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. XXX Figure of geometric phase gate. XXX
- 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. XXX Figure of multiple motions. XXX
- Mølmer Sørenson (MS) interaction is common two-qubit gate which requires a bichromatic field incident on the ions. Using travelling waves gives the Hamiltonian

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

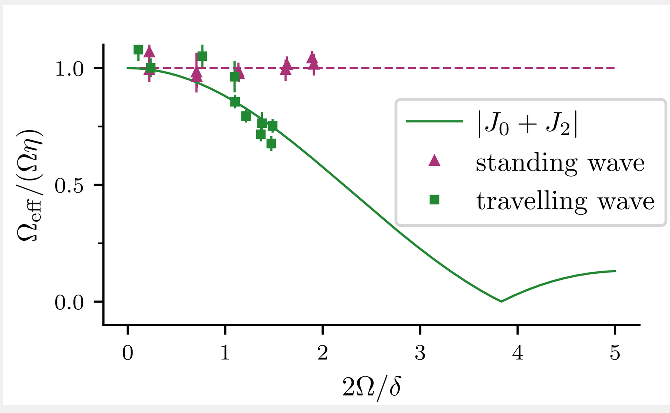
with the first term being the carrier whilst the second is the desired coupling. XXX Figure of TW MS .

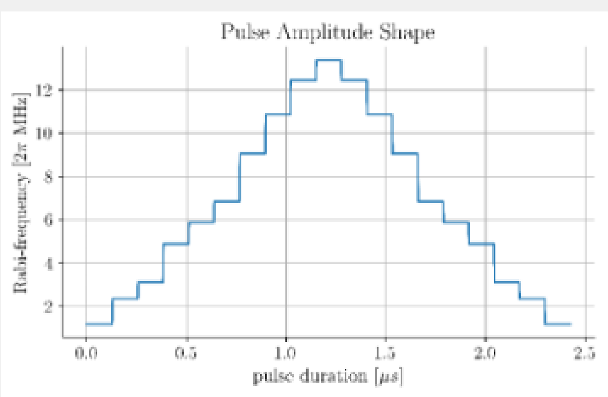
XXX

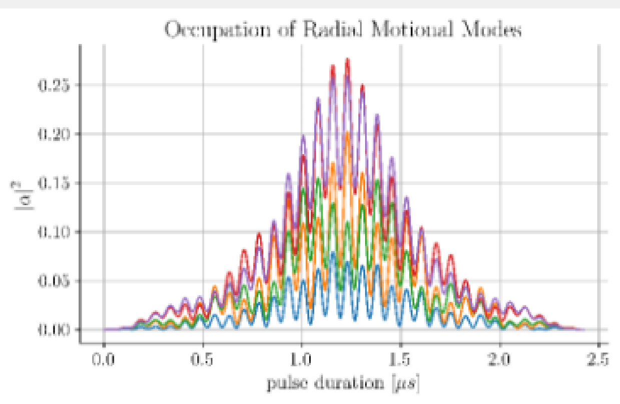
- As these terms do not commute, in the ??interaction picture?? this Hamiltonian may be expressed as [Xref Canzz?X]:

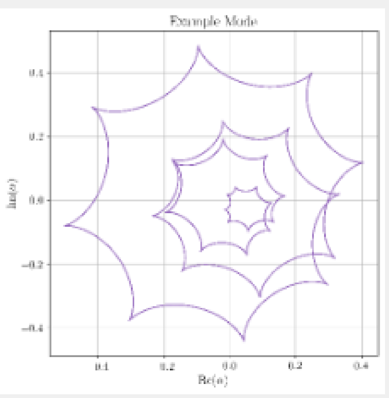
$$\hat{H}_{MS-TW} = \hbar\eta\Omega(J_0(2\Omega/\delta) + J_2(2\Omega/\delta)) \cdot \cos(\delta t)\hat{S}_{\phi}(\hat{a}e^{-i\omega_z t} + \hat{a}^\dagger e^{i\omega_z t})$$

- **Carrier term:** causes the spin dependent force coupling to be modulated by (J0+J2).
- **Spectator excitation:** Amplitude shaped pulses [ref vera] effectively remove "spectator" error by closing phase loops of all excited modes.









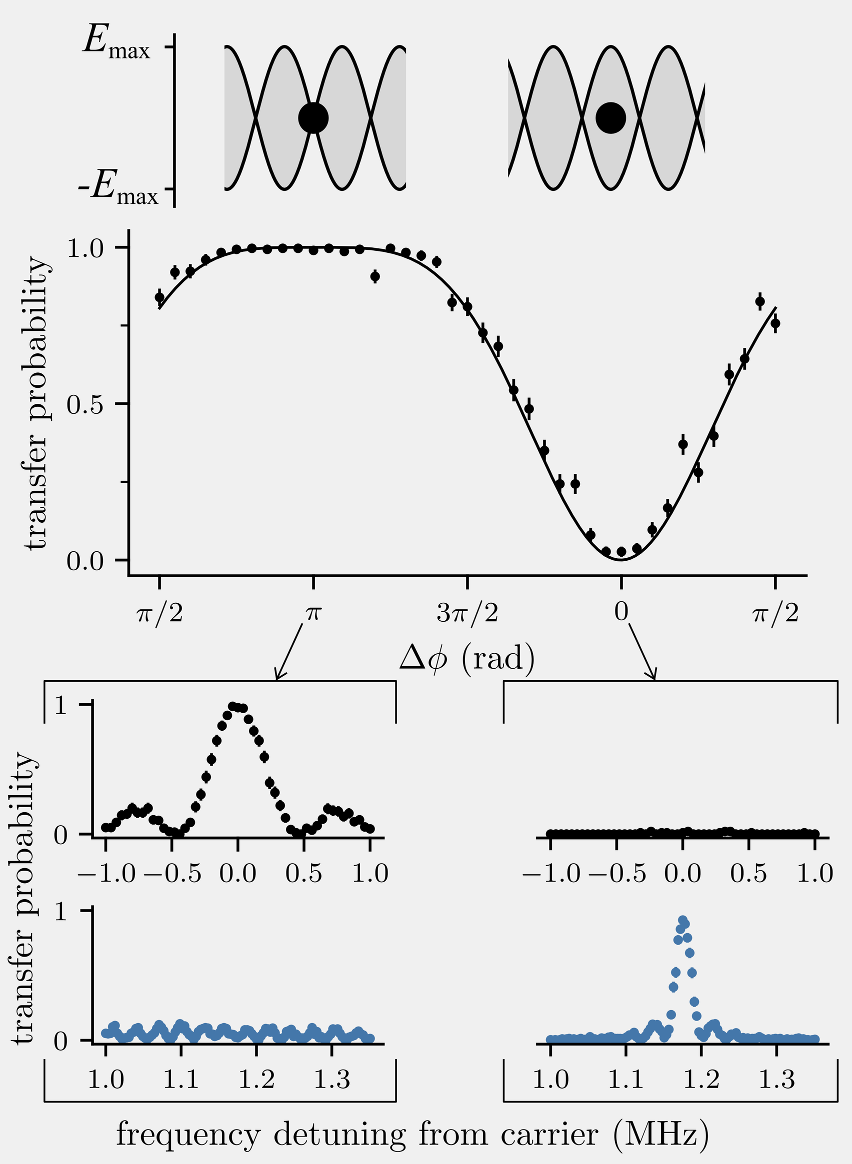
Standing Wave Single and MS Gates

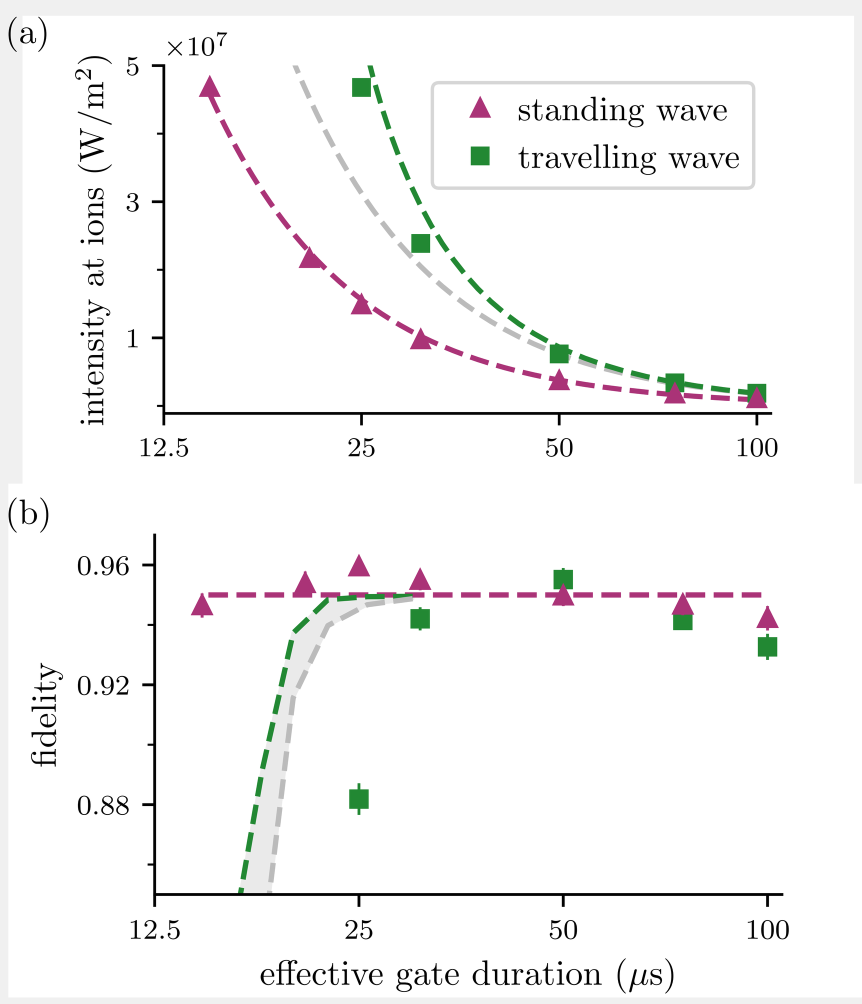
Bichromatic standing wave Hamiltonian where ions are seperated by $n\lambda/2$:

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

XXX Figure of SW MS (1b) . XXX

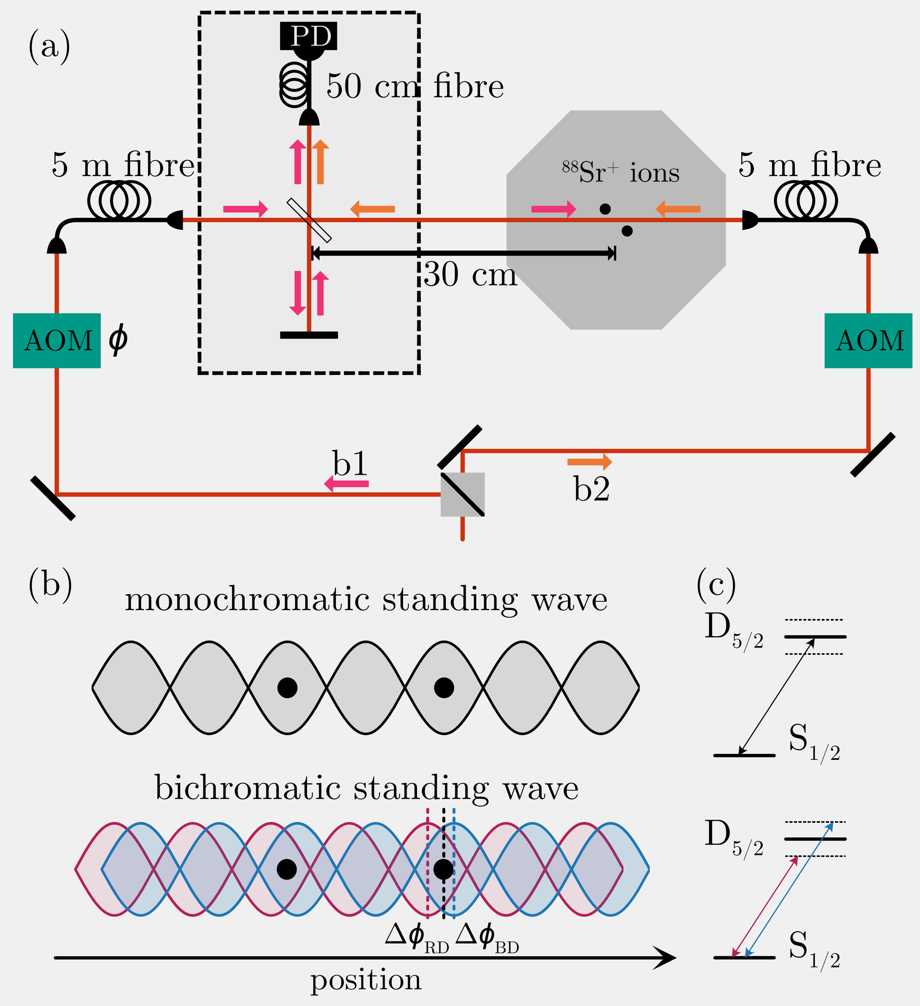
- Setting $\Delta\phi = 0$ (ions sitting at antinodes) we suppress the carrier term and maximise sideband coupling.
- Enables fast gates by preventing the saturation effect seen in the travelling MS.
- Using optical lattice gives complete control over phase visible to ions.





Results from Cnulling:

Phase Stabilization



- Optical lattice requires phase stabilisation to perform coherent interactions.
- Phase stabilised passively using enclosure and actively by two-step process:
  1) Fast drifts removed utilising interference of light from the two branches on a photodiode (PD).
  2) As PD lockpoint is 30 cm away from ions, a second feedback loop using the ion as a sensor is required. We do this by performing a $\pi/2$-pulse using arm 1 ($\pi/2$, b1) followed immediately by a $\pi/2$-pulse using arm 2 ($pi/2$, b2). This is equivalent to a zero-delay Ramsey sequence, which gives a signal sensitive on the difference in phase between the two pulses, hence the relative phase be- tween the branches.
- No detriment using lattice: Standard Randomized Benchmarking gave quality of our single qubit rotations per gate to be $\epsilon = 0.173(3)\%$ for a travelling wave and $\epsilon = 0.144(3)\%$ for the standing wave.

New Platform

- New ion trap experiment in development for exploring fast gate regime.
- Two high NA lenses allow optical access on both faces of the trap to create an array of singly addressing standing waves.
- 3D segmented trap design from NPL facilitates low heating rates whilst enabling ion shuttling and crystal rotations.
- Calcium 40
- quadropole transition used.
- MuMetal shield and permanent magnets.
- fig: solidworks of new experiment