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NPL progress on TIQC with $^{88}Sr^{+}$

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Basic techniques with single $^{88}Sr^+$ ion

- Resolved sideband cooling $\langle n_z \rangle \sim 0.3$
- Coherent optical excitation: Rabi flopping, Ramsey spectroscopy

Problem #1: large heating rate

- electrode surface preparation
- contamination of electrodes

Problem #2: only one ion in the trap!

Outline

Photoionisation of ^{88}Sr

- Clean, reliable loading of a trapped ion
- Active control of loading process

Resolved sideband cooling

- Enhanced electrode preparation
- Zero-point cooling of single ion
- Heating rate measurements

Microfabricated linear segmented trap

- Uses established silica-on-silicon technology
- Scaleable
- Potential for photonic integration

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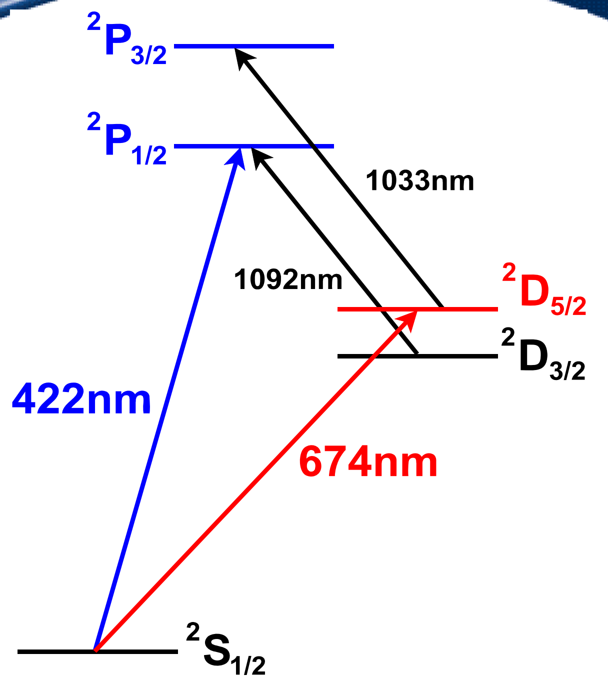
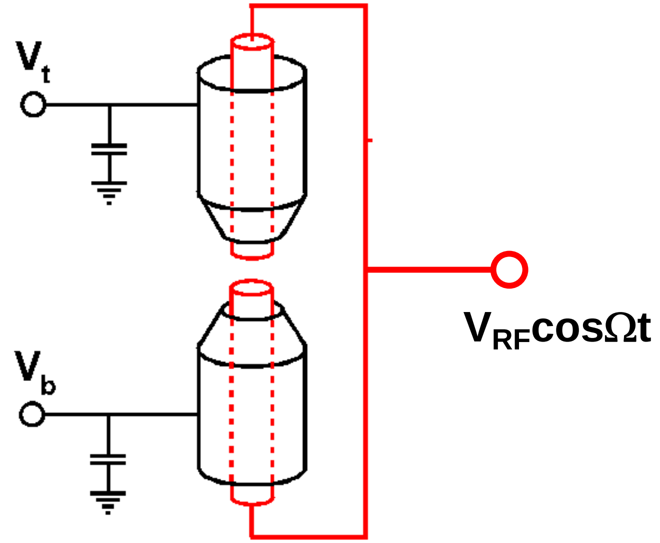
Cooling a single ion: $^{88}Sr^{+}$

- **422 nm**: laser cooling transition (frequency-doubled diode laser)
- **1092 nm**: repumper transition (Nd^{3+}-doped fiber laser)
- **674 nm**: narrow linewidth optical clock or qubit transition (diode laser system)
- **1033 nm**: clearout transition (diode laser)
- Also need 461 nm and 405 nm to photoionise ^{88}Sr to make $^{88}Sr^{+}$





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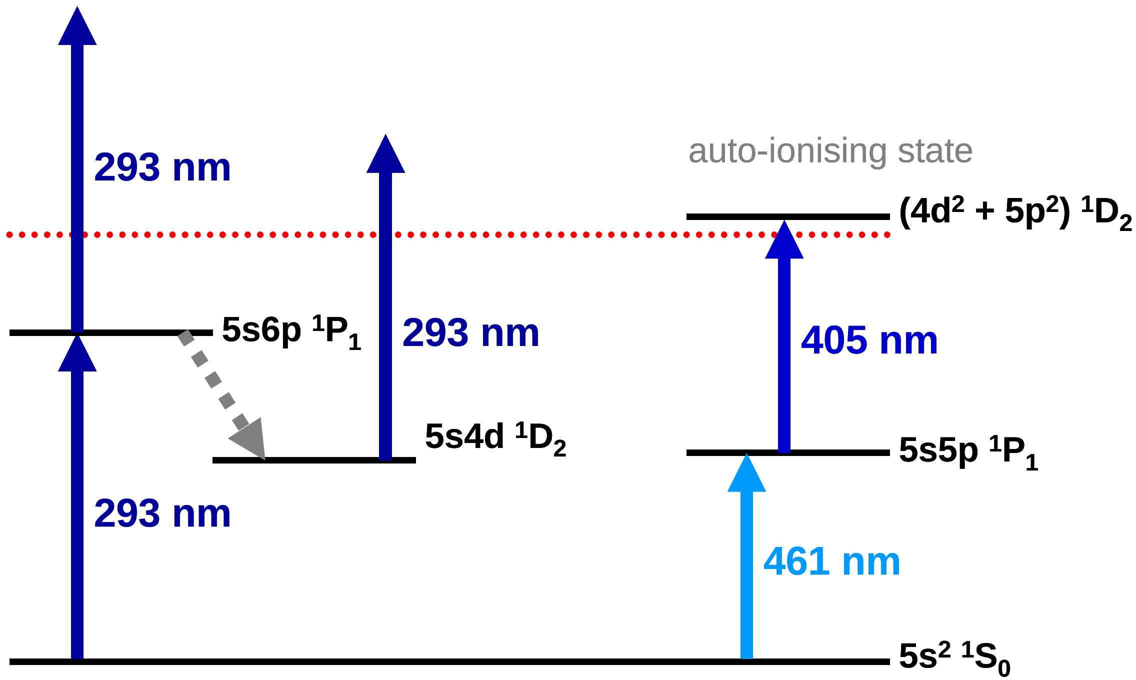
Strontium photoionisation

- preferred scheme is:

$5s^2\ {}^1S_0 \rightarrow 5s5p\ {}^1P_1 \rightarrow (4d^2+5p^2)\ {}^1D_2$

- transition to auto-ionising state is around ~1 nm wide [4]

Neutral ^{88}Sr



similar to Kjærgaard *et al* [1] for Ca

similar to Gulde *et al* [2] and Lucas *et al* [3] for Ca

[1] Kjærgaard *et al*, Appl. Phys. B 71, 207 (2000).

[2] S. Gulde et al, Appl. Phys. B 73, 861 (2001).

[3] D.M. Lucas *et al*, Phys. Rev. A 69, 012711 (2004).

[4] M.A. Baig *et al*, Chem. Phys. Lett. 296, 403 (1998).

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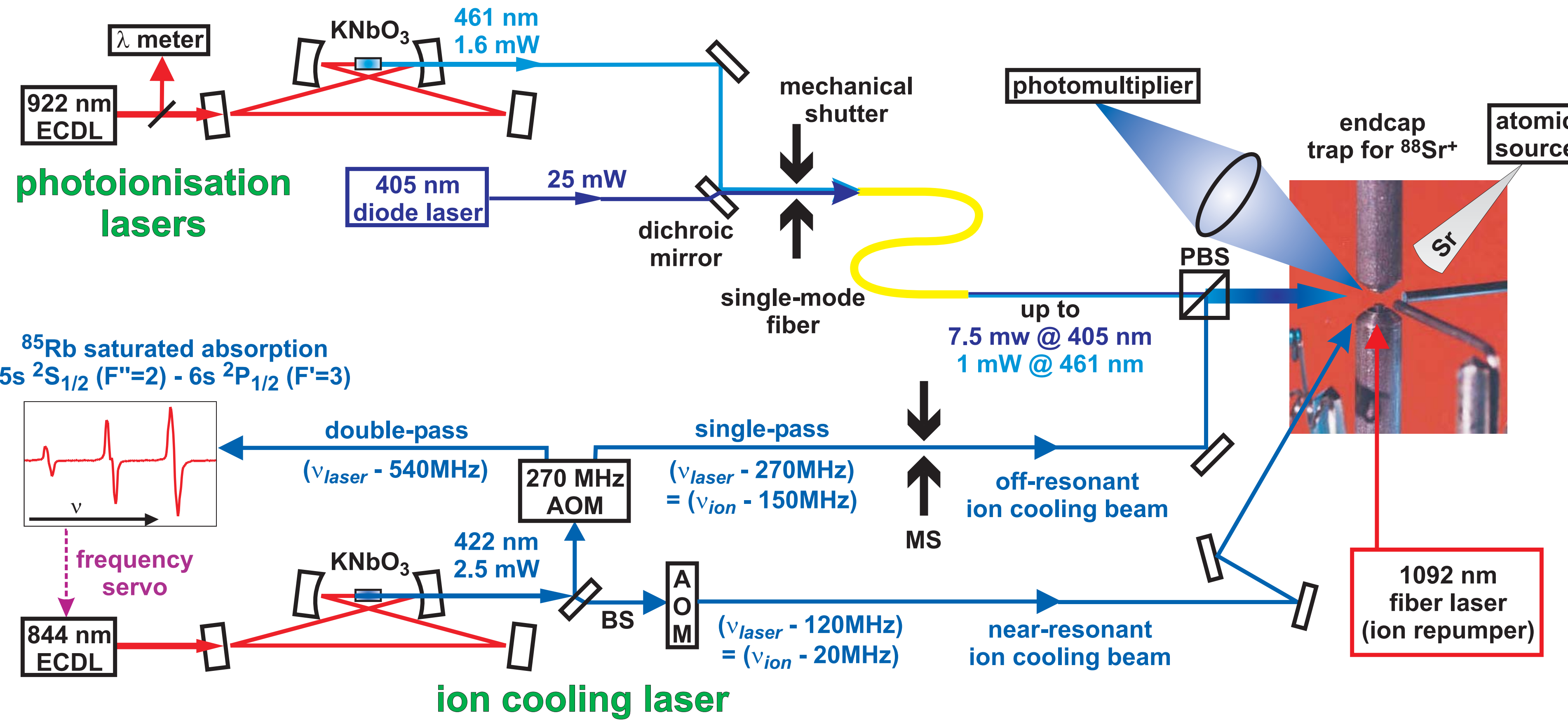
Photoionisation apparatus



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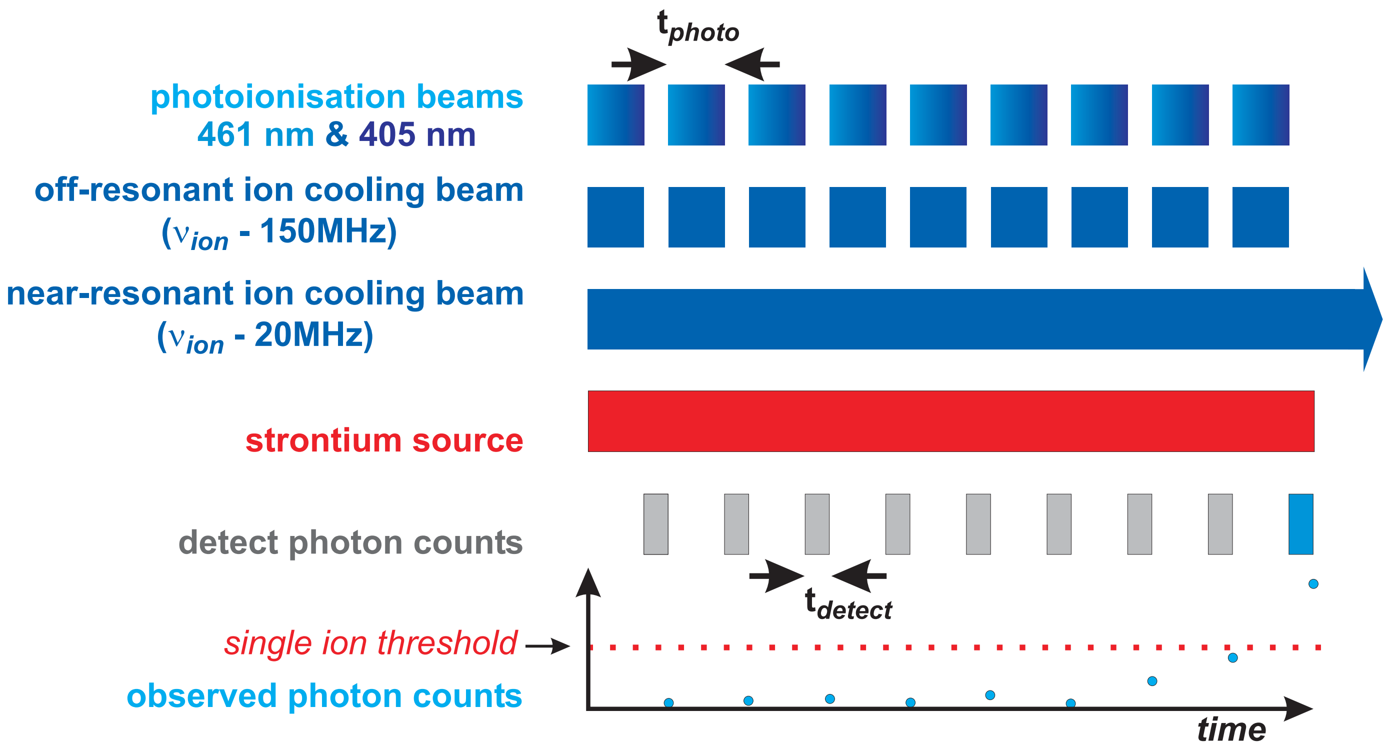
Controlled single ion loading

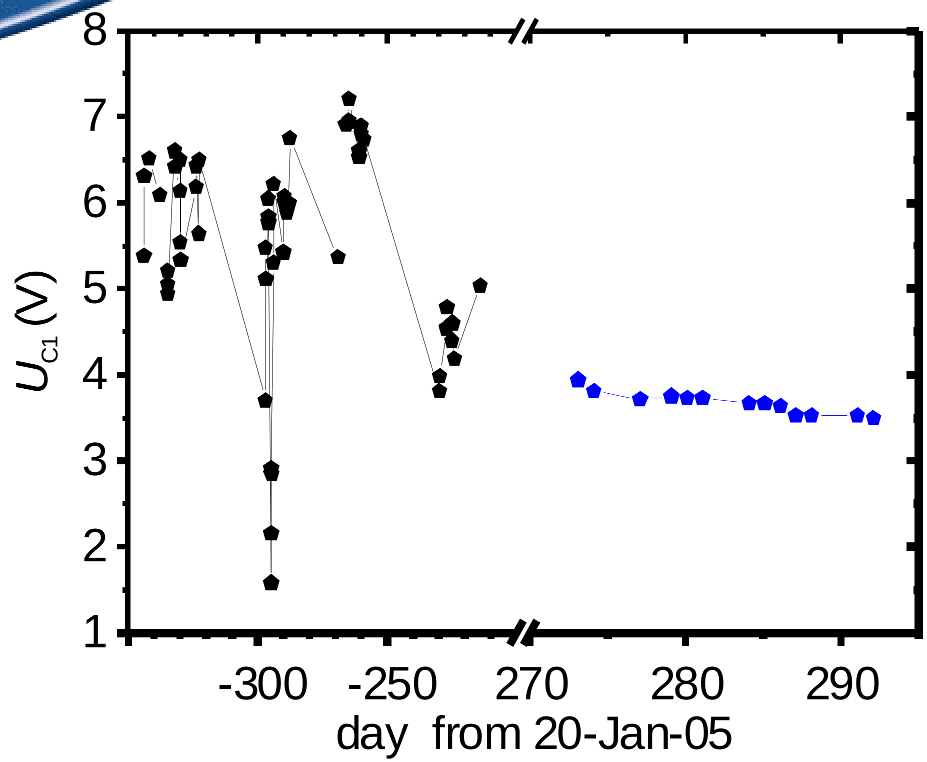
- modulate between loading/cooling & detection
- off-resonant beam slows hot ion
- cold ion scatters photons efficiently from near resonant beam
- source of atomic flux is switched off when a single ion is detected



- **technique can be extended to linear strings**

Photoionisation benefits

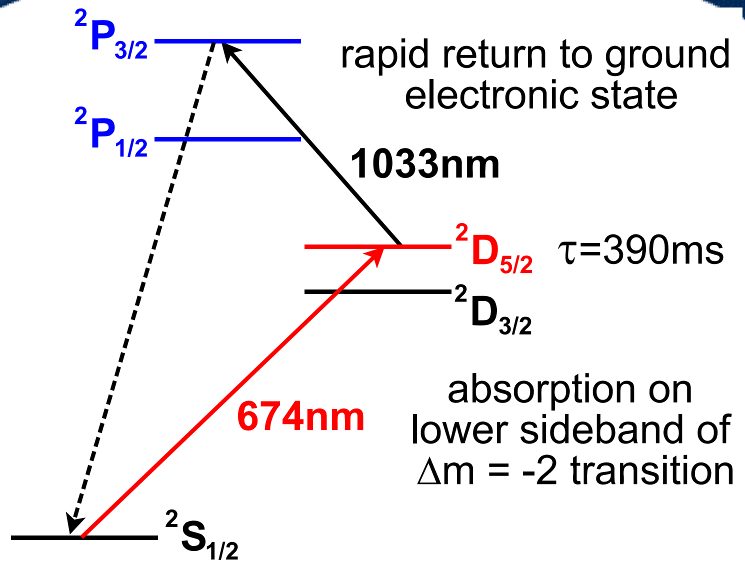
Reduced micromotion fluctuations



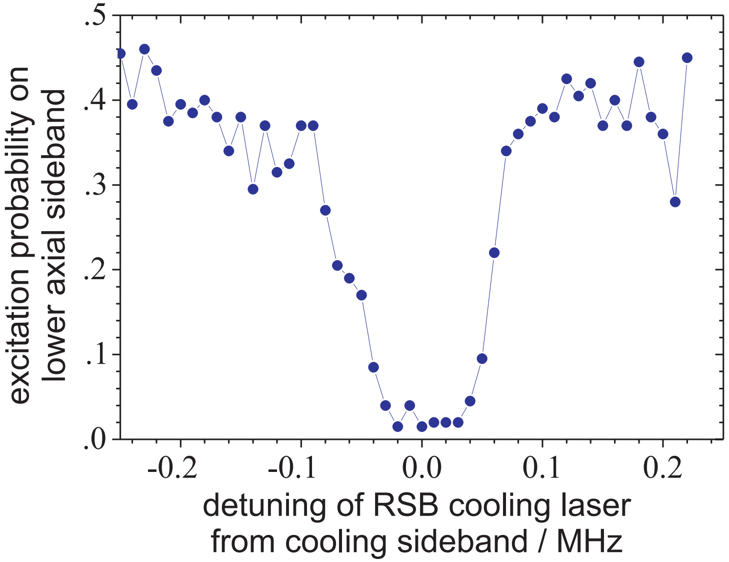
Reduced atomic flux

	electron impact ionisation	photoionisation
Loading temperature	~350°C (623K)	~200°C (473K)
Sr partial pressure	~10^{-5} torr	~10^{-9} torr
Observed loading efficiency (#loads / #attempts)	~0.25	~1

Zero-point cooling and heating rates of $^{88}Sr^{+}$



- trap electrodes: abrasively polished down to ~1 μm
- Doppler cooling to $\langle n_z \rangle = 8$
- drive lower axial sideband on Δm=-2 S→D transition and quench D-state using 1033 nm
- detect using sidebands of Δm = 0 transition



F. Diedrich, *et al*, PRL 62, 403 (1989), Ch Roos *et al*, PRL 83, 4713 (1999)

Cooling the axial motion

2 ms RSB cooling

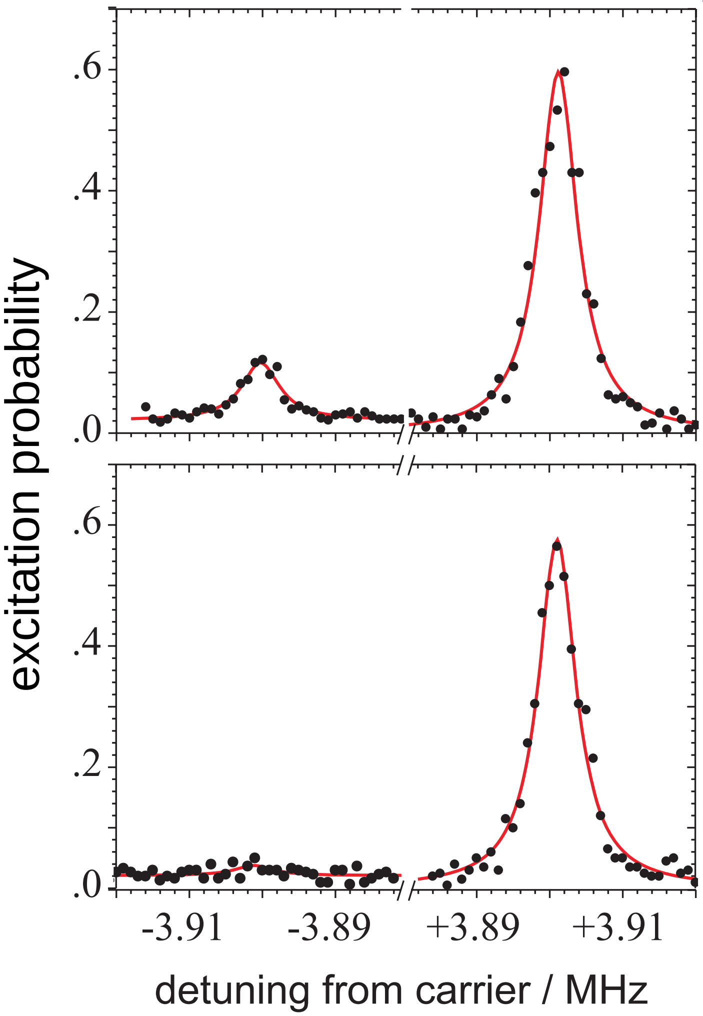
$\langle n_z \rangle = 0.19(2)$

Axial motion:

$\omega_z/2\pi = 3.90$ MHz

5 ms RSB cooling

$\langle n_z \rangle = 0.030(12)$



Measurement of $\langle n_z \rangle$ made 0.9 ms after cooling; limited by mechanical shutters switching times

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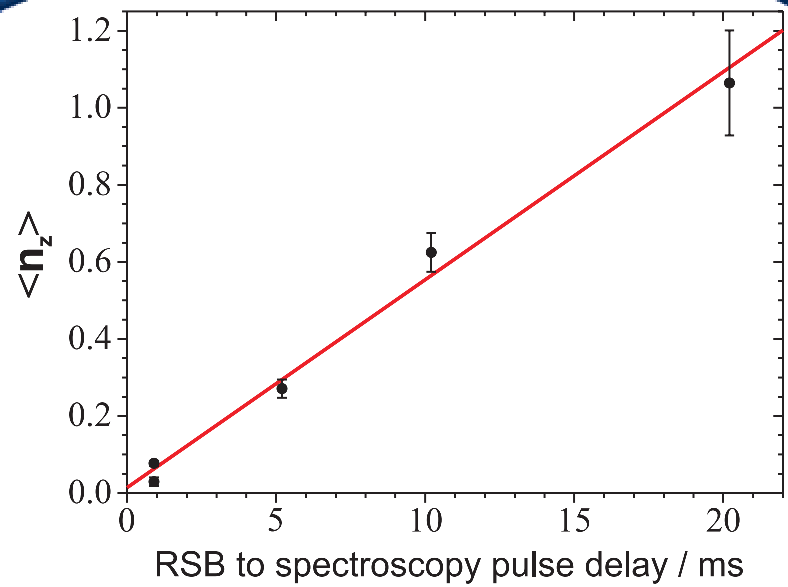
Heating rate of axial motion

$d\langle n_z\rangle/dt = 0.054(4)$ / ms

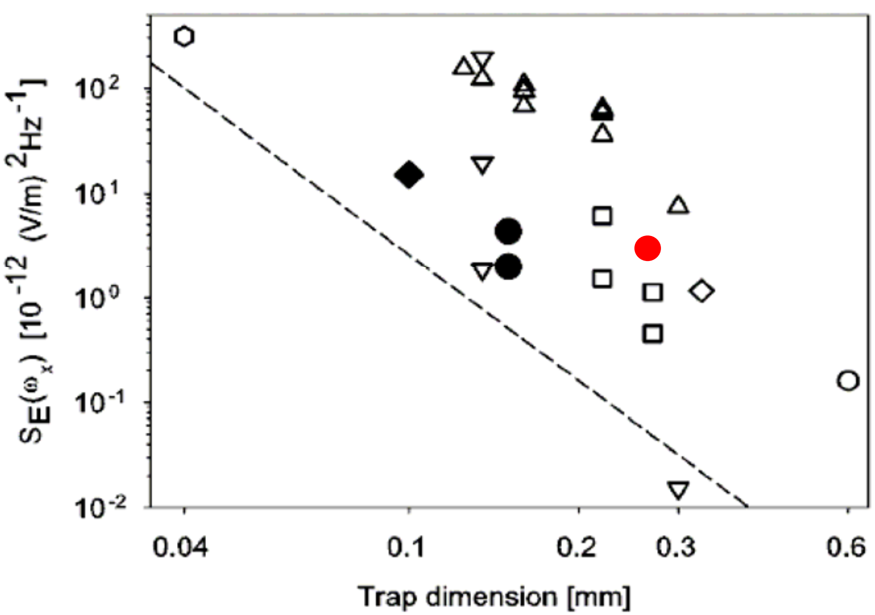
extrapolating to t = 0,

$\langle n_z\rangle(t=0) = 0.014(8)$



Deslauriers, Haljan, Lee, Brickman, Blinov, Madsen, Monroe

PRA 70 043408 (2004)



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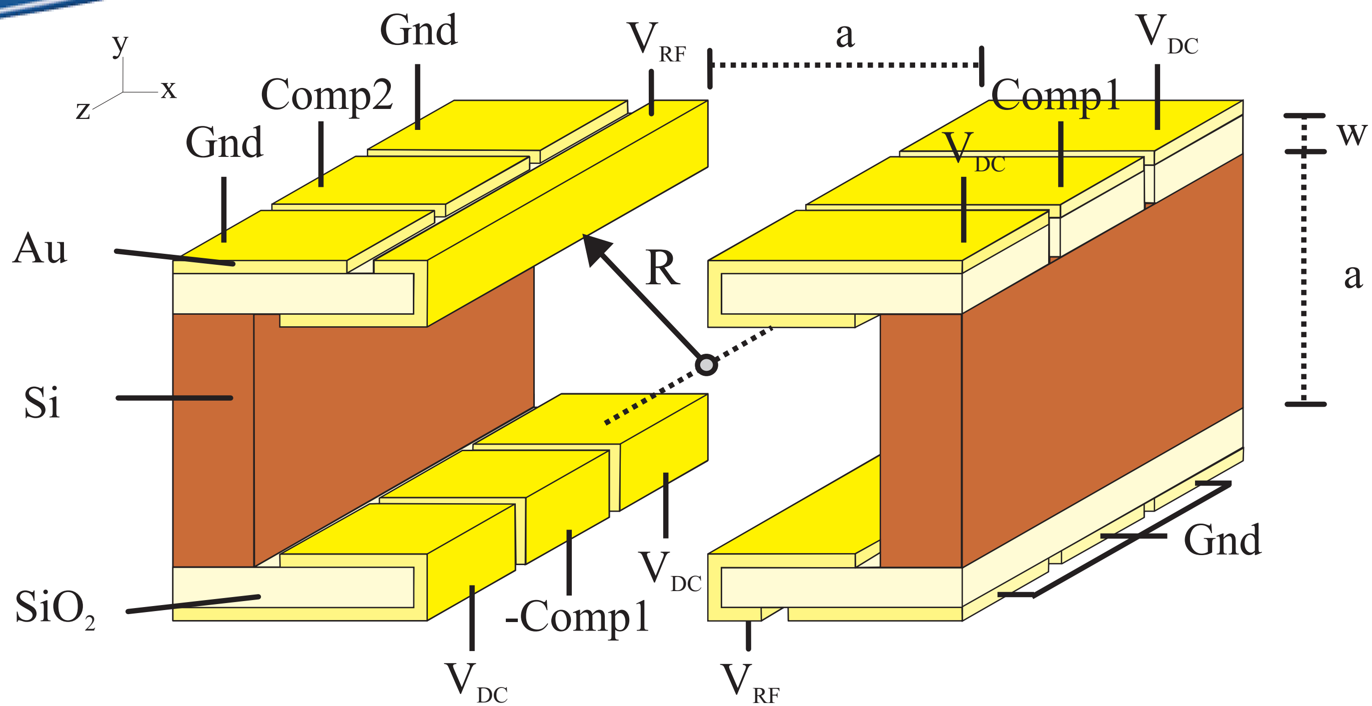
Scaleable microfabricated ion traps

Microfabricated using silica-on-silicon technology

- established fabrication process from photonics industry
- linear segmented traps created in a monolithic structure (no post-processing assembly required)
- three-dimensional structure
- unit aspect-ratio is possible
- length scale under current investigation: $\geq 100\ \mu m$
- length scale for future investigation: down to $20\ \mu m$

Microfabricated trap concept

Elementary trap unit



Physical parameters

Si thickness	100 → 500 μm
SiO_2 thickness	< 20 μm
Au thickness	≤ 5 μm
Au surface roughness	< 10 nm RMS
undercut	100 → 300 μm
Si resistivity	< 10^{-4} Ωm

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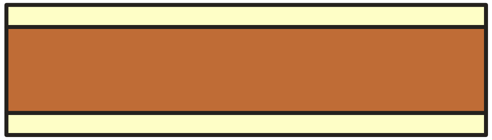
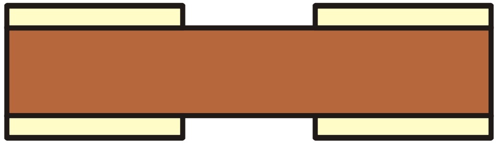
Fabrication process

silicon wafer, 500 → 100 μm thick

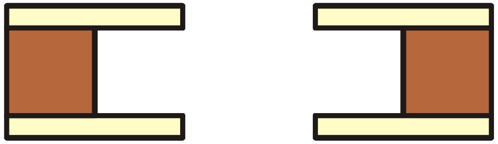
thermal oxidisation up to 20 μm thick



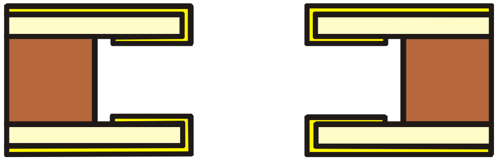
etch to remove SiO_2: create “fingers”



plasma and wet etches to remove Si



pattern gold electrodes



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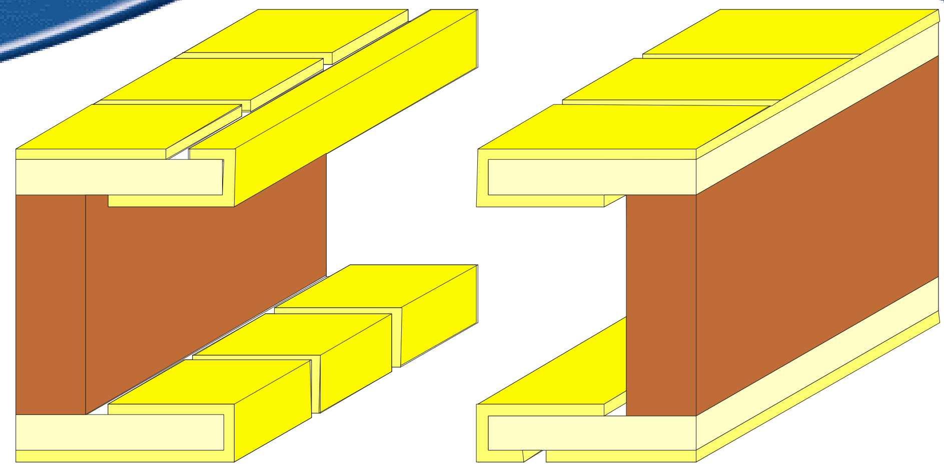
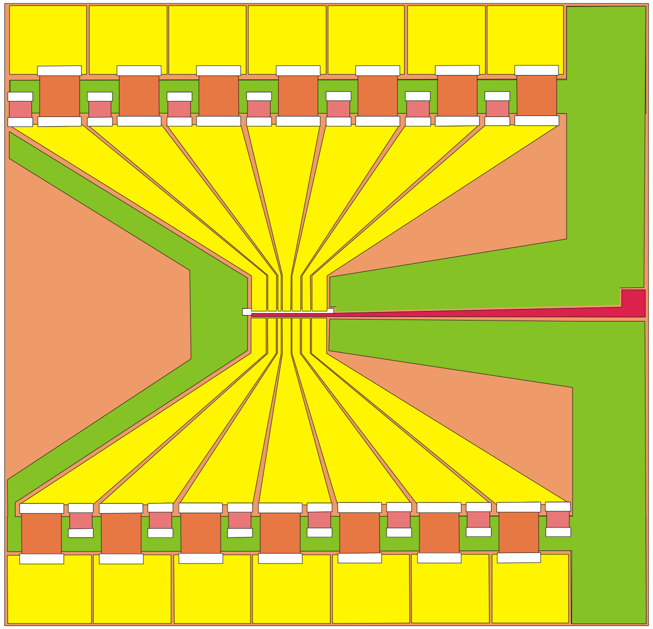
Example trap layout



15 mm x 15 mm chip size,
same pattern on both sides



DC and compensation electrodes

RF electrode

ground

exposed silica

resistors

capacitors

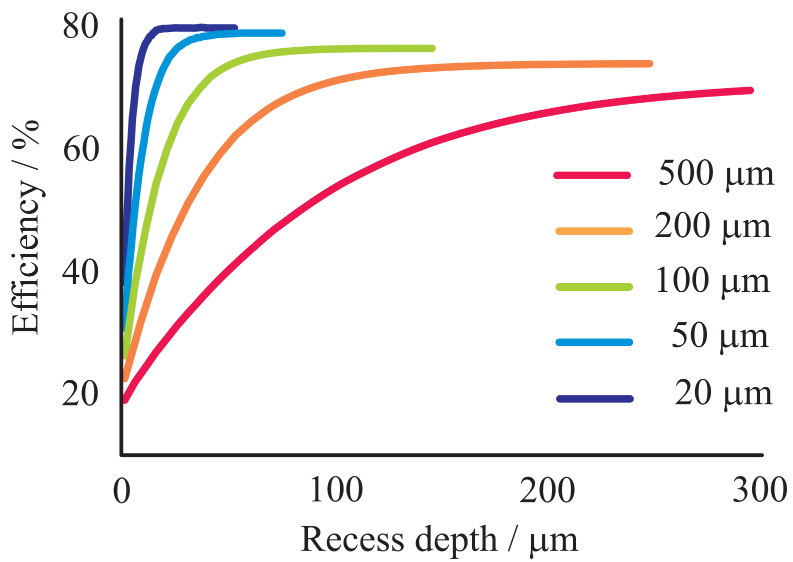
Modelling the trap potential

- Finite element modelling of trap in 2D and 3D
- Calculate the resultant pseudo-potential
- Calculate conditions for stable trap operation ($^{88}Sr^{+}$)

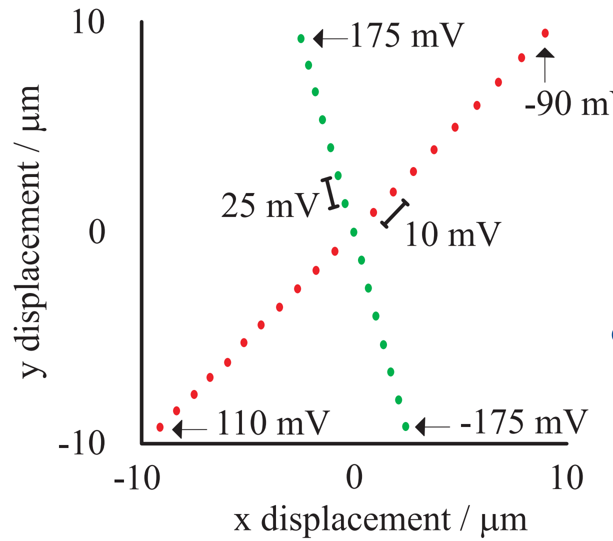
parameter					units
electrode separation		**200**	**100**	**20**	**μm**
SiO_2 thickness		15	15	15	μm
V_{RF}		160	40	10	V
V_{DC}		7	2	1	V
$\Omega_{RF}/2\pi$		33	33	33	MHz
$\omega_{r1}/2\pi$		3.4	3.3	10.0	MHz
$\omega_{r2}/2\pi$		2.8	2.9	6.7	MHz
$\omega_{z}/2\pi$		2.5	2.6	5.2	MHz

Operating practicalities

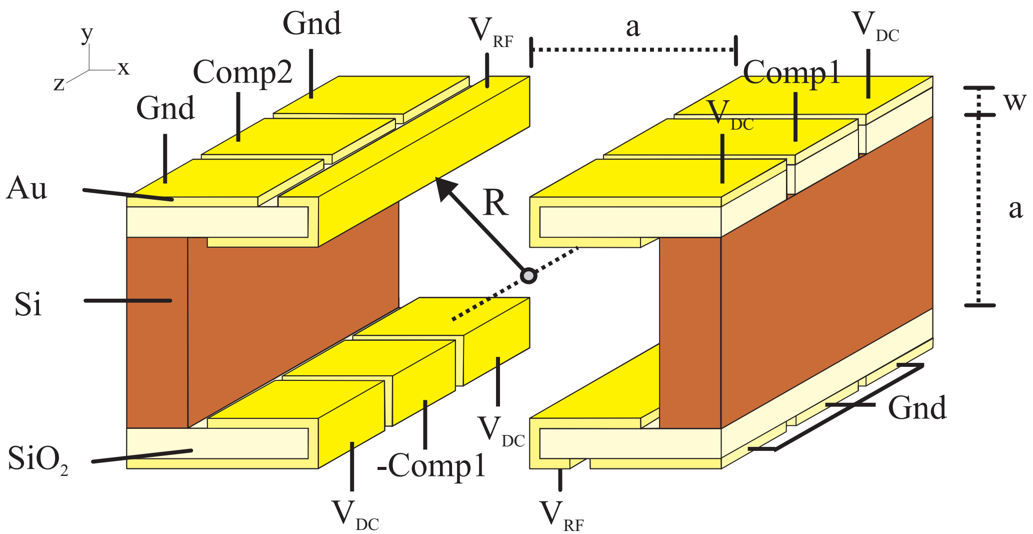
Trap efficiency



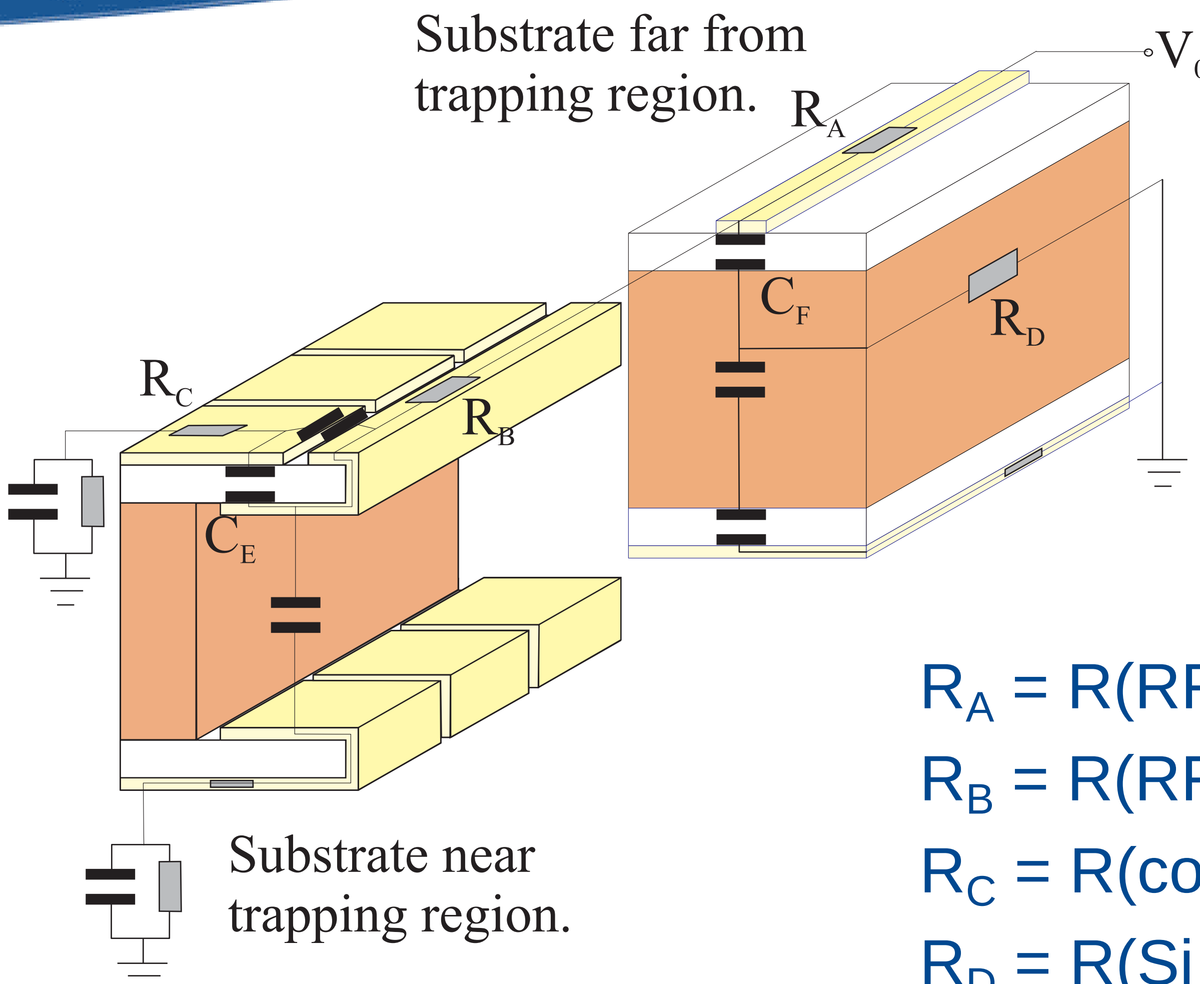
Micromotion compensation



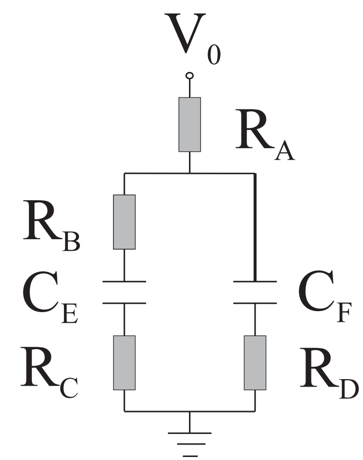
Comp 1 (●)
Comp 2 (●)
a = 200 μm
V_o = 56 V



RF heating of substrate



Lumped circuit model



R_A = R(RF line away from trap)

R_B = R(RF trap electrode)

R_C = R(comp. Electrode to gnd)

R_D = R(Si to gnd)

$C_{E,F}$ = C(SiO_2)

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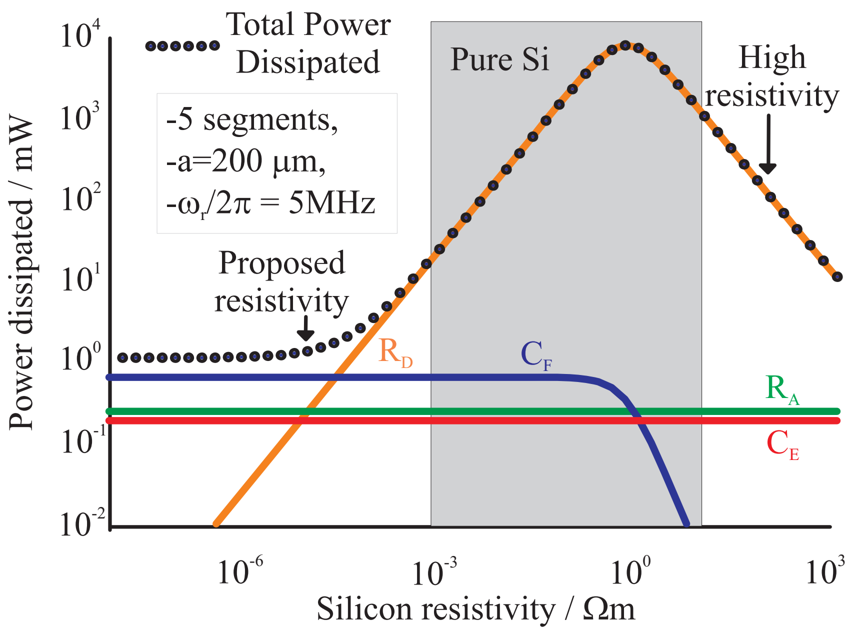
Power dissipation

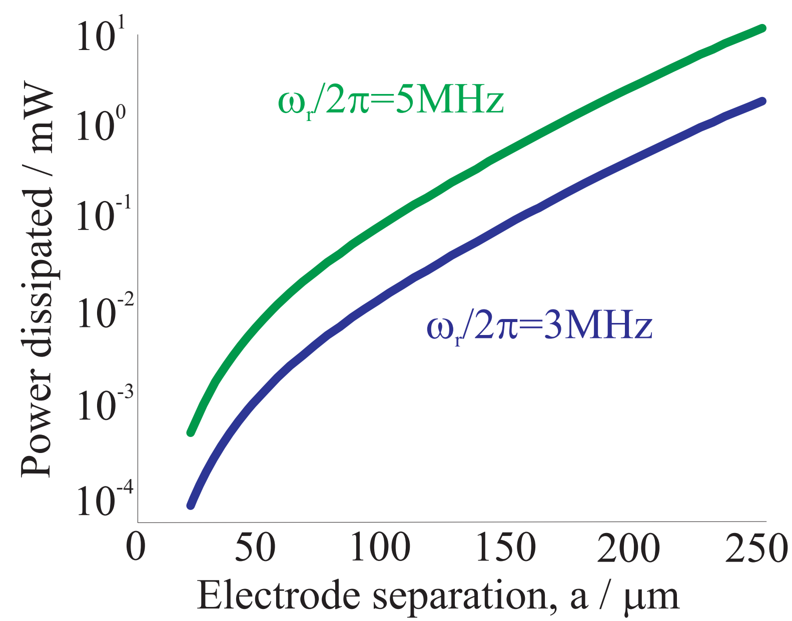
Power dissipated vs Si resistivity

5 segment trap, a = 200 μm, $\omega_r/2\pi$ = 5 MHz



Power dissipated vs trap size

5 segment trap



Assuming only radiation from gold-coated chip,
1 mW causes a 12°C rise in temperature

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Future upgrades & challenges

Lasers & control

- increase speed of high extinction of lasers: optical fiber and AOM
- improve 674nm laser stability: vertical cavity (Notcutt & Hall)
- enhance frequency and phase agility of 674 nm laser: DDS source for frequency and phase control
- increase Rabi frequency on S-D transition

200 μm & 100 μm traps

- interchangeable trap chip mounting: “the wiring problem” & fast turnaround
- zero-point cooling of strings; low heating rates
- entanglement of 2 & more ions

And beyond……

- fabricating structures with electrode separation below 100 micron
- single mode fibers in UHV direct to trap chip

Summary

Photoionisation for controlled loading

- 10^4 times less flux; micromotion drifts eliminated

Zero-point cooling

- $\langle n_z \rangle = 0.030(12)$ detected
- $d\langle n_z \rangle/dt = 0.054(4)$ / ms measured
- $\langle n_z \rangle(t=0) = 0.014(8)$ inferred

Microfabricated linear trap design

- 3D, unit aspect ratio, from planar SiO_2-Si technology
- monolithic trap chips
- potential for photonic integration

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