Loading, detection, and cooling

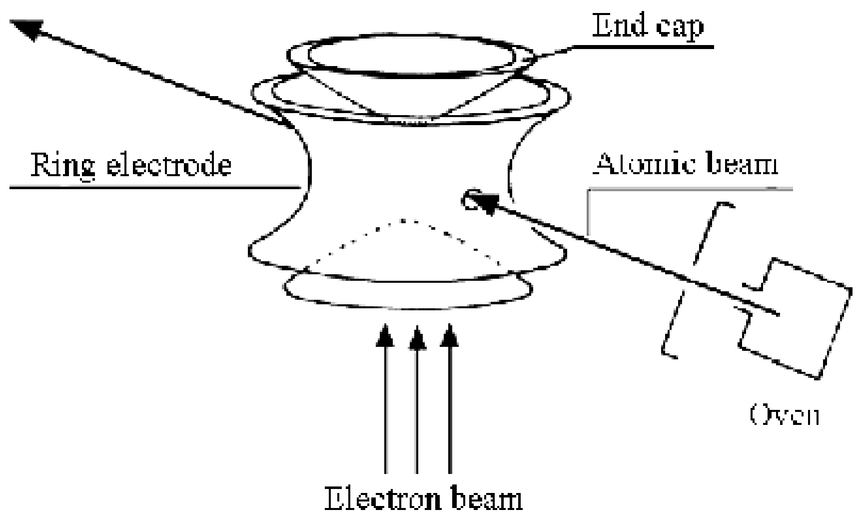
Loading of ions into traps

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

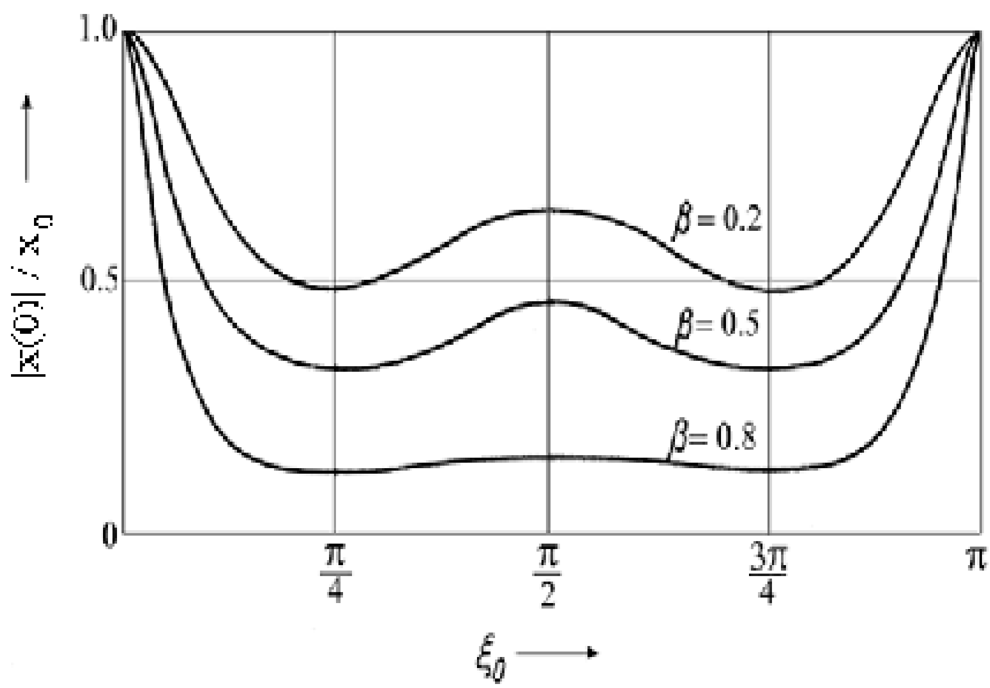
- injection of ions from outside sources
  Requires friction, provided by background gas collision, photon recoil

- dynamical catching of ions
  by switching of trap voltages

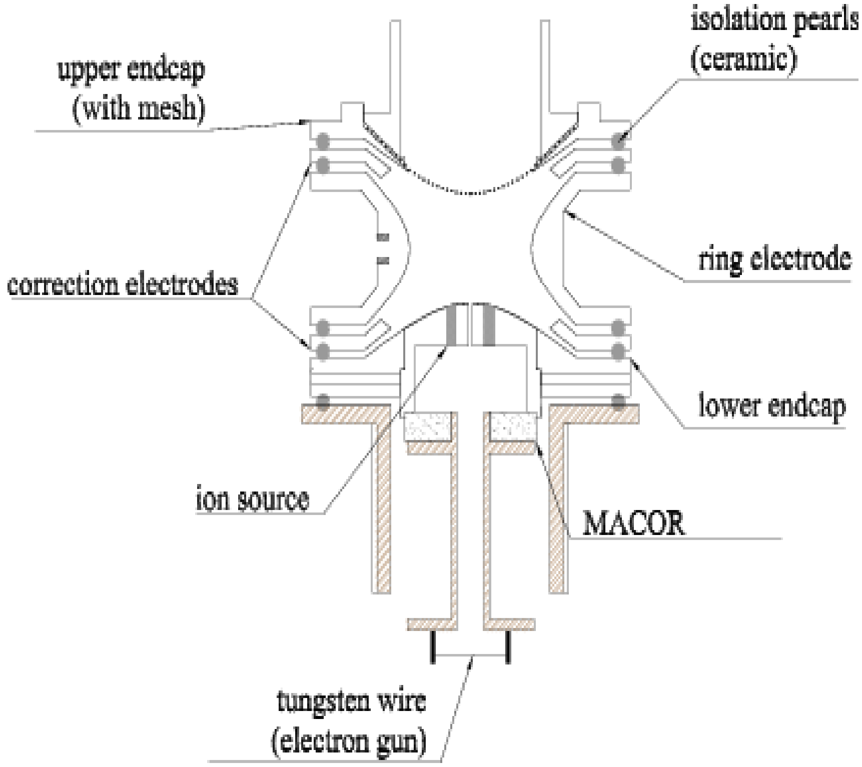
Creating ions inside the trap by electron-ionisation

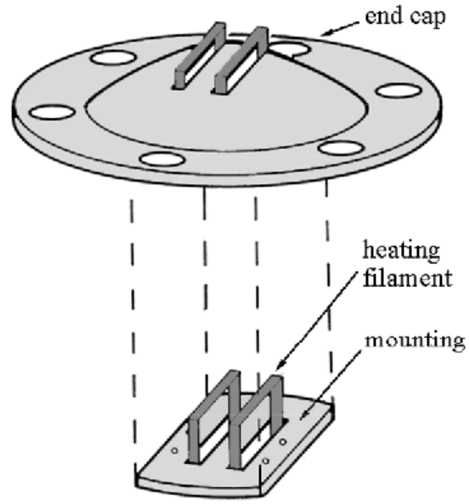


Trapping efficiency in Paul traps as function of rf phase for different trapping parameters



Ion creation near trap electrode by surface ionisation or laser ablation





Ion creation by laser ionisation of neutral atoms
Example: Ca

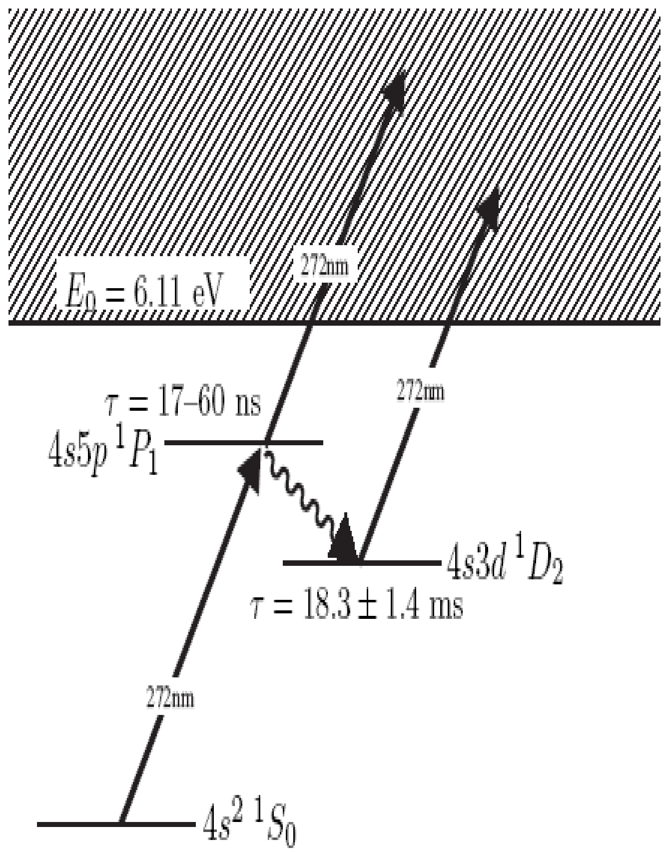


Fig. 4.1: Level scheme showing levels in calcium relevant for the photo-ionization of neutral calcium. The ionization threshold is 6.11 eV above the ground state in calcium [50]. The lifetimes of the excited levels are also indicated.

Advantages:

Element and isotope selective

Control of created ion number by laser power

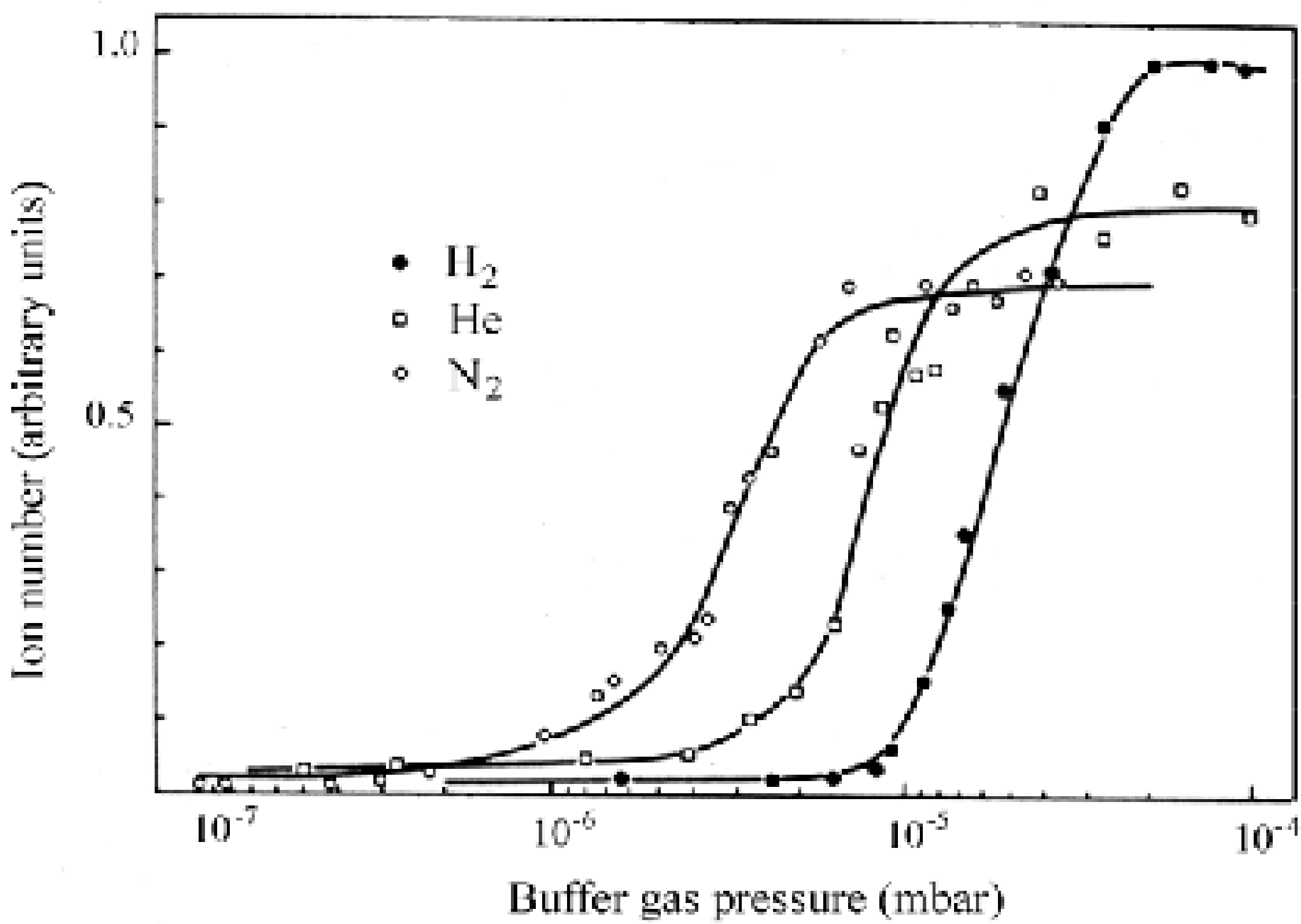
Ion injection from outside

Requires friction

Most simple by buffer gas collisions

Typical pressure: 10^{-5} mbar

(mean free path between ion-neutral collision ≈trap size)

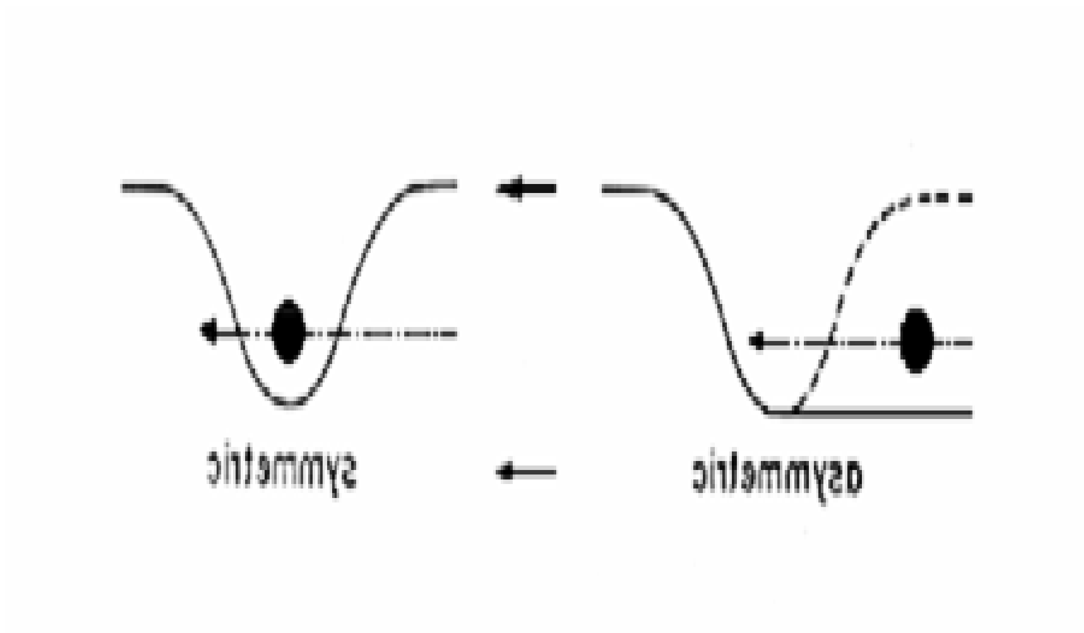


Trapped ion number at different background gas pressures from a 5 keV ion beam

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)

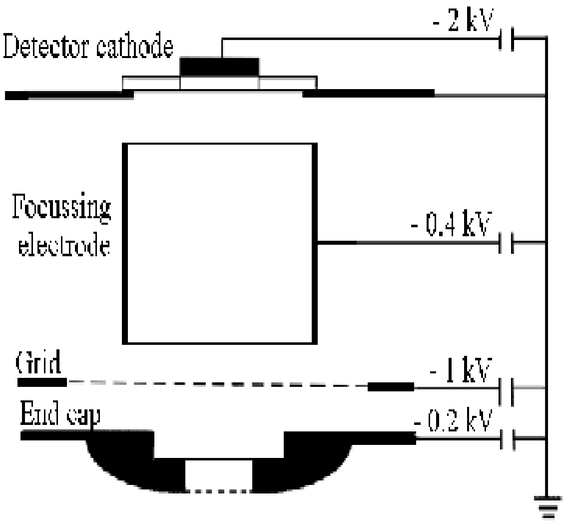


Works well for Penning traps, less well for Paul traps because of transient effects in rf voltage switching

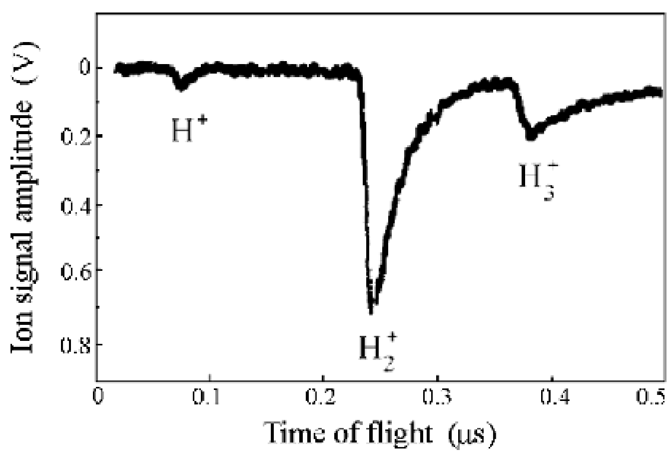
Ion detection

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

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

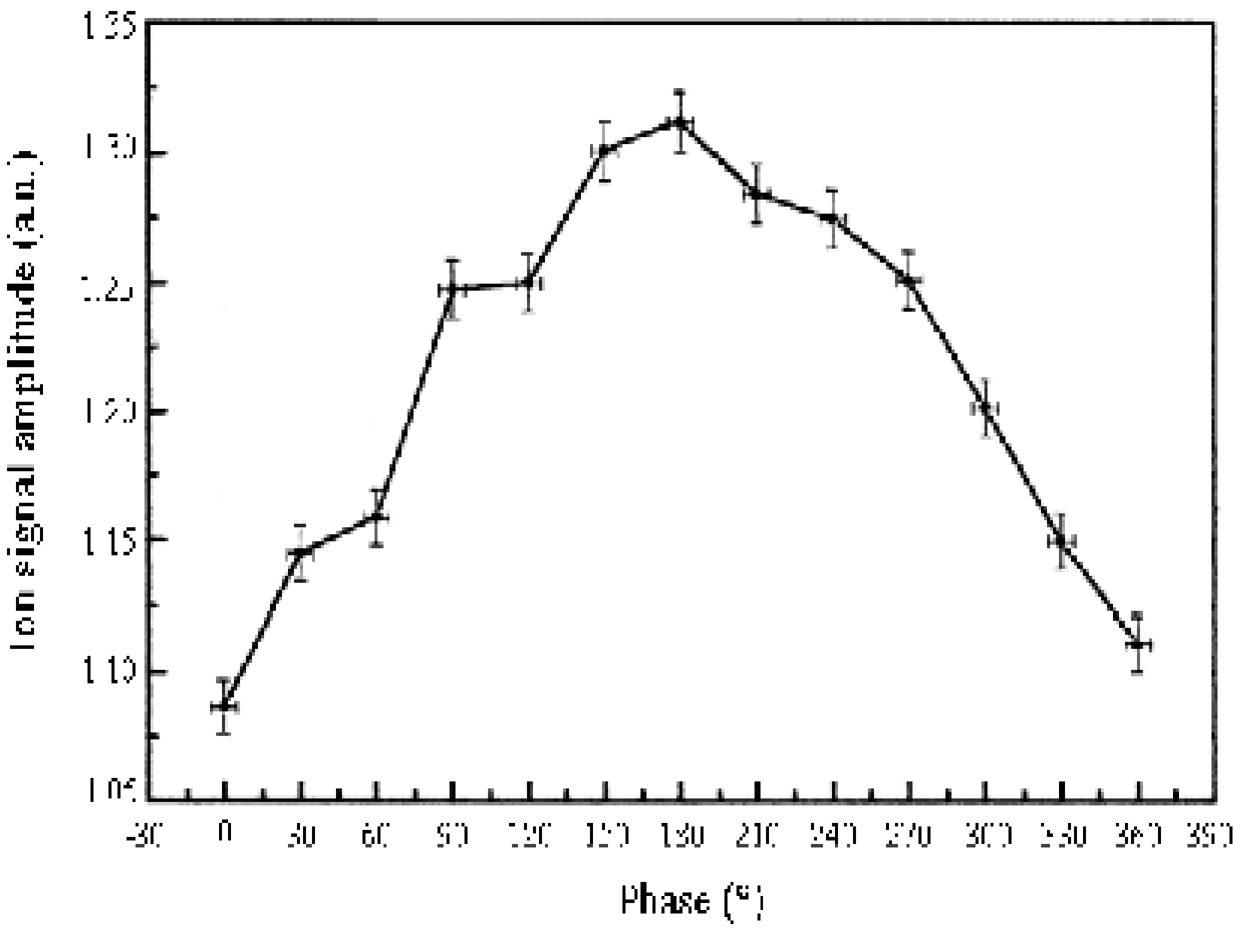


Extraction from Paul trap

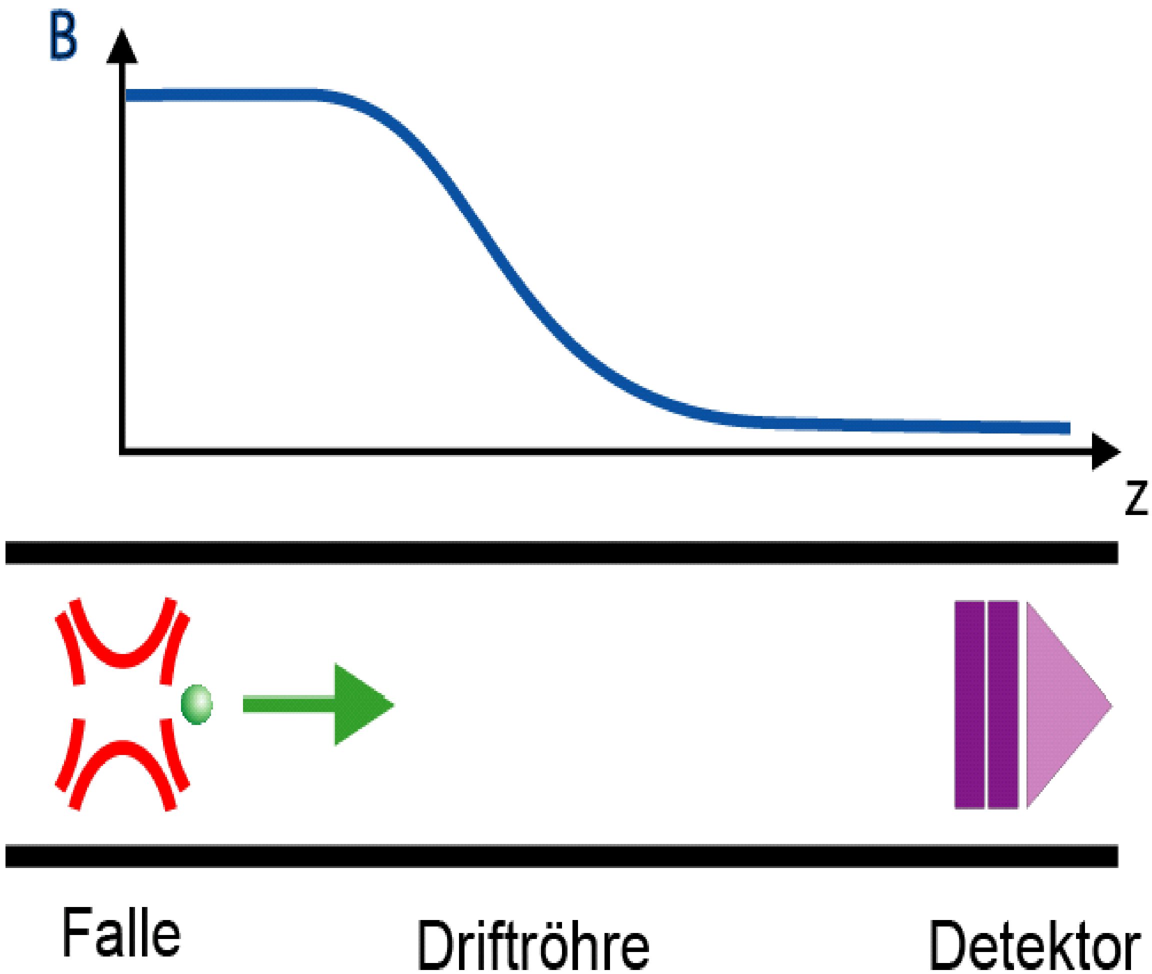


Sensitivity: Single ions

Signal height depends on phase of ejection pulse with respect to trap r.f. voltage

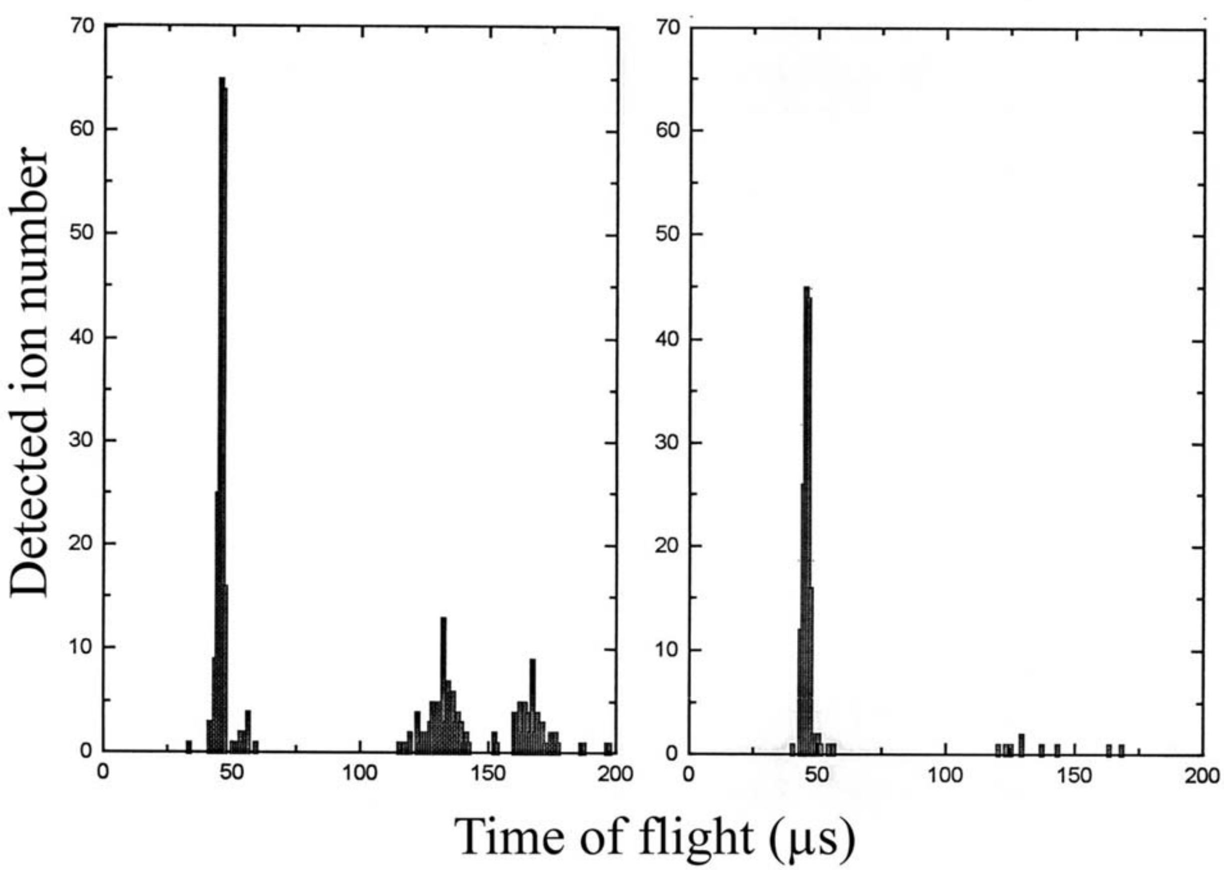


Ejection of ions from Penning trap



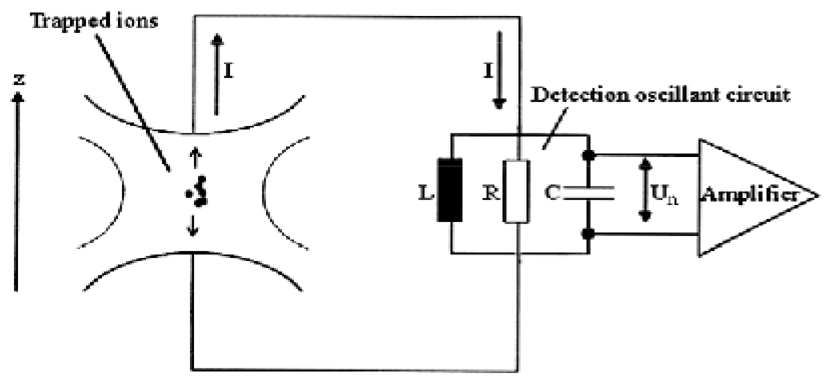
Accelerating force in fringe field: $F = \mu \, grad \, B$

Separation of different mass ions by time of flight



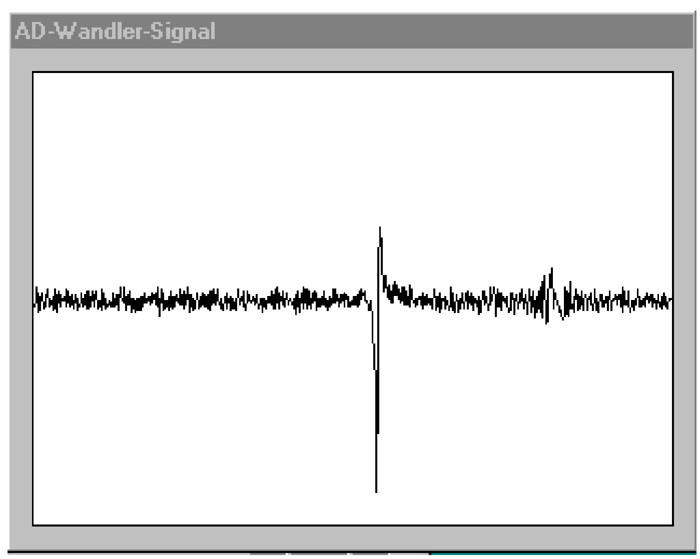
Nondestructive detection of trapped ions

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



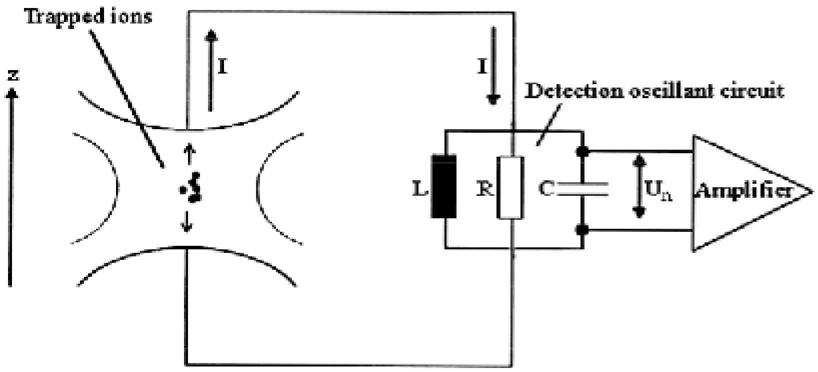
Ramping of d.c. trap voltage.
$\omega_z \sim V^{1/2}$. When $\omega_z = \omega_{Res}$, ions absorb energy from circuit ⇒ damping of circuit

Damping signal from ca. 10^4 ions



Sensitivity: ca.10^3 ions at room temperature circuit

Measurement of total induced noise



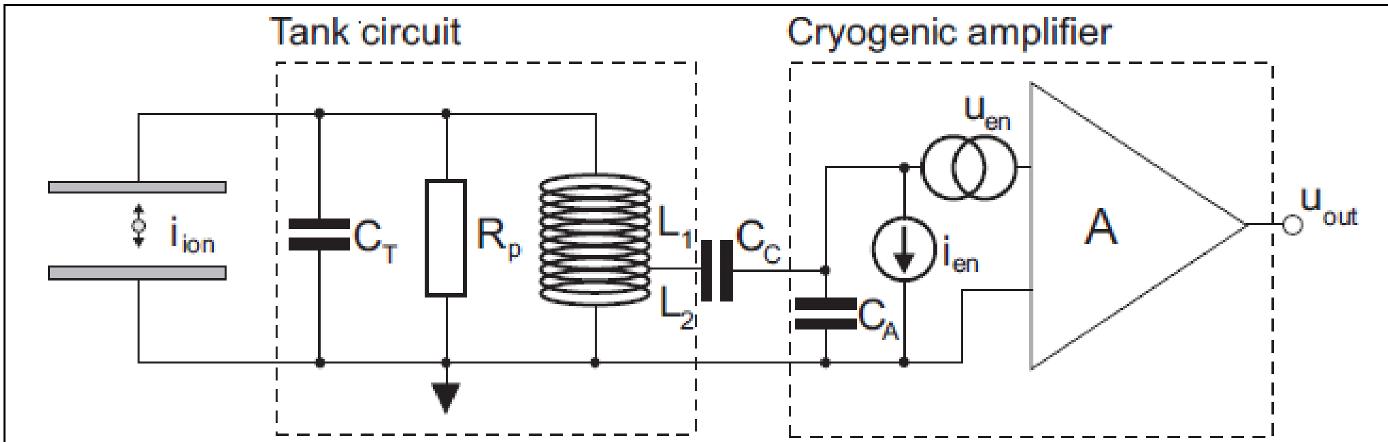


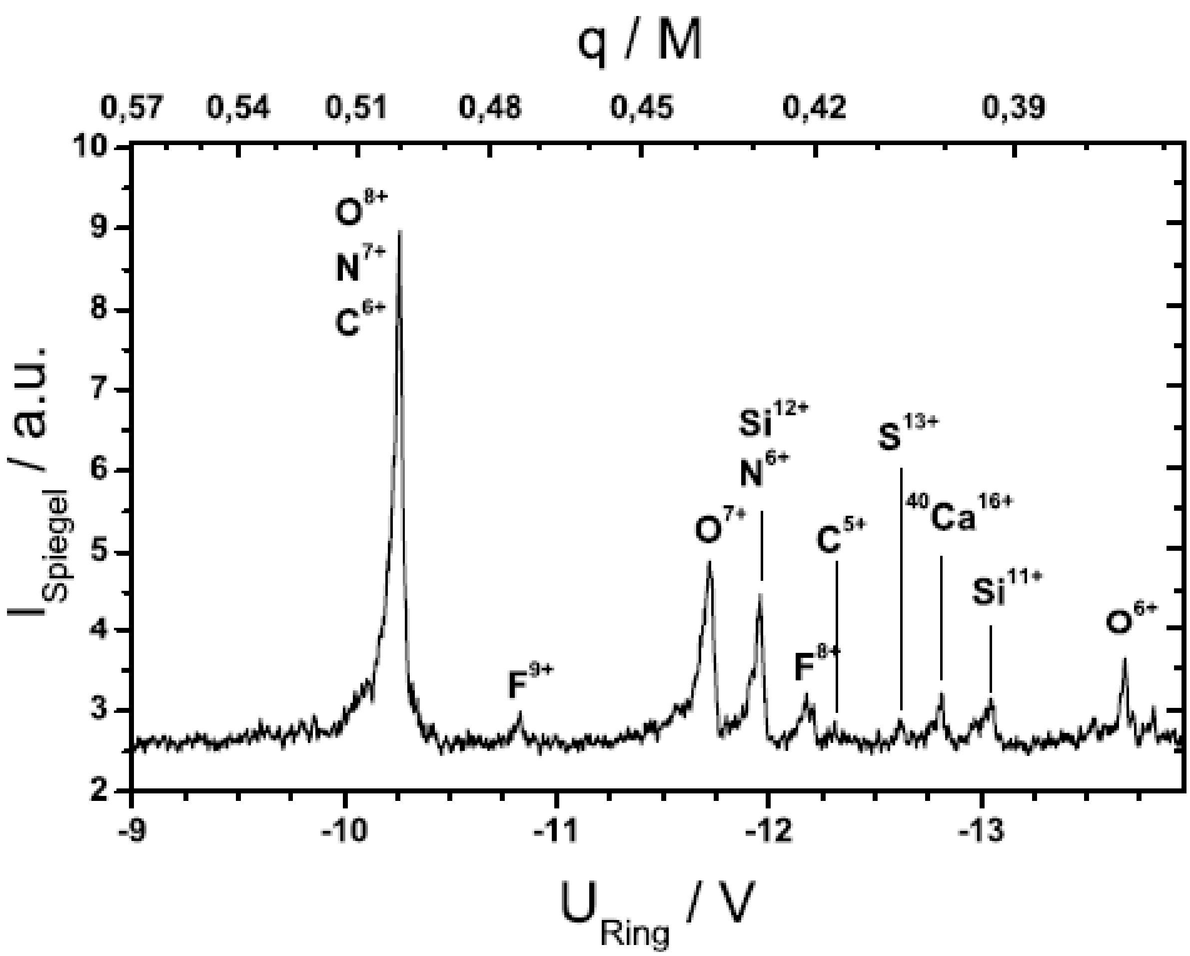
Figure 3.6: Equivalent circuit of the cryogenic detection system. The induced ion current i_{ion} is converted to a measurable voltage drop across the superconducting tank circuit, which is detected by the solid-state cryogenic amplifier. The amplifier can be in first approximation modeled using an ideal amplifier with input related voltage noise density u_n and current noise density i_n.

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

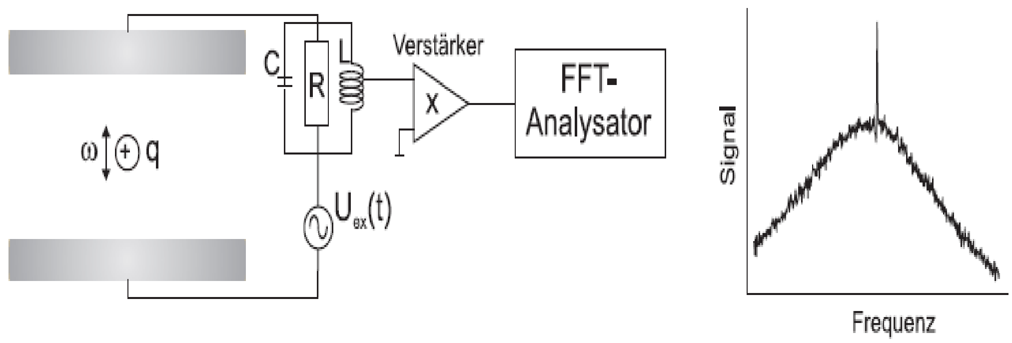
$$V_n = \sqrt{4k_b TR\delta\nu}$$

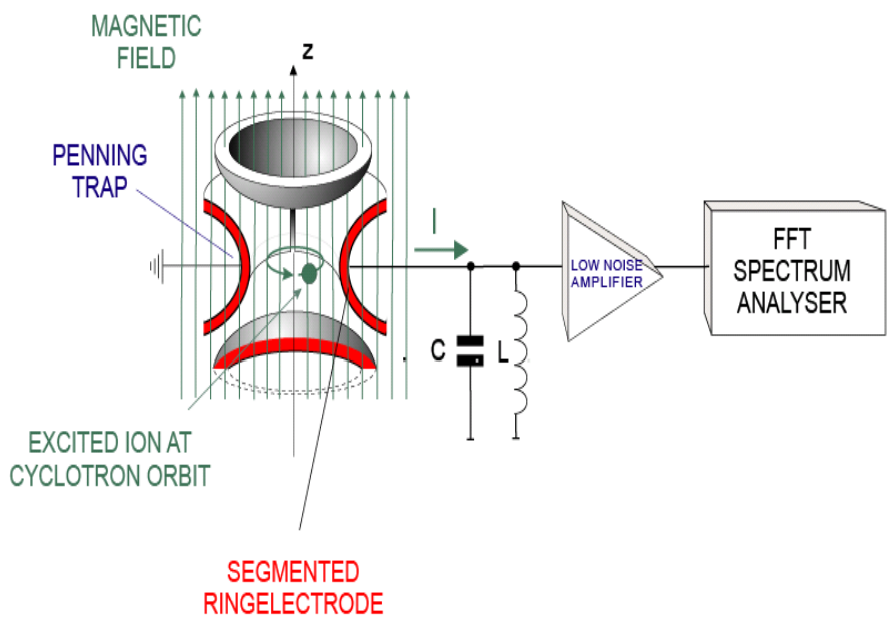
Single ion sensitivity when working at low temperatures and narrow detection bandwith (superconducting circuits)

Axial motion in a Penning trap:
Ramping of trap voltage brings different ions into resonance with circuit, depending om their charge/mass ratio

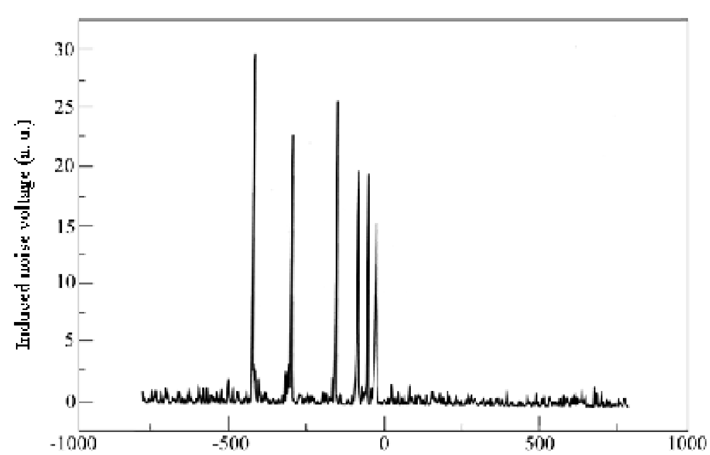


Fourier Transform of induced noise in external tank circuit





6 ions in a slightly inhomogeneous B-field:



Optical detection

Fluorescence strength from a single trapped ion, continuously excited at saturation intensity on an allowed electric dipole transition: ca.10^8 Photons/s

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

→ 10^3 detected Photons from a single ion

Fluorescence from a single trapped Sr+ ion

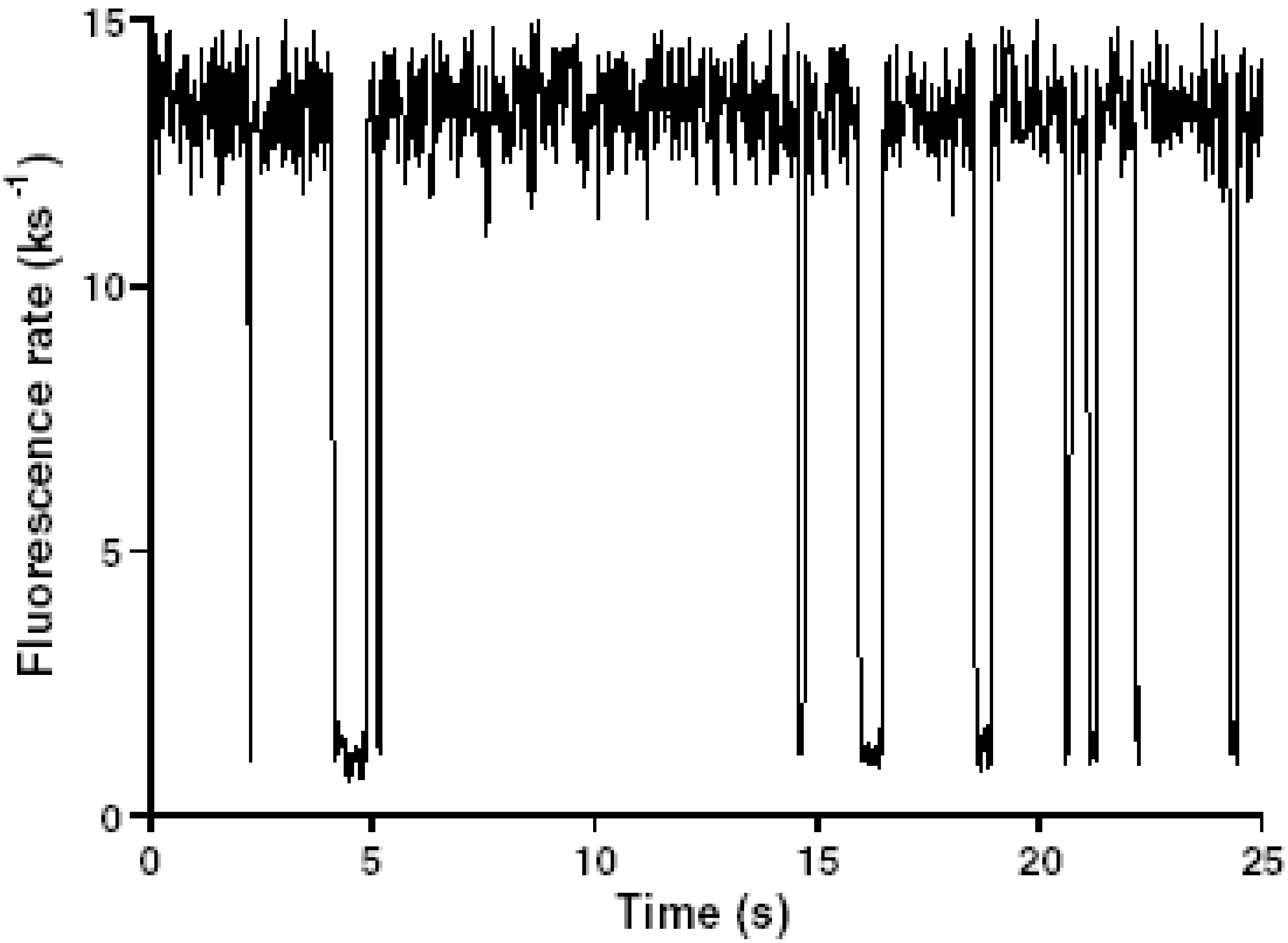
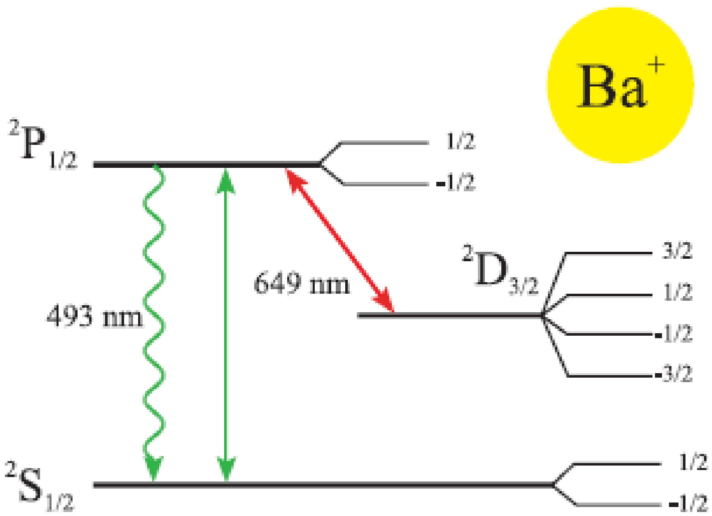
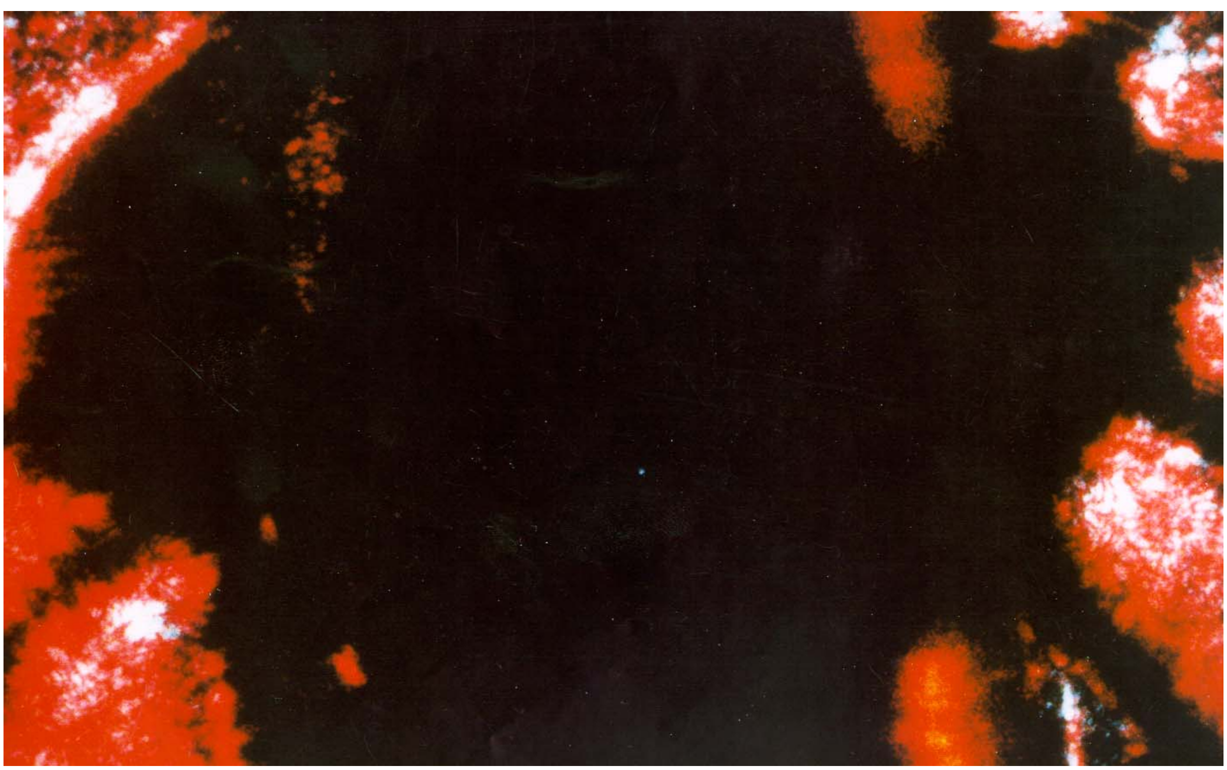


Photo of a single Barium ion in a Paul trap



Ba ion leven scheme



Dehmelt, Toschek, 1988

Ion Cooling

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 e few eV. This corresponds to temperatures of several 10 000 K. For high precision measurements energy reduction is required.

Cooling methods:

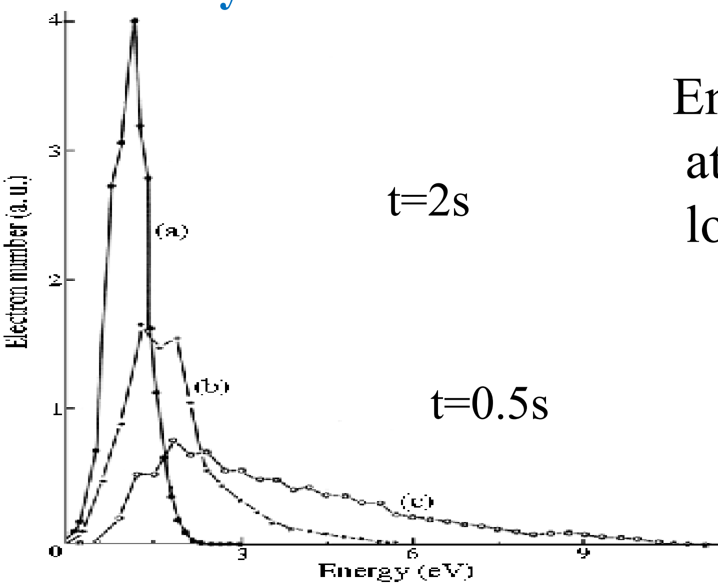
Radiative cooling
Collisional cooling
Resistive cooling
Laser cooling
Sympathetic cooling

Radiative cooling

Exponential energy loss by synchrotron radiation in strong magnetic fields.

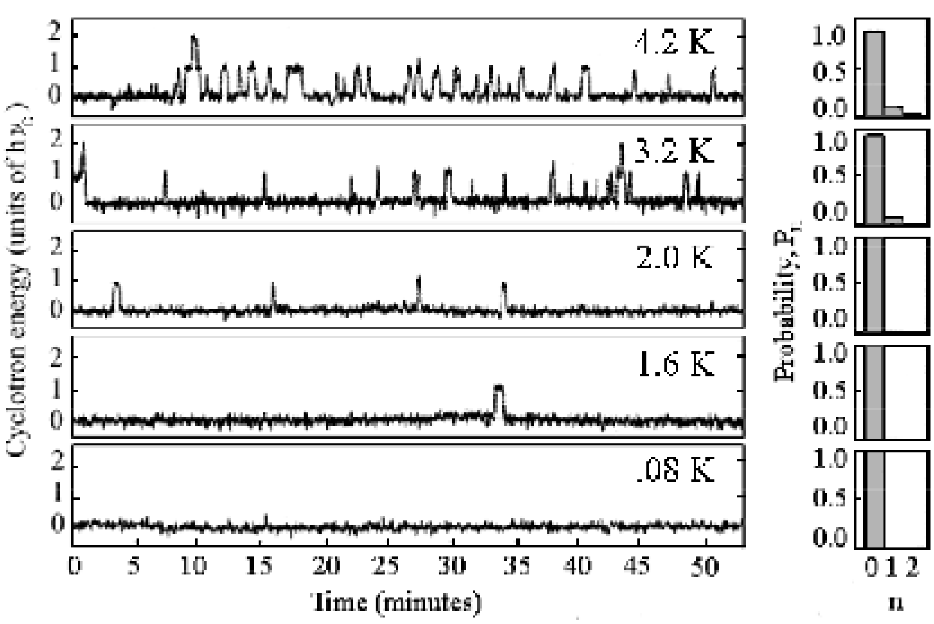
time constant: $\tau^{-1} = (4/3c^2)(e^4/m^3)\, B^2$

Effective only for electrons



t=0.1 s

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

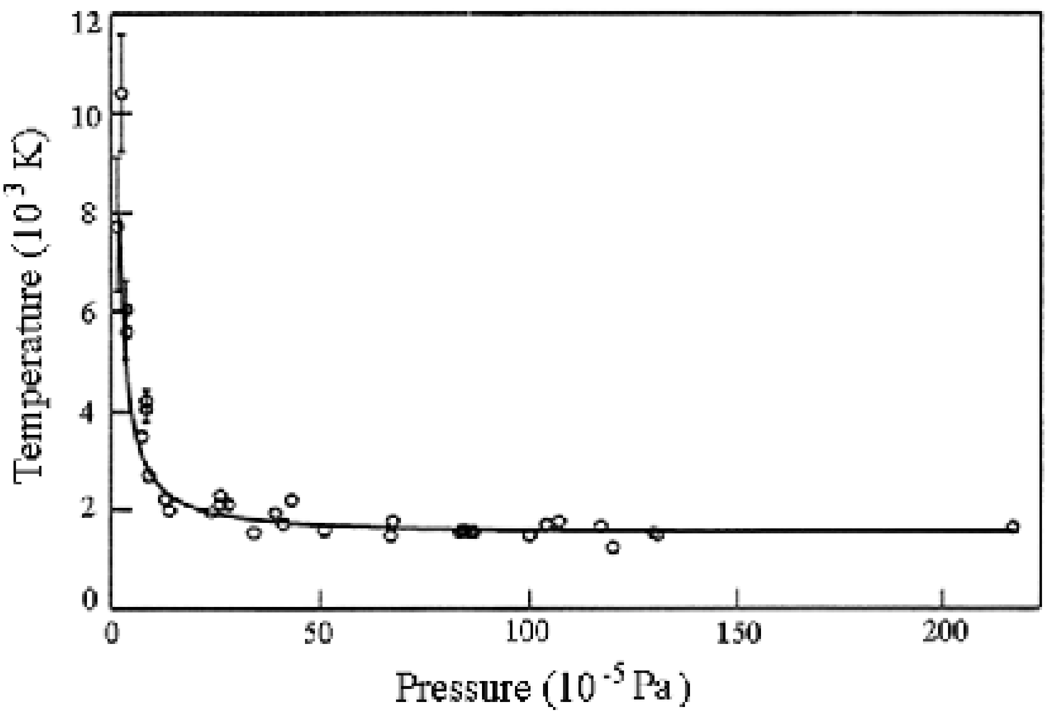


Noise from a single trapped electron at different temperatures

S. Peil and G. Gabrielse, Phys. Rev. Lett. **83**, 1287 (1999)

Buffer gas cooling in Paul traps

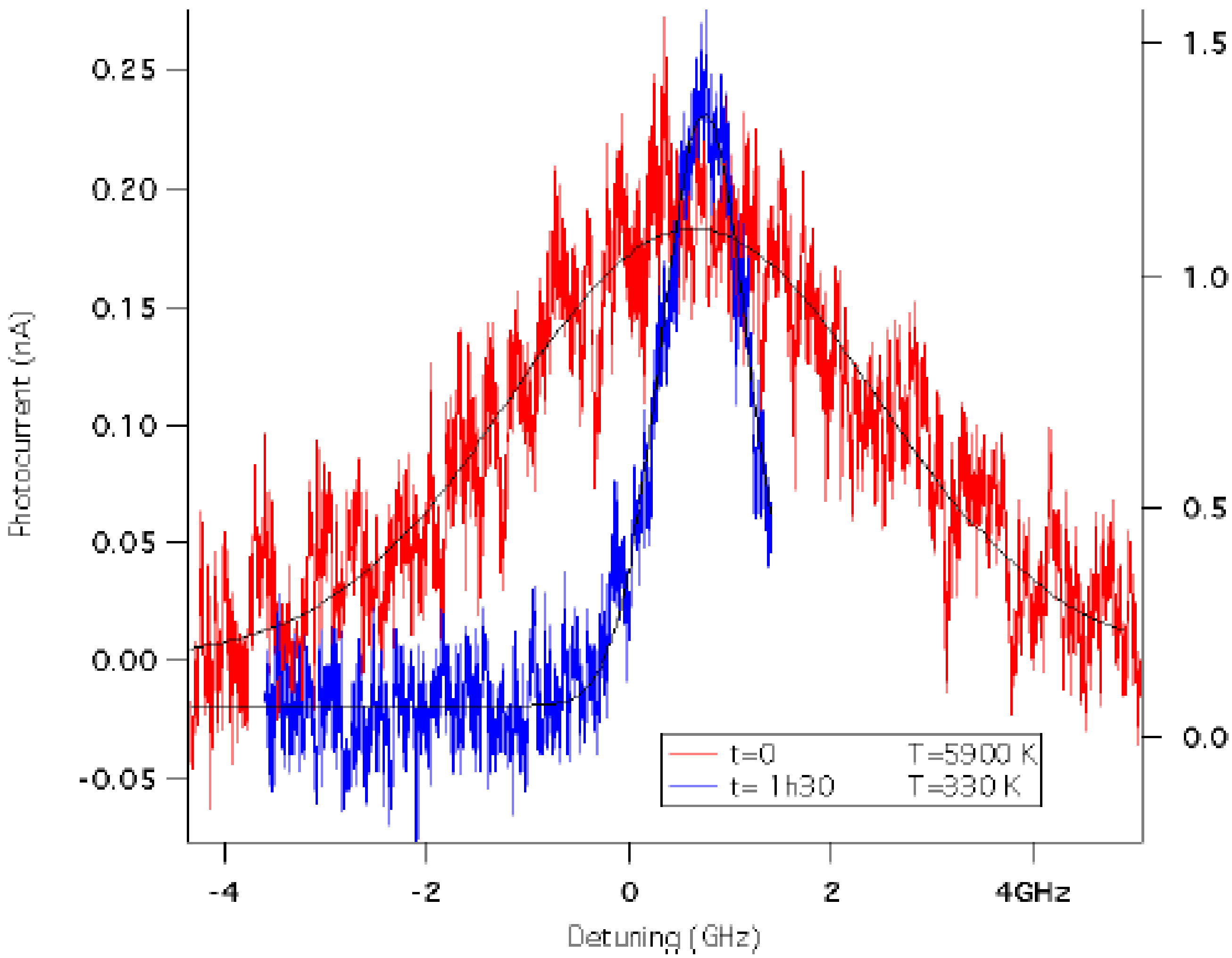
Requirement:
Ion mass smaller than neutral buffer gas mass



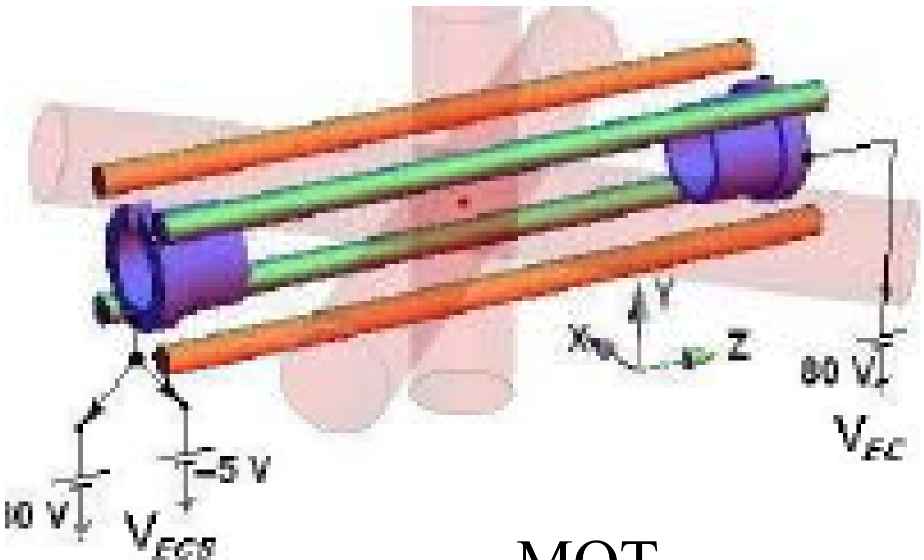
Cooling of Ba^+ by N_2

Final temperatur limited by micromotion and depends on ion number

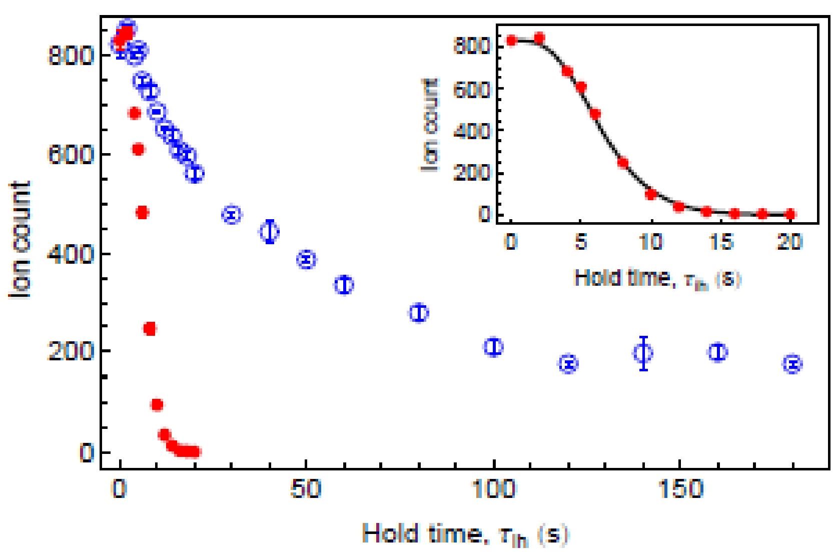
Reduced Doppler width of optical transition by collisional cooling



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

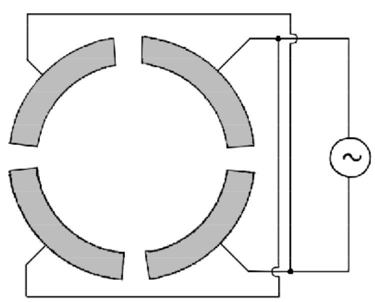
Buffer gas cooling in Penning traps

Axial and cyclotron motion are damped by collisions,
Magnetron motion becomes unstable and ions get lost

Solution:

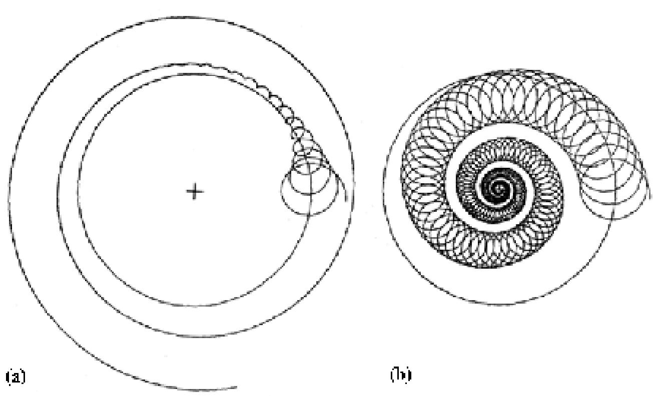
Coupling of magnetron motion to cyclotron motion by azimuthal r.f. quadrupolar field at frequency

$$\omega_+ + \omega_- = \omega_c$$



Ion trajectories with buffer gas collisions:

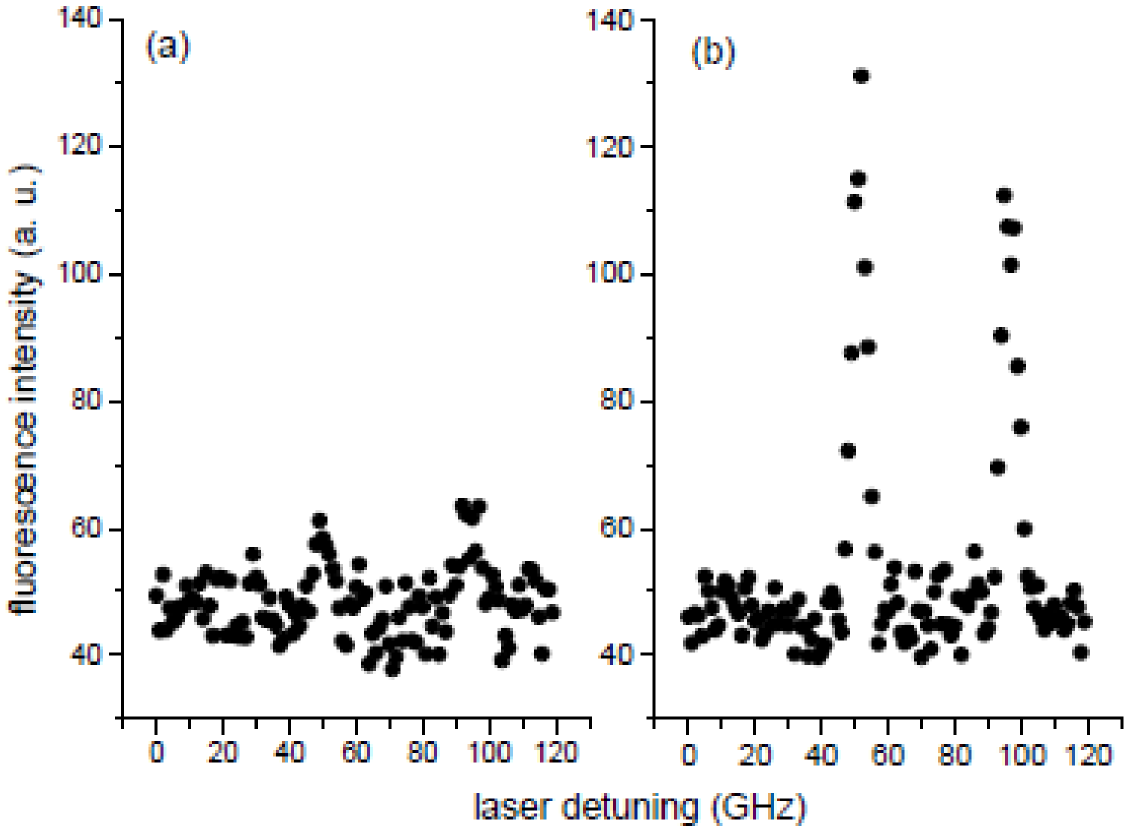
Without mode coupling



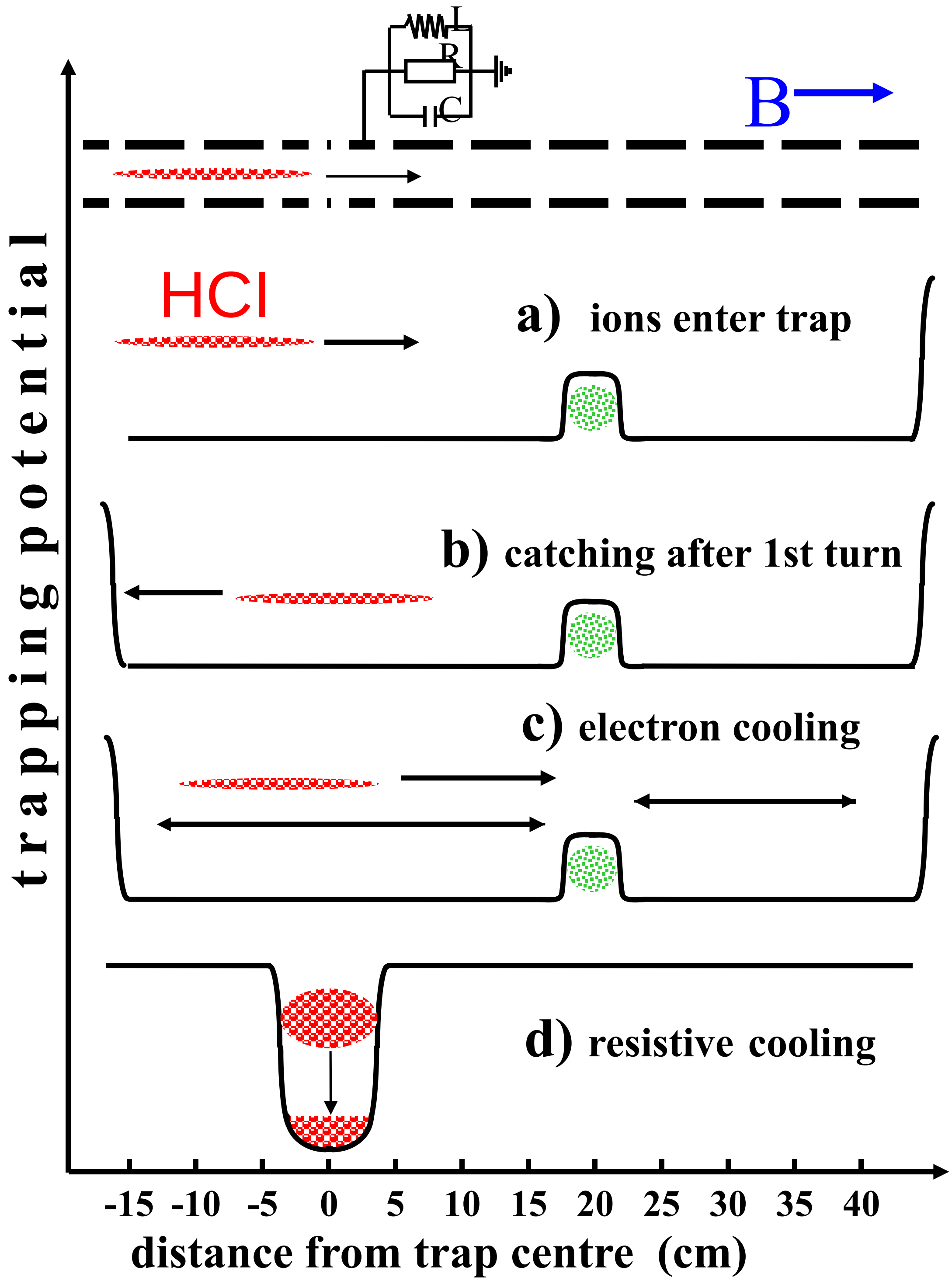
With mode coupling

Feature: Coupling frequency is mass dependent
→ stabilisation of ion of interest, others become unstab

Increased laser-induced fluorescence after axialisation of a Ba+ ion cloud



Ion cooling by Coulomb interaction with cold electrons in a Penning Trap



Cooling time constant :

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

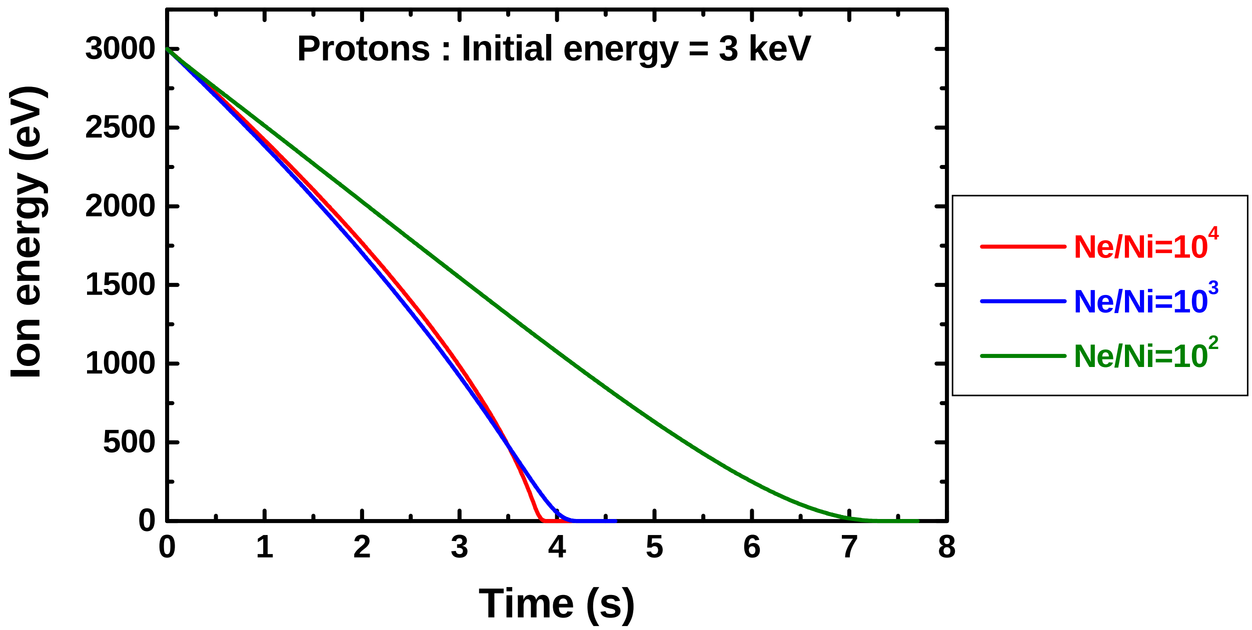
Decay rate equations :

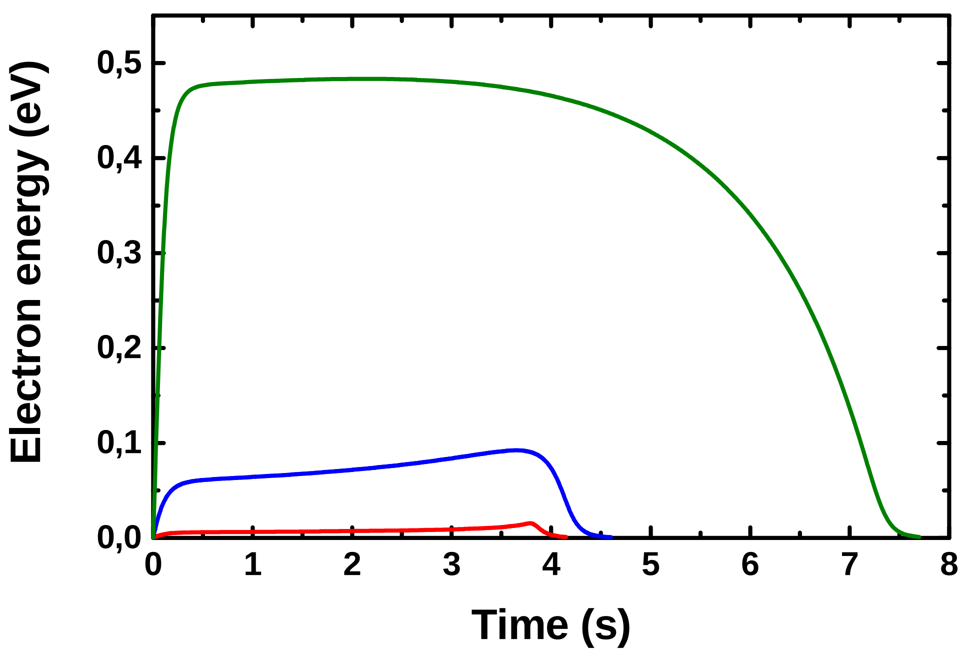
$$\begin{cases} \dfrac{d}{dt} T_i = -\dfrac{1}{\tau_c}\left(T_i - T_e\right) \\ \dfrac{d}{dt} T_e = \dfrac{1}{\tau_c}\left(\dfrac{N_e}{N_i}\right)\left(T_i - T_e\right) - \dfrac{1}{\tau_e}\left(T_e - 4.2\right) \end{cases}$$

S.L. Rolston and G. Gabrielse, Hyperfine Interaction 44 (1988) 233-2246
H. Poth, Physics Reports 196, (1990) 135-297

Example: Electron cooling of protons

Ion cooling by Cinteraction with could electrons

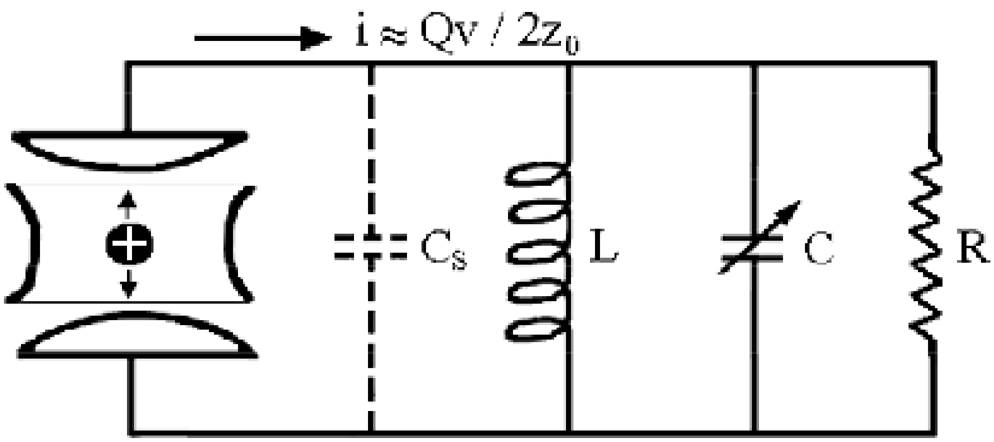




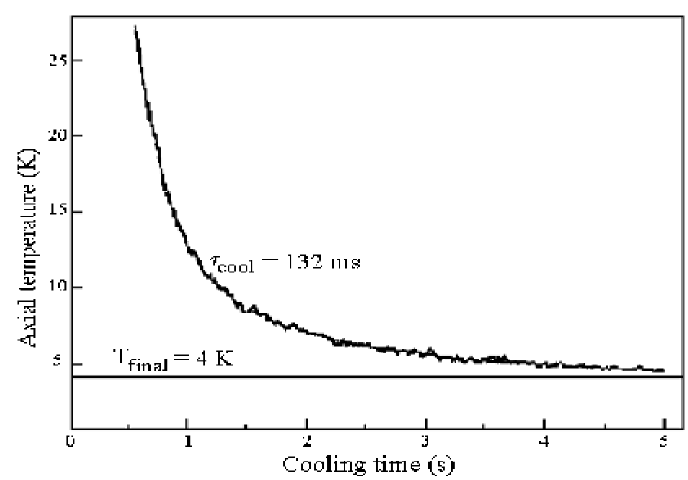
Resistive cooling

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

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

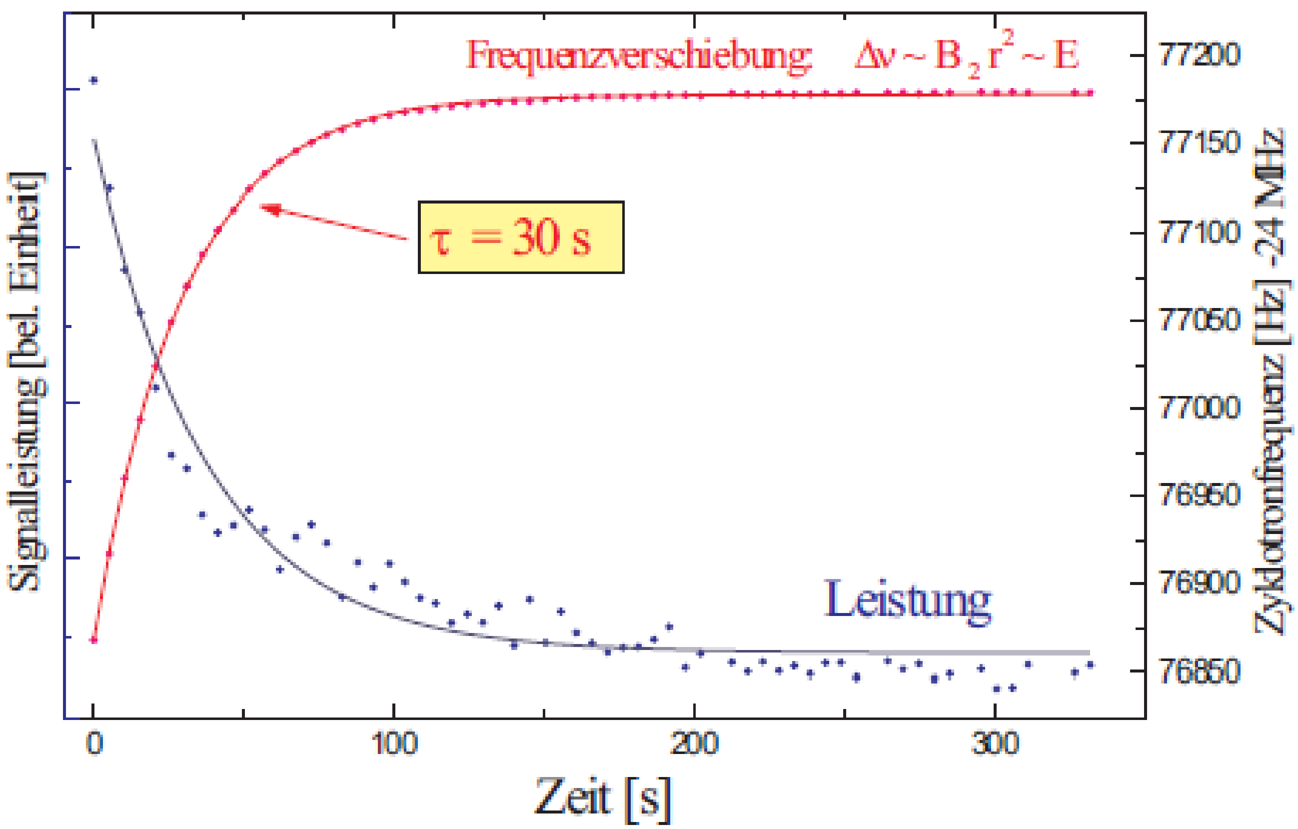


$U=iZ$, $Z=1/\omega C$
For $C=10\text{pF} \rightarrow U=10^{-8}\ z/z_0$ V



Resistive axial cooling of a single C^{5+} ion

Cooling of the cyclotron motion of a single ion in a Penning trap

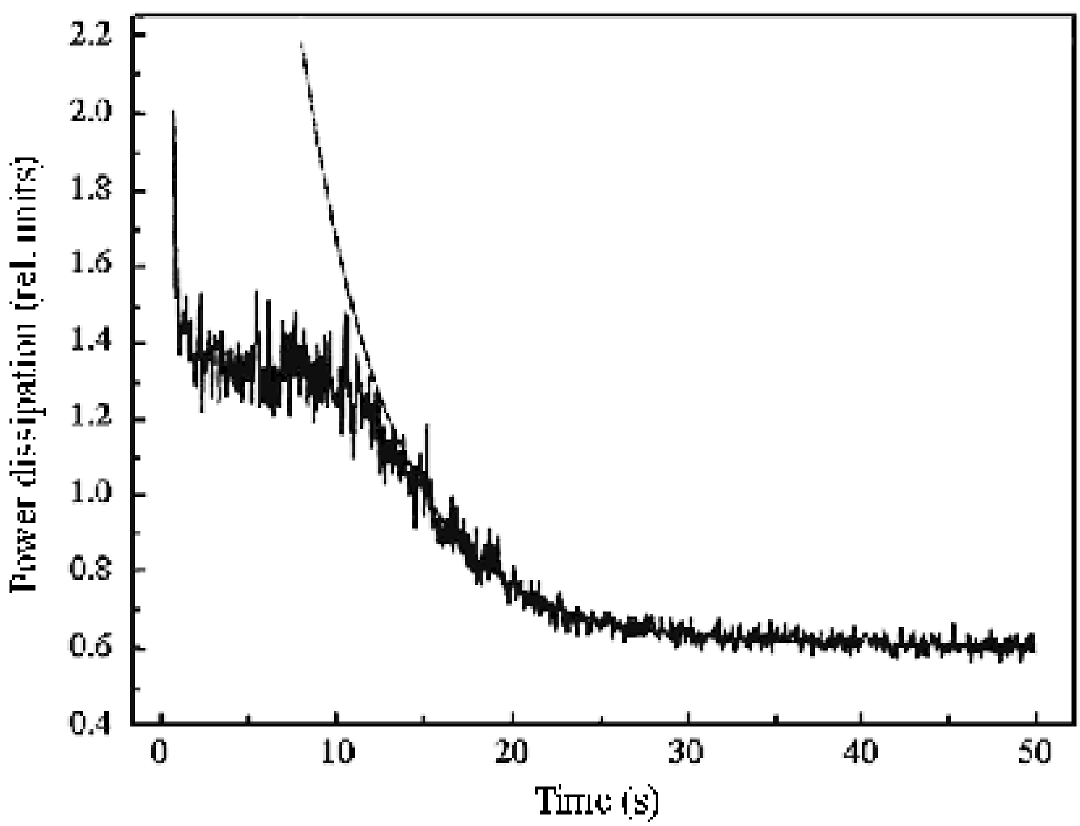


Shift of cyclotron frequency due to B-field inhomogeneity

Resistive cooling of an ion cloud:

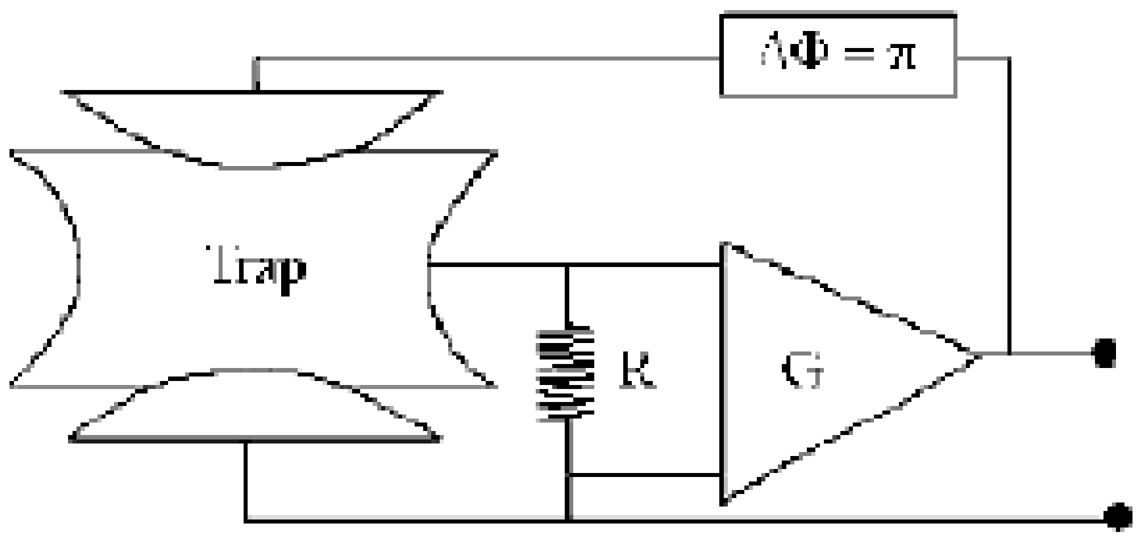
Resistive cooling applies only to center-of-mass motion.
Individual ion oscillation is coupled to center-of mass motion by Coulomb interaction

→ 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 equlibrium with environment

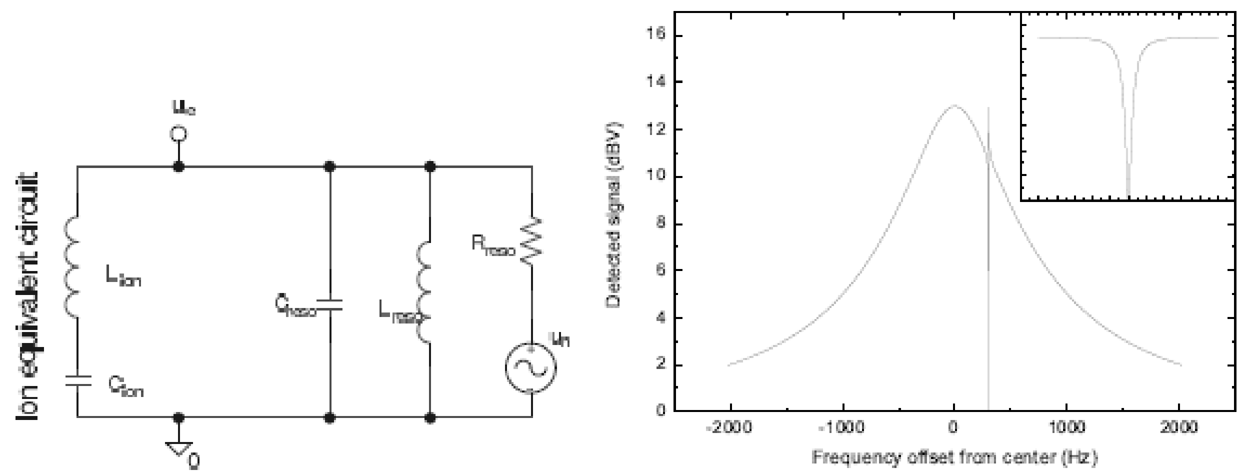
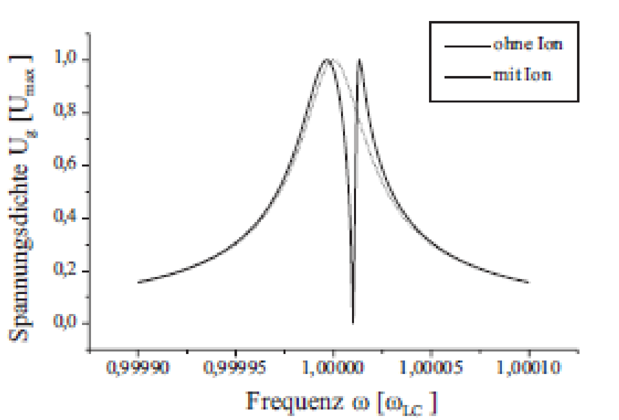
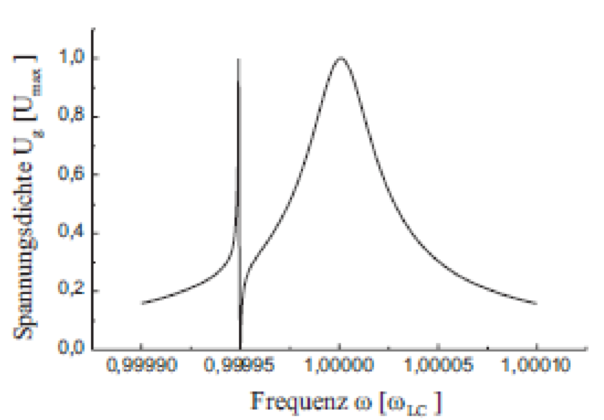
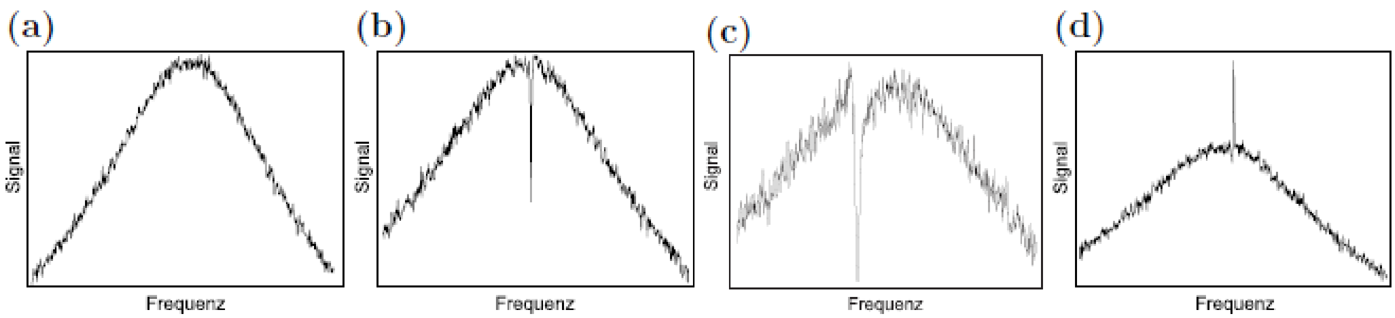


Figure 2.3: Equivalent circuit of the trapped ion (left) in contact with the resonator. The intrinsically lossless ion is mathematically directly equivalent to a series resonator with infinite quality factor. (right) The line-shape of a trapped $^{28}Si^{13+}$ ion in equilibrium with the precision trap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

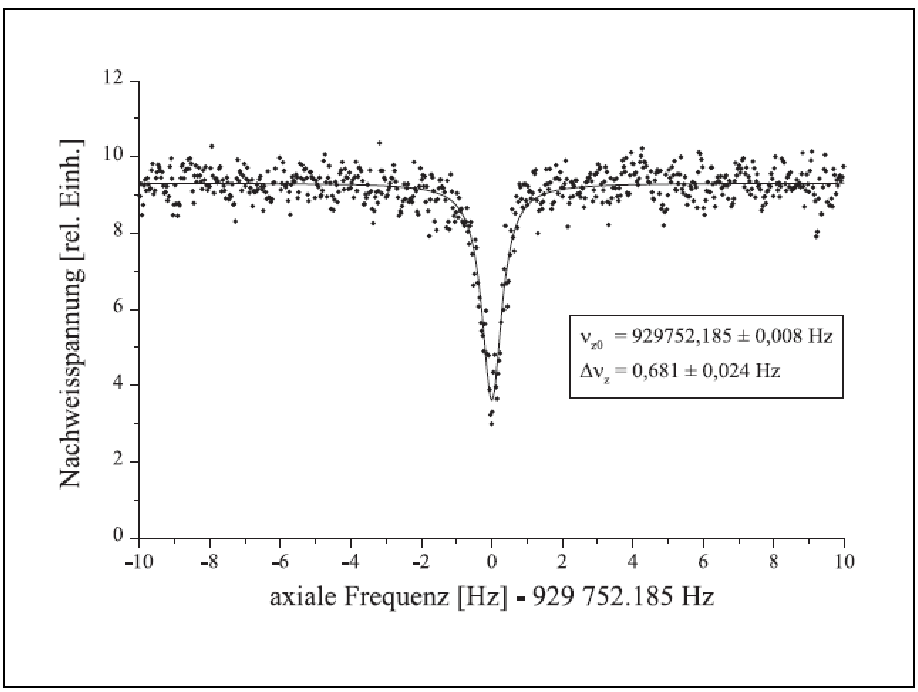




Single ion detection

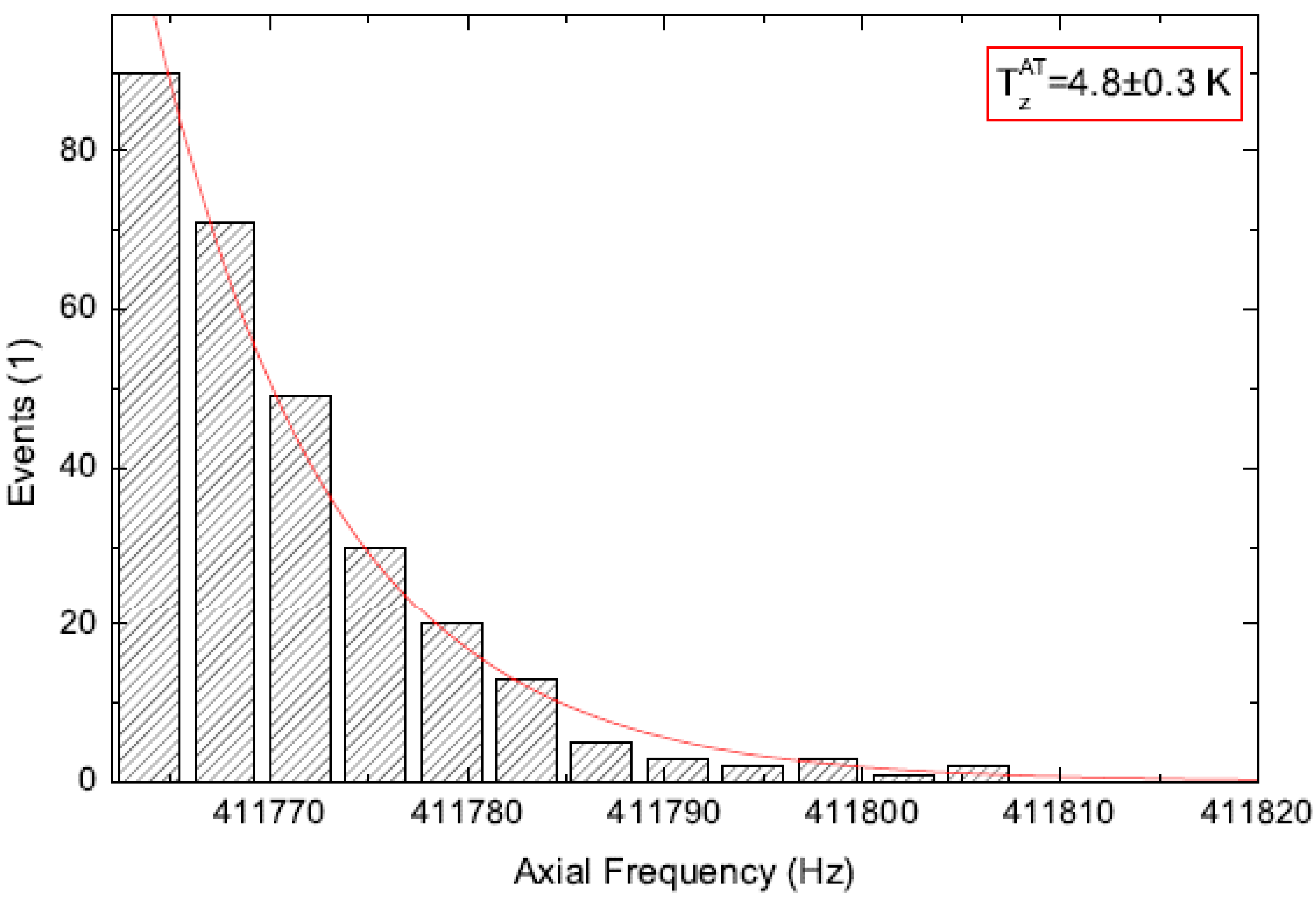


(a) no ion, (b) single ion close to resonance,
(c) single ion detuned from resonance
(d) excited single ion



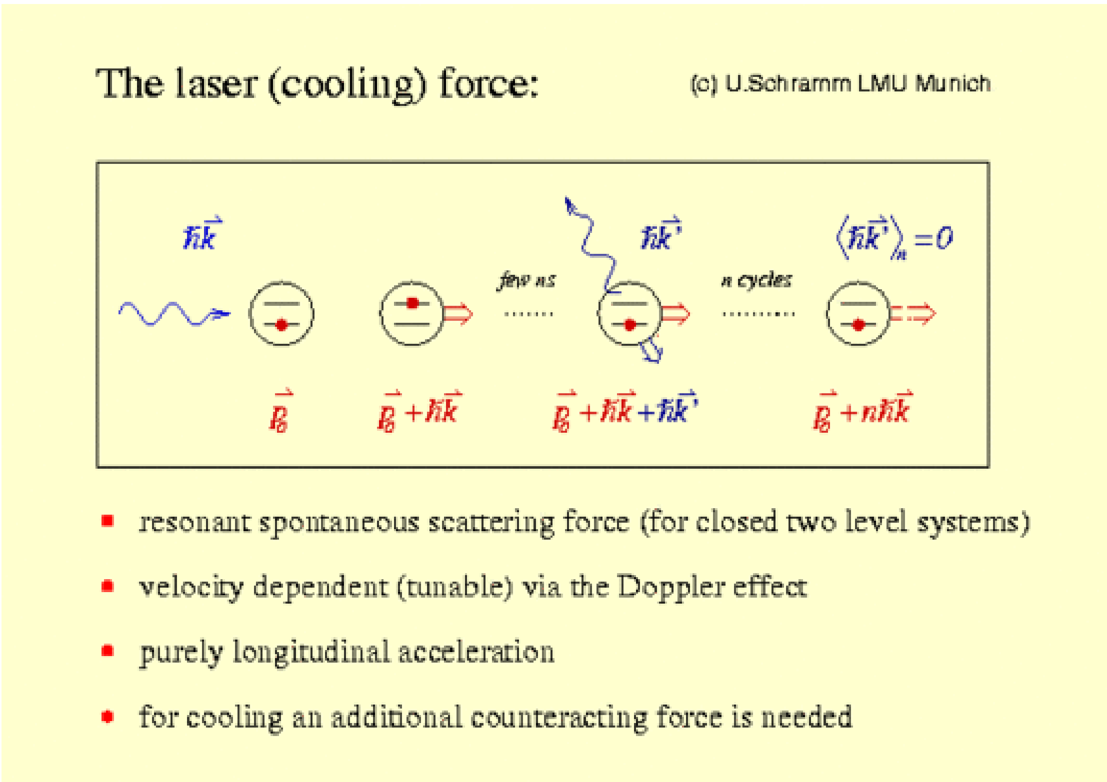
Single ion dip with high resolution

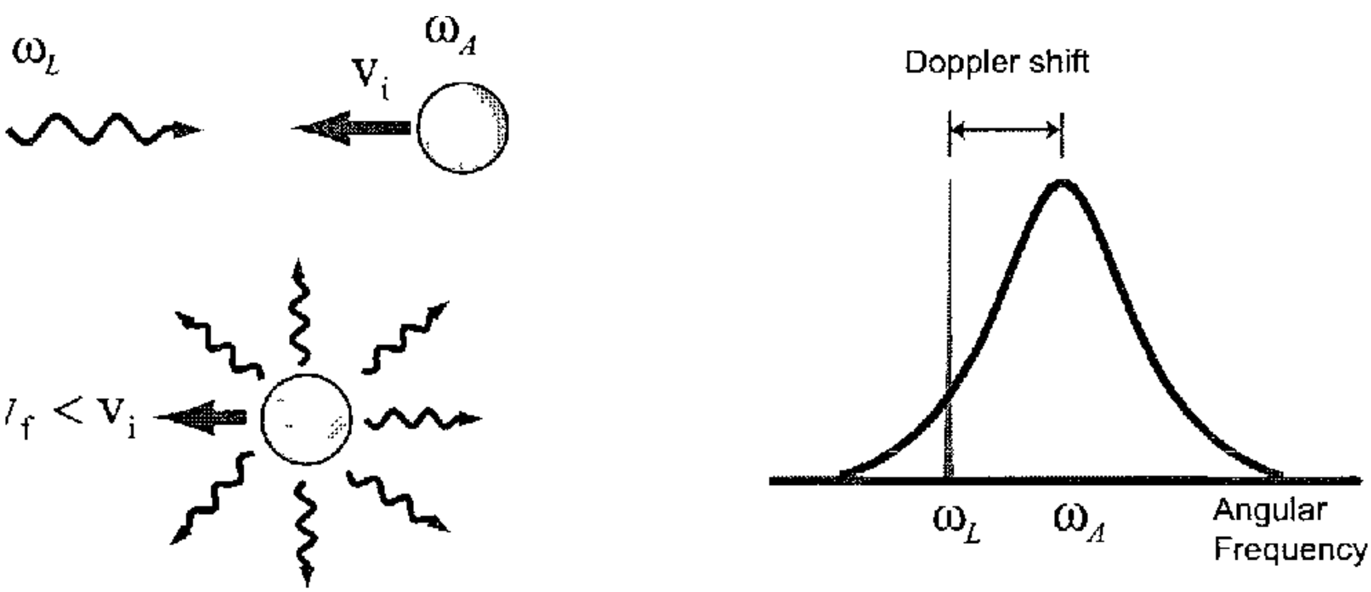
Single ion temperature: Distribution of oscillation amplitudes follows Boltzman distribution



Laser cooling of ions

Velocity reduction by photon recoil





(b)

Average force on atom of velocity v:

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

I: Laser Intensity
σ: photon scattering cross section
γ: spontaneous decay rate of excited level
Δ: Detuning from resonance
k: photon momentum

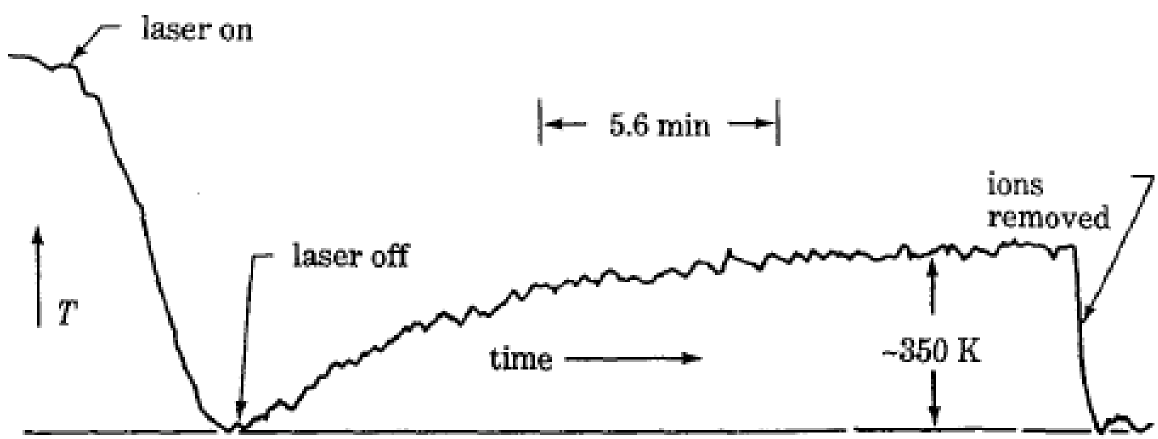
Energy loss: $$\frac{dE}{dt} = \langle v_z F_z(v_z) \rangle$$

Final temperature, when Doppler width equals natural linewidth

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

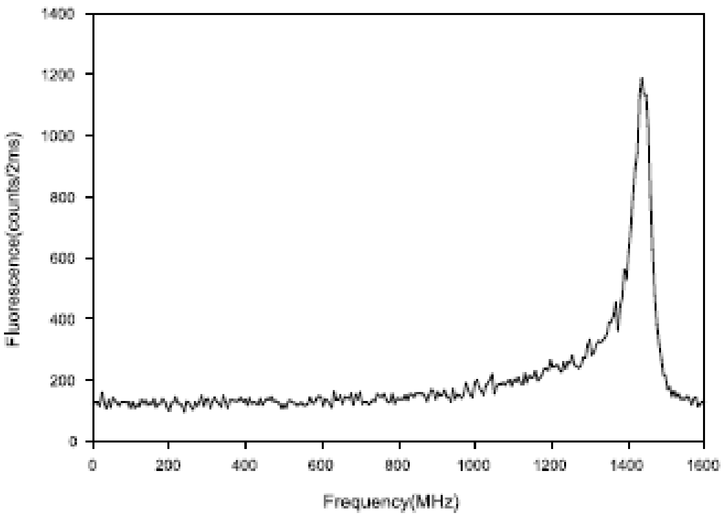
Typical: **γ=10^8 s^-1 → T≈1mK**

Ion temperature when laser is fixed below resonance wavelength



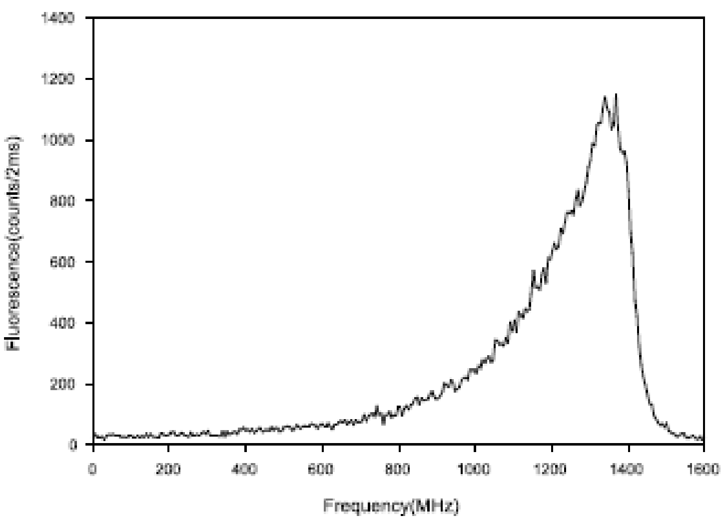
Wineland, D., R. Drullinger, and F. Walls, 1978, "Radiation-pressure cooling of bound-resonant absorbers," Phys. Rev. Lett. **40**, 1639.

Fluorescence from ion clouds induced by laser sweep across resonance



(a)

A: small ion cloud
B: large ion cloud



(b)

ance

Feature: Asymmetric line shape from ion heating when $\omega_{Laser} > \omega_0$

Temperature determination from residual Doppler linewidth?

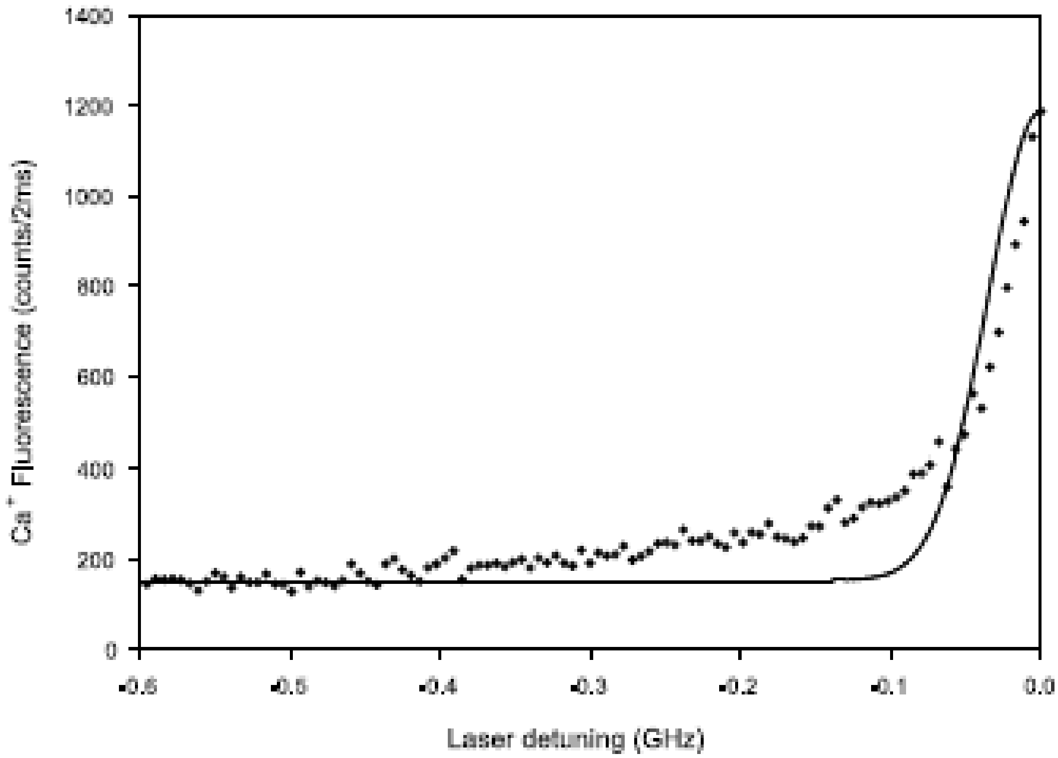


Figure A.1: An example of a fluorescence signal trace fitted to a Gaussian profile for a temperature measurement.

Gaussian lineshape give no good fit

Laser cooling in a Penning trap: Offset of laser beam from trap center required

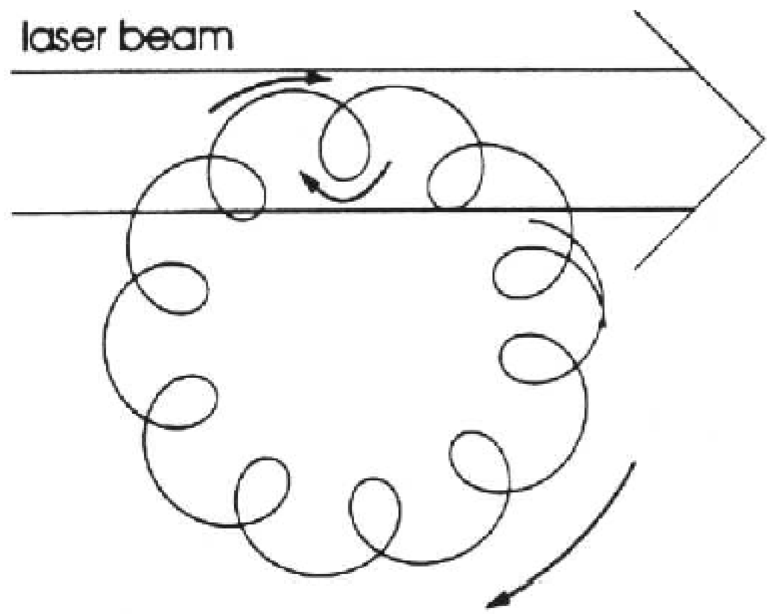
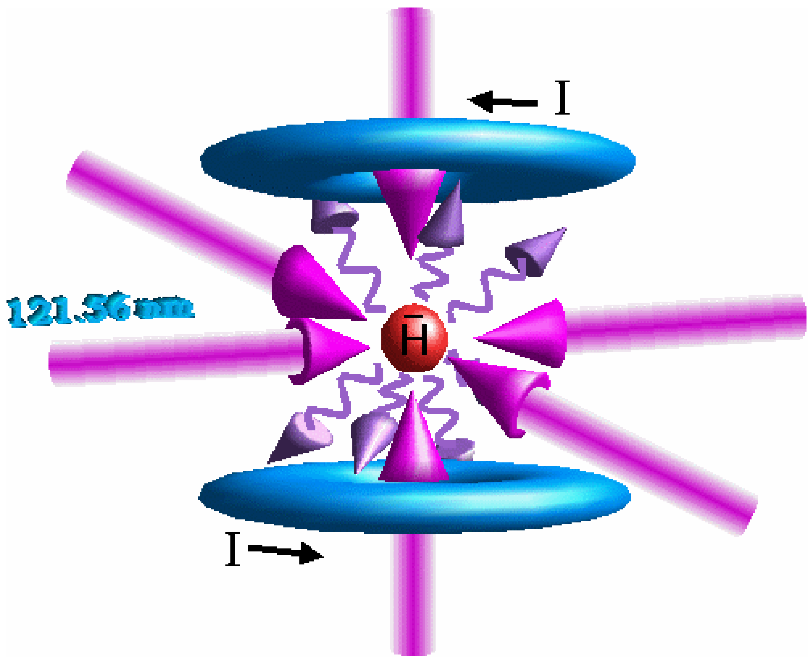
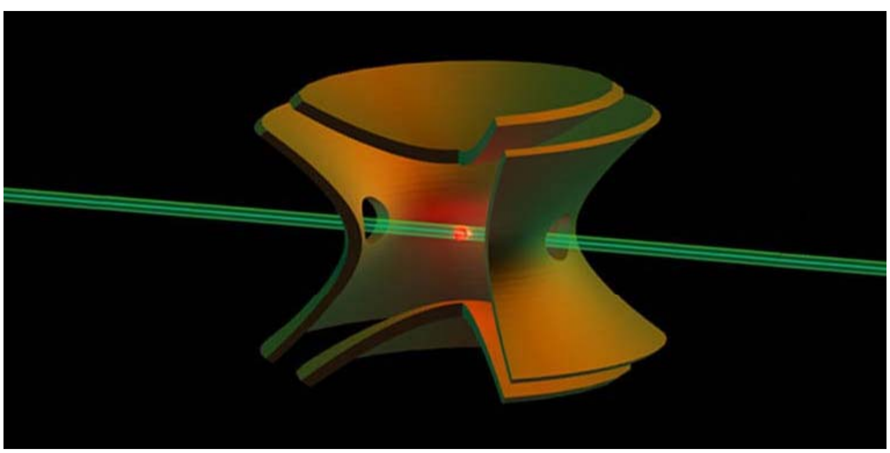


Figure 2.9: Beam offset position in the radial plane for cooling both the radial motions in the Penning trap.

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:

$$x = x_0 (sin\Omega \mathrm{t})$$

→

$$E = E_0 \sin(k x_0 sin\Omega t - \omega t)$$

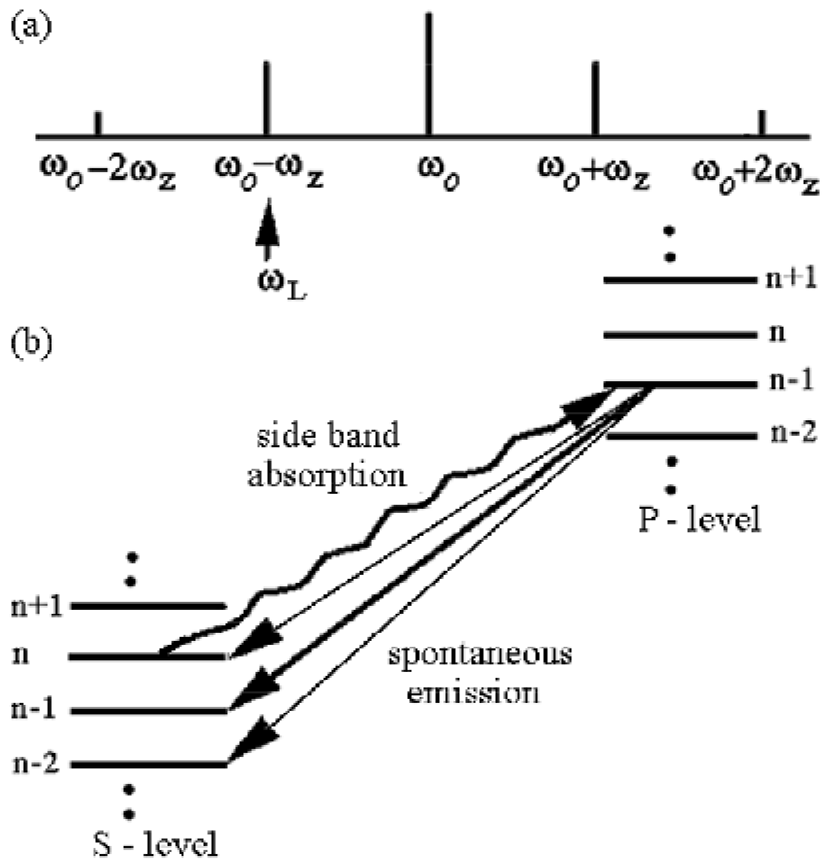
This can be written in terms of Bessel functions

$$E = E_0 \sum_{n=0}^{\infty} J_n(k x_0) \sin(n\Omega - \omega)\mathrm{t}$$

→

Spectrum contains carrier at ω and sidebands at multiples of ion oscillation frequency Ω

Quantum mechanical sideband cooling scheme



Cooling: Laser tuned to low frequency sideband

Problem:

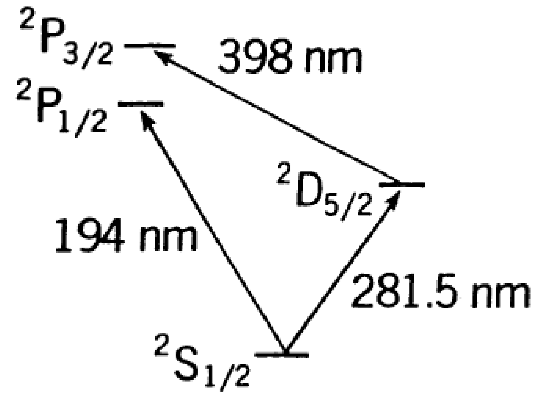
Sidebands must be resolved in optical transition.

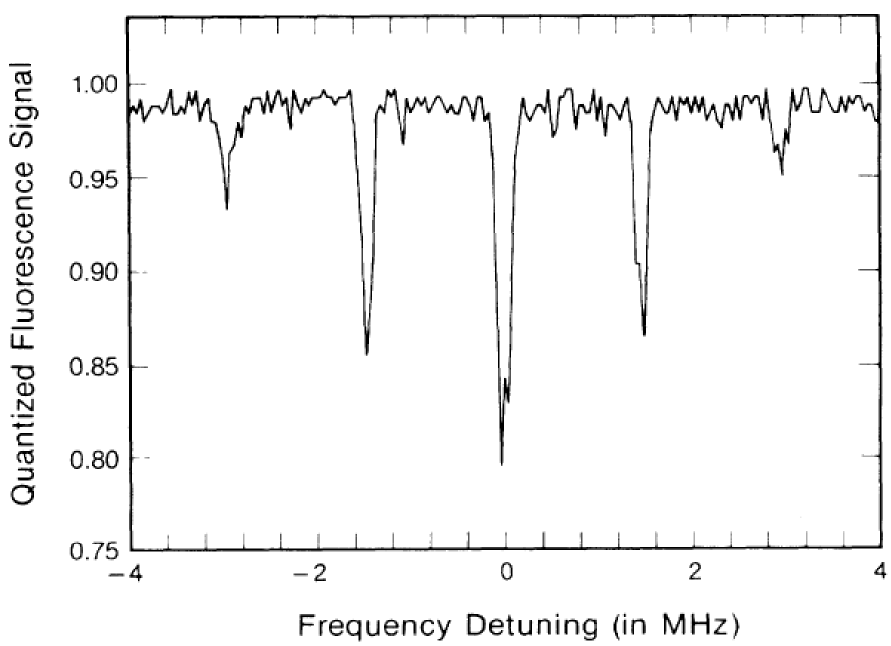
Not possible on dipole allowed transitions: Natural linewith (10^7-10^8 Hz) >> oscillation frequencies (10^5-10^6 Hz)

→ 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

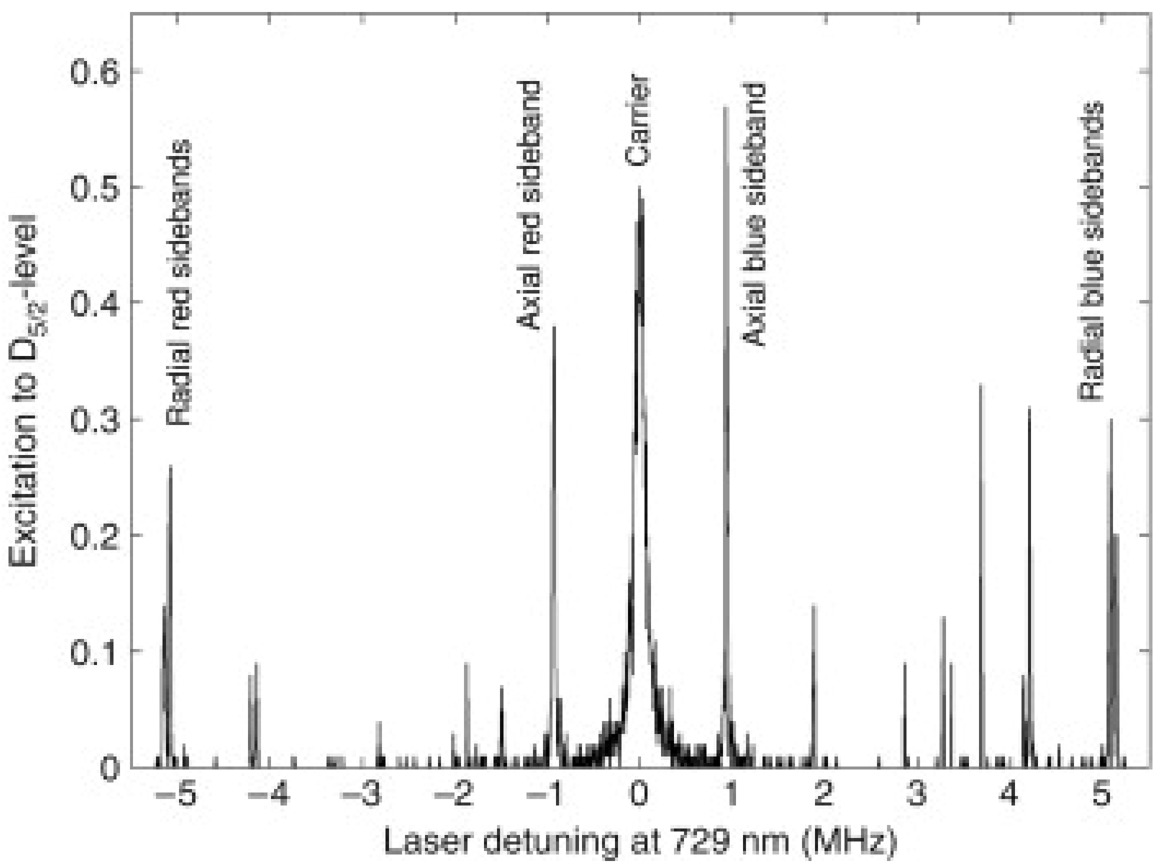




Absorption spectrum of S-D forbidden transition

Bergquist et al., 1997

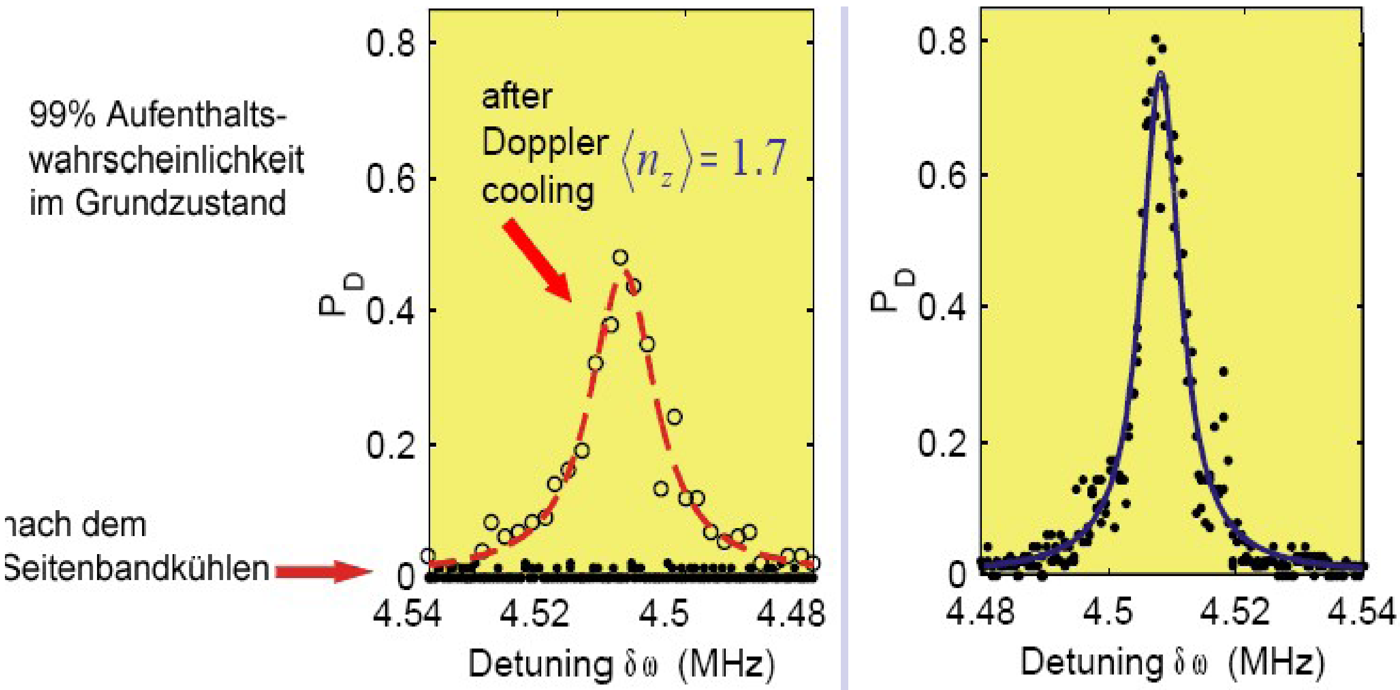
Spectrum of a single trappd Ca+ ion
cooled to the Doppler limit



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

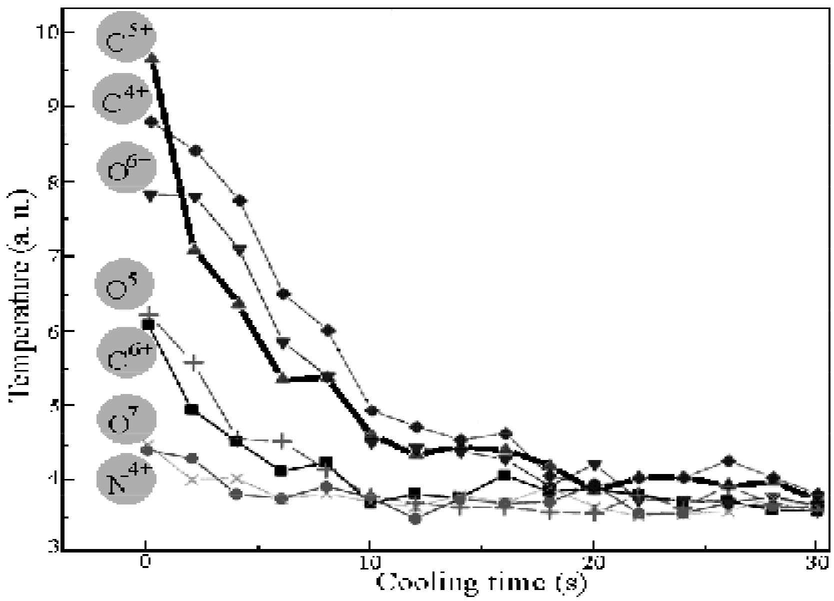
Final temperature given by zero-point energy of oscillation

$$\mathbf{E_{min} = \frac{1}{2} h\nu}$$

T~μK

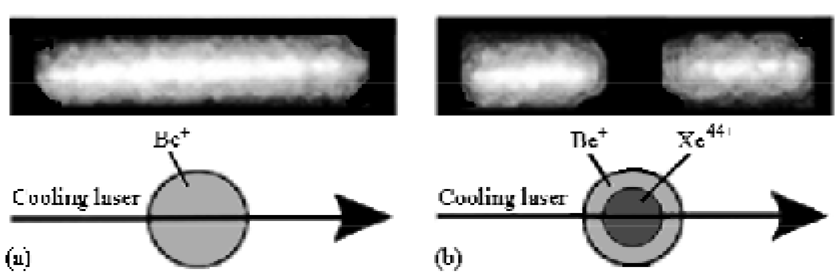
Sympathetic cooling

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



Resistive cooling of C^{5+} 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