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Single-qubit memory error metrology at short timescales

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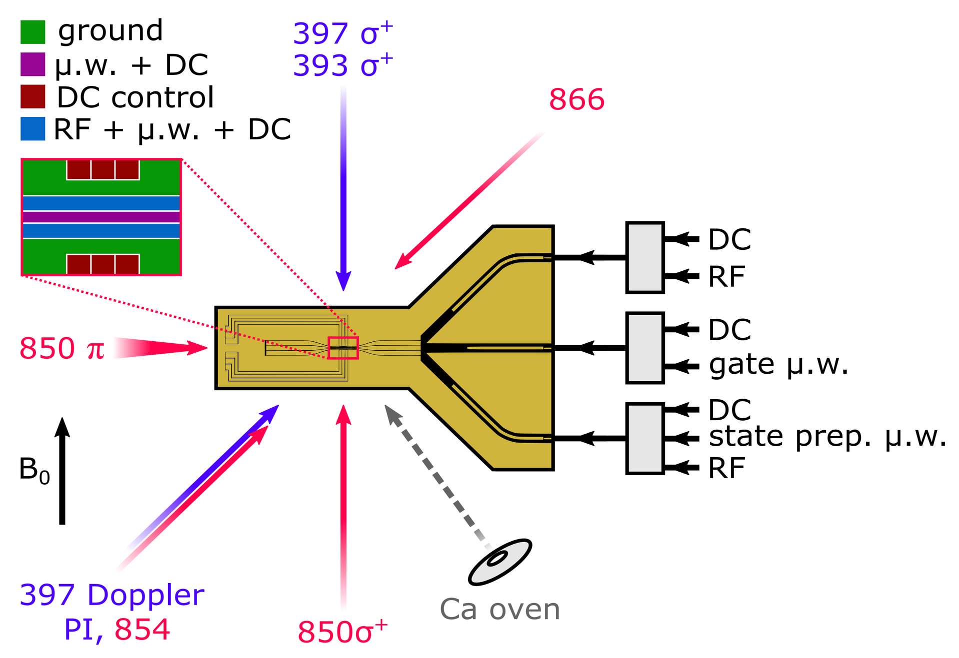
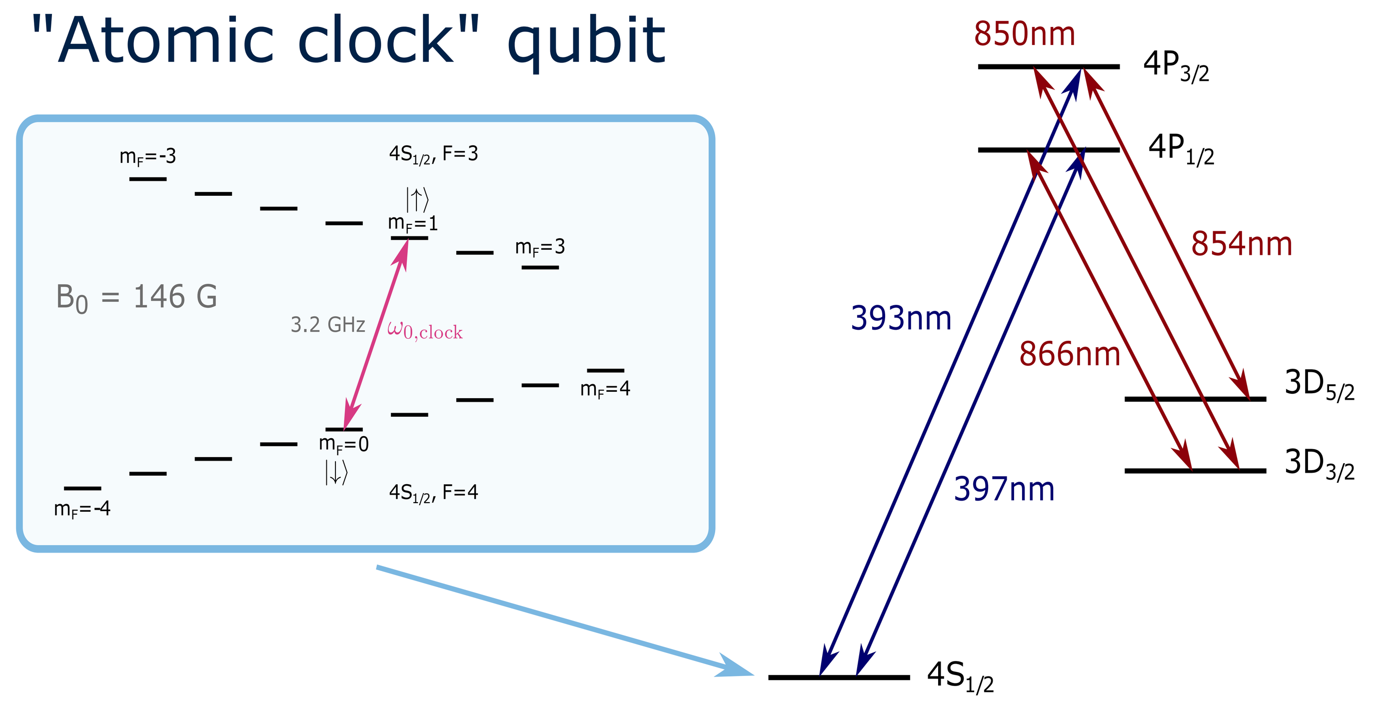
We achieve a coherence time of 1 minute in a $^{43}Ca^{+}$ qubit, but the relevant timescale for fault-tolerant quantum computing is the time for which the memory error remains < 10^{-2} – 10^{-4}. Information regarding these initial stages of decoherence is usually provided by extrapolation of models only verified at long timescales. Here we use randomised benchmarking techniques to directly measure errors at the 10^{-6} level and to characterise the underlying noise spectrum. We find ε_{memory} < 10^{-4} up to ~ 100 ms (far longer than predicted from the T2* time). Using a simple CPMG dynamical decoupling sequence, we observe ε_{memory} < 10^{-3} for storage times greater than 1 s. At this level, we conclude that our memory performance is primarily limited by microwave local oscillator noise.

Trap



- Surface (chip) rf trap featuring integrated microwave circuitry [1]
- Gates driven by near-field microwaves
- Heating rate 1.4(3) quanta/ms, axial secular frequency 2π × 500 kHz

"Atomic clock" qubit

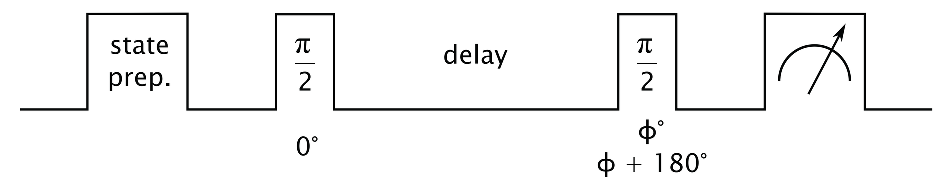


- $^{43}Ca^{+}$ hyperfine ground state clock qubit at 146 G
- Initialisation: optical pumping and microwave transfer pulses ~ 3.2 GHz
- Readout: "shelve" $|\uparrow\rangle \rightarrow 3D_{5/2}$ via $4P_{3/2}$, + fluorescence detection

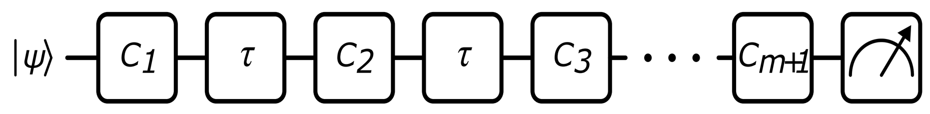
ref [2], [3]	SPAM	Single-qubit gate	Two-qubit gate
Error	**~10^{-3}**	**~10^{-6}**	**~10^{-3}**

Measuring short-timescale decoherence

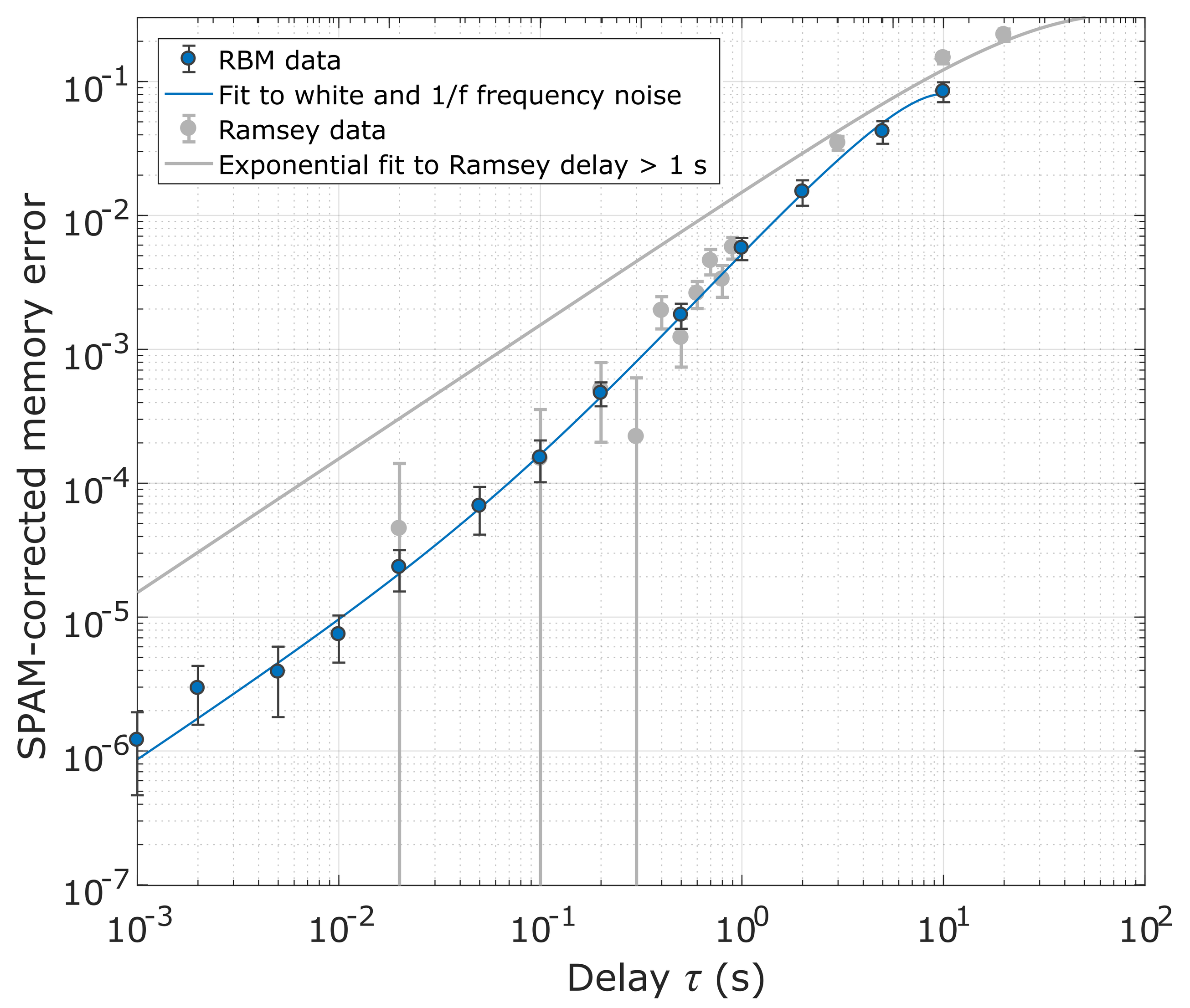
- "Memory error" over a time delay is often measured using Ramsey experiments to extract a T2* time
- **We measure T2* ~ 1 minute**



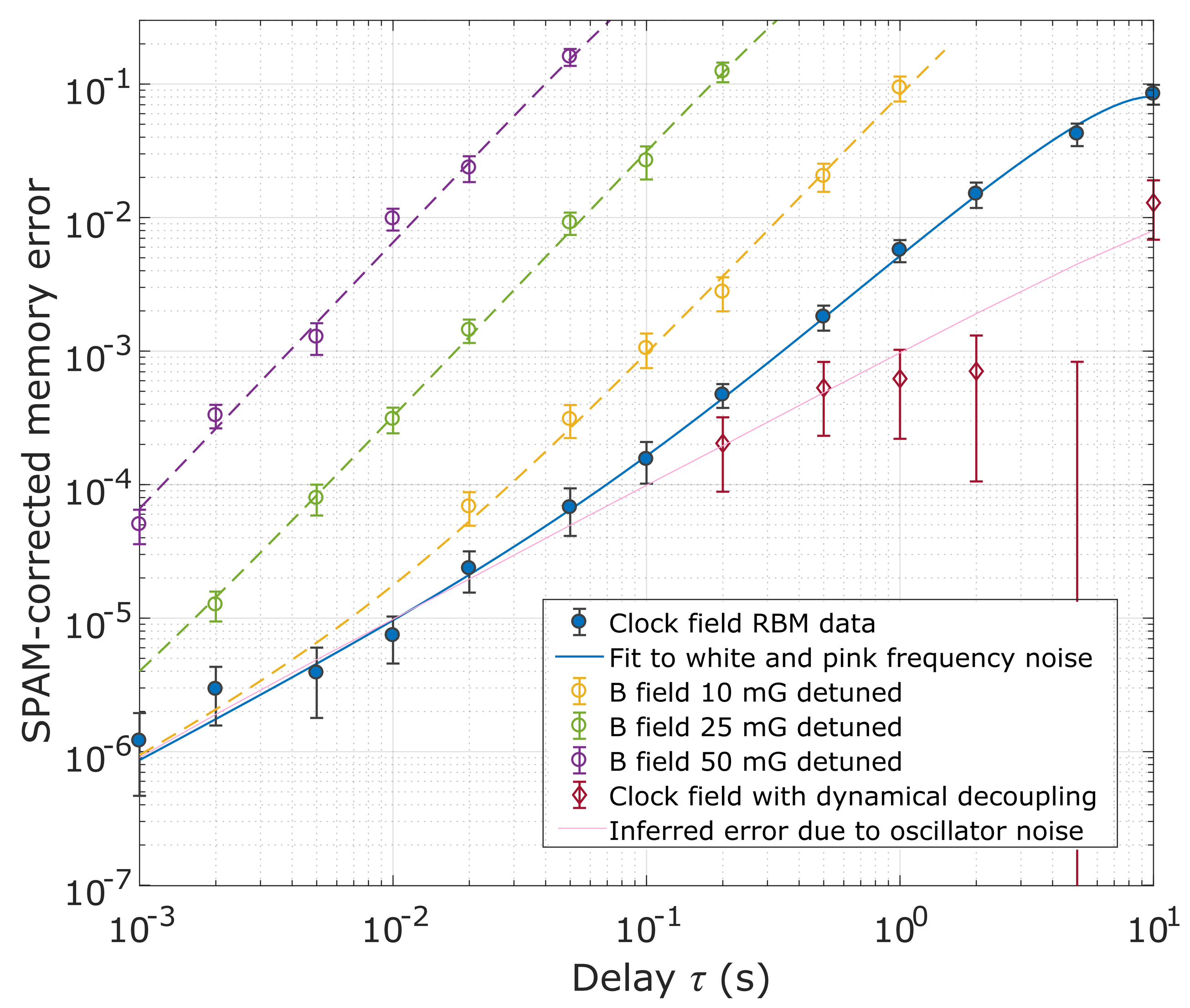
- At fault-tolerant threshold (~10^{-2} – 10^{-4}), ε_{memory} ~ ε_{SPAM} so measurement is inefficient
- Information about computationally relevant timescales is usually extrapolated from longer times
- Instead, we use **randomised benchmarking** [4], [5] to directly measure very small errors (~10^{-6})



Randomised benchmarking (RBM) results



- Ramsey experiments struggle when ε_{memory} ~ ε_{SPAM} (10^{-3})
- RBM allows probing of much smaller errors
- We measure **ε_{memory}< 10^{-4} up to ~100 ms** – at least 3 orders of magnitude longer than gate or measurement times
- **Extrapolating from data at T2*-like timescales overestimates memory errors at short timescales by an order of magnitude**



Detuning the field

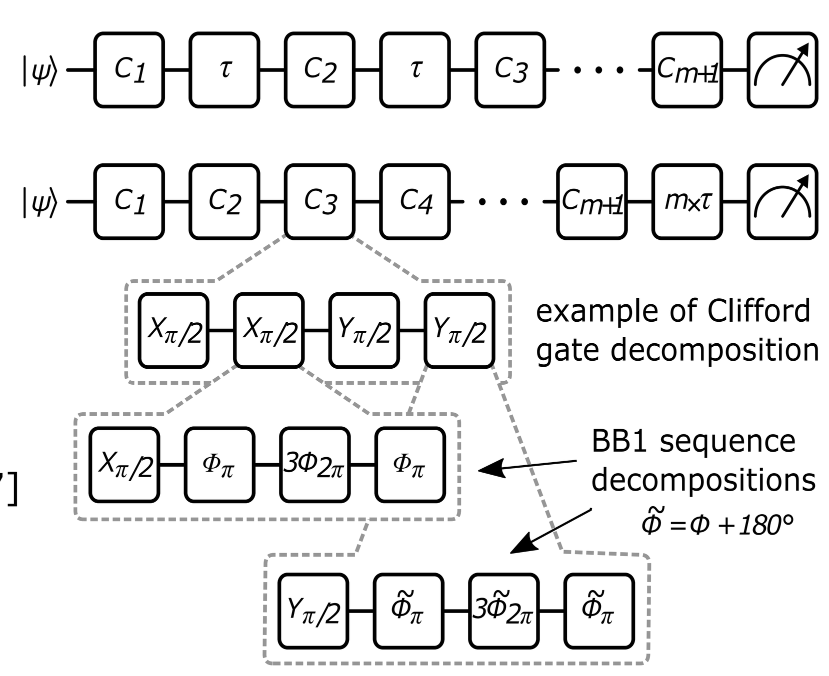
- Shuttling ions between regions of larger traps could improve scalability [6]
- During shuttling, an ion is likely to travel through areas of less well-controlled magnetic field strength
- We consider memory errors incurred by detuning the field from the clock field without adjusting the microwave frequency
- Qubit remains robust to memory errors over typical shuttling times at large detunings
- **ε_{memory} < 10^{-3} maintained for 20 ms even at 25 mG detuning**

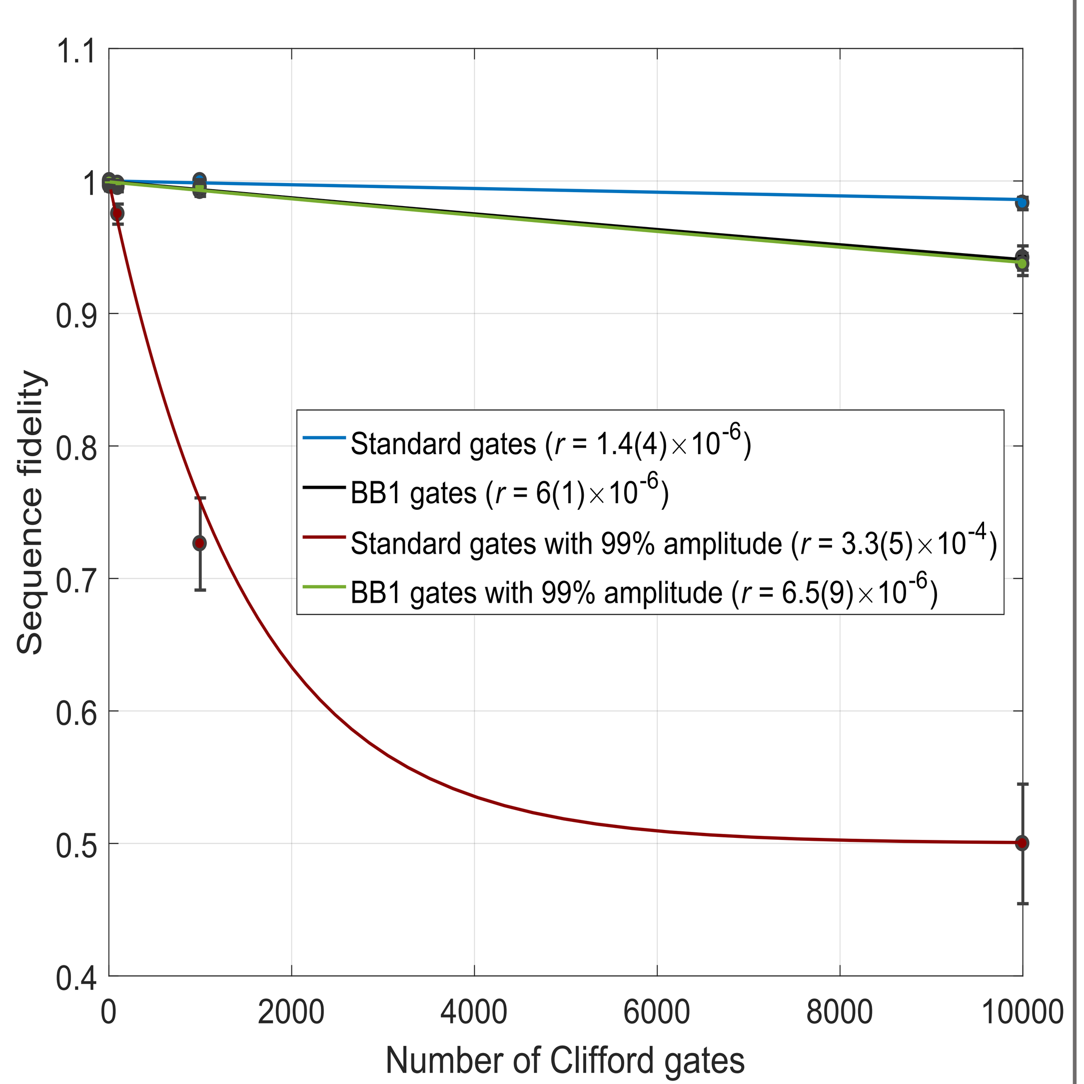
Dynamical decoupling

- Including a simple CPMG dynamical decoupling sequence of repeated X gates during the delay periods, at a rate of 1 per 100 ms, reduces **ε_{memory} to < 10^{-3} for longer than 1 s**
- **Memory performance at computationally relevant timescales is limited by microwave local oscillator noise (see below)**

RBM sequences and BB1 gates

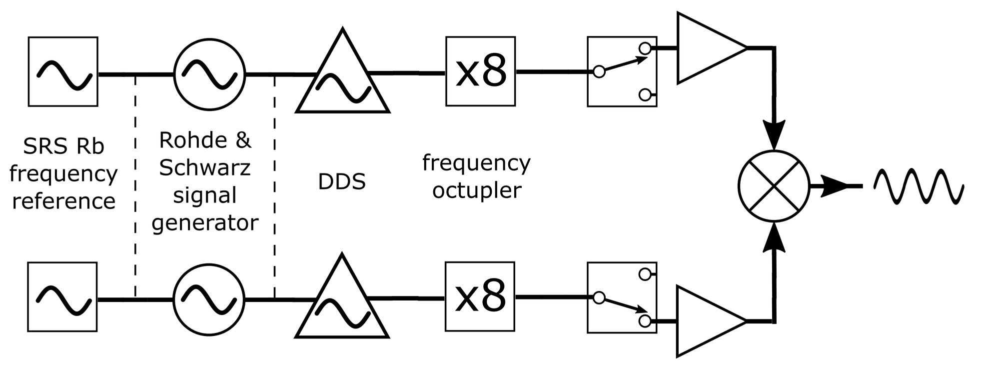
- RBM involves ***m* periods of dephasing** τ instead of a single one, and **interleaving** the delays with gates randomly sampled from the single-qubit Clifford group
- Memory error is enhanced and adds incoherently
- Error per delay can be calculated by **comparing the fidelity of interleaved sequences vs sequences without the interleaved delays**
  - Each Clifford is composed of $\pm X_{\pi/2}$, $\pm Y_{\pi/2}$ rotations
- Error per Clifford is very sensitive to drifts in microwave power - could limit accuracy of the RBM experiment
- Decomposing each $\pi/2$ rotation into a **BB1 composite pulse** [7] makes them more robust to these pulse area errors





Sources of decoherence

- **Memory data is well-approximated by a fit to a combination of white and 1/f frequency noise**
- CPMG sequence suppresses the 1/f component (possible candidate: varying AC Zeeman shifts due to movement of the ion in the trapping field)
- Noise on each component of microwave chain measured by duplicating chain and making any noise upstream of the component in question common mode (at dashed lines)



- **Direct measurement of noise on Rb reference oscillator agrees closely with white noise component of fit to RBM data**

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[3] T. P. Harty et. al., Phys. Rev. Lett. 117, 140501 (2016)
[4] E. Magesan et. al., Phys. Rev. Lett. 109, 080505 (2012)
[5] P. J. J. O'Malley et. al., Phys. Rev. Applied 3, 044009 (2015)
[6] D. Kielpinski et. al., Nature 417, 709711 (2002)
[7] S. Wimperis, J. Mag. Res. 109, 221231 (1994)

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