Approaches to scalable quantum computing towards error correction with long ion chains

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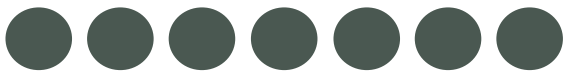
What are the key ingredients required for a *useful* trapped-ion quantum computer?

MANY IONS

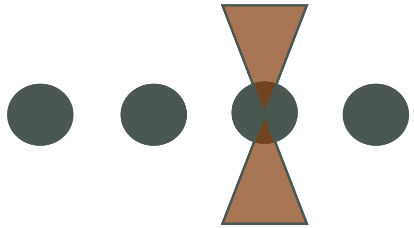


- Scalable ion traps
- Long chains / multidimensional architectures

TRANSFER OF INFORMATION

- Ion transport
- Photonic links

INDIVIDUAL MANIPULATION

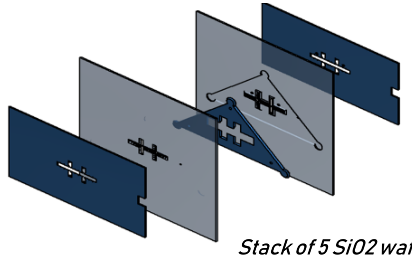


- Single ion addressing and readout

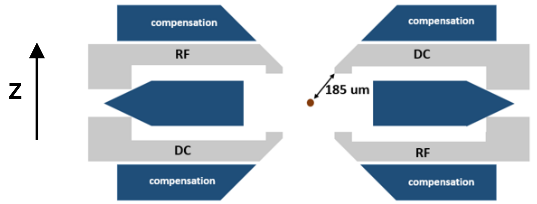
SCALABLE ION TRAPS: DESIGN

MANY IONS

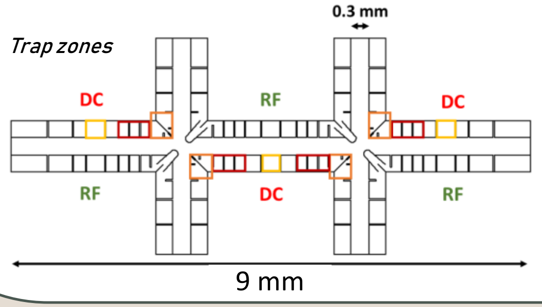
TRAP DESIGN



Stack of 5 SiO2 wafers



Trap zones



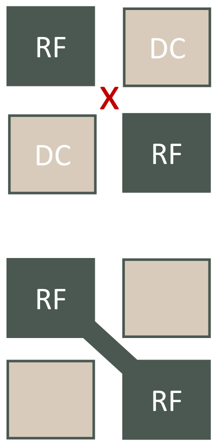
- 5 silica glass wafers
- Ion-to-electrode distance **185 um**
- Total of 145 electrodes
- Wafer machining precision: 1 um (xy), 20 um (z)

- Dedicated zones: experiment, splitting, transport
- Junctions allow for 2D scaling

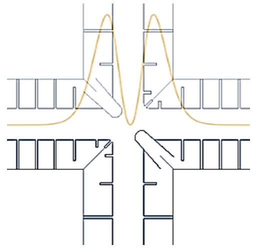
JUNCTION OPTIMISATION

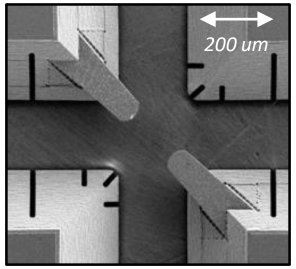
TRANSPORT

Top view



Yellow: pseudopotential barrier



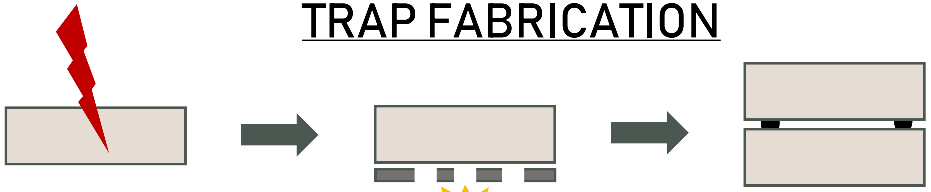


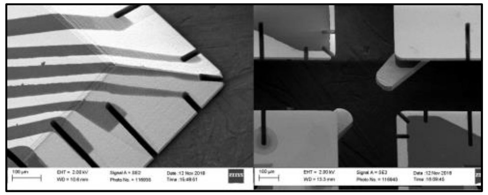
- X-junction traps don't confine in the junction centre x
- A symmetry breaking is required, such as a connection between RF electrode
- A 'bridge' creates pseudopotential barriers which the ion needs to traverse
- Size and shape of the 'bridge' matters: we can optimize it for minimal heating during transport
- Optimised bridges create low (0.02-0.05 eV) RF barriers while still confining at the centre (0.5-1MHz)

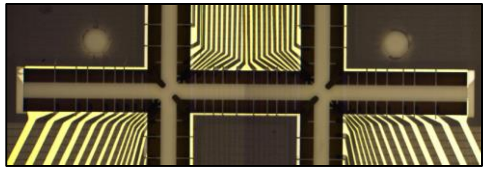
S. Ragg, C. Decaroli et al., ***Segmented ion-trap fabrication using high precision stacked wafers,*** Rev. Sci. Instr. 90 (2019)

SCALABLE ION TRAPS: IMPLEMENTATION

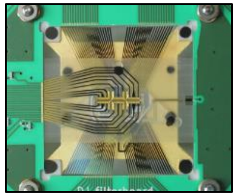
TRAP FABRICATION







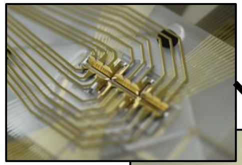
Top: SEM image after evaporation,
Middle: evaporation of DC electrodes
Bottom: trap stack attached to PCB



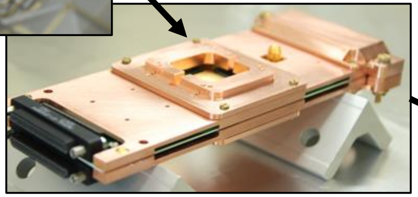
- Precise **manual** shadow mask alignment
- Smallest mask feature **10 um**
- Several evaporation rounds at different angles
- **Self-alignment** of wafers with **< 2 um** precision
- Wafers glued with **stycast** to each other and to alumina holder
- Attached to ROGERS PCB

SETUP

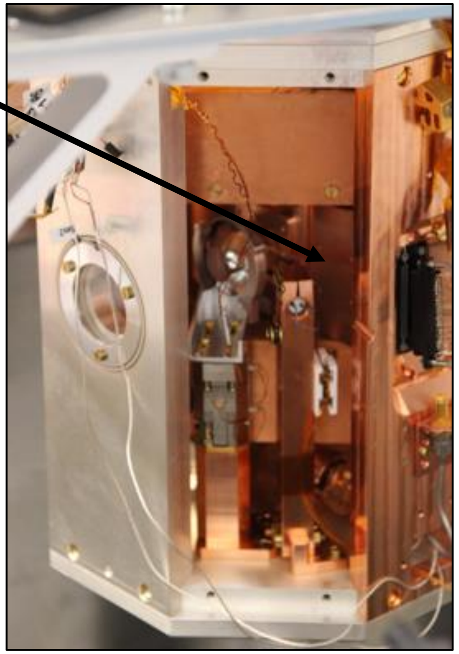
3D trap



Grounded copper sleeve



- Trap and PCB inserted in copper sleeve
- Effusion Calcium oven for loading
- Helical resonator provides **200 V RF @ 35.5 MHz**
- In cryostat @ 7K



Cryostat housing trap, resonator, oven, imaging lens and delivery optics

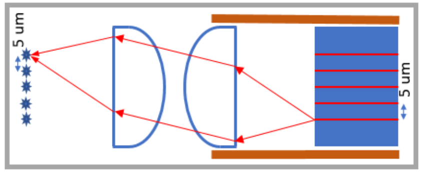
S. Ragg, C. Decaroli et al., ***Segmented ion-trap fabrication using high precision stacked wafers,*** Rev. Sci. Instr. 90 (2019)

INDIVIDUAL ION MANIPULATION

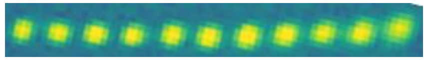
ADDRESSING

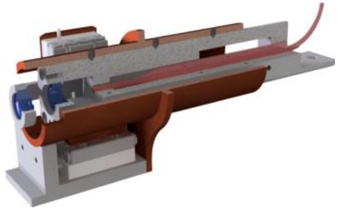
ADDRESSING: Pitch reducing fibre array

PROFA spatial schematic



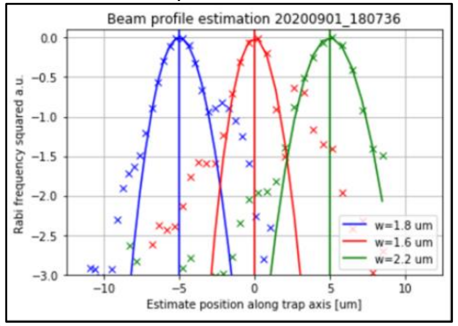
- **11** cores with **5 um** pitch





- 2um mode field diameter
- **In cryostat**, only 9mm from ions!
- Insensitive to trap vibrations
- Short paths mitigate phase noise

Beam profile estimation



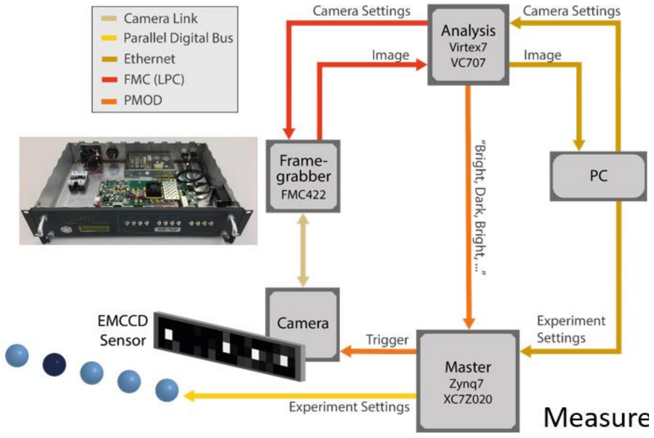
- Beam profile measured with an ion
- Side lobes indicate some **core to core crosstalk**
- Commercial device: improvements are possible

READOUT

READOUT

Traditional readout options:
-camera: slow (high latency)
-PMT: no spatial resolution

New low pixel count camera

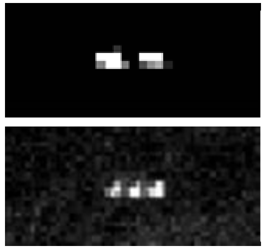


FPGA-based image processing with a low pixel count camera

- NUVU HNU 128 EMCCD
- Fast parallel **FPGA-based** image processing

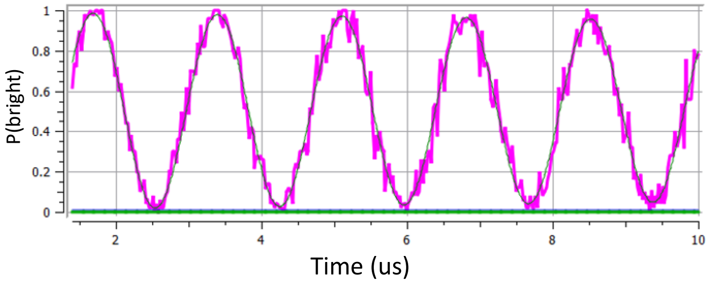
FIRST EXPERIMENTS IN A SCALABLE ION TRAP

TRAPPING OF IONS



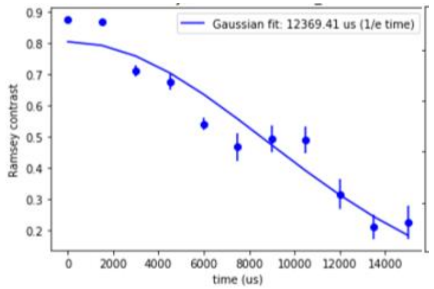
Camera image of trapped ions

First coherent operations using PROFA: Rabi flops



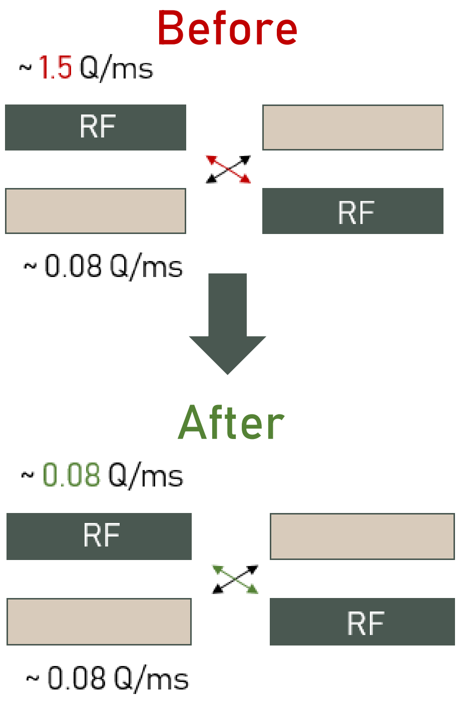
- Up to **4 ions** loaded simultaneously
- Ion stays trapped up to **30 days**: deep trap and good vacuum level

Ramsey measurement: 12 ms coherence time



- Superconducting coils can lock-in field
- Ramsey coherence measurement: 12 ms

RADIAL HEATING RATE



Side view of the Paul trap with heating components along the RF and DC electrodes

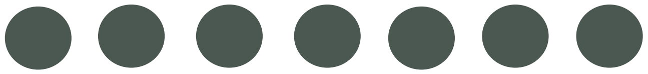
- Radial heating initially stronger along RF electrode axis
- Independent of RF power
- Insensitive to compensation

- Removed RF rectifier
- Added symmetric copper plate
- High -> Low resistance RF cable
- Rerouted nanopositioners far from RF line

- As a result: **0.08 Q/ms @ 5 MHz radial frequency**

OUTLOOK AND FUTURE EXPERIMENTS

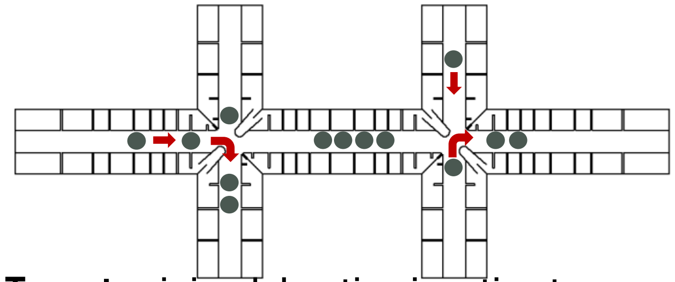
MANY IONS



Target: long chains (up to 50 ions)
Requirements: higher laser power, upgrades to optical setup

Physics outlook: quantum simulation / error correction

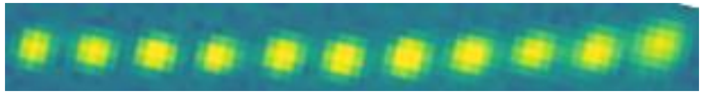
JUNCTION TRANSPORT



Target: minimal-heating junction transport
Requirements: noise investigation, transport waveforms

Physics outlook: manipulating many ions simultaneously / scaling

MULTI-QUBIT OPERATIONS



Target: individual addressing and readout of multiple ions with low crosstalk

Physics outlook: error correction

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