A Quantum Memory Qubit in ^{43}Ca^{+}

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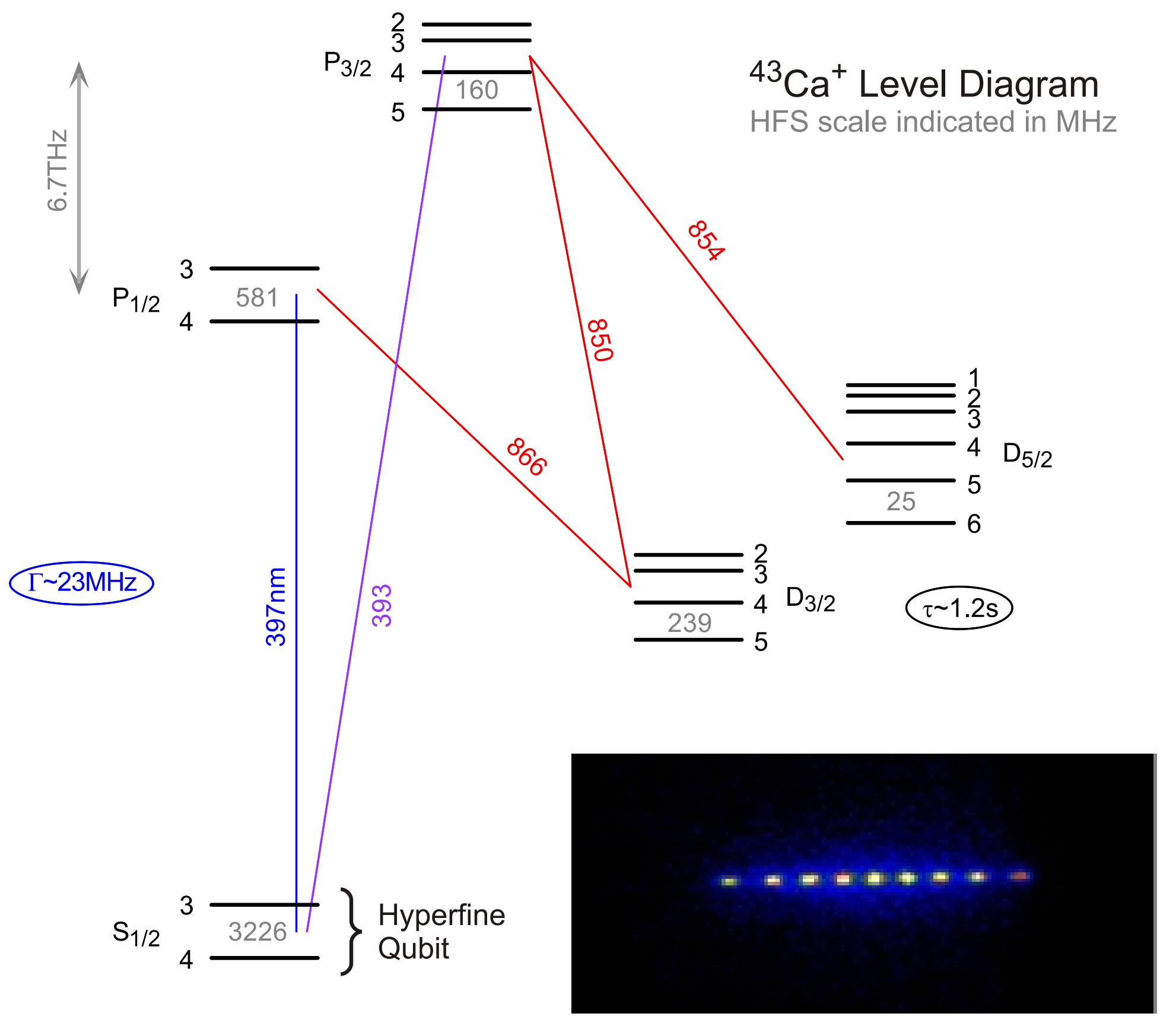
^{43}Ca^{+} qubits

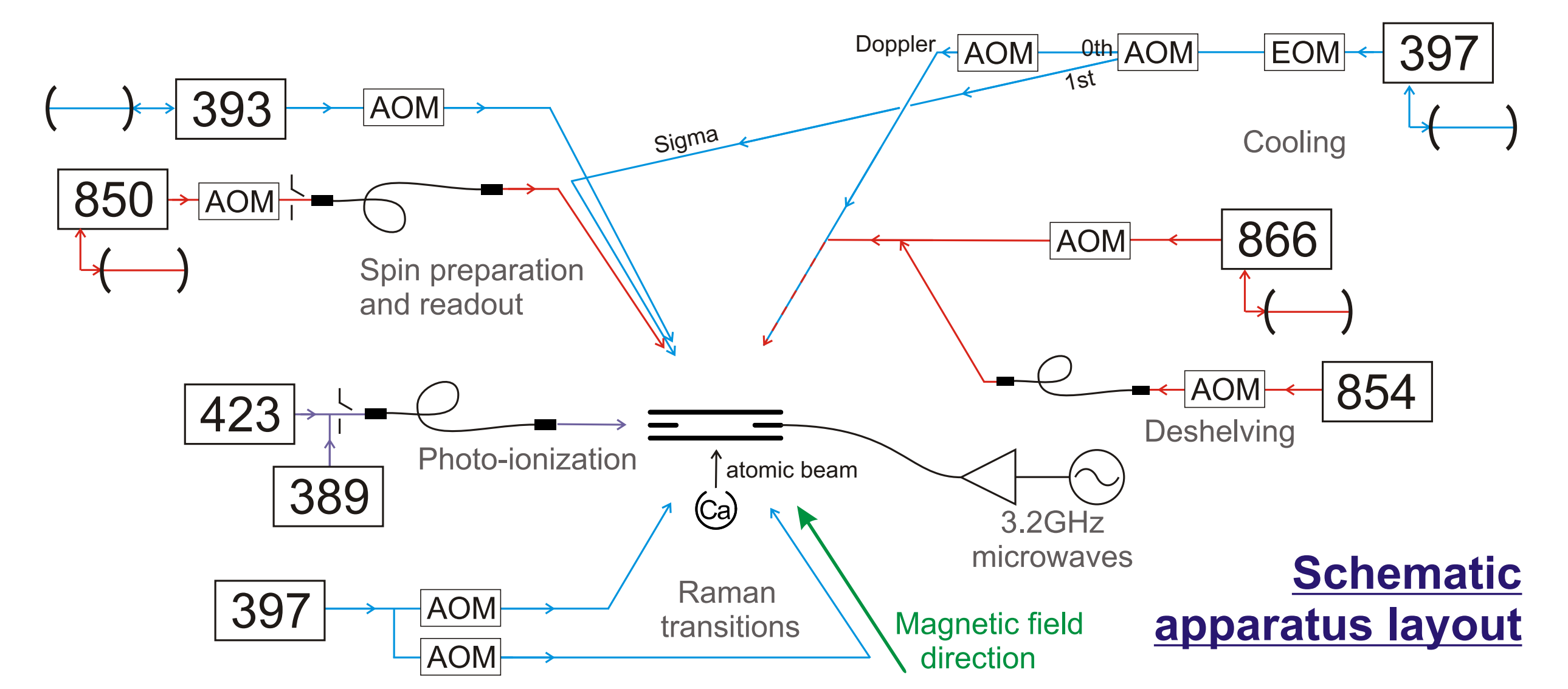
The ^{43}Ca^{+} isotope offers several advantages over ^{40}Ca^{+}:

- easier qubit read-out due to 3.2GHz ground state hyperfine structure splitting
- qubit states which are independent of magnetic field to first order, at both low field and moderate (~150G) field



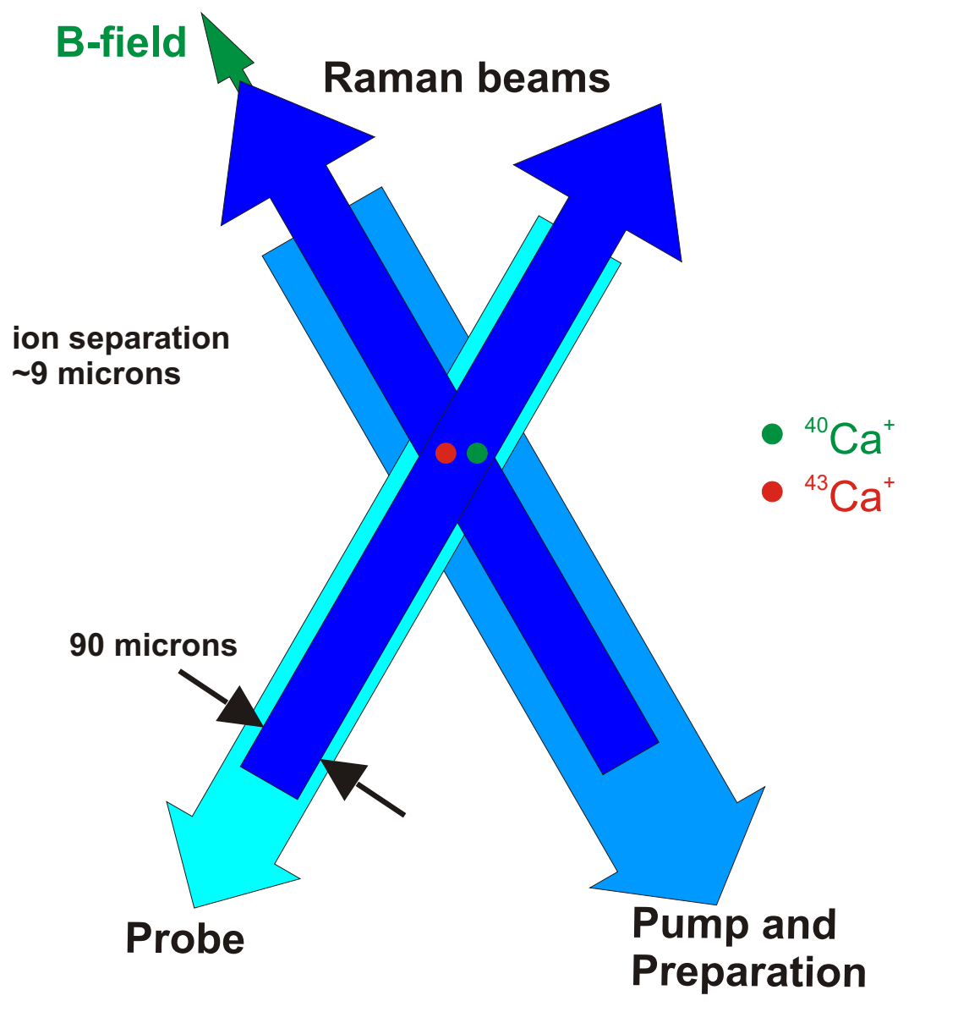
Above: pure crystals of ^{43}Ca^{+} can be loaded from a natural abundance (0.14%) source by isotope-selective photo-ionization
[Lucas *et. al.*, PRA 2004]

Experimental details



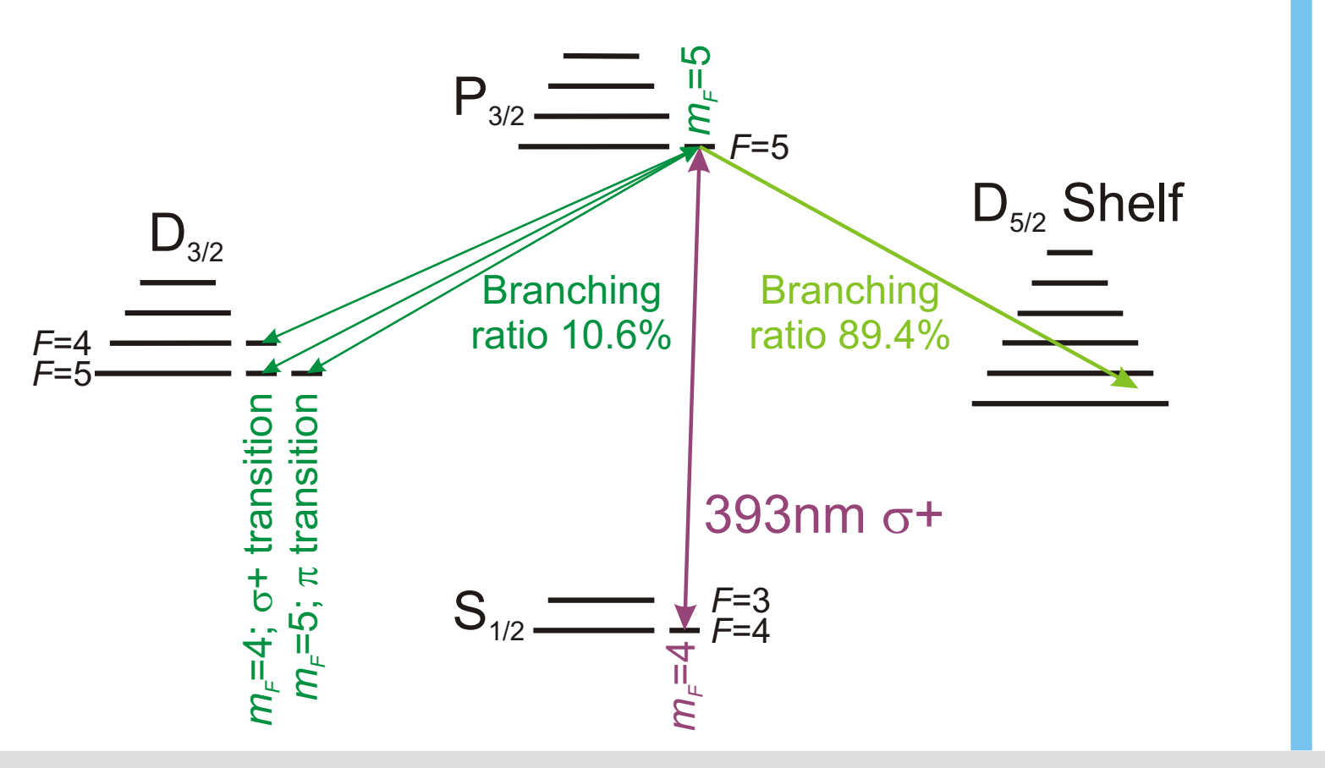
Schematic apparatus layout

Cooling Laser Beams

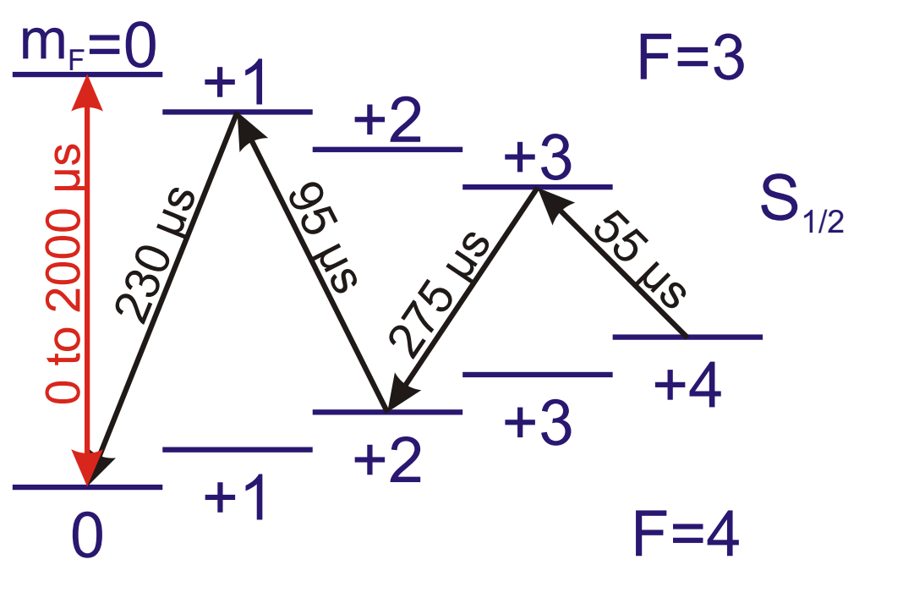


Readout

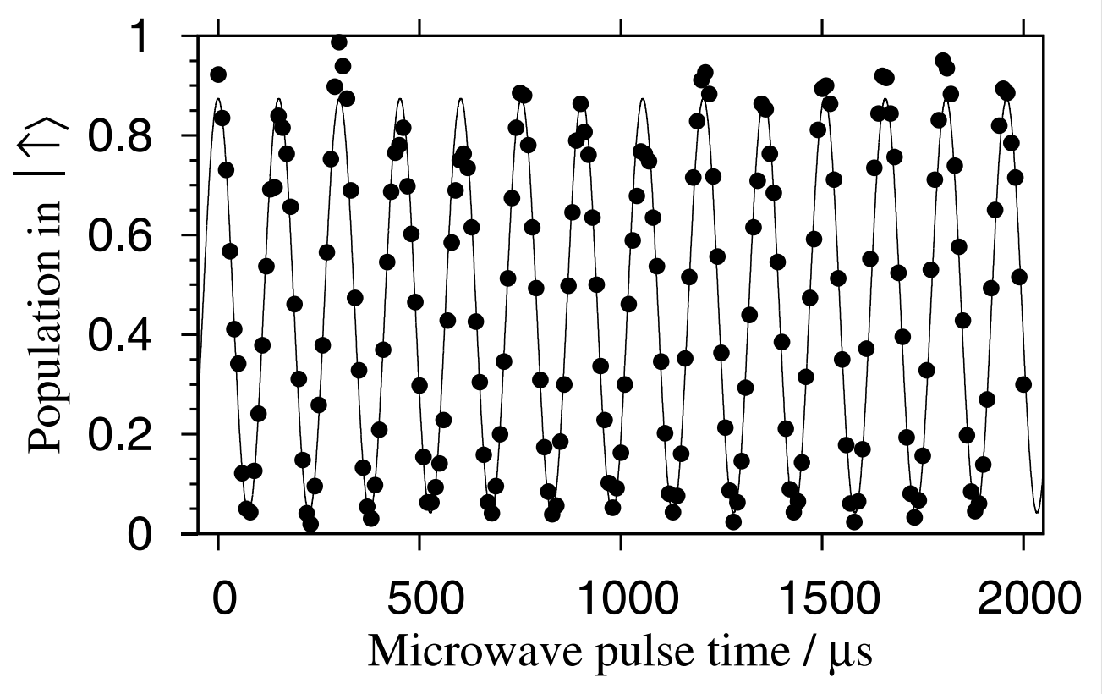
Qubit readout by state-selective shelving with ~95% accuracy by single pulse of 393nm laser on F=4>5 (no 850nm laser needed). Using 850nm as repumper yields ~99% accuracy (see panel below).



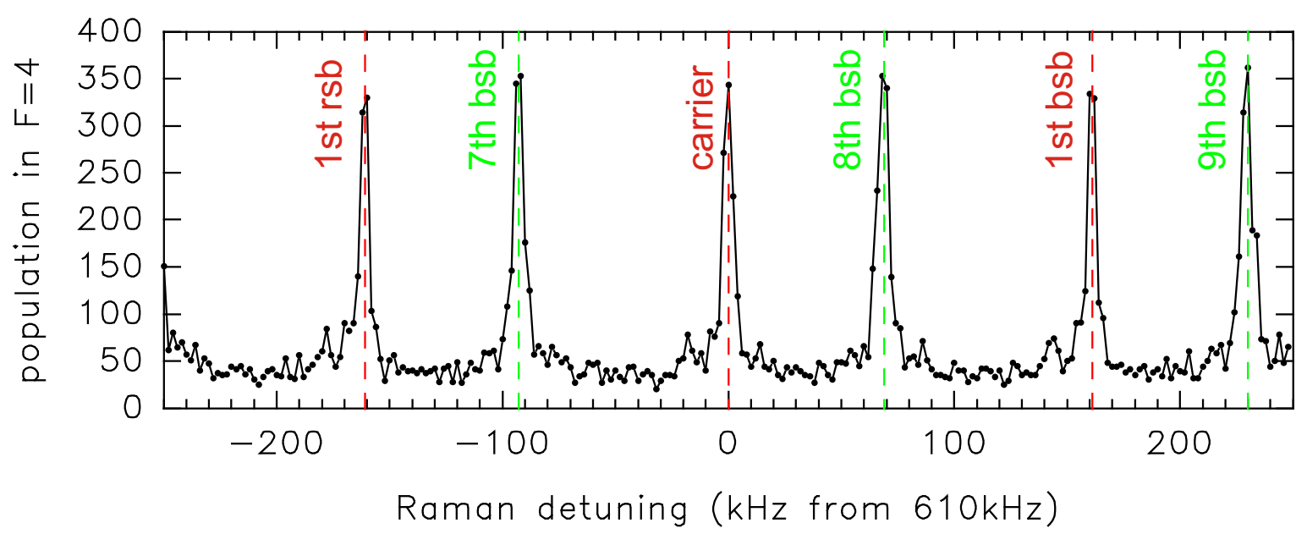
- 3.2GHz EOM in 397nm beam drives F=3>4 and F=4>4 transitions
- can prepare F=4, m_F=+4 "stretched" qubit state with ~99% efficiency, by optical pumping with σ^+ polarized 397nm beam
- can prepare F=3, m_F=0 field-independent "clock" qubit state with ~15% efficiency, by switching off EOM (no π polarized beam currently available)
- can prepare F=4, m_F=0 clock state with up to 90% efficiency, by applying a sequence of microwave π pulses to the F=4, m_F=+4 state (see below)
- 3.2GHz microwaves used for coherent state manipulation



Microwave pulses for F=4, m_F=0 preparation (variety of pulse lengths due to Clebsch-Gordan coefficients and varying microwave power).



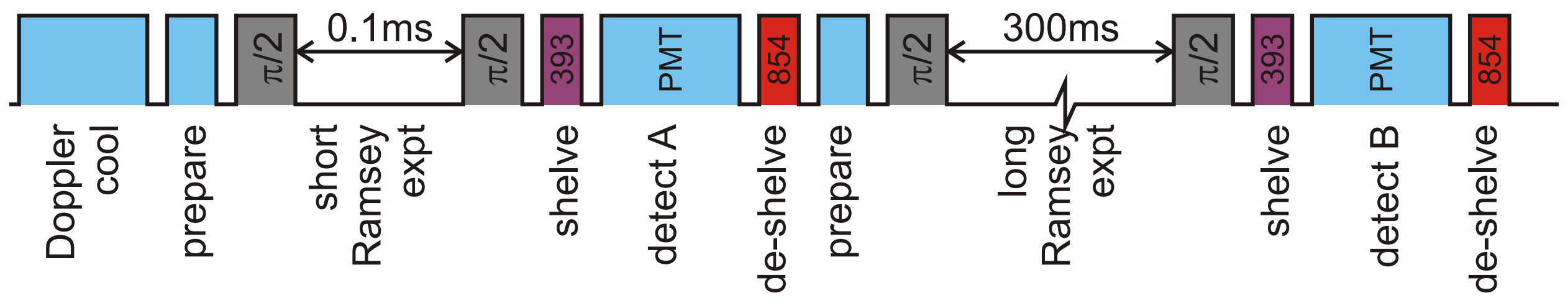
Rabi flops on m_F=0↔0: 83% average preparation of F=4, m_F=0 clock state.

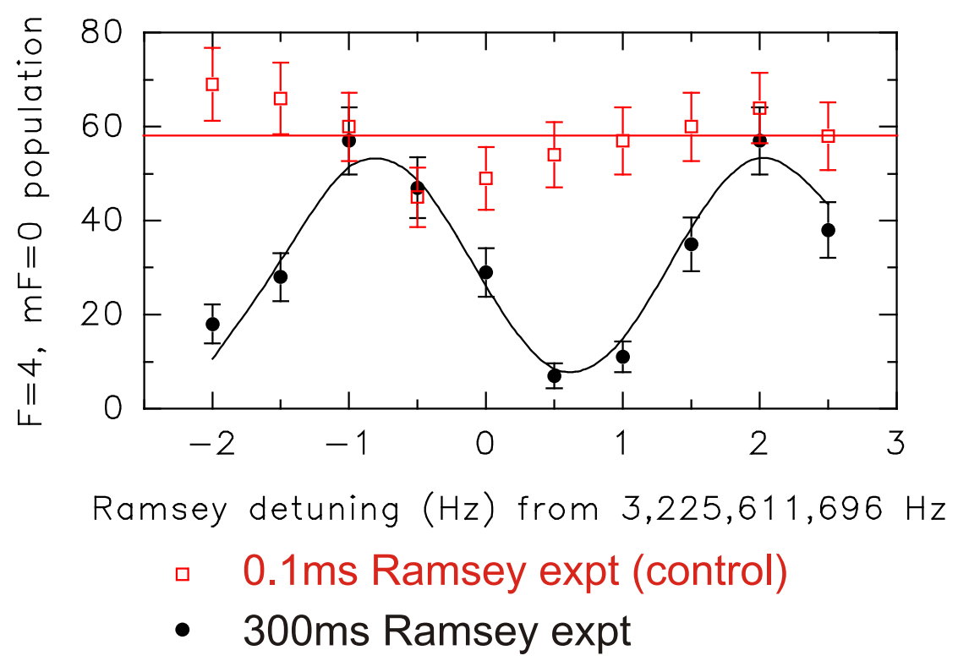


Raman sideband spectra on (F=4,m_F=+4)↔(F=4,m_F=+3). Two overlapping spectra (red & green) as Raman transition goes "both ways". Single hot ^{43}Ca^{+} ion in weak (160kHz) trap.

Long-lived memory qubit

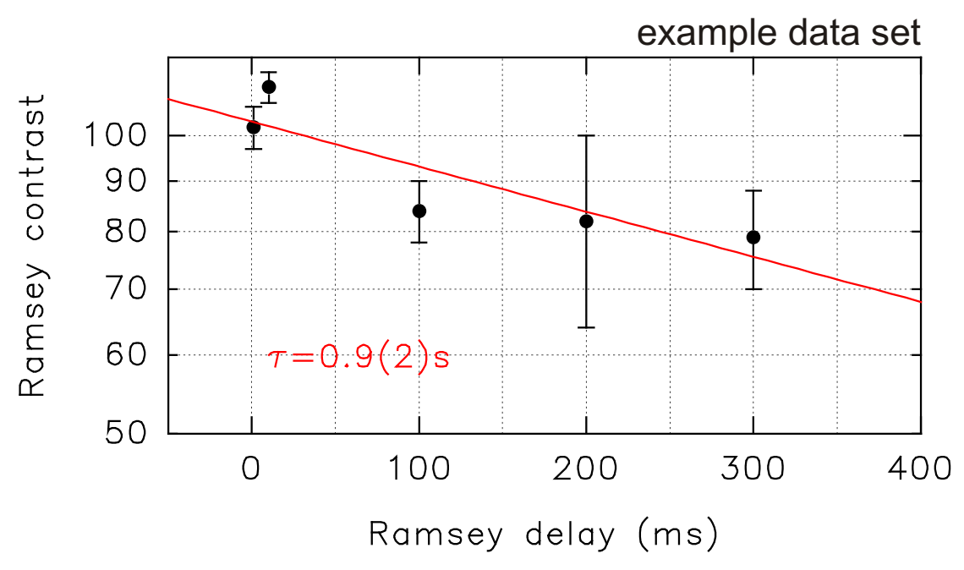
We can observe many (~270) Rabi flops on the m_F=0>0 field-independent transition, lasting >30ms (see plot at bottom of poster). This time-scale may be limited by microwave power stability, so we perform a Ramsey experiment to measure the qubit coherence time T_2. To check for, e.g. drift of readout efficiency, we *interleave* a short Ramsey experiment (0.1ms gap) with a long Ramsey experiment (up to 300ms gap). Since the microwave frequency is swept over only a few Hz, the short Ramsey experiment is essentially a π pulse.



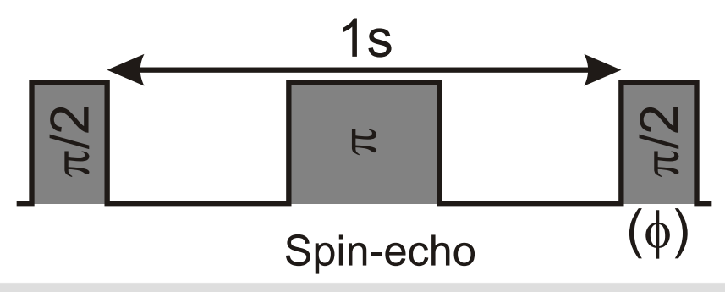


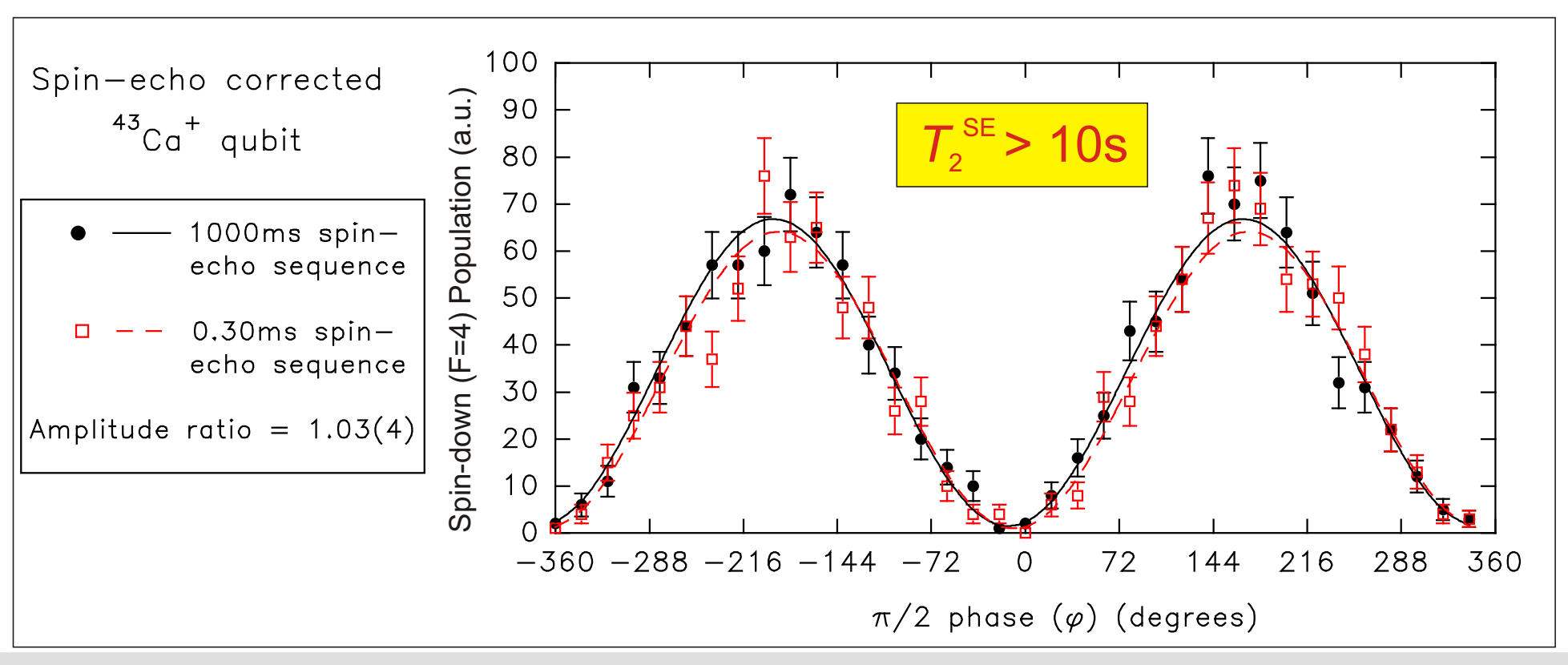
From several data sets we find an internal state coherence time of T_2=0.8(2)sec.

At working field of 1.7G, residual field-sensitivity is ~4Hz/mG. The reduction in fringe contrast is consistent with field drifts at the level of 0.1mG/hr.



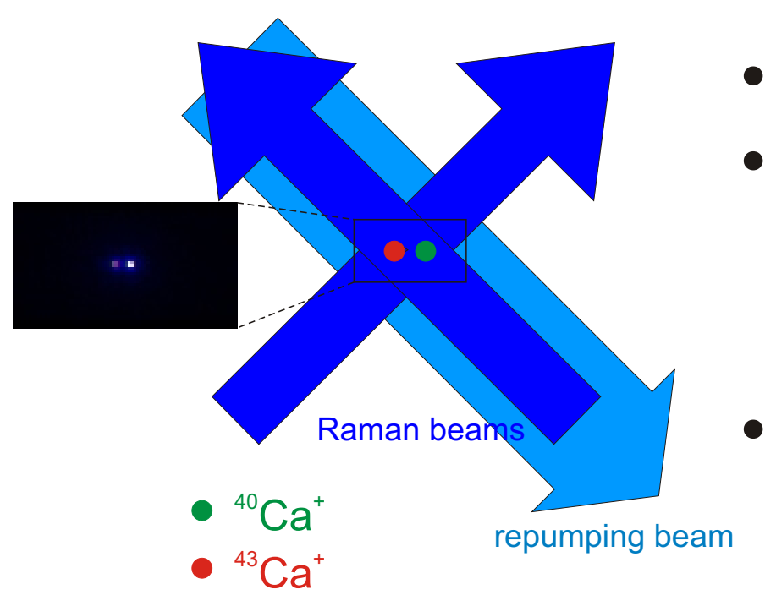
A single spin-echo π pulse can be used to protect the memory qubit from the residual field-sensitivity. We detect no decoherence in a 1 second experiment (Ramsey fringe contrast >99%, right), implying an effective coherence time of T_2^{SE}=10s–100s.





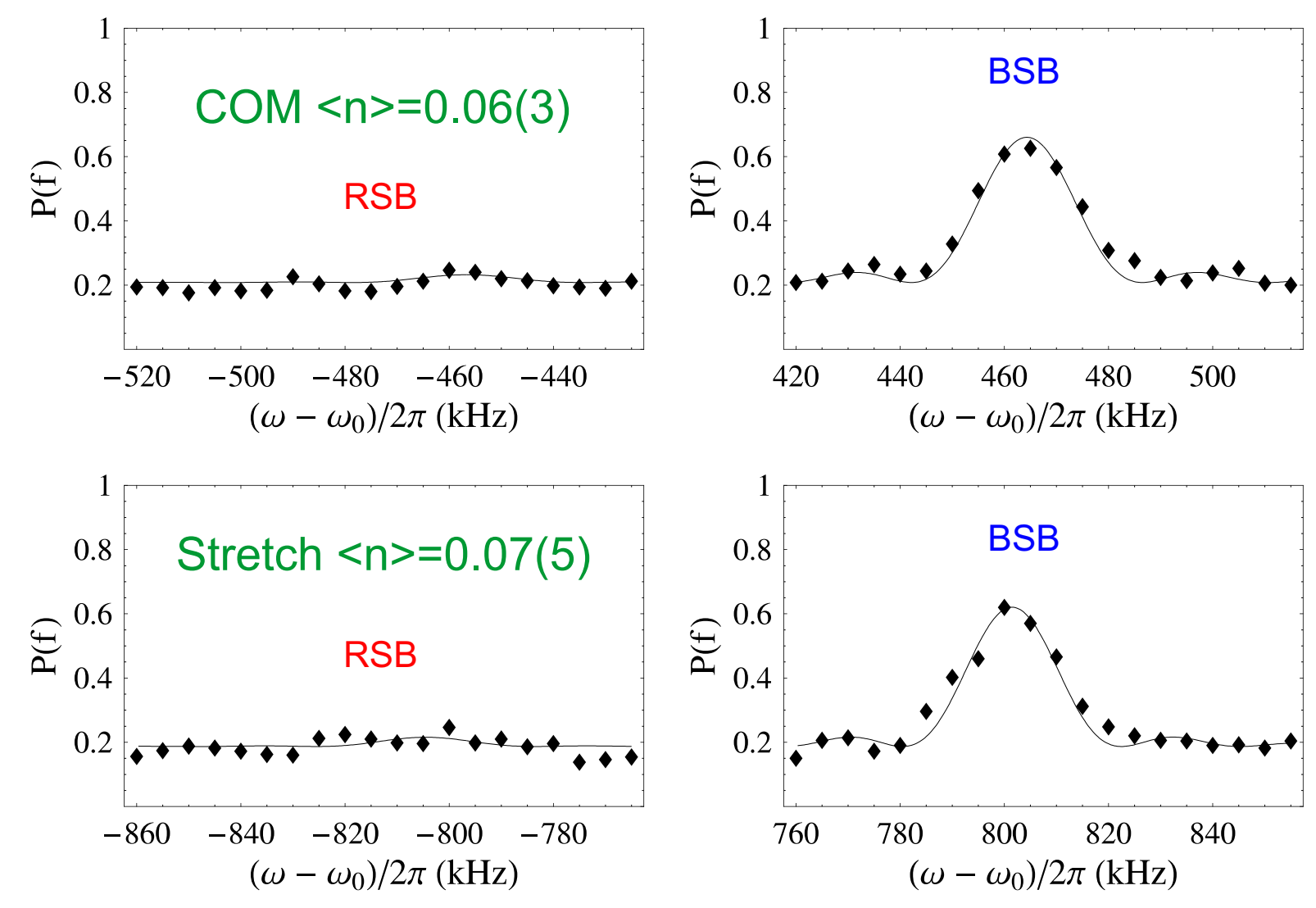
Coherence of an actively-cooled qubit

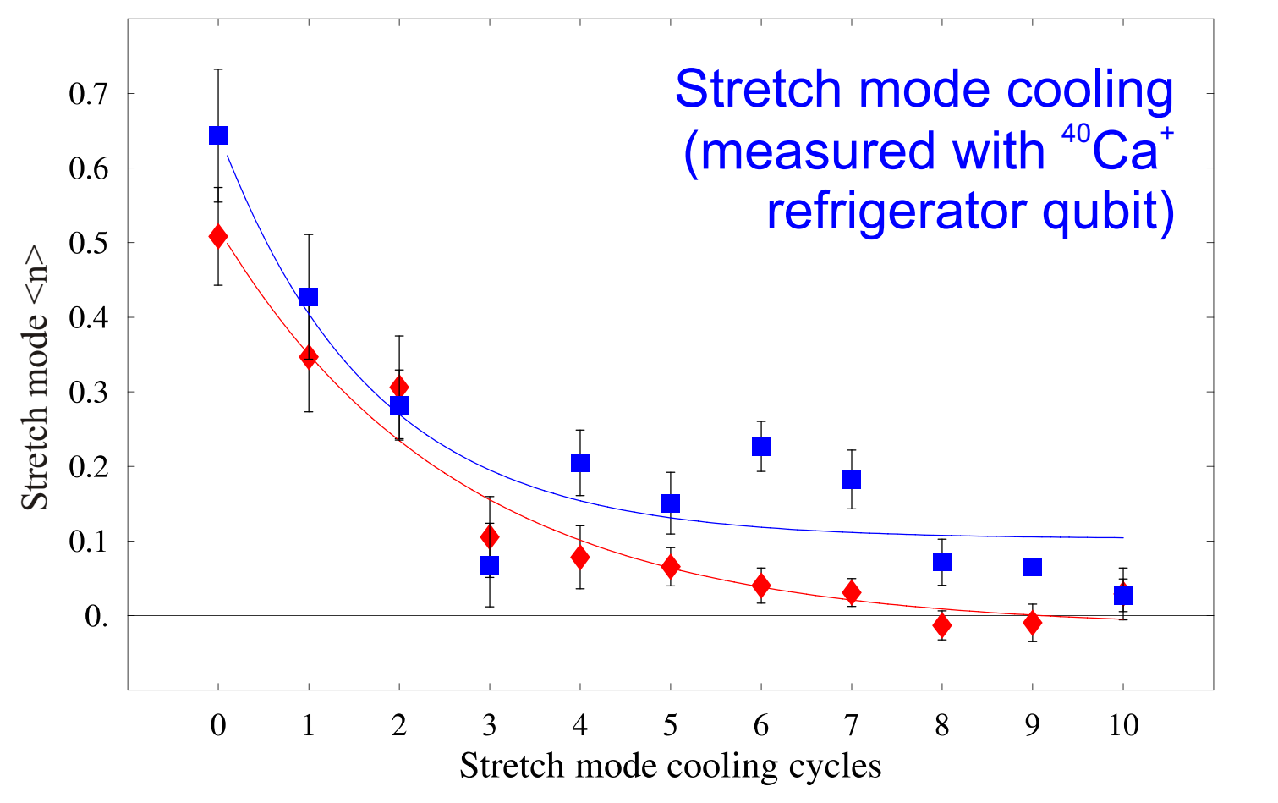
We measure the coherence of a "logic" qubit stored in the hyperfine clock states of ^{43}Ca^{+} *while* it is being actively cooled by a ^{40}Ca^{+} "refrigerator" ion in the same trap. The ^{40}Ca^{+} ion cools the ^{43}Ca^{+} ion sympathetically, through the Coulomb interaction. We cool the stretch motion of the ion-pair using pulsed Raman sideband cooling. Some decoherence of the logic qubit is expected due to photon scattering by the Raman laser and by the ^{40}Ca^{+}-resonant repumping beam applied between Raman pulses. We show that the Raman pulses are the dominant source of decoherence, which may in principle be eliminated with a higher-power far-detuned laser [Ozeri *et al.*, PRL 2005]. The repumping beam is calculated to give <0.1% decoherence per cooling cycle; it gives a measured qubit phase shift of 37mrad per cooling cycle.

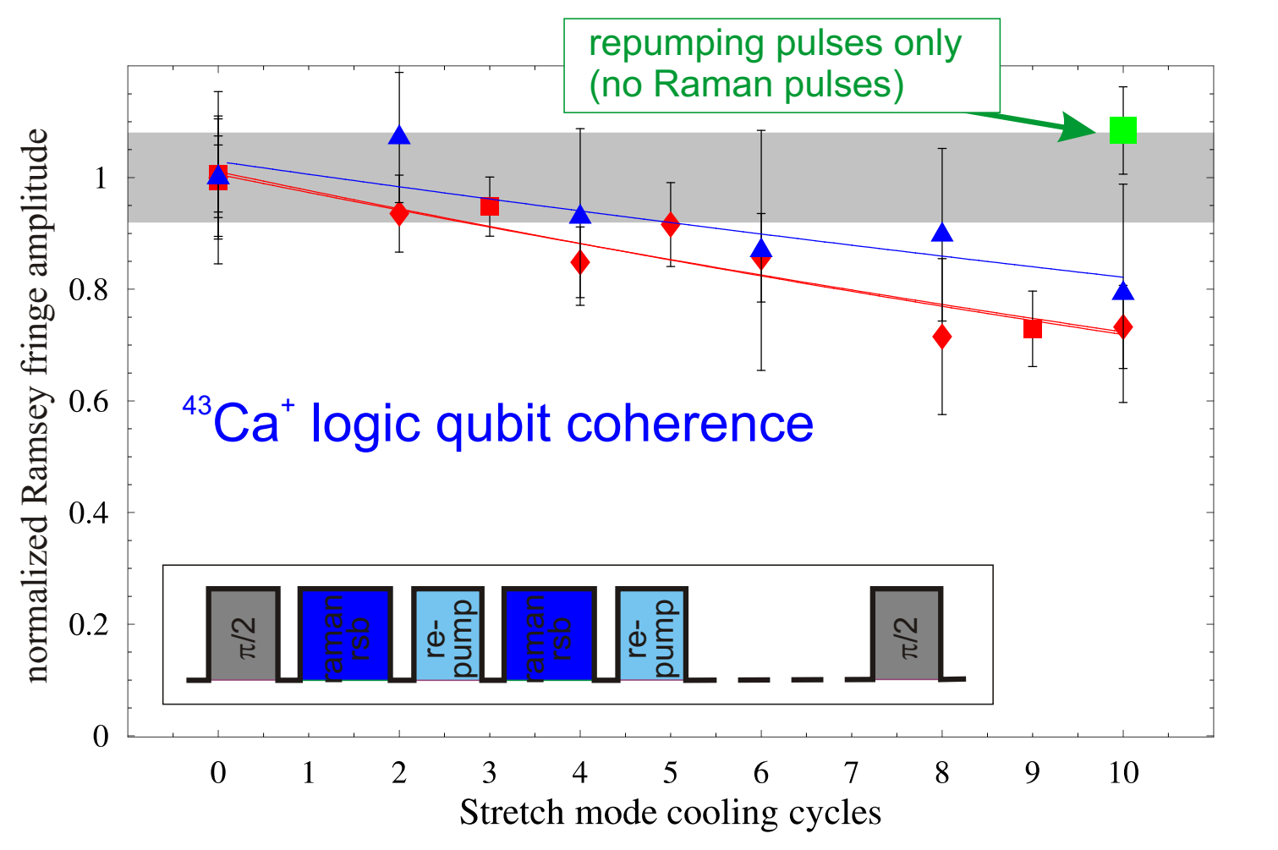


- cooling beams illuminate both ions
- isotope shifts ~1GHz between ^{40}Ca^{+} and ^{43}Ca^{+} 397nm transitions allow qubit coherence to be maintained while ^{40}Ca^{+} is actively cooled
- ^{43}Ca^{+} qubit coherence measured by microwave Ramsey experiment

^{40}Ca^{+} / ^{43}Ca^{+} Sympathetic Cooling results

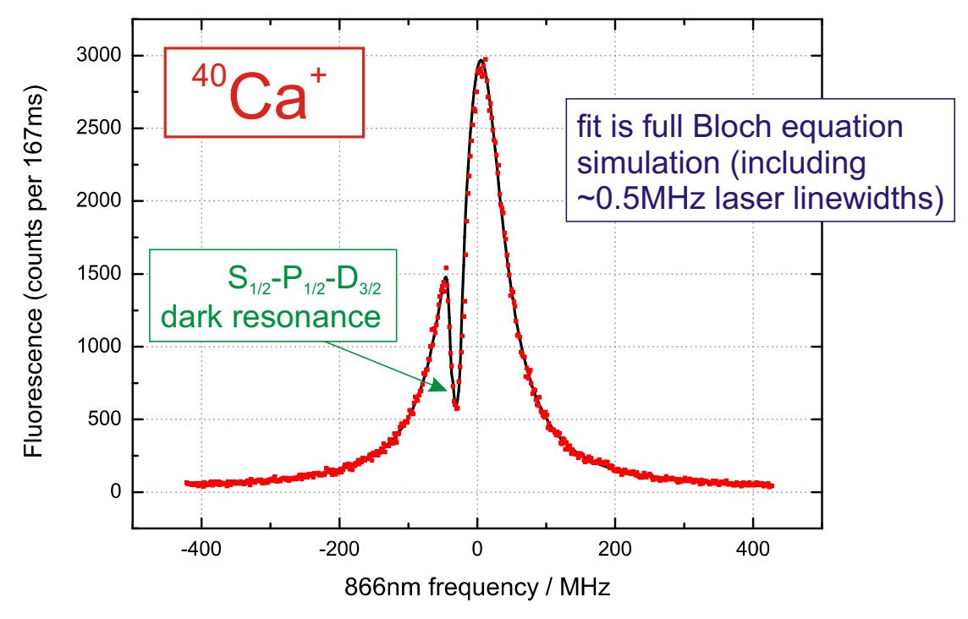


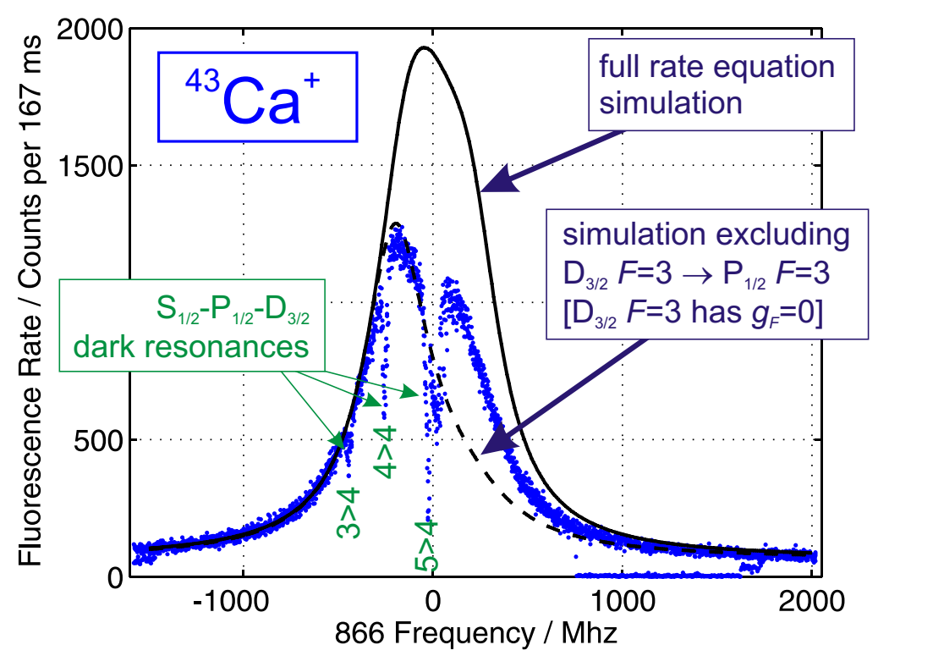




Simulations

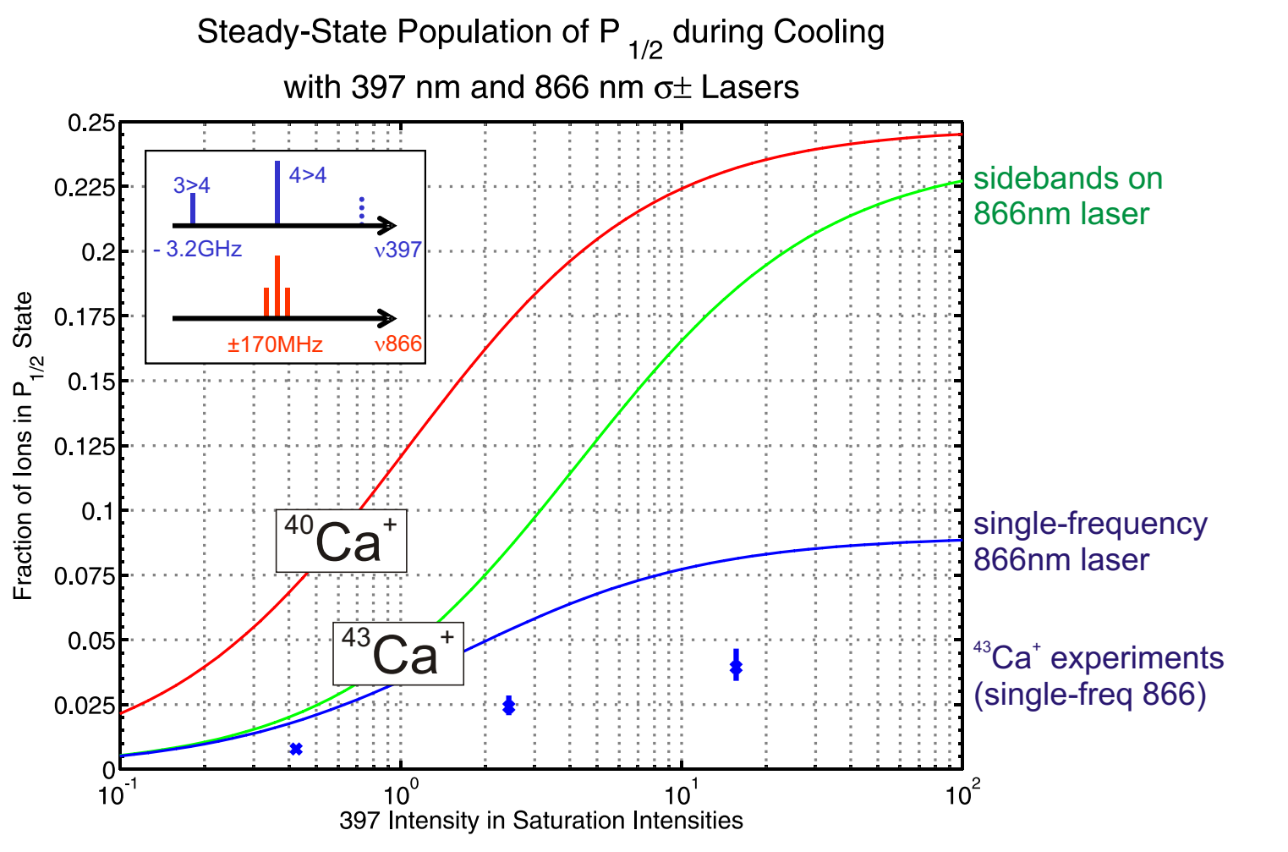
The energy levels of ^{43}Ca^{+}, and transitions between them, were simulated in MATLAB using a rate equations technique. The model includes the 4S, 4P and 3D terms (144 levels), and all the (optical frequency) electric dipole transitions. For ^{40}Ca^{+} we find quantitative agreement with experiment using a full Bloch equation treatment (right) and intend to extend this calculation to ^{43}Ca^{+}.





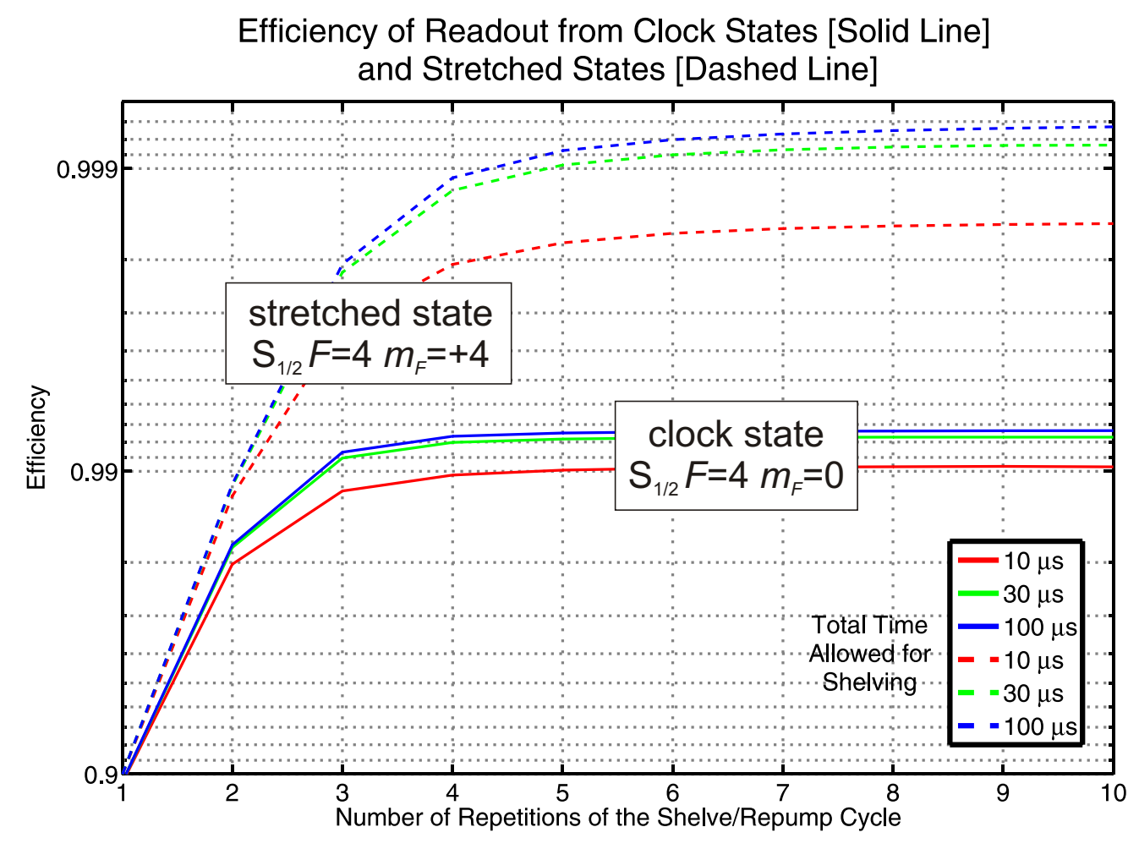
COOLING

- Doppler cooling with 397nm and 866nm lasers
- 3.2GHz sideband on 397nm laser repumps HFS
- 170MHz sidebands on 866nm laser improve fluorescence rate
- comparison with ^{40}Ca^{+} shows higher laser intensities are needed for given fluorescence
- low observed ^{43}Ca^{+} fluorescence may be due to optical pumping into dark states



PREPARATION

- prepare F=4, m_F=0 using π polarized 397nm beams tuned to F=3>4 and 4>4
- desired state is dark, but off-resonant F=4>3 transitions limit efficiency to 98.9%
- prepare F=4, m_F=+4 with σ+ polarized beams, efficiency only limited by σ+ purity

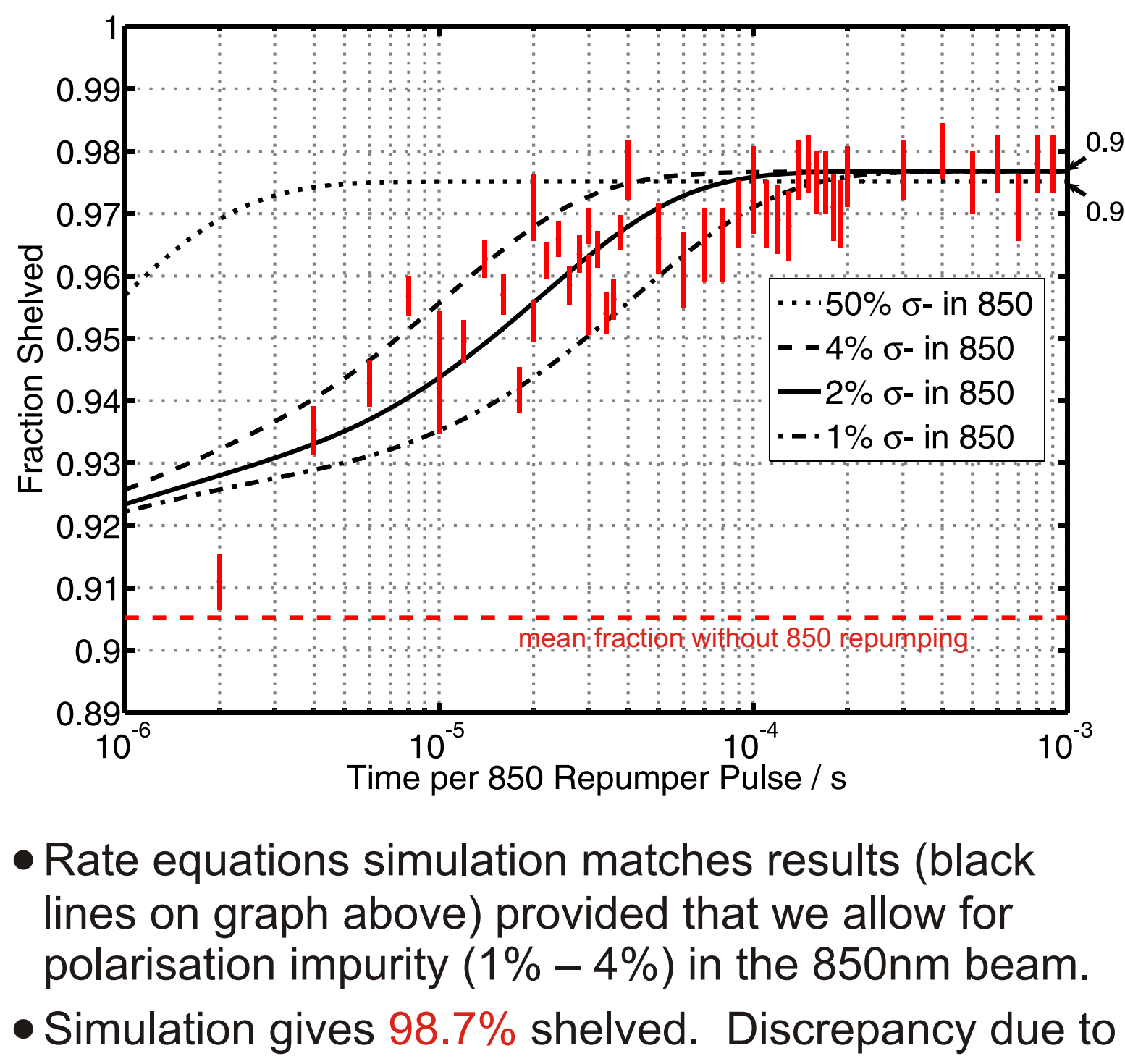


READOUT

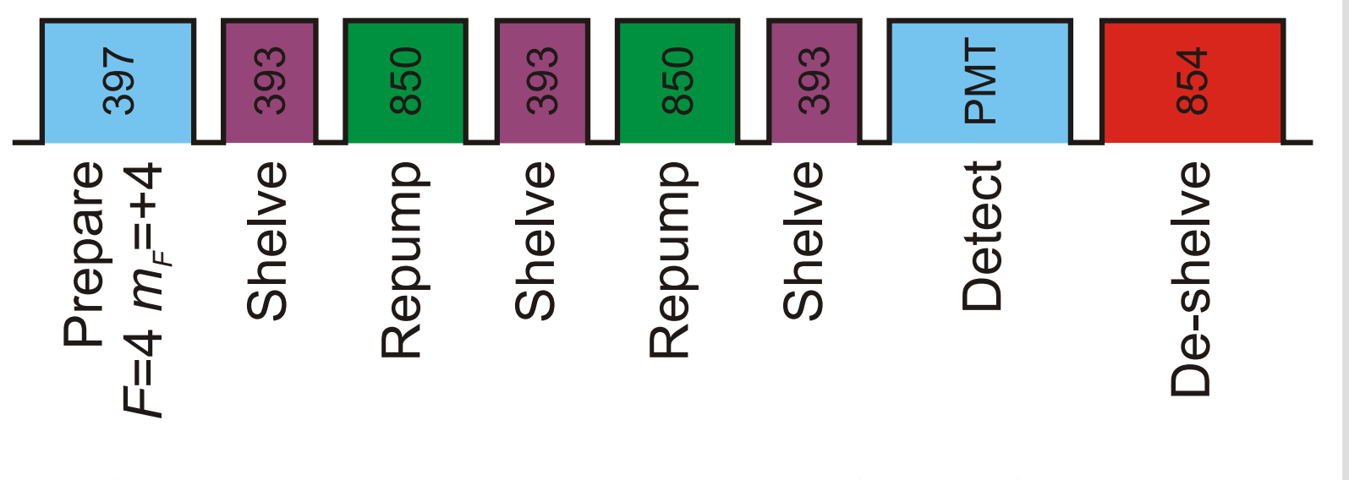
- read-out by transfer from $S_{1/2}$ F=4 states to $D_{5/2}$ "shelf" using 393nm and 850nm lasers
- 850nm σ and π beams repump population "lost" to $D_{3/2}$
- efficiency ε defined as: *P*(shelve F=4) – *P*(shelve F=3)
- repeating shelve/repump cycle gives ε>0.999 (m_F=+4 state) and ε>0.99 (m_F=0 state)

Readout

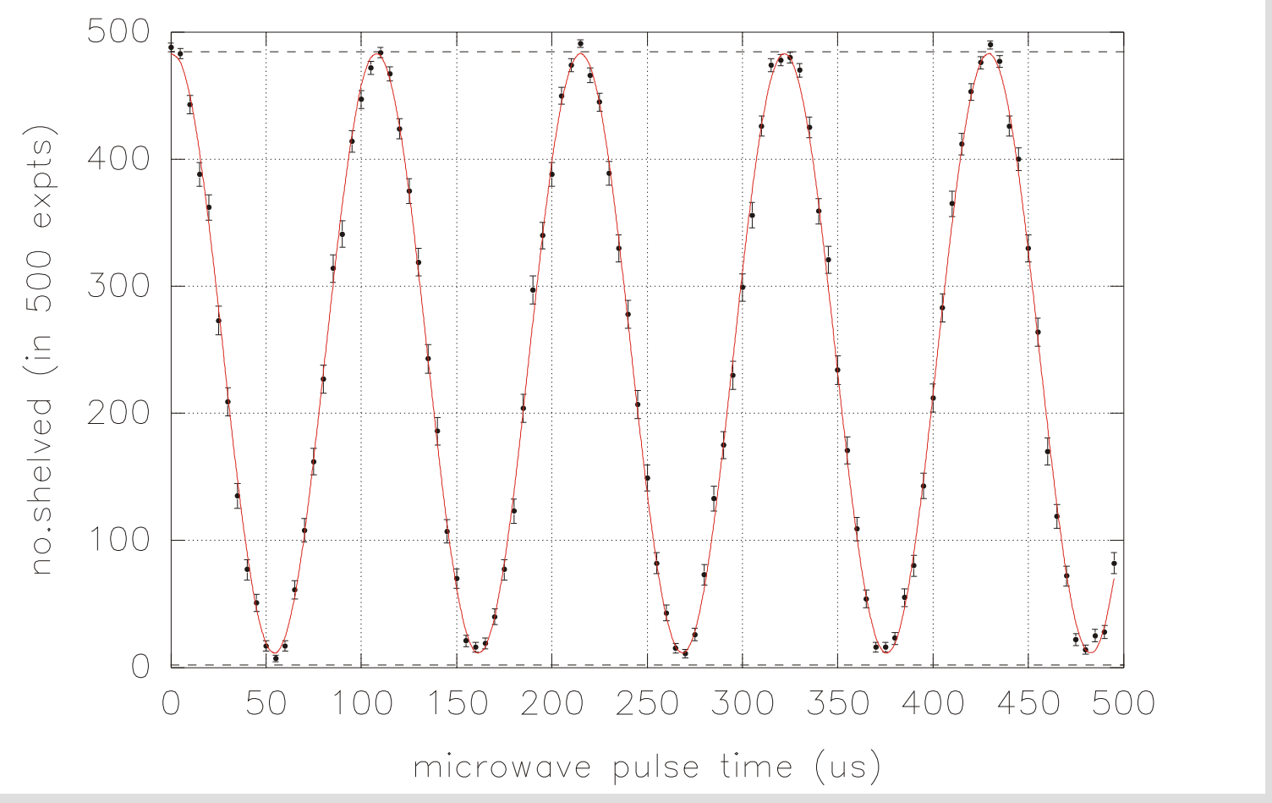
- For simulation of read-out transfer (please see simulation panel), separate σ+ and π 850nm beams were used. Otherwise ion could enter a $P_{3/2}$ *F*=4 state, and thence fall to the other qubit state ($S_{1/2}$ *F*=3) and fail to be shelved.
- Current experiment has no 850nm π access, so shelving was attempted with 850nm σ+ only.
- Pulse sequence shown was implemented with 100µs 393nm pulses, and variable-length 850nm pulses.
- *F*=4 m_F=+4 was shelved and detected with probability 0.977(2), *F*=3 shelved with probability 0.0037(5), implies 98.7(1)% average readout accuracy.

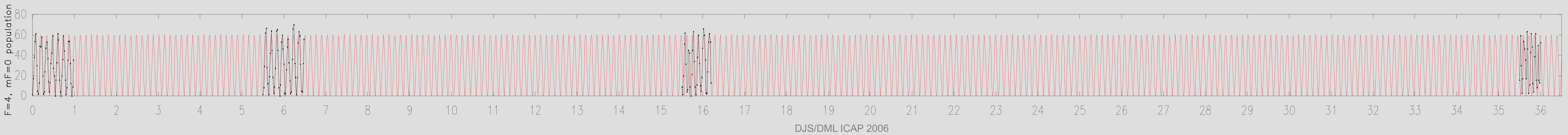


- Rate equations simulation matches results (black lines on graph above) provided that we allow for polarisation impurity (1% – 4%) in the 850nm beam.
- Simulation gives 98.7% shelved. Discrepancy due to ~0.5% probability of shelf decay during 3ms detection phase, and possibly state preparation only ~99.5% effective (simulation on graph takes this into account).
- Linearly polarised 850nm beam (equal σ+/σ-) predicted to give faster shelving for only a small decrease in efficiency (dotted curve).



- Graph below shows microwave flops of the *F*=4, m_F=+4 and *F*=3, m_F=+3 stretch state qubit, using readout sequence above.
- Readout levels 96.9(5)% from *F*=4, m_F=+4; 0.4(2)% from *F*=3.
- Fit: amplitude 94.4(6)% (97.8(8)% after scaling for readout), frequency 9339(6)Hz.





Rabi-flopping on field-independent ^{43}Ca^{+} qubit. (~270 flops)