Trapped ions meet solid state physics

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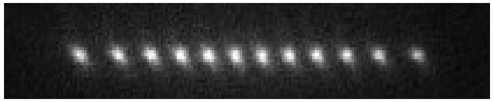
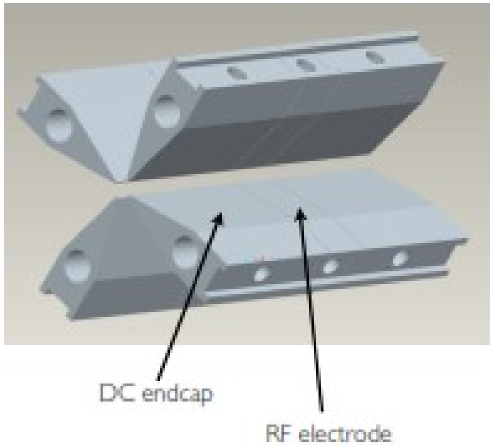
- Introduction
- Quantum emulation
- Shuttling charged particles in 3D
- Comments on anomalous heating
- Conclusions

Madrid, Apr 27th 2011

Trapped ions and condensted matter

Trapped ions

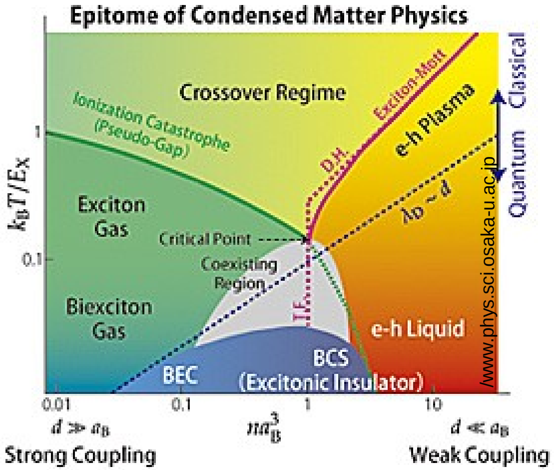




Simulation

Better traps

Condensed matter



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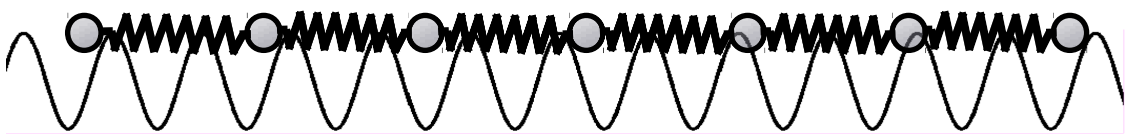
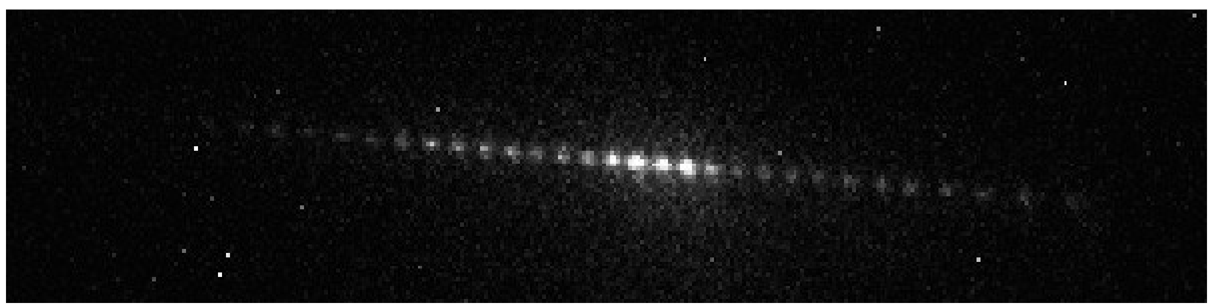
Quantum emulation

General idea: ions in microtraps to emulate quantum many-body physics





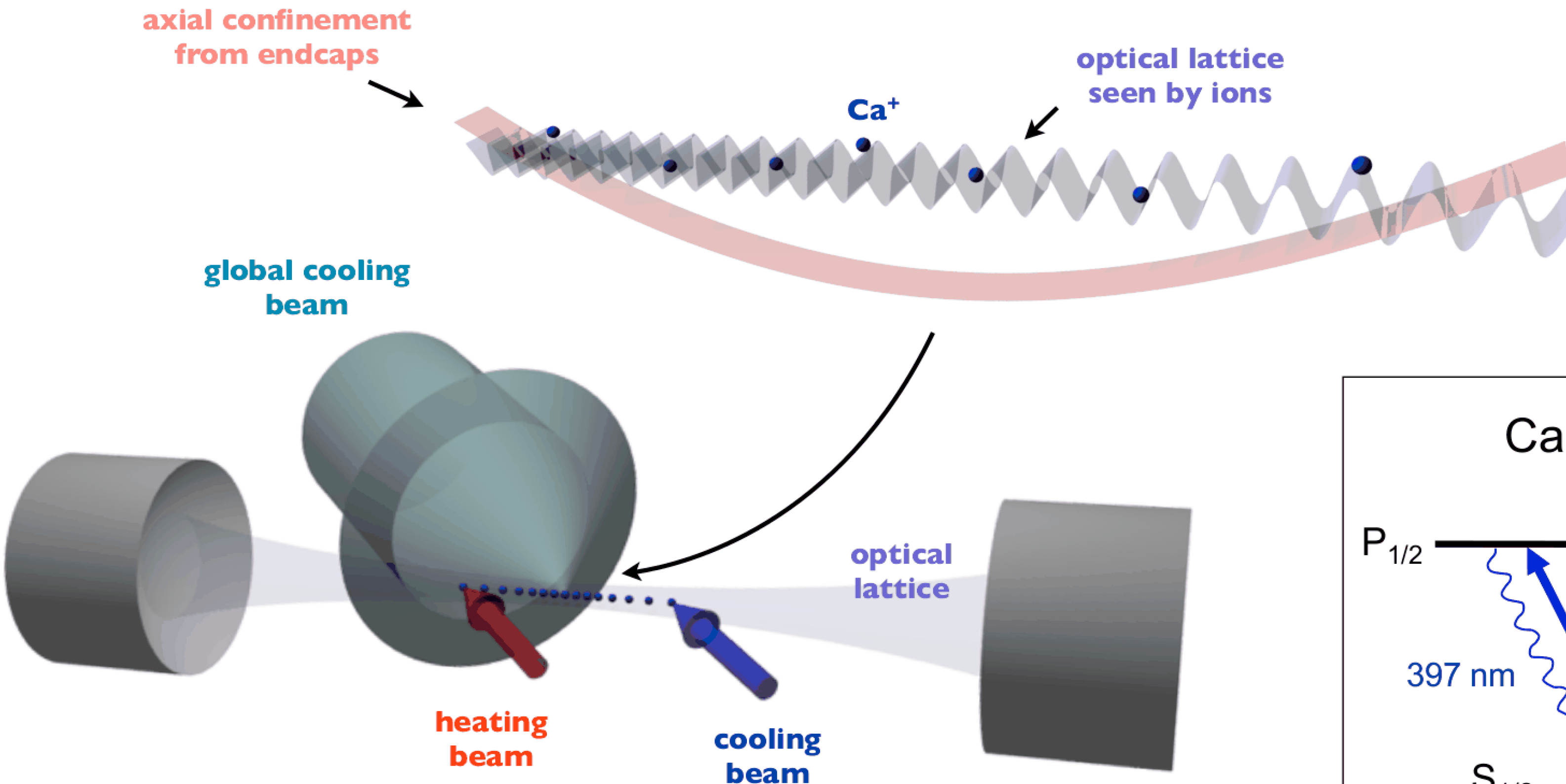
Questions:

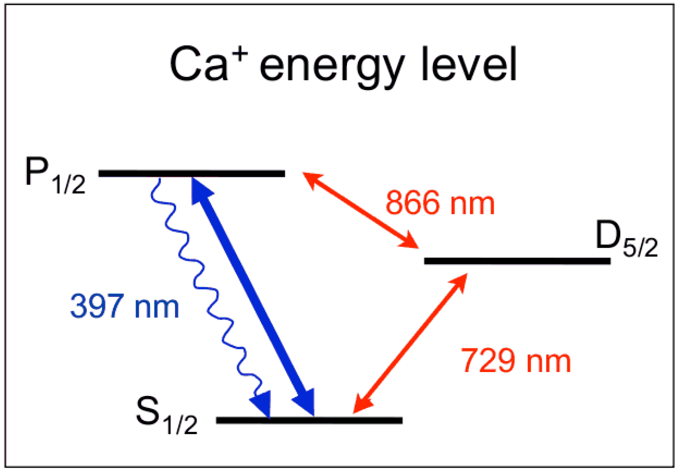
- how does energy flow?

- thermal equilibrium?

- can we trap an excitation by minimal reconfiguration?

Experimental set-up



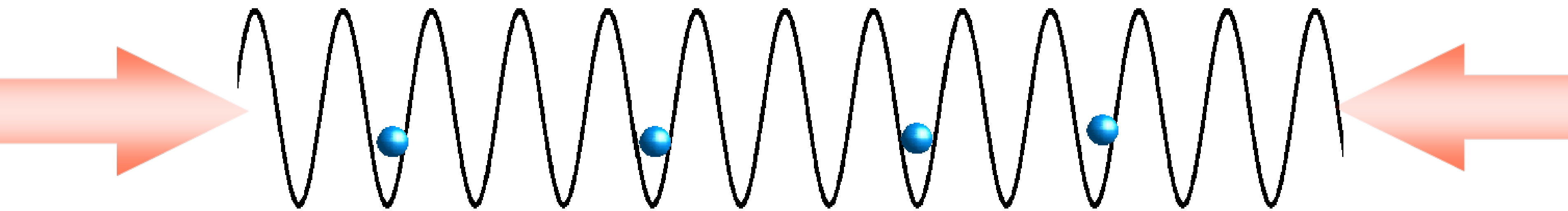


Optical trapping

Goal: optical force exceeds the electrical forces

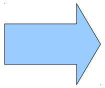
Schneider *et al.*, Nature Photonics **4** (2010)

Schmied *et al.*, NJP **10** (2008)



Parameters for Ca^+:

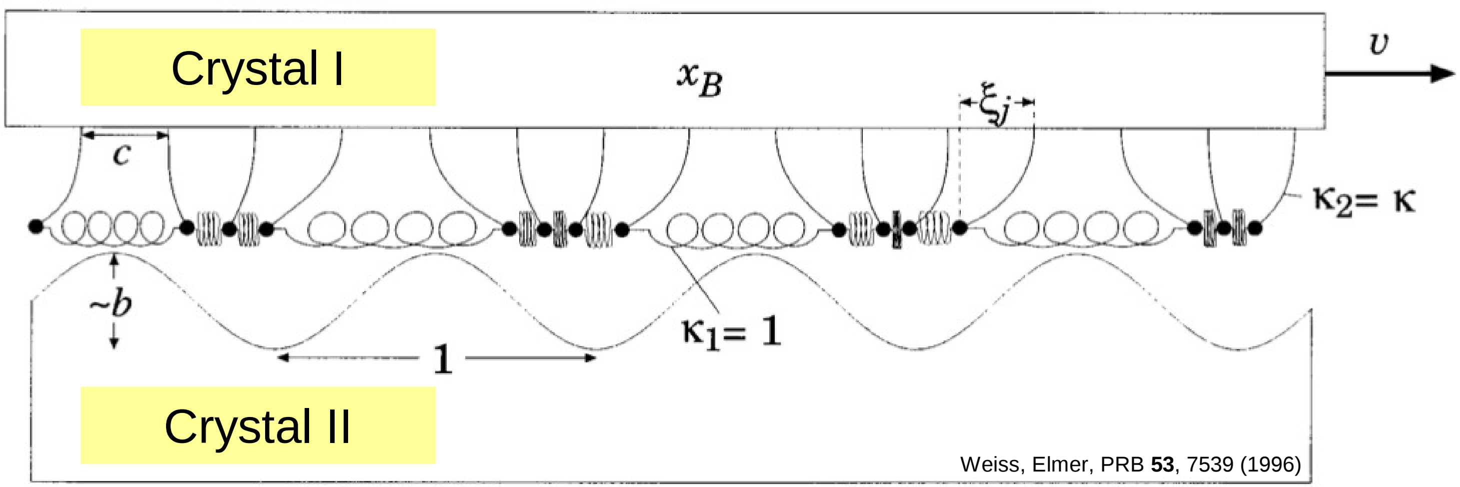
- waist: 25 μm
- power at 405 nm: 2 W
- detuning: 8 nm



- optical trap frequency: 1 MHz
- scatter events: 40 / s

Study emergent phenomena

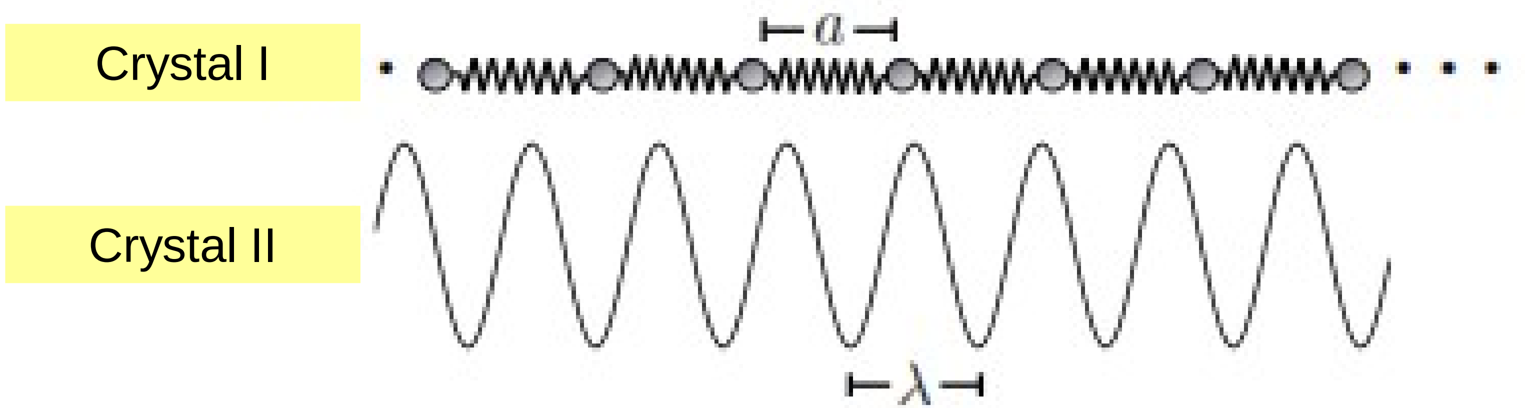
Dry friction (Prandtl-Tomlinson-Frenkel-Kontorova model, 1928-1938):



Weiss, Elmer, PRB **53**, 7539 (1996)

Quantum emulation of dry friction

A linear trap in an optical cavity: an ion string in a periodic potential



Frenkel-Kontorova model

$$\mathcal{H} = \sum_{i=1}^{N} \left(\frac{P_i^2}{2} + \frac{\omega^2}{2} x_i^2 - K \cos x_i \right) + \sum_{i>j} \frac{1}{|x_i - x_j|}$$

Features:

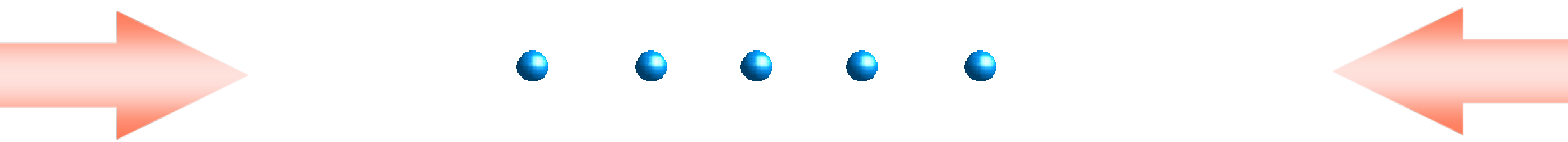
- quantum phase transition
- non-analytic breaking of KAM surfaces

Garcia-Mata *et al.*, EPJ D, **41** (2007)
Benassi *et al.*, Nature Communications **2** (2011)

Emulation of friction

Frenkel-Kontorova model:

How does a chain of ions move in a periodic potential ?

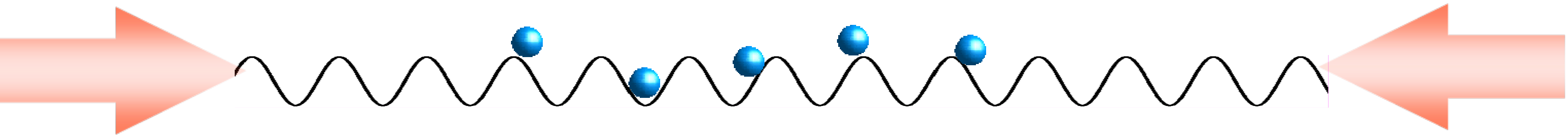


Ions move collectively

Quantum emulation

Frenkel-Kontorova model:

How does a chain of ions move in a periodic potential ?

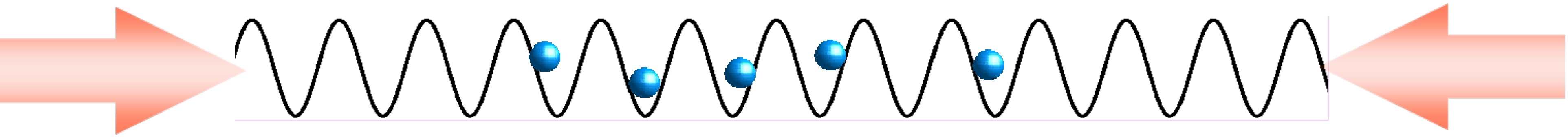


Ions move collectively

Quantum simulation

Frenkel-Kontorova model:

How does a chain of ions move in a periodic potential ?

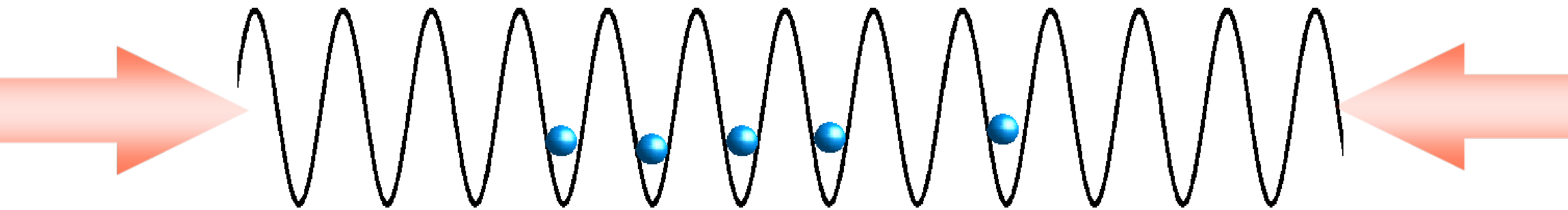


Ions move collectively

Quantum emulation

Frenkel-Kontorova model:

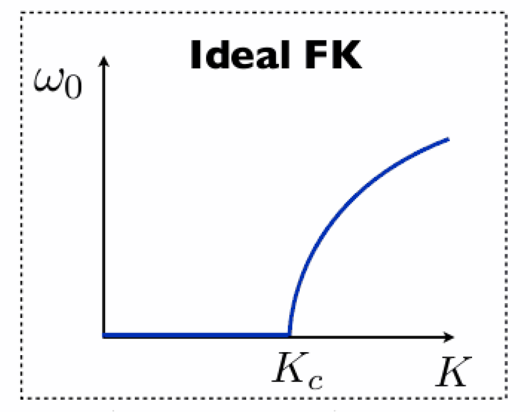
How does a chain of ions move in a periodic potential ?



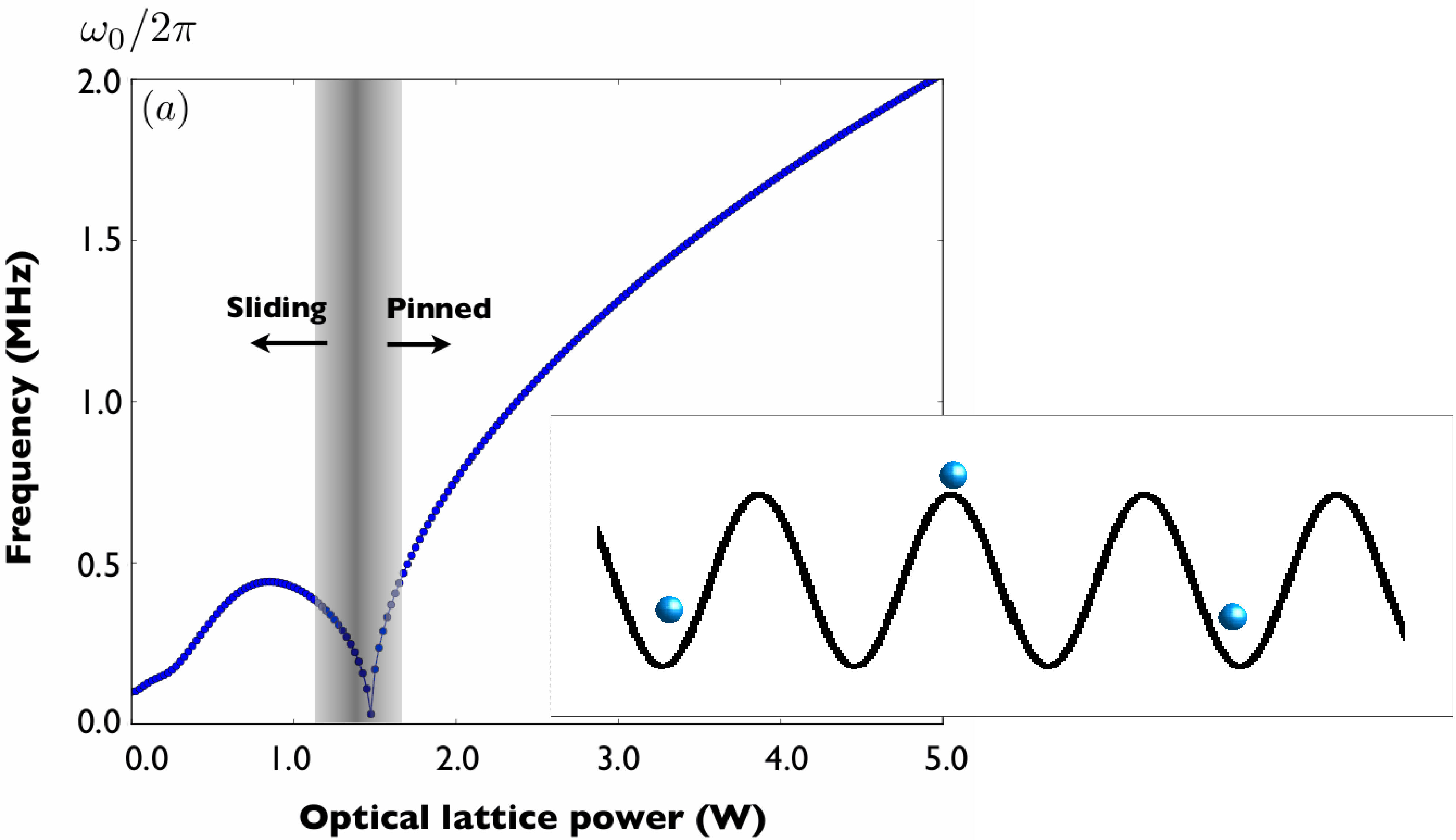
Ions are pinned

➡ Quantum phase transition

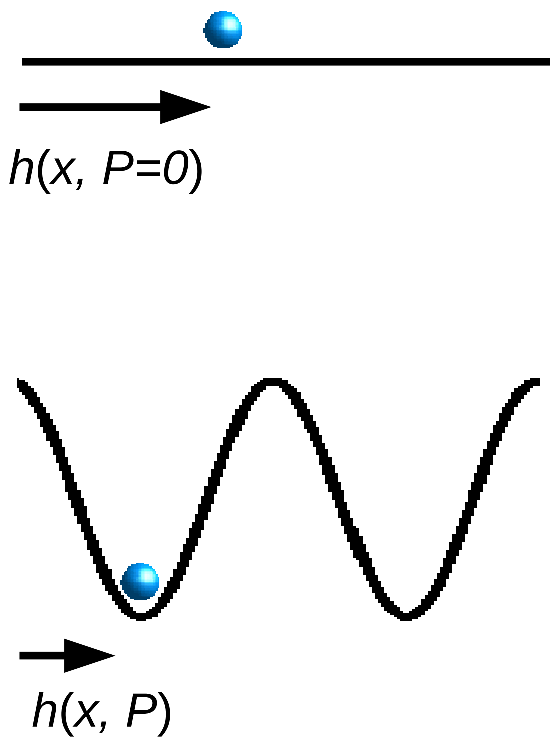
“Nanofriction”

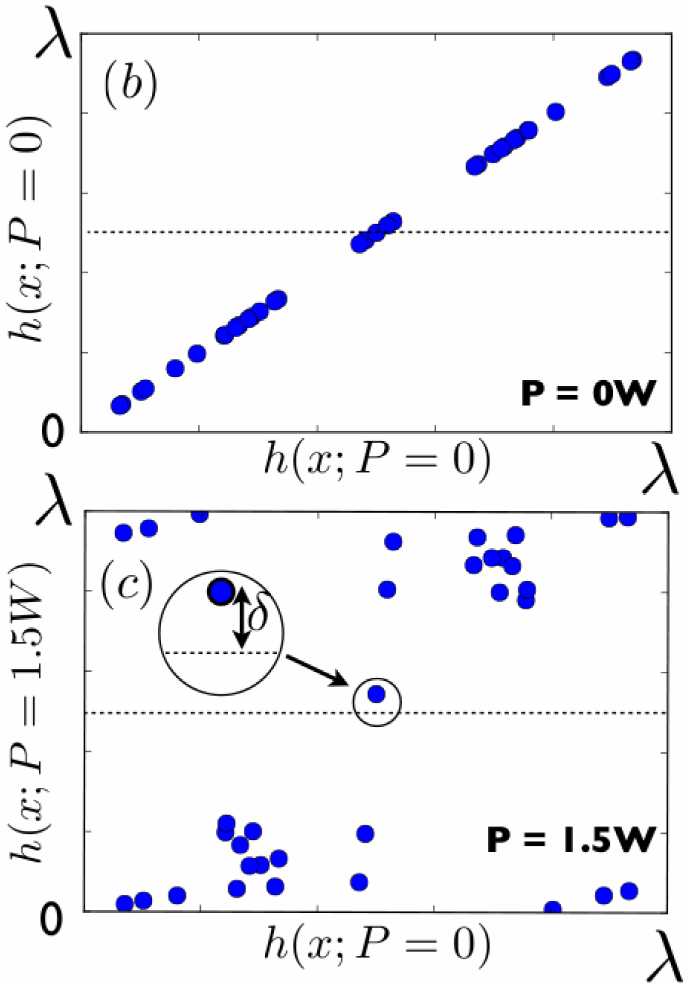


“Nanofriction”



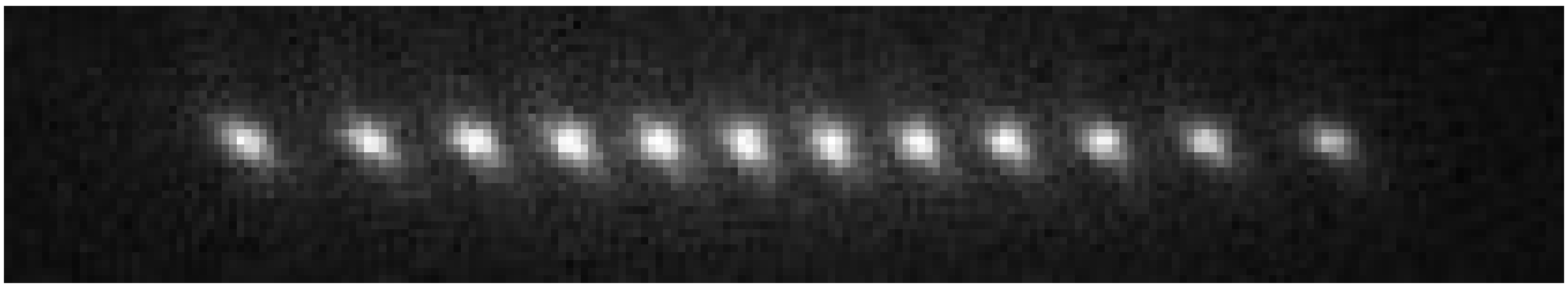
Characterization



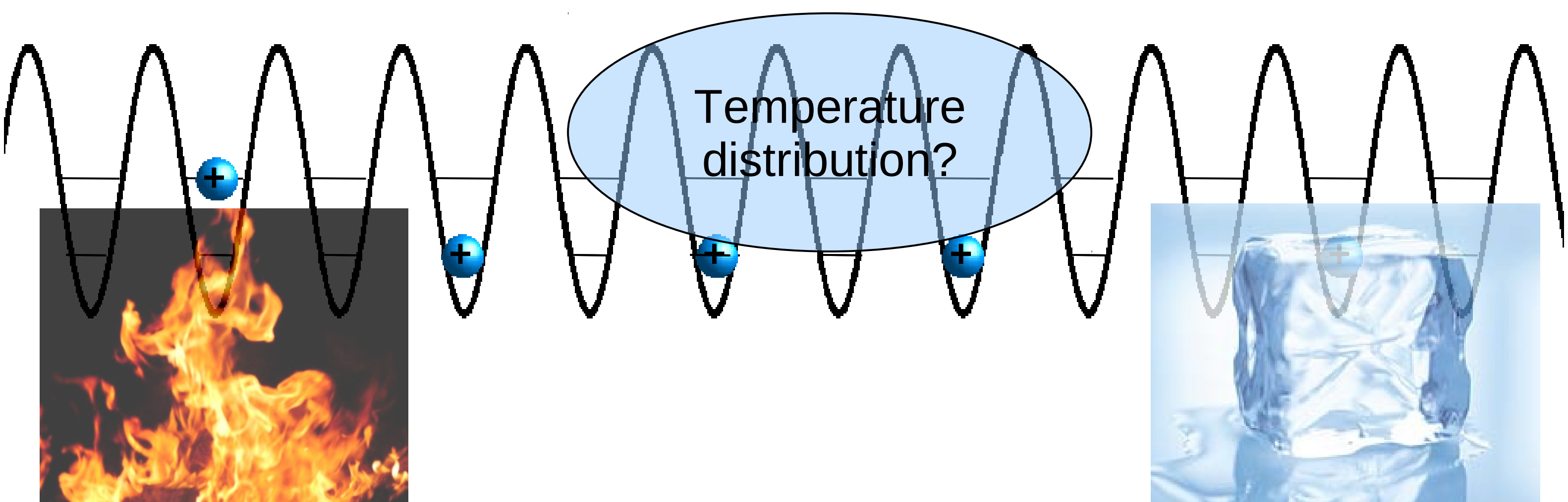


Heat transport

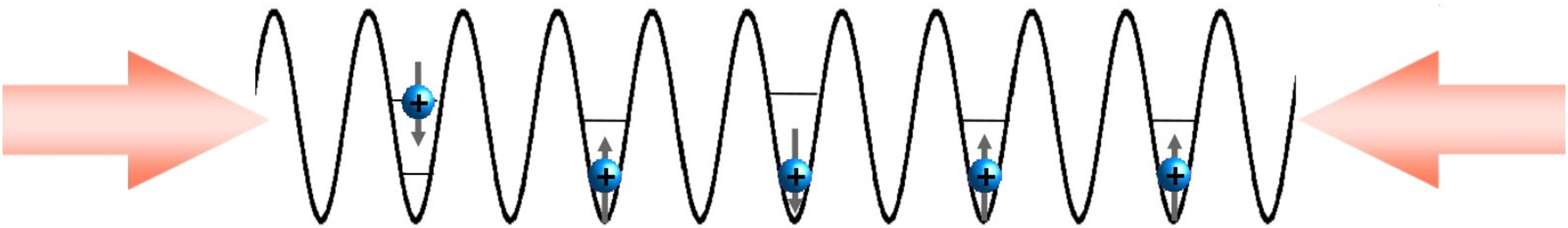
Wigner crystal of trapped ions ...



… forms a chain of contrallable oscillators.



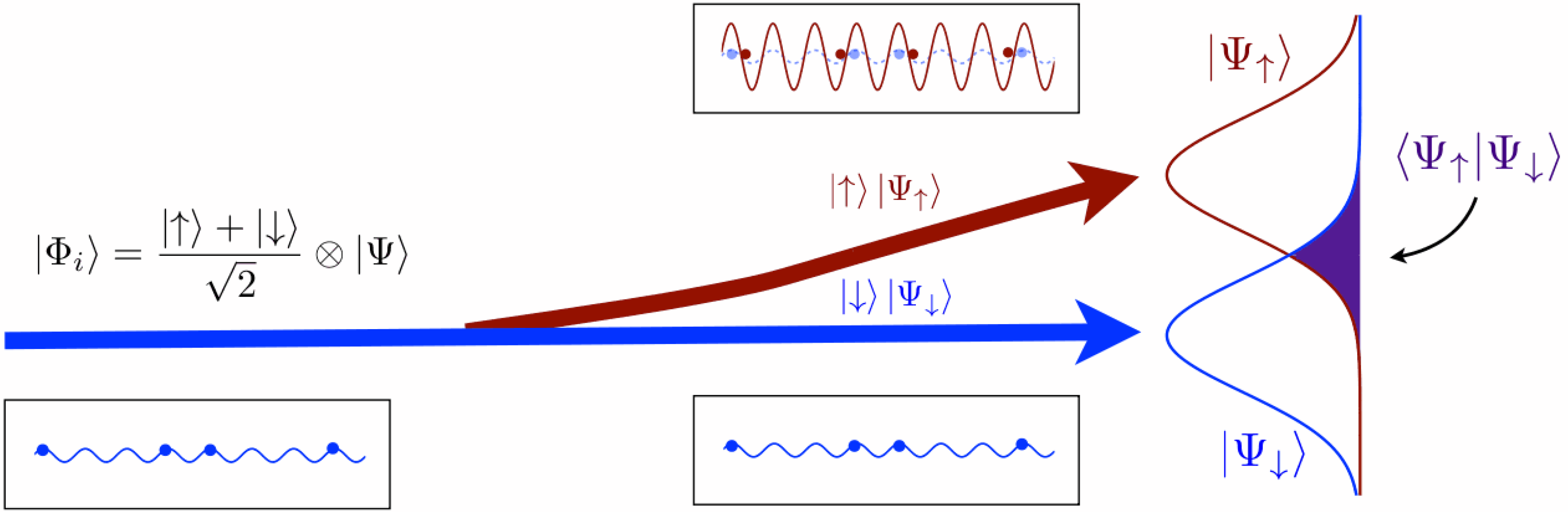
Spin dependent transport



Spin dependent potential:

- impurities in solids
- allows for superpositions of configurations
- coherence of a spin allows to determine the wavefunction overlap

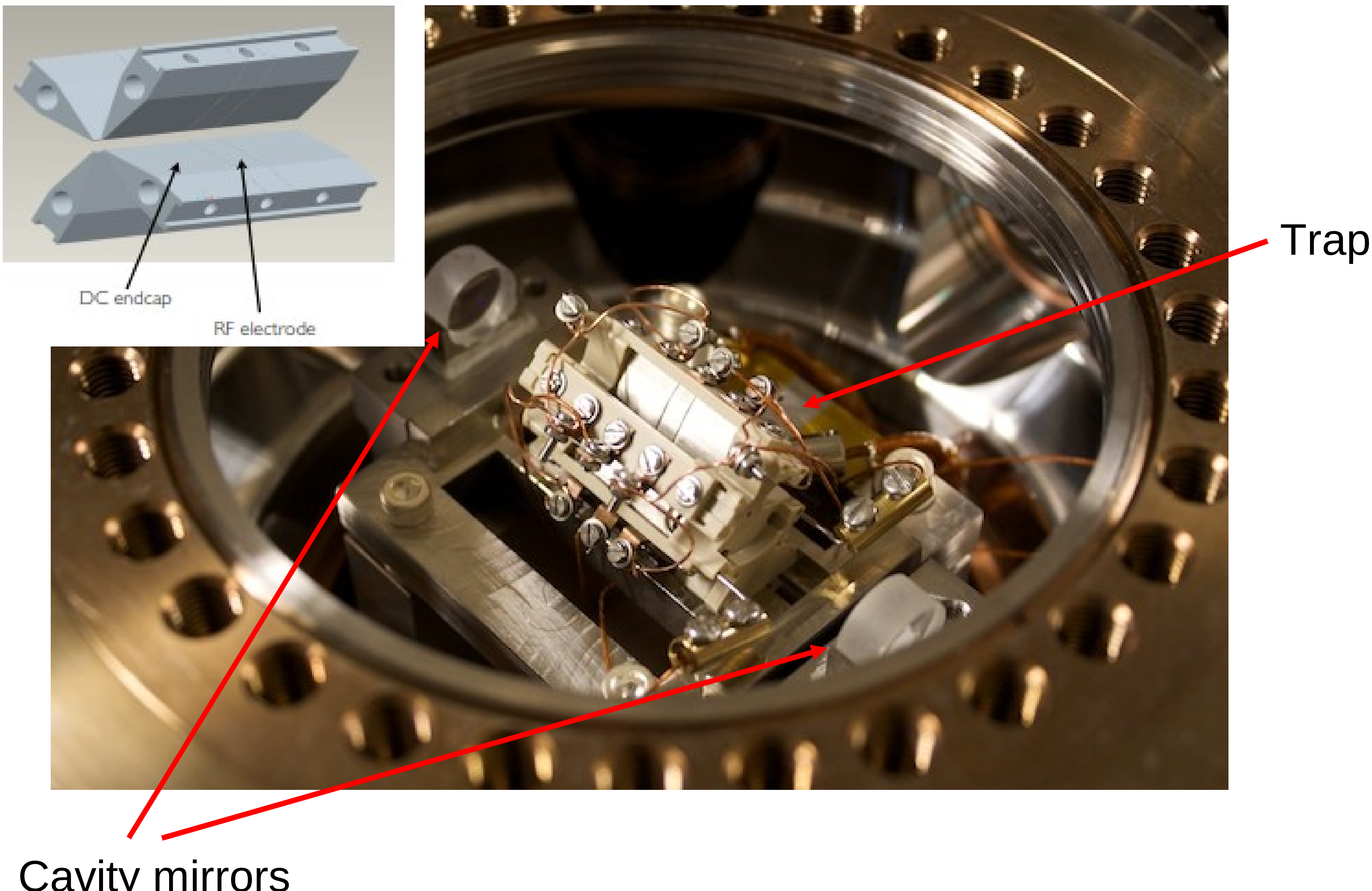
Sensitivity to imperfections



Sensitivity to imperfections in the evolution

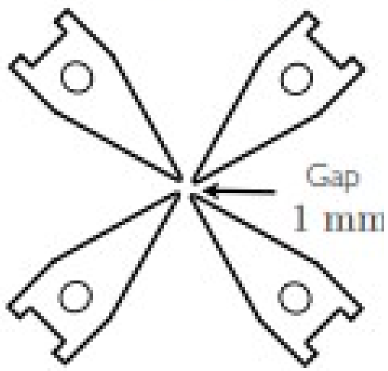
prepare a superposition of two quantum phases

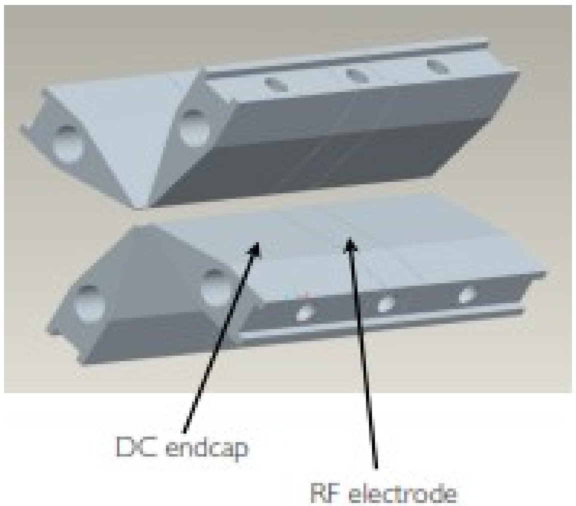
Experimental set-up

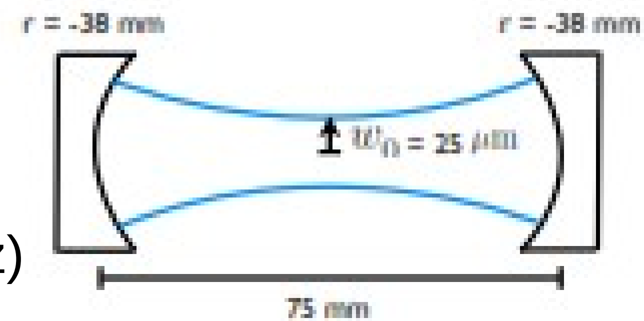


Experimental set-up

Linear Paul trap:







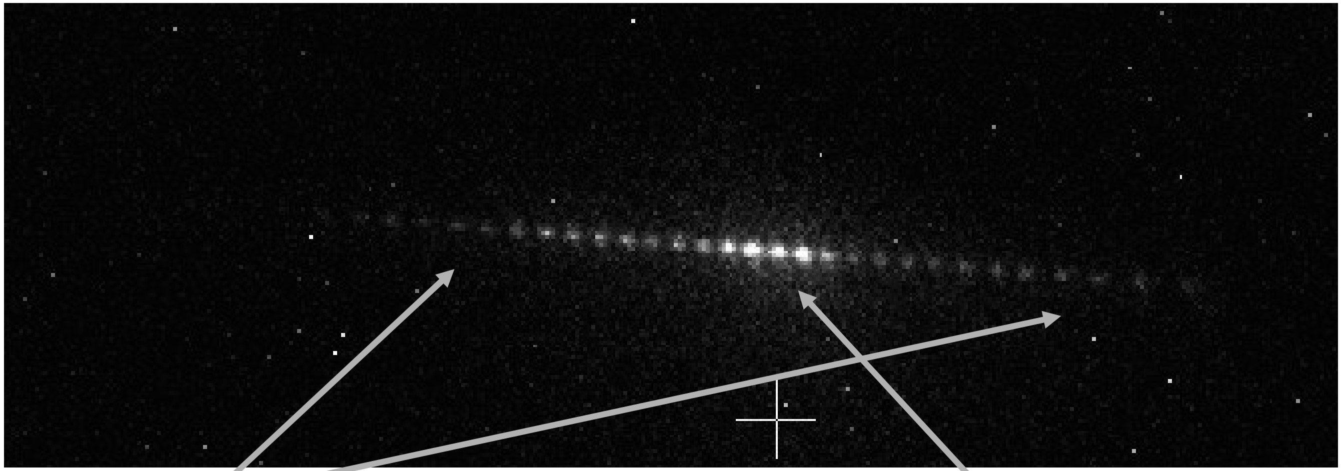
Trap frequencies:

3 MHz radially, 800 V_{ppp} (out-of-phase drive @ 16 MHz)
150 kHz axially, 40 V at endcaps

Finesse 600 at 405 nm

Expected lattice frequency
1 MHz @ intra-cavity power 2W

Heat flow in ion strings

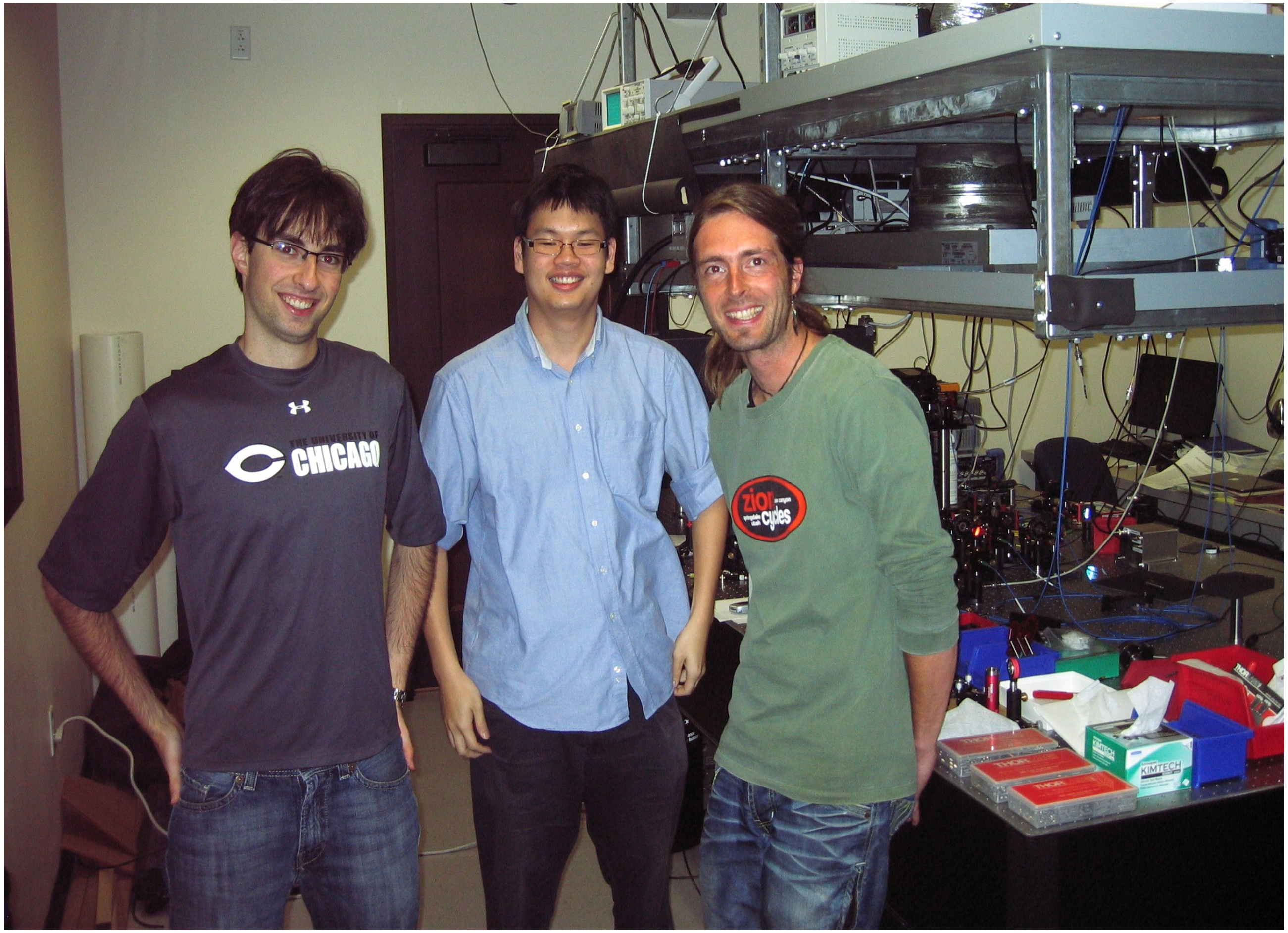


Global cooling beam

Focussed heating beam

Near term plans

Thaned (Hong) Pruttivarasin
Michael Ramm
Axel Kreuter
Ishan Talukdar



Thaned Pruttivarasin et al., arXiv:1104.0451 (2011)

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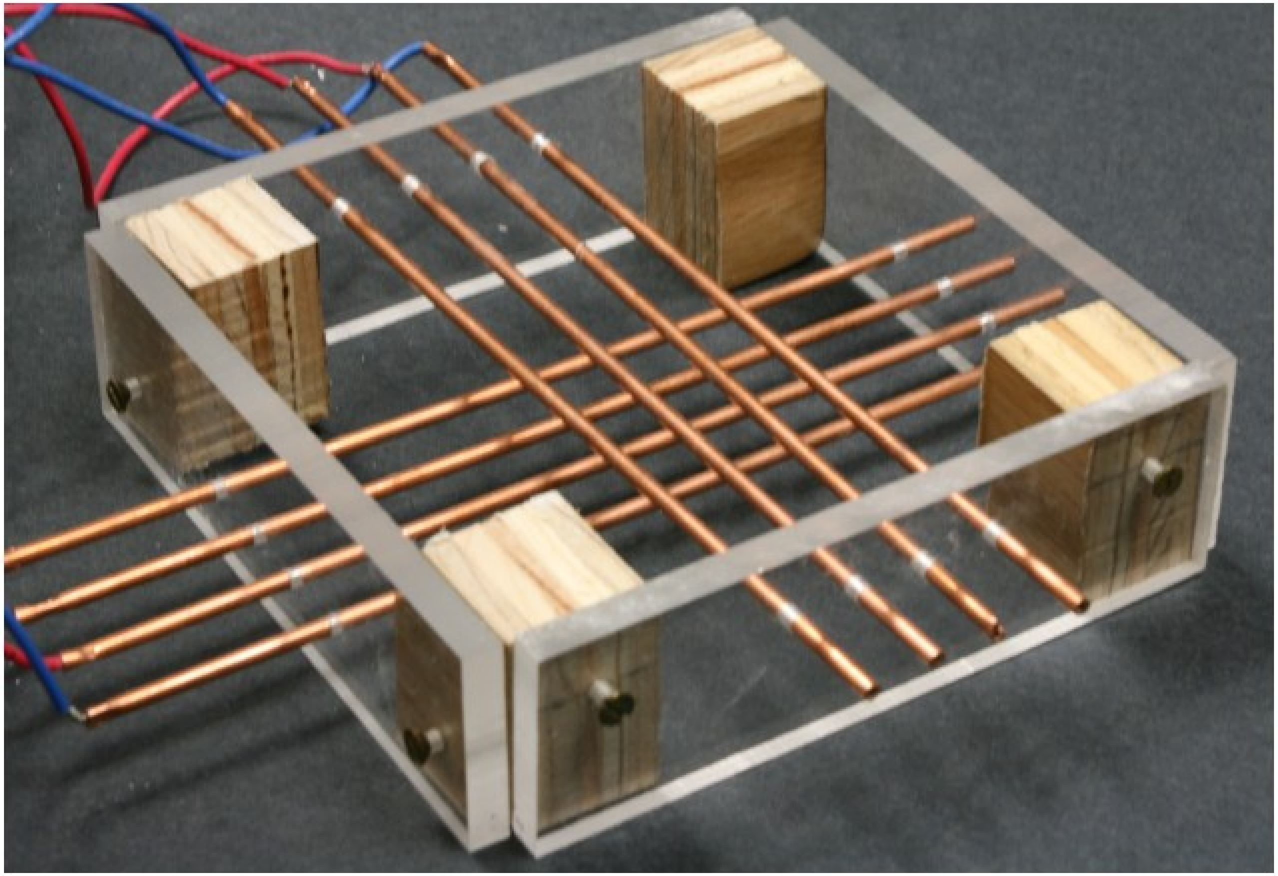
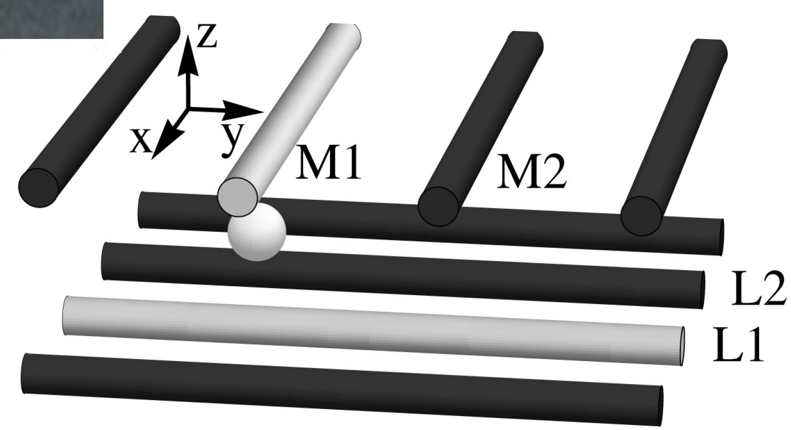
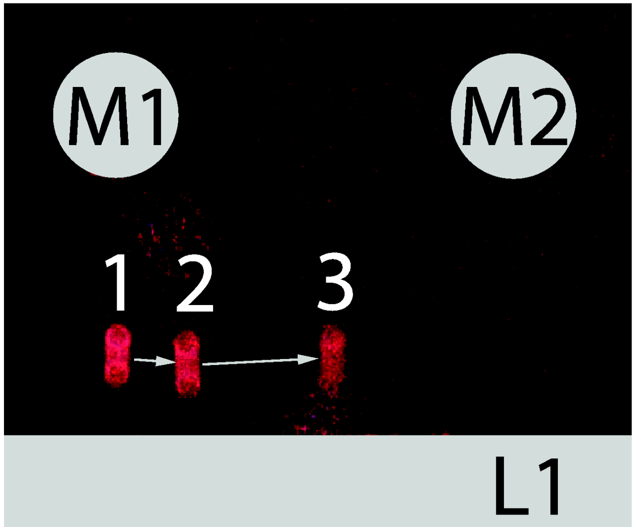
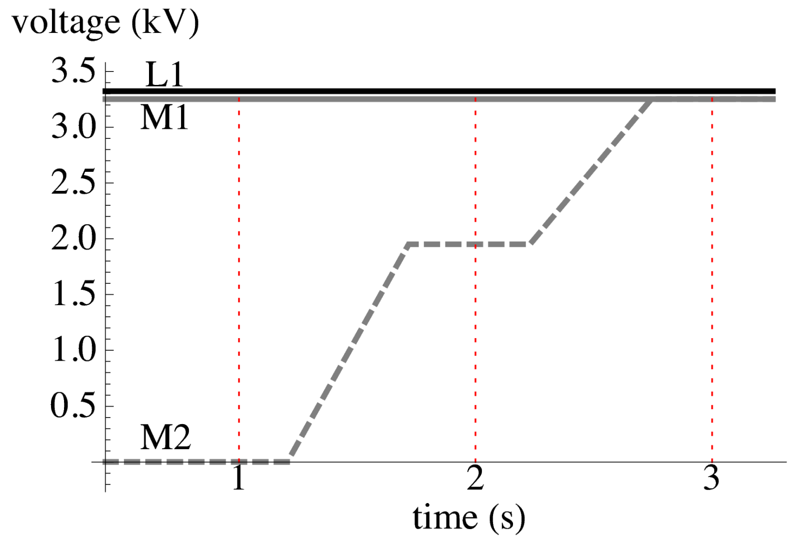
A lattice trap

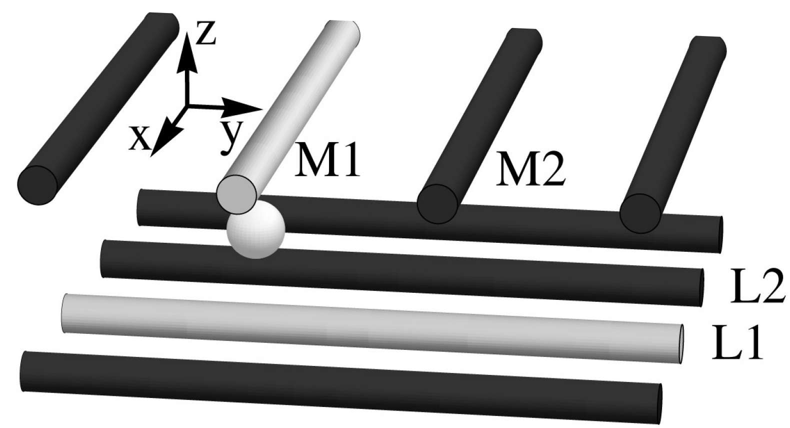




RF-transport







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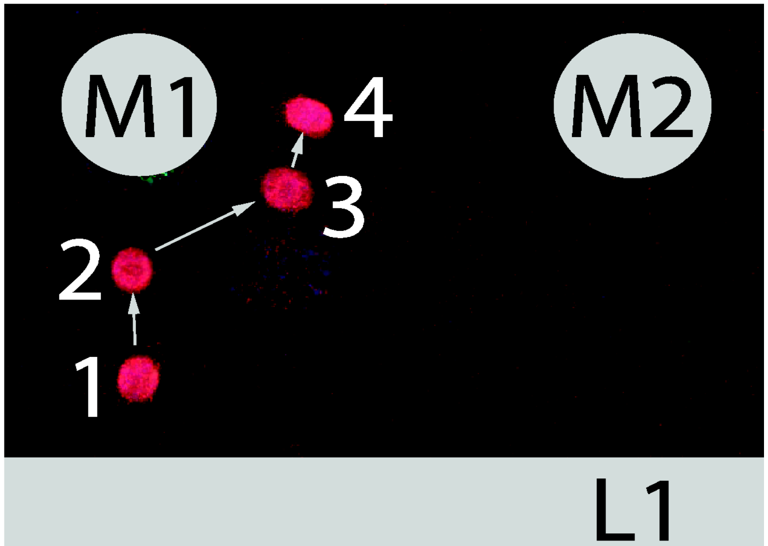
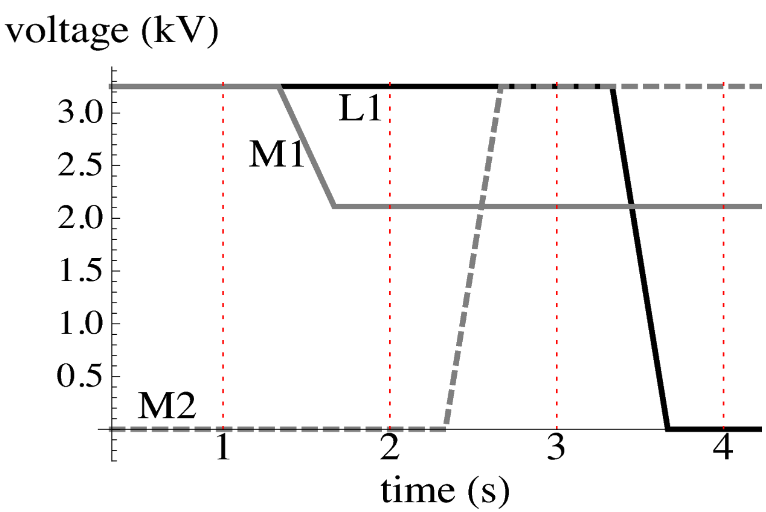
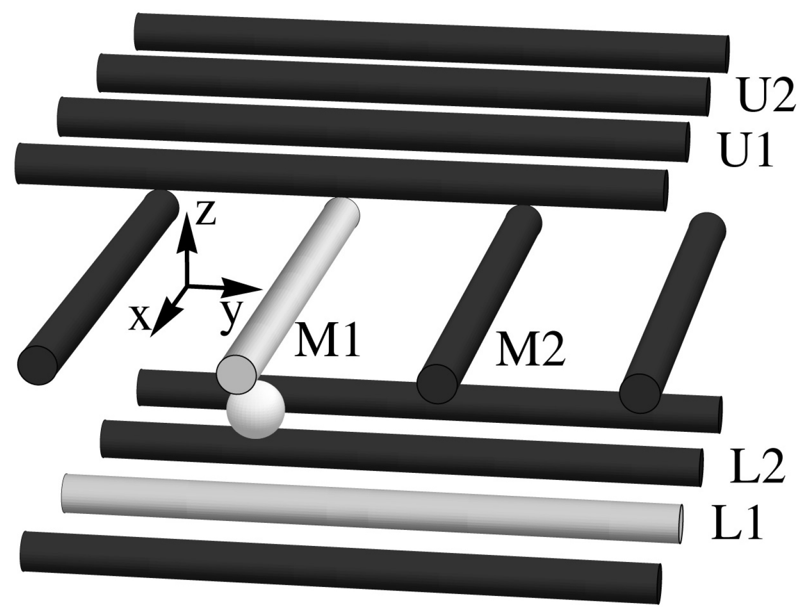
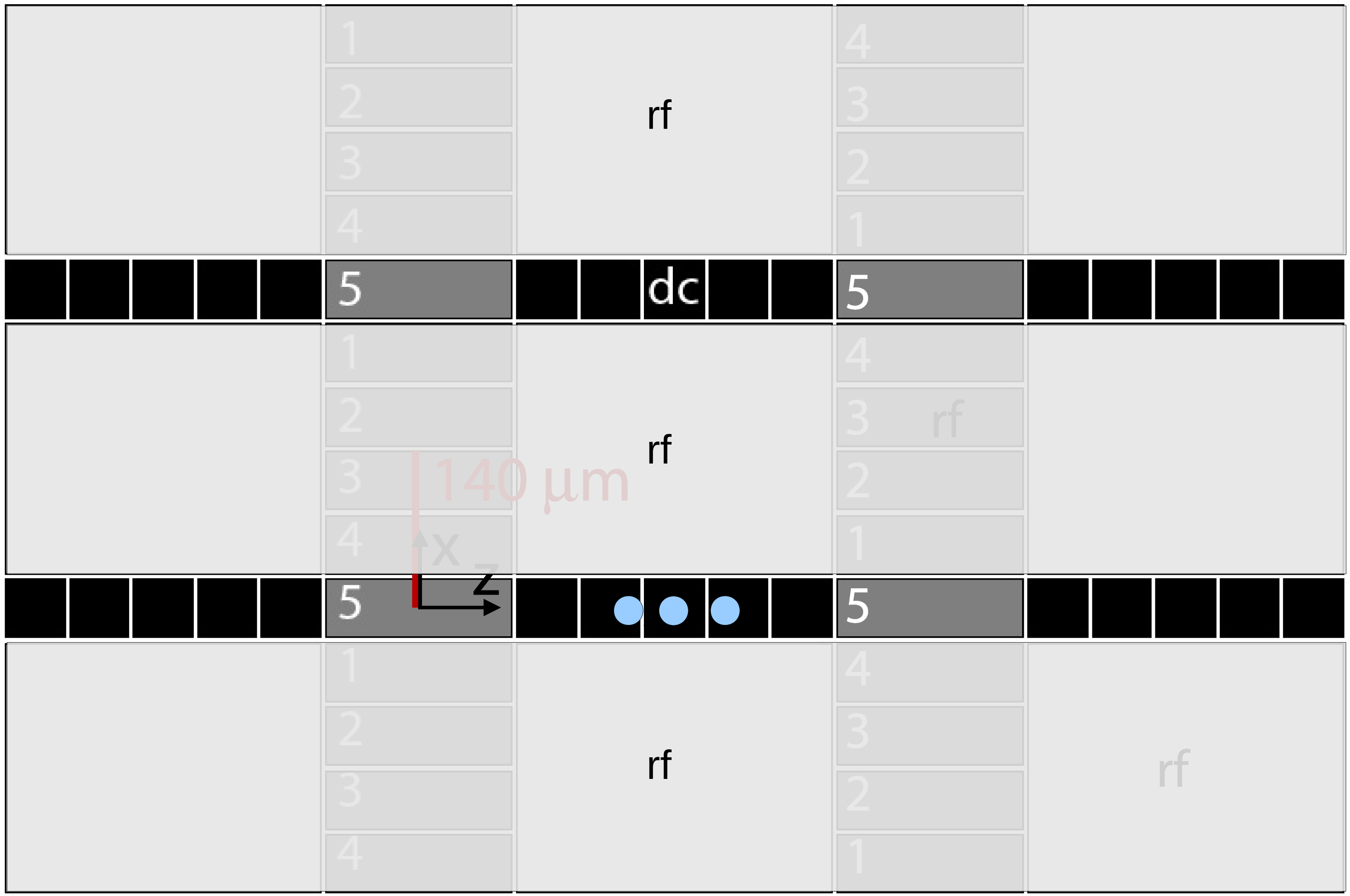






Karin et al., arXiv:1011.6116v2

Ion trap QIP proposal



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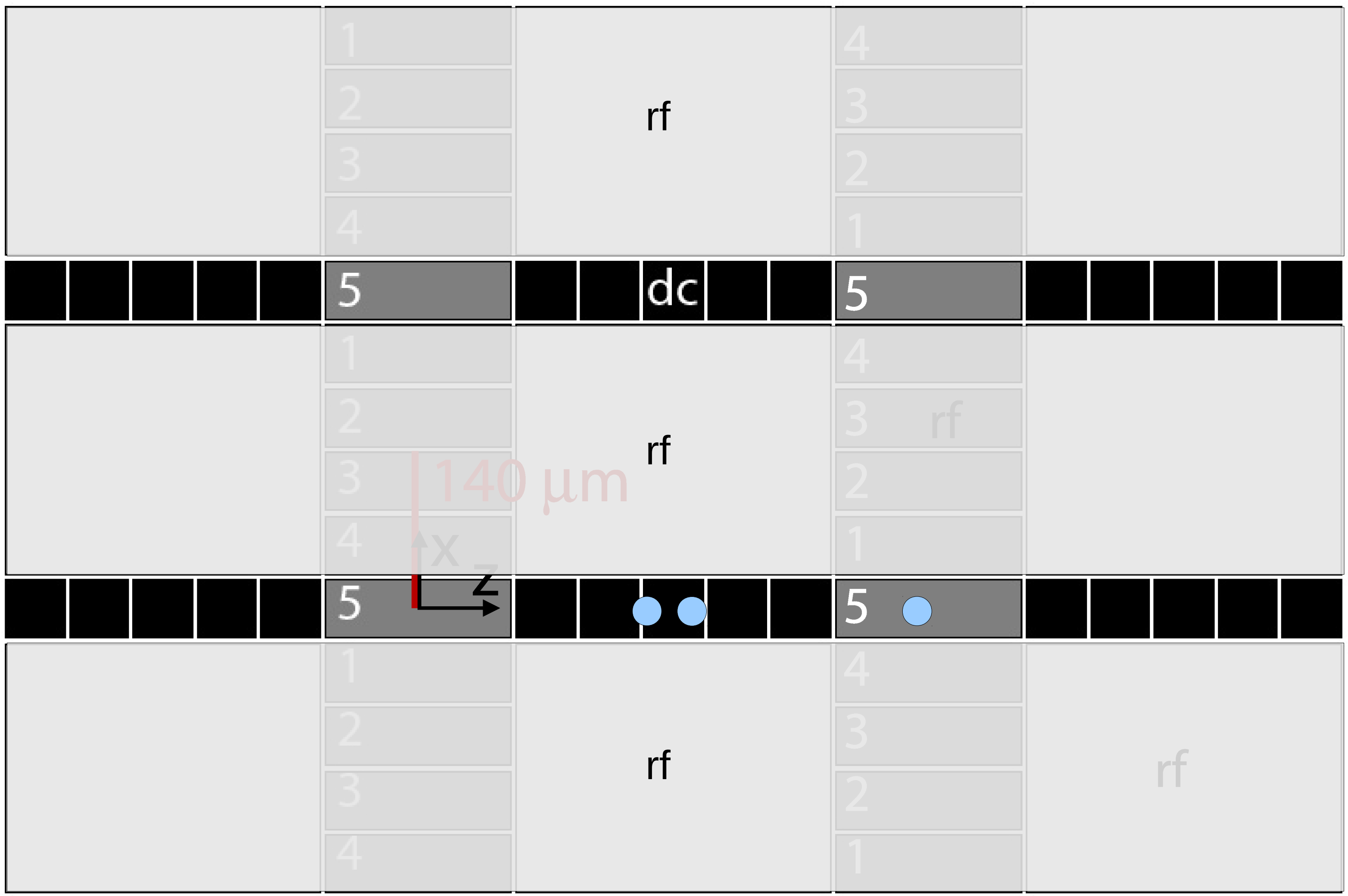

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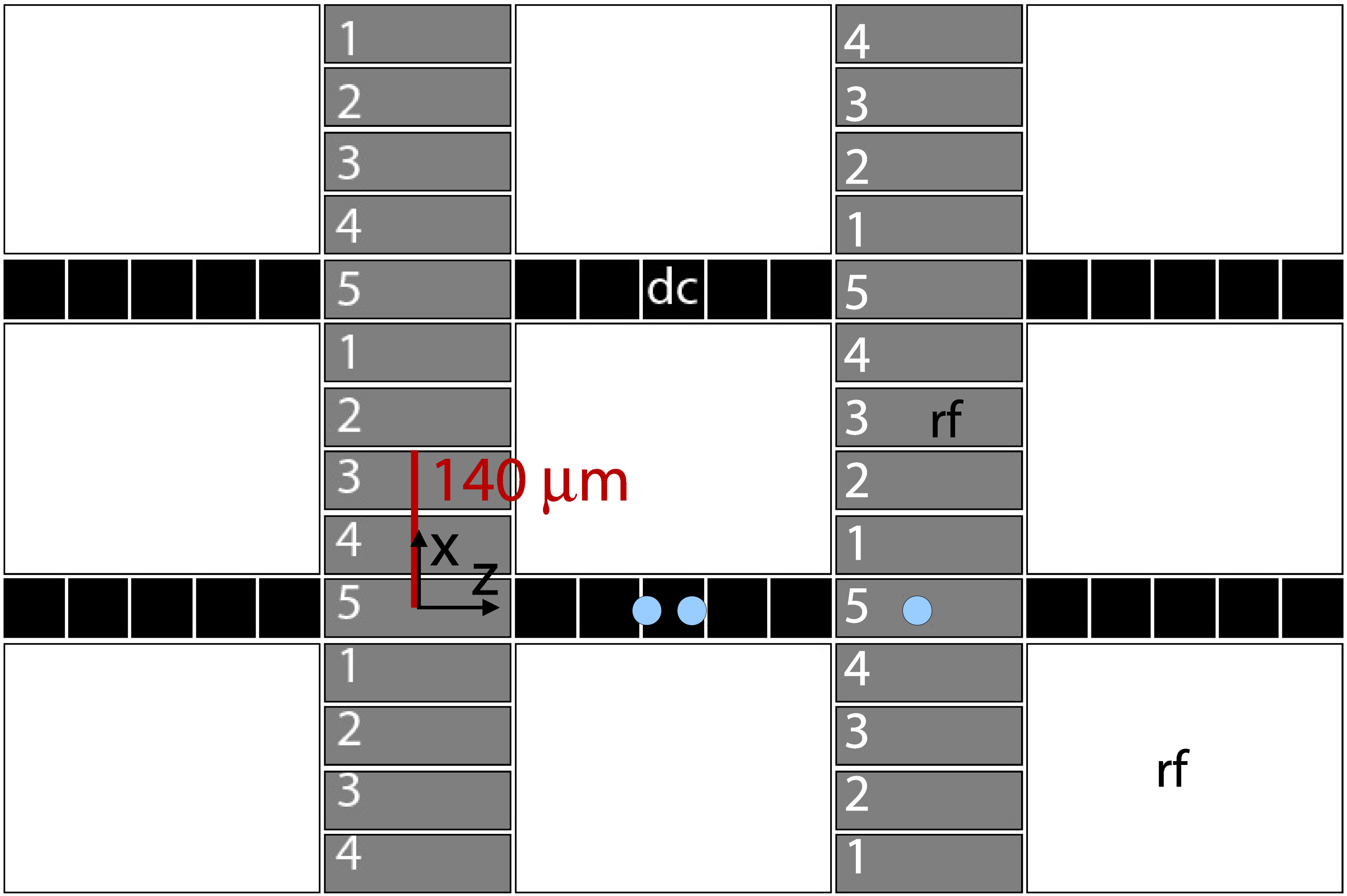
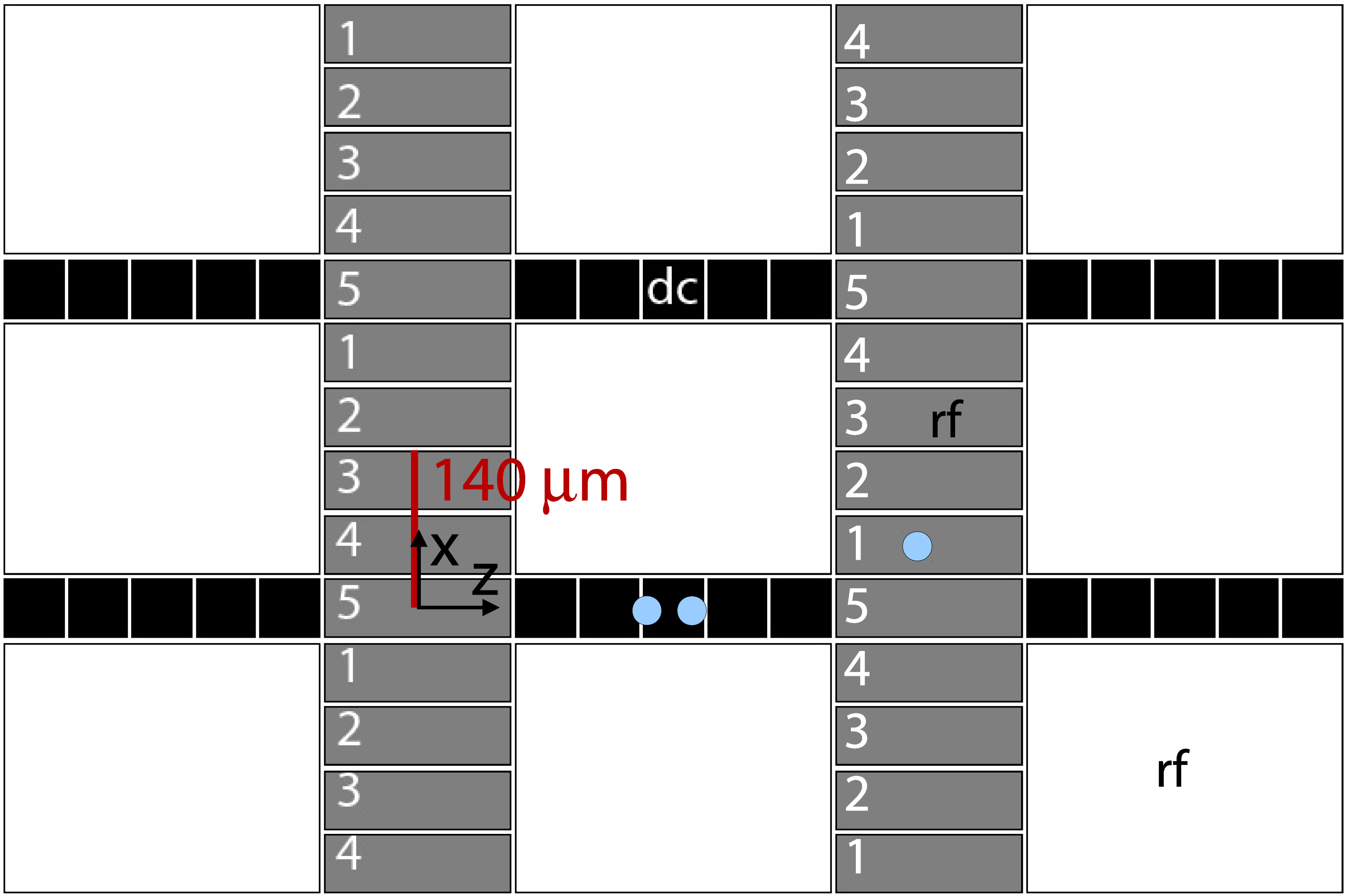


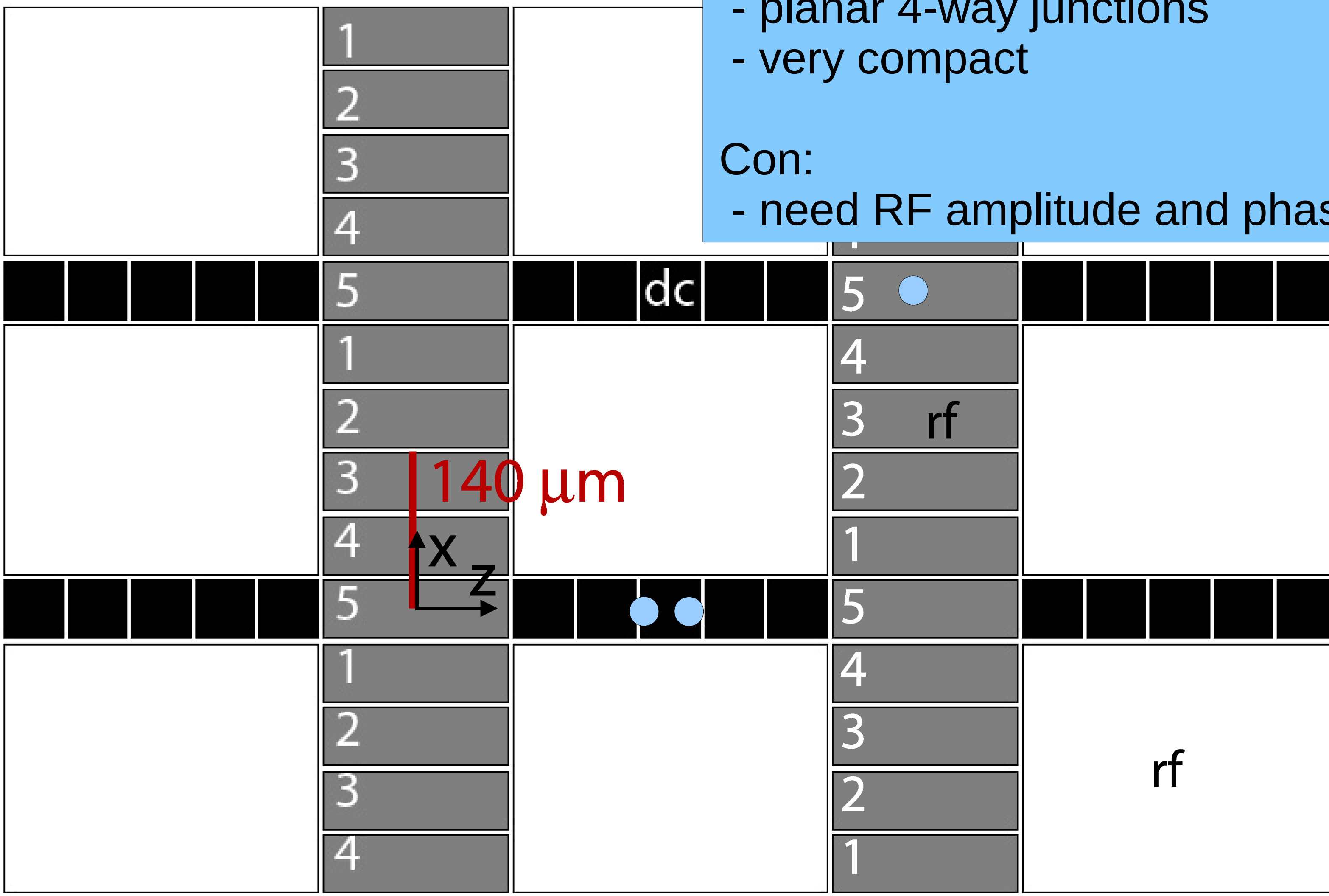
Ion trap QIP proposal



Ion trap QIP proposal

Pro:
- planar 4-way junctions
- very compact

Con:
- need RF amplitude and phase control



Karin *et al.*, arXiv:1011.6116v2

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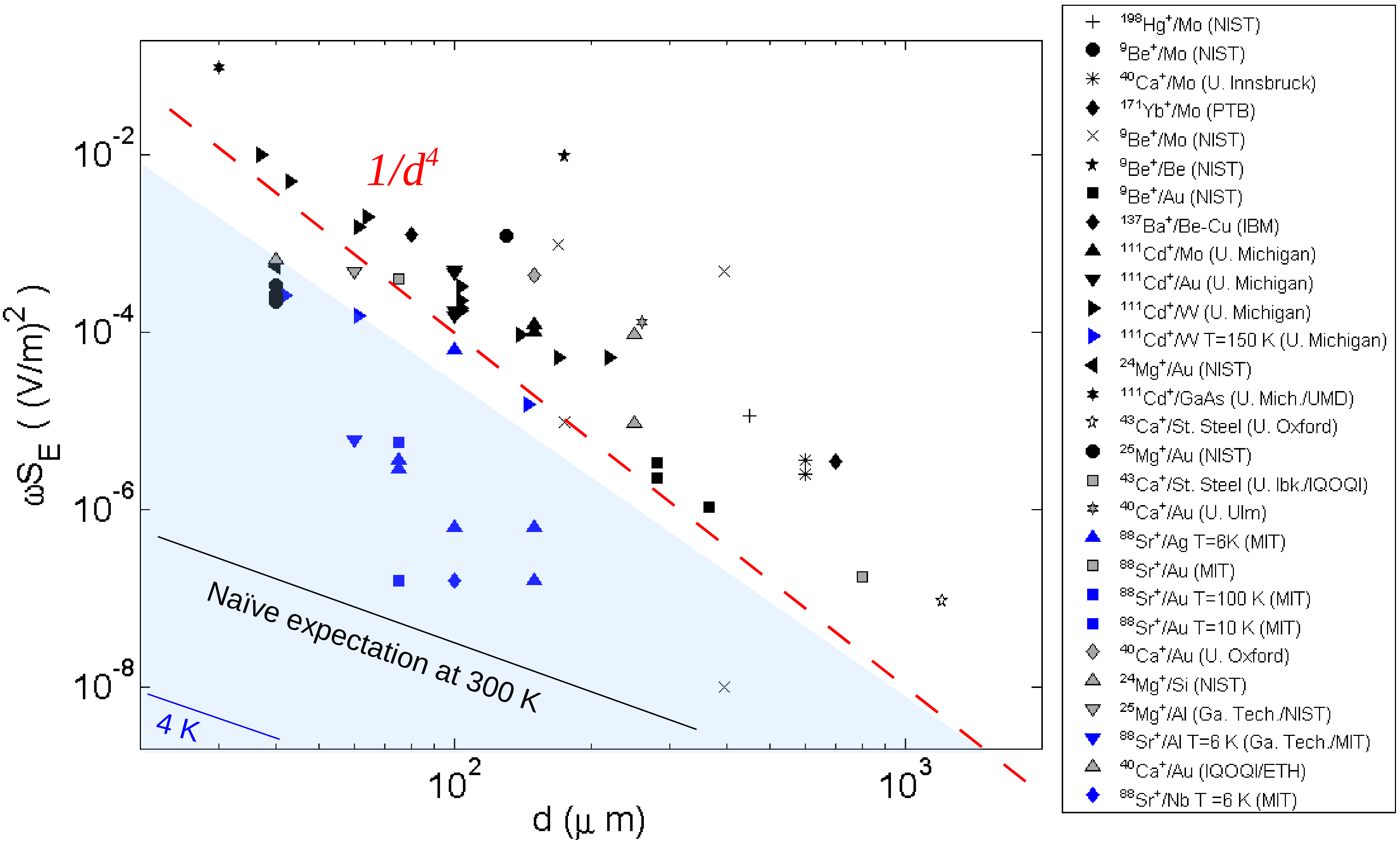
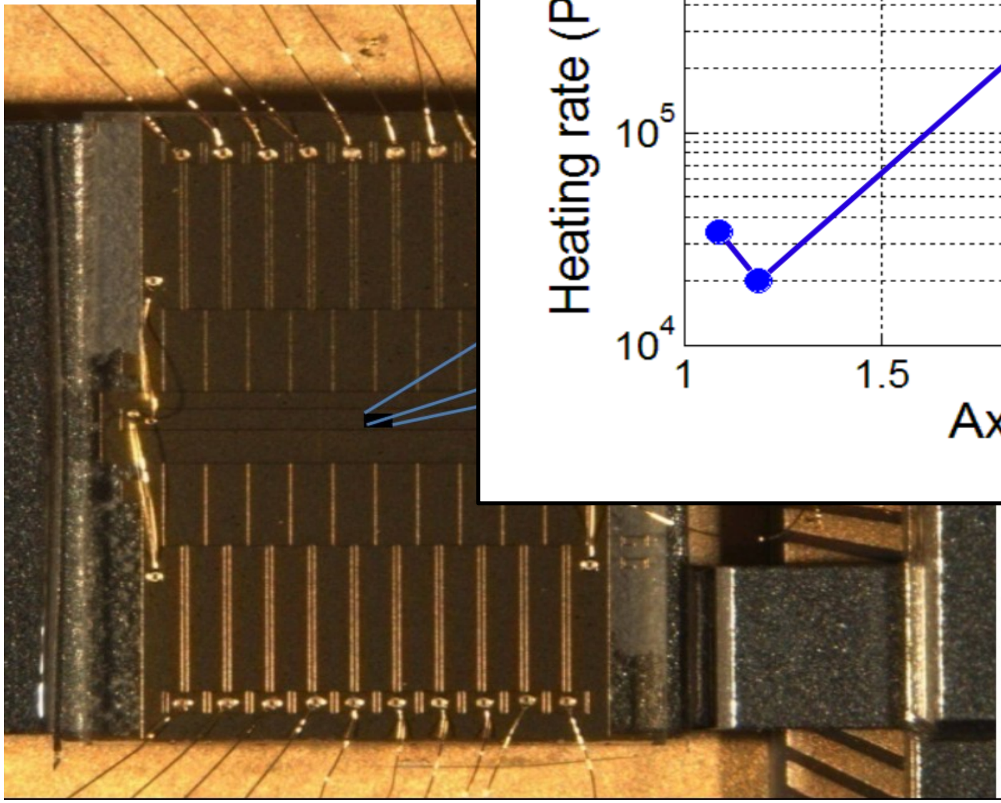
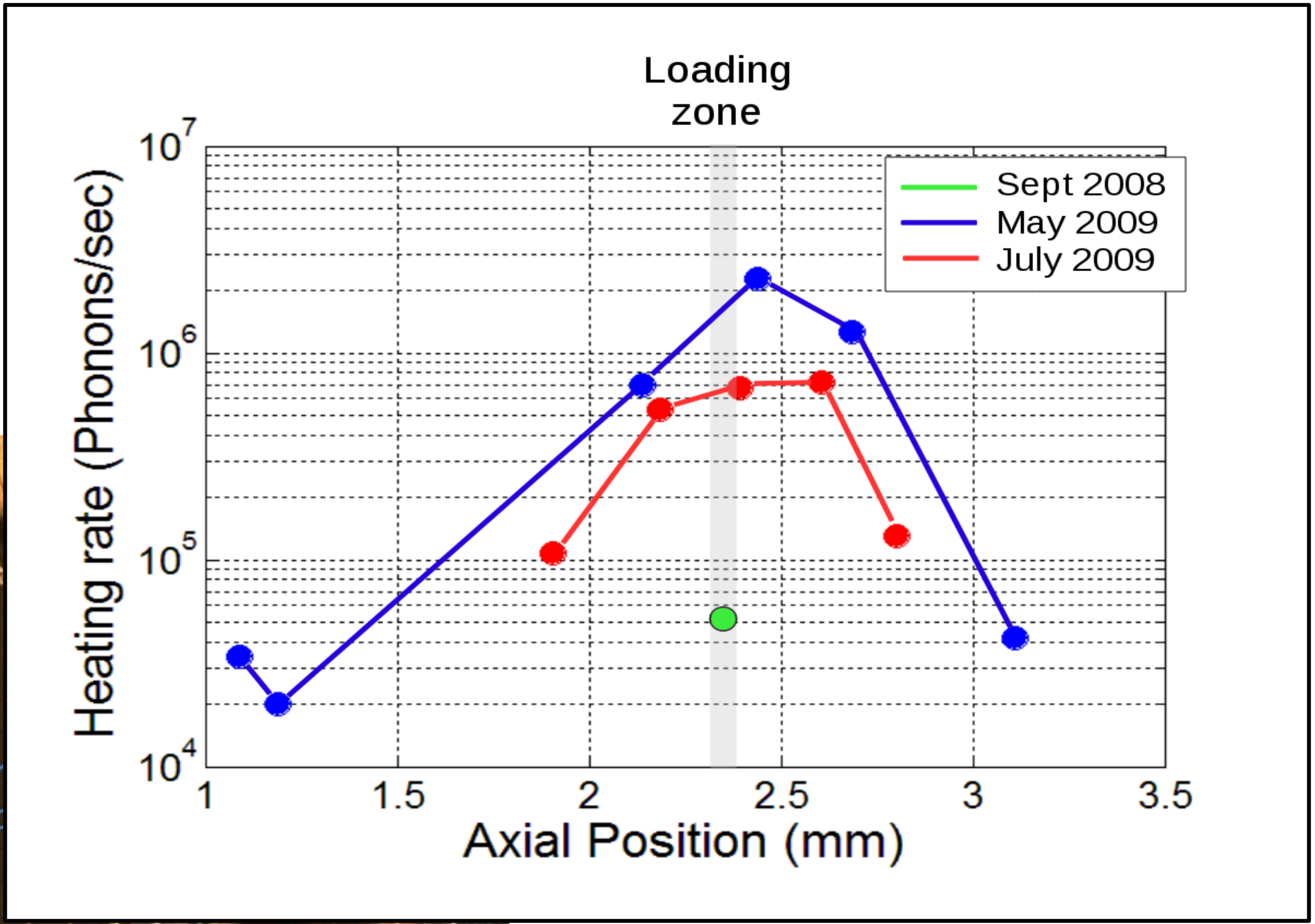
Anomalous heating



Unknown source for heating

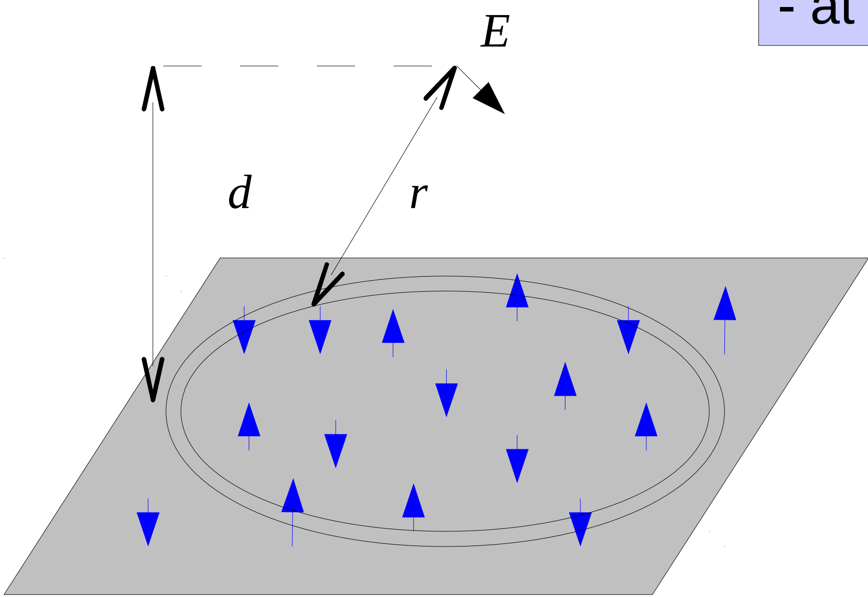
Gold on Sapphire





A suggestion for a heating mechanism

- no shielding from bulk metal
- one monolayer of adsorbates is sufficient!
- at 10^{-11} mbar: one monolayer / day



Sources on conducting surface produce dipole field

$$E_\mu(r) \sim \frac{\mu}{r^3}$$

Random dipole orientation

$$E_N(r) \sim \sqrt{N}\frac{\mu}{r^3}$$

Noise spectral density over trap surface

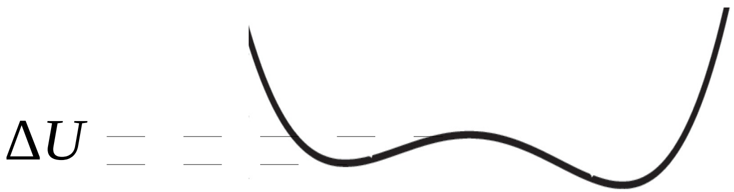
$$S_{\mathrm{E}} \sim \int_{\mathrm{surf}} n_{\mathrm{s}}(r) \left(\frac{\mu}{r^3}\right)^2 S_\mu \, d\alpha \sim \frac{n_{\mathrm{s}}\mu^2}{d^4} S_\mu$$

Nikos Daniliidis

Turchette *et al.*, Phys. Rev. A 61 63418 (2000)

Daniilidis *et al.*, New J. Phys. 13 013032 (2011)

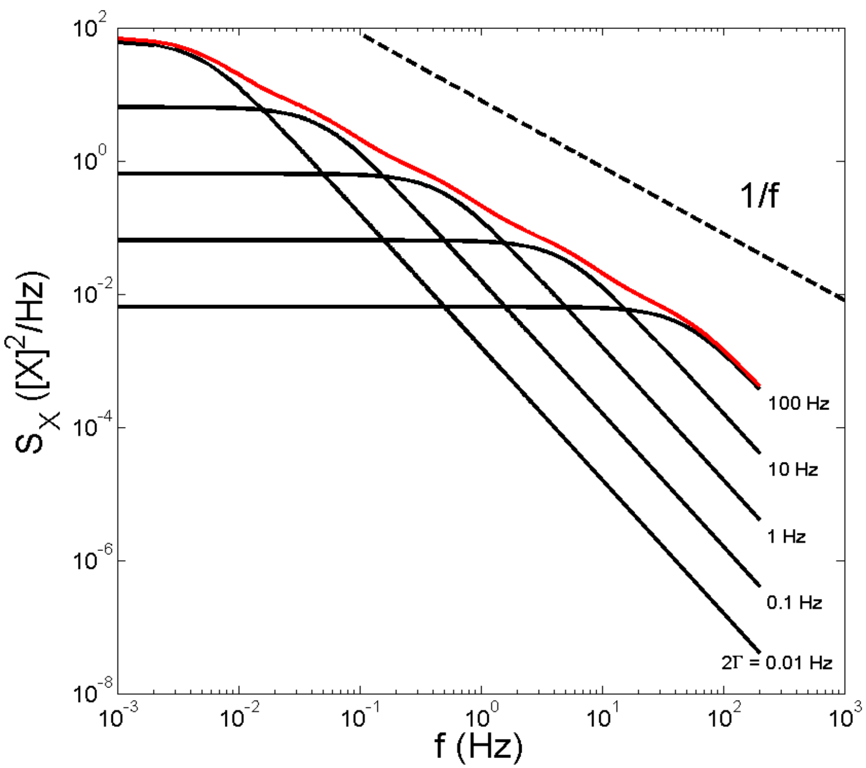
Hints from the spectrum



$$\Gamma = \omega_0 \exp(-\Delta U / k_B T)$$

Log-uniform distribution of relaxation rates

$$p(\Gamma) = \frac{\ln(\Gamma_{max}/\Gamma_{min})}{\Gamma}, \quad \Gamma_{min} < \Gamma < \Gamma_{max}$$



→ 1/f scaling

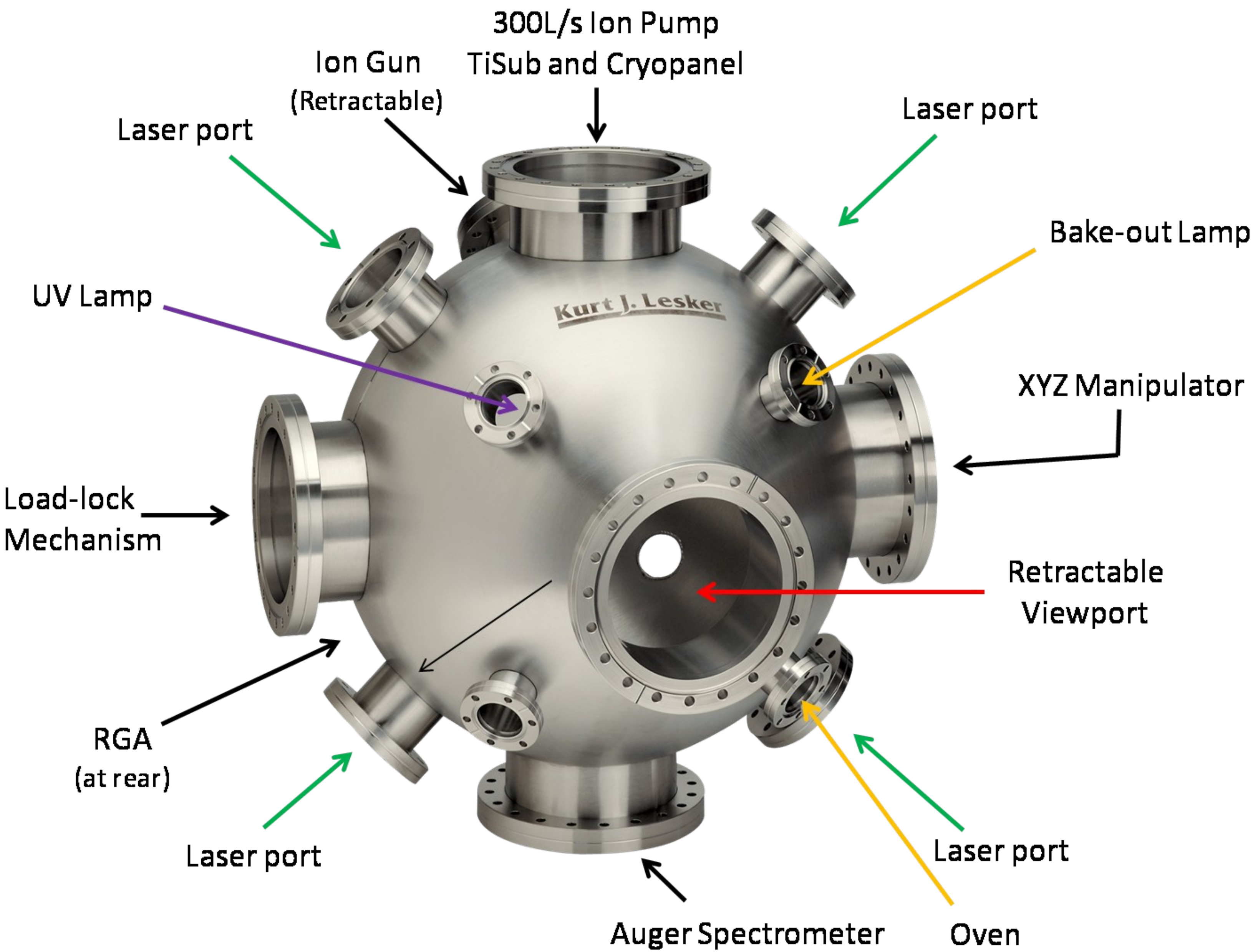
A standard surface cleaning recipe

Repeated cleaning / annealing cycles

1. Ar^+ ion bombardment
   - Ion energy 150 eV - 2 keV
   - Beam diameter 5 mm – 20 mm
2. Anneal at $400^{o}C$ – $800^{o}C$
3. Monitor surface contamination

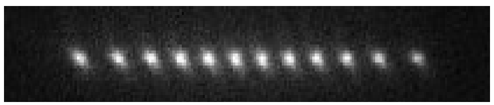
See also:
- NIST, Dustin Hite
- Innsbruck

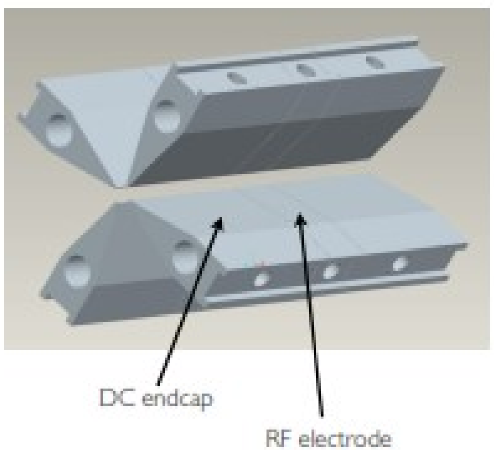
Trap testing and cleaning set-up



Conclusion

Trapped ions

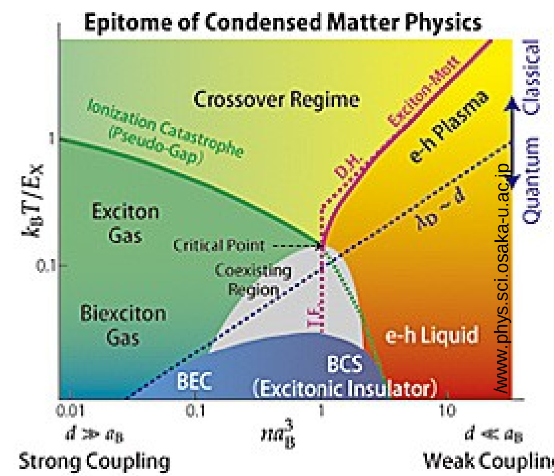




Emulation

Better traps

Condensed matter



- Study physics of ion crystals in microtraps
- Shuttling in 3D
- Candidate mechanism for anomalous heating

People

Greg Bolloton	Sankara Narayanan
Nikos Daniliidis	Oliver Neitzke
Dylan Gorman	Thaned (Hong) Pruttivarasin
Axel Kreuter	Christopher Reilly
Gebhard Littich	Michael Ramm
Sönke Möller	Ishan Taludkar