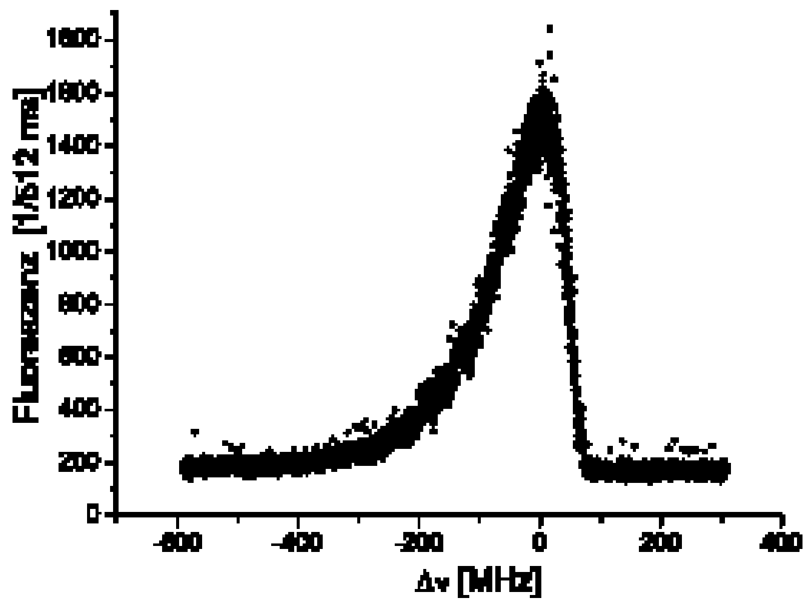
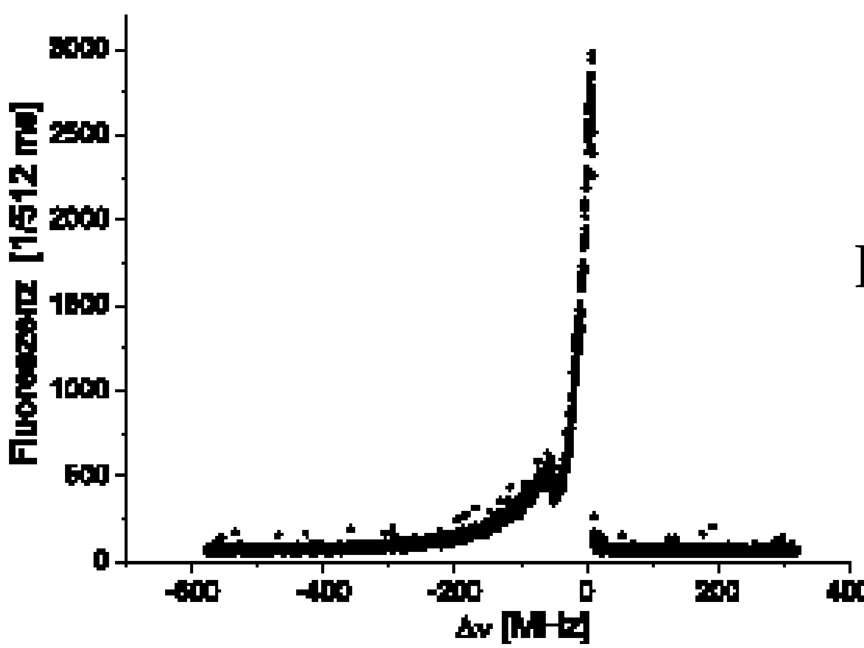
Ion crystallisation and application to quantum computing

Cooling with incrased laser power:
(a) reduced Doppler width
(b) Kink in the line profile

(b)

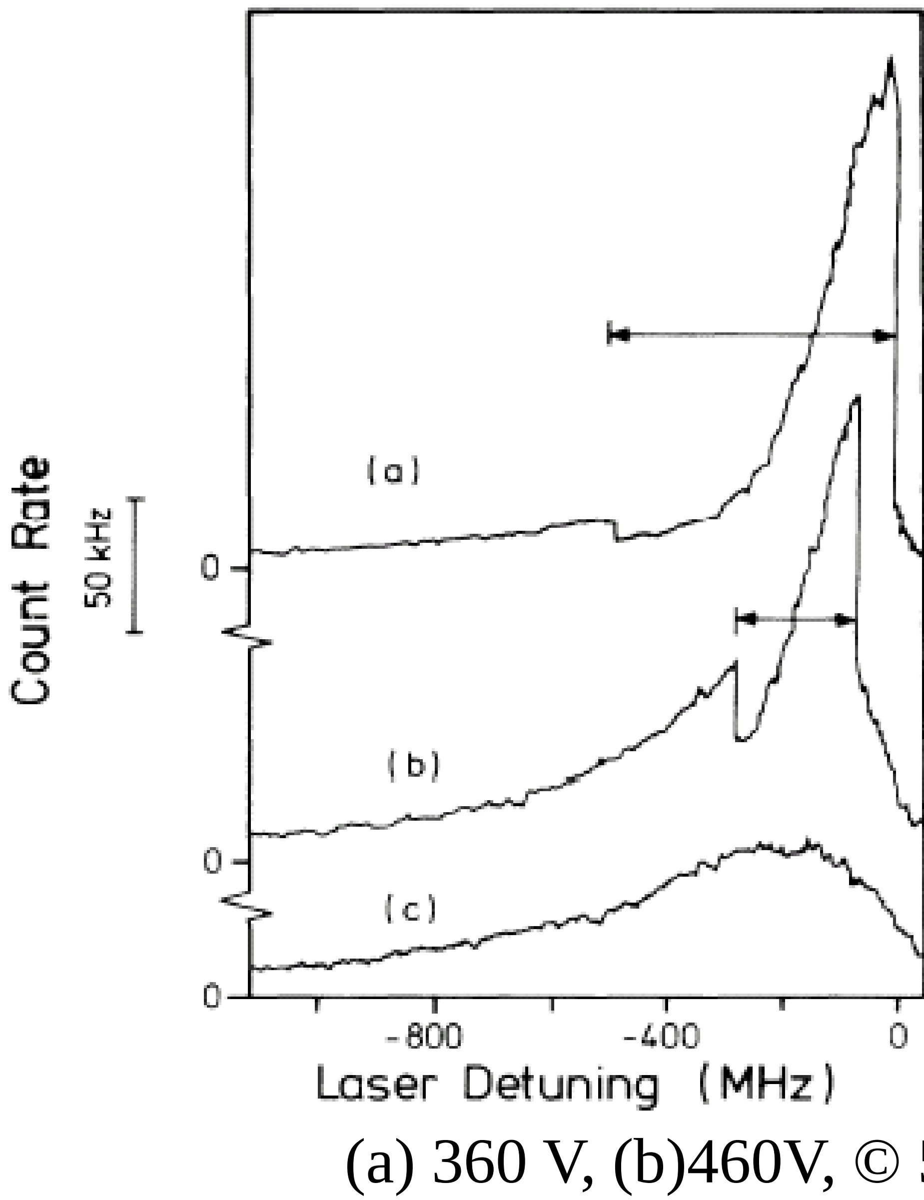


P=0.2 mW



P=0.5 mW

Excitation spectra of an ion cloud at different trap voltage amplitudes in a Paul trap



(a) 360 V, (b)460V, © 570V

F. Diedrich et al., Phys. Rev.Lett. 59, 2931 (1987)

Coulomb correlation parameter

$$\Gamma = \frac{1}{4\pi\varepsilon_0} \frac{Q^2 / a_{sw}}{k_B T}$$

a_{SW}: Seitz-Wigner Radius
= mean inter-ion istance

Γ: Ratio of Coulomb repulsion energy to thermal energy

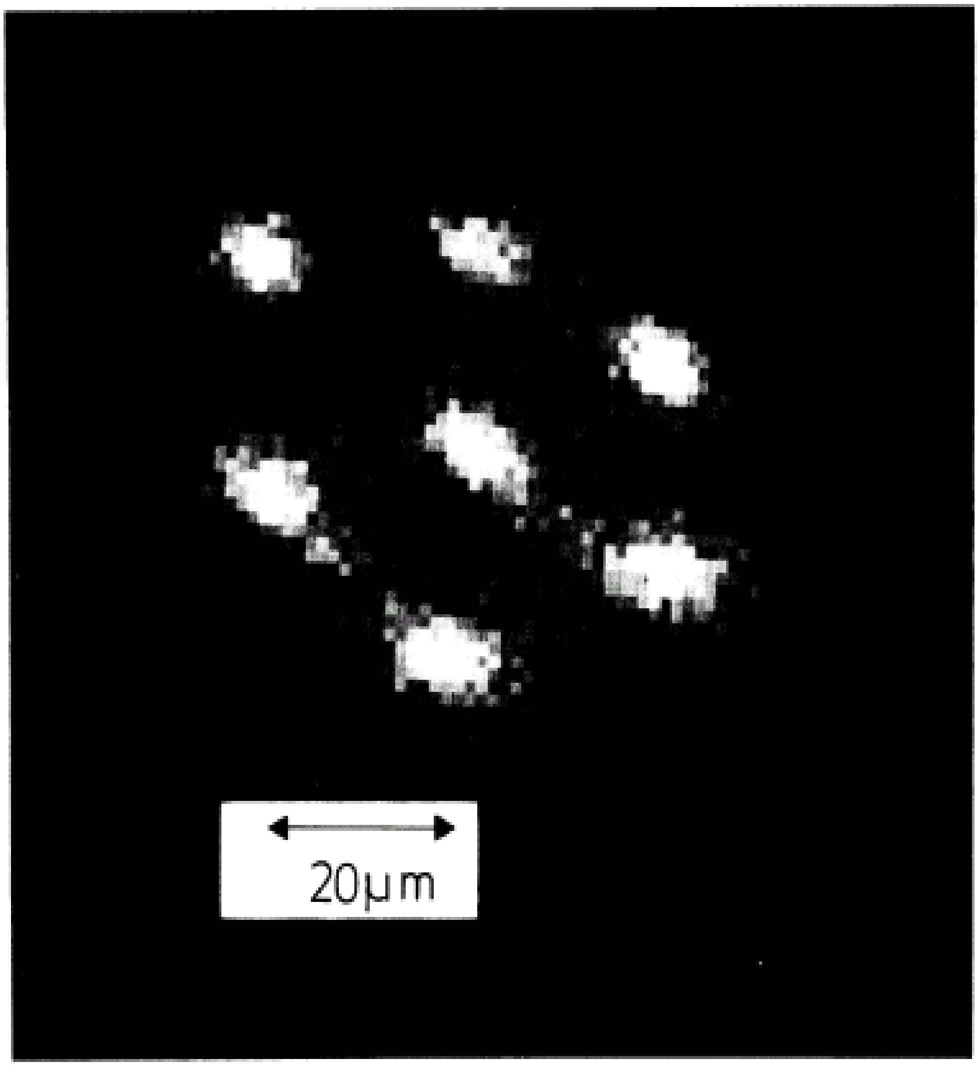
Γ<1: weakly correlated plasma, gas-like behaviour

Γ>173: strongly correlated plasma

At ion temperatures below 1 K we have
Γ > 173

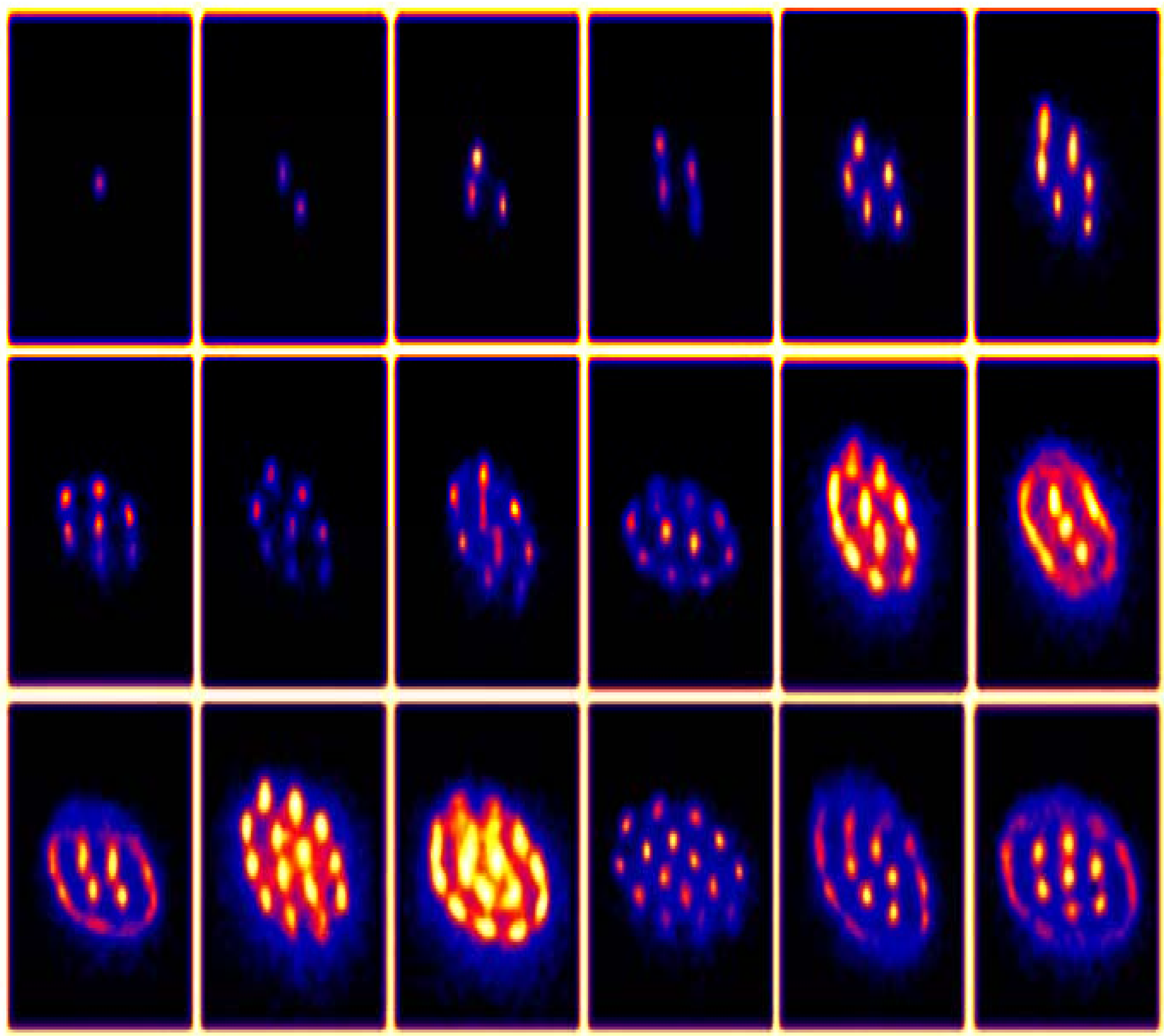
Phase transition to ion crystals

Image of 7 Mg^+ ions in a Paul trap

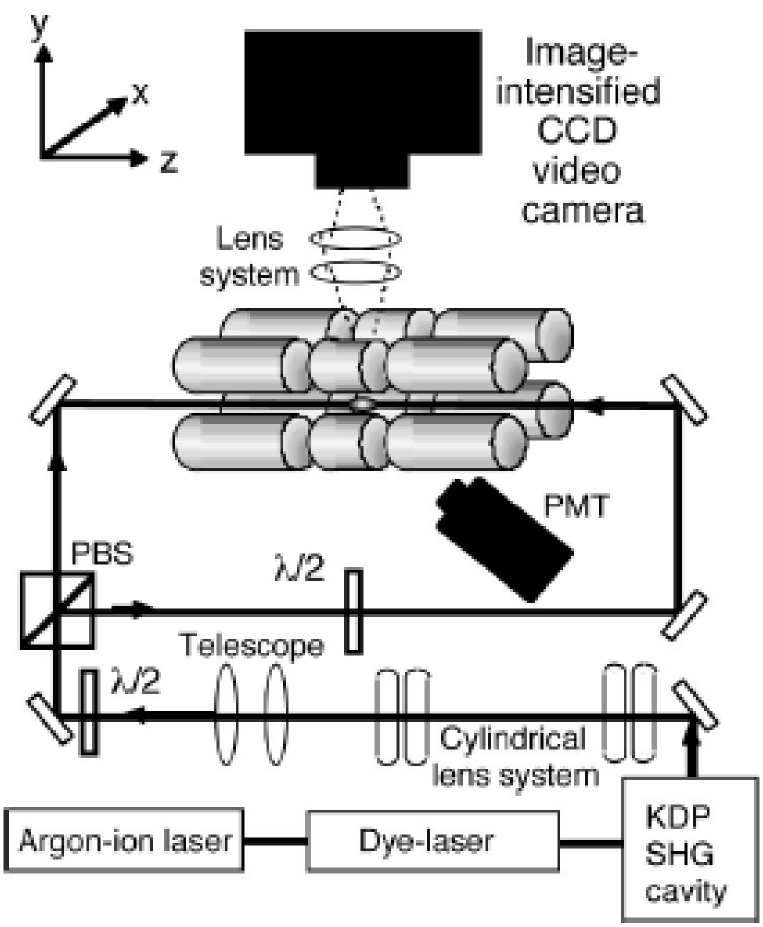


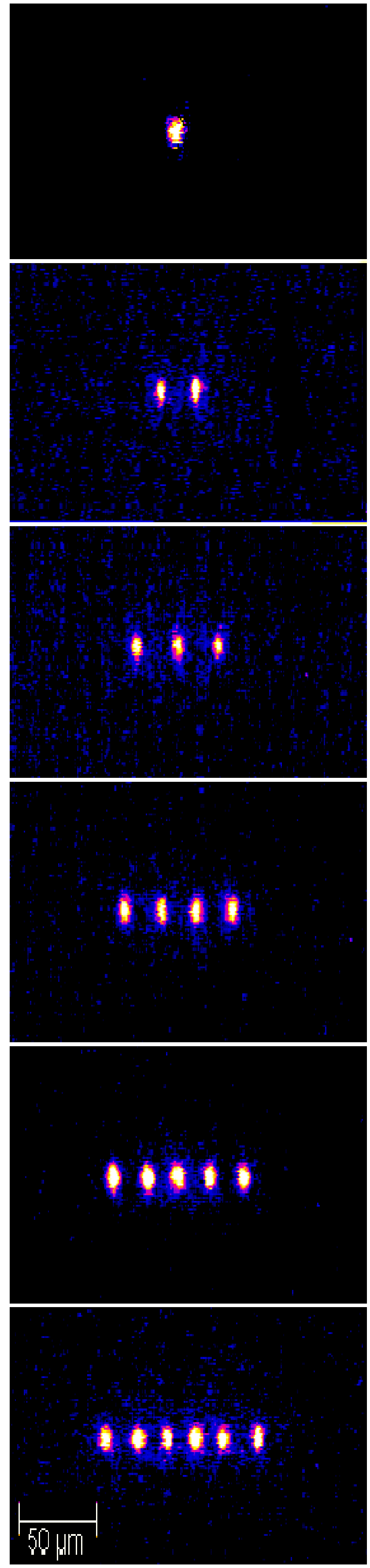
F. Diedrich et al., Phys. Rev.Lett. 59, 2931 (1987)

Coulomb crystals in a 3-D Paul trap



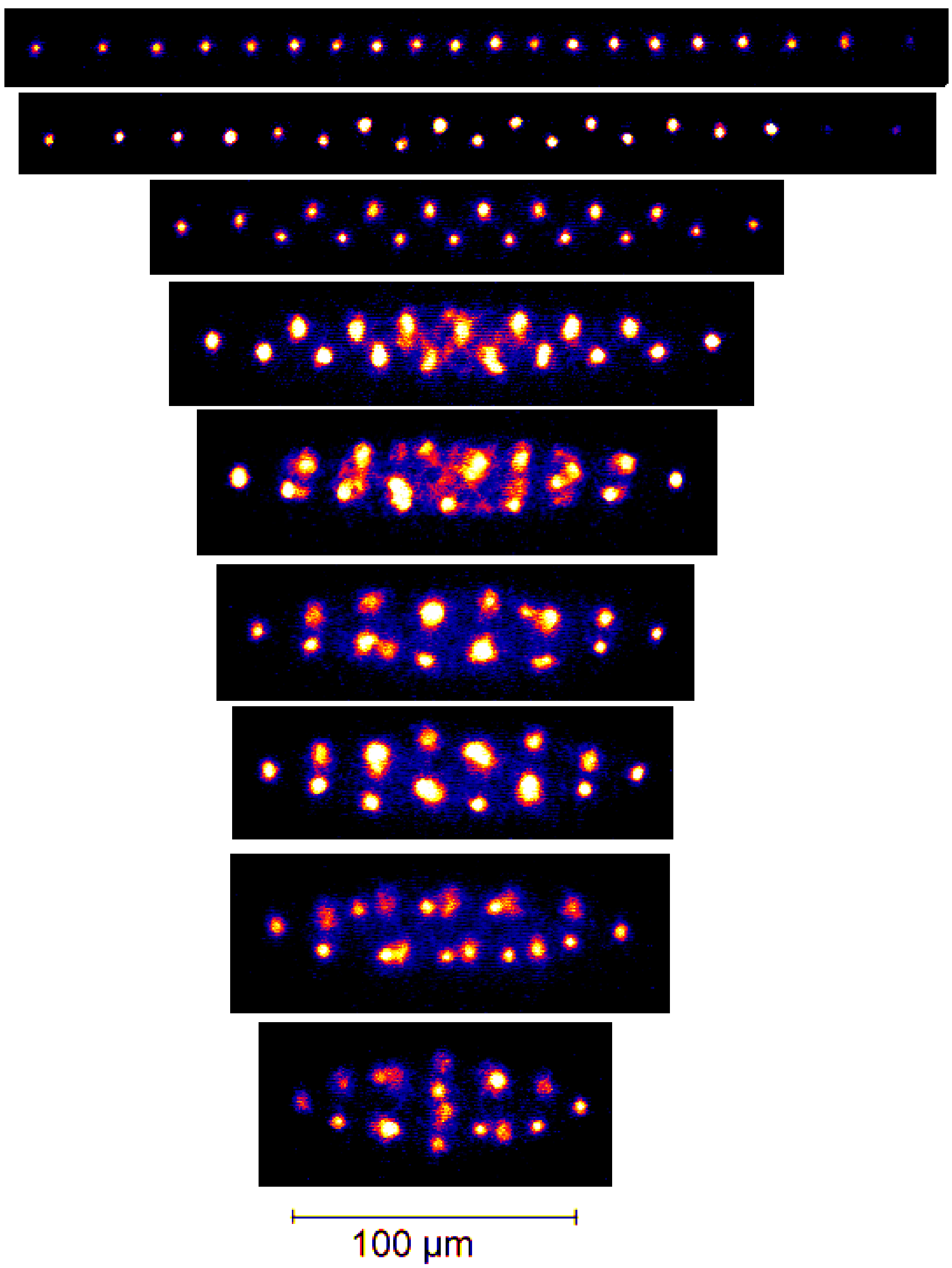
Ion strings in a linear Paul trap



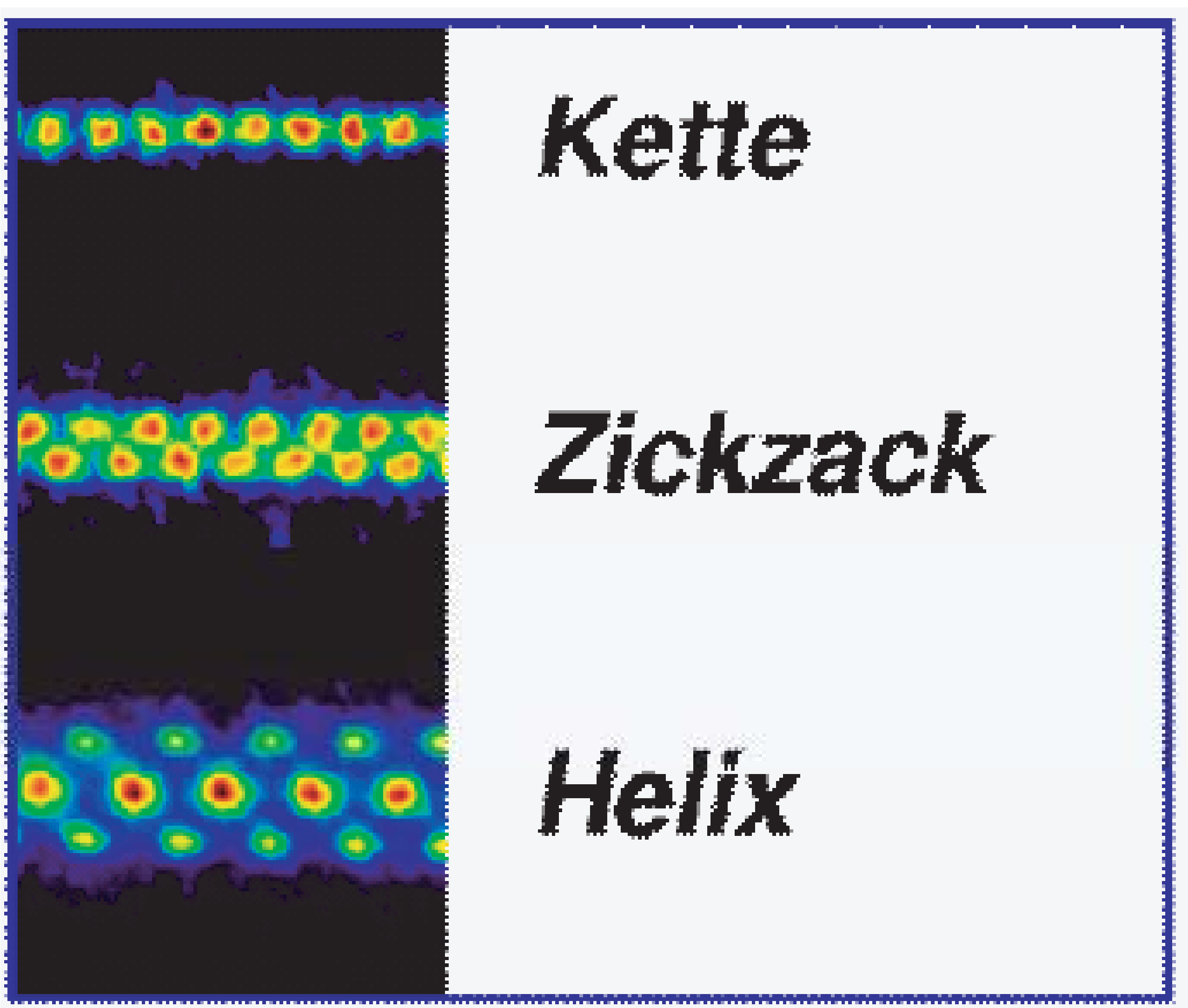


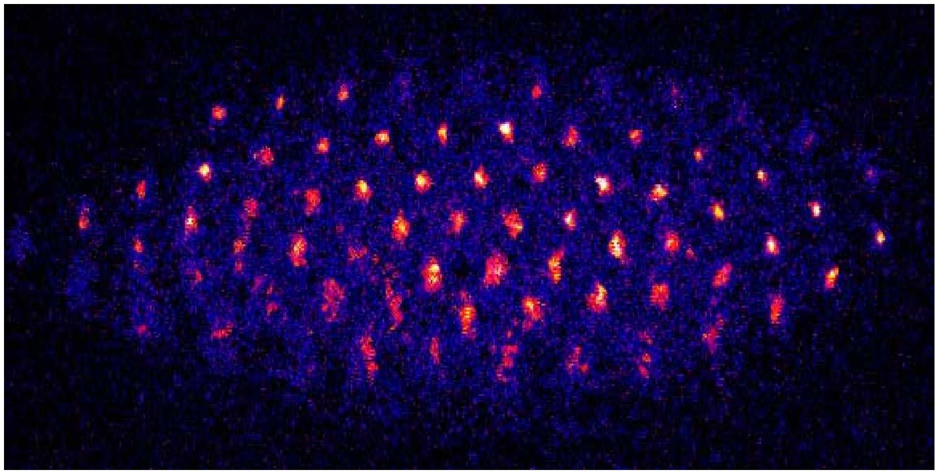
Ion strings in a linear Paul trap

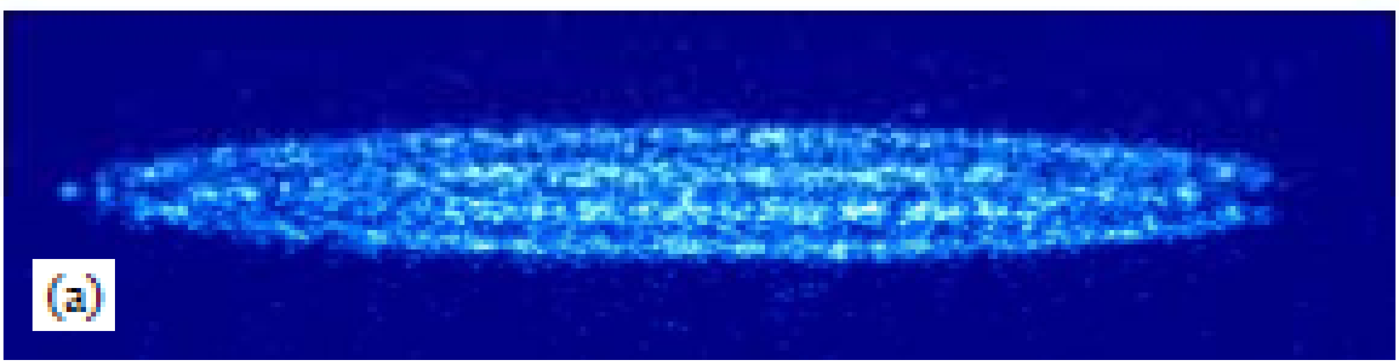
Increasing axial potential depth



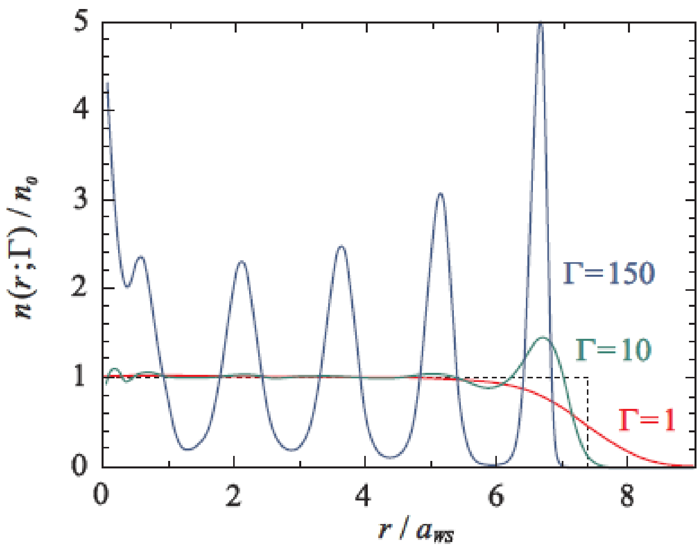
Different shapes of linear chains



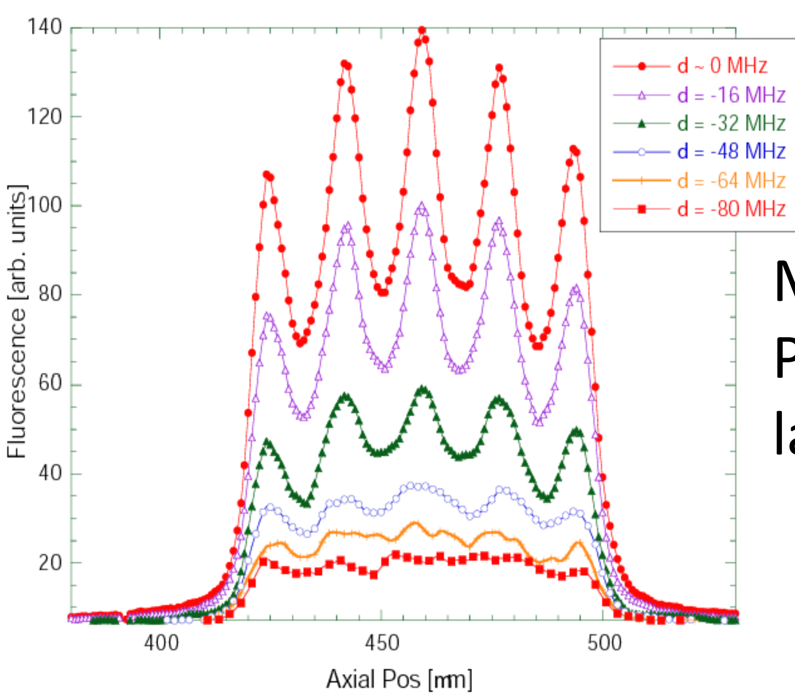



(a)

Ring structure of crystal in a linear Paul trap at different cooling powers



Calculated ion density profile for different Plasma parameters

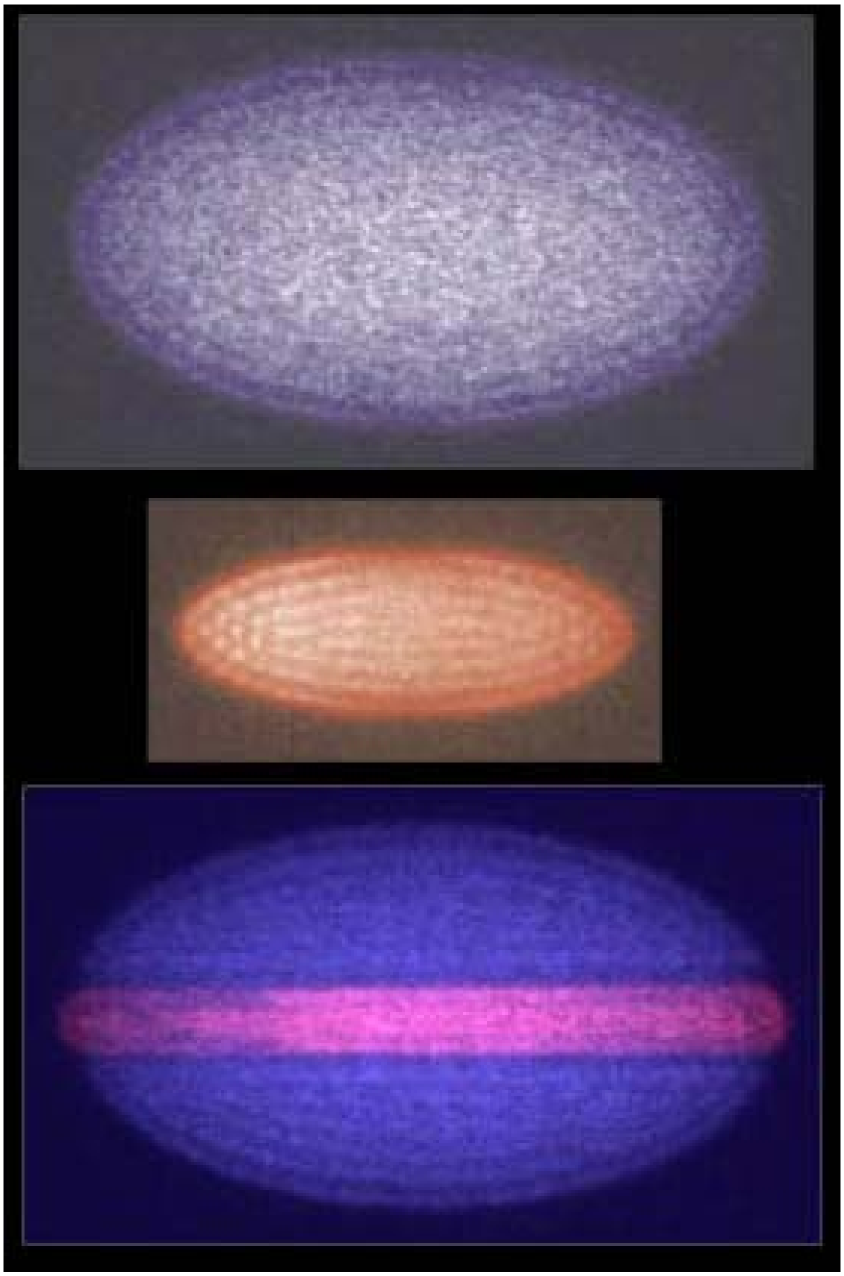


Measured density Profile at different laser detunings

M. Drewsen, Aarfus 1997

Large ion crystals in linear Paul trap

blue: Mg
red: Be

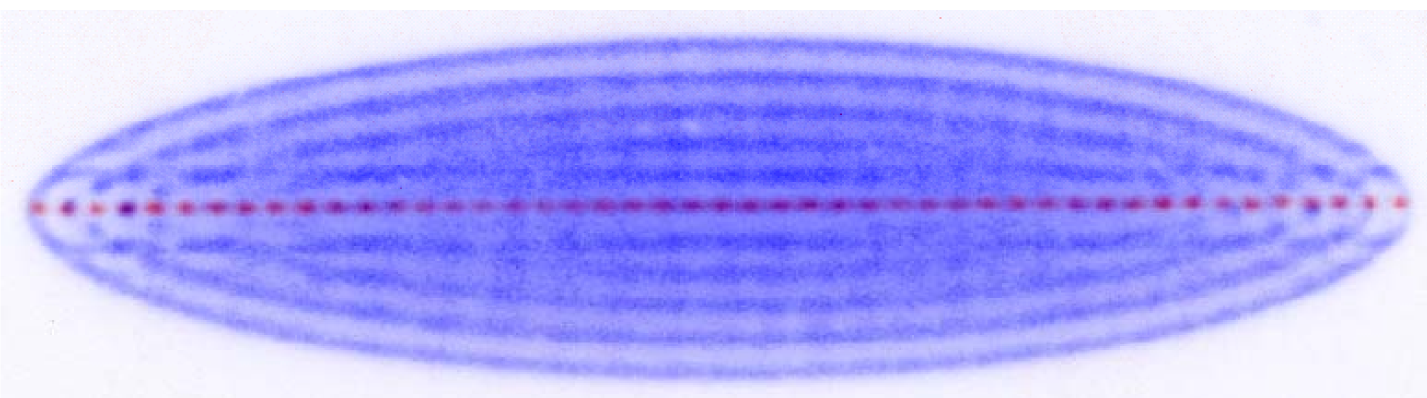


M. Drewsen, Aarhus 2002

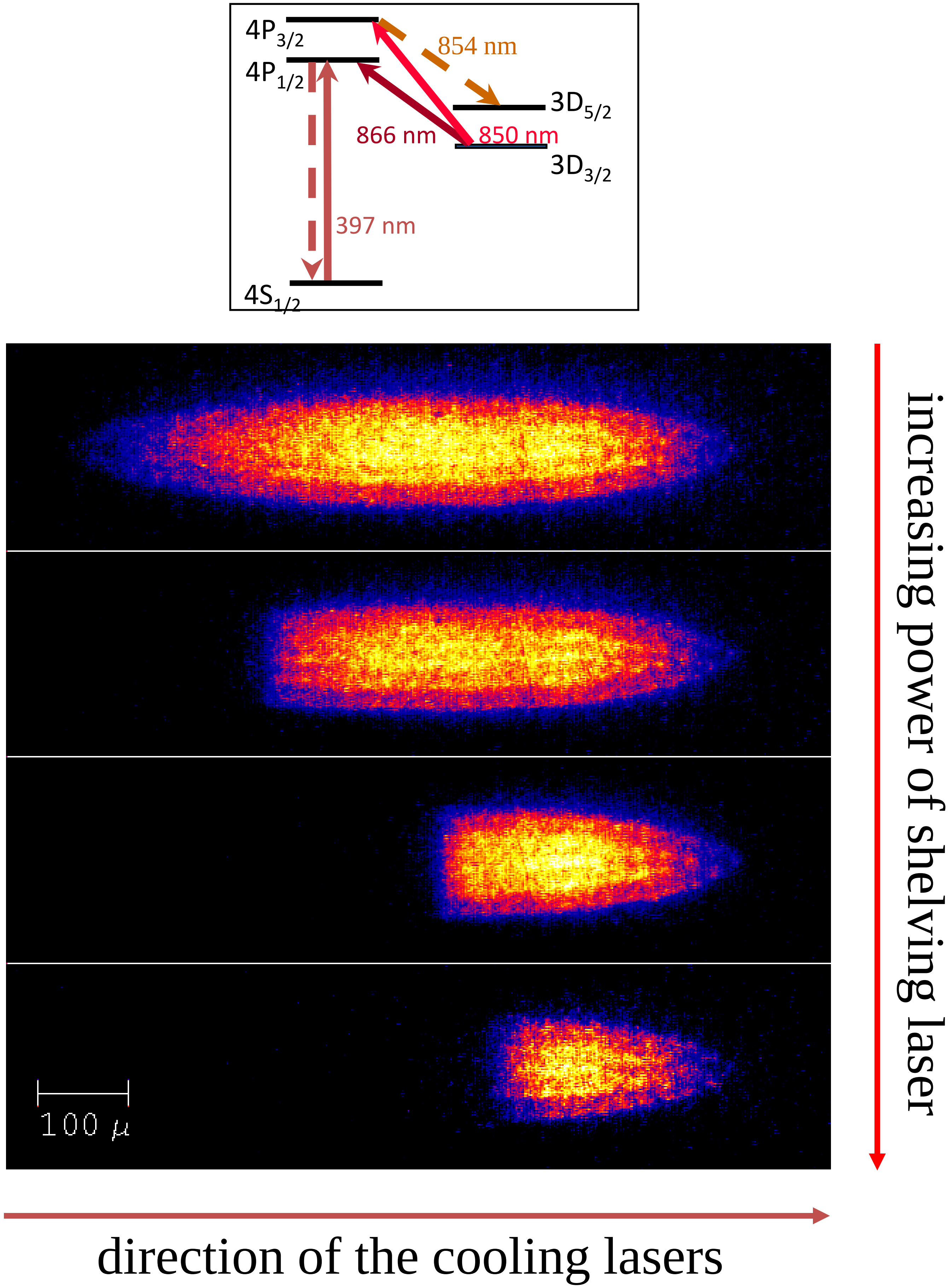
Mixed crystal

Be^{+} (red) and Mg^{+} (blue) ions

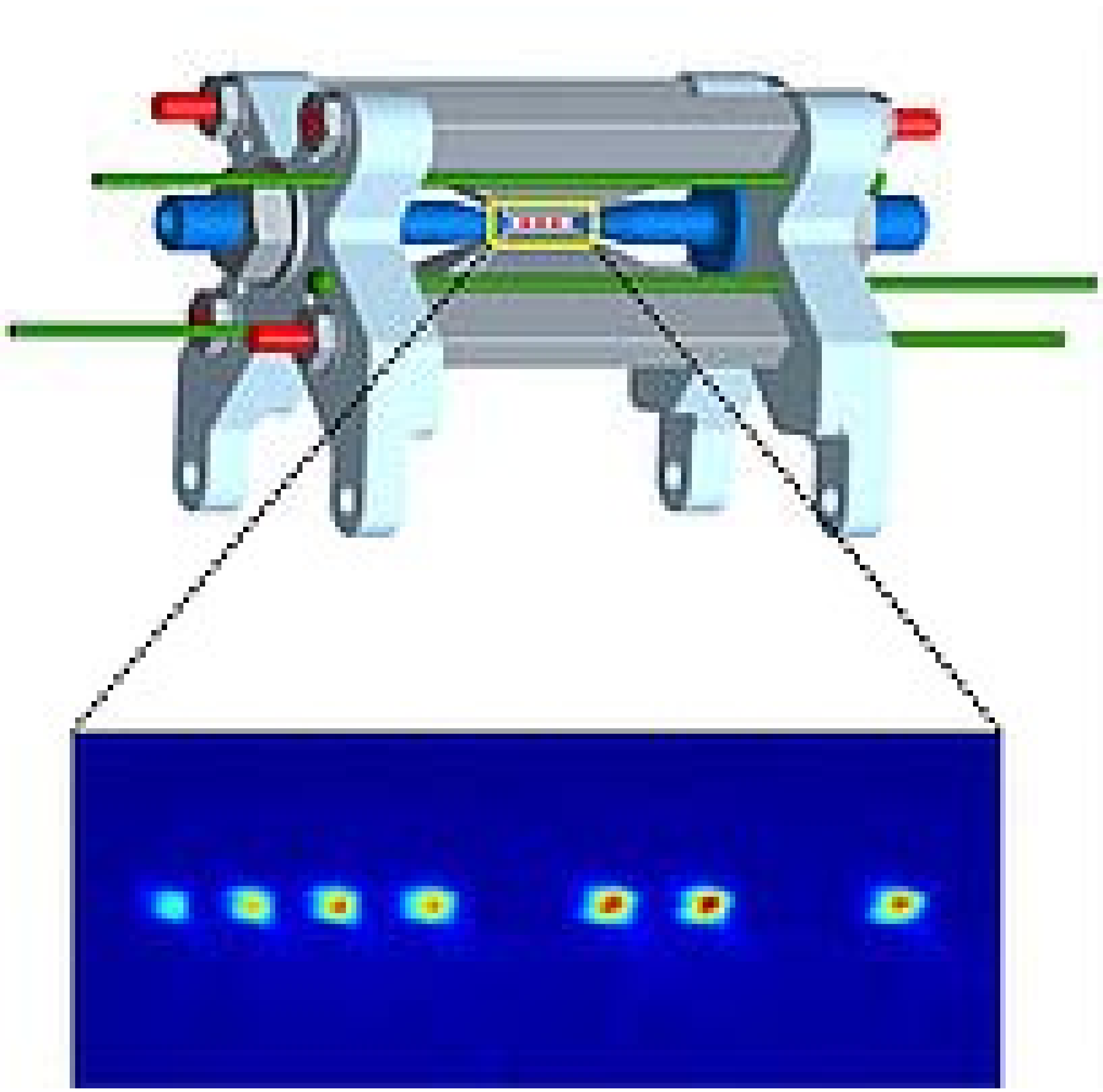
Aarhus Ion Trap Group, Denmark



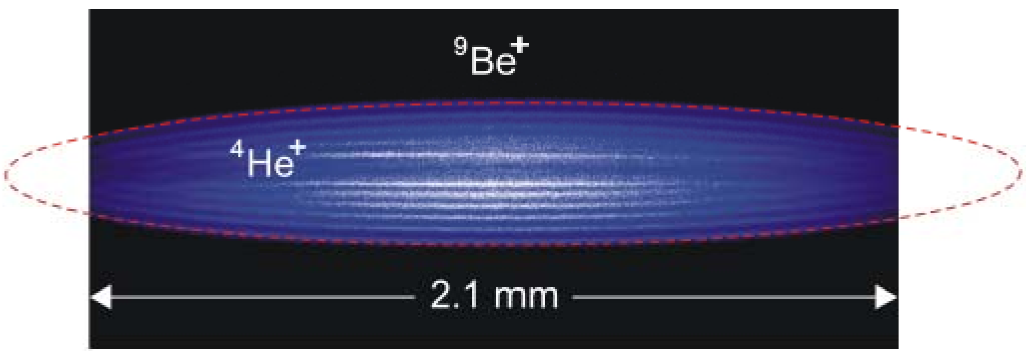
M. Drewsen et al, Aarhus University 2002

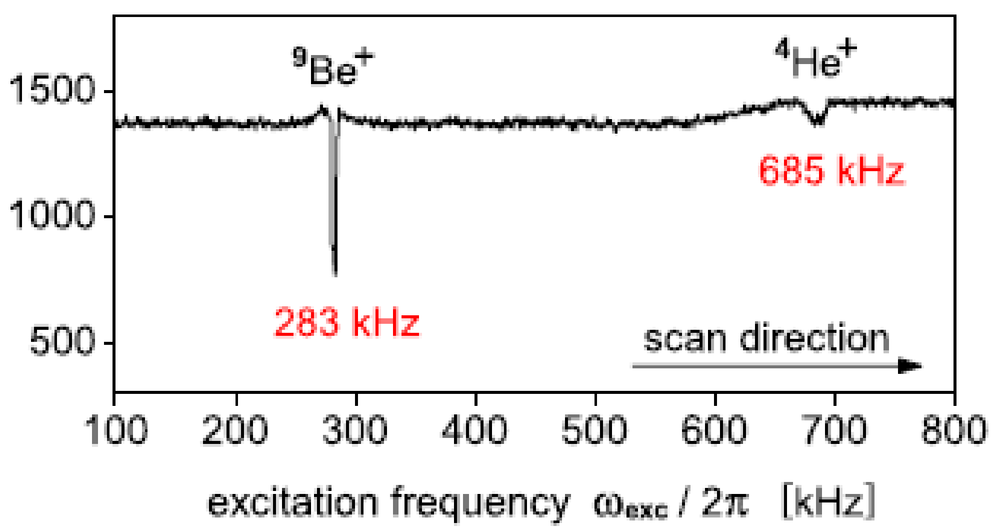

4P3/2
4P1/2
854 nm
3D5/2
866 nm
850 nm
3D3/2
397 nm
4S1/2
100 μ
increasing power of shelving laser
direction of the cooling lasers

ion string
with sympathetically cooled impurities



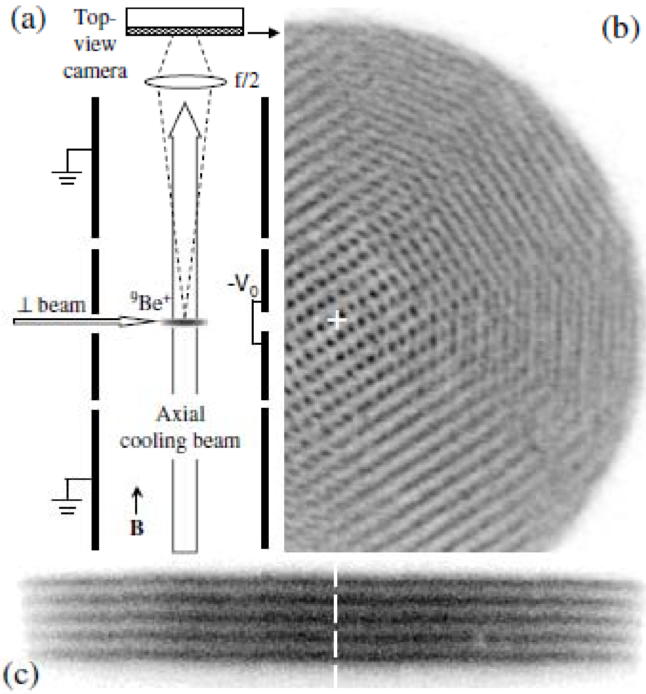
Mass spectrometry with Coulomb crystals

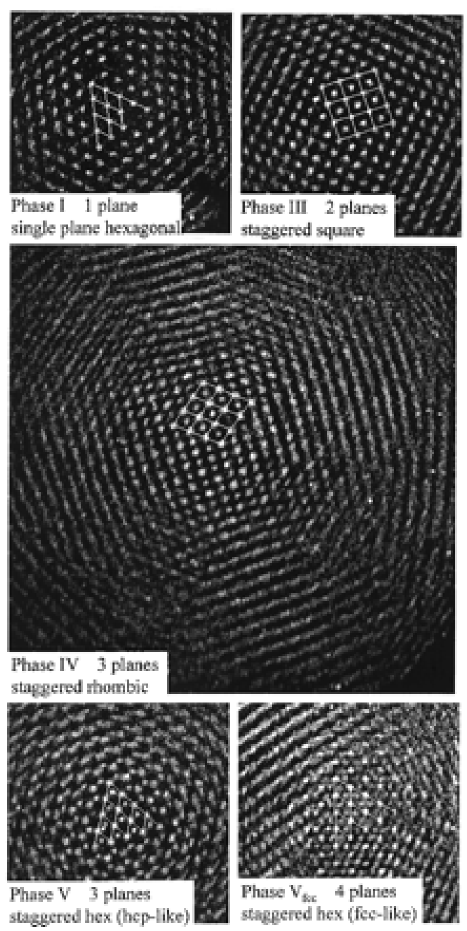




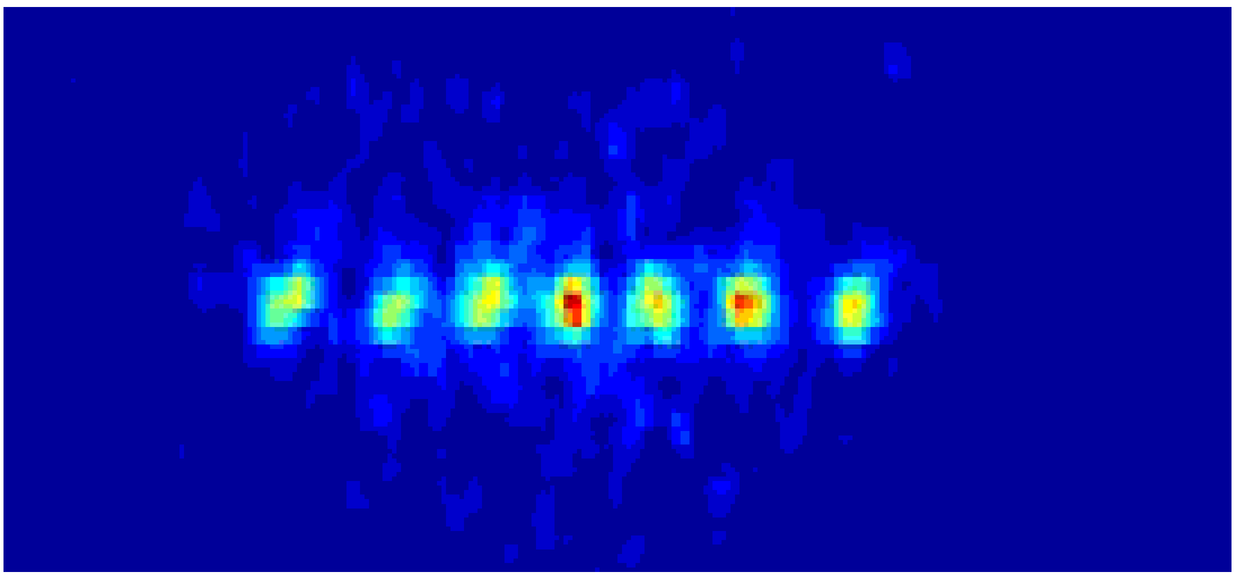
S. Schiller et al, Univ. Duesseklдorf, 2008

Coulomb crystals in Penning Traps





J. Bollinger et al.NIST



Courtesy R. Blatt, Innsbruck

Quantum computing with trapped ions

Basic elements of quantum computing

Quantum Computer:

Basic element is a **quantum bit**, or **qubit.** That is described by a state in a 2-level quantum mechanical system. The two basis states are conventionally written as $|0\rangle$ and $|1\rangle$. A pure qubit state is a linear quantum superposition of those two states. This means that each qubit can be represented as a linear combination of $|0\rangle$ and $|1\rangle$:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$$

where α and β are complex probability amplitudes. α and β are constrained by the equation

$$|\alpha|^2 + |\beta|^2 = 1$$

The probability that the qubit will be measured in the state $|0\rangle$ is $|\alpha|^2$ and the probability that it will be measured in the state $|1\rangle$ is $|\beta|^2$. Hence the total probability of the system being observed in either state $|0\rangle$ or $|1\rangle$ is 1.

This is significantly different from the state of a classical bit, which can only take the value 0 or 1.

A number of qubits taken together is a qubit register. Quantum computers perform calculations by manipulating qubits.

Quantum computer hardware must satisfy fundamental constraints:

(i) the qubits must interact very weakly with the environment to preserve their superpositions,

(ii) the qubits must interact very *strongly* with one another to make logic gates and transfer information,

(iii) the states of the qubits must be able to be initialized (that means, bring them into a desired state, usually |0>) and read-out the states with high efficiency.

(iv) quantum operations of any kind have to be performed with the qubits. It has been shown that there is a small *universal* set of operations involving at most two qubits at the same time that suffices to construct arbitrary operations

A linear chain of trapped ions may fullfill all the requirements

Main requiremens for candidate ions:

Laser cooling into ground state of oscillation
Internal 2-level system which can be brought into a superposition state

What does one have to do?

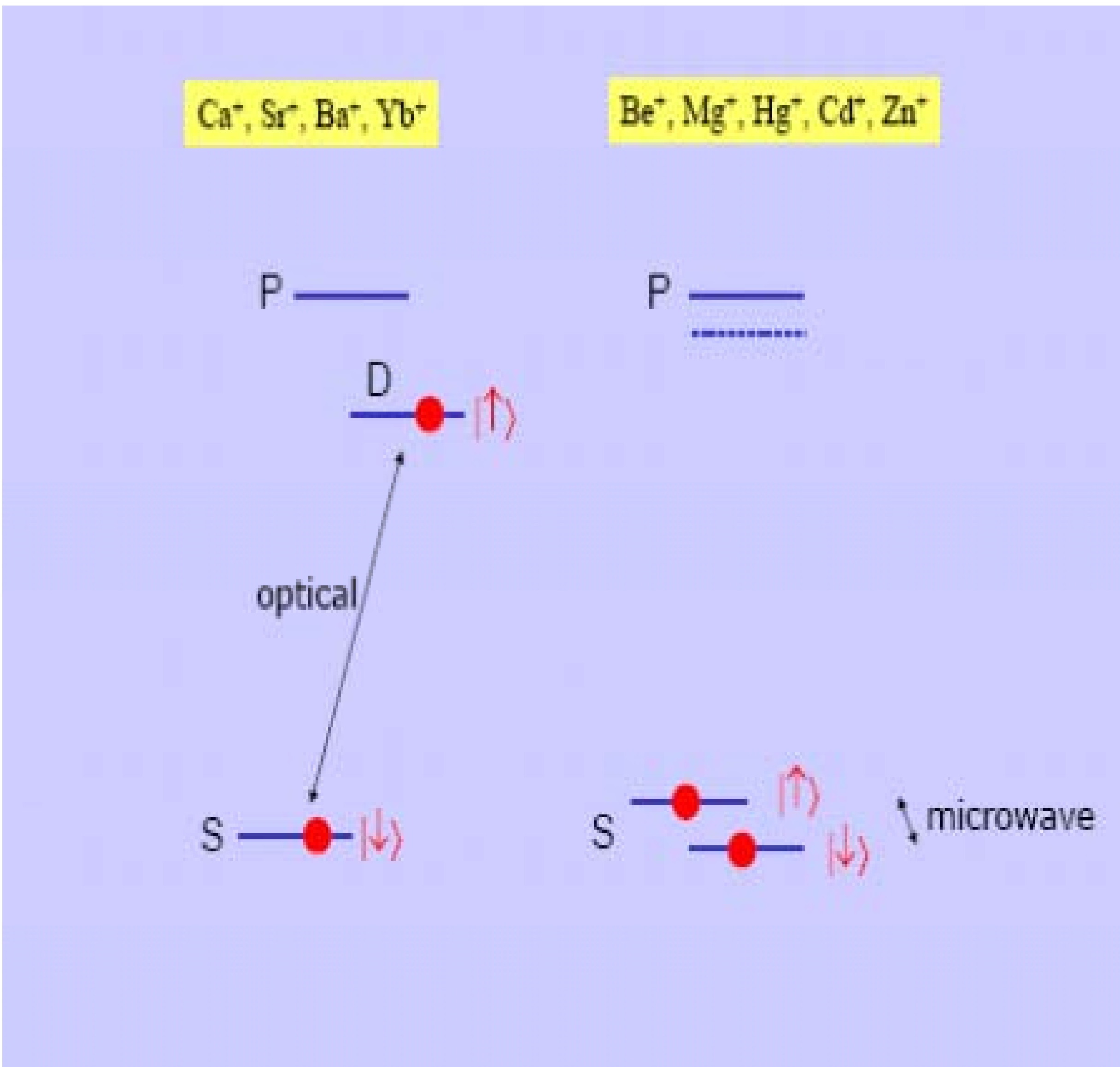
- Create a superposition of two internal states by applying a pulse of radiation of well defined amplitude and length
- Cool the ion motion into a well defined state of their oscillation. This will be the quantum mechanical ground state of their oscillation
- Couple the internal state to the oscillatory state
- Perform quatum logic oprerations
- Read out the system after the operation is completed
- Implement error correction schemes

A number of experimental problems have to be solved:

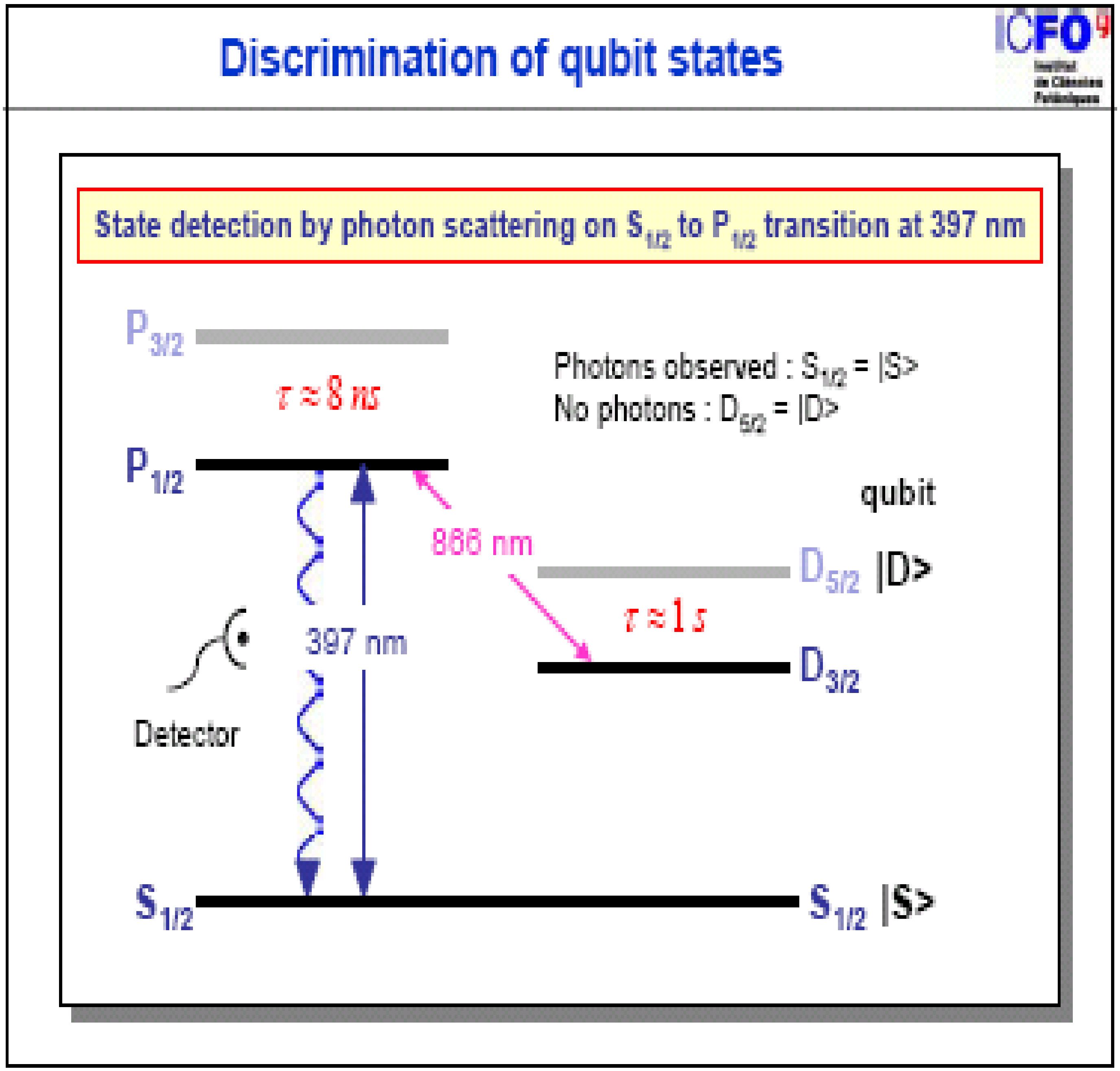
- To what extent can each ion´s levels be protected from environmental influences? (Decoherence)
- How many qubits can be added? (Scaling)
- How can the ions be addressed individually (Initialization and read-out))

Two-level systems considered for quantum computation:

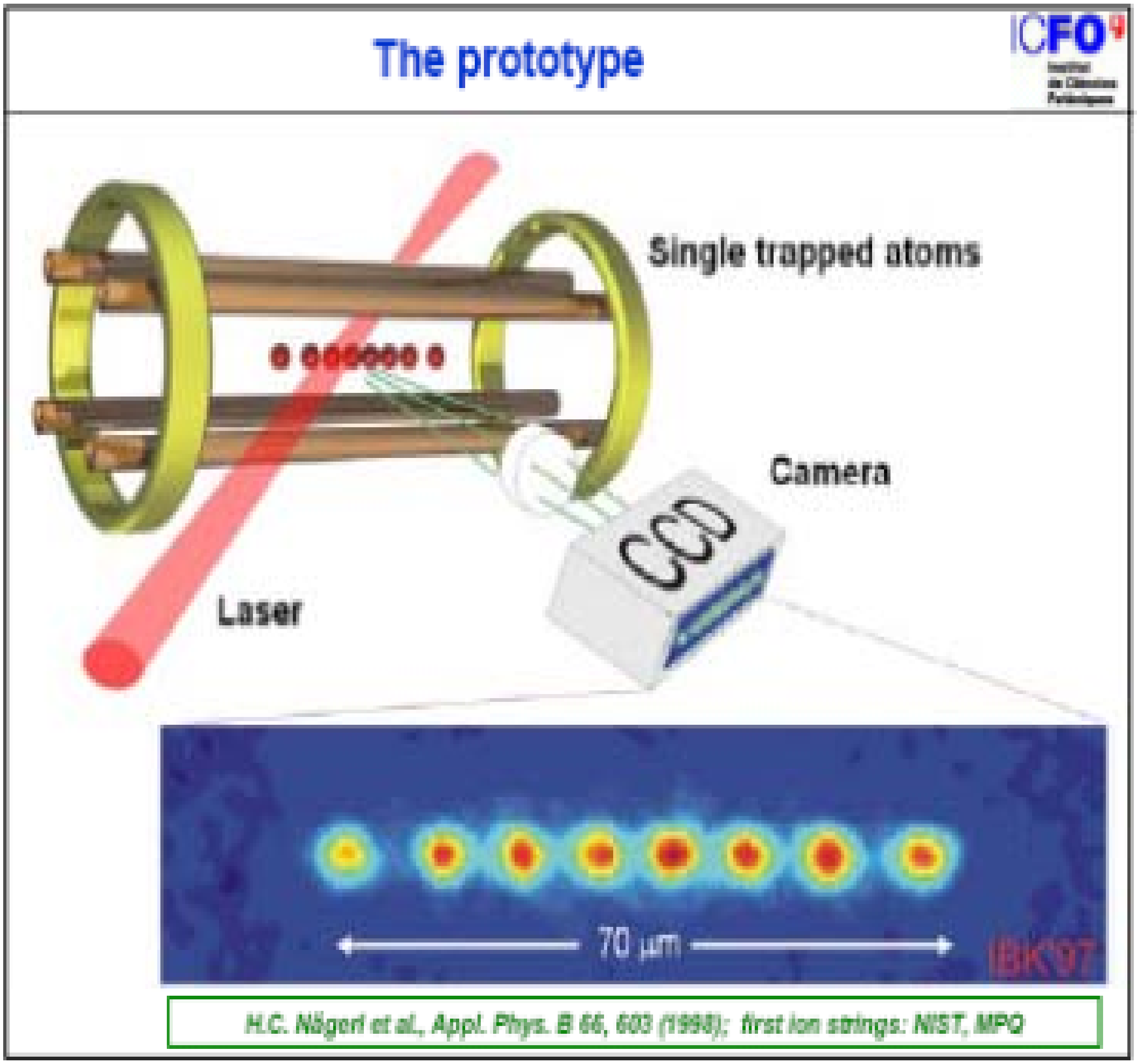
(1) Optical transition between ground state and long lived metastable state
(2) ground state hyperfine levels



Optical qbit states in Ca+ ion

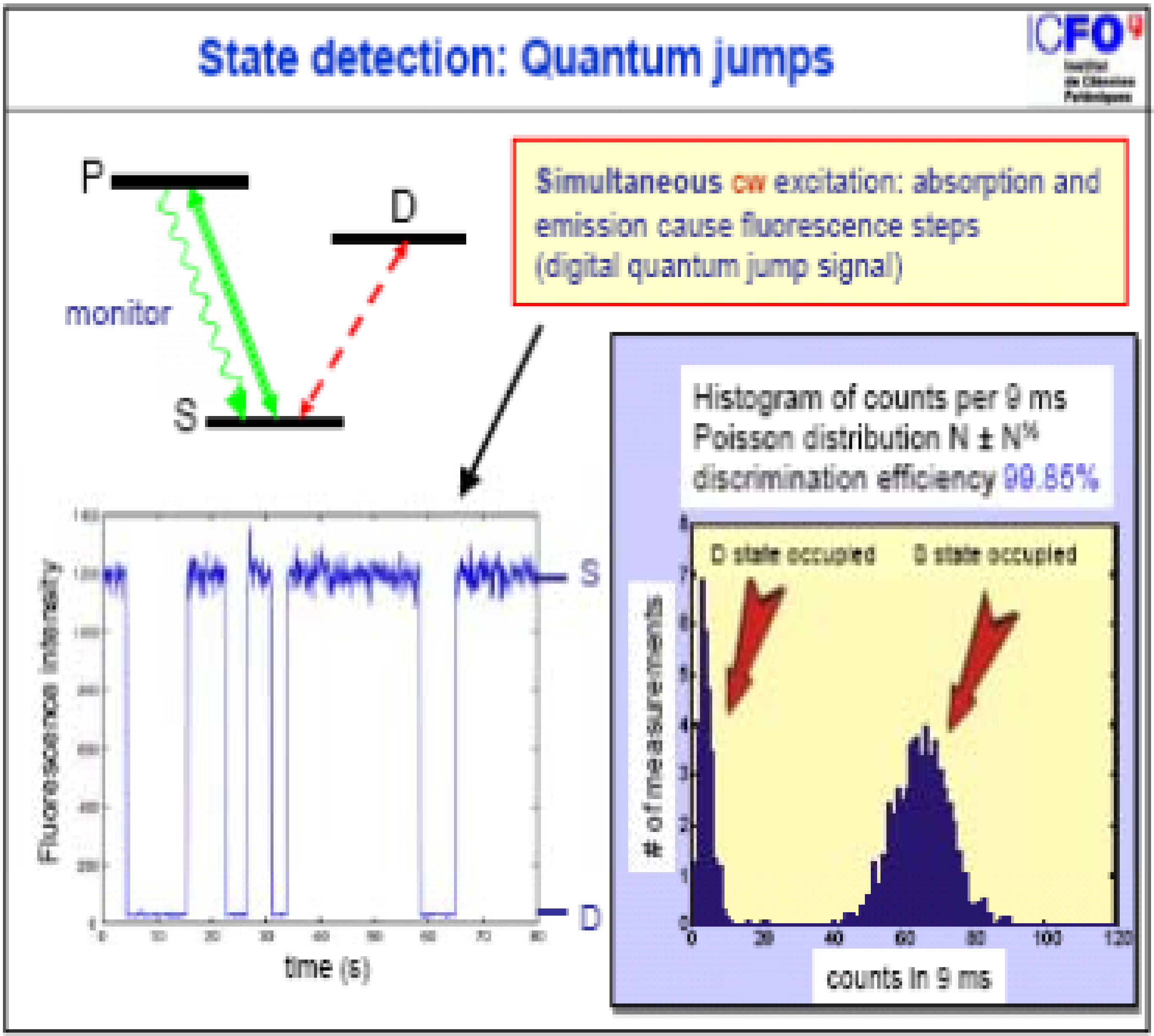


Initialisation of qbit state



When appropriate laser radiation is applied to the ions, only one of the two internal states fluoresces (in the figure below all ions were prepared in this state). This allows near-perfect detection of the state of each qubit.

(Courtesy R. Blatt et al, Innsbruck)


State detection: Quantum jumps
ICFO
P
D
S
monitor
Simultaneous cw excitation: absorption and emission cause fluorescence steps
(digital quantum jump signal)
Fluorescence intensity
time (s)
0 10 20 30 40 50 60 70 80
S
D
Histogram of counts per 9 ms
Poisson distribution N ± N½
discrimination efficiency 99.85%
D state occupied
S state occupied
# of measurements
counts in 9 ms
0 20 40 60 80 100 120

Adressing individual ions

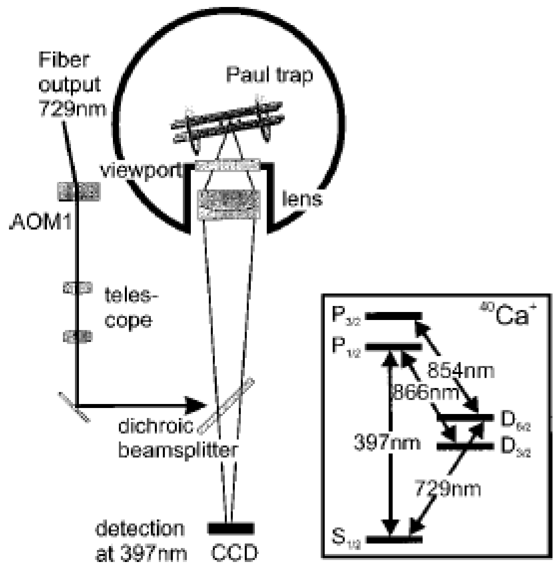
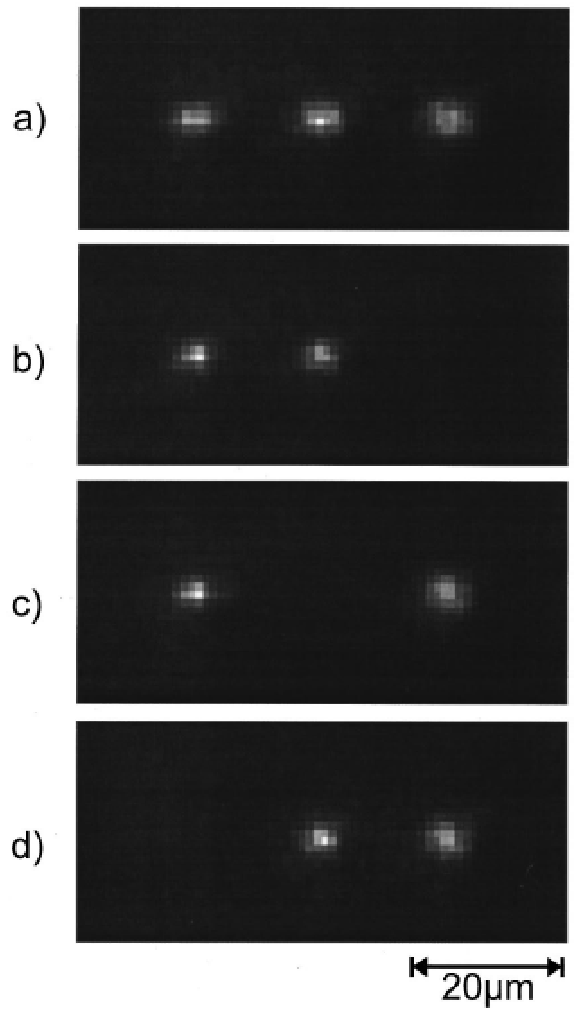


FIG. 1. Scheme of the experimental setup to address single ions in the string. Laser light at 729 nm from an optical fiber is superimposed with the fluorescence at 397 nm on a dichroic beam splitter. Thus, the laser is focused by the objective lens onto the ion string. A two-lens telescope transforms the fiber output for optimum focusing. The AOM1 can be used to shift the direction of the laser beam to address different ions in the string. Inset: relevant energy levels of $^{40}Ca^+$ and the corresponding transition wavelengths. Both D levels are metastable with a lifetime of 1 s.



The íons in a chain are coupled by their mutual Coulomb repulsion. A particular ion's internal state can be mapped onto the collective motion of the ions, which can subsequently be transferred to another ion's internal levels. In this way, the quantum motion of the ion ensemble acts as a "data bus," which allows any quantum computation to proceed.

External 2-level system: Quantized oscillation

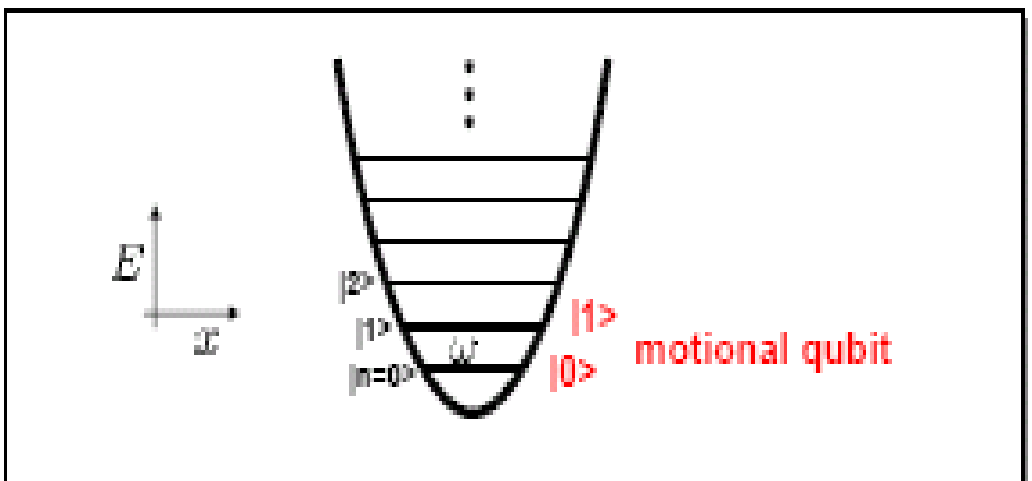
Quantized motion

ICFO

$$E_{harm.osc.} = \frac{m}{2}\omega^2 x^2 + \frac{1}{2m}p^2$$

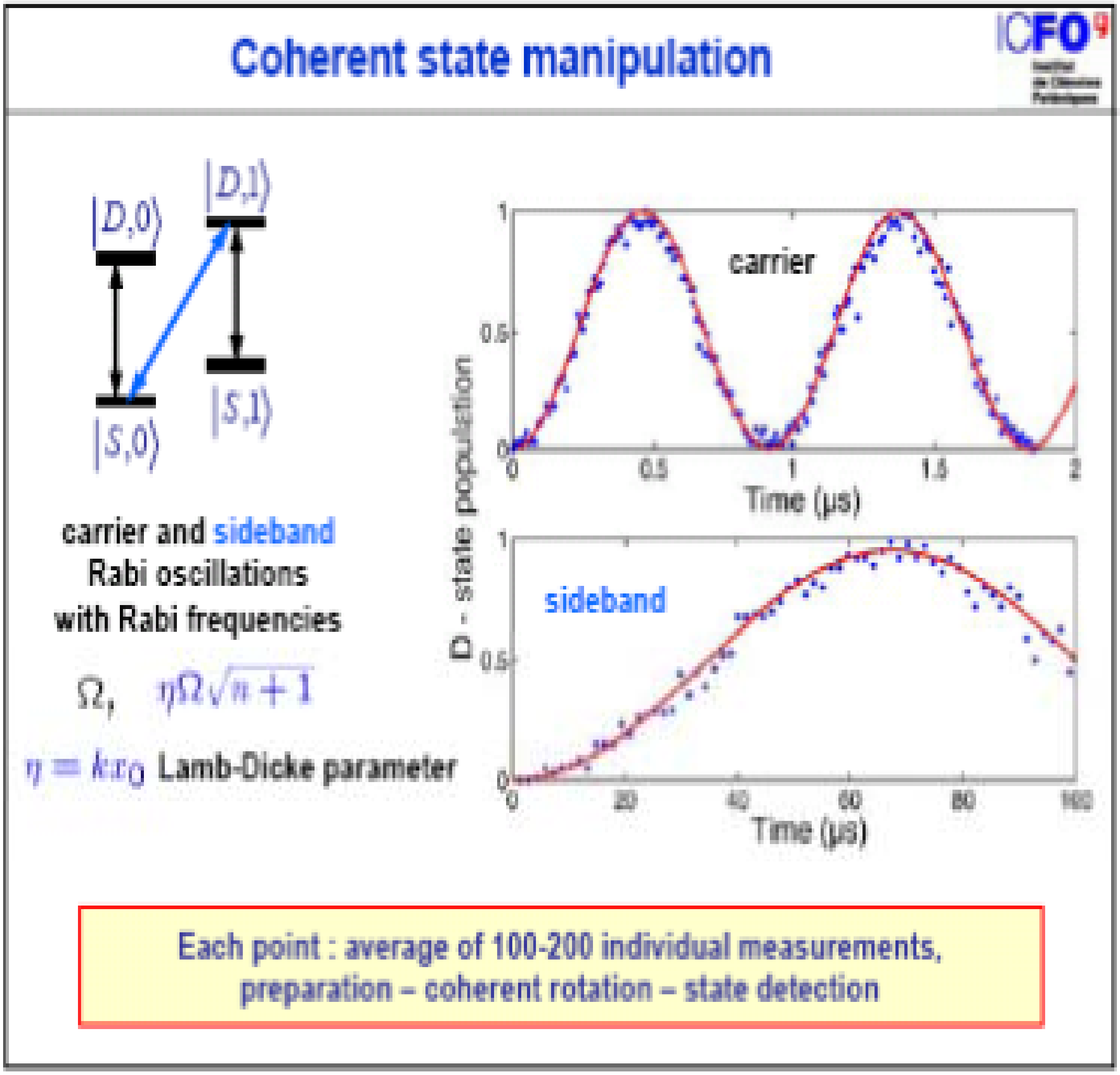
$$\rightarrow H_{mec} = \hbar\omega\left(a^\dagger a + \frac{1}{2}\right)$$

$$H_{mec}|n\rangle = E_n|n\rangle = \left(n + \frac{1}{2}\right)\hbar\omega|n\rangle$$

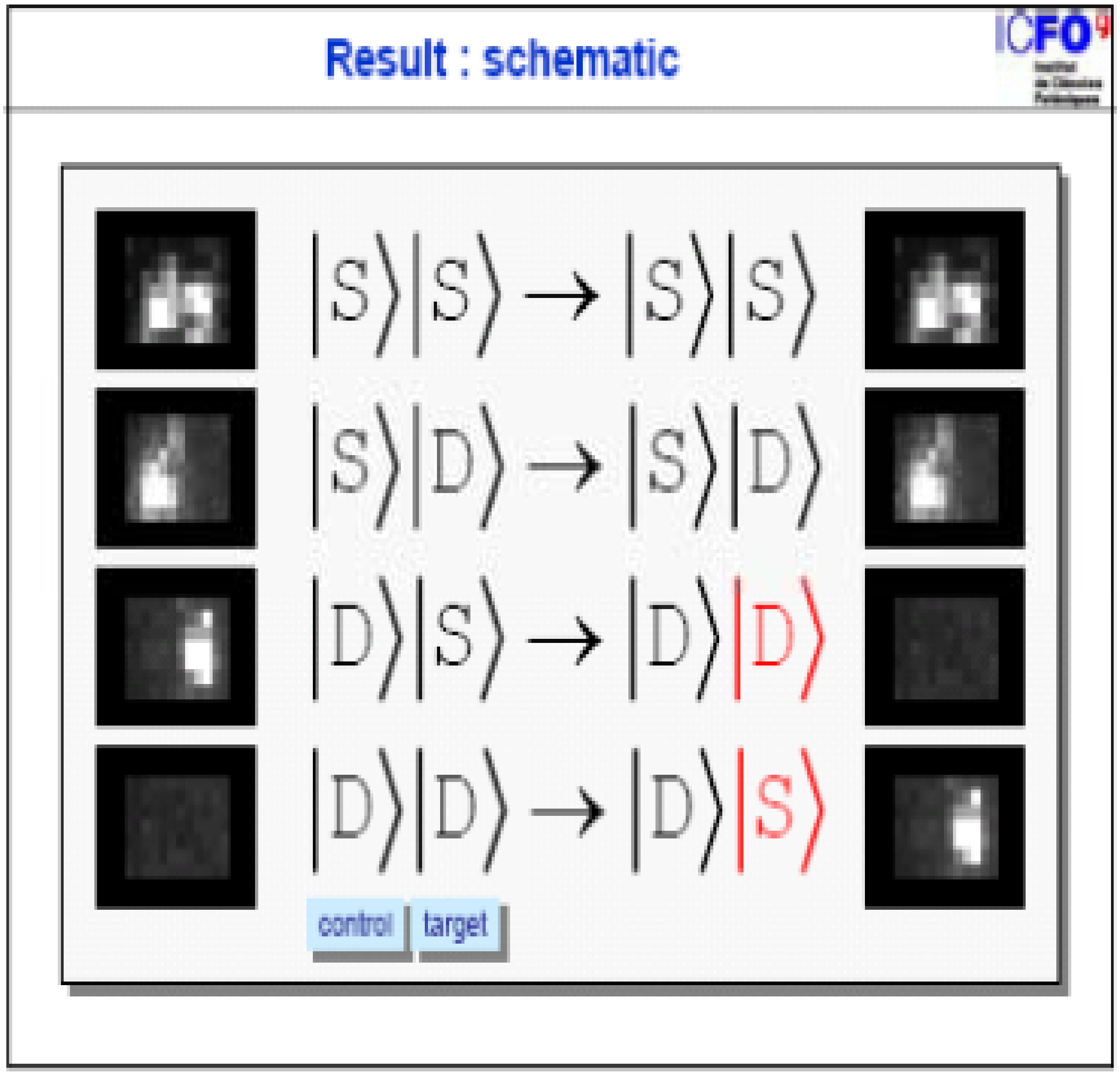


N ions → 3 N oscillators

Example of coupling of internal and external qubits



Example of experimental qubit operations

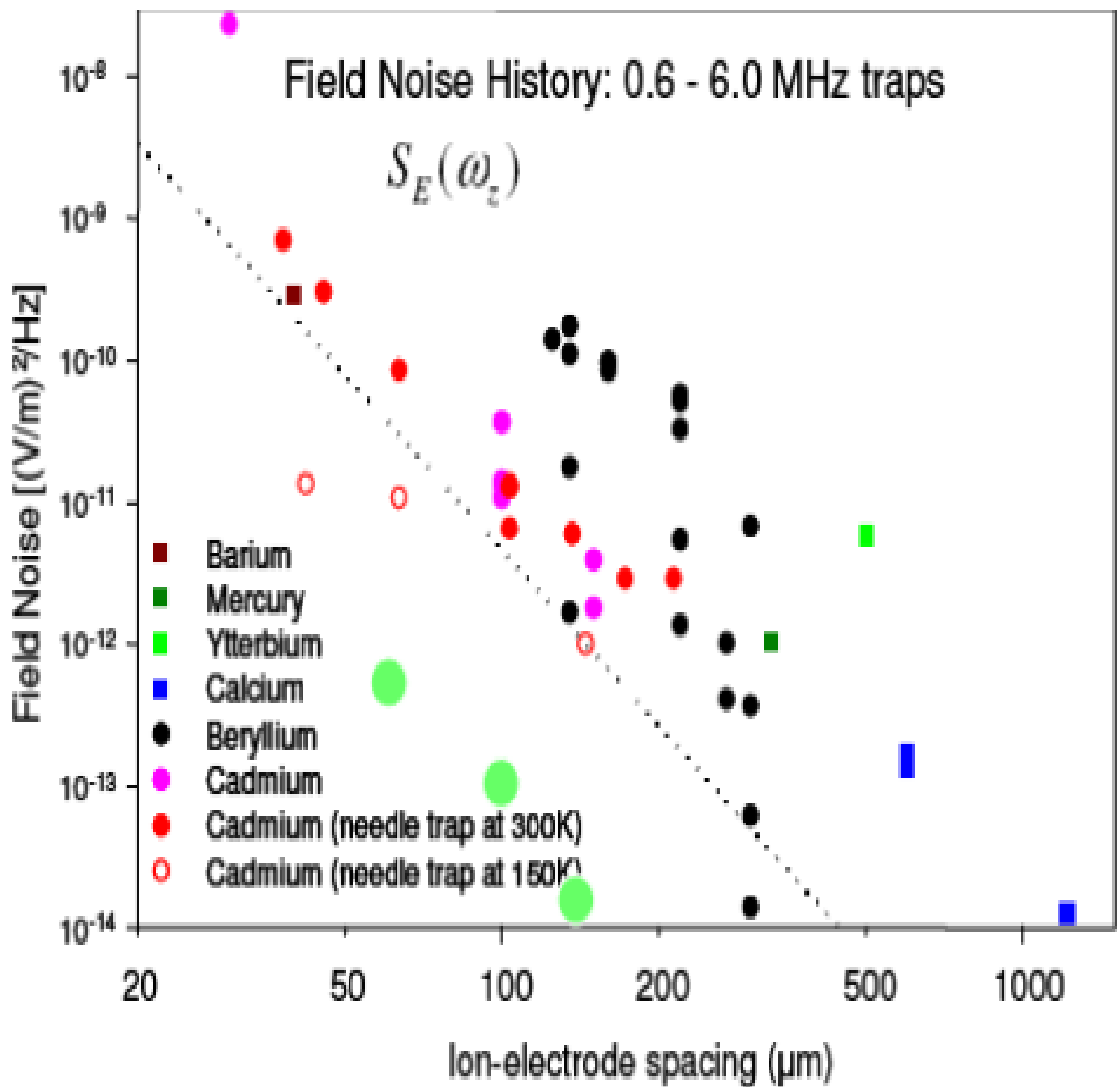


Fidelity obtained: 99.3%

Problems

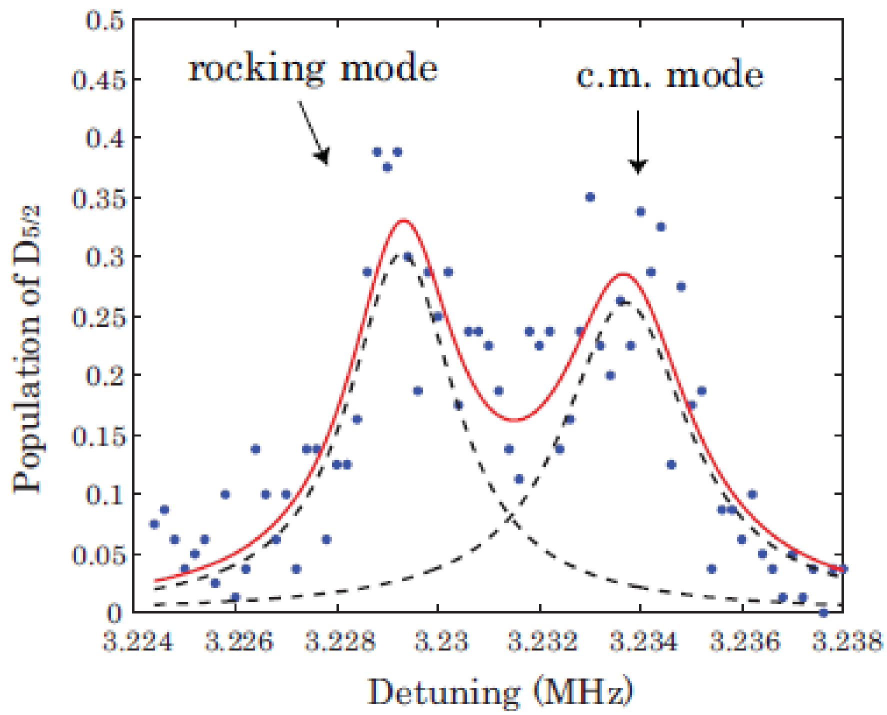
- Finite coherence time by spontaneous decay of excited level and by ion heating
- Mode coupling in long ion chains

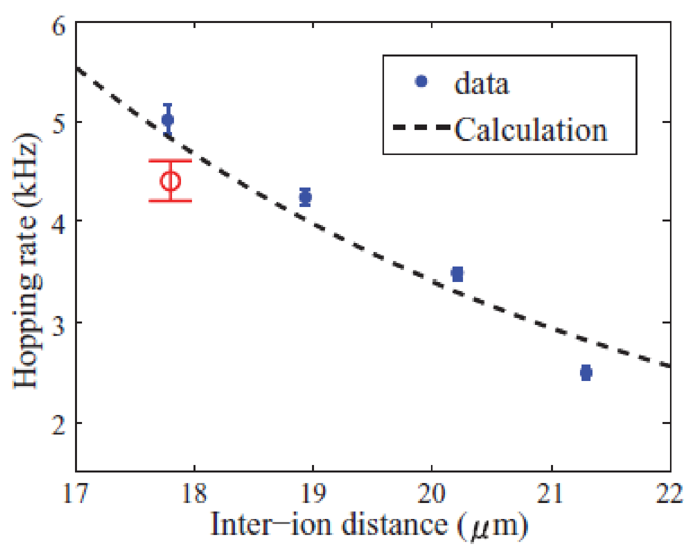
Decoherence from fluctuation potentials on trap surface



Courtesy W. Hensinger, Sussex

Frequencies of the two modes of oscillation in a 2-ion crystal

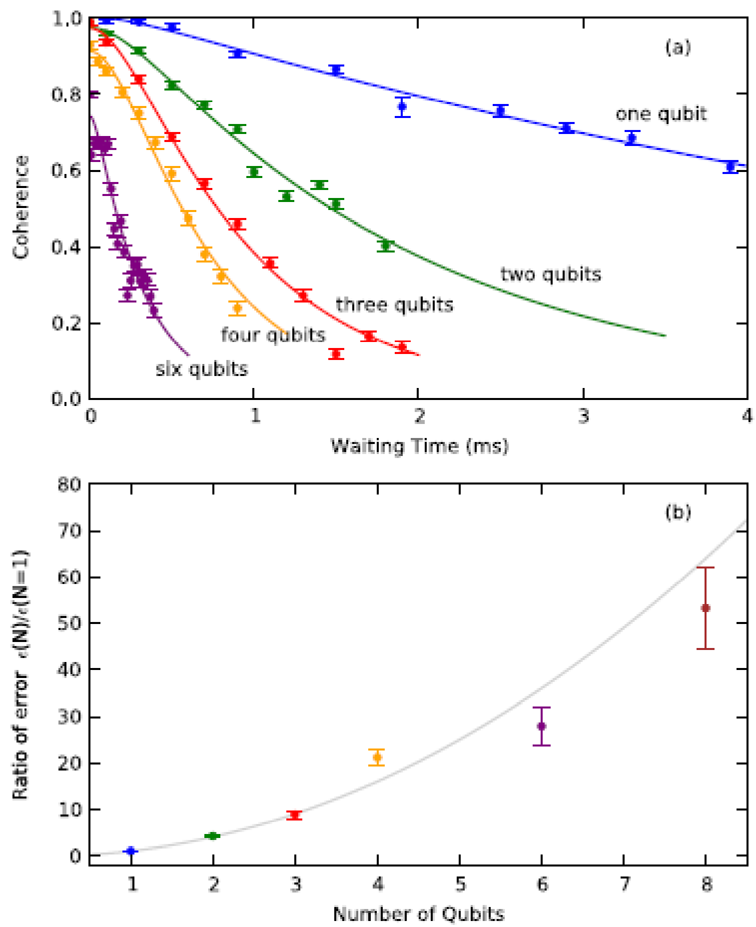




Hopping between radial oscillation modes at different ion distances

S. Haze et al., Phys. Rev. A **85,** 031401® (2012)

Decay of coherence for different numbers of entangled qbits



T. Monz et al., Phys. Rev. Lett. **106**, 130506 (2011)

What is the status?

- Coherence time limited by fluctuating electric field from the surface of the trap electrodes ($\tau < 1s$)

⇒ Number of qubit operation is limited (switching time ≈ μs)

- Coherence time decreases rapidly with increasing ion number

⇒ Largest number of entangled qbits so far: 14 (R. Blatt et al., 2011)

A new approach: Single eletrons in miniature planar Penning traps

Internal 2-level system:

Spin-up and spin down

External bus system:

Quantum mechanical ground state of cyclotron oscillation

What could be the advantage?

- No rf electric fields → less heating →longer coherence time (?)
- Cooling into the ground state automatically by synchrotron radiation in a strong magnetic field at low temperatures
- Coupling of different states by transfer of induced image voltages from ion oscillation to other traps by superconducting wires (Scalability)

Cooling electrons into the ground state of the cyclotron oscillation

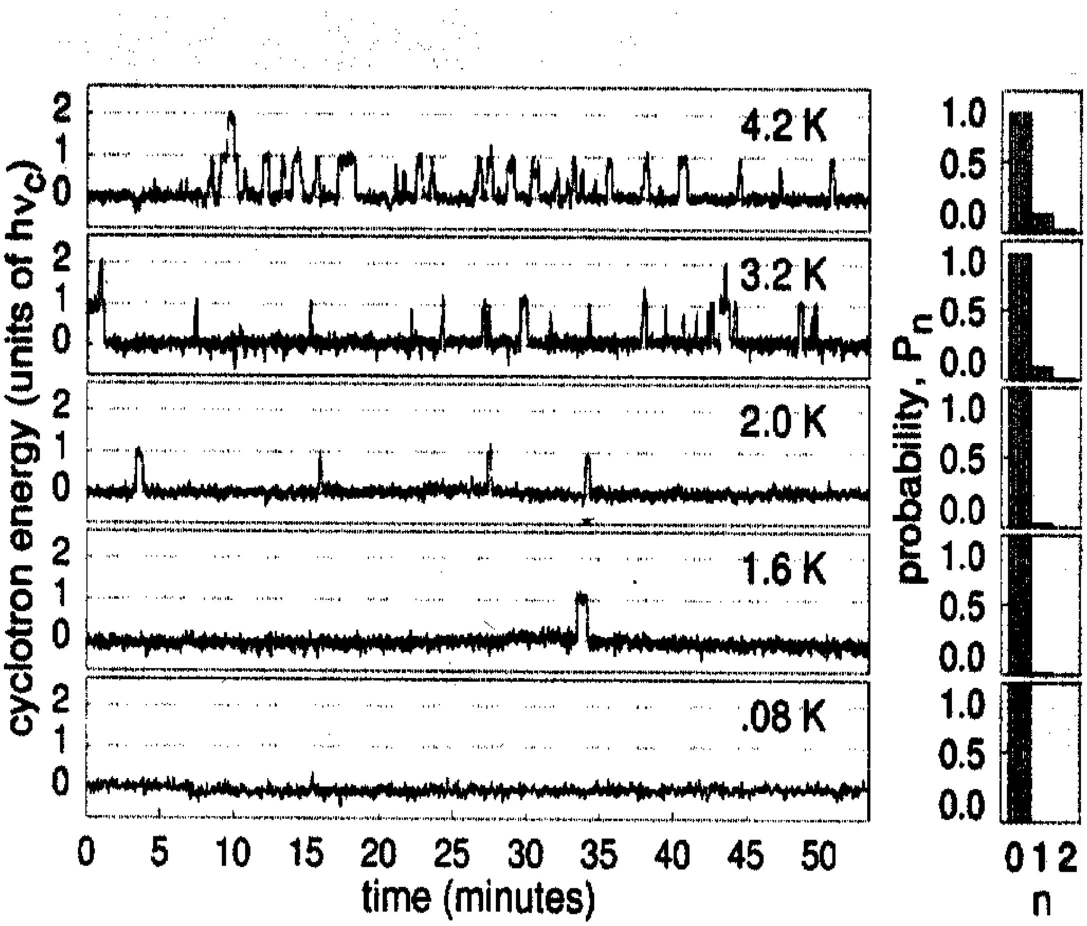
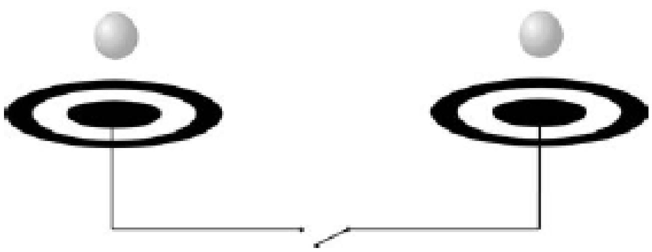


FIG. 2. Quantum jumps between the lowest states of the one-electron cyclotron oscillator decrease in frequency as the cavity temperature is lowered.

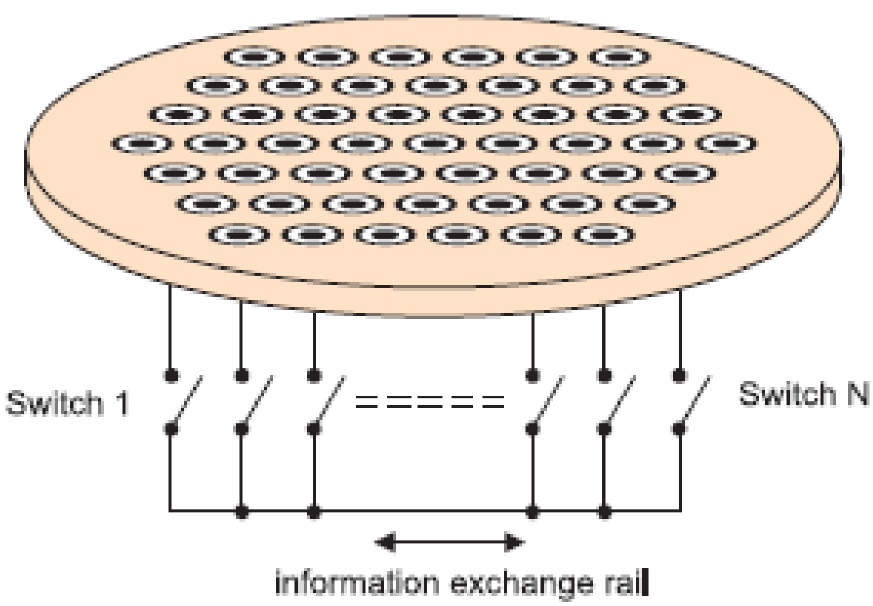
Peil and Gabrielse, PRL 83 (1999)

Proposed planar Penning trap for quantum computing with trapped electrons

S. Stahl et al., Eur. Phys. J. D 32,139 (2005)



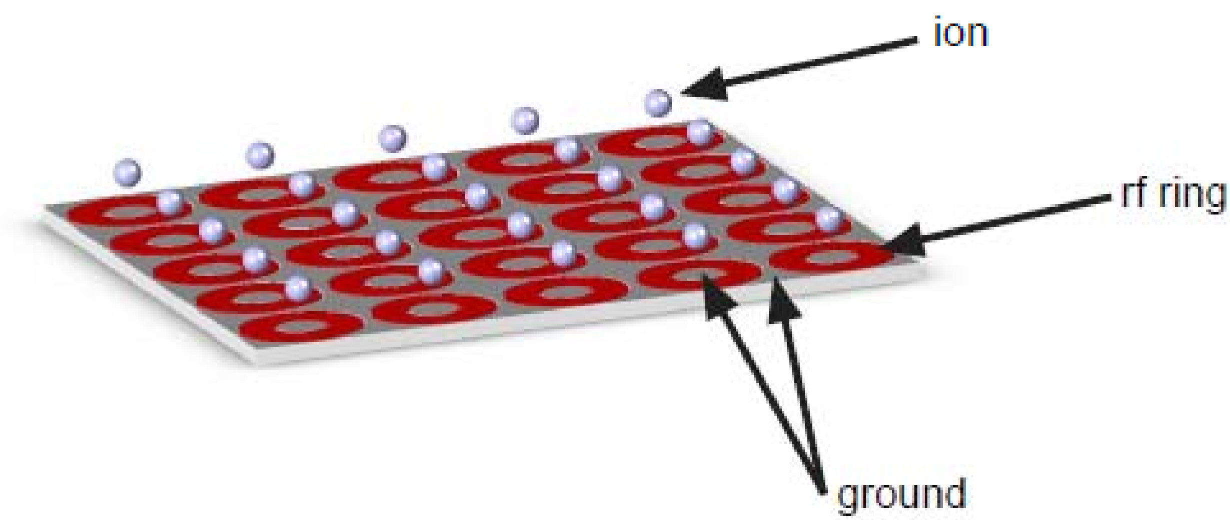
Coupling of traps
by superconducting wires



2-dim. array
of planar traps

Proposed array of circular planar rf traps

M. Kumph, M. Brownnutt, R. Blatt arXiv:1103.5428



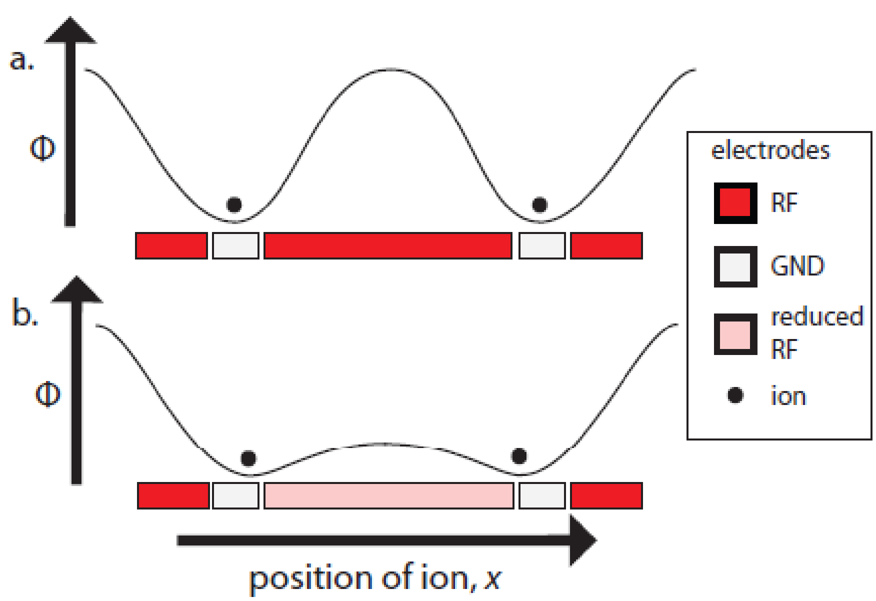


Figure 2. (a) schematic of the trapping potential Φ between two sites in an ion trap array, and (b) where the potential barrier between the two trapping sites is lowered to increase the relative Coulomb interaction between them.