Loading, detection, and cooling
Loading of ions into traps

• creation of ions inside trap
  (photo-ionisation, electron-ionisation, surface ionisation)

• injection of ions from outside sources
  Requires friction, provided by background gas collision, photon recoil

• dynamical catching of ions
  by switching of trap voltages
Creating ions inside the trap by electron-ionisation

Trapping efficiency in Paul traps as function of rf phase for different trapping parameters
Ion creation near trap electrode by surface ionisation or laser ablation
Ion creation by laser ionisation of neutral atoms
Example: Ca

Fig. 4.1: Level scheme showing levels in calcium relevant for the photo-ionization of neutral calcium. The ionization threshold is 6.11 eV above the ground state in calcium [50]. The lifetimes of the excited levels are also indicated.

Advantages:
Element and isotope selective
Control of created ion number by laser power
Ion injection from outside
Requires friction
Most simple by buffer gas collisions
Typical pressure: $10^{-5}$ mbar
(mean free path between ion-neutral collision $\approx$ trap size)

Trapped ion number at different background gas pressures from a 5 keV ion beam
Dynamical catching of ions

Catching of ions by fast switching of trap electrodes

Switching time fast compared to transit time of ions through trap (μs)

Works well for Penning traps, less well for Paul traps because of transient effects in rf voltage switching
Ion detection

**Destructive detection:** Extraction from trap by high voltage pulses at endcap electrode

Different trapped ions can be distinguished by time of flight to detector

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**Extraction from Paul trap**

Sensitivity: Single ions
Signal height depends on phase of ejection pulse with respect to trap r.f. voltage.
Ejection of ions from Penning trap

Accelerating force in fringe field: $F = \mu \text{ grad } B$
Separation of different mass ions by time of flight
Nondestructive detection of trapped ions

Absorption of energy from tank circuit, weakly excited at its resonance frequency

\[ \omega_z \sim V^{1/2} \]. When \( \omega_z = \omega_{Res} \), ions absorb energy from circuit \( \Rightarrow \) damping of circuit

Damping signal from ca. \( 10^4 \) ions

Sensitivity: ca. \( 10^3 \) ions at room temperature circuit
Measurement of total induced noise

Requirement: Thermal noise voltage $V_n$ of circuit small compared to induced noise

$$V_n = \sqrt{4k_B T R \delta \nu}$$

Single ion sensitivity when working at low temperatures and narrow detection bandwidth (superconducting circuits).
Axial motion in a Penning trap:
Ramping of trap voltage brings different ions into resonance with circuit, depending on their charge/mass ratio.
Fourier Transform of induced noise in external tank circuit

6 ions in a slightly inhomogeneous B-field:
Fluorescence strength from a single trapped ion, continuously excited at saturation intensity on an allowed electric dipole transition: \( \text{ca. } 10^8 \text{ Photons/s} \)

Detection efficiency (solid angle, transmission losses, detector quantum efficiency): \( \text{ca. } 10^{-5} \)

\[ \rightarrow 10^3 \text{ detected Photons from a single ion} \]
Fluorescence from a single trapped Sr$^+$ ion
Photo of a single Barium ion in a Paul trap

Ba ion leven scheme

Dehmelt, Toschek, 1988
The mean kinetic energy of stored ions depend on the trapping conditions. It is of the order of 10% of the total potential depth, typically of the order of a few eV. This corresponds to temperatures of several 10 000 K. For high precision measurements energy reduction is required.

Cooling methods:

Radiative cooling
Collisional cooling
Resistive cooling
Laser cooling
Sympathetic cooling
Radiative cooling

Exponential energy loss by synchrotron radiation in strong magnetic fields.

time constant: \( \tau^{-1} = \frac{4}{3}c^2 \left( \frac{e^4}{m^3} \right) B^2 \)

Effective only for electrons

Energy distribution of electrons at different times after loading in a field of \( B=6.5 \) T

Noise from a single trapped electron at different temperatures

Buffer gas cooling in Paul traps

Requirement:
Ion mass smaller than neutral buffer gas mass

Cooling of Ba\(^+\) by N\(_2\)

Final temperature limited by micromotion and depends on ion number
Reduced Doppler width of optical transition by collisional cooling
Ion cooling with cold ions of equal mass

MOT
Superimposed to lin. Paul trap

Red: without MOT
Blue: With MOT

Charge exchange

Ravi et al, 2012
Axial and cyclotron motion are damped by collisions. Magnetron motion becomes unstable and ions get lost.

Solution:
Coupling of magnetron motion to cyclotron motion by azimuthal r.f. quadrupolar field at frequency

\[ \omega_+ + \omega_- = \omega_c \]

**Ion trajectories with buffer gas collisions:**

Without mode coupling

With mode coupling

Feature: Coupling frequency is mass dependent → stabilisation of ion of interest, others become unstab
Increased laser-induced fluorescence after axialisation of a Ba\textsuperscript{+} ion cloud
Ion cooling by Coulomb interaction with cold electrons in a Penning Trap

- a) ions enter trap
- b) catching after 1st turn
- c) electron cooling
- d) resistive cooling

Distance from trap centre (cm)

HCl
Cooling time constant:

\[
\tau_c = \frac{3 m_i m_c C^3}{8\sqrt{2\pi} n_e Z^2 e^4 \ln(\Lambda)} \left( \frac{kT_i}{m_i C^2} + \frac{kT_e}{m_e C^2} \right)^{3/2}
\]

Decay rate equations:

\[
\begin{cases}
\frac{dT_i}{dt} = -\frac{1}{\tau_c} (T_i - T_e) \\
\frac{dT_e}{dt} = \frac{1}{\tau_c} \left( \frac{N_e}{N_i} \right) (T_i - T_e) - \frac{1}{\tau_e} (T_e - 4.2)
\end{cases}
\]

H. Poth, Physics Reports 196, (1990) 135-297
Example: Electron cooling of protons

Ion cooling by C interaction with could electrons

Ion energy (eV)

Time (s)

Protons: Initial energy = 3 keV

Electron energy (eV)

Time (s)
Resistive cooling

Oscillating ion induces image currents in trap electrodes
→ Exponential energy dissipation through external resistor

Time constant: $\tau = (2z_0/Q)^2 \ (m/R)$

$U = iZ, \ Z = 1/\omega C$

For $C = 10\text{pF} \rightarrow U = 10^{-8} \ z/z_0 \ V$

Resistive axial cooling of a single $\text{C}^{5+}$ ion
Cooling of the cyclotron motion of a single ion in a Penning trap

Shift of cyclotron frequency due to B-field inhomogeneity
Resistive cooling of an ion cloud:

Resistive cooling applies only to center-of-mass motion. Individual ion oscillation is coupled to center-of-mass motion by Coulomb interaction

→ 2 time constants

Cooling of a ion cloud containing about 30 particles
Resistive feedback cooling

G = Amplifier Gain

Final temperature:

\[ T_f = (1 - G)T_R \]

Increased time constant for cooling

\[ \tau_f = \frac{1}{1 - G} \tau_R \]
How to detect a single ion in thermal equilibrium with environment

Figure 2.3: Equivalent circuit of the trapped ion (left) in contact with the resonator. The intrinsically lossless ion is mathematically directly equivalent to a series resonator with infinite quality factor. (right) The line-shape of a trapped $^{28}$Si$^{13+}$ ion in equilibrium with the precision trap resonator, slightly off resonance and in resonance (inset).
Single ion detection

(a) no ion, (b) single ion close to resonance, (c) single ion detuned from resonance, (d) excited single ion

Single ion dip with high resolution
Single ion temperature: Distribution of oscillation amplitudes follows Boltzman distribution

\[ T_z^{\text{AT}} = 4.8 \pm 0.3 \text{ K} \]
Laser cooling of ions

Velocity reduction by photon recoil

The laser (cooling) force:

- resonant spontaneous scattering force (for closed two level systems)
- velocity dependent (tunable) via the Doppler effect
- purely longitudinal acceleration
- for cooling an additional counteracting force is needed

\[ \omega_L \quad \omega_A \]

\[ V_i \quad \hat{\omega} \]

\[ t_f < V_i \]

(b)
Average force on atom of velocity $v$:

$$F_{av} \approx \frac{I\sigma_0}{\hbar \omega} \frac{\gamma_2^2}{\left[\left(\Delta - kv\right)^2 + \gamma_2^2\right]} \hbar k$$

$I$: Laser Intensity  
$\sigma$: photon scattering cross section  
$\gamma$: spontaneous decay rate of excited level  
$\Delta$: Detuning from resonance  
$k$: photon momentum

Energy loss:

$$\frac{dE}{dt} = \langle v_z F_z(v_z) \rangle$$

Final temperature, when Doppler width equals natural linewidth

$$k_B T_{Dopp} = \frac{\hbar \Gamma}{2}.$$  

Typical: $\gamma = 10^8 \text{ s}^{-1}$ $\rightarrow$ $T \approx 1 \text{ mK}$
Ion temperature when laser is fixed below resonance wavelength

Fluorescence from ion clouds induced by laser sweep across resonance

A: small ion cloud
B: large ion cloud

Feature: Asymmetric line shape from ion heating when $\omega_{\text{Laser}} > \omega_0$
Temperature determination from residual Doppler linewidth?

Figure A.1: An example of a fluorescence signal trace fitted to a Gaussian profile for a temperature measurement.

Gaussian lineshape give no good fit
Laser cooling in a Penning trap: Offset of laser beam from trap center required

Figure 2.9: Beam offset position in the radial plane for cooling both the radial motions in the Penning trap.
Comparison of neutral atom and ion cooling

6 laser beams required to cool all degrees of freedom

One laser beam in any direction sufficient because of strong trapping force and coupling of motional degrees
Resolved sideband cooling

Laser field seen by the ion:

\[ E = E_0 \sin(kx - \omega t) \]

Oscillating ion:

\[ x = x_0 (\sin \Omega t) \]
\[ \rightarrow \]
\[ E = E_0 \sin(kx_0 \sin \Omega t - \omega t) \]

This can be written in terms of Bessel functions

\[ E = E_0 \sum_{n=0}^{\infty} J_n(kx_0) \sin(n\Omega - \omega)t \]
\[ \rightarrow \]
Spectrum contains carrier at \( \omega \) and sidebands at multiples of ion oscillation frequency \( \Omega \)
Quantum mechanical sideband cooling scheme

Cooling: Laser tuned to low frequency sideband

Problem:
Sidebands must be resolved in optical transition. Not possible on dipole allowed transitions: Natural linewidth (10⁷-10⁸ Hz) >> oscillation frequencies (10⁵-10⁶ Hz)
→ Precooling required, sideband cooling on narrow forbidden transition
Level diagram required for sideband cooling: Allowed transition for pre-Doppler cooling, narrow forbidden transition to resolve sidebands

Example: Hg ion

Absorption spectrum of S-D forbidden transition

Bergquist et al., 1997
Spectrum of a single trapped Ca+ ion cooled to the Doppler limit

Sidebands appear when ion oscillation amplitude is smaller than laser wavelength (Dicke effect)

Lamb-Dicke parameter $\eta = k\sqrt{\frac{\hbar}{2m\omega_{ax}}} < 1$
Cooling into the quantum mechanical ground state of ion oscillation.

Indication: Vanishing low frequency sideband

Left and right sideband in the absorption profile of a single stored ion
Left sideband vanishes when ion is in ground state

Final temperature given by zero-point energy of oscillation

$$E_{\text{min}} = \frac{1}{2} \hbar \nu$$

$$T \sim \mu \text{K}$$
Sympathetic cooling

When ion of interest has no suitable energy level scheme it can be cooled by Coulomb interaction with cold ions

Resistive cooling of C⁵⁺ ions, sympathetic cooling of other ions

Different mass ions separate in space:
Summary

Several different ways of ion cooling exist

- Radiative cooling is simplest but works only for electrons
- Buffer gas cooling is simple, risk of perturbations (ion loss, charge exchange)
- Laser cooling gives lowest temperature
- Resistive cooling works very well, particularly for highly charged ions
- Sympathetic cooling is almost universal