

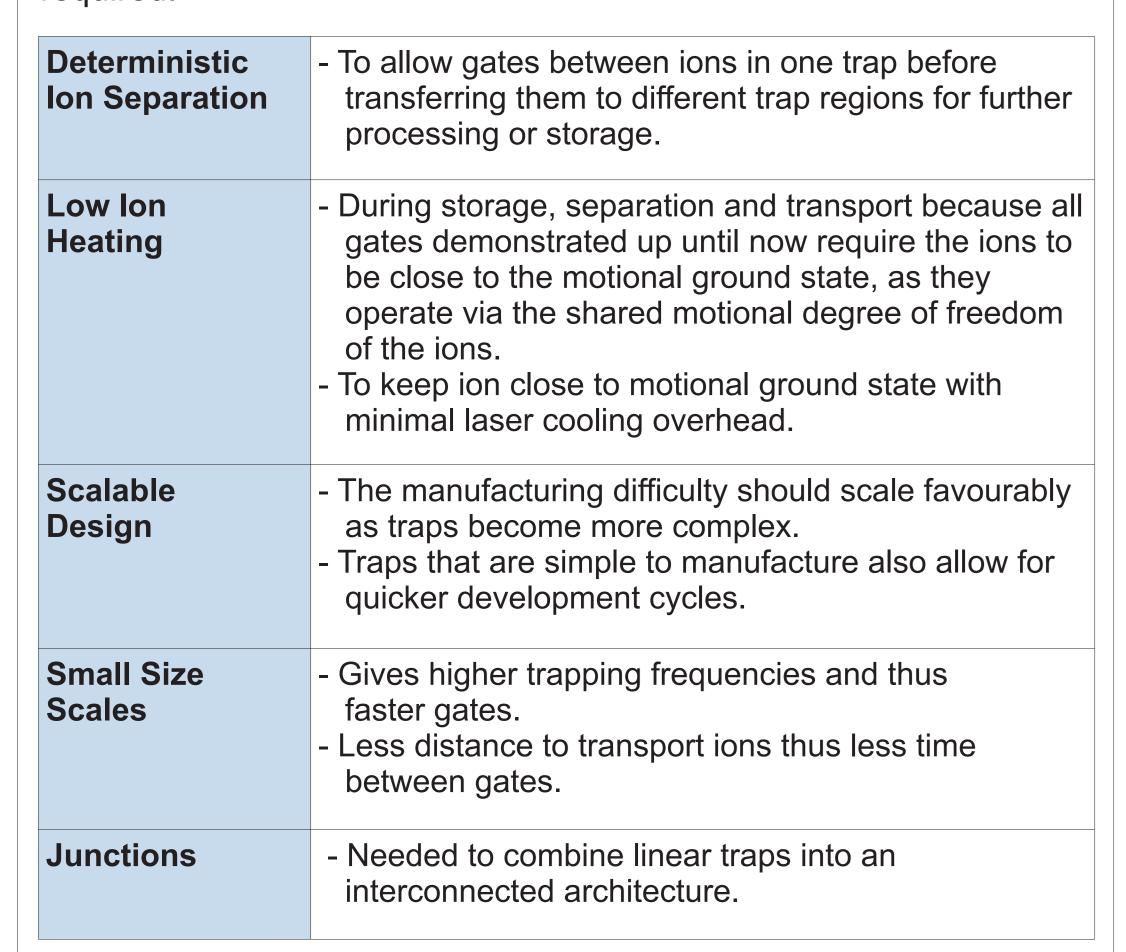
# Segmented Ion Traps for Quantum Computing

Ion Trap Quantum Computing Group - Department of Physics - University of Oxford

# Trap Technology Goals

Multiplexing many few-qubit ion traps provides a route to large scale ion trap quantum computing using demonstrated technology.

One way to do this would be with 'segmented traps' with many trapping regions and the ability to transport ions between them as required



# Sandia National Laboratories Planar Trap

Trap, designed and fabricated by Sandia National Laboratoies (Matt Blain) under DTO module 4 project. Materials: tungsten on silicon, with gold coat on backplane

1 r.f. electrode pair and 14 d.c. electrodes around a 2mm x 0.4mm vacuum slot

RF pseudo-potential and

perpendicular to (left) and

along (below) the trapping

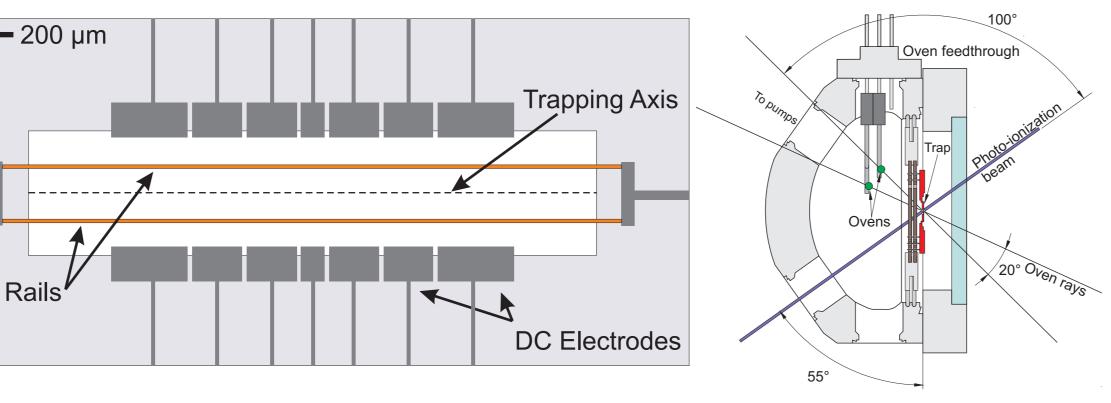
boundary-element analysis

27.25 MHz, 60V to 110V

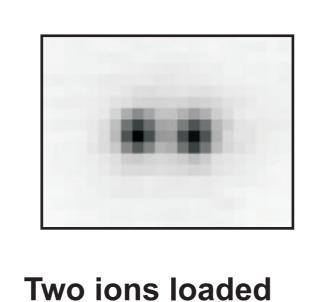
0.068eV

3 to 4.5 MHz

axis calculated using



Section showing geometry for photoionisation loading (above)



(above) in a trap with axial frequency ~317kHz, radial freq. ~3-3.5MHz. Separation is ~9.6um and the lifetime was ~1minute

with cooling

#### **General observations**

Ca<sup>40</sup> ions loaded by photoionisation. Background pressure 1x10<sup>-10</sup> mbar. Doppler cooling and fluorescence from copropagating 397 nm & 866 nm laser beams, waists = 25 x 85  $\mu$ m and 50 x 50  $\mu$ m. RC filters outside the

Initially we experienced difficulty loading the trap. This was owing to too high oven current (resulting in fast collisional

However, lifetime without laser cooling remains seconds.

**Ion Shuttling** (right) vacuum (R=1.8 k $\Omega$ , C=0.1  $\mu$ F). loss) and imperfect setting of the electrode voltages (resulting in lower trap depth). Consequently trap lifetime was of order seconds even with laser cooling, but is now of order hours.

Measured by 'heat and re-cool' method [1], observing the fluorescence during Doppler cooling. This is sensitive to temperatures O(1 to 100)K, i.e. far from trap ground state (a 1 MHz trap has  $50 \mu K$  level spacing), but ion orbit is still small and the heating rate near ground state is expected to be similar. [1] Wesenberg et al. PRA 76, 053416-1 (2007)

Example data (below). Cooling laser beams are turned off for Interpreted data set (below). The a period (0.1 to 1s), then reintroduced and the fluorescence monitored. This is repeated 200 to 500 times to accumulate statistics. The data is well fitted by an exponential curve (as expected for a thermal motional state).

Cooling time (ms)

Ion moved ~360µm from trap centre (in either direction on the trap axis) in 10ms. Fluorescence Plot (right) shows ion moving out, and back into, cooling beam (~100µm diameter) during shuttling. Maximum time ion can be moved out of beam for is 120ms, probably due to heating. Shuttling time was limited by computer update speed.

Trap Depth

Radial Secular Frequency

From simulations of Cd ion

cooling time constant implies a heating rate ~49(9) K/s. This is very high compared to other traps of similar dimensions.

Delay time (ms)

200 HAW JULY MAN HAVE LAND ALLER HAVE ANNOUNTED THE BUILD HAVE BUILD LAND HAVE HAVE HE

Ion-Electrode Distance 700µm RF Drive 5.8 Mhz 4.8eV Trap Depth Radial Secular Frequency 1.58MHz at  $V_{RF}$ =295 $V_{np}$ 

# Intermediate Scale Trap

Designed to investigate separation of ions in a regime where ion-electrode distances are large RF enough to give low motional heating, with a geometry optimised for a high octupole coefficient for a given breakdown voltage.

Fabricated by Uni. Liverpool (S. Taylor & B. Brkic)

#### Demonstrated:

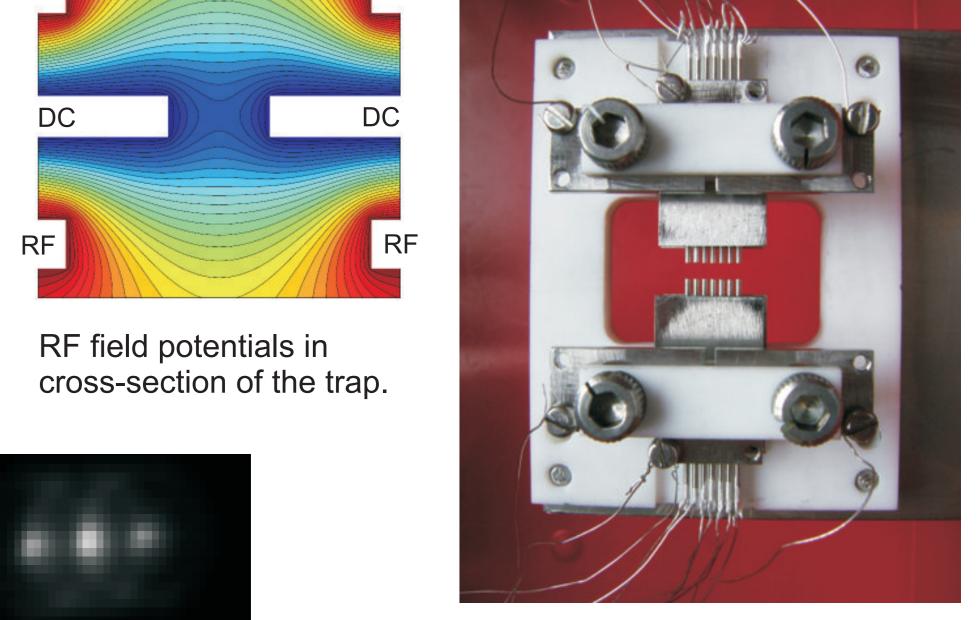
- Photoionization loading - Ion storage time of >1day
- Secular frequencies measured by electrode 'tickling'
- Doppler cooling and crystallisation
- of up to 3 ions - Micromotion compensation via RF
- correlated photon counting
- Heating rate by doppler re-cool method with preliminary data giving O(1K/s)

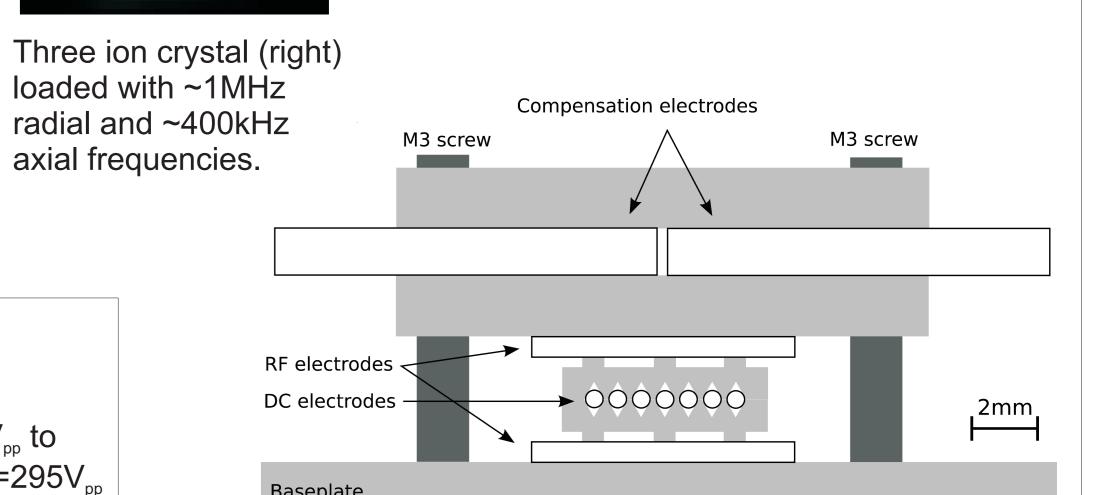
#### Future: - Sideband cooling and heating

rate measurement - Ion shuttling and separation

to quantum information science.

770kHz at  $V_{RF}$ =170 $V_{RR}$  to





# The Oxford Planar Trap Project

Ion-Electrode Distance

Radial Secular Frequency

RF Drive

Trap Depth

Heating Rate

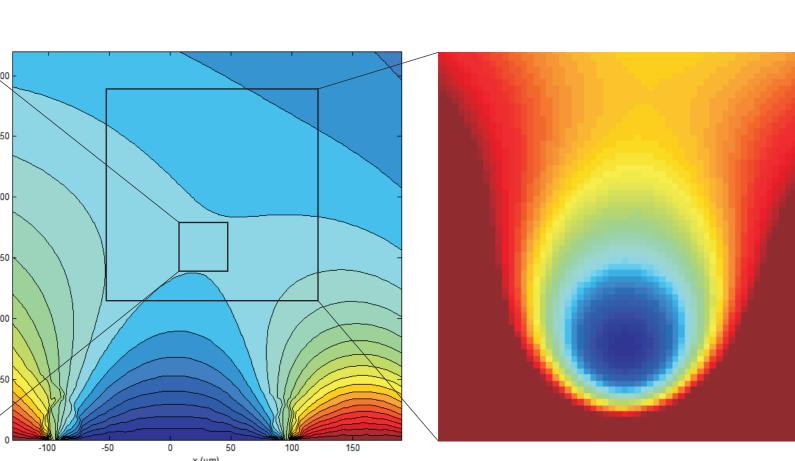
Planar traps based on a simple metal patterned substrate have recently been demonstrated at NIST [1] and MIT [2] with promisingly low heating rates measured. This type of trap is inherently easily scalable. Furthermore these particular traps are designed to be manufactured inhouse on short time scales to allow rapid testing and development of new electrode geometries.

[1] Seidelin et al. PRL 96, 253003 (2006) [2] Labaziewicz et al. PRL 100, 013001 (2008)

Ion-Electrode Distance RF Drive (at  $2\pi . \omega_{rad} = 1.5 \text{MHz}$ ) (at  $2\pi.\omega_{rad} = 2.5MHz$ )

120µm RF centre control electrode electrode 150µm DC 240µm RF electrodes electrode

14 MHz at 87 V 33 MHz at 241 V Prototype design for trap (above) with 9 DC electrode pairs for ion control



Model of RF potential (left and centre) and pseudopotential (right) in the plane perpendicular to the trap axis from numerical boundary-element analysis software. The asymmetry in the RF rails gives a 17° rotation of the traps normal modes. This allows a beam parallel to the trap's surface to cool both radial modes efficiently.

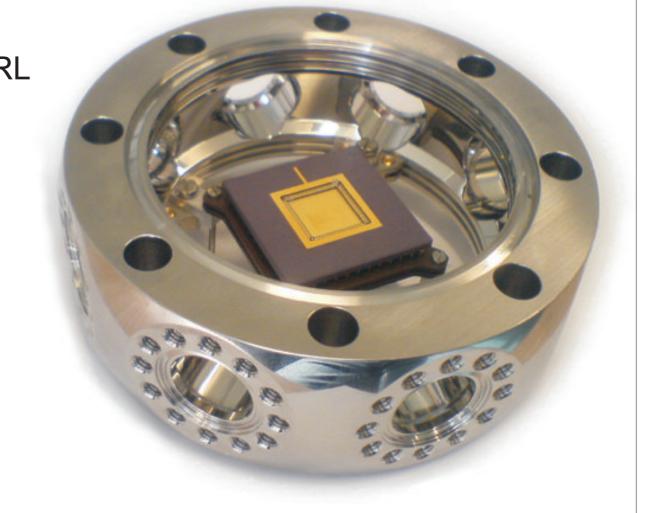
#### **Fabrication Process**

Currently under development at Oxford based on Seidelin et al. PRL 96, 253003 (2006) and B. Lev, Quant. Inf. Comp. 3, 450 (2003).

Substrate is 0.5mm thick polished fused silica (10mm x 10mm)

10nm chromium adhesion layer and 100nm copper seed layer evaporated onto substrate 6µm thick photoresist spun on and electrode pattern lithographically defined 5µm of Gold electroplated from gold sulphite solution onto copper seed layer Photoresist removed then copper

and chromium etched away



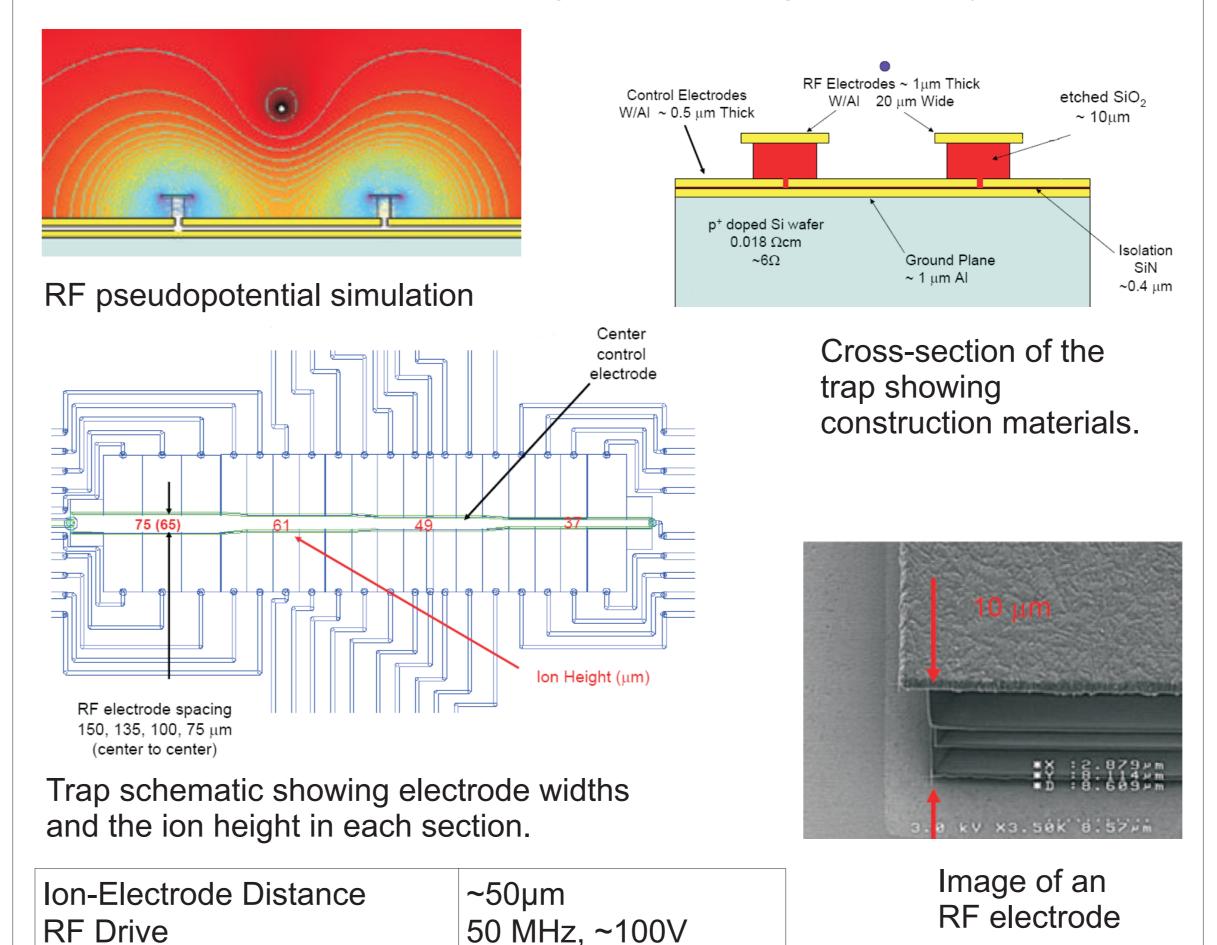
Trap will be wire bonded to CPGA chip carrier. Above is the carrier in a vacuum compatible socket. Imaging will be from above the trap and laser beams will enter through the side ports. Electrical and vacuum pump connections are made below the trap.



Optical and SEM closeups of a trap and a single DC electrode fabricated using this process. The high aspect-ratio of the insulating gaps shields the ion from the potentially charged substrate.

### Lucent Planar Trap

Traps by Lucent Technologies in collaboration with Bell Labs, MIT and NIST. VLSI fabrication is scalable and compatible with CMOS control circuitry. Oxford's trap under vacuum, trapping attempts to begin imminently.



# Photos and parameters below from working prototype of the project's first trap at Ulm University. See Schulz et al. New Journal of Physics 10 (2008) 045007 for details. - Ti/Au (10μm) on Al<sub>2</sub>O<sub>3</sub> wafer (400μm) cut with femtosecond laser - Three wafers stacked, glued and wire-bonded to package - 500µm wide storage zone (Ulm's results below) - 250µm wide processing zone (awaiting results)

Ion-Electrode Distance

RF Drive

Trap Depth Radial Secular Frequency Heating Rate Images and simulations: Dick Slusher (Lucent)





250µm

0.755eV

1.26 MHz

24.8 MHz, 140V

2.1(3) quanta/ms

EU Microtrap Project

A collaboration between National Physical Laboratory (UK) and the Universities of Aarhus, Innsbruck, Oxford,

Siegen and Ulm. Aimed at developing an EU technology capability in trapped ion microstructures for application





Oxford trap and vacuum

system (below) currently

under construction



0.025eV