Modern Non-Destructive Electronic Detection Techniques

in Cryogenic Trap Systems

Stefan Stahl

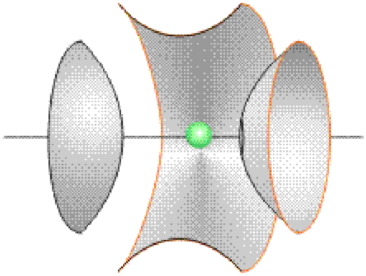
- *Basic Principles of Electronic Detection Systems*
- *Applications in Recent and Futural Experiments*

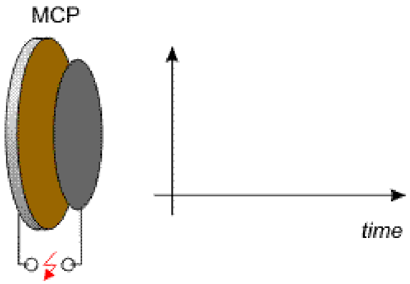
Workshop @ GSI, 2004

Motivation:

Why Non-destructive Detection?

example TOF (time-of-flight, destructive)



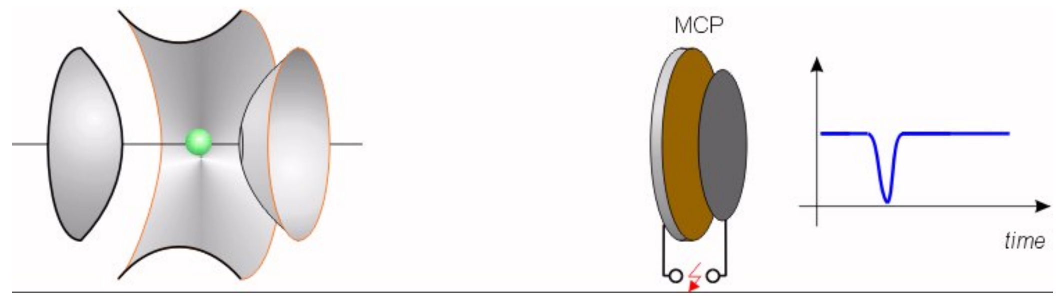


- advantage: single particle sensitivity is possible, easy to use
- disadvantage: removes ion out of your trap

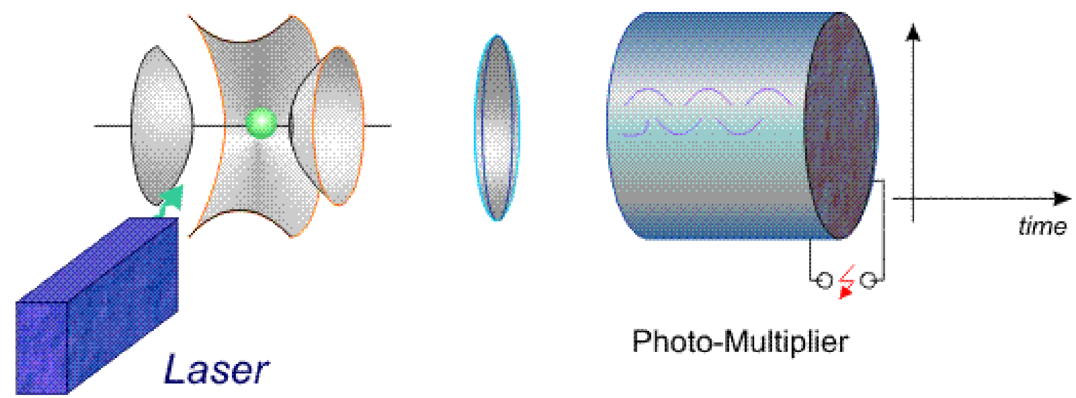
Motivation:

Why Non-destructive Detection?

example TOF (time-of-flight, destructive)



Laser-Spectrosc. (non-destructive)



- advantage: few ... single particle sensitivity possible
- disadvantage: costly, only for <u>very</u> few species applicable, optical access needed

Motivation:

Why Non-destructive Detection?

Keeping the particles inside your trap....

- *no need to load the trap again*
  (saving time, efforts & costs)
- *longer observation time*
  (=> good for high precision experiments)
- *possibility to electronically cool them down to very low energies (~ few Milli-eV) in ~ 1sec. („resistive cooling“)*
- *tool for high precision experiments*

How can we detect ?

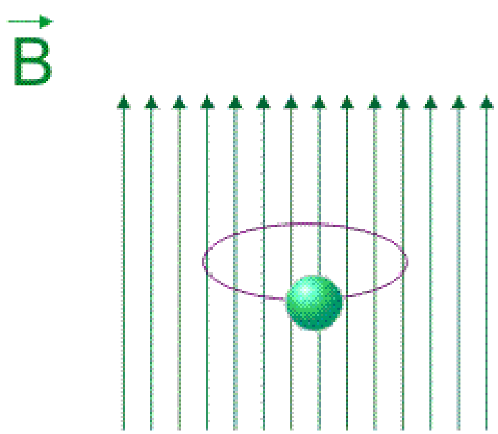
Make use of the fact, that Ions, Electrons, Protons, ...
are electrically charged particles

Every Moving Charge = Electrical Current

=> you can measure it !

How can we detect ?

Motion in a Penning Trap:



$$\omega_c = \frac{qB}{m}$$

How can we detect ?

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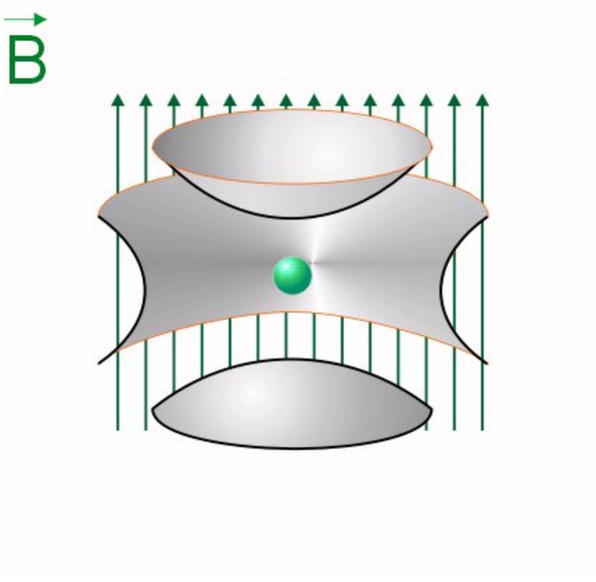

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How can we detect ?

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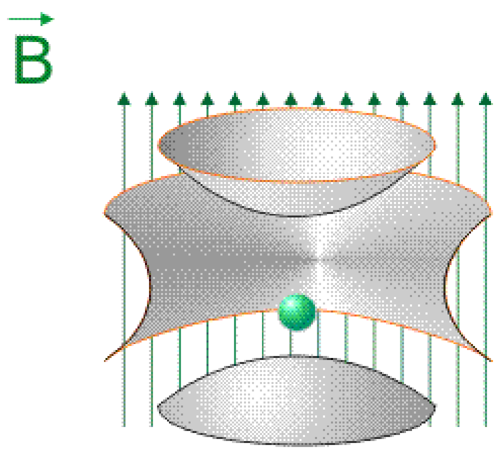


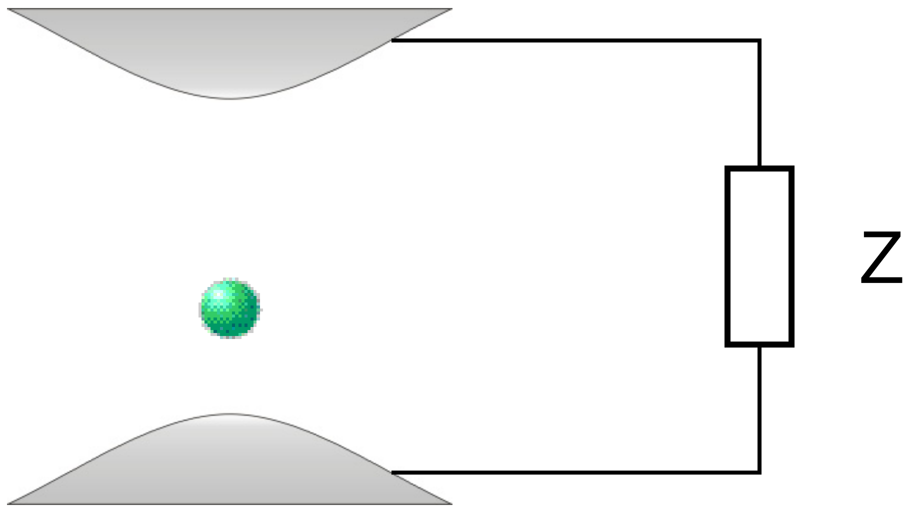
$$\omega_c = \frac{qB}{m}$$

$$\omega_z = \text{const.} \sqrt{\frac{qU_0}{m}}$$

$$\omega_- = \frac{U_0}{B\, r_0^2}$$

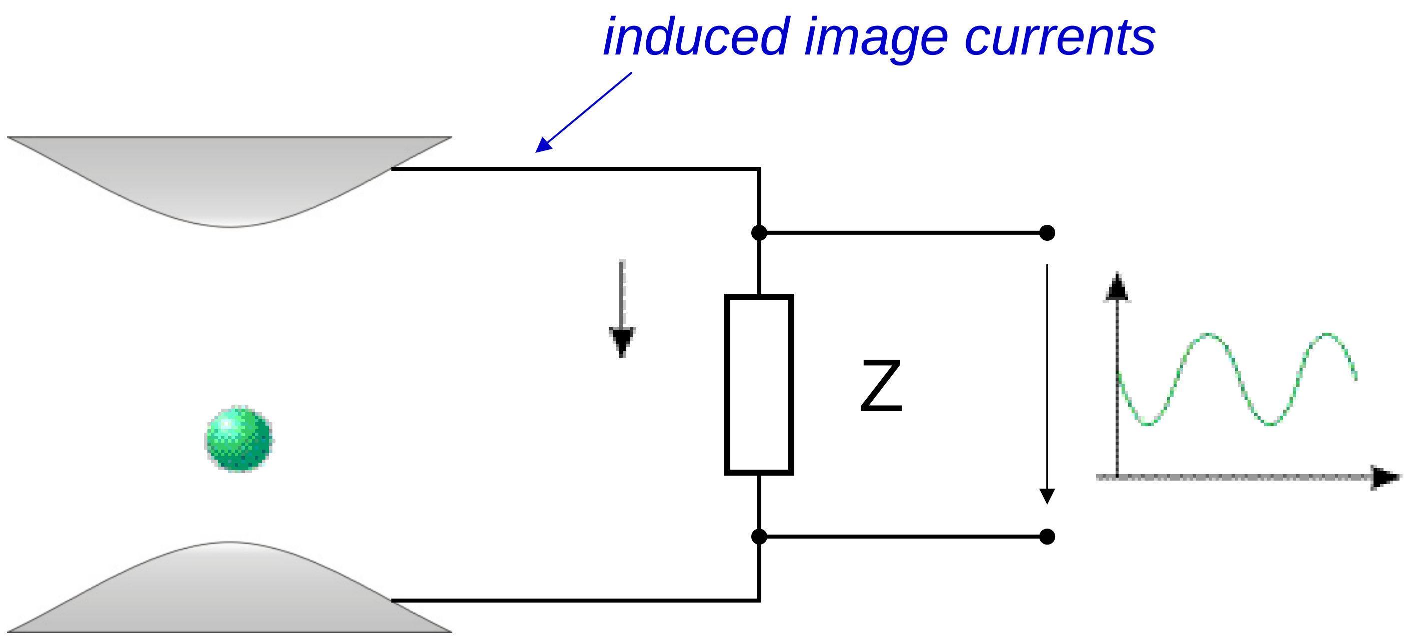
How can we detect ?

Axial Motion:



How can we detect ?

Axial Motion:



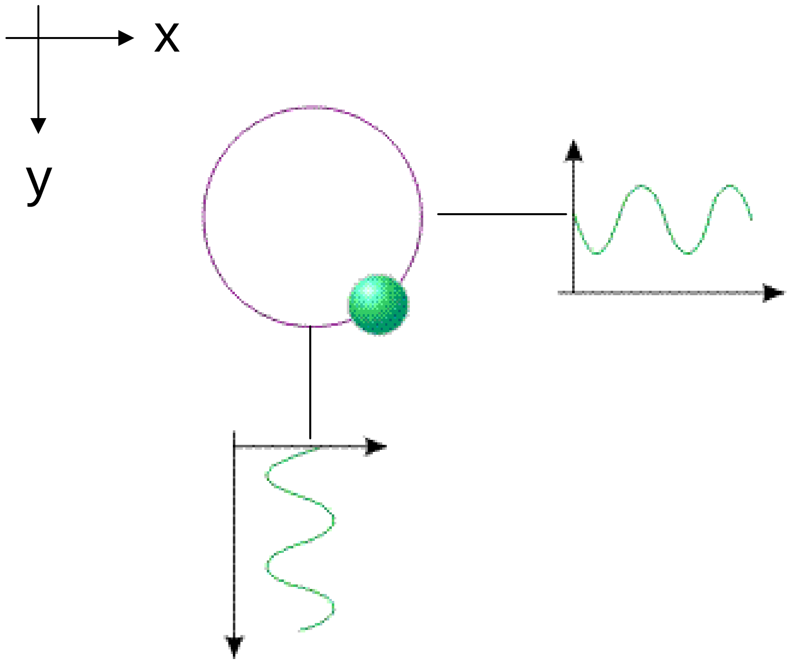
induced current: $I_{eff} = 1/\sqrt{2} \cdot r_{ion} / D \cdot \omega \cdot q$

still small: $0.2pA_{eff}$

(Schottky et al. ...)

Detection of excited ions (few eV)

- cyclotron motion



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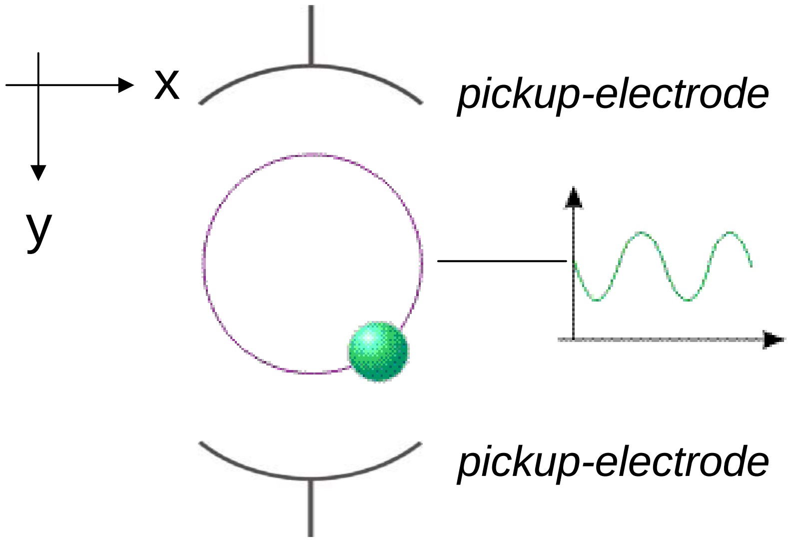

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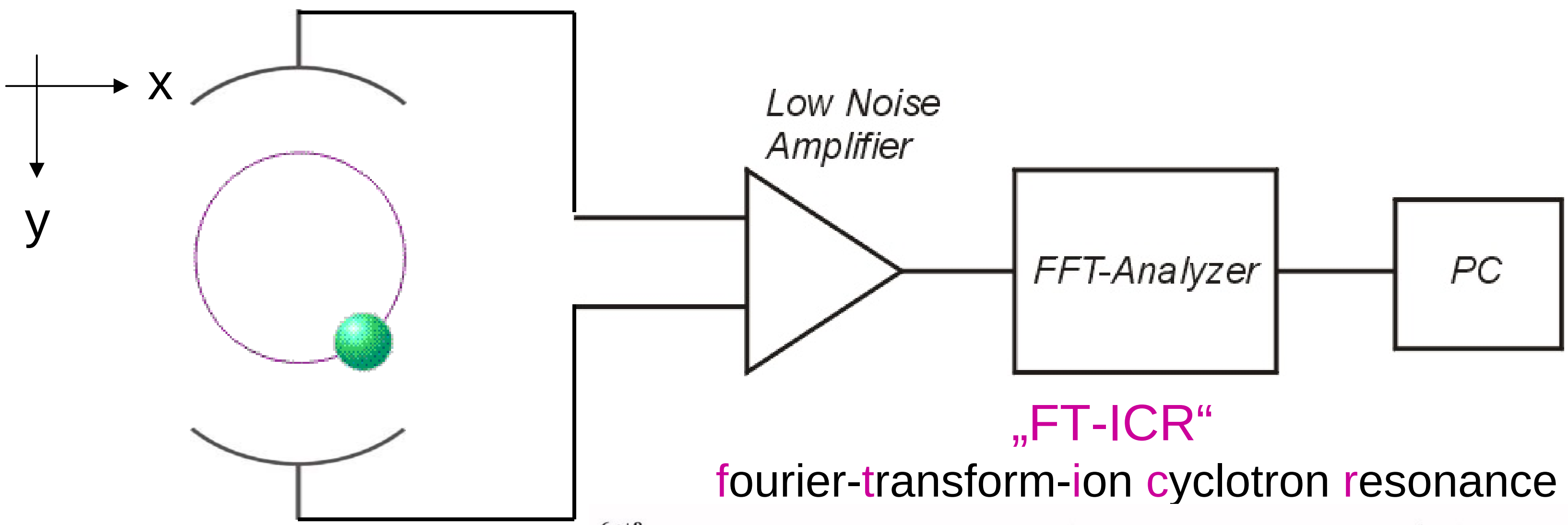
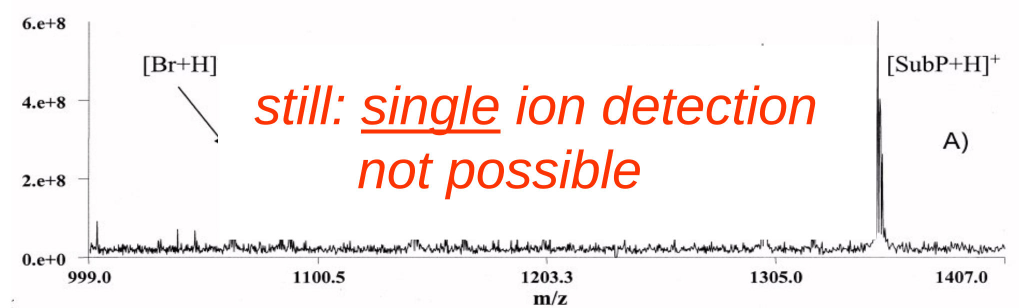


„FT-ICR“

fourier-transform-ion cyclotron resonance

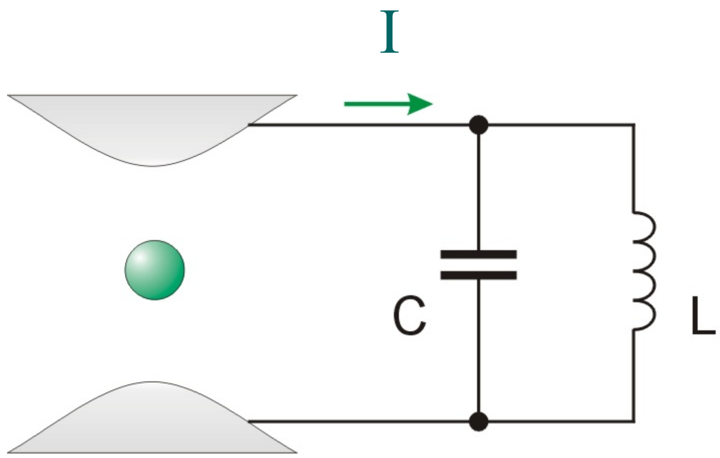


still: single ion detection not possible

„FT-ICR-cells“
used in chemistry/biology
m/q-resol. ~$10^5 ... 10^6$

Sensitivity Improvement:

Resonant instead of broadband detection

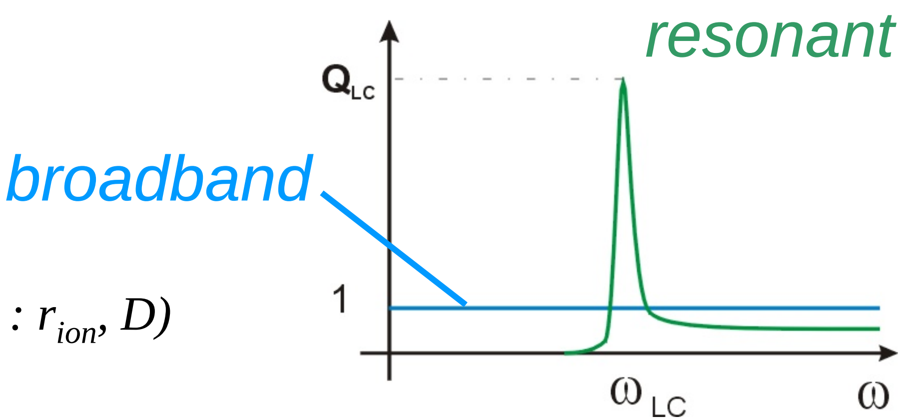


measured signal:

$$U = Z \cdot I$$

$$Z_{LC} = Q_{LC} \cdot |Z_{C,parasitic}|$$

$$\omega_{ion} = \omega_{LC} = 1/\sqrt{(LC)}$$

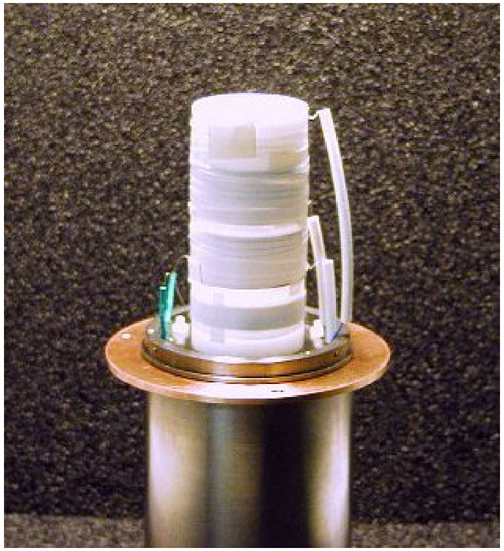


$(given : r_{ion}, D)$

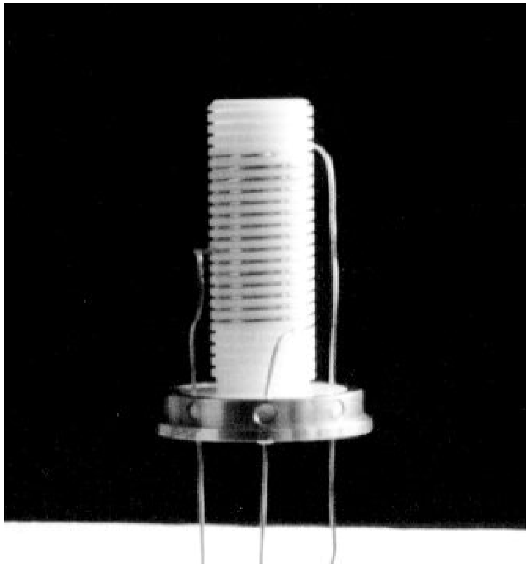
enhancement factor
~100 (T=300K)
~2000 (T = 4K)
⇒cryogenic components

this idea applies for axial detection as well as for FT-ICR !

Examples of high-Q-coils:



500kHz-coil
for FT-ICR detection of heavy masses
(Shiptrap / MATS)
NbTi wire on Teflon



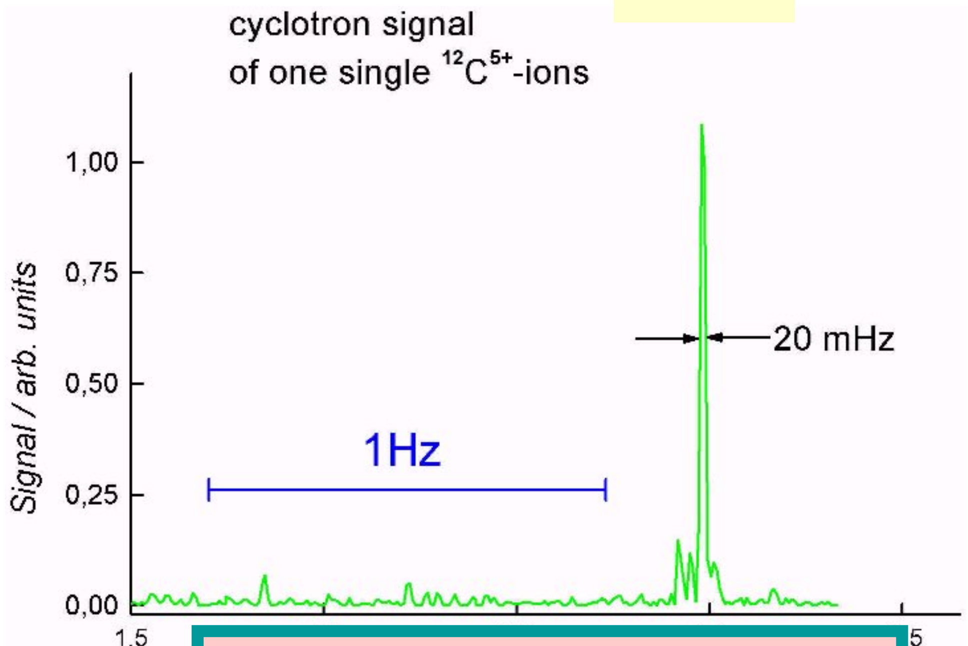
30MHz-coil
for FT-ICR of hydrogenlike ions
(g-factor, Mainz)
gold plated copper

Applications and Examples
of non-destructive electronic detection schemes

g-factor measurements: neccessity to know the magnetic field strength B

$^{12}C^{5+}$

FT-ICR-signal (resonant):



FWHM of $6 \cdot 10^{-10}$,
measurement time: 120sec
(=Fourier-Limit)

$E_{kin} \sim 1eV$

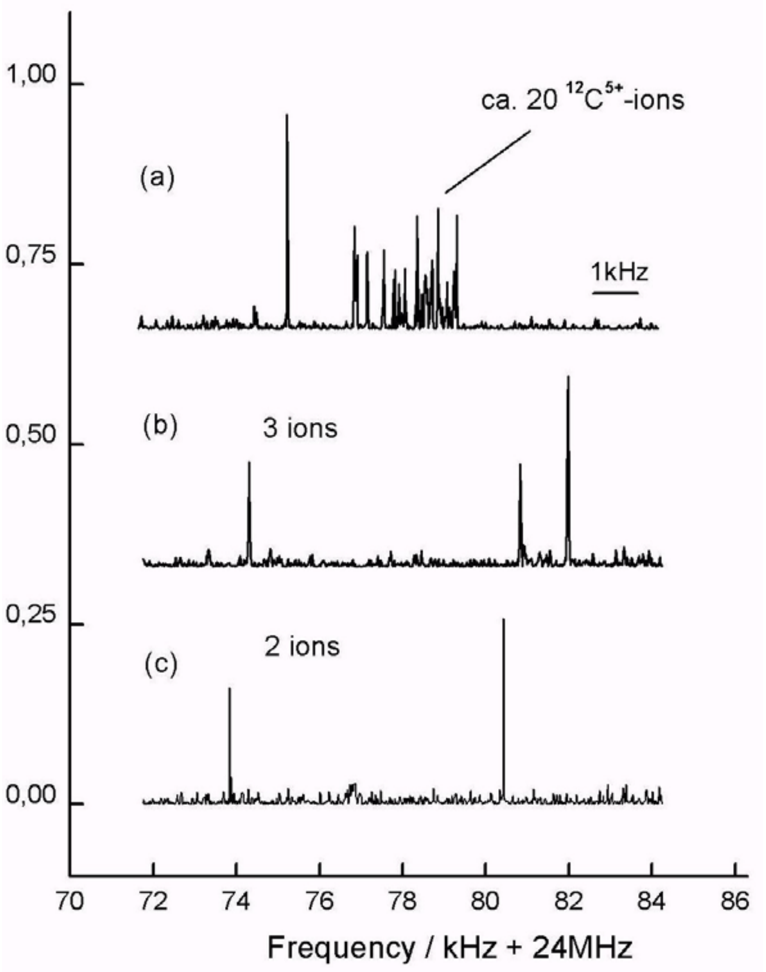
$$\omega_c = \frac{qB}{m} = \omega_+ + \omega_-$$

Limitation: B-field drifts
⇒short measurement times

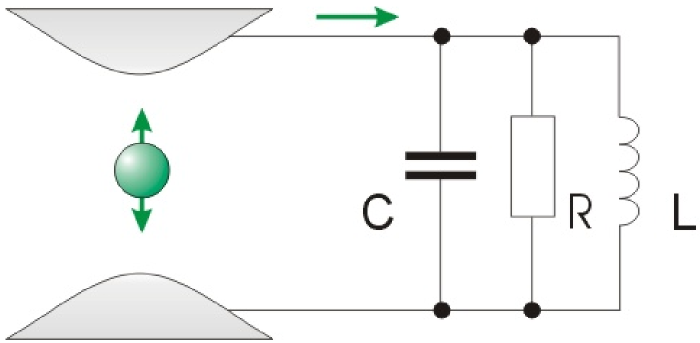
Counting single ions...

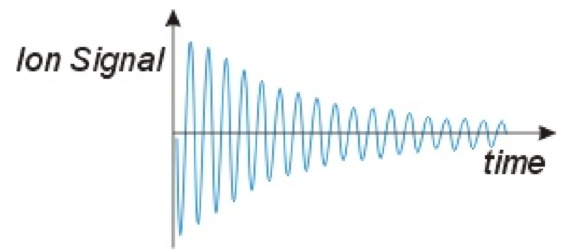
how many ions are
inside the trap?
=> just count them!

without magnetron centering ions show a considerable frequency spread



Resistive Cooling





induced current creates thermal energy in R => dissipative effect,
=> exponential decay of amplitude

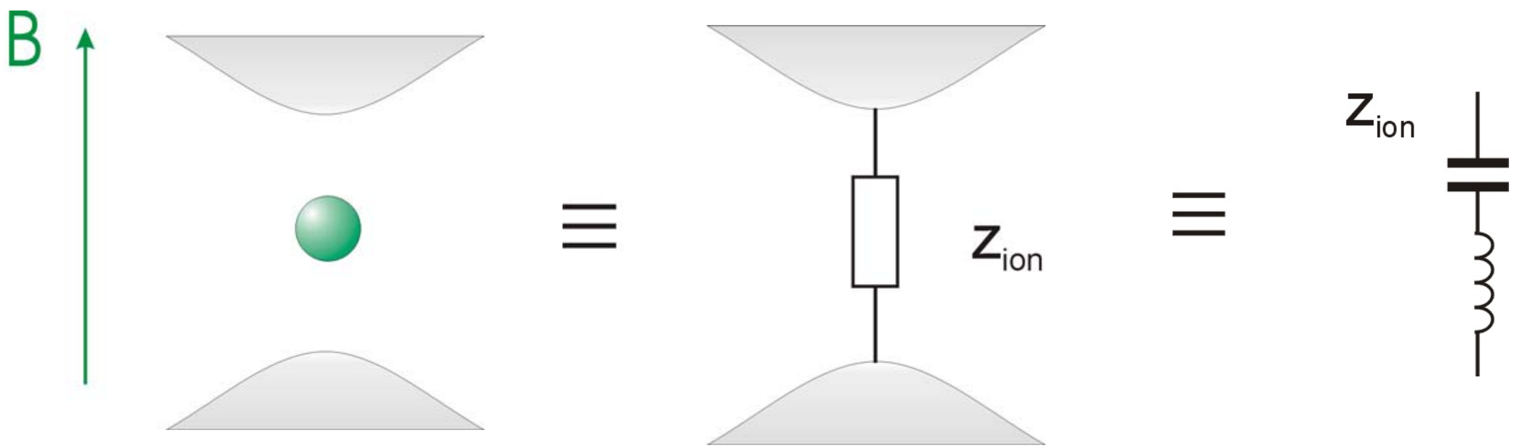
$$\tau = \frac{m \cdot D^2}{q^2 \cdot R}$$

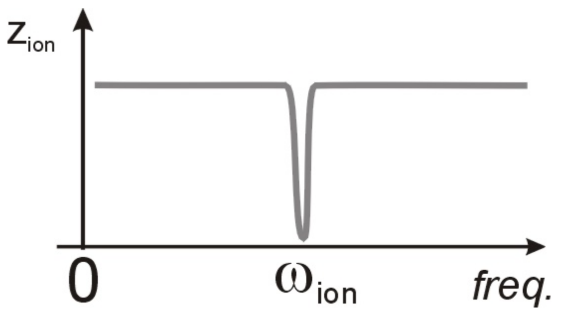
$$R = \frac{Q}{\omega \cdot C}$$

ion	D	τ
$^{12}C^{5+}$	5.5mm	23ms
Protons,	‘‘’	49ms
$^{131}Xe^{44+}$,	20mm	3.3ms
e^-, e^+,	0.7mm	10.9µs

for Q = 2000, f = 0.4MHz, C = 20pF *(except e^-, e^+)*

Detection of cold particles:

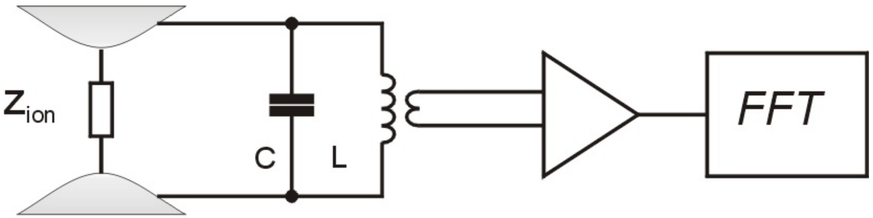


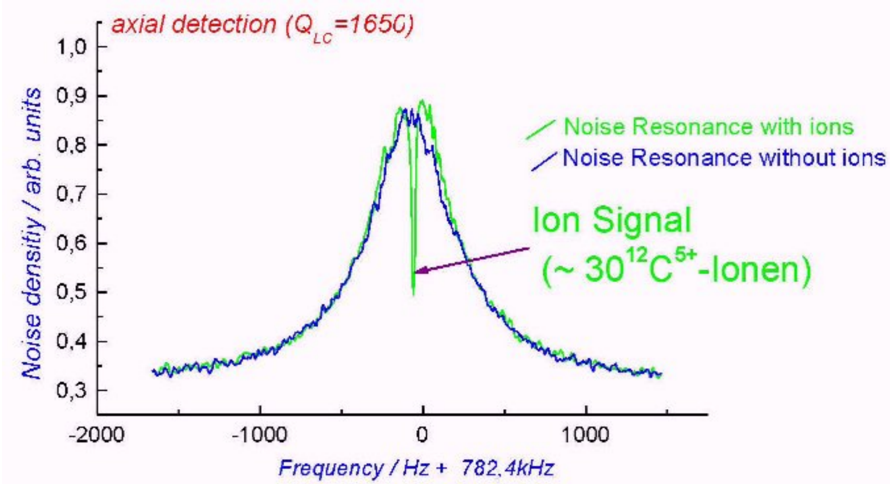


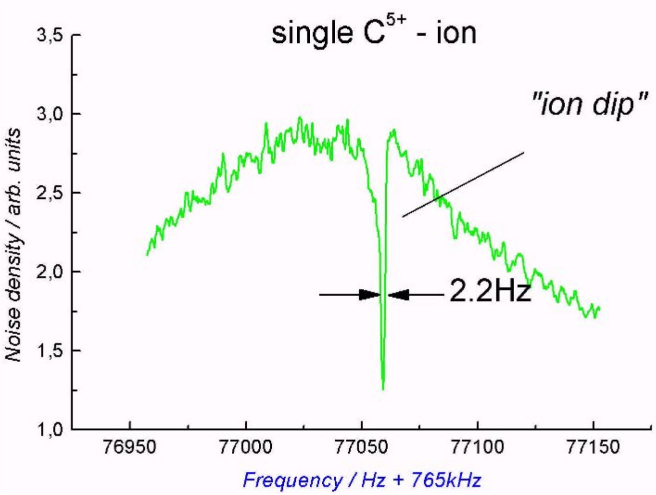
⇒possibility to detect cold ions

Bolometric Detection

of single cold ions





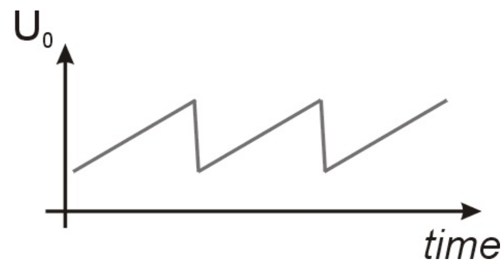


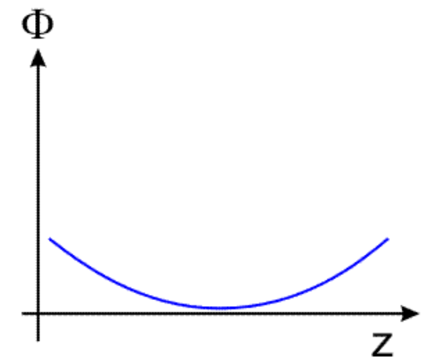
Mass Spectra (ramping method)

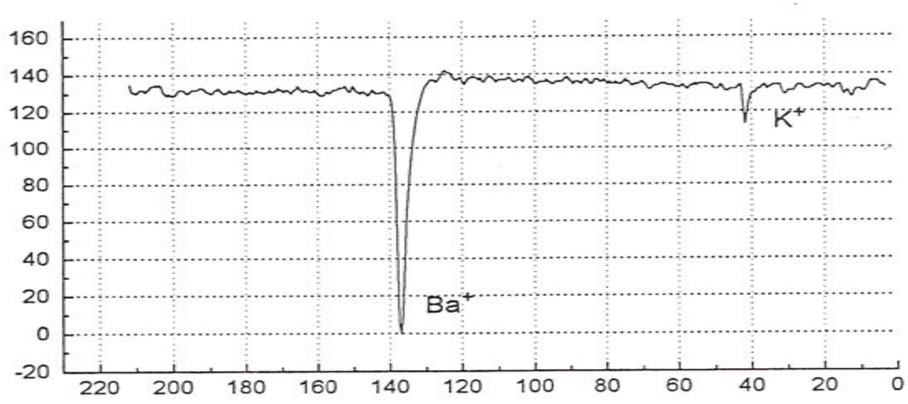
(Rettinghaus at al. 1967)

Axial Motion:

$\omega_z \sim (qU_0/m)^{1/2}$





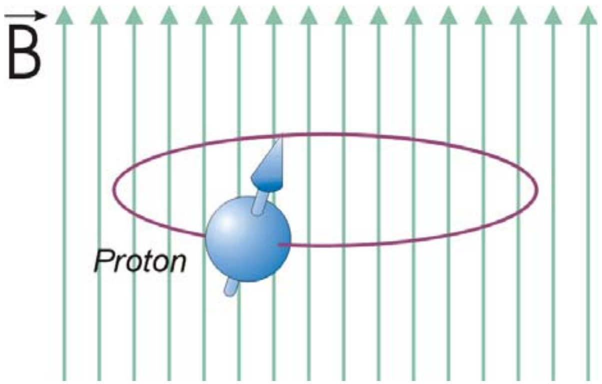


Ion Signal in
Barium-Penning Trap,
(Mainz)
@ 300K Q_{LC} = 250

=> simple and cost effective method

Determination of the free Proton Magnetic Moment

$$\frac{\left|\vec{\mu}_p\right|}{\mu_N} = g_p \cdot \frac{\left|\vec{s}\right|}{\hbar}$$



- *first direct high precision measurement of a free nuclear particles magnetic moment*
- *proton / antiproton comparison, matter / antimatter symmetry (CPT-Test)*

Application of Cryogenic Electronics at the Proton Trap:

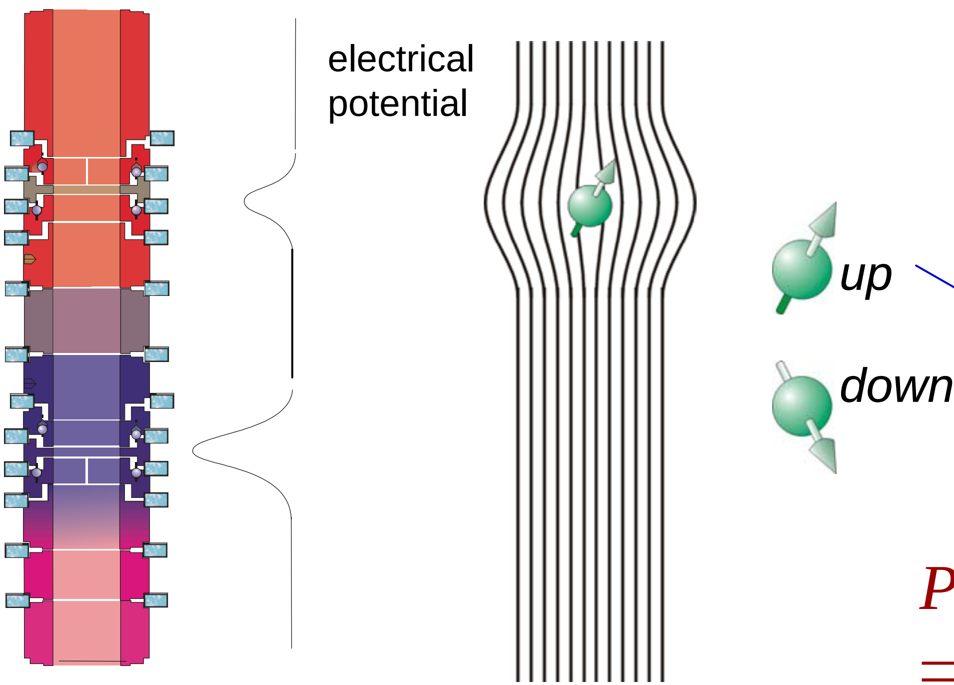
-calibration of B (magnetic field)
-determination of the ω_z, ω_-
-cooling the degrees of freedom down to 4K
by resistive cooling (and magnetron centering)

-detection of the spin direction

→ *not quite easy...*

Measurement Principle: Continious Stern-Gerlach Effect

Magnetic Bottle in „Double Trap“:

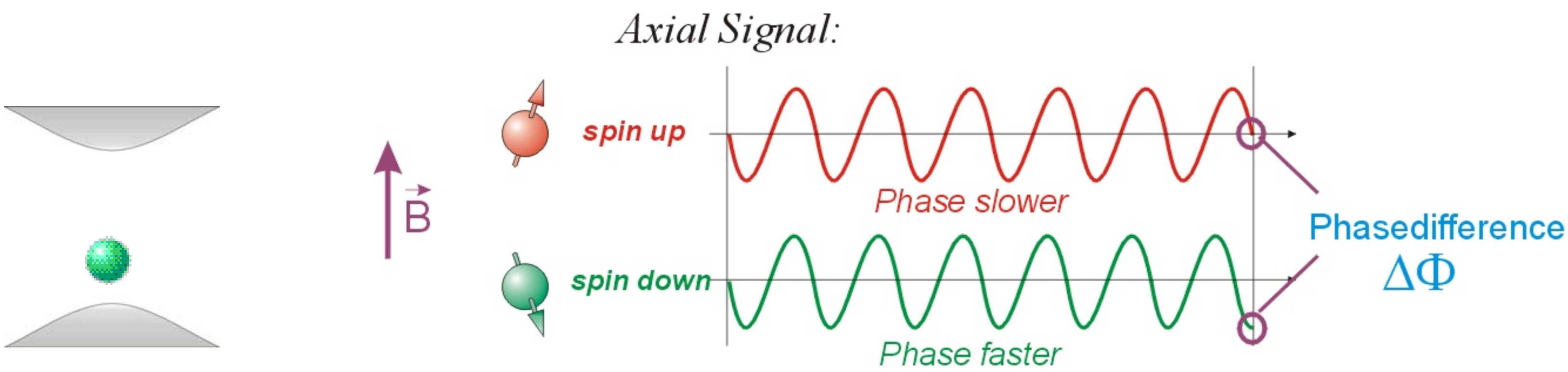


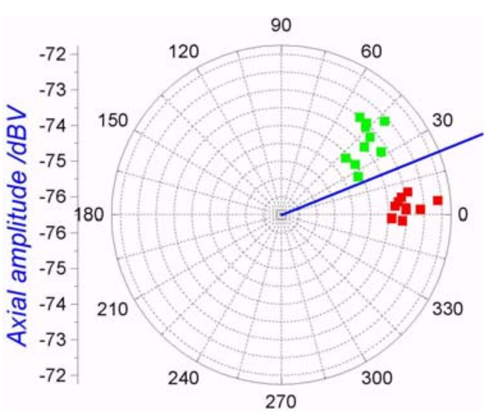
Axial Frequency depends on Spin State!

$$\Delta\omega_z = \mu_P \cdot B_2/(m\cdot\omega_z)$$

Problem: μ_P is <u>very</u> small
$\Rightarrow \Delta\omega_z$ frequency jump only few mHz in a „normal“ Trap

Motional Phase Detection makes very small frequency changes visible





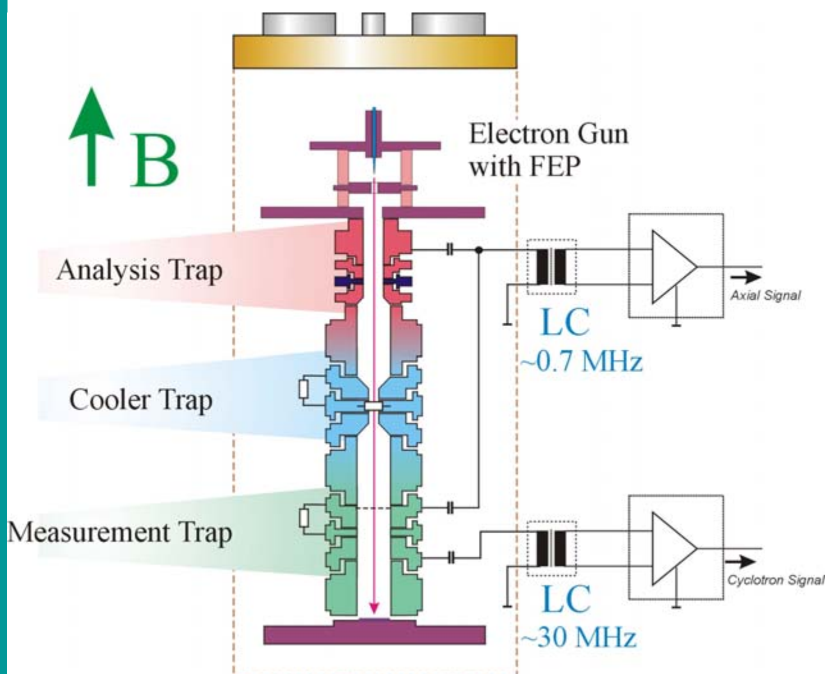
extension of the Fourier- Limit:

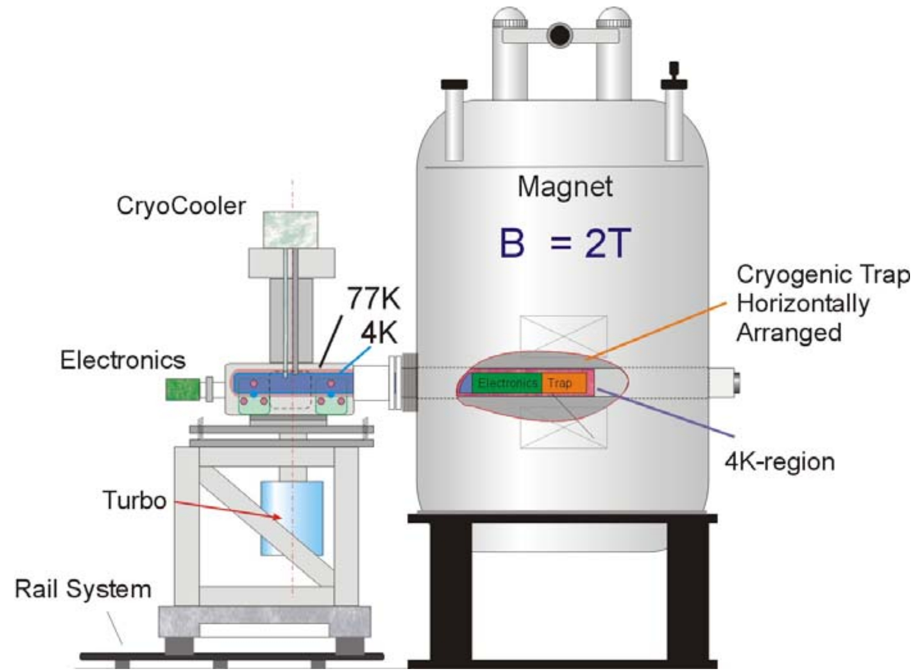
$$\Delta f = \frac{1}{T} \cdot \frac{\sigma(\Delta\Phi)}{2\pi}$$

one order of mag. improvement expected:
e.g. 45° phase difference after 1s => 125mHz

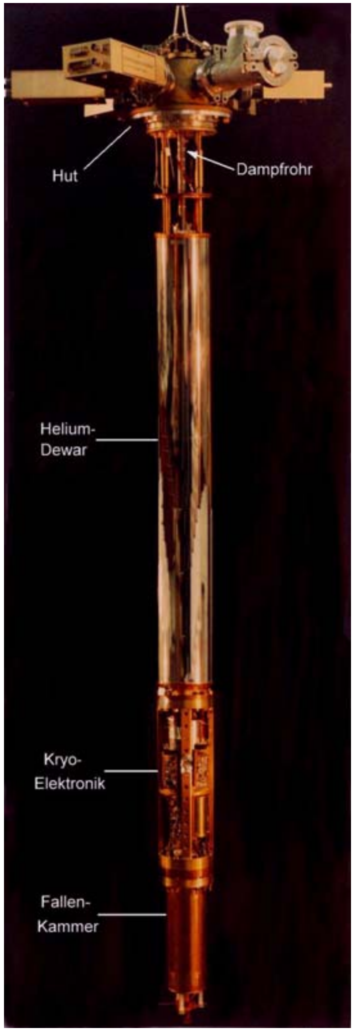
Setup Details

Proton Experiment

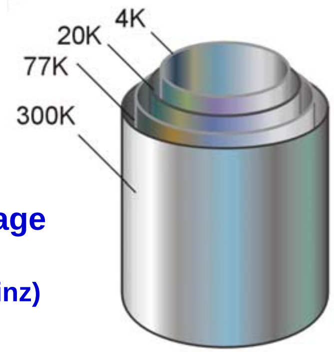




Having a glance at cryogenic setups....



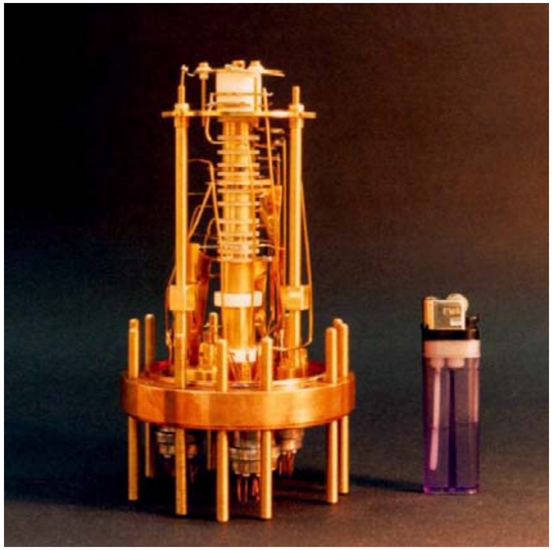
vertical 4K-dewar setup
(g-factor, Mainz)



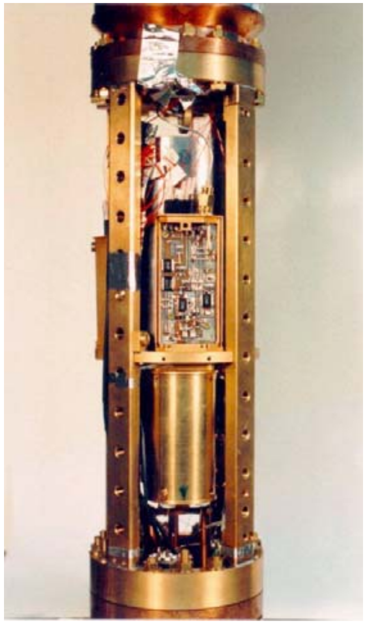
4K-multistage shielding
(g-factor, Mainz)

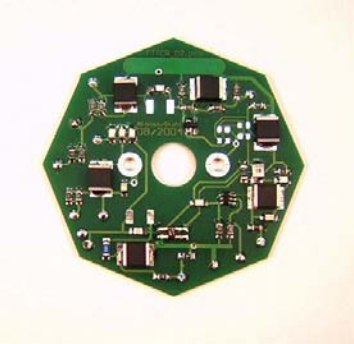
4K-axial amplifier

g-factor trap



4K-electronics section





4K-broadband FT-ICR amplifier
(Mainz 2004)

Conclusion

Modern non-destructive electronic detection principles open up a variety of possibilities

- *to detect ion clouds at roomtemperature in a quick and cost-effective way*
- *at 4K to detect single particles and cool them to sub milli-eV level with superconducting elements*
- *can be used in high precision experiments like*

  - g-factor measurements (HCI‘s, Proton, Anti-p)

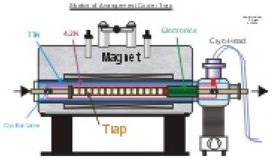
  - ultra-high precision mass-determinations

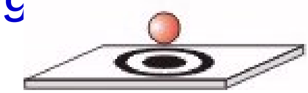
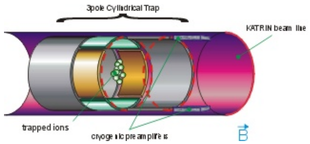
Outlook:

recent and futural experiments using
cryogenic electronic detection systems

- *High precision g-factor determination on medium-heavy HCI Ca^{17+}, Ca^{19+}*
  including 3 superconducting circuits, resonant FT-ICR and cryogenic broadband FT-ICR
- *Proton g-factor determination*
- *Hitrap Cooler Trap*
  cooling down HCI by collision and by resistive cooling
- *Quele-Trap for Quantum Computing*
- *Broadband FT-ICR for KATRIN (Karlsruhe)*
- *FT-ICR ultrahigh precision mass determination (MATS, Mainz)*
- *and.... ?*





many thanks to the teams in Mainz and GSI (Shiptrap, MATS, g-Factor)

Thanks for your attention!

Dr. Stefan Stahl

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