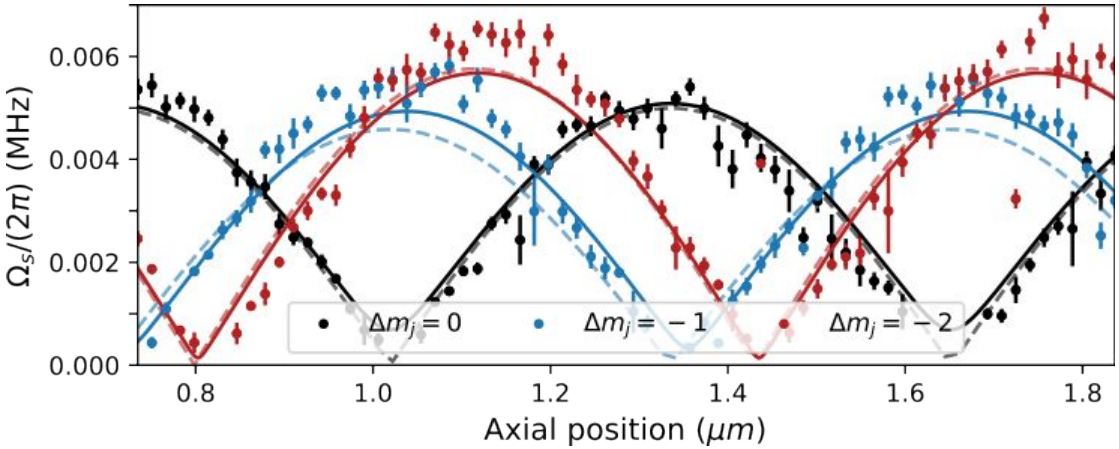
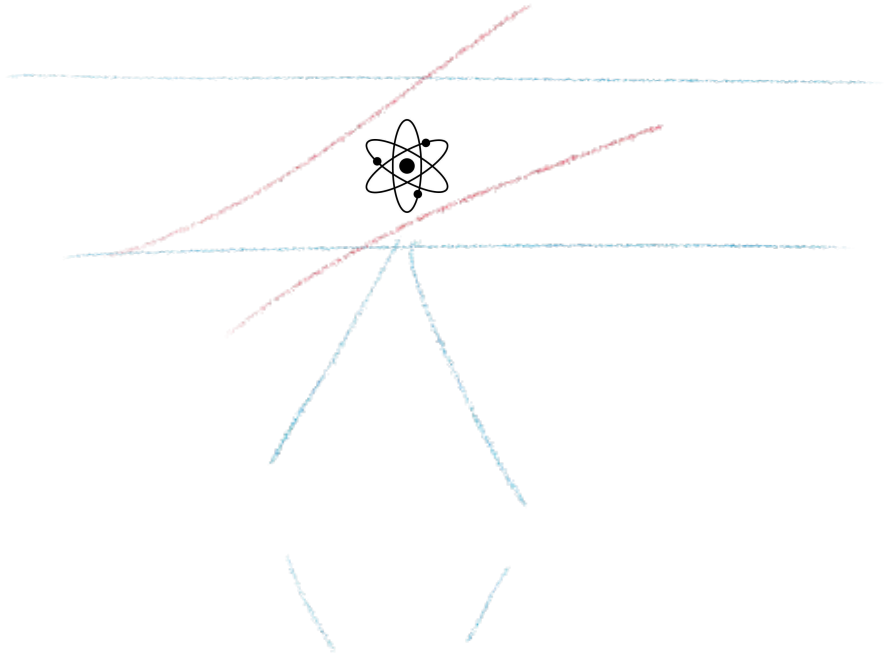
Integrated photonics for trapped ions quantum computing

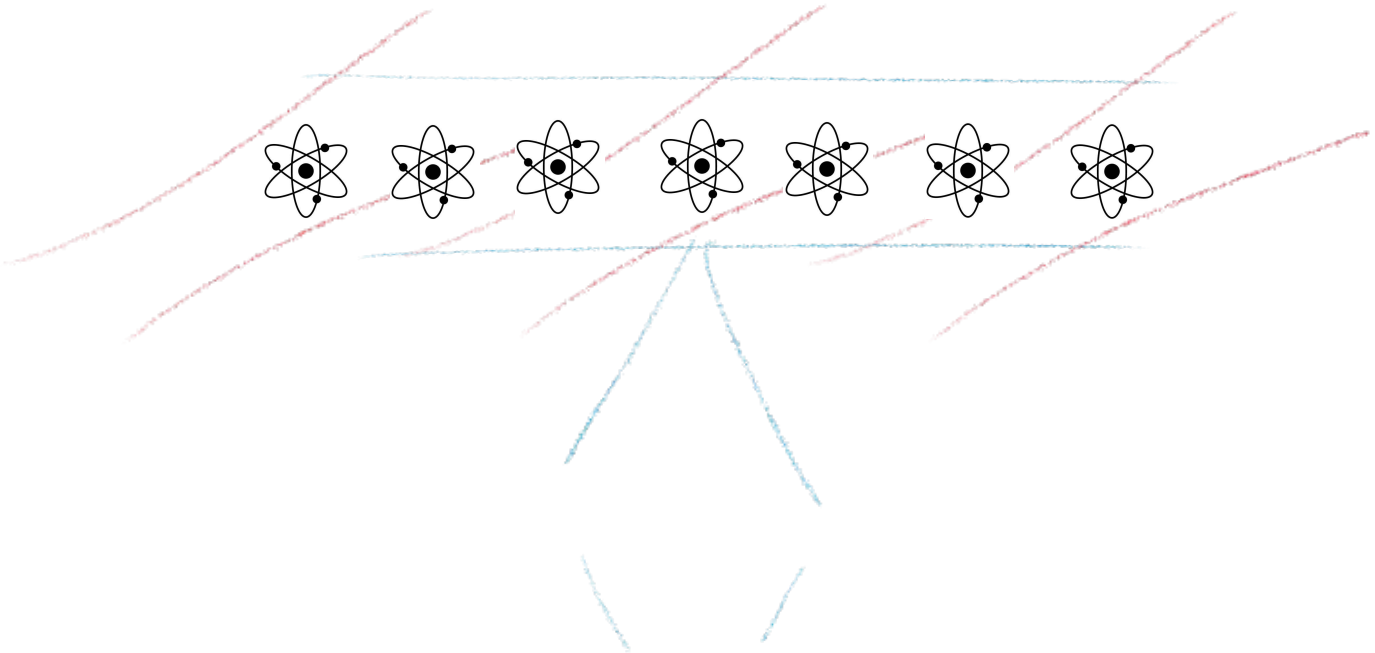
Carmelo Mordini
Trapped Ions Quantum Information
ETH Zurich



Let’s build a quantum computer!



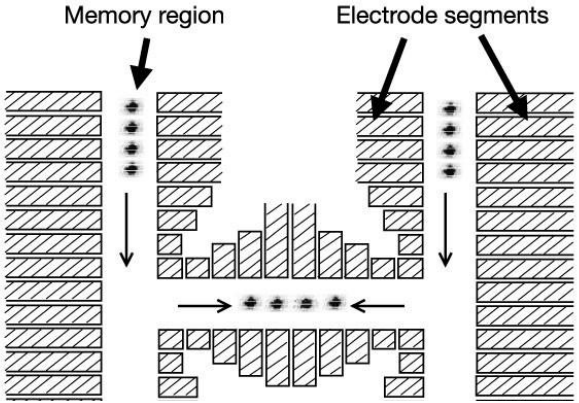
Let's build a quantum computer!



Surface traps

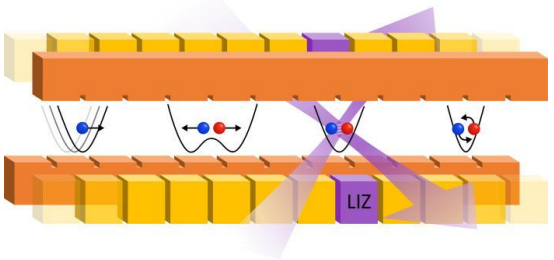
Surface traps
distribute ions over the chip

QCCD



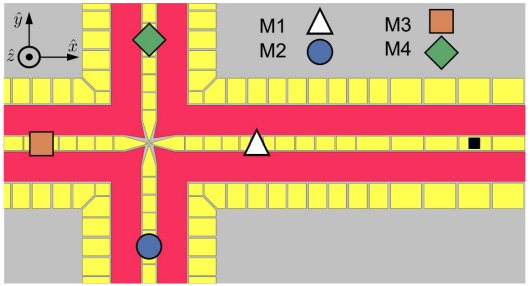
Kielpinski et al. Nature 2002

Linear transport / splitting



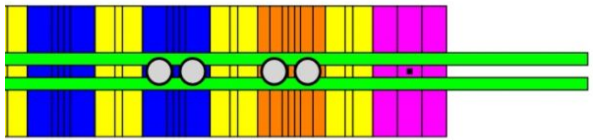
Schmidt-Kahler (review 2020)
(yeah, not a surface trap)

Junctions



Quantinuum, 2022

Mixed species

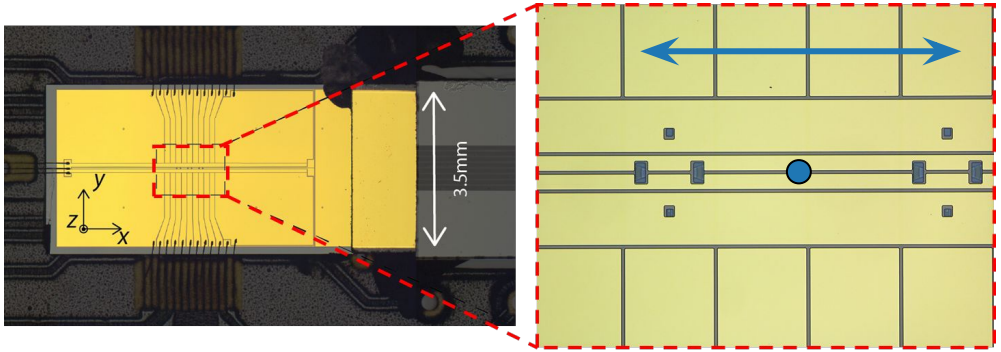


Pino et al. Nature 2021

Surface traps + integrated photonics

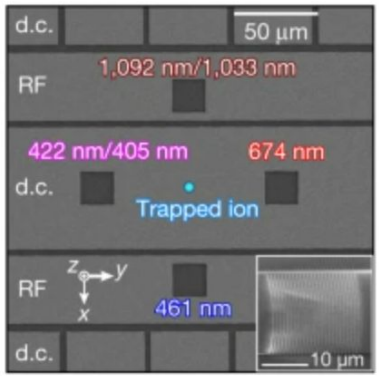
Photonics
distribute light over the chip

Multiple zones

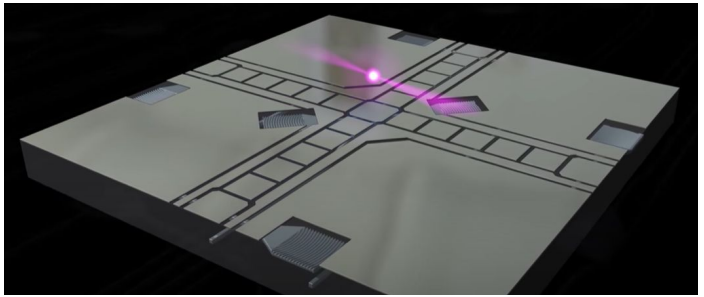


Mehta et al. Nature 2020

Multiple wavelengths



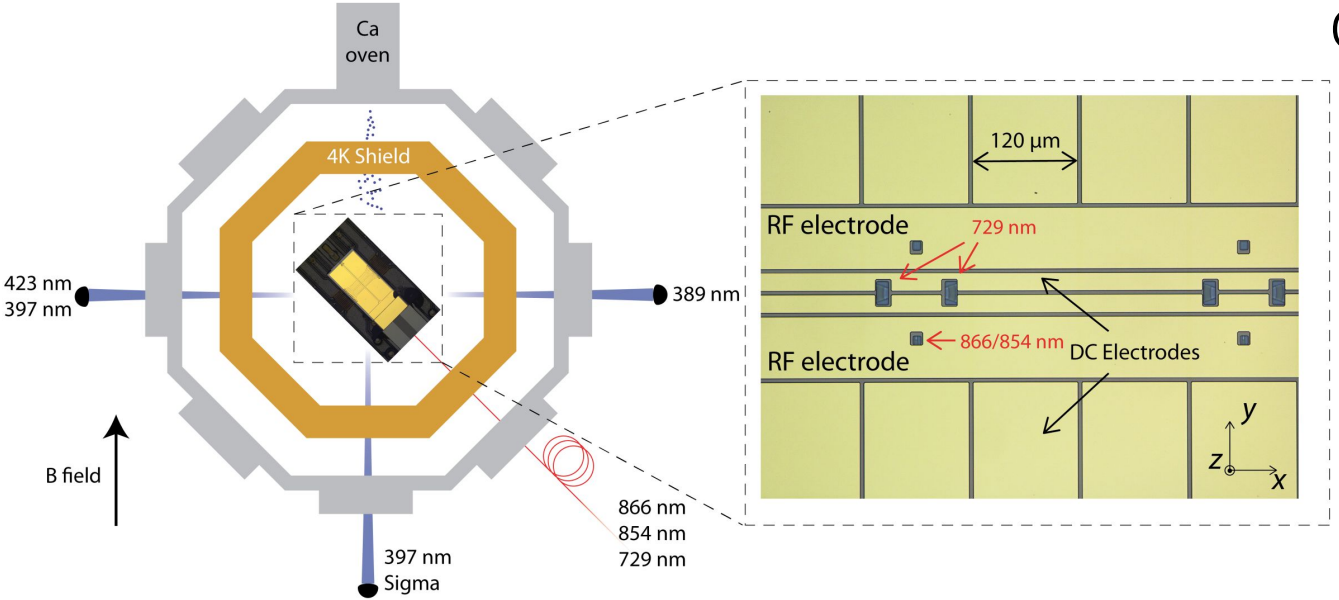
Niffenegger et al. Nature 2020

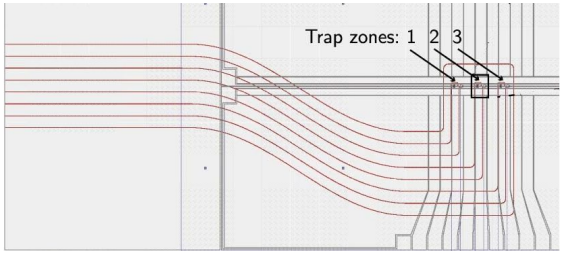


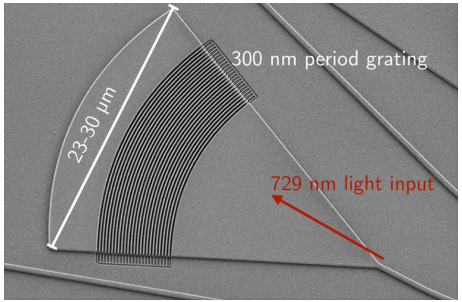
credits: MIT Lincoln Lab
https://www.youtube.com/watch?v=UT3ev90gkmY

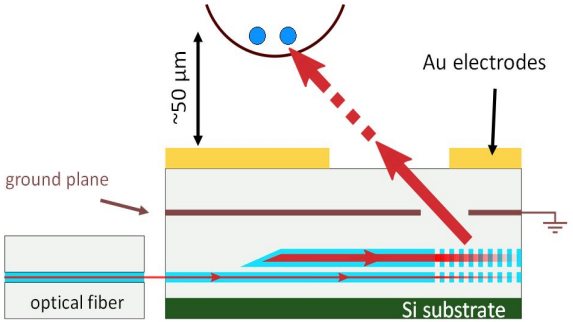
Photonic surface traps at ETH Zürich

Ca+



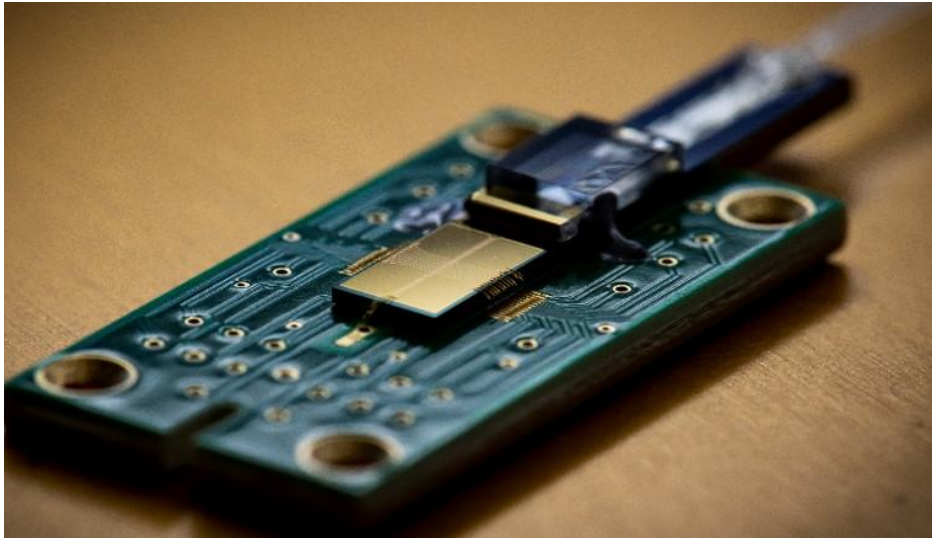






Roadmap

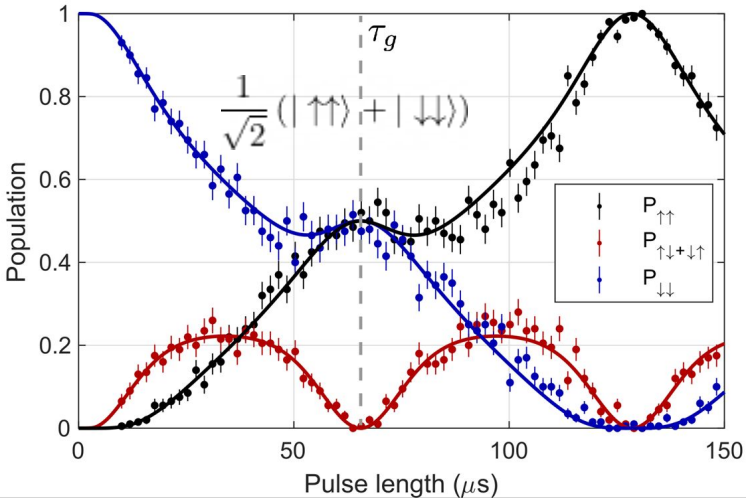
- Single ion operations
  Mehta et al. Nature Nanotech. 2016
- Multi-wavelength integration
  Niffenegger et al. Nature 2020
- Multi-qubit operations
  Mehta et al. Nature 2020
- Engineered light: map of a standing wave
  Ricci et al. PRL 2023
- Engineered light: optical potentials
- Multi-zone trapping and transport
- Multi-zone operations
- Multi-(qubit, wavelength, zone) operations

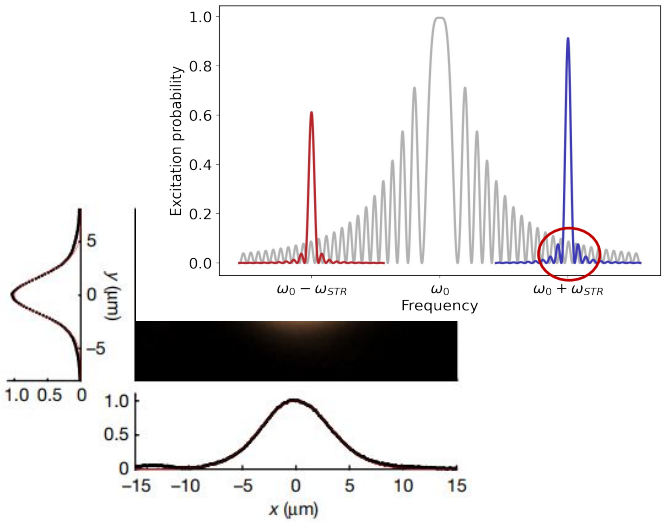


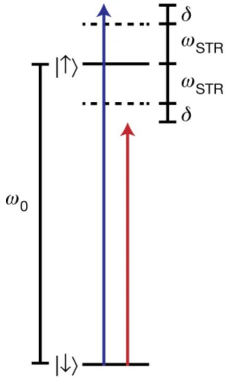
Multi-qubit operations

MS gate using integrated photonics (F = 99.3(2)%)

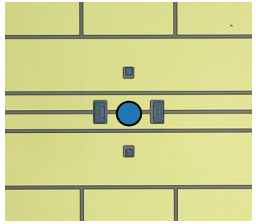
- Beam shape optimized at ions location: high intensity
- No phase noise from vibrations
- Improvement: reduce gate time
  - Requires more laser power
  - Limited by off-resonant exc. of carrier

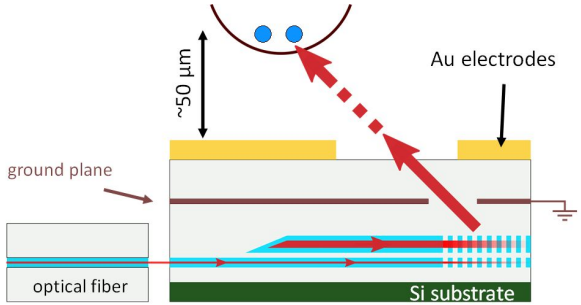






Just add one more beam...

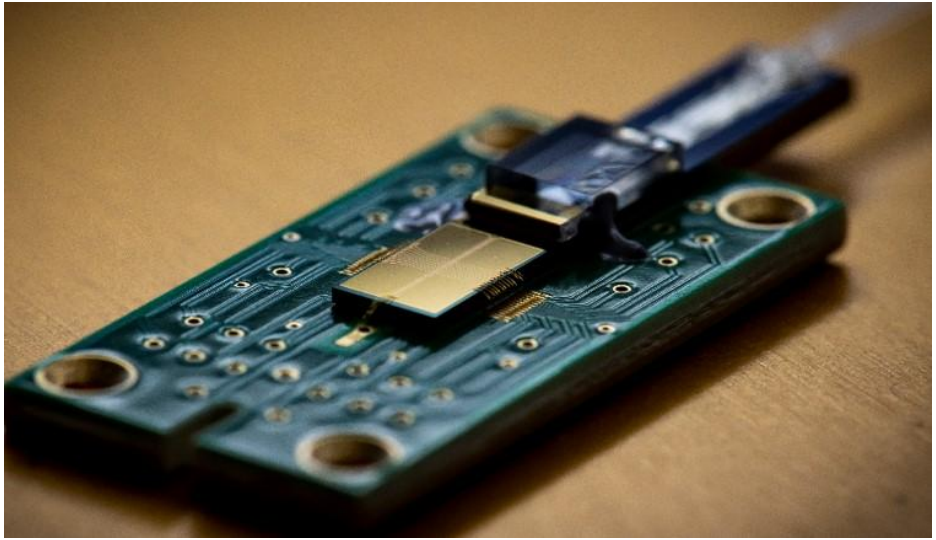




Mehta et al. Nature 2020

Roadmap

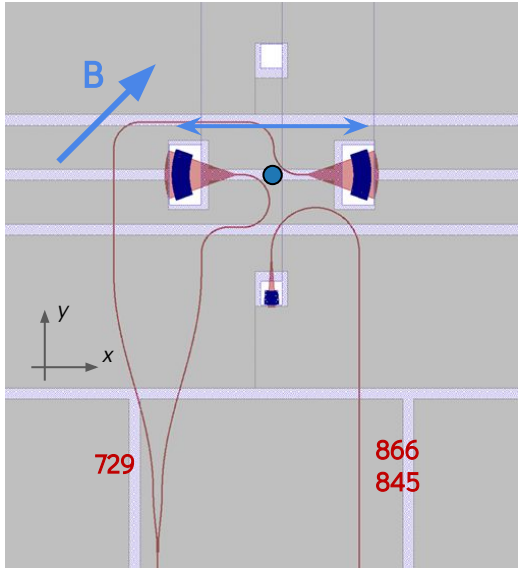
- Single ion operations
  Mehta et al. Nature Nanotech. 2016
- Multi-wavelength integration
  Niffenegger et al. Nature 2020
- Multi-qubit operations
  Mehta et al. Nature 2020
- Engineered light: map of a standing wave
  Ricci et al. PRL 2023
- Engineered light: optical potentials
- Multi-zone trapping and transport
- Multi-zone operations
- Multi-(qubit, wavelength, zone) operations

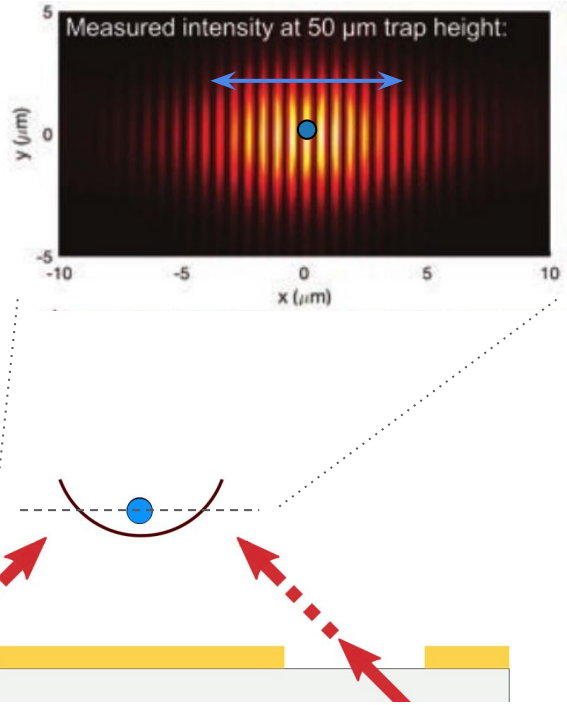


Coupling 1 ion to a standing wave

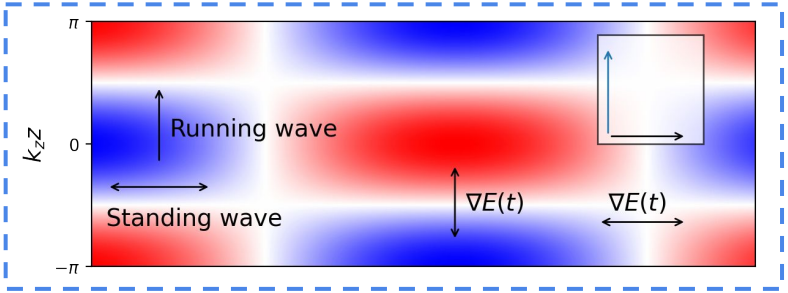
$$E(\vec{r}) \propto e^{i(k_z z)} \cos(k_x x)\mathbf{e}_y$$

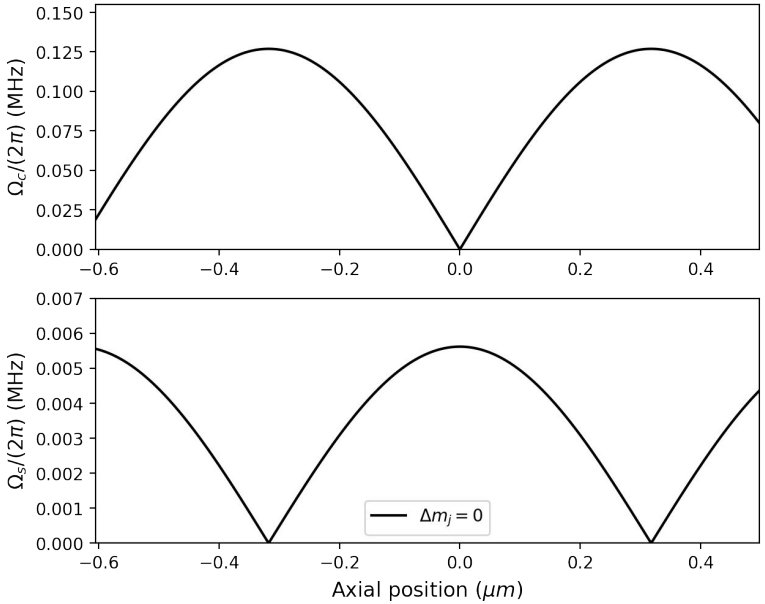
- Selectively null carrier or sidebands removing off-resonant coupling
  Mehta et al. Proc SPIE 2019
- Requires stable positioning of the ion in the interference pattern
  - In a cavity
    Mundt et al, PRL (Innsbruck, 2002)
  - In a stabilized optical lattice
    Schmiegelow et al, PRL (Mainz, 2016)
    WIP in D. Lucas group (Oxford)
- With integrated beams
  - Standing/running wave
  - Passive stability
- Experiment: scan 1 ion through the SW
  Ricci et al, PRL (2023)
  - measure couplings
  - measure Stark shifts
  - measure stability





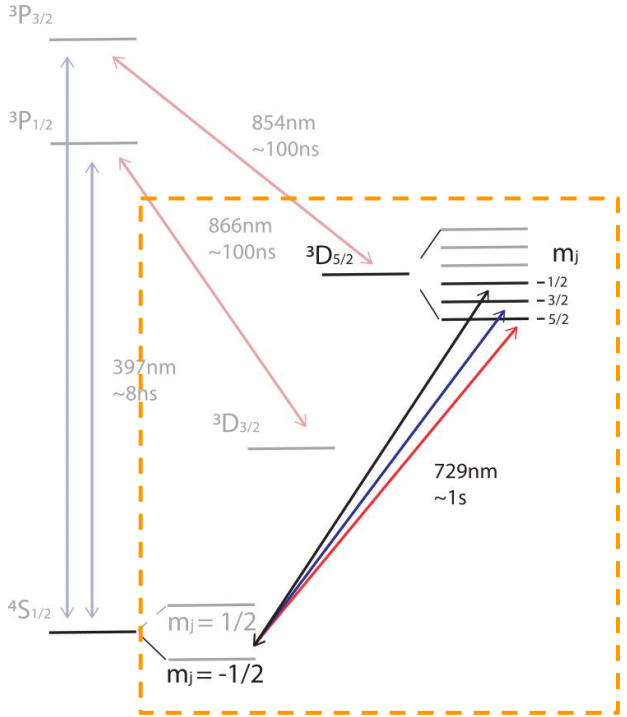
Standing wave: Rabi couplings



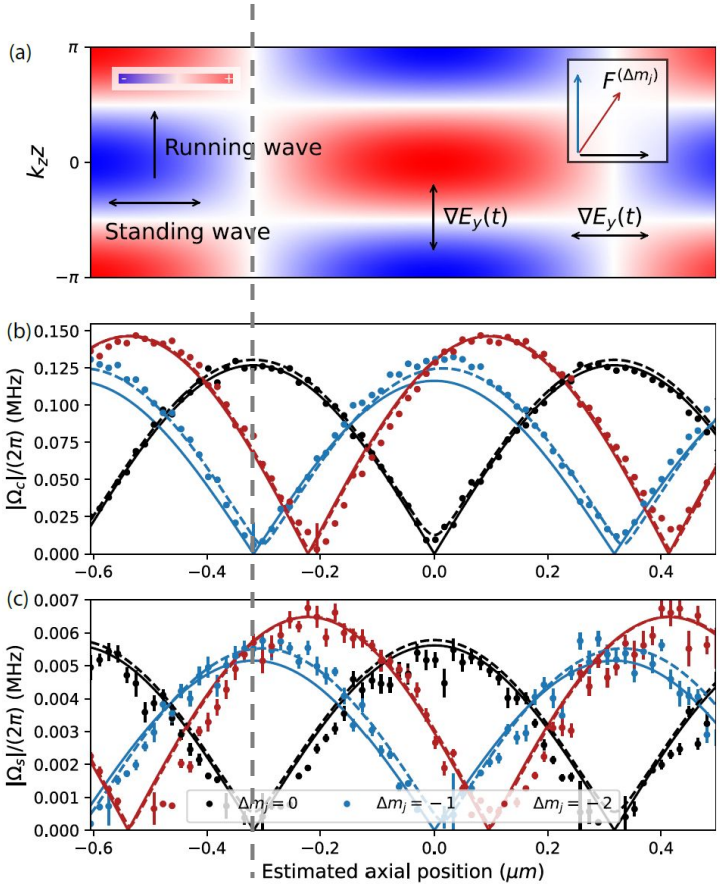


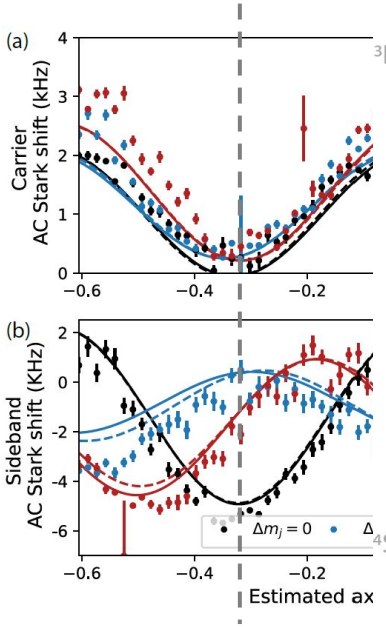
$$E(\vec{r}) \propto e^{i(k_z z)} \cos(k_x x)\mathbf{e}_y$$

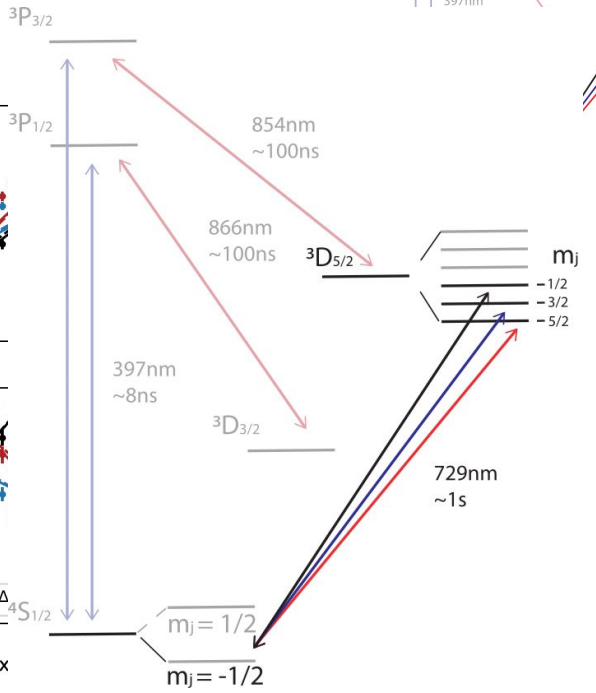
$$\Omega_c \propto \langle g | \hat{r}_i \hat{r}_y | e \rangle \partial_i \mathbf{E}_y$$



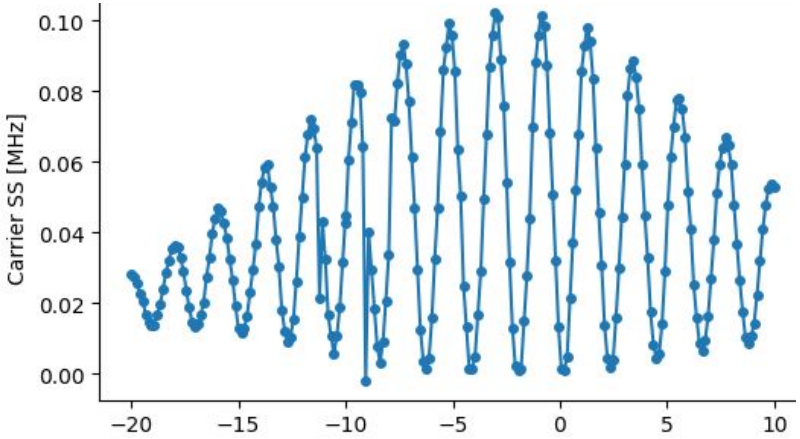
Standing wave: Rabi couplings + AC Stark shifts

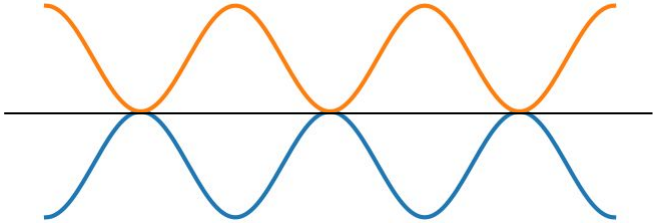






Standing wave: optical potentials



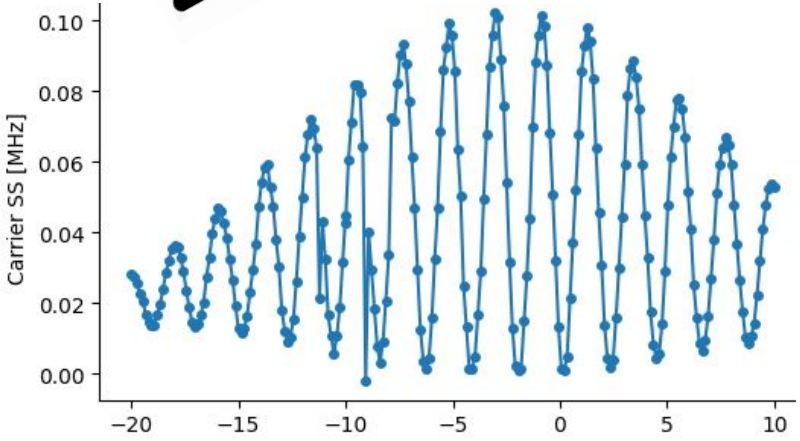


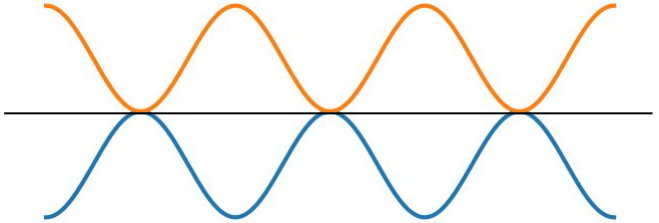
$$\omega\,(a^\dagger a + 1/2) + \Delta\,\sigma_z\cos^2(kx)$$

$$\sim \Delta\sigma_z\,x^2 \rightarrow \omega_c\,\sigma_z a^\dagger a$$

max/min ->
state-dep. curvature

Standing wave: optical potentials





$$\omega\,(a^\dagger a + 1/2) + \Delta\,\sigma_z\cos^2(kx)$$

$$\sim \Delta\sigma_z\,x^2 \rightarrow \omega_c\,\sigma_z a^\dagger a$$

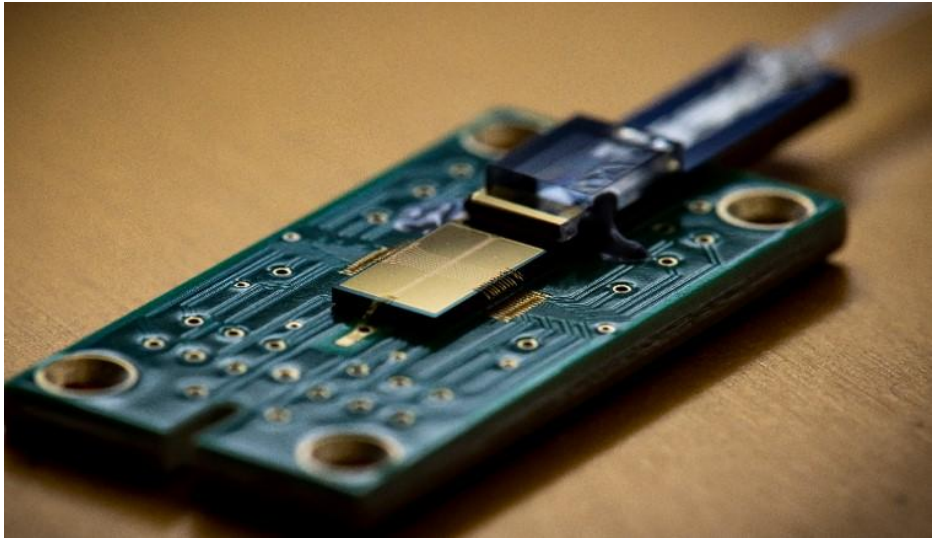
max/min ->
state-dep. curvature

$$\sim \Delta\sigma_z\,x \rightarrow F\,\sigma_z(a^\dagger + a)$$

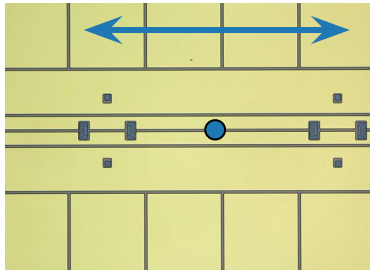
slope ->
state-dep. force

Roadmap

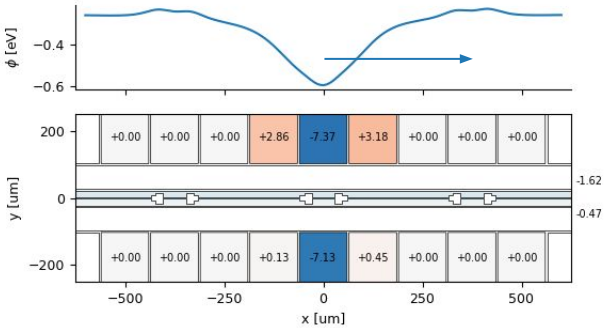
- Single ion operations
  Mehta et al. Nature Nanotech. 2016
- Multi-wavelength integration
  Niffenegger et al. Nature 2020
- Multi-qubit operations
  Mehta et al. Nature 2020
- Engineered light: map of a standing wave
  Ricci et al. PRL 2023
- Engineered light: optical potentials
- Multi-zone trapping and transport
- Multi-zone operations
- Multi-(qubit, wavelength, zone) operations

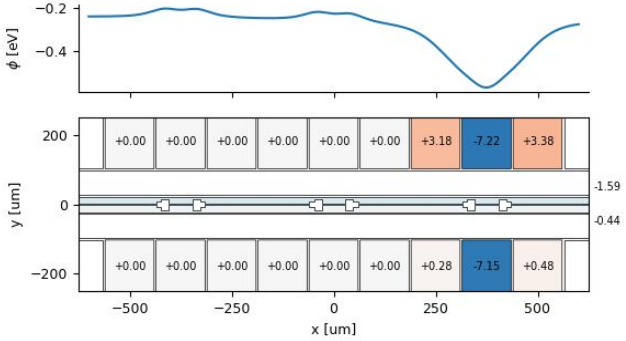


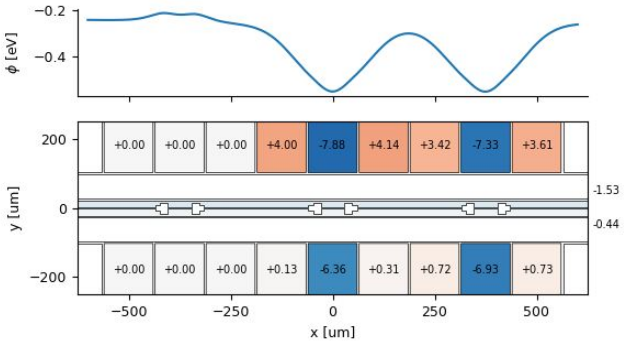
Multizone operations: multiple trapping sites



shuttling between zones *

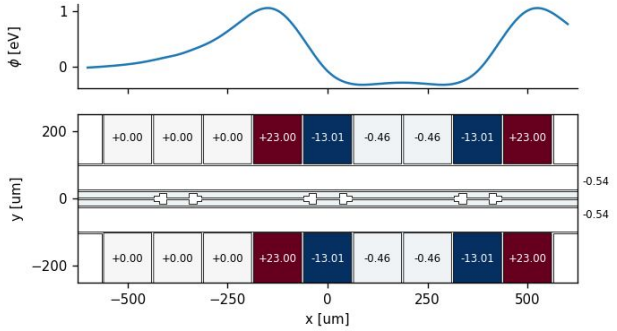






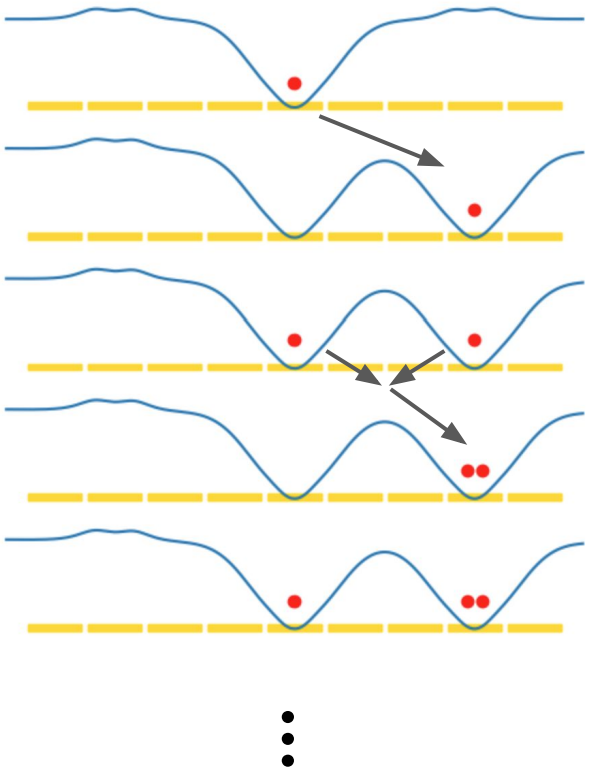
ions in multiple zones

splitting/merging ion crystals

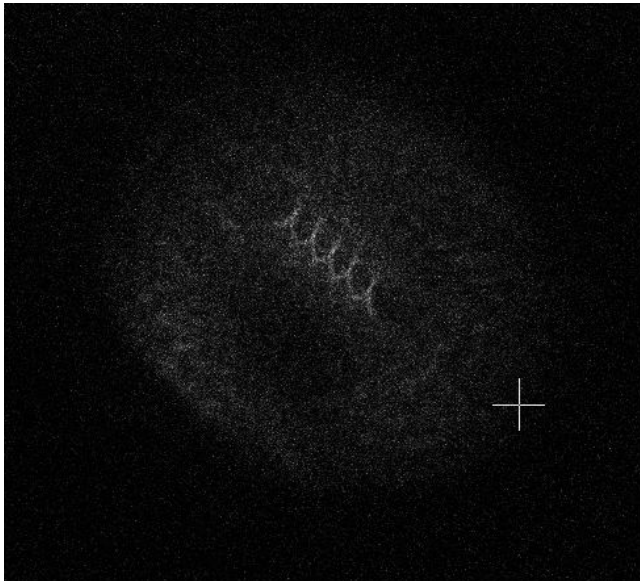


* The optical couplers start to be bothering if you want to go fast!

Multizone operations: loading from dedicated zone



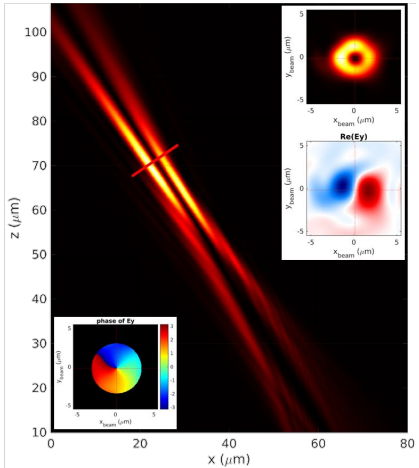
- fully compatible with waveguide couplers
- faster loading of multiple ions
- no stray fields from PI:
  less drifts and calibrations

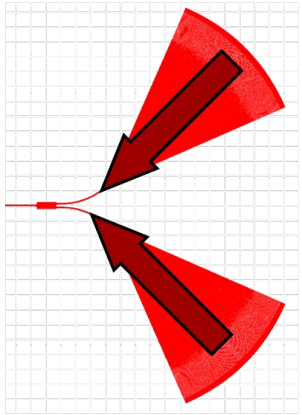


Next-gen: engineered light beams

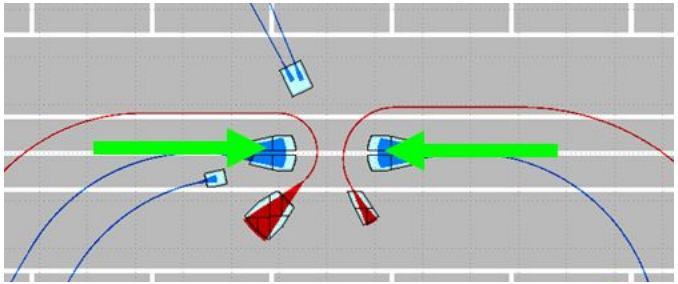
All wavelengths integrated:

Silicon nitride / alumina waveguides





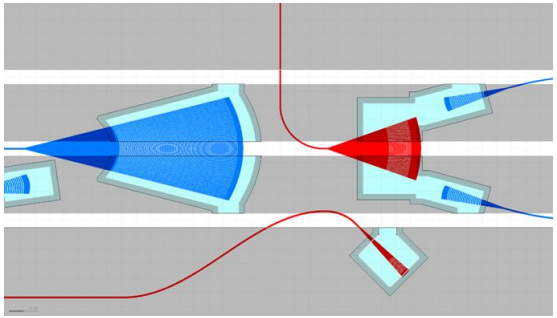
Vortex beams
(qubit, optical trapping)



SW at 532 for light-shift gate

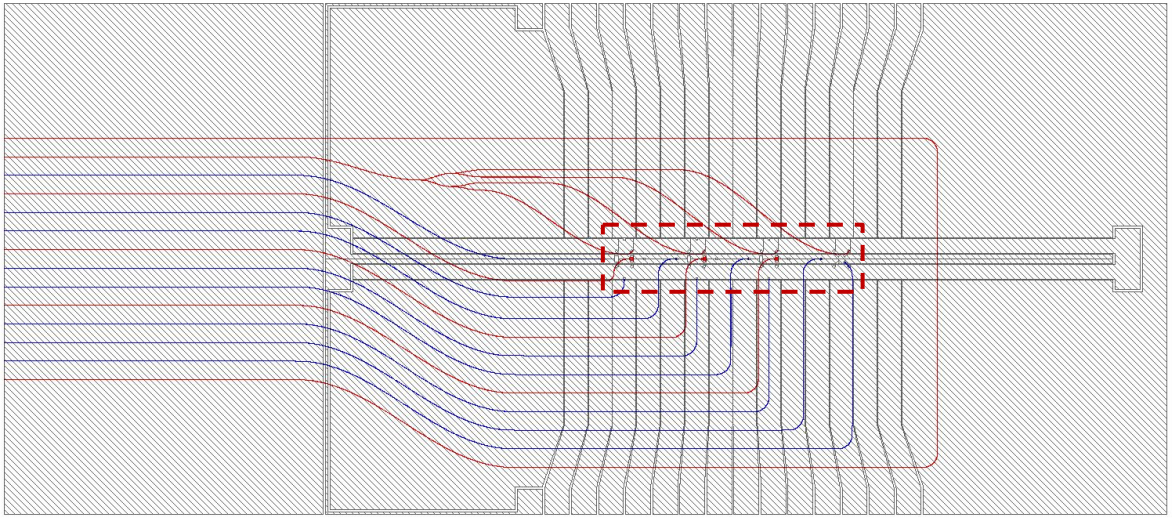
Clark, PRL (2021)

397 collection / cooling

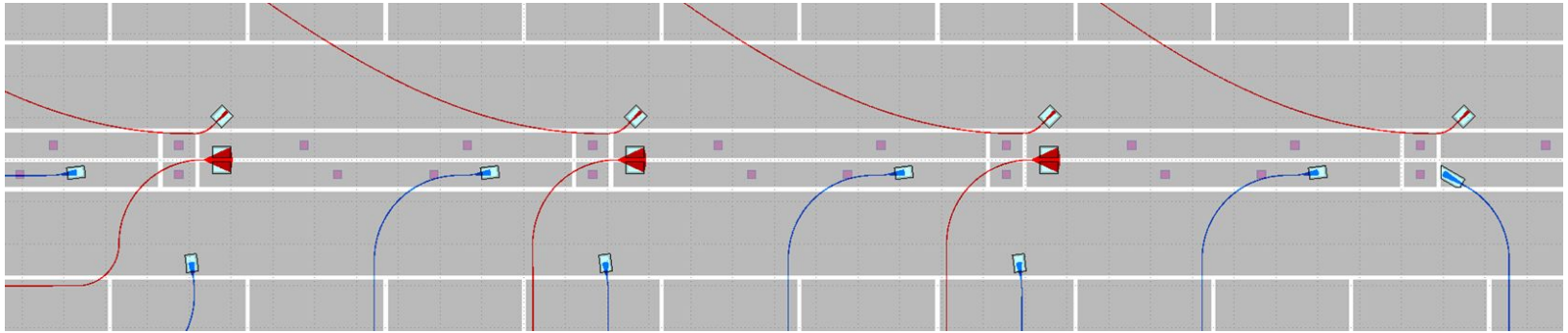


Credits: Karan Mehta, Gillen Beck

Next-gen: multizone fully integrated chip



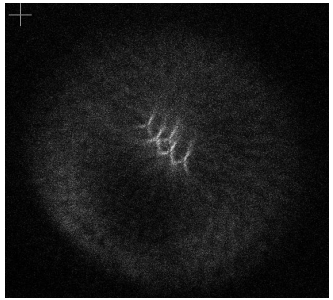
- Si_3N_4 / Al_2O_3
- ITO coverings
- 1 loading + 3 gate zones
- full integration: cooling + gates

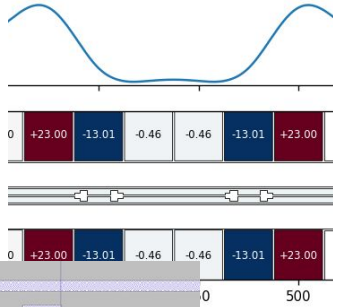


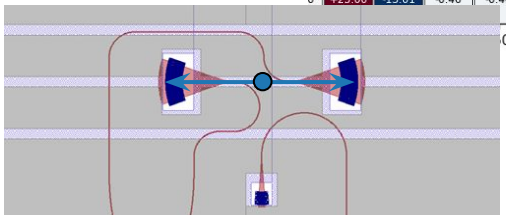
TIQI

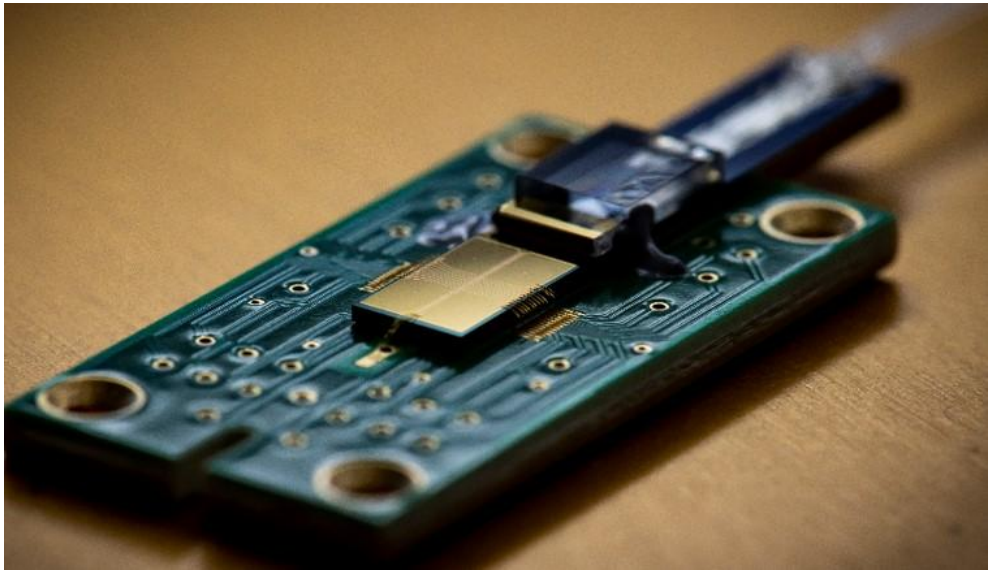
Jonathan Home
Daniel Kienzler
Karan Mehta
Chi Zhang
Maciej Malinowski
Gillen Beck
Alfredo Ricci
Chloé Vernière
CM
Bettmeralp (CH)
21/08/2022

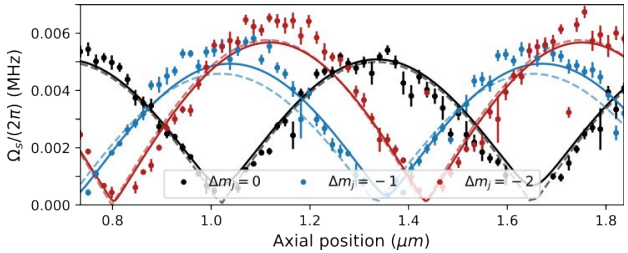
Thank you









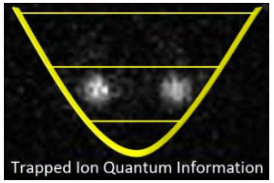


cmordini@phys.ethz.ch

FNSNF

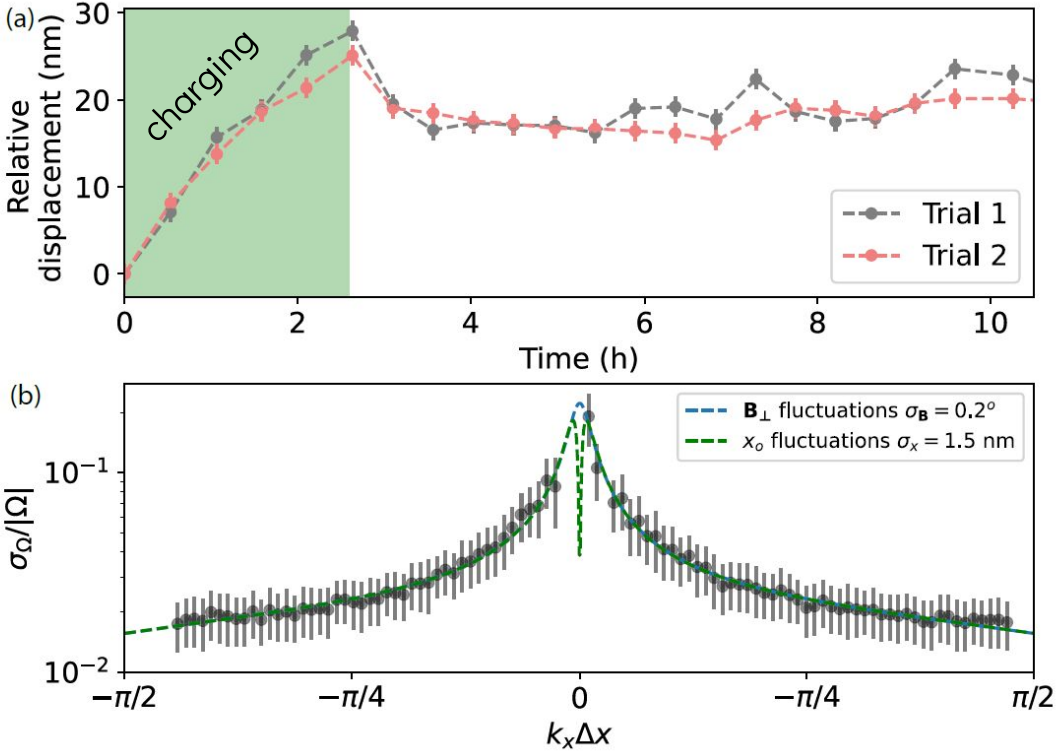
QSIT Quantum Science and Technology
National Centre of Competence in Research

ETH zürich



Standing wave: drift and fluctuations

Here we have a pretty precise ruler!

- Drifts: repeatedly measure ion/SW relative position from the Rabi pattern
  - (long term) shift from PI light

- Noise: measure flop decay vs position explained by
  - noisy B field orientation
  - noisy ion position (σ_V = 50 μV)