Integrated photonics for trapped-ion quantum science

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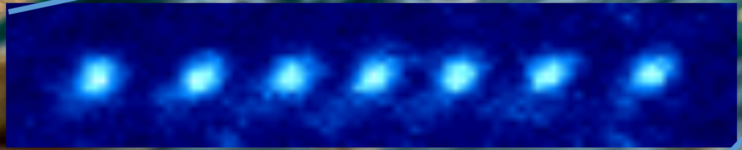

Science to Shape the Future of the Army – Army Research Office 1951
Office of the Director of National Intelligence IARPA Be the Future
FNSNF Swiss National Science Foundation
erc European Research Council Established by the European Commission
European Innovation Council
ALUVIA PROJECT
Innosuisse

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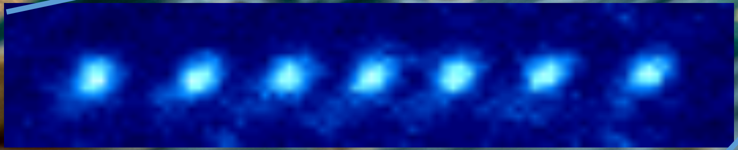

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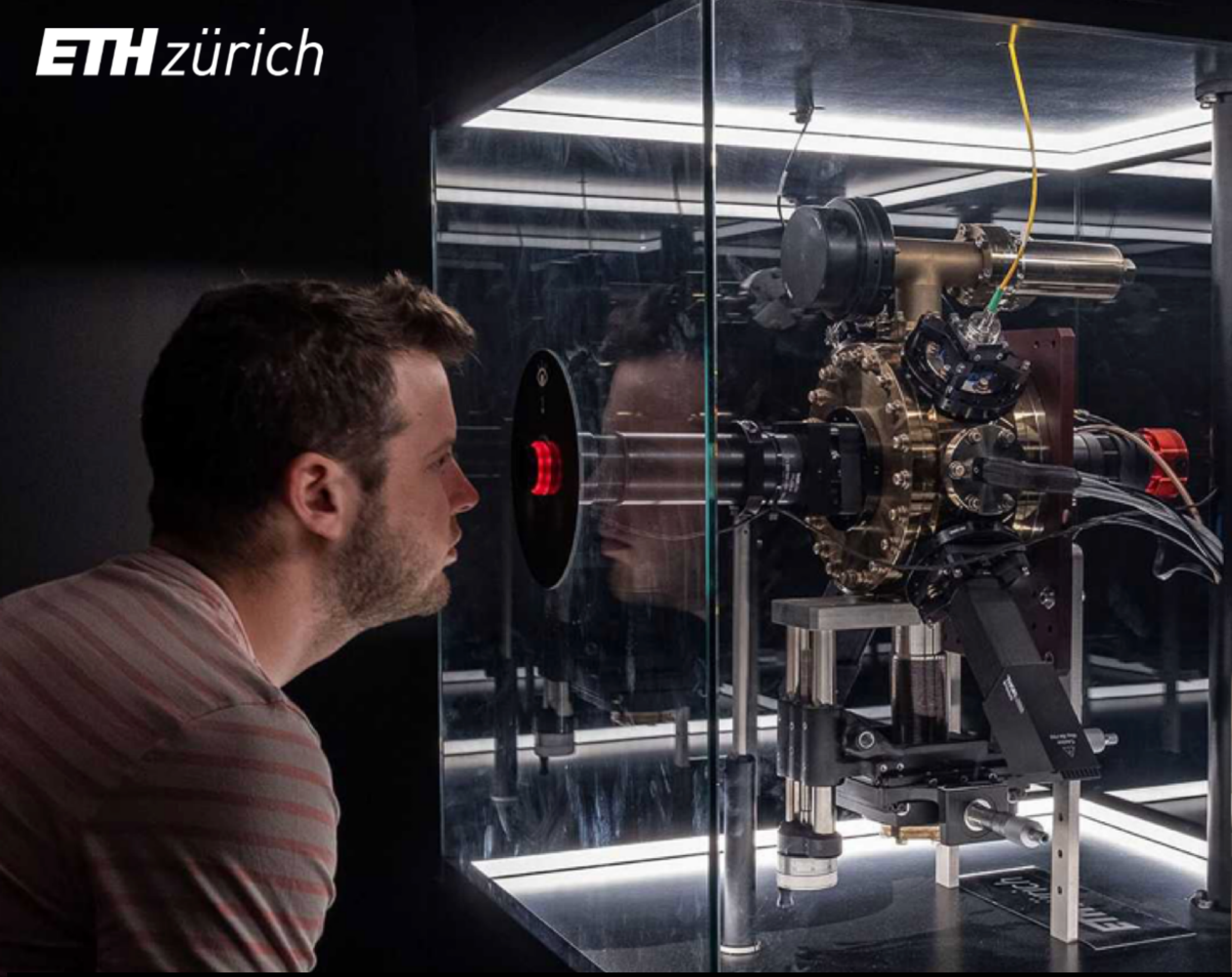
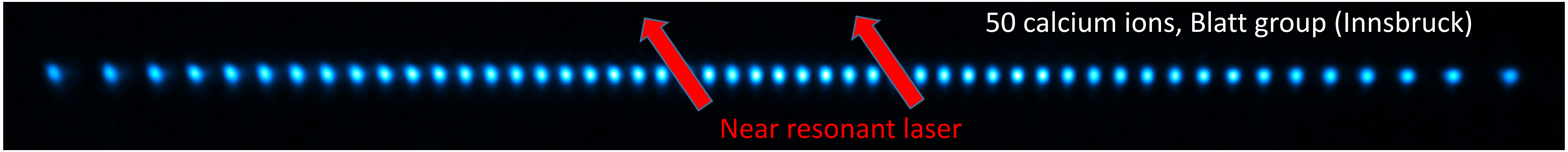


A stable, simple system, but much higher complexity needed for scaling quantum science

“Linear chain” Trapped-Ion Quantum Computing

Ion chain is semi-rigid: all ions can be coupled



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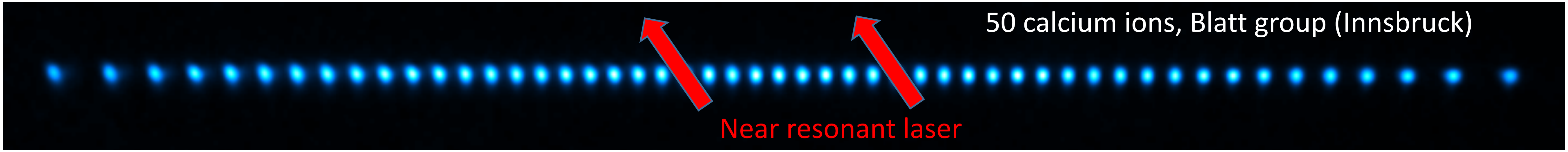


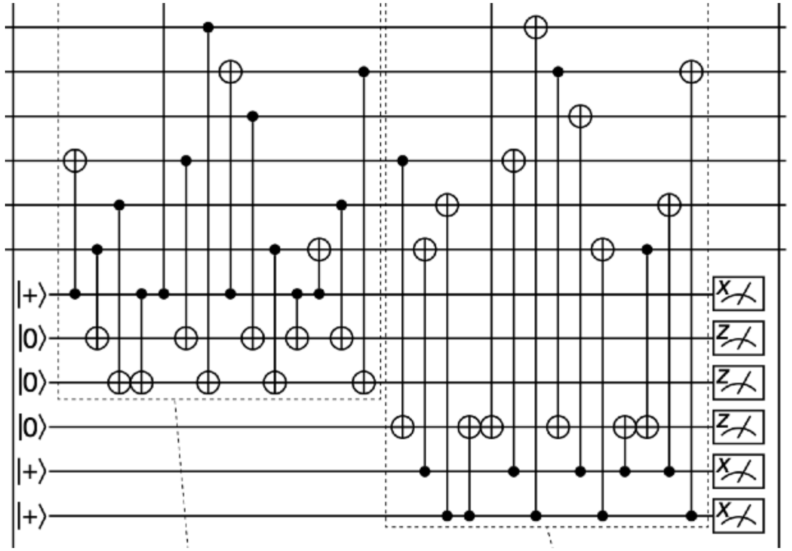
NISQ

- quantum simulation experiments etc. with 50 qubits
- Variational algorithms with up to 20 qubits
- Basic error correction gadgets
- All-to-all connectivity, flexible

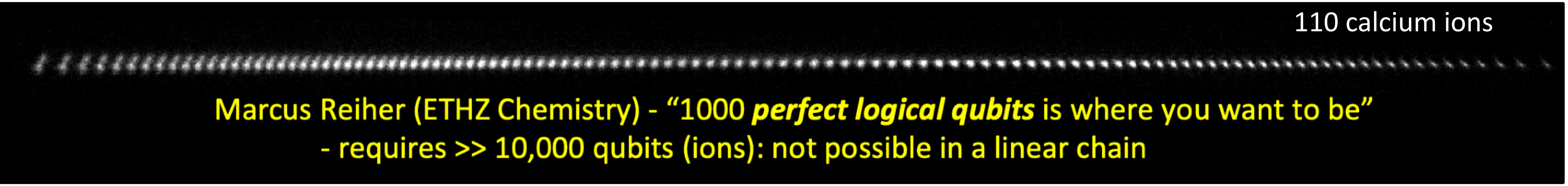
AQT IONQ

Error-Corrected

Fault-tolerant gate set on logical qubit (Innsbruck, Aachen)
Postler et al. Nature 605, 675–680 (2022)



Modular trapped-ion quantum computing



Marcus Reiher (ETHZ Chemistry) - “1000 ***perfect logical qubits*** is where you want to be”

- requires >> 10,000 qubits (ions): not possible in a linear chain

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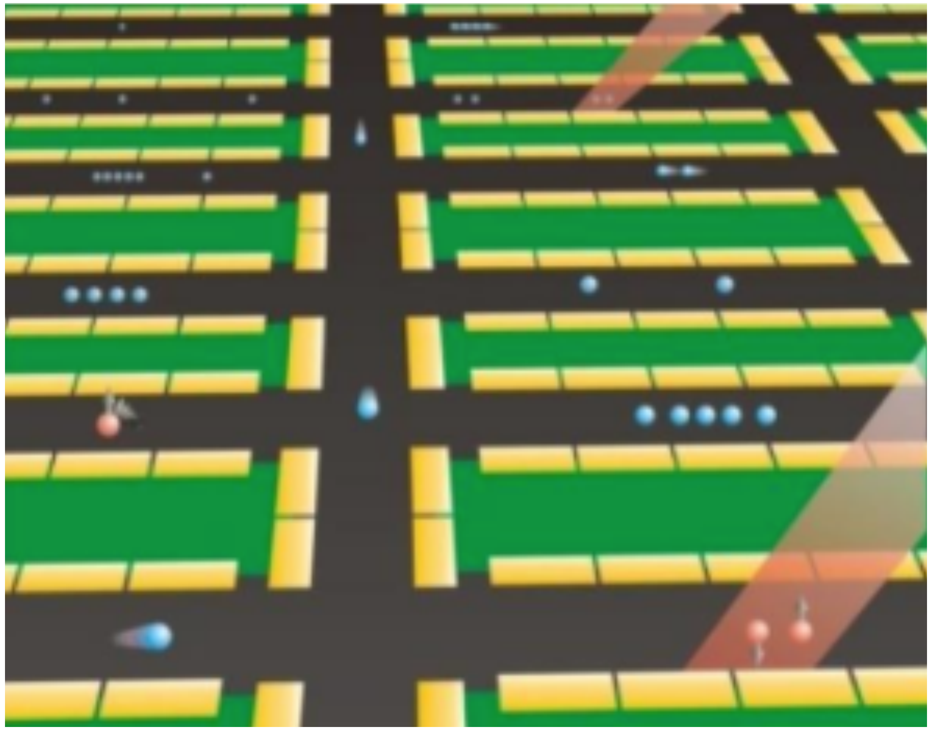
Quantum CCD: split + shuttle

Wineland et al. 2000



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110 calcium ions

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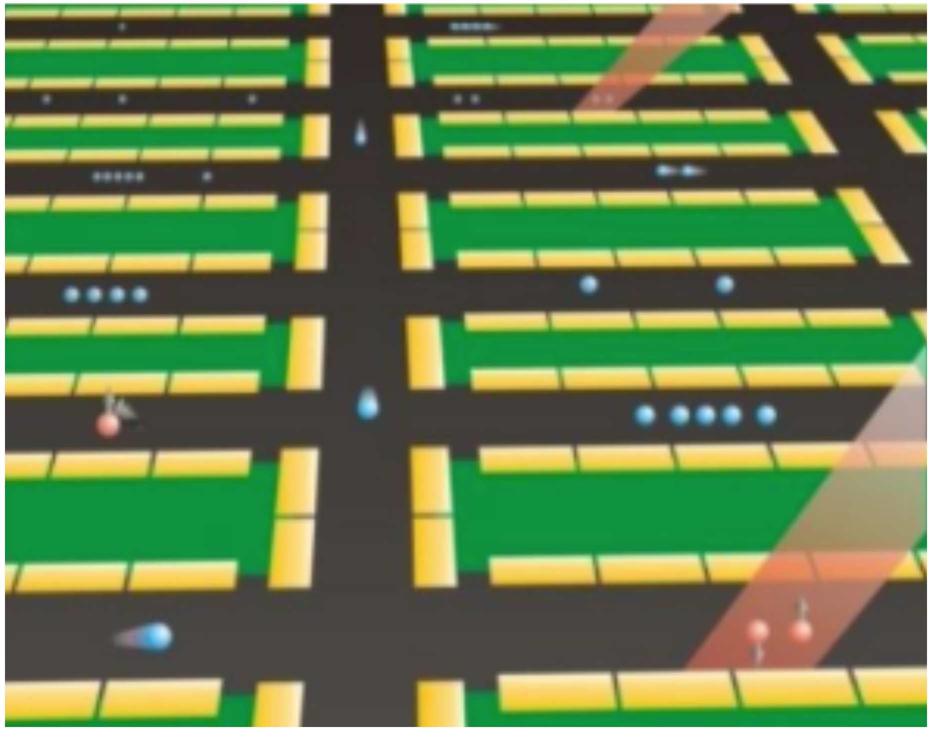
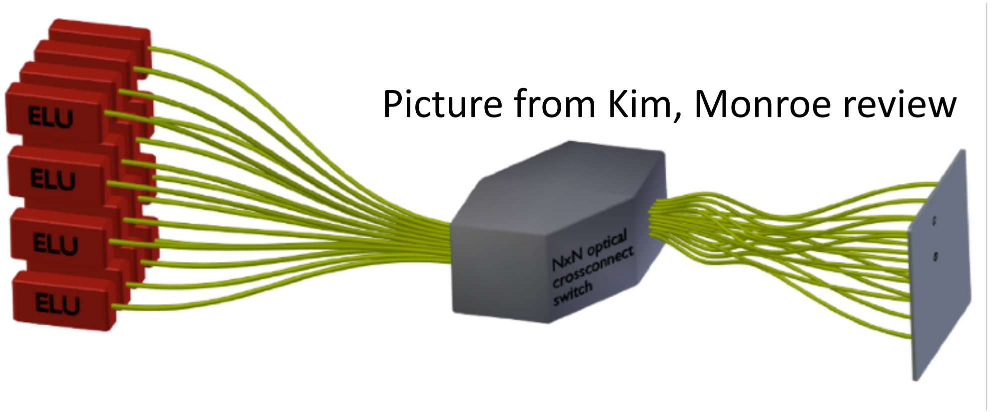


Photonic links:

probabilistic remote entanglement

Duan, Cirac, Zoller, Lukin et al. (2000)



Picture from Kim, Monroe review

Modular trapped-ion quantum computing

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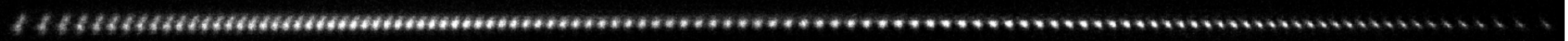

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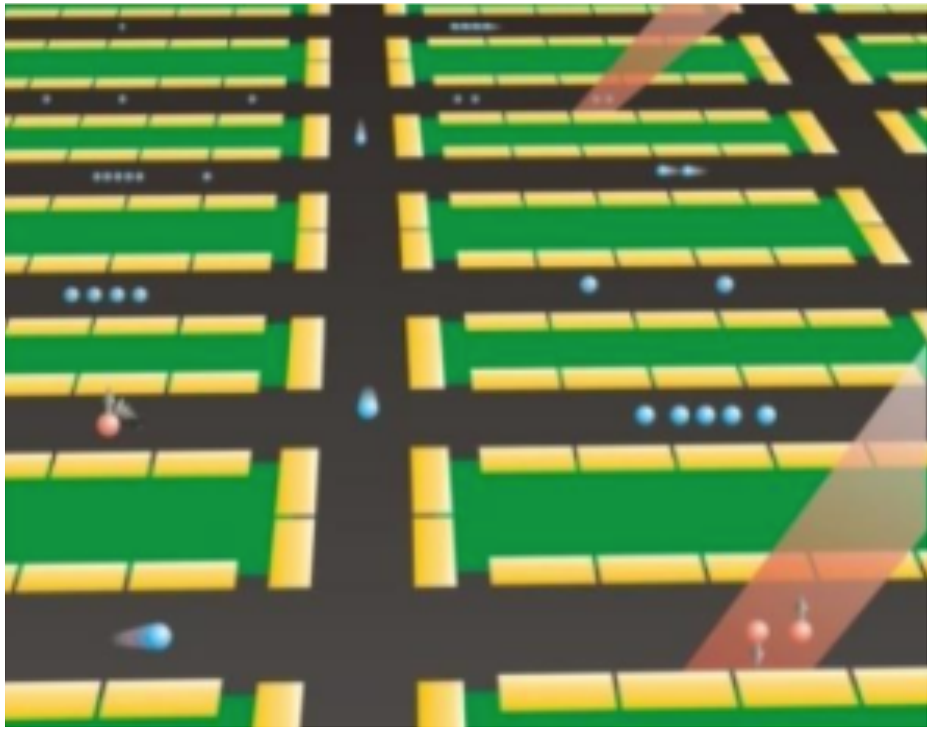

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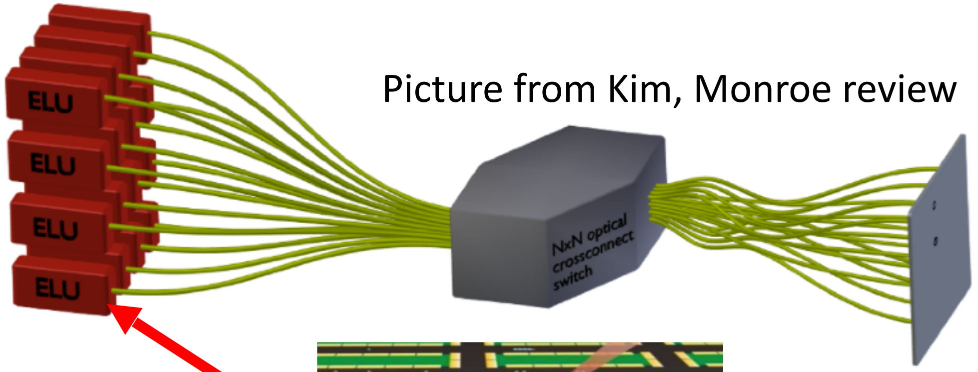

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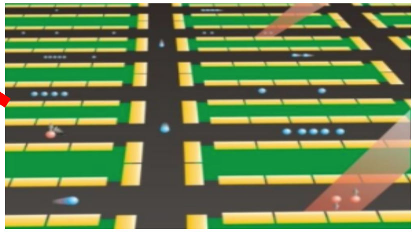
Hybrid



Quantinuum “56 qubit” device (QV 20 qubits): following QCCD approach

- “A Race Track Ion Trap Quantum Processor” Phys. Rev. X 13, 041052 (2023)
- Repeated QEC (Steane code): PRX 11, 041058 (2023)
- Random (fully connected) circuits on 56 qubits https://arxiv.org/pdf/2406.02501

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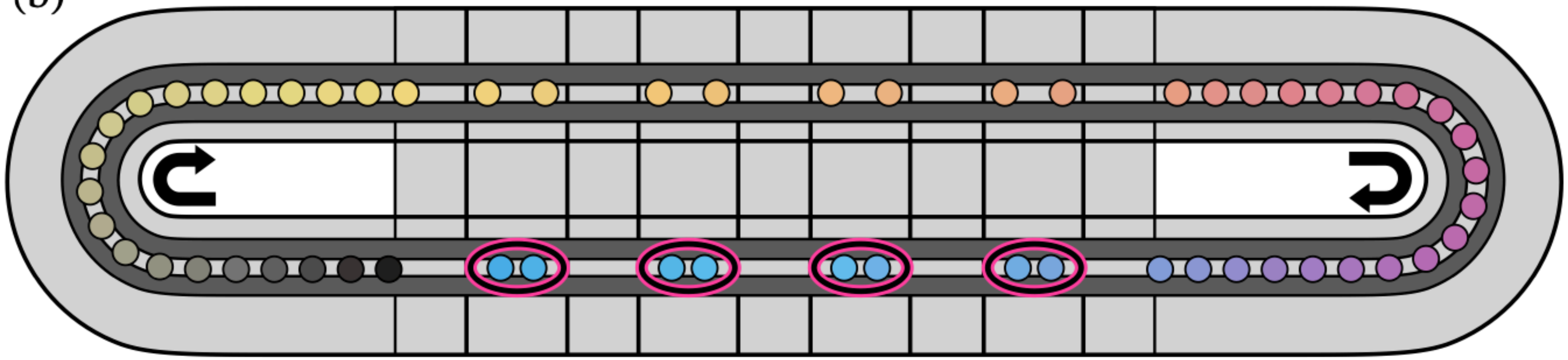

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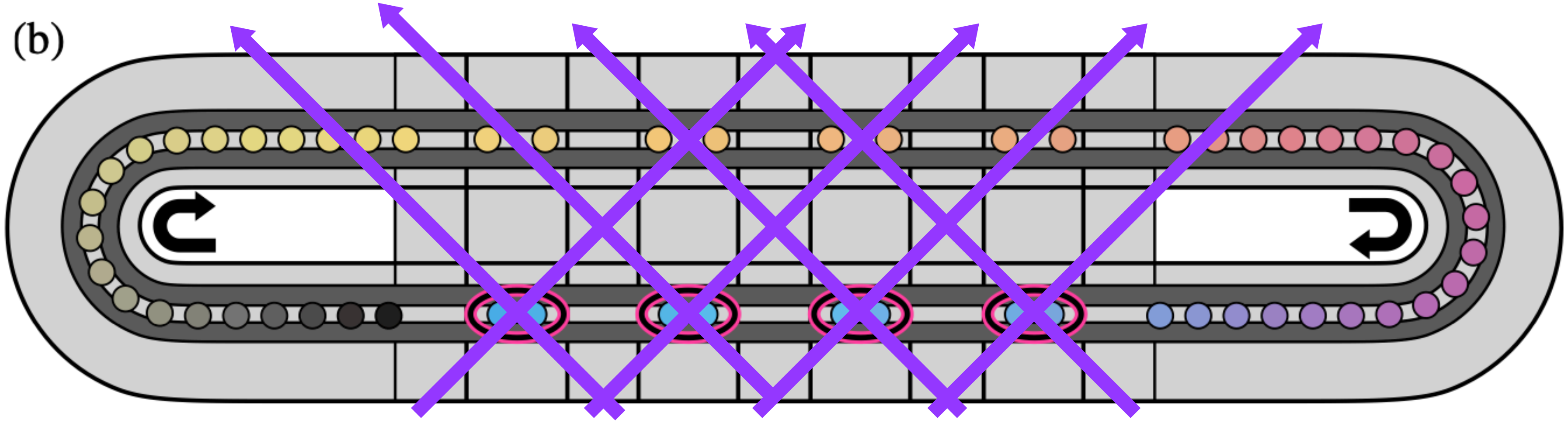

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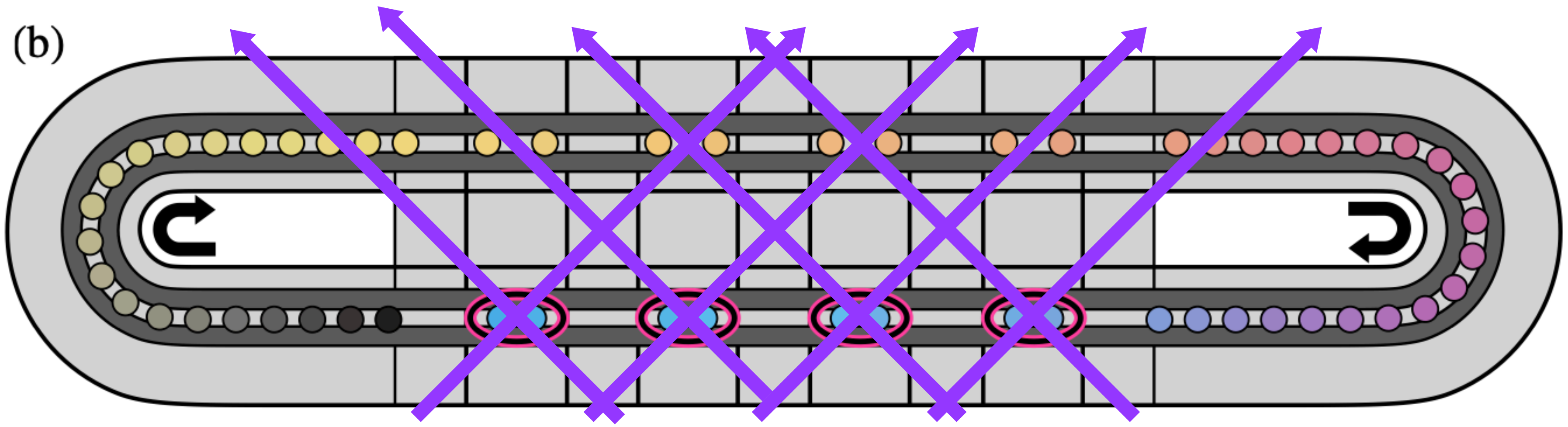
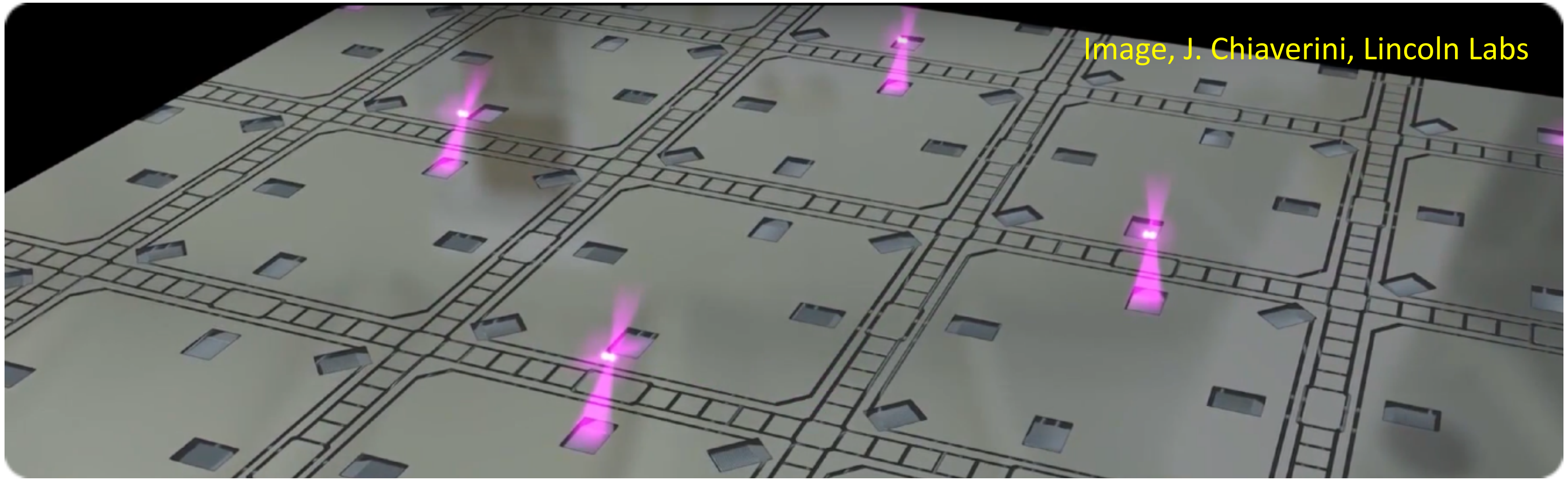


- Light delivered in free space to 4 zones

Integrated optics in ion trap chips



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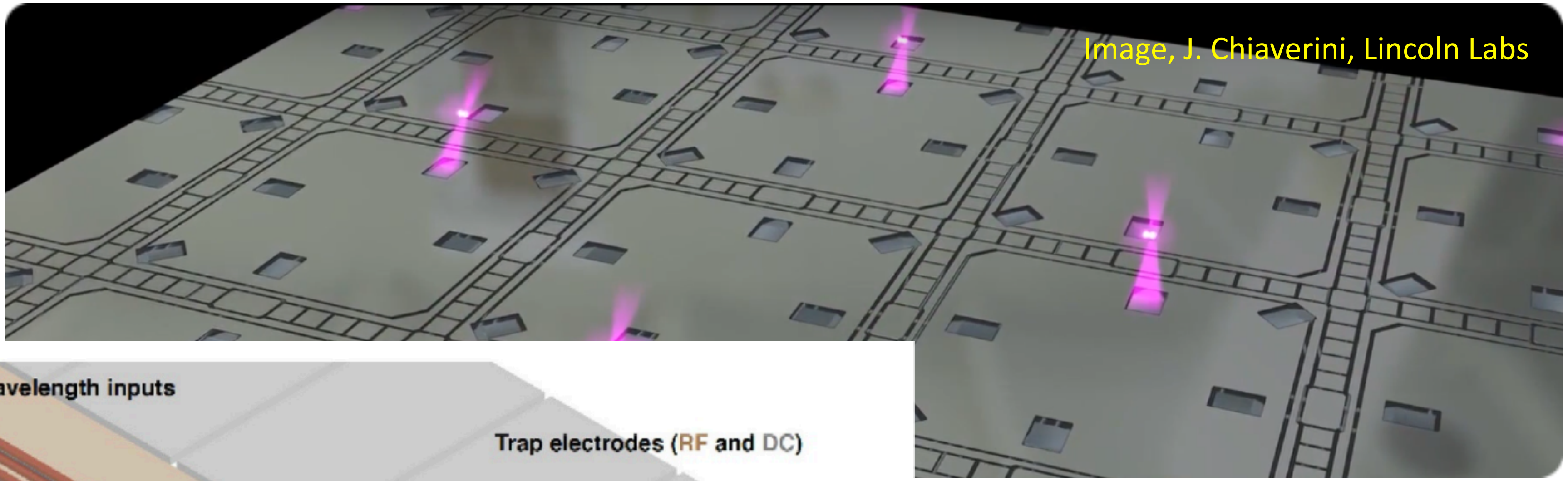
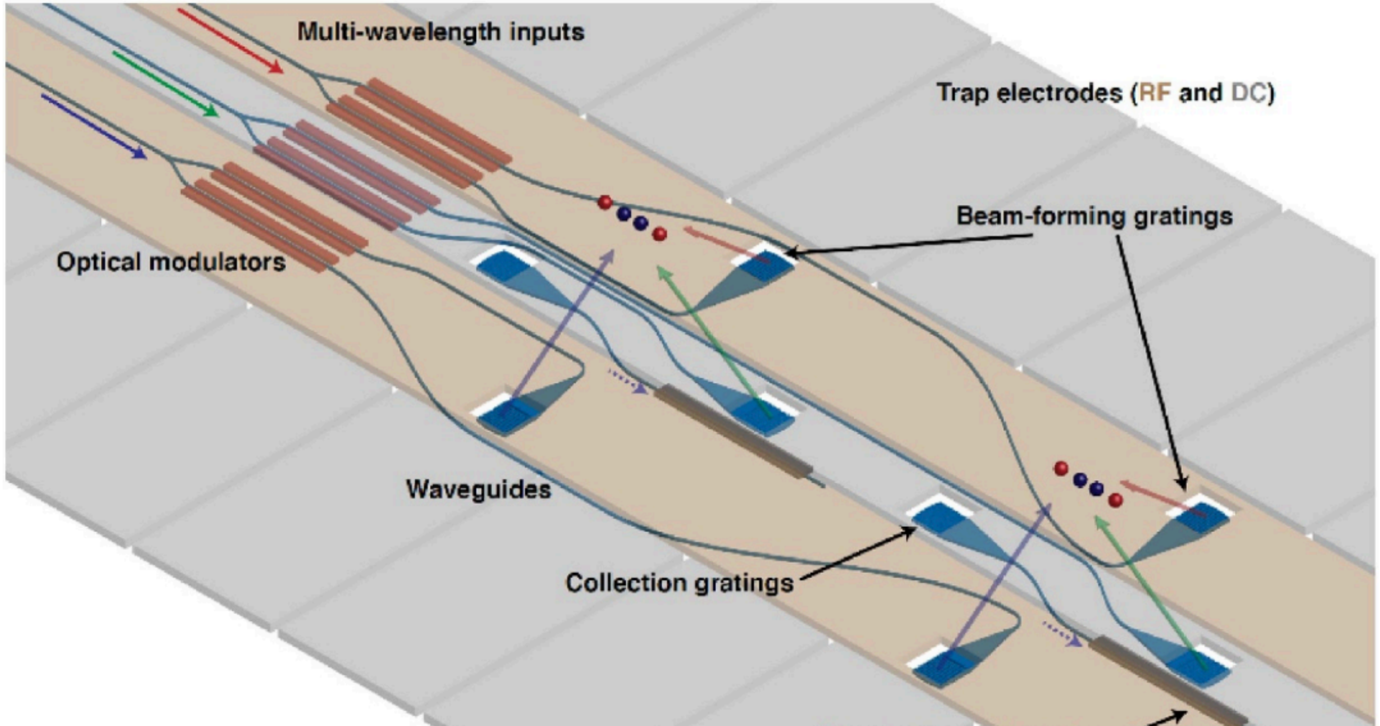
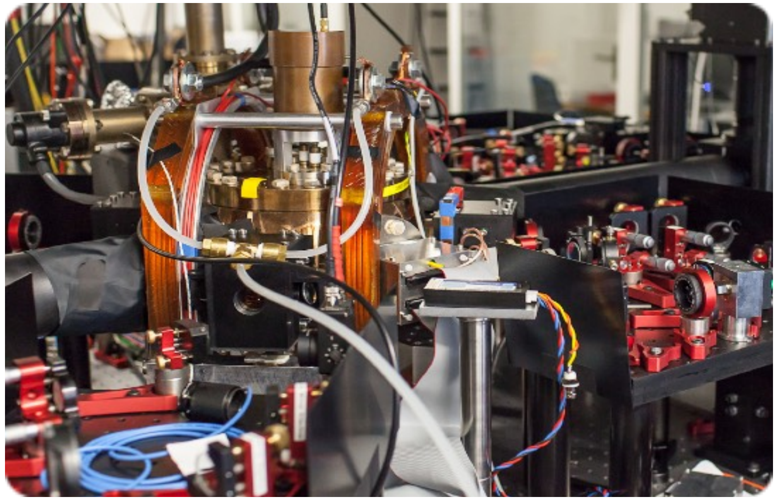


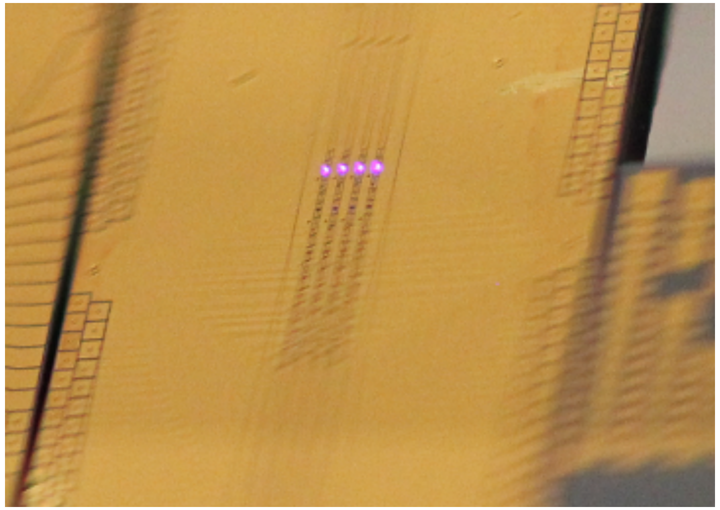


K. Mehta, also in J. Phys. Photonics 4 (2022)

- Integrated light delivery (multiple colours)
- Integrated light collection (near UV)
- Compatibility with high voltage RF (100 V, 40 MHz)
- Scalable modulation + detection?

An “optically wired” ion trap processor





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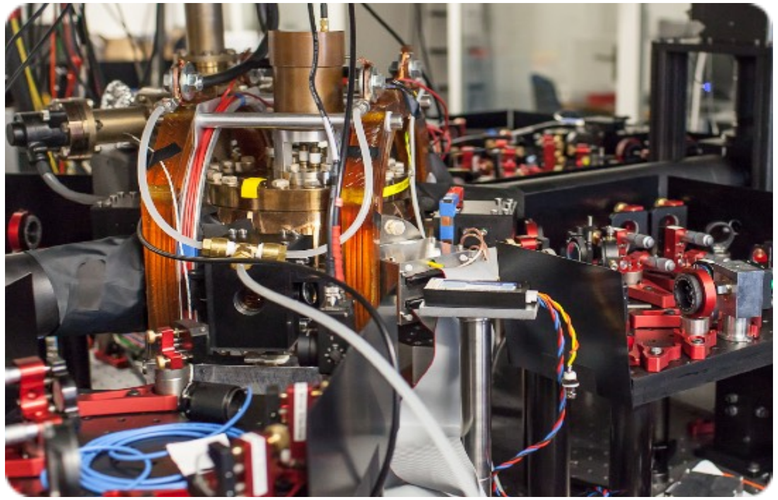
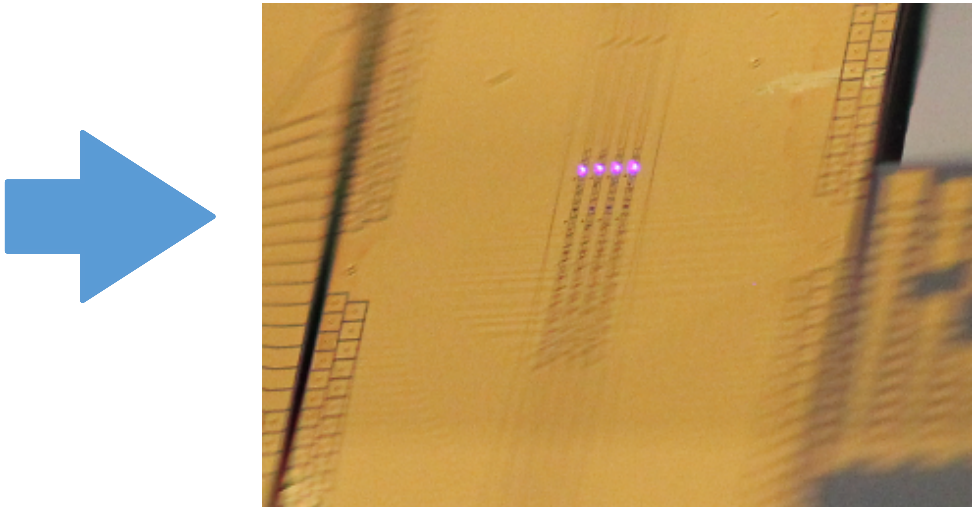
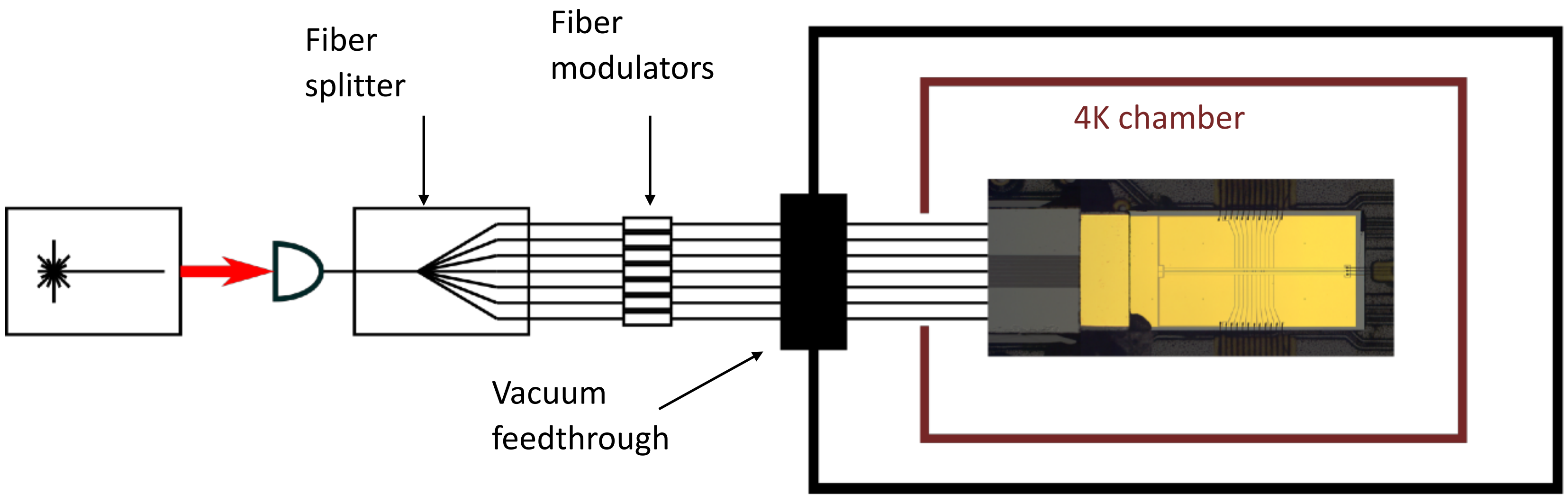


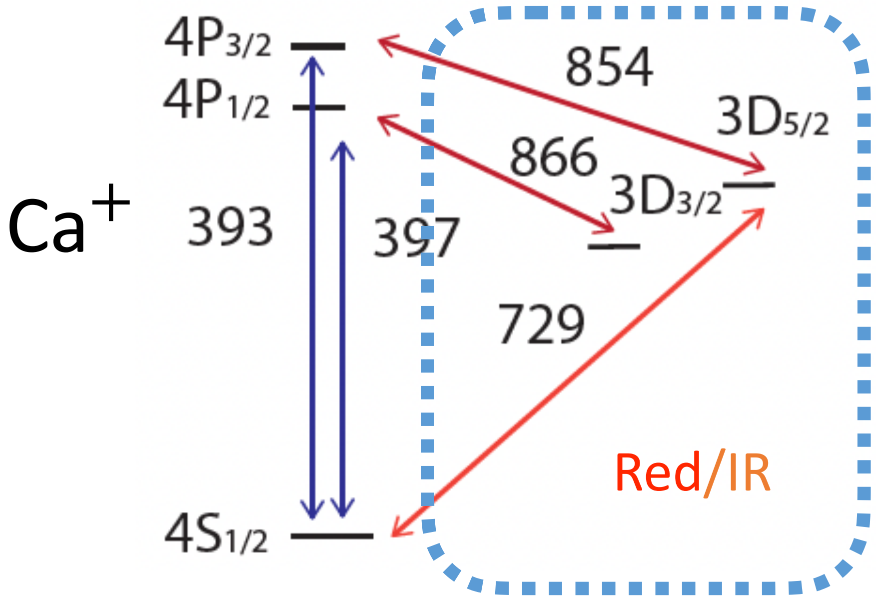


First steps: passive chips,
fibre-based approach



An “optically wired” ion trap processor - 1st ETH generation

K. Mehta et al. Nature 586, 7830 (2020)



MIT + Lincoln labs, strontium ions: K. Mehta et al. Nature Nano 11 1066 (2016), first single-qubit gates

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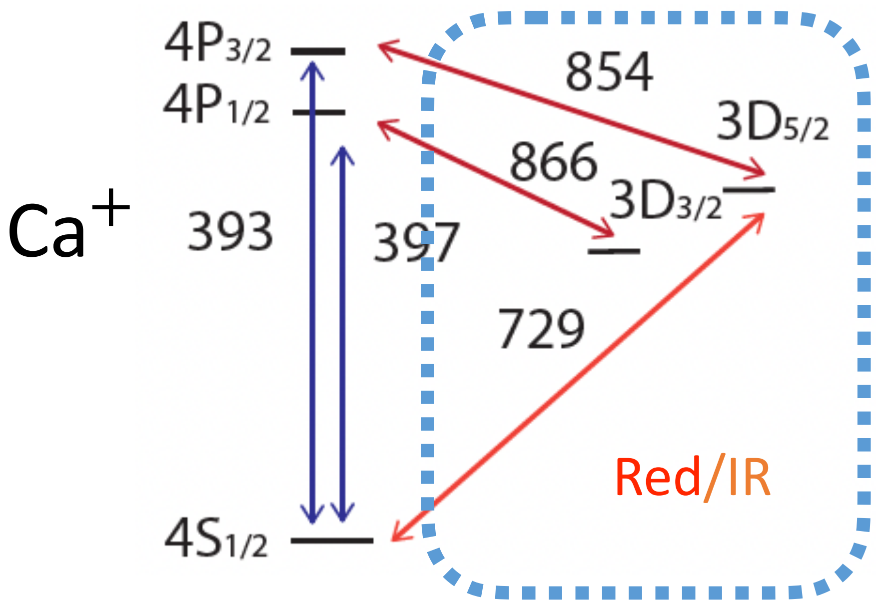

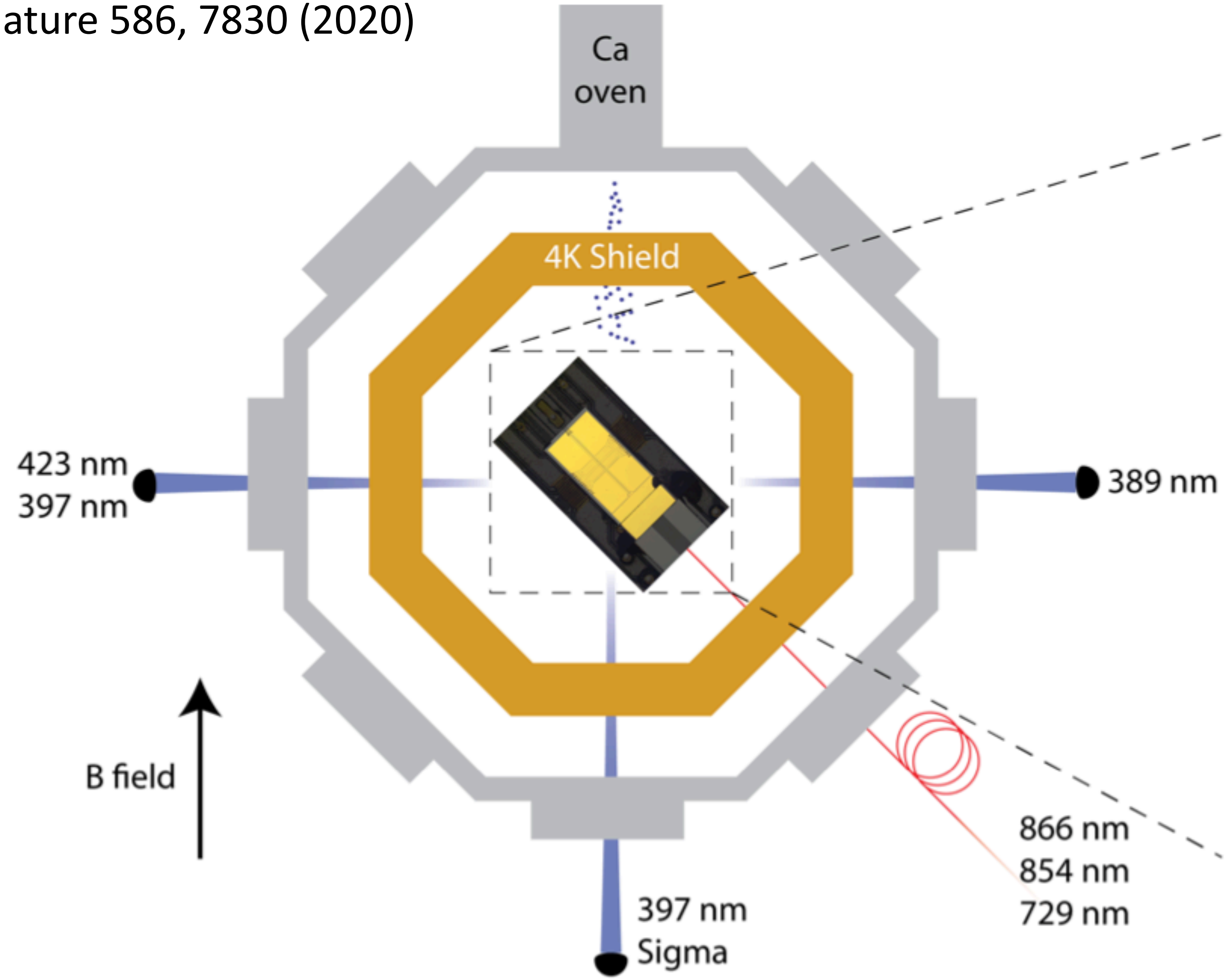

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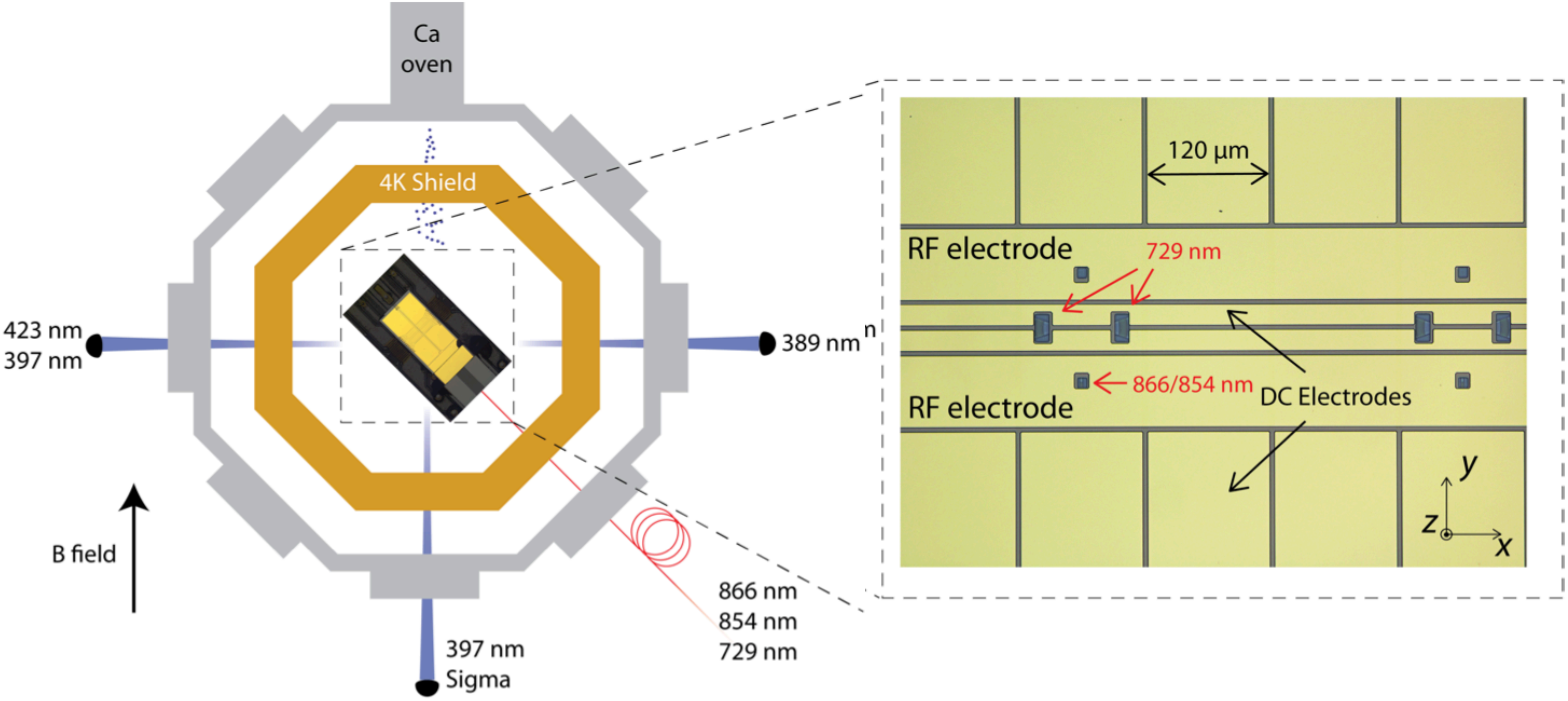
Integrated waveguide chips: ETH no. 6



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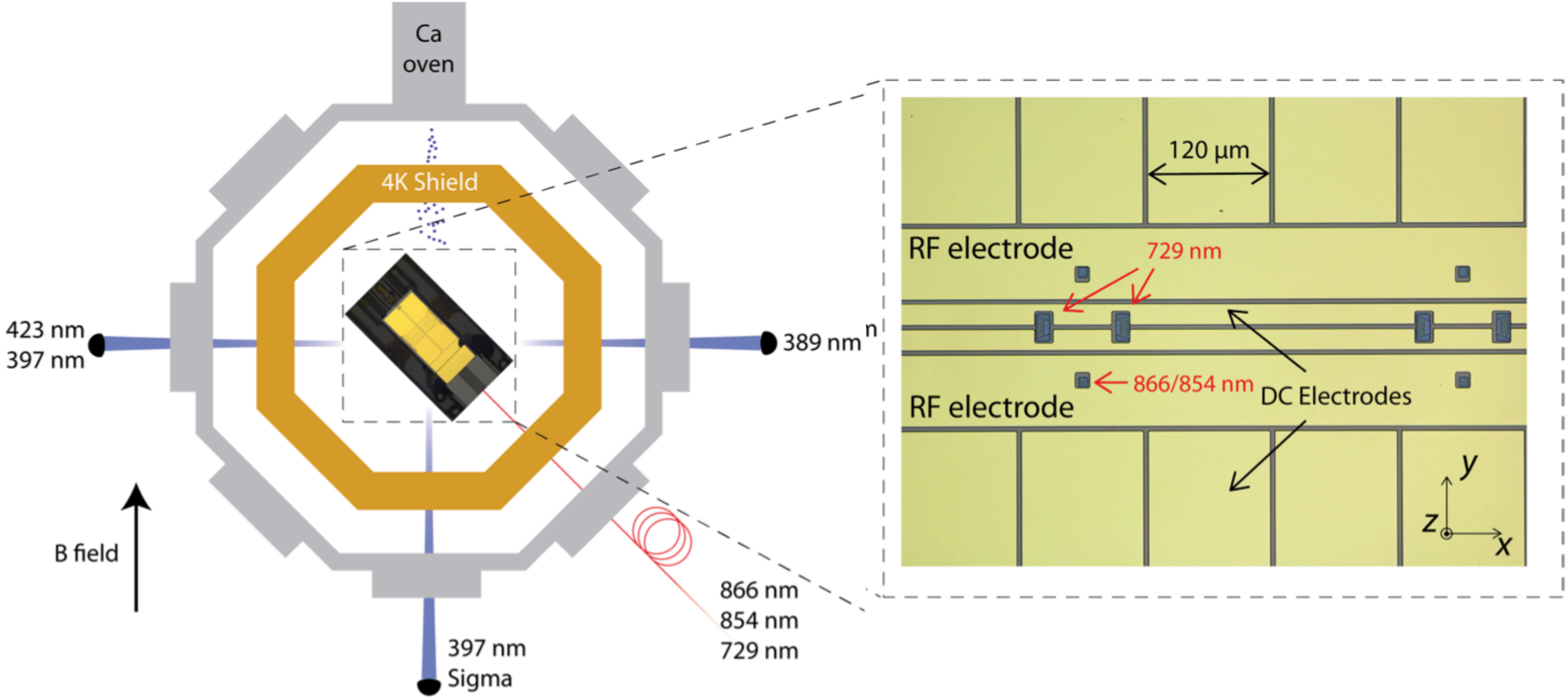

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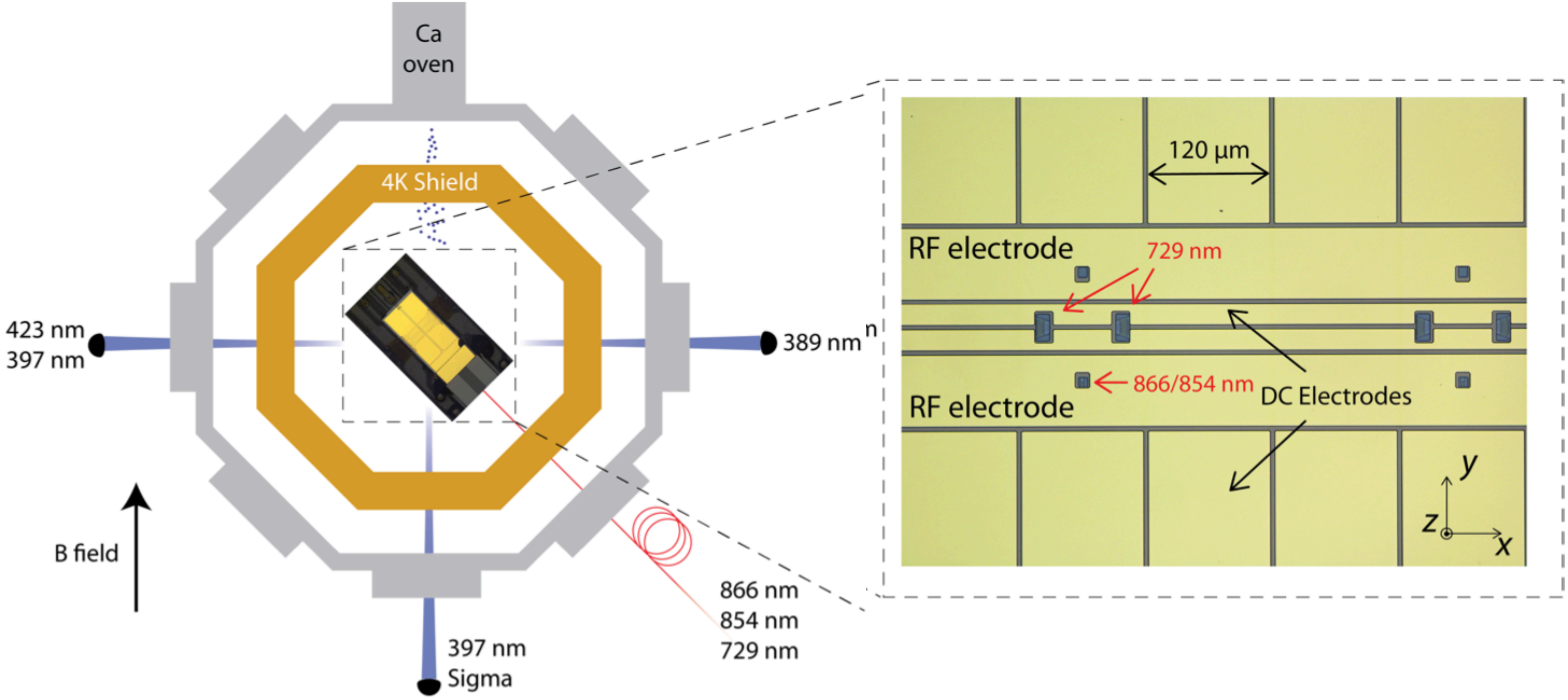

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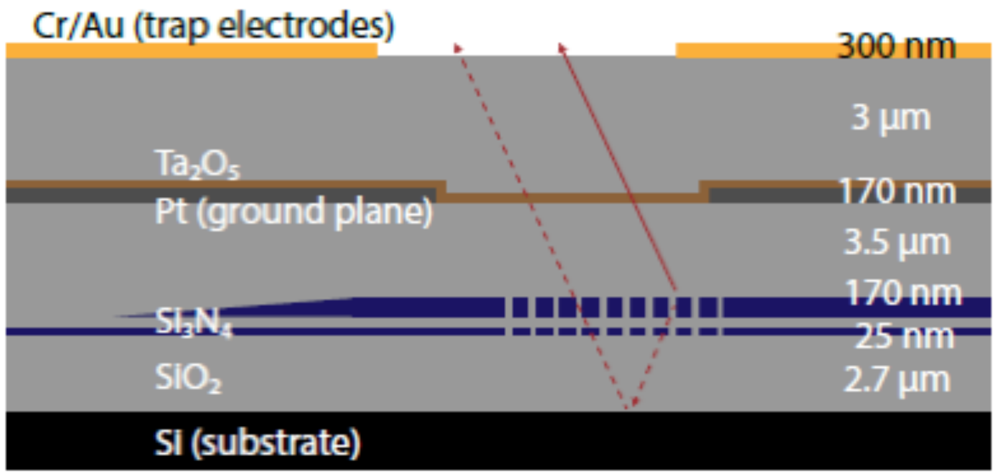

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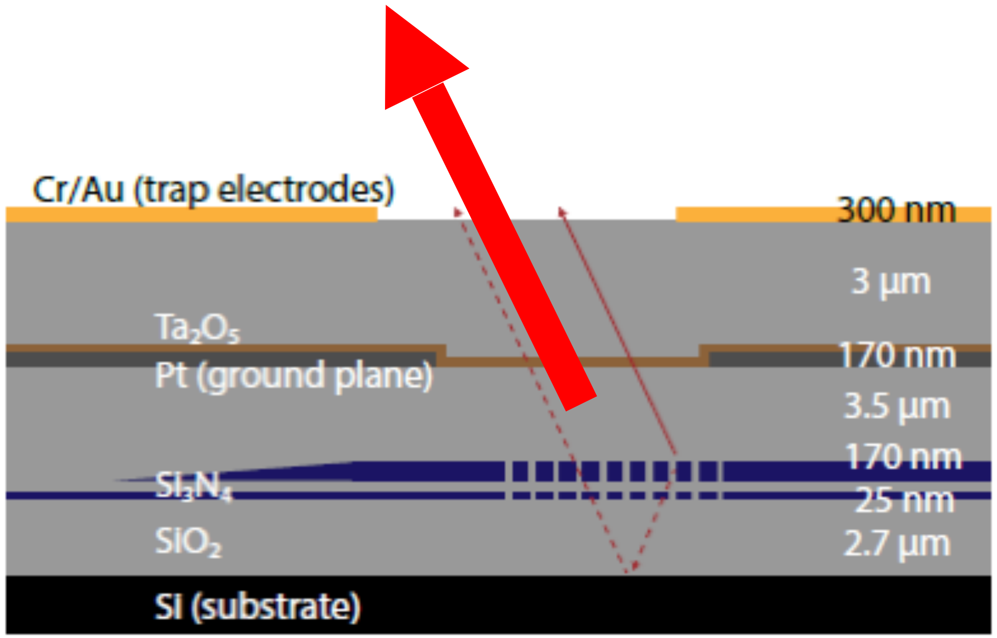
Light to ion
50 micron above surface



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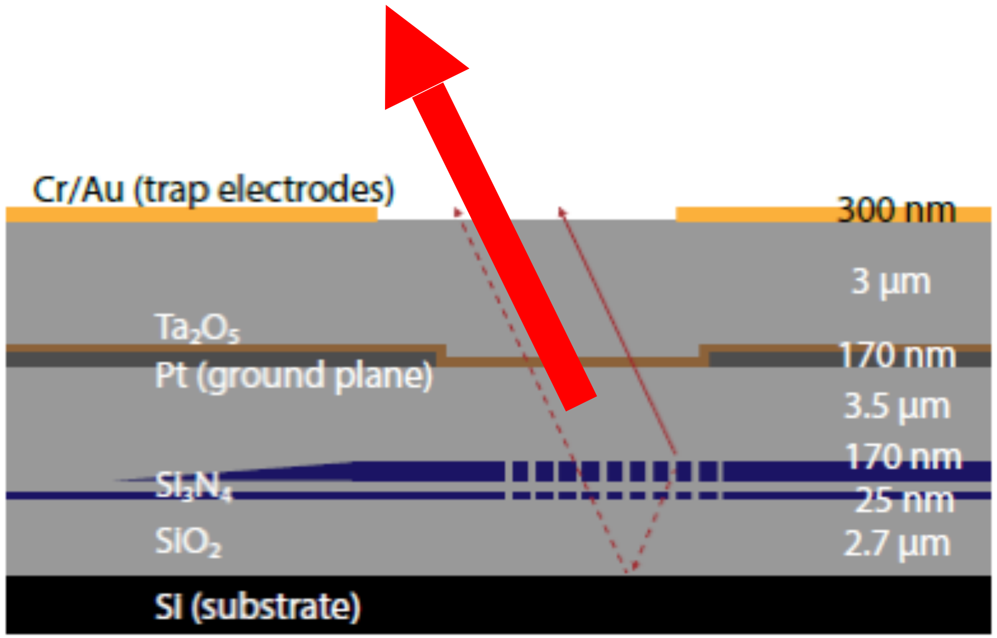

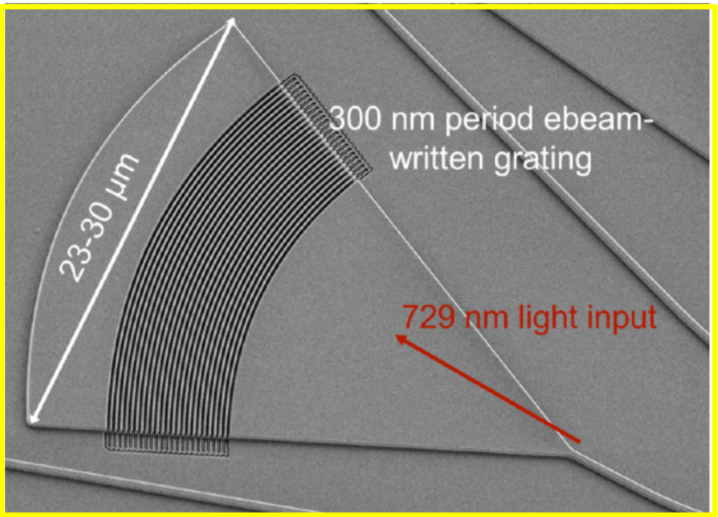

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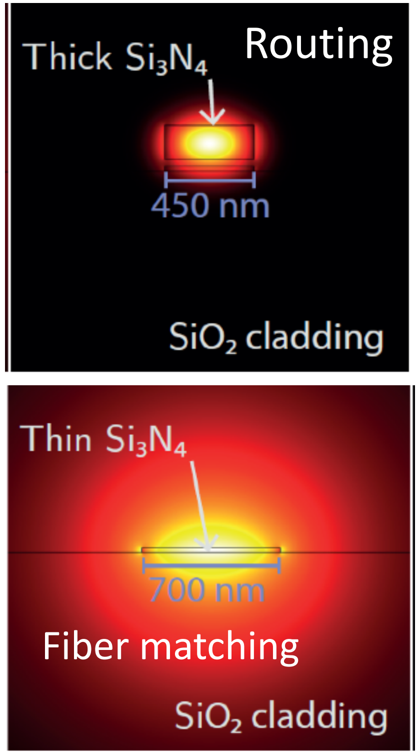

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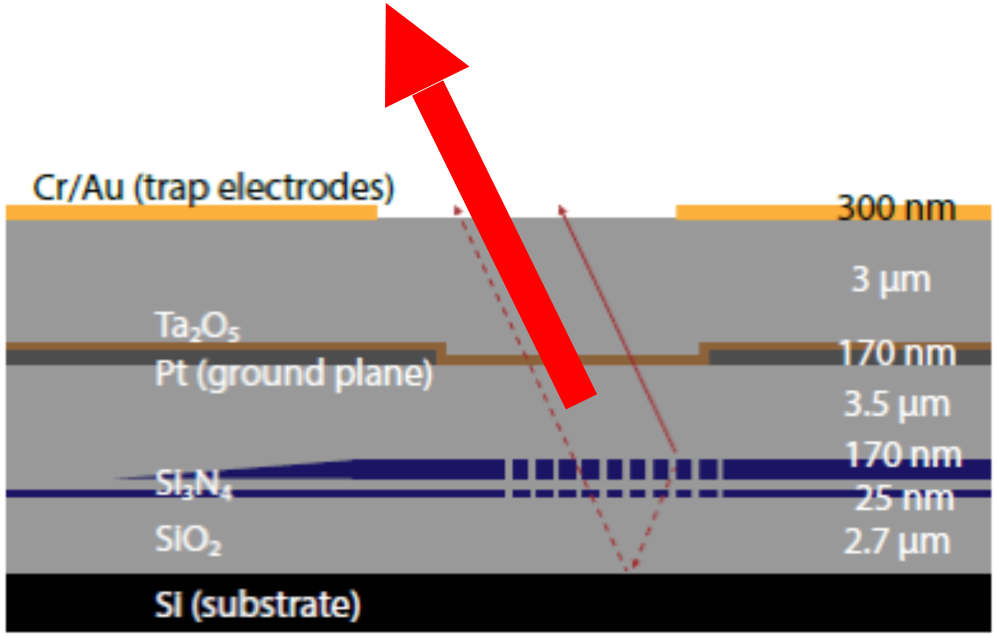

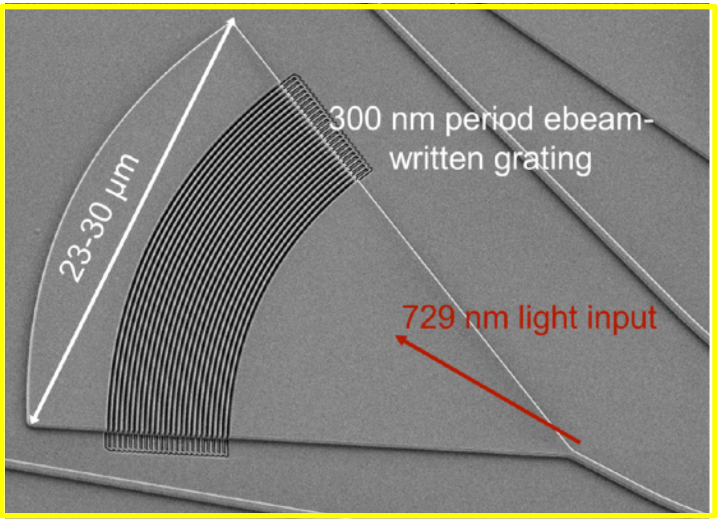

Light coupled onto the chip by butt-coupling optical fibre arrays

Multi-qubit gates + multi-zone operations

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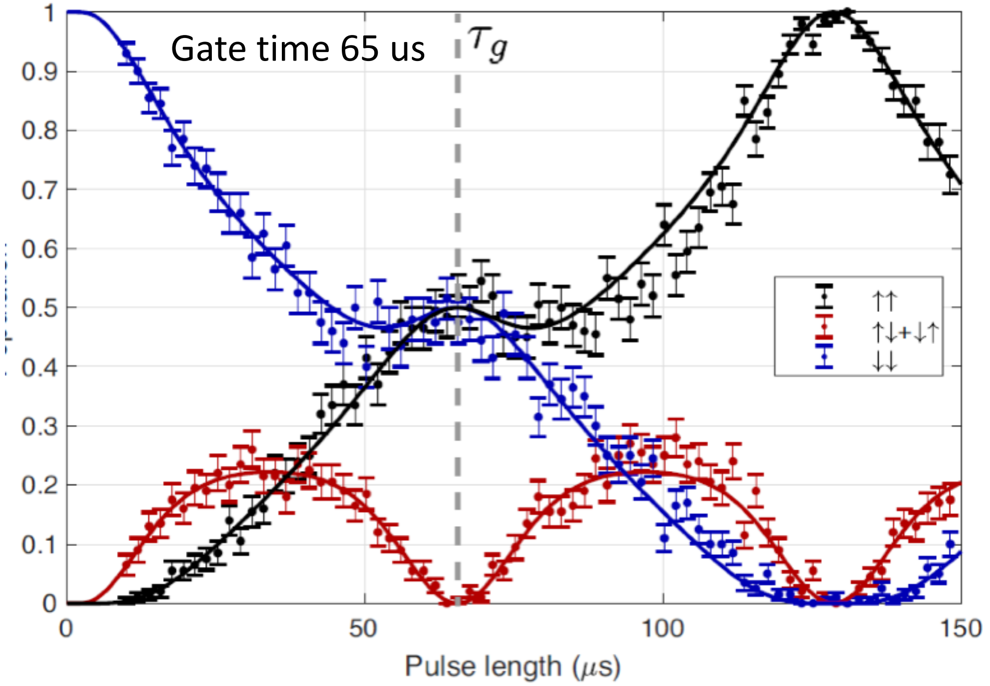
Single beam: 1.5 mW emitted from single output coupler



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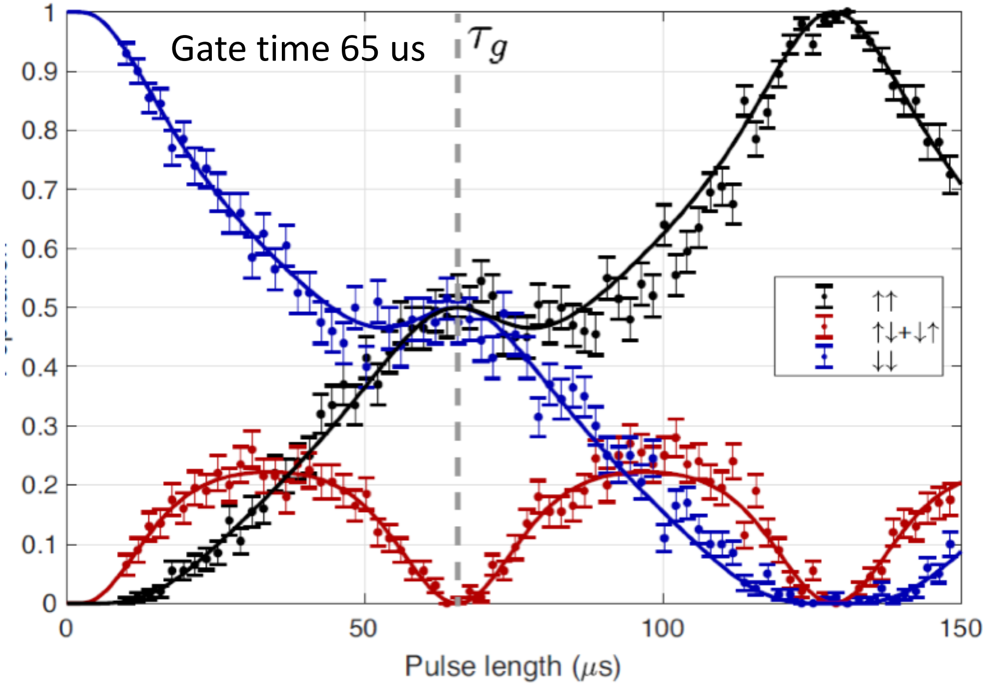

$$|00\rangle + e^{2i\phi}\,|11\rangle$$

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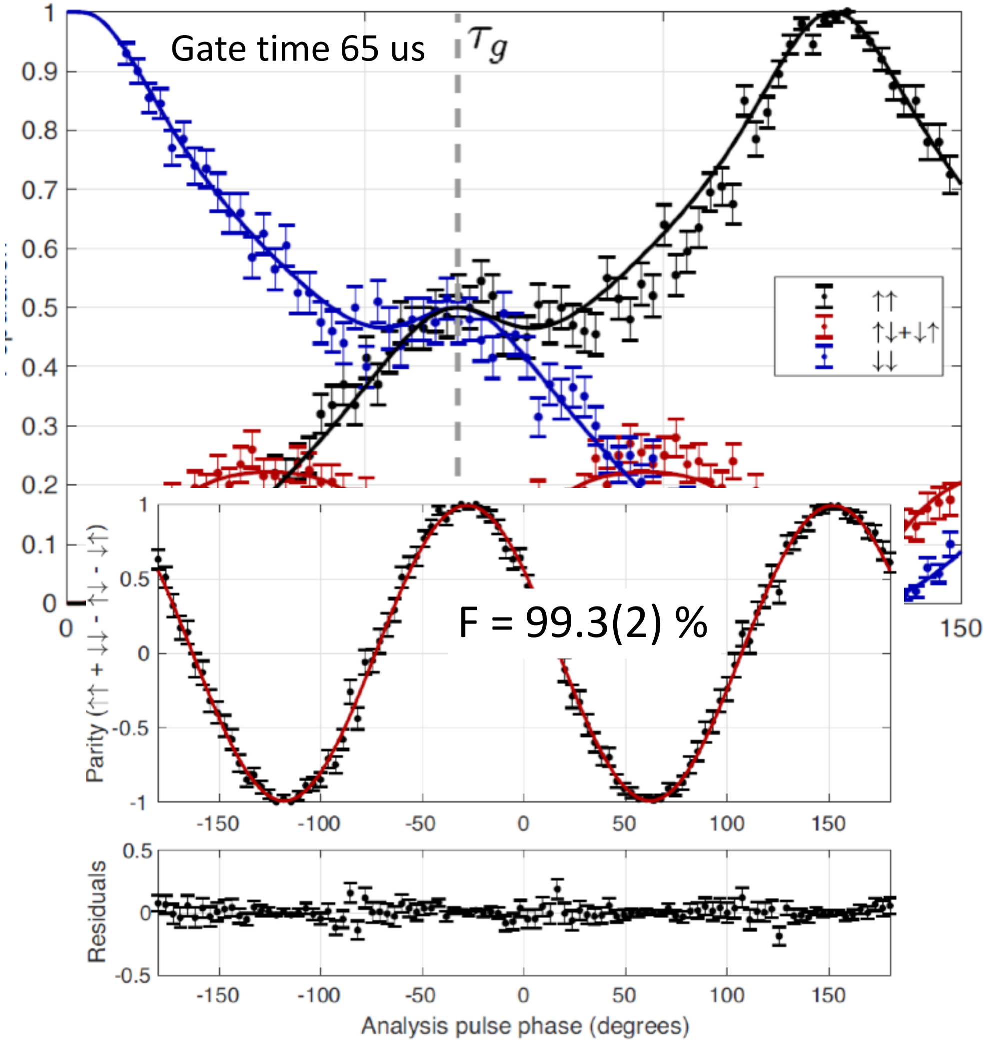

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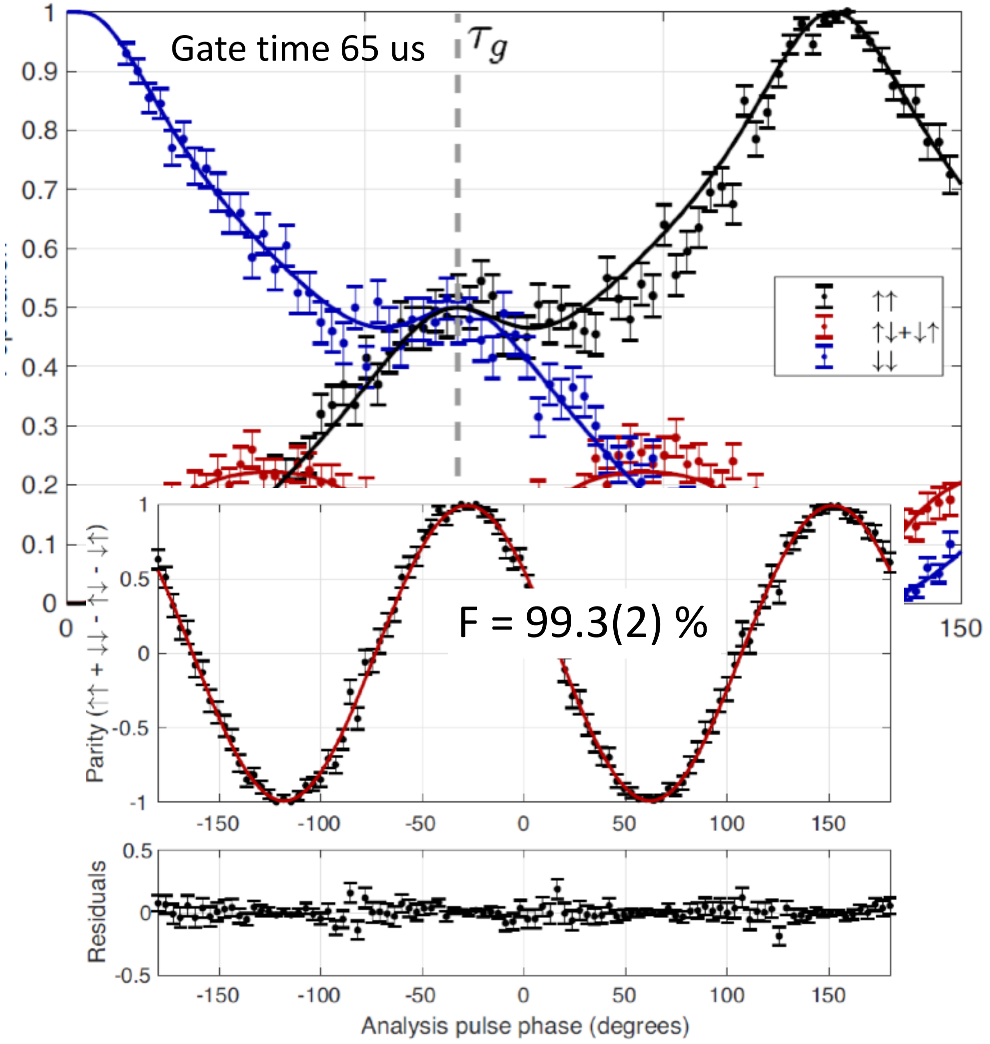

Error source	Infidelity ($\times 10^{-3}$)
Motional mode heating	2(1)
Motional frequency drifts	1
Laser frequency noise	1
Two-ion readout error	0.5
Kerr cross-coupling	0.4
Spectator mode occupancies	0.3
Spontaneous emission	0.03
Total	$\sim 5 \times 10^{-3}$

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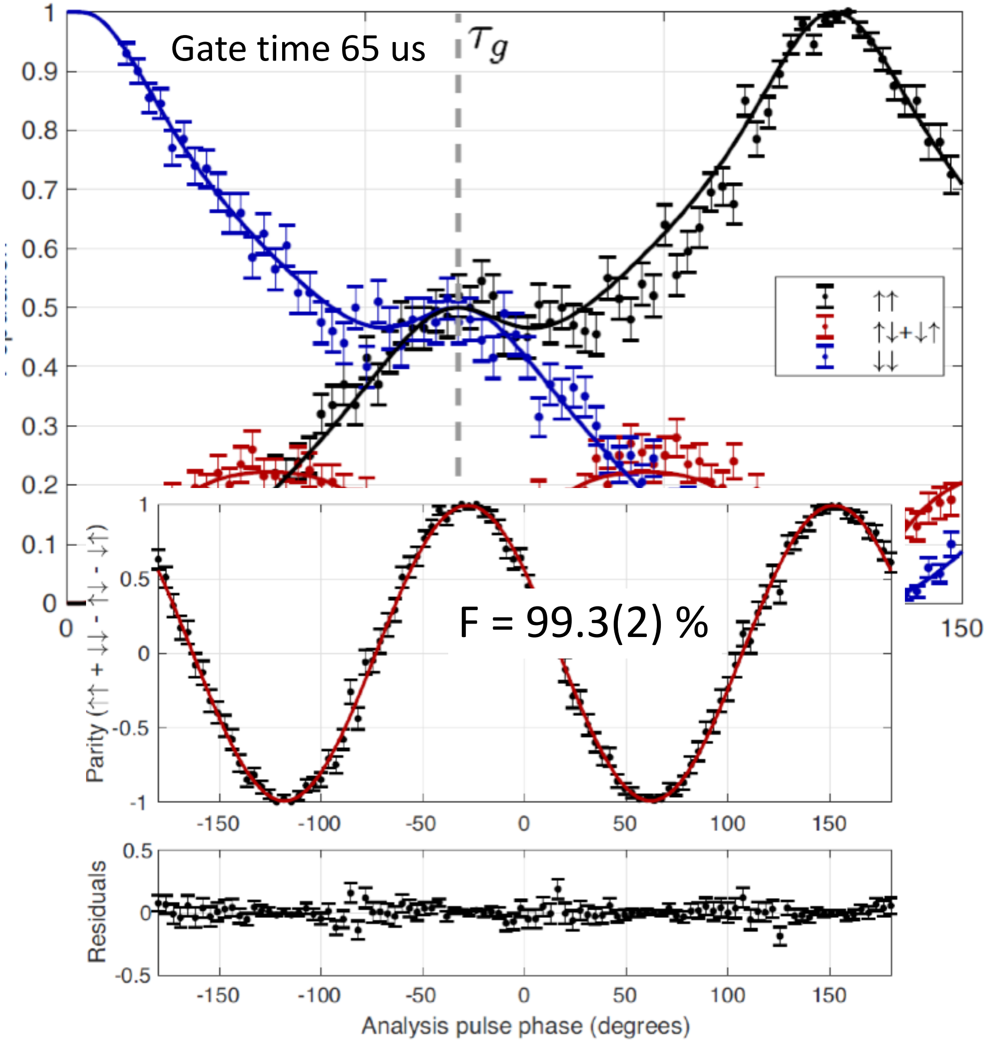

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"Raw" fidelity – mitigation techniques known for many errors

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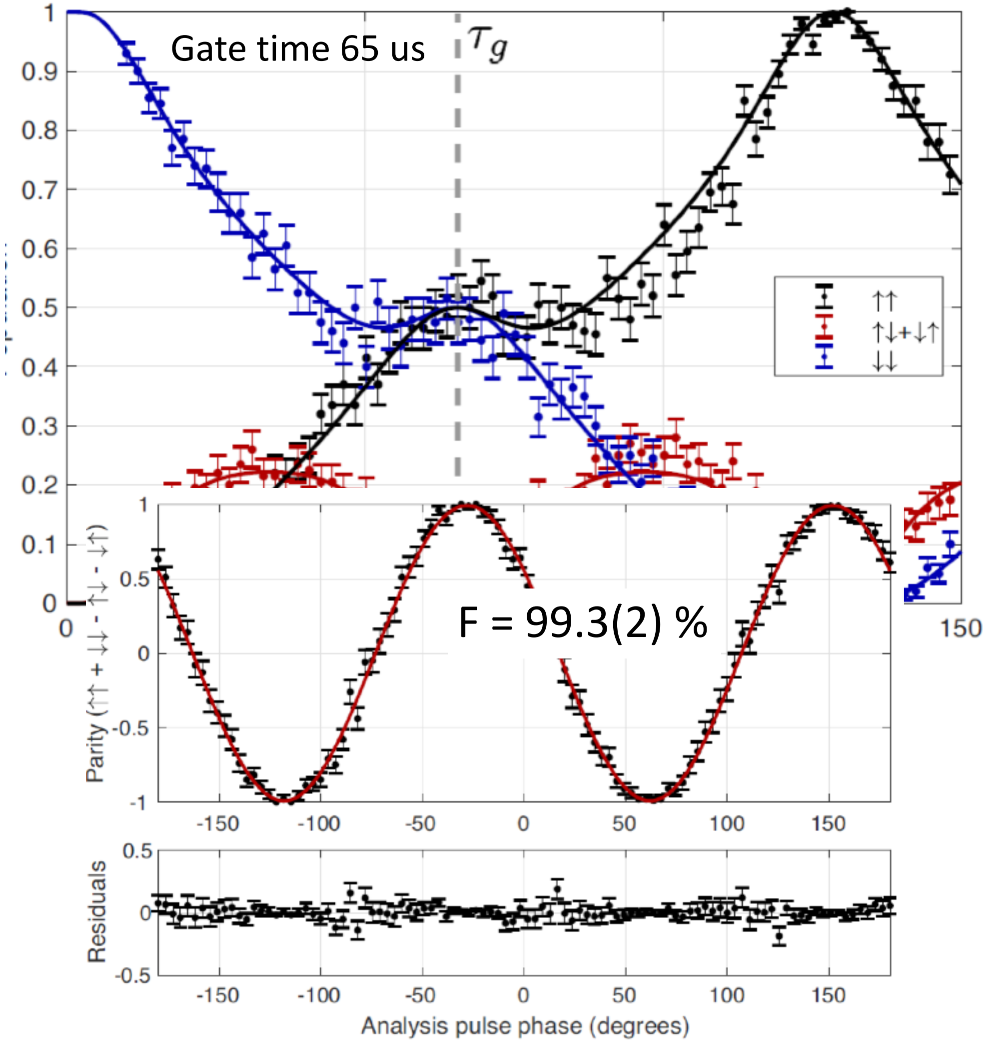

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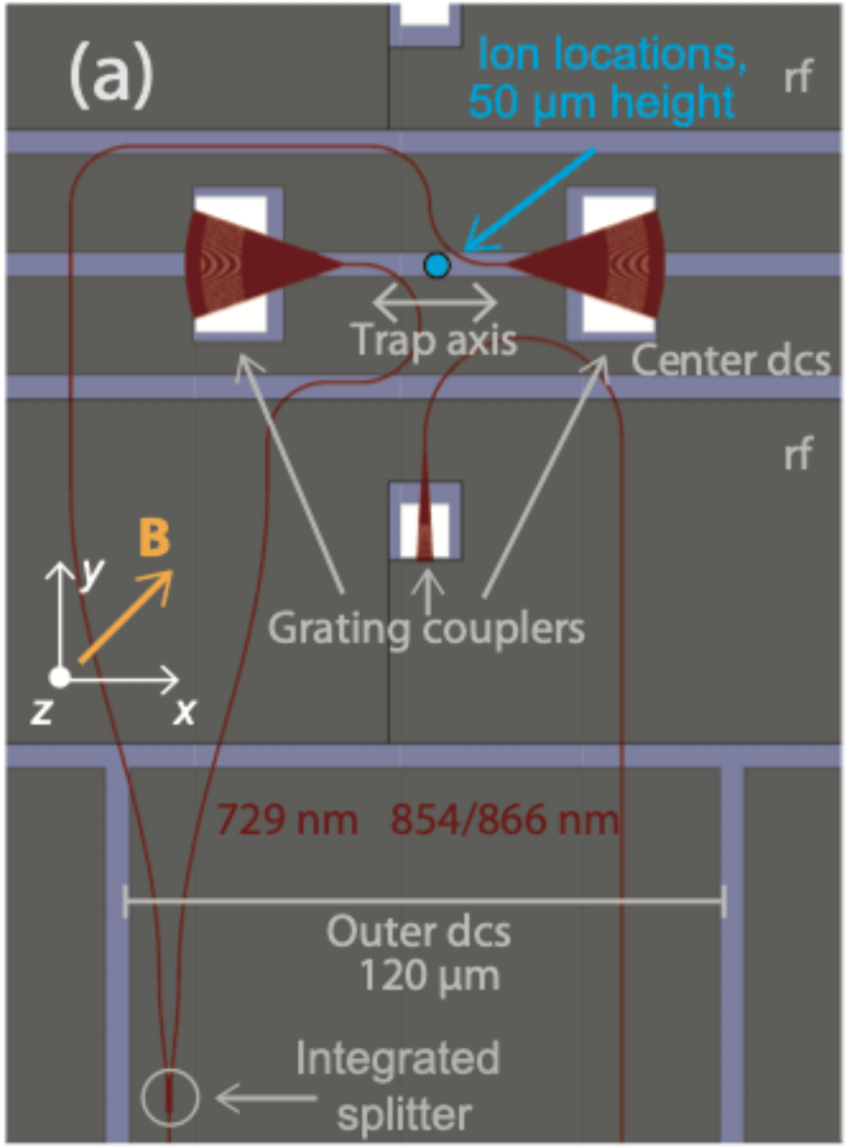
"Raw" fidelity – mitigation techniques known for many errors

Principle difference to standard (free space operations)

- Single ion heating rates are high ~ 1 quanta/ms vs. 10 quanta/s
- Trap frequencies drift when long-term emitted power average changes

Phase stable optical standing waves



A. Ricci-Vasquez, C. Mordini et al. PRL **130**, 133201 (2023)

Phase stable standing wave formed on-chip
(Propagates away from surface)

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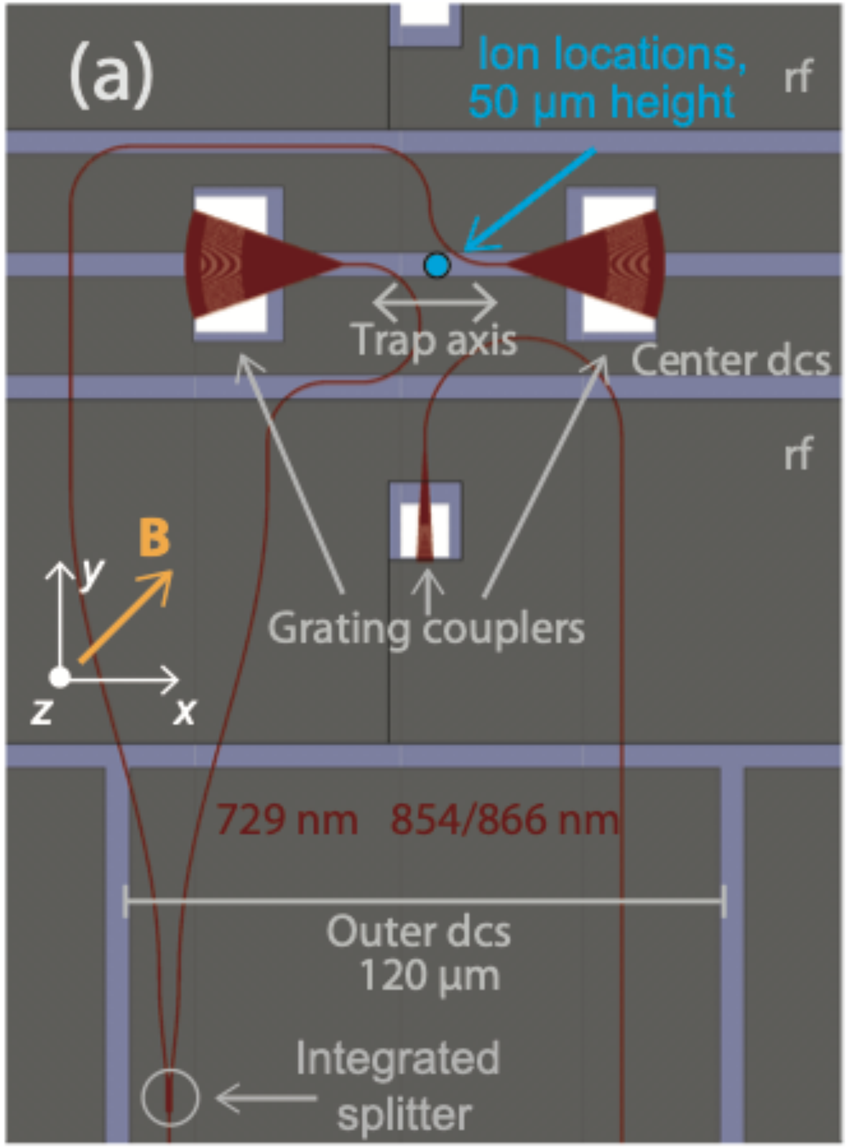

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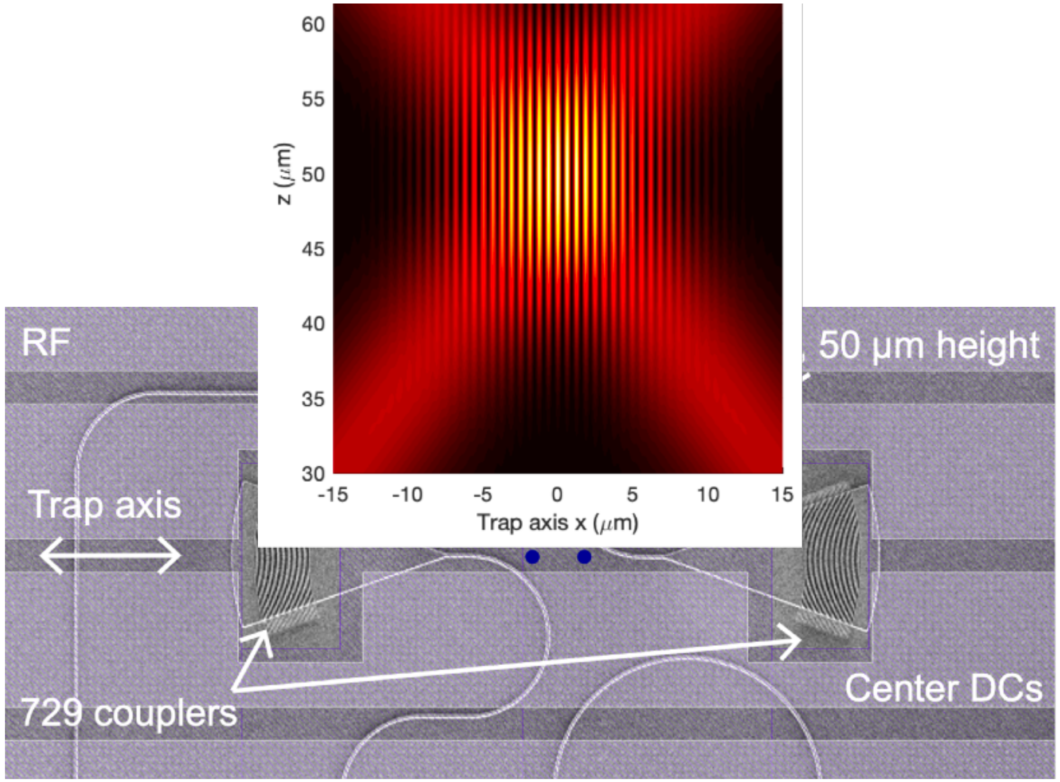

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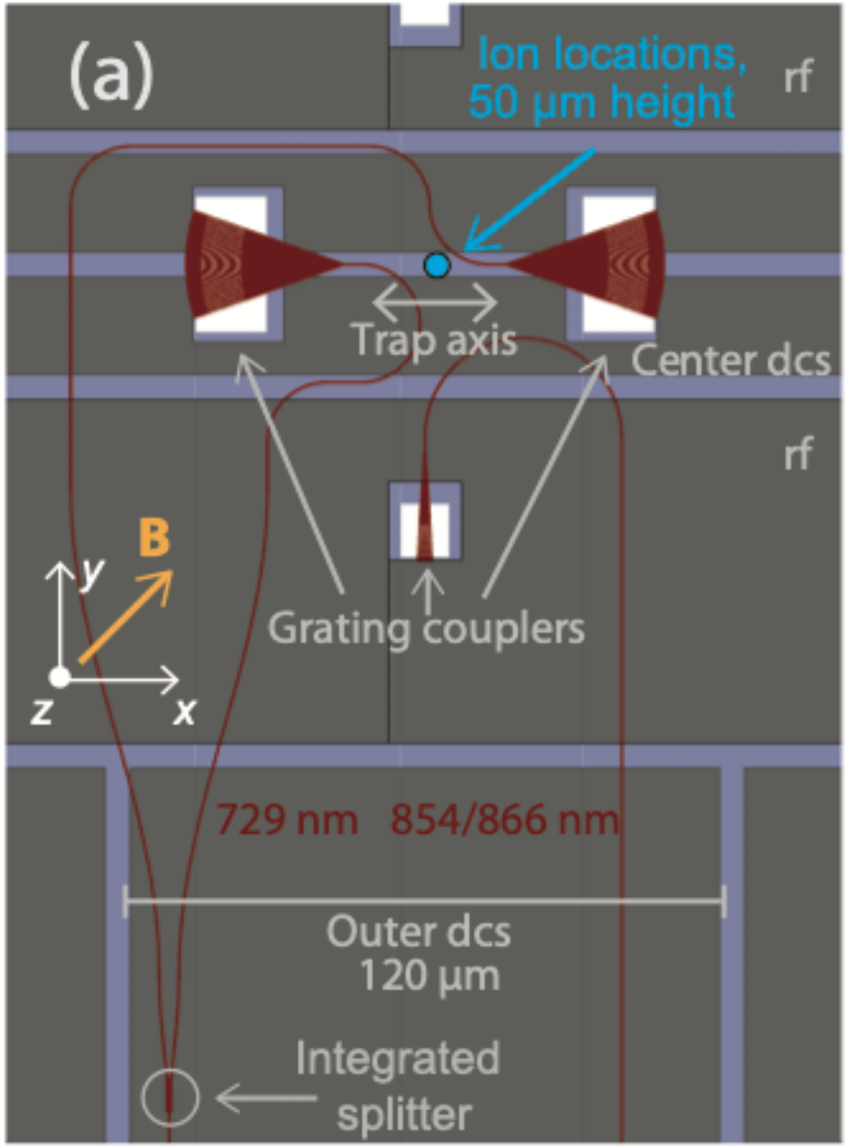

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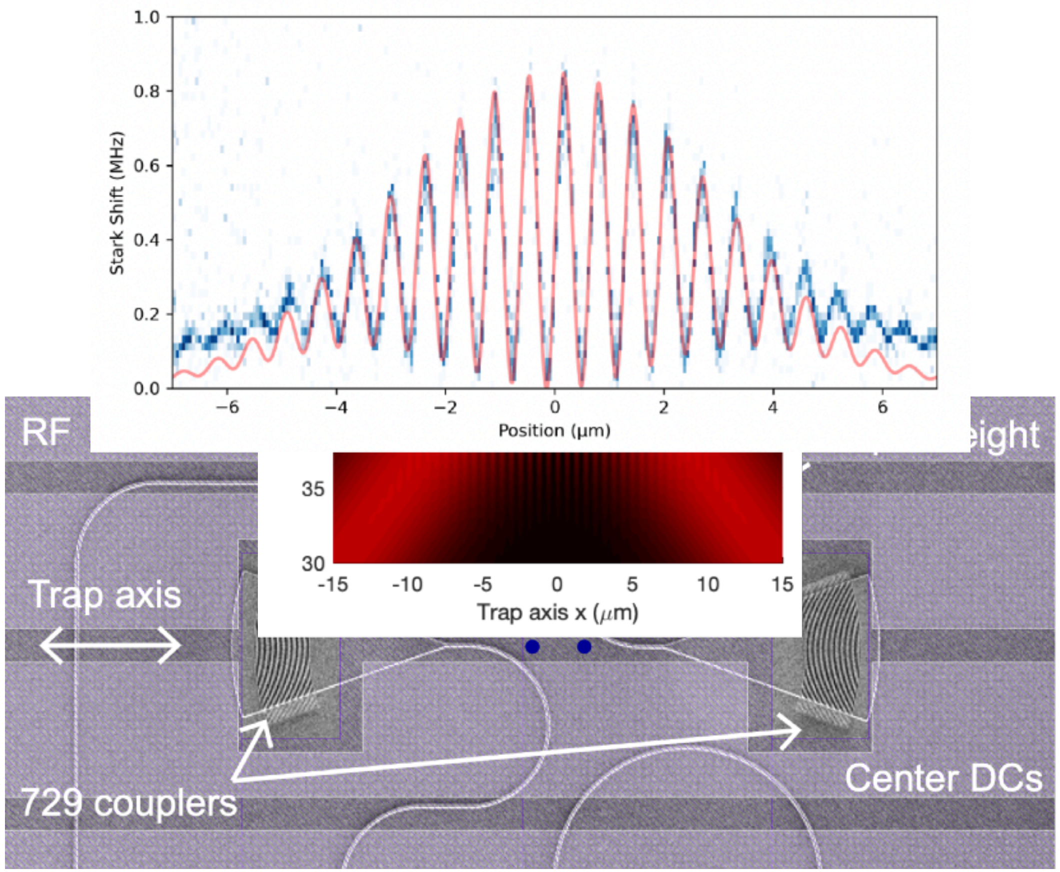

Standing waves as a probe of stability

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Use of a phase-stable standing wave is an excellent probe of ion positioning (good to few nm level)

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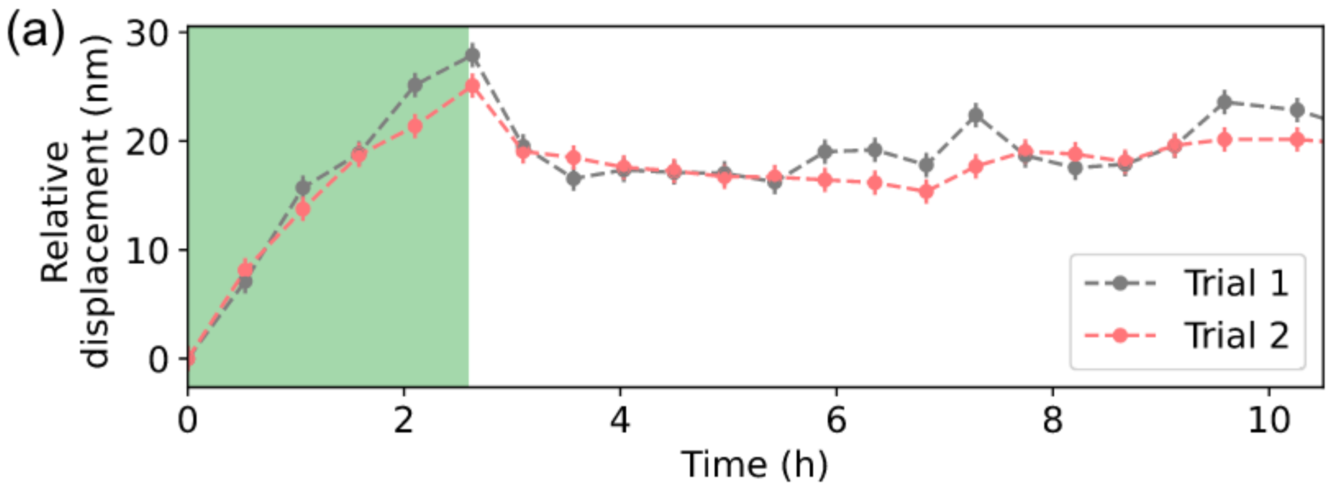

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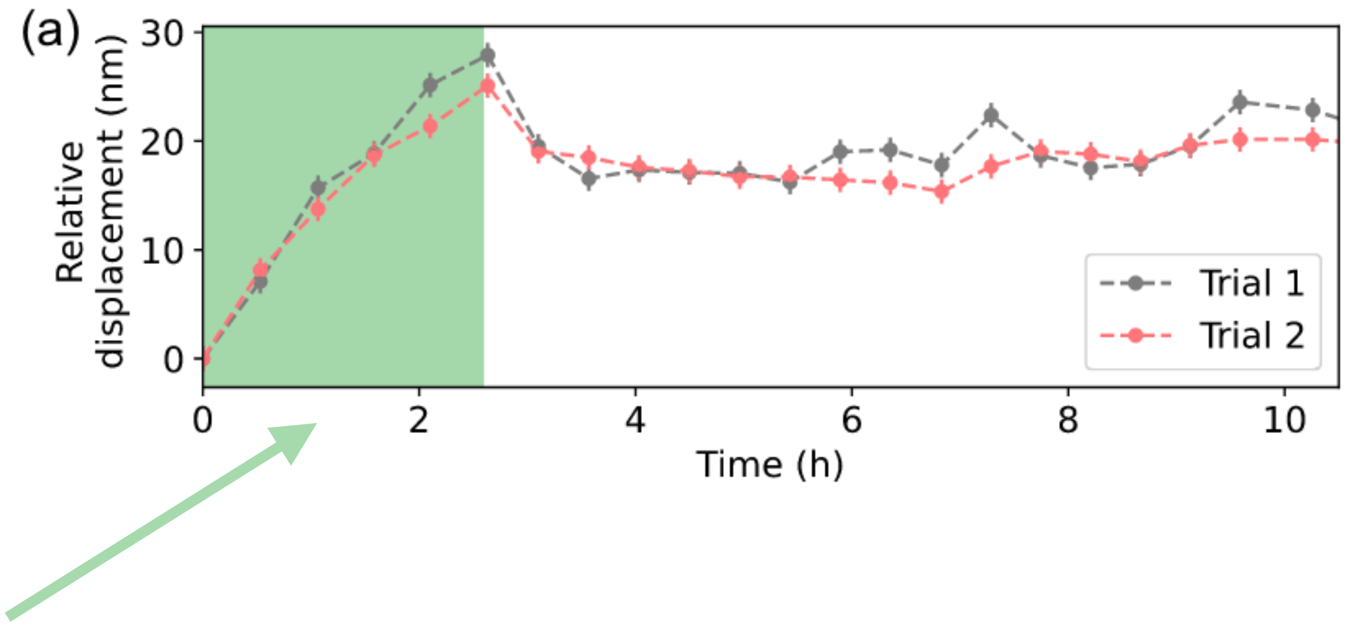

Ultra-violet (375 nm) light charging the dielectric

Standing waves as a probe of stability

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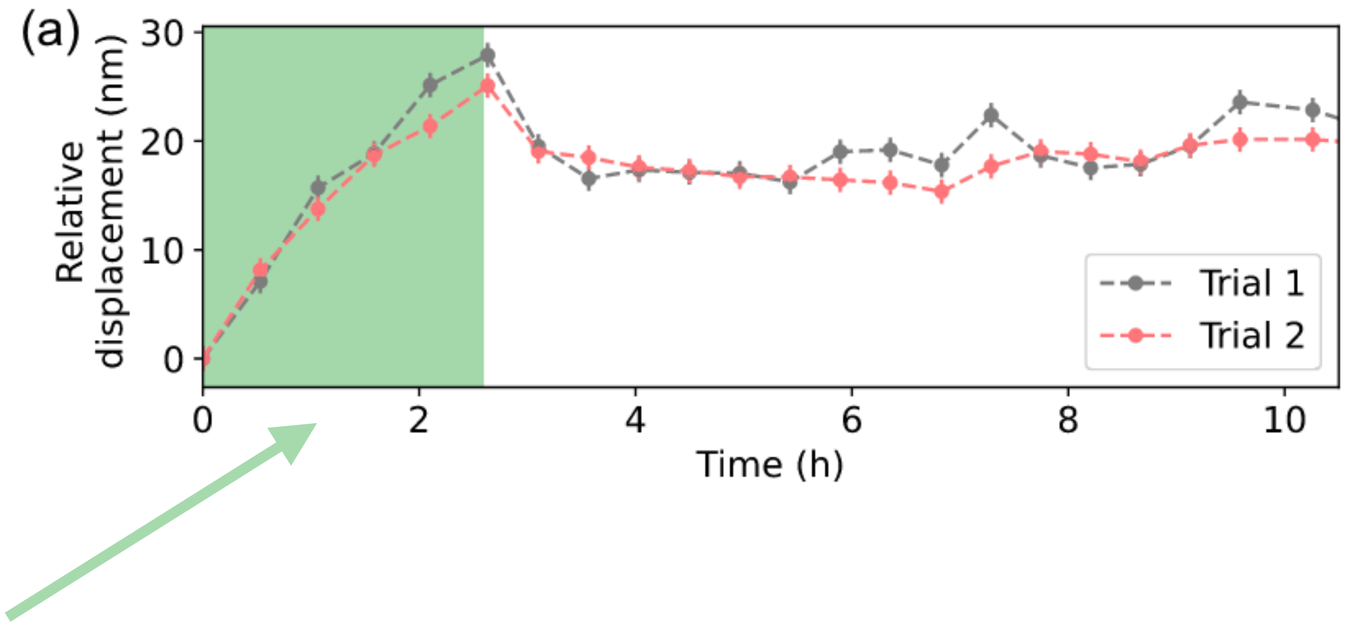


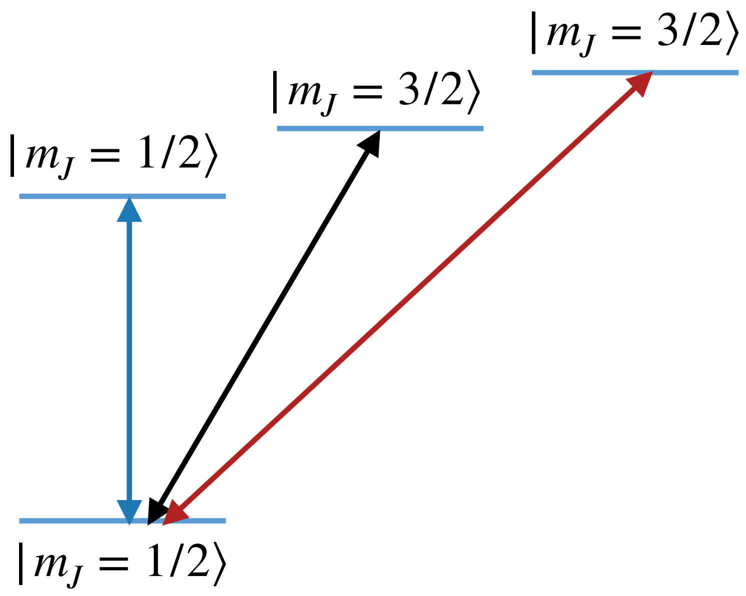
Ultra-violet (375 nm) light charging the dielectric

Future: cover emission gratings with conducting material (ITO)

Quadrupole transition **driving in an optical standing wave**

Expt: A. Ricci-Vasquez, C. Mordini et al. PRL **130**, 133201 (2023)

Calcium octopole qubit has many possible transitions



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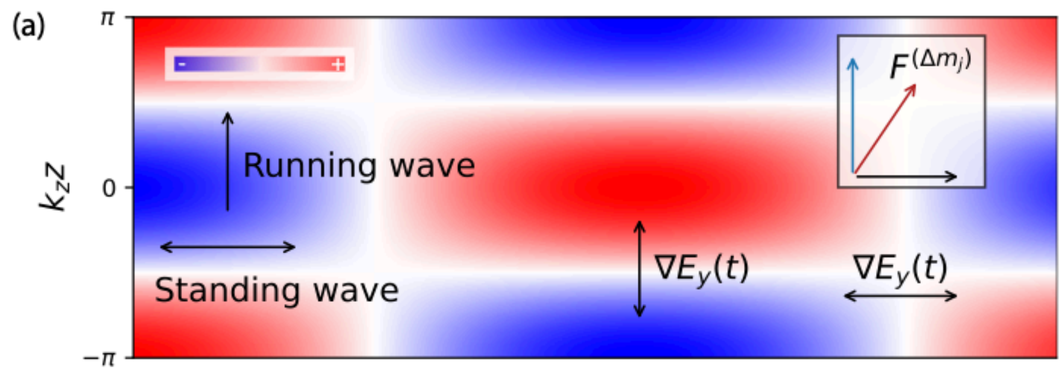

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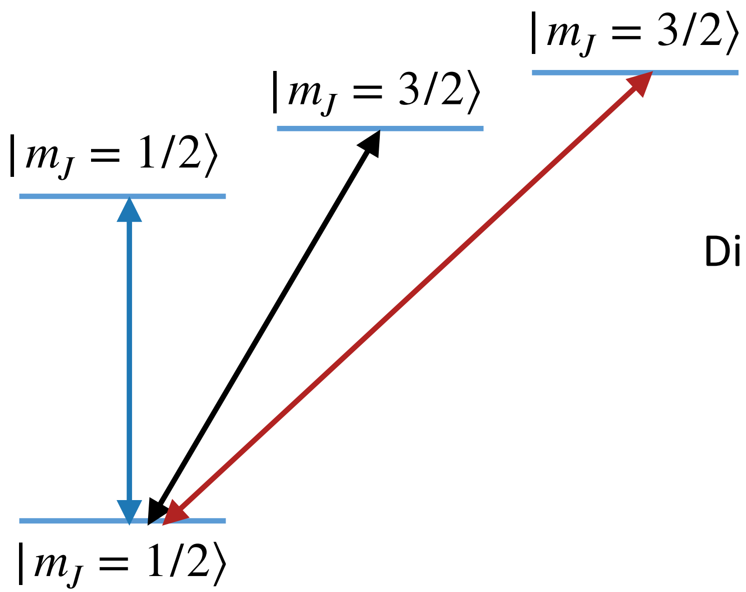

Direct transition $\Omega \propto \nabla E_i$

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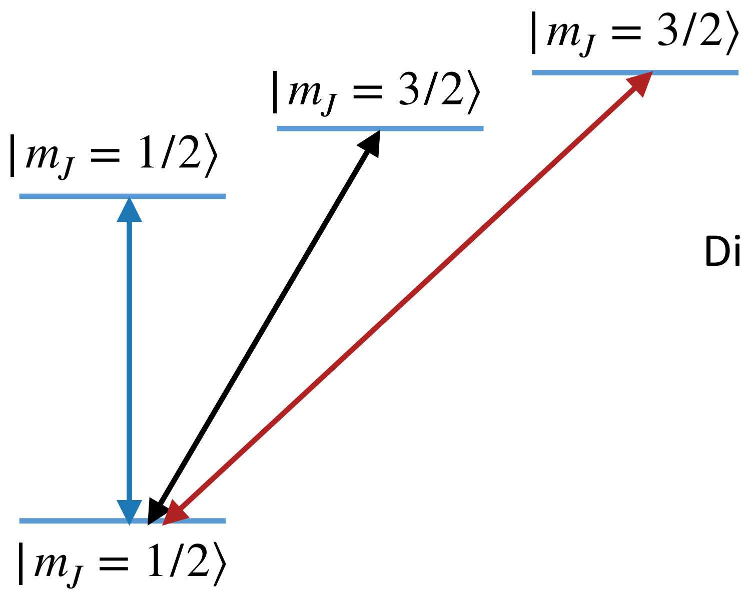

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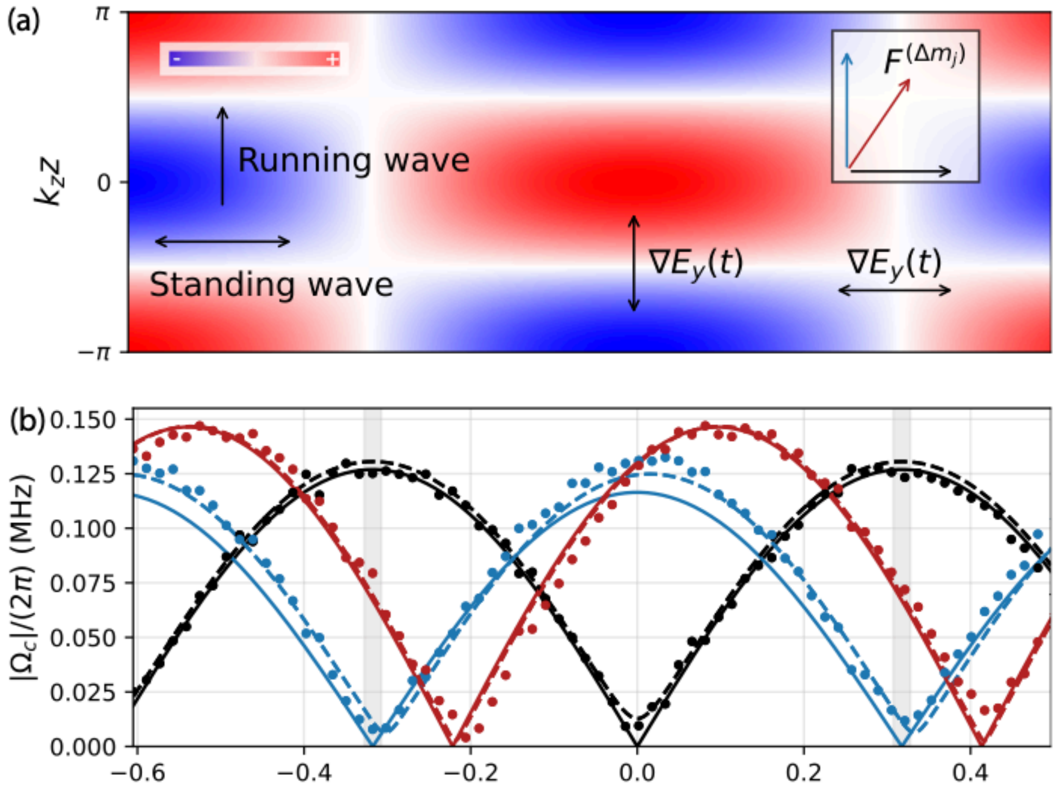

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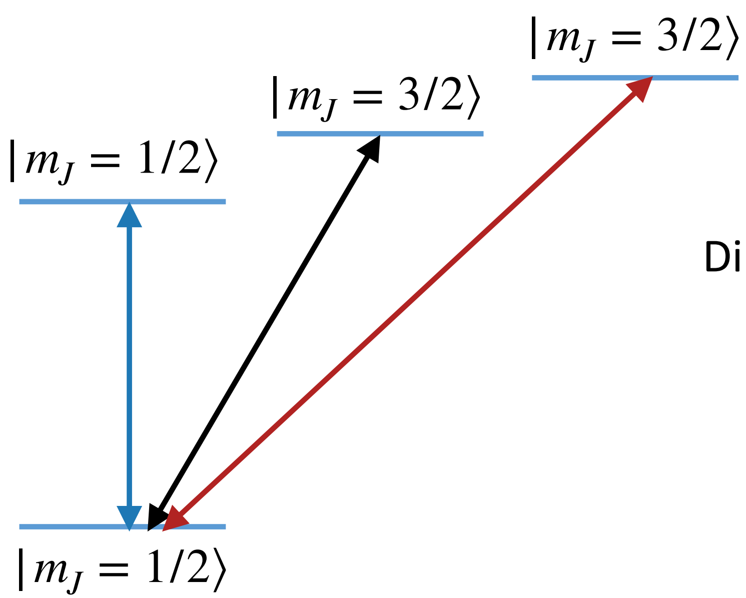

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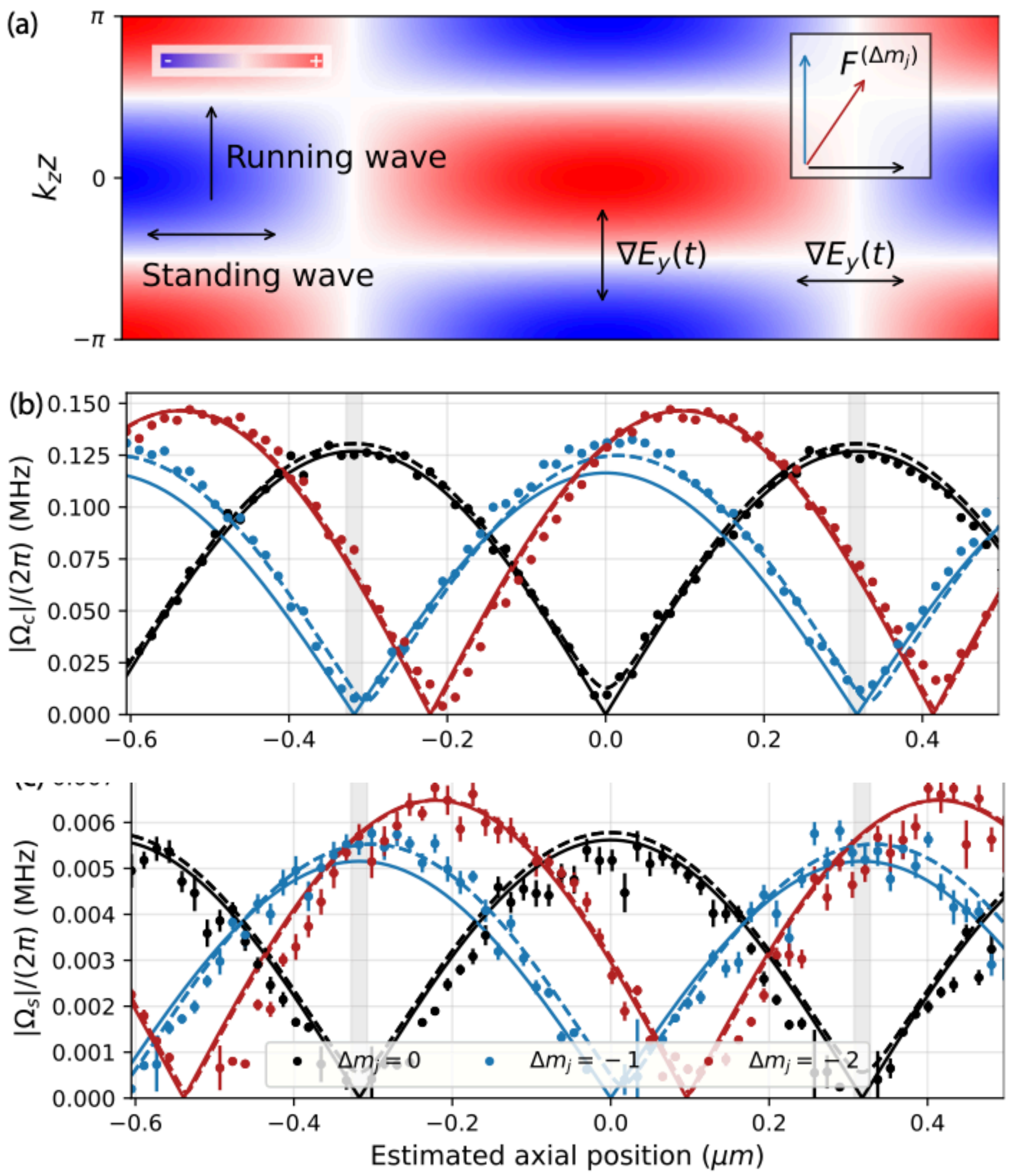

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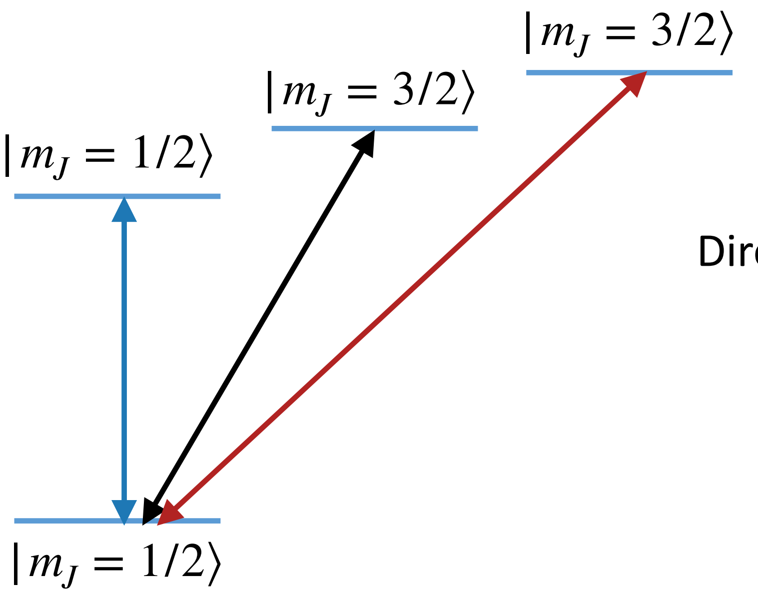

Direct transition $\Omega \propto \nabla E_i$

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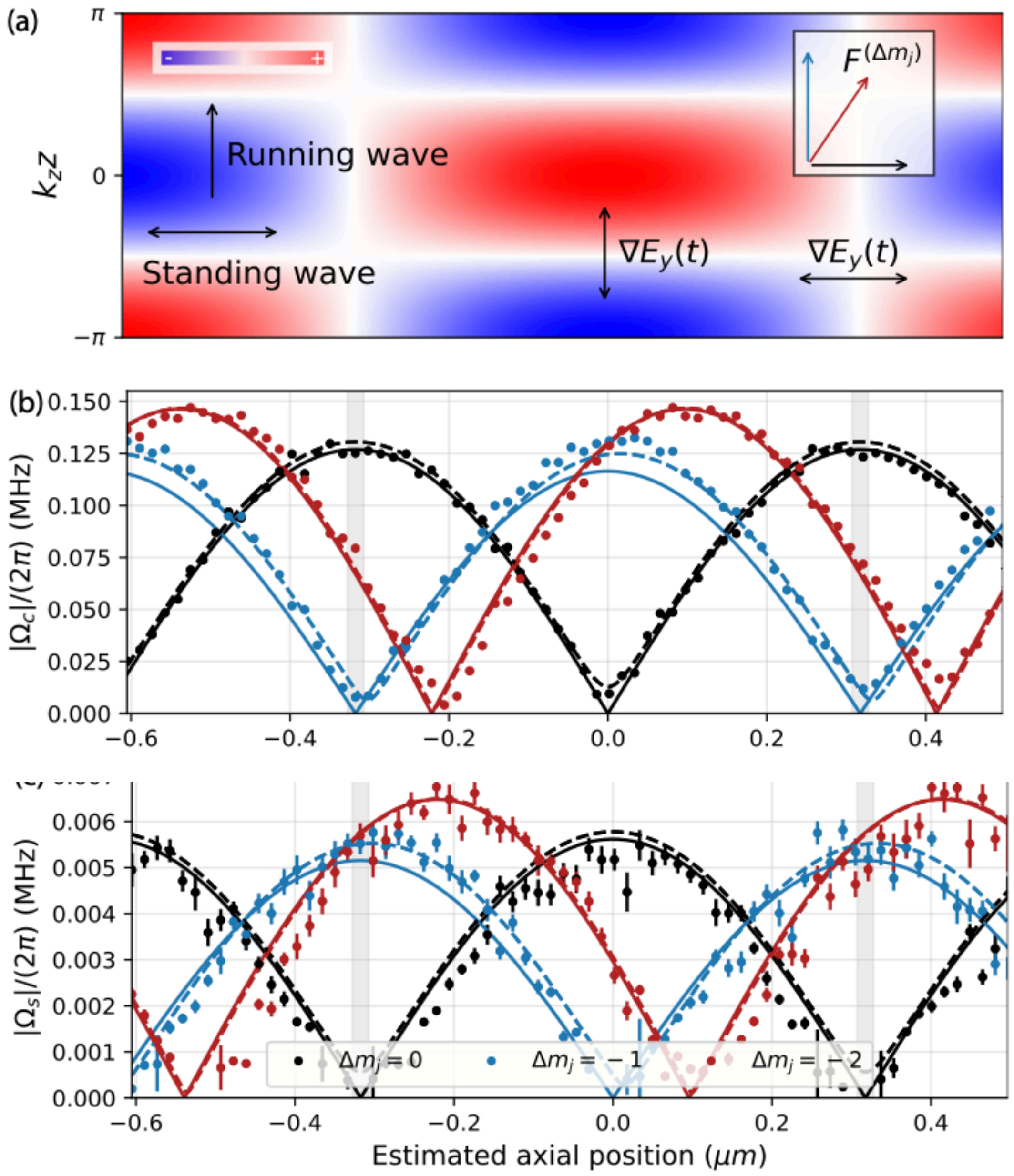
Idea: Two-qubit gates at position of zero intensity
- no off-resonant direct drive, no AC Stark shifts



Standing waves for Internal-state dependent ***dipole*** potentials

A. Ricci-Vasquez et al arXiv:2411.03301 (2024)

Gate $\propto \nabla\Omega \propto \sqrt{I}$. Spectator Stark shifts $\propto \Omega^2 \propto I$

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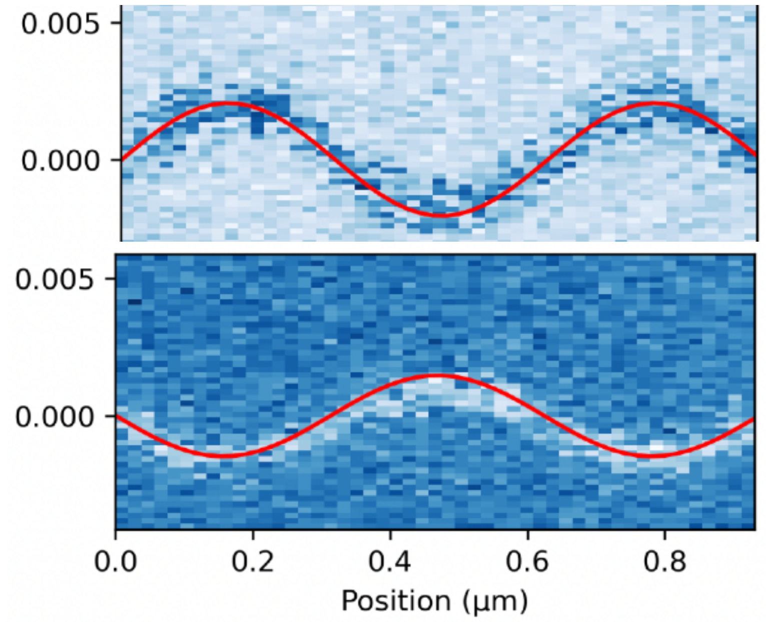
Dipole Stark shifts = SD trap freq: probed at 733 nm

Trap frequency $S_{1/2}$

Trap frequency $D_{5/2}$



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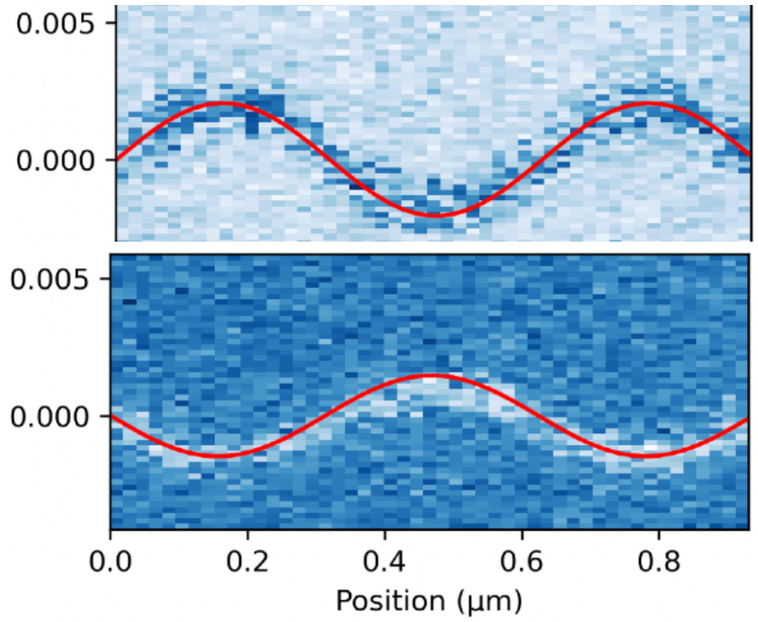

Even when no light is present at the ion centre position, the curvature of the potential modifies the motion

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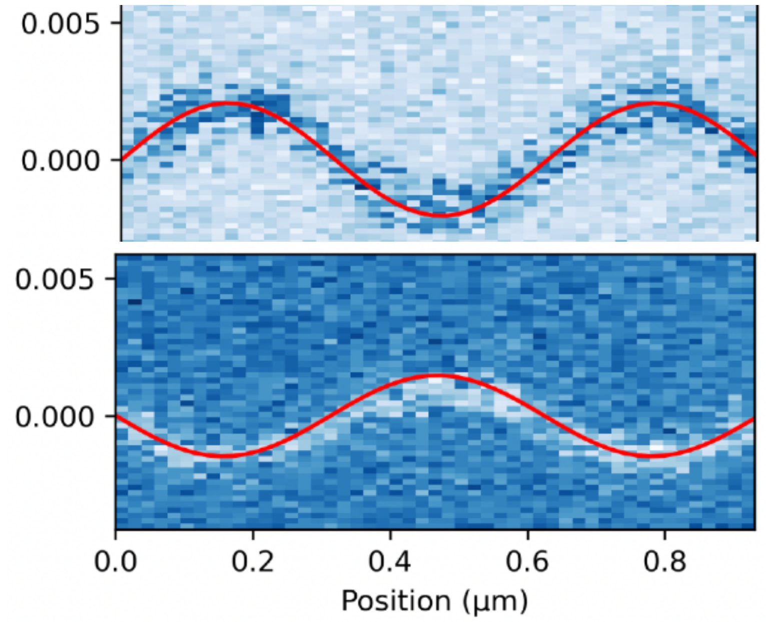
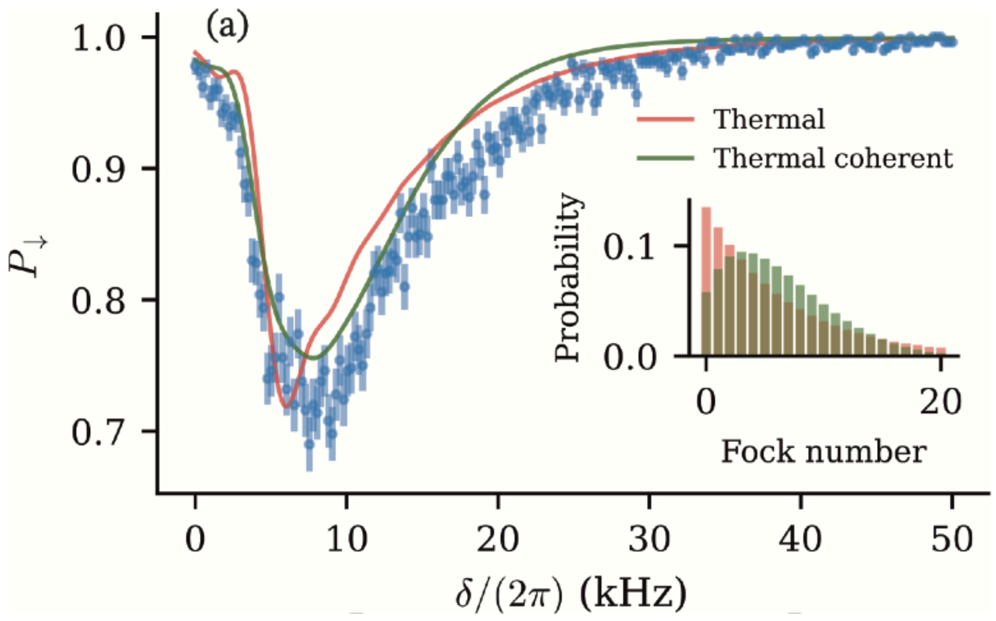


Ion temperature measurement by direct qubit spectroscopy

$H_q \propto \sigma_Z \hat{n}_{\text{oscillator}}$



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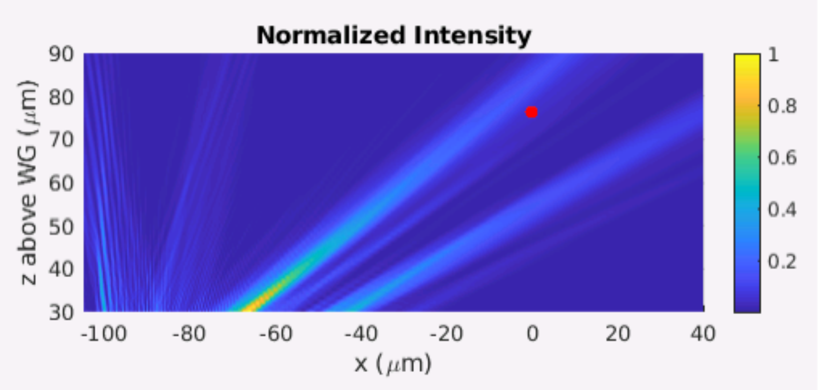
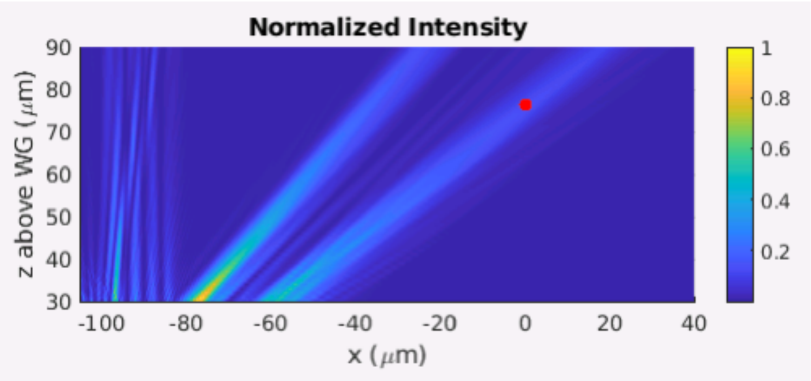
Exploration: grating design for advanced beam configurations

Layout, grating design: G. Beck, JH, K. Mehta J. Lightwave Technology 42, 4939-4951 (2024)

Hybrid gratings for 423/375 nm light





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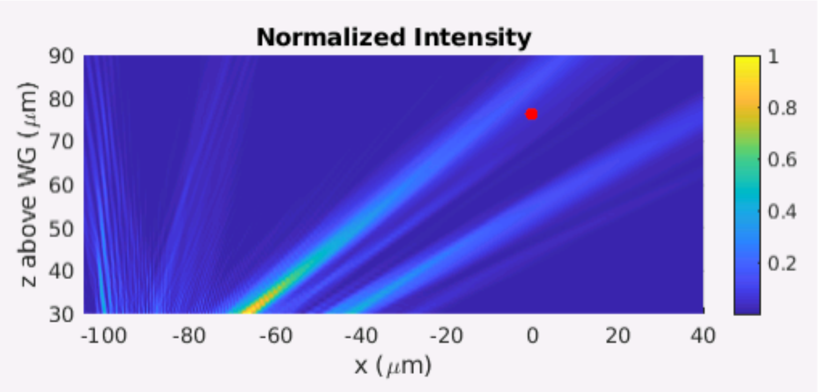
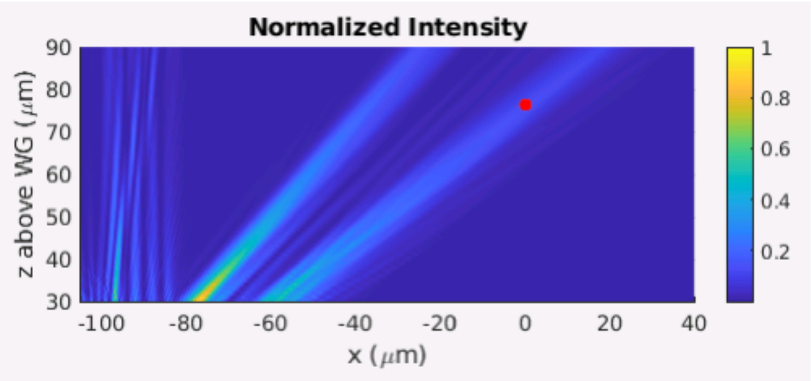
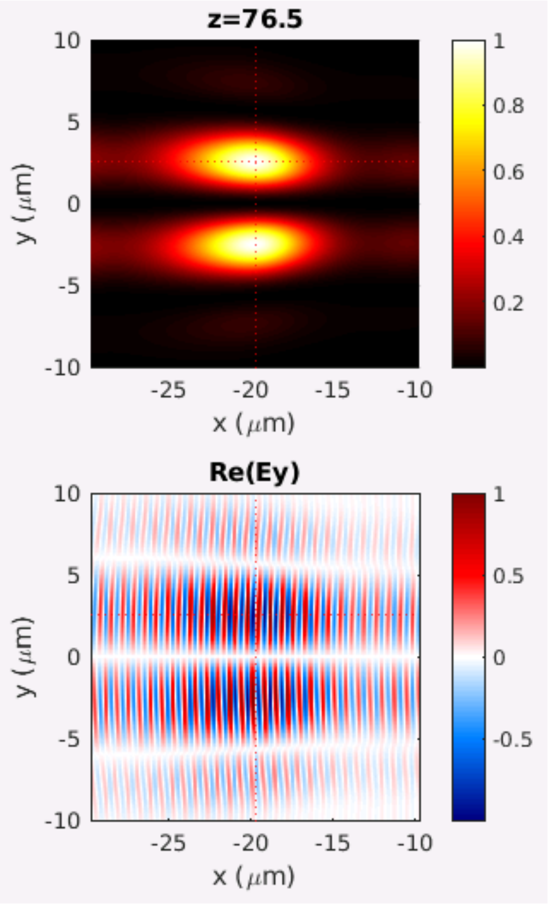
TEM 10







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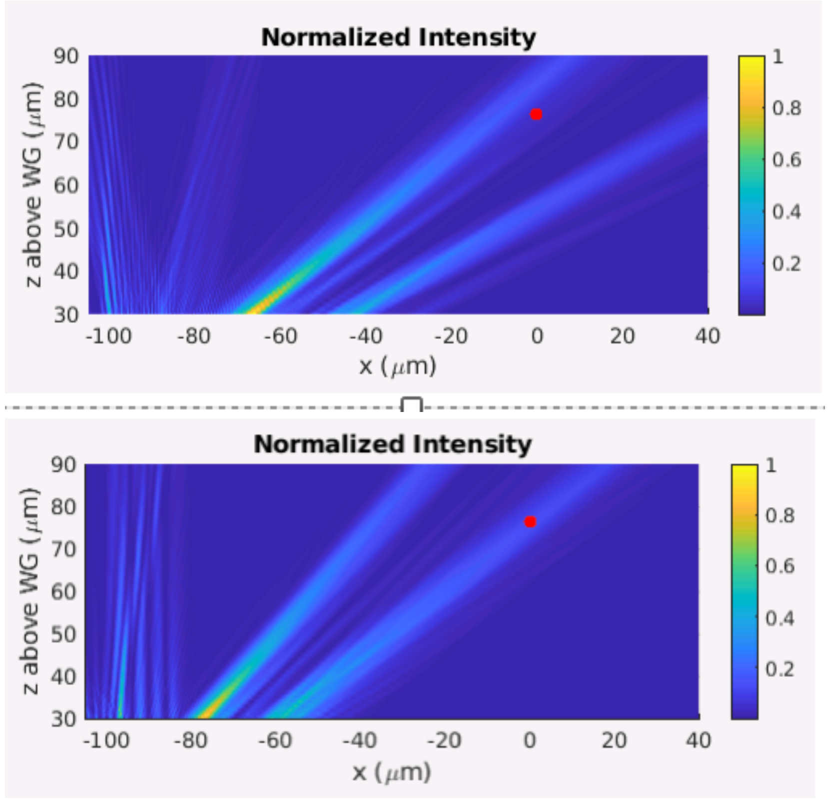

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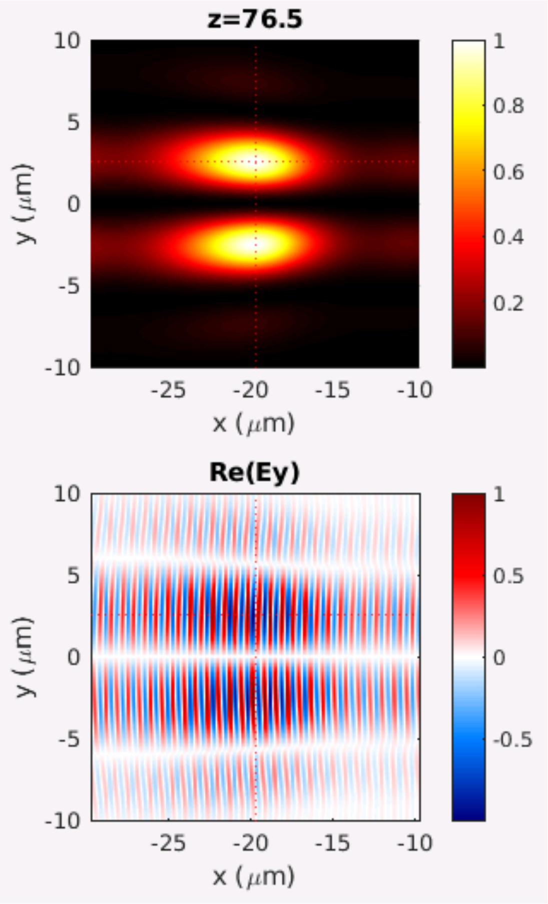
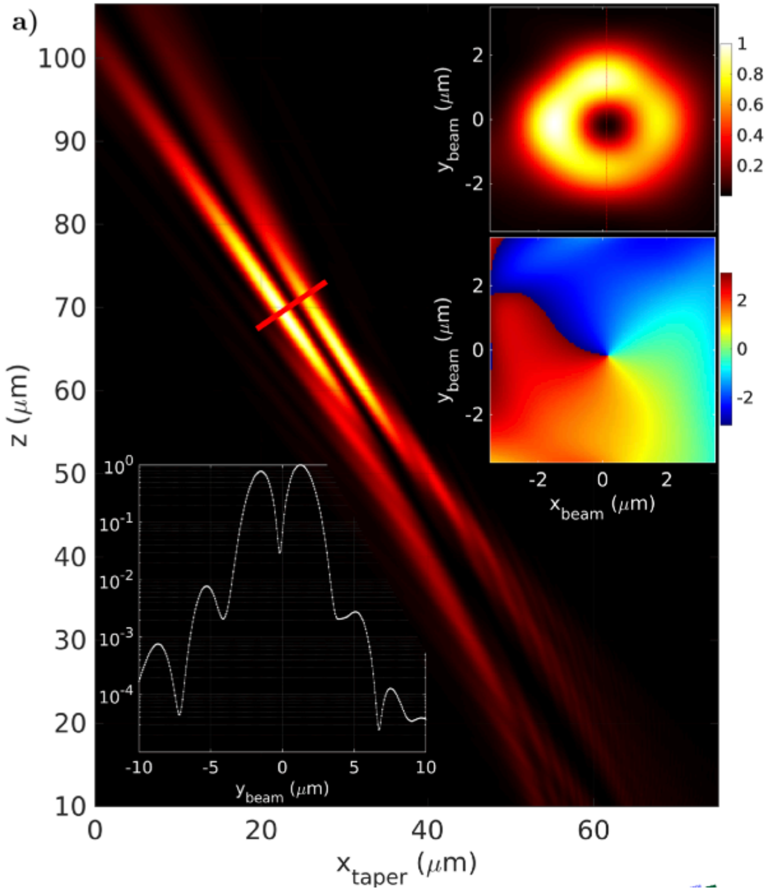


Laguerre-Gaussian beams



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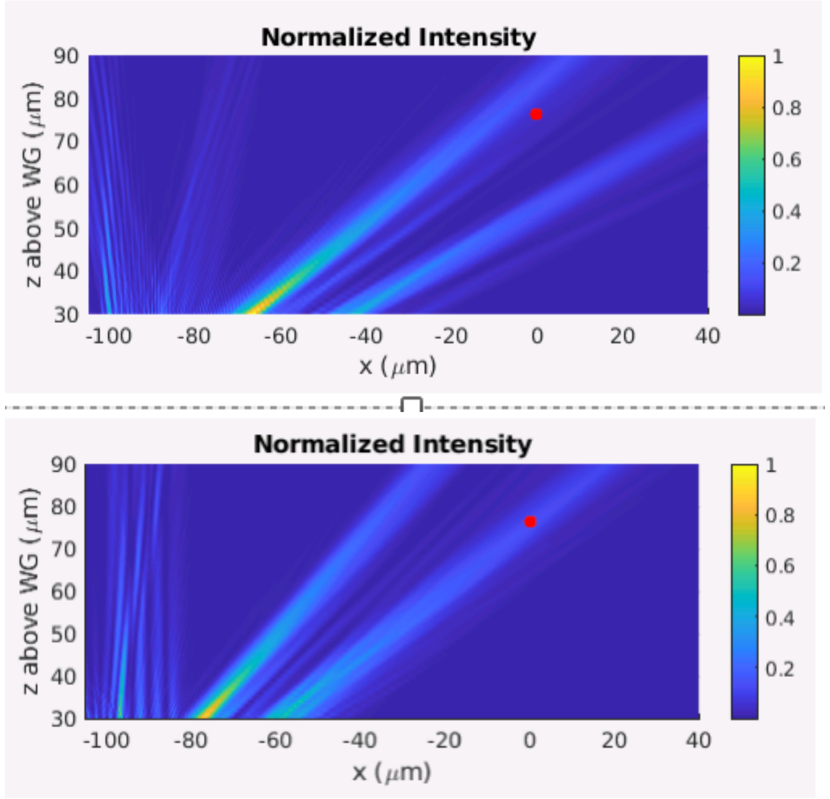

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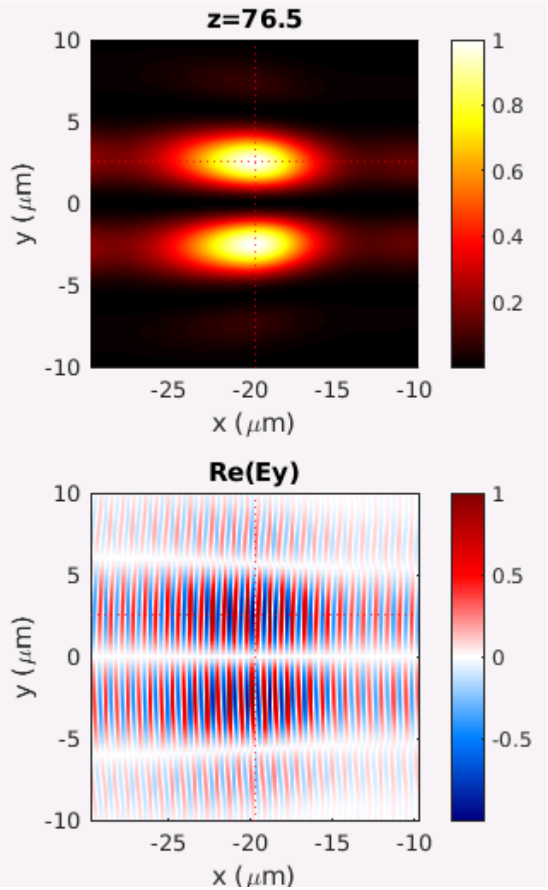

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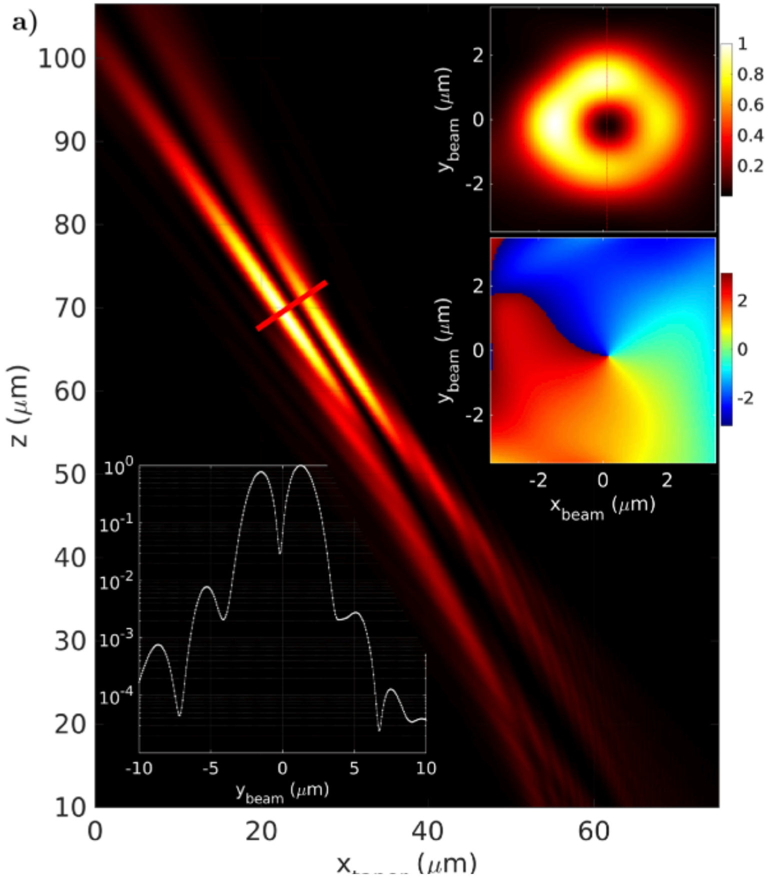
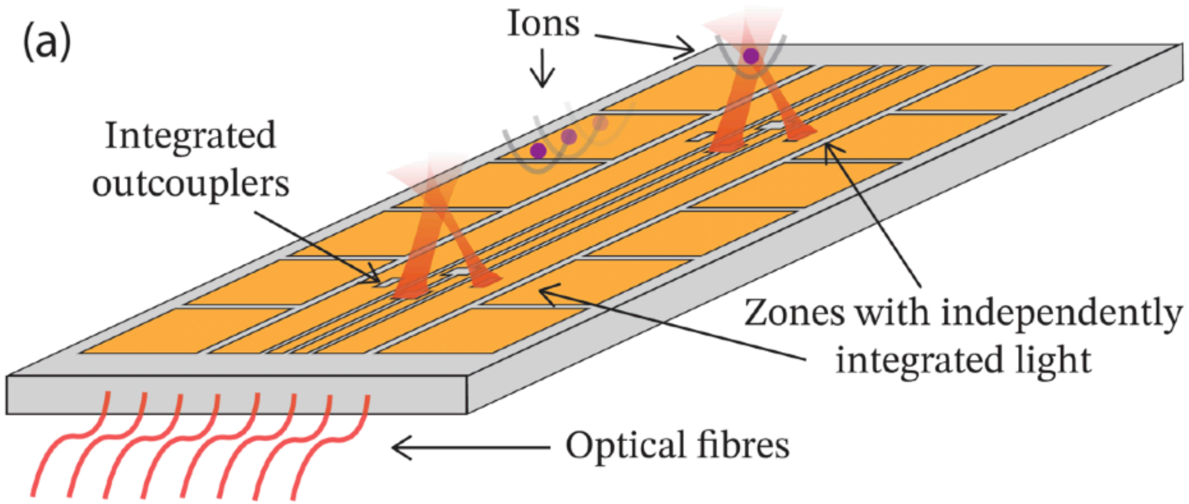


Novel modes useful for atomic clocks (drive higher order transitions at position of no intensity)

Operation of multiple zones with integrated photonics

C. Mordini, A. Ricci-Vasquez et al. PRX 15, 011040 (2025)



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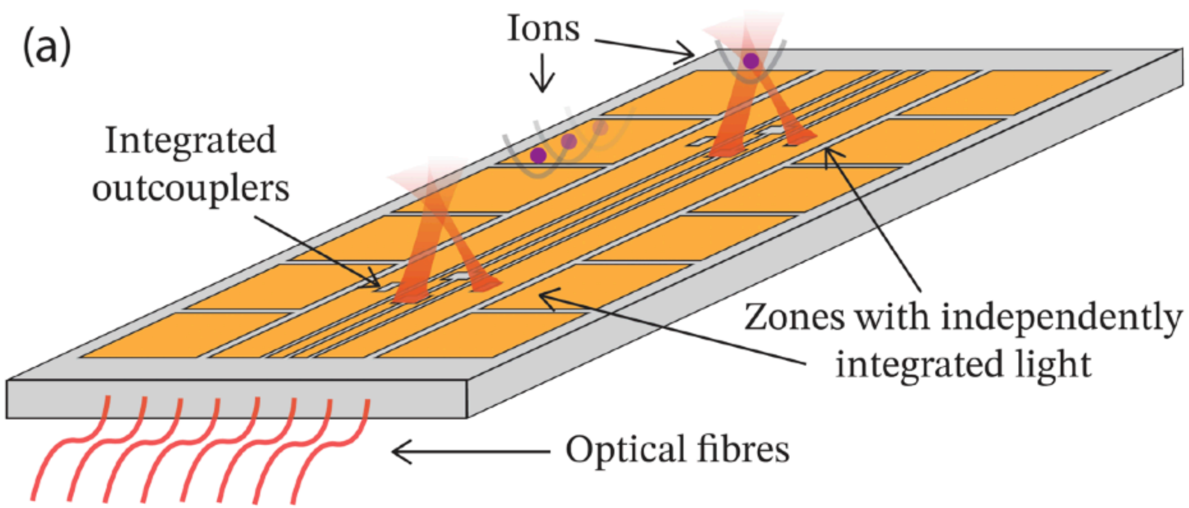

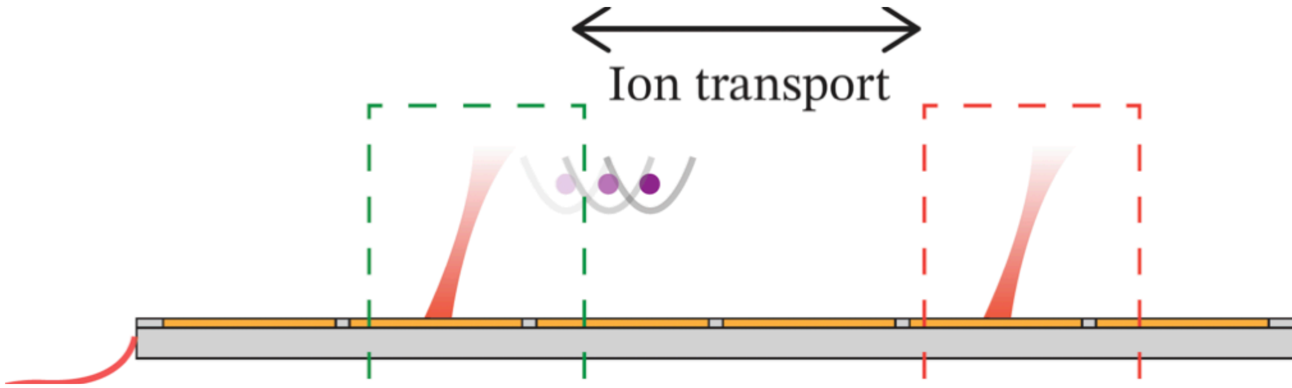

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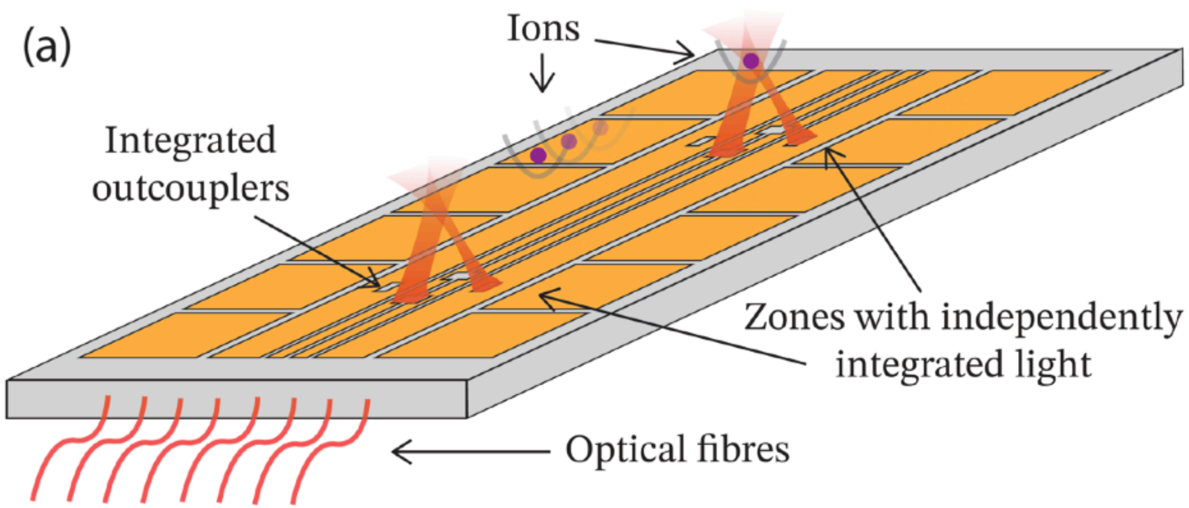

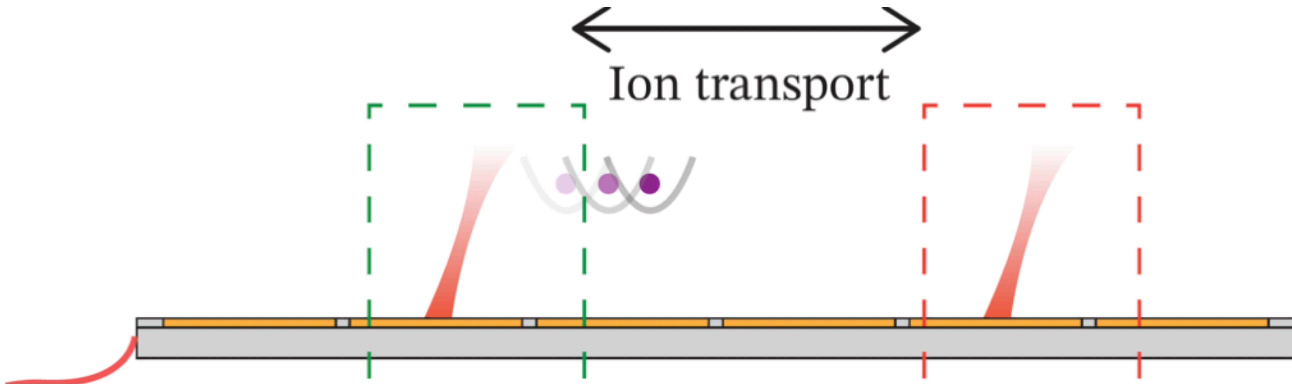

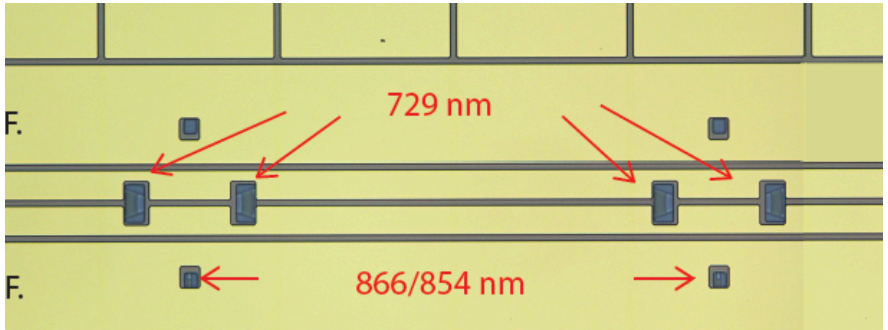

Open di-electric regions cause problems with transport

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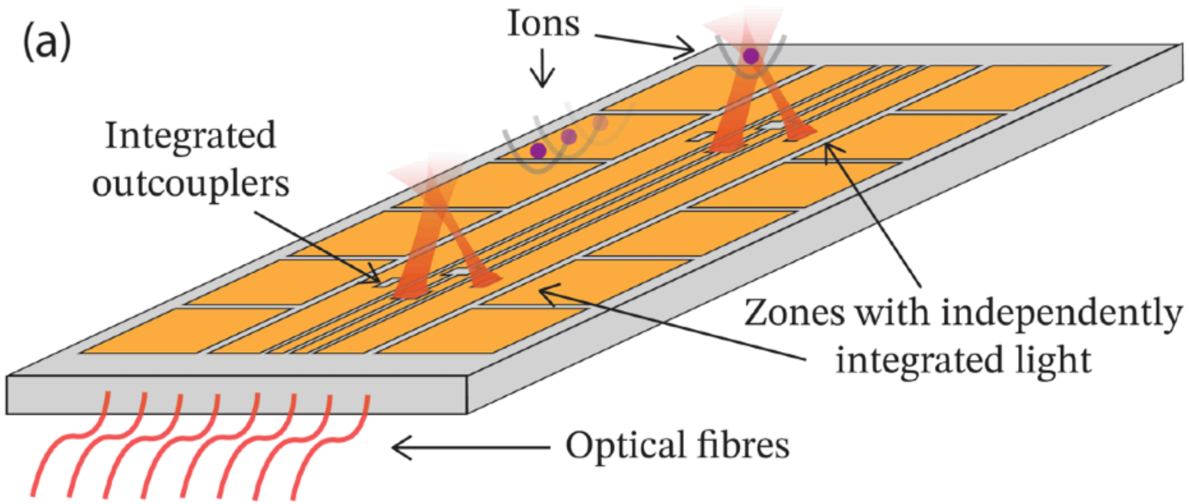
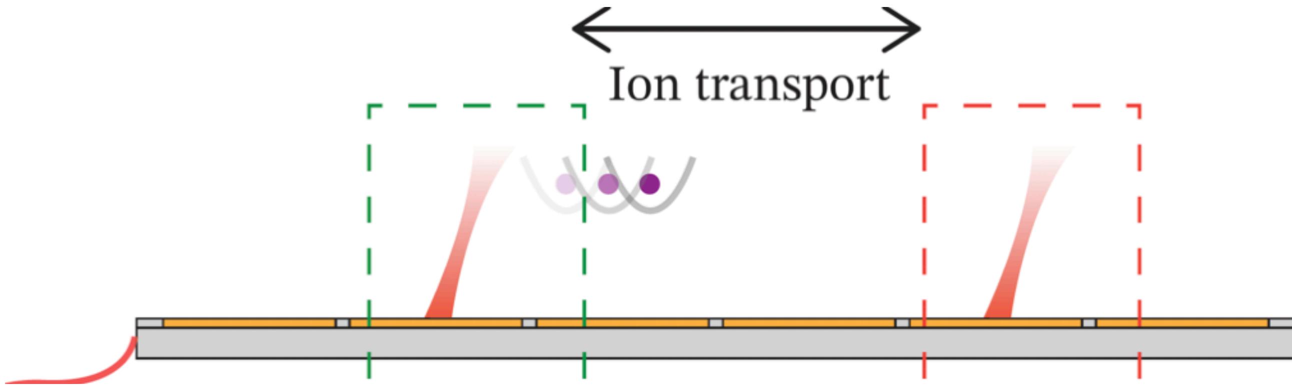
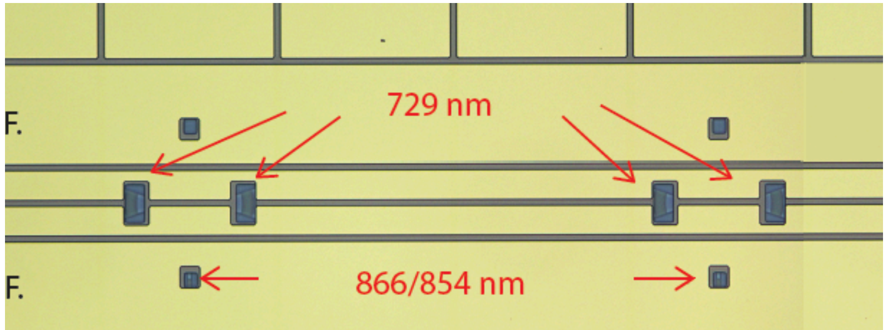
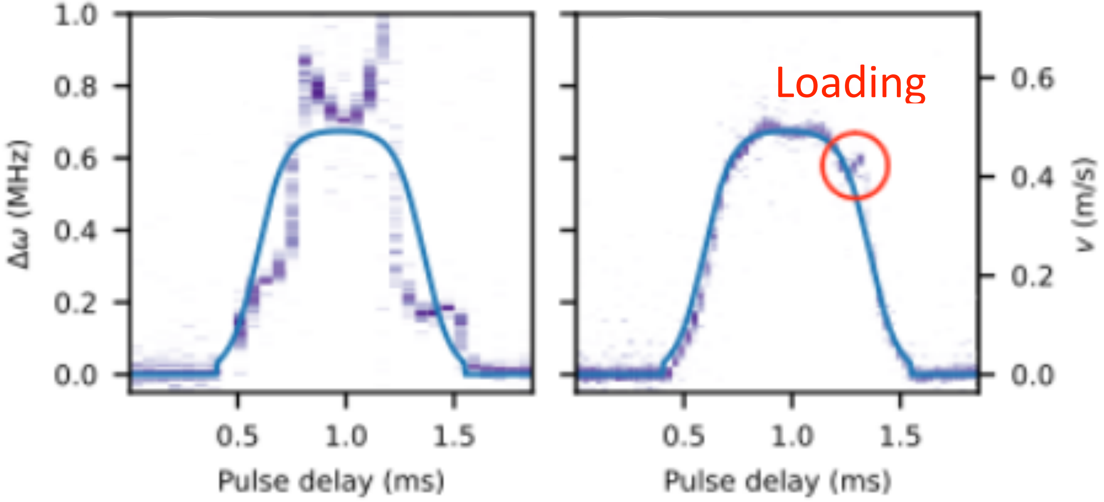






Open di-electric regions cause problems with transport

Calibration (Doppler velocimetry) and correction



Ramsey experiment between multiple zones

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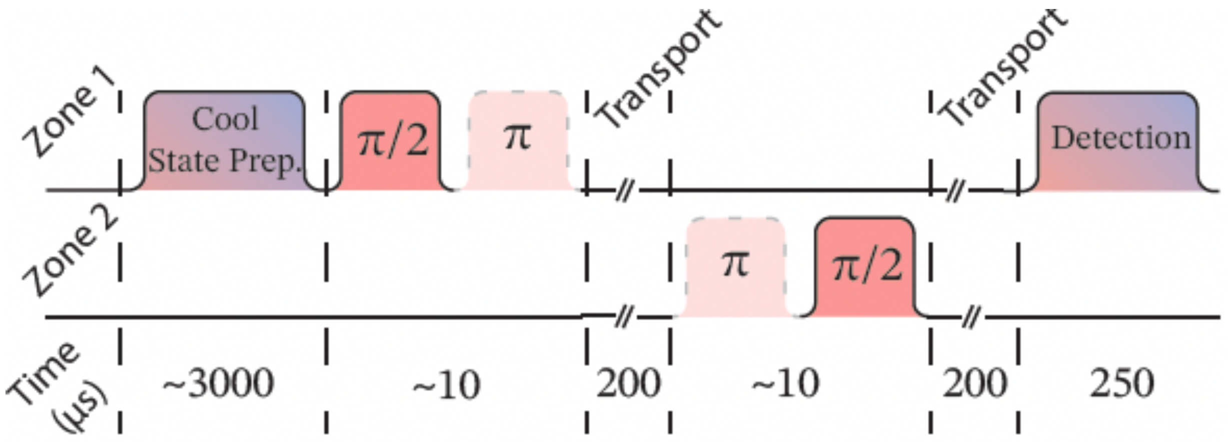

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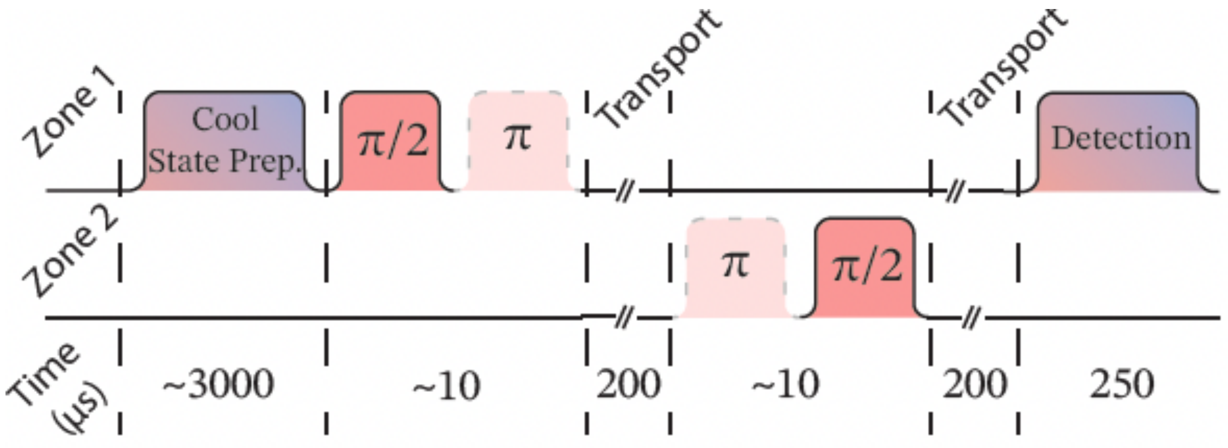

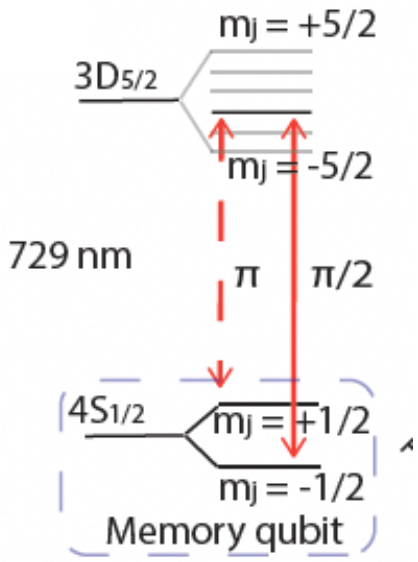

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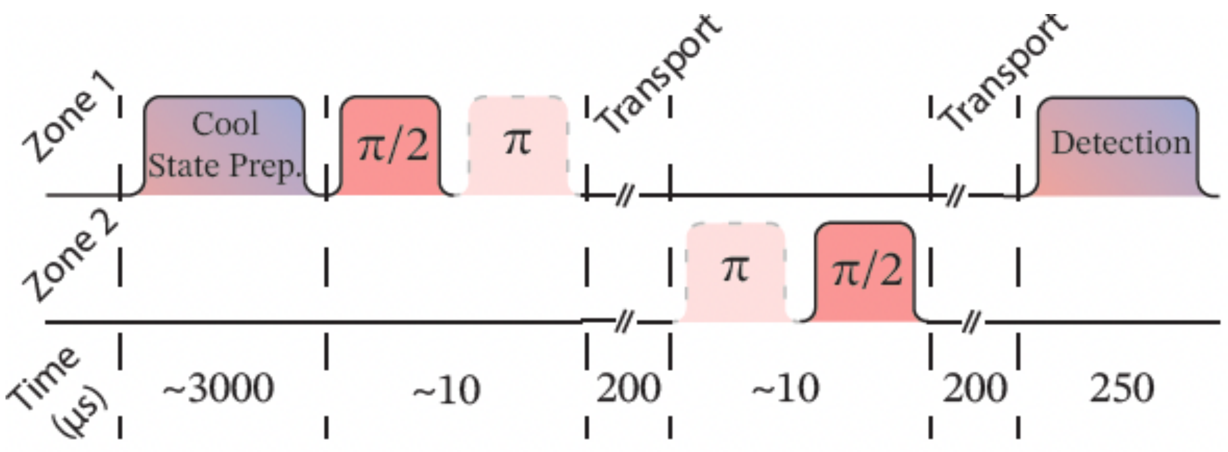

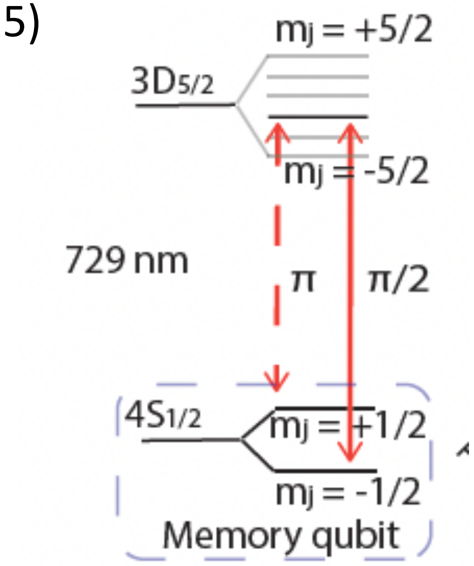

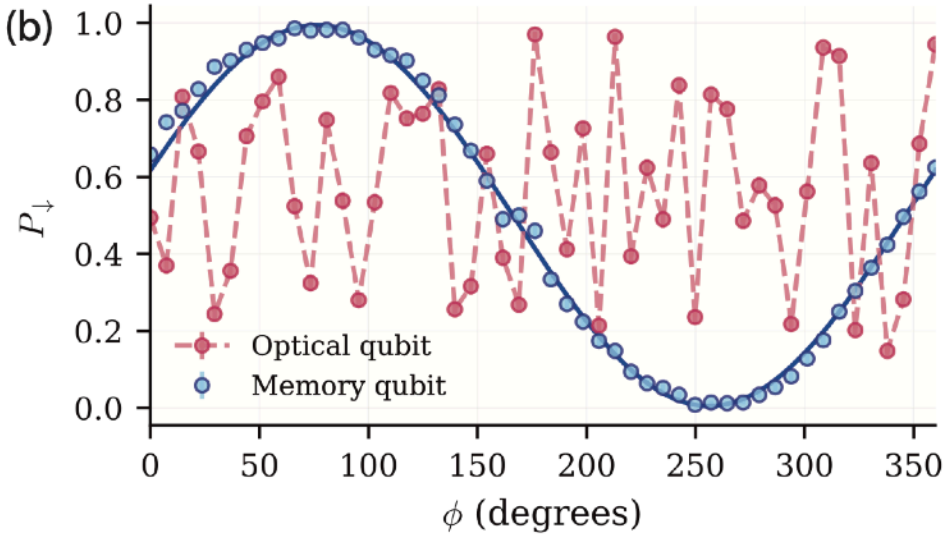

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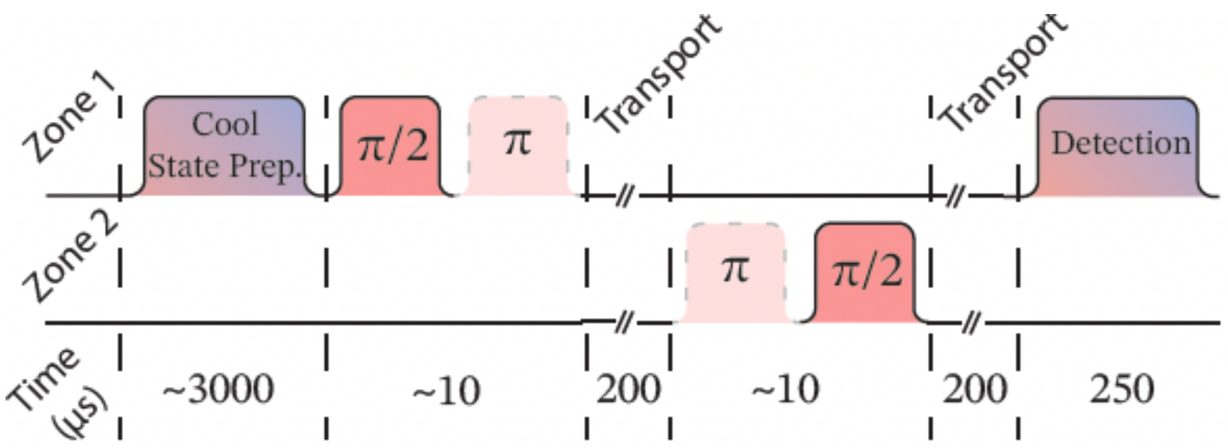
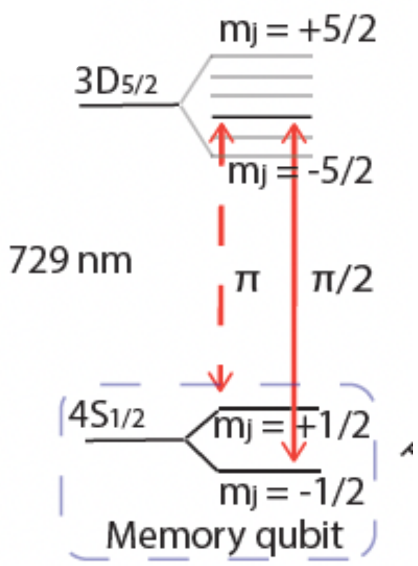
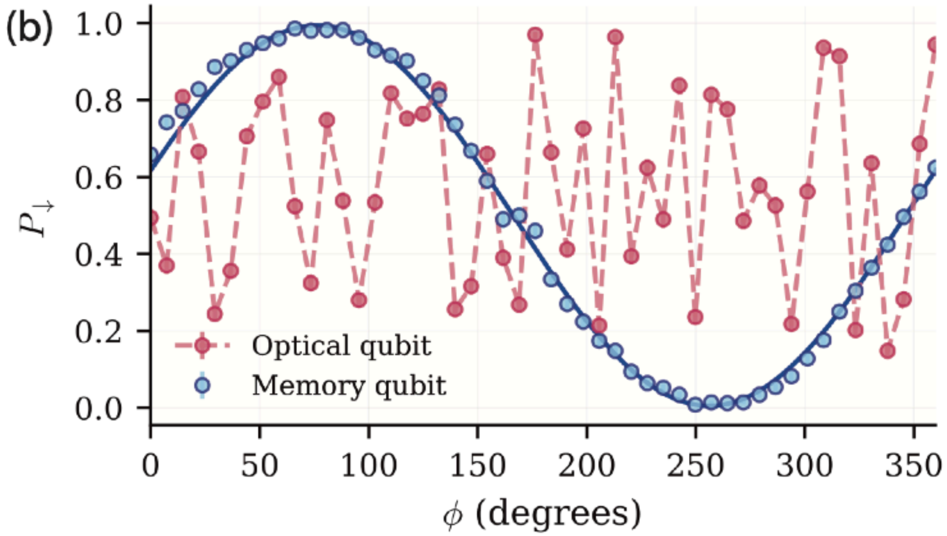
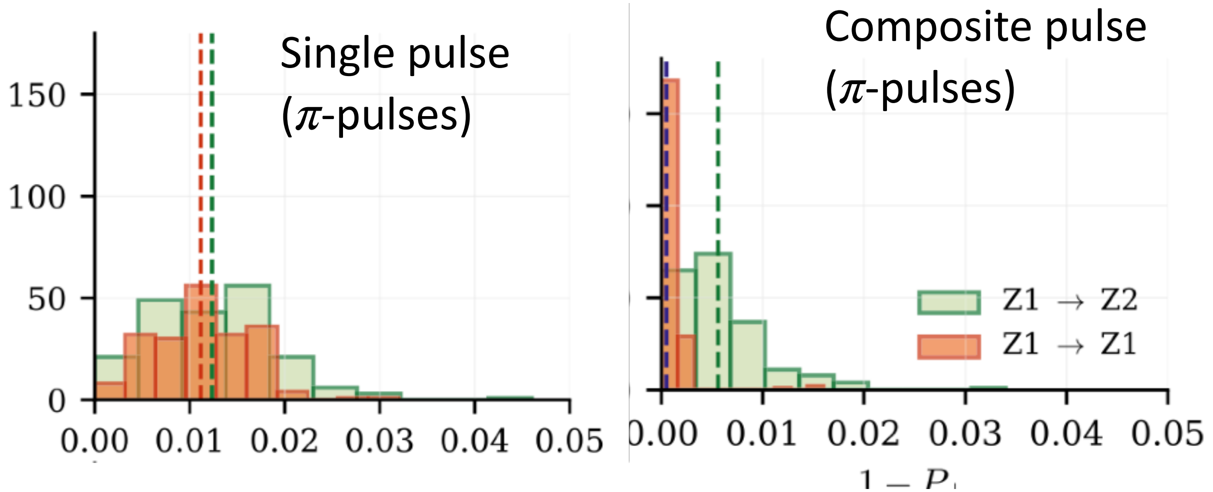




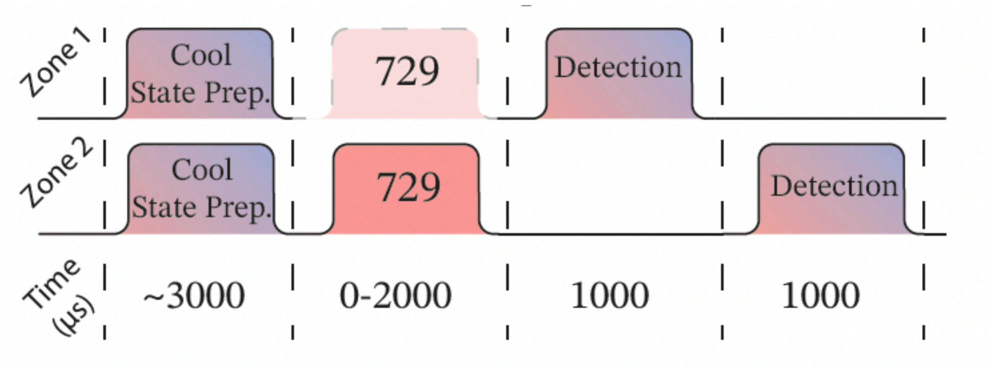




Limited by the (residual) imperfect transport into “loading” region

Parallel operations + crosstalk with ions in multiple zones

C. Mordini, A. Ricci-Vasquez et al. PRX 15, 011040 (2025)



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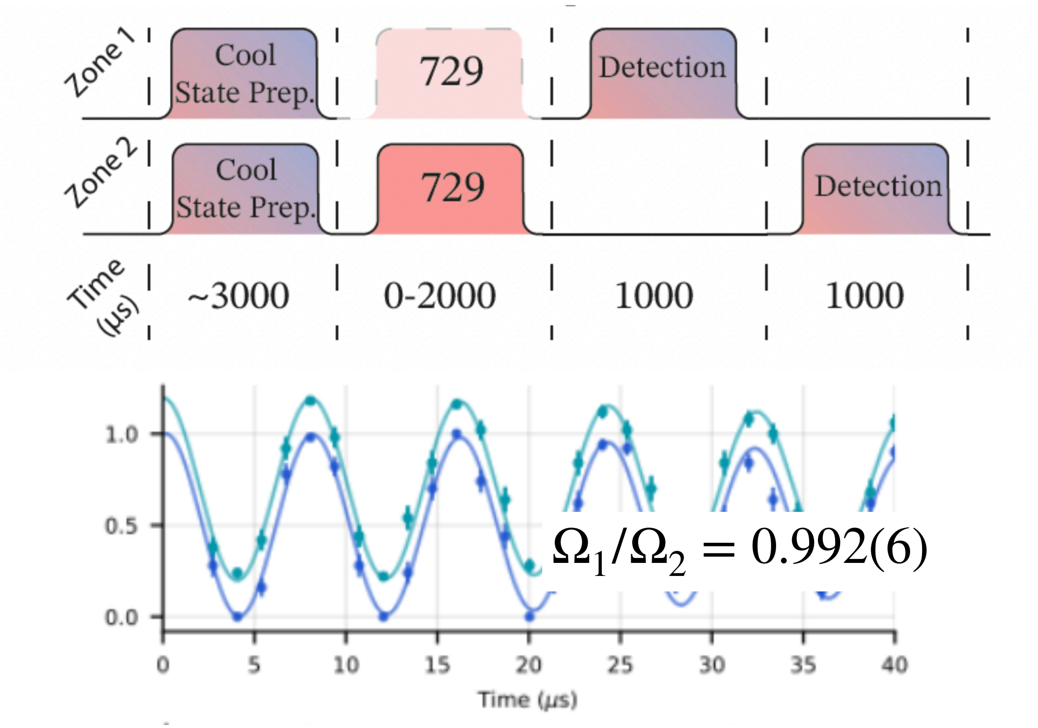

$\Omega_1/\Omega_2 = 0.992(6)$

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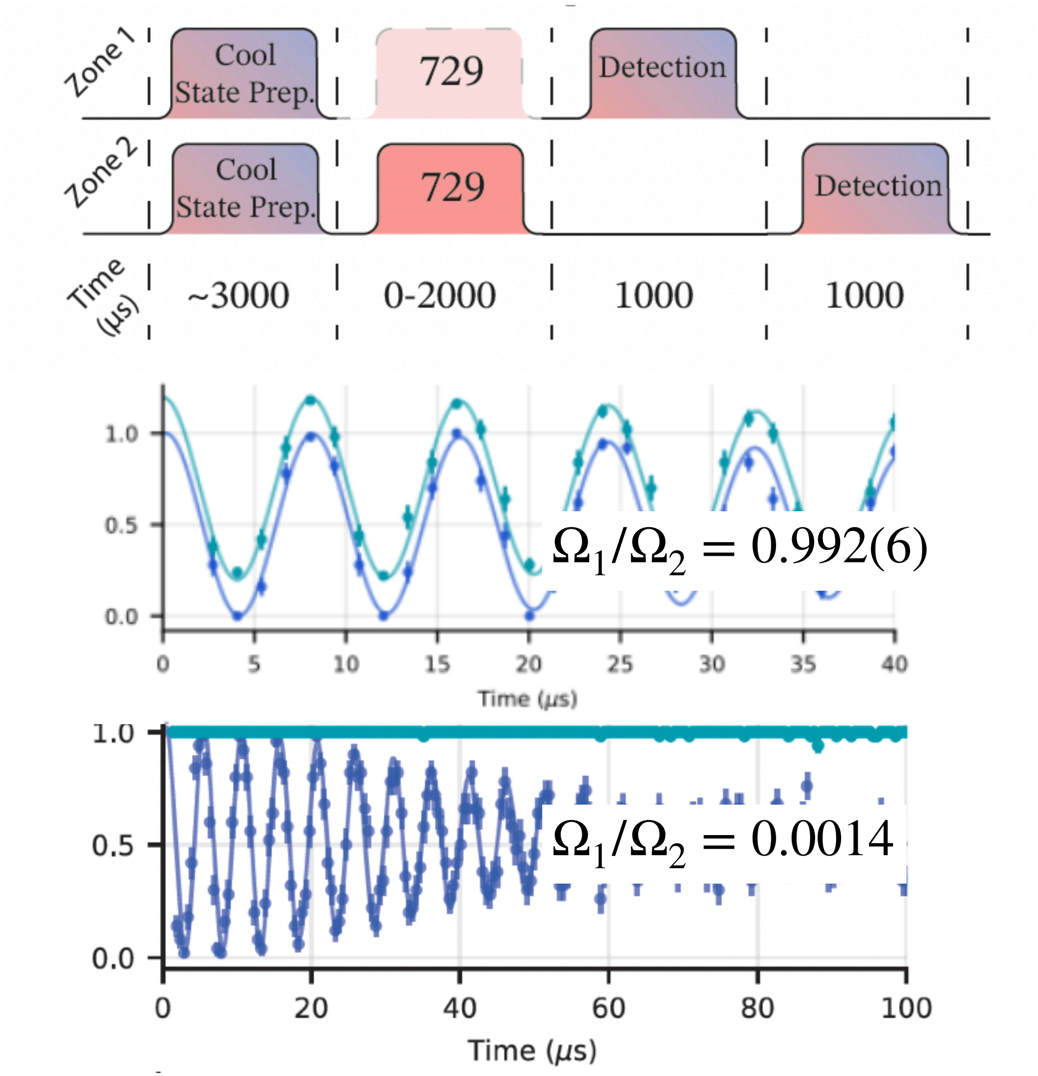

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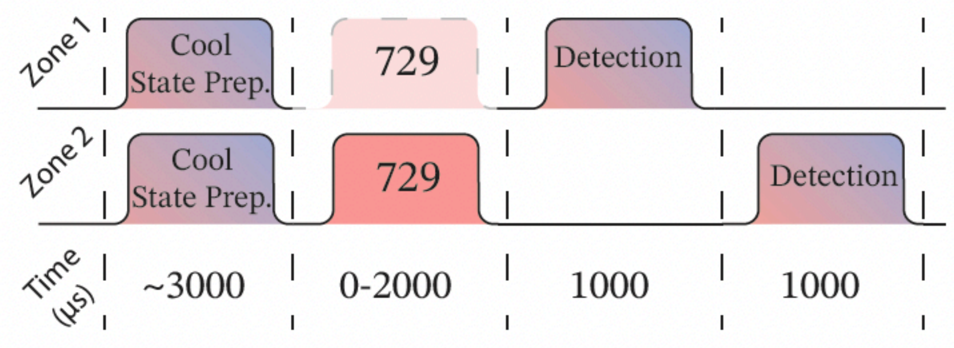

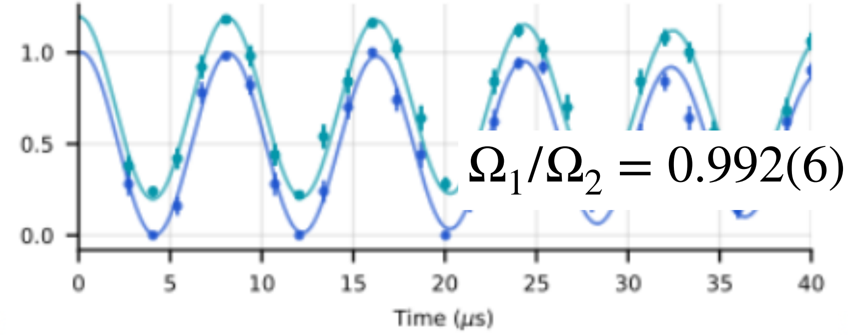

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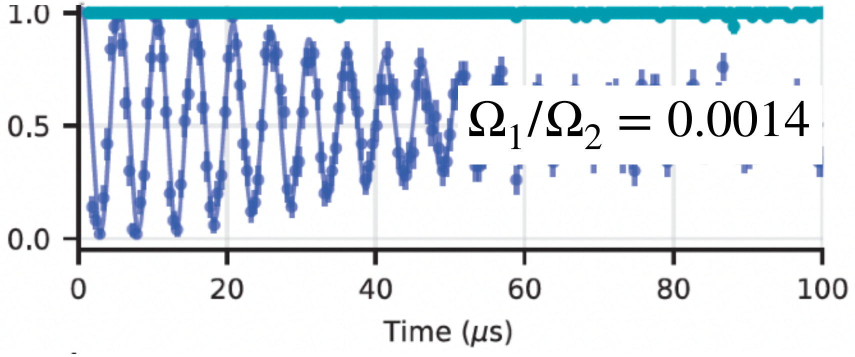
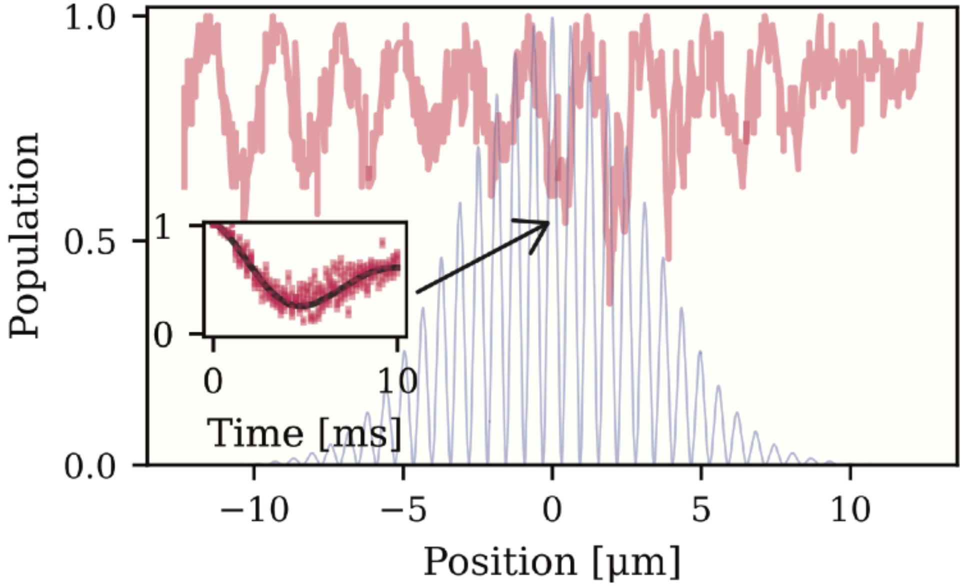


$\Omega_1/\Omega_2 = 0.0014$

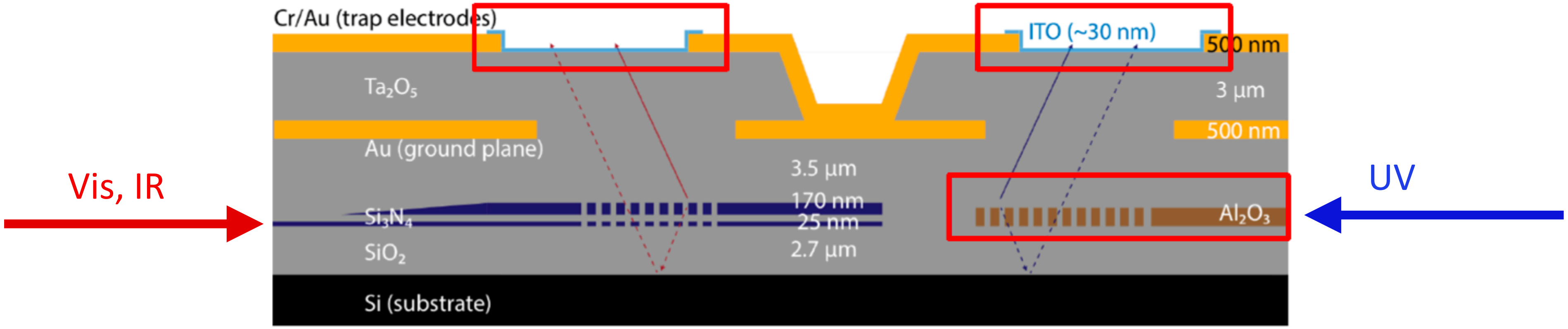
Crosstalk limit seems to be $I_1/I_2 = 10^{-8}$: not sure what is the cause

As a function of position



Next generations: multi-colour integration and scaling

Designs: Gillenhaal Beck, Karan Mehta



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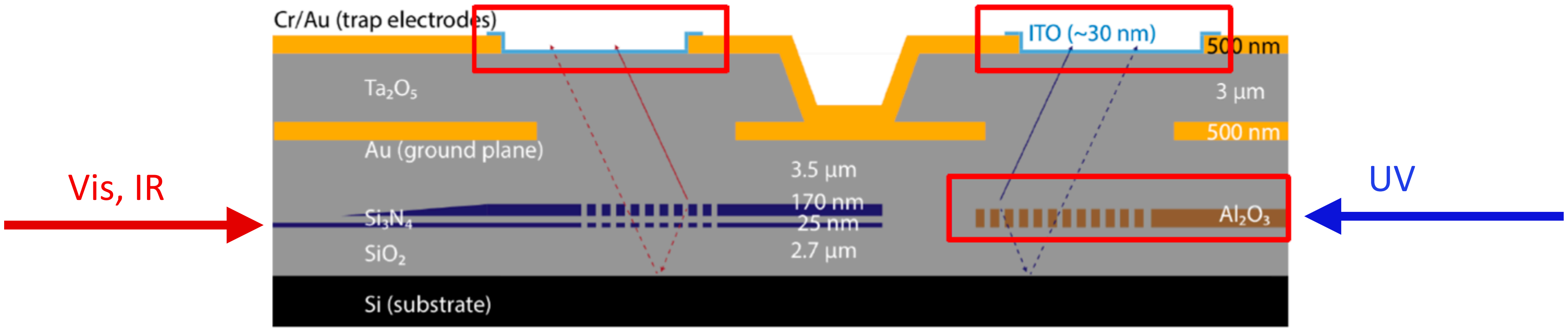

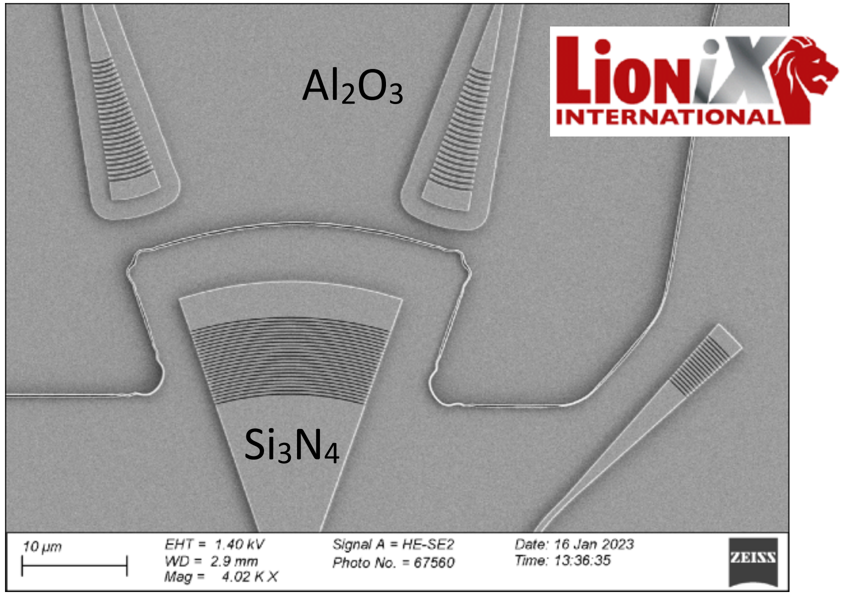

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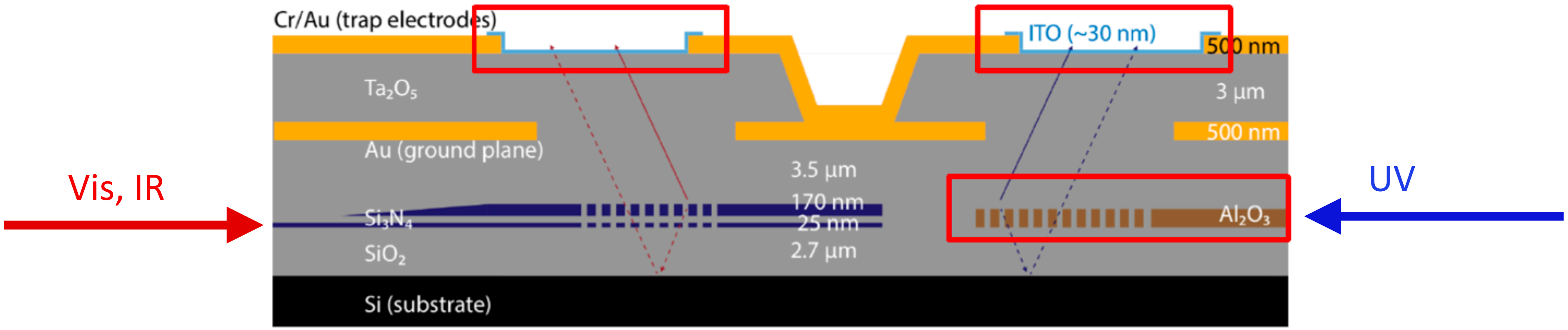
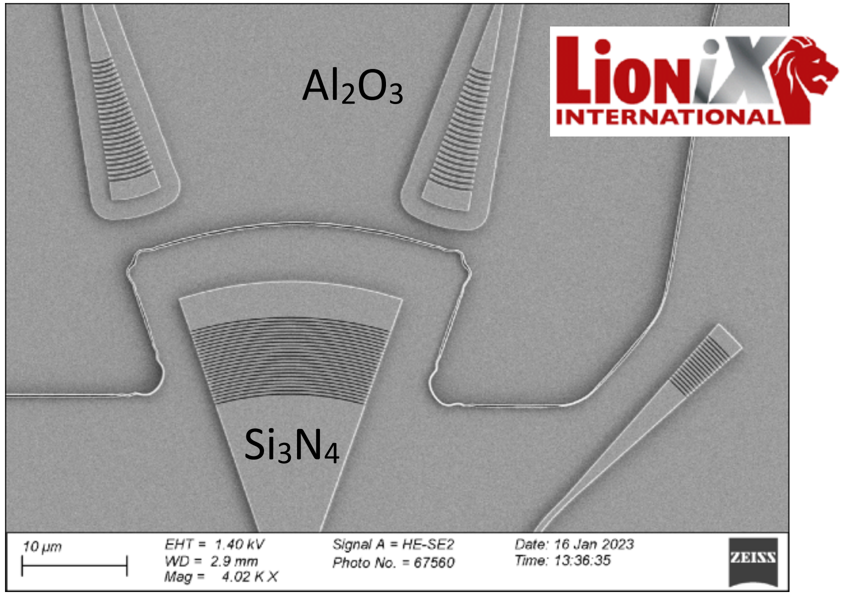
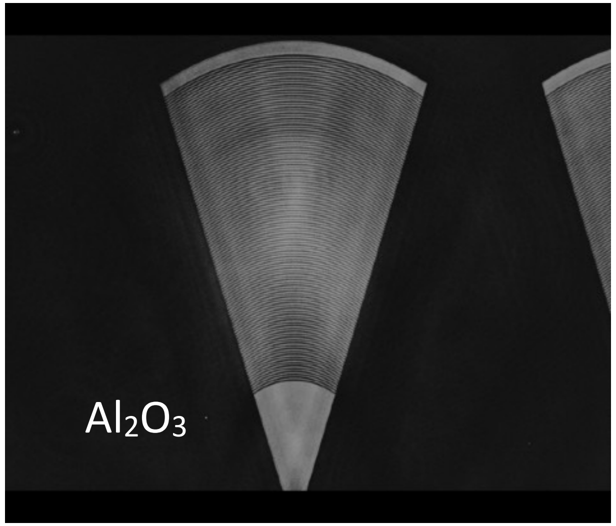


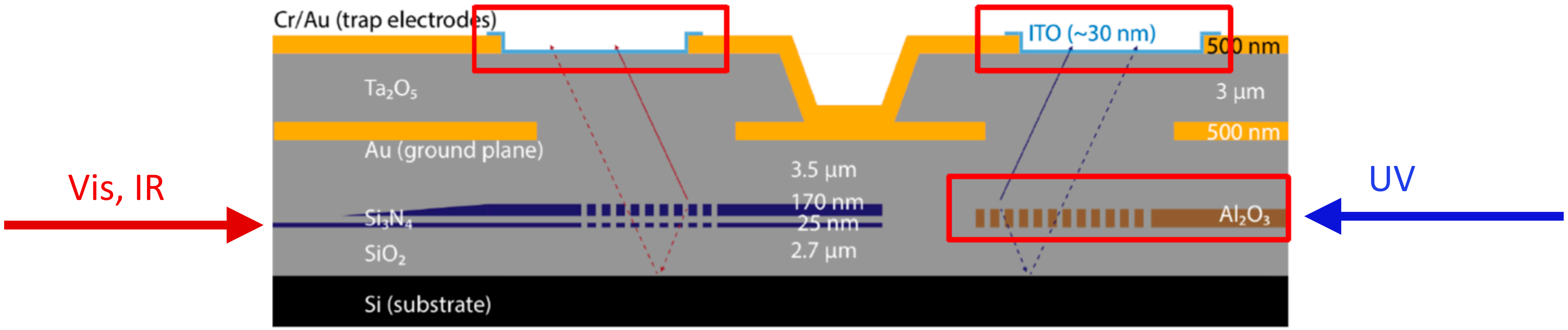


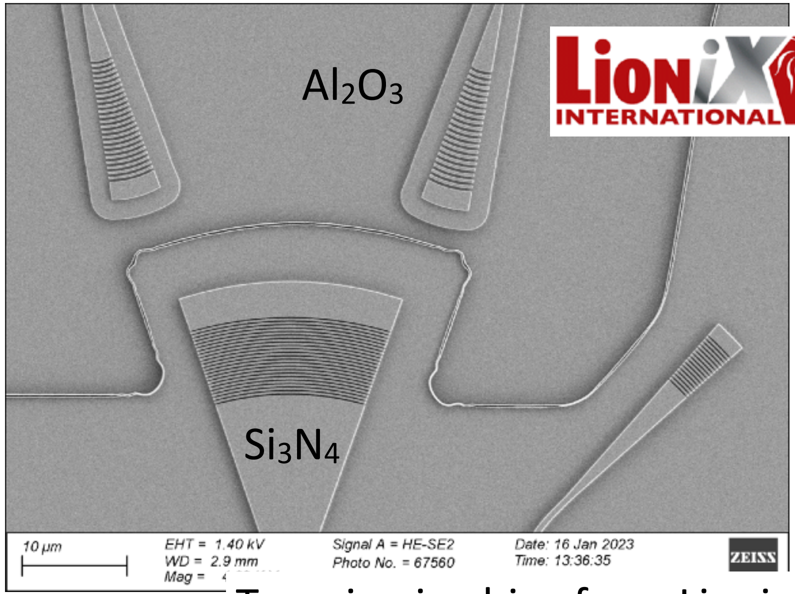
ALUVIA PROJECT

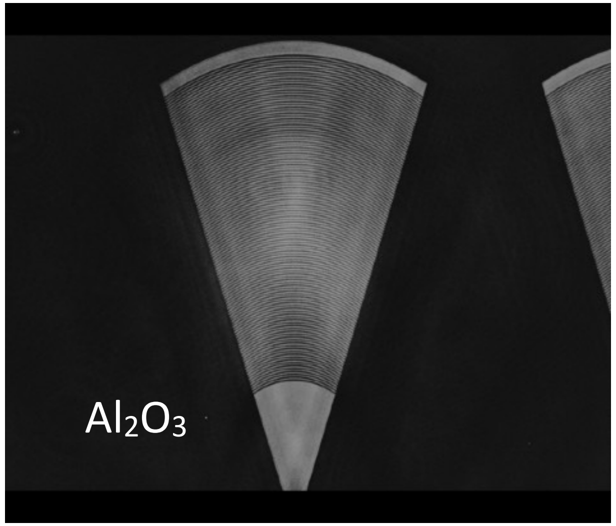


Next generations: multi-colour integration and scaling

Designs: Gillenhaal Beck, Karan Mehta







Trapping in chips from Lionix fabrication run has been achieved at ETH Zurich and Cornell

Beam design + characterisation

Gillen Beck, Karan Mehta, Tereza Viskova (PSI), Flavia Timpu (PSI), Julian Schmidt (PSI)

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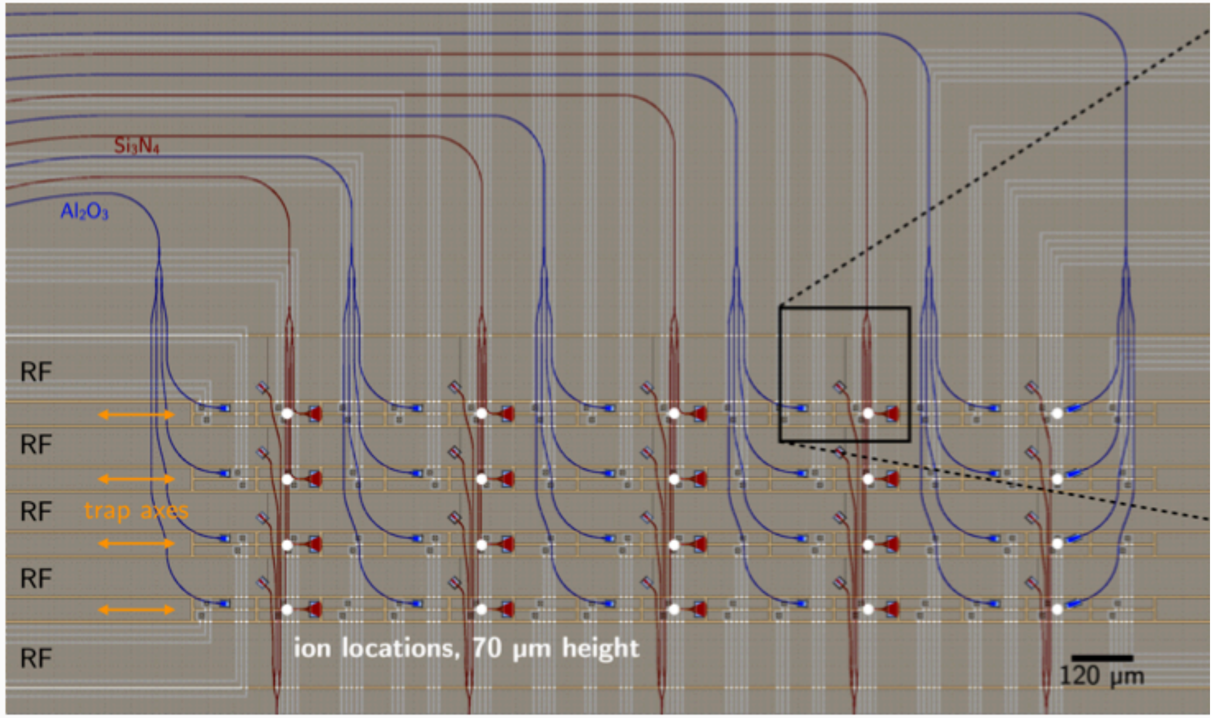
20 trap zones = 4 x 5-zone linear RF traps



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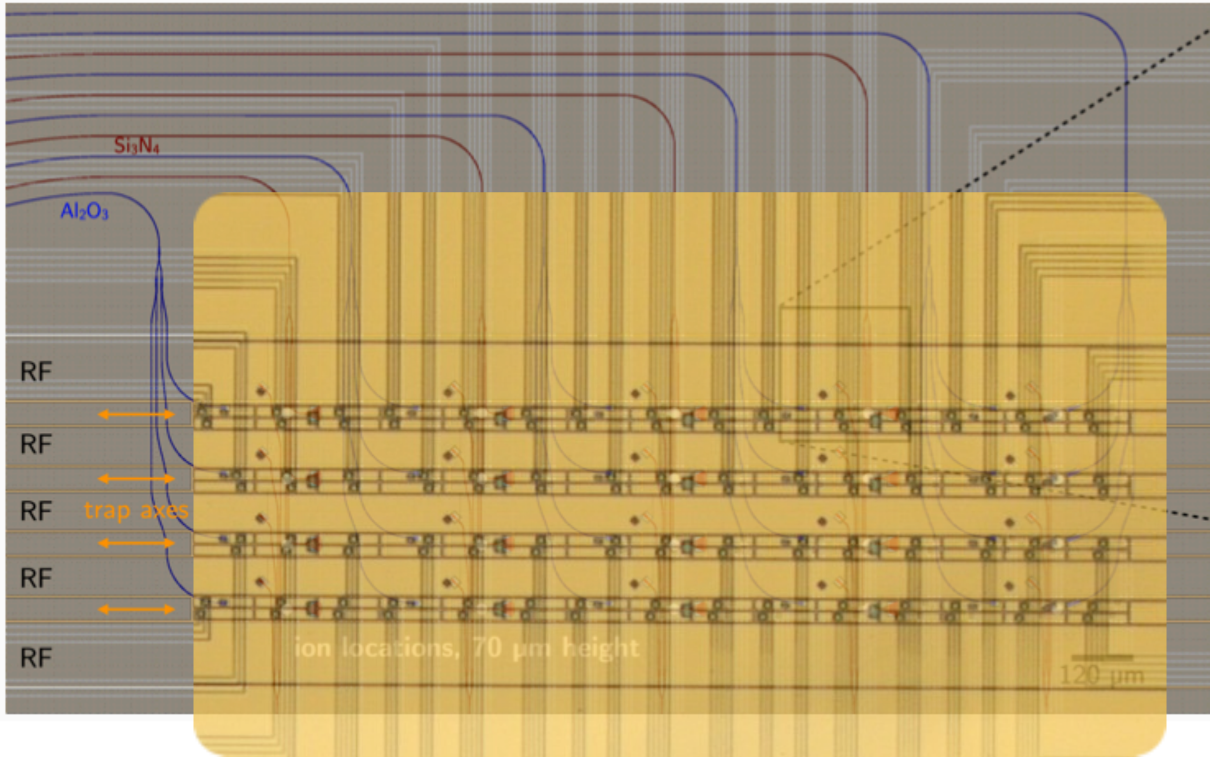

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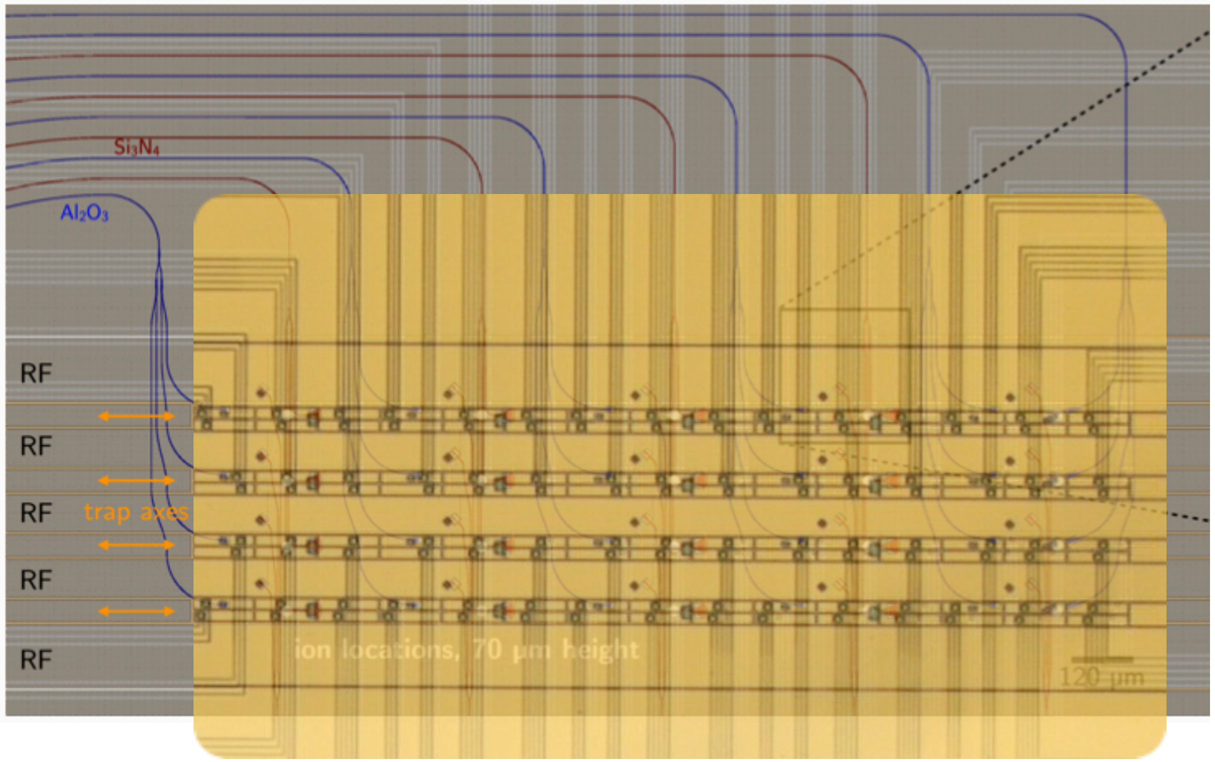

Fibre-attach/Routing of waveguides becomes a new challenge

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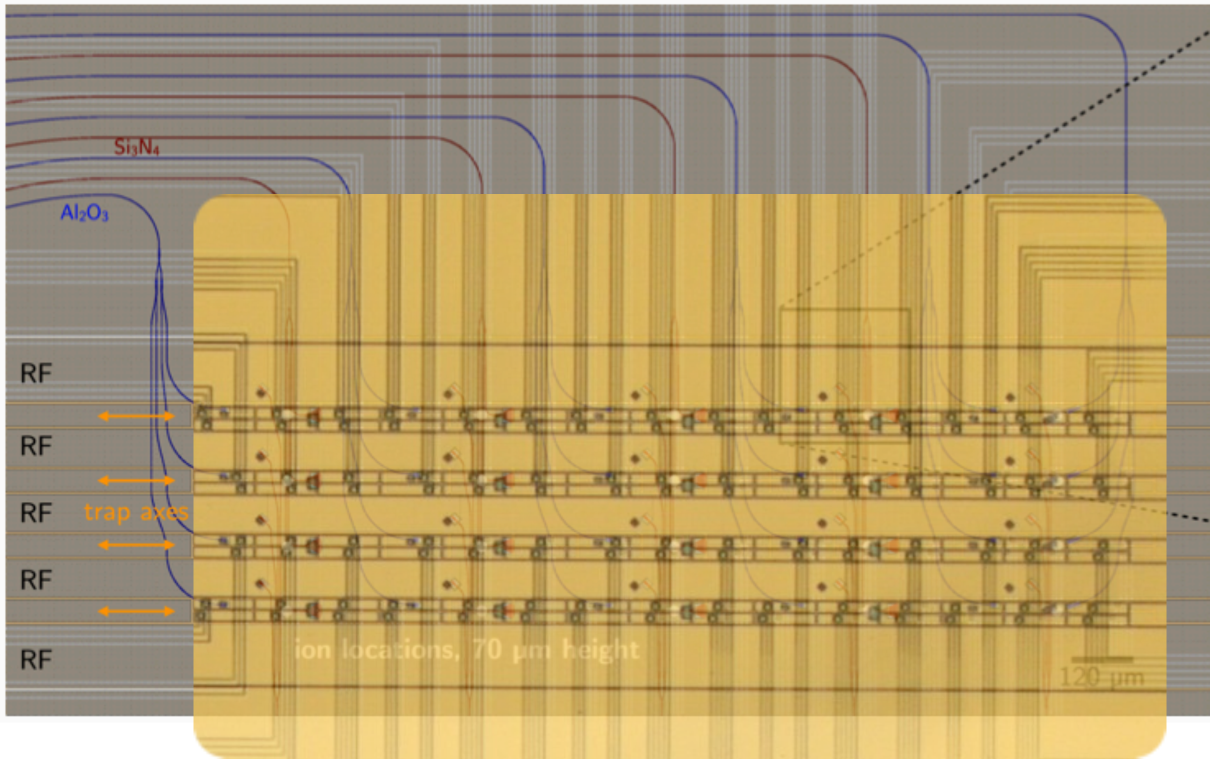
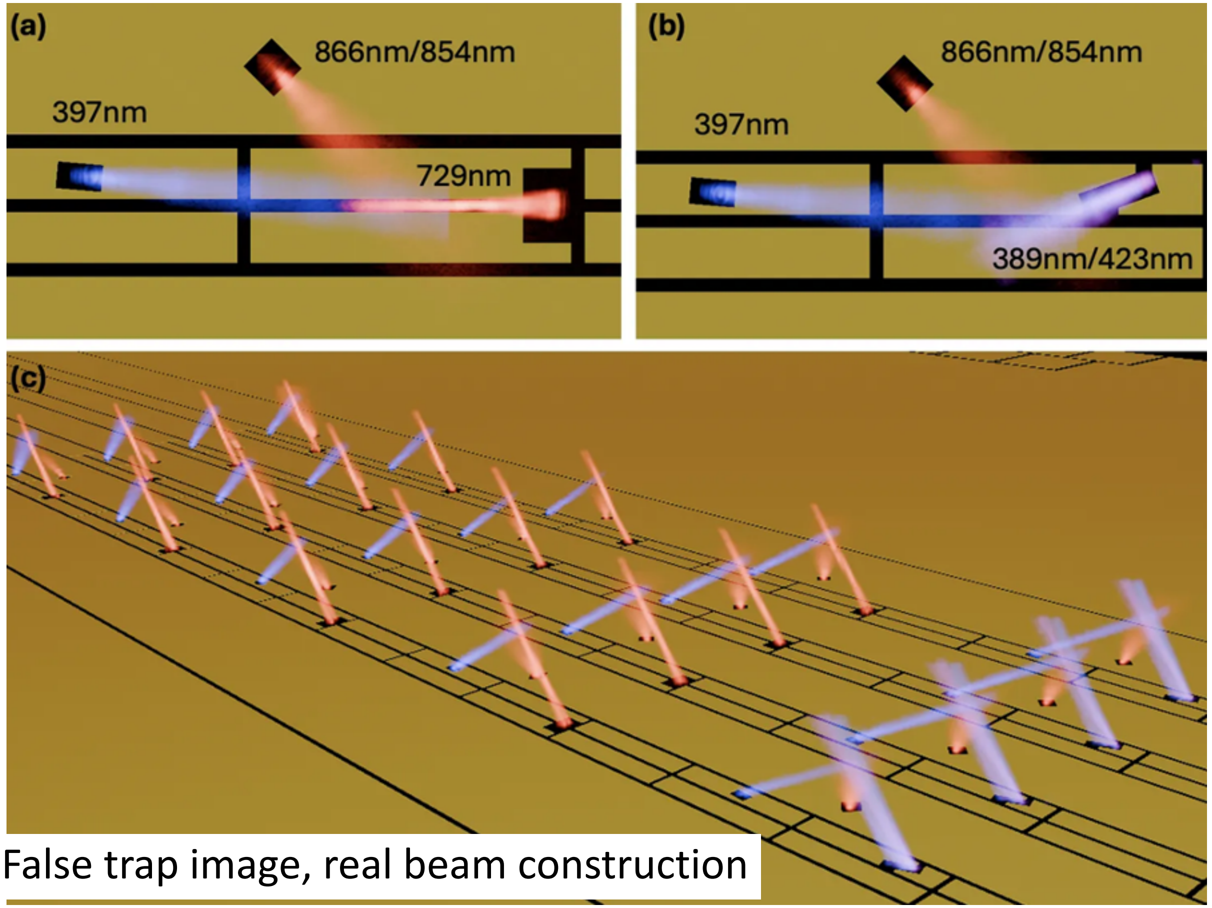


Fibre-attach/Routing of waveguides becomes a new challenge

20-zone chip @ Paul Scherrer Institute Quantum Computing Hub



False trap image, real beam construction

Broader progress

Integrated optics work at MIT + Lincoln Labs, Cornell, Sandia, various companies (Quantinuum, Infineon, Oxford Ionics, ZuriQ)

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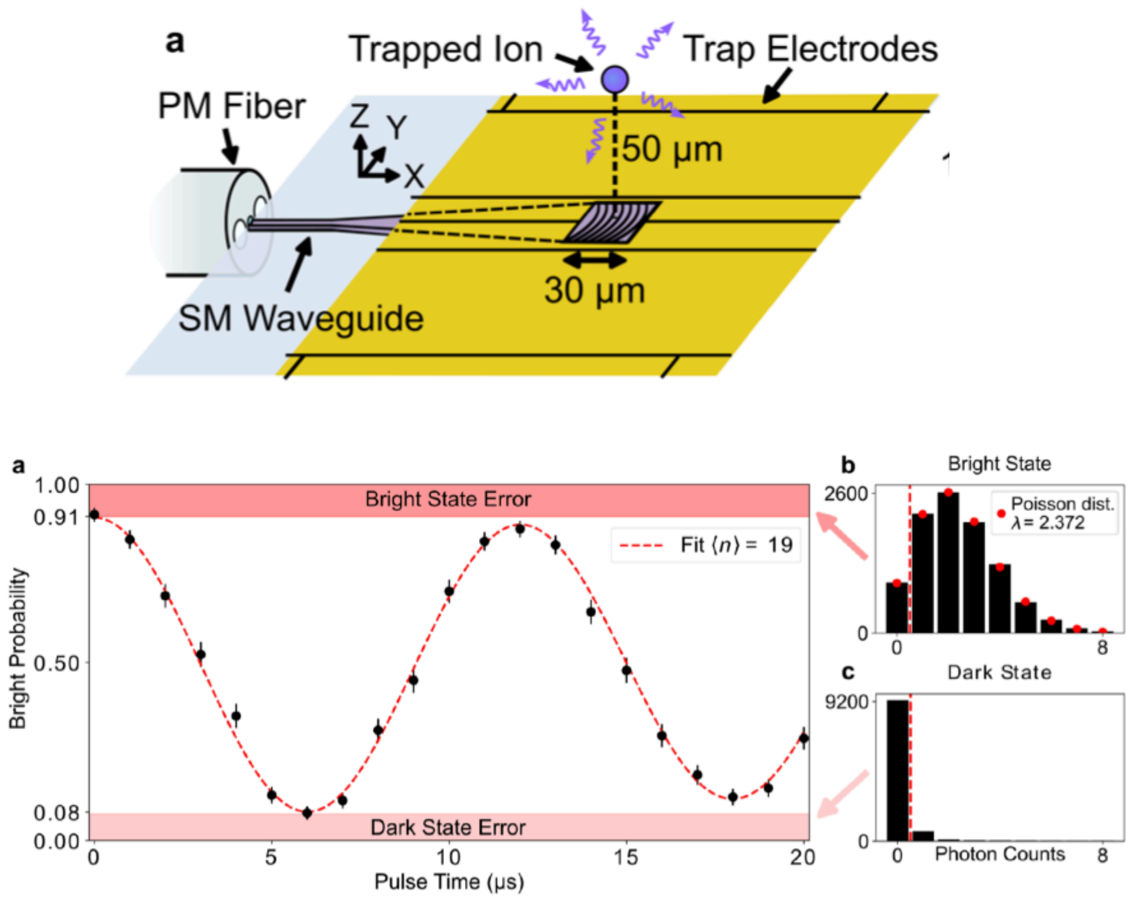
Expt: F. Knollman et al. arXiv:2505.01412



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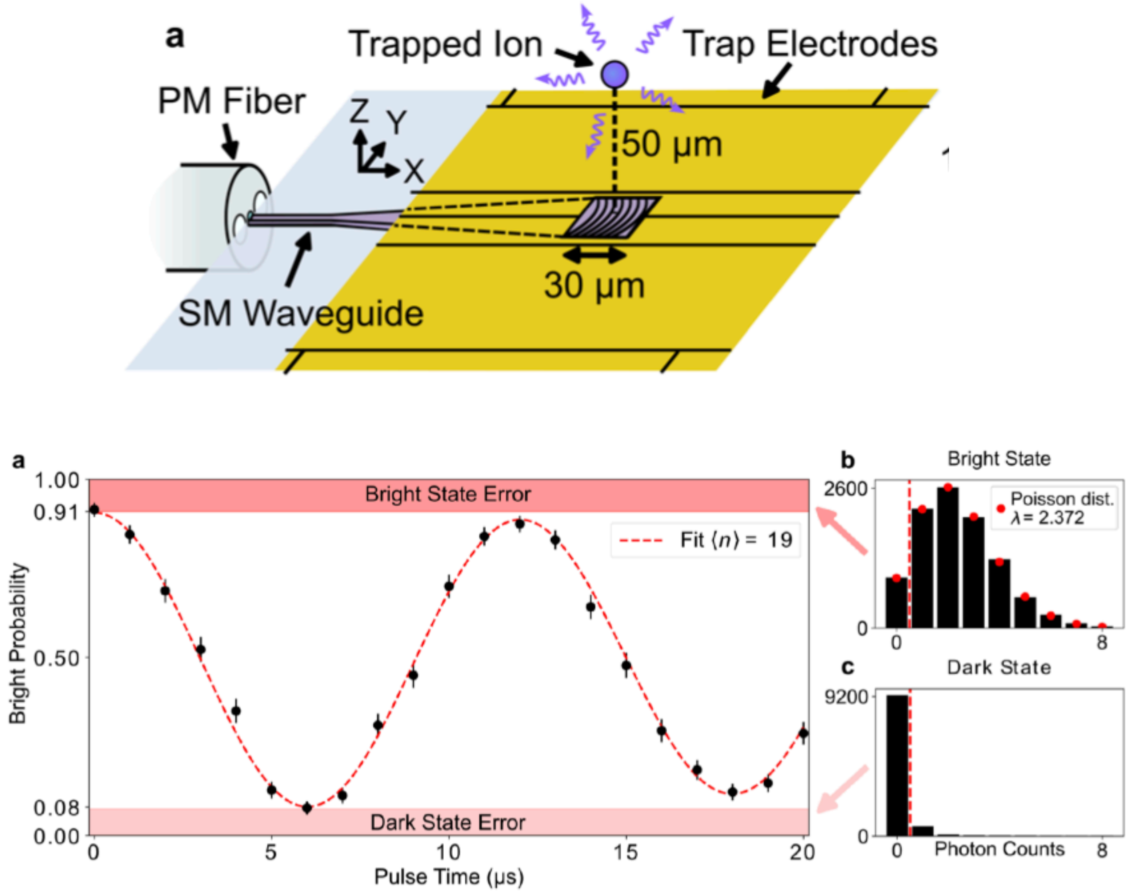
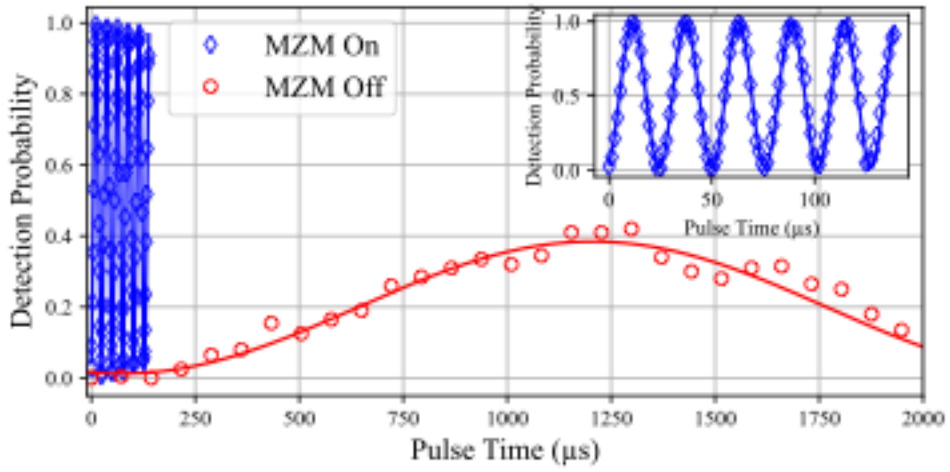
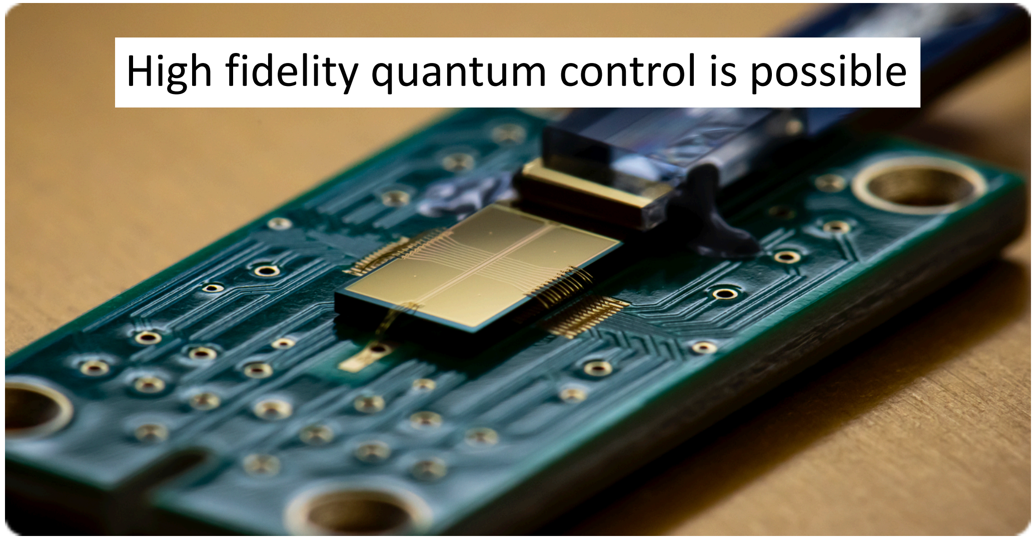


Mach-Zehnder modulation (not on the ion trap chip)

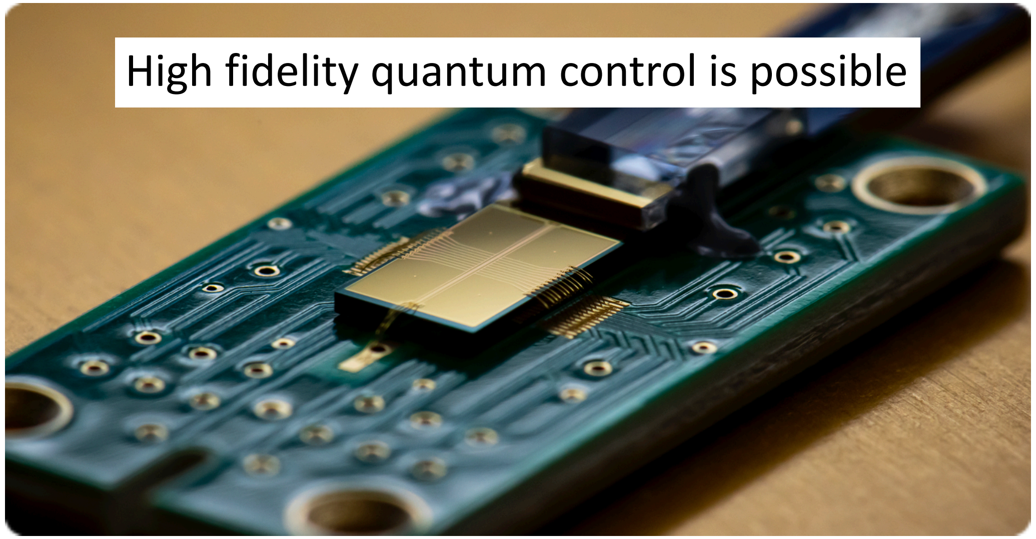
C. Hogle et al. arXiv:2210.13368, 729 nm, relatively low powers

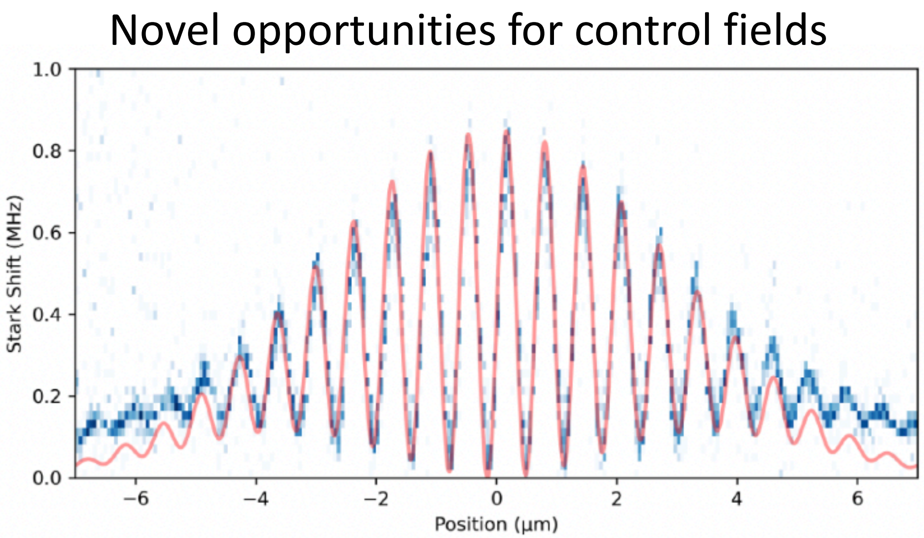


Summary + outlook



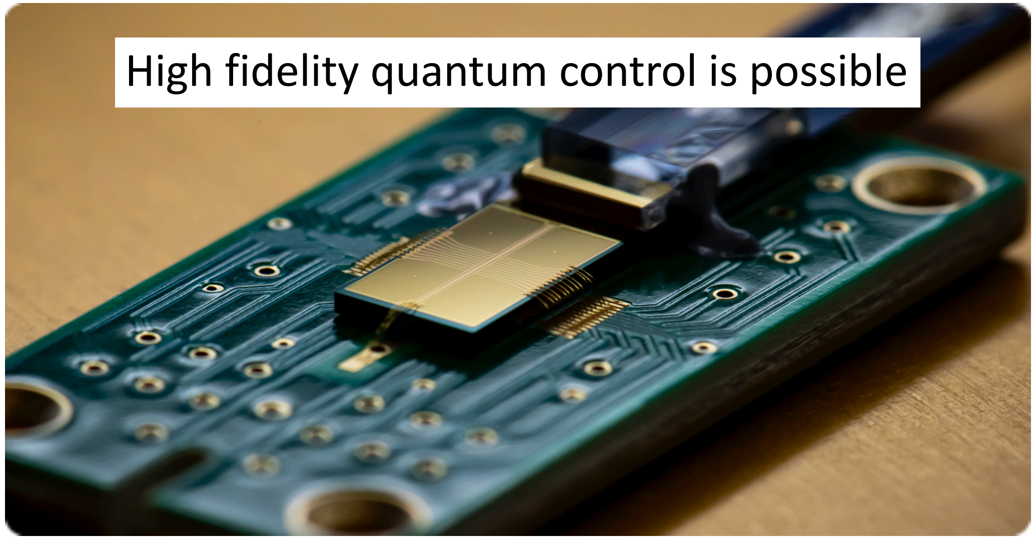
Summary + outlook



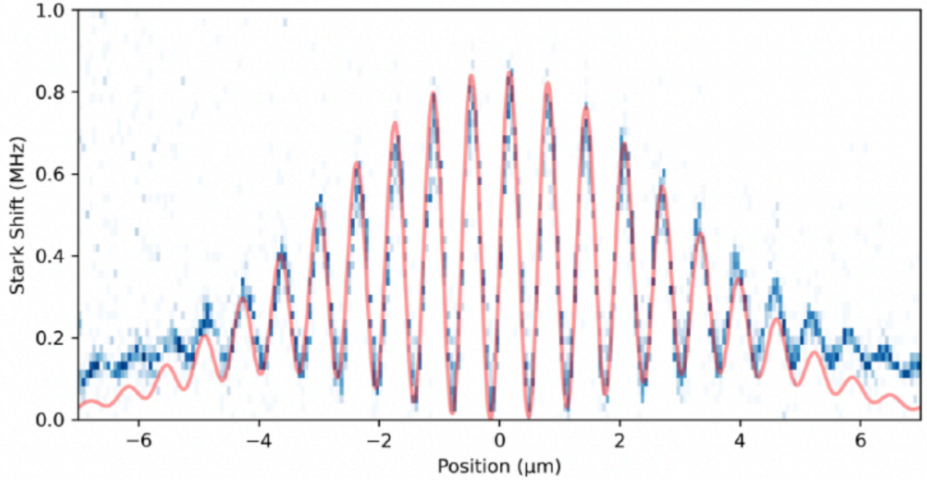


Summary + outlook

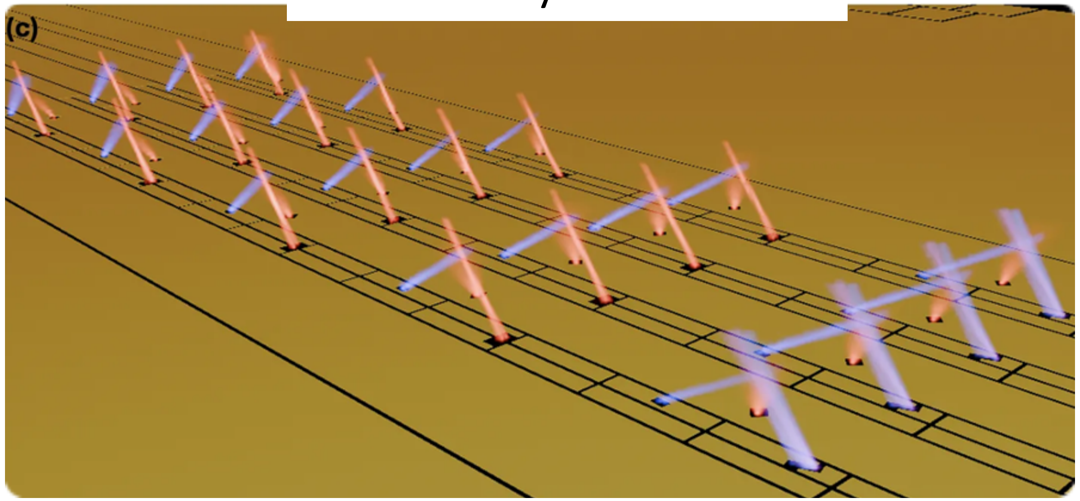
High fidelity quantum control is possible



Novel opportunities for control fields

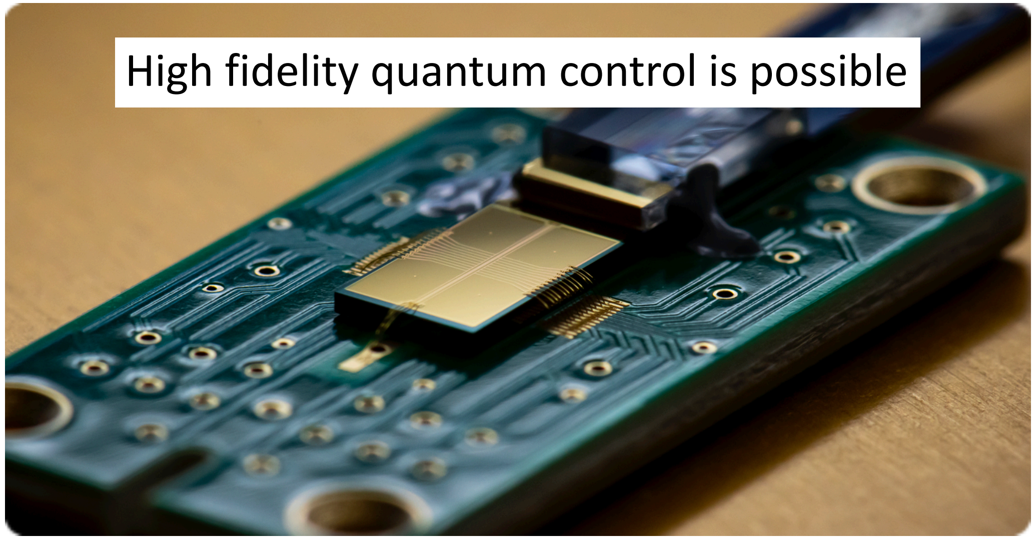


Can we really scale control?



Summary + outlook

High fidelity quantum control is possible



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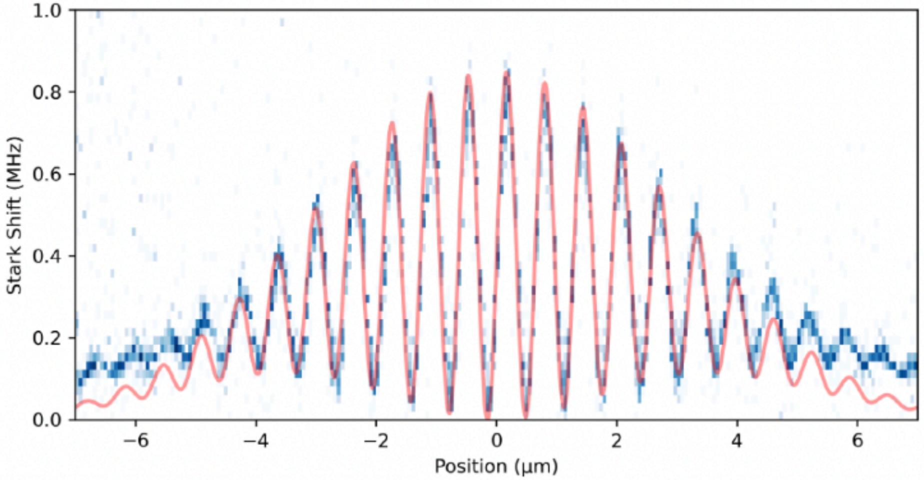

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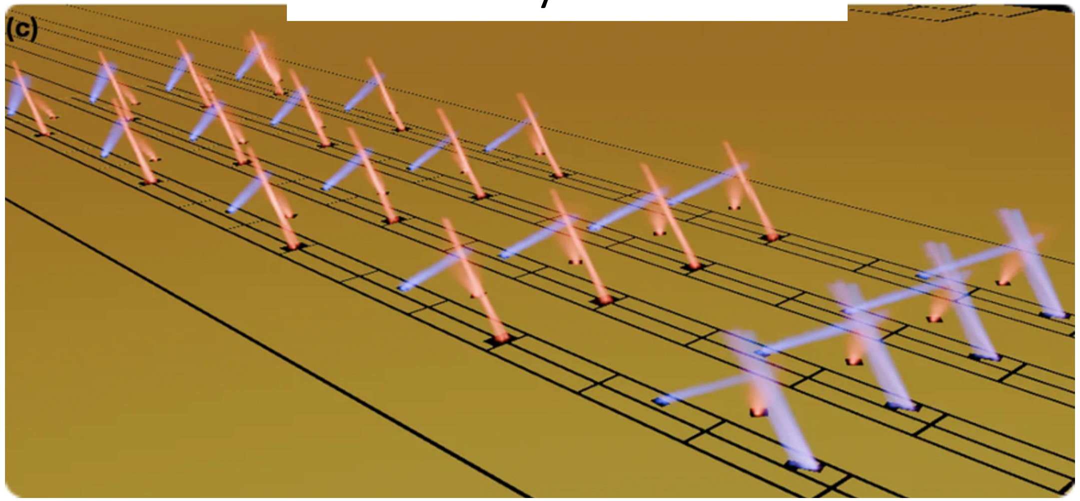

Integrated modulators?
Heating problems specific to integrated optics chips?
How do we deliver and route light efficiently?
Materials for UV photonics?
Shielding of charge?


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