Ultrafast Control of Spin and Motion of Trapped Atomic Qubits

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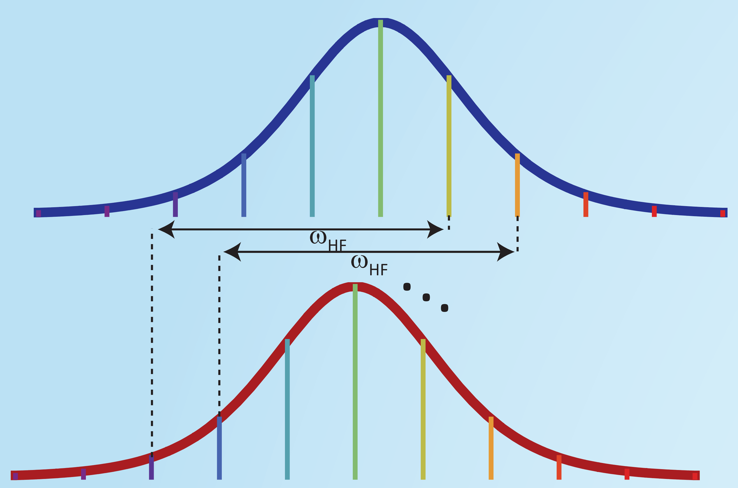
Using Pulsed Lasers

- Pulses are very short (1-10 ps) → large bandwidth (0.1-1 THz) → large frequency gaps are easily bridged.
- Fast pulses + high power → Low noise, high speed operations.
- Extremely high power readily available → Efficient frequency doubling and tripling, large detunings OK → Reduced AC Stark shift, spontaneous emission.
- No carrier - envelope phase stablization necessary
- Allow implementation of gates faster than trap frequency.



Weak pulse regime: two pulse trains, one with shifted comb teeth, drive Raman transitions.

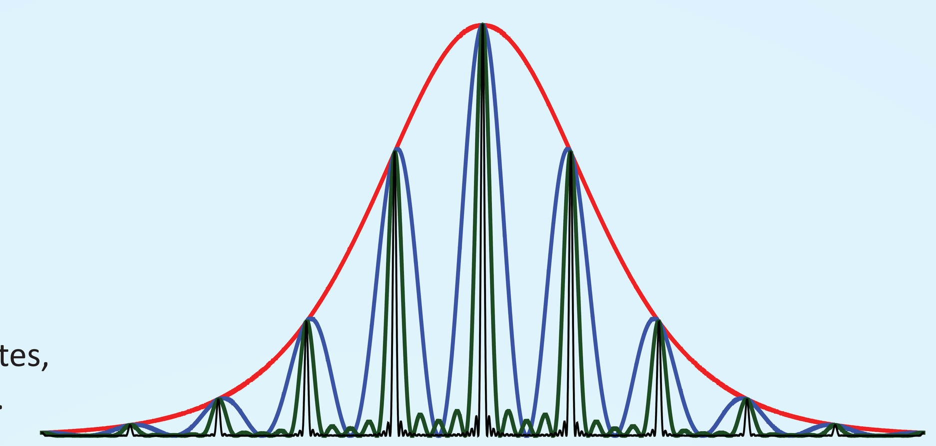
Two Regimes:

Weak Pulse Regime[1]

- Individual pulses have very little effect on the spin state
- Many pulses add to produce frequency comb
- Raman transitions driven by teeth separated by hyperfine frequency
- Can perform tasks traditionally done by CW lasers, e.g. sideband cooling, Mølmer-Sørenson gate

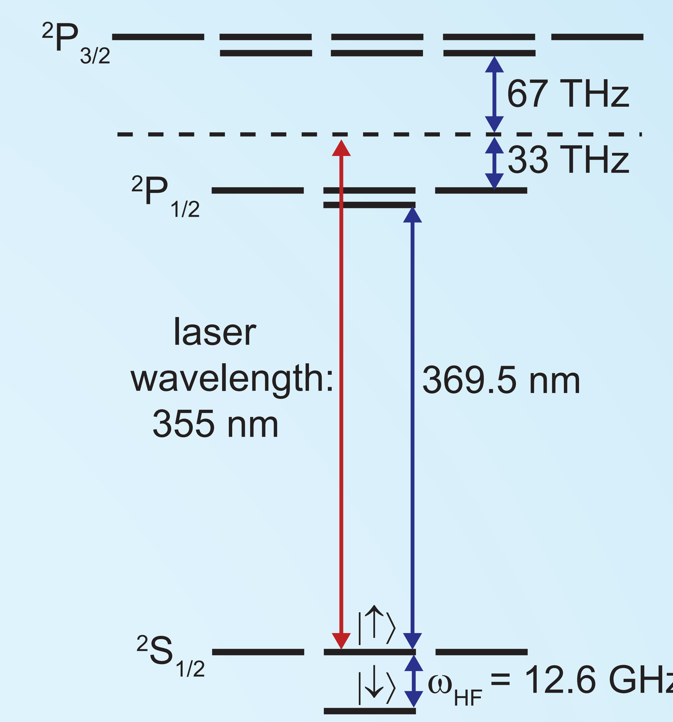
Strong Pulse Regime[2]

- Individual pulses have large effect on the spin state
- Raman transitions driven directly by very small number of pulses.
- Allows complete single qubit control in tens of picoseconds.
- Will allow extremely fast motional gates, which are faster than the trap period.



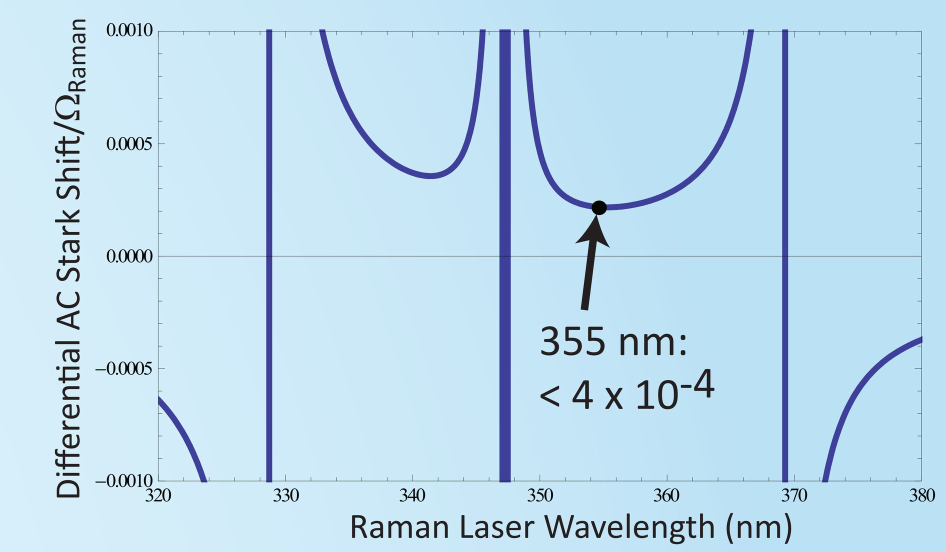
Strong pulse regime spectra for 1, 2, 5, and 20 pulses.

Advantages of 355 nm



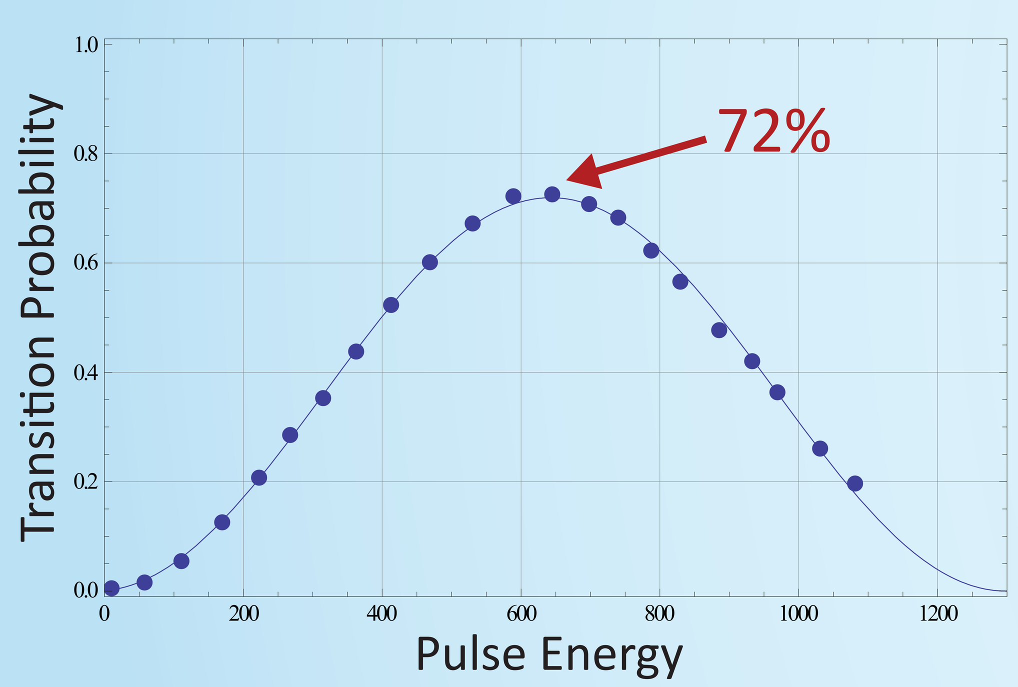
$^{171}Yb^+$ energy level diagram

- 3rd harmonic of YAG, so high power systems are readily available.
- High power allows very large detuning (33 THz)
- Spontaneous emission negligible
- AC Stark shifts from $^2P_{1/2}$ and $^2P_{3/2}$ nearly cancel, making the differential AC Stark shift extremely small.



Ultrafast Single Qubit Control

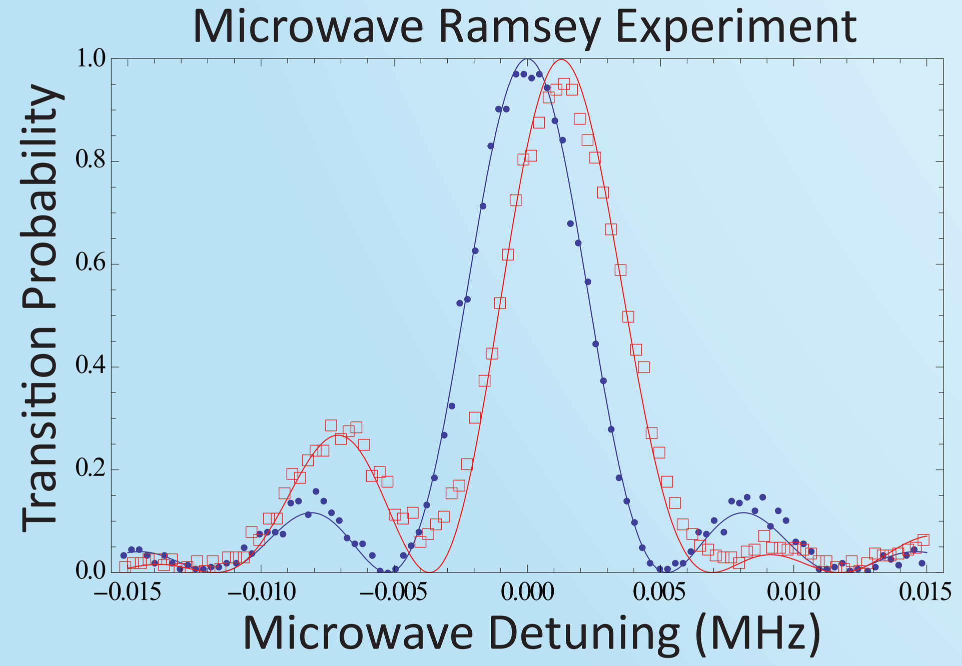
Single Pulse Qubit Rotation



Spin flip vs. pulse energy for single 355 pulse. Limited by bandwidth -- Acts like Rabi flopping with a detuning.

Pure σz Rotation

Microwave Ramsey Experiment

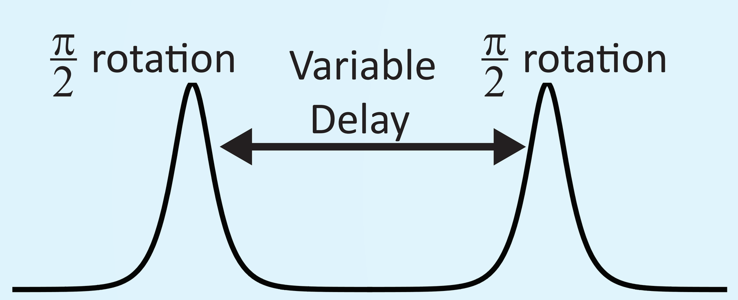


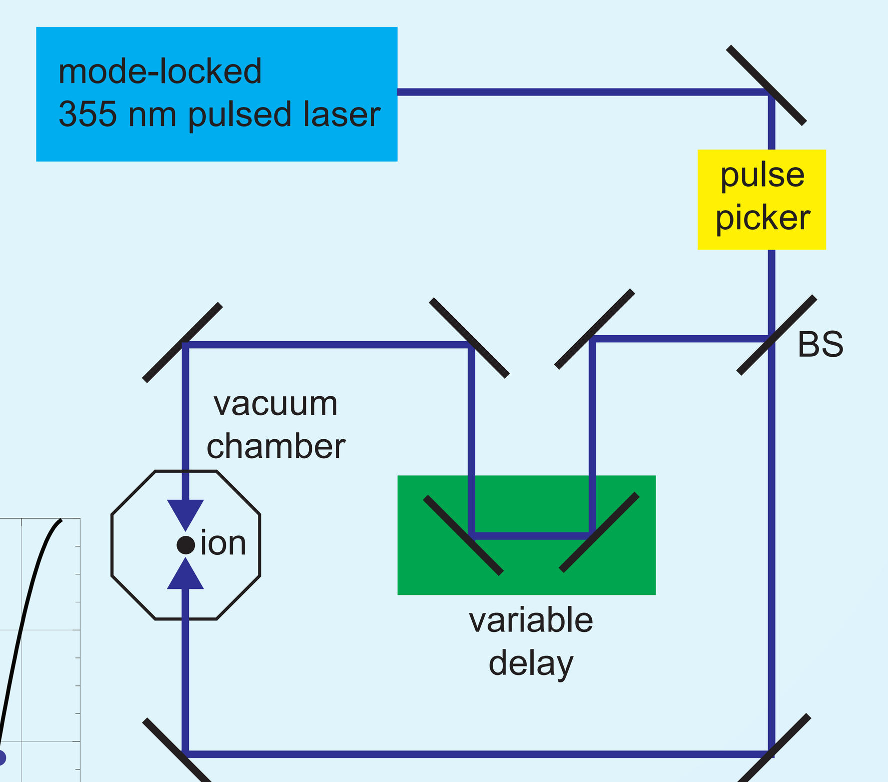
Ramsey experiment demonstrating pure σ_z rotation.

Blue: Two microwave $\pi/2$ pulses, free evolution in between.

Red: Two microwave $\pi/2$ pulses, with σ_z rotation pulses and free evolution in between.

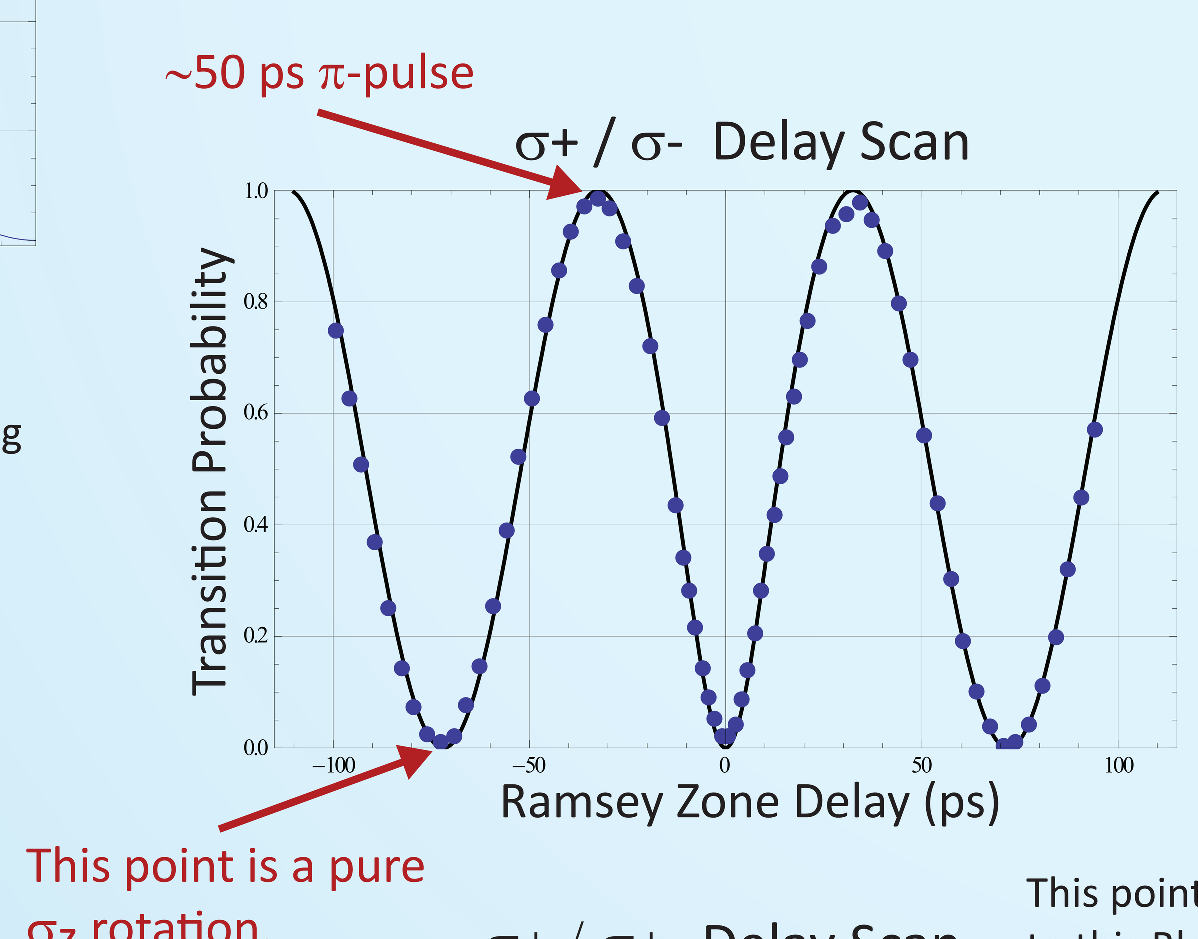
Two Pulse Qubit Rotation



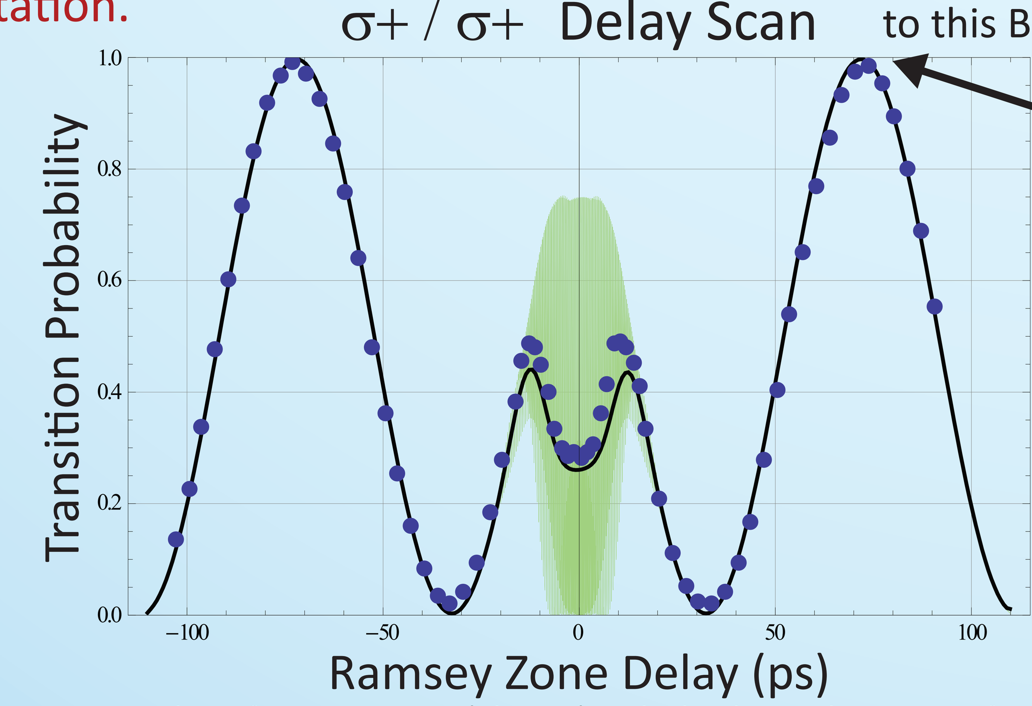


- Pulse is split, with each half a $\pi/2$ pulse.
- Delay between pulses is controlled.
- Different polarizations lead to different behavior in the overlap region.

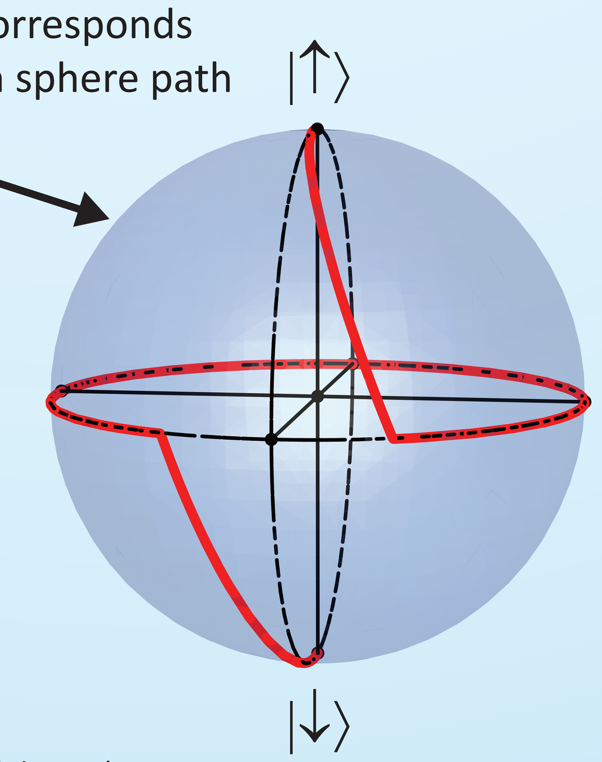
σ+ / σ- Delay Scan



σ+ / σ+ Delay Scan



This point corresponds to this Bloch sphere path

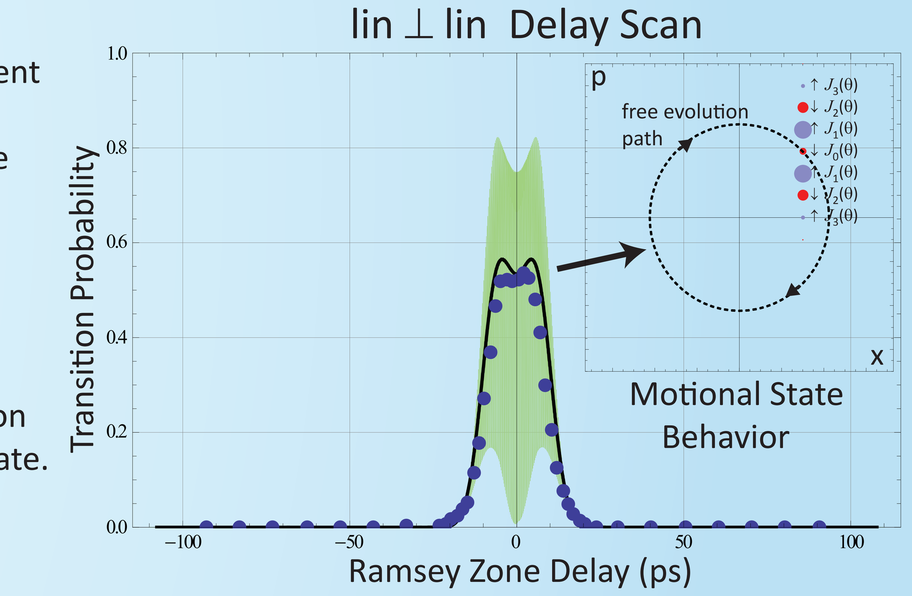


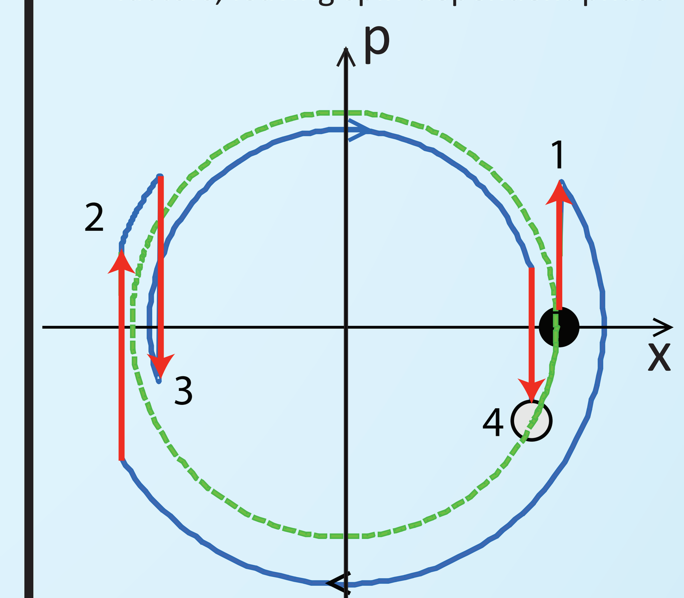
Green: Optical inteference region (Theory) Black: Thermal average of green (Theory)

Future Plans

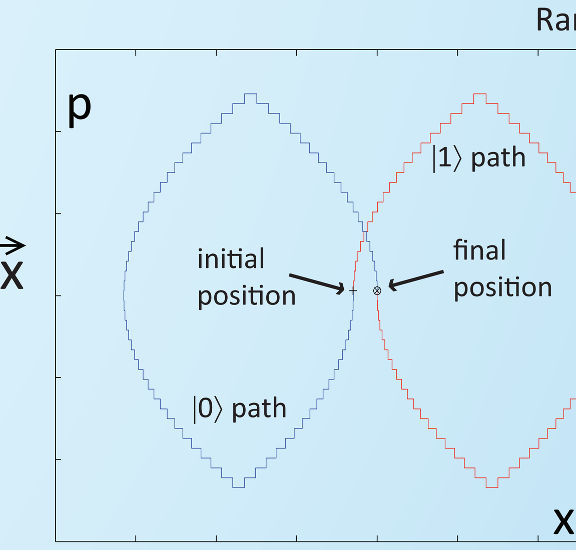
- Counterpropagating pulses produce spin-dependent momentum kicks.
- Kicks are much faster than the trap period → pure vertical displacements in phase space.
- These kicks allow implementation of a gate faster than the trap frequency.
- Gates work by rapidly enclosing an area in phase space in a spin-dependent way, then returning to the free-evolution location in phase-space. Motion factors, leaving spin-dependent phase → phase gate.

lin ⊥ lin Delay Scan





Fast gate scheme using spin-dependent kicks proposed in [3].



Fast gate proposed in [4].

- If counterpropagating pulses have lin ⊥ lin polarizations, transitions only occur by absorbing from one pulse and emitting into the other.
- This gives the ion a momentum kick.
- In phase space, ion's motional state diffracts.
- Sequences of counter-propagating lin ⊥ lin pulse pairs can produce true spin dependent kick.

Conclusions

- Pulsed lasers allow very fast, very clean qubit control.
- Complete arbitrary control of a trapped ion qubit in tens of picoseconds, with negligible AC Stark shift and spontaneous emission.

REFERENCES:

[1] D. Hayes et al., "Entanglement of Atomic Qubits Using an Optical Frequency Comb", Phys. Rev. Lett. **104**, 140501 (2010)

[2] W.C. Campbell et al., "Ultrafast Gates for Single Atomic Qubits", Phys. Rev. Lett. **105**, 090502 (2010)

[3] Garcia-Ripoll et al., "Speed Optimized Two-Qubit Gates with Laser Coherent Control Techniques for Ion Trap Quantum Computing", Phys. Rev. Lett. **91**, 157901 (2003)

[4] Duan, "Scaling Ion Trap Quantum Computation through Fast Quantum Gates," Phys. Rev. Lett. **93**, 100502 (2004).