Wiring up trapped ions

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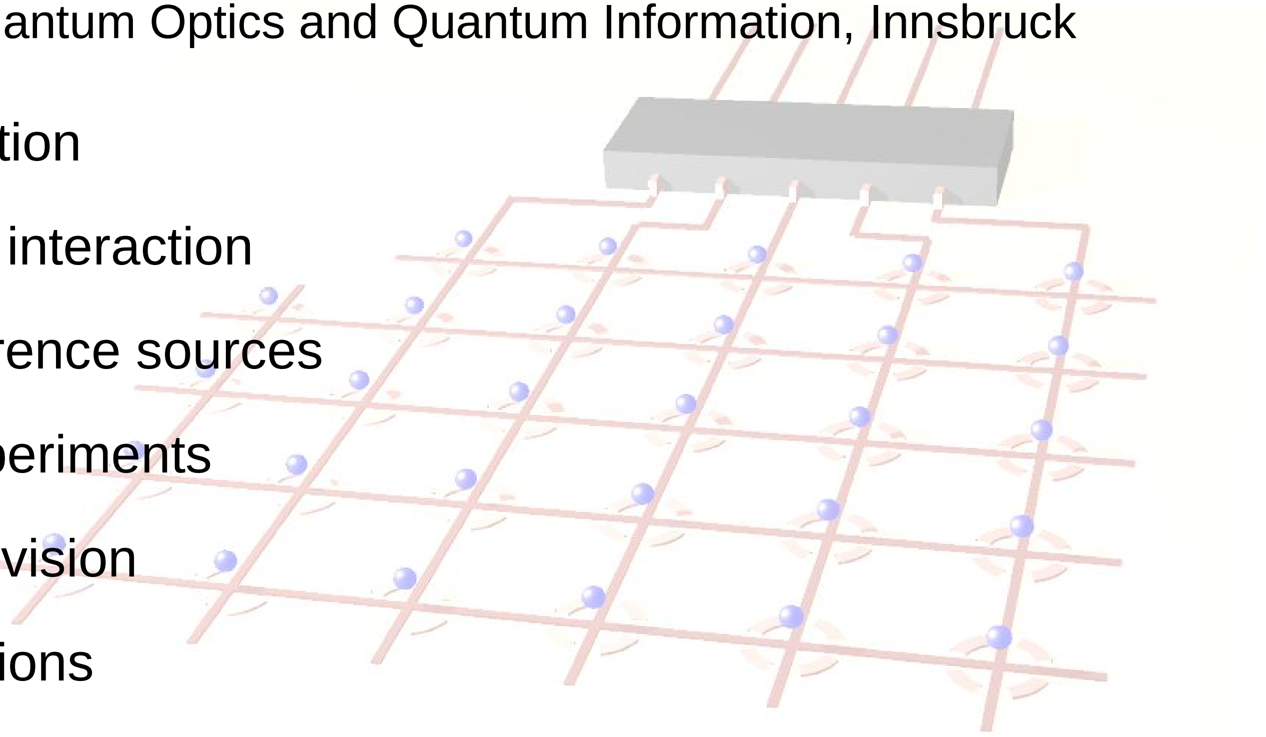
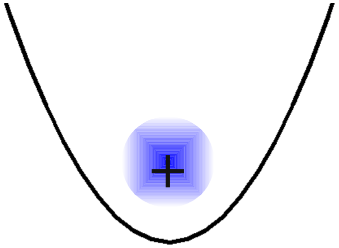
- Introduction
- Ion-wire interaction
- Decoherence sources
- First experiments
- Plans & vision
- Conclusions

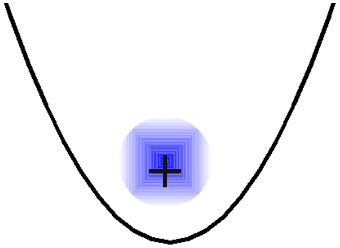


UCLA, Dec 9th 2009

Wiring up trapped ions

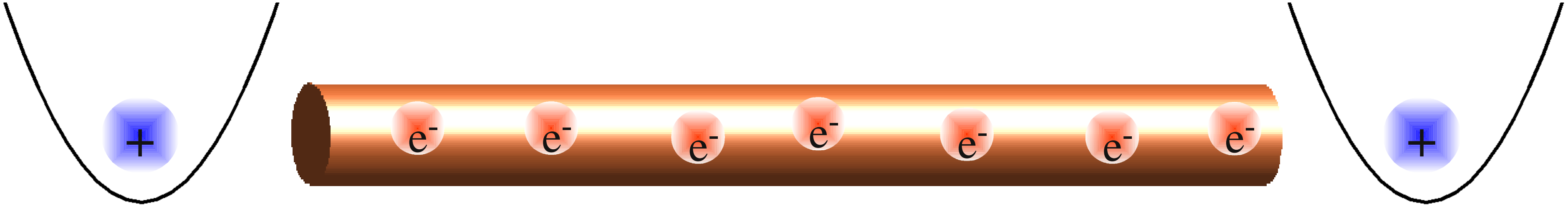
Two trapped ions …



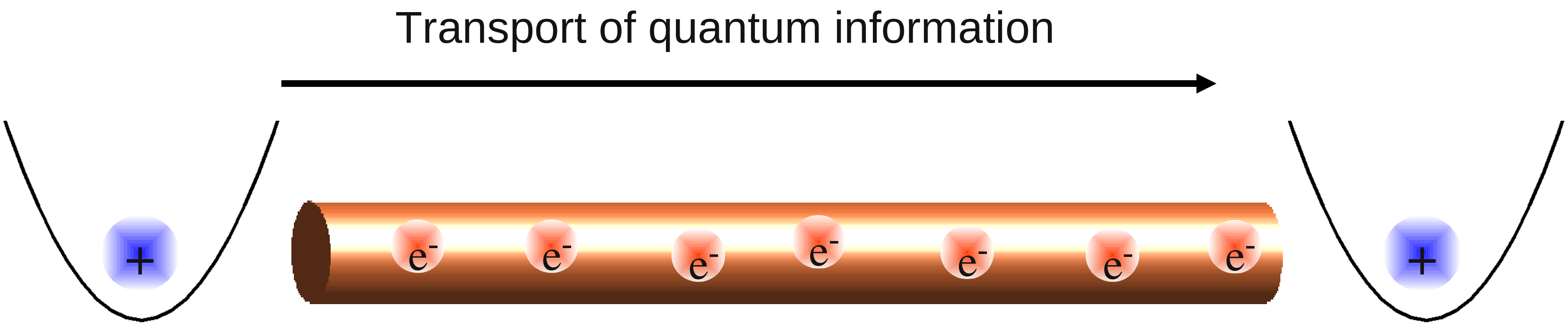


Wiring up trapped ions

Two trapped ions + a wire

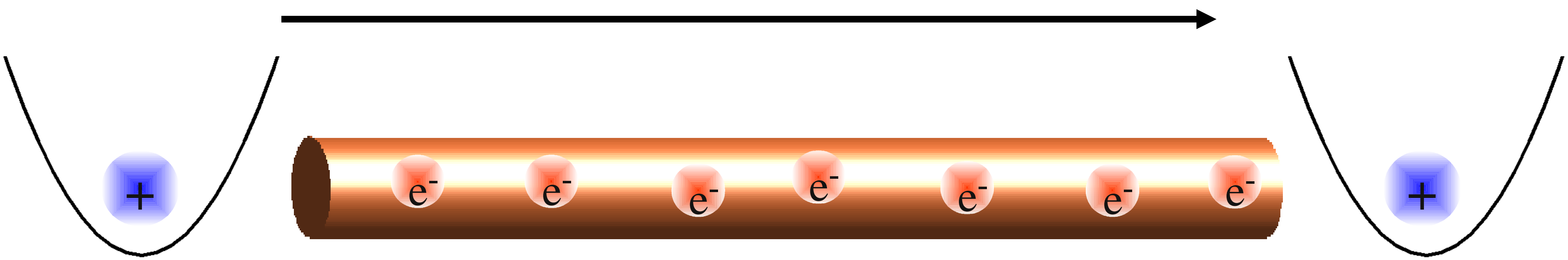


Wiring up trapped ions



Wiring up trapped ions

Transport of quantum information

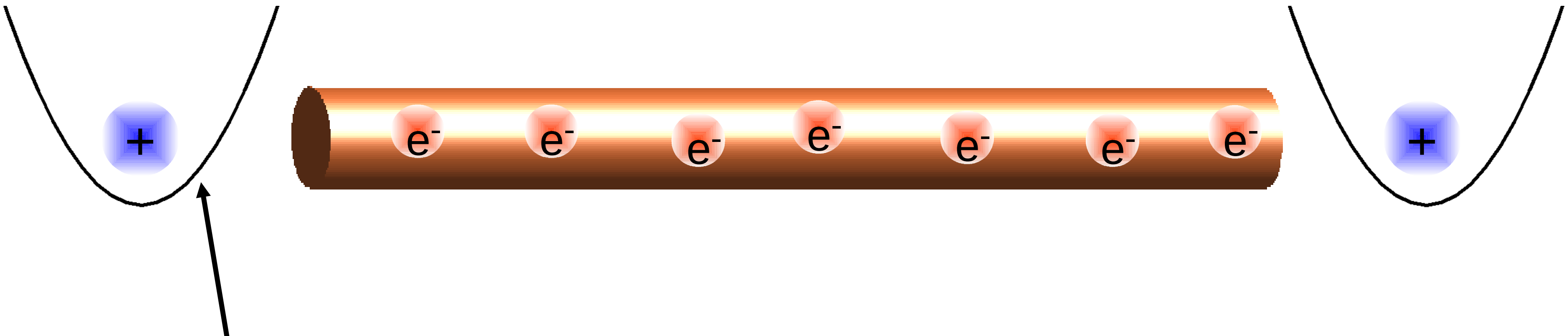


No trace of the quantum information should remain in the wire

➡ ~~super conducting~~ wire

Wiring up trapped ions

Two trapped ions + an ordinary wire



Ultimate control

- cooling to “0 Kelvin”
- quantum state manipulation
- “perfect” state detection
- carry quantum information

Applications

- excellent quantum sensors
- study quantum conductivity
- connect quantum computers

Applications

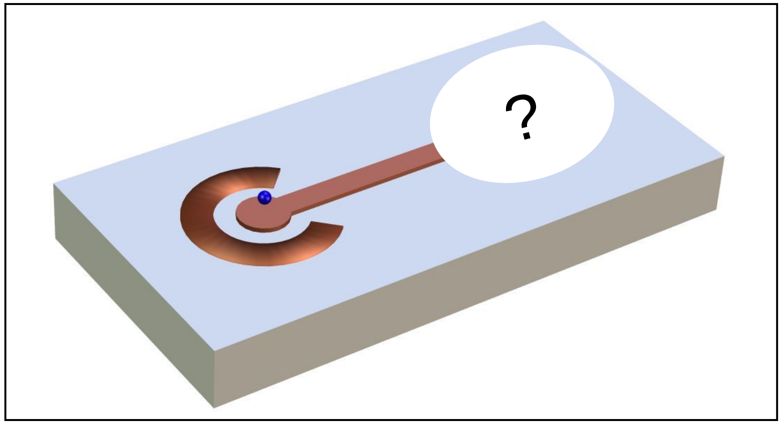
Physics:

- Decoherence in charge transport
- Wire mediated laser cooling to a few μK
- Cooling of LC resonators

Heinzen and Wineland, PRA **47**, 2977 (1990).

Technology:

- Scalable quantum computing with trapped ions/electrons
- Hybrid quantum computing
- Quantum detectors



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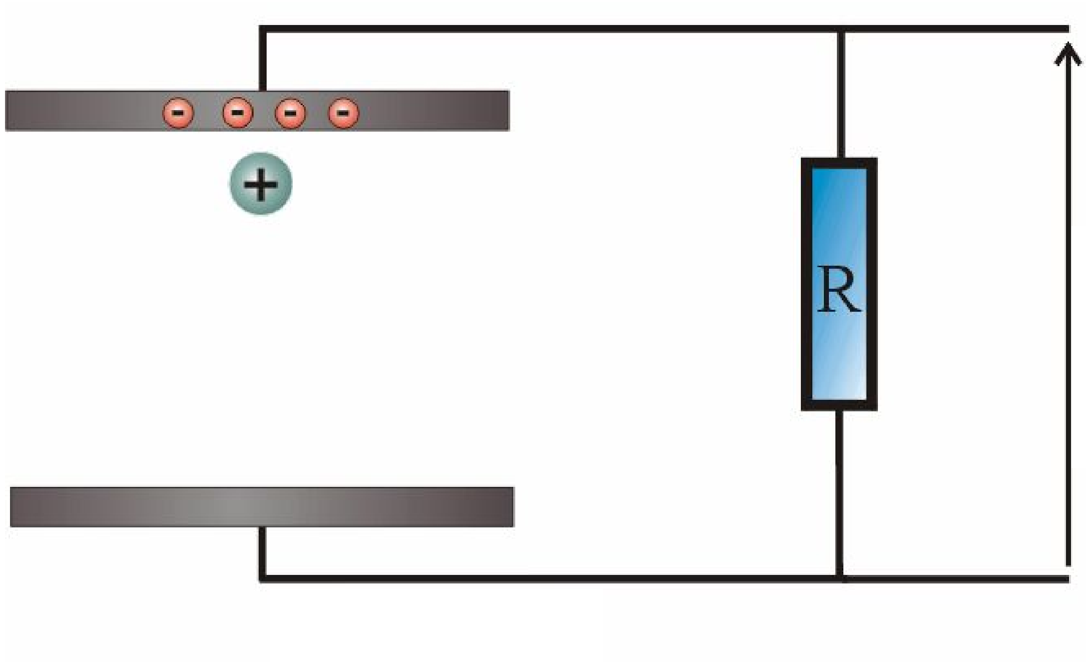
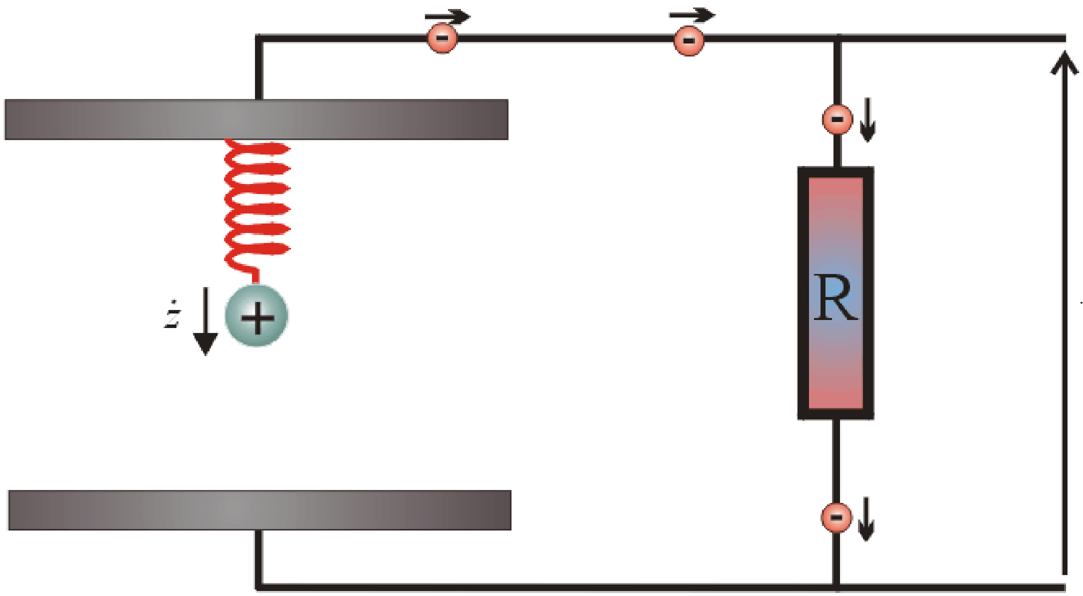
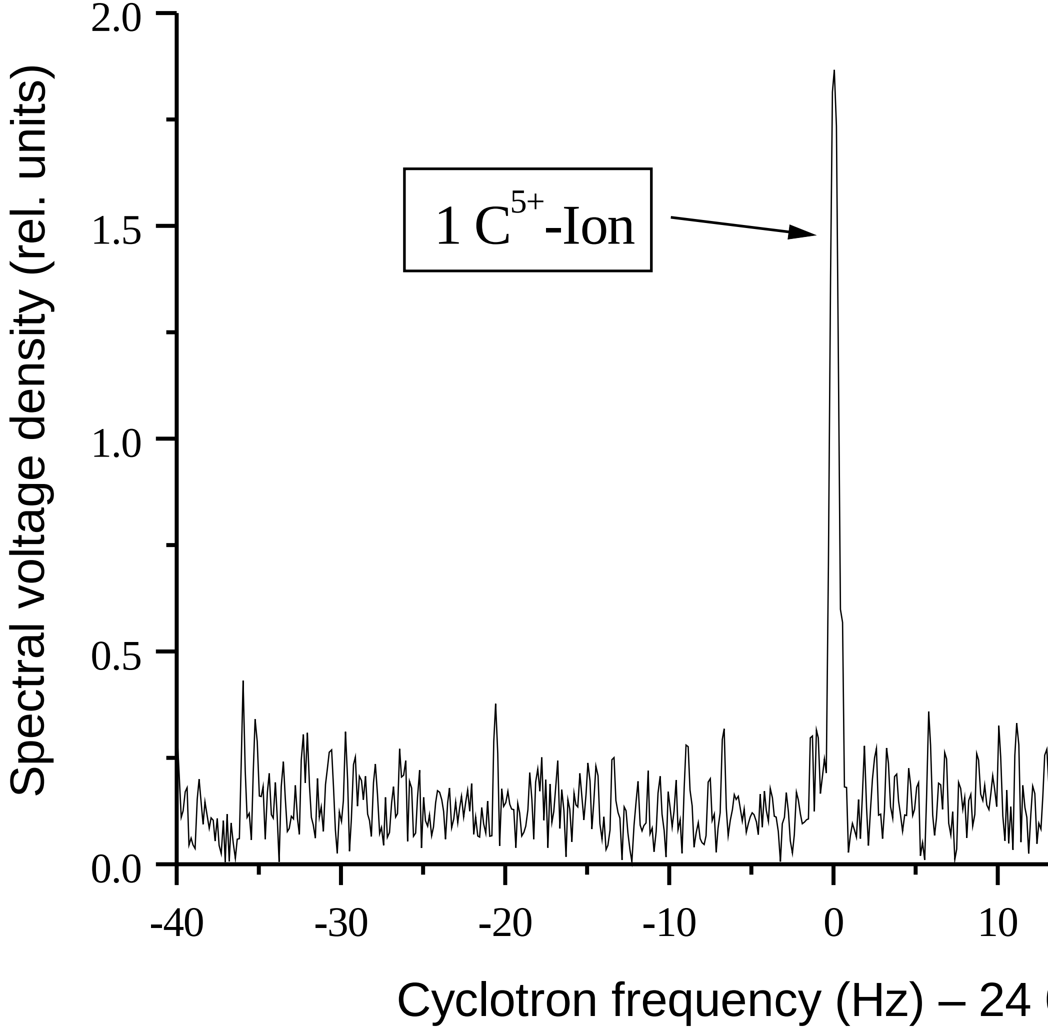
Ion-electronics

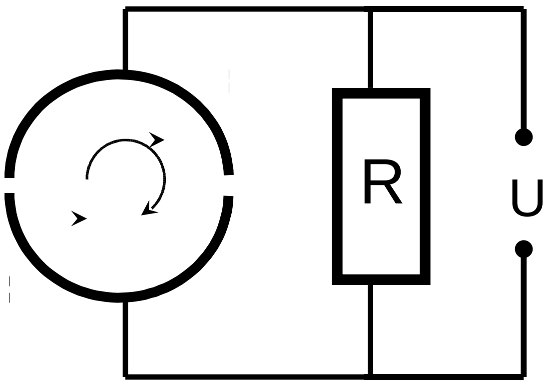


Ion-electronics

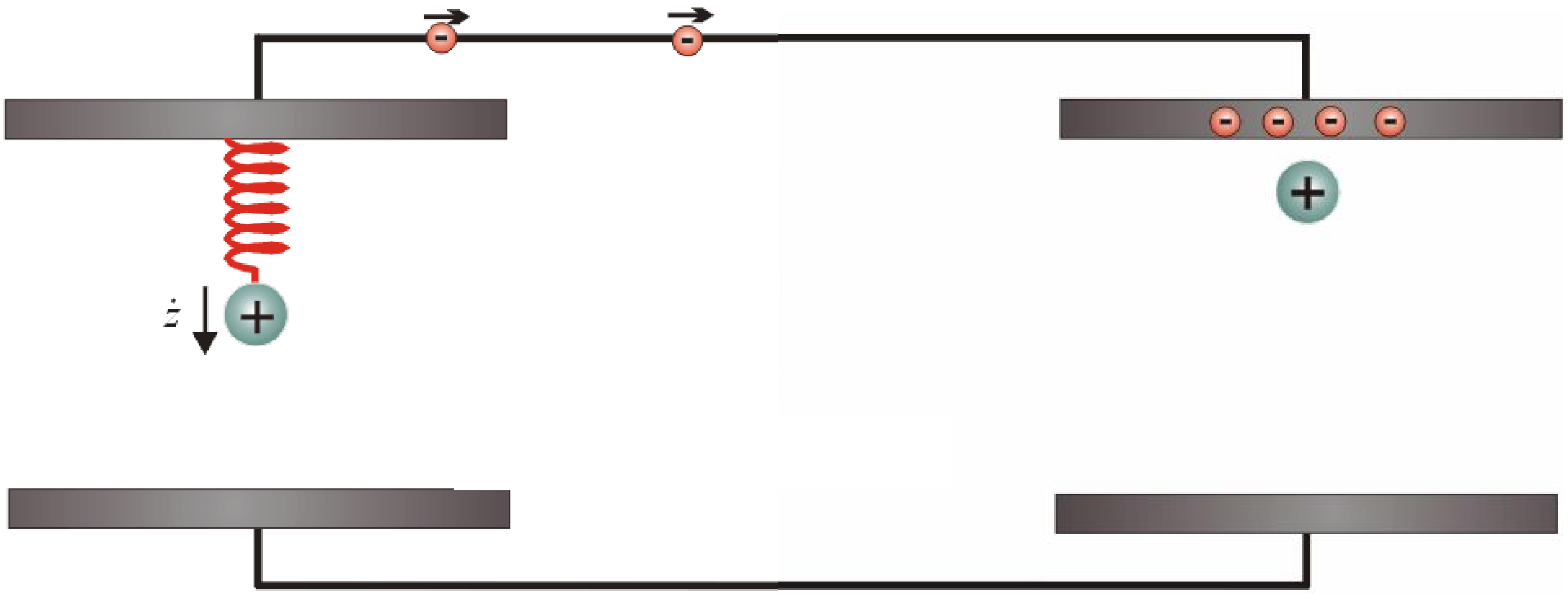


Ion-electronics

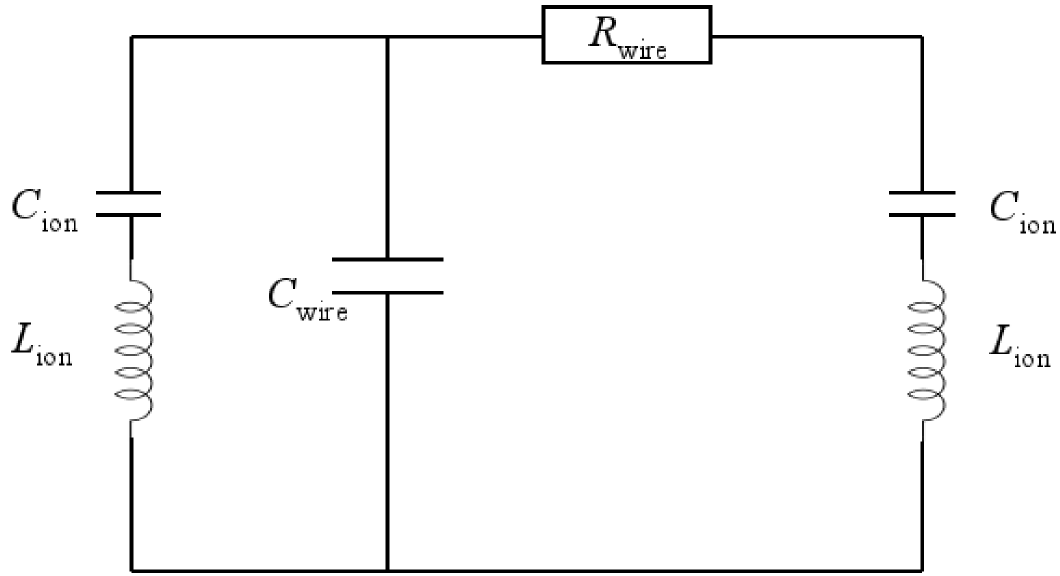




Wiring up ions



Ion-electronics



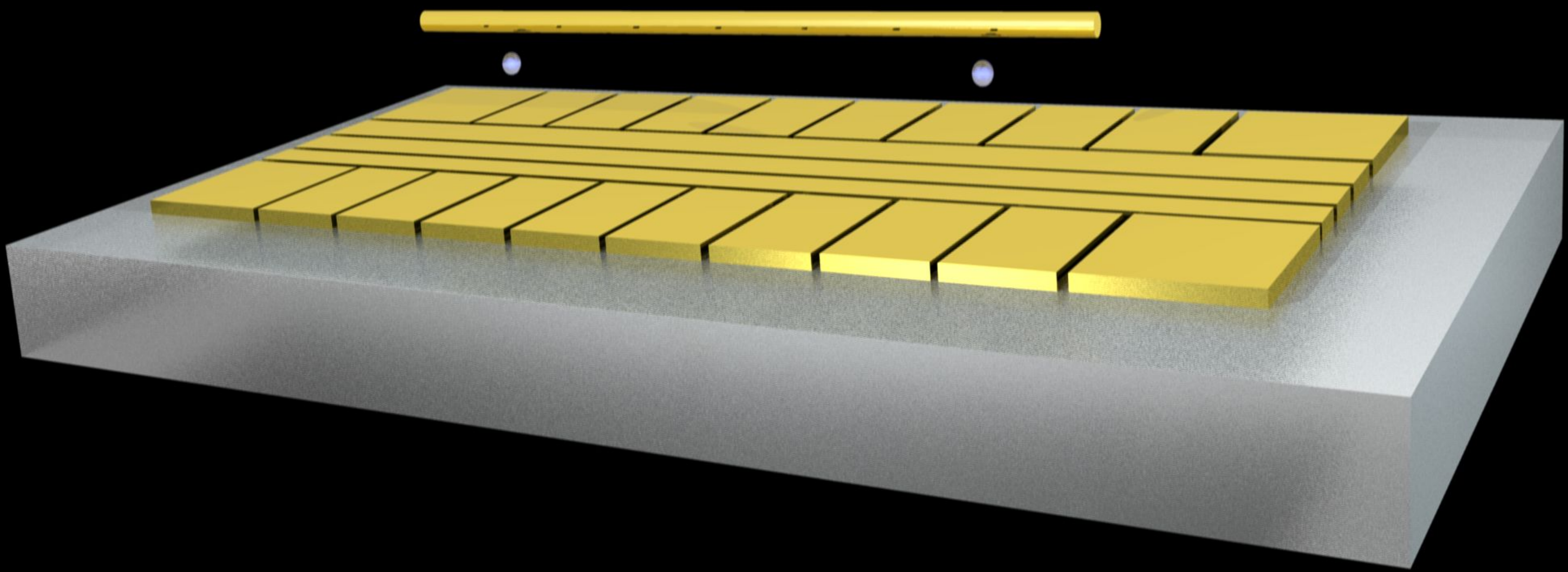
with $I = \frac{q}{D}\dot{x}\,,\quad L_{\text{ion}} = \frac{mD^2}{q^2},\quad C_{\text{ion}} = \frac{1}{\omega^2 L_{\text{ion}}}$

Energy exchange rate: $\boxed{\frac{1}{T} = \frac{1}{2\pi}\frac{q^2}{mD^2}\frac{1}{\omega}\frac{1}{C_{\text{wire}}}}$

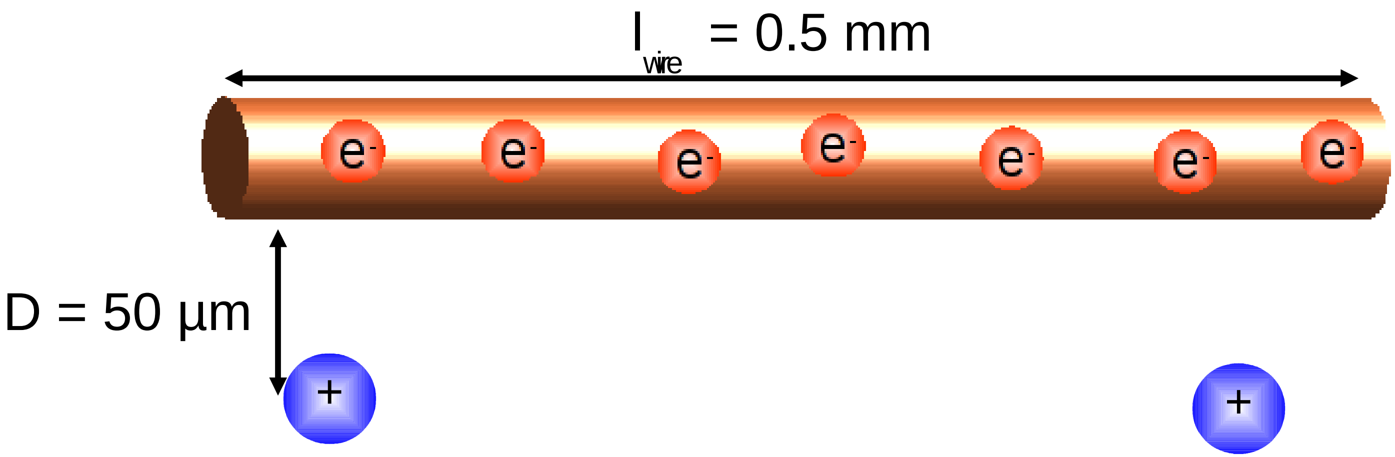
D.J. Wineland and H.G. Dehmelt, J. Appl. Phys **46**, 919 (1975).

D.J. Heinzen and D.J. Wineland, PRA **47**, 2977 (1990).

Experimental set-up



Some numbers



Projected numbers:

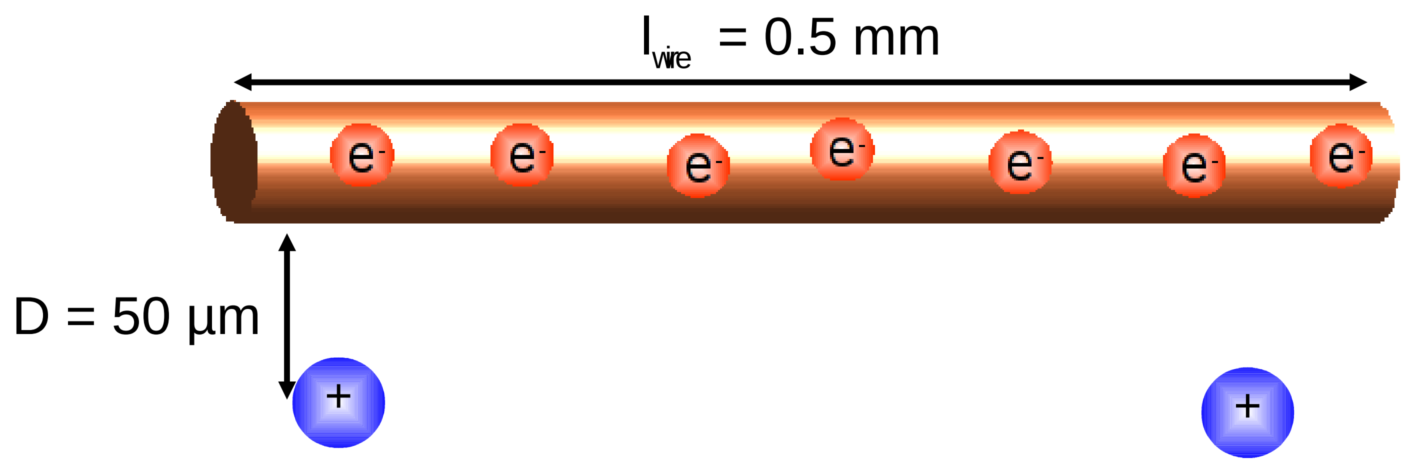
D_{eff} = 3.6 x 50 μm

$\omega = 2\pi$ x 500 kHz

C_{wire} = 6 fF (l_{wire} = 0.5mm)

$\gamma = 2\pi$ x 100 Hz

Some numbers



Current numbers:

D_{eff} = 3.6 x 300 μm

ω =2π x 500 kHz

C_{wire} = 120 fF (l_{wire} = 1cm)

γ would be 2π x 0.14 Hz

Projected numbers:

D_{eff} = 3.6 x 50 μm

ω =2π x 500 kHz

C_{wire} = 6 fF (l_{wire} = 0.5mm)

γ = 2π x 100 Hz

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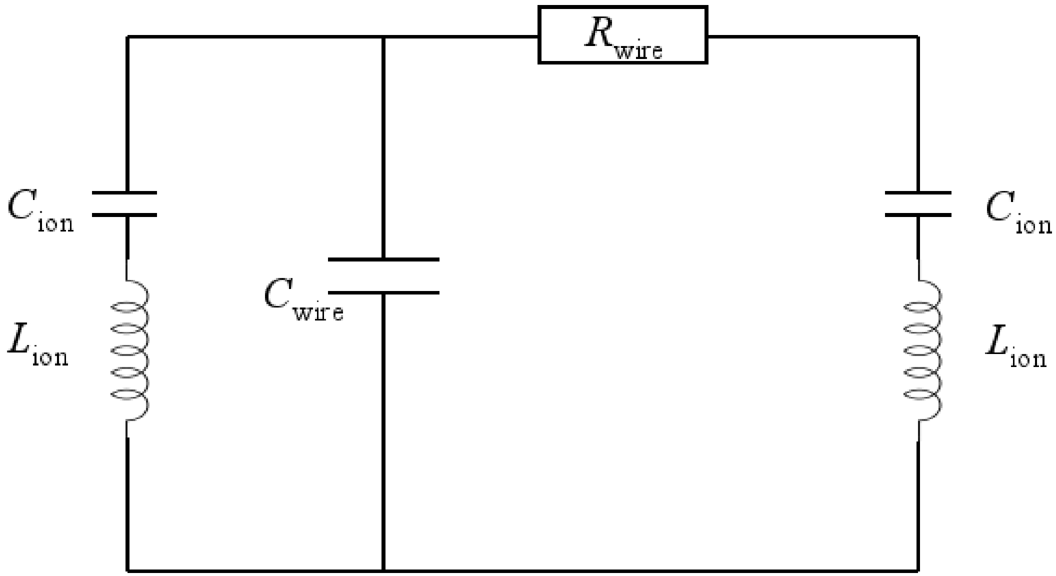
Coupling



with $I = \frac{q}{D}\dot{x}\,, \quad L_{\text{ion}} = \frac{mD^2}{q^2}, \quad C_{\text{ion}} = \frac{1}{\omega^2 L_{\text{ion}}}$

Energy exchange rate: $\frac{1}{T} = \frac{1}{2\pi}\frac{q^2}{mD^2}\frac{1}{\omega}\frac{1}{C_{\text{wire}}}$

D.J. Wineland and H.G. Dehmelt, J. Appl. Phys **46**, 919 (1975).

D.J. Heinzen and D.J. Wineland, PRA **47**, 2977 (1990).

Decoherence sources

Dissipation in the wire

Trap parameters: $\omega = 2\pi \cdot 500$ kHz, $D = 3.6 \cdot 50\ \mu m$, $R = 0.1\ \Omega$

Induced current: $$I = \frac{q}{D}\dot{x} = \frac{q}{D}\sqrt{\frac{\hbar\omega}{m}} \approx 10^{-16}\ A$$

Dissipation rate for motional quantum: $$\gamma = \frac{I^2 R}{\hbar\omega} \approx 10^{-6}\ \frac{1}{s}$$

But what about Johnson noise?

Decoherence sources

Dissipation in the wire

Trap parameters: $\omega = 2\pi \cdot 500$ *kHz, D=3.6 ·50 µm, R=0.1 Ω*

Induced current: $I = \frac{q}{D}\dot{x} = \frac{q}{D}\sqrt{\frac{\hbar\omega}{m}} \approx 10^{-16}\, A$

Dissipation rate for motional quantum: $\gamma = \frac{I^2 R}{\hbar\omega} \approx 10^{-6}\frac{1}{s}$

Johnson noise heating

Heating rate : $\gamma_J = \frac{P_J}{\hbar\omega} = \frac{k_B T\gamma}{\hbar\omega} \approx 14\frac{1}{s}$

Expected coupling over 0.5 mm: $\gamma_c > 2\pi \times 100$ 1/s

Decoherence sources

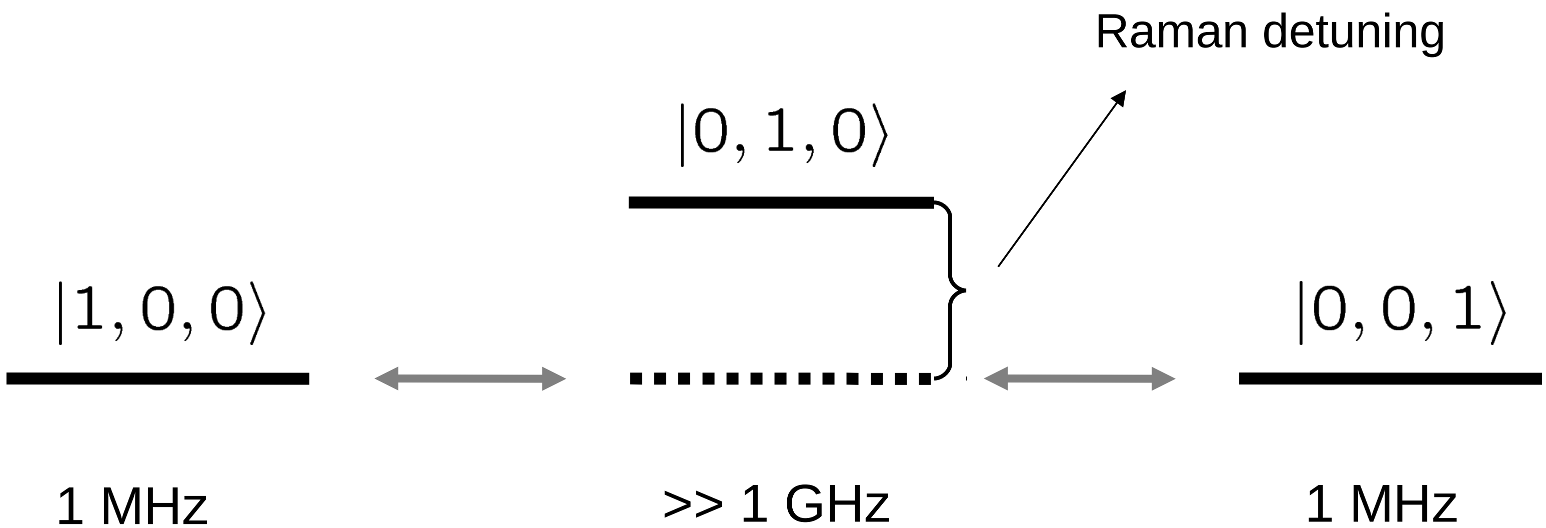
Three coupled harmonic oscillators:

$$|1,0,0\rangle \longleftrightarrow |0,1,0\rangle \longleftrightarrow |0,0,1\rangle$$

$$|\mathrm{ion}_1, \mathrm{wire}, \mathrm{ion}_2\rangle$$

Decoherence sources

Three coupled harmonic oscillators:

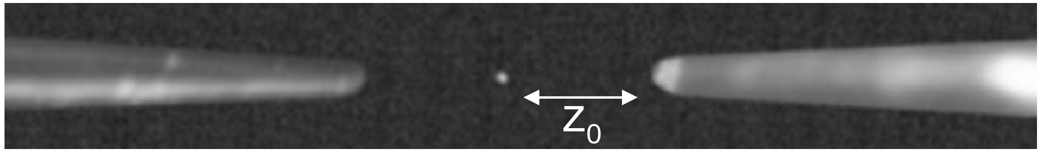


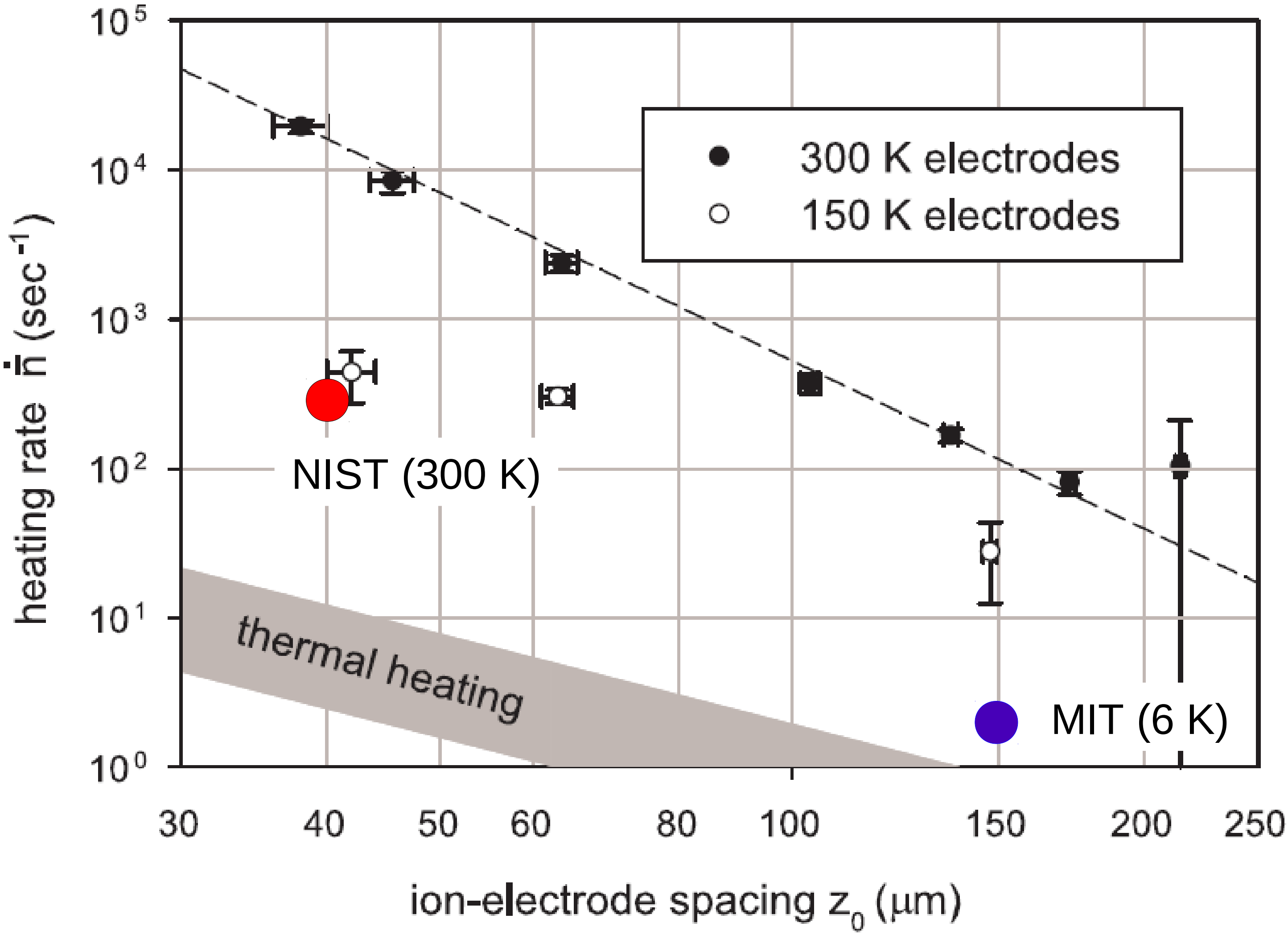
$$|\mathrm{ion}_1, \mathrm{wire}, \mathrm{ion}_2\rangle$$

Decoherence sources

Anything else ?

Anomalous heating





From: L. Deslauriers et al.,PRL 97, 103007 (2006).

Projected numbers

- Trap size: ~ 50 μm, trap distance 500 μm
- Induced current: ~10^{-16} A
- Coupling time: ~10 ms
- Wire resistivity: 1 Ω

=> Time scales for decoherence:

Dissipation of the induced current in the wire	10^5 s
Johnson noise heating at 300 K	100 ms
Anomalous heating at 300 K	???

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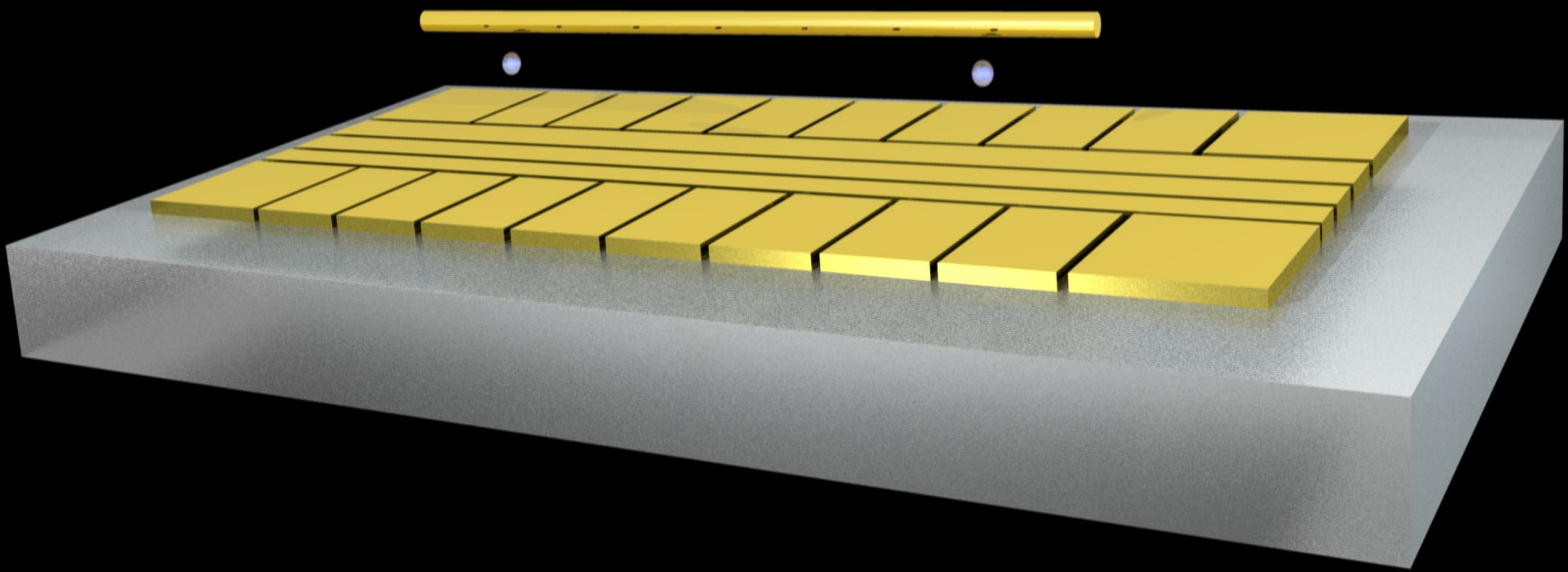
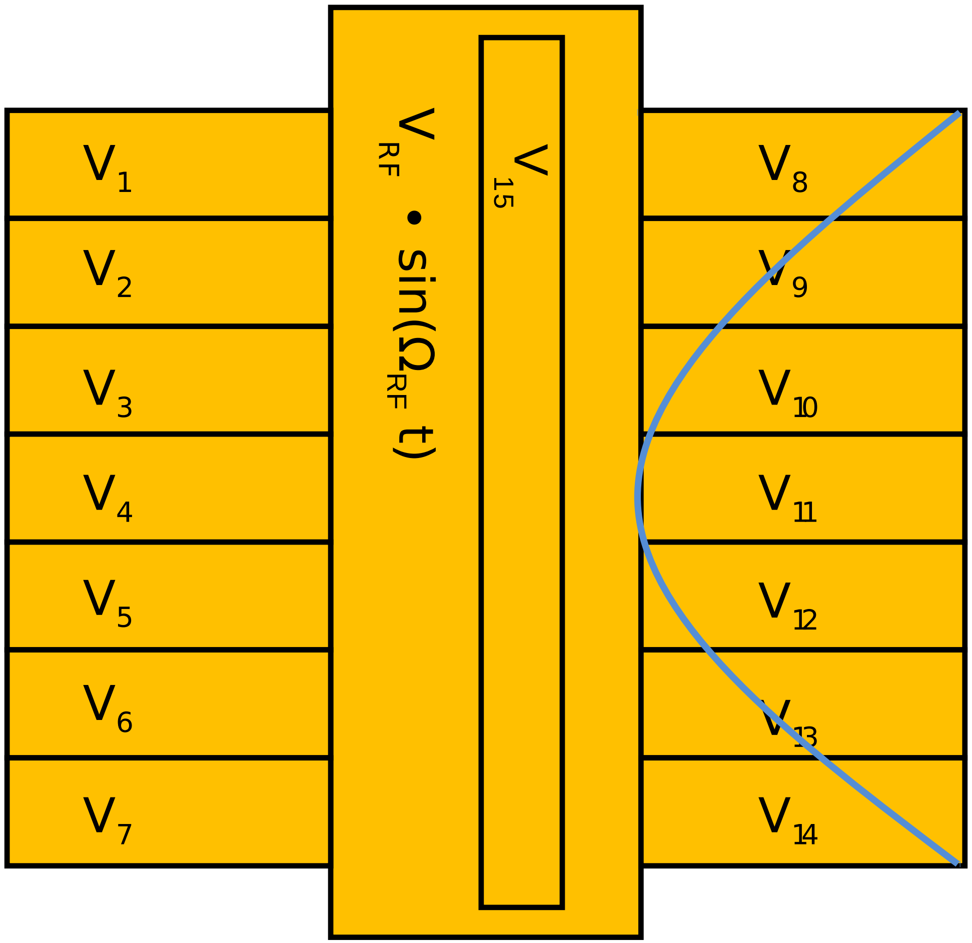
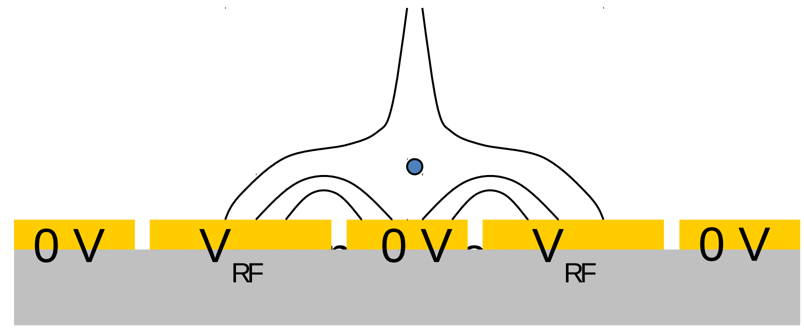
Experimental set-up



Experimental set-up





Ion height $\approx 220\ \mu m$

$\Omega_{RF} \approx 2\pi \cdot 15$ MHz

$V_{RF} \approx 100$ V

$V_{DC} < 10$ V

$\omega_H \approx 2\pi \cdot 1.3$ MHz

$\omega_V \approx 2\pi \cdot 1.5$ MHz

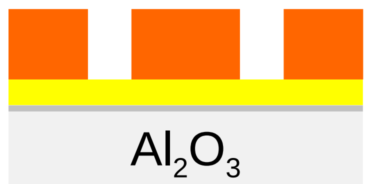
$\omega_A \approx 2\pi \cdot 300$ kHz

Trap fabrication

1. Evaporation

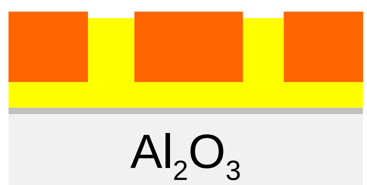
i. 5 nm Ti adhesion layer
ii. 100 nm Au seed layer

2. Lithography



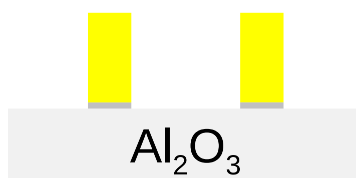
5 μm thick photoresist

3. Electroplating



4-5 μm thick Au plated layer

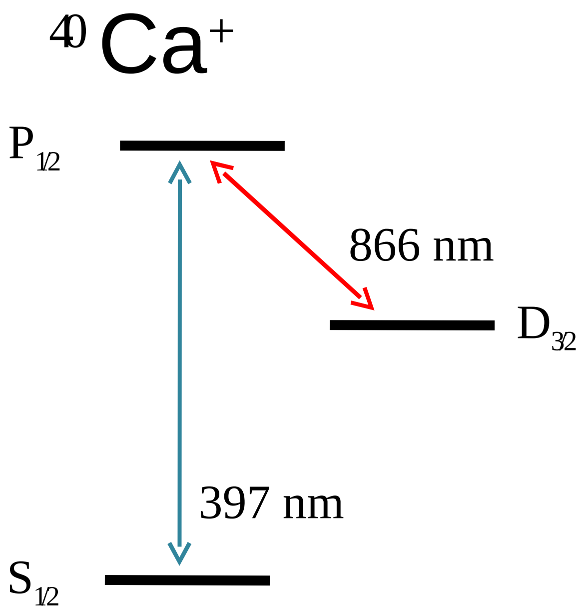
4. Cleaning/Etching



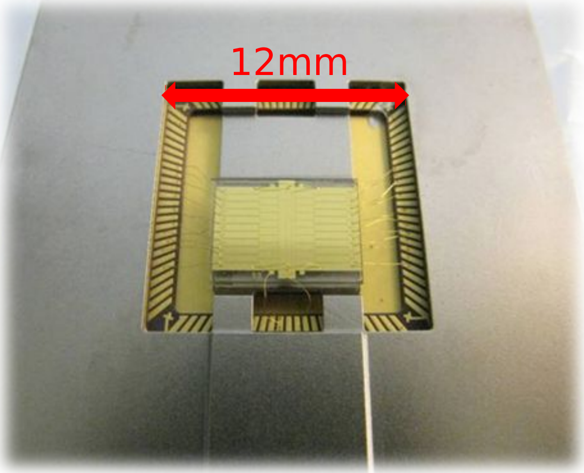
i. Resist removal
ii. Au etch
iii. Ti etch

N. Daniilidis *et.al.* in preparation,
Collaboration with A. Wallraff, ETH, Zürich

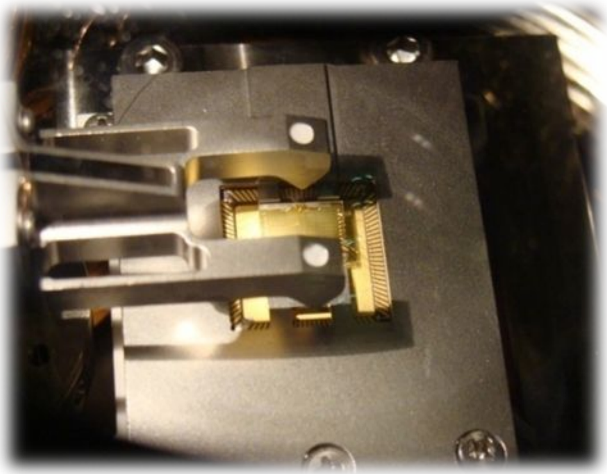
Experimental set-up



Laser cooling and detection:
397nm and 866nm laser

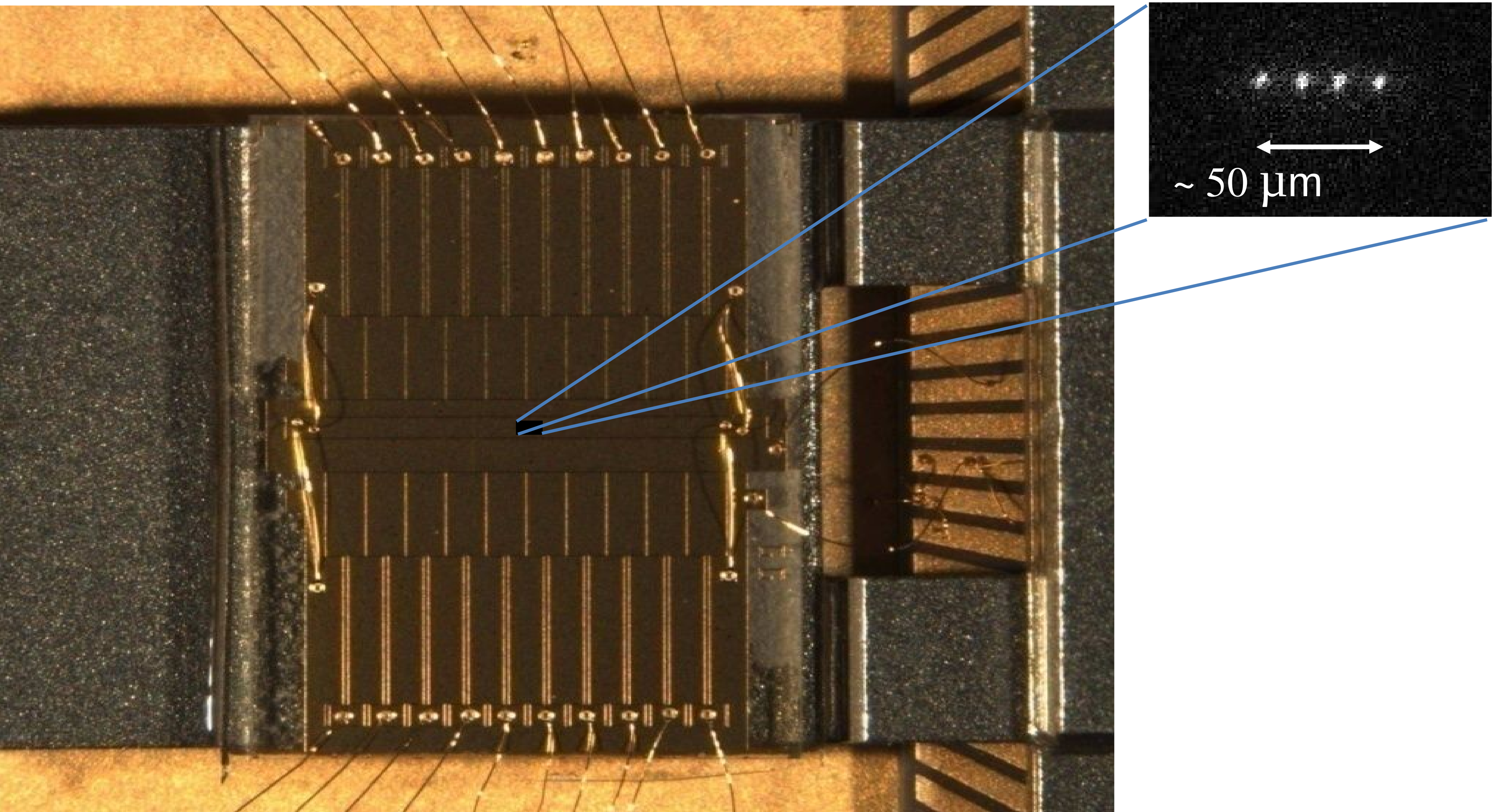


Gold on sapphire microfabricated trap

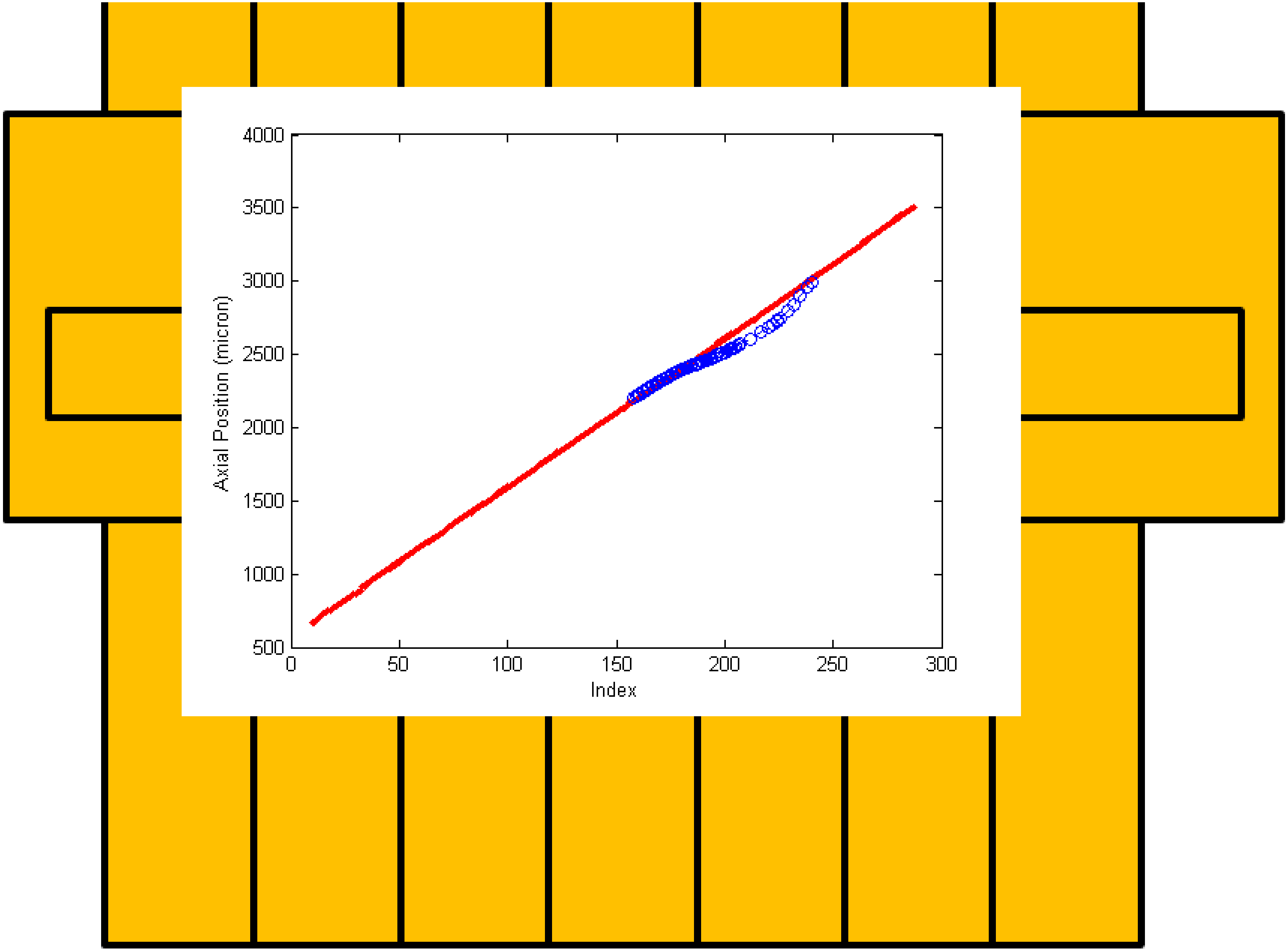


Wire on translation stage

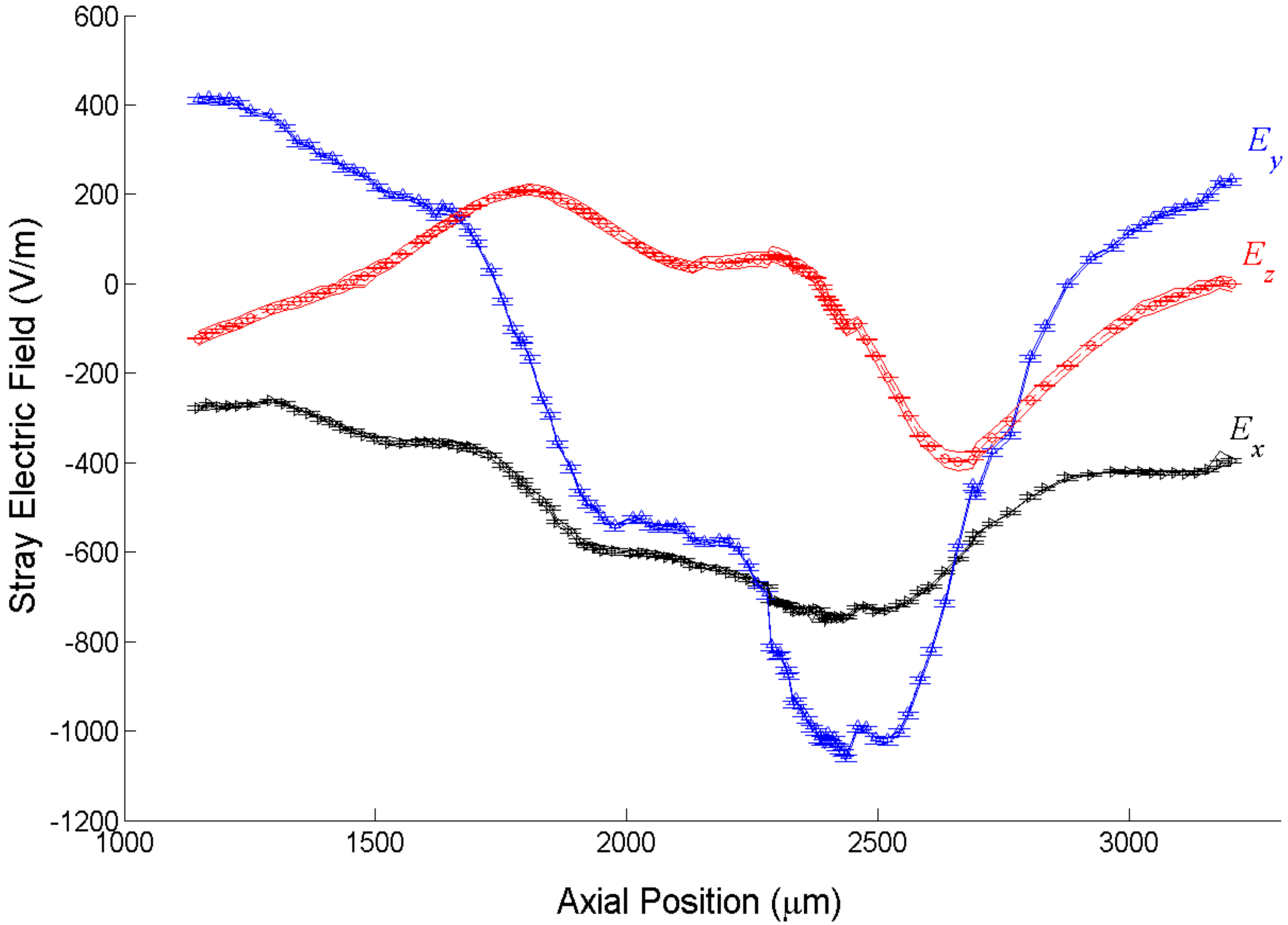
Experimental set-up



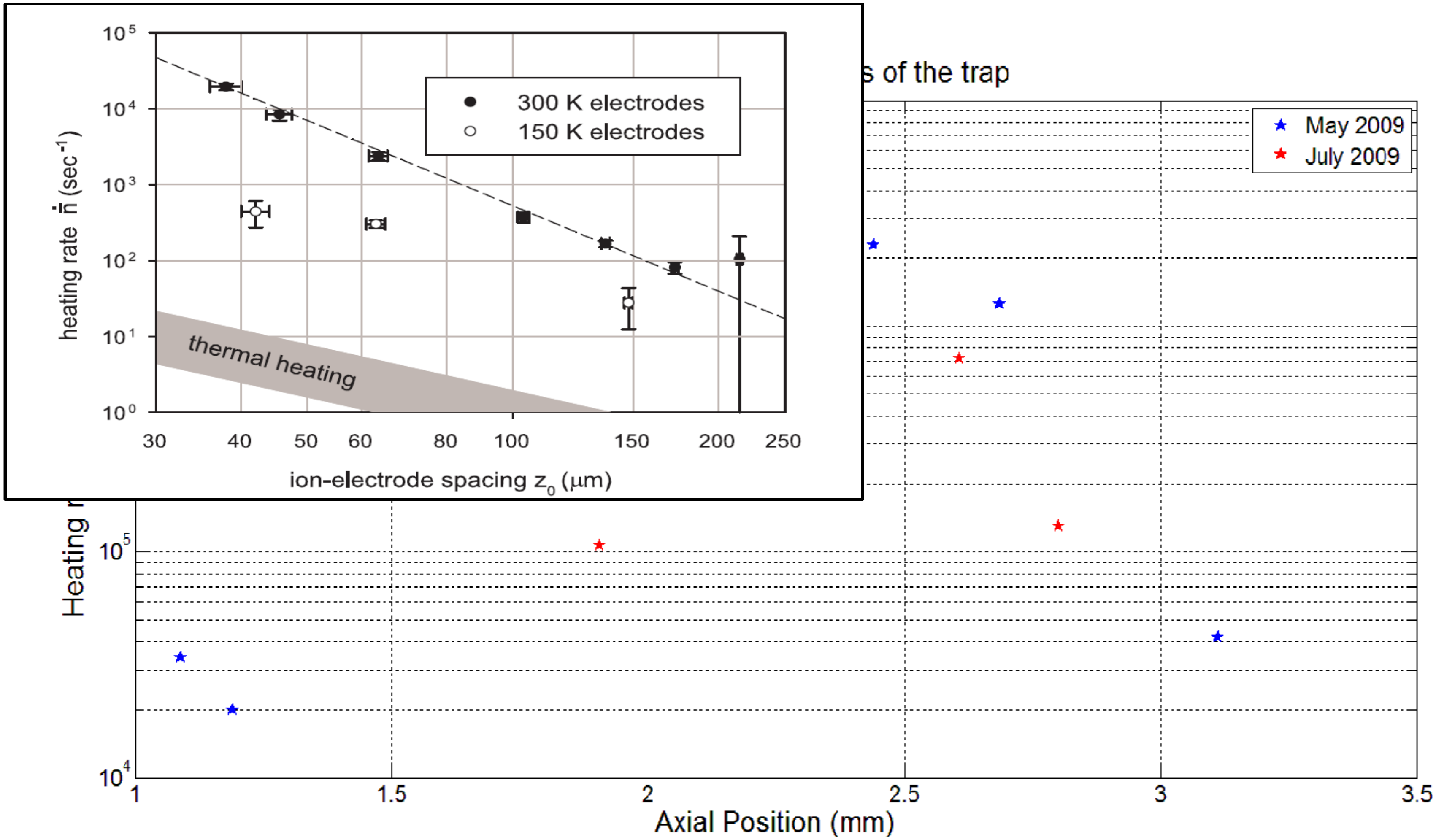
Ion transport



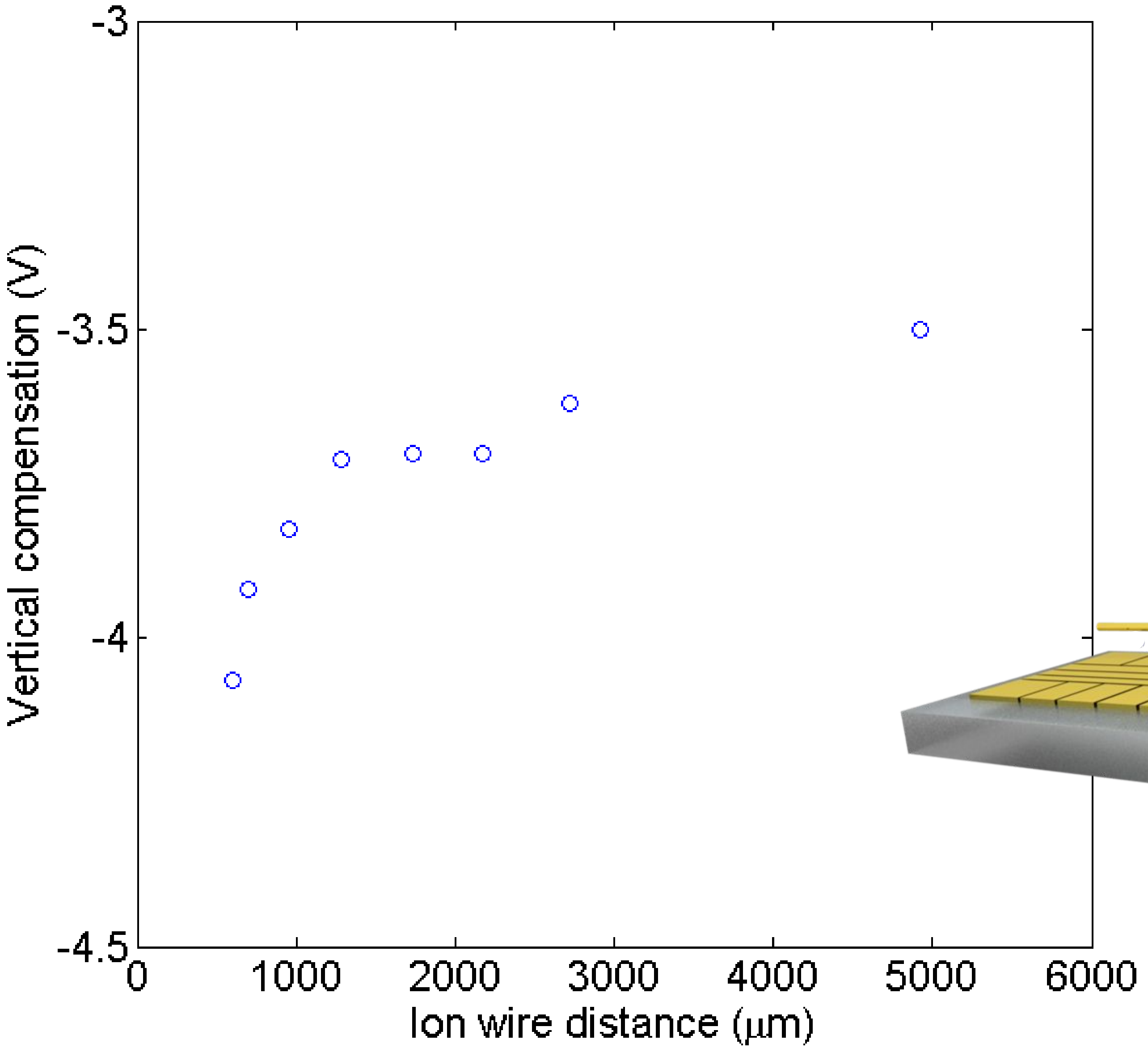
Derived electric stay fields

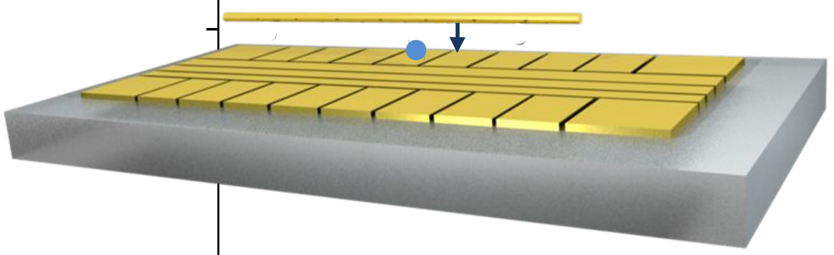


Heating of the ion motion

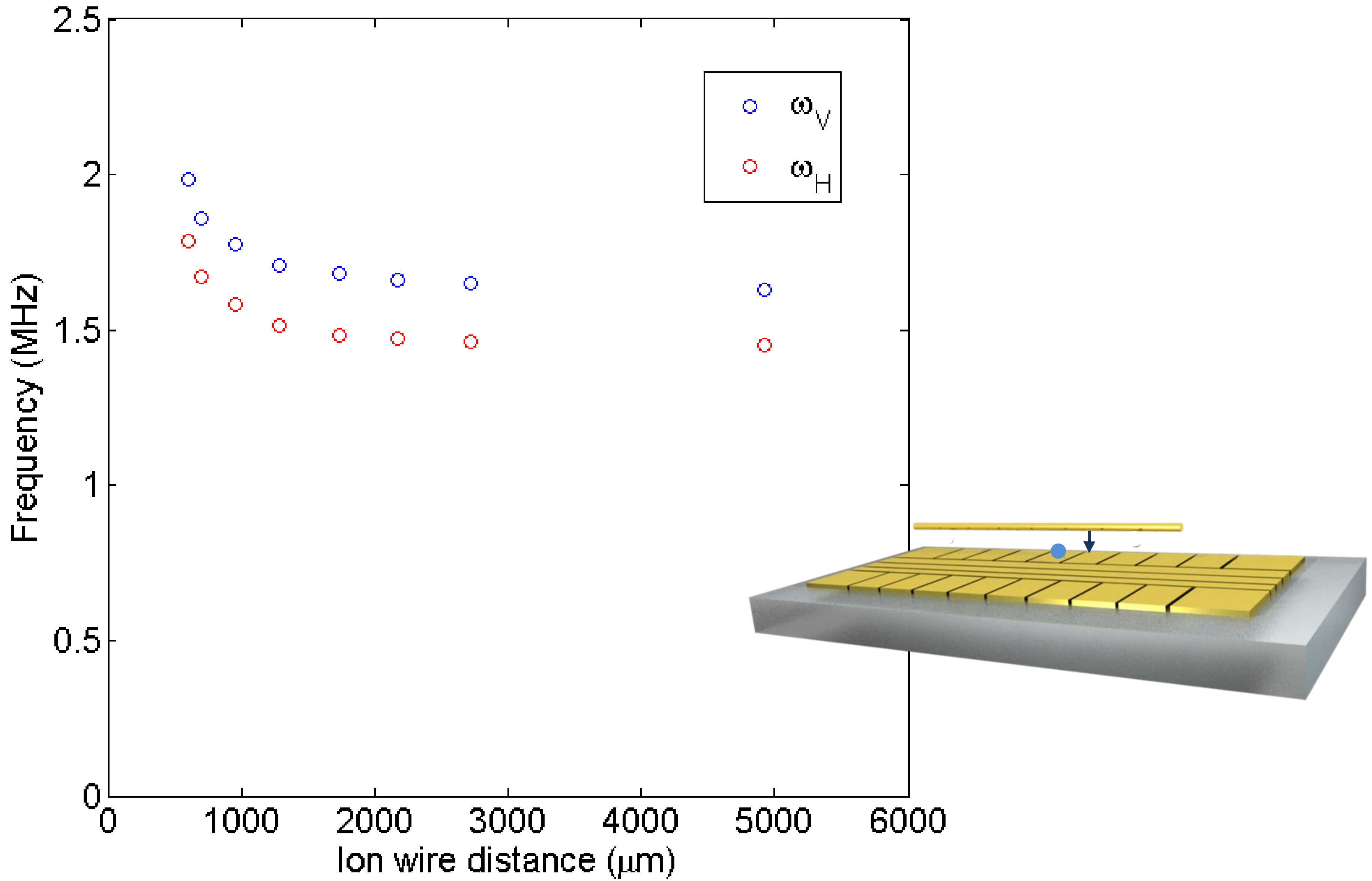


Moving the wire closer

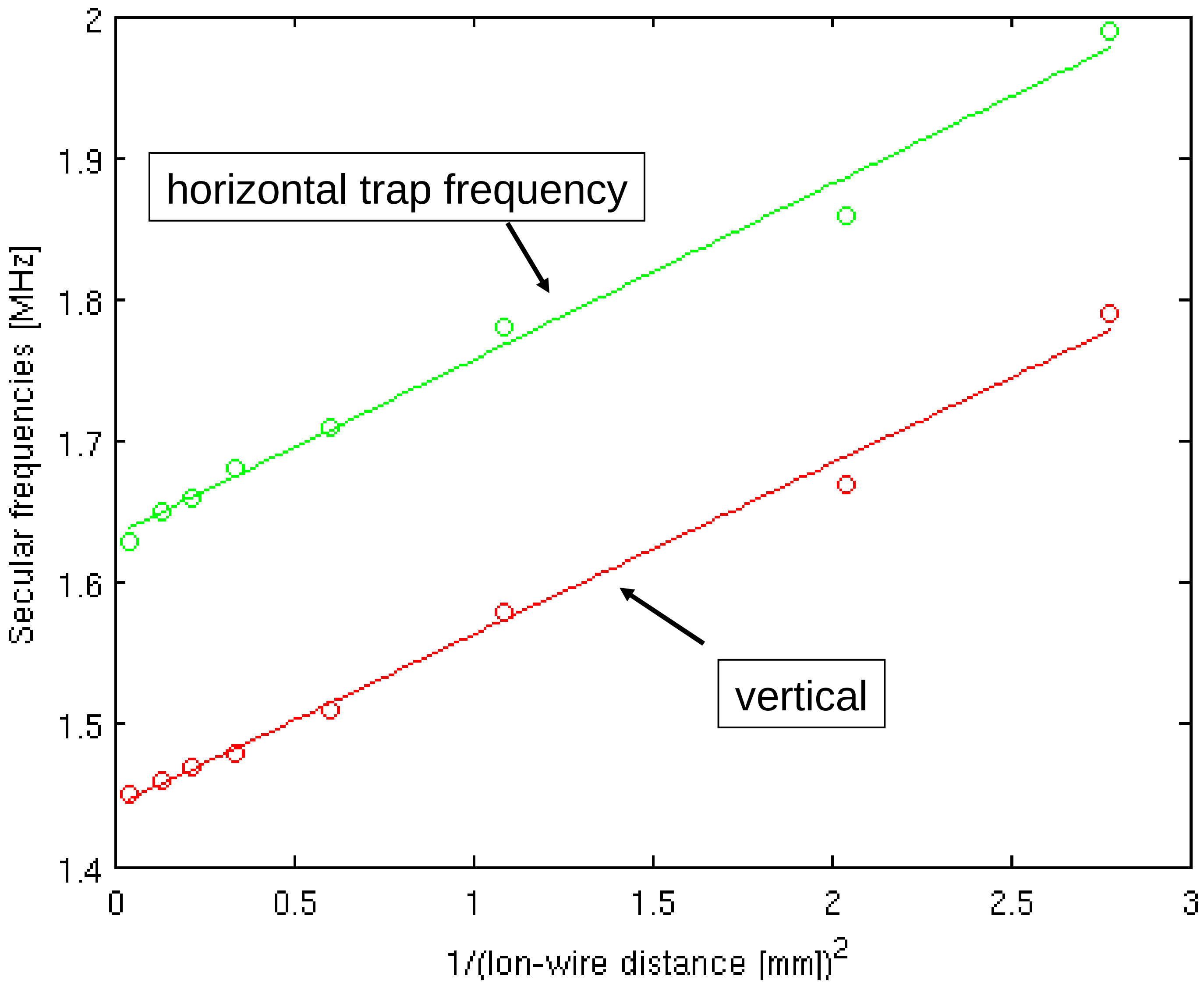




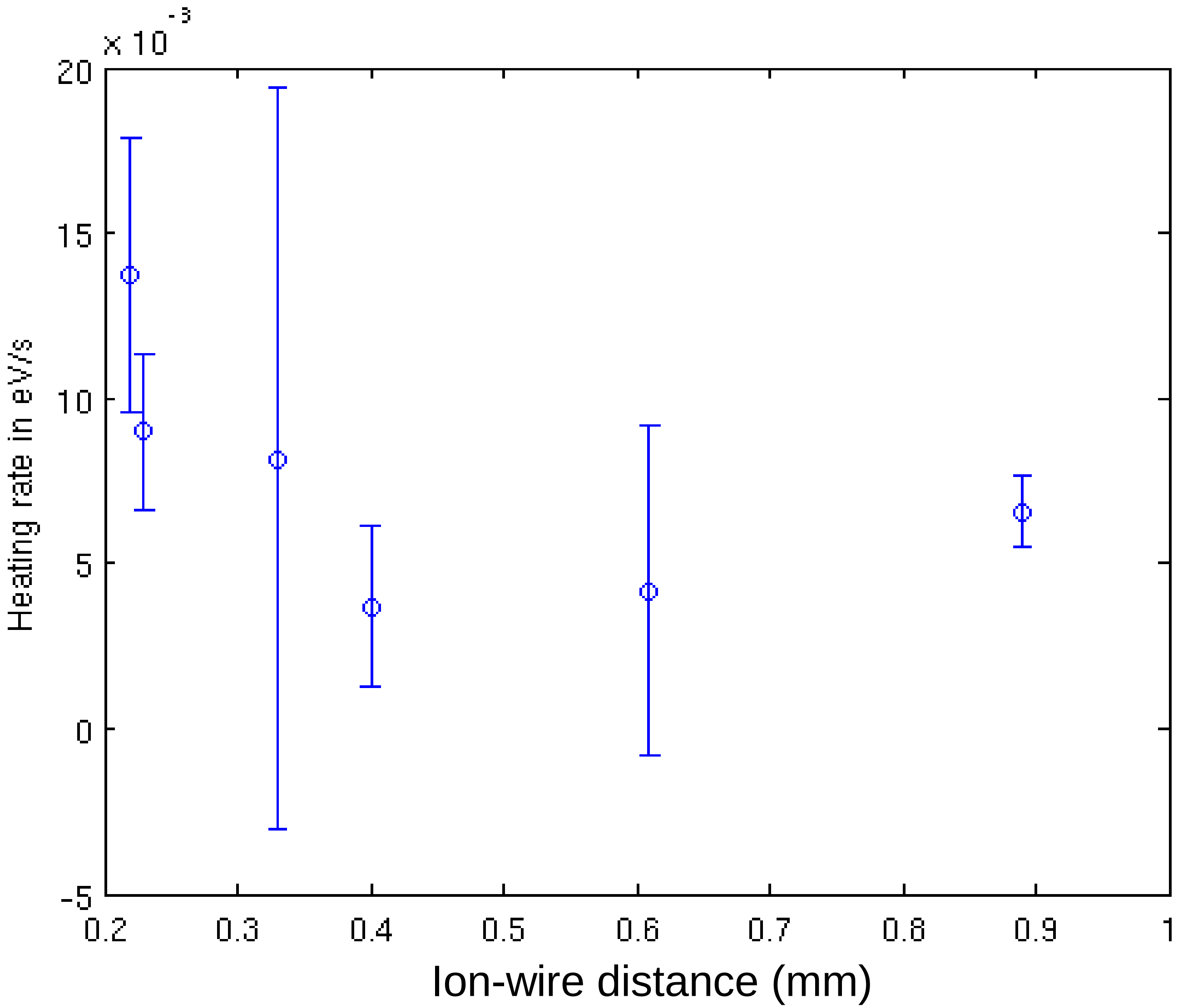
Moving the wire in



Moving the wire in



Moving the wire in



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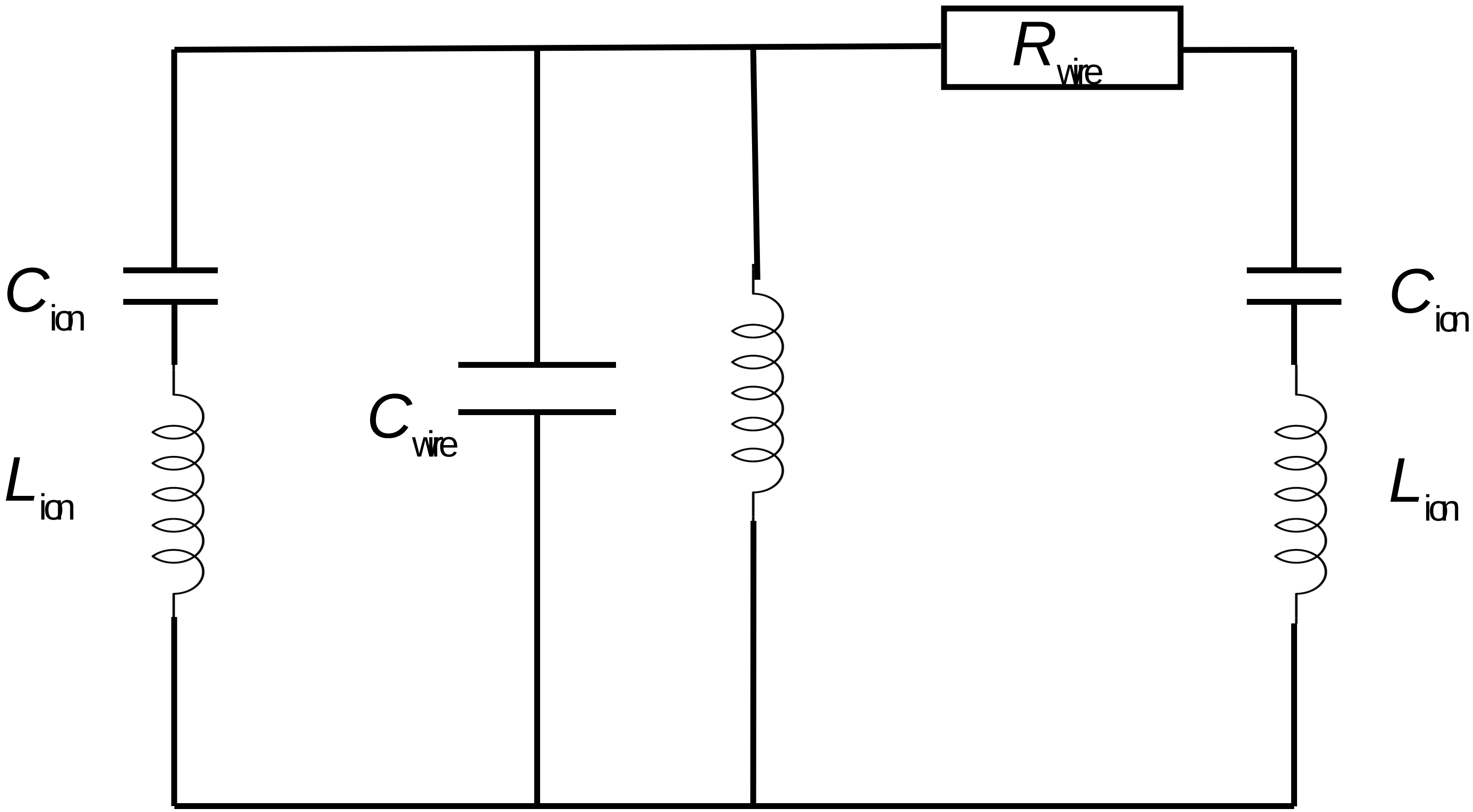
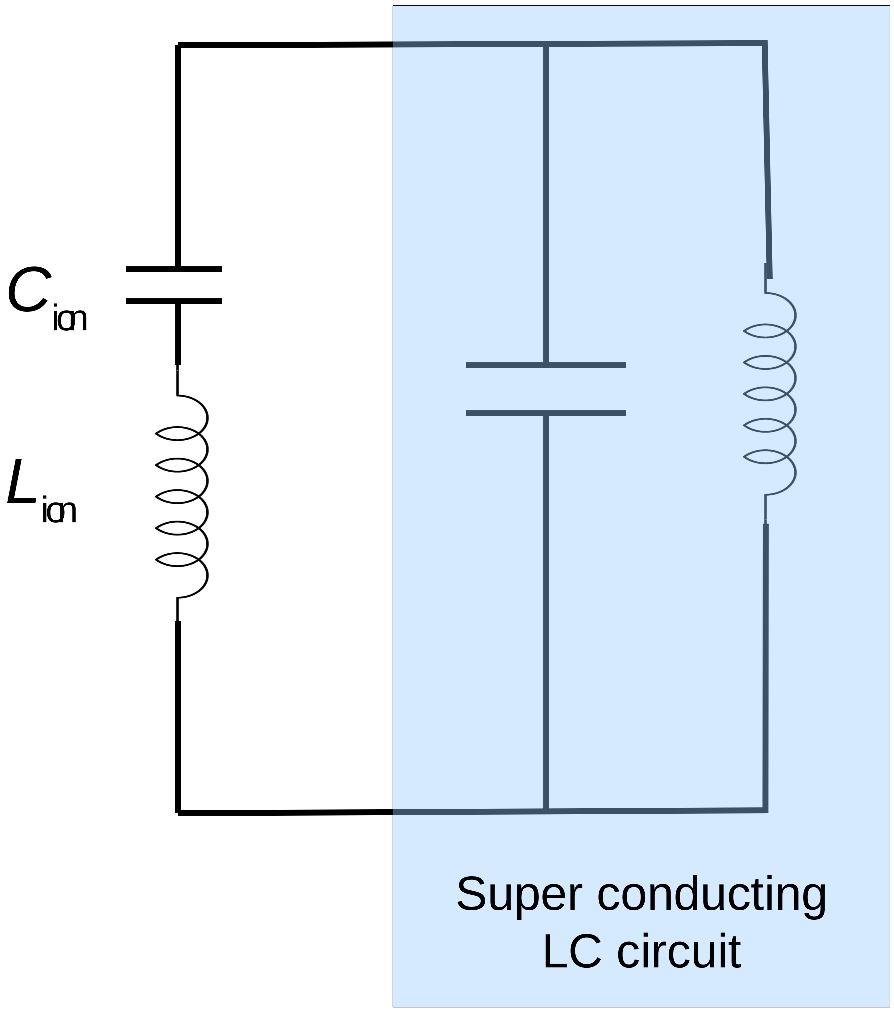
Enhancing the coupling



Laser cooling a resonator mode



$$T_r = \frac{\gamma_{\text{res}}}{\gamma_{\text{coupling}}\left(1 + \frac{\gamma_{\text{res}}}{\gamma_{\text{coupling}}}\right)} T$$

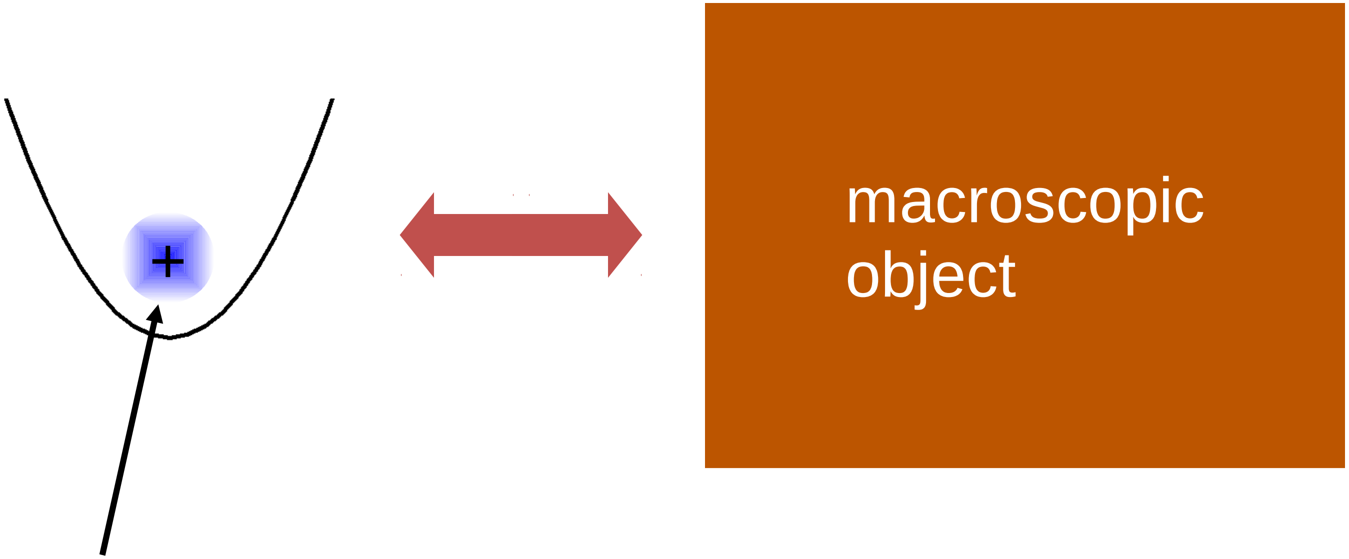
Example:

γ_{res} = 2π 10 1/s
(Q= 10 000, ω = 2π 100 kHz)

$\gamma_{coupling}$ = 2π 1000 1/s

=> temperature reduction by two orders of magnitude

Quantum sensors



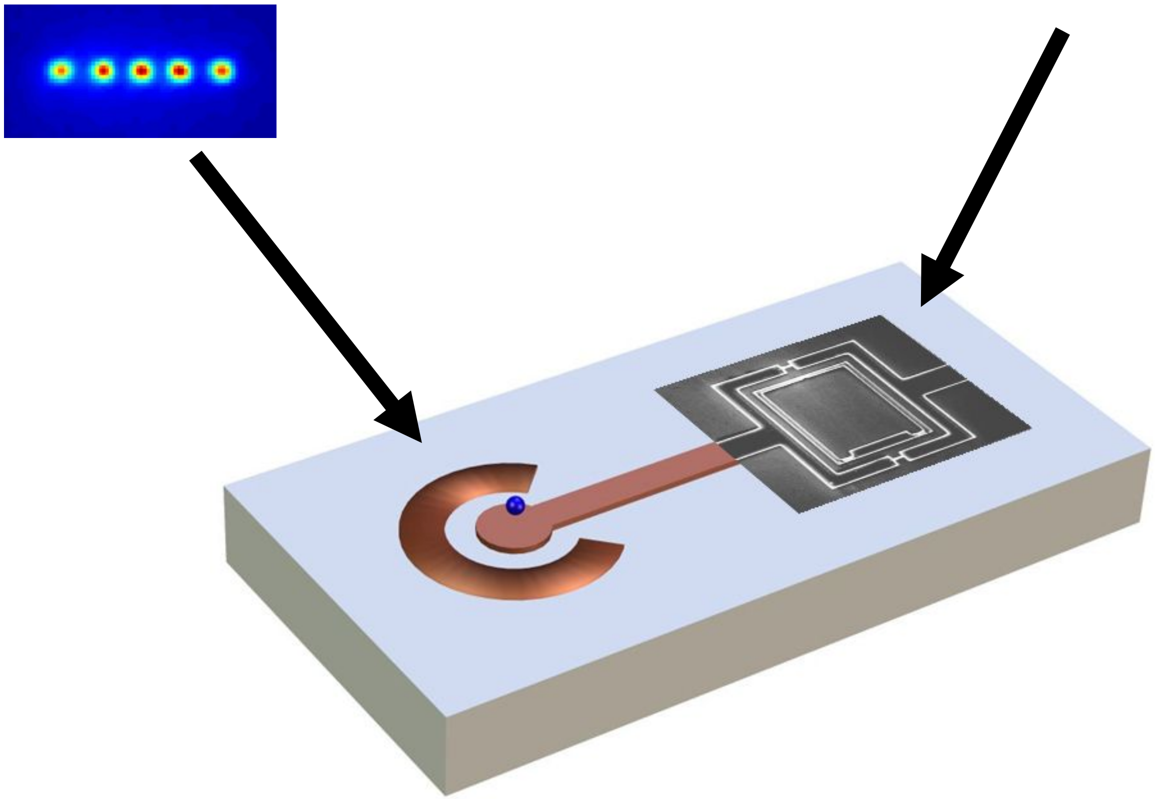
Quantum sensor

Ultimate control and detection

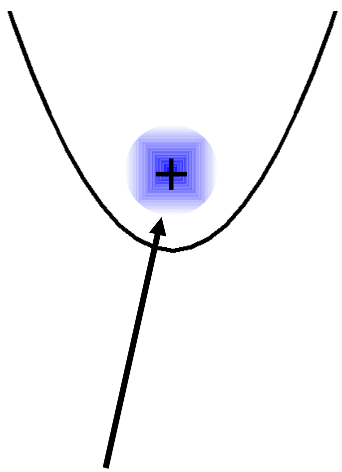
Hybrid devices

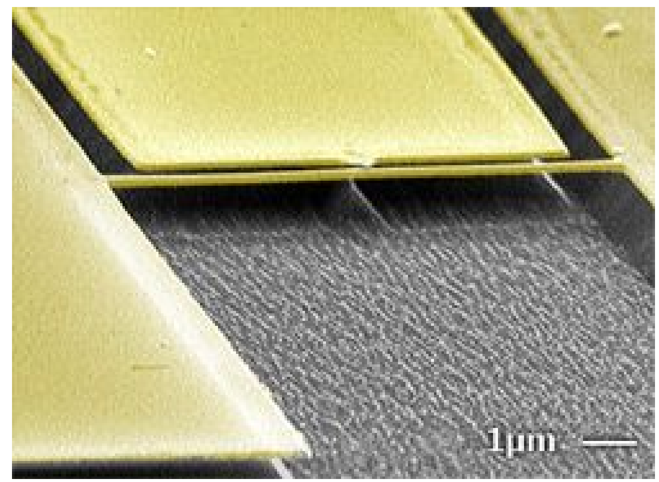
Trapped ions

Josephson qubits



Quantum sensors





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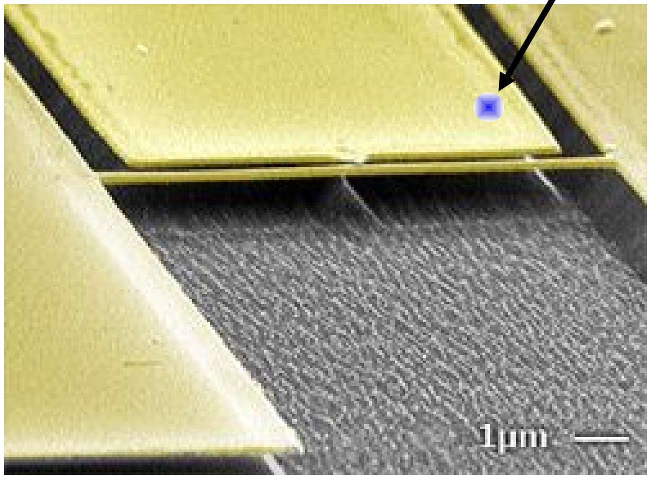
Quantum sensor

Ultimate control and detection

Quantum sensors

Ion?



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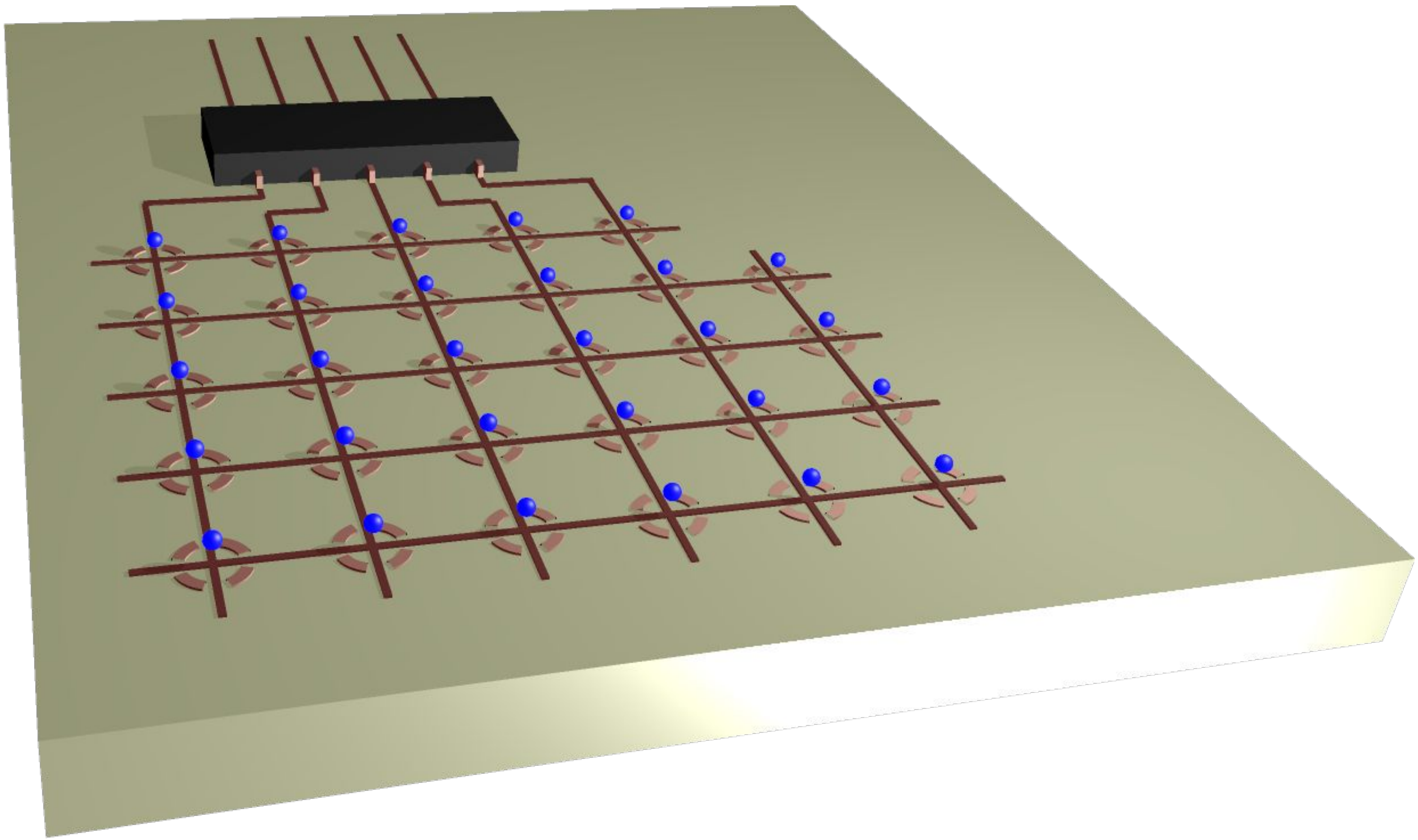
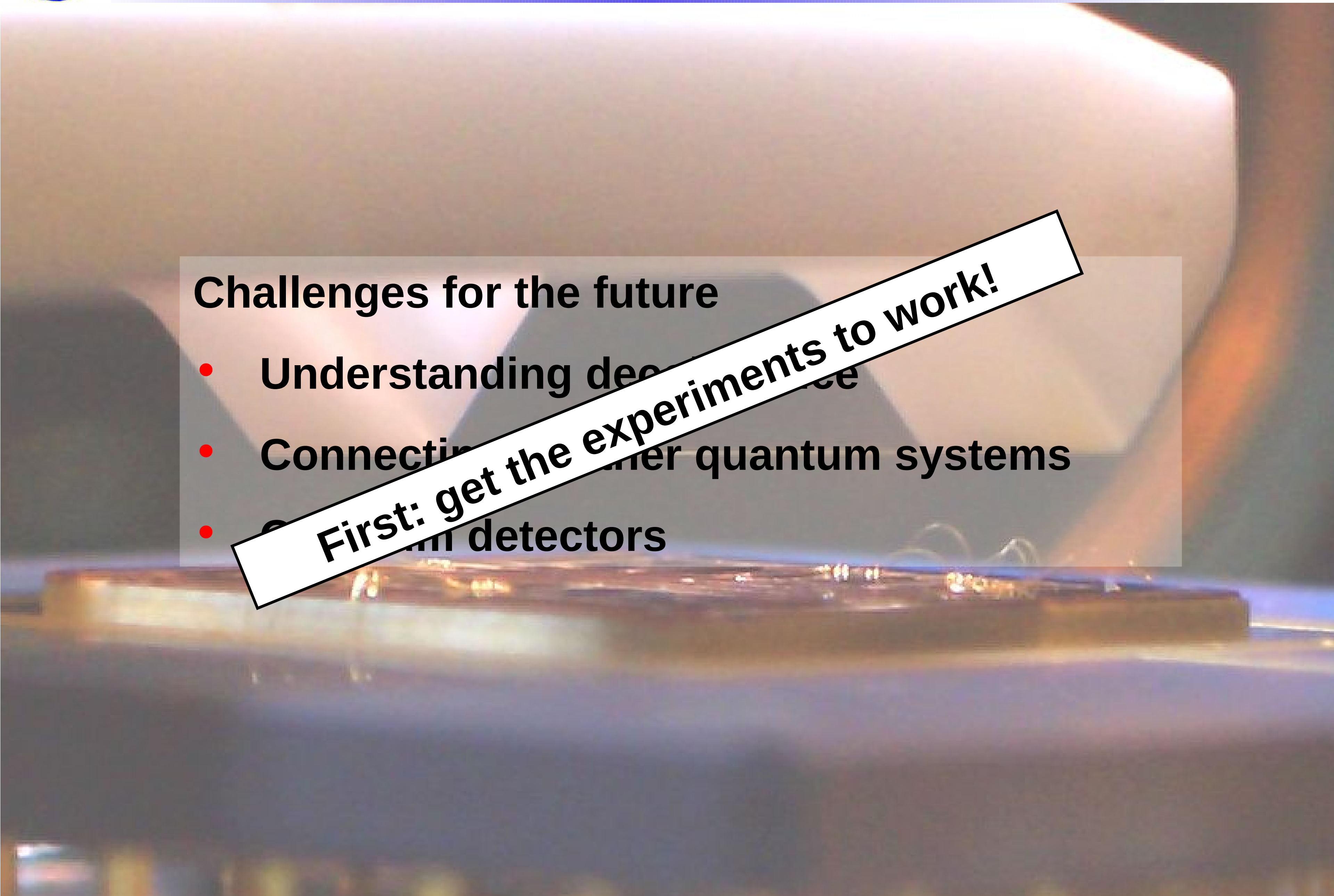
See: L. Tian, P. Zoller, PRL 9**3**, 266403 (2004).
W. K. Hensinger, PRA **72**, 041405R (2005).

A vision



Summary

- Quantum electronics
- Status of the experiments
- Laser cooling of an LC resonator



Challenges for the future

- Understanding decoherence
- Connecting to other quantum systems
- Quantum detectors

First: get the experiments to work!