PRECISION TRAPS

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Fundamental Symmetries Lab

2018 / 01 / 15

Outline

- Motivation and Introduction
- Trapping of Charged Particles
- Basic Methods
- Antiproton Measurements in Penning traps
    - Charge – to – Mass Ratios
    - Magnetic Moments

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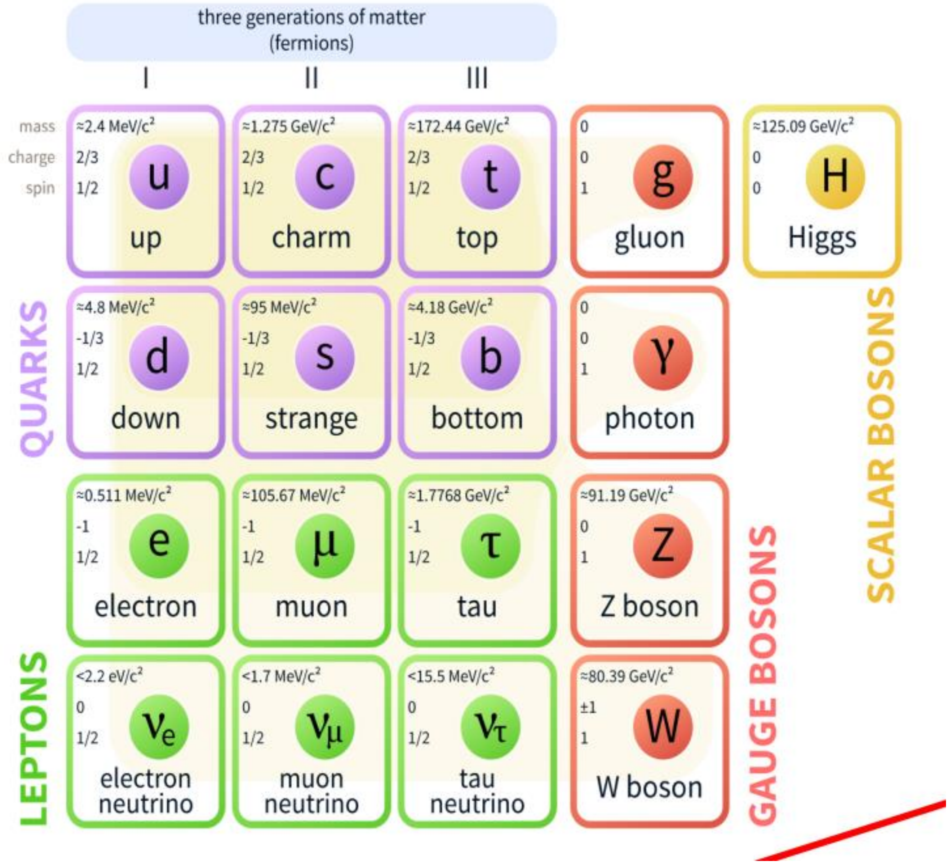
www.physik-journal.de

Physik Journal

In die Falle gegangen
An der Schwelle zum Laser
Auf Dauer befristet
DPG-Preise 2017

Deutsche Physikalische Gesellschaft DPG

Fundamental Physics in 2018



three generations of matter (fermions)

	I	II	III		
mass charge spin	≈2.4 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈172.44 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c² 0 0 H Higgs
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c² -1 1/2 e electron	≈105.67 MeV/c² -1 1/2 μ muon	≈1.7768 GeV/c² -1 1/2 τ tau	≈91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<1.7 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c² ±1 1 W W boson	
				GAUGE BOSONS	

- Relativistic quantum field theories of the standard model describe a plethora of particle physics phenomena
- The Standard Model is not just a list of particles and a classification - it is a theory that makes detailed, precise quantitative predictions!

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

$$g / 2 = 1.001\,159\,652\,180\,73\,(28)$$

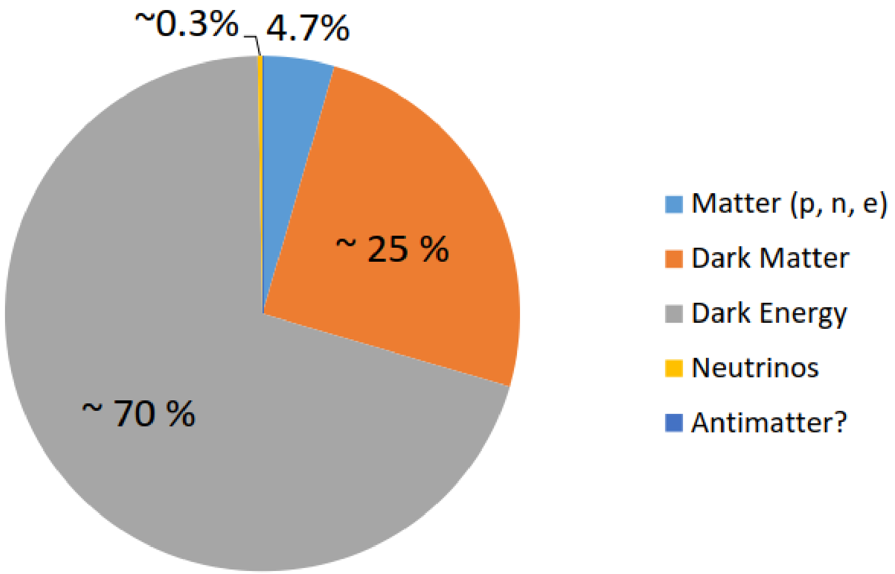
!!! At the same time, the Standard Model is the biggest success and the greatest frustration of modern physics !!!

Beyond Standard Model Physics

- Standard model is incomplete
  - contains 19 free parameters which need to be tuned by experiments

- observations beyond the SM
  - neutrino oscillations
  - dark matter
  - energy content of the universe
  - several fine-tuning problems
  - origin of lepton helicity
  - absence of antimatter in the universe:

known Standard Model CP violation produces one baryon in 10^{18} photons observed CMBR density: one baryon in 10^{9} photons



so at least we know, that we know quite a lot about almost nothing

what’s next?

how can we produce input to solve at least some of the problems?

How to solve problems in physics?

- Prominent and rather fruitful strategy:
  - Investigate very well understood, simple systems and look of unexpected deviations.

Example: Hydrogen

Basic models	Relativistic models	HFS – coupling and nuclear effect	QED effects Asymmetric WI-effects
Bohr / Schroedinger	Dirac	Pauli / Bloch etc.	Bethe / Schwinger
1	10^{-4}	10^{-7}	10^{-4} to 10^{-11}

!!! A single particle in a trap is one of the simplest systems you can think of !!!

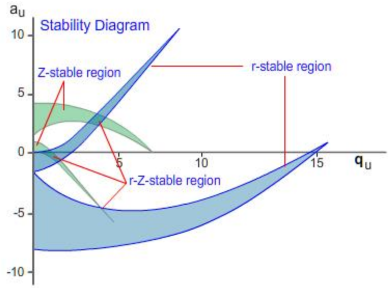
How to trap charged particles…

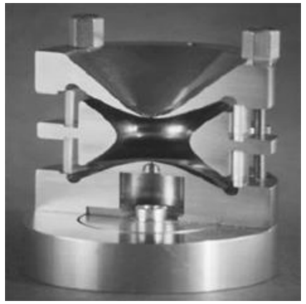
- Maxwell equations: $$\Delta\Phi = 0$$
- Harmonic potential: $$\Phi(x,y,z) = C_x x^2 + C_y y^2 + C_z z^2$$

- Earnshaw theorem: Not possible to trap particles in static electric fields.

Dynamic approach: Paul Trap

Physics idea: Oscillating rf-fields drive particles back to center – time average attractive (particle ping/pong)

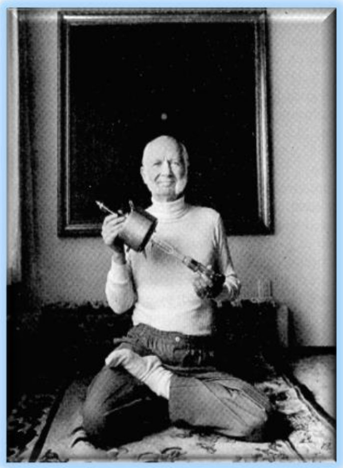




Nobel prize in 1989

Static approach: Penning Trap

Physics idea: counteract the radial saddle-potential by superimposing a strong magnetic field



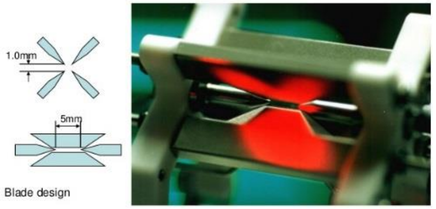
- Natural consequence: both trap-types have stability issues…

Paul Trap vs. Penning Trap

- Cheap
- Variable
- Open access

- Noisy
- Micromotion

Innsbruck linear ion trap



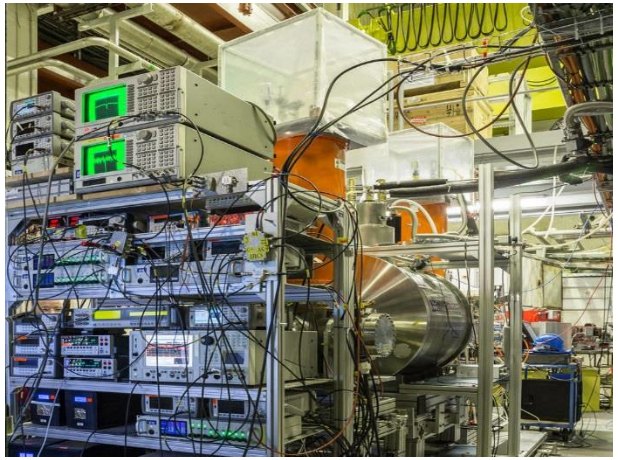
$\omega_{axial} \approx 0.7 - 2\ \mathrm{MHz}$ $\omega_{radial} \approx 5\ \mathrm{MHz}$

$\mathit{trap\ depth} \approx eV$

F. Schmidt-Kaler, et al., Appl. Phys. B 77, 789 (2003).

- Expensive
- Constrained
- Closed system

- STABILITY
- Controlability
- Reliability



Use Paul trap once you’re interested in physics properties which are defined by internal interactions in composed charged systems.

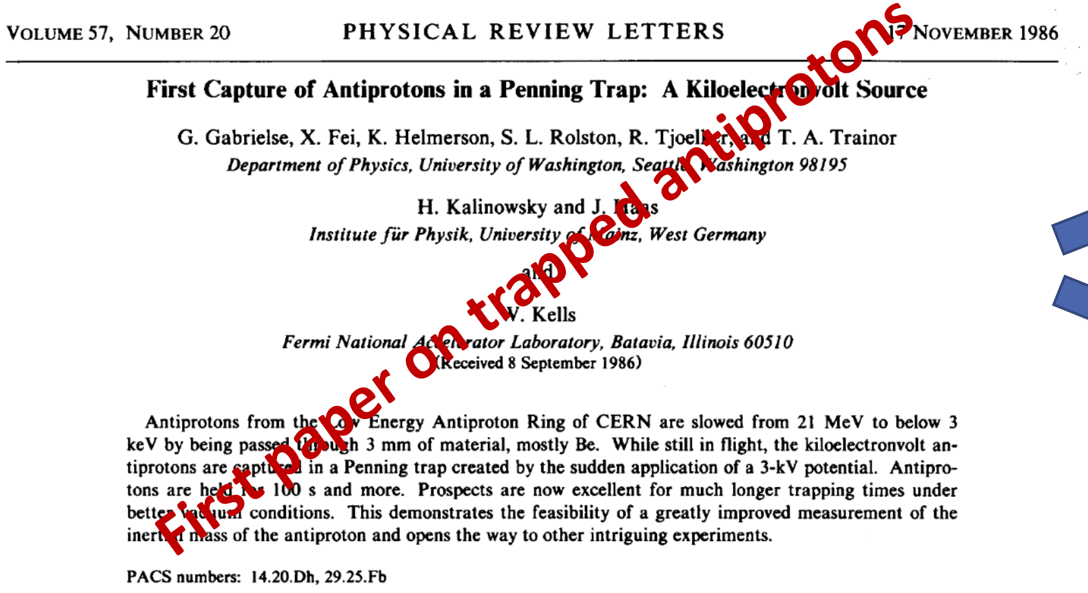
Use the Penning trap for ultra-high precision studies or experiments dealing with complex many particle systems.

Prominent in quantum information

Prominent in fundamental studies

Traps in Antimatter Physics

- The **Penning trap** is the “work-horse” of the antimatter physics community.



VOLUME 57, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

First Capture of Antiprotons in a Penning Trap: A Kiloelectronvolt Source

G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. Tjoelker, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

H. Kalinowsky and J. Haas
Institute für Physik, University of Mainz, West Germany

and

W. Kells
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 8 September 1986)

Antiprotons from the Low Energy Antiproton Ring of CERN are slowed from 21 MeV to below 3 keV by being passed through 3 mm of material, mostly Be. While still in flight, the kiloelectronvolt antiprotons are captured in a Penning trap created by the sudden application of a 3-kV potential. Antiprotons are held for 100 s and more. Prospects are now excellent for much longer trapping times under better vacuum conditions. This demonstrates the feasibility of a greatly improved measurement of the inertial mass of the antiproton and opens the way to other intriguing experiments.

PACS numbers: 14.20.Dh, 29.25.Fb

First paper on trapped antiprotons

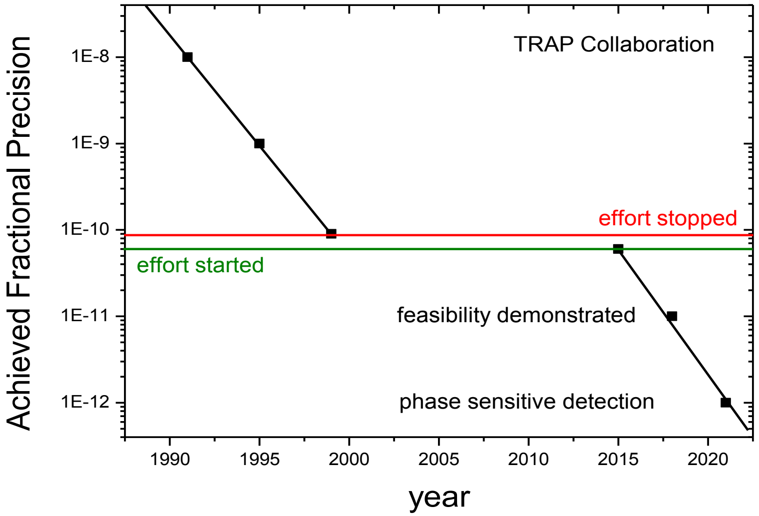
Trap as a container for positrons and antiprotons to produce antihydrogen (see lectures by Testera and Yamazaki)

Trap as an instrument to study the fundamental properties of trapped antiparticles (this lecture / Smorra lecture).

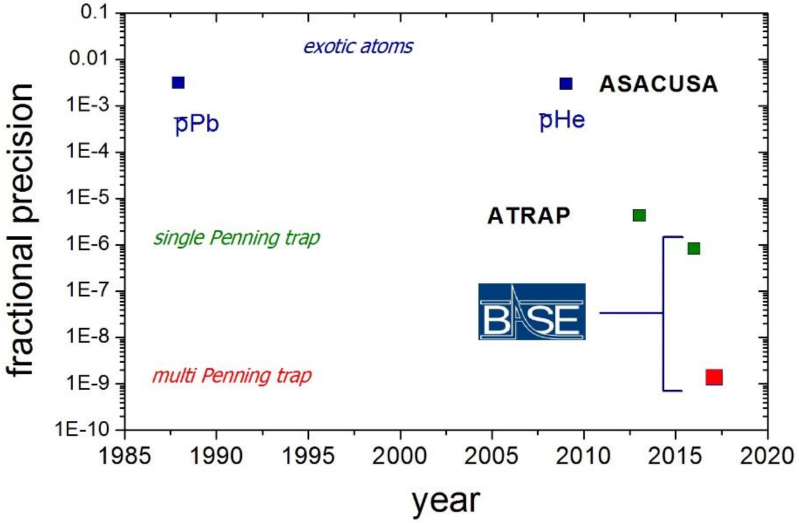
This entire field of physics would likely NOT EXIST without traps!

Trap Results in Antimatter Physics

- Two collaborations dealing with single particles in traps – ATRAP and BASE
  - (A)TRAP pioneered fundamental experimental methods.
  - BASE enhanced fractional precision of these experiments.



BASE 2017: $\mu_{\bar{p}} = -2.792\,847\,344\,1\,(42)\,\mu_{nucl}$

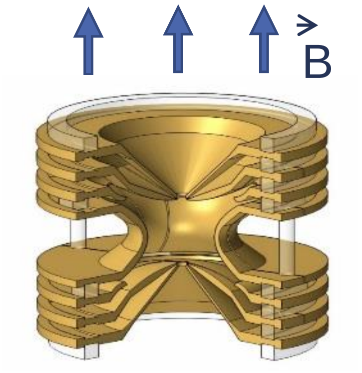


??? What is behind all that ???

Penning Trap

radial confinement of charged particles by a constant magnetic field

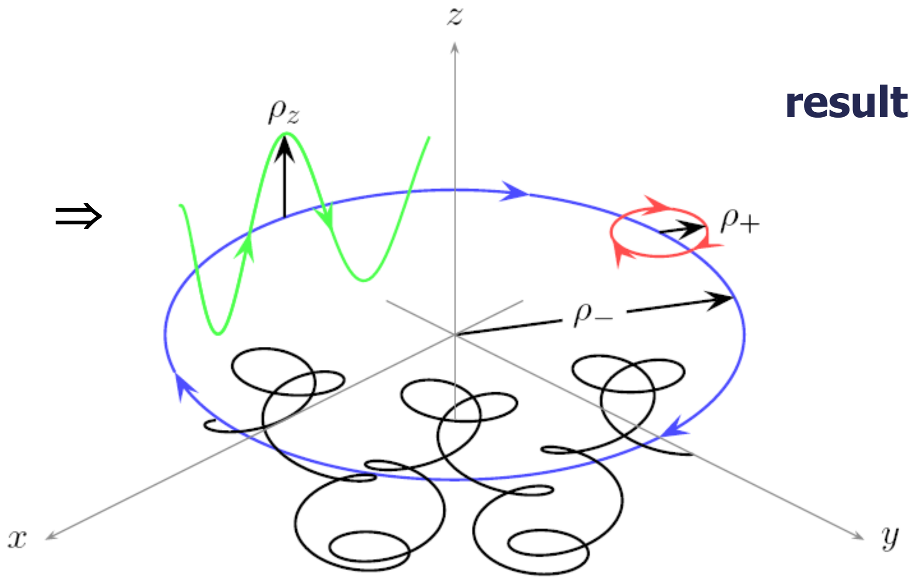
$$\vec{B} = B_0 \hat{z}$$



Superimpose the simplest electrostatic potential you can think of

$$\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$$

$\Rightarrow$



results in three harmonic oscillator modes

axial mode

$$\omega_z = \sqrt{\frac{2e_0 U_0}{m d_0^2}}$$

modified cyclotron mode

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

magnetron mode

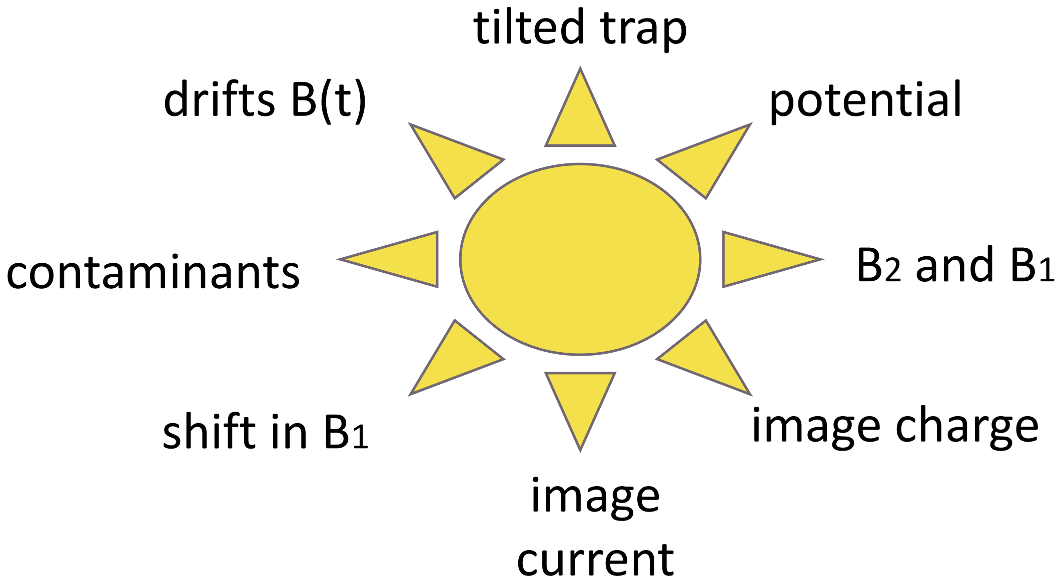
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

- **single particle in a trap:** simplest superimposed static magnetic and static electric fields result in three fully decoupled harmonic single-particle oscillators.

The Invariance Theorem

- The three trap frequencies can be combined to a robust invariance relation

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$



tilted trap

drifts B(t)

potential

contaminants

B_2 and B_1

shift in B_1

image charge

image current

- **misalignment of B-axis and E-axis cancels out**
- **ellipticities of trap potential cancel out**

- Single particles in Penning traps give direct access to the fundamental properties of trapped particles

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2} = \frac{1}{2\pi}\frac{q}{m}B$$

Precise frequency measurements in traps provide information about fundamental properties of trapped particles.

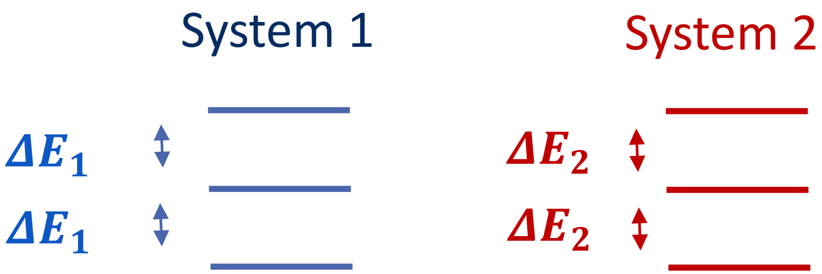
Different Perspective: Fundamental Symmetries

- Within the framework of classical physics, a single particle in a Penning trap is a **well understood**, **very simple system (three harmonic oscillators).**
- Penning traps thus provide perfect boundary conditions to test exotic theories and search for physics beyond the Standard Model.
- **How would a yet undiscovered physics effect look like?**
- **Whatever it is:**

$$H\,\psi = (H_0 + V_{exotic})\,\psi$$

$$\Delta E_{exotic} = \langle\psi|V_{exotic}|\psi\rangle$$

- **Need to ask the right questions**



$$E_1 - E_2 = \Delta E_{exotic} = \langle\psi|V_{exotic}|\psi\rangle$$

A precision trap is an artificial, highly modular, extremely exotic atom

Interaction Potentials – Minimal SME

- Example: Standard Model Extension

$$\left(\boxed{i\gamma^\mu D_\mu - m} - \boxed{a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu}\right)\psi = 0$$

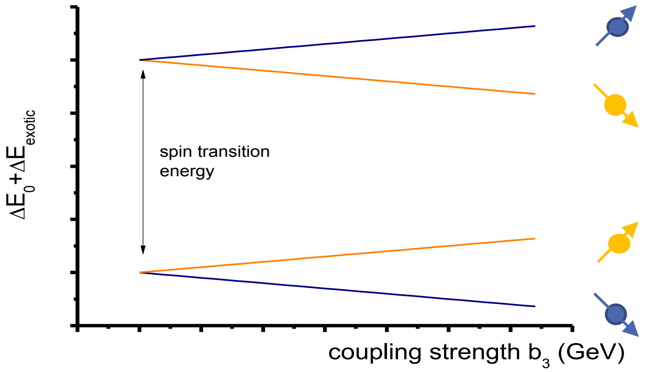
Dirac equation   CPT-odd modifications

Inspired by string theory translated to SM via effective field theory
Idea of construction: Consider all possible low dimension bi-linears within the Poincare group *(useful but not fundamental)*.

$$b_\mu\gamma_5\gamma^\mu \rightarrow b_x\begin{pmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} \end{pmatrix}\begin{pmatrix} \mathbf{0} & \boldsymbol{\sigma_x} \\ -\boldsymbol{\sigma_x} & \mathbf{0} \end{pmatrix} + b_y\begin{pmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} \end{pmatrix}\begin{pmatrix} \mathbf{0} & \boldsymbol{\sigma_y} \\ -\boldsymbol{\sigma_y} & \mathbf{0} \end{pmatrix} + b_z\begin{pmatrix} \mathbf{0} & \mathbf{1} \\ \mathbf{1} & \mathbf{0} \end{pmatrix}\begin{pmatrix} \mathbf{0} & \boldsymbol{\sigma_z} \\ -\boldsymbol{\sigma_z} & \mathbf{0} \end{pmatrix}$$

$$b_x\begin{pmatrix} -\boldsymbol{\sigma_x} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma_x} \end{pmatrix} + b_y\begin{pmatrix} -\boldsymbol{\sigma_y} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma_y} \end{pmatrix} + b_z\begin{pmatrix} -\boldsymbol{\sigma_z} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\sigma_z} \end{pmatrix}$$

Pseudo-magnetic field, with different coupling between matter and antimatter



Measurements:

coefficients can be constrained by searching for **diurnal variations** in comagnetometer measurements.

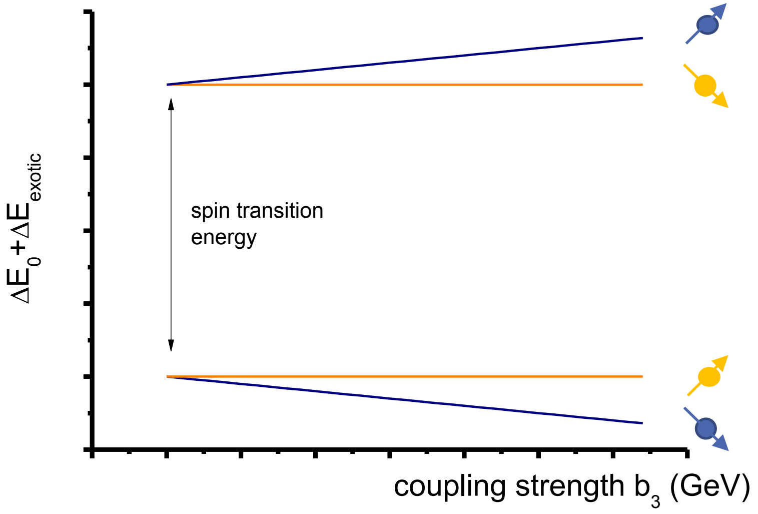
comparisons of particle/antiparticle magnetic moments in traps

Physics: such interactions can e.g. be induced by CPT-odd dark matter couplings

Interaction Potentials – Non-Minimal SME

$$\Delta V_{int} = \widetilde{b_{z,D}} \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \pm\boldsymbol{\sigma_z} \end{pmatrix}$$

these types of interactions can only be uncovered by explicit measurements on antimatter



Yukawa picture: $$\left[\left(\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) + \left(\frac{mc}{\hbar}\right)^2\right]\psi = 0$$

Stationary Yukawa potential: $$V(r) = -\frac{g}{r} exp\left(-\frac{r}{R_0}\right)$$

Effective interaction length: $$R_0 = \frac{\hbar}{mc}$$

Potentially sensitive to exchange bosons, **exclusively coupling to antimatter.**

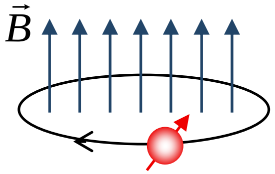
Potentially sensitive to heavy exchange bosons at strong interaction strenghts.

Complementary approach to HEP

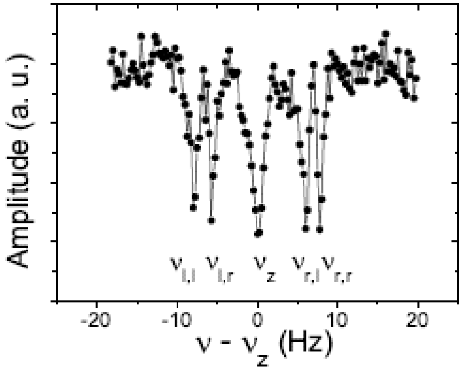
The Penning Trap – Key Techniques

Blueprint Measurements in Penning traps

Cyclotron Motion



simple



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

g: mag. Moment in units of nuclear magneton

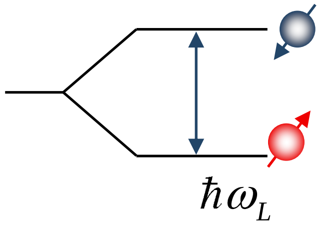
$$\boxed{\omega_c = \frac{e}{m_p} B}$$

$$\boxed{\omega_L = g \frac{e}{2m_p} B}$$

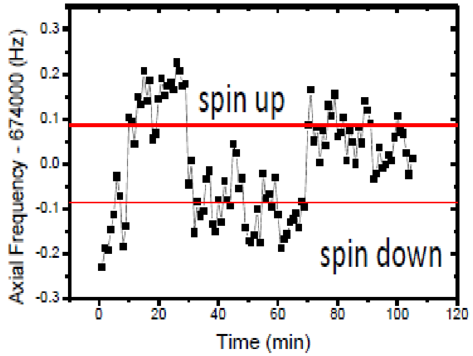
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Larmor Precession



difficult

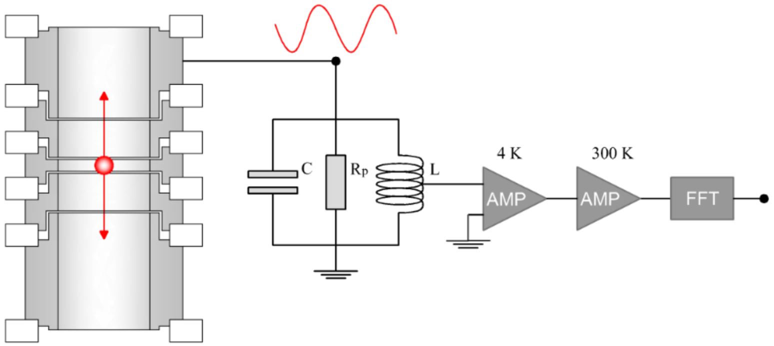


S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

Non Destructive Particle Detection (see Smorra lecture)

Idea: Oscillating particle induces image currents in trap electrodes.



What are we dealing with?

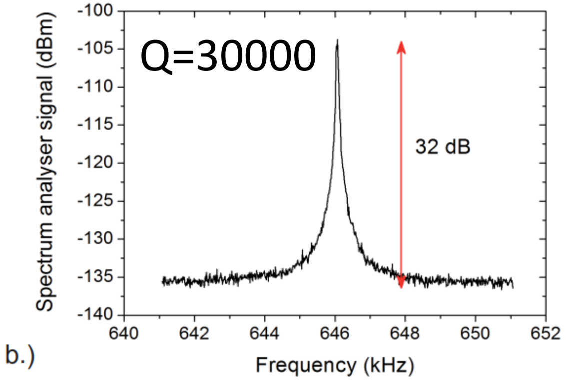
$$I_p = \frac{q}{D_i}\dot{\rho}_i = 2\pi\frac{q}{D_i}\nu_i\rho_i$$

single charge

10^{-16} A/mm

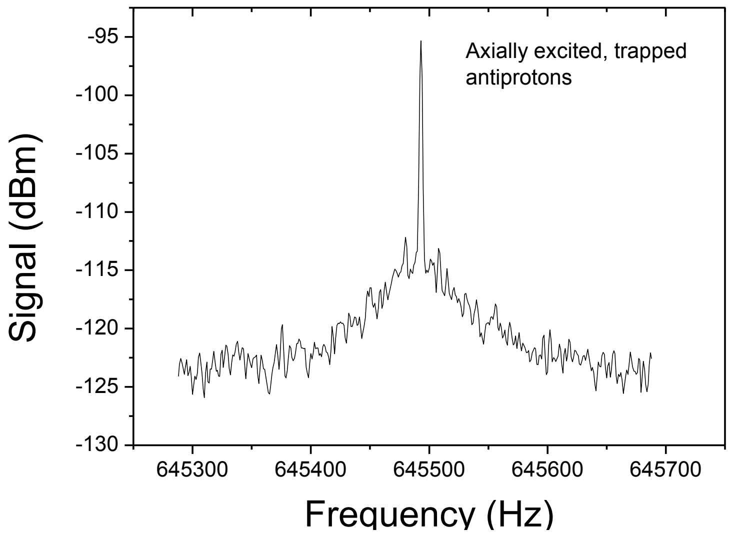
Image current detection:

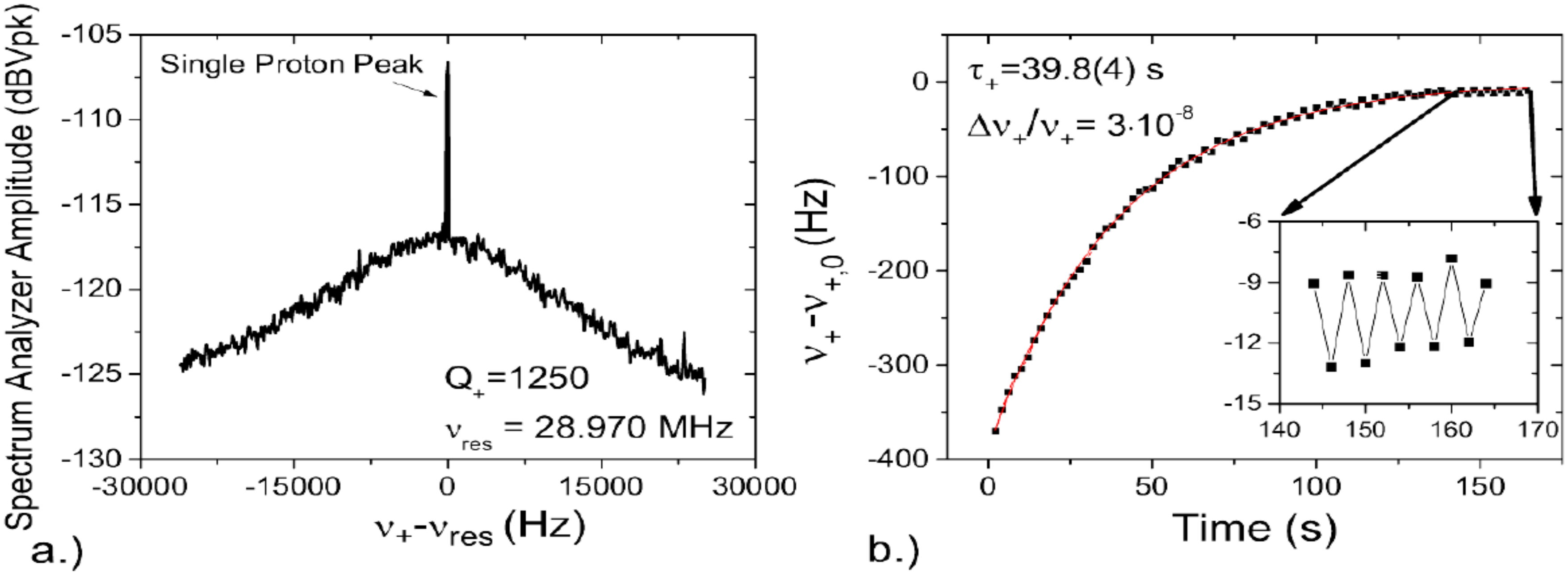
- Requires detection systems with high sensitivity
- Non destructive – long observation times – precise information about trapped particle
- Real time observation of particle manipulation



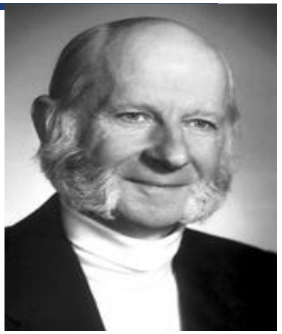
Example: Resistive Cooling and Peak Detection

- Power dissipated in detection resistor
- Particle is cooled resistively





The Continuous Stern-Gerlach Effect



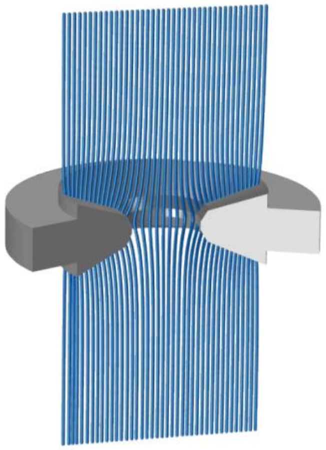
Measurement based on continuous Stern Gerlach effect.

Energy of magnetic dipole in magnetic field

$$\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$$

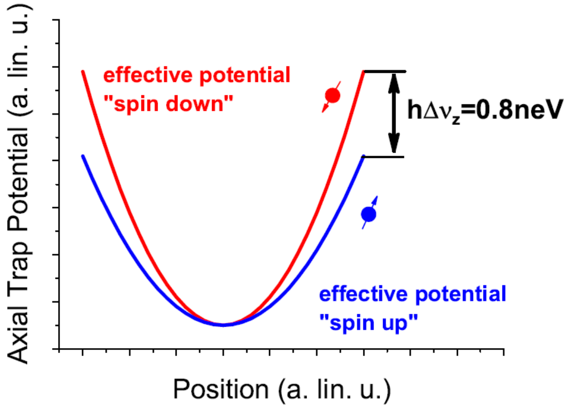
Leading order magnetic field correction

$$B_z = B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)$$



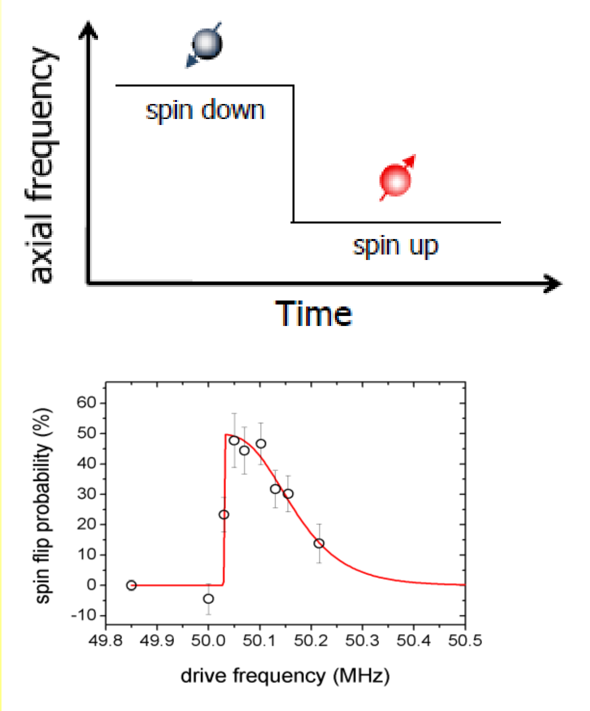
This term adds a spin dependent quadratic axial potential -> Axial frequency becomes function of spin state

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$



Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement



S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Single Penning trap method is limited to the p.p.m. level

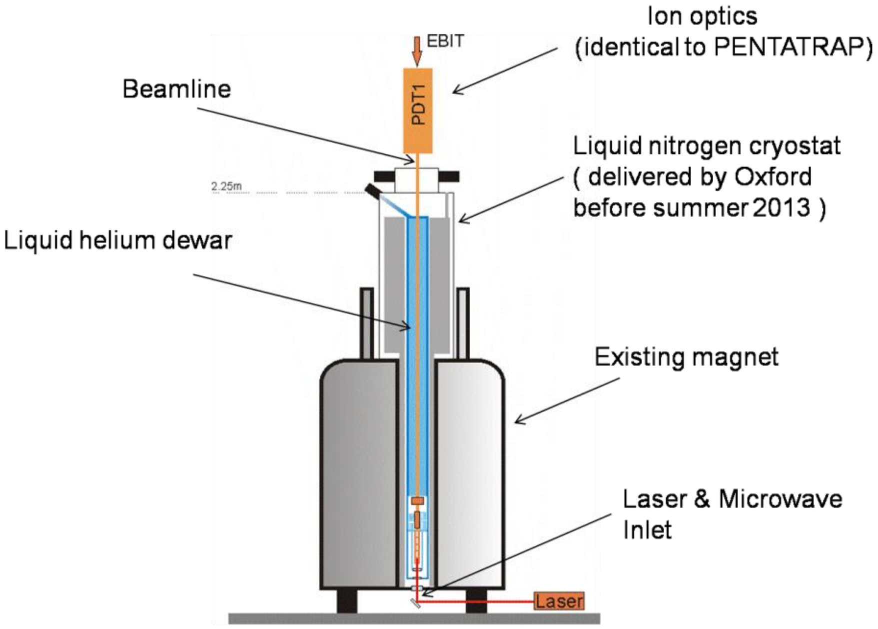
The Penning Trap – Ingredients

Some basic homework

- Typical ingredients of Penning trap experiments
  - Stable and homogeneous superconducting solenoid
  - Precisely machined trap electrodes
  - RF electronics
  - Ultra stable power supplies
  - Most of the high-precision experiments are operated under cryogenic conditions.
  - Cryogenic operation -> good vacuum

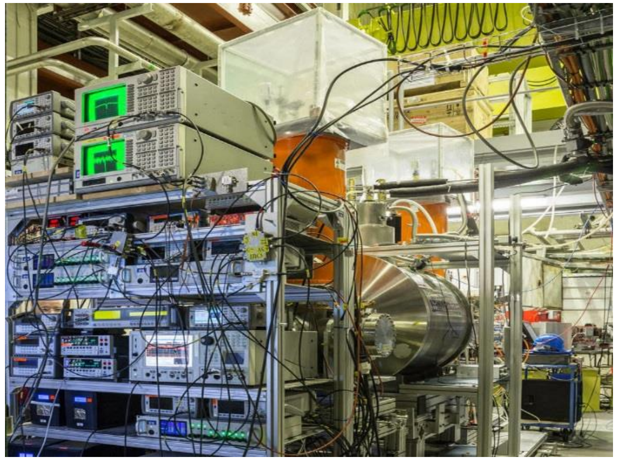
- Centre of a good magnet

Paramter	Value
dB/dt	$< 10^{-11}$/h
B1	< mT/m (NMR shimming limit)
B2	< 0.5 T/m^2 (NMR shimming limit)



HCI experiment at University of Mainz

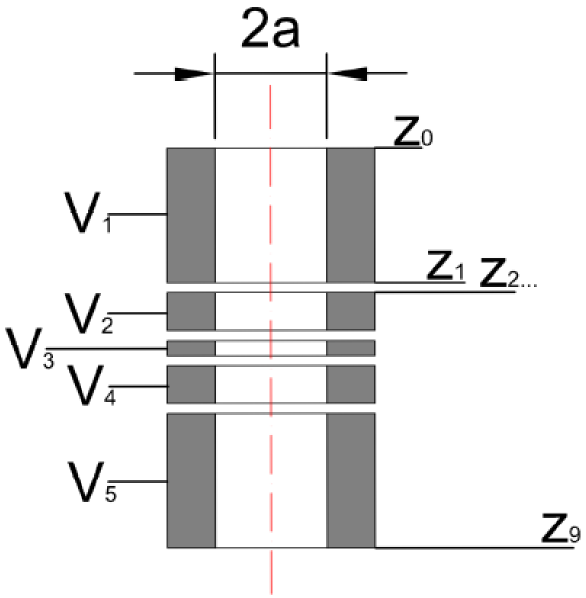
Sturm / Blaum / Quint / Werth



Supplies-rack of CERN’s BASE experiment

Ulmer / Mooser / Smorra

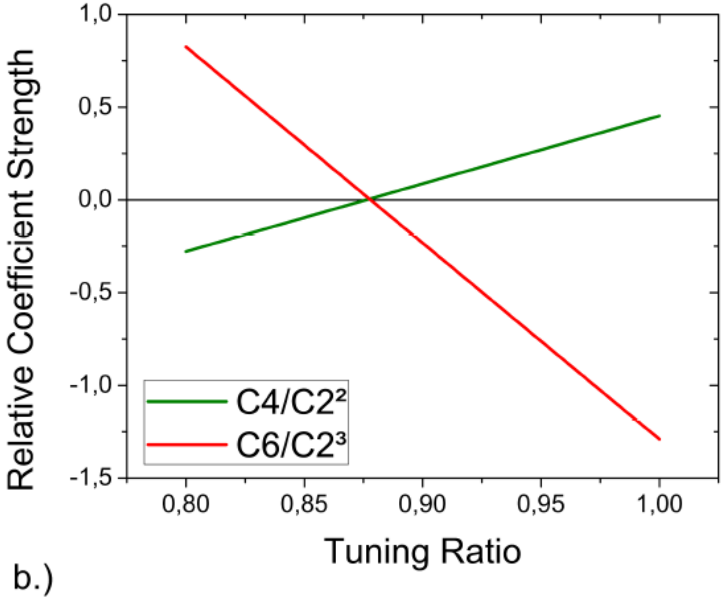
Cylindrical Trap Design

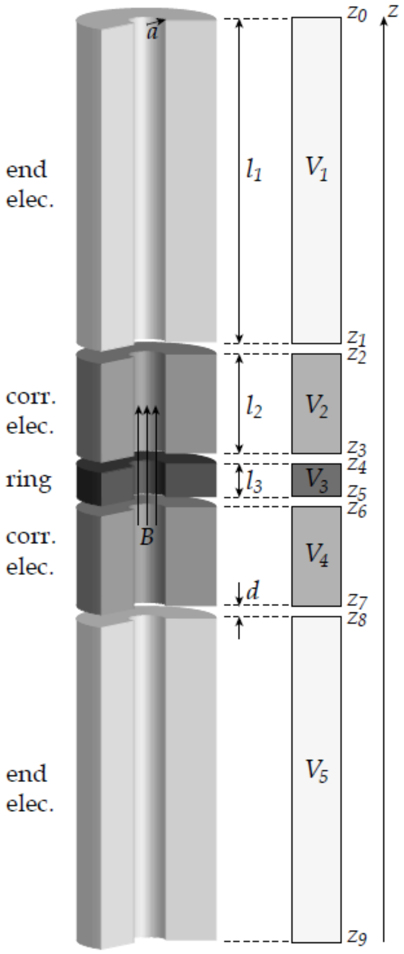


1.) C4 = 0
2.) C6 = 0
3.) orthogonality

Degrees of freedom for defined radius:

1.) Length of ring electrode
2.) Length of correction electrode
3.) Compensation/Ring voltage

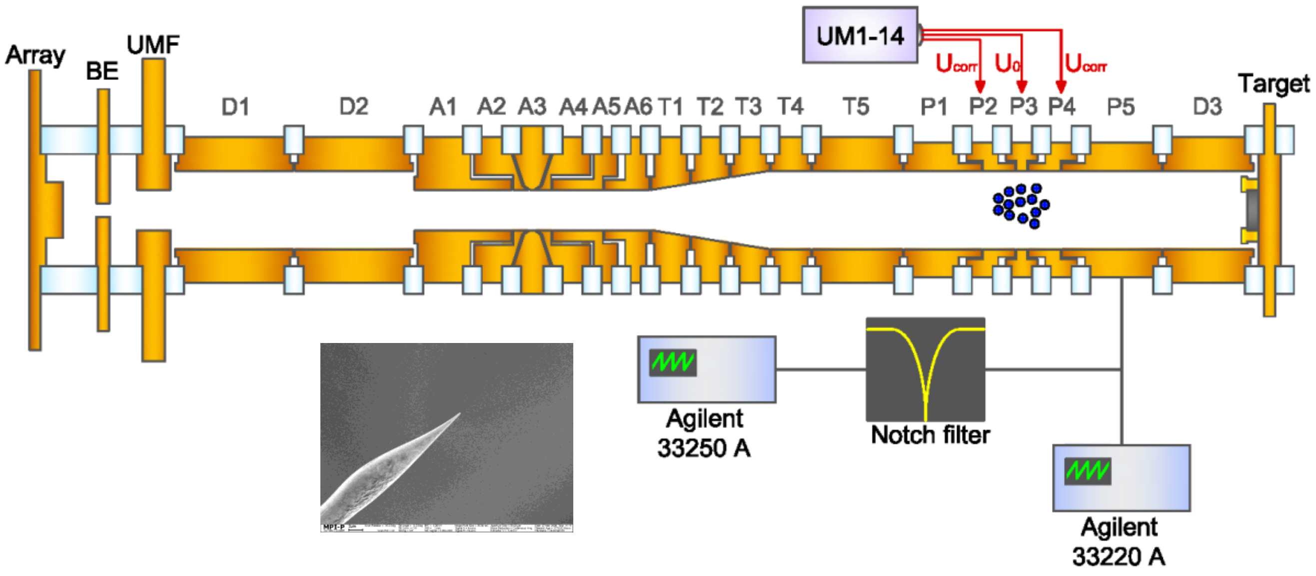


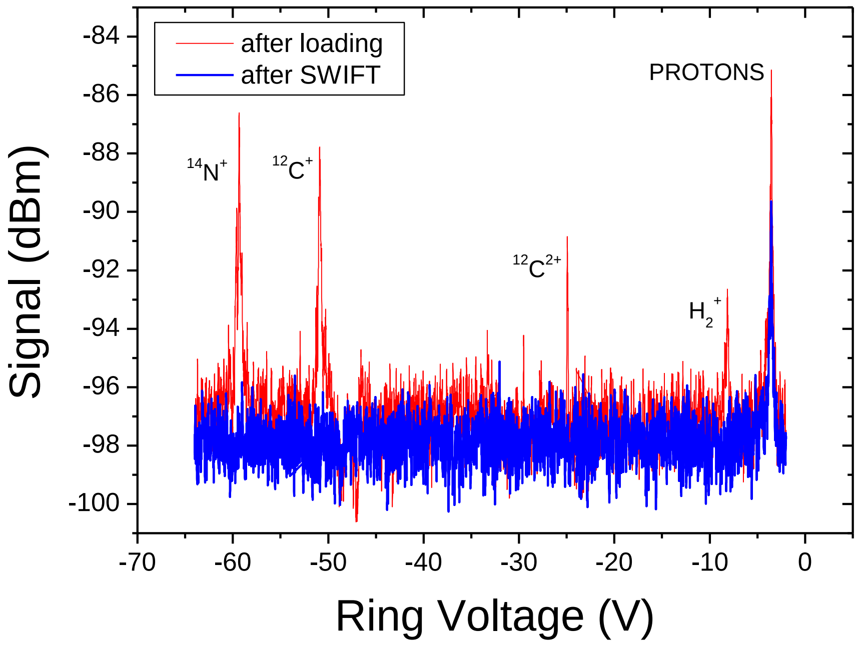


easy to understand / simple to optimize / easy to machine

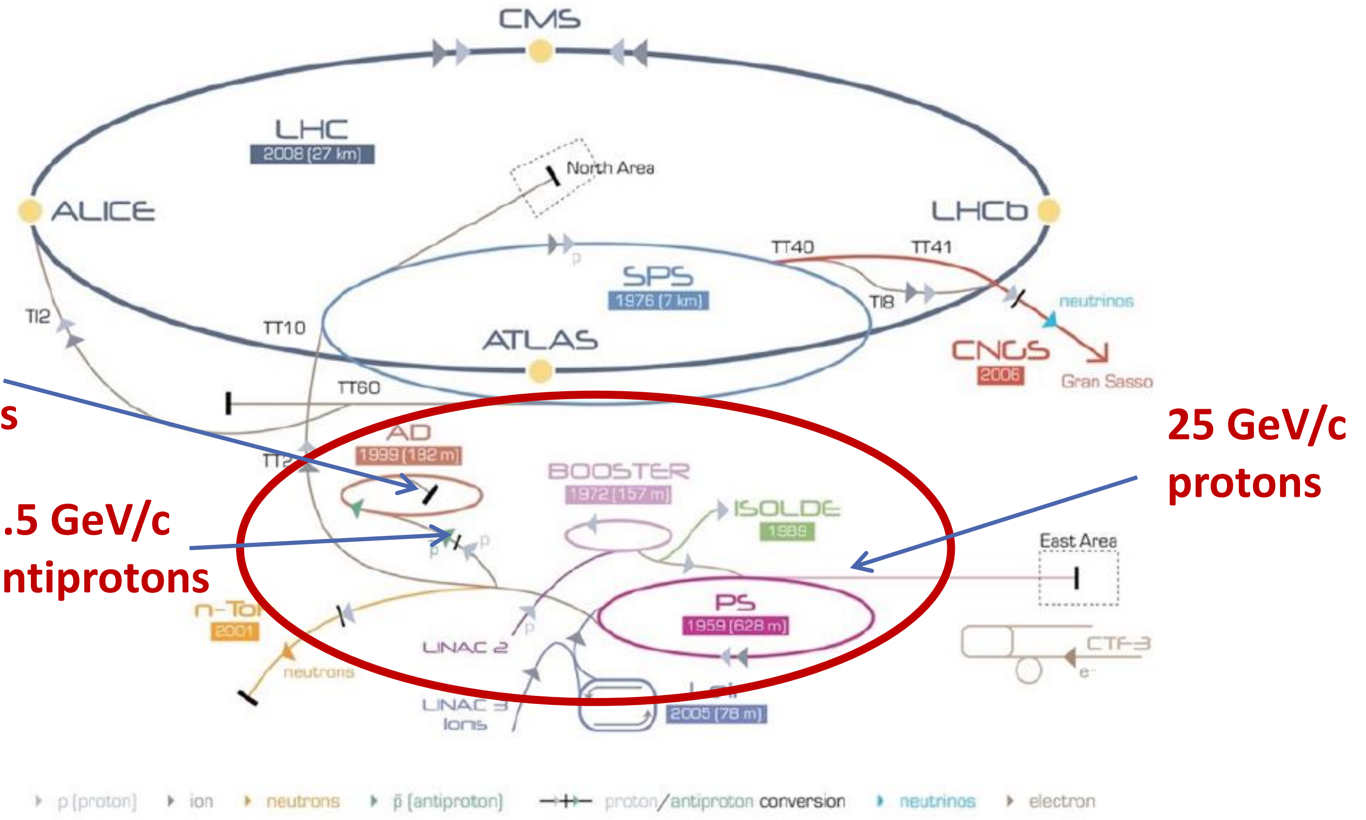
Particle Loading – Matter (here protons)

- In-trap creation by bombarding an appropriate target with an electron beam





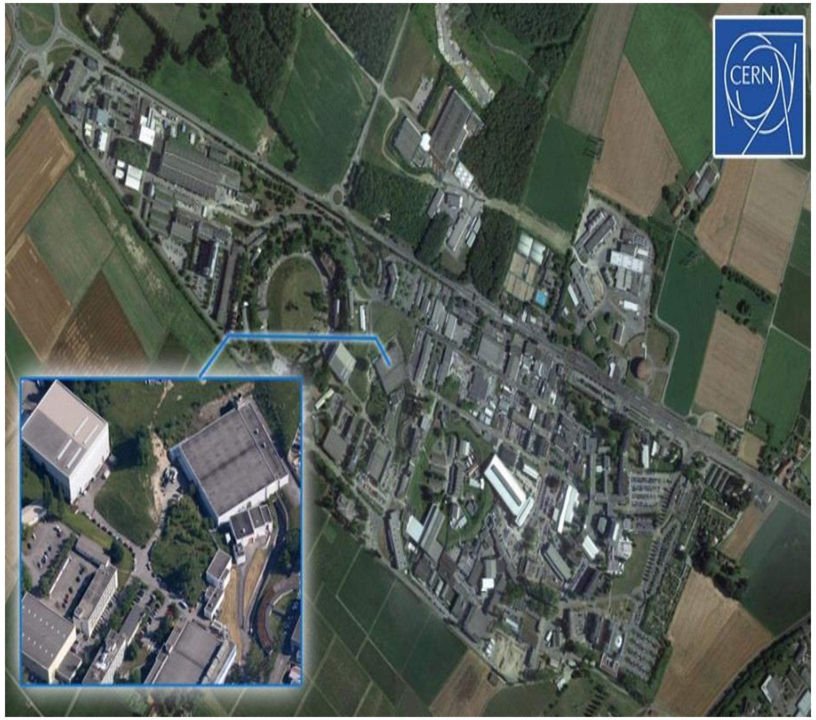
Particle Loading - Antiprotons



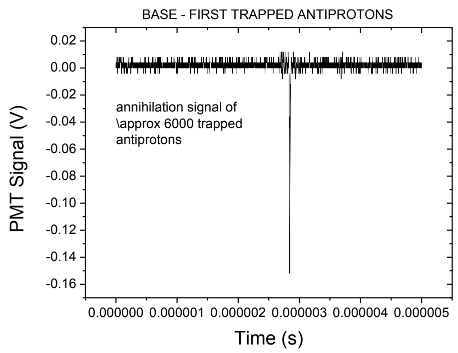
5.3 MeV antiprotons

3.5 GeV/c antiprotons

25 GeV/c protons



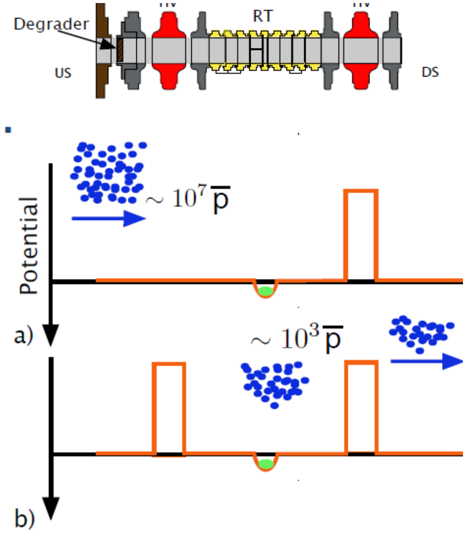
-> Degrader -> 1keV

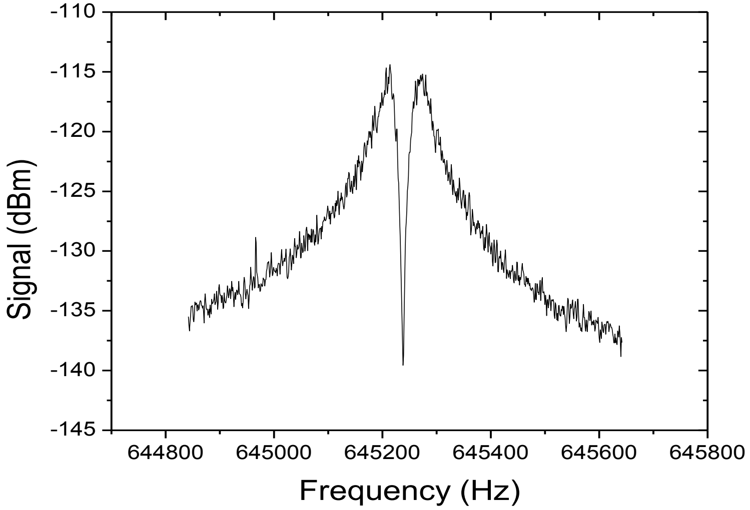


Particles in the trap, what's next?

Electron Cooling / Electron Kickout

- Idea: Store antiprotons and electrons in the same trap volume
- Coulomb interaction -> electrons cool fast due to cyclotron radiation
- Obtain a cold cloud of antiprotons
- Get rid of electrons…



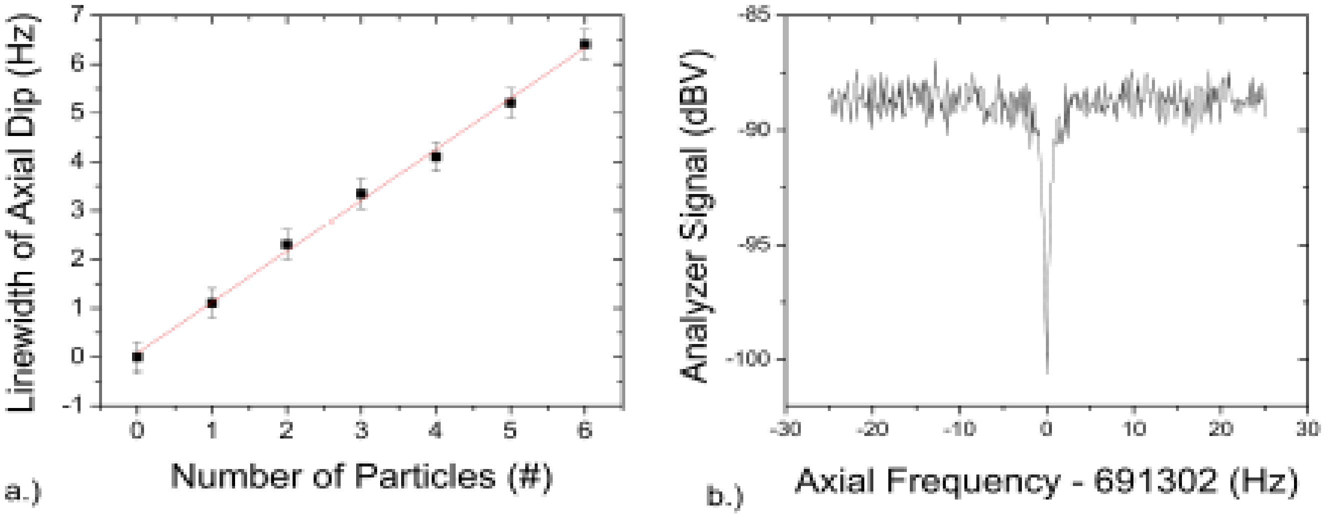


Cold particles in the trap, what's next?

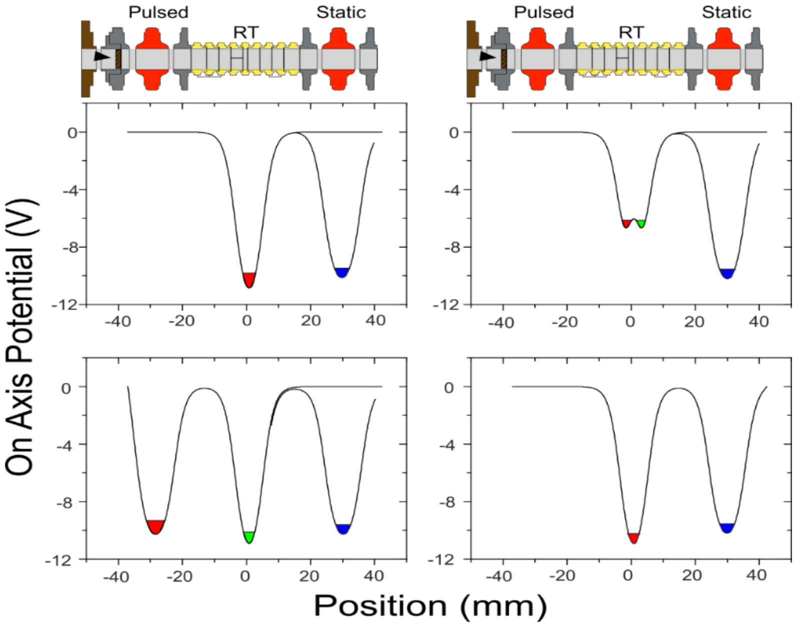
Preparation of a Single Particle

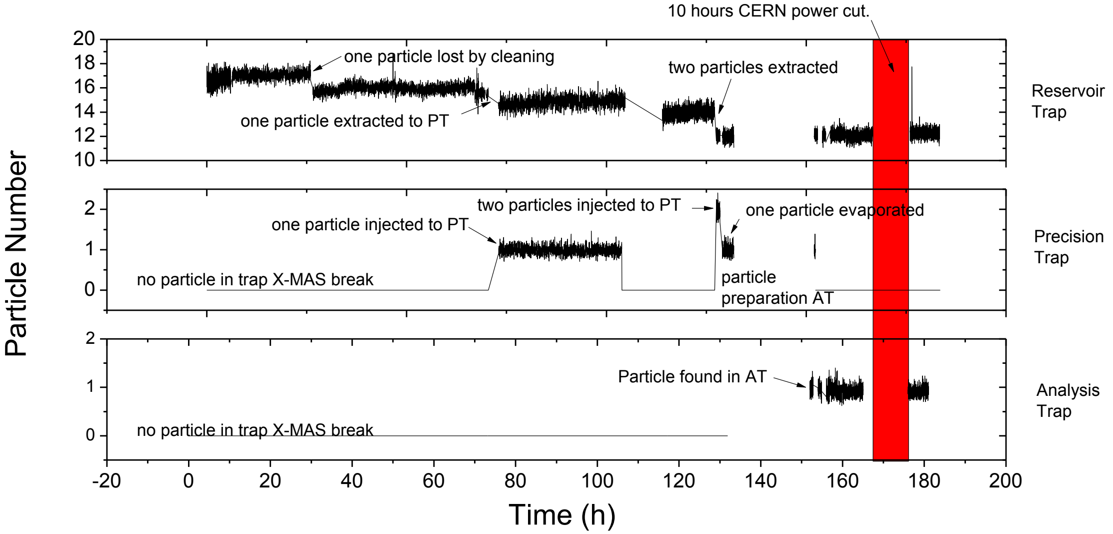
- Evaporation:

$$\Delta\nu_z(N) = \frac{N}{2\pi}\frac{R_p}{m}\left(\frac{q}{D_{eff}}\right)^2$$



- Single particle extraction by trap potential manipulation:





C. Smorra, Int. Journ. Mass. Spec (2015)

Sideband Coupling/Cooling

- Application of a quadrupolar drive at sum or difference frequency of two involved modes:

$$\vec{E}\left(x_i, x_k\right) = \mathrm{Re}\left(E_0 \exp\left(i\omega_{\mathrm{rf}}t\right)\right)\boxed{\left(x_i\vec{e}_k + x_k\vec{e}_i\right)} \xrightarrow{\text{coupled system}}$$

$$\begin{aligned} \imath\hbar\frac{d}{dt}a_z(t) &= \hbar\omega_z a_z(t) + \hbar g \exp\left(-\imath\omega_d t\right) a_-(t) \\ \imath\hbar\frac{d}{dt}a_-(t) &= -\hbar\omega_- a_-(t) + \hbar g \exp\left(\imath\omega_d t\right) a_z(t) \end{aligned}$$

important coupling

practically applied by injecting rf on segmented, rf-blocked electrodes

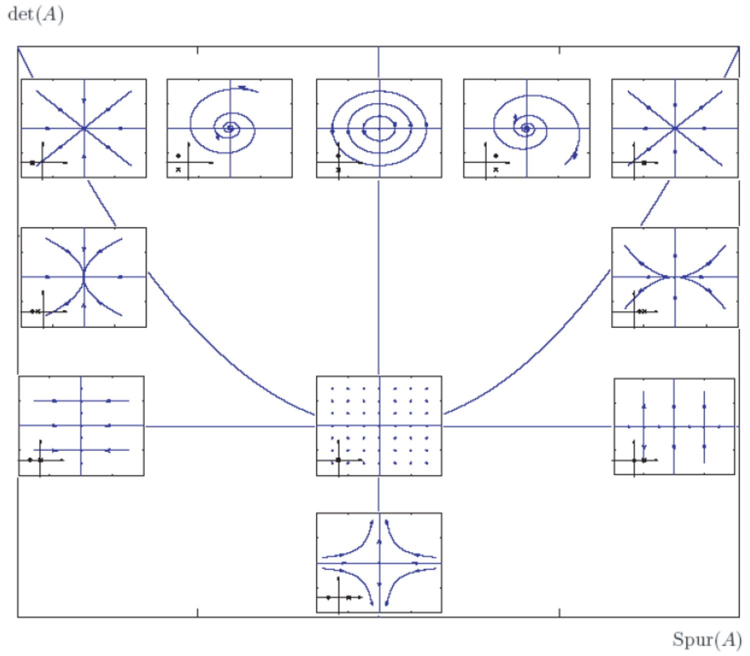
- Rotating wave approximation

$$\begin{aligned} \frac{d}{dt}\begin{pmatrix} b_z \\ b_- \end{pmatrix} = &- \frac{\imath}{2}\left(\omega_z - \omega_-\right)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} b_z \\ b_- \end{pmatrix} \\ &- \boxed{\frac{\imath}{2}\begin{pmatrix} -\delta & 2g \\ 2g & \delta \end{pmatrix}}\begin{pmatrix} b_z \\ b_- \end{pmatrix} \end{aligned}$$

coherent TRACELESS system at complex eigenvalues

- Diagonalization

$$\frac{d}{dt}\begin{pmatrix} \tilde{b}_z \\ \tilde{b}_- \end{pmatrix} = -\frac{i}{2}\begin{pmatrix} \omega_z - \omega_- + \Omega & 0 \\ 0 & \omega_z - \omega_- - \Omega \end{pmatrix}\begin{pmatrix} \tilde{b}_z \\ \tilde{b}_- \end{pmatrix}$$



Examples: Sideband Coupling

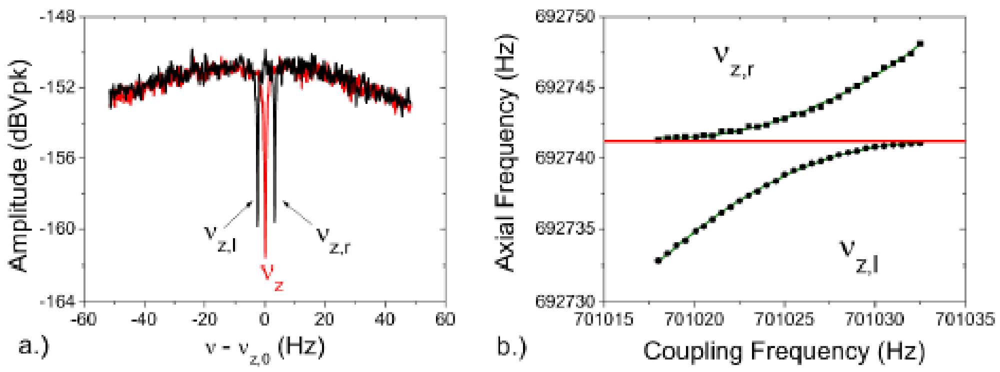
Effectively: Amplitude modulation of particle motion

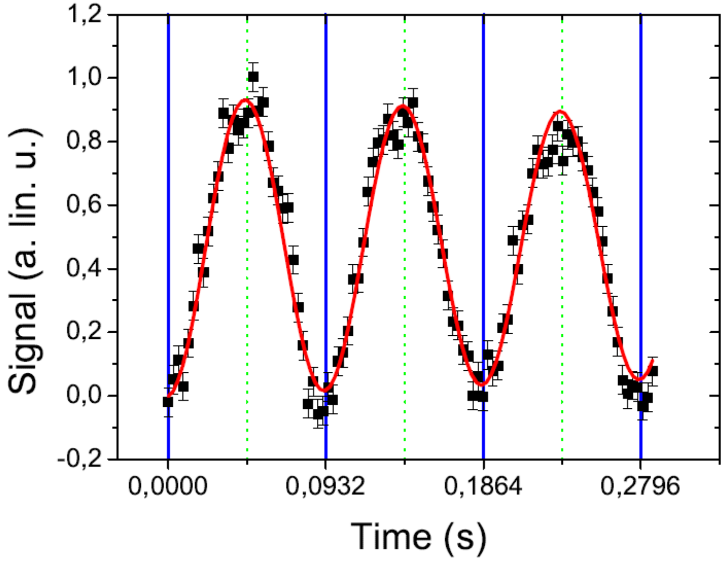
$$z(t) = z_0 \cos\left(\frac{\Omega}{2}t\right)\sin(\omega_z t + \varphi_z)$$

Classical “Dressed states”

$$\nu_l = \nu_z - \frac{\delta}{2} - \frac{\Omega}{4\pi} \qquad \nu_r = \nu_z - \frac{\delta}{2} + \frac{\Omega}{4\pi}$$

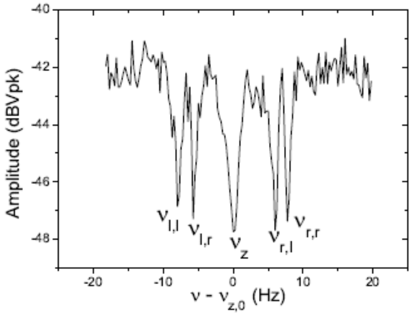
practically nothing else but the FFT of an amplitude modulated signal





$$\nu_l + \nu_r = \nu_z + \nu_{rf} - \nu_\pm$$

widely used to measure temperature of the radial modes.



also useful for efficient cooling of radial modes

S. Ulmer *et al.* **Phys. Rev. Lett** 107, 130005 (2011)

Temperature in Sideband Cooling

- Sideband cooling -> dynamics in quantum states and cooling dynamics stops if $n_{+,-}=n_z$

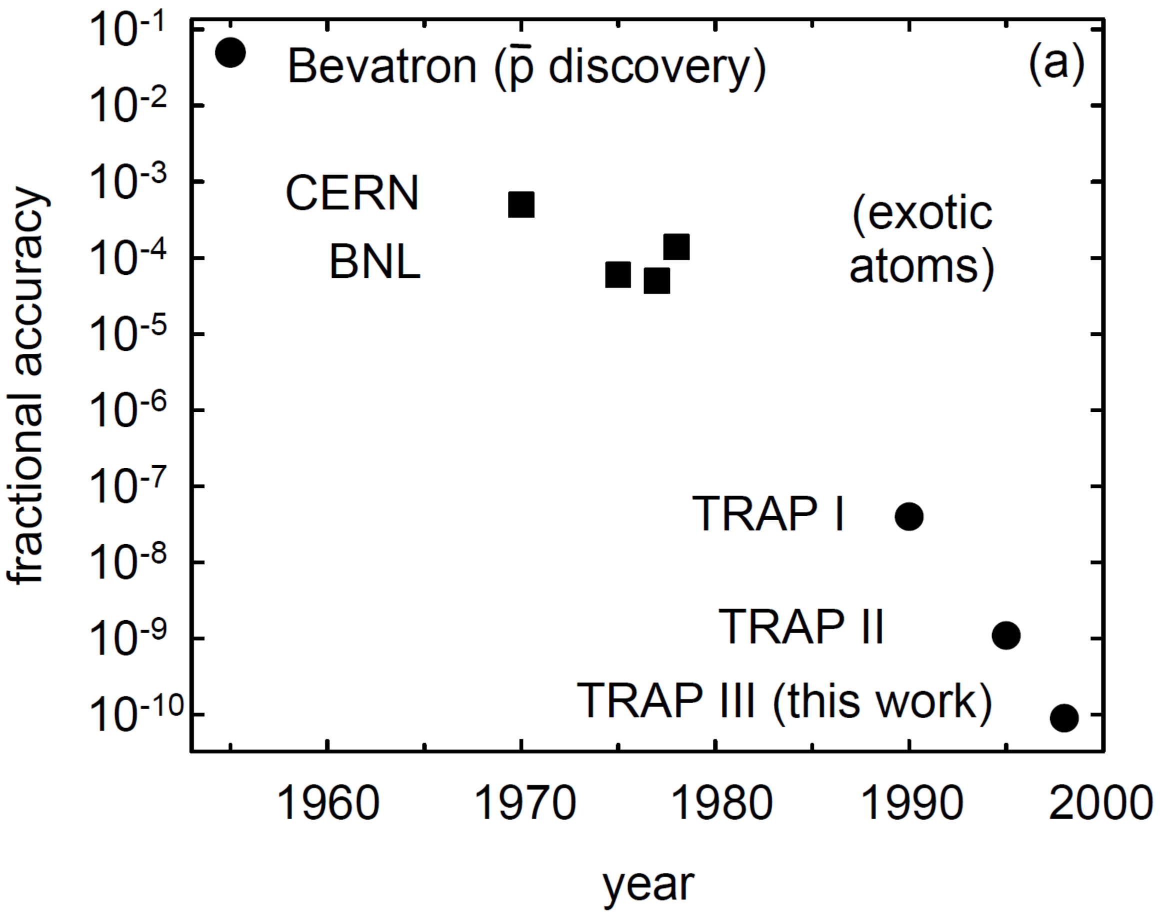
- Cooling Limit:

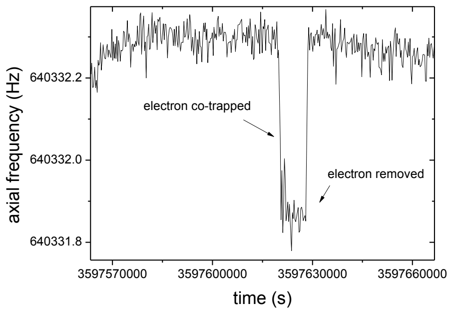
$$\frac{T_+}{T_z} = \frac{< E_+ >}{< E_z >} = \frac{\nu_+}{\nu_z} \qquad \frac{T_-}{T_z} = \frac{< |E_-| >}{< E_z >} = \frac{\nu_-}{\nu_z}$$

EXPERIMENTS – Charge to Mass Ratios

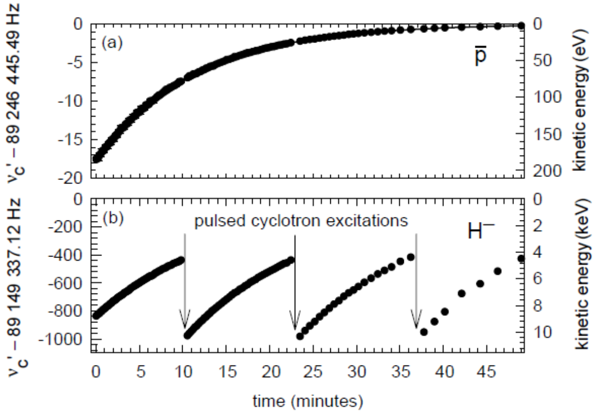
Results of proton/antiproton mass comparisons

Historical measurements for current antimatter physics program

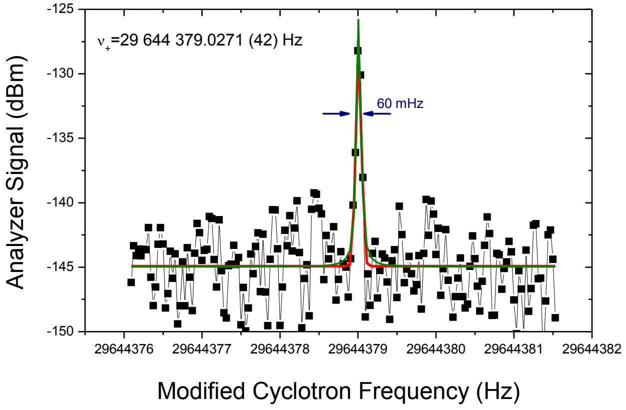




Progress ???



[J. Harrington et al., XXX **XX**, (201X)]<



Limitations of 1995 measurement and last factor of 10 improvement?

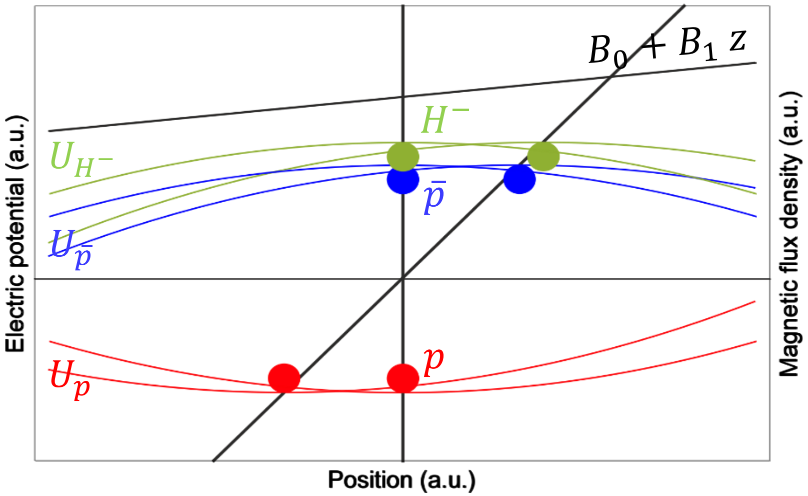
[G. Gabrielse et al., PRL **82**, 3198 (1999)]

Why would we want to use a hydrogen ion rather than a proton

- Slightly inhomogeneous magnetic field.
- Offset potentials on the electrodes of the cryogenic trap.

- Change of polarity leads to position shift of the particle.
- Systematic uncertainties due to the particle position are large (~10^{-9})

- For protons (polarity inversion (dV=10V)) much larger as for H- ions (dV=0.005V).



Take a ratio of measured cyclotron frequency of antiproton $\nu_{c\bar{p}}$ to H$^-$ ion ν_{cH^-} => reduces to antiproton to proton charge-to-mass ratio

Magnetic field cancels out!

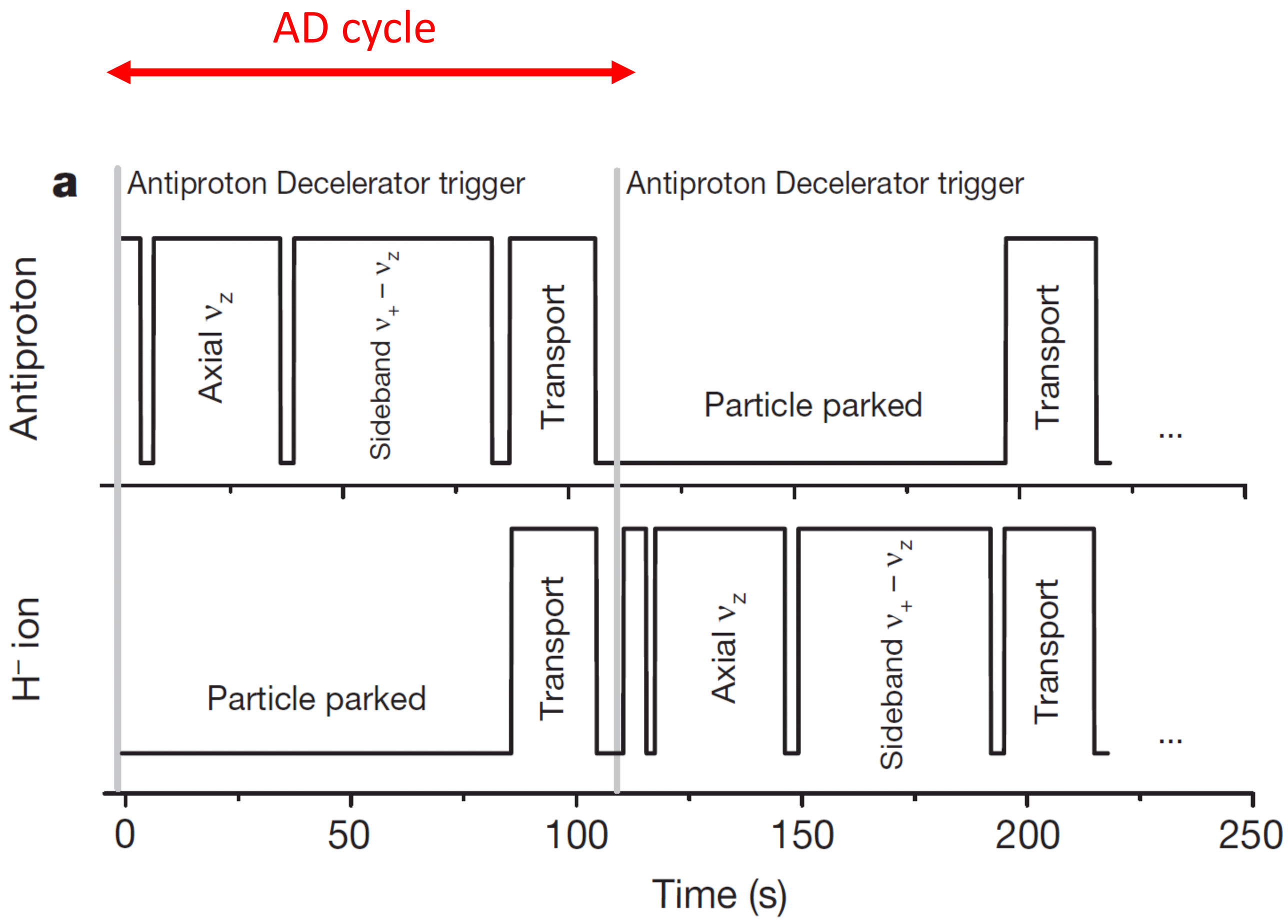
$$R = \frac{\nu_{c\bar{p}}}{\nu_{cH^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \text{x} \frac{\cancel{B/2\pi}}{\cancel{B/2\pi}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

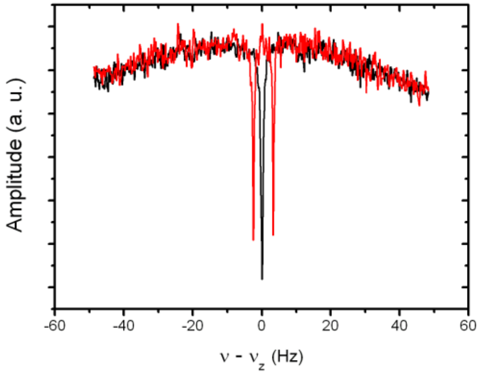
$$\boxed{m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-}\, B_0^2}{m_p}\right)}$$

$R_{theo} = 1.001\,089\,218\,754\,2(2)$

Measurement

$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$





$$\nu_l = \nu_z - \frac{\delta}{2} - \frac{\Omega}{4\pi}$$

$$\nu_r = \nu_z - \frac{\delta}{2} + \frac{\Omega}{4\pi}$$

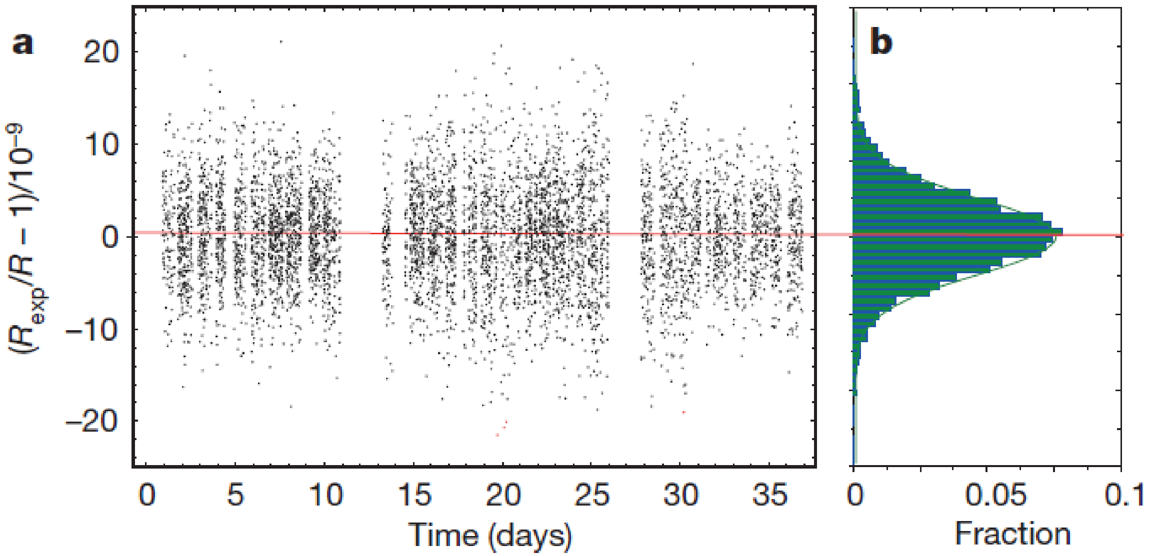
$$\nu_l + \nu_r = \nu_z + \nu_{rf} - \nu_\pm$$

Measurement cycle is triggered by the antiproton injection into the AD

One BASE charge-to-mass ratio measurement is by 50 times faster than achieved in previous proton/antiproton measurements.

First high-precision mass spectrometer which applies this fast shuttling technique

BASE Measurements – Proton to Antiproton Q/M



Result of 6500 proton/antiproton Q/M comparisons:

$R_{exp,c} = 1.001\ 089\ 218\ 755\ (64)\ (26)$

$$\boxed{\frac{(q/m)_{\bar{p}}}{(q/m)_p} - 1 = 1(69) \times 10^{-12}}$$

Most precise test of CPT invariance with Baryons.

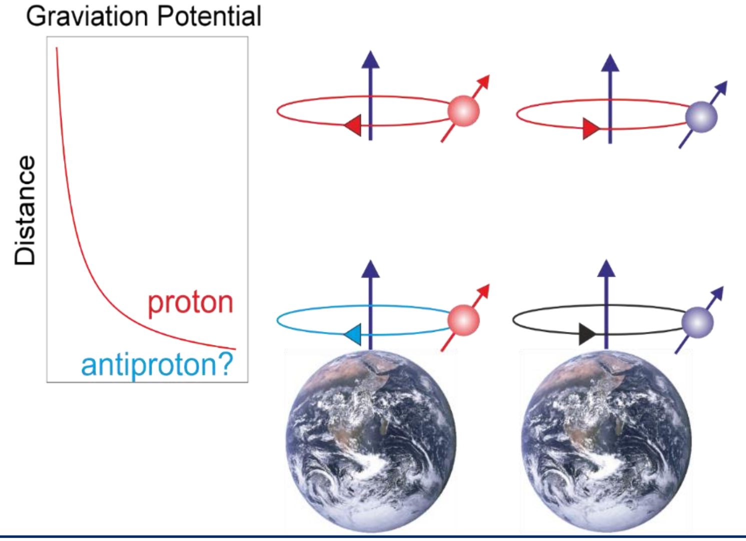
Consistent with CPT invariance

- Constrain of the gravitational anomaly for antiprotons:

$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\ U/c^2$$

Our 69ppt result sets a new upper limit of

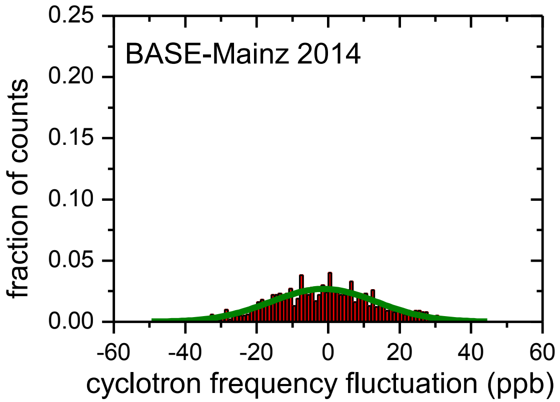
$$|\alpha_g - 1| < 8.7 \times 10^{-7}$$

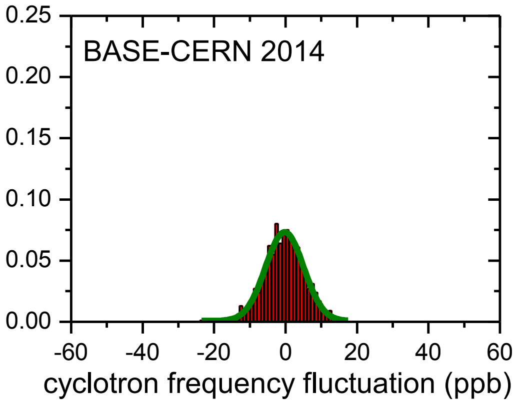


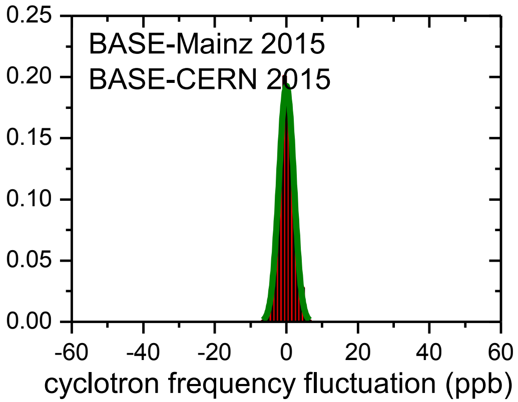
S. Ulmer et al., *Nature* **524** 196 (2015)

Example: Resolution Limit in BASE

- Sideband based magnetic field measurements:







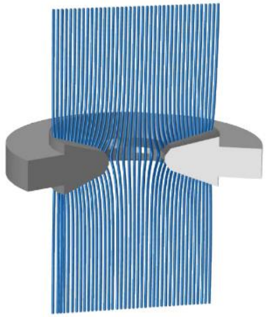
- Sideband measurement in presence of a magnetic field inhomogeneity
- Sideband measurement in homogeneous magnetic field, in presence of running accelerator
- Sideband measurement using a self shielding solenoid

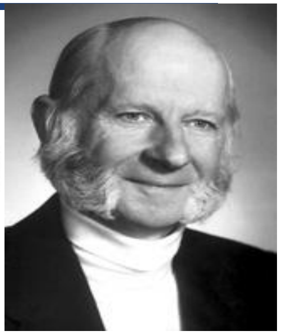
??? Physics understood ???

Further improvement by direct measurement methods

EXPERIMENTS – Magnetic Moments

Magnetic Moment Measurements





Measurement based on continuous Stern Gerlach effect.

Energy of magnetic dipole in magnetic field $\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$

Leading order magnetic field correction $B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$

This term adds a spin dependent quadratic axial potential
-> Axial frequency becomes function of spin state

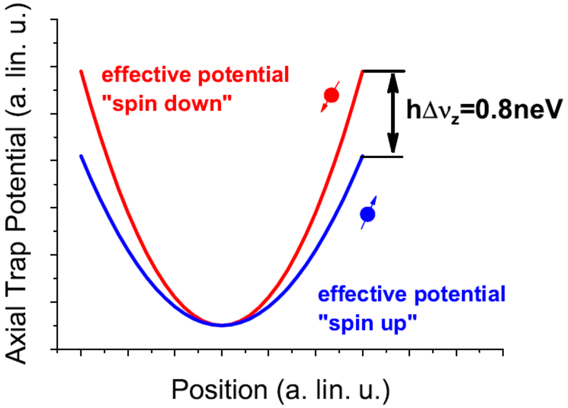
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

- Most extreme magnetic conditions ever applied to single particle.

$$\Delta\nu_z \sim 170\ mHz$$



Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

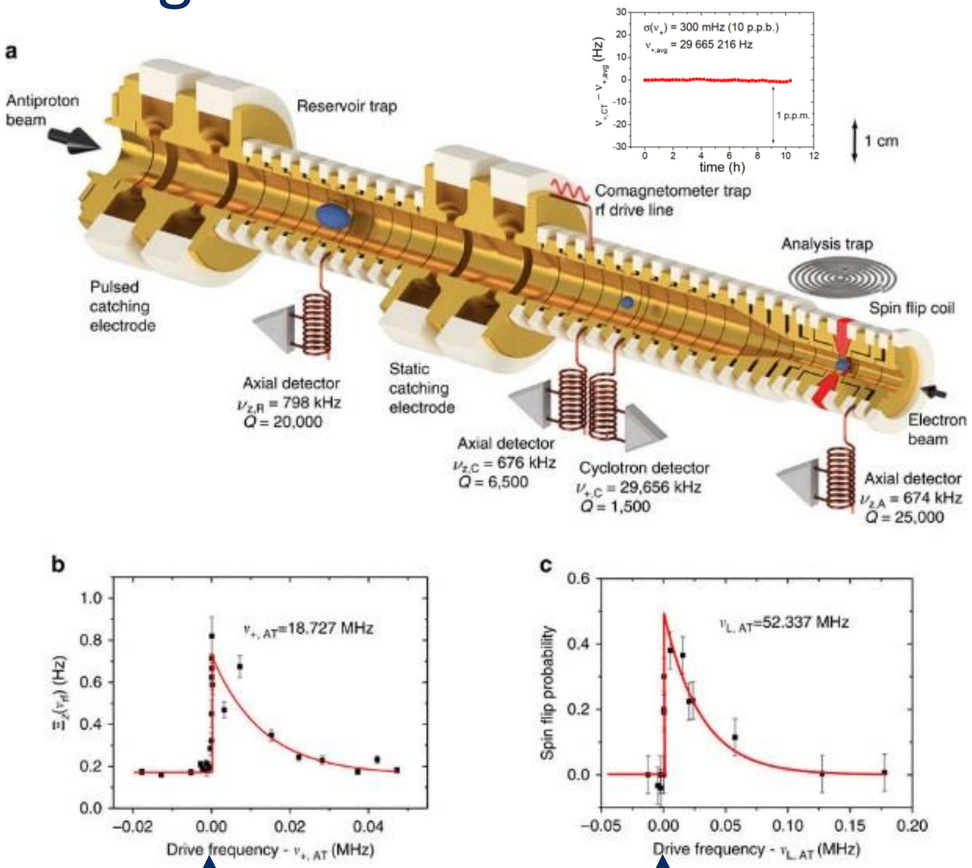
$$\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$$

$$B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$$

S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

0.8 p.p.m. Measurement

- co-magnetometer measurement

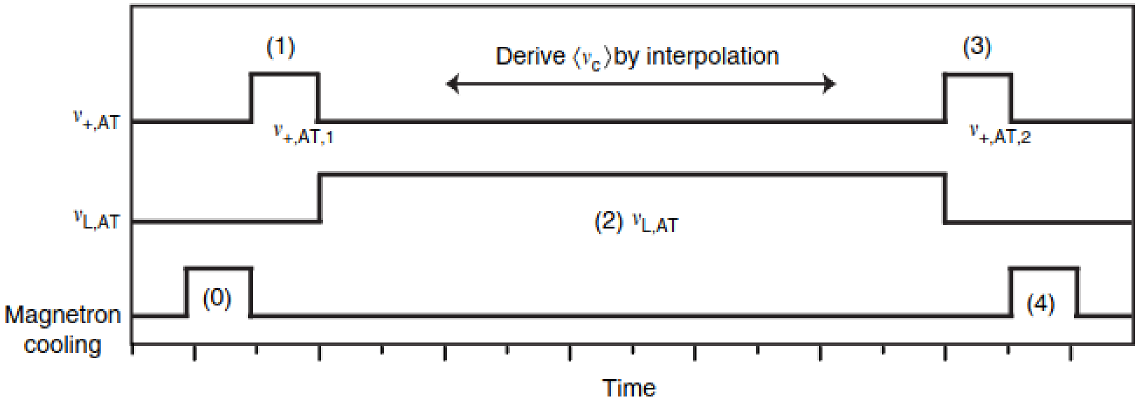


ν_c ν_L

task: resolve these two «cut» frequencies

$$\frac{g_{\bar{p}}}{2} = \frac{\nu_L}{\nu_c}$$

- single particle in the magnetic bottle
- measurement

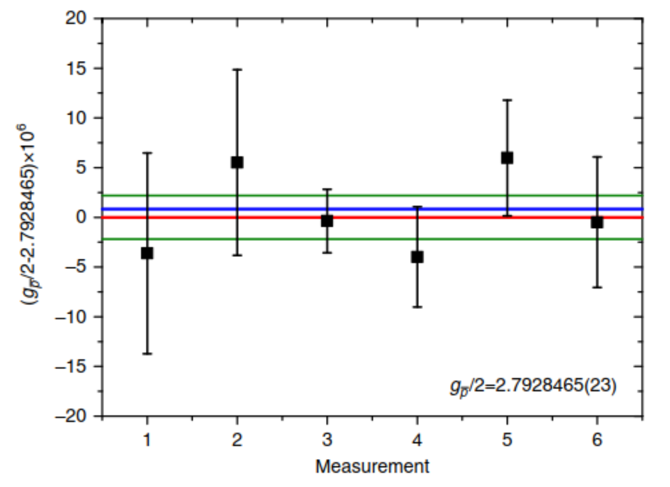


- evaluate g-factor
- repeated the scheme in total six times

Result and Limitations

Result

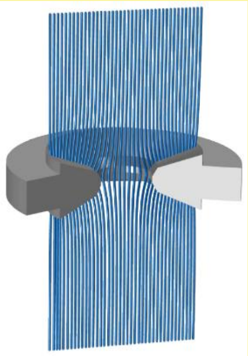
- from six independent g-factor measurements

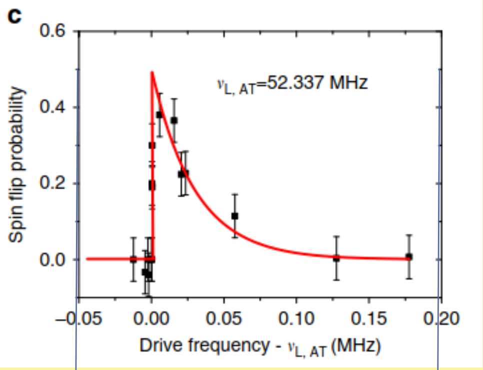


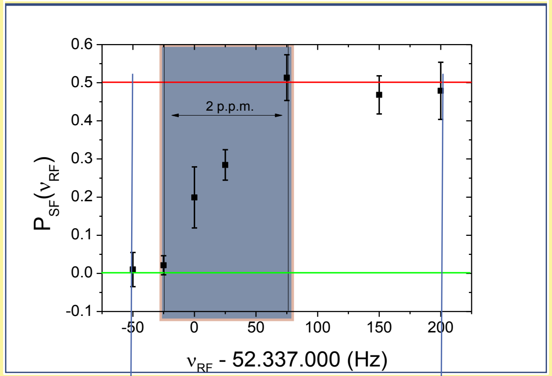
$$\frac{g_{\bar{p}}}{2} = 2.792\,846\,5\,(23)$$

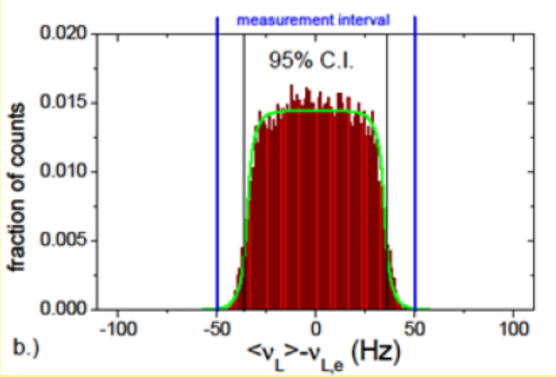
- noise driven random walk in the magnetron mode traces magnetic field.

$$\frac{d\nu_c}{\nu_c} = -\frac{1}{2\pi^2 m_{\bar{p}} \nu_z^2}\frac{B_2}{B_0}dE_- = \frac{5.2\ \mathrm{p.p.m.}}{\mu\mathrm{eV}}dE_-$$









250 kHz

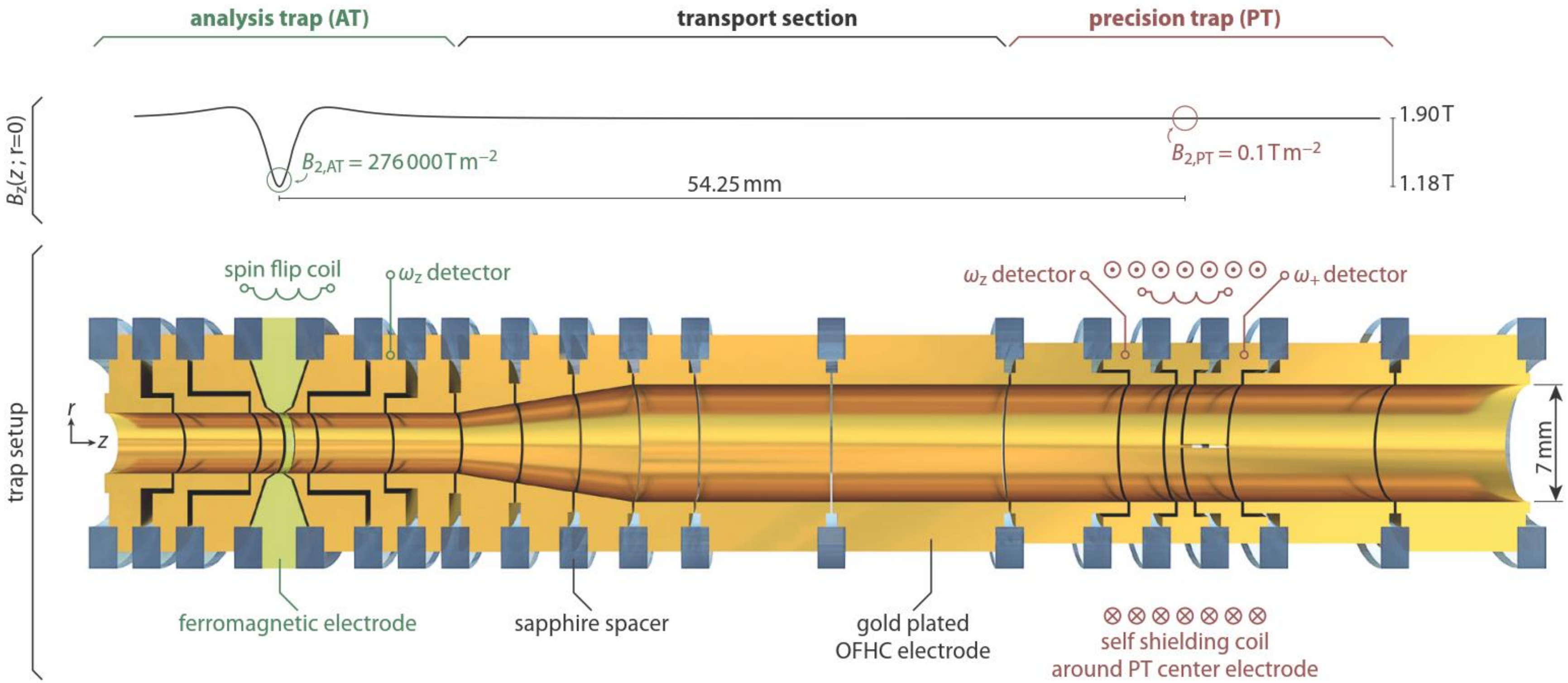
250 Hz

Ultimately limits g-factor measurement to the 1 p.p.m. to 0.1 p.p.m. level

Can we do better ?

- probably, by putting a lot of effort in we would be able to reach with the single-trap method the 0.1 p.p.m. - level.

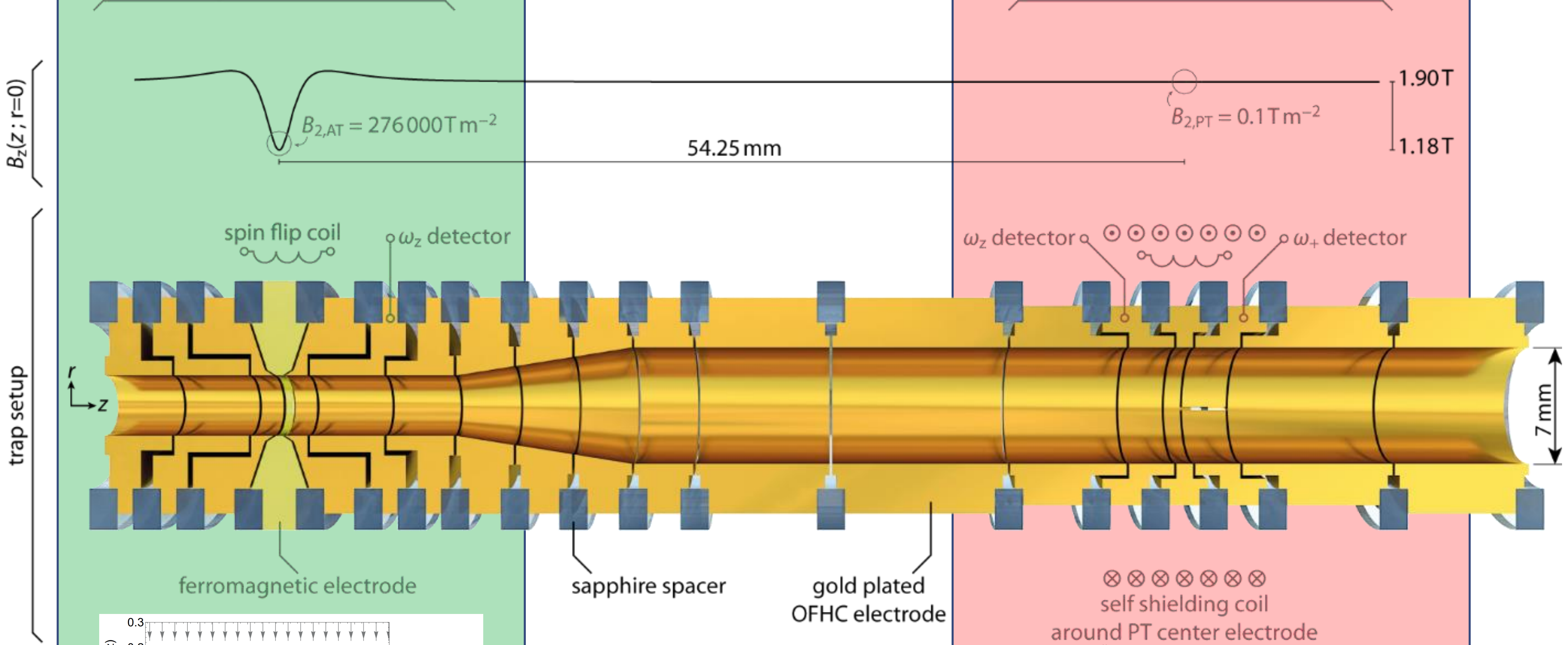
- apply alternative measurement schemes: **multi-trap methods**

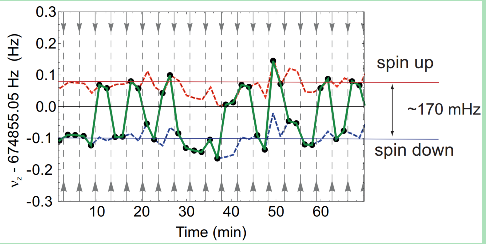


«Simplest»: The Double Penning-Trap Method

analysis trap (AT)

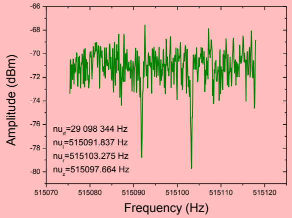
precision trap (PT)





inhomogeneous magnetic field for spin state analysis

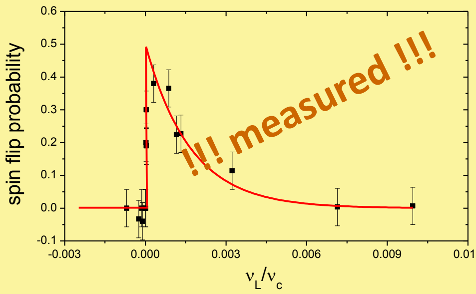
$$\boxed{\frac{B_{2,AT}}{B_{2,PT}} > 10^6}$$



homogeneous magnetic field for frequency measurements

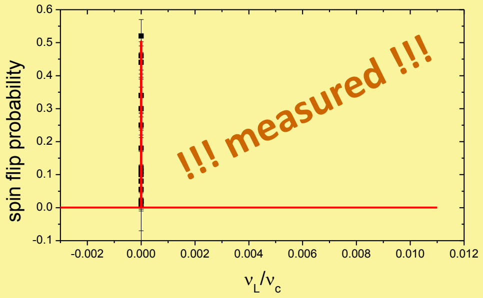
comparison

single-trap method

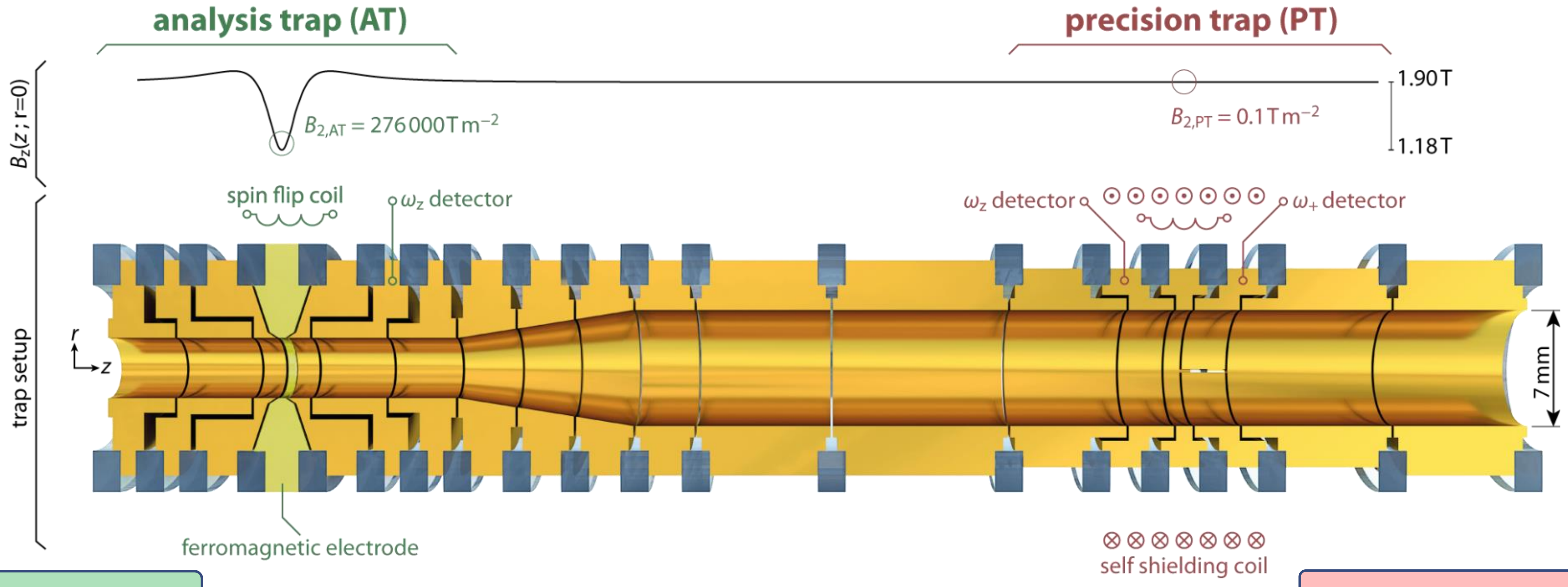


$$\boxed{\frac{B_{2,AT}}{B_{2,PT}} > 10^6}$$

multi-trap method



The Double Penning-Trap Method



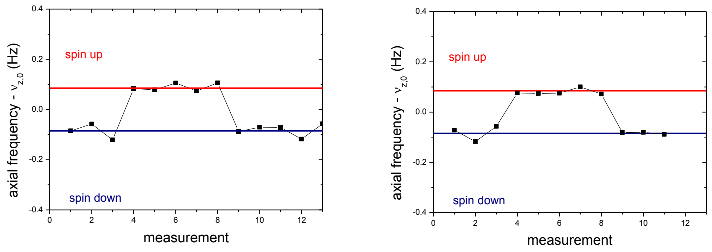
Initialize the spin state

particle transport

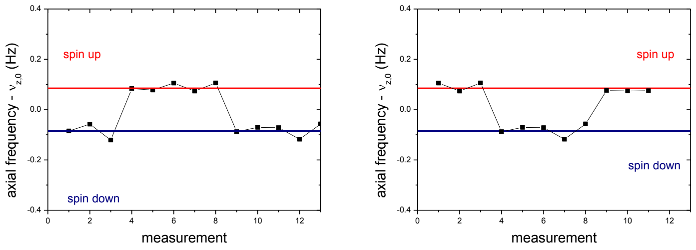
1.) measure cyclotron ν_c

2.) drive spin transition at ν_{rf}

analyze the spin state



no spin-flip in PT



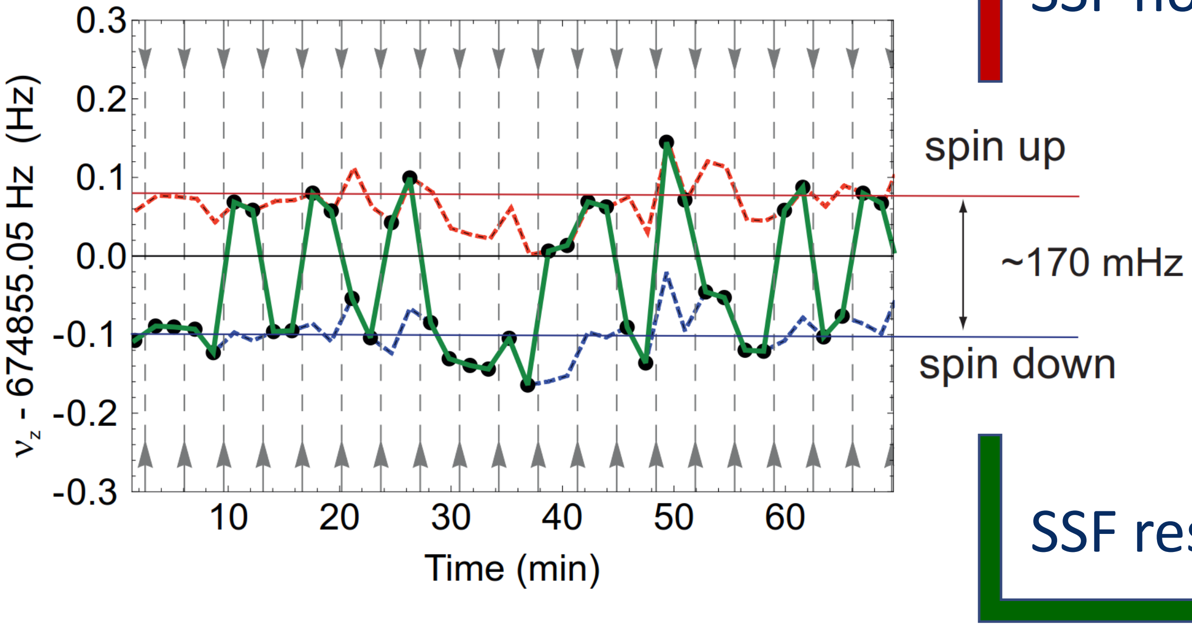
spin flipped in PT

measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap

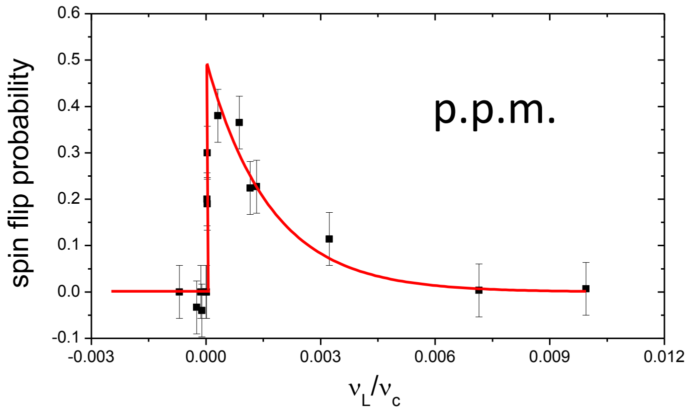
Challenges – High-Fidelity Single Spin-Flip Resolution

- To conclude in which quantum state the particle leaves / returns from precision trap, the double trap method requires **high-fidelity spin-state resolution**

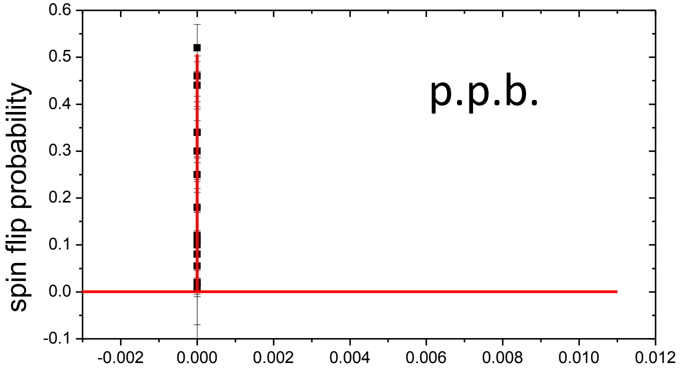
- this is the game changer...



SSF not resolved



SSF resolved



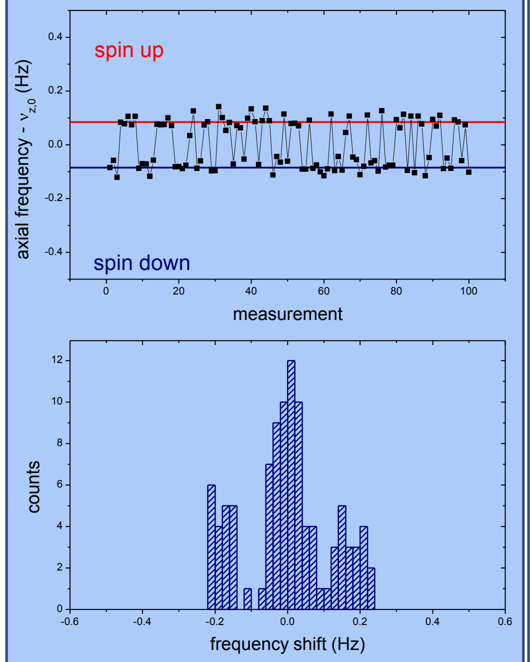
...where all the work is in...

resolving single antiproton spin flips is a challenge

Challenges – High-Fidelity Single Spin-Flip Resolution

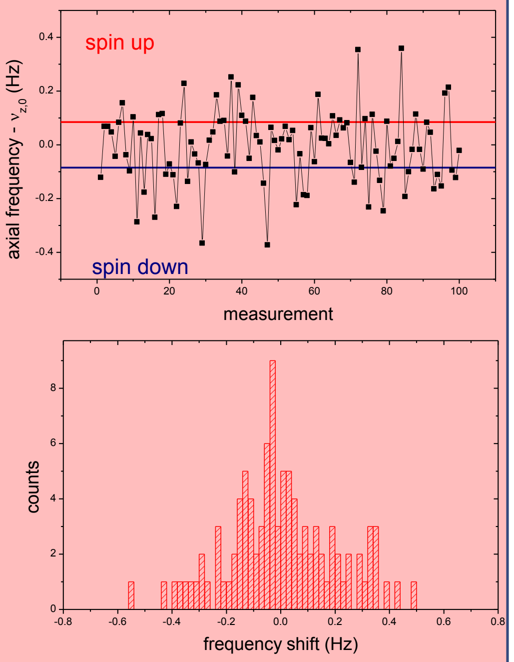
observation of antiproton spin transitions with high-fidelity requires ultra-cold particles

cold particle (50mK)



high-fidelity spin state resolution

hot particle (1K)



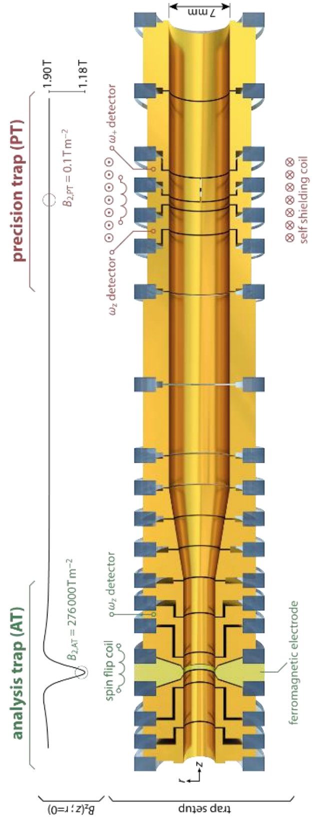
fidelity at 65%, not useful for measurements

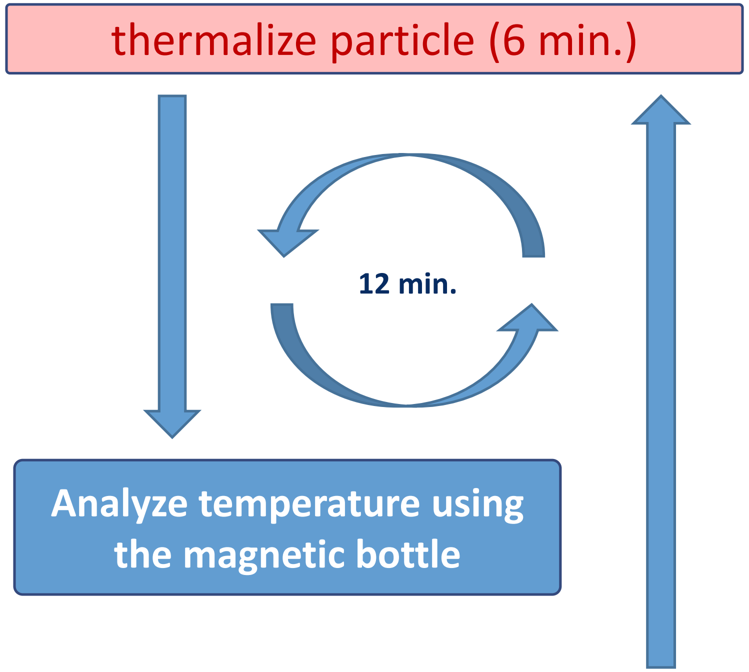
- Physics
  - heating by rf at a noise density of about $100\ \mathrm{pV}/\sqrt{\mathrm{Hz}}$ drive radial cyclotron quantum transitions.
  - transition rates scale with the cyclotron quantum number.

$$\frac{dn_{+,-}}{dt} \approx \frac{q^2}{2m_{\bar{p}}h\nu_{+,-}} \boxed{n_{+,-}} \Lambda^2 \langle e_n(t), e_n(t-\tau)\rangle$$

Sub-Thermal Cooling

- Cold particle is prepared by resistive cooling in the PT



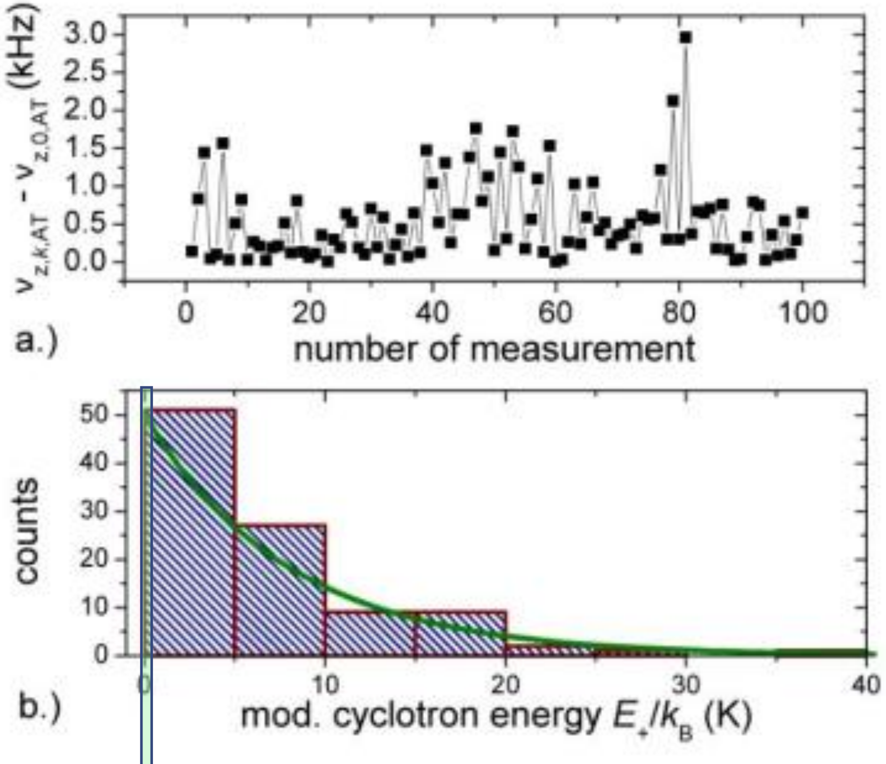


thermalize particle (6 min.)

Analyze temperature using the magnetic bottle

particle below threshold
-> **MEASURE**

particle above threshold

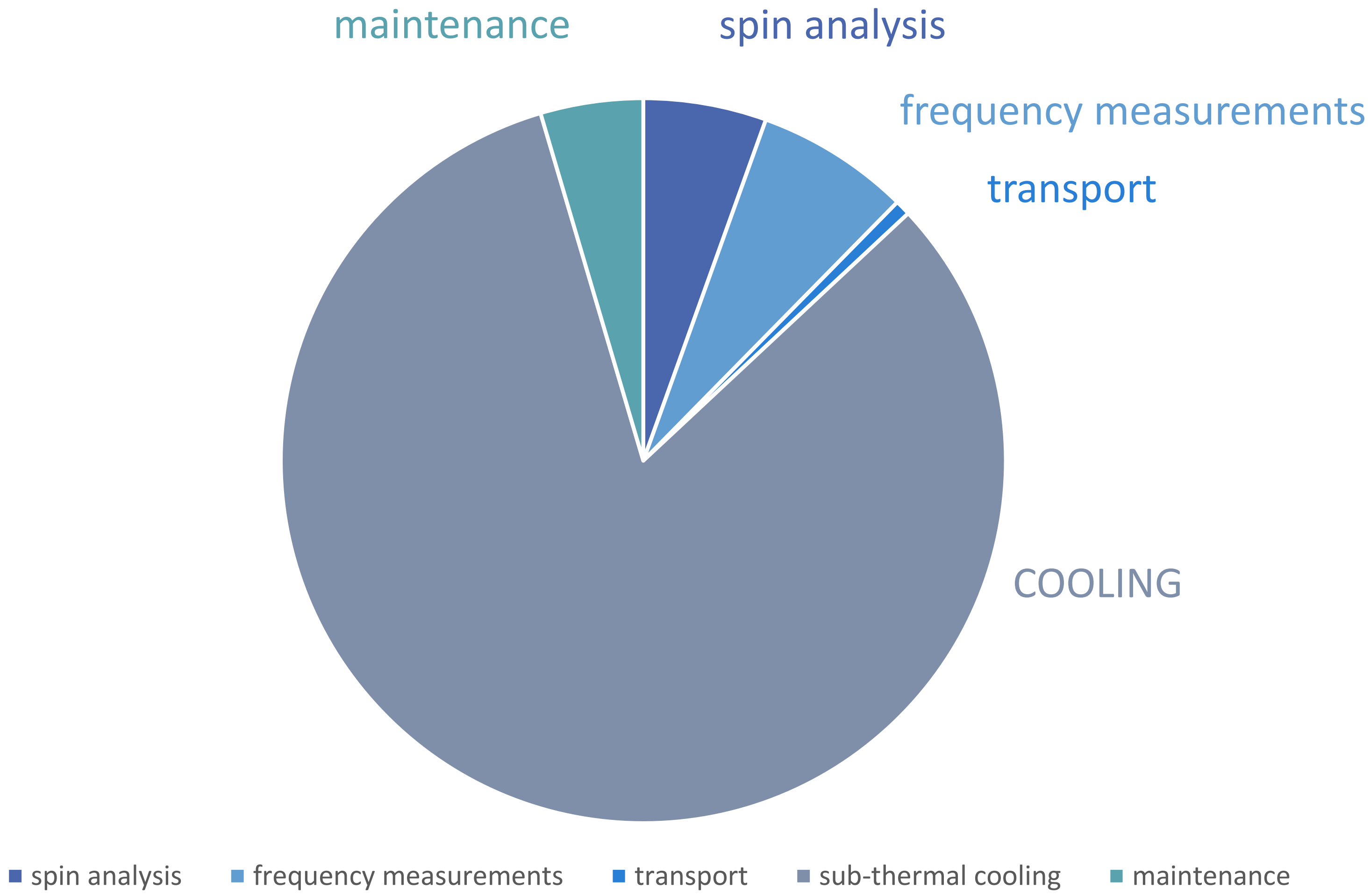


particles with single spin-flip resolution are in this temperature range

NOTE: each cyclotron frequency measurement heats the particle to about 300K

works (see BASE-Mainz measurements), but sub-thermal cooling is EXTREMELY time consuming

Current Time Budget of a (CERN) Double-Trap Experiment



Cooling is a problem

requires new ideas

multi-trap multi-particle methods

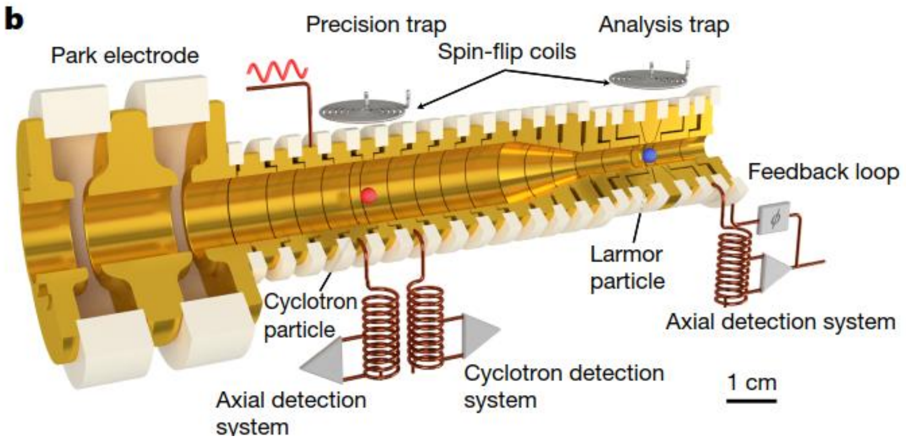
This talk

Sympathetic cooling of protons and antiprotons

MOOSER

BASE Two-Particle Method

Idea: divide measurement to two particles

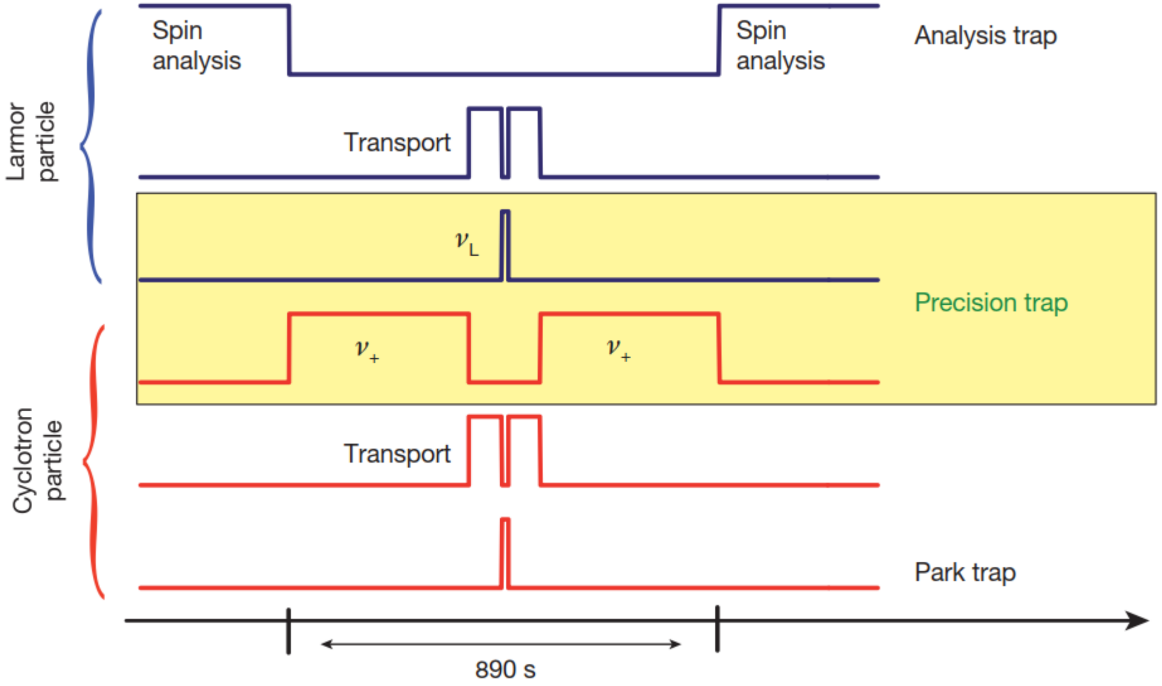


«hot» cyclotron particle which probes the magnetic field in the precision trap

«cold» cyclotron particle to flip and analyze the spin-eigenstate

pay: measure with two particles at different mode energies

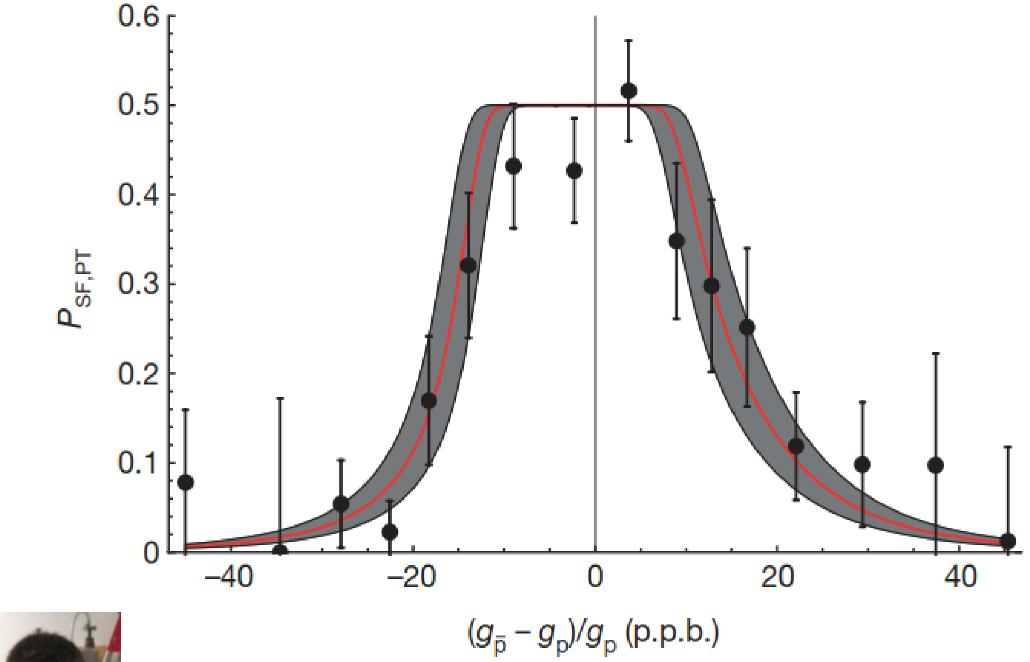
win: 60% of time usually used for sub-thermal cooling useable for measurements



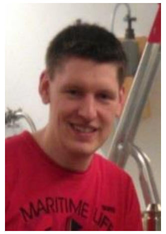
challenges:

- transport without heating
- more challenging systematics

The Magnetic Moment of the Antiproton



G. Schneider *et al.*, Science **358**, 1081 (2017)

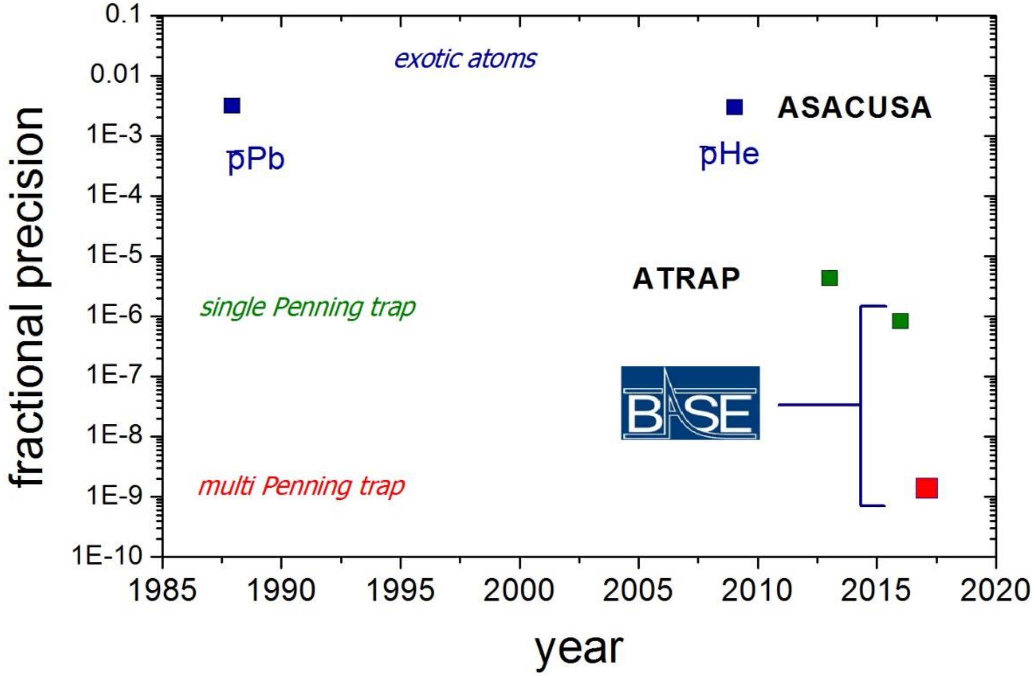


$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(82)$$

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

C. Smorra *et al.*, Nature **550**, 371 (2017)

BASE 2017: $\mu_{\bar{p}}$ = -2.792 847 344 1 (42) μ_{nucl}



first measurement more precise for antimatter than for matter...

...so how about the proton magnetic moment?

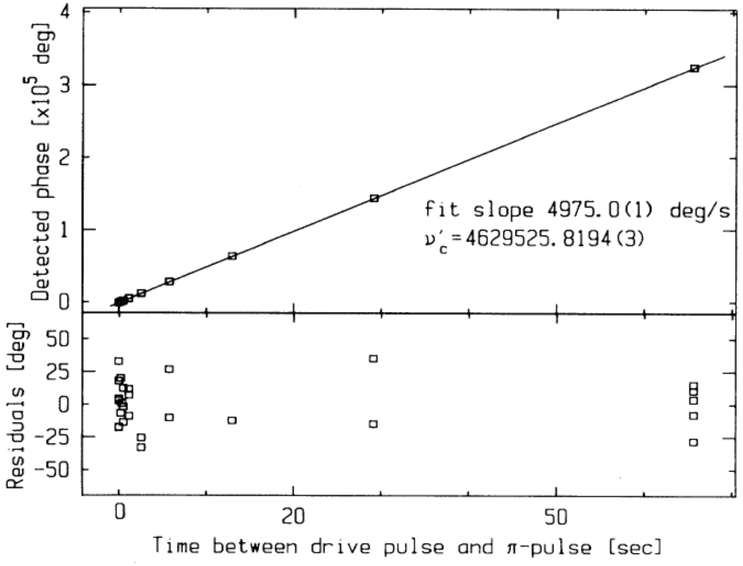
Thanks very much for your attention

Phase Sensitive Methods I

- prepare a **coherent cyclotron state** with well-defined phase:

$$\varphi(t) = 2\pi\, f_+ T + \varphi_0$$

- wait for certain evolution time
- Apply sideband pi-pulse and couple cyclotron energy to axial mode, which conserves the phase
- ...thus, imprints cyclotron phase to axial phase
- Measure for different evolution times and unwrap phase.

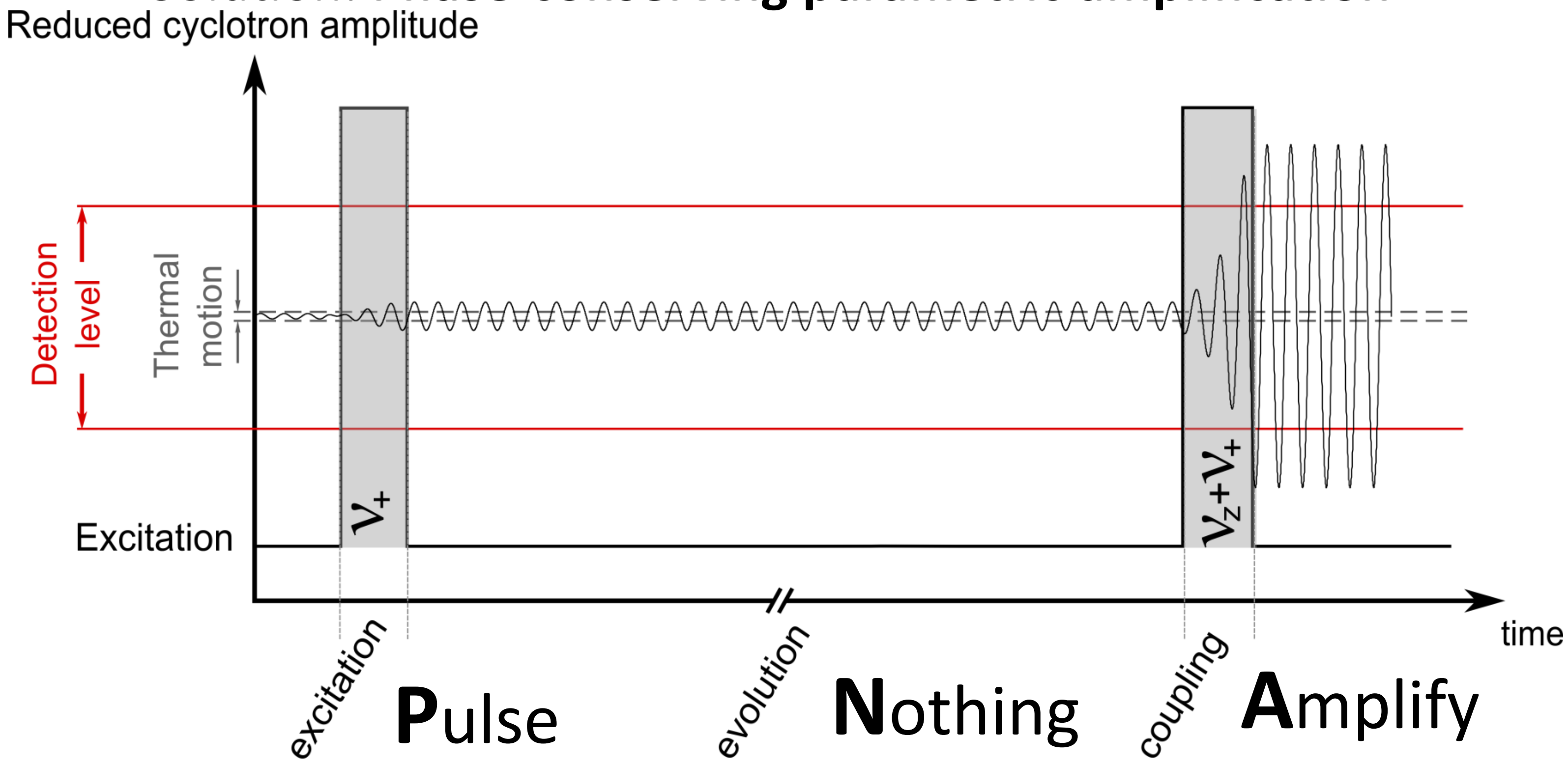


- Direct measurement of cyclotron frequency (more stable)
- BUT: Systematic error (special relativity, B_2) ~ r_+^2 !

D. Pritchard, J Thompson, S. Rainville, E.Cornell, E. Myers, M. Redshaw,…..many papers

P’n’A - Method

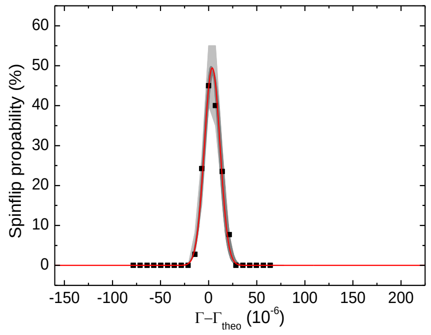
Solution: **Phase-conserving parametric amplification**

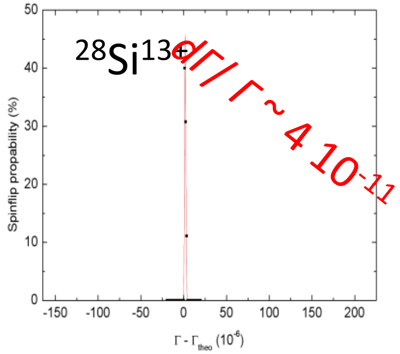


Pulse

Nothing

Amplify





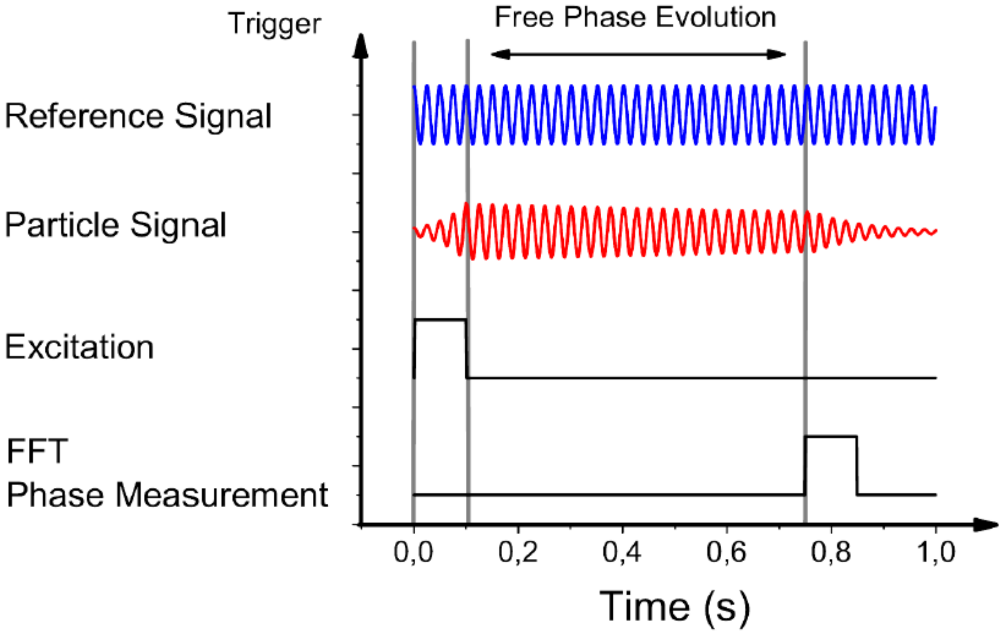
- E.g. applied in recently published most precise measurement of the electron mass.

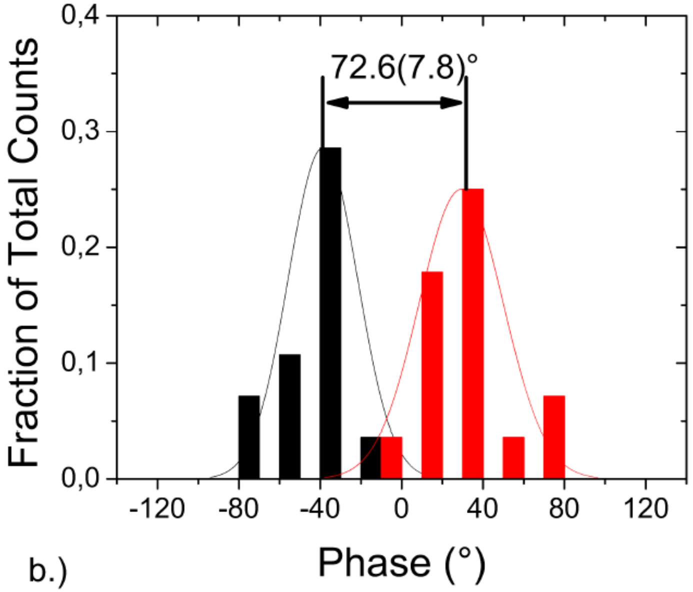
[S. Sturm et al., PRA **87**, 030501 (2013)]

Phase Sensitive Axial Detection

- Idea: Instead of frequency measurement – measurement of phase relative to locked drive

$$\Delta\phi(^\circ) = \Delta\phi_1(^\circ) - \Delta\phi_2(^\circ) = 360\Delta\nu_z \cdot t_{\mathrm{evol}}$$

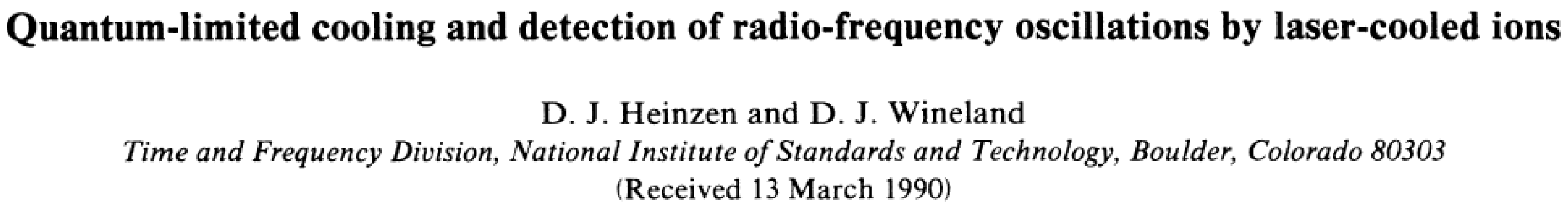




- Measured in 1s per trial.

[S. Ulmer et al., PhD Thesis (2011)]

Sympathetic Cooling



Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions

D. J. Heinzen and D. J. Wineland
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303
(Received 13 March 1990)

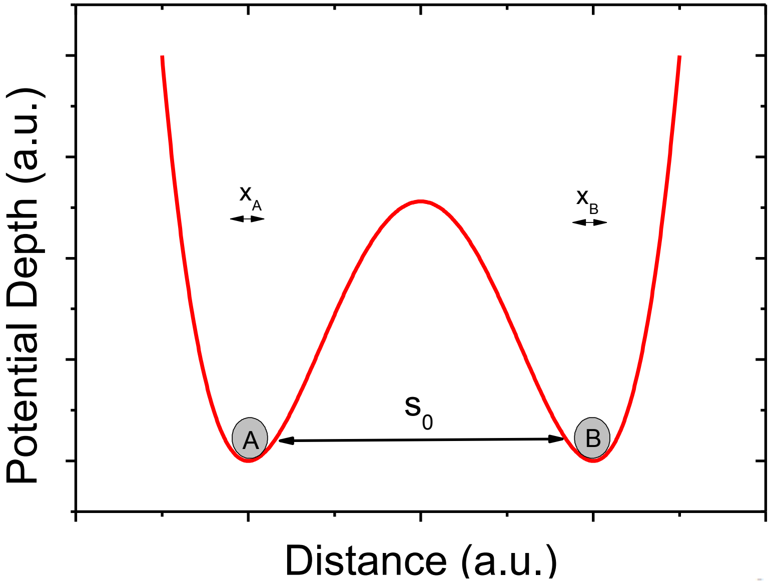
- Idea:
  - Laser-cool $^{9}\mathrm{Be}^{+}$ ion(s)
  - Design a trap for resonant coupling
  - Energy exchange

«Laser-cooled» antiprotons (mK-cooling within ms) !!! -> Higher precision, specifically in magnetic moment measurements.

[C. Ospelkaus Group, PTB Braunschweig]

Coupled Oscillators

Two charged particles trapped in direct vicinity interact via coulomb interaction.



$$U(x_a,x_b)=\frac{1}{4\pi\varepsilon_0}\frac{q_aq_b}{s_0-x_a+x_b}$$

$$\approx\frac{1}{4\pi\varepsilon_0}\frac{q_aq_b}{s_0}\left(\underbrace{1+\frac{x_a-x_b}{s_0}+\frac{x_a^2}{s_0^2}+\frac{x_b^2}{s_0^2}}_{\text{Static}}-\underbrace{\frac{2x_ax_b}{s_0^2}}_{\text{Dynamic}}\right)$$

$$\frac{-q_aq_b}{2\pi\varepsilon_0 s_0^3}(x'_a x'_b)=-\hbar\Omega_{\mathrm{ex}}(a+a^\dagger)(b+b^\dagger)\approx-\hbar\Omega_{\mathrm{ex}}(ab^\dagger+a^\dagger b)\longrightarrow\Omega_{\mathrm{ex}}\equiv\frac{q_aq_b}{4\pi\varepsilon_0 s_0^3\sqrt{m_am_b}\sqrt{\omega_{0a}\omega_{0b}}}$$

Resonant Coupling:

$$a^\dagger(t)=\exp(i\omega_0 t)(a^\dagger(0)\cos(\Omega_{\mathrm{ex}}t)-ib^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

$$b^\dagger(t)=\exp(i\omega_0 t)(b^\dagger(0)\cos(\Omega_{\mathrm{ex}}t)-ia^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

$$\downarrow$$

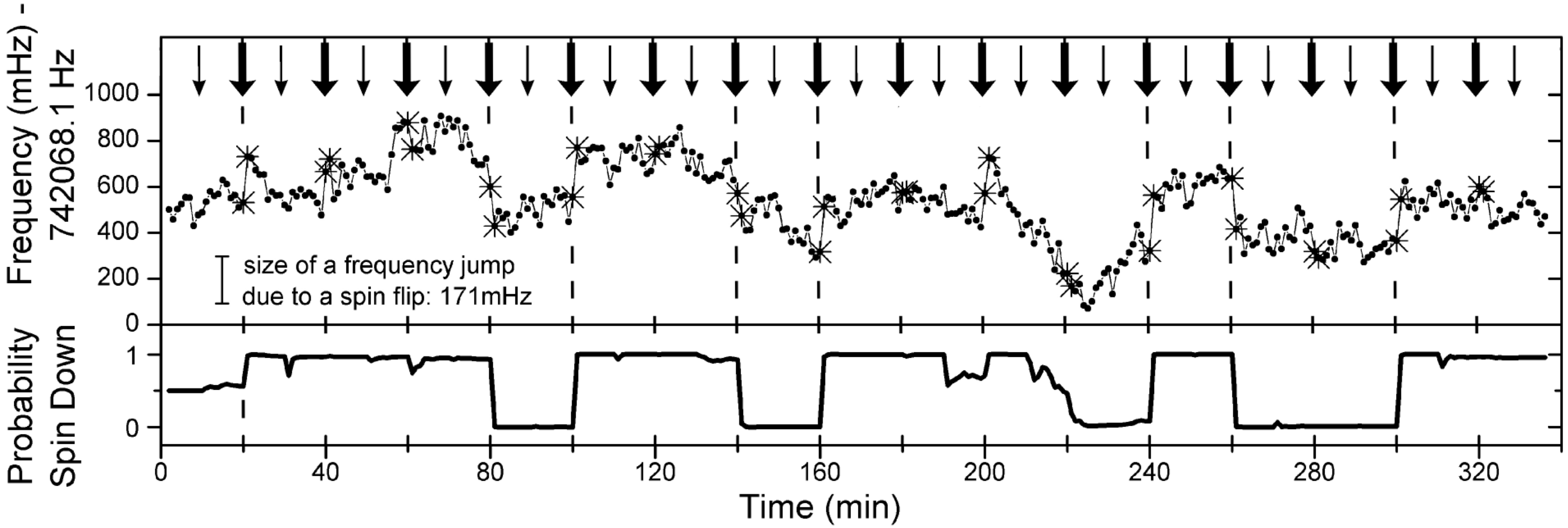
0.5s/mm^3

Effective Energy Exchange

[C. Ospelkaus Group, PTB Braunschweig]

Proton Spin Quantum Transitions

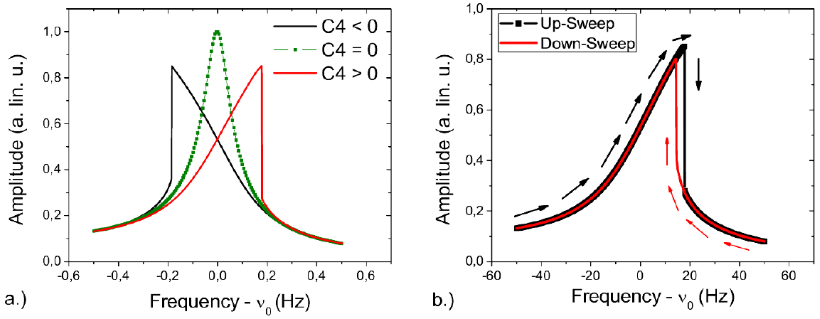
- Improvement of apparatus, trap wiring, quality of detection systems (lower noise, faster measuring cycles).
- Based on Bayesian filter -> fidelity of > 90% achieved



A. Mooser, K. Franke, S. Ulmer *et al.* Phys. Rev. Lett. **723**, 78 (2013)

Frequency Shifts in Penning Traps

Particles in imperfect Penning traps -> Anharmonic Oscillators

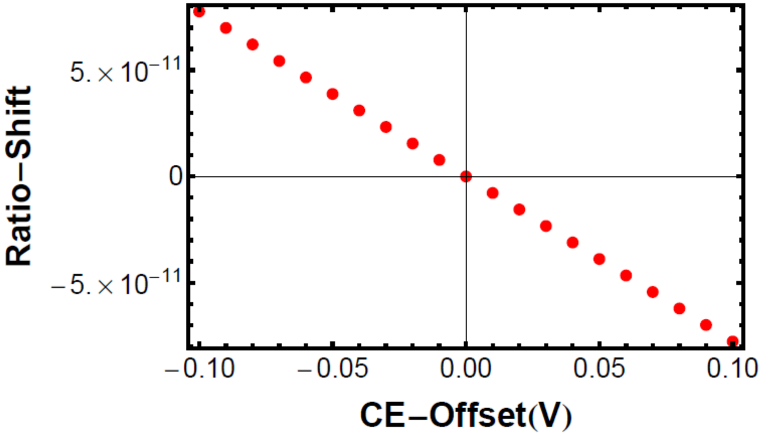


$$\frac{\Delta\omega_+}{\omega_+} = \frac{1}{qV_0}\frac{3C_4}{C_2^2}\left(-\left(\frac{\omega_z}{\omega_+}\right)^4 E_+ + \frac{1}{2}\left(\frac{\omega_z}{\omega_+}\right)^2 E_z - \left(\frac{\omega_z}{\omega_+}\right)^2 |E_-|\right)$$

$$\frac{\Delta\omega_z}{\omega_z} = \frac{1}{qV_0}\frac{3C_4}{C_2^2}\left(-\frac{1}{2}\left(\frac{\omega_z}{\omega_+}\right)^2 E_+ + \frac{1}{4}E_z - |E_-|\right)$$

$$\frac{\Delta\omega_-}{\omega_-} = \frac{1}{qV_0}\frac{3C_4}{C_2^2}\left(-\left(\frac{\omega_z}{\omega_+}\right) E_+ + E_z - |E_-|\right)$$

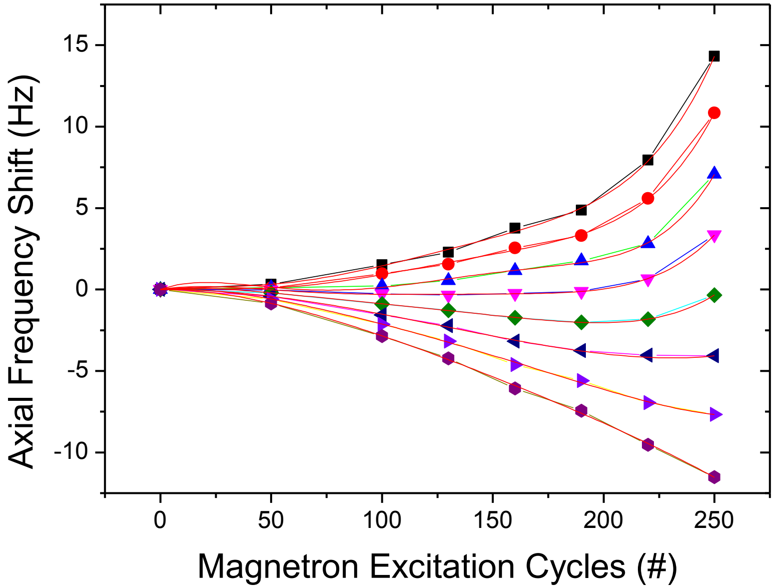
This can be one of the considerable limitations in frequency ratio measurements !

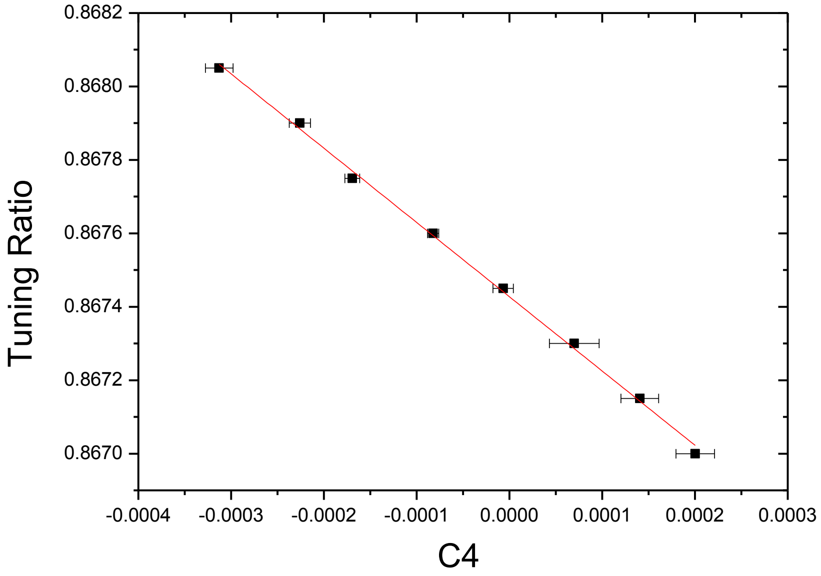


e.g. a not considered offset potential (50mV) and adjustment of resonance voltage shifts ratio (p/pbar comparison) by already 30ppt!

Trap Tuning

- Adjust voltages of correction electrodes to make the trap harmonic.

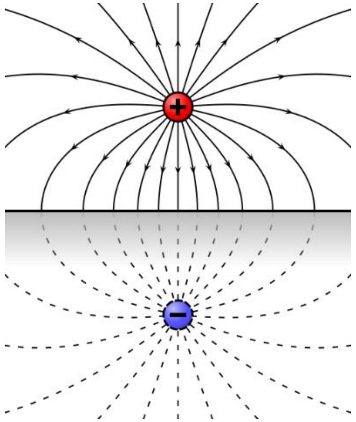




- Allows for trap tuning to mV.

Additional Frequency Shifts

What else modifies the result of your precision experiment?



Effective potential of the induced image charge

- Modification of the quadrupolar potential
- Correction of the invariance theorem

$$\left(\frac{\Delta\omega_c}{\omega_c}\right)^{(L)}_{ion} = \frac{3m_{ion}c^2}{2\rho^3 B_0^2}$$

Strong scaling with trap radius.

Typical traps (1cm diameter) ->

Modifies cyclotron frequency at level of 1e-10

QUESTION

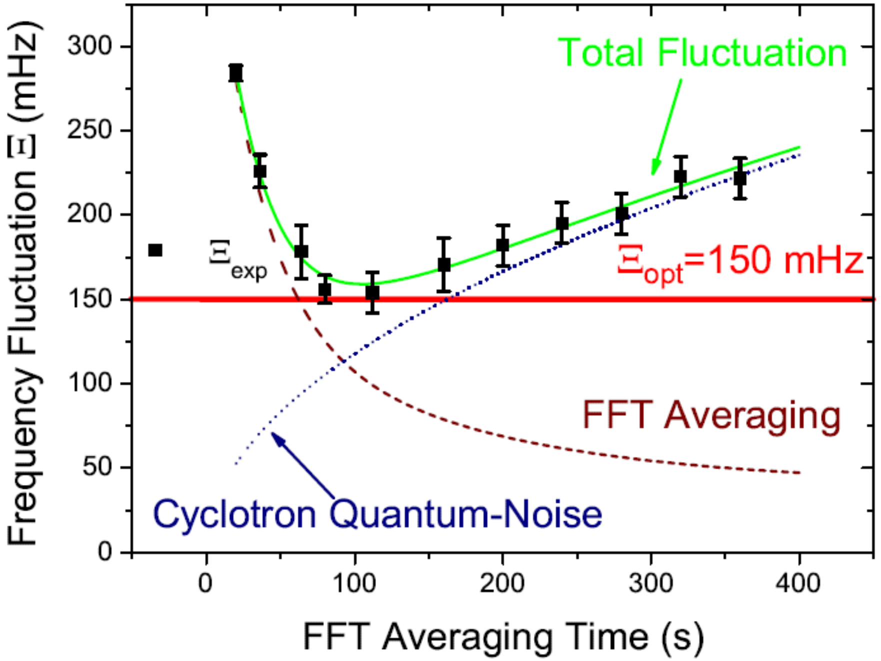
In a perfect Penning trap

- Homogeneous magnetic field
- Perfect electric quadrupole
- large trap (no image charge shift)

Any additional frequency shift?

Resolution Limits

- Dip measurements are limited to a certain precision
  - Line width
  - Signal-to-noise ratio
  - Averaging time
  - Voltage drifts and scatter



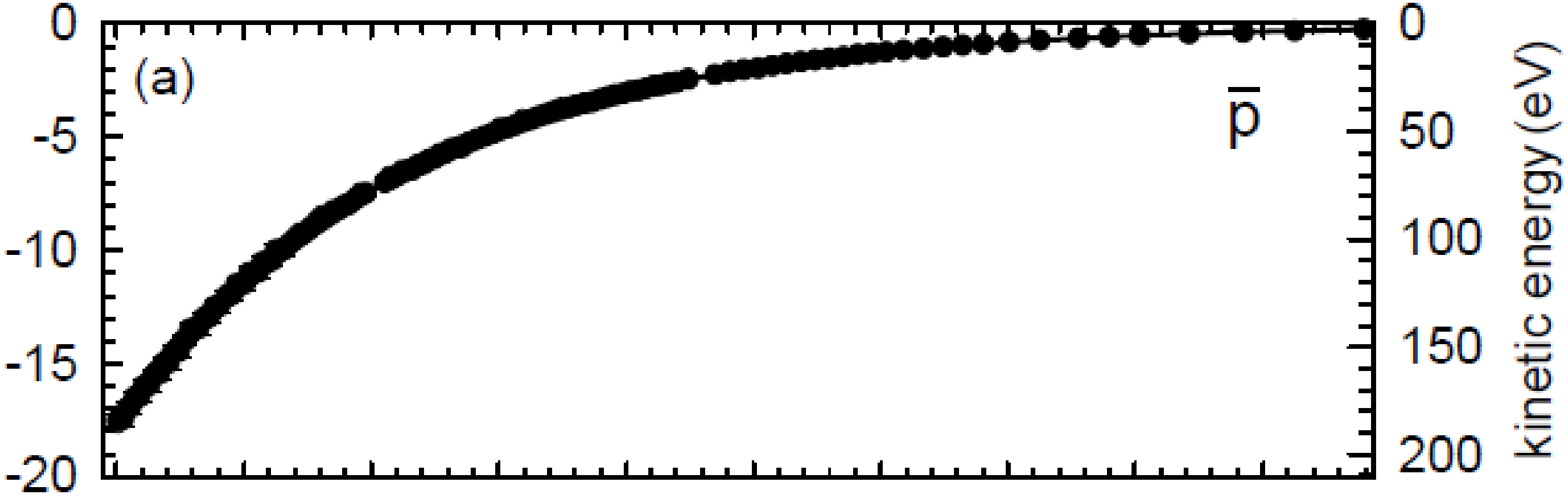
$$\nu_l + \nu_r = \nu_z + \nu_{rf} - \nu_{\pm}$$

scatters scatters scatters

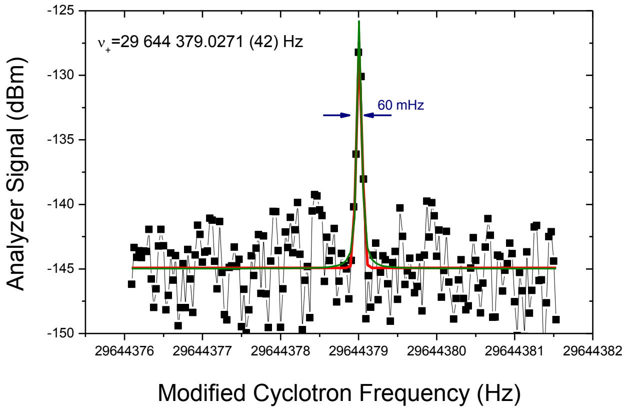
$$\sigma(f_0) = \alpha\,[\mathrm{window},\ \mathrm{overlap}] \times \sqrt{\frac{1}{4\pi}\frac{\Delta f'}{T_s}\frac{\sqrt{\mathrm{SNR}}+1}{\sqrt{\mathrm{SNR}}-1}}$$

Direct Measurements

- Measurement of cyclotron frequency with cyclotron resonator



[J. Harrington et al., XXX **XX**, (201X)]<



- Problem: Cyclotron detectors are not very sensitive (small inductance) -> considerable frequency shifts due to large particle energy.

[G. Gabrielse et al., PRA **82**, 3198 (1999)]