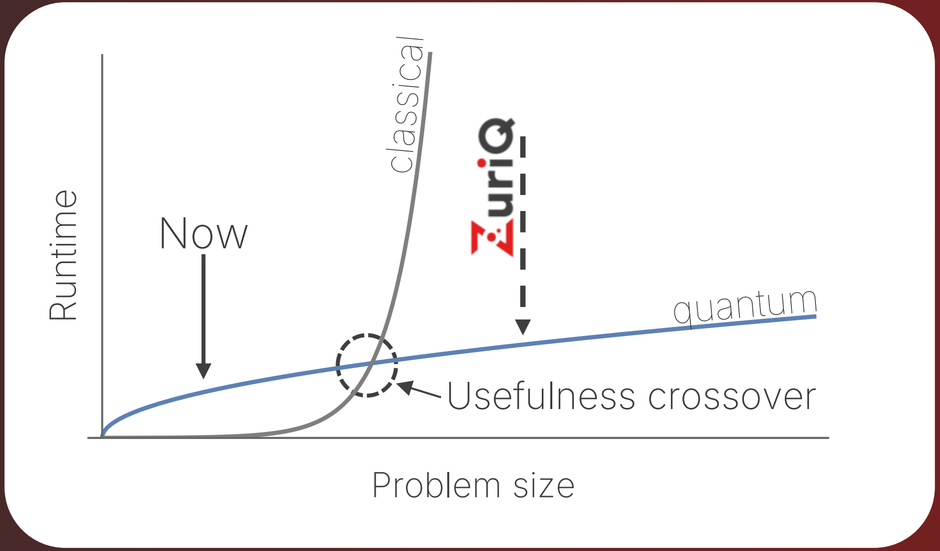
ZuriQ

Integrated photonics for scaling trapped ion quantum computing.

Quantum Computing Overview

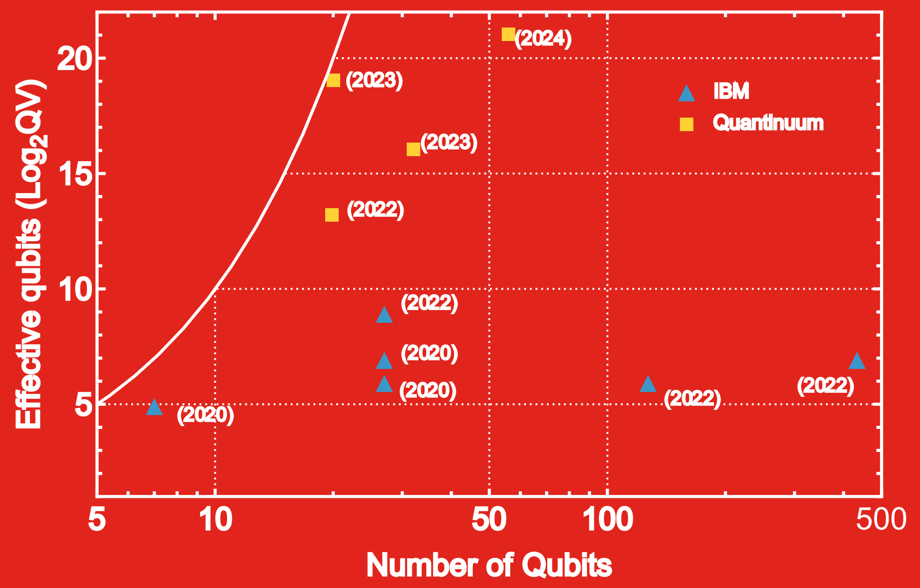
- **THE PROMISE:** Massive *algorithmic speedup:* a quantum computer isn't *faster* – it simply needs far *fewer steps* to reach solution.

- **THE APPLICATIONS:** Drug design, cybersecurity,materials, chemistry....
- **PROBLEM:** To be useful, QCs need to be able run much larger circuits



The Trapped-Ion Value Prop

Quantum **computers** need higher qubit **quality** and **quantity**



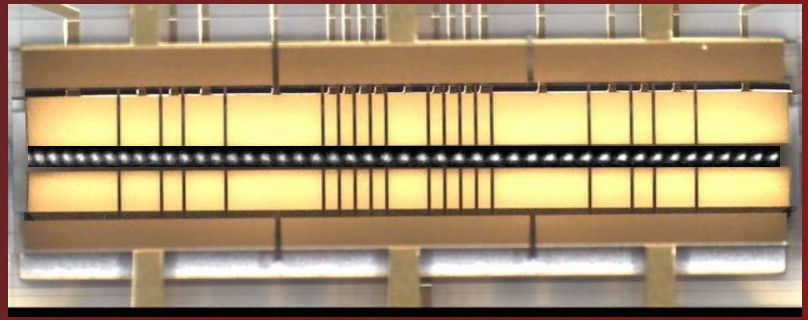
Trapped Ions

QUALITY

- 'Ideal qubits' – not manufactured
- All-all connectivity
- Error Correction/Logical Qubits
- Highest fidelities - $\mathcal{F}_{2q} \geq 0.9999$

QUANTITY

- 'Only' 50-98 qubits so far
- Already reached the limit of 1D architecture



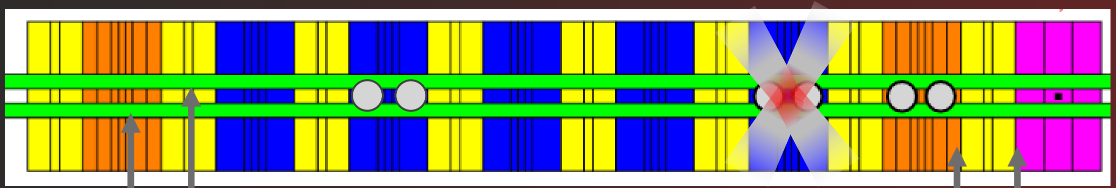
Trapped Ion Quantum Information group, ETH Zurich

State-of-the-art Trapped Ion QC

The method: Physical *shuttle*, *split*, *join*, *rotation* operations in RF trap

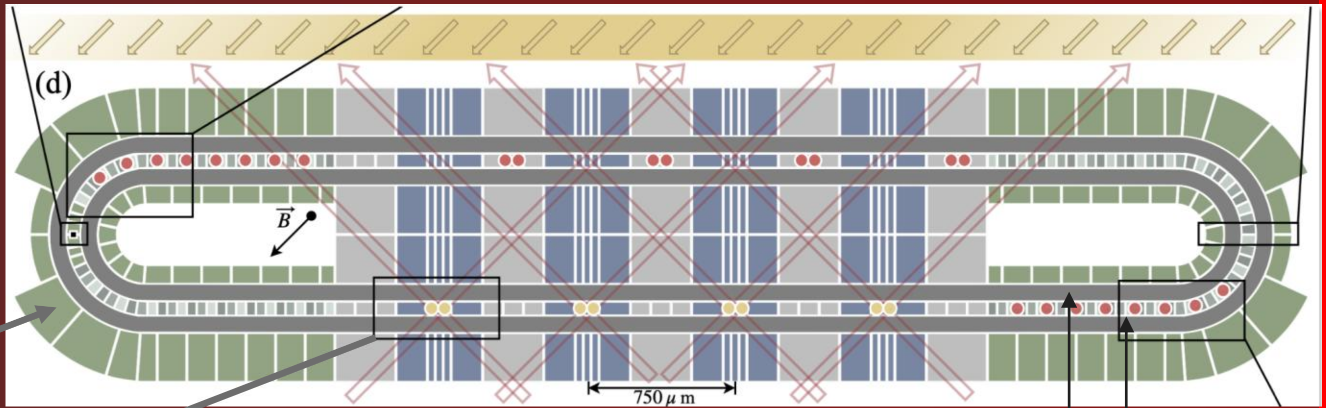
The cost of all-all connectivity:
Majority of time spent rearranging ions into fixed beam interaction zones

1D: Quantinuum HS1 (20 ions)



Pino, J. M., et. Al. (2021). *Nature*, *592*(7853), 209–213.

Pseudo-2D: Quantinuum HS2 (56 ions)



Moses, S. A., et. al. (2023). *Physical Review X*, *13*(4), 041052.

RF electrodes

DC electrodes

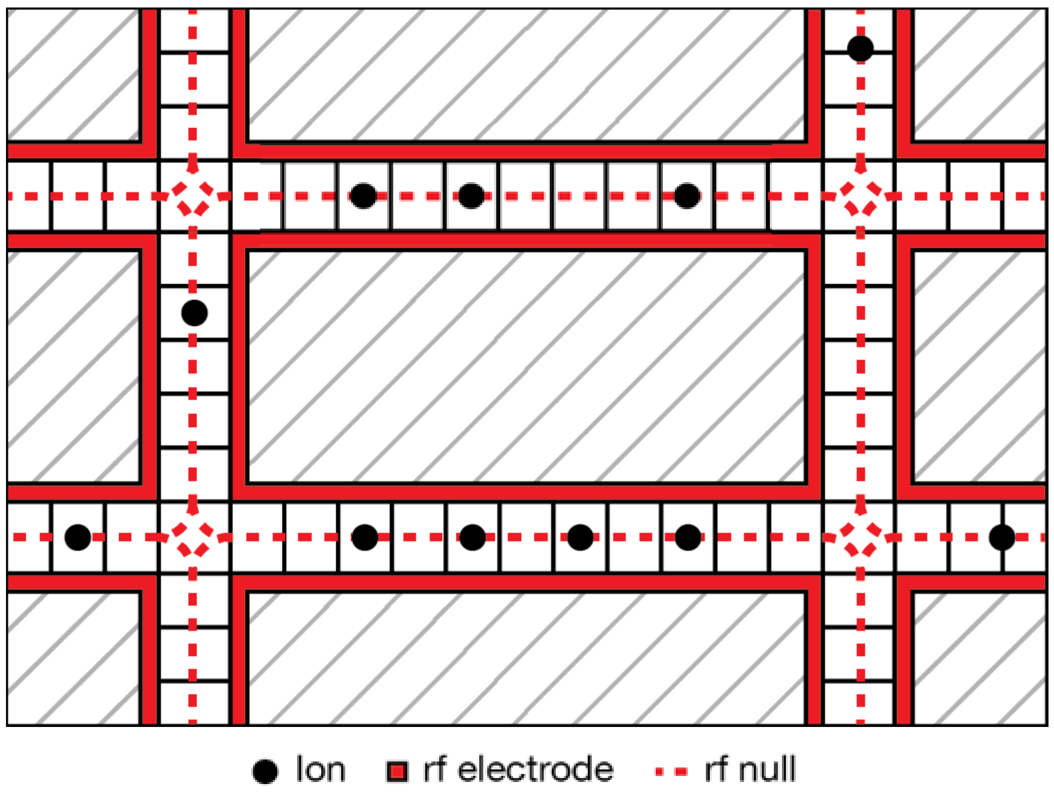
Beam Interaction Zone

RF electrodes

As of Nov 25, Quantinuum Helios launched with 1 junction and 98 ions

The Scaling Challenges of RF-Trapped Ion Quantum Computing

- 1-D approaches simply won't scale
- 2-D QCCD is the mainstream roadmap



RF poses significant engineering challenges

- Scalability constrained by RF rails
- Complicates:
  ease-of-manufacture
  ease-of-use

The Penning Quantum Computer

INNOVATION

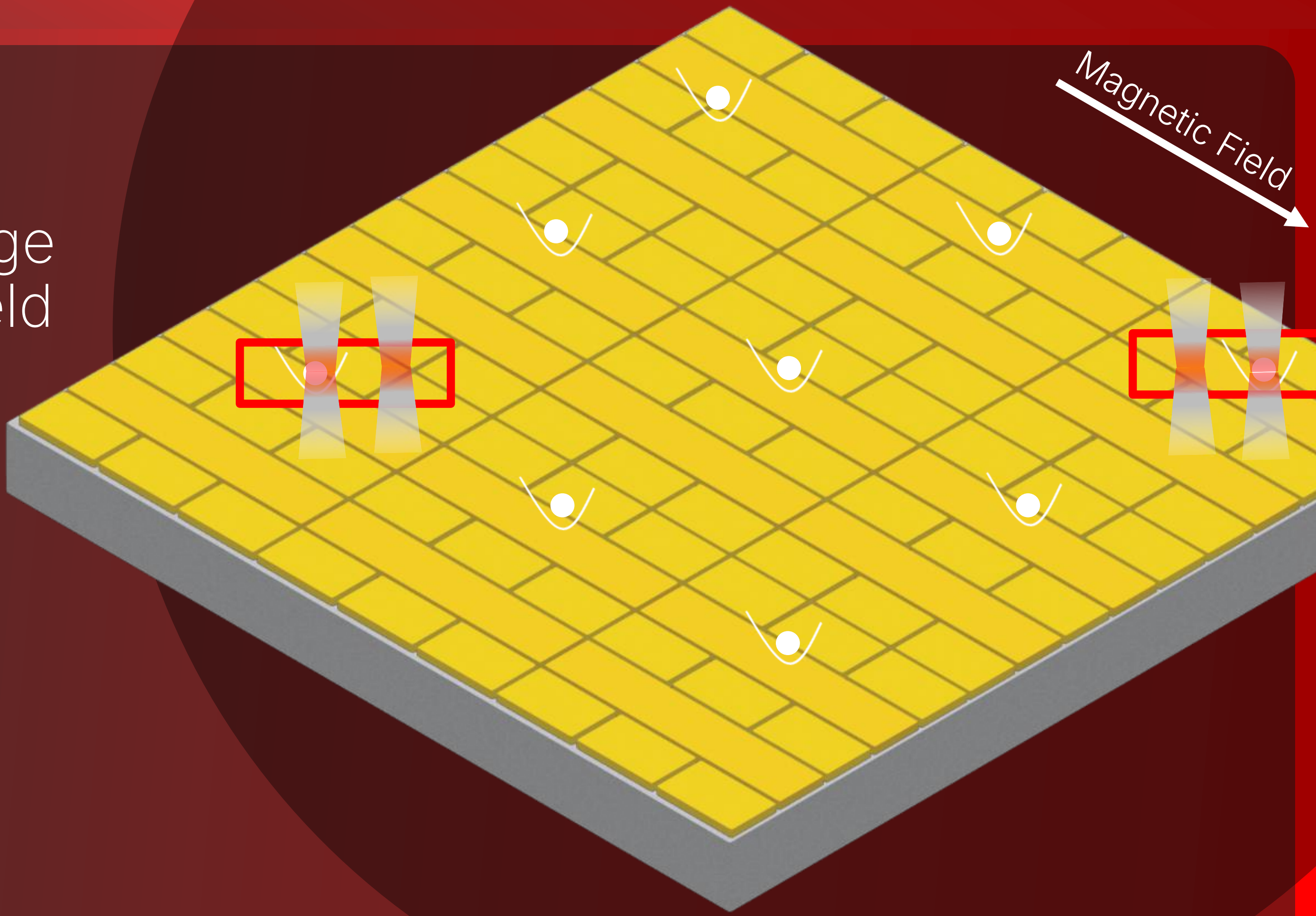
Remove the RF fields; replace with large (~T) static, homogeneous magnetic field

ARCHITECTURE

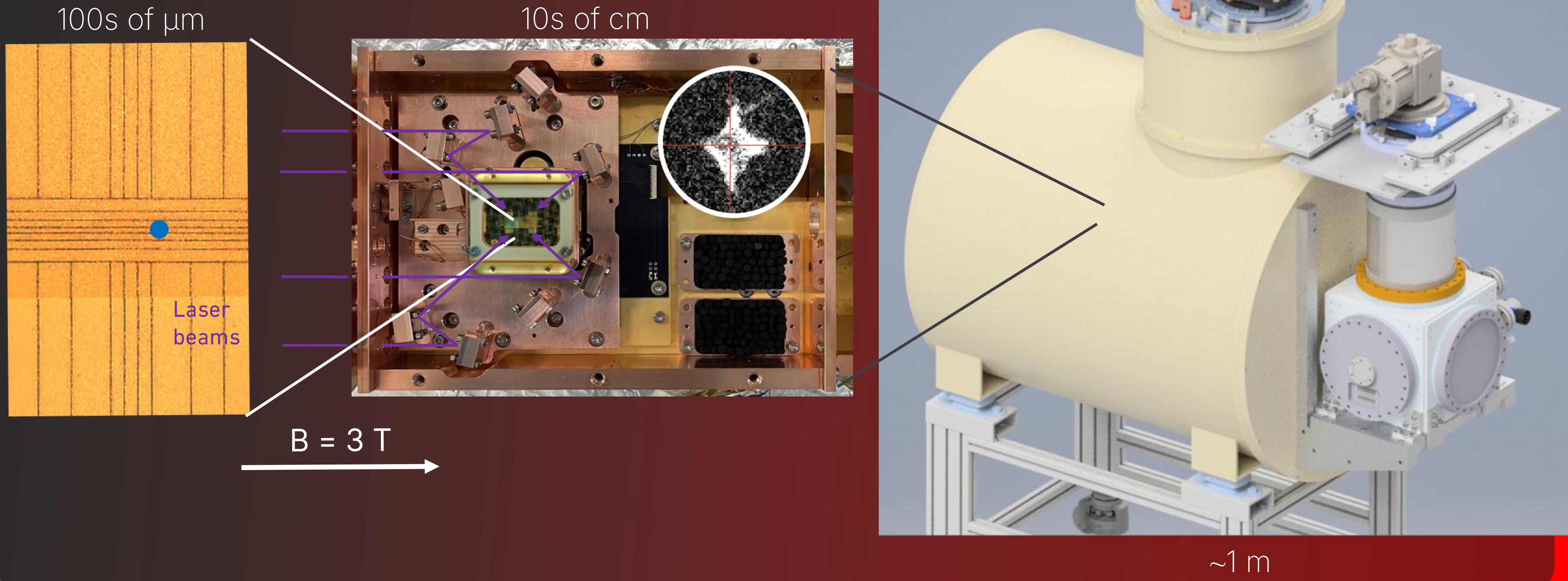
Trap only with static voltages
2-D grids of ions with higher density
Free rearrangement

BENEFITS

Ease-of-use: no ‘traffic jam’ at junctions
Ease-of-manufacture: low heating, low voltage
10x larger density – 10’000 ions on cm sized chip.

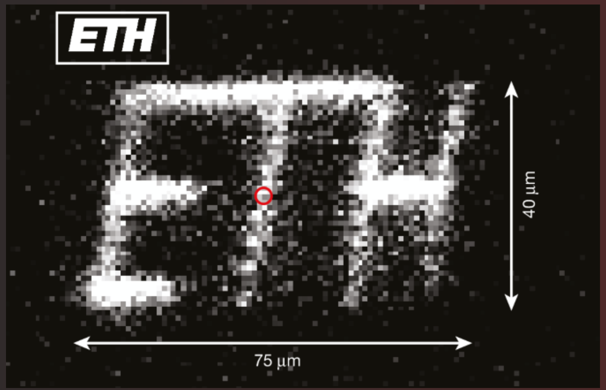


First micro-Penning trap unit cell

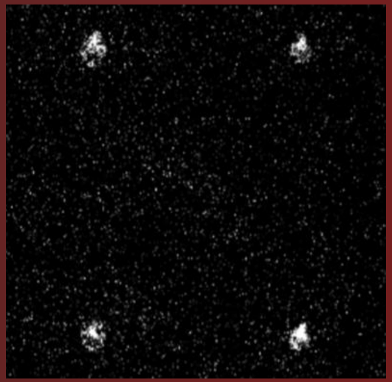


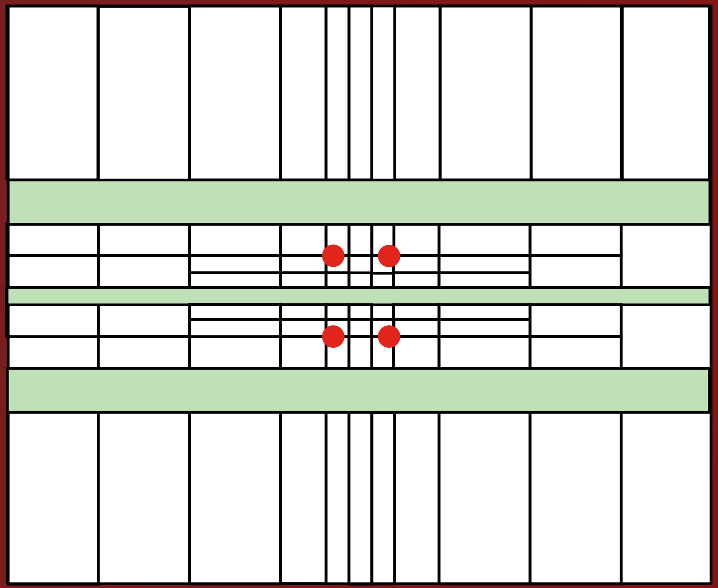
The ZuriQ Scalable Architecture

KEY VALIDATION: From single ion drawing to reconfigurable 2 x 2 array @ ETH Zurich!



Jain, S., Sägesser, T., Hrmo, P. et al. Penning micro-trap for quantum computing. *Nature* 627, 510–514 (2024).



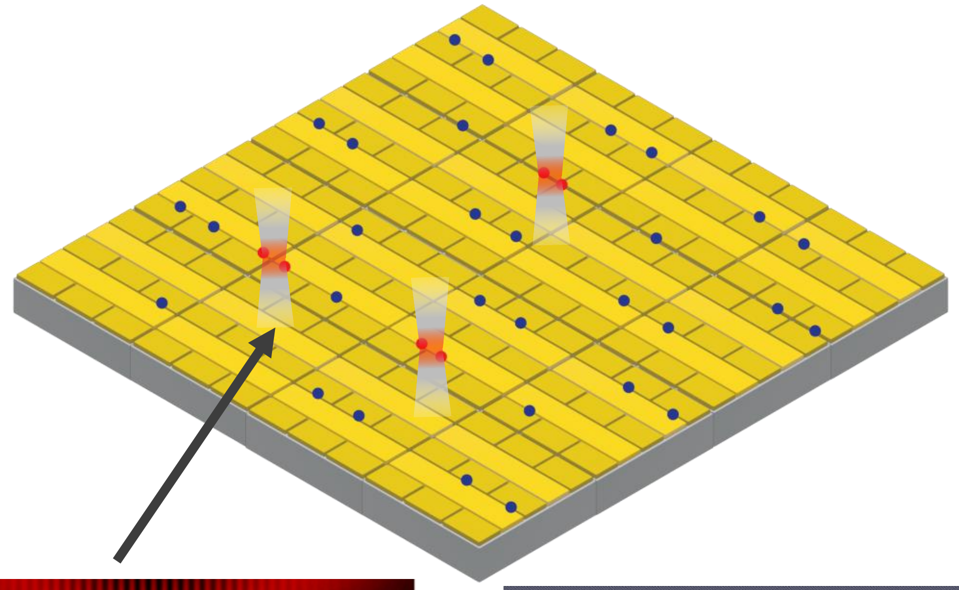


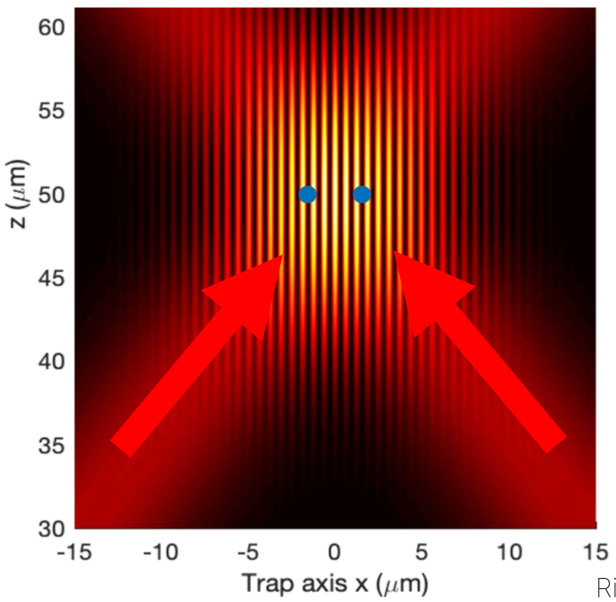
Integrated Optics for Laser Delivery

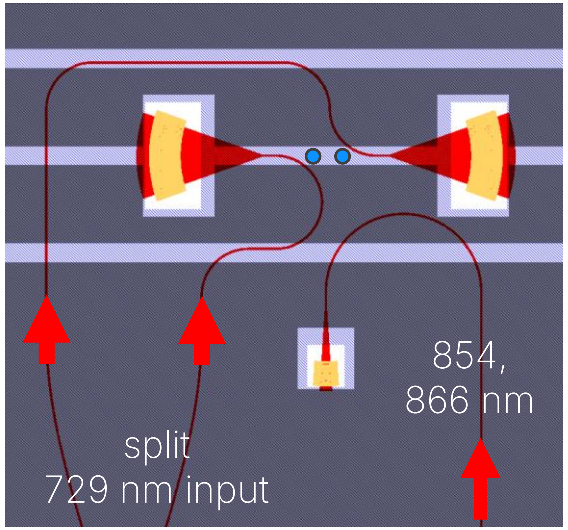
PARALLELISM
Waveguides and gratings deliver light to many zones

ALIGNMENT
Electrode-grating alignment is critical.
Penning advantage: no need to stay in RF null – bring ions to focus.

STABILITY
Passive phase stability allows for higher fidelity gate operations - standing waves







Ricci Vasquez et. al., Phys. Rev. Lett. **130**, 133201 (2023)

ZuriQ

The Ion Trap Wishlist

- Atomic species dependent **wavelengths**
  i.e. $^{40}Ca^+$ - 375, 393, 397, 729, 850, 854, 866 nm
  $^{137}Ba^+$ - 493, 650, 1760 nm
  $^{9}Be^+$ - 313 nm
- Variety of **beam foci** (1 – 10s µm) and **emission angles**
- **Low losses** – dissipation in chip highly undesirable
- **High intensities** - faster gate speed
- **No exposed dielectric** – well defined voltage level over gratings
- **Light collection** – gratings, lenses, fibres
- **Modulation** – AM for fast extinction
  – PM for frequency sideband generation

Light Collection & Networks

- Quantum links between chips will require photonic information transfer
- Quantum state readout/remote entanglement generation requires high photon collection efficiency. State of the art: 250 Hz, 94% Fidelity (Duke, 2024)
- Fast, localised readout suitable for mid-circuit error detection/correction

Grating collection

To detector or network

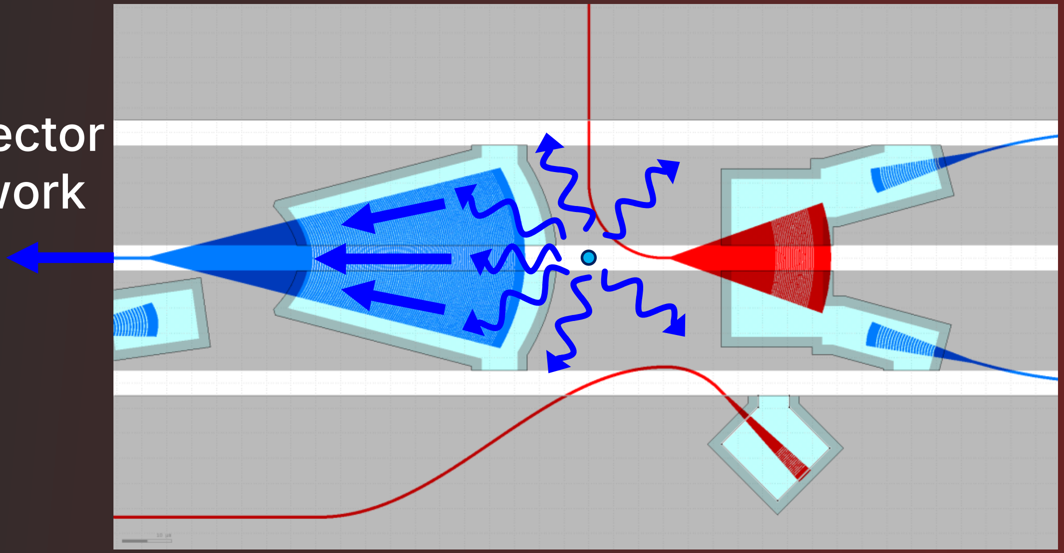
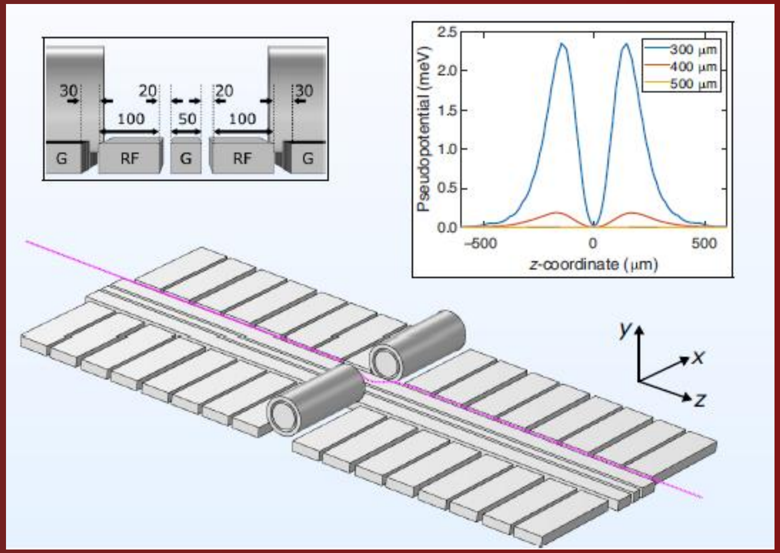


Image: Gillen Beck (ETHZ)

Cavity enhanced collection rate

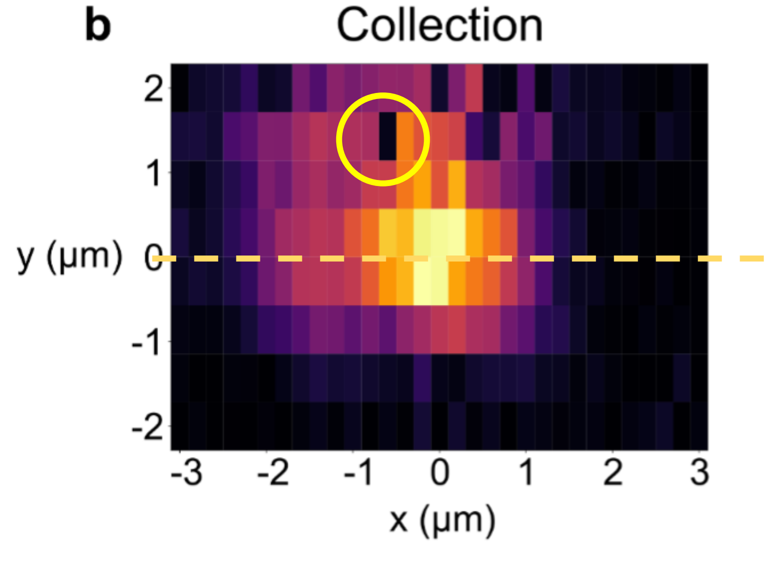


Kassa et. al. Phys. Rev. Applied **23**, 024038 (2025)

Light Collection & Networks

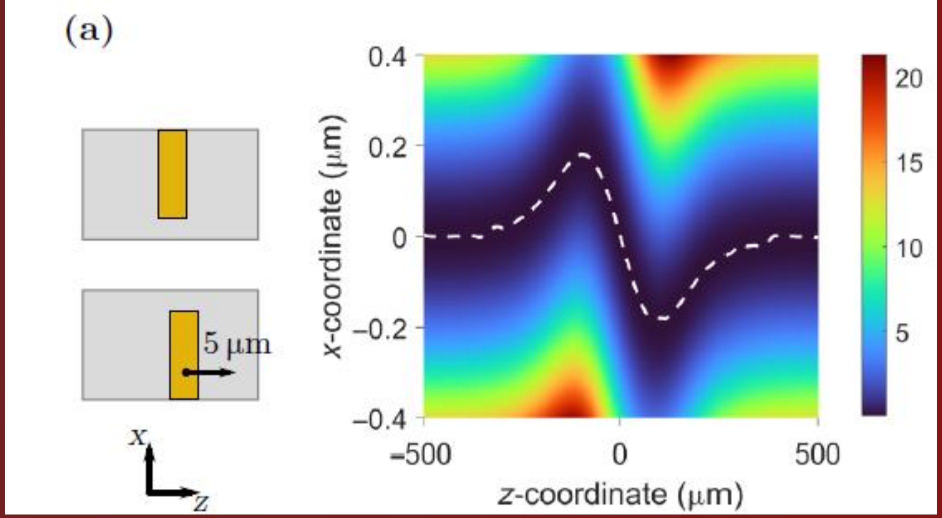
New challenges appear when combining these techniques with RF trapping fields.

Grating collection



Knollmann et. al. *Collection of fluorescence from an ion using trap-integrated photonics* (2025) arxiv.org/pdf/2505.01412

Cavity enhanced collection rate

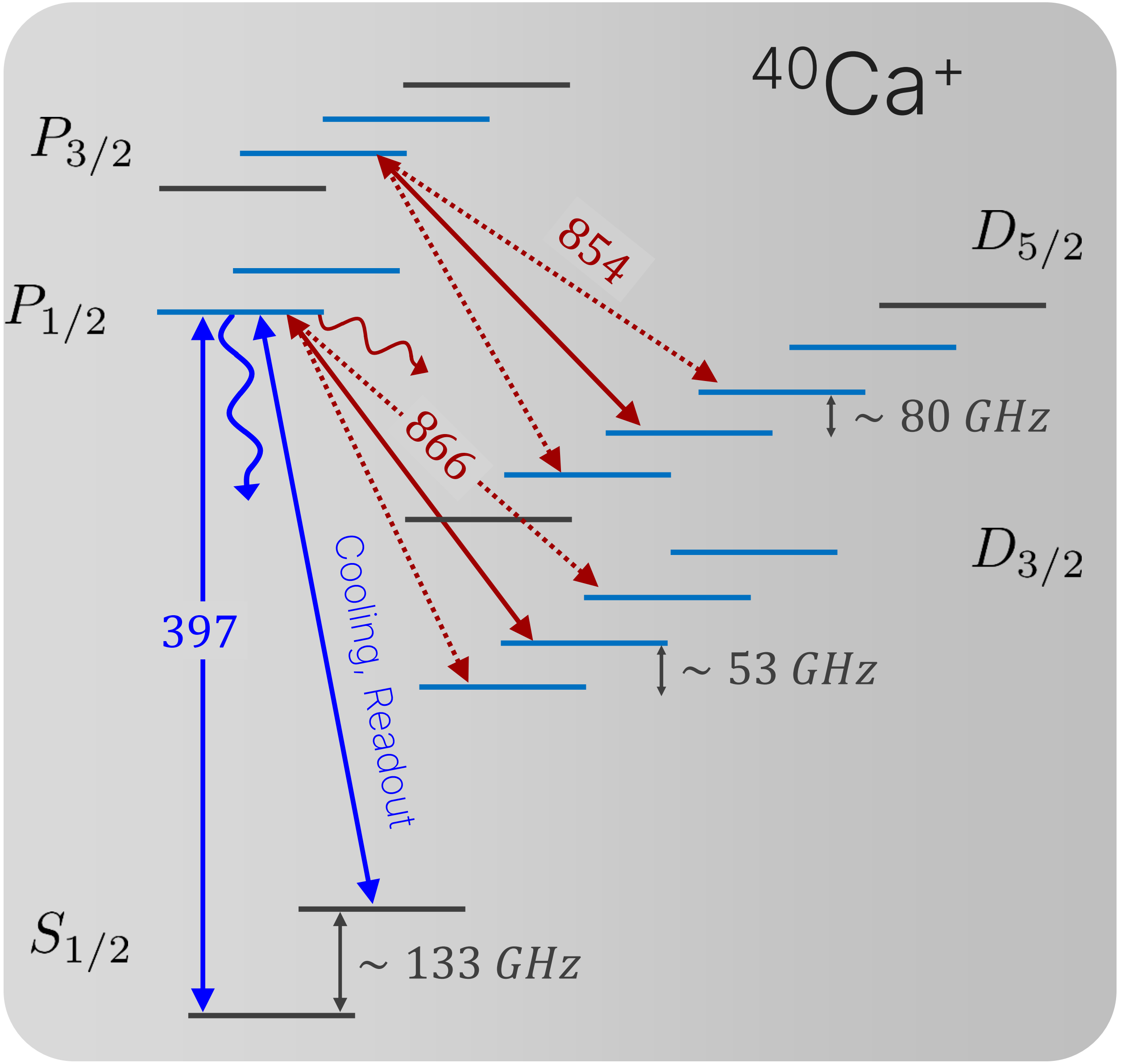


Kassa et. al. Phys. Rev. Applied **23**, 024038 (2025)

No RF micromotion at grating focus and nor RF potential disturbance near cavity shield in Penning traps!

Phase Modulators for Penning

- Large B field leads to big Zeeman shifts
- Lasers need high frequency sidebands at 50-150 GHz
- Current solution: fibre EOMs off chip.
- Advantage: spectral separation removes need for polarization purity.



Thank you

www.zuriq.com