V.M. Schäfer, C.J. Ballance, K. Thirumalai, L.J. Stephenson, A.M. Steane, D.M. Lucas

UNIVERSITY OF OXFORD

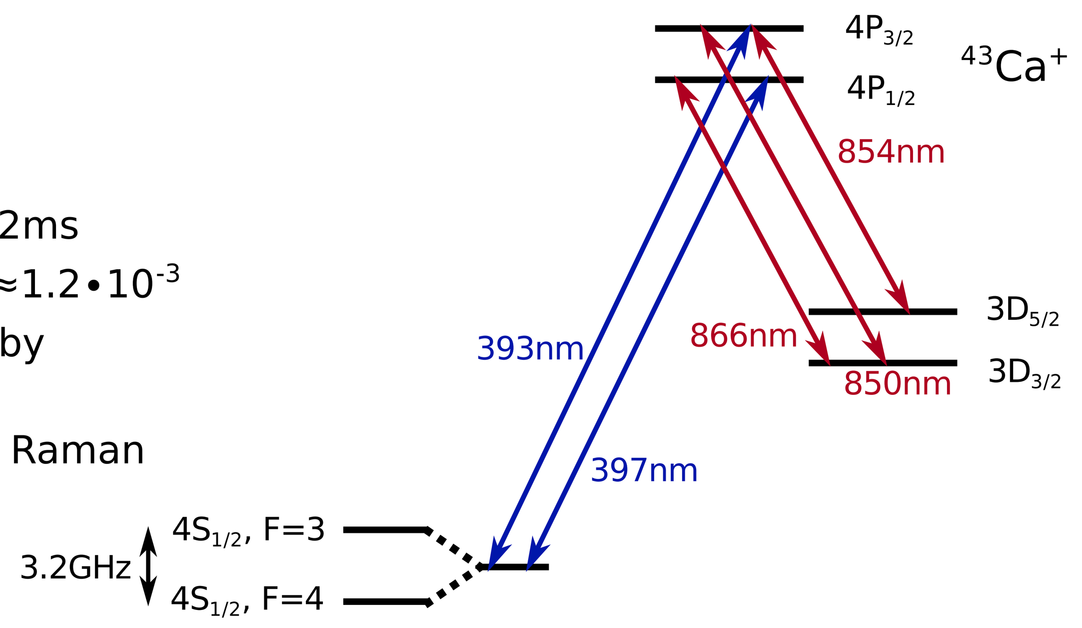
Fast Gates with trapped ions

Ion Trap Quantum Computing Group
Department of Physics, University of Oxford

Trapped ions are a promising candidate for building a quantum computer - the qubits have long coherence times and state-preparation, readout, single- and two-qubit operations have all been demonstrated with high fidelities and above the threshold for quantum error correction.
However all two-qubit entanglement gates demonstrated so far have been performed in the adiabatic regime, where their speed is limited by the trap frequency to gate times typically ≫1μs. Many schemes have been proposed to overcome these limitations, for example [1,2,3] - but none have been implemented yet.
When performing entangling gates at speeds comparable to the motional period of the ions the gate detuning and Rabi frequency are so large that the motional modes are no longer spectrally resolved - both motional modes contribute to the entanglement sensitively depending on the initial phase of the driving force. We follow the proposal [3] that uses cw-laser pulses modulated with fast AOMs on the 10ns scale to perform entangling gates independent of the initial phase of the optical field.
We demonstrate the generation of entanglement in 480ns, less than a motional period of the ion. We also perform entangling gates in 1.6μs with state-of-the-art fidelities F=99.75(4)%, over an order of magnitude faster than the current highest fidelity gates [4,5].

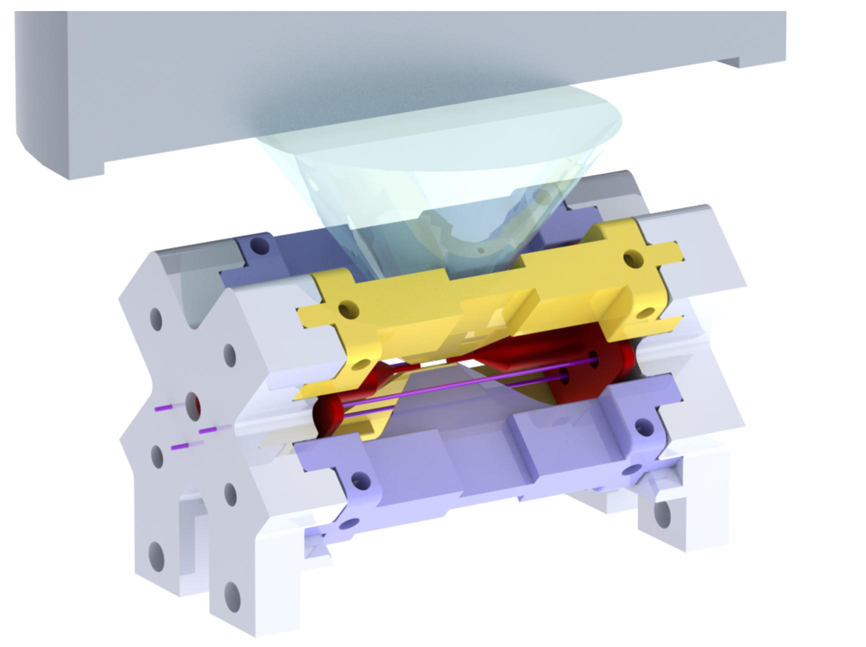
The Qubit

- hyperfine qubit in $^{43}Ca^+$ at 146G, $T_2^* \approx$2ms
- state-preparation and readout errors ≈1.2•10^{-3}
- single qubit operations can be driven by microwaves or pair of Raman lasers
- two-qubit operations driven by pair of Raman lasers



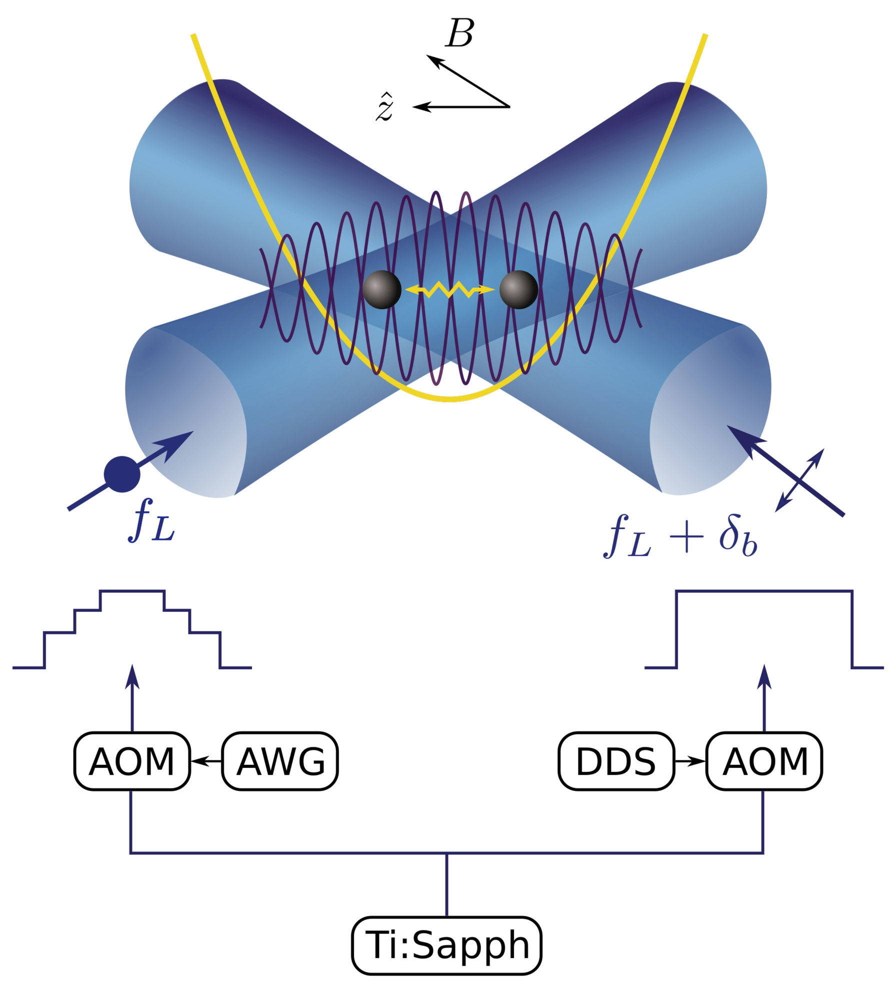
The Trap

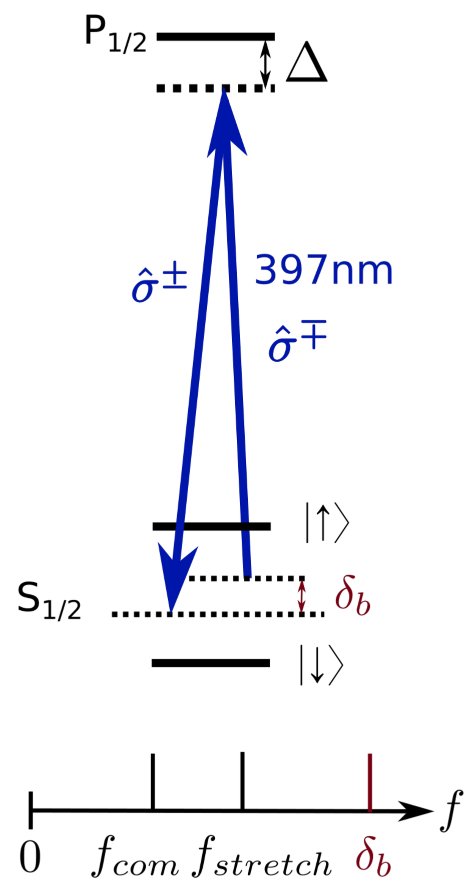
- blade-type linear Paul trap
- high photon collection efficiency of ≈1% due to high NA=0.6 lens
- unusually large heating rate of ≈100 quanta/s



Fast Gates

Experimental setup

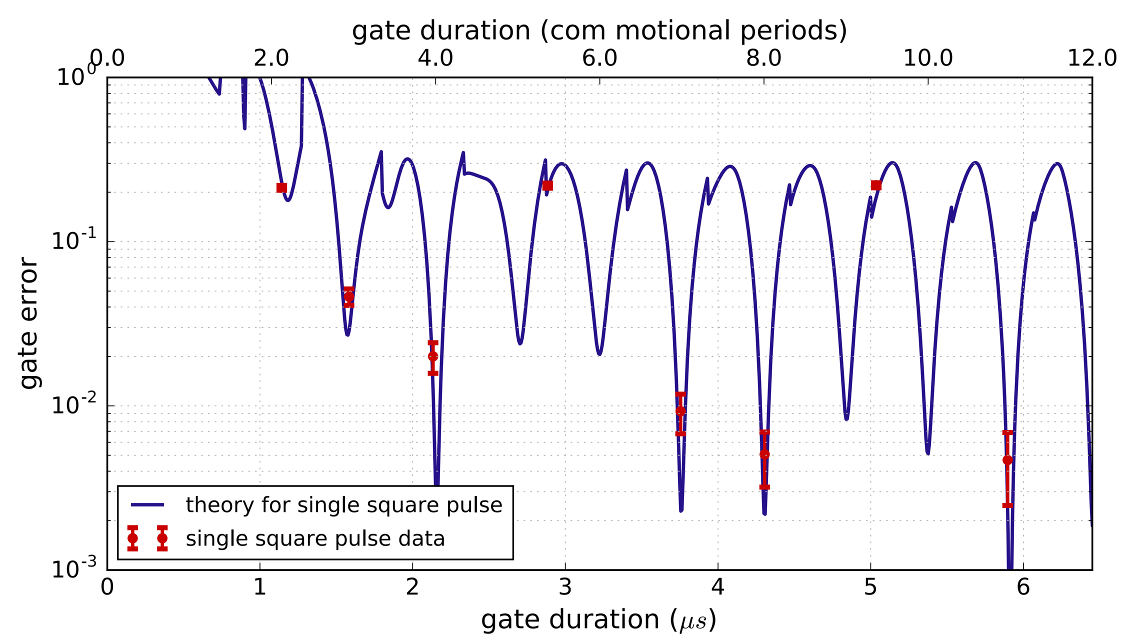




- both Raman beams derived from single frequency-doubled Ti:Sapphire laser
- one Raman beam has shaped amplitude controlled by arbitrary waveform generator (AWG)
- fast AOMs with risetime ~20ns
- up to 150mW per beam (45MHz Rabi frequency)

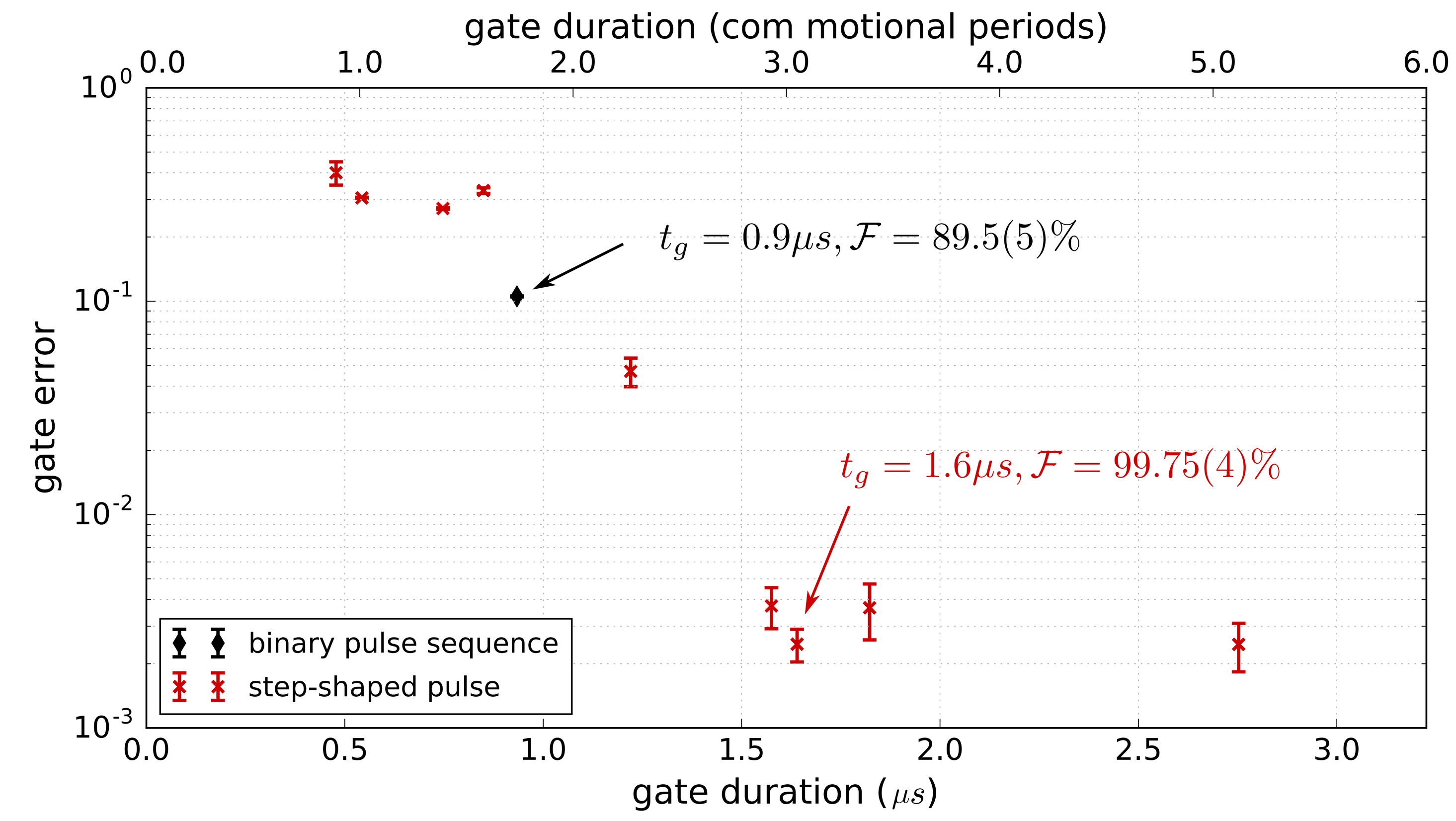
- two Raman beams provide the spin-dependent force driving the gate
- beat note frequency between Raman lasers on same order of magnitude as motional frequencies of the ion

Single square pulses



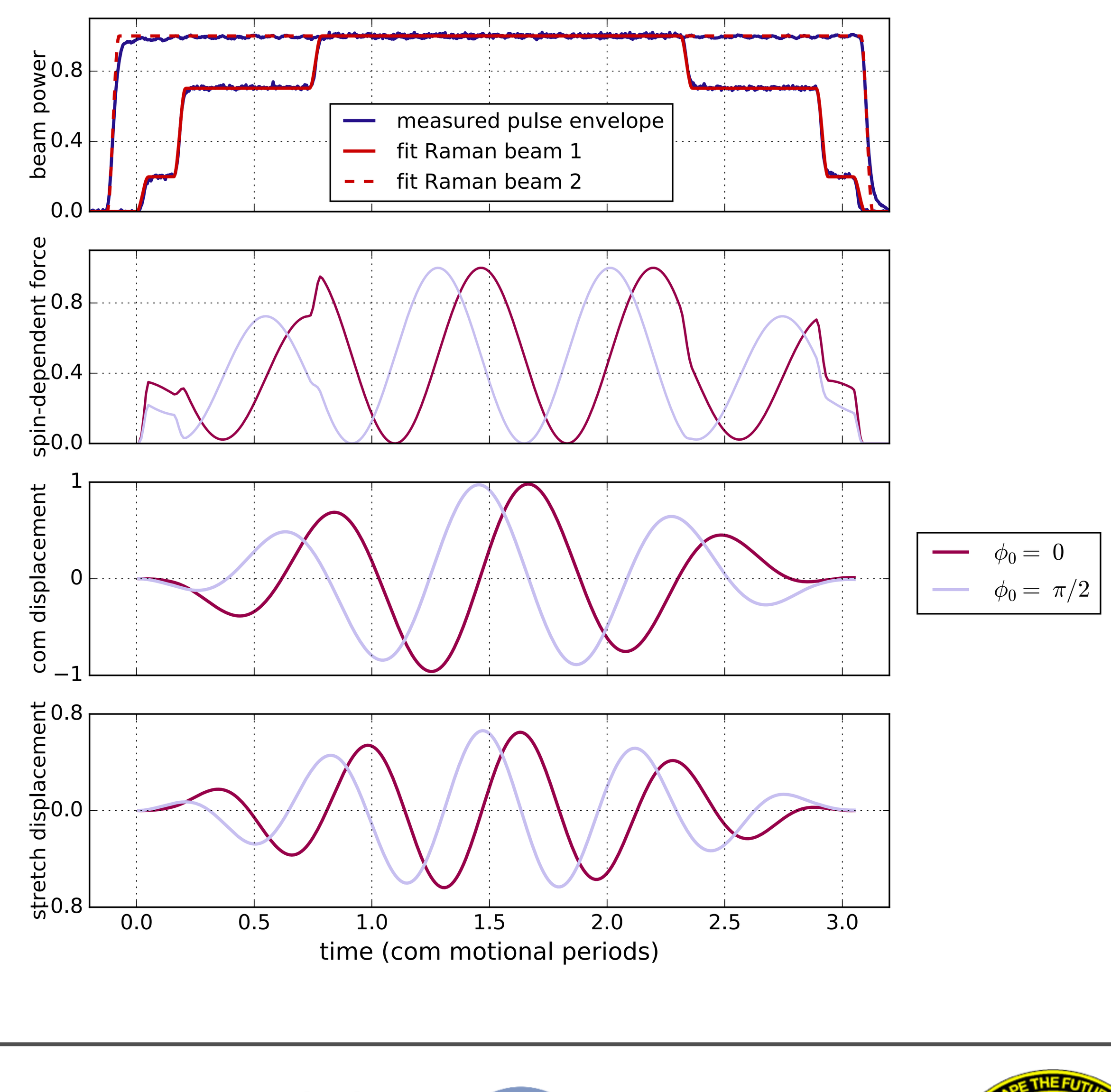
- can achieve over 99% fidelity below 4 μs with a single unshaped pulse
- Nelder-Mead optimisation of beam-power, gate detuning and single-qubit phase compensation for finding optimal gate parameters
- errors rapidly increase below 3 com motional periods due to excitation of stretch mode

Results



- can achieve state-of-the-art entangling fidelities down to gate durations of 3 motional periods
- entanglement creation possible below 1 com motional period, albeit with large errors (40%)
- below 3 motional periods large displacements in phase space cause the Lamb-Dicke approximation to fail and errors increase
- faster gates can be implemented by reducing the Lamb-Dicke parameter or stabilising the optical phase

- spin-dependent force strongly depends on the phase of the optical control field
- total pulse sequences are chosen such that they are independent of the optical phase
- pulse amplitudes adjusted to 0.2% accuracy, pulse length accuracy 0.2 ns
- AOMs driven at centre-frequency to reduce phase-chirps



[1] J. Garcia-Ripoll et al., Phys. Rev. Lett. 91, 157901 (2003)
[2] L. M. Duan, Phys. Rev. Lett. 93, 100502 (2004)
[3] A. M. Steane et al., New J. Phys. 16, 053049 (2014)
[4] C. J. Ballance et al., Phys. Rev. Lett. 117, 060504 (2016)
[5] J. P. Gaebler et al., Phys. Rev. Lett. 117, 060505 (2016)

[dstl] EPSRC Pioneering research and skills
NQIT Networked Quantum Information Technologies
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

www.physics.ox.ac.uk/users/iontrap/ vera.schafer@physics.ox.ac.uk Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom