J E Tarlton A C Hughes M A Sepiol J F Goodwin T P Harty C J Ballance T G Ballance D P L Aude Craik
A M Steane D M Lucas

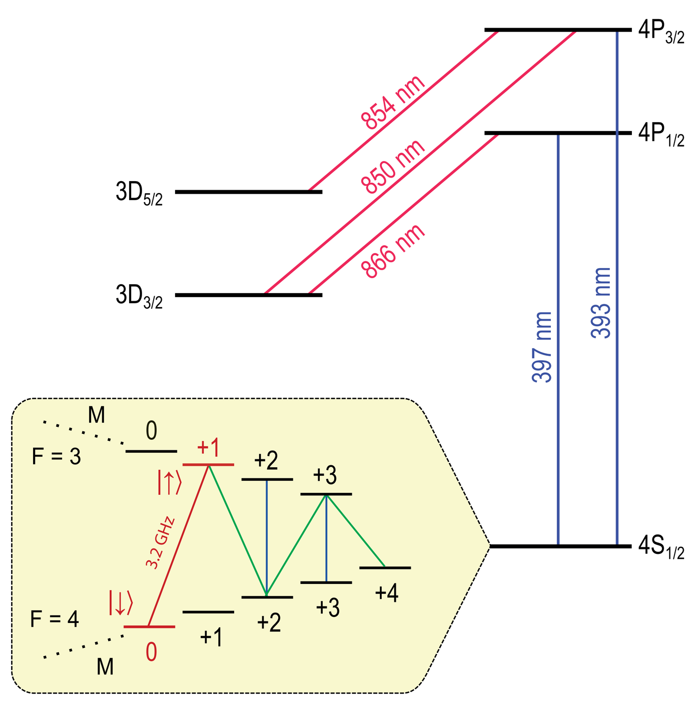
Qubit Decoherence Metrology over Short Timescales

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

Introduction

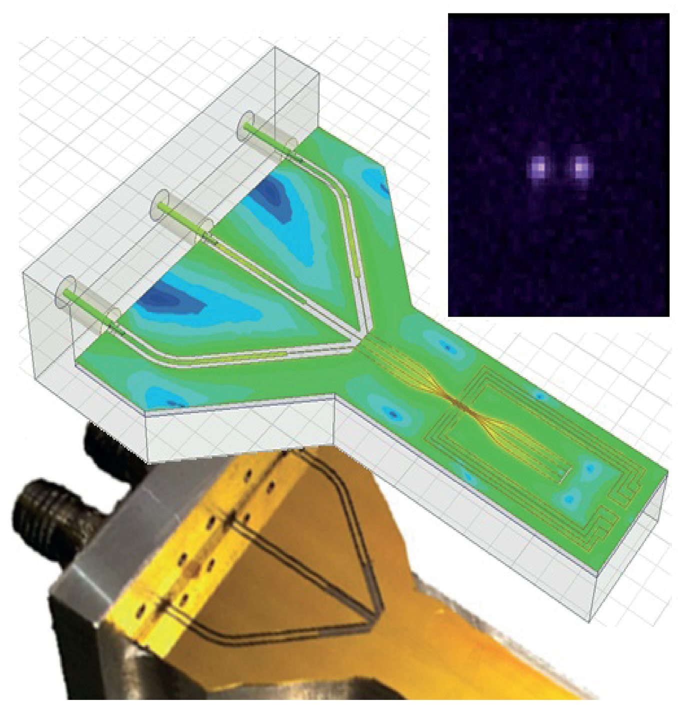
It is possible to achieve exceptionally long trapped-ion qubit coherence times by using atomic clock transitions, which we implement in $^{43}Ca^+$ with T_2* of order a minute, which can be extended to of order 10 minutes with a simple dynamical decoupling sequence. With state preparation and measurement (SPAM) errors typically greater than 10^{-3}, quantum memory performance is usually quantified via Ramsey contrast measurements with delays approaching the coherence time. Information regarding the initial stages of decoherence relevant to quantum computation, where errors remain below 10^{-3}, is then provided by extrapolation of decoherence models only verified at long timescales. We exploit the very small SPAM errors in our qubit to directly investigate the decoherence on timescales much shorter than T_2*.

Intermediate-field "atomic clock" hyperfine qubit



- Qubit transition frequency independent of magnetic field at 146G
- 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)
- Low-error 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)]

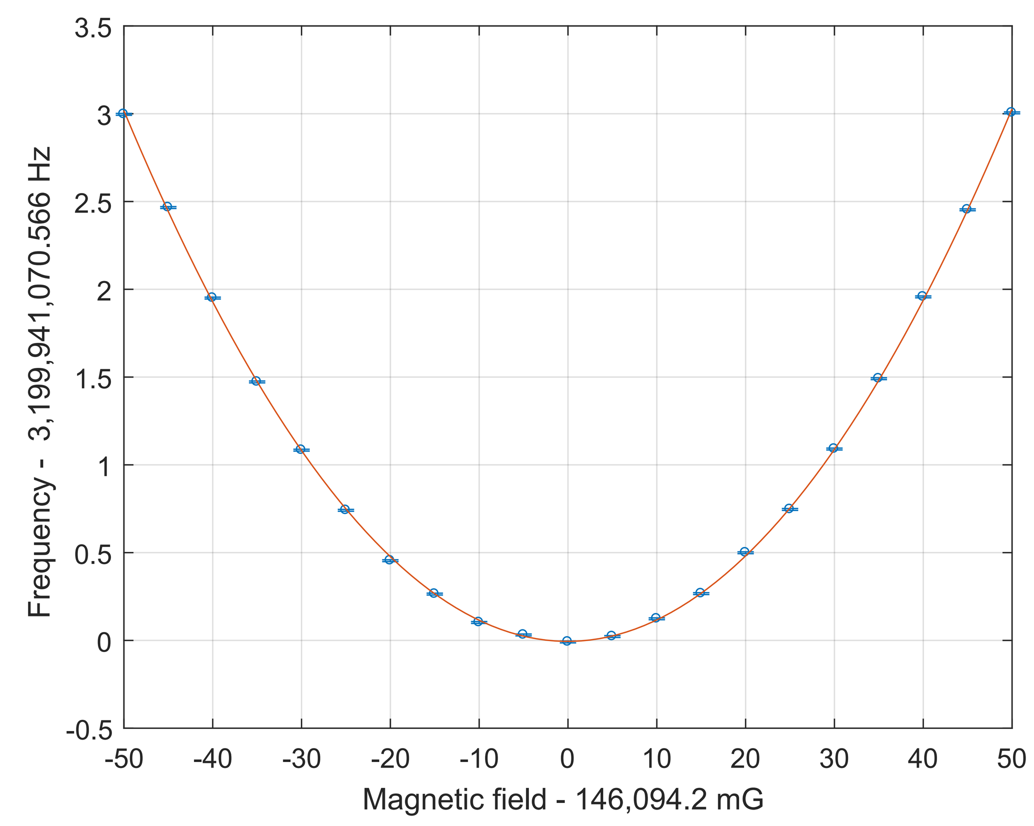
Trap performance



Summary of performance achieved for calcium-43 hyperfine 146G "clock" qubits in this trap

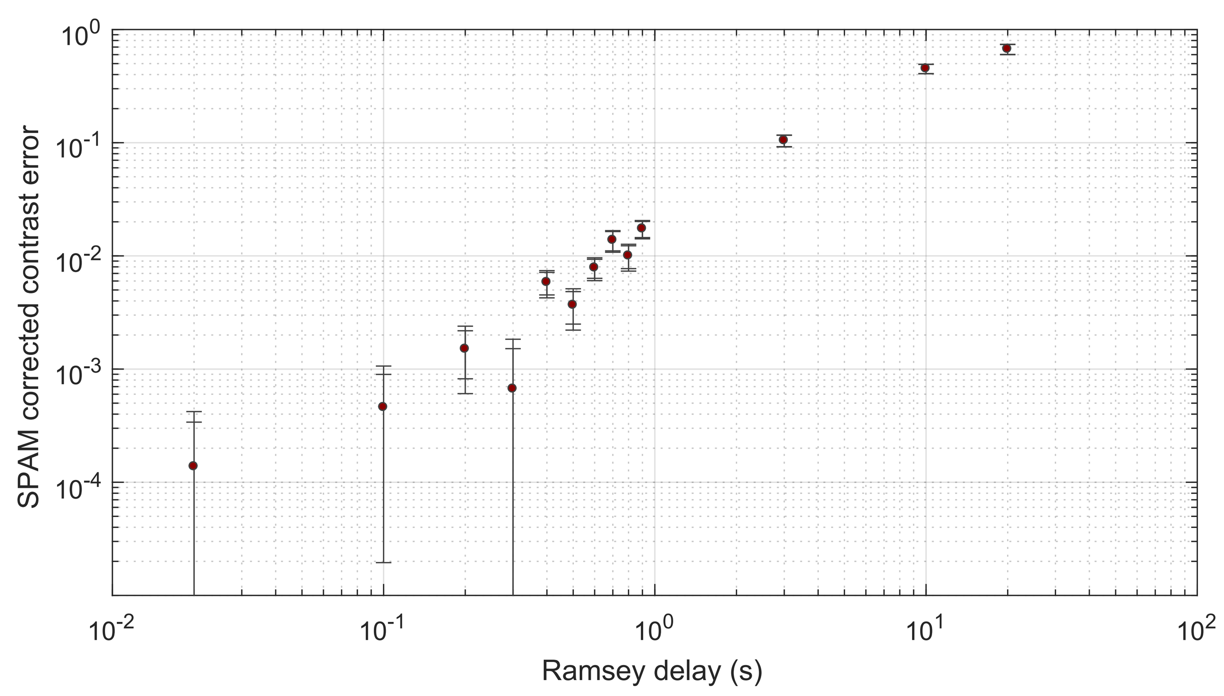
coherence time	Ramsey	T_2* ≈ 1 min
coherence time with DD	Ramsey+π-pulses	≈ 10 min
qubit state preparation	m.w.+laser	99.98%
single-shot qubit readout	m.w.+laser	99.95%
global single-qubit gates	m.w. (benchmarked)	99.9999%
two-qubit "DDMS" gate	m.w. (tomography)	99.7%

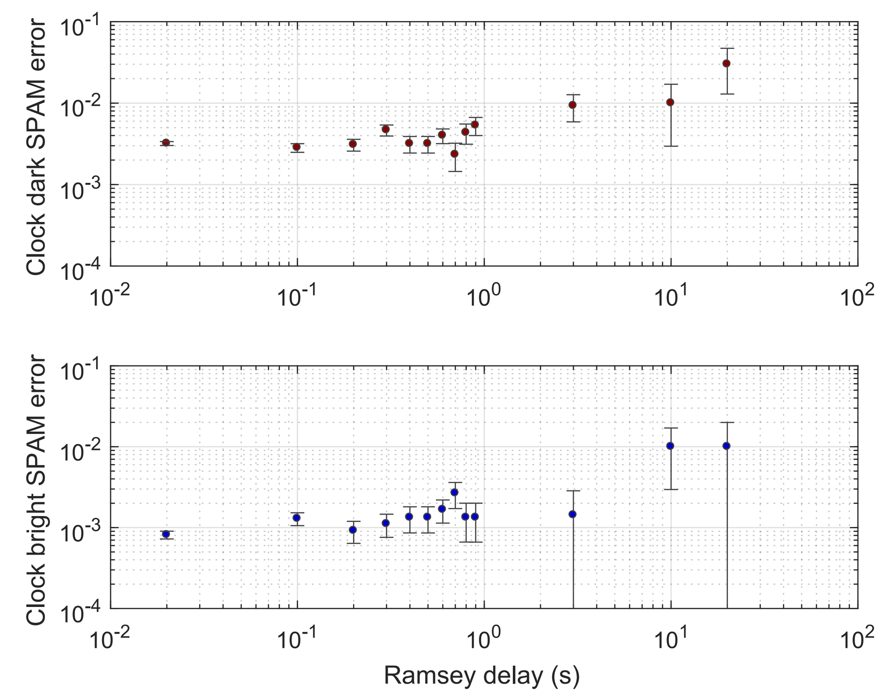
Field-insensitive qubit

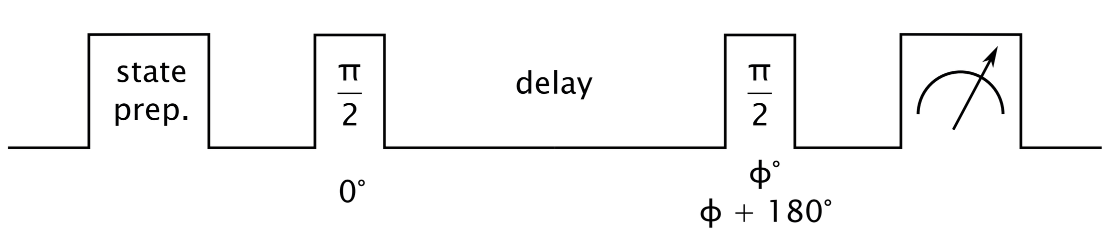


- Magnetic field independent "clock" qubits allow long coherence times
- Intermediate-field clock qubits are preferable to zero-field clock qubits, as the Zeeman shifts required to break state degeneracy induce first-order field dependances

Short timescale qubit decoherence

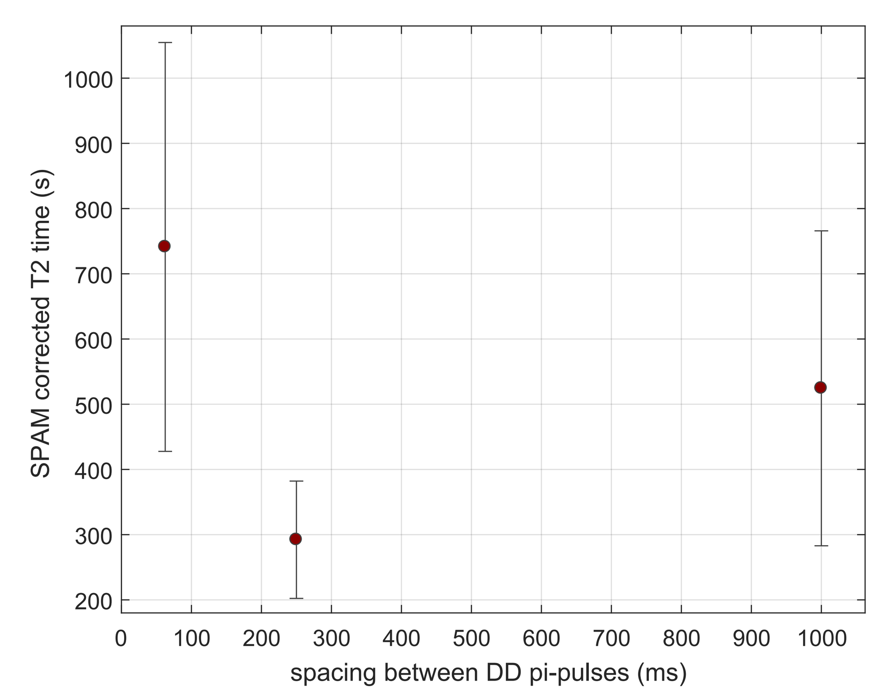






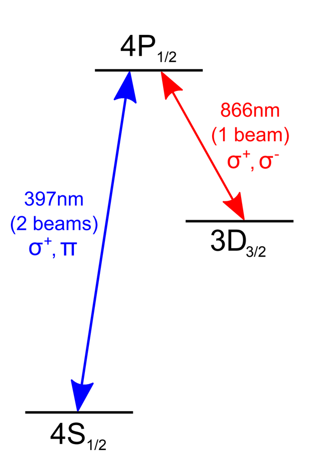
- Memory error measurements performed with short delays to probe qubit decoherence at short timescales
- π/2 pulse followed by second π/2 pulse with phases ϕ and ϕ+180°
- Contrast extracted from difference in two populations
- Analysis phase offset ϕ accounts for residual local oscillator frequency offset, calibrated only once for entire dataset

Dynamically decoupled qubit lifetime

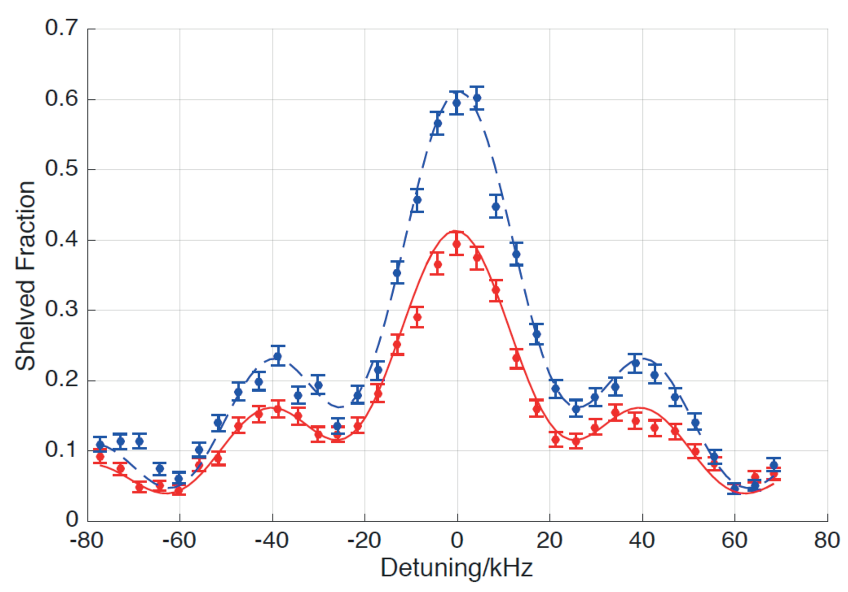


- T_2* of order a minute without dynamical decoupling
- Increases to several minutes when applying π pulses throughout the sequence

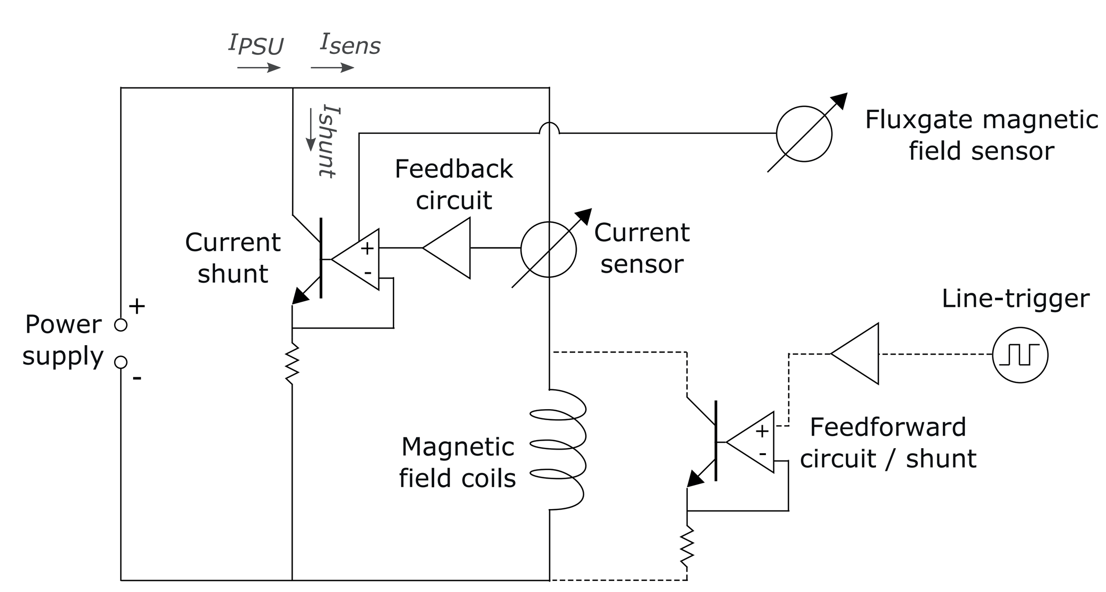
Dark resonance Doppler cooling



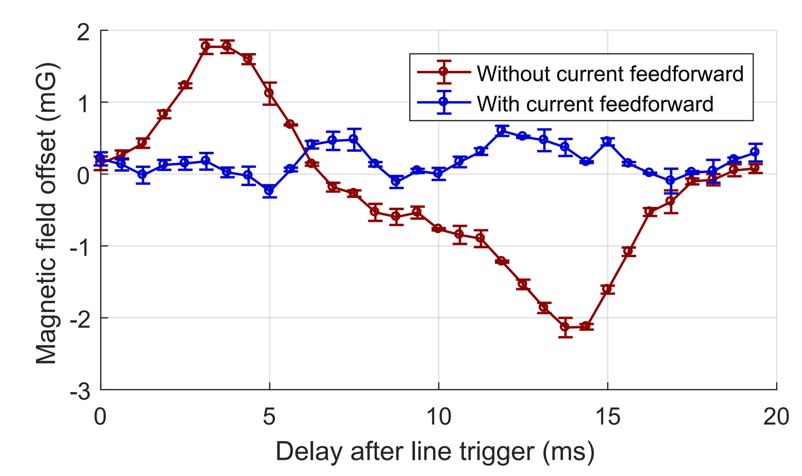
- 64 frequency-separated states relevant for Doppler cooling
- Simple scheme involving a dark resonance used to achieve 0.3mK, slightly below the Doppler limit (see plot)
- Raman sideband cooling used to reach the ground state (only necessary for two-qubit gate work)
- See [Allcock et al. New J. Phys. (2016)]

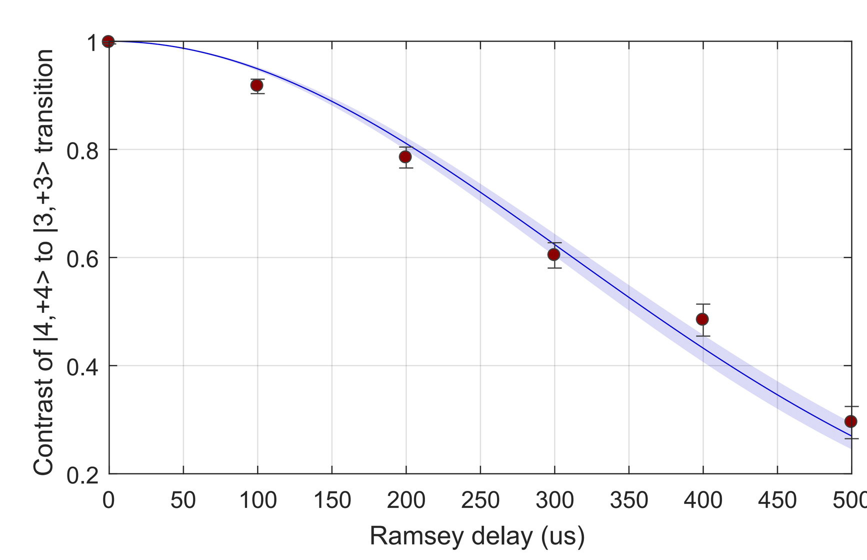


Magnetic field control



- Magnetic field carefully controlled to improve SPAM and reduce decoherence
- Feedforward on coil current reduces variation of magnetic field due to 50Hz mains and harmonics to <1mG (measured by tracking |4,+4>↔|3,+3> transition frequency with delay after line trigger, see plot)
- Feedback on coil current with bandwidth 3kHz reduces non-coherent field noise to 200μG rms (as measured with Ramsey experiments on |4,+4>↔|3,+3> transition, see plot)
- Fluctuations in ambient field measured with fluxgate sensor and fed forward to current controller setpoint with 1Hz bandwidth
- Fluxgate periodically calibrated against microwave local oscillator driving field-sensitive transition on ion





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