Paul traps

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*Physics with Trapped Charged Particles, Les Houches/F*
Radiofrequency Paul traps

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Physics with Trapped Charged Particles, Les Houches/F
A. Paul’s work on ion traps
   1. Wolfgang Paul
   2. An ion cage
   3. Nobel prize
   4. The quadrupole ion trap

B. Basic operation of Paul trap (single ion, no interaction)
   1. Mathieu equations, stability diagram
   2. Motion of the ion in the trap
   3. The adiabatic approximation

C. Lamb-Dicke regime
   1. for microwaves; for optics
   2. how to reach LD, micromotion issues
   3. how to reduce micromotion; different techniques

D. More than one ion
   1. space charge effects

E. Characterisation of trap
   1. nonlinear resonances and canyons
   2. experimentally: how do I measure frequencies of motion of the trapped ions
      1. by fluorescence, or other optical means
      2. electronically (tickle, image currents;)

F. Modified geometries
   1. how, why, for what
   2. linear traps
   3. more exotic forms: the race track, the ion circus
   4. linear multipoles
   5. 2D, 3D and surface traps
   6. other geometries, school experiments demonstration

G. Microfabricated traps and heating

H. How to set up a Paul trap,
   1. experimental set-up; rf drive, helical resonator, how to p the drive +V0 or +V/2
   2. how to detect ions in the trap
      1. by construction (die glaserne Paulfalle, with inegr fibers, stylus ion trap)
      2. by optical means
      3. by electronic means

I. Tutorial: how to design an ion trap?
A. Paul’s work on ion traps

« Mich dünkt , es ist ein trauriger Umstand bei unserer ganzen Chemie, dass wir die Bestandteile der Körper nicht frei suspendieren können »

« I believe, it is a sad fact in all our chemistry, that we are not able to freely suspend the elementary constituents »

Georg Christoph Lichtenberg  (1742-1799)
A. Paul’s work on ion traps

Wolfgang Paul
- 1913 – 1983
- was an expert in mass filters
- since 1952, professor at University Bonn
- responsibilities at KFA Jülich, CERN (director of Nuclear Physics Division), DESY
- intended to work on « strong focussing » for a 500 MeV synchrotron
- the ion trap was a by-product of the mass selection efforts
A. Paul’s work on ion traps

1958 « An ion cage »
The Nobel Prize in Physics 1989

The Royal Swedish Academy of Sciences has awarded this year's Nobel Prize in Physics for contributions of importance for the development of atomic precision spectroscopy

Hans Dehmelt
University of Washington
Seattle, USA

for the development of the ion trap technique

Wolfgang Paul
Universität Bonn
Federal Republic of Germany

Norman F. Ramsey
Harvard University
Cambridge, USA

for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

www.nobel.se
A. The ion cage
B. Operation of Paul trap

- a ring and 2 endcaps of hyperboloid shape

- apply an oscillating voltage between the electrodes

- the resulting potential is:

\[
\phi(x,y,z,t) = (U_{DC} + V_{AC}\cos\Omega t) \frac{x^2 + y^2 + 2z^2}{2r_0^2}
\]

\[r_0^2 = 2z_0^2\]
B. Operation of Paul trap
B. Motion of a single trapped ion

The motion of a single particle with e/m evolving in this potential is described by

\[ \varphi(x,y,z,t) = (V_{DC} + V_{AC}\cos\Omega t) \frac{x^2 + y^2 + 2z^2}{2r_0^2} \]

\[ \frac{d^2u}{dt^2} + \frac{\Omega^2}{4} (a_u - 2q_u \cos \Omega t) u = 0 \]

for \( u=x,y,z \)

with \( a_x = -\frac{a_z}{2} = \frac{8eU_{DC}}{2r_0^2m\Omega^2} \) and \( q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2r_0^2m\Omega^2} \)

→ Mathieu equations
B. Motion of a single trapped ion

The motion of a single particle with $e/m$ evolving in this potential is described by

$$\frac{d^2u}{dt^2} + \frac{\Omega^2}{4} (a_u - c)$$

with $a_x = -\frac{a_z}{2} = \ldots$

$\Rightarrow$ Mathieu equation
B. Mathieu equations

The motion of a single ion $\frac{e}{m}$ evolving in this potential is described by

for $u=x,y,z$

$$\frac{d^2 u}{dt^2} + \frac{\Omega^2}{4} \left( a_u - 2q_u \cos \Omega t \right) u = 0$$

with

$$a_x = -\frac{a_z}{2} = \frac{8eU_{DC}}{2 r_0^2 m \Omega^2}$$

$$q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2 r_0^2 m \Omega^2}$$

stability of the solution only depends on $e/m$, $r_0$, $\Omega$, $U_{DC}$ and $V_{AC}$

⇒ stability diagram
B. Stability diagram of Mathieu equations

\[ a_x = -\frac{a_z}{2} = \frac{8eU_{DC}}{2r^2_0m\Omega^2} \]

\[ q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2r^2_0m\Omega^2} \]
B. Stability diagram of Mathieu equations

\[(a_1;q_1) = (0.237; 0.706)\]
B. Stability diagram of Mathieu equations

\[ a_x = -\frac{a_z}{2} = \frac{8eU_{DC}}{2 r_0^2 m \Omega^2} \]

\[ q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2 r_0^2 m \Omega^2} \]
B. Frequencies of motion

exact solutions of the Mathieu equations are

\[ u(t) = A \sum_{n=-\infty}^{\infty} C_{2n} \cos(\beta + 2n)\Omega t/2 + B \sum_{n=-\infty}^{\infty} C_{2n} \sin(\beta + 2n)\Omega t/2 \]

where \( A \) and \( B \) are constants depending on initial conditions. The coefficients \( C_{2n} \), which are the amplitudes of the Fourier components of the particle motion, decrease with increasing \( n \).

\[ \omega_u = \beta_u \Omega \]

\( \beta \) can be exactly determined by

\[ \beta_u^2 = a_u + \frac{q_u^2}{(\beta_u + 2)^2 - a_u - q_u^2} \]

\[ + \frac{q_u^2}{(\beta_u - 2)^2 - a_u - q_u^2} \]

\[ + \frac{q_u^2}{(\beta_u + 4)^2 - a_u - q_u^2} \]

\[ + \frac{q_u^2}{(\beta_u - 4)^2 - a_u - q_u^2} \]

\[ + \frac{q_u^2}{(\beta_u + 6)^2 - a_u - \cdots} \]

\[ + \frac{q_u^2}{(\beta_u - 6)^2 - a_u - \cdots} \]
B. Motion of the single particle

for the large majority of cases the adiabatic approximation is sufficient:

for $q_u < 0.4$ and $a_u \ll q_u$

$$u(t) = R_u \cos \omega_u t \left(1 + \frac{q_u}{2} \cos \Omega t\right)$$

with

$$\omega_u = \beta_u \Omega$$

and

$$\beta_u = \sqrt{a_u + \frac{q_u^2}{2}}$$

B. Motional frequencies

- harmonic oscillation
- secular motion $\omega_u$ and micro-motion $\Omega$

\[ u(t) = R_u \cos \omega_u t \left(1 + \frac{q_u}{2} \cos \Omega t\right) \]
B. Motion of the single particle

for \( q_u < 0.4 \) and \( a_u << q_u \)

\[
u(t) = R_u \cos \omega_u t \left( 1 + \frac{q_u}{2} \cos \Omega t \right)
\]

with \( \omega_u = \beta_u \Omega \)

and

\[
\beta_u = \sqrt{a_u + \frac{q_u^2}{2}}
\]

!! Values diverge rapidly for \( q > 0.4 \) !!

A better approximation can be found in

J.P. CARRICO Applications of inhomogeneous oscillatory electric fields in ion physics

\[
\beta_\xi \approx \left[ a_\xi - \frac{(a_\xi-1) \cdot q_\xi^2}{2(a_\xi-1)^2-q_\xi^2} - \frac{(5a_\xi+7) \cdot q_\xi^4}{32(a_\xi-1)^3(a_\xi-4)} - \frac{(9a_\xi^2+58a_\xi+29) \cdot q_\xi^6}{64(a_\xi-1)^5(a_\xi-4)(a_\xi-9)} \right]^{1/2}
\]
C. Strong confinement

- the amplitude of the ion motion increases with the distance from the trap center
- only in the trap center \( r=0 \) can it be 0

- harmonic oscillator in a potential well of limited length
\[ \rightarrow \text{discretisation of frequencies (energy levels)} \]

\[ u(t) = R_u \cos \omega_u t \left(1 + \frac{q_u}{2} \cos \Omega t\right) \]

- if amplitude of motion \( R_u \) is smaller than \( \lambda/2\pi \) \( \rightarrow \) discrete spectrum for \( \omega_u > \gamma \)
- for a given energy (Doppler limit) : \( R_u \) is smaller for higher motional freq.s
\[ \frac{\omega_u}{2\pi} > 1 \text{ MHz} \rightarrow \frac{\Omega}{2\pi} > 10 \text{ MHz} \]

\[ \rightarrow \text{single ion(s) in miniature traps} \]
C. Lamb-Dicke regime

- secular motion $\omega_u$: laser-cooled
  
  **Doppler limit** $T_{\text{limit}} = \hbar/(2k_B\tau_{\text{nat}})$
  
  (Ca$^+$: $0.55mK@23MHz$)

- micromotion $\Omega$: driven motion

!!! simplified illustration!!!

Vibrational energy levels of the ion, $<n>$

*DW Wineland & W Itano, Phys. Rev. A 20, 1521-1540 (1979),
Single ions or electrons

Schroedinger 1952:

Erstens ist es angemessen festzustellen, dass wir mit einzelnen Teilchen nicht experimentieren, ebensowenig wie wir Ichtyosaurier im Zoo züchten können. Wir prüfen Spuren von Ereignissen, lange nachdem sie stattgefunden haben...

*First it has to be stated, that we do not experiment with single particles, as much as we do not raise ichtyosauri in a zoo. We look for evidences of facts, long after they have happened*

Zweitens ... ist... die Tatsache ...zuzugeben, dass wir nie mit EINEM Elektron, Atom oder (kleinen) Molekül experimentieren. In Gedankenexperimenten geben wir manchmal vor, es zu tun, allerdings stets mit lächerlichen Konsequenzen.

*Second, the fact is, that we never experiment with a single electron, atom, or (small) molecule. In gedankenexperiments, we sometimes pretend to do so, but always with ridiculous consequences*
Visual observation of a single Ba\(^+\) - ion

Experiment Heidelberg, Toschek group, 1980

D. More than ion

space charge effects

- limit the ion density to $10^6$/cm$^3$

- shift the frequencies of motion to lower values (depending on the geometry of trap and size of cloud)

- distort the observed stability diagram
D. Spatial and density distribution of an ion cloud

Fig. 1.7. (a) Fluorescence $I_F$ of Ba$^+$ ions in axial and radial direction in a Paul trap of 4 cm ring radius showing a Gaussian density distribution [10]. (b) Calculated density distributions for different ion temperatures [11]


D. Density distribution of an ion cloud

\[ n(r)/n_0 = \begin{cases} \text{Red, } T=5 \text{ K} \\ \text{Blue, } T=300 \text{ K} \\ \text{Black, } T=10,000 \text{ K} \end{cases} \]

C. Champenois
D. Optimal trapping point

Ifflaender and Werth, Metrologia 1977

Fig. 3. Computed iso-density lines. Dotted lines: boundary of stable region

Fig. 4. Experimental lines of equal fluorescence intensities. The numbers give relative intensities
E. Characterisation of ion trap

- number of stored ions
- maximum 5000 ions
E. Instabilities in an ion trap

- number of stored H2+ ions
E. Instabilities in an ion trap


Wang, Franzen & Wanczek, IJMS (1993) showed that for a 3D trap in the first stable region ($\beta_r > 0, \beta_z < 1$)

\[
\frac{n_r}{2} \beta_r + \frac{n_z}{2} \beta_z = 1
\]

with $N$ the order of perturbation and $|n_r| + |n_z| = N$

where $n_r$ and $n_z \geq 0$

also coupling between macro- and micromotion produces « black holes » for higher-order contributions

for example $\beta_z = 1/2$ (octupole) or $\beta_z = 2/3$ (hexapole)
E. Instabilities in an ion trap


for example N=4

\[ \beta_r = \frac{1}{2}; \, \beta_z = \frac{1}{2} \]

\[ \frac{1}{2} \beta_z + \frac{3}{2} \beta_r = 1 \]

\[ \frac{3}{2} \beta_z + 1/2 \beta_r = 1 \]

\[ \beta_z + \beta_r = 1 \]
E. Instabilities


« black canyons »
Nonlinear resonances – *used for isotope separation*


\[ a = -0.013, \quad q_z = 0.719, \quad \Delta q/q = 90 \]

Laser-induced fluorescence from a cloud of natural mixture Eu+ showing the hyperfine structure of the \(^{9}S_4 - ^{9}P_5\) resonance line at 382 nm.

Operated at resonance for \(m=151\) amu.
2\textsuperscript{nd} part of lecture
Ejection with tickle

F Vedel, M Vedel, RE March, IJMSIP 99, 125 (1990)
Ejection with tickle

Long acquisition times

Max Ion cloud

Trap empty

Variation of tickle frequency

M Knoop, PhD thesis
Detection of image currents

![Diagram of Penning trap with magnetic field and induced ac-current]

Image from K Blaum
Detection of image currents

Ramping of d.c. trap voltage.
\[ \omega_z \sim V^{1/2} \]
When \( \omega_z = \omega_{\text{Res}} \), ions absorb energy from circuit \( \rightarrow \) damping
Cloud with “tickle”

- Additional small amplitude exciting secular frequencies
- $\Rightarrow$ heating

![Fluorescence signal vs. Tickle frequency](image)

**NON - DESTRUCTIVE**
Characterization of the miniature trap

- application of an additional $V_{\text{AC}}$-voltage of small amplitude (« tickle »)

\begin{align*}
L_{mr} eU_{\text{DC}} \zeta^2 + \frac{8eU_{\text{DC}}}{m r_i^2 \Omega^2 L} & = 583 V_{\text{eff}} \\
L_{mr} eV_{\text{AC}} \zeta^2 & = 634 V_{\text{eff}} \\
L_{mr} eV_{\text{AC}} \zeta^2 & = 685 V_{\text{eff}} \\
L_{mr} eV_{\text{AC}} \zeta^2 & = 737 V_{\text{eff}}
\end{align*}

- for the Paul-Straubel case: $a_z = \frac{8eU_{\text{DC}}}{m r_i^2 \Omega^2 L}$ and $q_z = \frac{4eV_{\text{AC}}}{m r_i^2 \Omega^2 L}$

- different geometric defects lead to: $a_z L_z = -2a_x L_x$ and $q_z L_z = -2q_x L_x$

- for $580V_{\text{rms}} \leq V_{\text{AC}} \leq 790V_{\text{rms}}$ : $8.0 \geq L_z \geq 7.6$ and $7.0 \leq L_x \leq 7.1$
Stability diagram: limits and canyons

- scan of the applied continuous voltage $U_{DC}$ gives information about the confinement efficiency of the trap without any external perturbation

- « black canyons » can be followed through the stability diagram

\[ E_{ur.Phys.J.D15,105-111(2001)} \]
F. Modified geometries

holes, truncated electrodes…

spectroscopy and lasers?
Linear ion trap – Paul’s mass filter!

- extend along the $z$-axis
- add end electrodes

➤ a line where the potential is 0!
Linear ion trap

- RF field yields transverse pseudopotential

- End electrodes yield axial confinement

- Large storage capacity
- Many particles near axis with small micromotion
- Good optical access

Simulation of quasipotential for linear rf trap
Linear ion trap

The Aarhus linear Paul trap

The linear Paul trap

Sinusoidal RF potential:

\[ U_{RF}(t) = U_{RF} \sin(\Omega t) \]

Effective oscillation freq.'s:

\[ \omega_r = \frac{1}{2} \beta \Omega, \quad \beta = \left( \frac{1}{2} q^2 + \alpha \right)^{1/2} \]

\[ \omega_z = \left( -\frac{1}{2} a_{z0} \right)^{1/2} \Omega \]

Stability parameters:

\[ q = \frac{4Q U_{RF}}{m \Omega^2 r_0^2} \quad a = -\frac{\alpha Q U_{end}}{m \Omega^2 r_0^2} \]

Atomic density:

\[ n_i = \frac{\epsilon_0 U_{rf}^2}{M_i r_0^4 \Omega^2} \]
Linear ion trap

The Aarhus linear Paul trap

Photo-ionizing laser

Electron beam

Cooling laser

Atomic beam

Cooling laser
Linear ion trap

- symmetric stability diagramm

Linear ion trap

- shape of the rods

ideal case: $d_0/2 = 1.1468 \, r_0$

Reuben et al., *Ion trajectories in exactly determined quadrupole fields*, IJMS 154, 43-59 (1996)
Linear ion trap

200 V<sub>pp</sub> AC
6.2 MHz

300–750 V DC

v<sub>z</sub> = 0.5–0.8 MHz (axial)
v<sub>r</sub> = 1.0 MHz (radial)

10μm
Crystals

Innsbruck

Oxford

Aarhus
The race-track trap

Observation of multi-shell structures in a quadrupole storage ring

G. Birkl, S. Kassner & H. Walther
NATURE • VOL 357 • 28 MAY 1992
The ion circus

The ion circus project

- The ion circus is a circular Paul trap that can simultaneously cool and mass separate isobaric nuclides.

- The resolving power is increased as the ions orbit in the ring. Since they are buffer-gas cooled, the transmission is not degraded.
The ion circus

Main characteristics

- The ion circus is composed of 36 segments of radiofrequency quadrupole mass filter bent into a circle
- Ring diameter : 400 mm
- Distance between two opposite electrodes : 10 mm
- Acceptance : 3 mm
- Energy @ injection : 100 <> 1500 eV
- Frequency ~ 2 MHz
- Potential on electrodes : +/- 500 V
- Time of trapping < 1 s
- Energy @ ejection : a few eV

Goal $m/\Delta m=5000$

« The ion circus: A novel circular Paul trap to resolve isobaric contamination »
E. Minaya Ramirez, S Cabaret, D Lunney, NIM B 266, 4460-4465 (2008)
The ion circus

Main challenge:
capacity of electrodes

ions injected from an external source.
2k-pole traps

Pseudo-potential $V^*(r)$:

$$V^*(r) = \frac{k^2 q^2 V_0^2}{16m\Omega^2 r_0^2} \left( \frac{r}{r_0} \right)^{2k-2} + \frac{q\kappa V_{end}}{2z_0^2} (2z^2 - r^2)$$

radial part

axial part

k=2 : quadrupole

k=4 : octupole
**2k-pole traps**

Pseudo-potential

\[ V^*(r) = \frac{k^2 q^2 V_0^2}{16m\Omega^2 r_0^2} \left( \frac{r}{r_0} \right)^{2k-2} + \frac{q\kappa V_{end}}{2z_0^2} (2z^2 - r^2) \]

- Stability of the trajectories governed by Mathieu’s equations
- Mathieu parameter
- Non-linear dynamics.
- No more exact stability criteria and sensibility to initial conditions
- Adiabaticity parameter \( \eta_{ad}(r) \) empirically limited to \( \sim 0.36 \).
Motion in a multipole

- In the radial potential
- Molecular Dynamics to accompany the evolution of structures
- Monte-Carlo methods for crystal structures
Non-neutral plasma (cold charged fluid)


Non-neutral plasma (cold charged fluid)


Radial potential $V^*(r) \propto r^{2k-2}$

Potential well depth $V^*(R_{max}) \propto k^{-2}$

Higher order $\rightarrow$ flatter and more shallow

22 pole trap
D Gerlich, Uni Chemnitz, Germany

2k- poles

😊😊😊😊
- Less rf heating
- Creation of different (crystal) structures: tubes, rings
- Symmetric structures (2D)

😢😢😢😢
- ?? Trapping range, initial conditions
- Laser power
- Detection efficiency
Miniature traps
### Systematic effects - experimental constraints -

\[ \Delta \nu_{\text{nat}}/\nu \approx 3 \cdot 10^{-16} \]

to resolve 1Hz at 411 THz (2.4 \cdot 10^{-15}) :

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion cooled to Doppler limit, ( \langle n \rangle \approx 10 )</td>
<td>Doppler 2(^\text{nd}) order</td>
</tr>
<tr>
<td>A magnetic field &lt; (0.1 ± 0.05 ( \mu )T)</td>
<td>Quadratic Zeeman quadratique, AC Stark</td>
</tr>
<tr>
<td>A residual electric field &lt;1V/mm</td>
<td>DC Stark</td>
</tr>
<tr>
<td>Gradient of electric field &lt;1V/mm over 1 mm (spherical traps)</td>
<td>Quadrupole moment</td>
</tr>
<tr>
<td>3 optical axis (orthogonal)</td>
<td>Measurement of quadrupole moment</td>
</tr>
<tr>
<td>T= 300K</td>
<td>BBR</td>
</tr>
<tr>
<td>P&lt;0.75( \mu )W/mm(^2) @ 729nm</td>
<td>AC Stark (light shift)</td>
</tr>
</tbody>
</table>
Miniature traps

to reach strong confinement at Doppler limit
→ need high motional frequencies
→ requires high trapping frequencies \((\Omega/2\pi > 10 \text{ MHz})\) with non-negligible amplitudes (a few 100 V)

\[
q_x = -\frac{q_z}{2} = \frac{4eV_{AC}}{2r_0^2m\Omega^2}
\]

reduce \(r_0\)

- shows that if the potential is harmonic in the central 10% of the structure this is largely sufficient for a single ion!
Miniature ion traps

Endcap traps

Univ. Washington
MPQ, Garching

Marseille
The stylus trap (or 4 $\pi$ trap)

Stylus ion trap for enhanced access and sensing
Robert Maiwald, Dietrich Leibfried, Joe Britton, James C. Bergquist, Gerd Leuchs and David J. Wineland, Nature Physics 2009, DOI: 10.1038/NPHYS1311
Microfabricated traps

- scalable architectures


\[ \omega_r = \frac{eV_{\text{AC}}}{\sqrt{2} m \Omega d^2} \]

with \( d \) the distance to the electrodes
Microfabricated traps

- 3D and surface traps
Microfabricated surface traps

Simulated pseudopotential

\[ \Phi_{\text{sec}} = \frac{Q^2|\nabla \phi_{\text{rf}}|^2}{4m\Omega^2} + Q\phi_{\text{dc}} \]

- \(Q\): ion charge, \(m\): ion mass
- \(\phi_{\text{rf}}\): rf potential
- \(\phi_{\text{dc}}\): dc potential
- \(\Omega\): rf frequency

\[ \Omega = 2\pi \times 10^6 \text{ Hz} \]
\[ V_{\text{rf}} = 700 \text{ V}_{\text{amp}} \]
\[ V_1 = V_7 = -15\text{V} \]
\[ V_2 = +90\text{V} \text{ (End electrode)} \]
\[ V_3 = +2\text{V} \text{ (Center electrode)} \]
\[ V_4 = V_5 = -15\text{V} \]

\[ \Phi_{\text{rf}} = \frac{Q^2|\nabla \phi_{\text{rf}}|^2}{4m\Omega^2} \]
\[ \Phi_{\text{dc}} = Q\phi_{\text{dc}} \]
\[ \Phi_{\text{sec}} = \Phi_{\text{rf}} + \Phi_{\text{dc}} \]
Microfabricated surface traps

Simulated pseudopotential -trap depth-

\[ \Omega = 2\pi \times 11 \times 10^6 \text{ Hz} \]
\[ V_{rf} = 700 \text{ V}_{\text{amp}} \]
\[ V_2 = +60 \text{ V(End)}, \quad V_3 = +4 \text{ V(Center)} \]
\[ V_1 = V_7 = V_4 = V_5 = 0 \text{V} \]

[Graphs showing rf voltage dependence and end electrode voltage dependence]
Microfabricated surface traps

Simulated pseudopotential - dc dependence -

rf 11.2 MHz
400V_{amp}

V_3 (Center)

V_2 (End)

Potential minimum along y axis

Height of potential minimum above substrate [\mu m]

V_3 = 2V
V_3 = 4V
V_3 = 6V

Secular oscillation frequency \omega_z

V_3 = 4[V]
Micro-traps with junctions

49-electrode
11-zone
T-junction

multiplexer chip
Mk 0.1: Mary Rowe et al. (’02)
Mk 0.2: Murray Barrett, John Jost et al. (’04)

1.5 cm

200 μm
typical ion spacing ≈ 2 μm

400μm
NIST trap

Planar Trap Chip

Magnified trap electrodes

CCD pictures of strings of Mg\(^+\) ions (trapped 40 \(\mu\)m above surface)

John Chiaverini, Signe Seidelin

NIST race-track

NIST trap chip module
(Jason Amini)

- 2 load zones
- 6 improved junctions
- 150 control electrodes

- backside loading
- motion through junctions
- utilize for multi-qubit work

slide Didi Leibfried
Mainz trap

Mainzer segmentierte Mikrofalle

- Mikro-Struktur - viele Ionen können gespeichert werden
- Segmentierung - Prozessor und Speichereinheit
- Transport von Ionen

S. Schulz, F. Schmidt-Kaler
Mainz trap

segmentierte Mikrafalle

- Ti/Au on Al₂O₃-Wafer (10nm/400nm)
- fs-Laser Schnitt in Au/Ti and Al₂O₃
- Justage und Fixierung in den Chiphalter
- bonding
Motional heating

Heating rate orders of magnitude over Johnson noise, physical origin unknown

Electric field noise

$$\dot{n} = \frac{e^2}{4m\hbar\omega} S_E(\omega) \sim 1/d^4$$

- IBM
- NIST
- NPL
- Innsbruck
- Oxford
- Michigan
- MIT

Distance to nearest electrode, $d(\mu m)$

- Electrode temperature $< 12$ K
Integrated fibers

- Fluorescence detection
- Cavity

W. Lange, Univ Sussex