Next generation platform for implementing fast gates in ion trap quantum computation

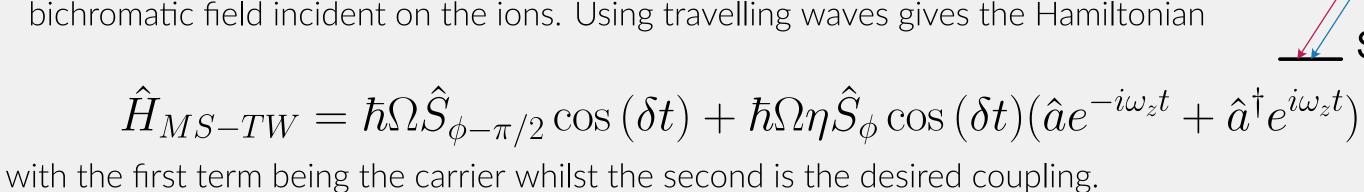
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Scalable trapped-ion quantum computation relies on the development of high-fidelity fast entangling gates in a many ion crystal. Conventional geometric phase gates either suffer from scattering errors or off-resonant carrier excitations. A potential route to achieve fast entanglement is creating a standing wave which can suppress the unwanted carrier coupling.

Non-Adiabatic Mølmer Sørenson Gates

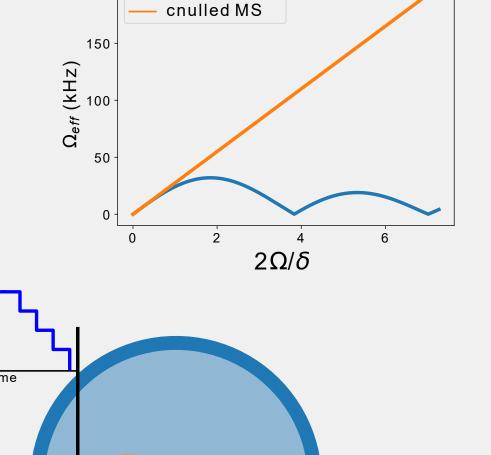
- Two qubit gates are implemented by coupling spin with shared motion of the ions.
- Fast entangling gates enable deeper quantum computational circuit depths for given level of incoherent error.
- But going fast excites multiple motional modes ("spectator modes") which can introduces errors.
- Mølmer Sørenson (MS) interaction is common two-qubit gate which requires a bichromatic field incident on the ions. Using travelling waves gives the Hamiltonian



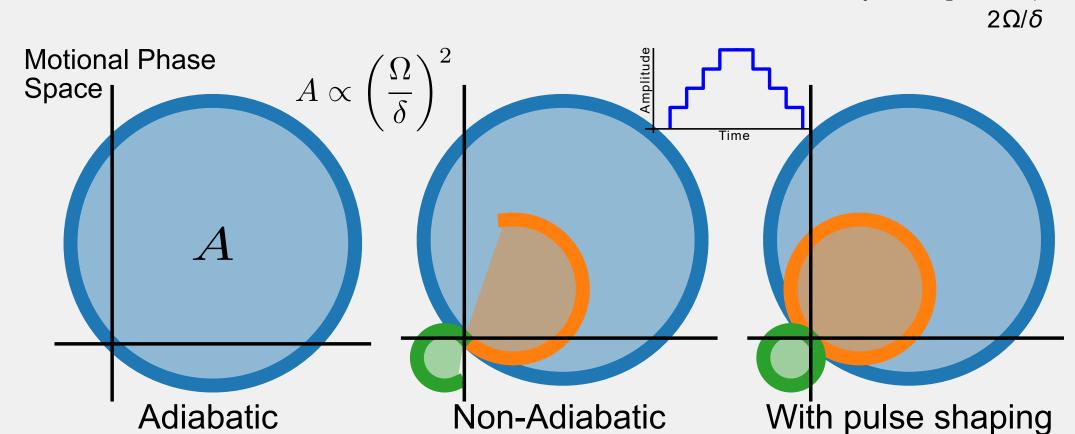
• As these terms do not commute, in the interaction picture this Hamiltonian may be expressed as [1]:

$$\hat{H}_{MS-TW} = \hbar \eta \Omega (J_0(2\Omega/\delta) + J_2(2\Omega/\delta)) \cdot \cos(\delta t) \hat{S}_{\phi}(\hat{a}e^{-i\omega_z t} + \hat{a}^{\dagger}e^{i\omega_z t})$$

- Carrier term: causes the spin dependent force coupling to be modulated by (JO+J2).
- Spectator excitation: Amplitude shaped pulses [2] effectively remove "spectator" error by closing phase loops of all excited modes.



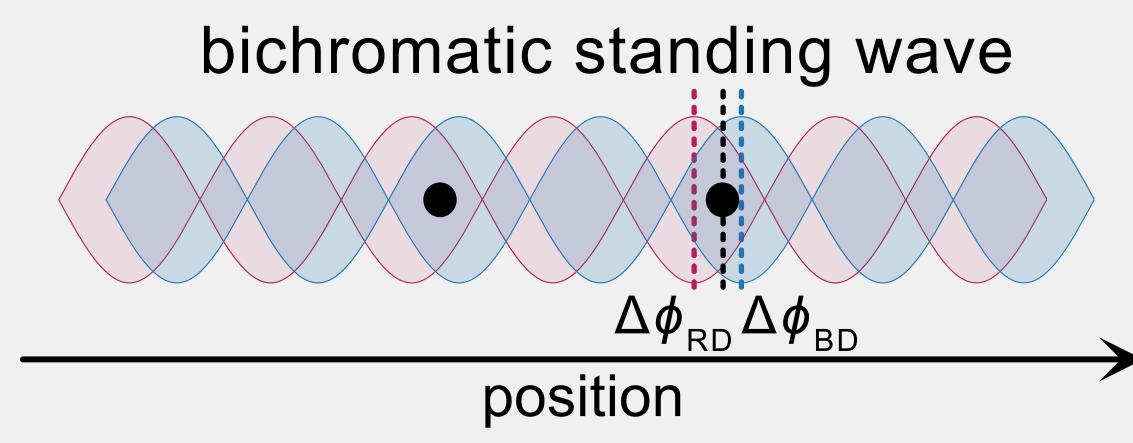
standard MS



Standing Wave Single and MS Gates

- Using standing wave gives complete control over phase visible to ions.
- This extra freedom allows fast gates by preventing the saturation effect seen in the travelling MS.
- Bichromatic standing wave Hamiltonian where ions are seperated by $n\lambda/2$:

 $\hat{H}_{MS-SW} = \hbar 2\Omega \hat{S}_{\phi} \cos{(\delta t)} \sin{(\Delta \phi/2)} + \hbar 2\Omega \eta \hat{S}_{\phi} \cos{(\delta t)} (\hat{a}e^{-i\omega_z t} + \hat{a}^{\dagger}e^{i\omega_z t}) \cos{(\Delta \phi/2)}$

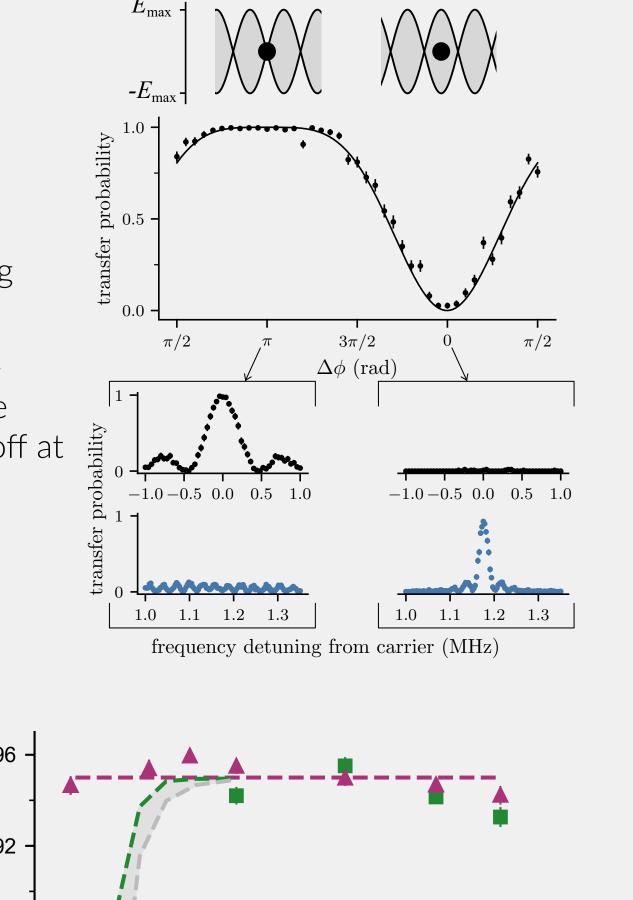


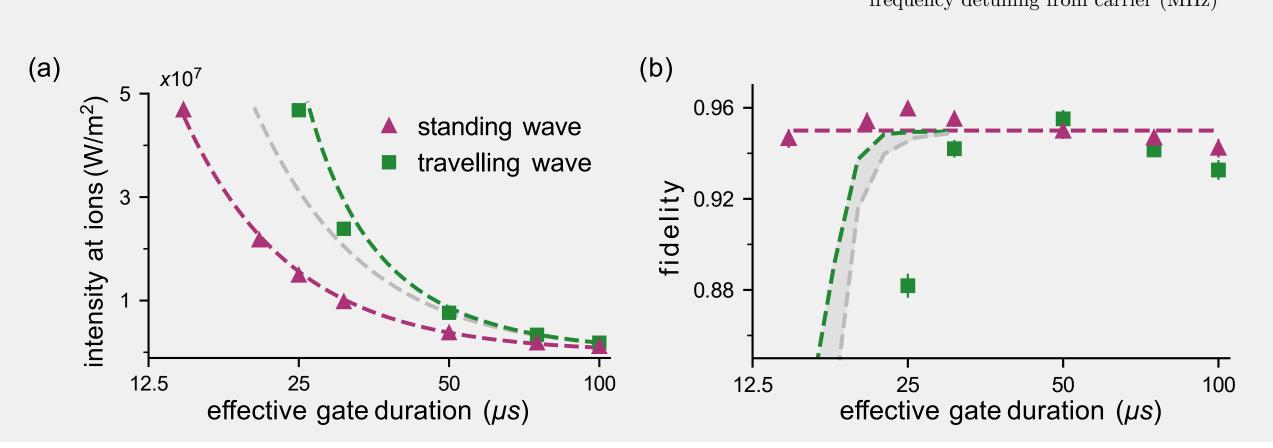
- Setting $\Delta \phi = 0$ (ions sitting at antinodes) we suppress the carrier term and maximise sideband coupling.
- However standing waves require phase stabilisation to perform coherent interactions.

Phase Stabilization Passively using enclosure and actively by feedback process to AOM. **5**0cm 1) Fast drifts removed utilising interference of light from the two branches on a photodiode (PD). 5 m 88Sr⁺ions 2) Ion used as phase sensor to feedback onto an AOM ($\pi/2$ pulse on b1 and b2). i30cm $(\pi/2)_{b1}, (\pi/2)_{b2}$ \times number of shots \times number of shots ion feedback main exp. sequence one scan point

Carrier Nulling Results

- Phase stability of standing wave to $\lambda/50$.
- Standard Randomized Benchmarking of single qubit rotations found gate errors of $\epsilon=0.173(3)\%$ for travelling wave, $\epsilon=0.144(3)\%$ for standing wave.
- Universal gate set with phase stabilised standing-waves.
- Standing wave MS maintains > 95% fidelity at short gate durations in contrast to travelling wave MS sharp drop off at $\sim 25 \mu s$.





New Platform

- New ion trap experiment in development for exploring fast gate regime.
- Two high NA lenses create an array of singly addressing standing waves.
- 3D segmented trap design from NPL facilitates low heating rates (< 10 q/s @ 1.5 MHz[XXref?XX]) whilst enabling ion shuttling and crystal rotations.
- MuMetal shield and permanent magnets for stable B field.

