PSI

ETH zürich

ETHZ-PSI Quantum Computing Hub

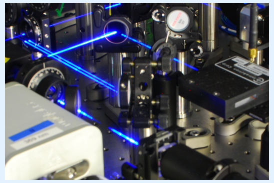
Control system for ion trap quantum applications

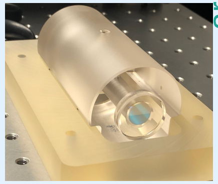
Simon Thür – Ion Trap Quantum Computing

July 31st 2024

Activities

are a 08
Stable lasers / atomic clocks

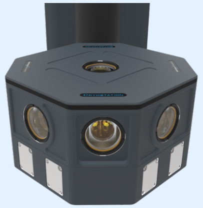




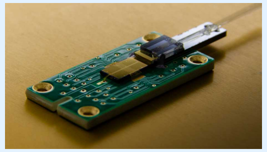
are a 07
Atom Sources

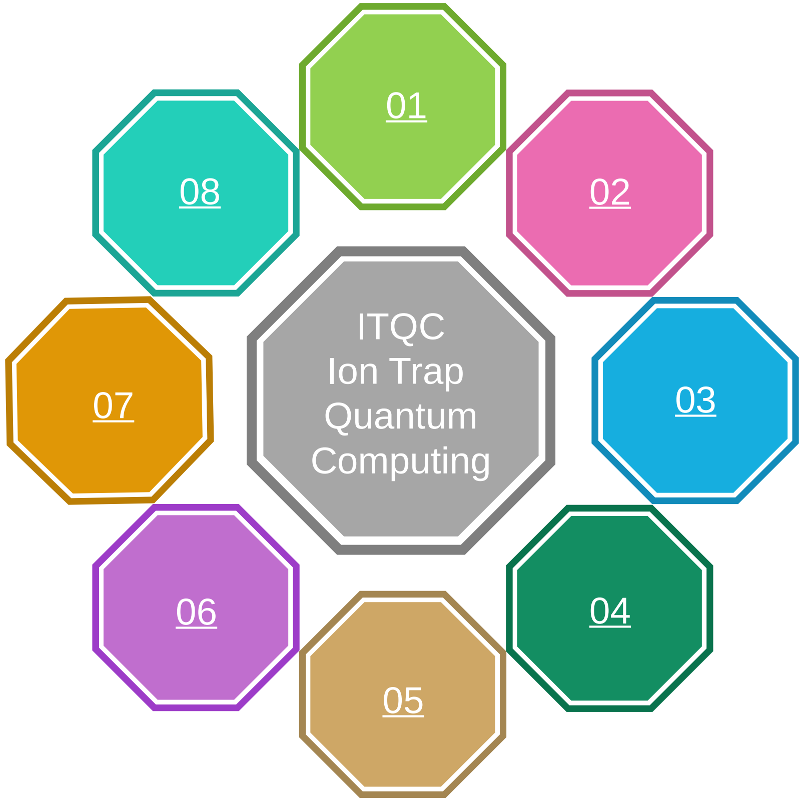
QuantumGuide

are a 06
Cryogenic component testing



are a 05
“Cryogenic setup” (System 2)





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QuCoS^2

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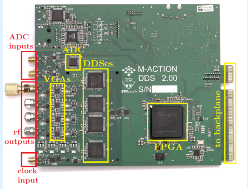

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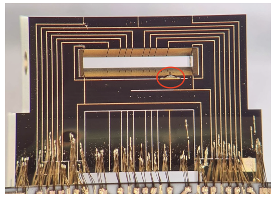
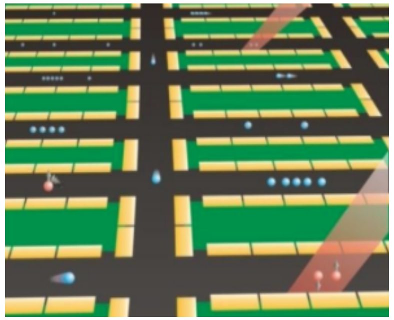
”RT” setup (System 1)

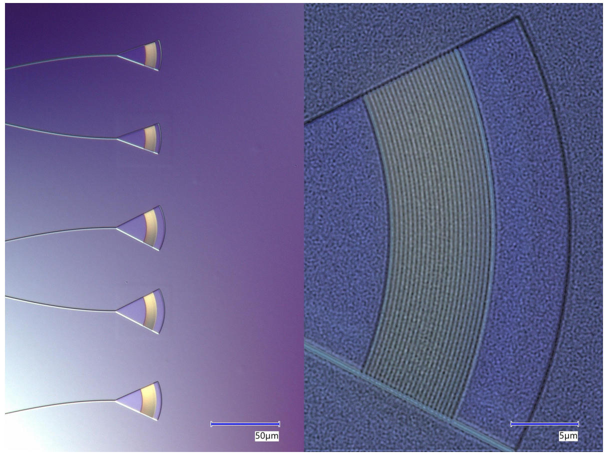


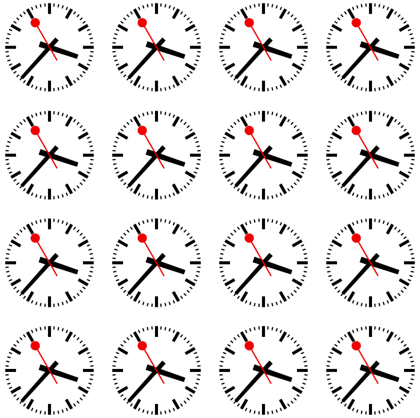
Outline



Intro to trapped
ion qubits and scaling

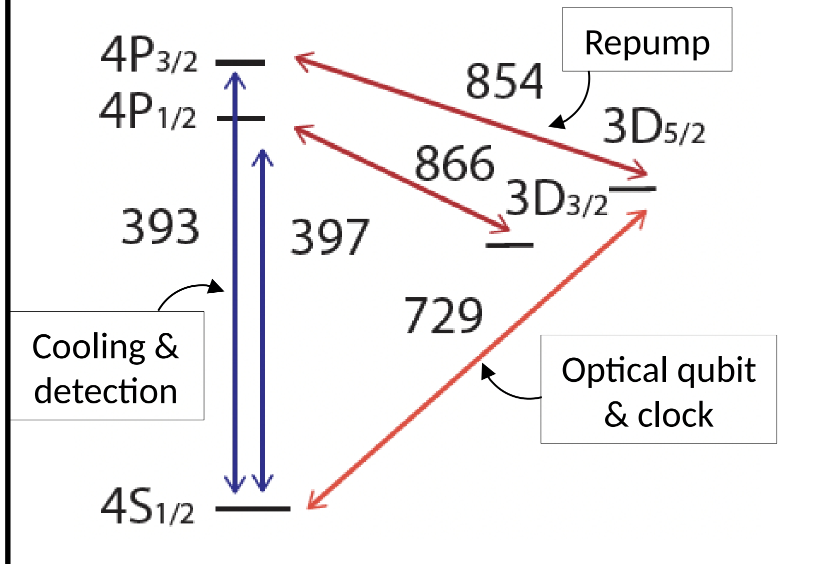
Architecture: ion traps
with integrated optics



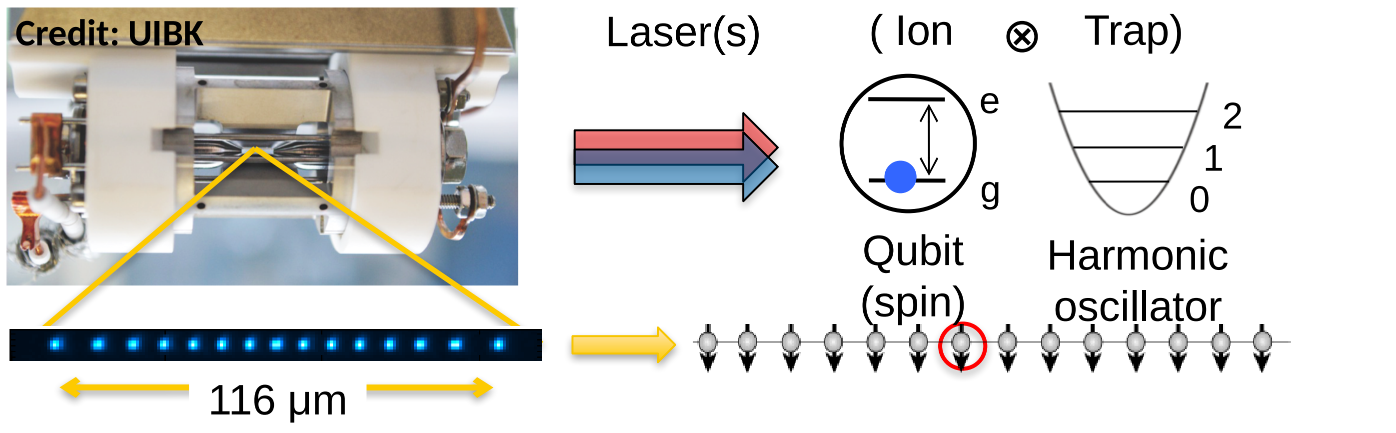


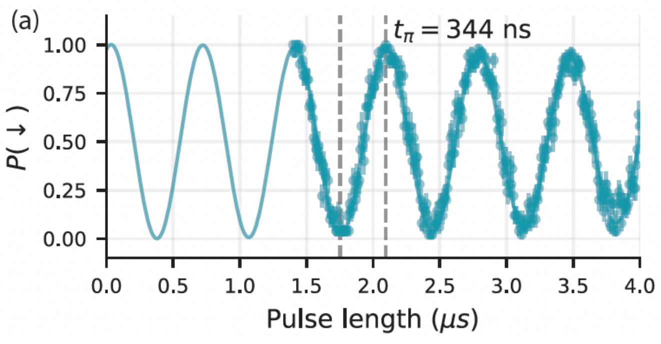
Benchmark: operating arrays of
optical atomic clocks

Trapped ion qubits

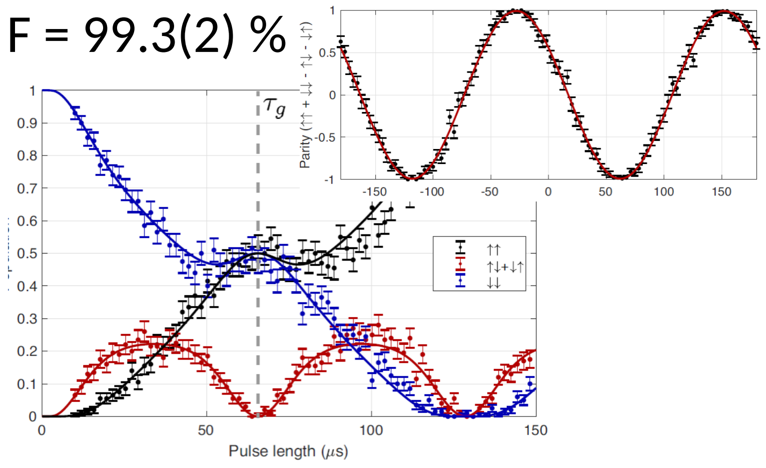


Calcium ion level scheme





Single qubit gates
(Rabi flops)



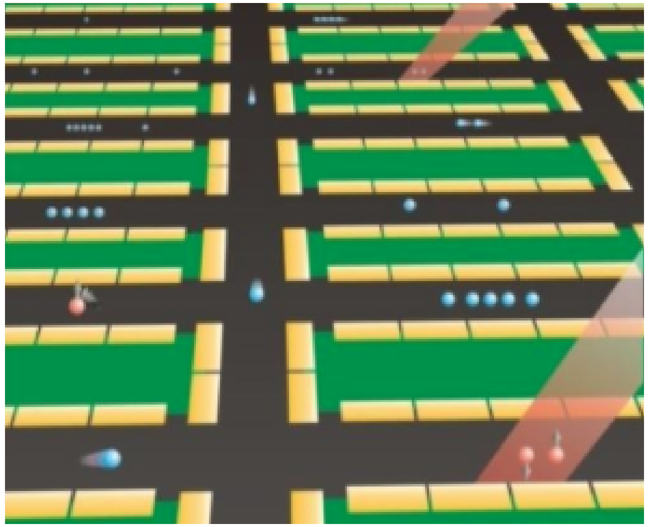
Two-qubit gates (entangling gates)

NIST, UIBK, Oxford and many more

Data: TIQI group, ETHZ (A. Ricci / K. Mehta)

Scaling

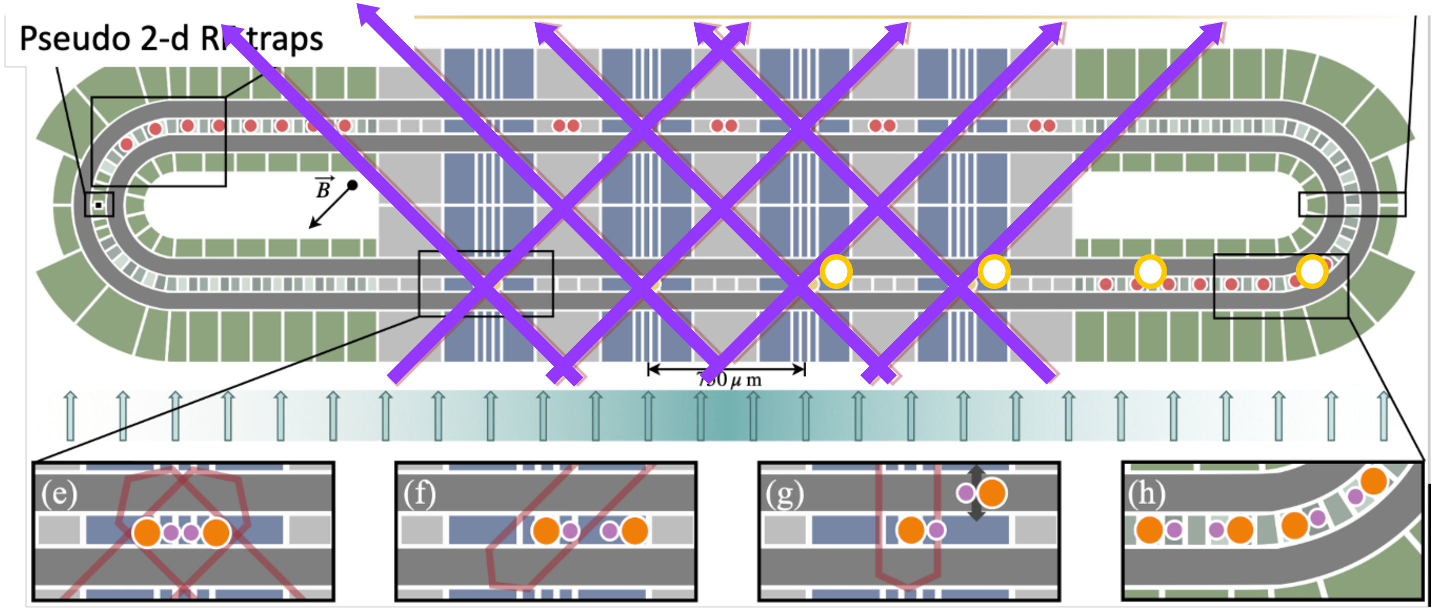
Quantum CCD:
split + shuttle
Wineland et al. 2000



- ❑ High fidelity qubit operations
- ❑ Parallel and individual control and readout
- ❑ Mid-circuit measurement and feedback
- ❑ Continuous calibration
- ❑ Connectivity through ion transport
- ❑ Logical qubits

State-of-the-art ?

“A Race Track Ion Trap Quantum Processor”
S. Moses et al. PRX 13, 041052 (2023)



- Light delivered in free space to 4 zones
- 2-d loop is a 1-dimensional ion array (with swaps for connectivity)

https://www.youtube.com/watch?v=UT3ev9OgkmY

Activities

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Stable lasers / atomic clocks
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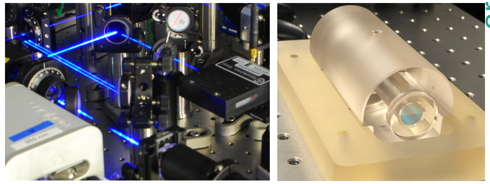

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QuantumGuide

Cryogenic component testing
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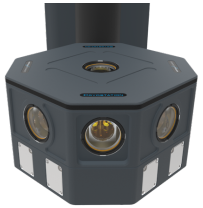

“Cryogenic setup” (System 2)
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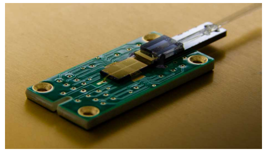

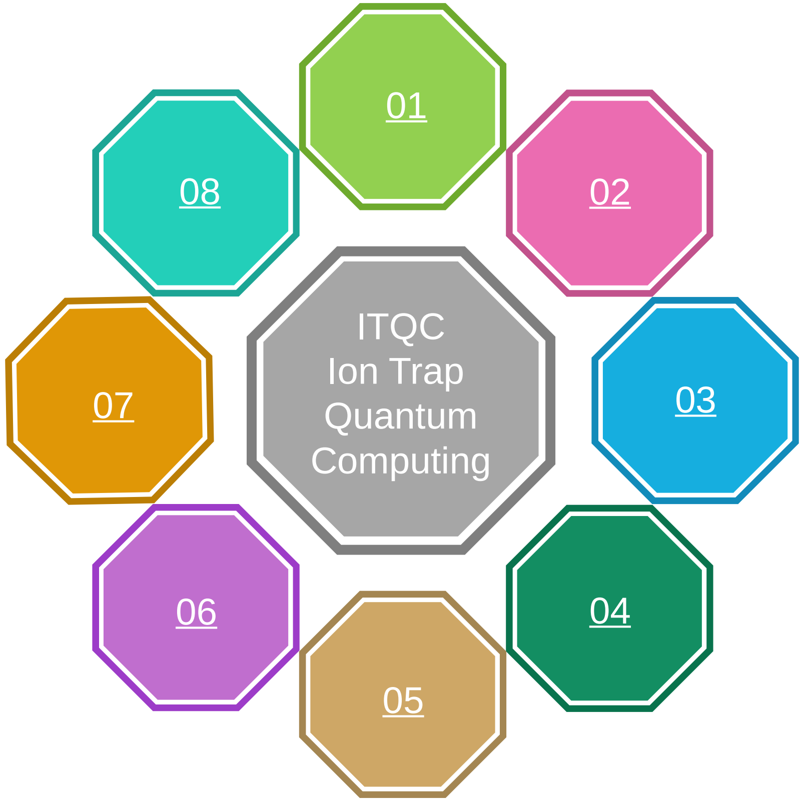

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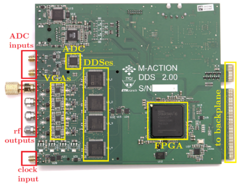

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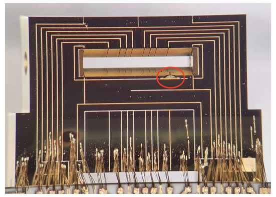
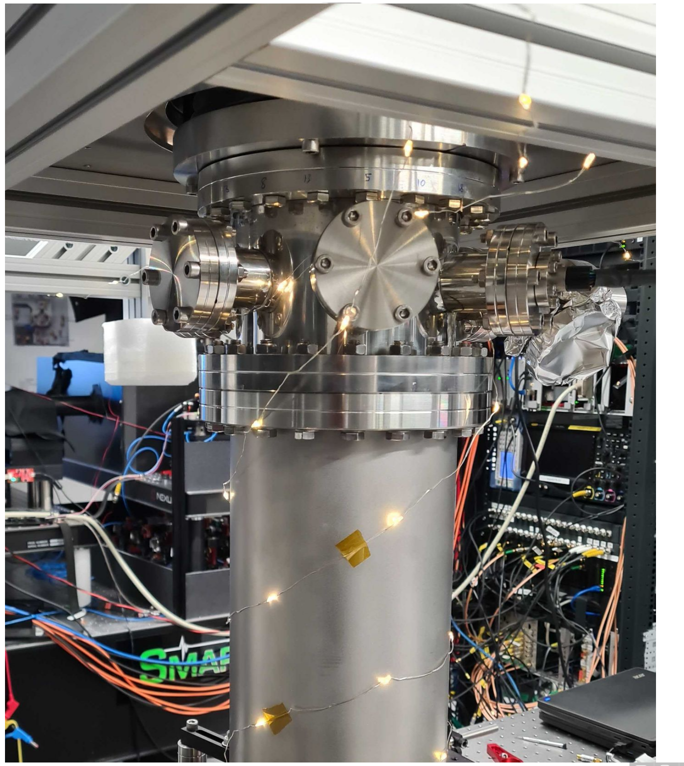
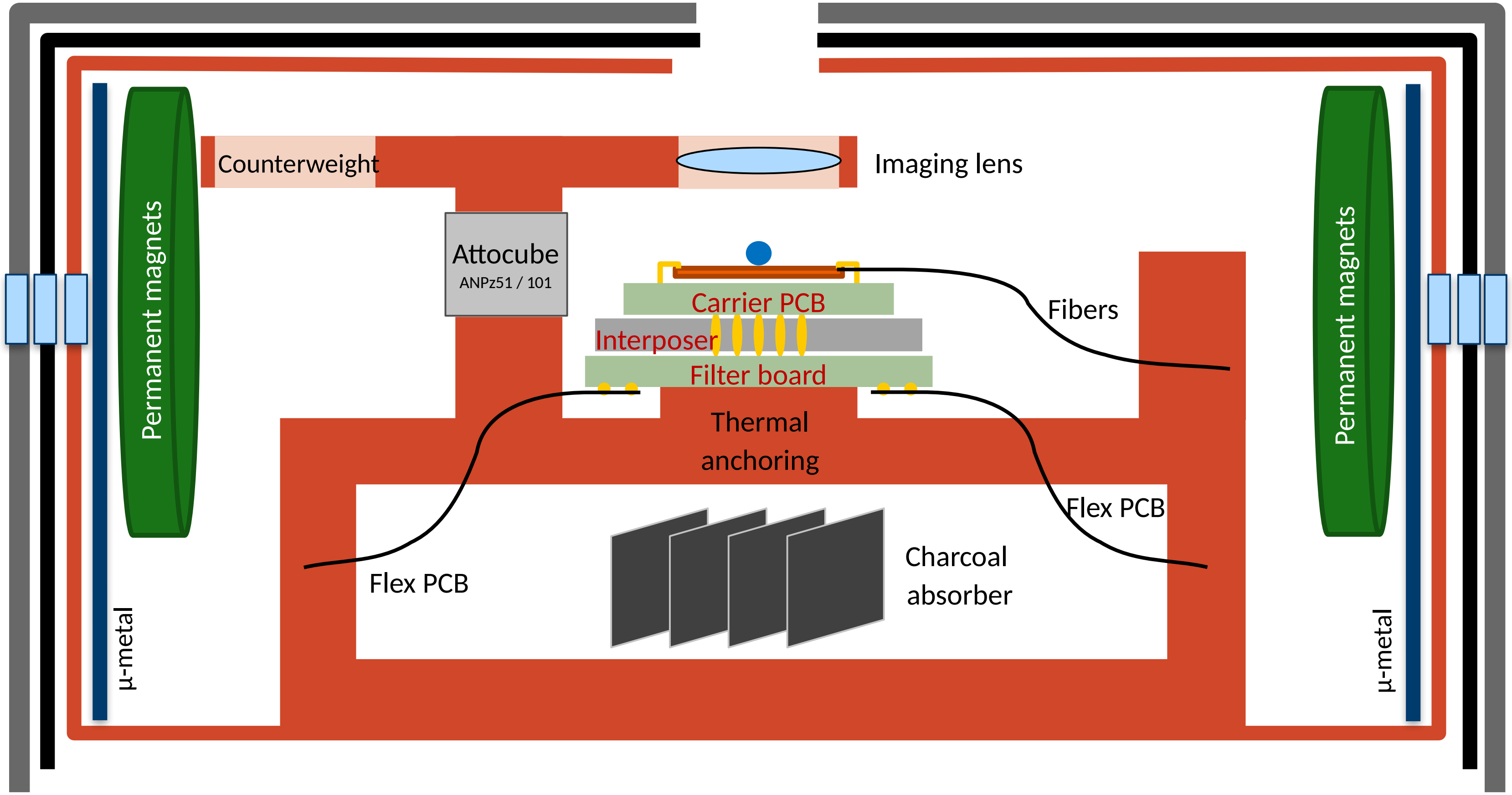


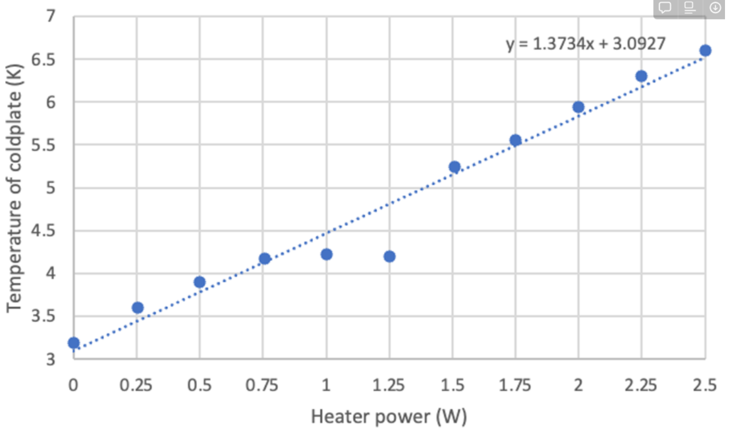
Cryo / UHV system

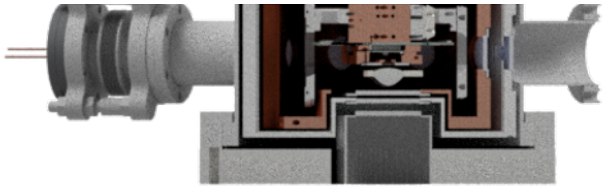
Tereza Viskova

→ based on several generations of ETH system
→ designed for flexibility to scale up connectivity and rapid turn-around
→ UHV / 40 K / 4 K chambers and high cooling power (~1.5 W tested)





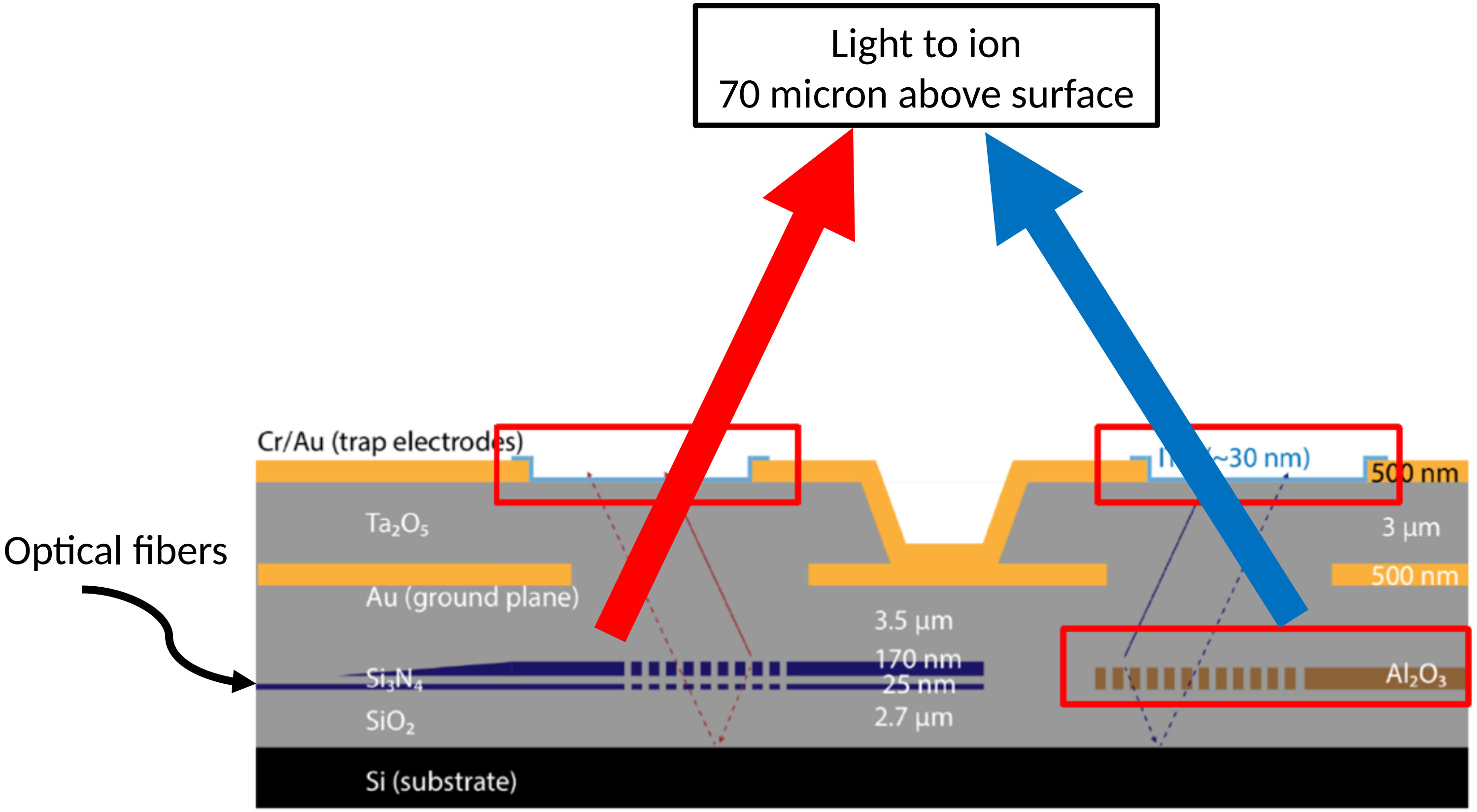


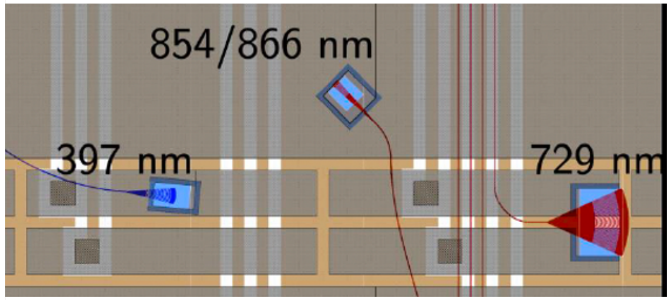


2D trap array with integrated optics

LioniX INTERNATIONAL PSI

For 20 zones:
- 60 laser beams, 15 fibers
- 120 DC electrodes





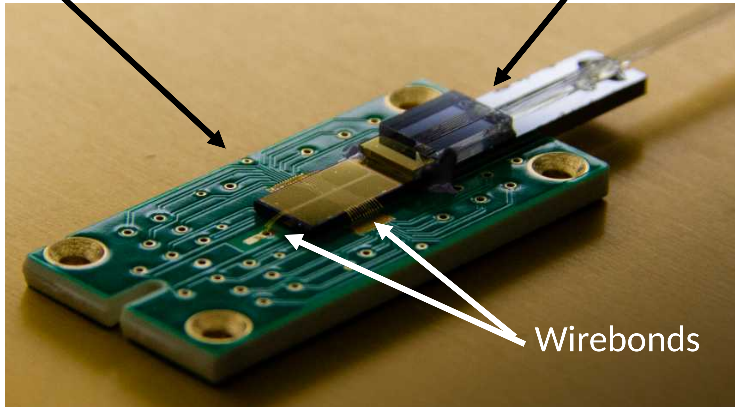
For 1 zone (1-2 ions):
- three laser beams
- 6 DC electrodes

Chip design: Karan Mehta (now Cornell) ; fab: LioniX ; related work at Sandia, MIT-LL

Packaging

Carrier PCB

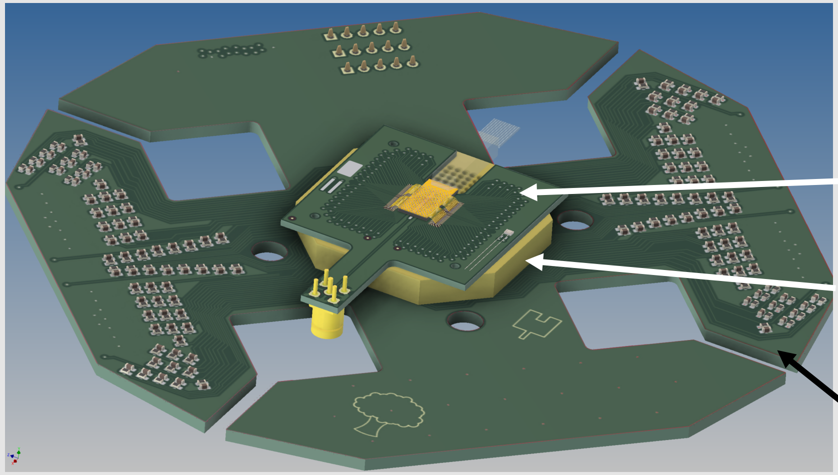
Fiber V-groove array

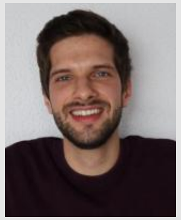


Wirebonds

K. Mehta / ETH

Electrical / RF (M. Marti)





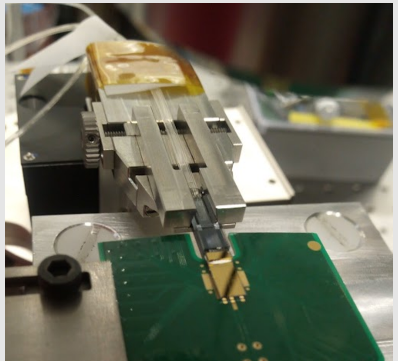
Carrier PCB

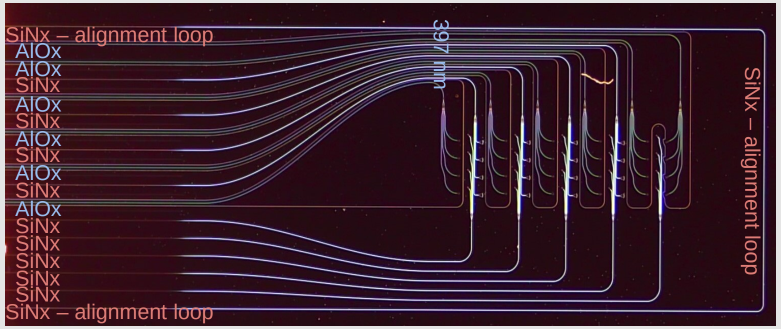
Interposer up to 400 channels

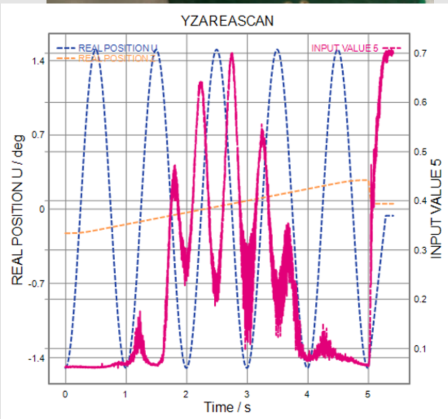
Filterboard with flex cable connections

Optical (F. Timpu)

Automate alignment:
-> Faster (and better) results





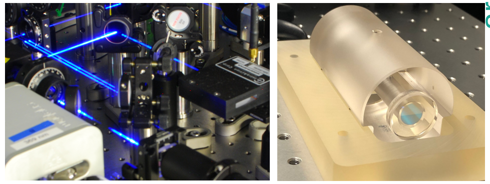


Mehta et al., Nature (2020)

Clock experiments

PSI

Stable lasers / atomic clocks



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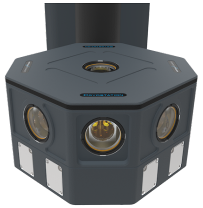

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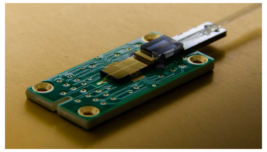

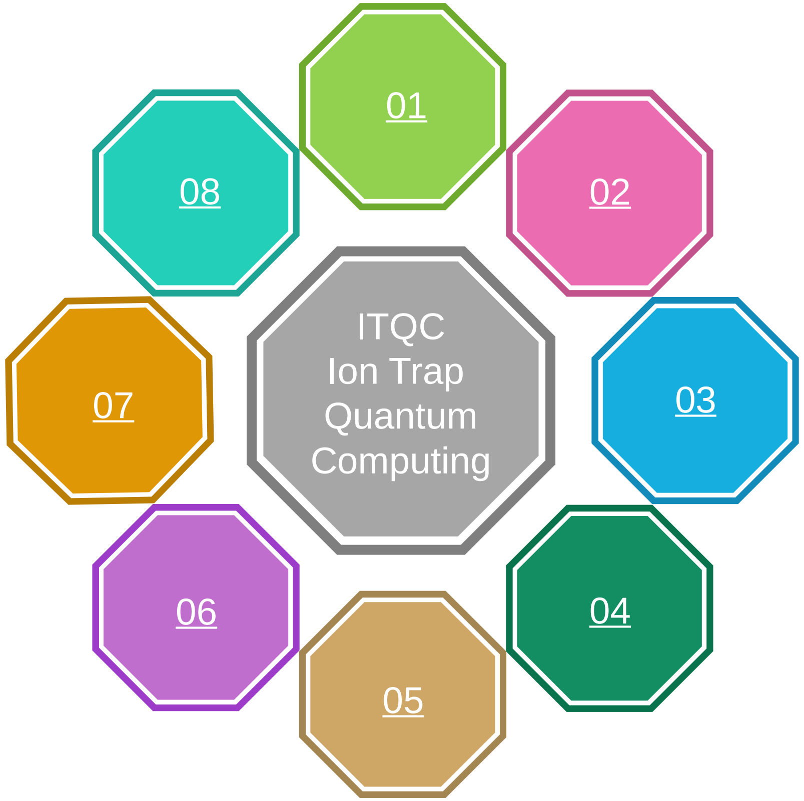

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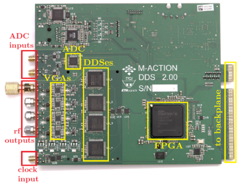

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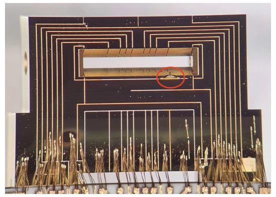
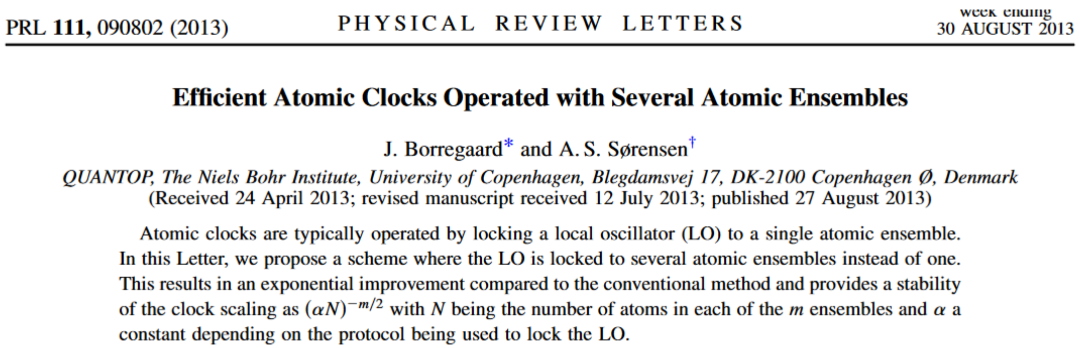


Multi-zone clock operation

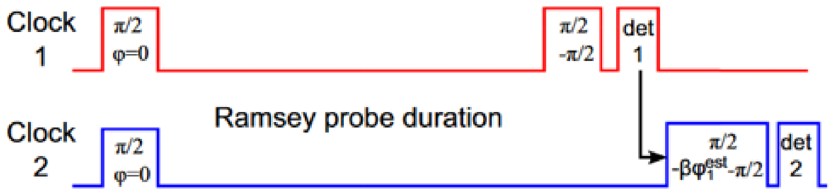

PRL **111,** 090802 (2013) PHYSICAL REVIEW LETTERS week ending 30 AUGUST 2013

Efficient Atomic Clocks Operated with Several Atomic Ensembles

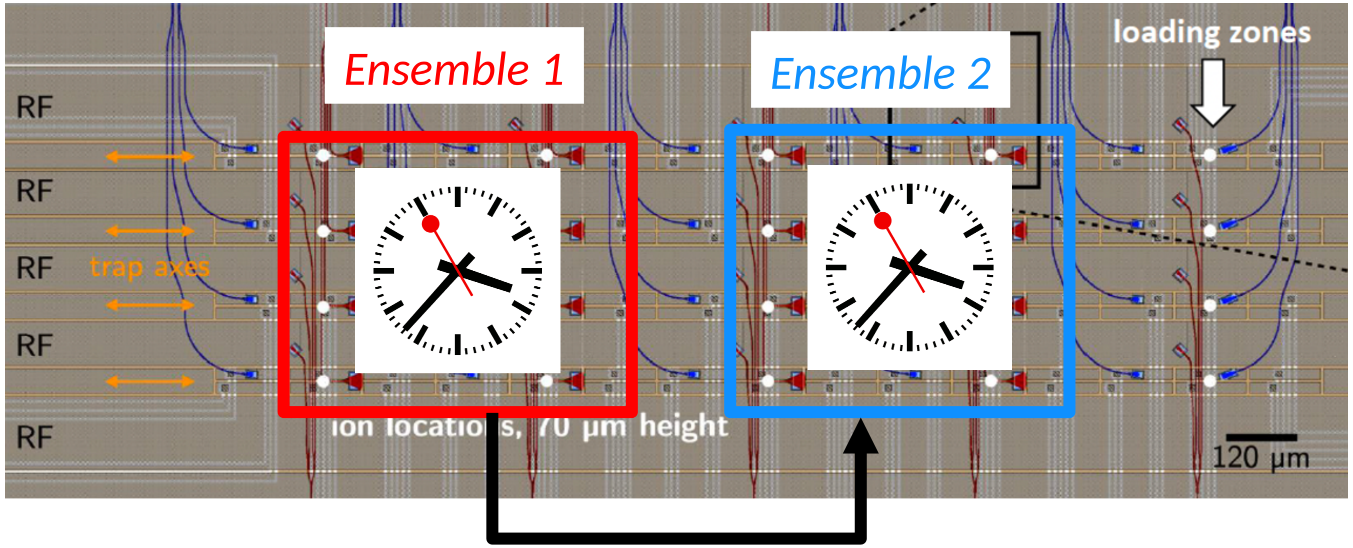
J. Borregaard* and A. S. Sørensen†

QUANTOP, The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark
(Received 24 April 2013; revised manuscript received 12 July 2013; published 27 August 2013)

Atomic clocks are typically operated by locking a local oscillator (LO) to a single atomic ensemble. In this Letter, we propose a scheme where the LO is locked to several atomic ensembles instead of one. This results in an exponential improvement compared to the conventional method and provides a stability of the clock scaling as $(\alpha N)^{-m/2}$ with N being the number of atoms in each of the m ensembles and α a constant depending on the protocol being used to lock the LO.



- ✓ Single qubit operations *(high fidelity?)*
- ✓ Parallel and individual control and readout
- ✓ Mid-circuit measurement and feedback
- ✓ Continuous calibration
- ❑ Connectivity (transport in 1D and 2D)
- ❑ Logical qubits

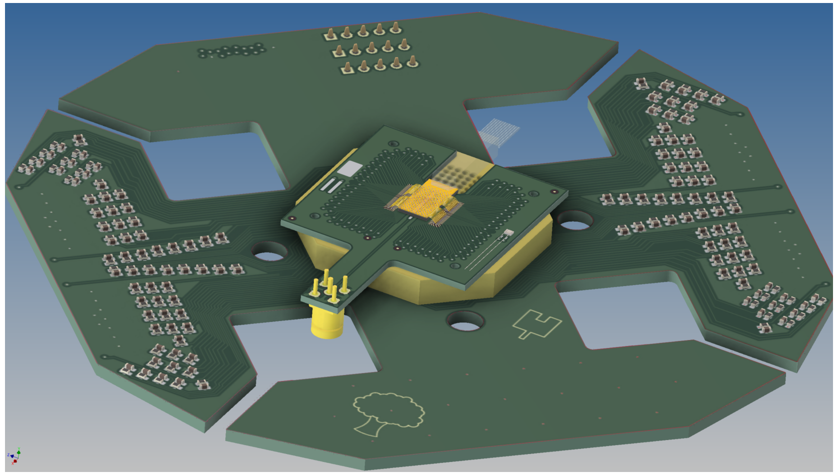
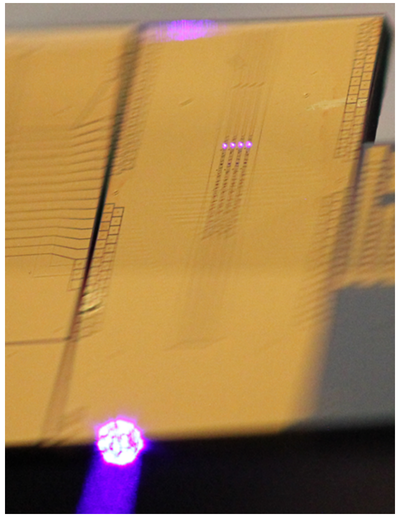
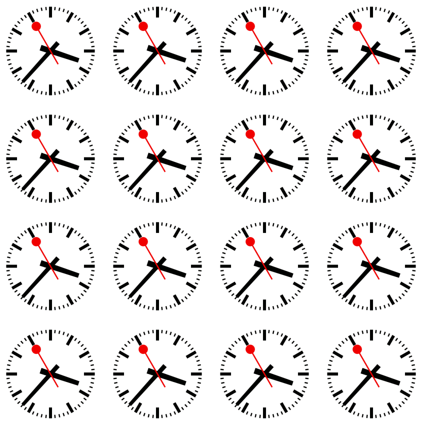


Phase correction

Original proposal: Rosenband and Leibrandt (2013)
Pulse sequence: Hume and Leibrandt PRA 93, 032138 (2016)
Also see: Correlation spectroscopy, Clements et al. PRL 125, 243602 (2020)
Neutral atoms: Shaw et al. Nat. Phys. (2024)

Summary

New integrated photonics ion traps with 2D geometry
Benchmark traps, lasers, and control systems using advanced clock protocols

Future avenues: active optical devices,
transport between zones*, integrated readout

* Mordini et al., in preparation (2024)
Lancelotti et al., arXiv:2312.1400 (2023)

The ARTIQ system

ARTIQ

ARTIQ (Advanced Real-Time Infrastructure for Quantum physics)

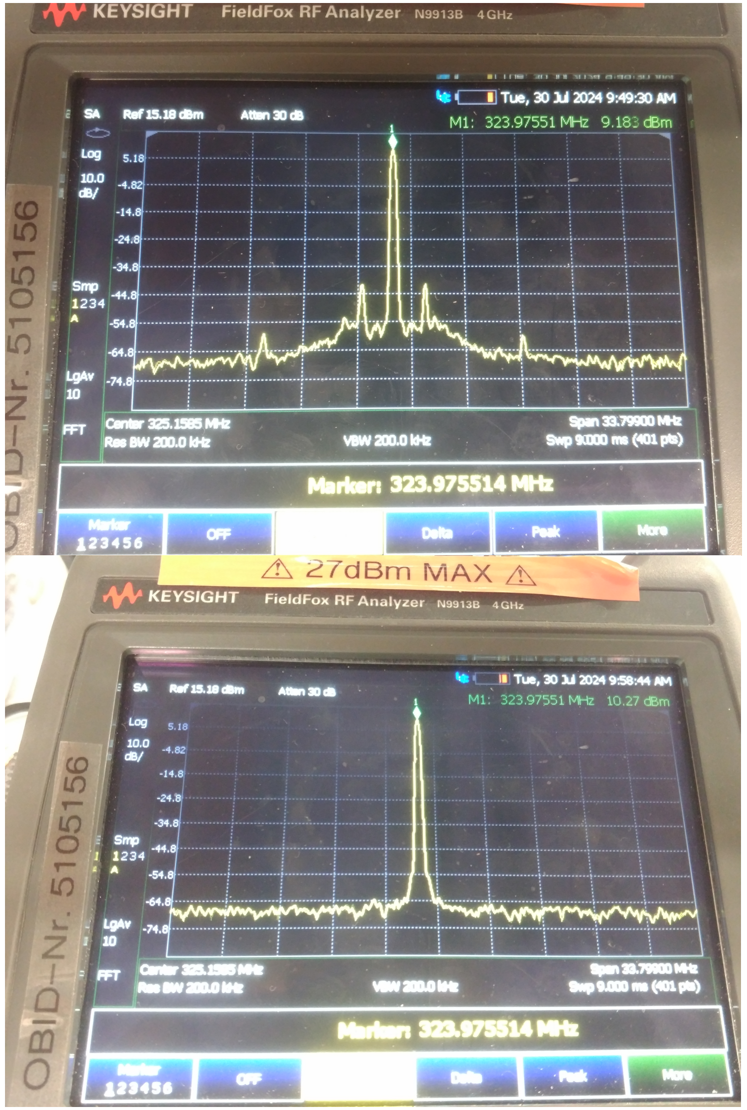
- Nano second timing
- Time critical code running on an FPGA
- RPCs, subkernels, DMAs

- Existing Hardware
  - DDS (4 Channels per module)
  - ADC (4 Channels per module)
  - DAC (32 Channels per module)
  - TTL (4 Channels per module)

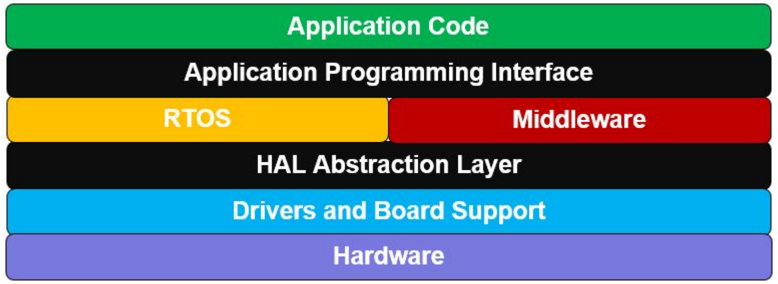
What is my Project though?

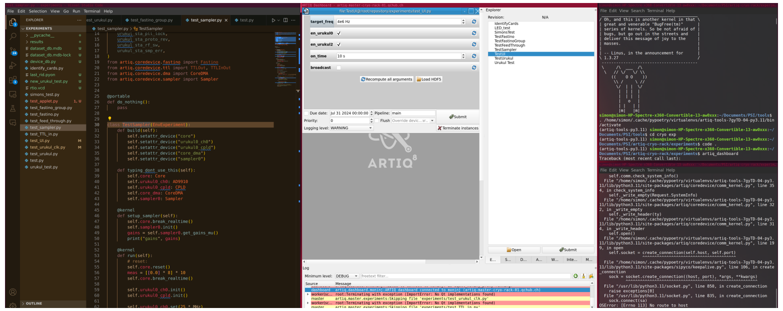
PSI

Debugging and Characterizing HW

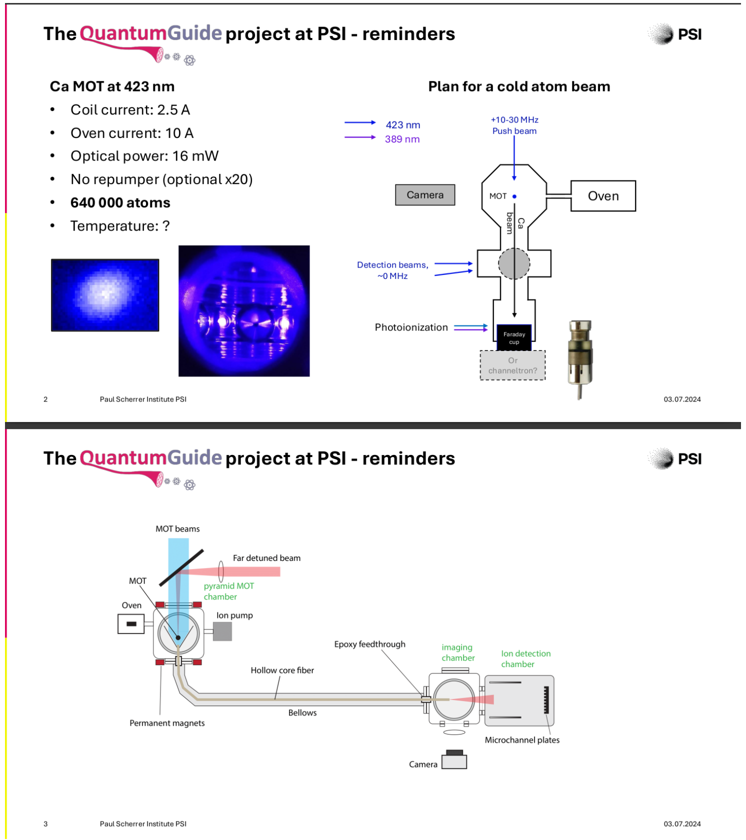


Create an abstraction layer





“Help” with experiments



Questions?