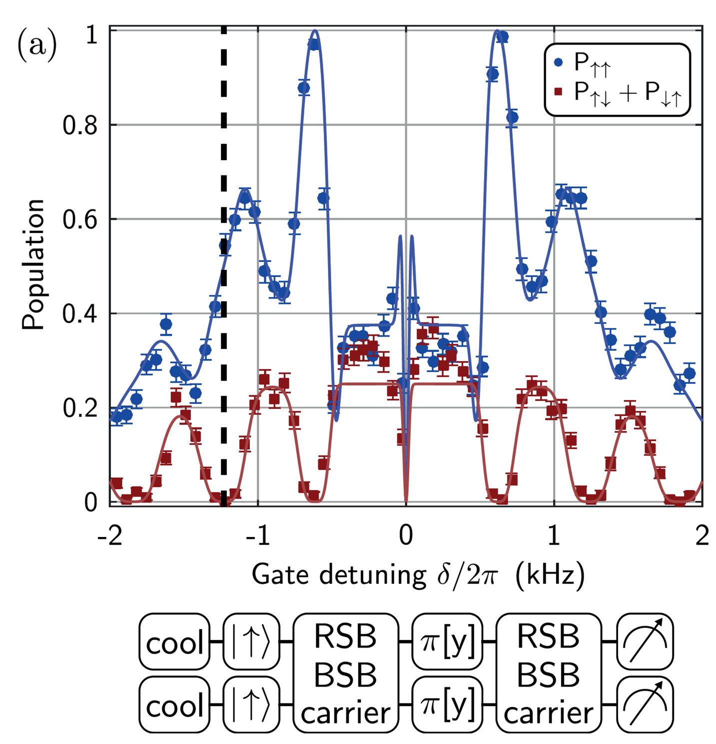
- Bichromatic field with frequencies near first red and blue sidebands as for Mølmer-Sørensen gates
- Dynamical decoupling with a σ_x carrier drive protects against fluctuations in AC Zeeman shift ($\Delta_\uparrow$-$\Delta_\downarrow$)
- Carrier drive Rabi frequency of 4kHz compared with 436Hz for single-ion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

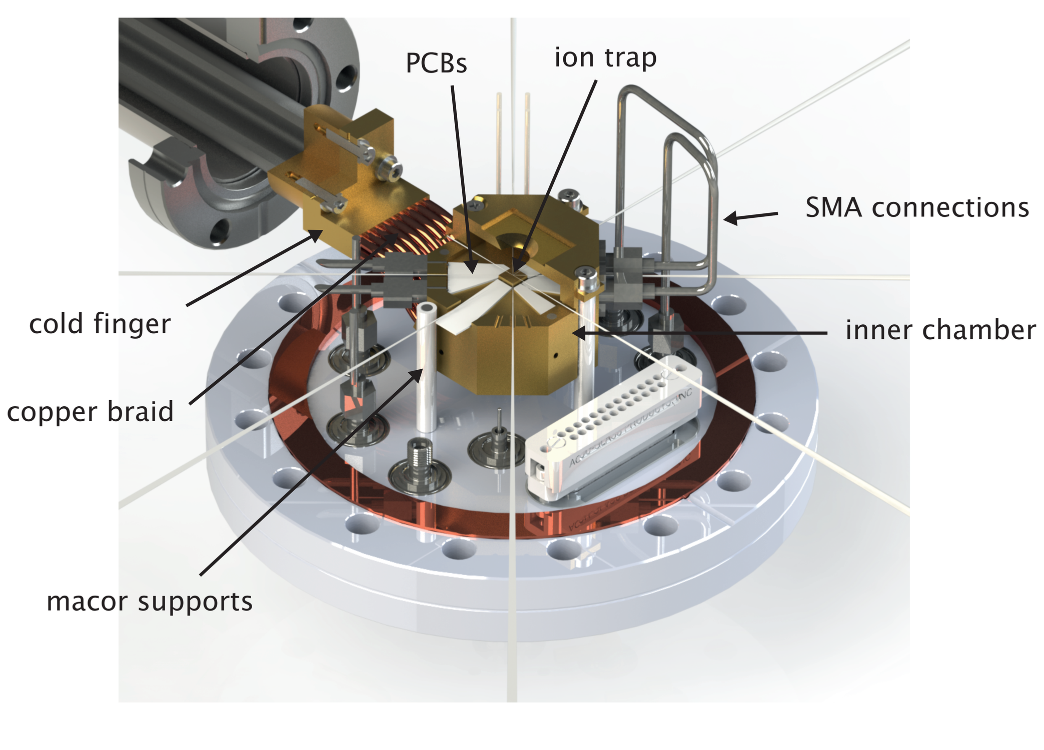
Detuning scans



- 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

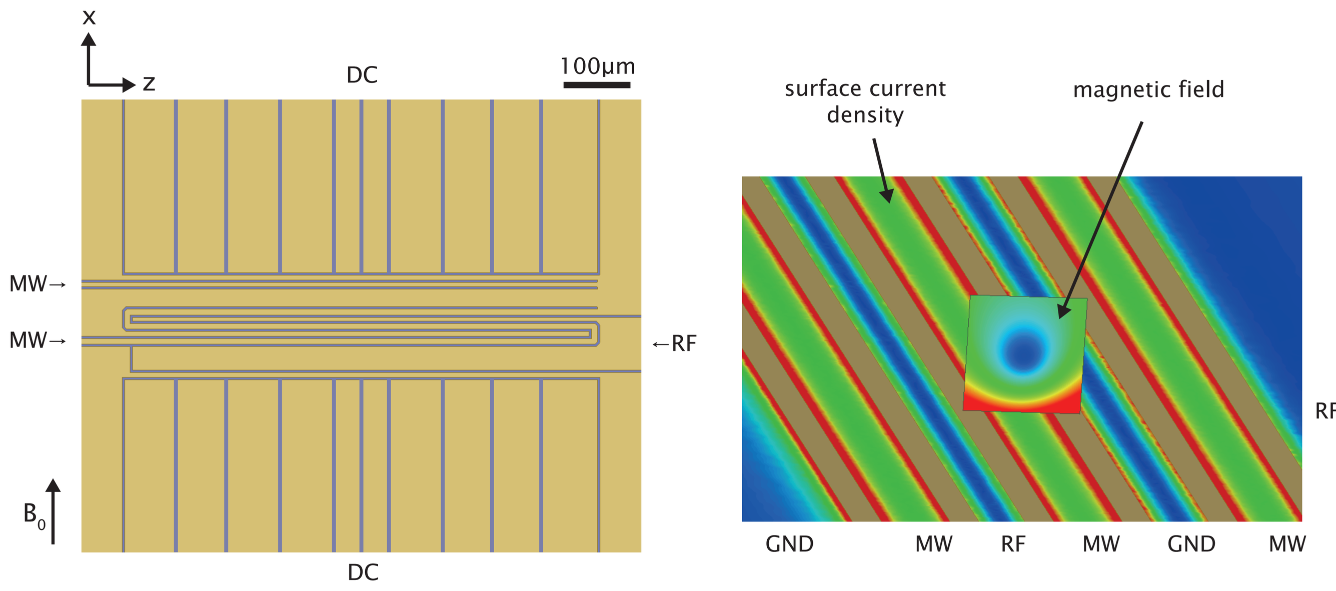
Next-generation system

Cryogenic vacuum system design



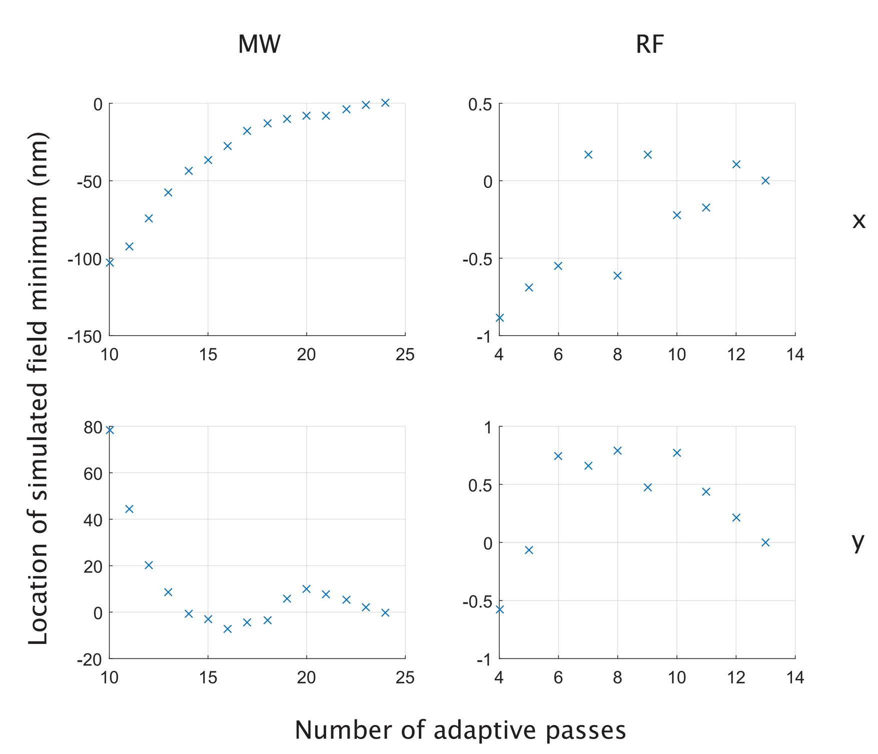
- Cryogenic cooling with Janis ST-400 cryostat
- Cold finger thermally connected to inner chamber with copper braid to minimise vibrational coupling
- Inner chamber attached to base of vacuum chamber with macor supports to minimise thermal load

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 microwave 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

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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