Long-lived coherence in ^{43}Ca$^+$ and ^{40}Ca$^+$ trapped-ion qubits

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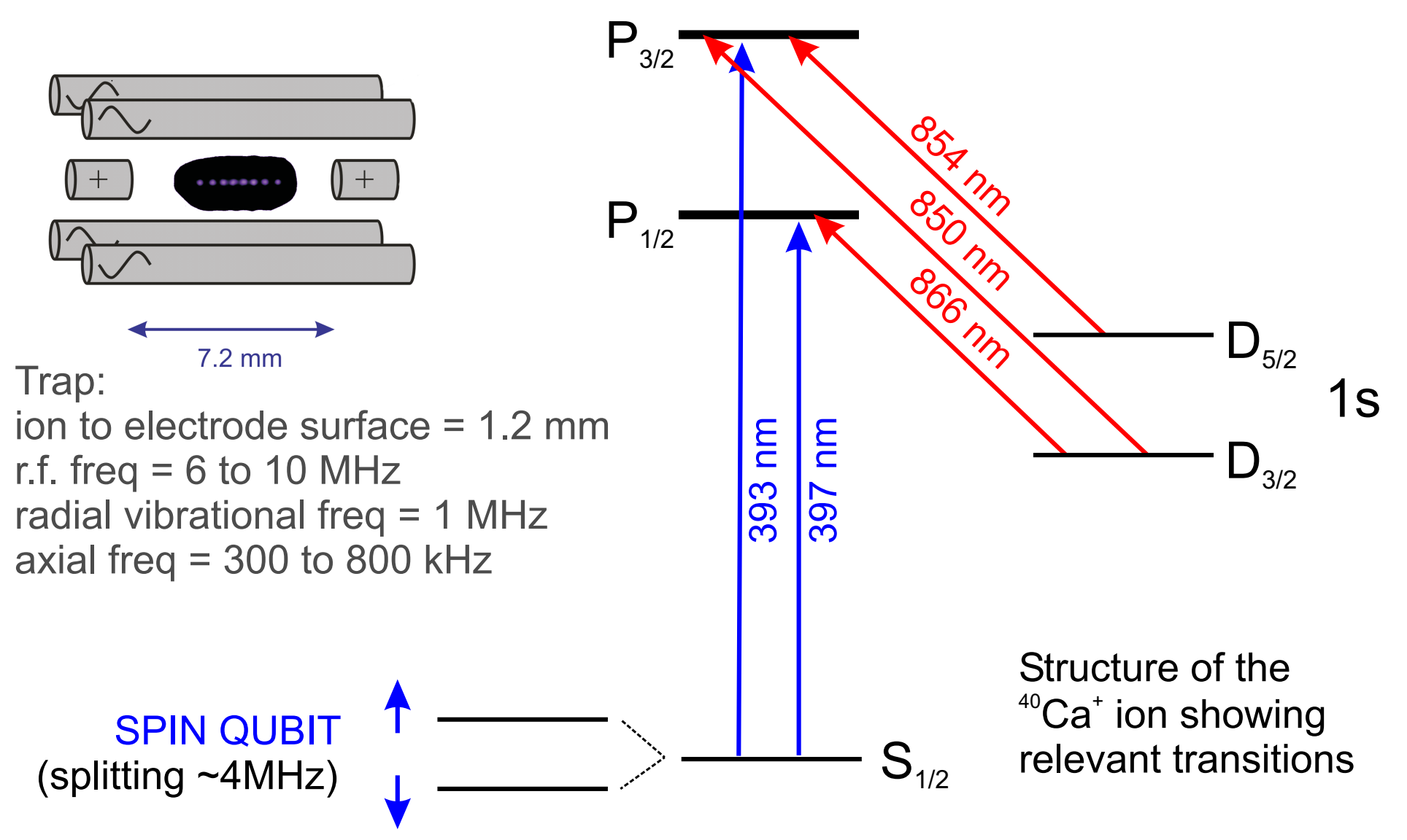
^{40}Ca$^+$ qubits

Long coherence times are essential for implementing quantum information processing. We use ^{40}Ca$^+$ spin-qubits to investigate the coherence of motional states (used in an ion trap for qubit-qubit coupling) and, below, we measure coherence times of ^{43}Ca+ hyperfine qubits.



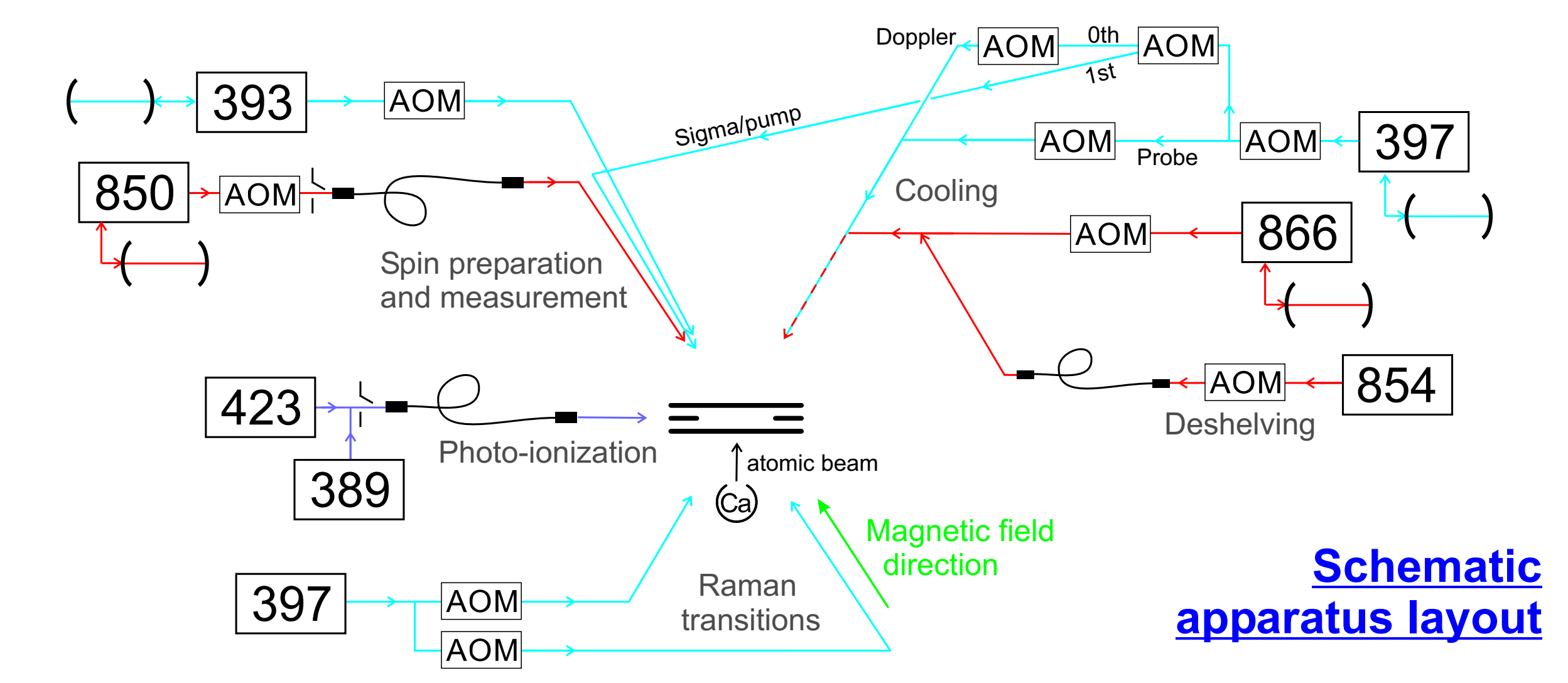
Trap:
ion to electrode surface = 1.2 mm
r.f. freq = 6 to 10 MHz
radial vibrational freq = 1 MHz
axial freq = 300 to 800 kHz

Structure of the ^{40}Ca$^+$ ion showing relevant transitions

Experimental studies:

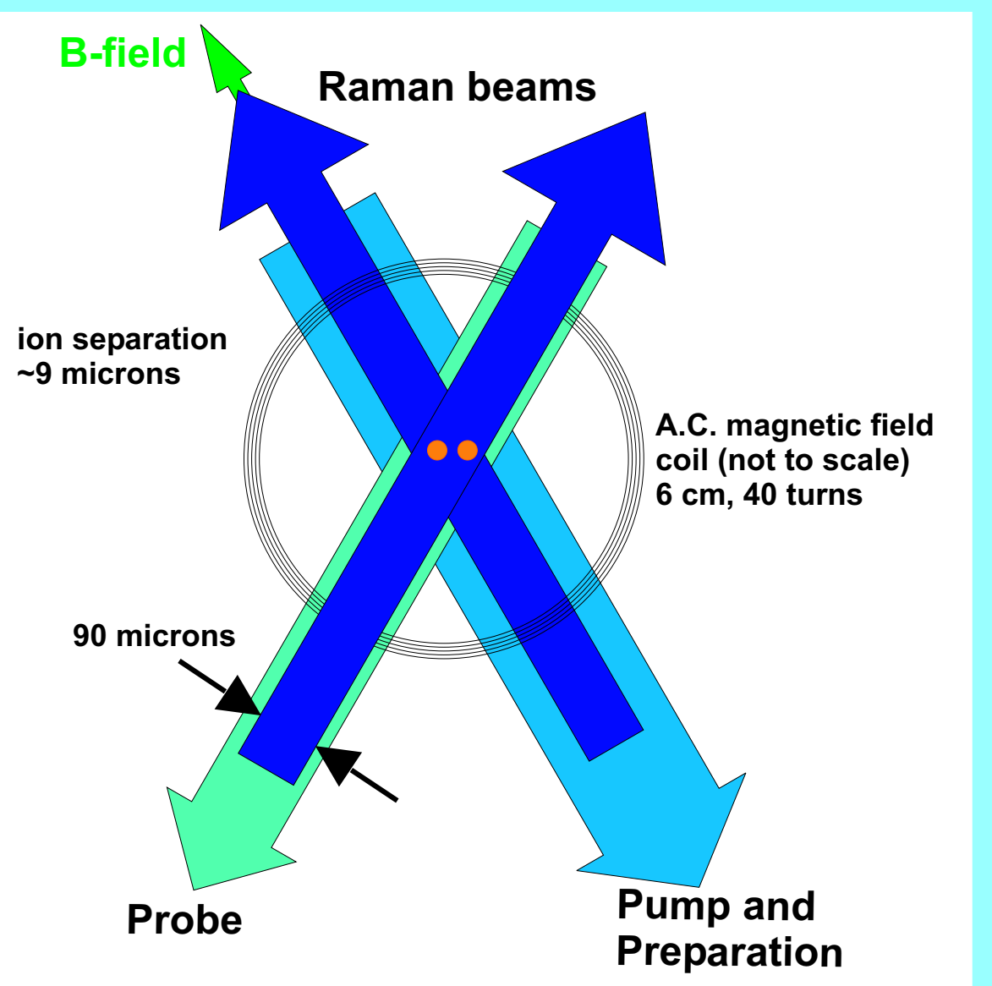
- cooling of a single ion to ground state in one dimension by three varieties of Raman sideband cooling, <n>=0.02
- cooling of both axial modes of an ion pair close to ground state
- motional heating rate <2 phonon/s (best), <10 phonon/s (typical)
- motional coherence time ~200ms (between n=0 and n=1 states)
- magnetic field independent qubit (^{43}Ca$^+$) coherence time 0.9(2)sec (compared with ~1ms for field-dependent states)

Experimental details



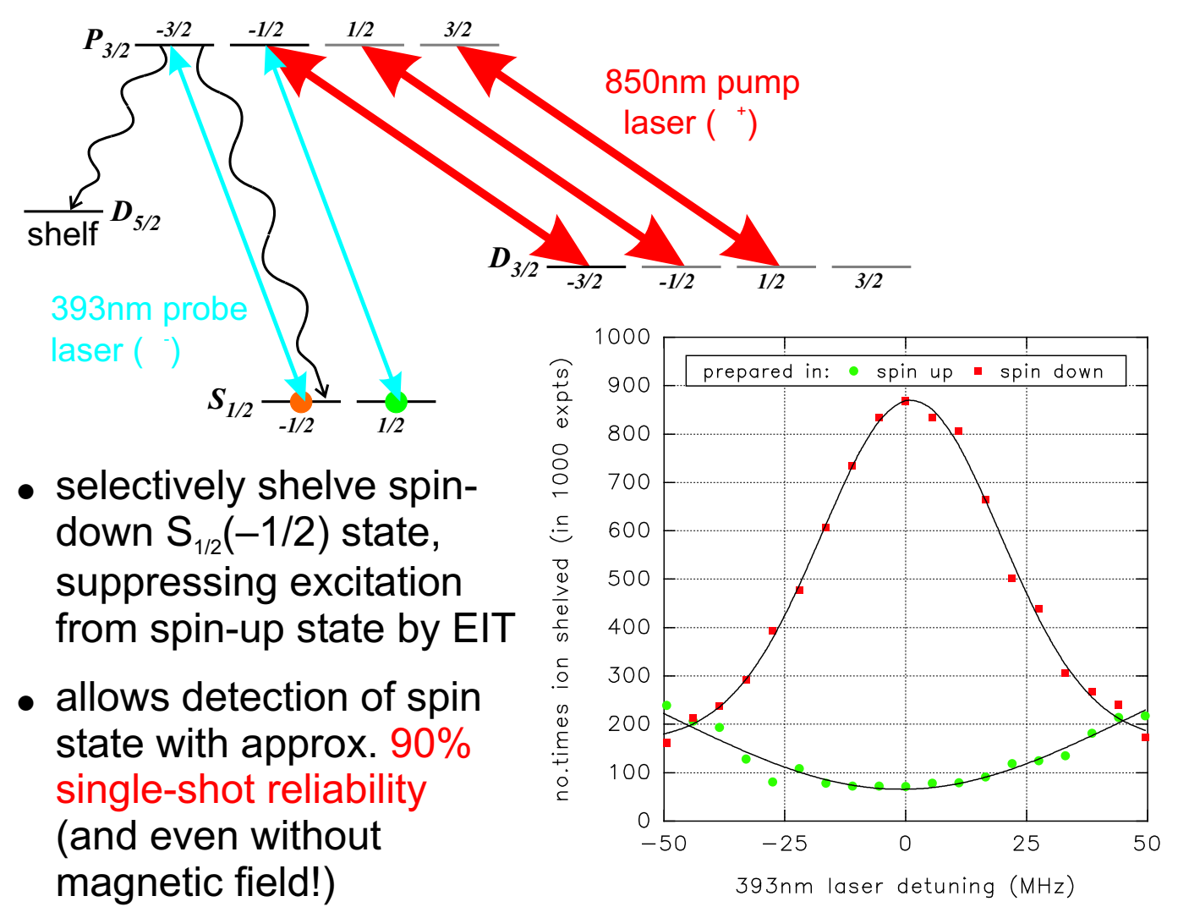
Schematic apparatus layout

Cooling and Logic Laser Beams



Qubit state readout method

M.J.McDonnell *et al*., Phys.Rev.Lett. **93**, 153601 (2004).



- selectively shelve spin-down $S_{1/2}$(–1/2) state, suppressing excitation from spin-up state by EIT
- allows detection of spin state with approx. 90% single-shot reliability (and even without magnetic field!)

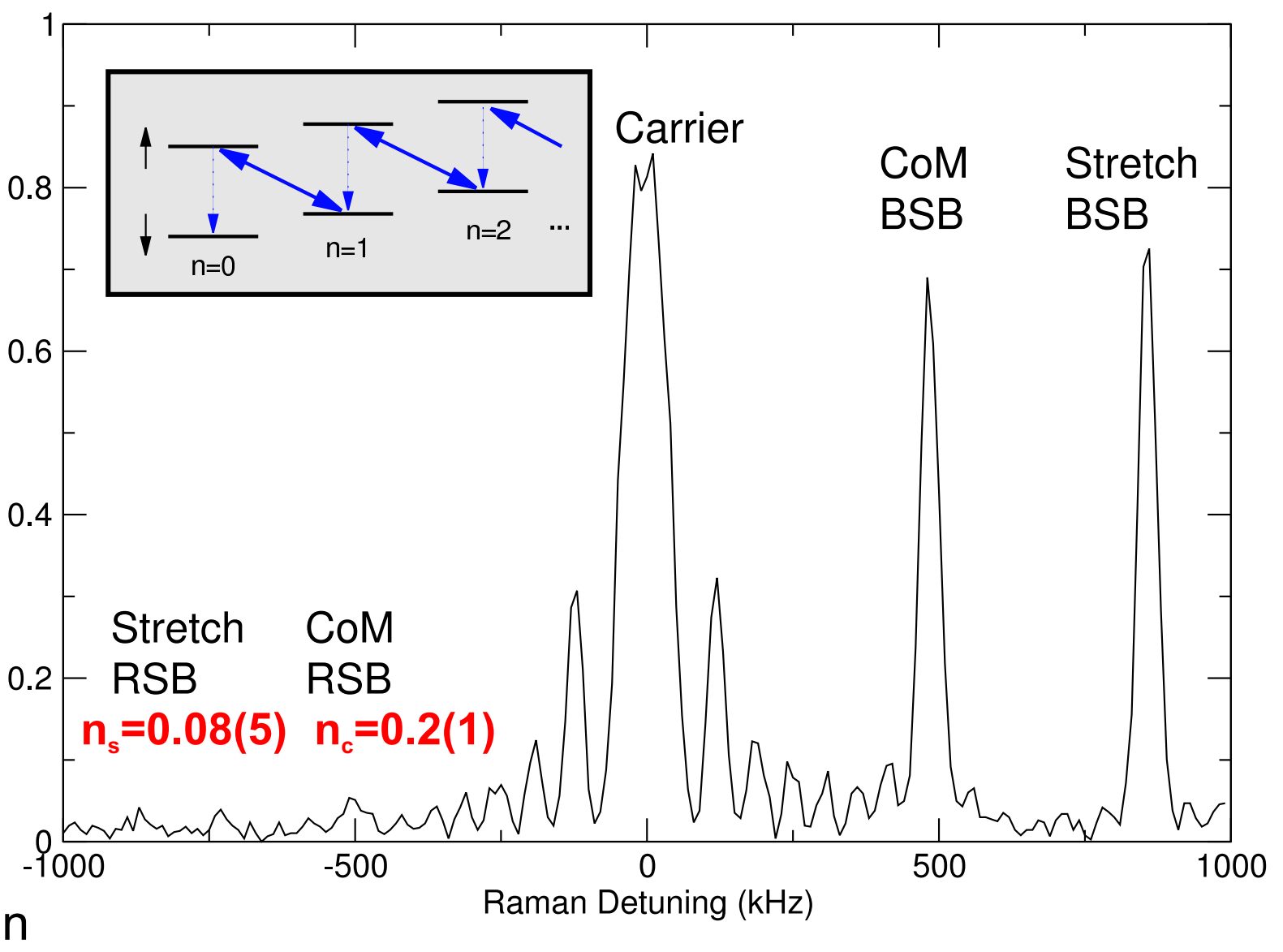
Ground state cooling

The motional state of the string of ions acts as an extra degree of freedom that can be used to couple the ions together coherently. In order to use the modes of vibration of the ion strings as a quantum “bus” the ions must be cooled to the ground state of the trapping potential. Cooling is performed in three stages:

- Doppler cooling 500 K
- Continuous Raman sideband cooling <n> 1
- Pulsed Raman sideband cooling <n> 0

The final ion temperature can be obtained from the ratio of the red sideband (RSB) height to the blue sideband (BSB) height for a given mode of vibration.

For a single ion, we achieve <n>=0.02(1), in an 820kHz trap, giving T=10 K.



Two-ion Raman spectrum

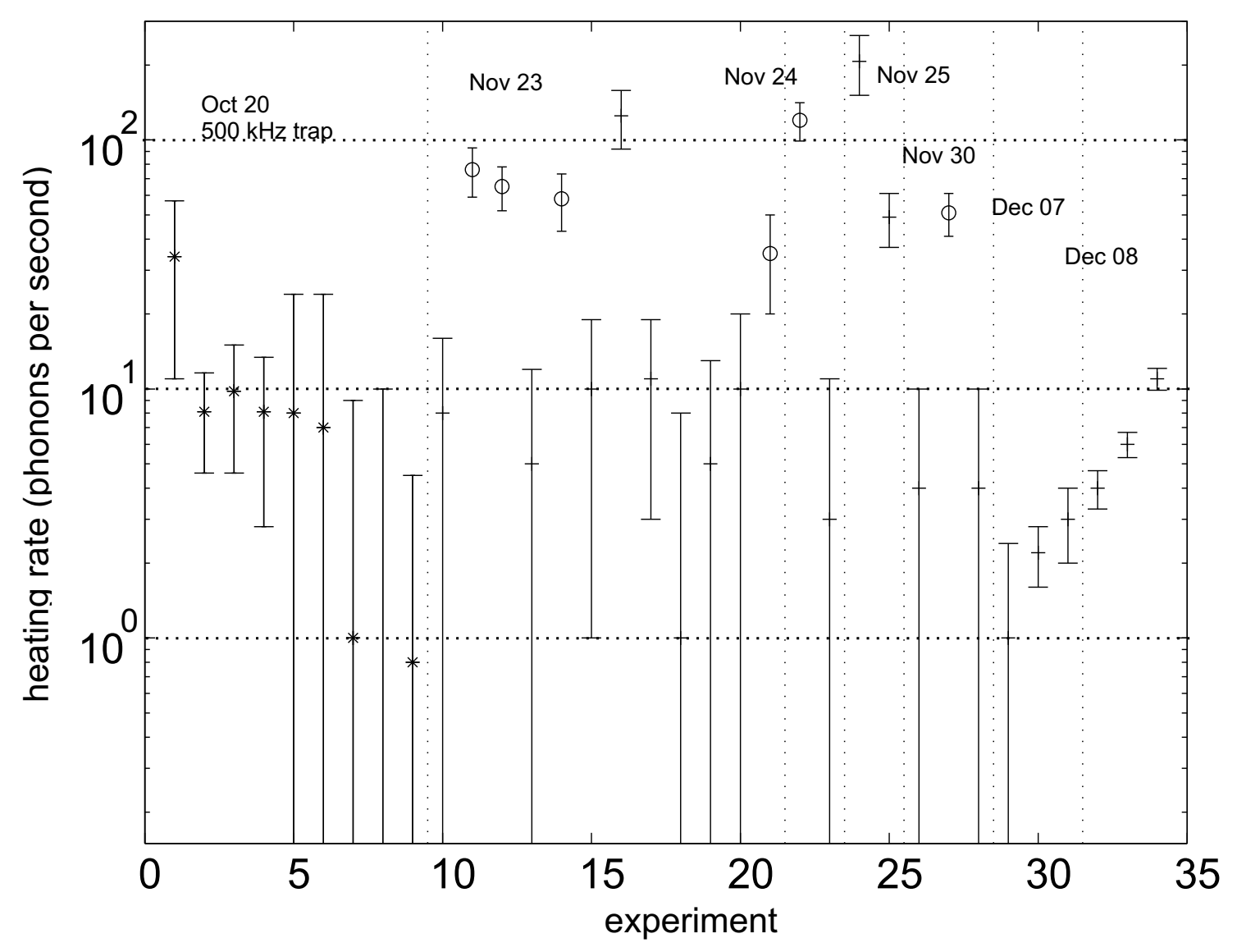
0.2ms Doppler cooling
6ms continuous Raman
2x20 cycles pulsed Raman

Long-lived motional coherence

Single-ion heating rate measurements

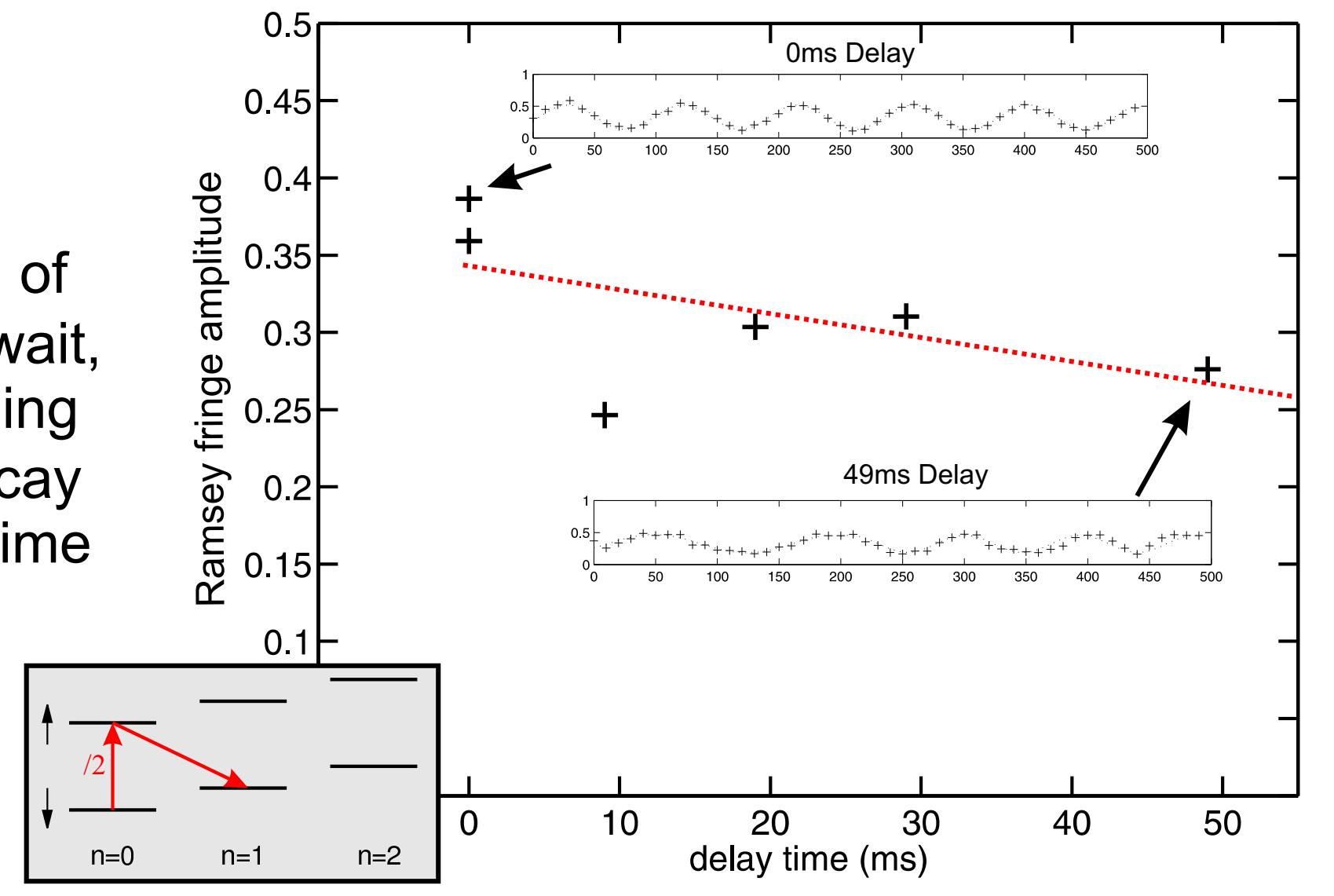
Method: cool to the ground state, wait 10-50ms, measure temperature by sideband strengths.
Circled points: with weak laser heating

Results: <2 phonon/sec (best)
<10 phonon/sec (typical)
(but occasionally anomalously high!)



Motional decoherence

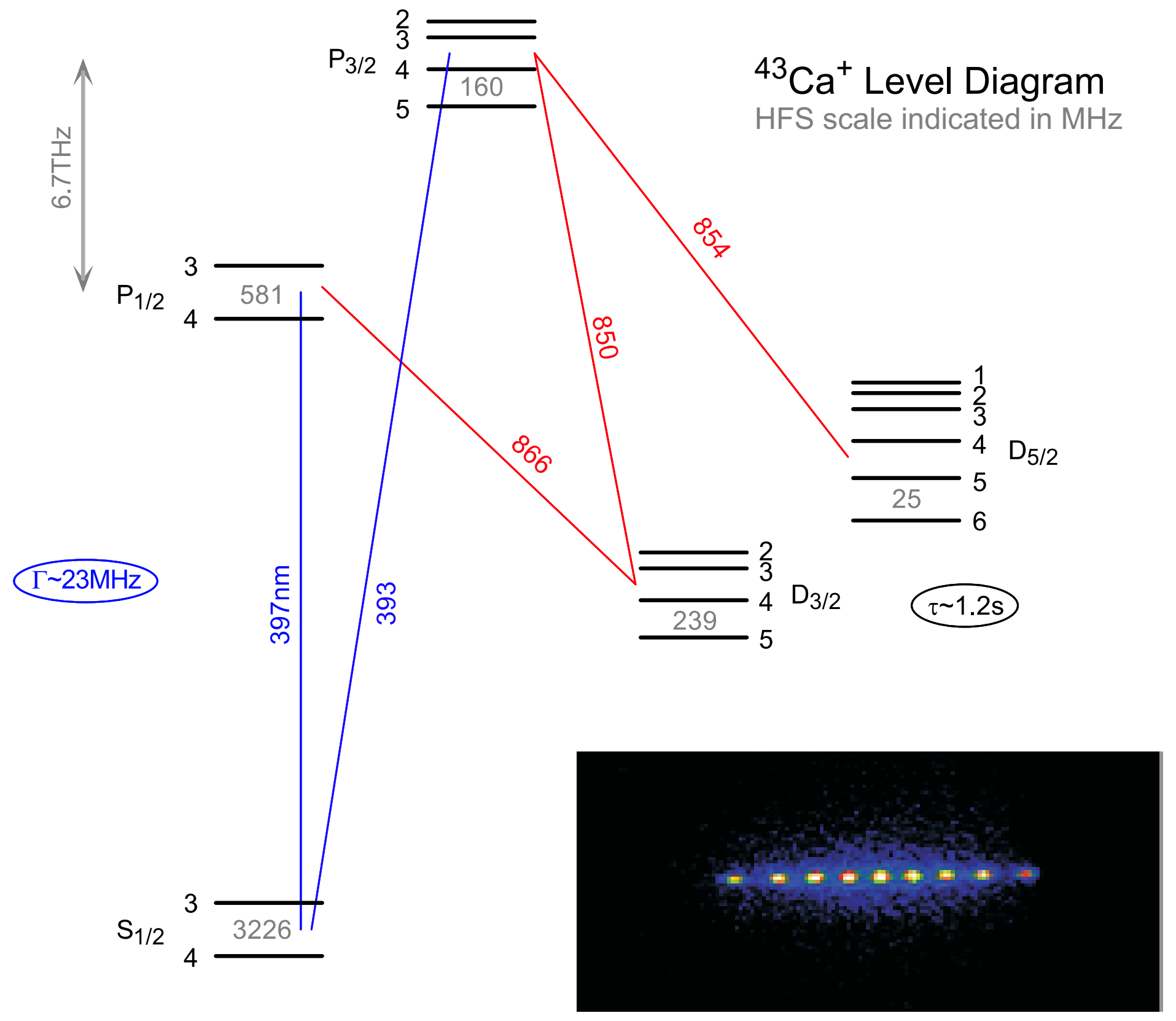
A “Ramsey” experiment on the *motional* state:
carrier /2, RSB superposition of (,n=0)+(,n=1) vibrational levels, wait, undo the superposition while scanning the phase of the final /2 pulse. Decay of fringe contrast gives coherence time of ~200ms.



^{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

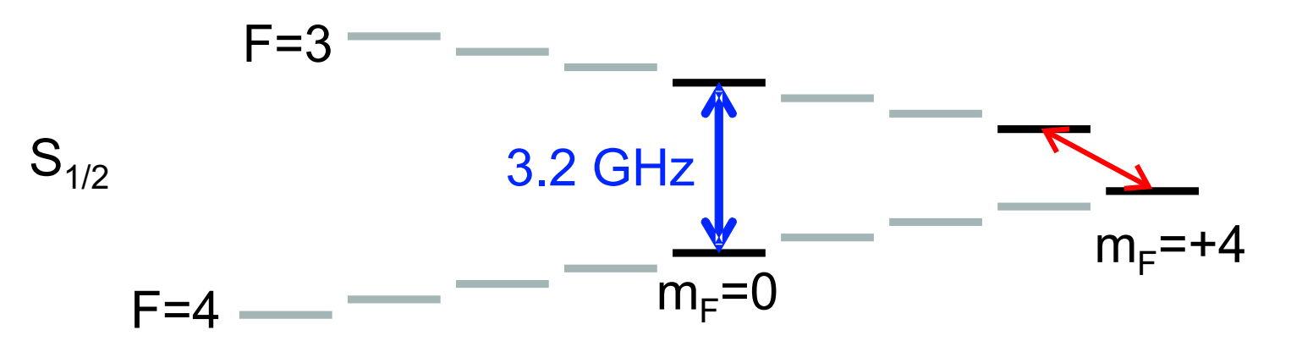


Above: Pure crystals of ^{43}Ca$^+$ can be loaded from a natural abundance (0.14%) source by isotope-selective photo-ionization

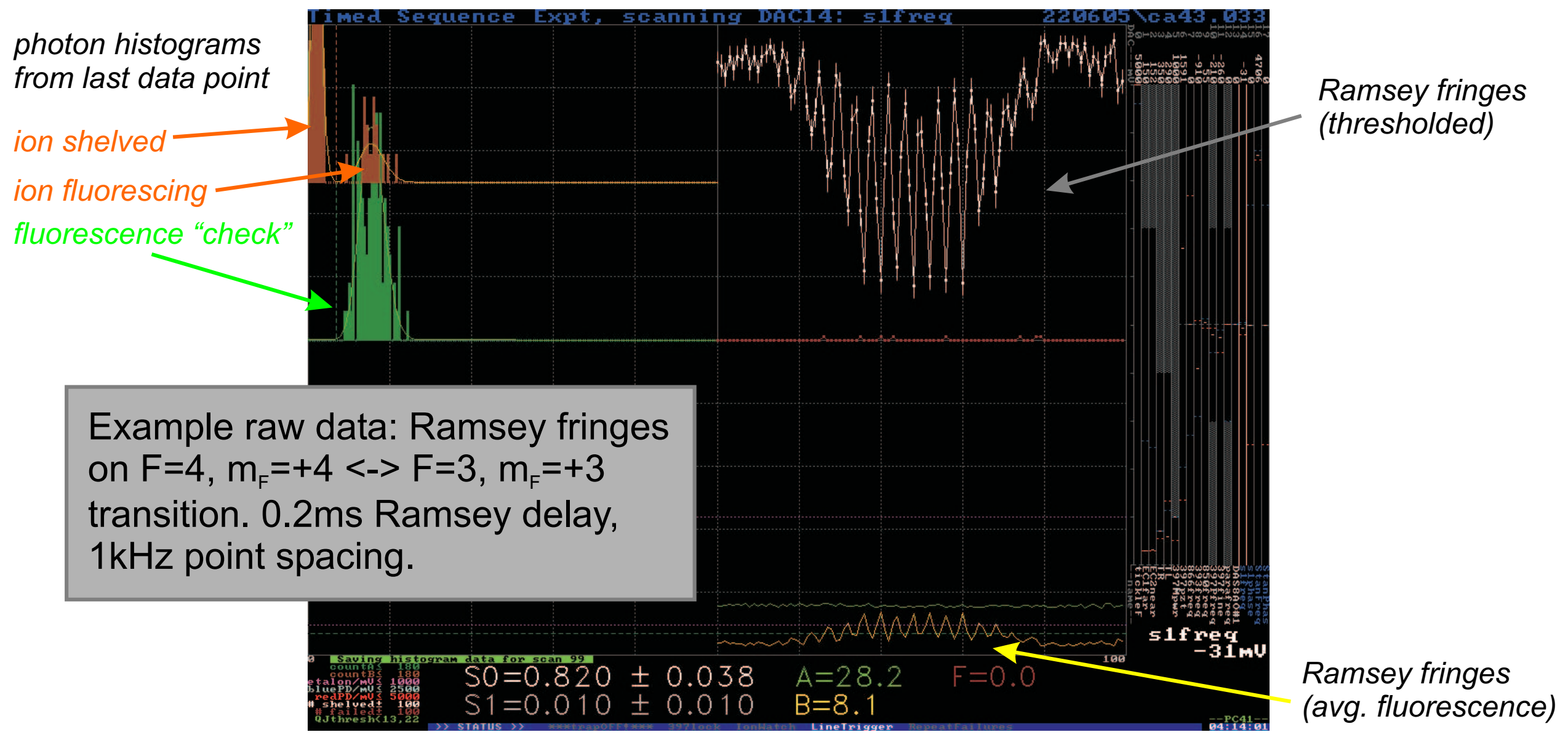
Experimental details

Same apparatus as ^{40}Ca$^+$, above, but:

- one of “Raman” laser beams used as hyperfine repumper on 397nm F=3>4 transition
- can prepare F=4, m_F=+4 qubit state with ~100% efficiency, by optical pumping with + polarized 397nm beams
- can prepare F=3, m_F=0 field-independent qubit state with only ~15% efficiency, by switching off 397nm F=3>4 beam (no polarized beam available)
- shelving readout with ~95% efficiency, by single pulse of 393nm laser on F=4>5 (no 850nm laser needed)
- 3.2GHz microwaves used for coherent state manipulation



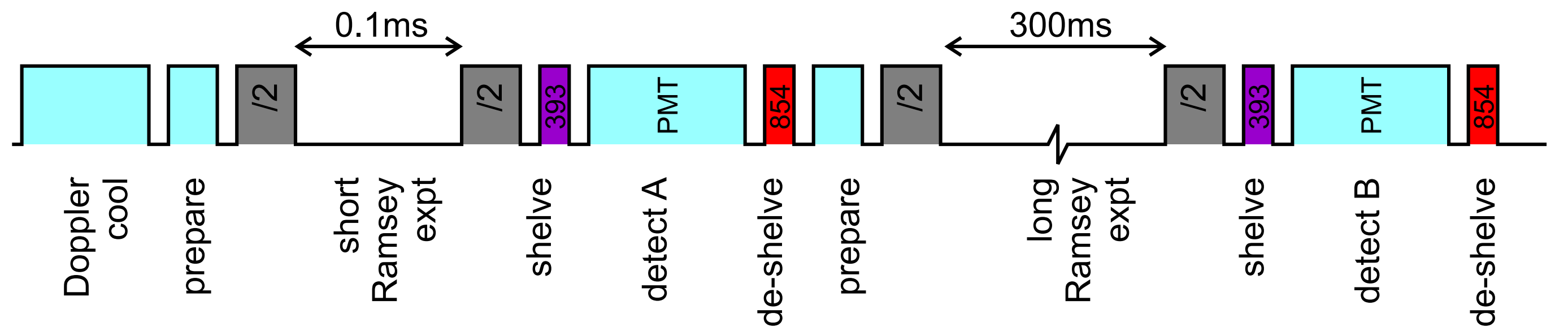
Qubit transitions studied:
field-independent m_F=0>0
field-dependent m_F=+4>+3

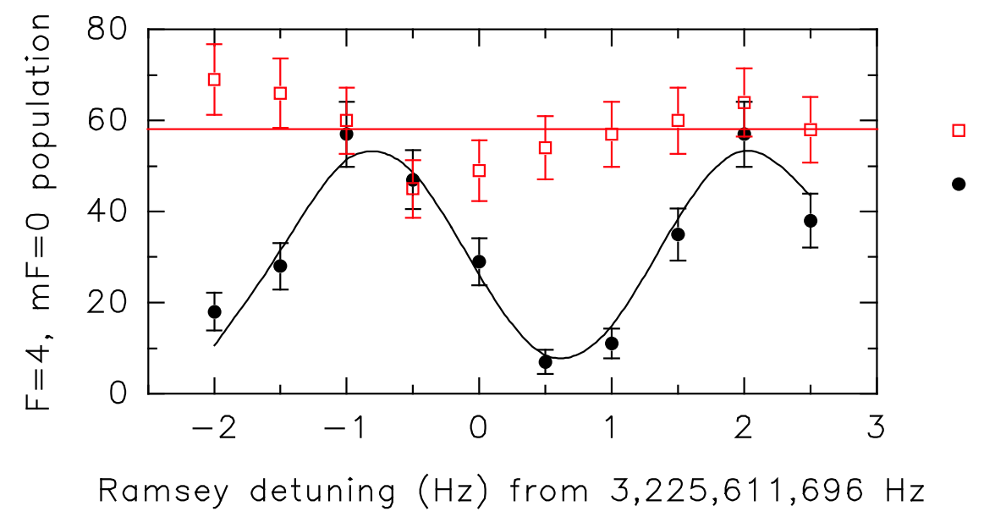


Example raw data: Ramsey fringes on F=4, m_F=+4 <-> F=3, m_F=+3 transition. 0.2ms Ramsey delay, 1kHz point spacing.

Long-lived internal coherence

We can observe many (~270) Rabi flops on the m_F=0>0 field-independent transition, lasting >30ms (see plot at bottom of poster). However, this time-scale may be limited by microwave power stability, so we perform a Ramsey experiment to measure the qubit coherence time. 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 pulse.



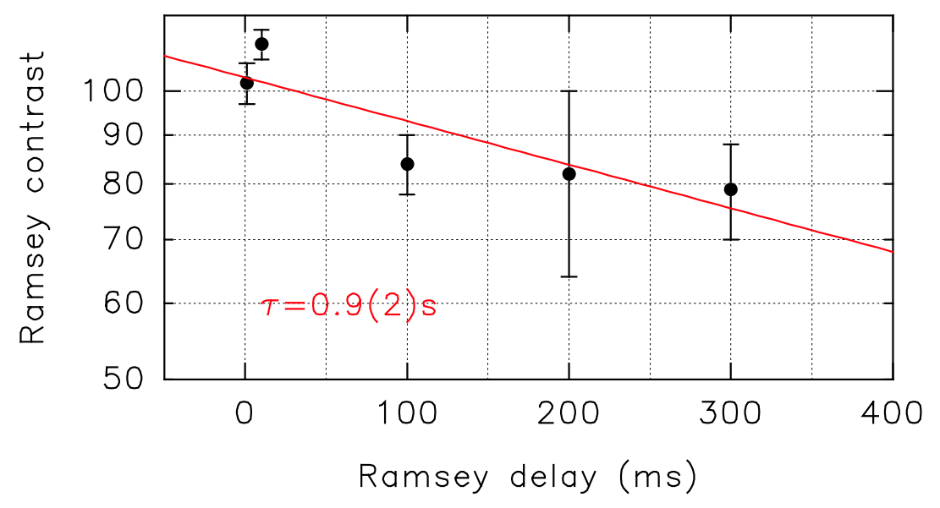


- ▫ 0.1ms Ramsey expt (control)
- ● 300ms Ramsey expt

Ramsey experiments on field-independent qubit

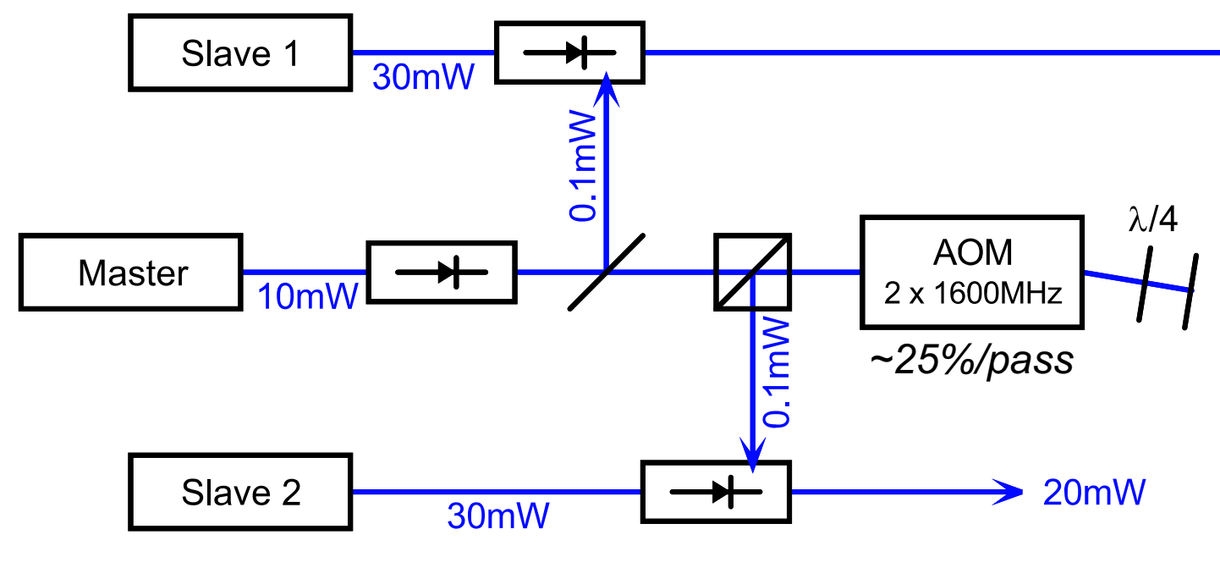
Varying the long Ramsey delay (right), we find an internal state coherence time of T_2=0.9(2)sec.

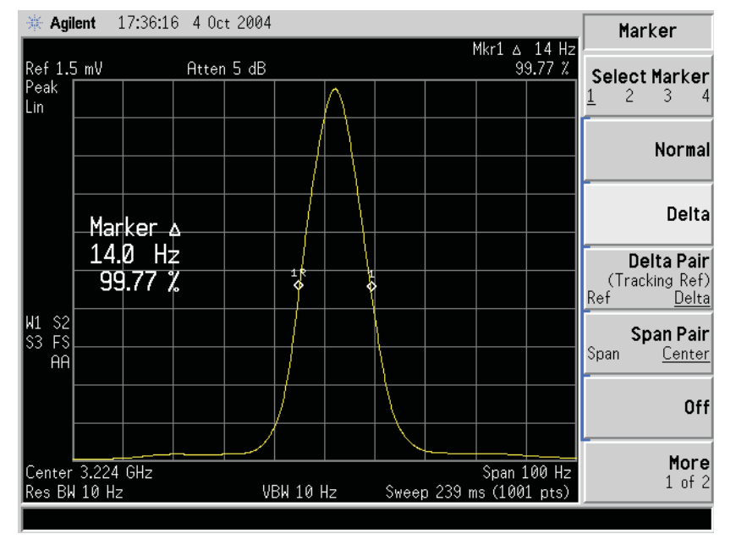
At working field of 1.7G, residual field-sensitivity is ~4Hz/mG. The reduction in fringe contrast is consistent with field drifts at the level of 0.1mG/hr.



Next steps

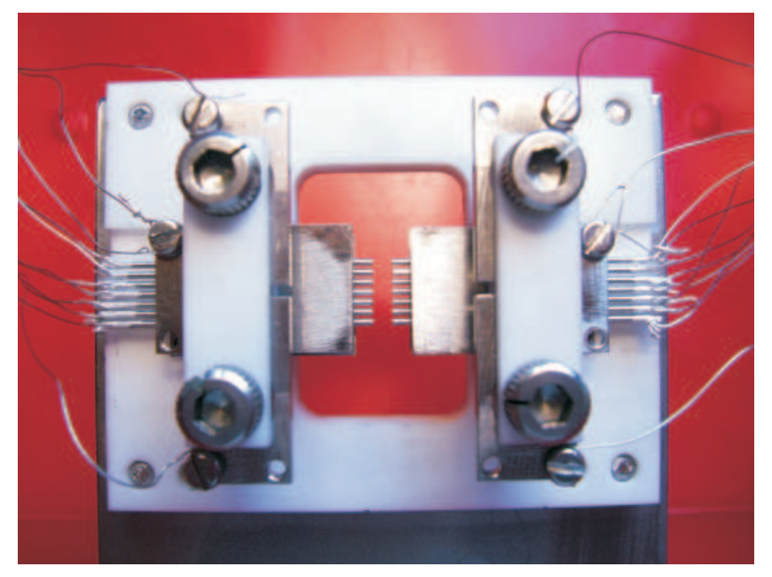
- try using intermediate-field states, where we can work at field-independent point (sensitivity=1200Hz/G^2) [*cf* Langer *et al.*, PRL **95** 060502 (2005)]
- manipulate qubit states using 3.2GHz Raman laser instead of microwaves (allows faster transitions and manipulation of motional states as in ^{40}Ca$^+$ expts)



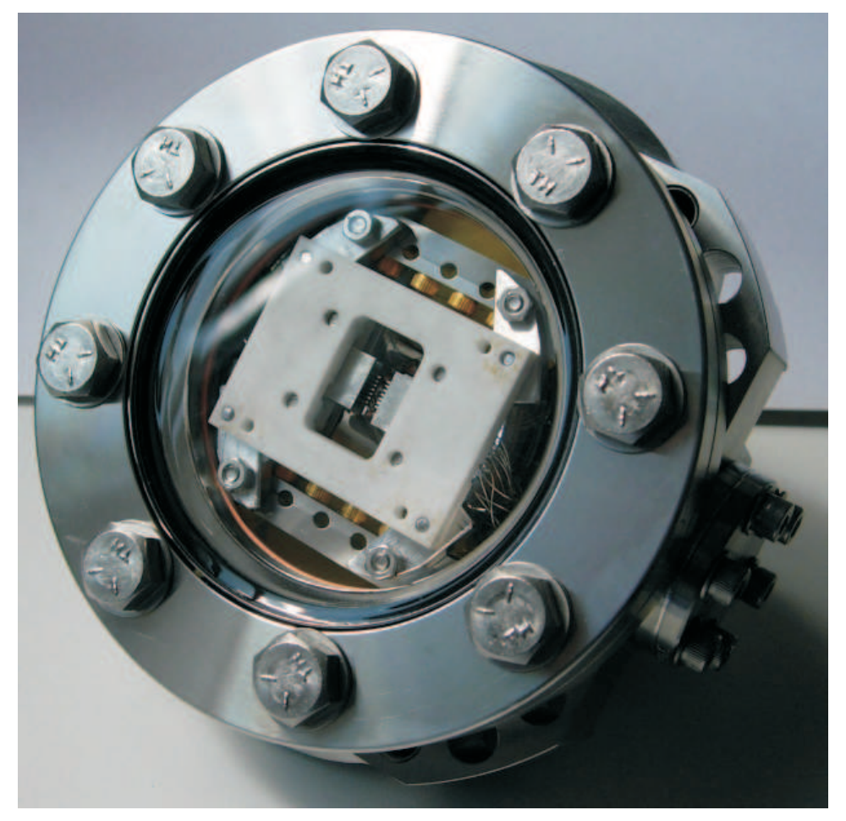


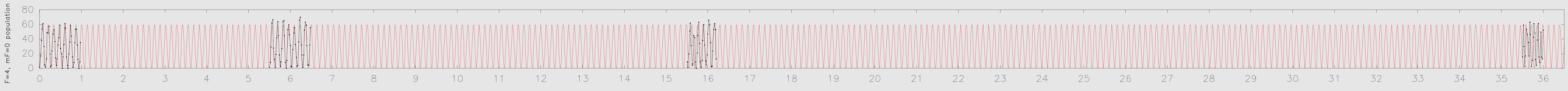
Violet diode laser system for Raman beams, and beat signal between slave beams: fwhm 14Hz (instrument-limited) at 3.2GHz

- use 6-zone multiple trap to shuttle ions between different trapping regions, to allow individual addressing of ions



6-zone trap (built by U.of Liverpool) installed in new vacuum chamber. Ion-electrode distance = 0.7mm, trap-trap separation = 0.8mm.





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