Status of Trapped-Ion Physics in Europe

Rainer Blatt
Institute for Experimental Physics, University of Innsbruck,
Institute for Quantum Optics and Quantum Information,
Austrian Academy of Sciences

- Trapped-ion physics in Europe
- trap technology and experiments
- coupling quantum information in separate traps
- quantum information toolbox
- repetitive quantum error correction
- quantum simulations

universität innsbruck

AG Quantenoptik
und Spektroskopie

€ SFB FoQuS FWF SFB
MICROTRAP
AQUTE
Industrie
Tirol
IQI
GmbH
FWF bm:bwk erc
$ IARPA
IQI
ÖAW
Österreichische Akademie
der Wissenschaften

Status of Trapped-Ion Physics in Europe

M. Drewsen	Aarhus	Ca^+, Mg^+, Be^+	CQED
A. Steane, D. Lucas	Oxford	Ca^+	QIP, μTraps
Th. Coudreau, S. Guibal	Paris	Sr^+	QMemory
C. Wunderlich	Siegen	Yb^+	QIP, μTraps
F. Schmidt-Kaler	Mainz	Ca^+	QIP, μTraps
J. Eschner	Saarbrücken	Ca^+	CQED, QComm
T. Schätz	München	Mg^+	QSim, QIP
M. Knoop, C. Champenois	Marseille	Ca^+	QMetrology
D. Segal, R. Thompson	London	Ca^+	Penning trapology
W. Henzinger, W. Lange	Sussex	Yb^+, Ca^+	CQED, QIP, μTraps
P. Gill, A. Sinclair	Teddington	Sr^+, Yb^+	QMetrology
P. Schmidt, T. Mehlstäubler	Braunschweig	Ca^+, Mg^+	DIFCOS, QMetrology
C. Tamm, E. Peik	Braunschweig	Yb^+	QMetrology
J. Hecker-Denschlag	Ulm	Ba^+	Ion & BEC
M. Köhl	Cambridge	Ca^+	Ion & BEC
J. Home	Zürich	Ca^+	QIP
R. Blatt et al.	Innsbruck	Ca^+, Ba^+	QIP, μTraps, CQED

Status of Trapped-Ion Physics in Europe

G. Werth, K. Blaum	Mainz	highly charged ions	mass measurements
G. Leuchs	Erlangen	Yb^+, Yb^{2+}	quantum optics
J. v. Zanthier	Erlangen	Mg^+	quantum optics
T. Hänsch, T. Udem	München	Mg^+, He^+	spectroscopy
L. Hilico	Paris	H_2^+	spectroscopy
S. Schiller	Düsseldorf	Ba^+, HD^+	spectroscopy
L. Schweikhard	Greifswald	clusters	mass measurements
R. Wester	Innsbruck	molecular ions	spectroscopy
K. Wendt	Mainz	heavy ions	laser ion sources
W. Quint	Darmstadt	heavy ions	mass measurements
S. Willitsch	Basel	Ca^+	cold chemistry, µtrap

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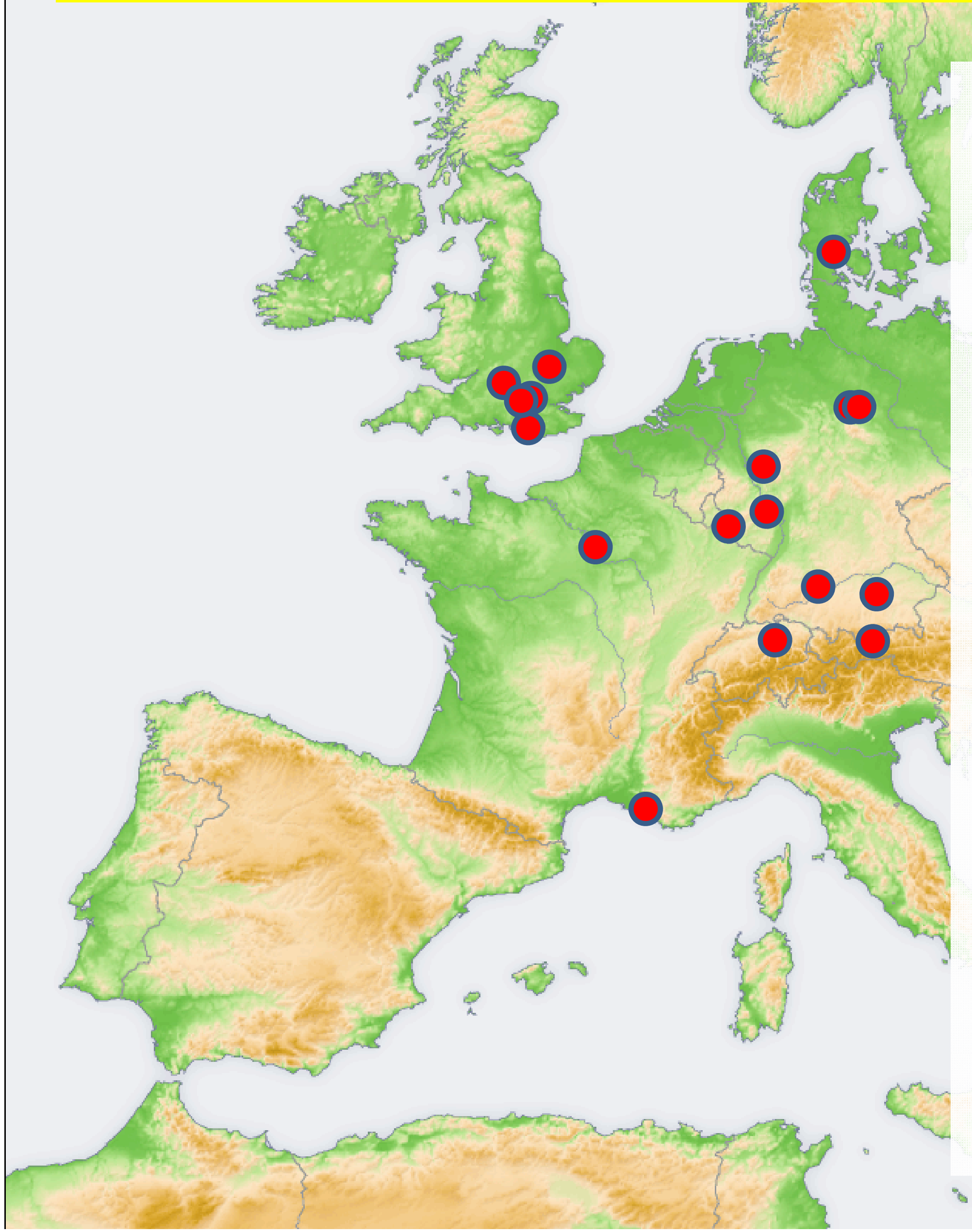
and others in molecular physics, physical chemistry …

Status of Trapped-Ion Physics in Europe



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F. Schmidt-Kaler	Mainz
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P. Schmidt, T. Mehlstäubler	Braunschweig
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J. Hecker-Denschlag	Ulm
M. Köhl	Cambridge
J. Home	Zürich
R. Blatt et al.	Innsbruck

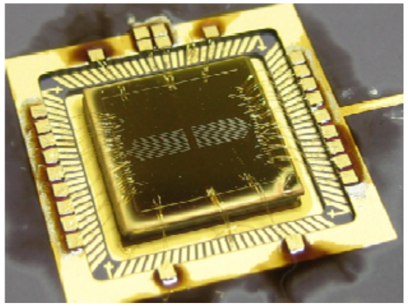
Status of Trapped-Ion Physics in Europe

- **Trap technology (trapology)**
  (Oxford, München, Siegen, Sussex, Teddington, Mainz, Innsbruck)
- **Quantum Information Processing**
  (Oxford, Mainz, Siegen, München, Zürich, Innsbruck)
- **Cavity QED with ions**
  (Aarhus, Sussex, Zürich, Innsbruck)
- **Quantum Simulations**
  (München, Innsbruck)
- **Quantum Metrology**
  (Braunschweig, Teddington, Marseille)
- **Quantum Memory**
  (Paris, Saarbrücken)
- **Ion(s) and BEC** (Cambridge, Ulm)

The Oxford planar ion trap project

D T C Allcock T P Harty H A Janacek C J Ballance N M Linke D N Stacey A M Steane D M Lucas

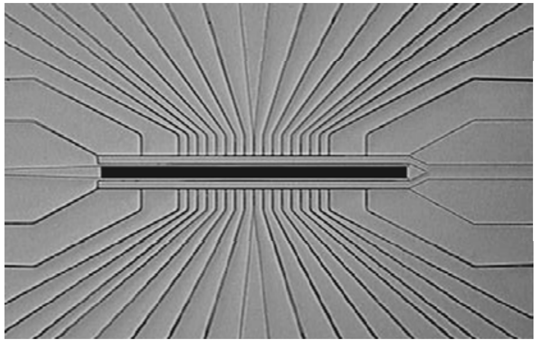
Oxford Fabrication

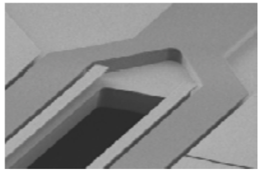


- Gold on quartz `six-wire' design
- New technique for out-of-plane micromotion compensation

Sandia Fabrication

- Three traps tested at Oxford
- Micromotion, heating rate and trap charging issues under investigation



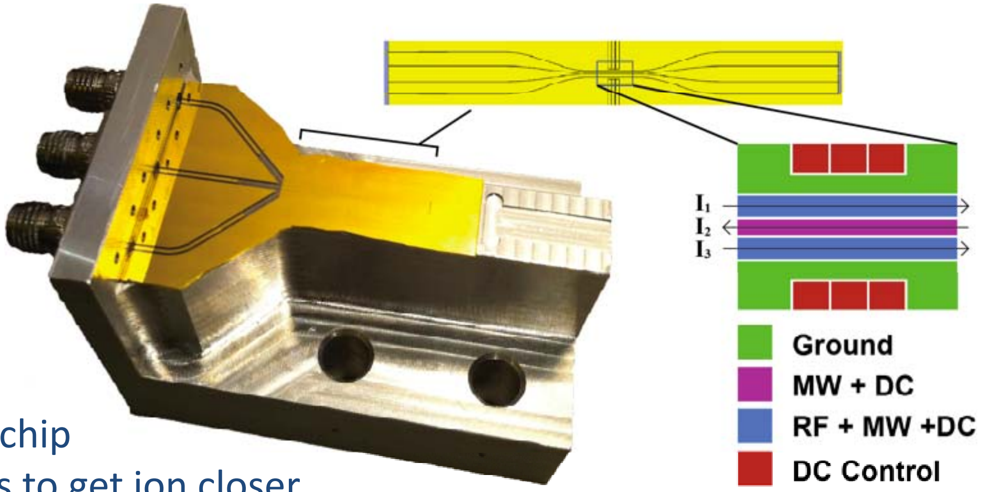


- Monolithic silicon, glass and aluminium fabrication

See talk by D. Stick and poster by D. Allcock

Microwave-driven gates

- Two-qubit entanglement by driving motion with microwave near-field (Ospelkaus scheme)
- High field (140G) $^{43}Ca^{+}$ clock state qubit
- M-S gate directly on qubit using radial modes

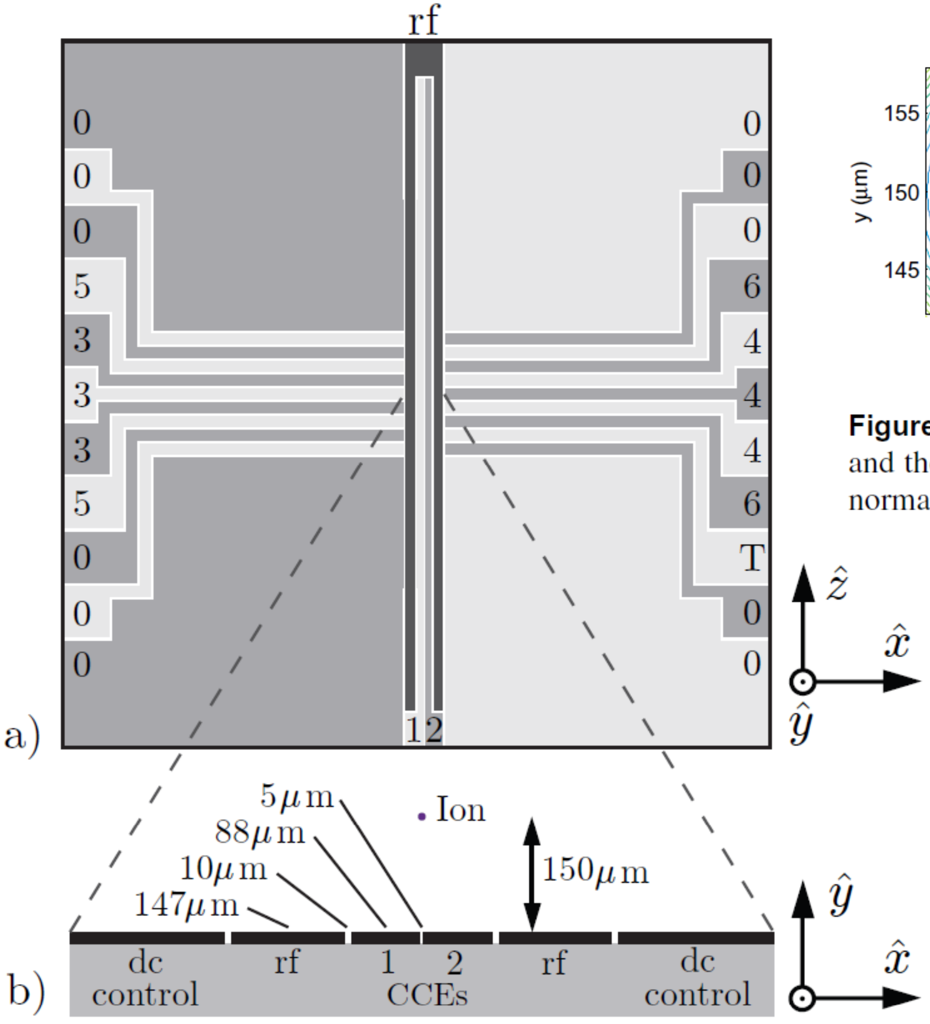


  - Gold on sapphire
  - Half-wave microwave cavities on-chip
  - Combined microwave and rf wires to get ion closer
  - Trap ready for testing this spring.

See poster by T. Harty

The Oxford planar ion trap project

D T C Allcock T P Harty H A Janacek C J Ballance N M Linke D N Stacey A M Steane D M Lucas



six-wire design

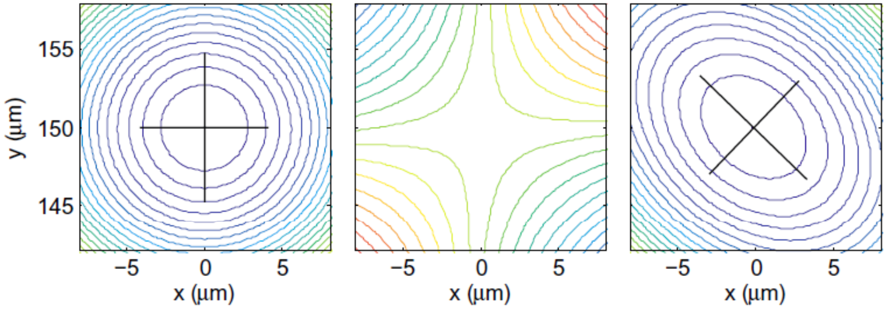


Figure 2. The rf pseudopotential (left), the rotation quadrupole potential (centre) and the superposition of the two (right). The straight lines show the axes of the normal modes of the secular ion motion.

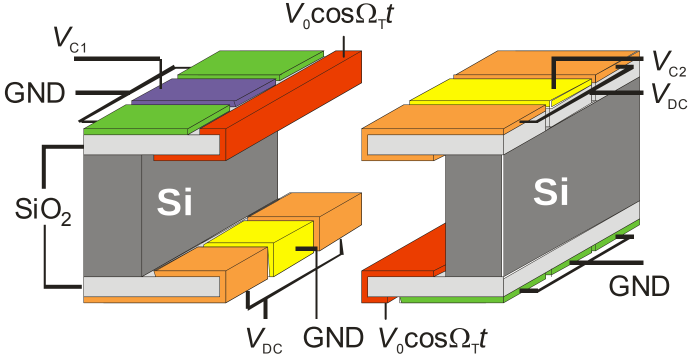
D.T.C. Allcock et al.,
New Journal of Physics ***12 (2010) 053026***

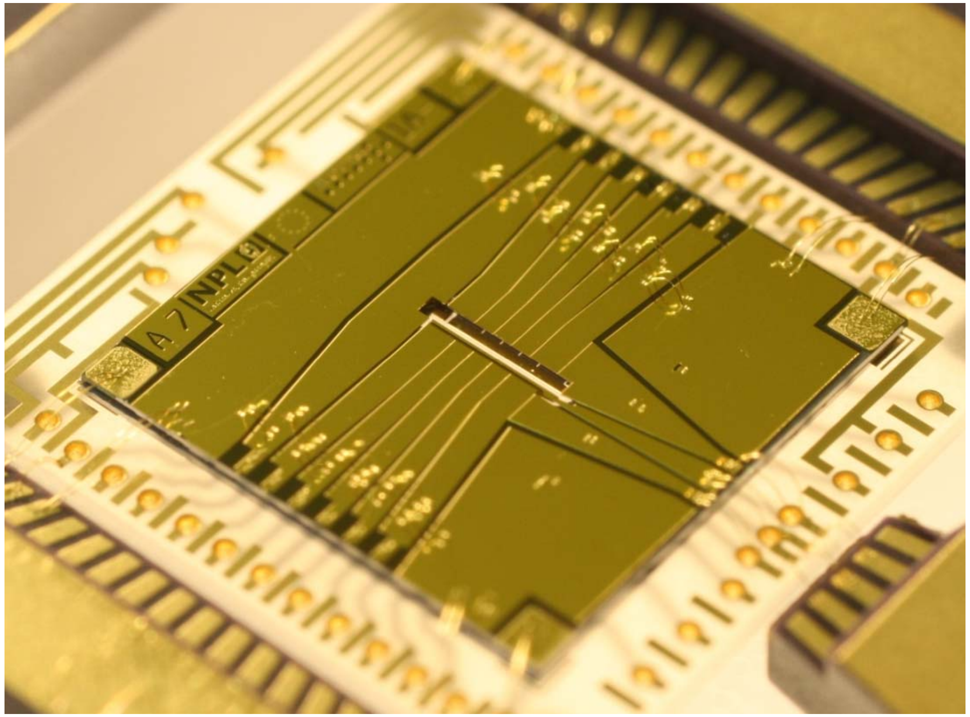
See poster by D. Allcock

3D monolithic microfabricated trap

NPL National Physical Laboratory

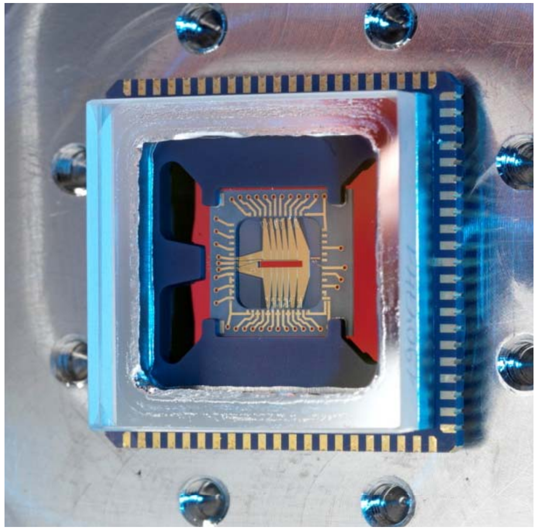
- Oxidised Si wafer (highly doped Si)
- Au-coated SiO_2 forms electrodes
- 6 processing steps: 3 metallisation, 2 etch, 1 plating





Design: M Brownnutt, G Wilpers, P Gill,
R Thompson, A G Sinclair N. J. Phys 8, 232 (2006)

Compact, multi-pin UHV feedthrough:CLCC



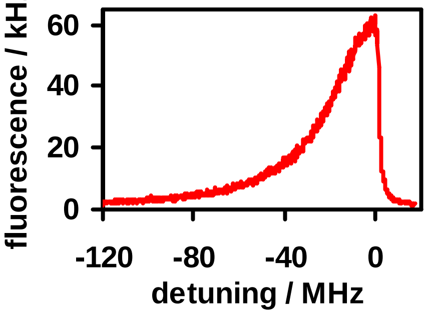
€ € EU: MICROTRAP

Operating microtrap: $^{88}Sr^{+}$

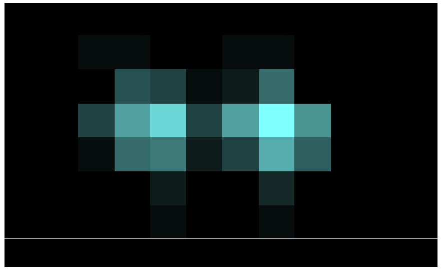
3D trap, monolithic, unit aspect ratio

- Ion-electrode separation = 250 μm
- Deep potential(> 5 eV), high efficiency (η > 0.7)
- Low RF loss, low substrate heating
- 3-segment trap operating (330 μm segment width)

1 ion



2 ions



Ion Storage: preliminary

cooled	≥ 24 hrs
un-cooled	≥ 5 mins

Expected parameters (based on measured U_{RF})

$\Omega_{RF}/2\pi$	U_{RF} (0-pk)	q	$\omega_r/2\pi$	$\omega_z/2\pi$
18.0 MHz	180 volts	0.4	2.5 MHz	1.2 MHz
23.5 MHz	400 volts	0.5	4.2 MHz	2.0 MHz

G Wilpers, P See, P Gill, A G Sinclair

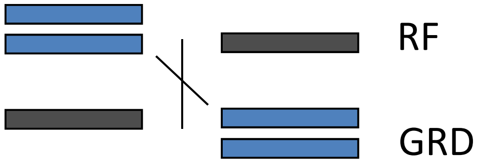
€ € EU: MICROTRAP

Scalable High-Precision Traps for Optical Clocks

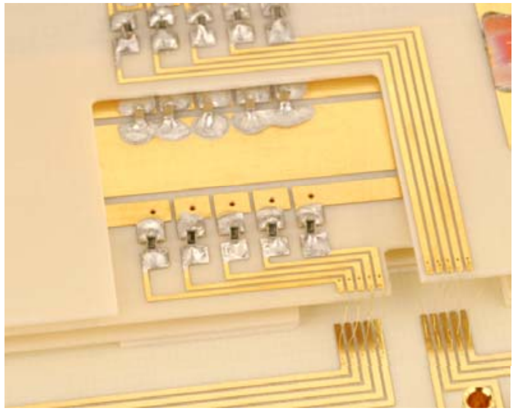
FEM Simulations of RF-fields for reduced micromotion(*)

- → finite length effects
- → alignment (angle, translation)
- → tolerances on notches

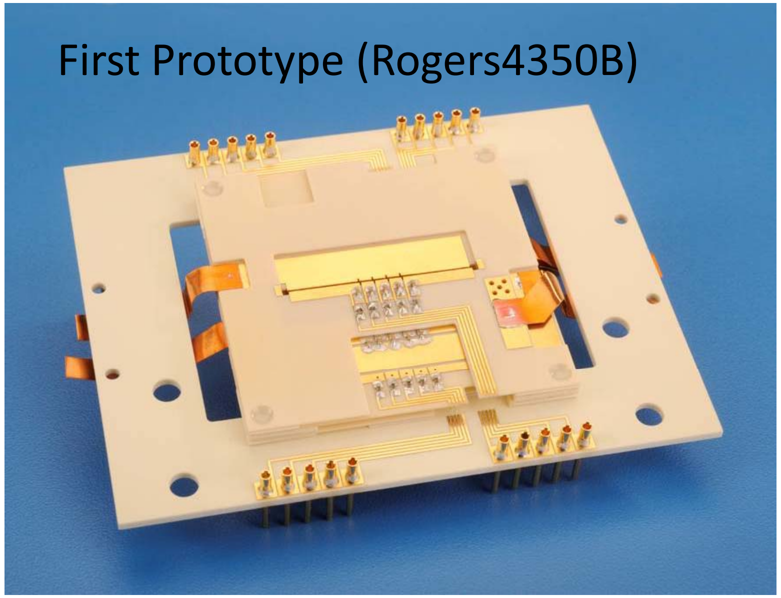
3-layer design for full control of micromotion



on board low pass filters $(2\pi RC)^{-1} = 110$ Hz
non magnetic SMD parts (+Kester solder)
gold wire bonded



stacked with
Optocast 3410
Gen2:
UV+heat cured

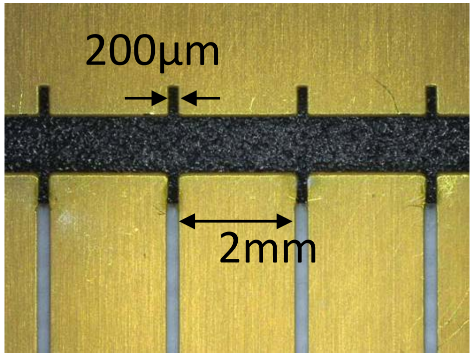


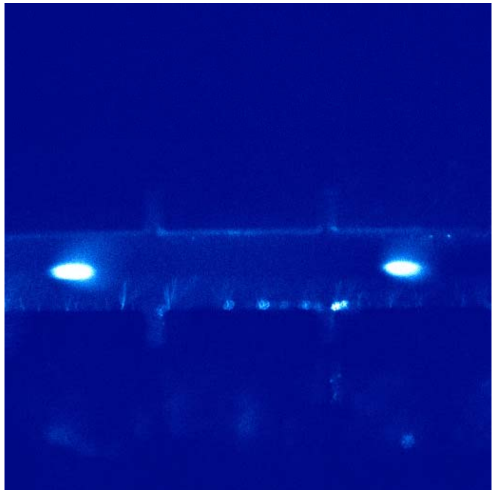
JRG T.E.Mehlstäubler

(*) to be published in Appl. Phys. B

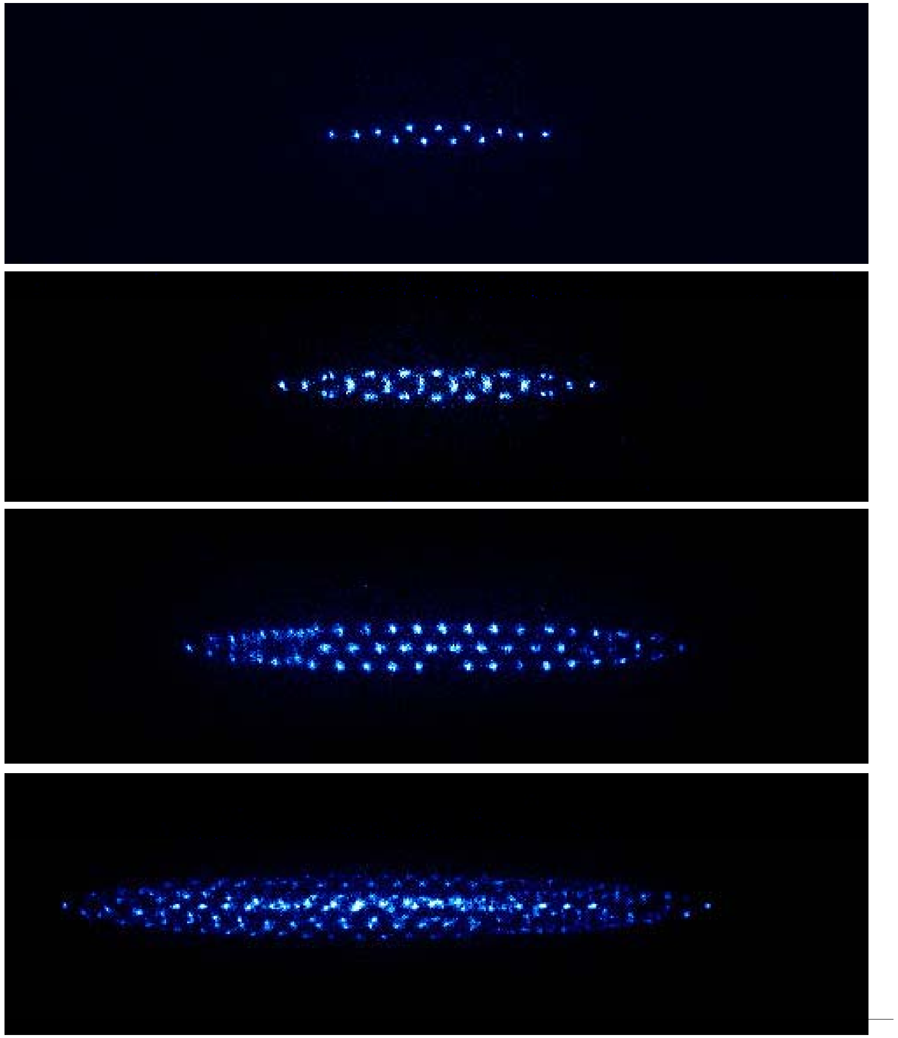
Trapping and shuttling in all trapping segments

segmented electrodes (CO2-laser)





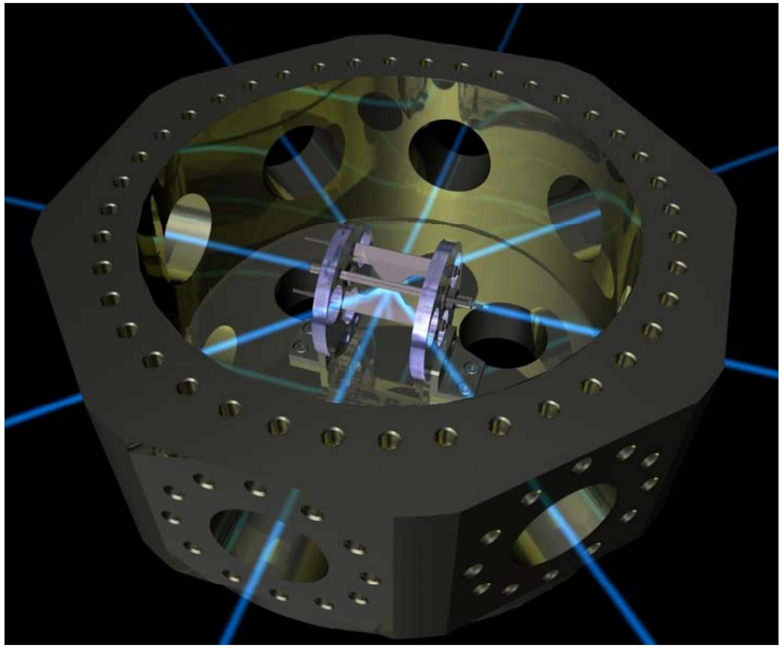
Coulomb crystals of $^{172}Yb^{+}$ ions

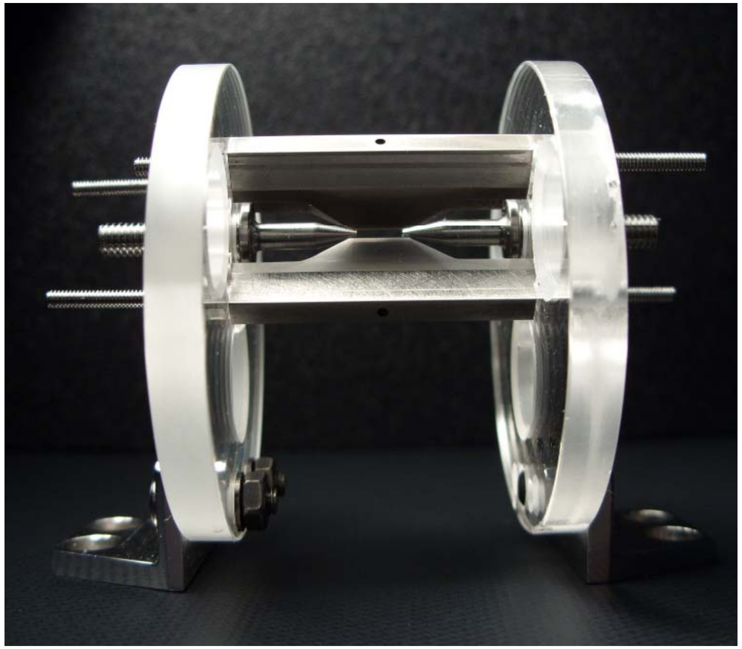


JRG T.E.Mehlstäubler

1^{st} Generation Al^+/Ca^+ trap @ PTB

- Innsbruck Blade Design
- Materials:
  - Sapphire: small rf losses ($\tan\delta \sim 10^{-4}$), high thermal conductivity (~20 W/m·K)
  - Titanium: high thermal (22 W/m·K) & electrical (0.4 μΩ·m) conductivity, non-magnetic





P.O. Schmidt

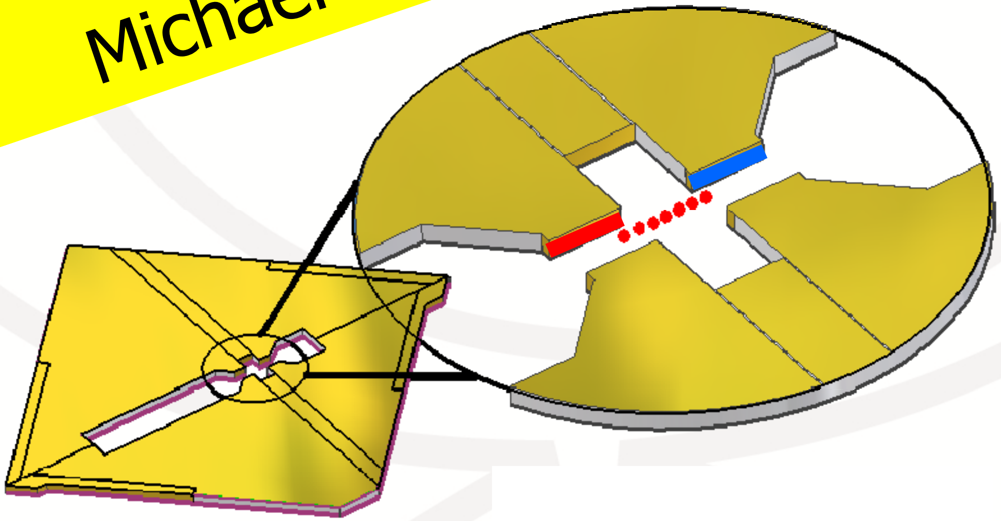
C. Wunderlich et al.

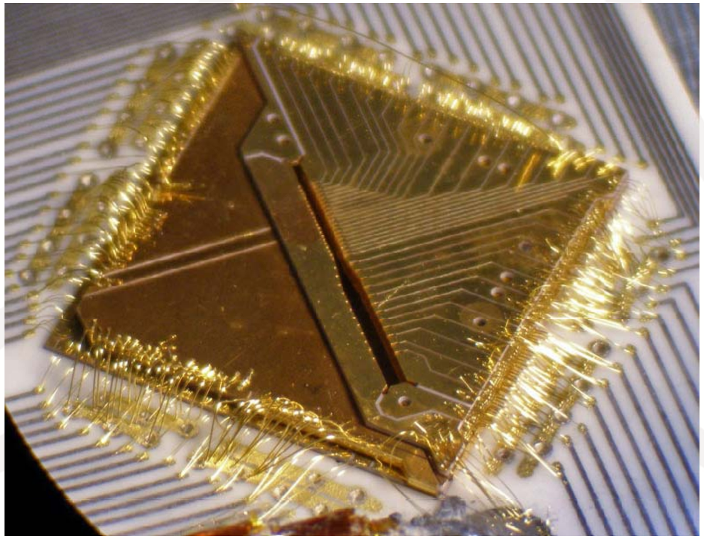
UNIVERSITÄT
SIEGEN

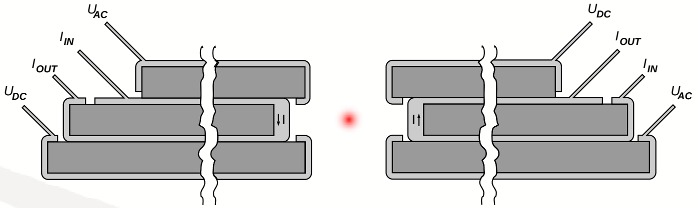
Poster
Michael Johanning

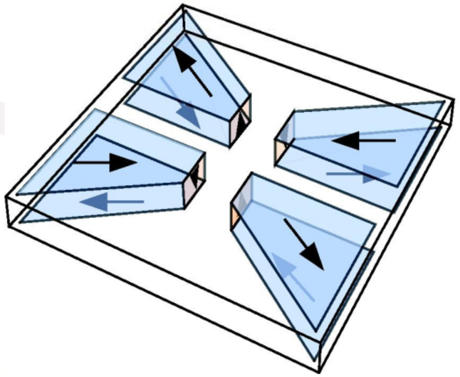
ctured Trap

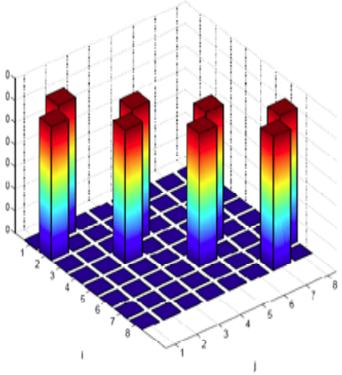
field gradients

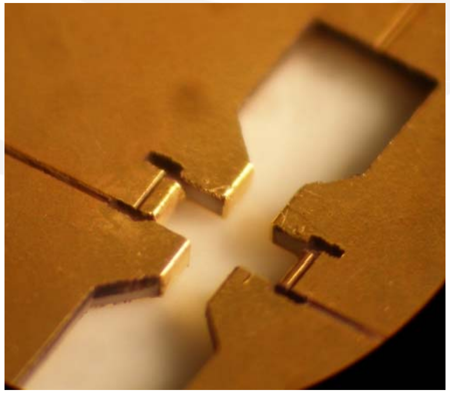






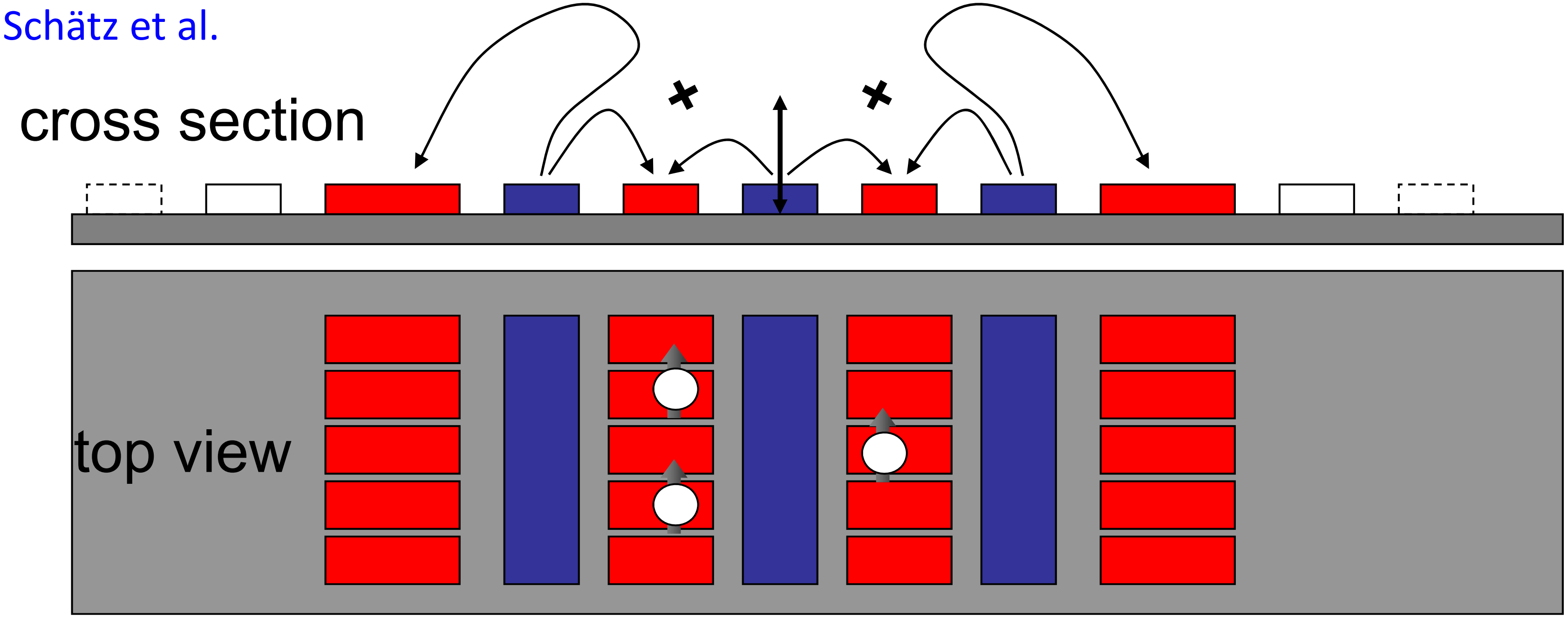






2D-surface traps for QS

T. Schätz et al.

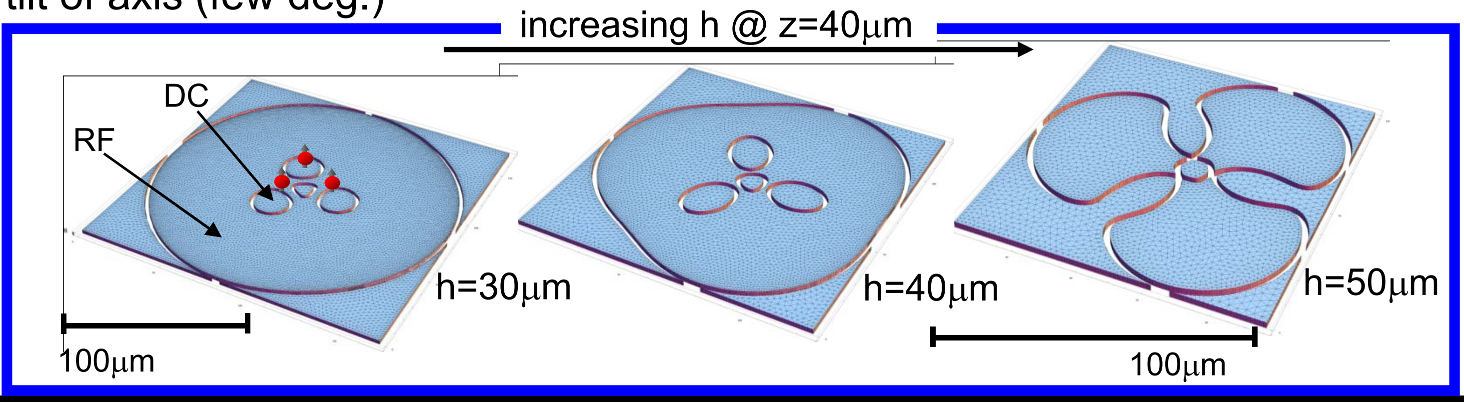


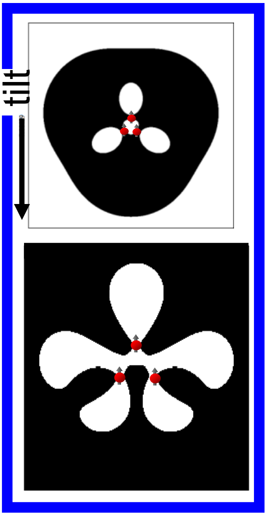
*Journal of Modern Optics (2007)

optimize (2D) trap architecture*:

*collab. NIST,SANDIA,R.Schmied

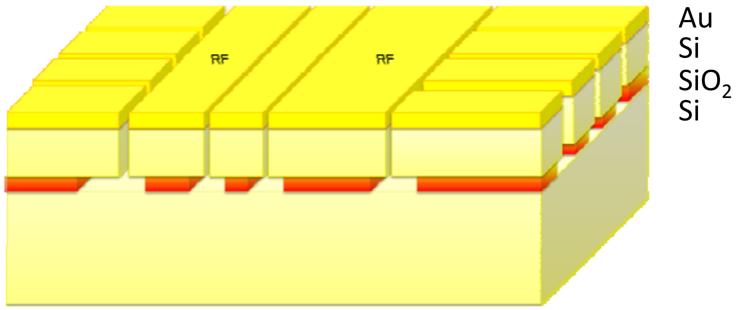
- minimal distance z~40µm (J~z^{-3}~kHz)
- maximal height h>50µm
- tilt of axis (few deg.)





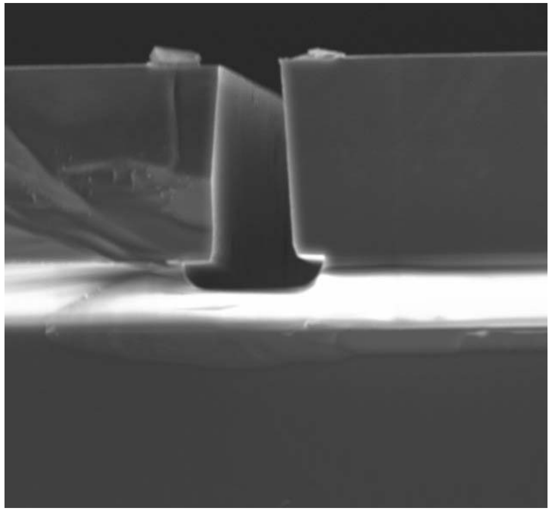
W. Hensinger et al.

Sussex Silicon-on-Insulator Junction Chip



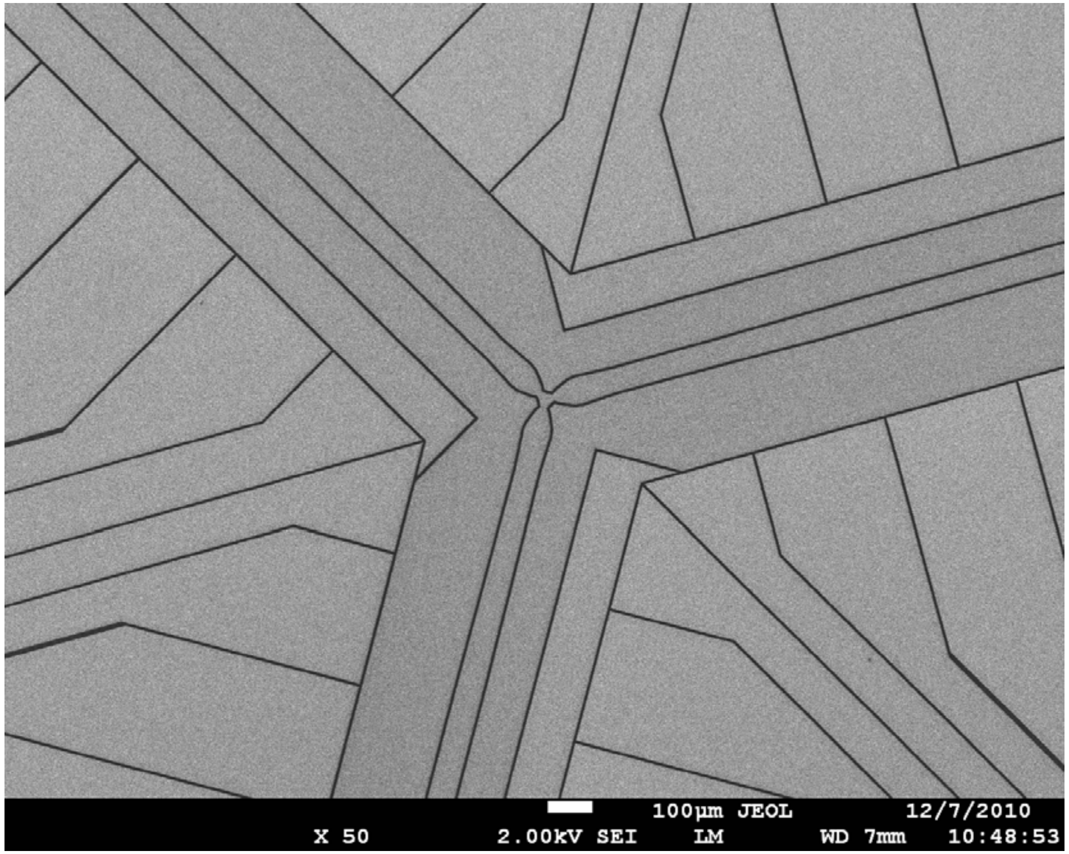
Fabrication design

Similar approach as used in J. Britton et al., Appl. Phys. Lett. **95**, 173102 (2009)



Side-view

M. D. Hughes et al., arXiv:1101.3207 (2011)

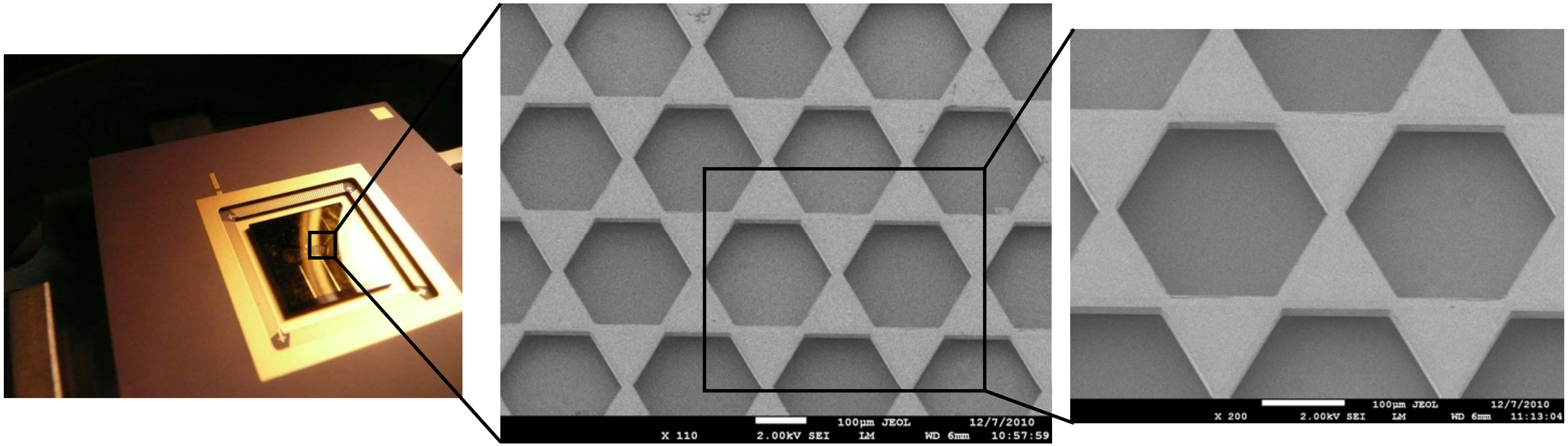


Chip ready for testing

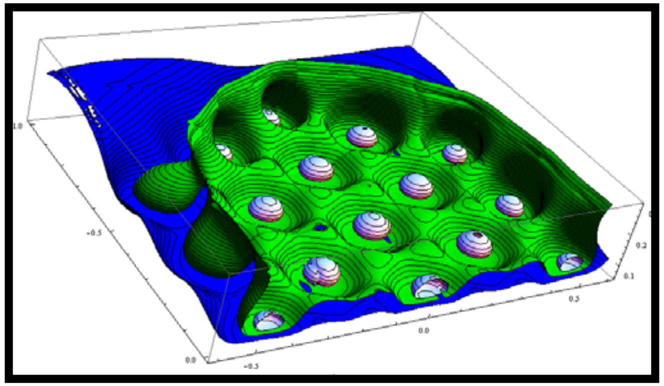
Robin Sterling (Sussex), Hwanjit Rattanasonti (Southampton), Prasanna Srinivasan (Southampton), Michael Kraft (Southampton) and Winfried Hensinger (Sussex)

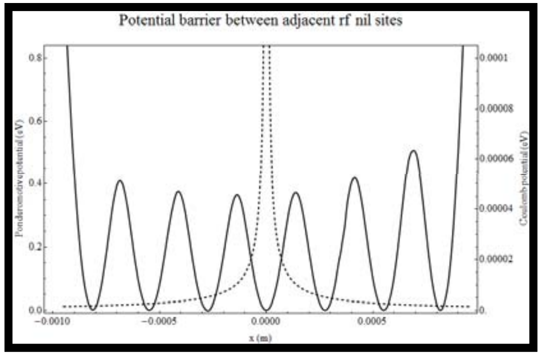
W. Hensinger et al.

Sussex 2-D Ion Trap Arrays



Chip ready for testing





Robin Sterling (Sussex), Hwanjit Rattanasonti (Southampton), Prasanna Srinivasan (Southampton), Michael Kraft (Southampton) and Winfried Hensinger (Sussex)

F. Schmidt-Kaler et al.

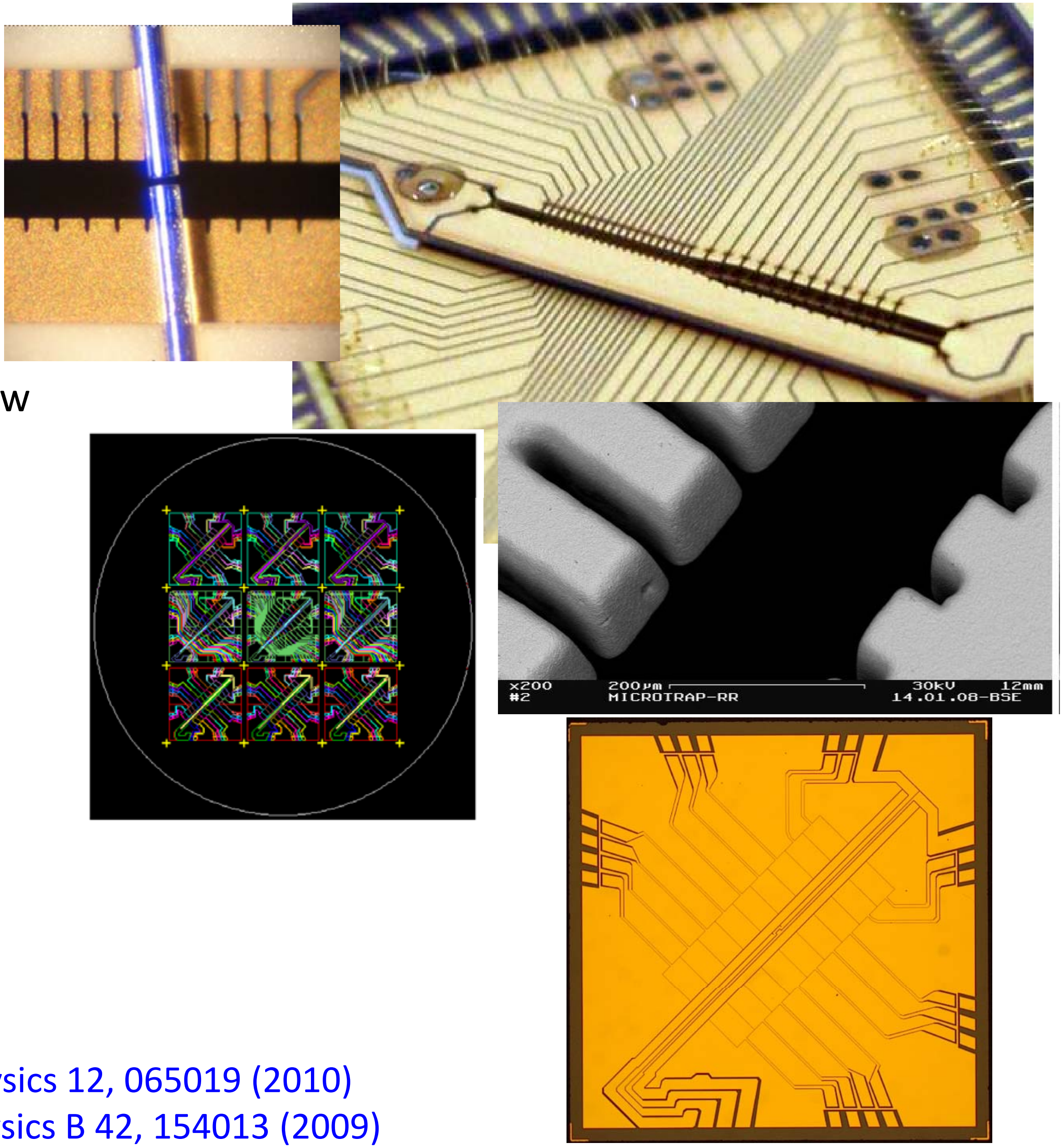
Mainz: Trap Fabrication

3D Microchip Traps

- Ti/Au on Al_2O_3-Wafer (10nm/400nm)
- fs-Laser cut Au/Ti and Al_2O_3 (accurate to 1µm)
- mounting on Chip Carrier
- second one mounted to He flow cryostat, 300K … 77K … 4.2K
- Integration of fiber cavity

Planar Traps

- Thick resist technique, lift-off, evaporation or electroplating
- Au (few µm) on Sapphire, Borosilicate glass-wafer
- Optionally mounted to He flow cryostat, 4.2K
- Integration of high magnetic field gradient current lead



M. Hellwig, et al., New Journal of Physics 12, 065019 (2010)
U. G. Poschinger et. al, Journal of Physics B 42, 154013 (2009)

Fast Ion Transport – Electronics and Tools

F. Schmidt-Kaler et al.

Development of fast multichannel voltage supplies

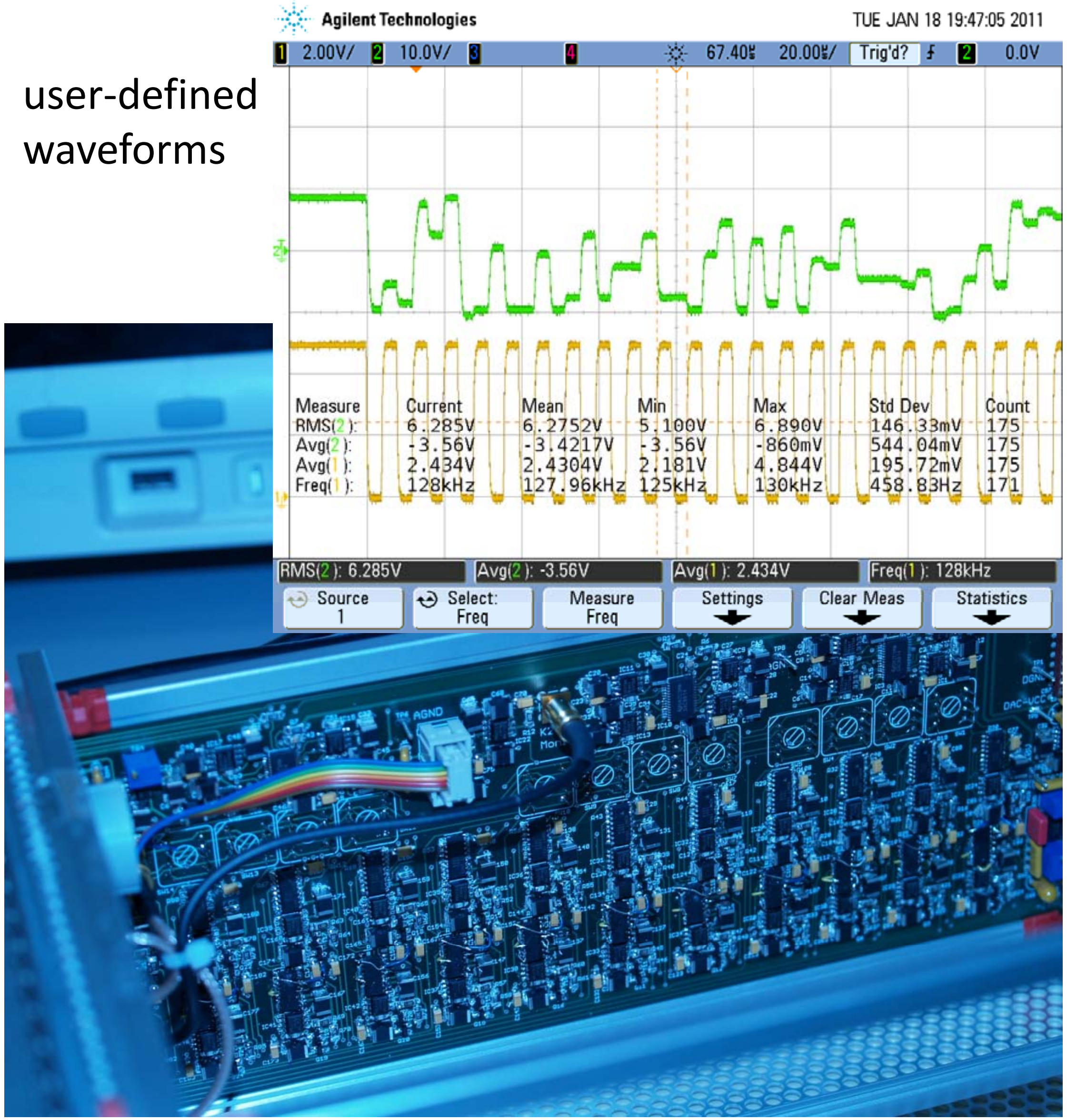
- FPGA based system
- Data supply via Gbit Ethernet
- High slew rate 20 MV/s
- Low interchannel crosstalk
- 1 μs update on 60 channels
- 16 bit resolution

Electrostatic field simulations

- Boundary element method
- Helpful for design of future traps
- Numerical solver and ion trajectory calculator
- Calculation of optimized transport ramps
- Optimal control scheme for quantum operations

K. Singer, et al., Rev. Mod. Phys. 82, 2609 (2010)

user-defined waveforms



Measure	Current	Mean	Min	Max	Std Dev	Count
RMS(2):	6.285V	6.2752V	5.100V	6.890V	146.33mV	175
Avg(2):	-3.56V	-3.4217V	-3.56V	-860mV	544.04mV	175
Avg(1):	2.434V	2.4304V	2.181V	4.844V	195.72mV	175
Freq(1):	128kHz	127.96kHz	125kHz	130kHz	458.83Hz	171

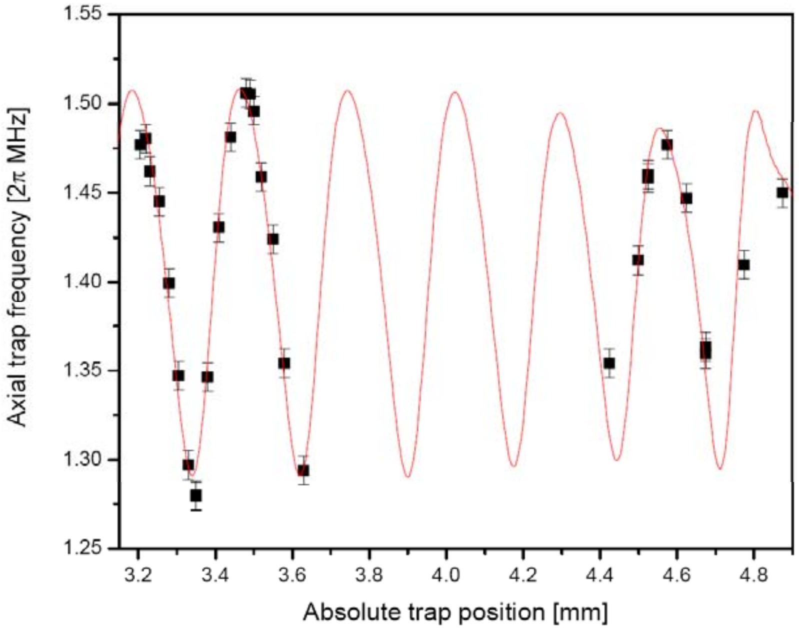
Fast Ion Transport – Measurement with Ions

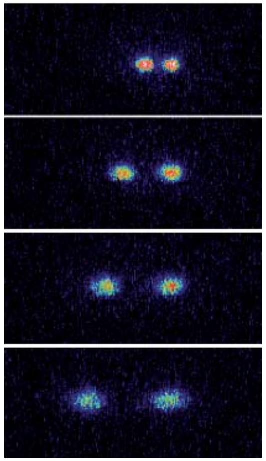
Transport spectroscopy

- Agreement of calculated and measured trap frequencies on the 1% level

G. Huber et al., Applied Physics B 100, 725 (2010)

F. Schmidt-Kaler et al.





Feedback-optimized transport and splitting

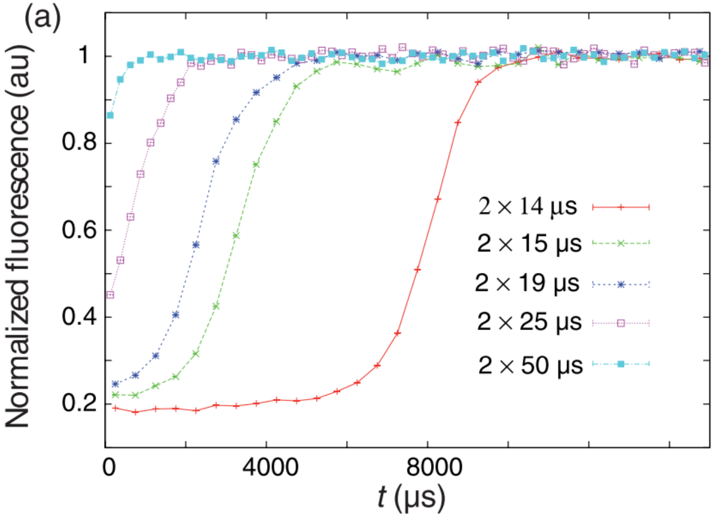
- CCD image information for servo
- works without calculation
- slow „learning“ of the voltage ramp – fast „replay“
- asymmetric splitting operations

J. Eble et al., JOSA B 27, A99 (2010)

Non-adiabatic transport

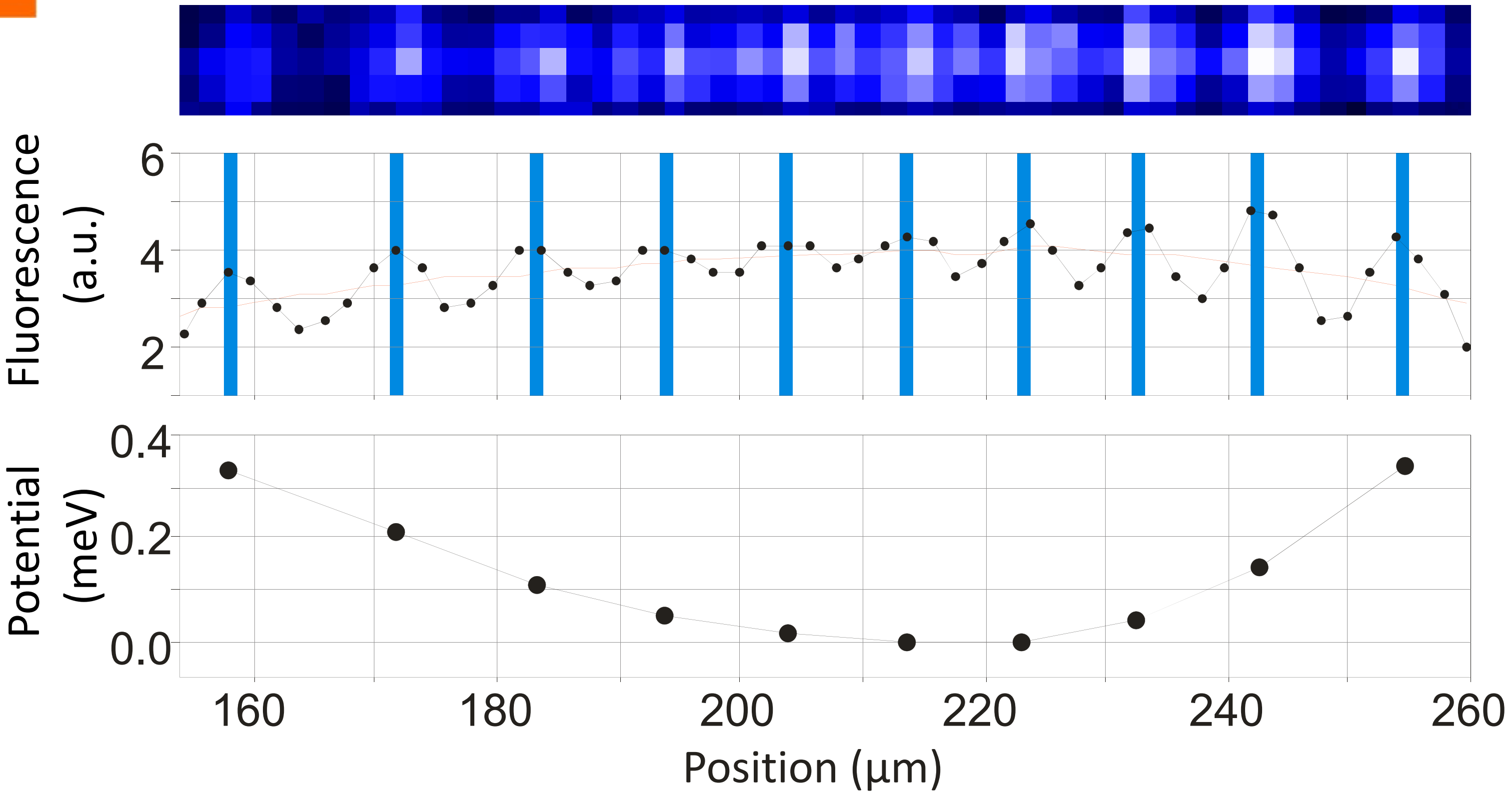
- transport on time scale of the trap frequency
- optimized ramp
- recooling measurements

G. Huber et. al., NJP 10, 013004 (2008)



Ion-crystal field sensor

- Image ions onto CCD Camera
- Measure the inter-ion distances
- Calculate the potential seen by string

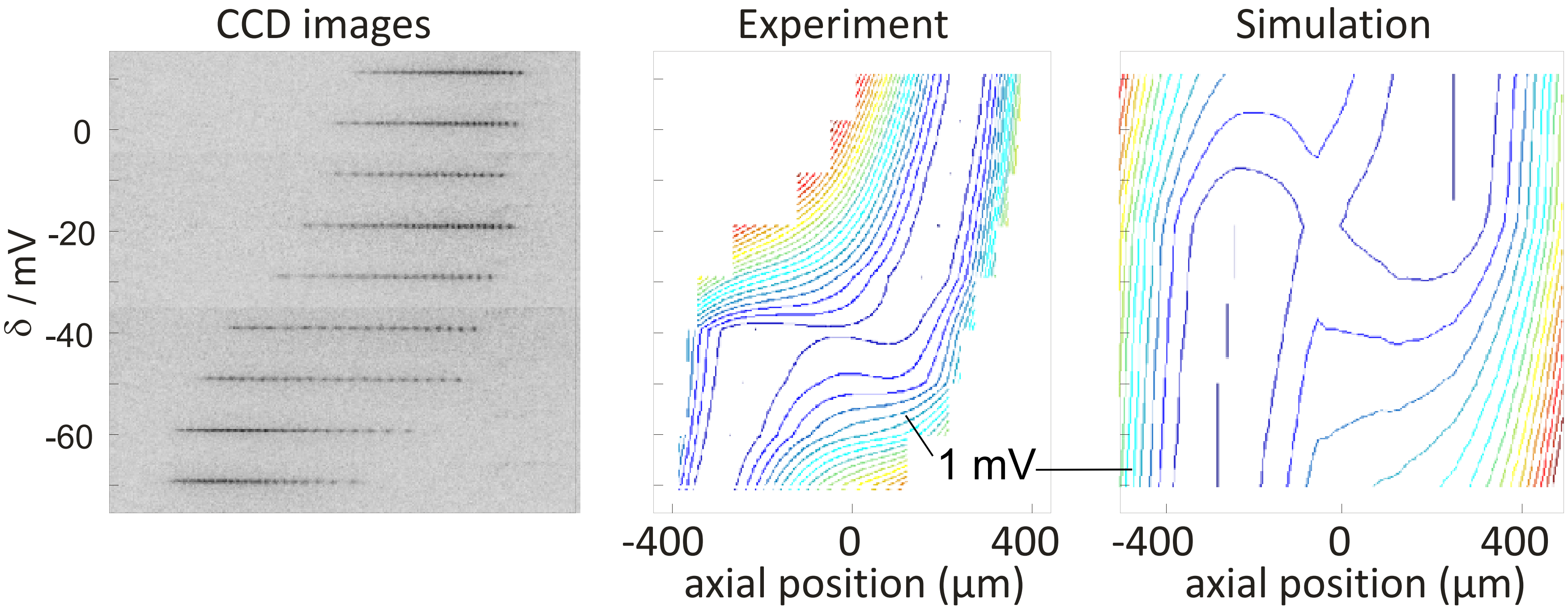


M. Brownnutt, M. Harlander, W. Hänsel and R. Blatt
"Spatially-resolved potential measurement with ion crystals" In preparation

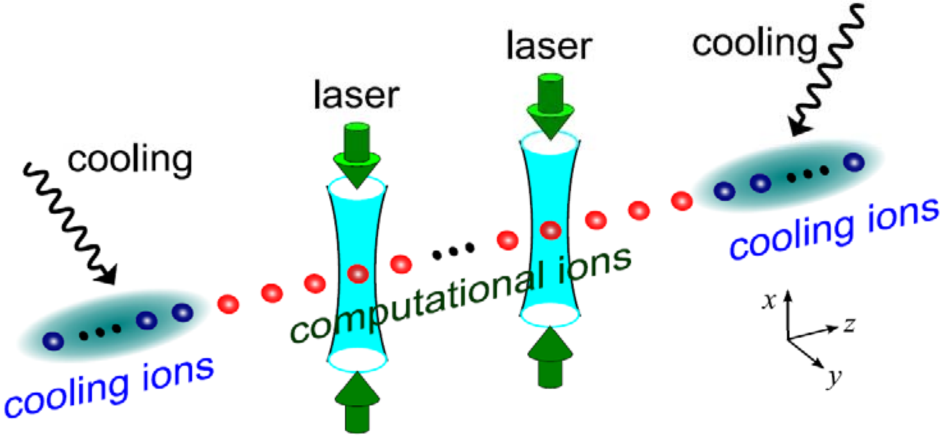
Ion-crystal field sensor

- Image ion string for different electrode potentials
- Reconstruct the potential
- Compare this to simulations
- Simulations very sensitive to small changes in voltage

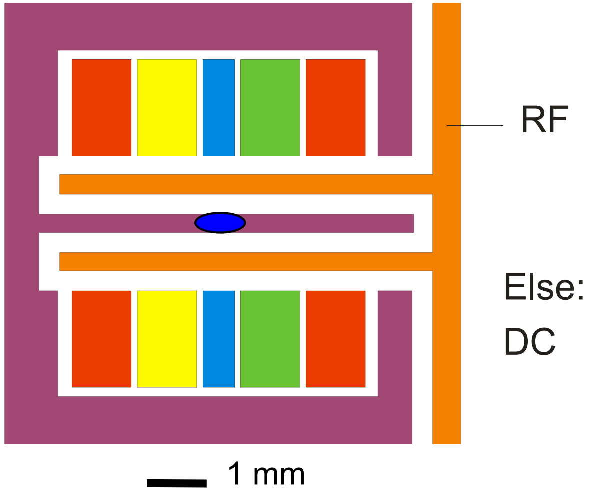
⇨ not accurate enough to be predicitve



Long ion chains

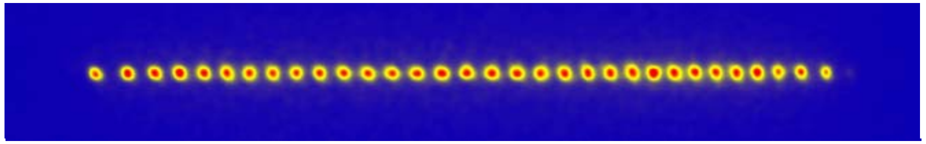


Lin et al., Europhys. Lett. **86**, 60004 (2009)

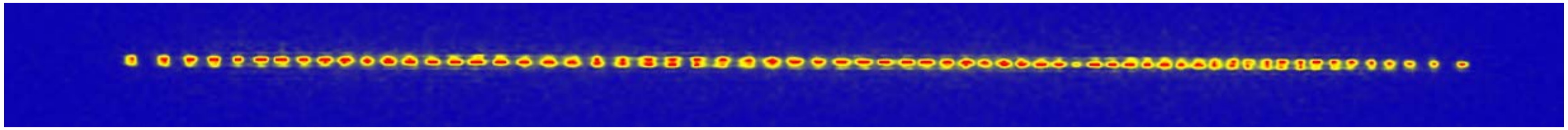


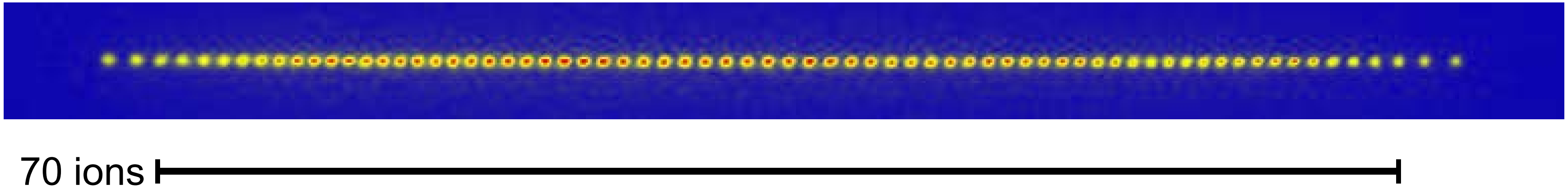
“Bastille” design

32 ions



64 ions

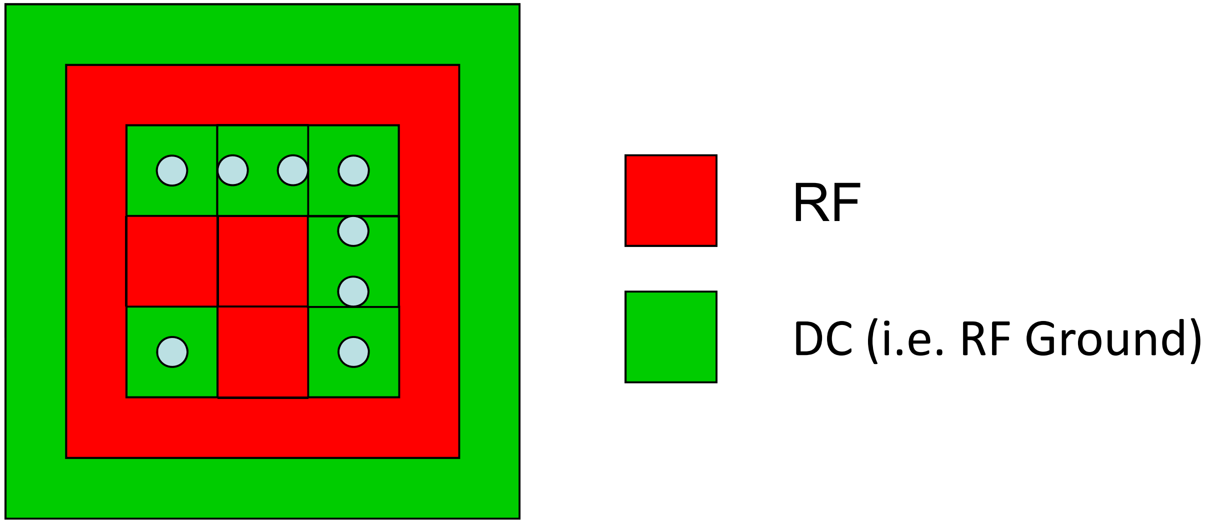




70 ions

11.7 µm per ion → 760 µm

2-dimensional RF shuttling array (“Folsom” design)



Pros: Surface topology
Shuttling in 2D
Never leave the RF null

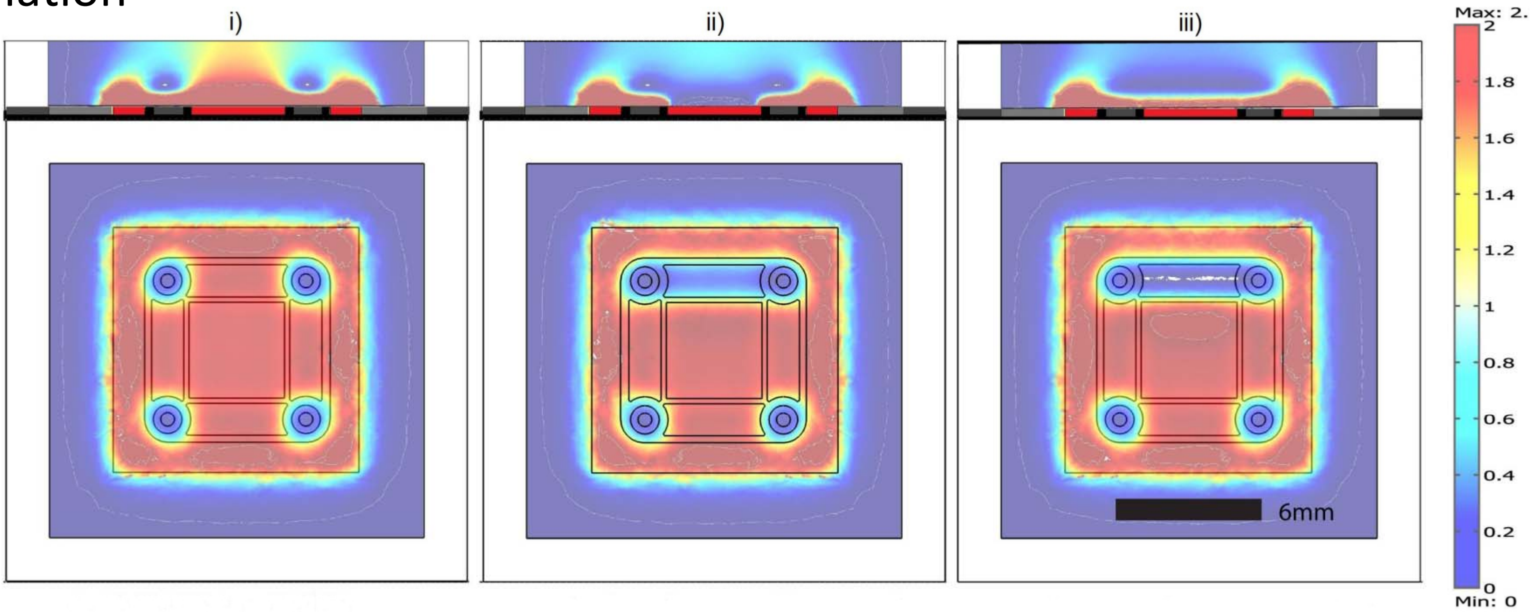
Cons: Need ~2N independently variable,
phase locked RF sources

M. Kumph, M. Brownnutt, and R. Blatt
“2-Dimensional Arrays of Addressable Interacting Ion Traps” In preparation

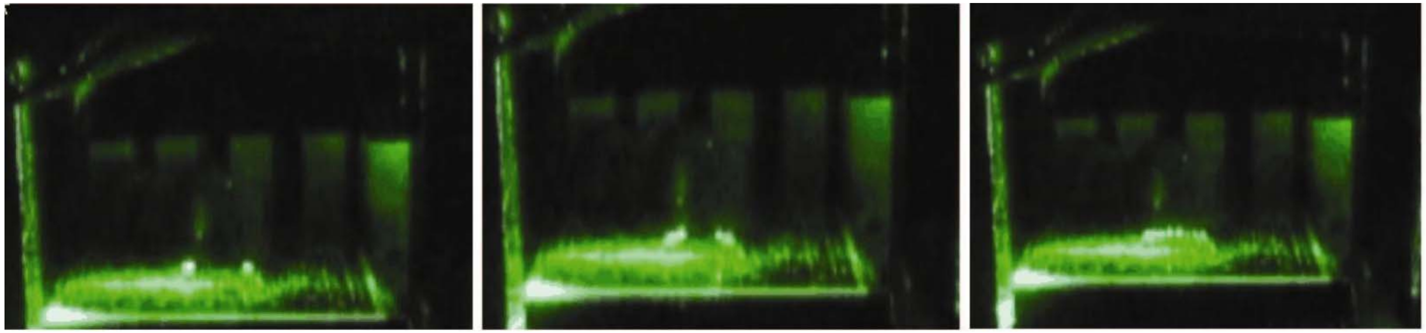
2-dimensional RF shuttling array ("Folsom" design)

Proof of principle in a dust trap

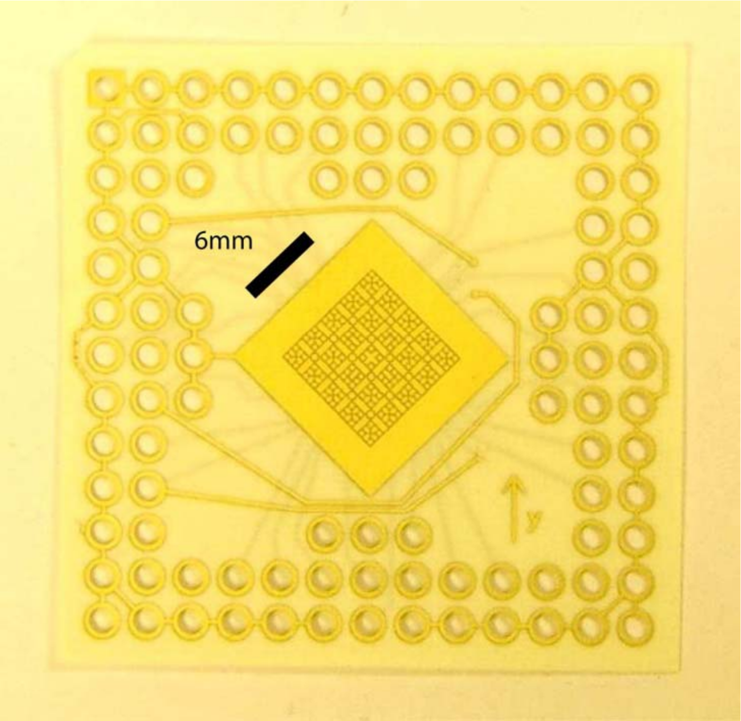
FEM Simulation



Experiment (using dust particles and variacs to tune the RF voltage)



2-dimensional RF shuttling array (“Folsom” design)



Trapping Ca$^+$

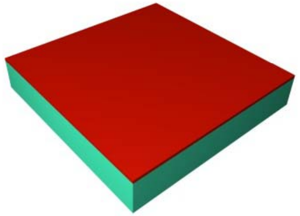
Traps fabricated by Andus GmbH

- Au-plated Cu 15 µm thick
- PCB (RO4350b) substrate,
- 50µm gap between electrodes
- 1.5 mm inter-trap spacing

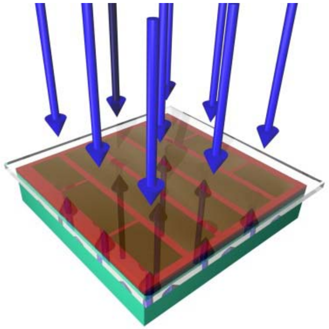
Status:

Fabricated
Wired up (including 32 independent RF supplies)
Baking out

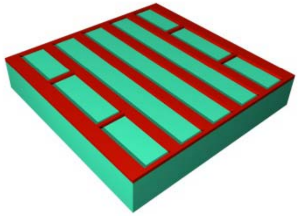
Surface trap fabrication @ Innsbruck



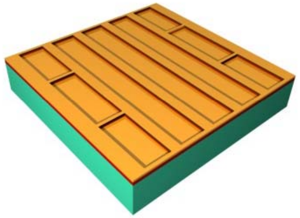
Spin coating



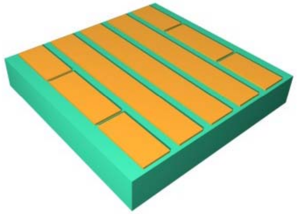
Exposure



Development

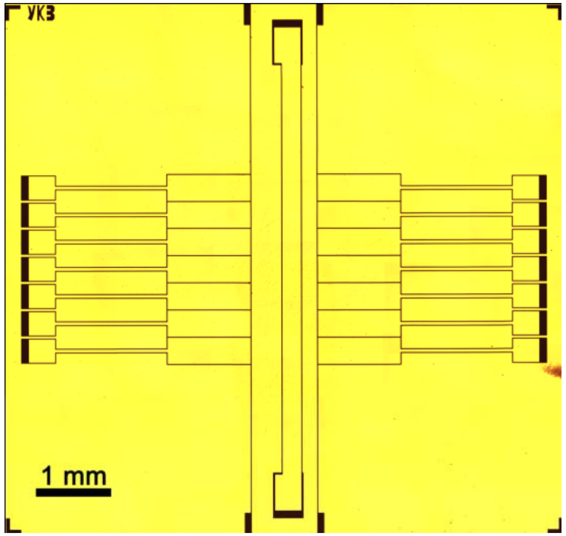


Gold evaporation

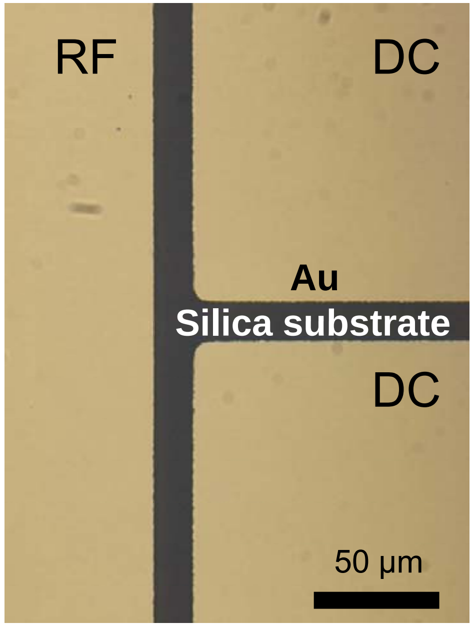


Final trap

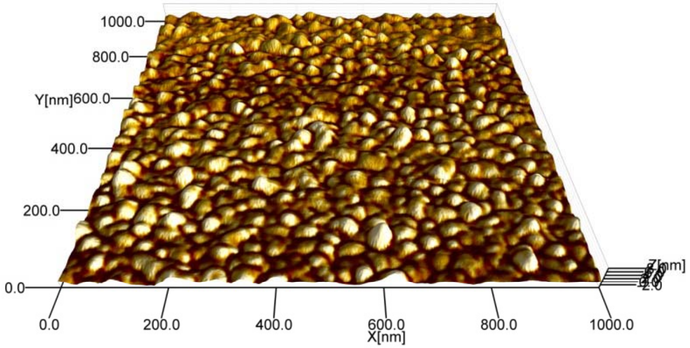
Surface trap fabrication @ Innsbruck



“Yedikule”
design

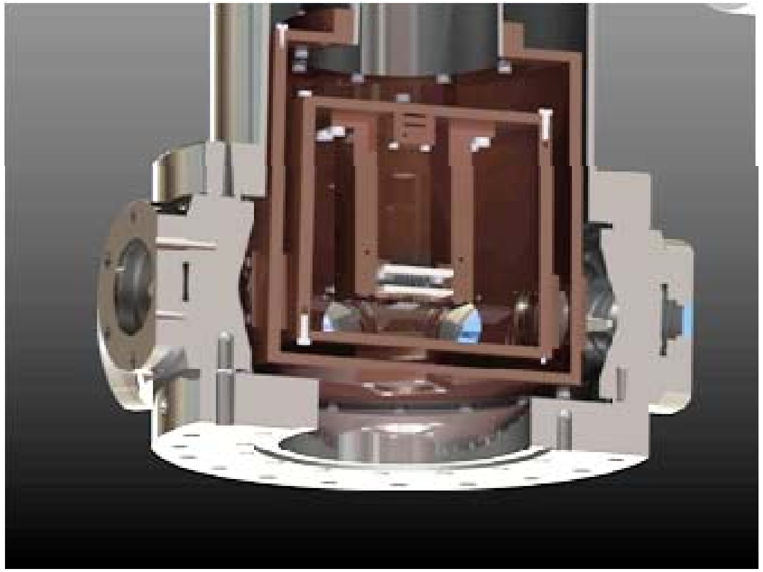


2 µm resolution

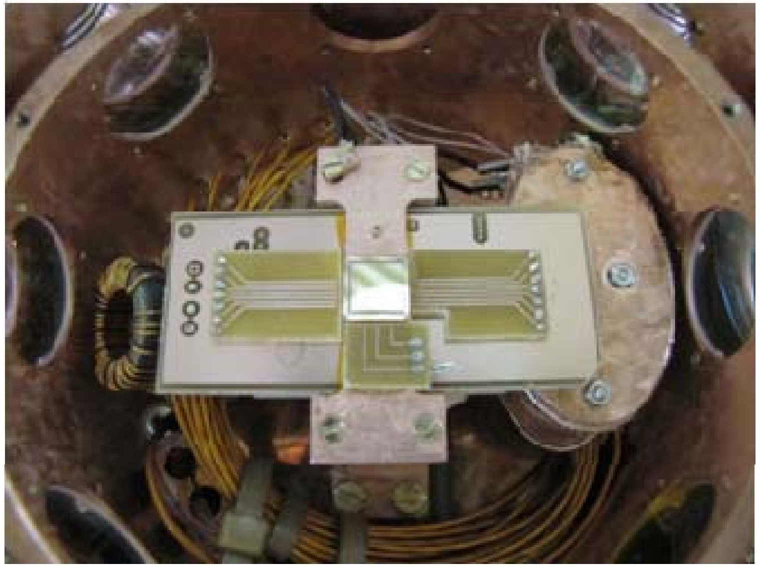


1.6 nm roughness

Cryotrap project @ Innsbruck



Gifford McMahon Cryostat
(ARS)



Our setup:

Trap @ 5 K (at the moment)

Cooling power: 500 mW

Cool down: 130 min

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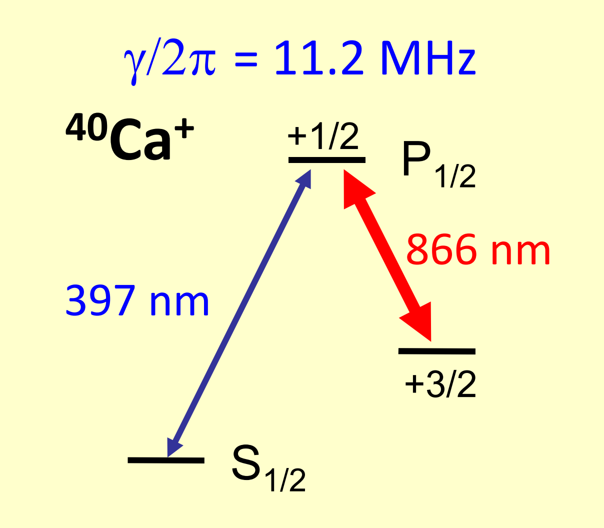
The Aarhus Cavity Trap Setup

M. Drewsen et al.



$\gamma/2\pi$ = 11.2 MHz

$^{40}\mathbf{Ca}^{+}$

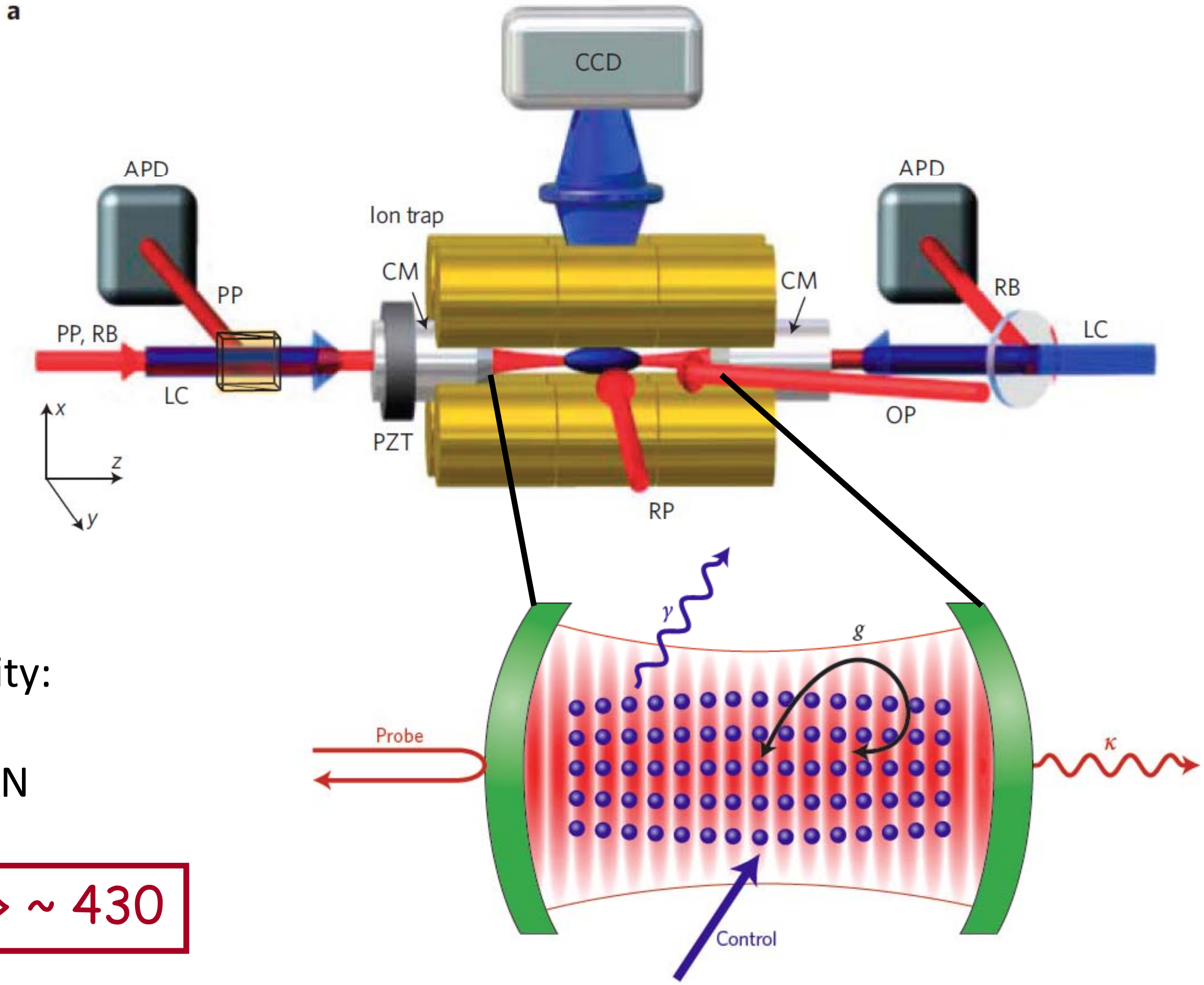
+1/2 $P_{1/2}$

866 nm

397 nm

+3/2

$S_{1/2}$



Coulomb crystal inside a cavity:

- collective strong coupling ~N

$g_{eff} = gN^{1/2} > \gamma, \kappa$ => $N > \sim 430$

→ towards a Quantum Memory

P. Herskind et al., Nature Physics 9, 494 (2009)

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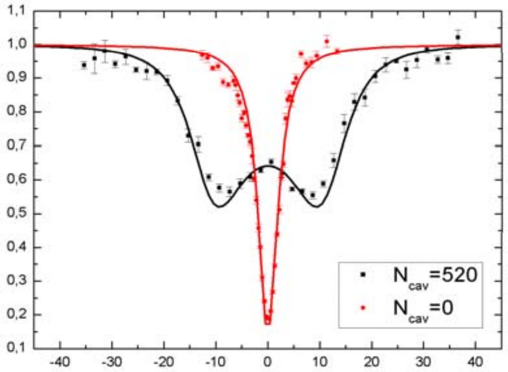
Scientific results

M. Drewsen et al.

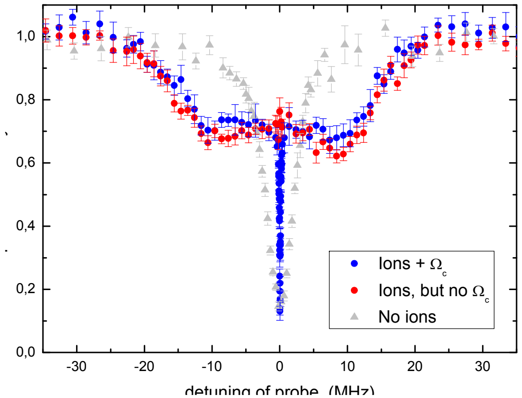
- Collective strong coupling has been realized with ion Coulomb crystals.

Nature Physics **5**, 494 (2009)



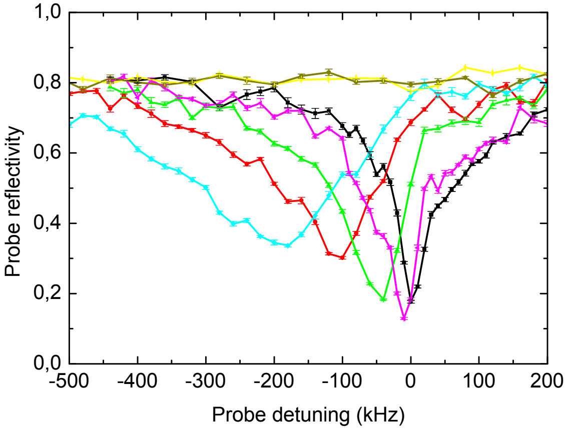
- Cavity EIT in the collective strong coupling regime has been demonstrated.

Unpublished

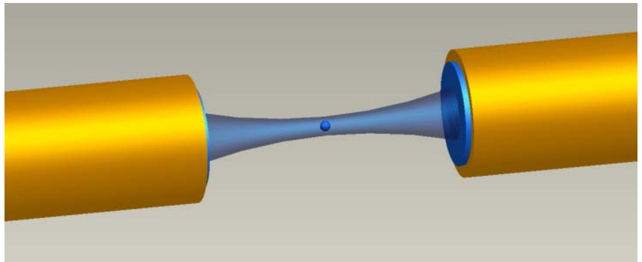


- A photon blockade mechanism has been demonstrated via a 4-level scheme in the $^{40}Ca^{+}$ ion.

Unpublished

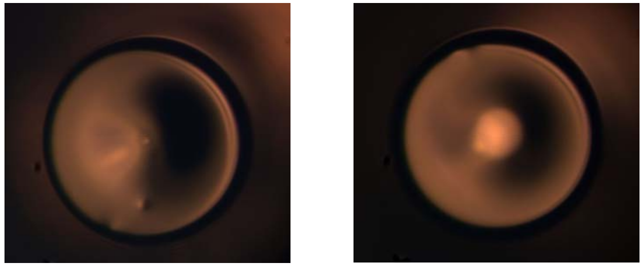


Ion-trap fiber-cavity apparatus



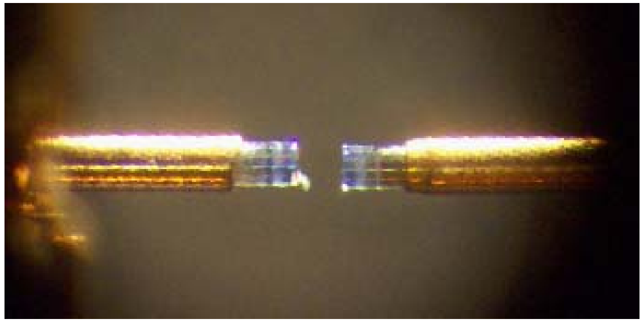
Fiber cavity production:

- together with Jakob Reichel, ENS Paris
- cavities up to a length of ~100µm possible with fibers of cladding size of 125µm
- longer cavities: bigger cladding necessary
- SM fiber to couple light into cavity
- MM fiber on output



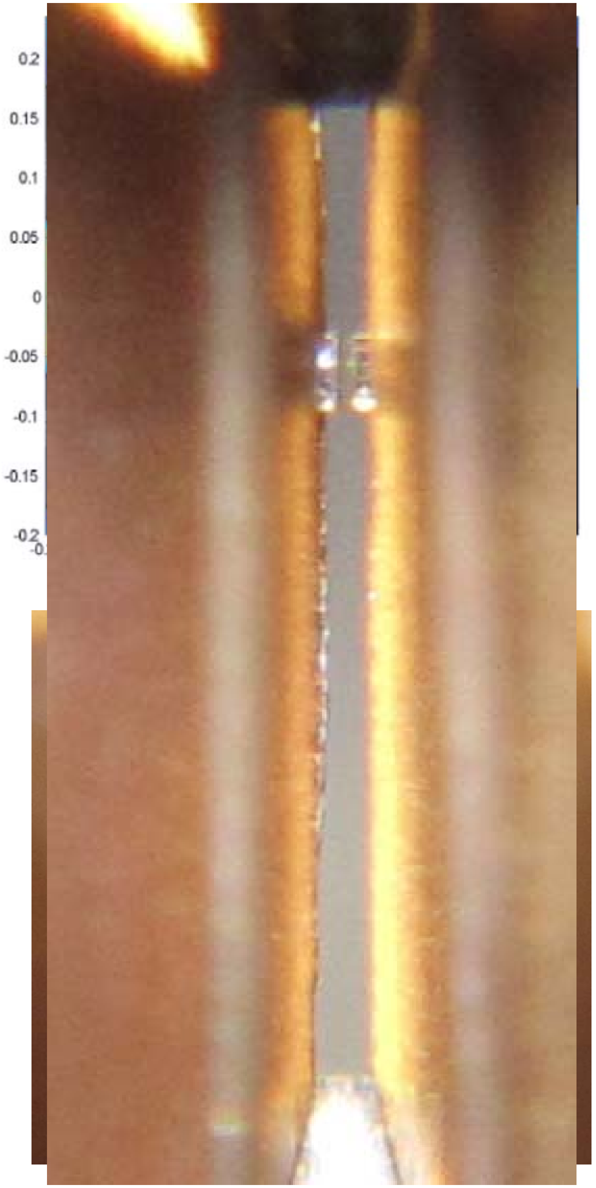
Fiber cavities:

- fiber diameter: 200µm
- fiber to fiber distance: 200µm
- F = 71 000 @ 844nm
- $(g,\kappa,\gamma) = 2\pi\,(39,7,11)$MHz
- used @ 866nm or 854nm
- stabilized with 785nm light



B. Brandstätter, T. Northup, J. Reichel, RB, Innsbruck (2010)

Ion-trap fiber-cavity apparatus



Trap geometry:

- angle between blades: 120° and 60°
- blade distance: 340µm
- diameter of compensation electrodes: 200µm
- distance of comp. el. to trap center: 1.5mm
- endcap distance: 2.4mm
- hole in endcaps: 0.3mm

Trap parameters from simulations:

CPO3D including dielectrics, analysis in Matlab

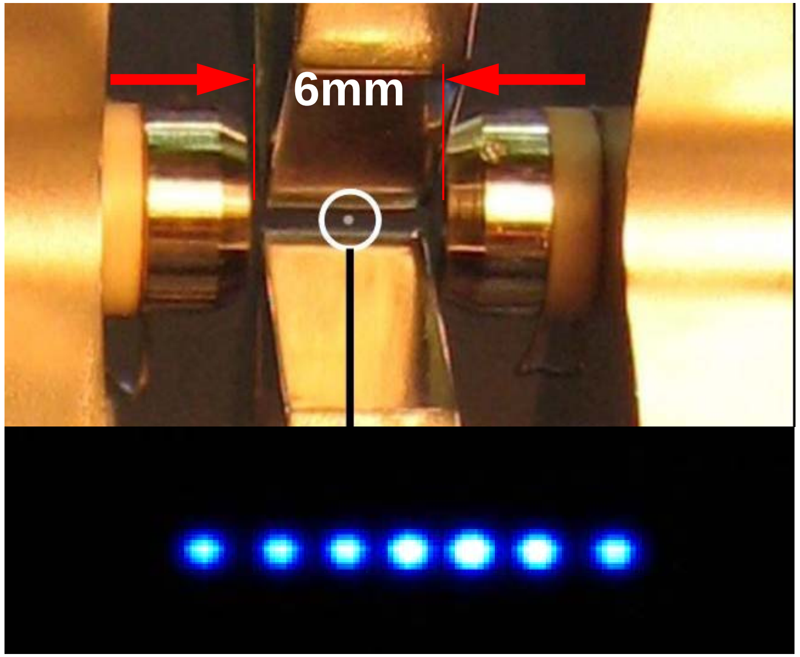
- RF amplitude: 150V @ 2π 40MHz
- endcap voltage: 1000V

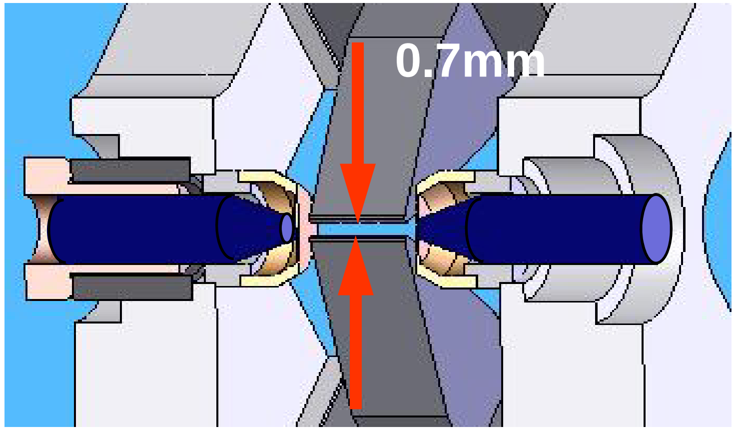
we calculate

- $q = 0.36$
- trap depth: 2.6eV
- $\omega_r = 2\pi\ 4.2/6.4$ MHz, $\omega_z = 2\pi\ 1.7$ MHz

B. Brandstätter, T. Northup, J. Reichel, RB, Innsbruck (2010)

Linear ion trap + collinear cavity





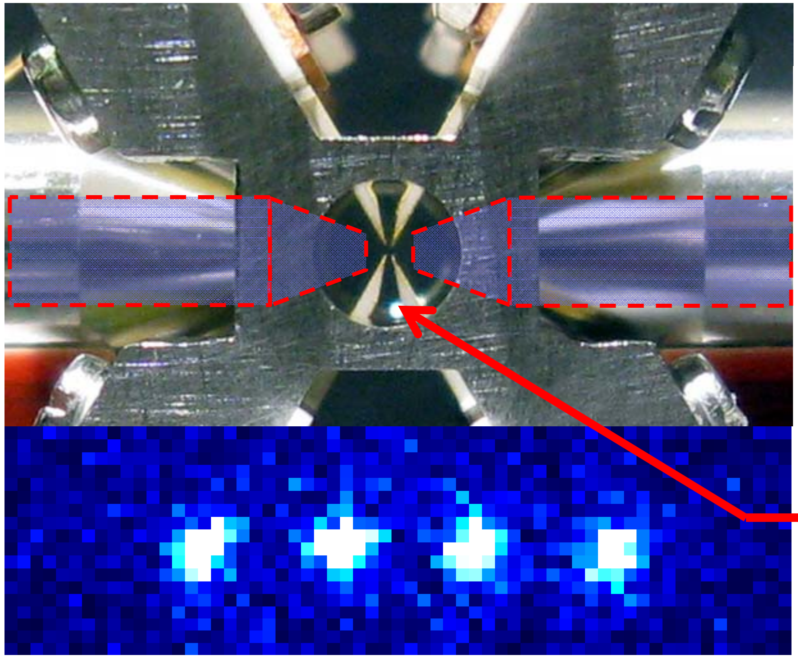
- cavity with conventional mirrors
- oriented along trap axis

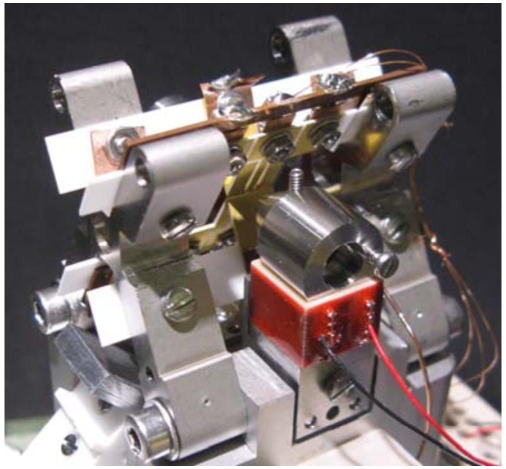
Projected coupling: $g = 2\pi \times 1.1\ \mathrm{MHz}$

Long strings with selected ions weakly coupled to cavity mode

Objective: cluster states of multiple ions

Linear ion trap + transverse cavity





Miniature linear trap

electrode separation 200 μm
cavity length down to 500 μm
conventional mirrors

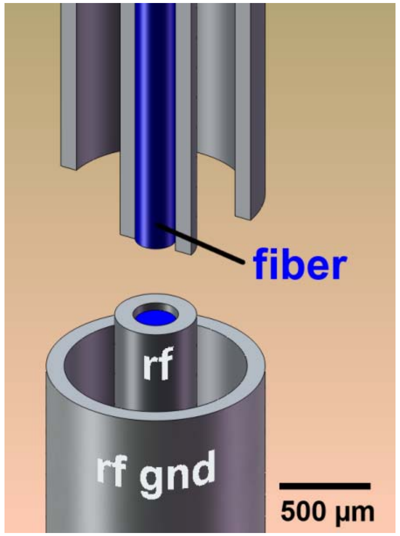
Projected coupling: $g = 2\pi \times 6.4$ MHz

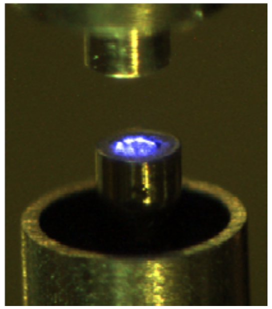
Up to 4 ions strongly coupled to cavity mode

Objective: photon-mediated ion-ion coupling

Fiber-coupled ion-photon interface

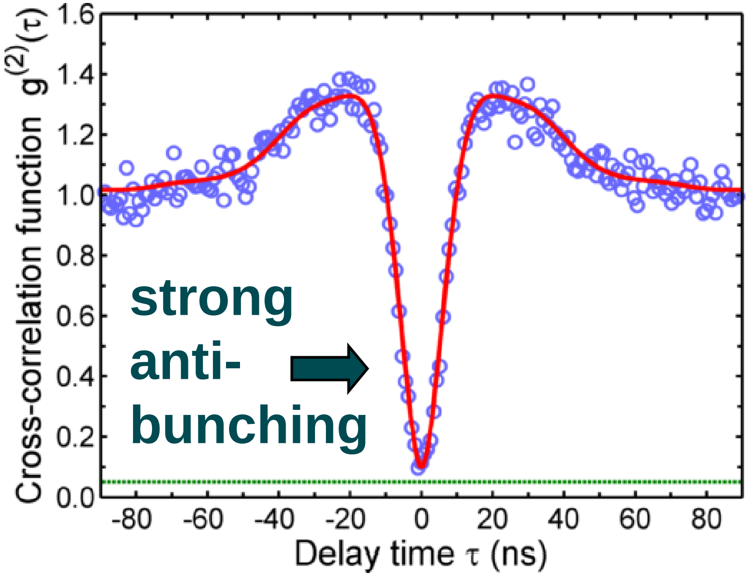
Single ion in endcap trap with integrated pair of optical fibers

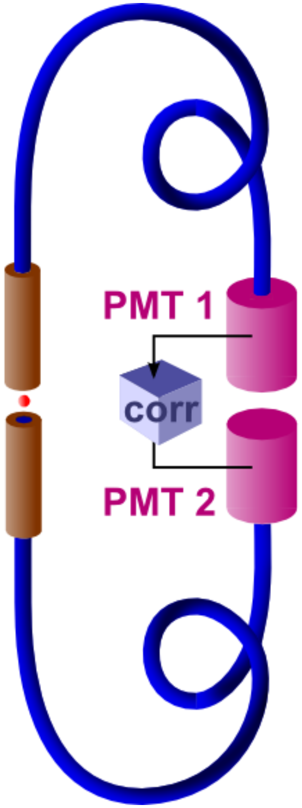




NA of optical fiber:	0.34
Light capture efficiency:	6%
Signal/background ratio:	49

Fiber-based $g^{(2)}$ function

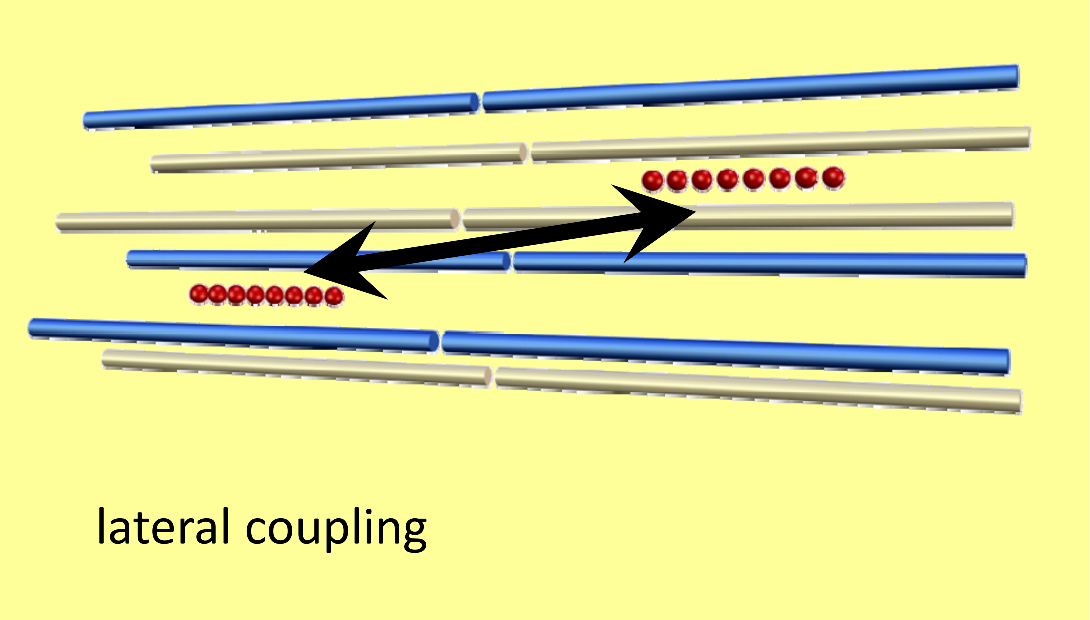




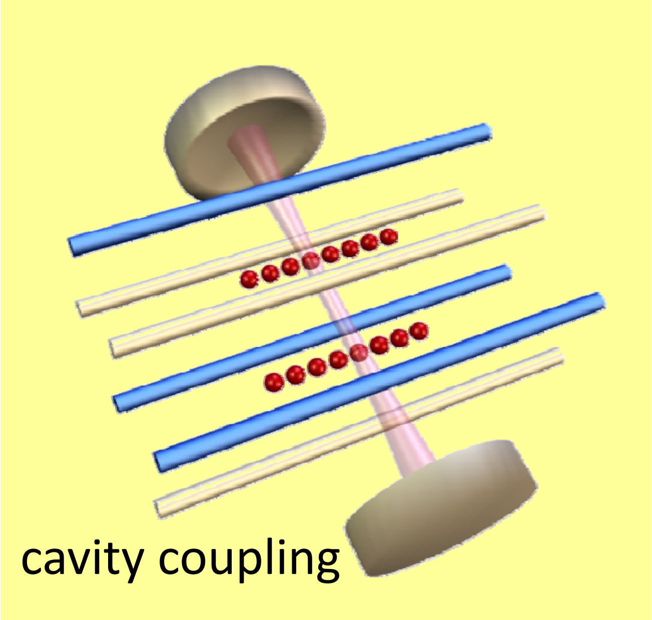
arXiv: 1101.5877

Objective: single ion coupled to fiber-cavity

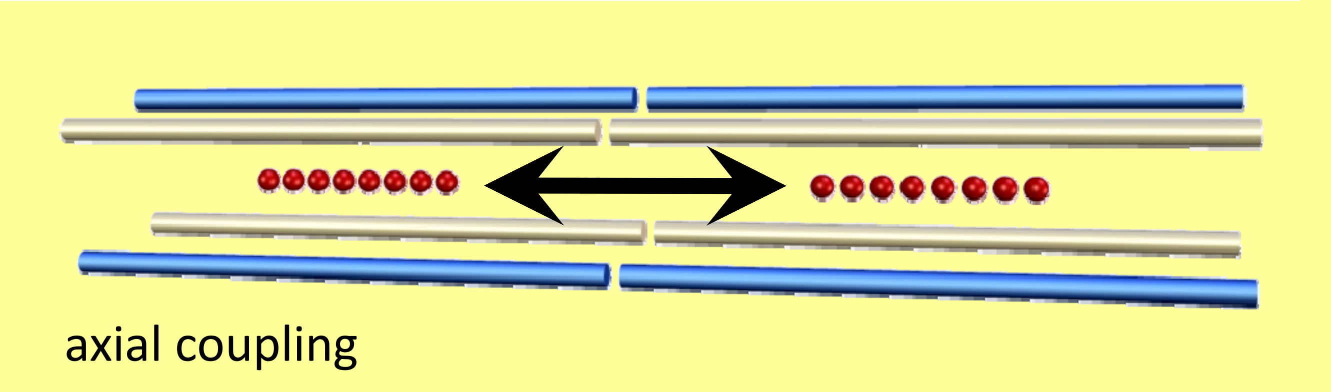
Coupling Quantum Information



lateral coupling



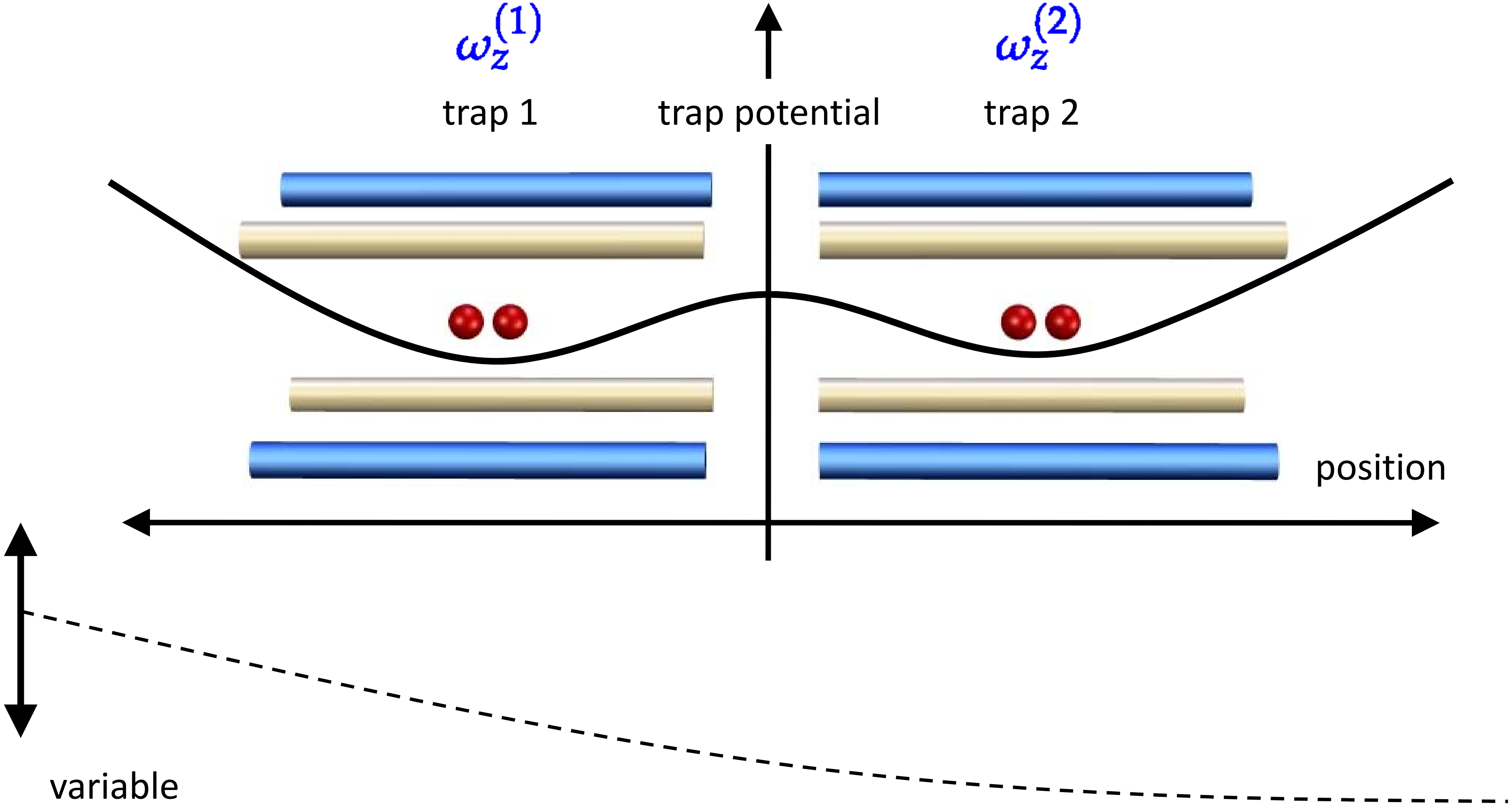
cavity coupling



axial coupling

RB, W. Hänsel, P. Schmidt, H. Häffner, M. Hennrich, C. Roos; ERC (2008)

Coupled Traps: Double Well Potential



$\omega_z^{(1)}$

trap 1

trap potential

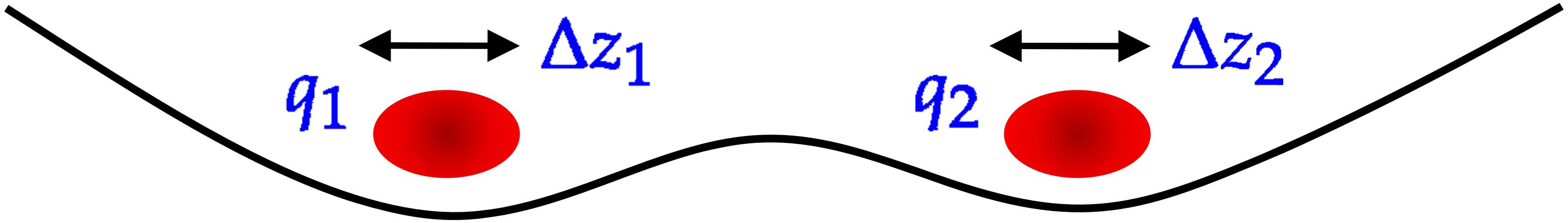
$\omega_z^{(2)}$

trap 2

position

variable
additional potential:
changes curvature of trap potentials, i.e. trap frequencies $\omega_z^{(1)}, \ \omega_z^{(2)}$

Motional Dipole-Dipole Coupling



Dipole-Dipole interaction

$$\boxed{U_{dd} = -\frac{q_1 q_2}{2\pi\epsilon_0}\frac{\Delta z_1 \Delta z_2}{r^3}}$$

$$= -\hbar\frac{\Omega_c}{2}(a_1 + a_1^\dagger)(a_2 + a_2^\dagger)$$

Coupled oscillators

$$\approx -\hbar\frac{\Omega_c}{2}(a_1 a_2^\dagger + a_1^\dagger a_2)$$

oscillation amplitudes

$$\Delta z_i = \sqrt{\frac{\hbar}{2 m_i \omega_i}}(a_i + a_i^\dagger)$$

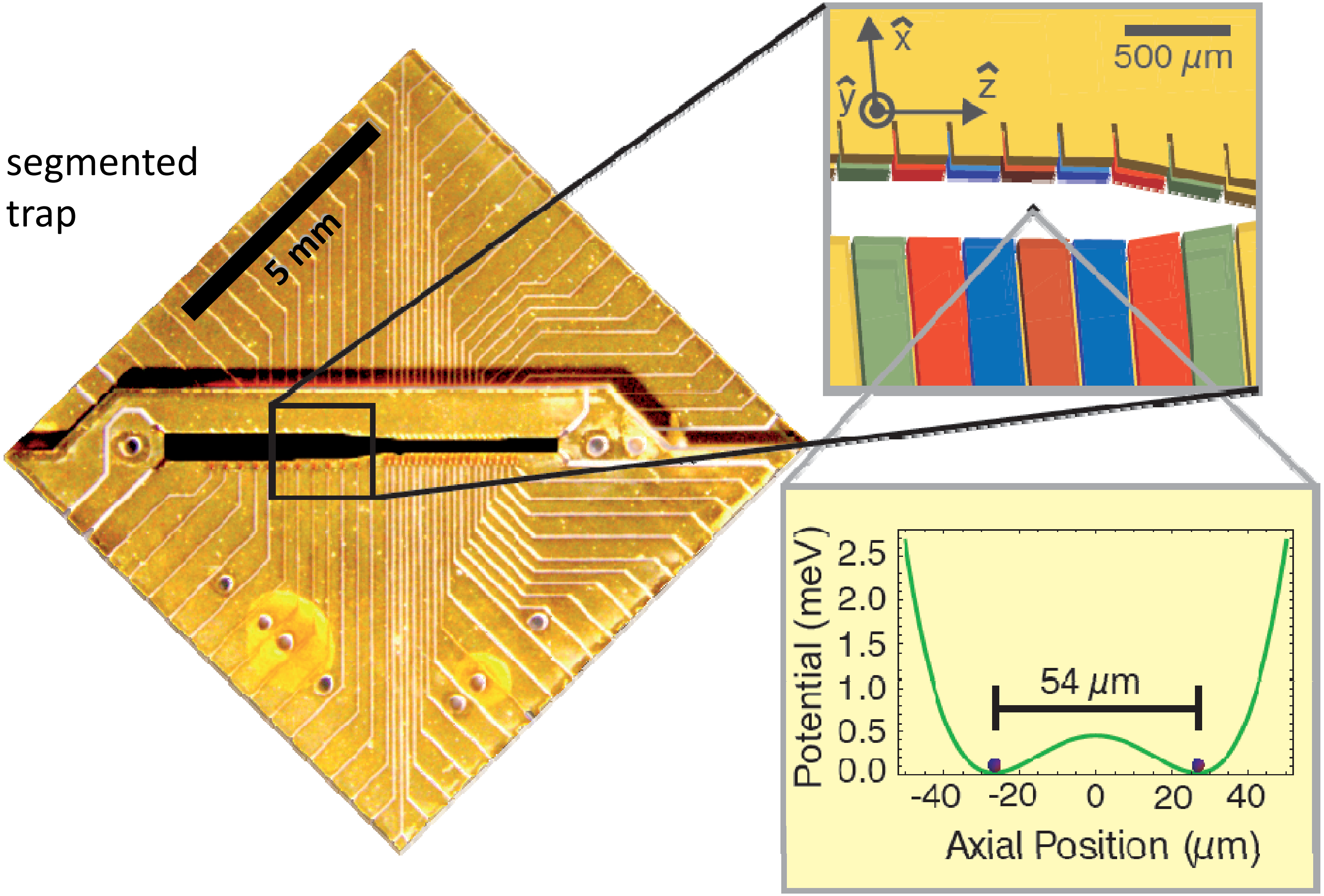
Coupling strength

$$\boxed{\Omega_c = \frac{q_1 q_2}{2\pi\epsilon_0\sqrt{m_1 m_2 \omega_1 \omega_2}}\frac{1}{r^3}}$$

I. Cirac, P. Zoller, Nature **404**, 579 (2000), M. Harlander et al., arXiv:1011.3639

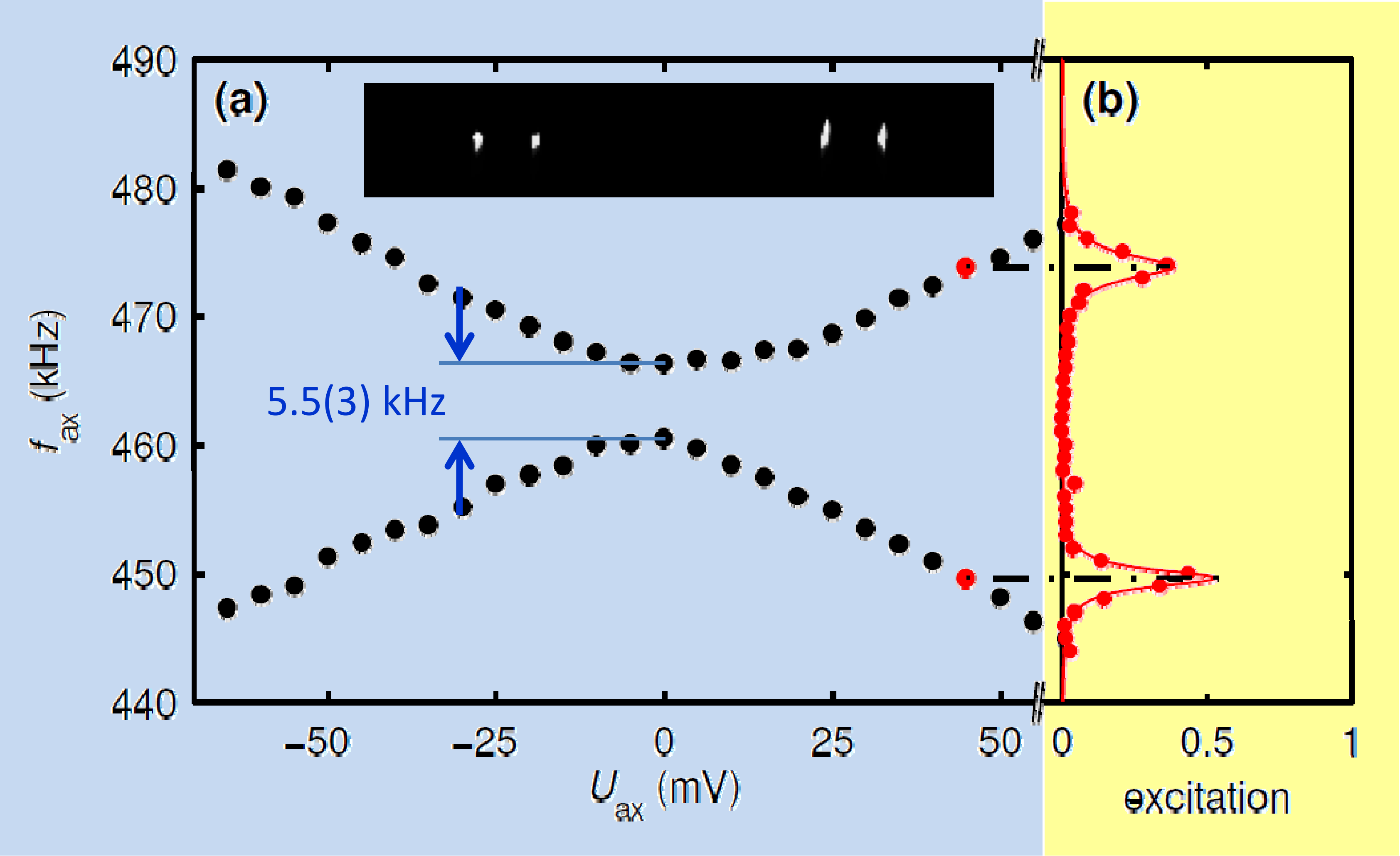
Double Well Potential in a Segmented Ion Trap

segmented
trap

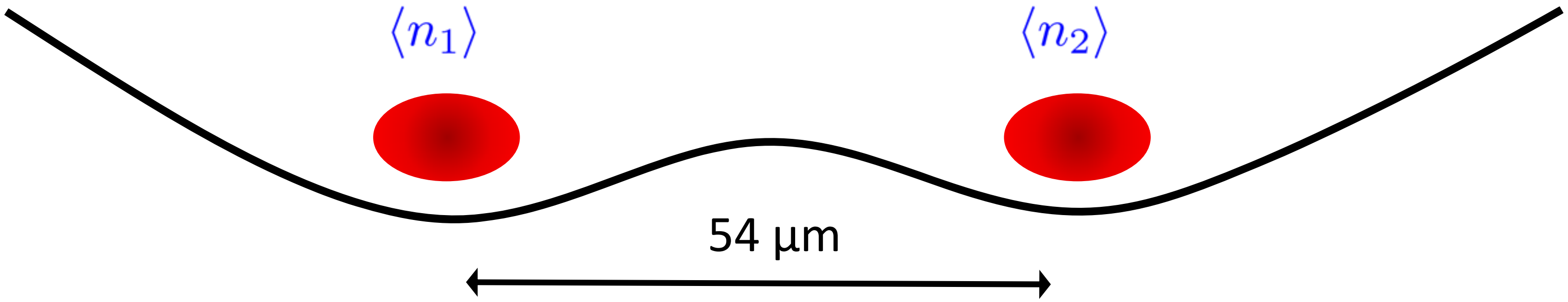


Coupled Quantum Oscillators

avoided crossing, when changing the trap frequencies, 2 ions in each well



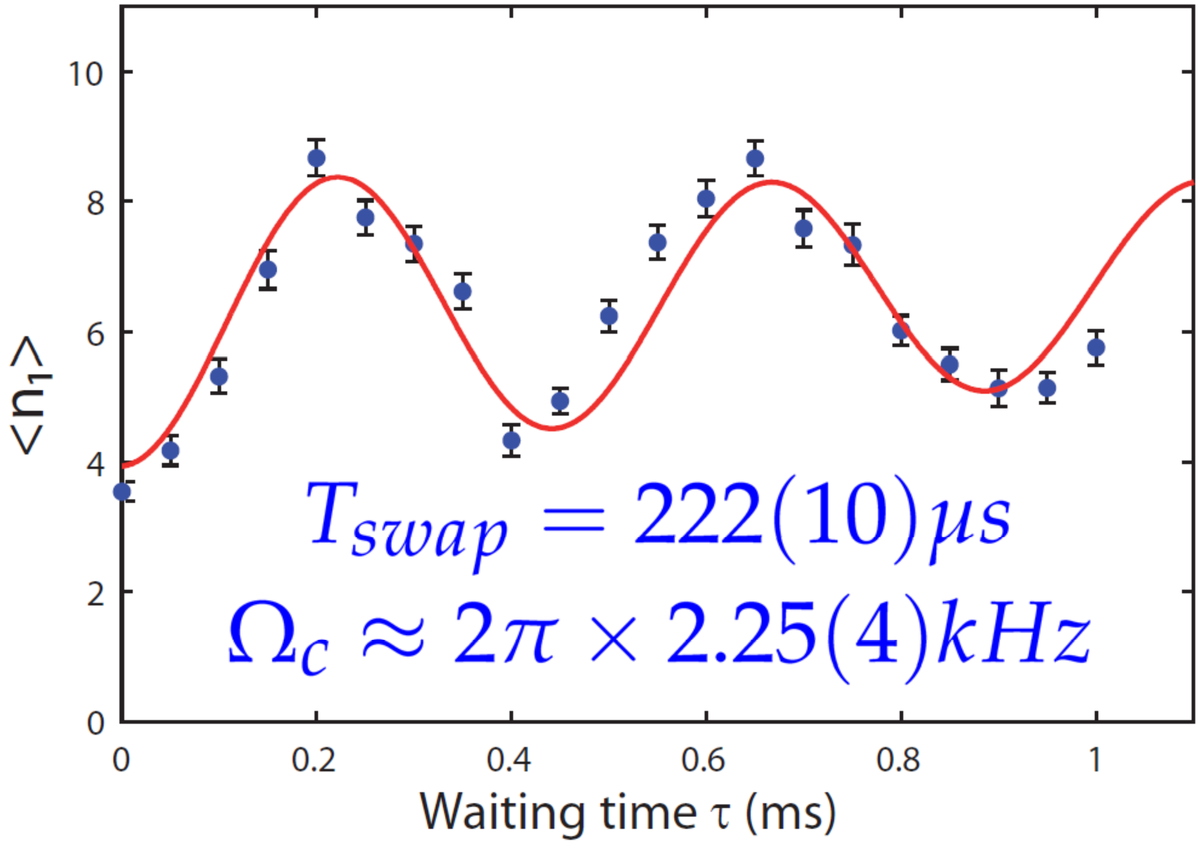
Coherent Energy Exchange



coherent energy exchange between two single ions

- sideband cooling
- wait time τ
- observe Rabi flops
- determine $<n_1>$

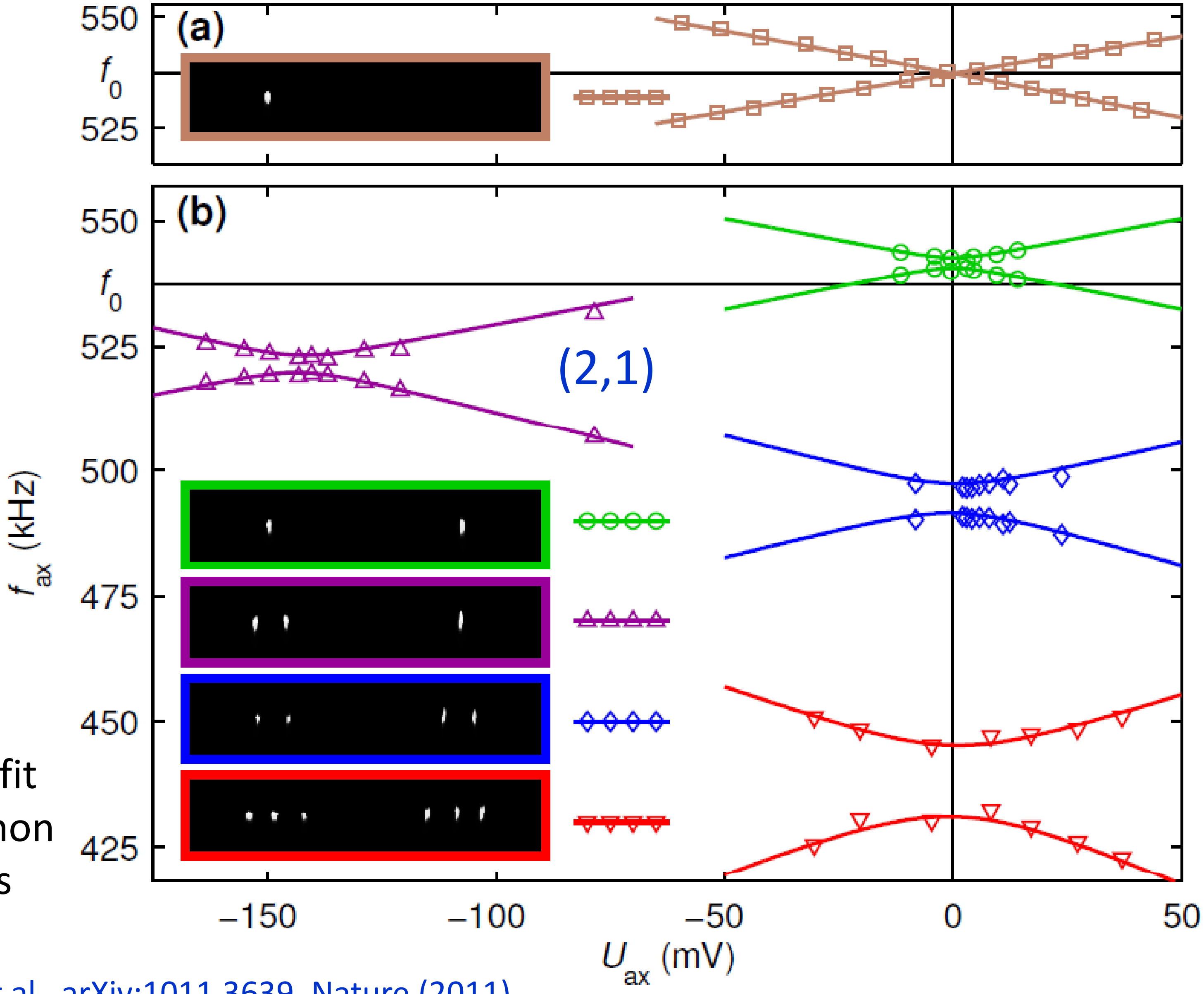
heating: 1.3(7) quanta/ms



Trapped-Ion Antennae for Transmitting Quantum Information

numbers
of atoms:

(L,R) =



(1,0)

(1,1)

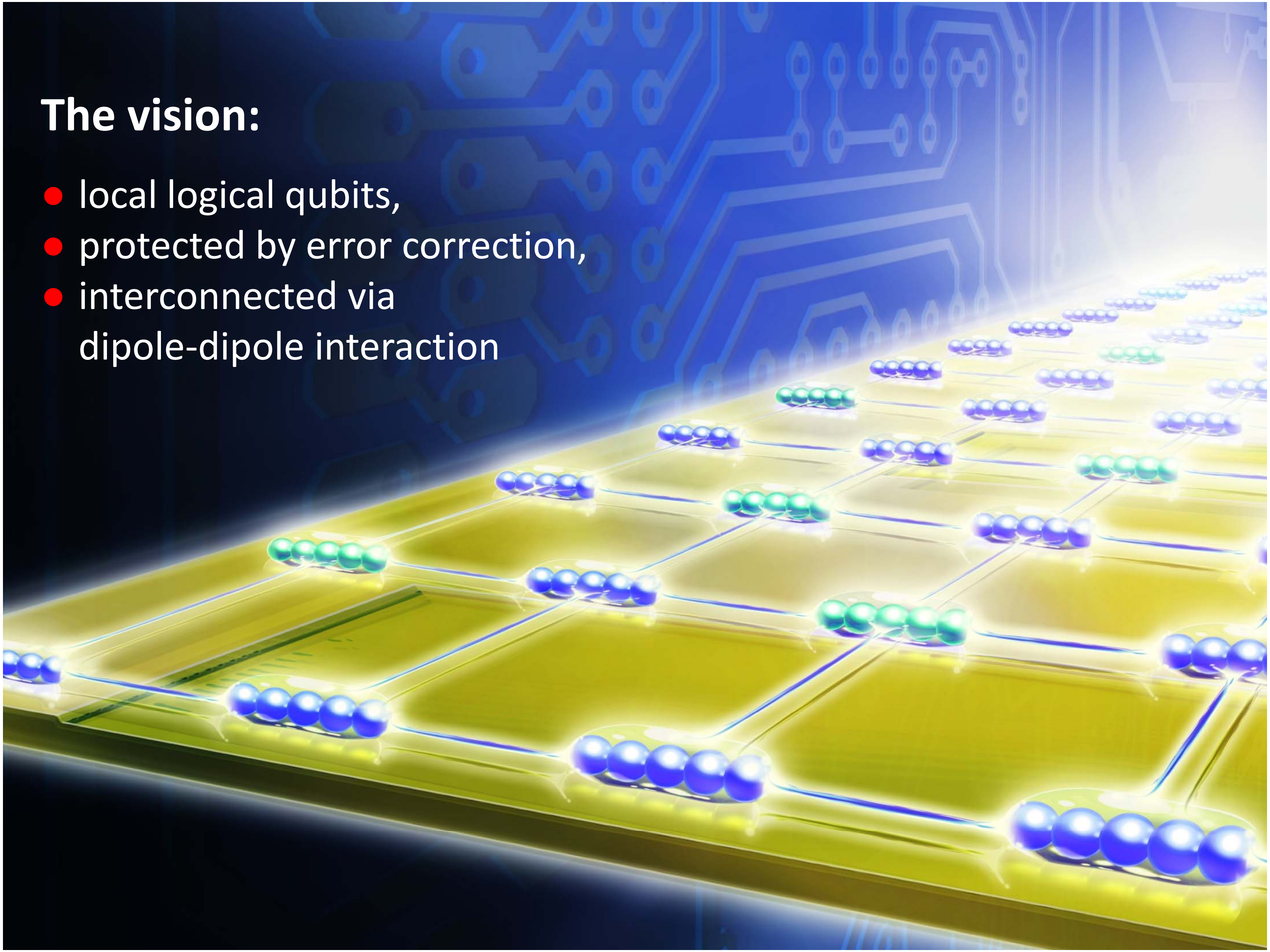
(2,1)

(2,2)

(3,3)

lines are a fit
with common
parameters

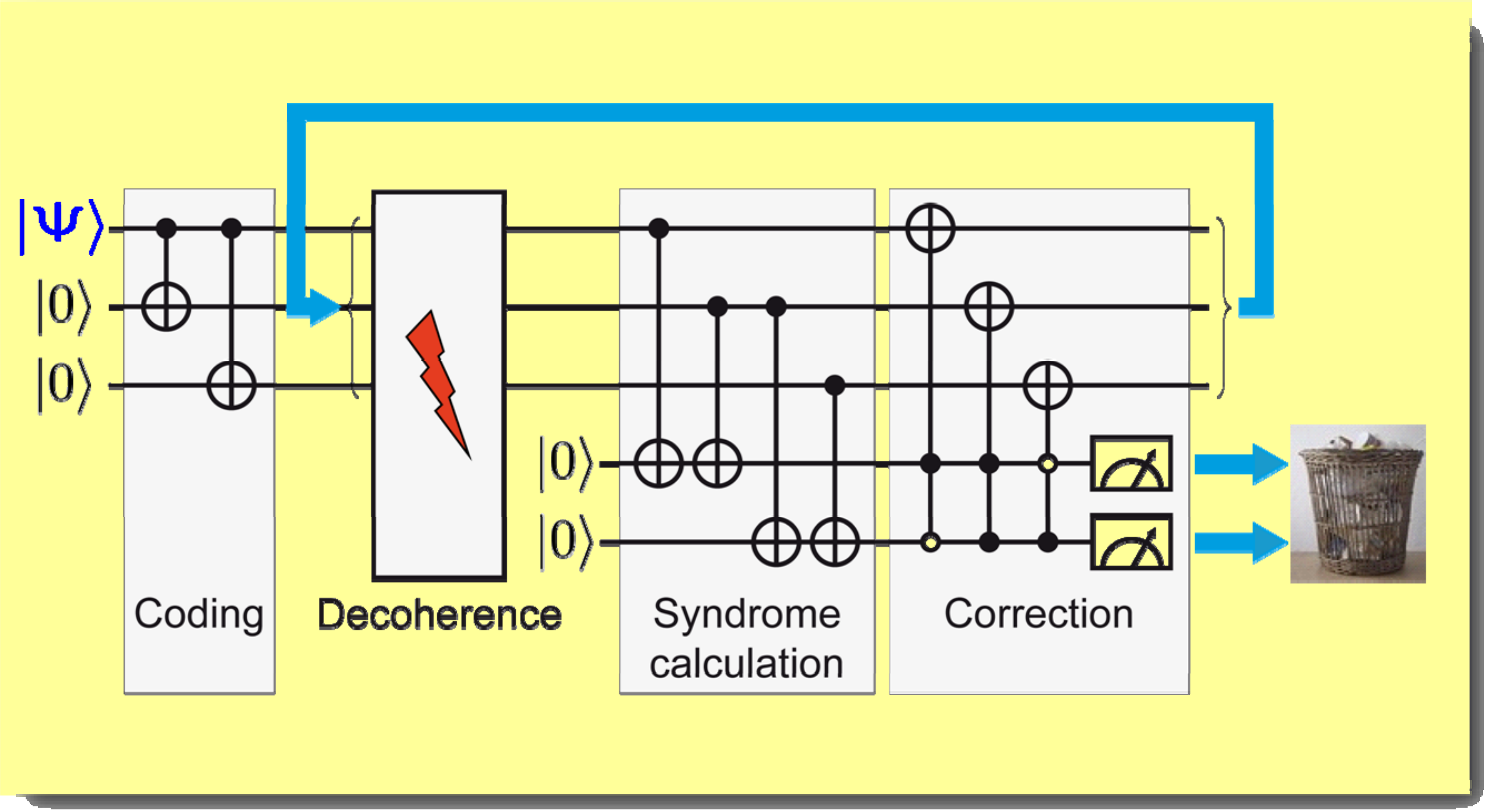
M. Harlander et al., arXiv:1011.3639, Nature (2011)



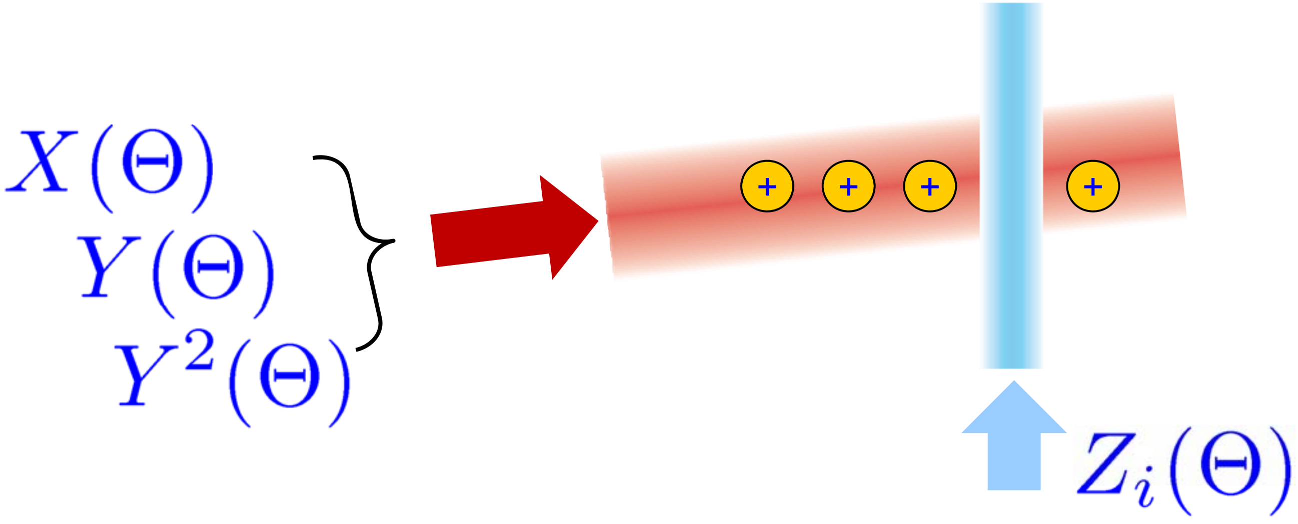
The vision:

- local logical qubits,
- protected by error correction,
- interconnected via dipole-dipole interaction

Scalable quantum computation requires error correction



Quantum gate operations: universal toolbox



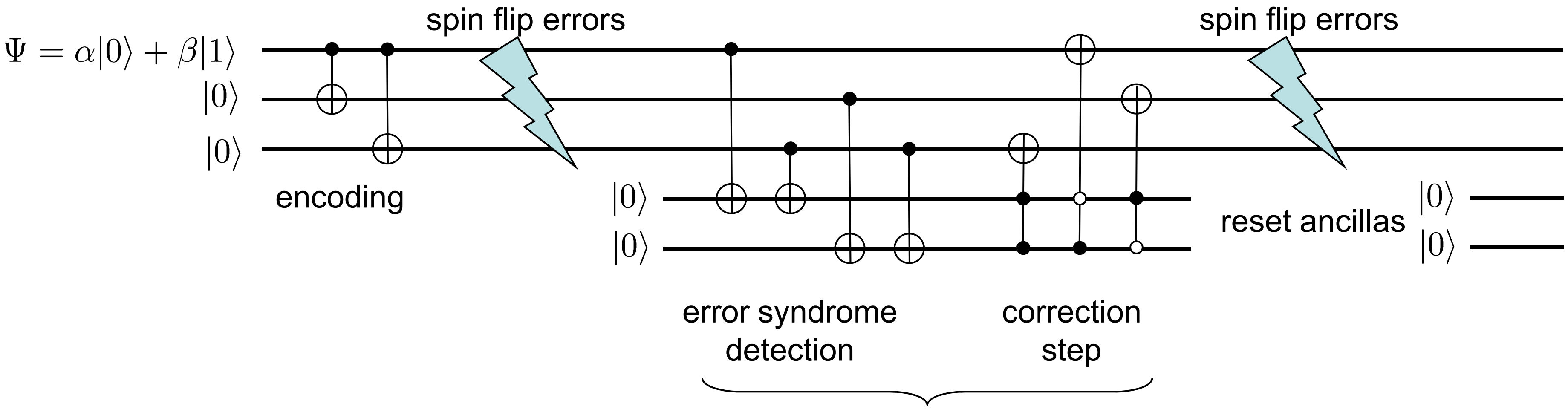
$X(\Theta)$, $Y(\Theta)$: collective local operations, F = 99%

$Z_i(\Theta)$: single-qubit z-rotations, F = 99%

$Y^2(\Theta)$: Mølmer-Sørensen entangling operations, F = 98%

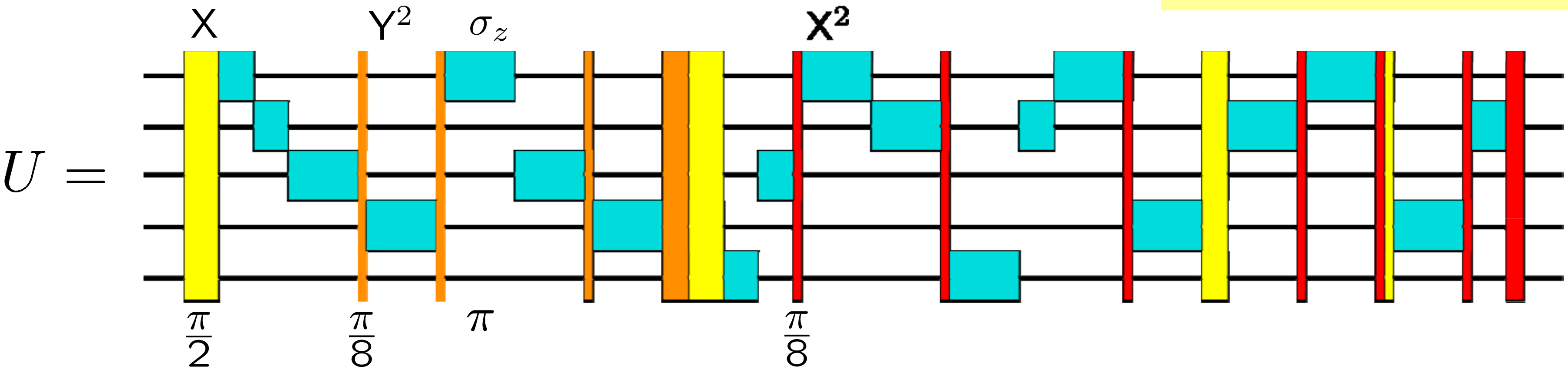
Optimal control : Quantum Error Correction

Quantum Error Correction: 3 qubits encode logical qubit (protection against spin flips)

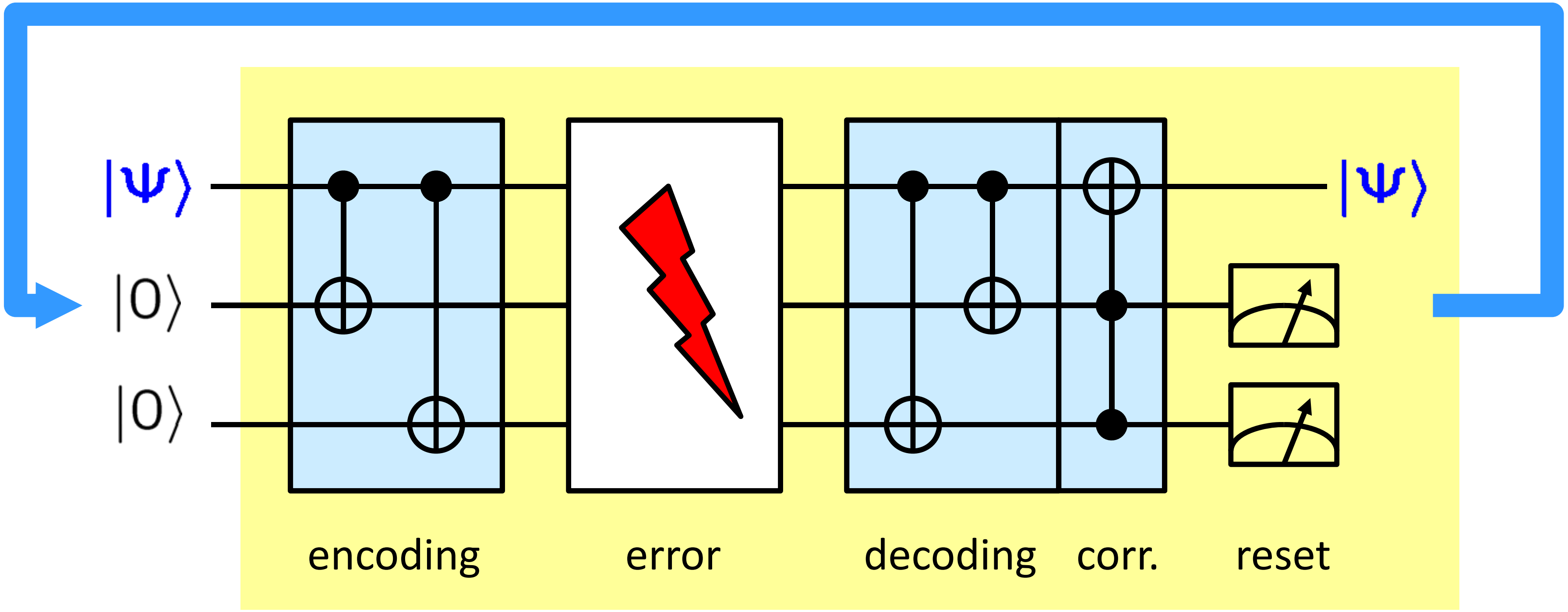


V. Nebendahl et al., Phys. Rev. A **79**, 012312 (2009)

Implementation : 34 laser pulses (11 entangling pulses)



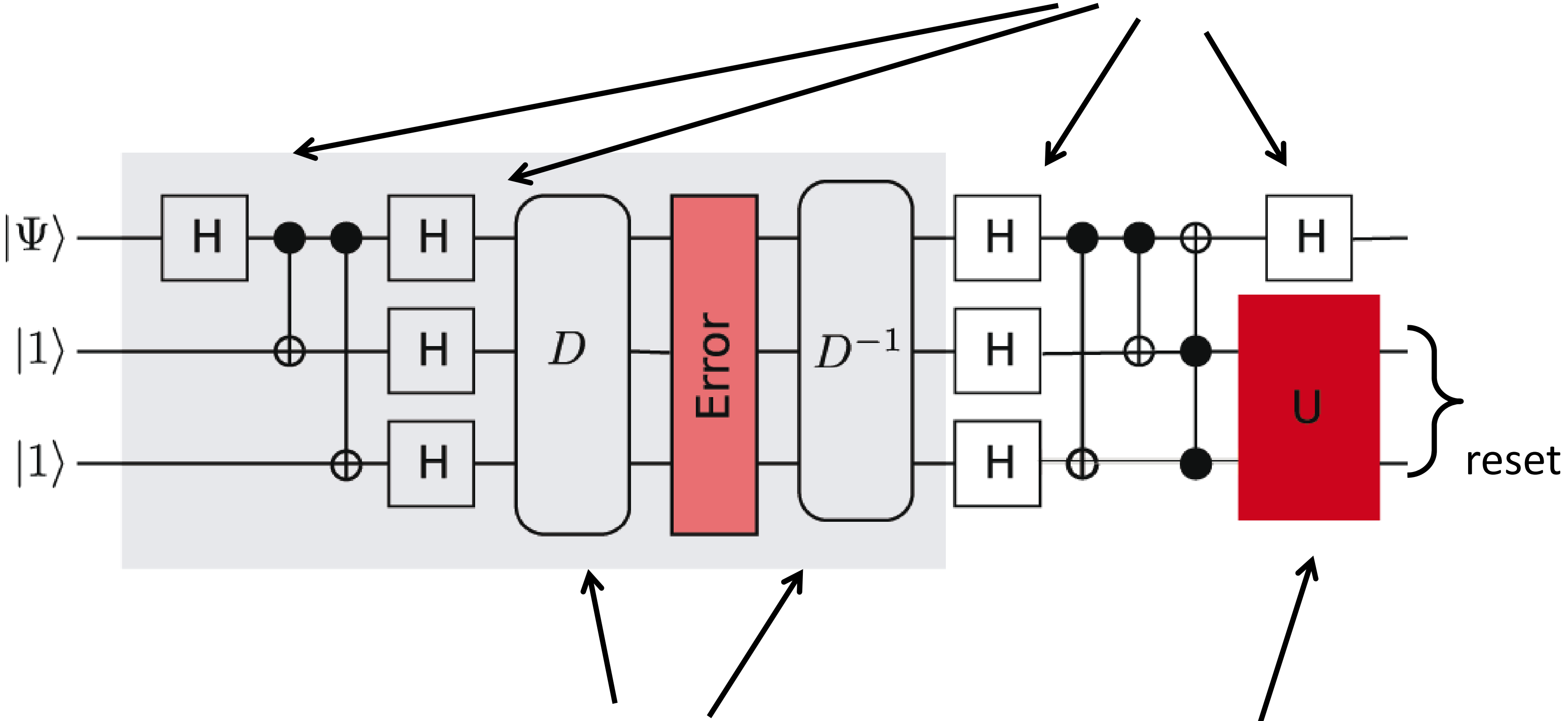
Quantum Error Correction, reduced



- requires only three instead of five qubits
- repetition requires **re-encoding**

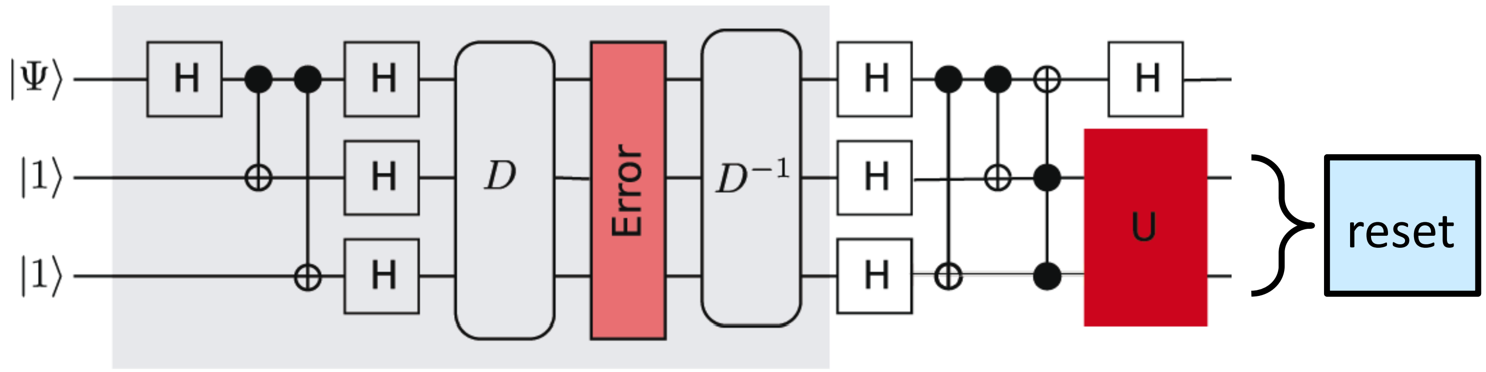
Quantum error correction, our implementation

- correct for phase errors instead of bit flips -> add Hadamards

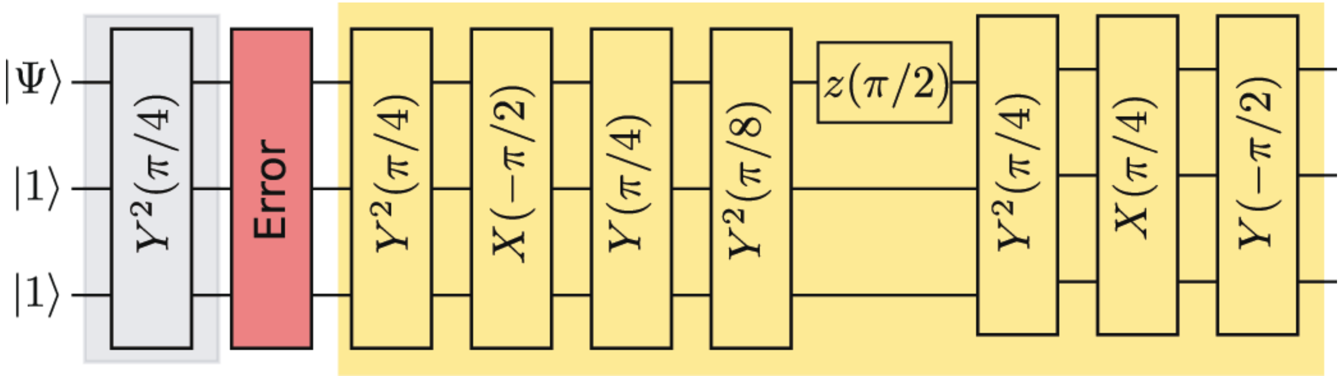


- add a dummy operation D, D^{-1} that simplify encoding
- operation U does not matter since ancillas are reset
  (but gives an additional degree of freedom for optimisation)

Quantum error correction, our encoding

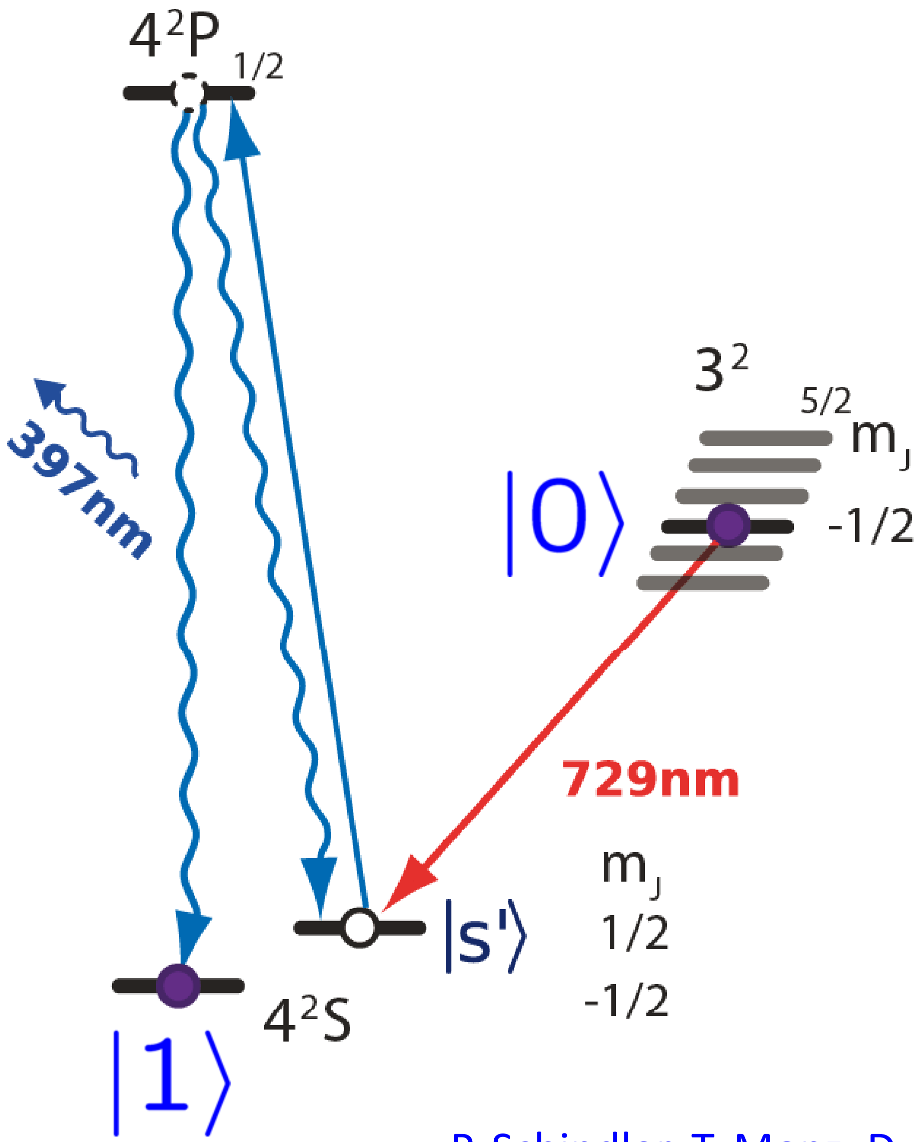


optimization procedure using a modified GRAPE algorithm



V. Nebendahl et al., Phys. Rev. **A 79**, 012312 (2009)

Quantum error correction: reset procedure



reset the ancillas:

shelve population of ancillas

$$|0\rangle \longrightarrow |S'\rangle$$

optical pumping

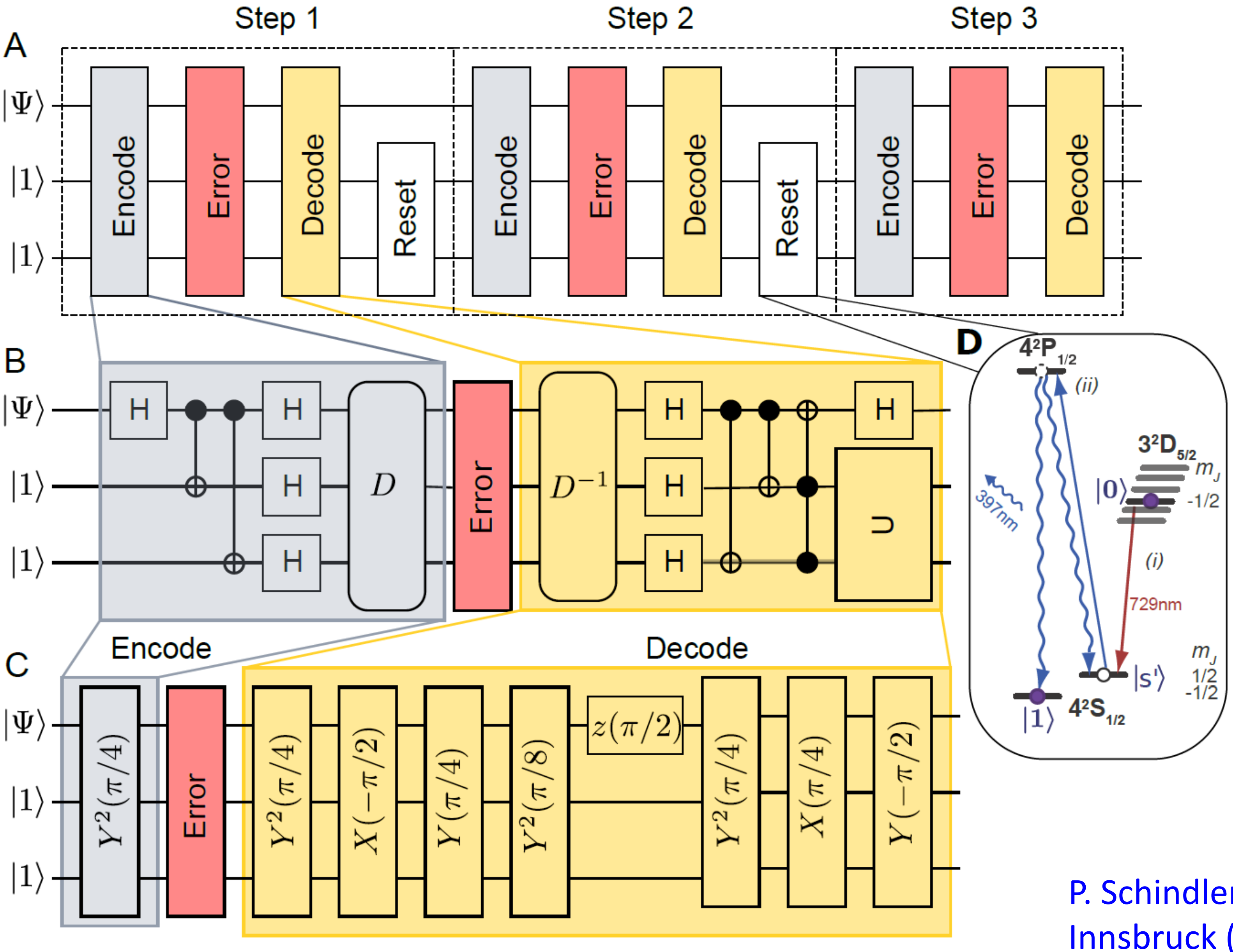
$$|S'\rangle \longrightarrow |1\rangle$$

heating:

0.014 phonons/reset

P. Schindler, T. Monz, D. Nigg, J. Barreiro, M. Hennrich, RB, Ibk (2010)

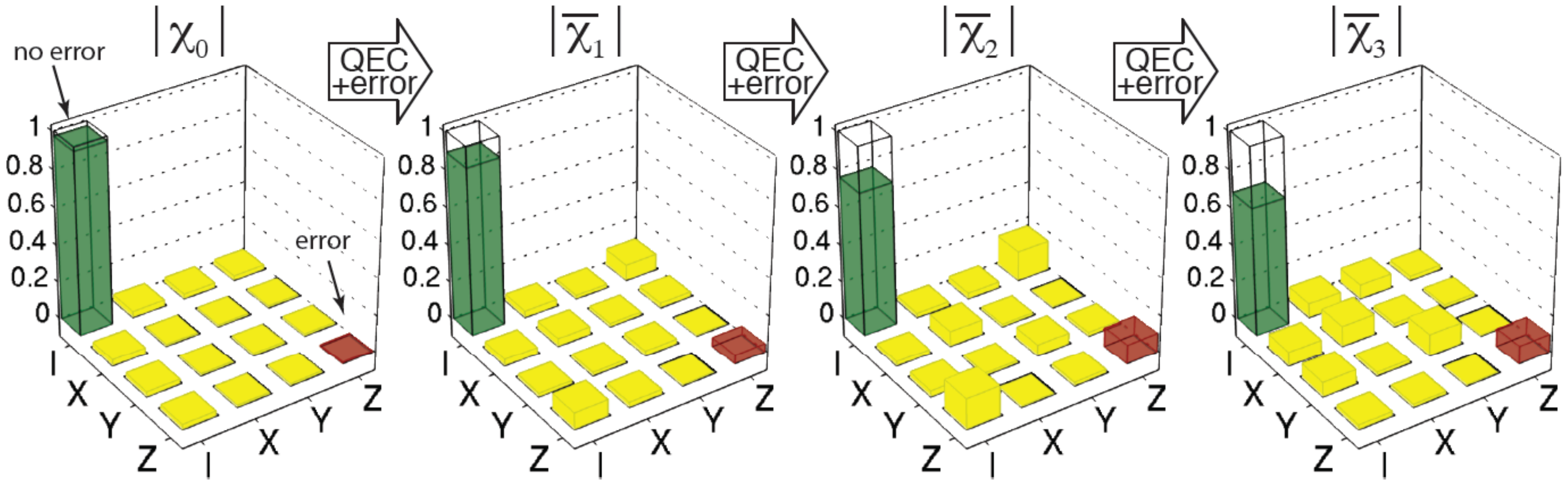
Repetitive Quantum Error Correction: full procedure



P. Schindler et al.,
Innsbruck (2010)

Repetitive Quantum Error Correction: Experiment

process tomography after each step

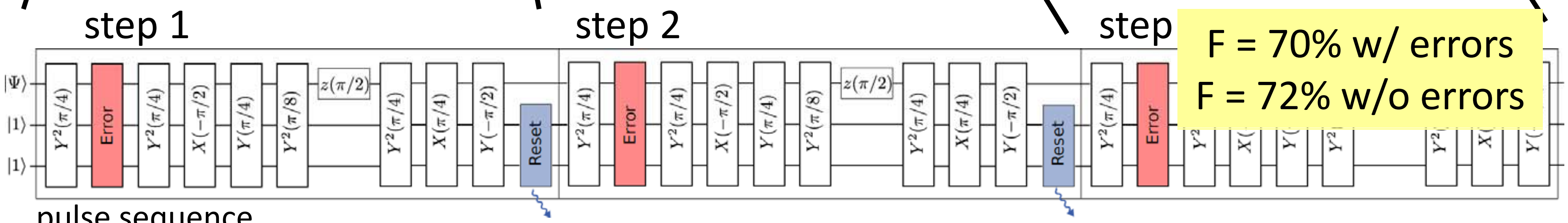


F = 97%
identity process

F = 90% w/ errors
F = 90% w/o errors

F = 80% w/ errors
F = 80% w/o errors

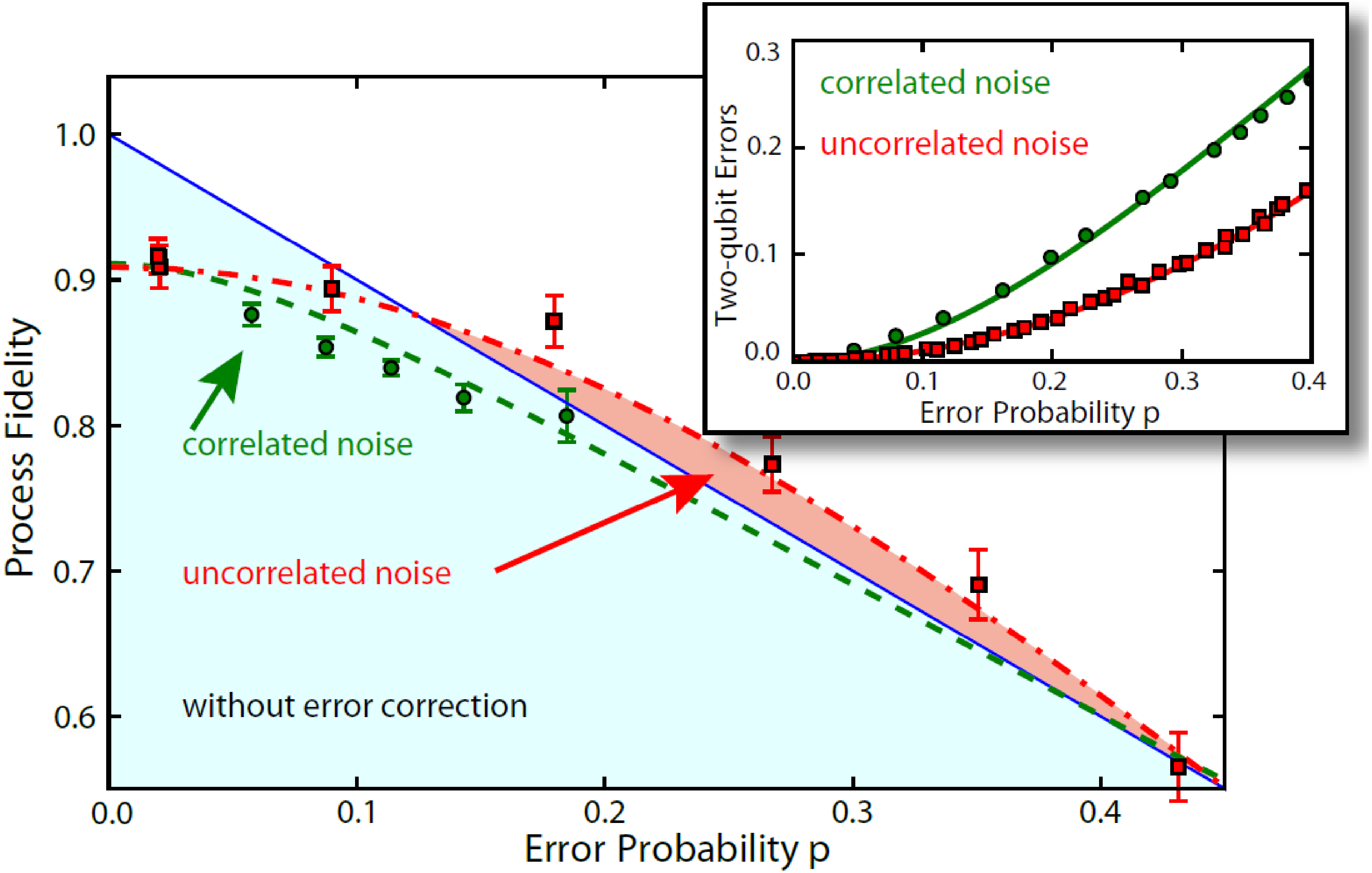
F = 70% w/ errors
F = 72% w/o errors



pulse sequence

P. Schindler, T. Monz, D. Nigg, J. Barreiro, M. Hennrich, Ibk (2010)

Repetitive Quantum Error Correction: Results



Status of trapped-ion physics in Europe

Trap technology:

● conventional traps	(Innsbruck, München, Aarhus, London, Saarbrücken, Sussex ….)
● 1-d surface traps	(Oxford, Mainz, Innsbruck, Paris, Sussex …)
● sandwich traps	(Mainz, Siegen, Teddington, Innsbruck)
● 2-d surface traps	(München, Innsbruck, Sussex)
● traps and mirrors, CQED	(Aarhus, Saarbrücken, Mainz, Sussex, Innsbruck, …)

Experiments:

● coupling quantum information via CQED	(Sussex, Aarhus, Saarbrücken, Innsbruck)
● coupling via dipole-dipole interaction	(Innsbruck)
● coupling via ion transport	(Mainz, Innsbruck)
● towards error correction	(Oxford, Innsbruck)
● quantum simulations	(München, Innsbruck)
● quantum metrology	(Braunschweig, Teddington, Marseille, …)
● quantum memory	(Aarhus, Paris)
● …	

Teams in Europe (presented here)

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AG Quantenoptik
und Spektroskopie

The international team 2010

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