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Lifting the speed limit: fast entangling gates using phase stable optical lattices in trapped ions

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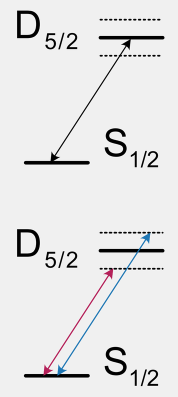
Abstract: Scalable trapped-ion quantum computation relies on the development of high-fidelity fast entangling gates in a many ion crystal. Conventional geometric phase gates either suffer from scattering errors or off-resonant carrier excitations. A potential route to achieve fast entanglement is creating a standing wave which can suppress the unwanted carrier coupling.
We present an experimental realization of this carrier suppression in the 674 nm quadropole transition of $^{88}Sr^+$. We produce a phase stable standing wave with residual fluctuations at the ion position of $\lambda/50$. Carrier suppression of 26 dB is demonstrated leading to two qubit MS gates with improved fidelity at shorter gate durations.

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 circuits for a given level of incoherent error.
- Mølmer Sørenson (MS) interaction is common two-qubit gate which requires a bichromatic field incident on the ions. Using a quadropole transition, travelling wave to interact with the ions gives the Hamiltonian



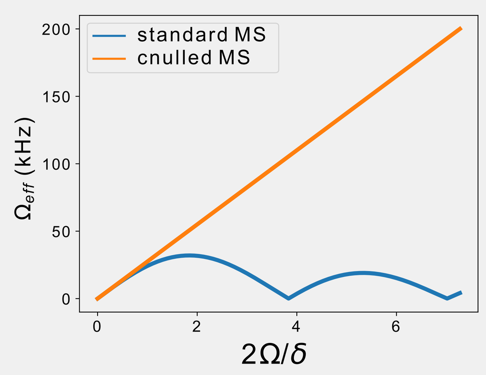
$$\hat{H}_{MS-TW} = \hbar\Omega \hat{S}_{\phi-\pi/2}\cos(\delta t) + \hbar\Omega\eta \hat{S}_{\phi}\cos(\delta t)(\hat{a}e^{-i\omega_z t} + \hat{a}^\dagger e^{i\omega_z t})$$

with the first term being the carrier whilst the second is the desired coupling.

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

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

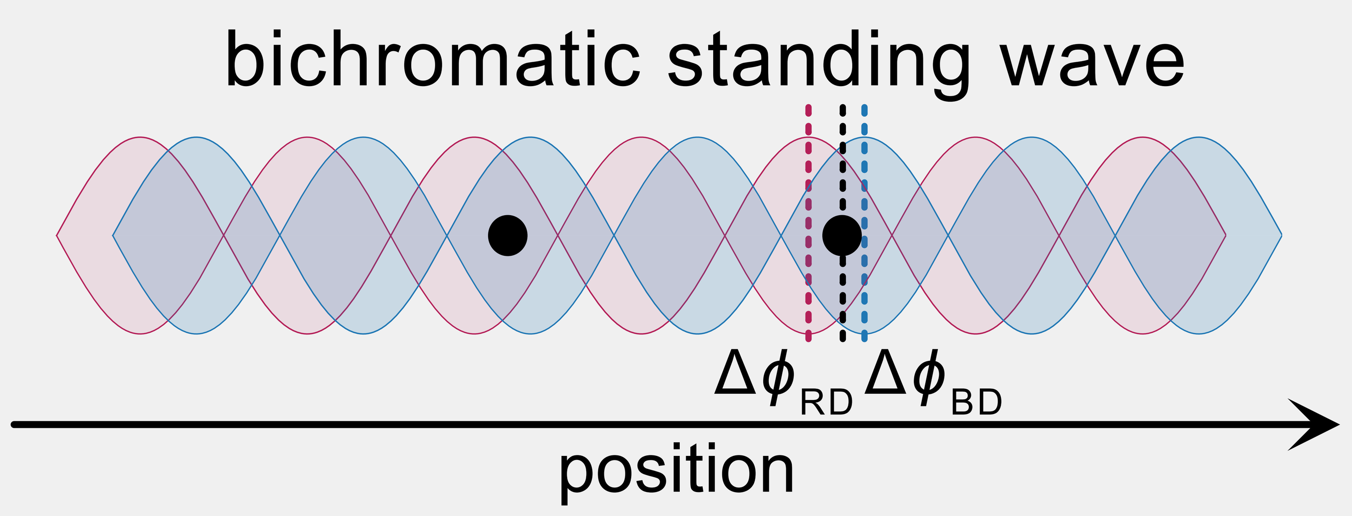
- **Carrier term:** causes the spin dependent force coupling to be modulated by $(J_0 + J_2)$.
- Imperfectly transferring to the interaction picture leads to further gate errors.



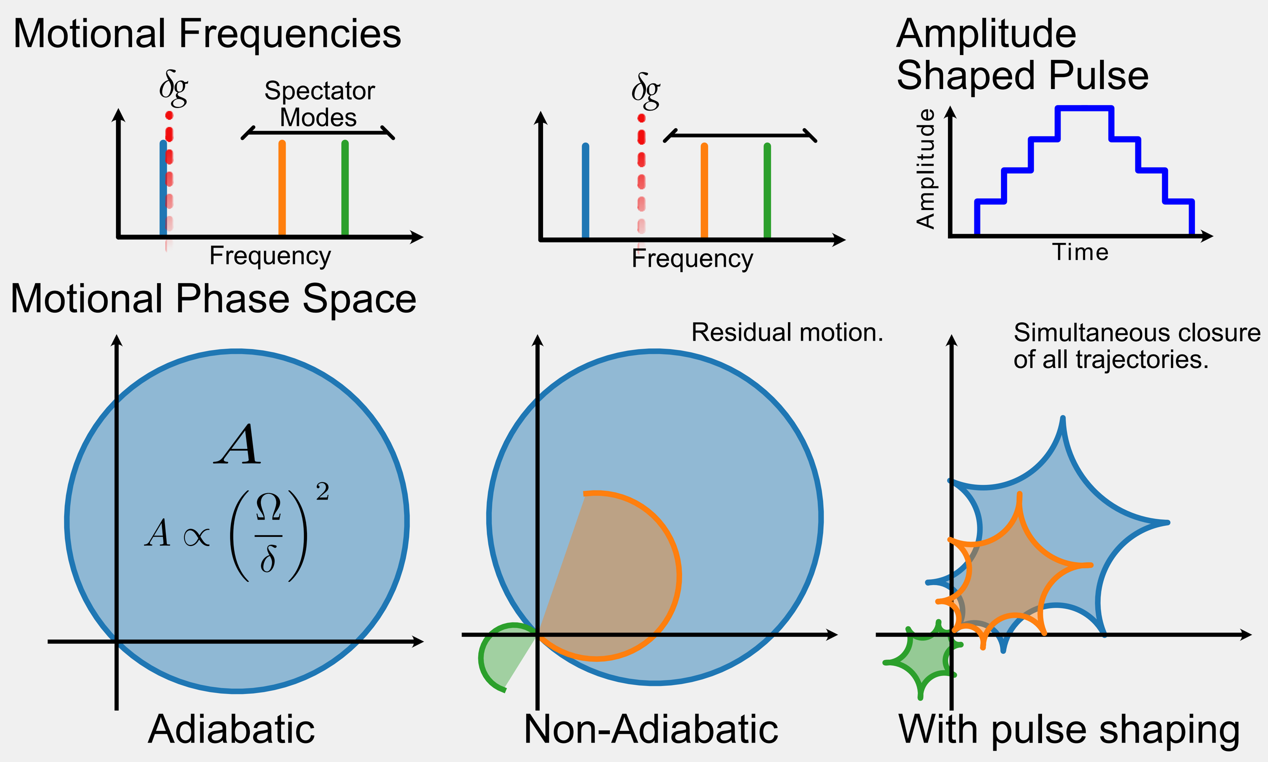
Standing Wave Single and MS Gates

- Using standing wave gives complete control over phase visible to ions.
- Bichromatic standing wave Hamiltonian where ions are seperated by $n\lambda/2$:

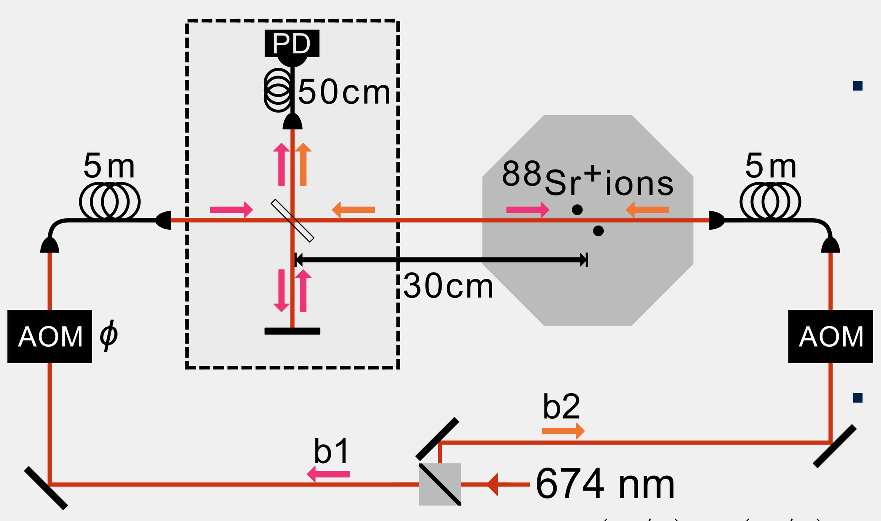
$$\hat{H}_{MS-SW} = \hbar 2\Omega \hat{S}_{\phi}\cos(\delta t)\sin(\Delta\phi/2) + \hbar 2\Omega\eta\hat{S}_{\phi}\cos(\delta t)(\hat{a}e^{-i\omega_z t} + \hat{a}^\dagger e^{i\omega_z t})\cos(\Delta\phi/2)$$



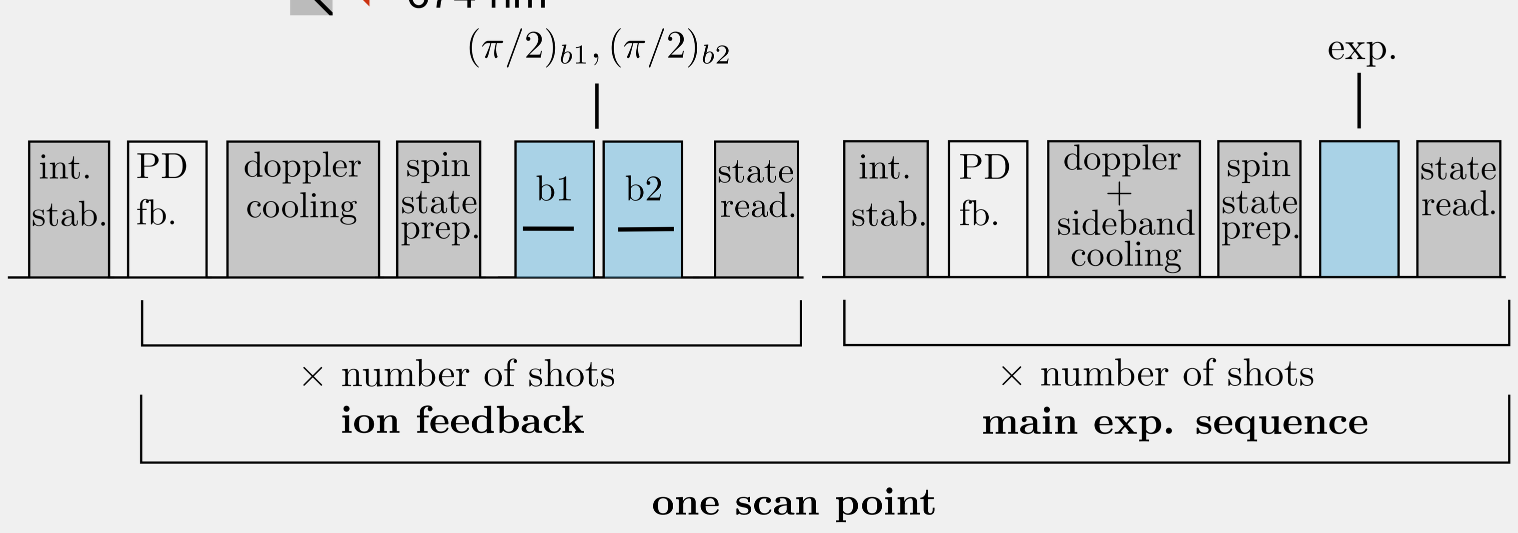
- Setting $\Delta\phi = 0$ (ions sitting at antinodes) we suppress the carrier term and maximise sideband coupling.
- This extra freedom allows fast gates by preventing the saturation effect seen in the travelling MS.
- Requires standing wave phase stable with respect to the ion position for coherent interactions.
- Additional errors as Non-Adiabatic (fast) gates excite multiple motional modes ("spectator modes").
- **Spectator excitation:** Amplitude shaped pulses [2, 3] effectively remove "spectator" error by closing phase loops of all excited modes.



Phase Stabilization

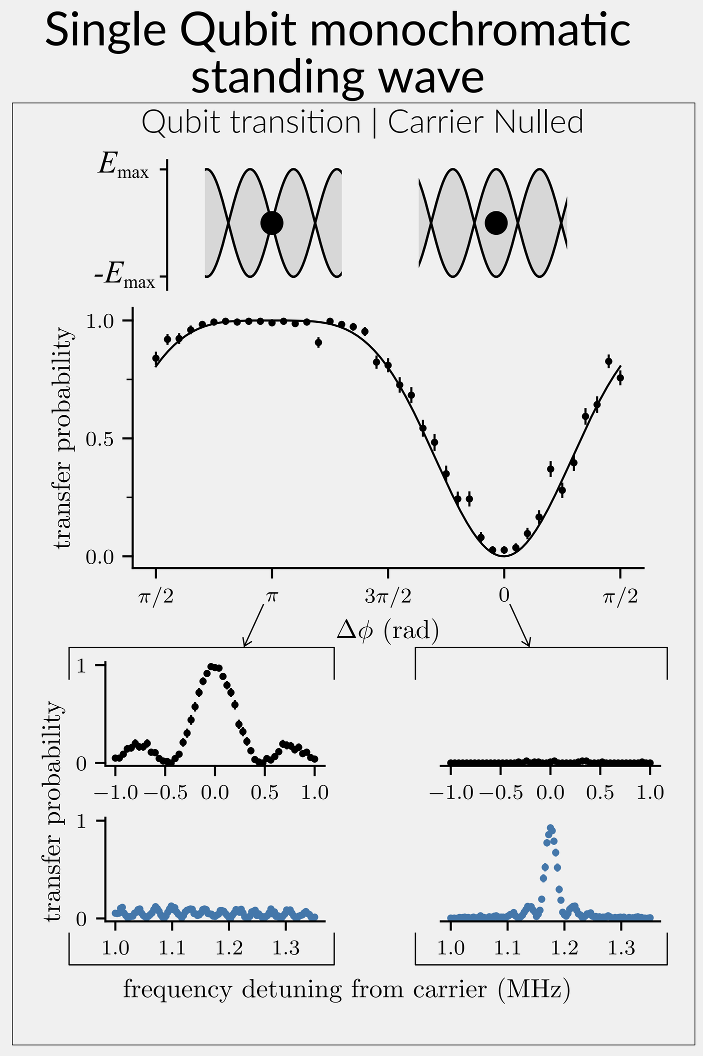


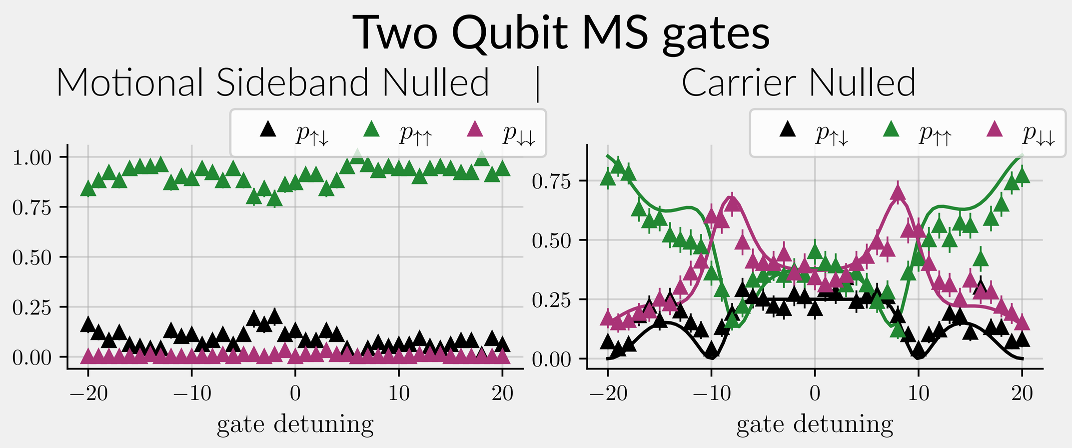
- Passively using enclosure and actively by feedback process to AOM.
  1) Fast drifts removed utilising interference of light from the two branches on a photodiode (PD).
  2) Ion used as phase sensor to feedback offset between PD and ion site ($\pi/2$ pulse on b1 and b2).
- Phase stability of standing wave experimentally demonstrated to $\lambda/50$ with $^{88}Sr^+$ and 674 nm laser.

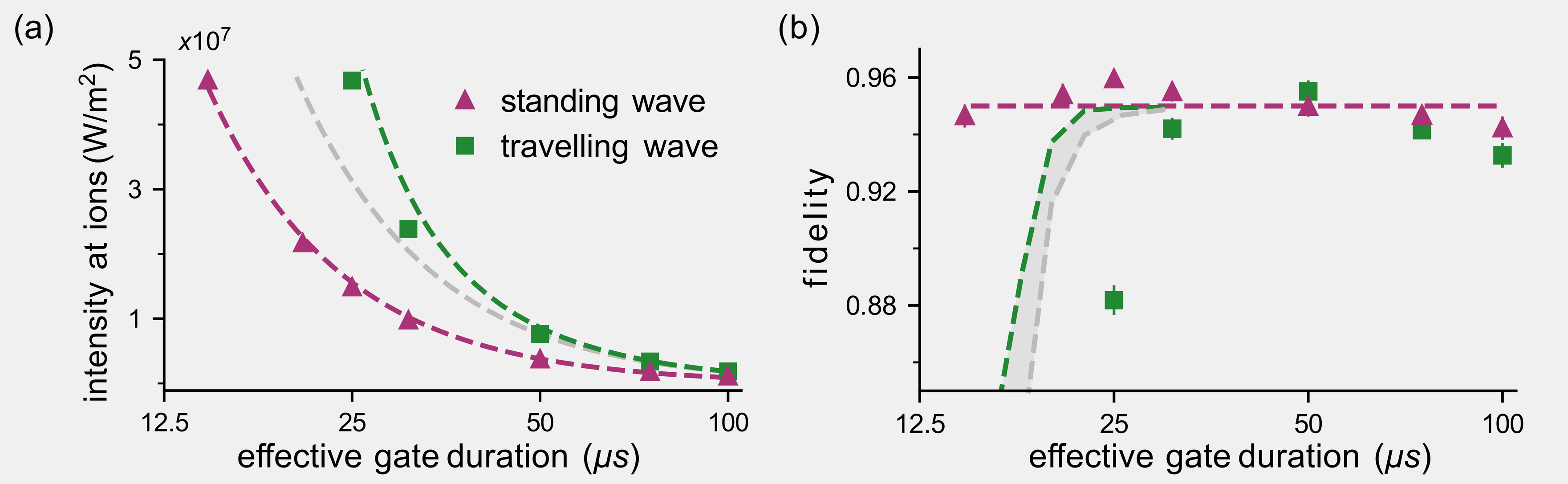


Optical lattice driven two qubit gates

- Experimental demonstration of gates at carrier null point with $^{88}Sr^+$ and 674 nm laser.
- 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 stabilized standing-waves.
- Carrier suppression by 26 dB.
- Standing wave MS maintains $\geq 95\%$ fidelity at short gate durations in contrast to travelling wave MS sharp drop off at $\sim 25\ \mu s$.

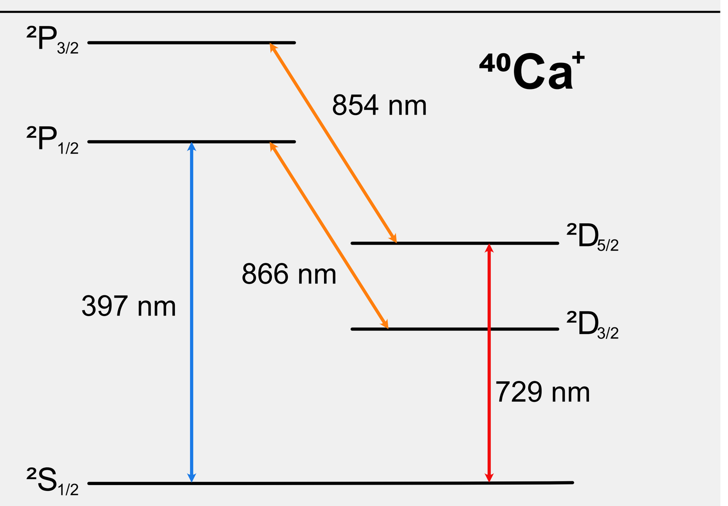


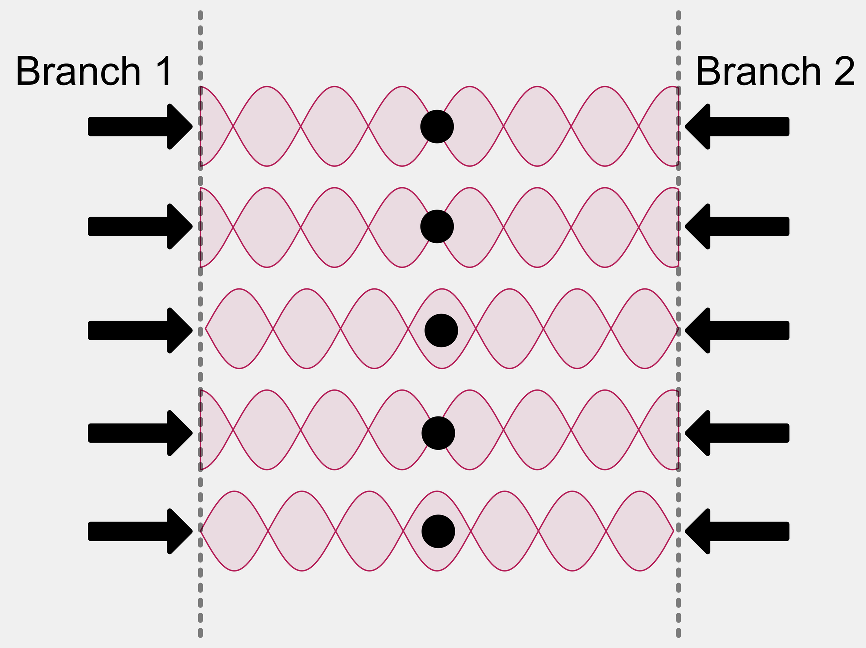


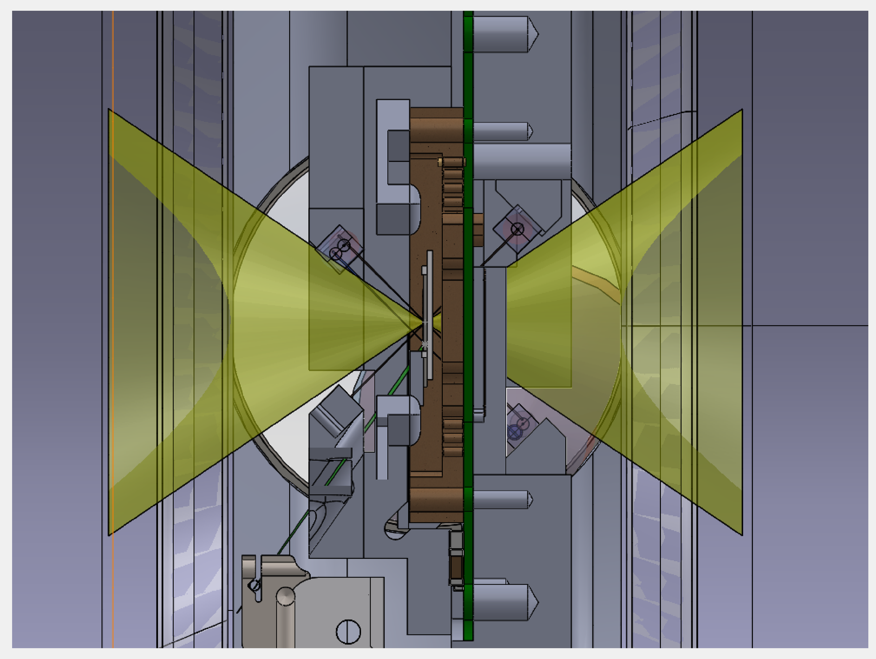


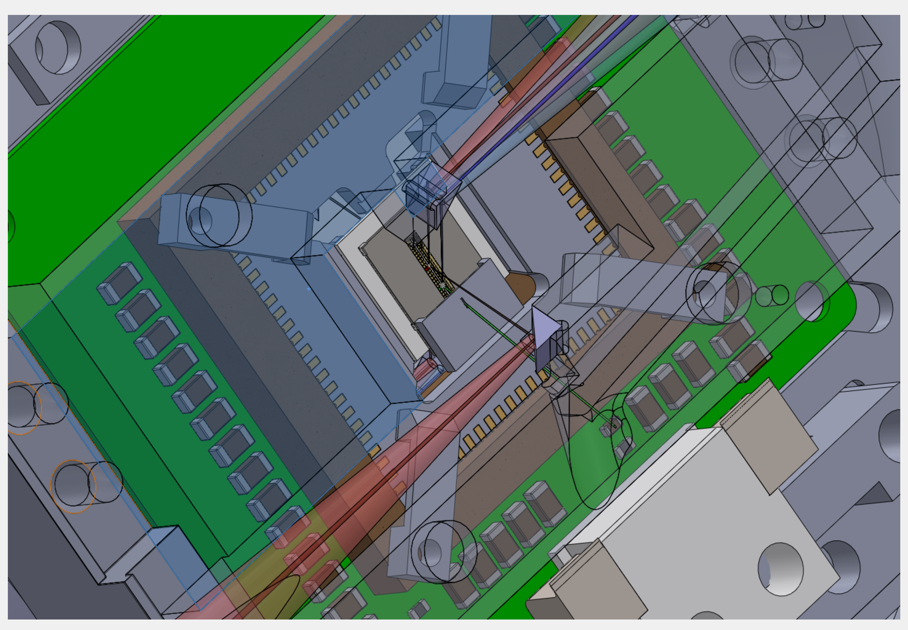
New Platform

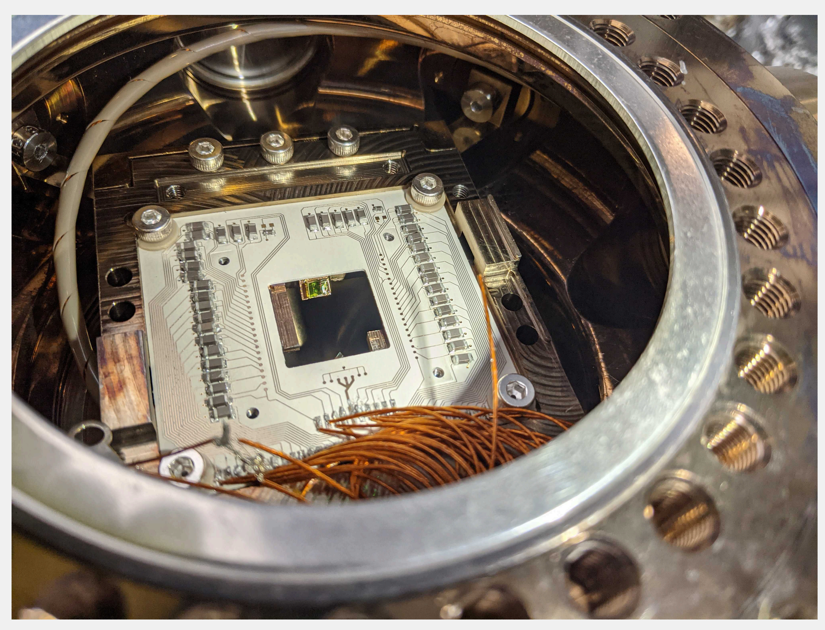
- New $^{40}Ca^+$ ion trap experiment in development for exploring fast gate regime using 729 nm quadropole laser.
- Two high NA lenses create an array of singly addressing standing waves.
- 3D segmented trap design from NPL facilitates low heating rates (expected: < 10 q/s @ 1.5 MHz) whilst enabling ion shuttling and crystal rotations.
- MuMetal shield and permanent magnets for stable B field.











[1] O. Băzăvan and S. Saner et al., Phys. Rev. A, vol. 107, no. 2, p. 022617, 2023
[2] V. M. Schäfer et al., Nature, vol. 555, no. 7694, Art. no. 7694, 2018
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