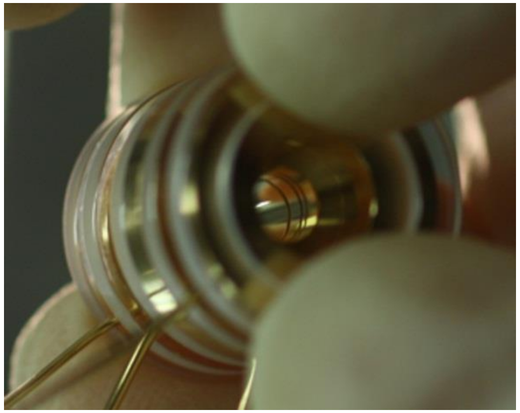
The g-Factor of the Proton and the Antiproton

A. Mooser, K. Blaum, K. Franke, S. Van Gorp, T. Higuchi, P. Koß, N. Leefer, Y. Matsuda, H. Nagahama, W. Quint, G. Schneider, C. Smorra, J. Walz, Y. Yamazaki and S. Ulmer

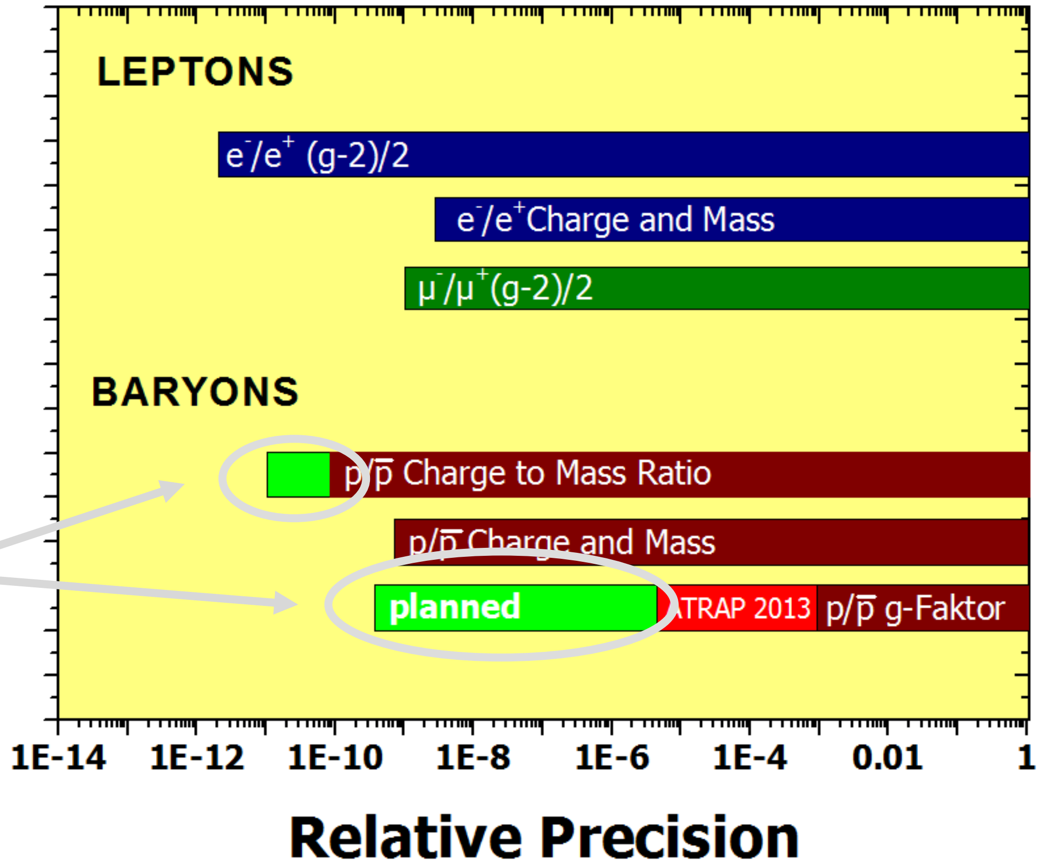
Outlook

- Motivation
- g -factor measurement principle in a Penning trap
- Observation of single spin flips of a single proton
- Measurement of proton g –factor
- Status on Antiproton g-factor at BASE - CERN

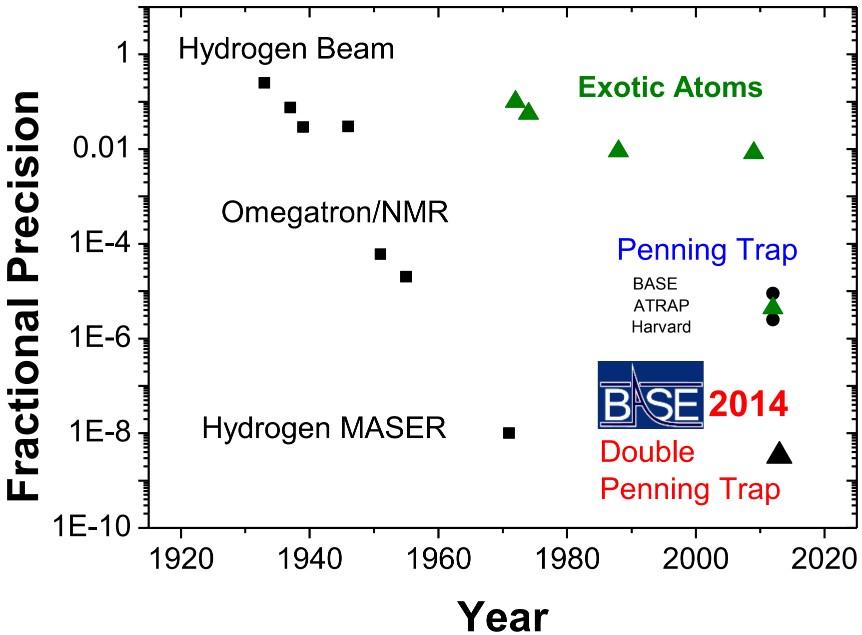


Test of CPT invariance

- CPT invariance is the most fundamental symmetry in the Standard Model.
- Strategy: Compare properties of matter and antimatter conjugates with high precision.



Proton / Antiproton Magnetic Moments



Proton Magnetic Moment

0.4ppb　　　　　10 ppb

$$g_p = g_e \cdot \frac{m_p}{m_e} \cdot \boxed{\frac{g_p}{g_p(H)} \cdot \frac{g_e(H)}{g_e}} \cdot \frac{\mu_p(H)}{\mu_e(H)}$$

0.78ppt　　　　　≈ppb

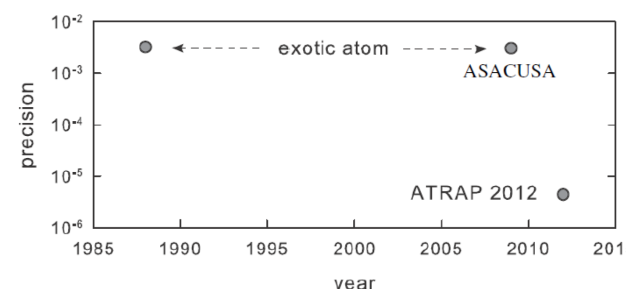
Requires theoretical corrections at the level of 17.7ppm.

P. F. Winkler *et al.*, Phys. Rev. A **5**, 83 (1972).

Proton magnetic moment has never been measured directly AND with high precision

Antiproton Magnetic Moment

- Until 2012: Exotic atom spectroscopy (ASACUSA) with at per-mille level
- 2012: First direct single particle measurement with 4.4 ppm in precision



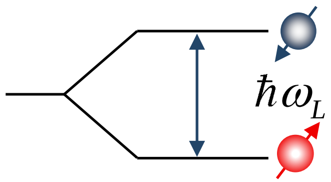
$$\mu_{\bar{p}}/\mu_N = -2.792\,845 \pm 0.000\,012 \qquad [4.4\ \text{ppm}].$$

J. DiSciacca et al., PRL **110**, 130801 (2013)

Determination of the g-factor

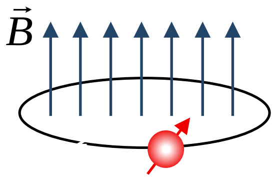
Determination of Larmor frequency in a given magnetic field

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



Monitoring magnetic field via simultaneous measurement of the free cyclotron frequency

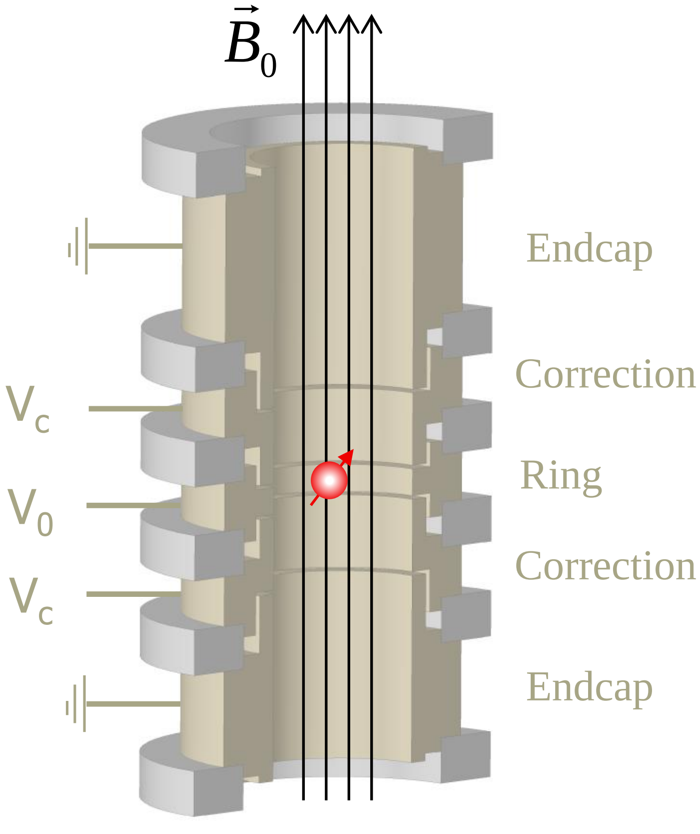
$$\omega_c = \frac{e}{m_p}B$$



$$g = 2\frac{\omega_L}{\omega_c} = 2\frac{\nu_L}{\nu_c}$$

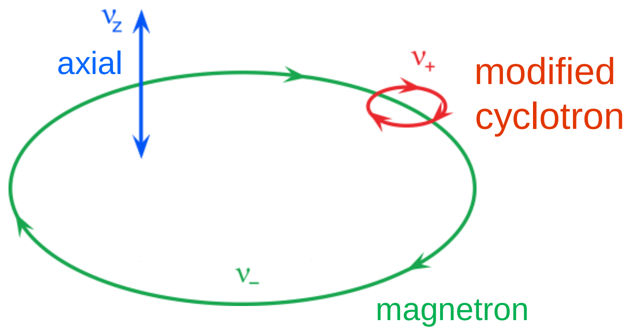
The Penning trap

Superposition of homogeneous magnetic field and electrostatic quadrupole potential



$\vec{B} = B\vec{e}_z$ → radial confinement

$\Phi(z,\rho) = U_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$ → axial confinement



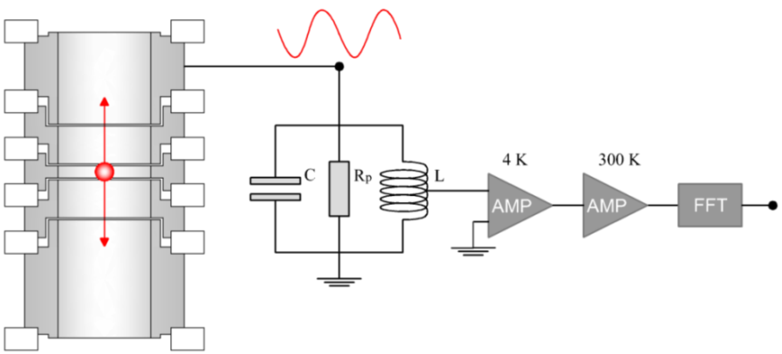
axial	$\nu_z = 700\,\mathrm{kHz}$
modified cyclotron	$\nu_+ = 29\,\mathrm{MHz}$
magnetron	$\nu_- = 10\,\mathrm{kHz}$

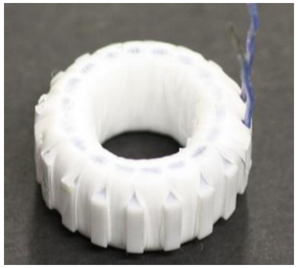
Invariance Theorem: $\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$

[L. S. Brown and G. Gabrielse, Phys. Rev. A, 25:2423, 1982.]

Measurement of eigenfrequencies

Ion in thermal equilibrium - axial frequency





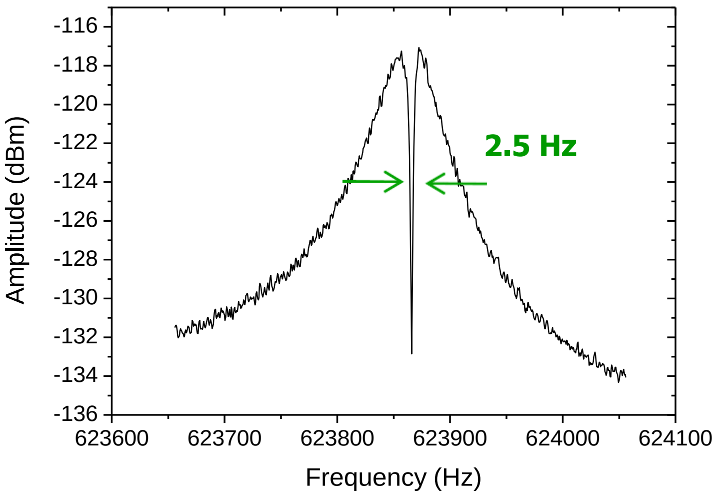
$Q = 12000$

$R_P = 120\text{M}\Omega$

- Detection of tiny image currents [fA]
- Highly sensitive detection circuits – High-Q

$$Signal \sim R_P \sim Q$$

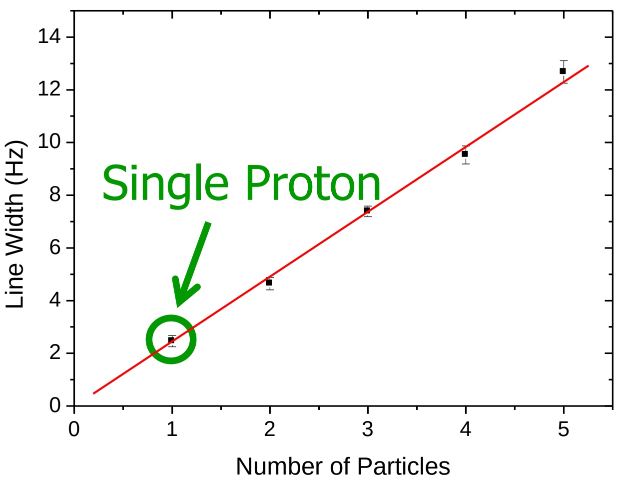
Particle acts as a perfect short



Linewidth:

$$\delta\nu_z \propto N_p$$

Auto-resonant excitation for energy selective particle reduction

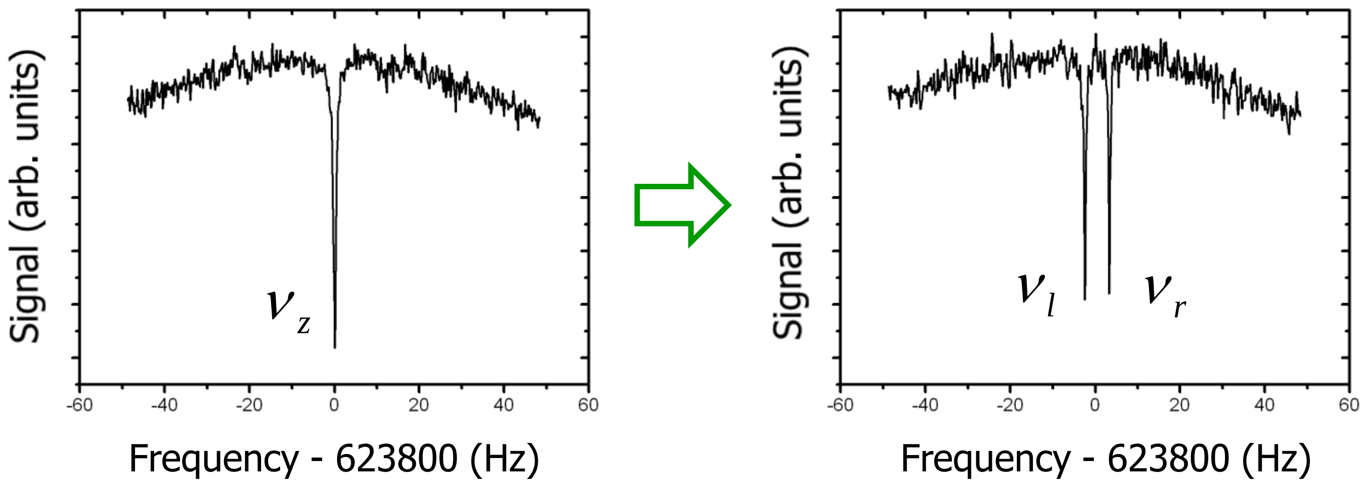


Measurement of eigenfrequencies

Access to radial modes

Coupling of modes via rf-sideband coupling, e.g. $\nu_{rf} = \nu_+ - \nu_z$

Amplitude modulation of the axial motion



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

Same principle for remaining magnetron mode

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

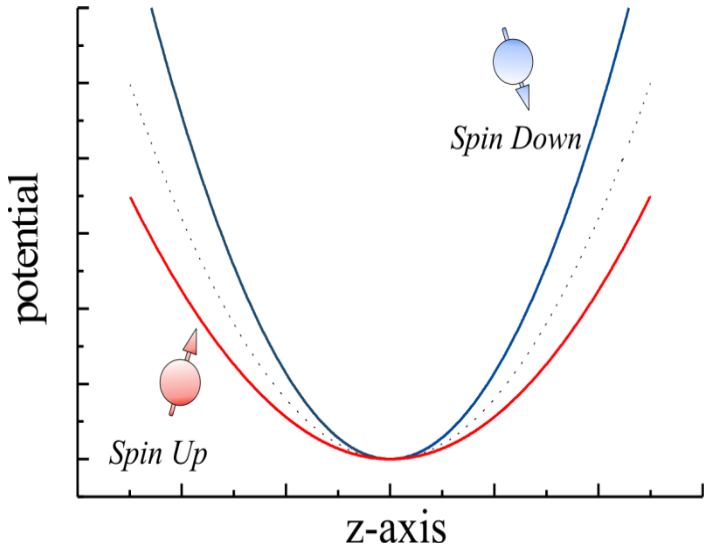
$$\boxed{\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2} \qquad \boxed{\frac{\Delta\nu_c}{\nu_c} \approx 10^{-9}}$$

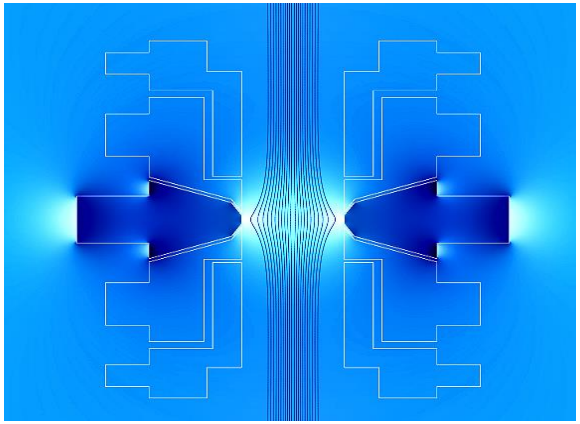
Detection of the spin state

The continuous Stern-Gerlach effect

Introduce magnetic inhomogeneity, the magnetic bottle

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



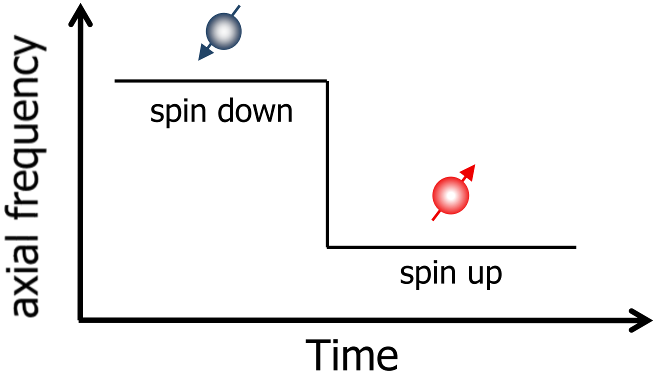


Coupling of spin moment to axial oscillation

$$\Phi_z = \pm\mu_p B_z$$

Spin flip results in shift of the axial frequency

$$\nu_z \propto \frac{\mu_p}{m} B_2$$



Detection of spin state
Challenge

Applied with great success for electron g-factors – Bohr magneton

$$\nu_z \propto \pm \frac{1}{2\pi^2 \nu_{z,0}} \frac{\mu_z}{m} B_2$$

spin momentum

Dealing with nuclear magneton requires huge magnetic bottle of

$$\boxed{B_2 = 30\,\mathrm{T/cm^2}}$$

to obtain frequency jump due to spin transition of

$$\boxed{\Delta\nu_z = 190\,\mathrm{mHz} \rightarrow \Delta\nu_z / \nu_z = 2*10^{-7}}$$

<u>BUT</u>

$$\nu_z \propto + \frac{1}{2\pi \nu_{z,0}} \frac{B_2}{B_0} E_{radial}$$

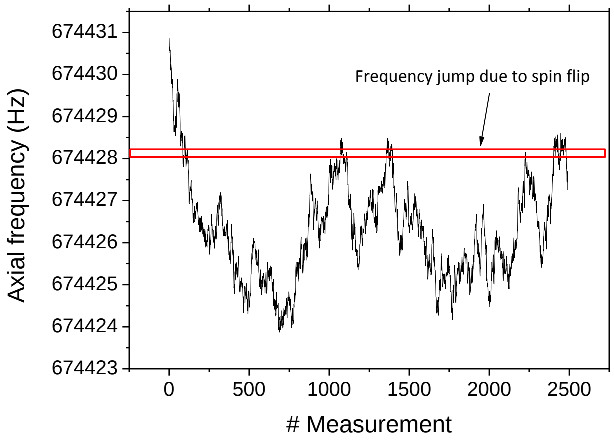
radial angular momentum

Challenging!

Tiny energy fluctuations in radial modes cause huge axial frequency shifts

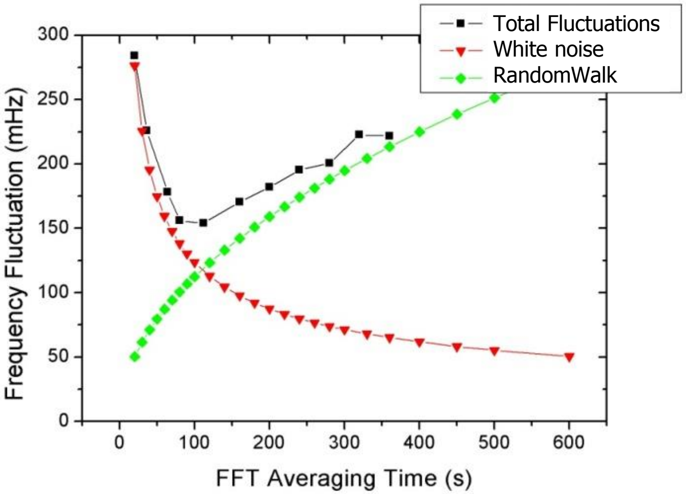
$$\boxed{\Delta\nu_z / E_+ = 1\,\mathrm{Hz/\mu eV}}$$

Frequency fluctuation Ξ



$$\Delta\nu_z = (\nu_z(t+T) - \nu_z(t))$$

$$\Xi^2 = \frac{1}{n}\sum(\Delta\nu_z - \overline{\Delta\nu_z})^2$$



$\Xi = 150$mHz - not stable enough for observation individual spin transition

Axial frequency fluctuation Ξ increases due to frequency jump caused by spin transitions

$$\boxed{\Xi_{SF} = \sqrt{\Xi^2_{ref} + P_{SF}\Delta\nu^2_{z,SF}}}$$

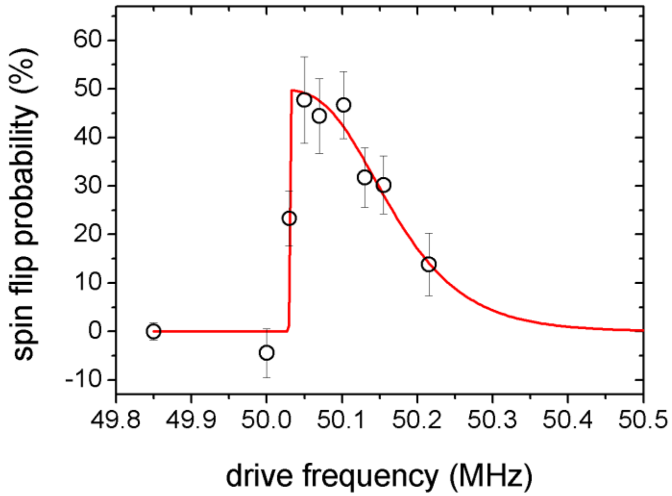
Measure Ξ_{SF} and $\Xi_{ref} \rightarrow$ obtain SF-Probability!!!

Detecting spin transitions in a statistical measurement!

g-Factor measurement

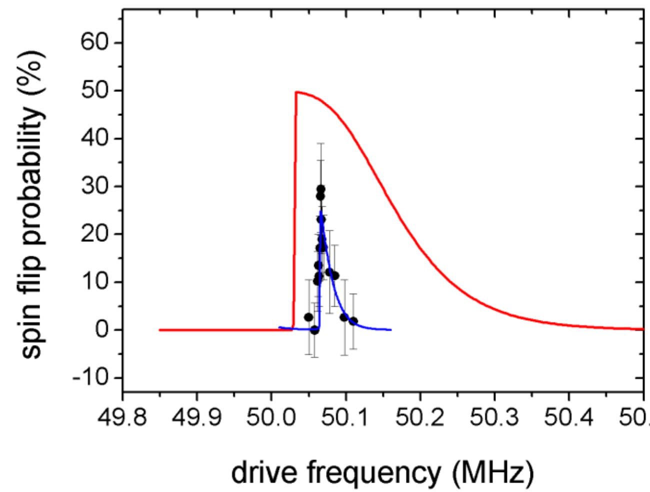
relative precision of 10^{-4}

S. Ulmer et al., Phys. Rev. Lett **106**, 253001 (2011)



reduction of line broadening using feedback cooling

C. C. Rodegheri et al., *New J. Phys.* **14** 063011 (2012)



- Larmor frequency measurement with a relative uncertainty of $1.8*10^{-6}$
  - With cyclotron frequency measurement

g = 5. 585 696 (50)

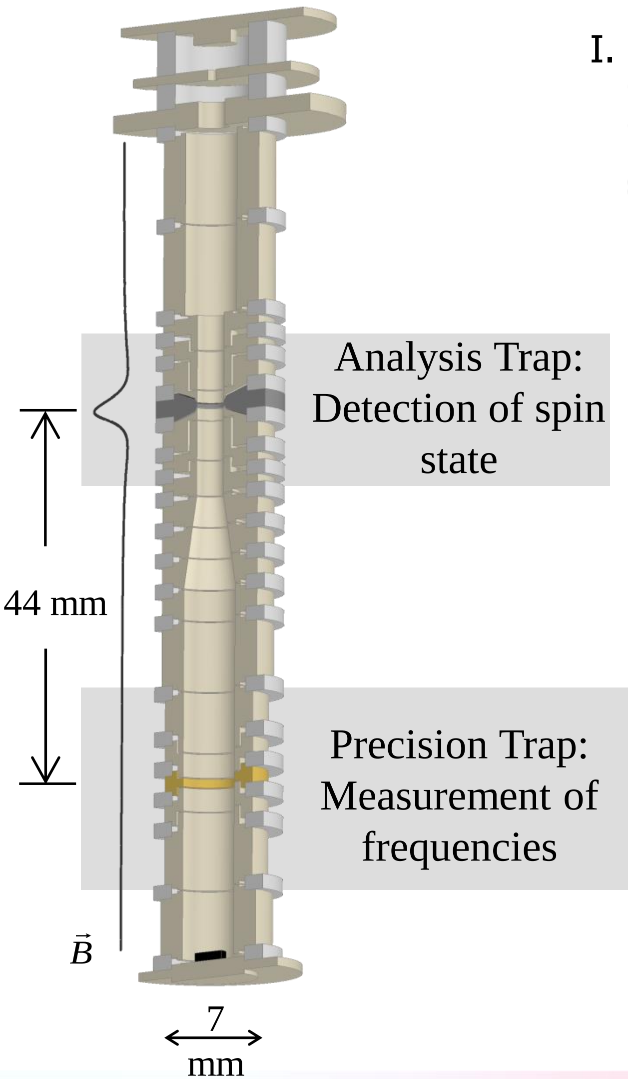
Limited by magnetic field inhomogeneity

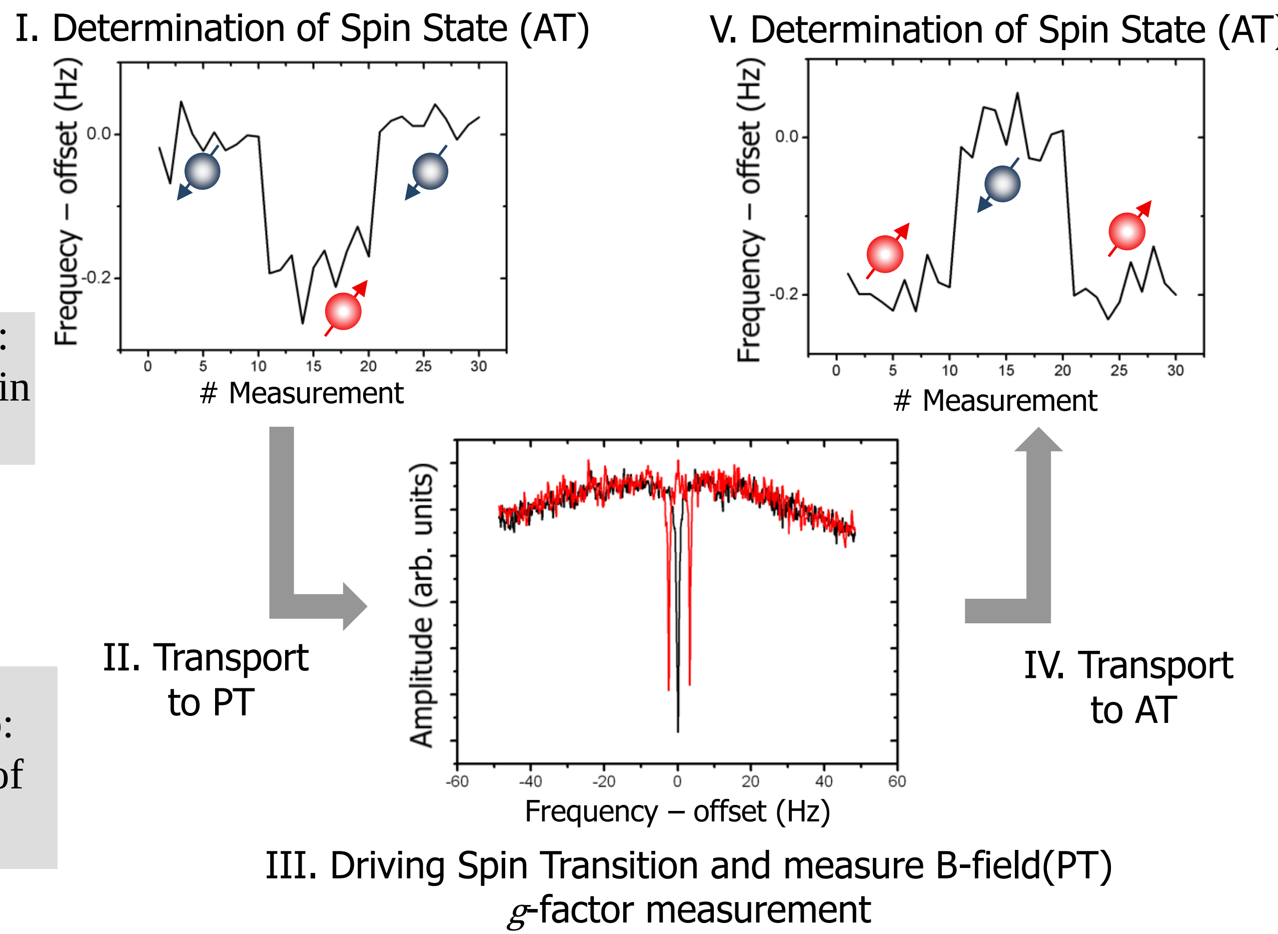
similar method used by Harvard group – relative precision of 2.5 ppm

di Sciacca et al., PRL 108, 153001 (2012)

Double Penning trap technique

- High Precision measurement demands homogeneous magnetic field
- Introduce two traps – double Penning trap setup (*H. Häffner, Phys. Rev. Lett.85, 5308 (2000)*)

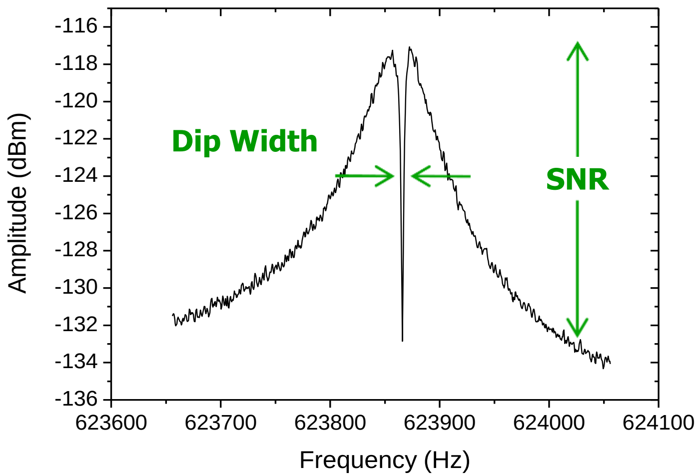




Demands detection of every single spin transition!

Improvement of frequency stability

White noise



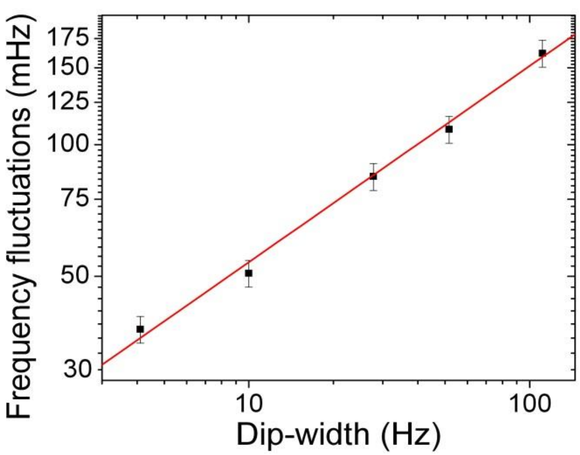
Higher signal-to-noise ratio

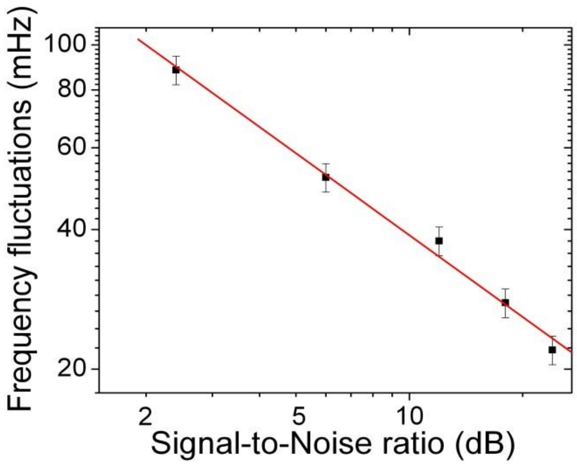
$$\boxed{SNR \propto R_p \propto Q}$$

results in improved frequency measurement in but

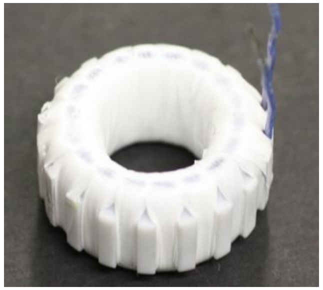
$$\boxed{\delta\nu_z = \frac{1}{2\pi}\frac{q^2}{m}\frac{R_p}{D}}$$

Can be overcome by increased effective Electrode distance *D*



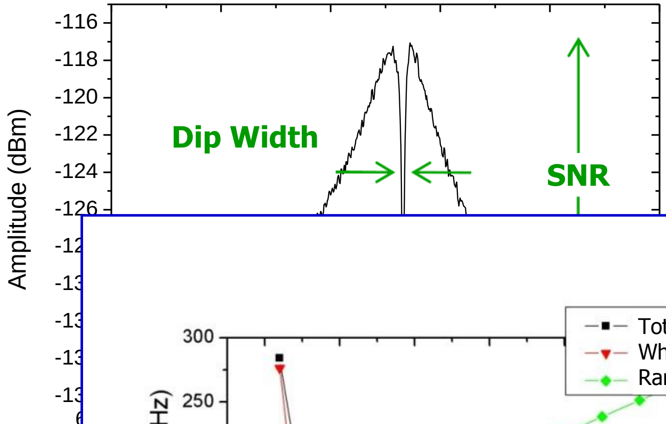


$$Q = 12000$$
$$R_P = 120\ M\Omega$$
$$u_n = 0.9\ nV/\sqrt{Hz}$$



Novel toroid detection coils allow for 4 times faster and precise frequency measurements

Improvement of frequency stability
White noise



Higher signal-to-noise ratio

$$\boxed{SNR \propto R_p \propto Q}$$

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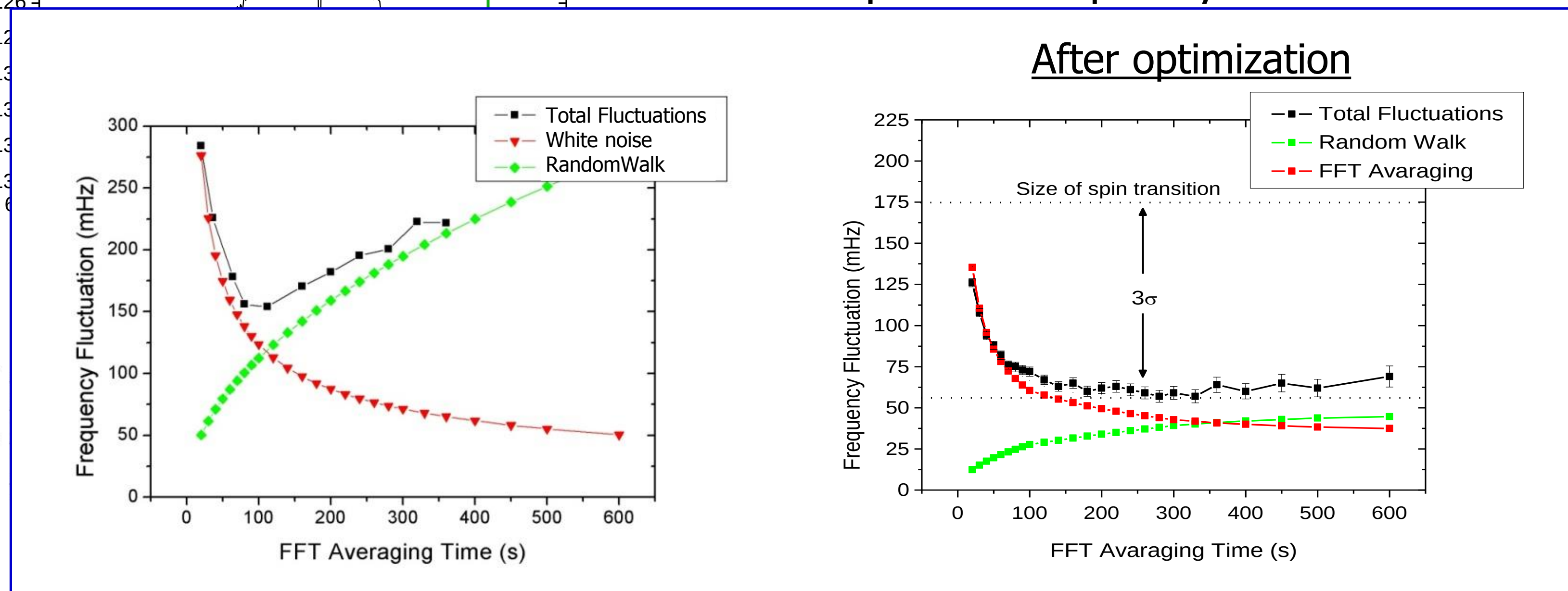
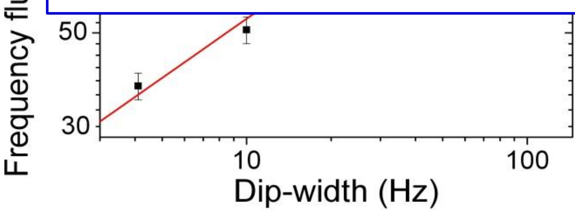
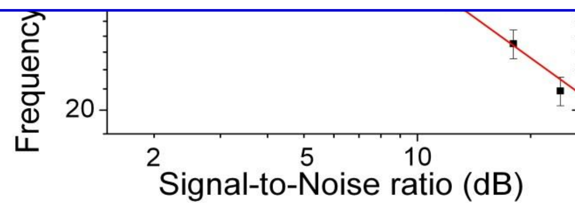
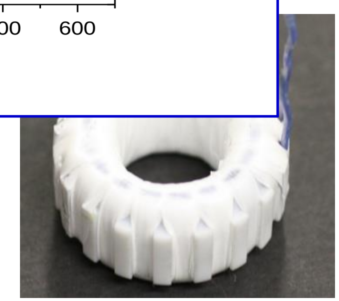








Novel toroid detection coils allow for 4 times faster and precise frequency measurements

Quality of spin state detection
Bayes and threshold method

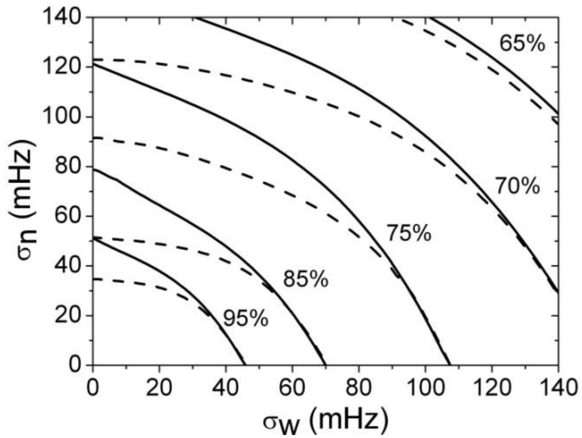
Threshold method: Accept spin flip if frequency jump above given threshold

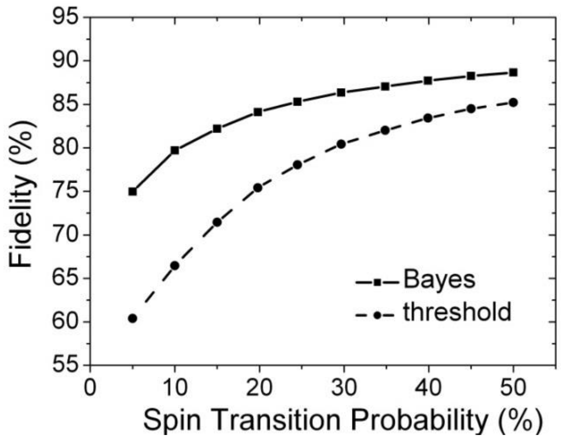
Bayes rule – conditional probability of having a spin state

$$P(S \mid f_2, f_1) \propto P(f_2 \mid S, f_1) P(S, f_1)$$

Update of state probability given complete frequency, noise and previous state information

Fidelity: fraction of correctly assigned spin states in a series of measurements



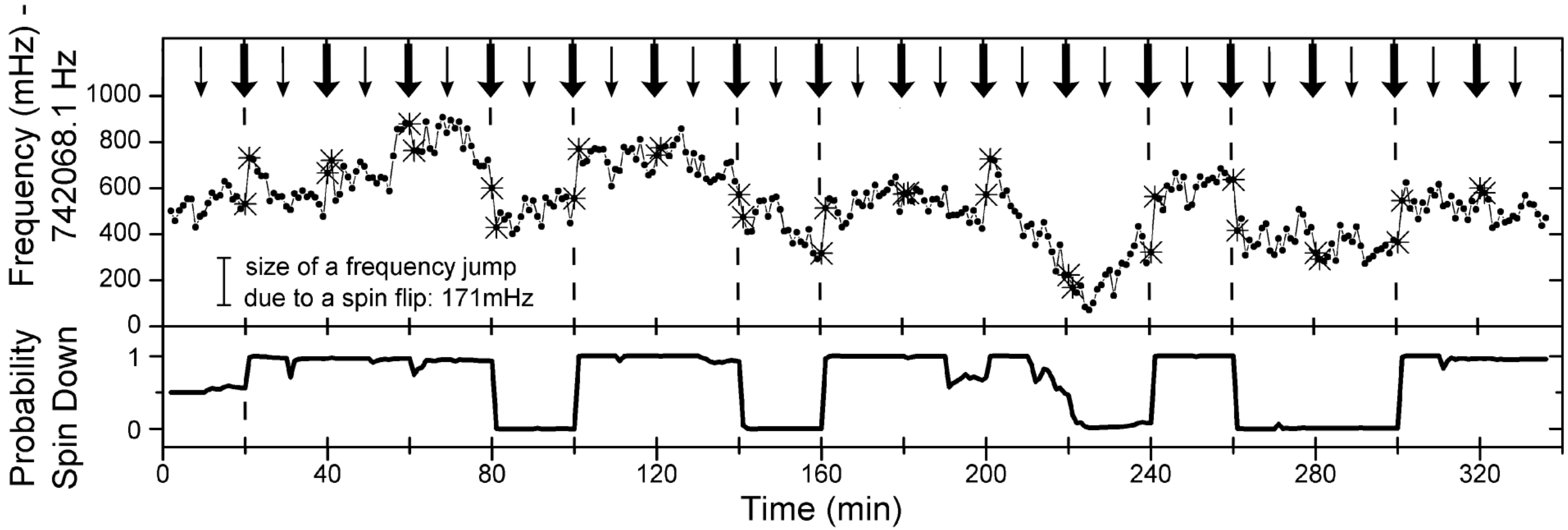


Bayes method superior to threshold method - Optimal fidelity of 88%

Observation of Single Spin Flips

Series of axial frequency measurements in AT

Apply resonant and off-resonant spin flip drives – background check



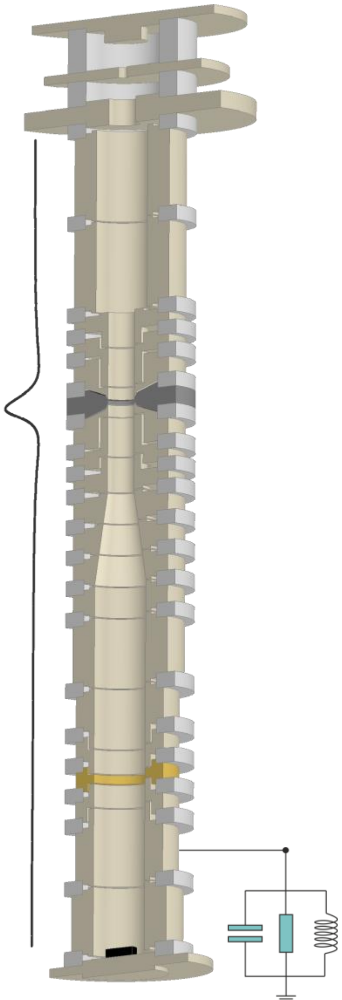
Algorithms initialized with maximum uncertainty (p=50%)

No extraordinary frequency jumps at off-resonant drives – cyclotron mode not affected

A. Mooser, K. Franke *et al.,* Phys. Rev. Lett. **110**, 140405 (2013).

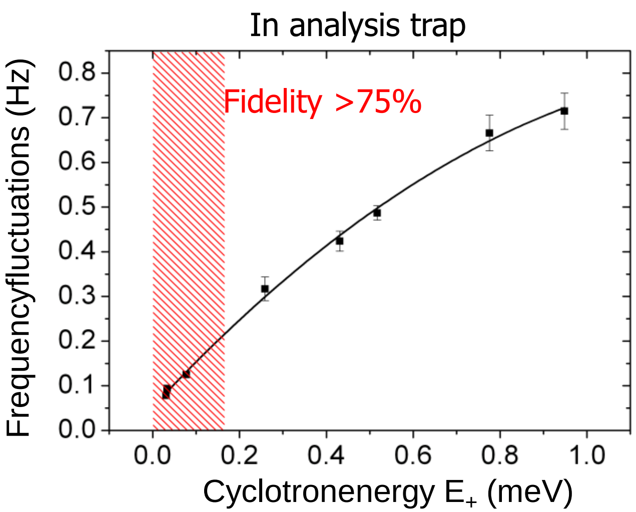
Related observations are discussed in J. DiSciacca *et al.,* Phys. Rev. Lett. **110**, 140406 (2013).

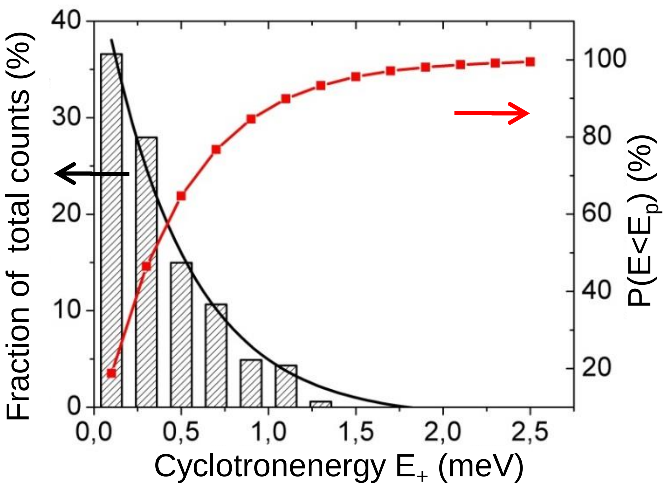
Double Penning trap technique



- Additionally spin-state has to be detected two times
  ⟶ Reduction of detection fidelity

- Cyclotron frequency measurement heats cyclotron mode to 30 meV
- Low energies required in analysis trap for high fidelity spin state detection





- Coupling to thermal bath in precision trap
- Preparation of subthermal E_+

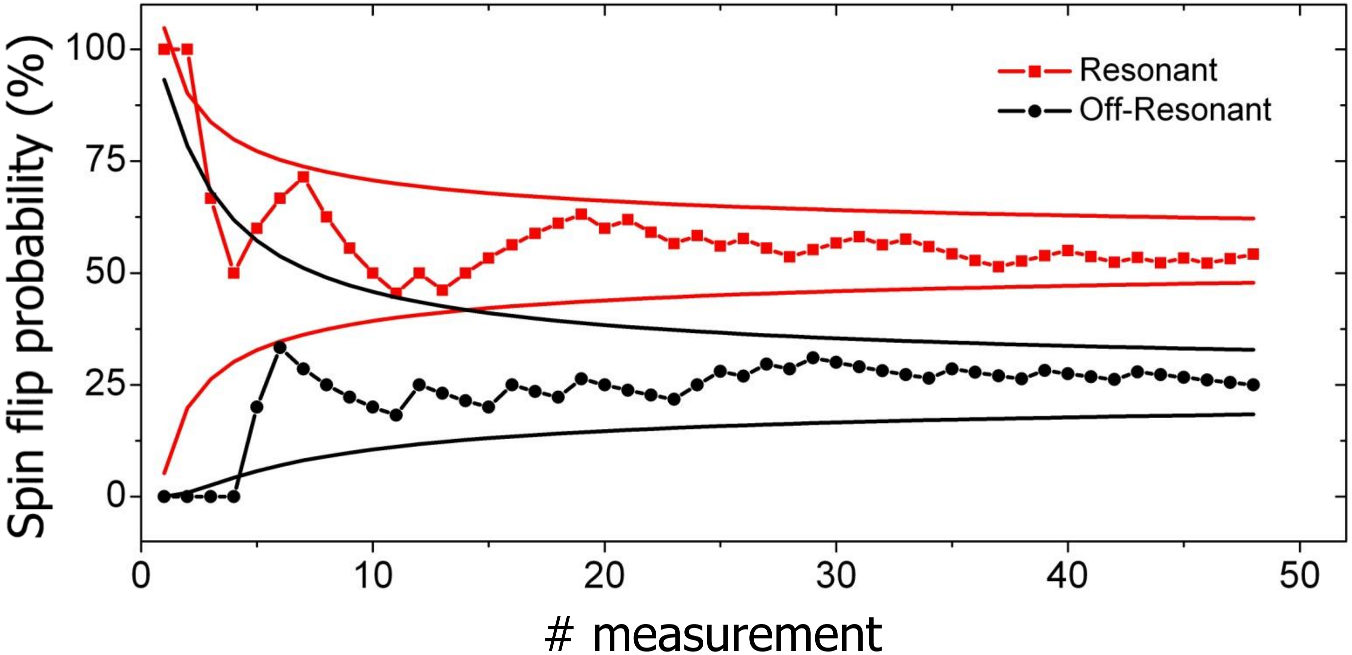
3 hours for one spin flip trail in precision trap with fidelity of 75%

Demonstration of double Penning trap technique

Measurement:
- Detect spin state - magnetic bottle in analysis trap
- Excite spin transition in precision trap
- Detect spin state - magnetic bottle in analysis trap

After two weeks of data taking

Observation of spin flips excited in the homogeneous magnetic field

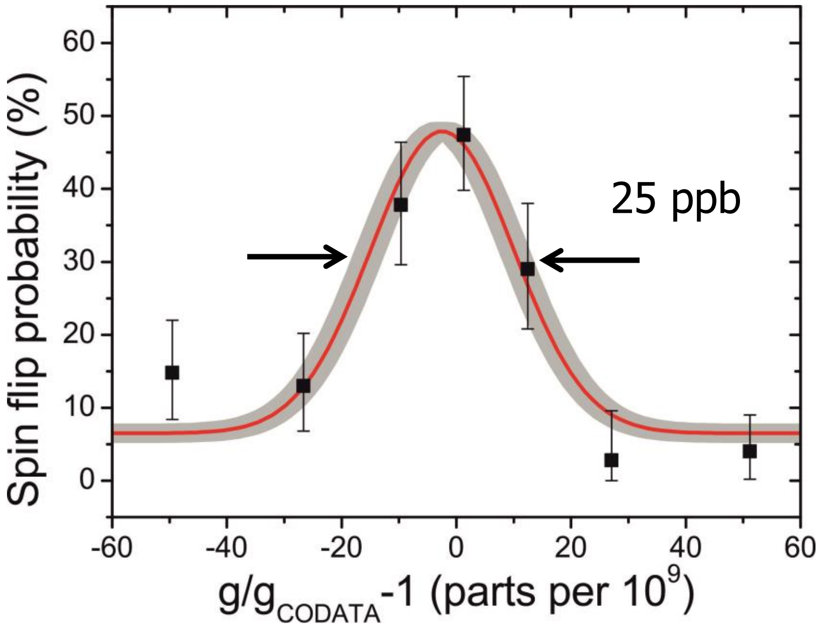


Finite spin flip probability for off-resonant drive due to finite spin state detection fidelity

A. Mooser *et al.*, Phys. Lett. B **723**, 78–81 (2013).

The g-factor of the proton

Sweep spin flip excitation frequency to obtain g-factor resonance



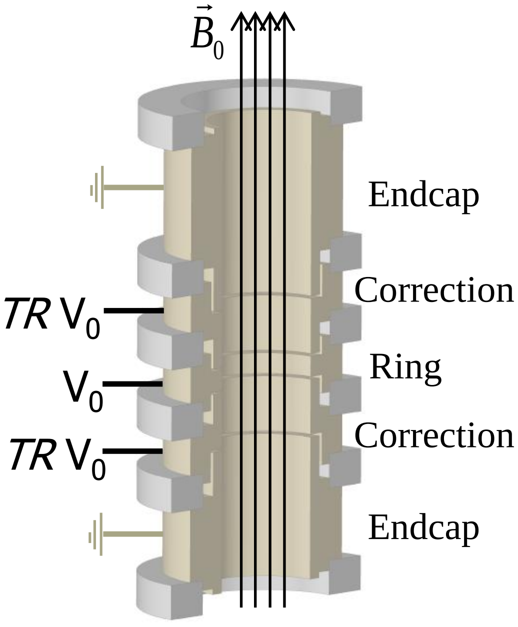
- To avoid systemtic effects spin flip excitation frequency randomly chosen
- Blindfold analysis of axial frequency in analysis trap for spin state detection using Bayesian analyses
- Line width: due to residual B_2 in precision trap and satuartion

$$g = 5.585\,694\,704(14) \text{ that is } 2.6\,\text{ppb}$$

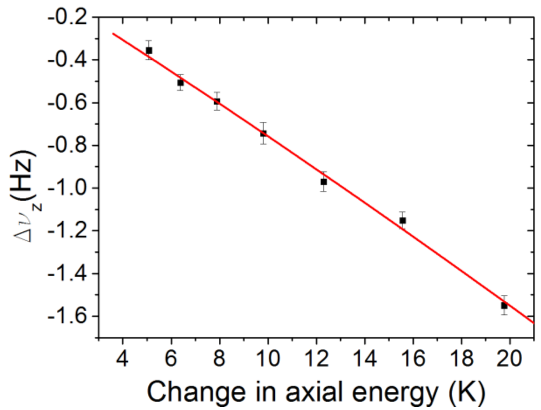
The g-factor of the proton
Systematic errors

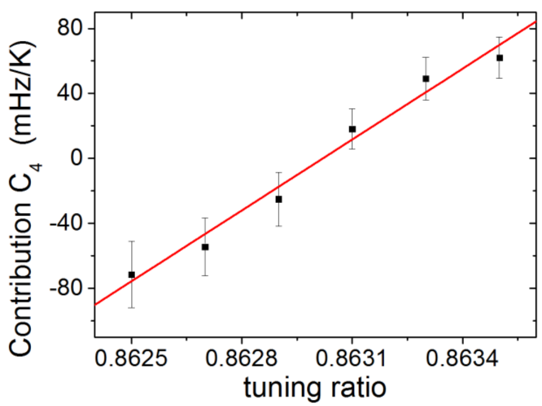
Parameter	Relative Shift of $g_p/2$	Uncertainty
Trapping Potential (C_4)	0	0.2 ppb

- Octupolar contribution - energy dependent frequency shift (not for Larmor frequency)



$$\frac{\Delta\omega_z}{\omega_z} = \frac{3}{2}\left(\frac{C_4}{C_2^2} + \frac{5}{4}\frac{C_6}{C_2^3}\left(\frac{E_z}{qV_0}\right)\right)\frac{E_z}{qV_0} \quad \text{with} \quad C_4, C_6 \propto TR$$





C_4 contribution can be optimized to better than 10^{-5} hence uncertainty of $\frac{\Delta\omega_z}{\omega_z} = 10^{-9}$ which contribute 0.2ppb to cyclotron frequency via double dip

Direct cyclotron frequency shift

$$\frac{\Delta\omega_p}{\omega_p} \propto \left(\frac{\omega_z}{\omega_p}\right)^2 E_z \quad \sim 1\text{ppt}$$

The g-factor of the proton

Systematic errors

Parameter	Relative Shift of $g_p/2$	Uncertainty
Relativistic Shift	0.030 ppb	<0.003 ppb
Image-Charge Shift	-0.088 ppb	<0.010 ppb

- Negligible systematic shifts due to
  - Relativistic effects - proton at cryogenic temperature

$$\boxed{\frac{\Delta\omega_p}{\omega_p} = -\frac{1}{mc^2} k_b T_p}$$

→ Compare electron:

- Groundstate cooling
- Cyclotron quantum jump spectroscopy

  - Additional Electrostatic Potential due to image charge - single charge

$$\boxed{\frac{\Delta\omega_c}{\omega_c} = \left(\frac{\omega_-}{\omega_c} - \frac{\omega_+}{\omega_c}\right) \frac{q^2}{4\pi\epsilon_0 m {r_0}^3 {\omega_c}^2}}$$

→ Compare highly charged ions $^{12}C^{5+}$:

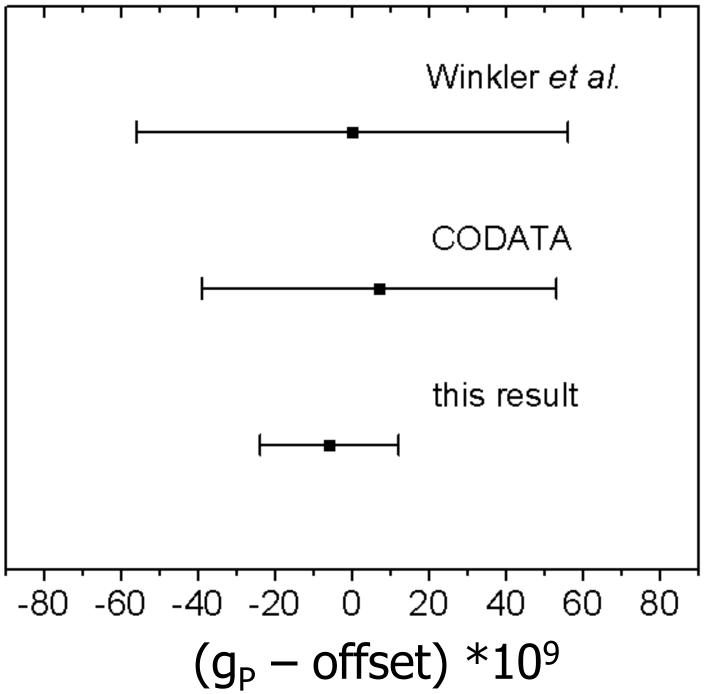
- Dominant systematic shift
- Increase trap radius r_0

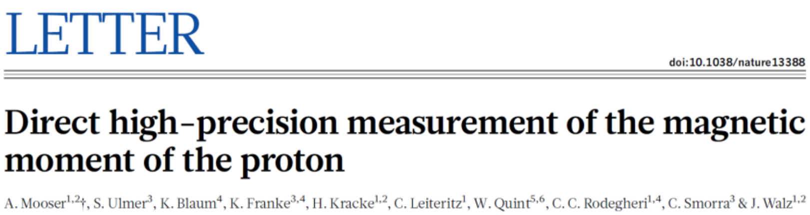
The *g*-factor of the proton
Systematic errors

Parameter	Relative Shift of $g_p/2$	Uncertainty
Trapping Potential (C_4)	0	0.2 ppb
Relativistic Shift	0.030 ppb	<0.003 ppb
Image-Charge Shift	-0.088 ppb	<0.010 ppb
Nonlinear Magnetic Field Drift	0	2 ppb
Cyclotron Cooling	-0.51 ppb	0.08 ppb
Voltage Stability	-0.07 ppb	0.35 ppb
Total Systematic Shift	**-0.64 ppb**	**2 ppb**

- Voltage Stability – accounts for possible drift of applied potentials due to DC-Filters after transport from AT to PT
- In addition at level of << ppt :
    - Detector damping – damped harmonic oscillator
    - Bloch Siegert Shift – linear polarization of SF-driving field
    - retarded part of image charge found negligible

The *g*-factor of the proton




LETTER

doi:10.1038/nature13388

Direct high-precision measurement of the magnetic moment of the proton

A. Mooser[1,2]†, S. Ulmer[3], K. Blaum[4], K. Franke[3,4], H. Kracke[1,2], C. Leiteritz[1], W. Quint[5,6], C. C. Rodegheri[1,4], C. Smorra[3] & J. Walz[1,2]

A. Mooser, S. Ulmer, K. Blaum, K. Franke, H. Kracke, C. Leiteritz, W. Quint, C. Smorra, J.Walz, Nature 509, 596 (2014)

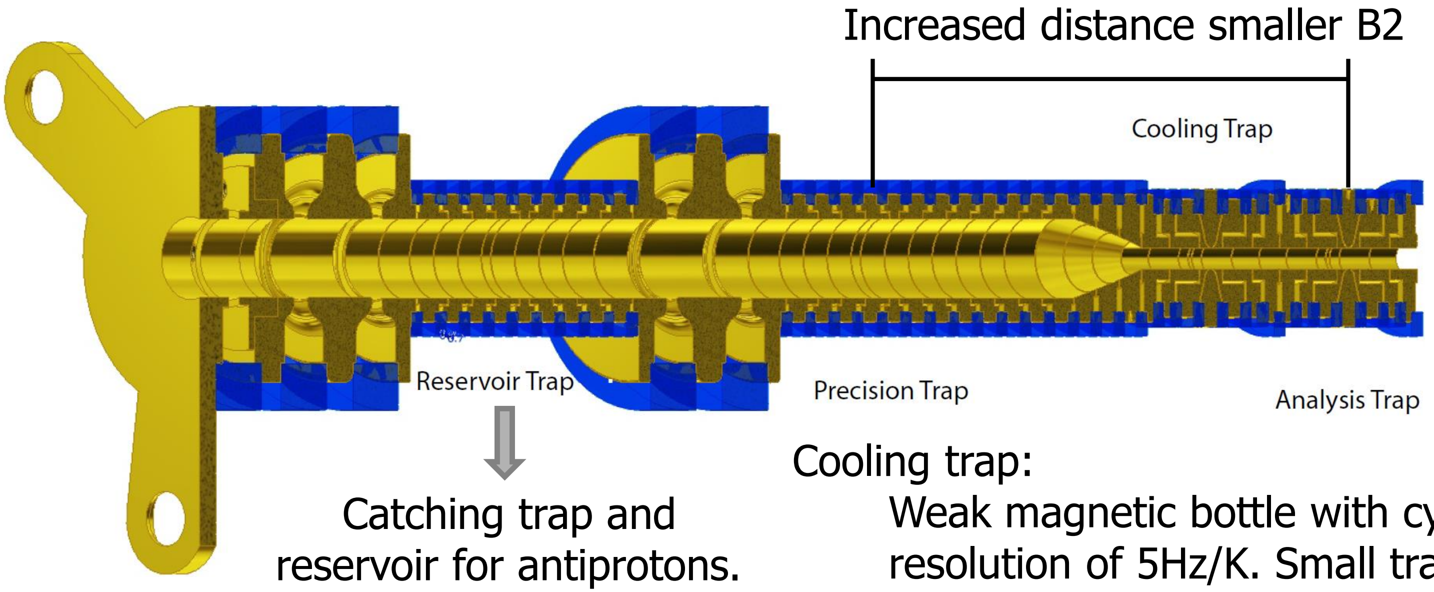
$$\boxed{g = 5.585\,694\,700(14)_{\text{stat}}(11)_{\text{sys}}}$$

- First direct and high precision measurement of the proton magnetic moment.
- Improves 42 year old MASER value by factor of 3.3 (P. F. Winkler *et al.*, Phys. Rev. A **5**, 83 (1972))
- Value in agreement with accepted CODATA value, but 2.5 times more precise

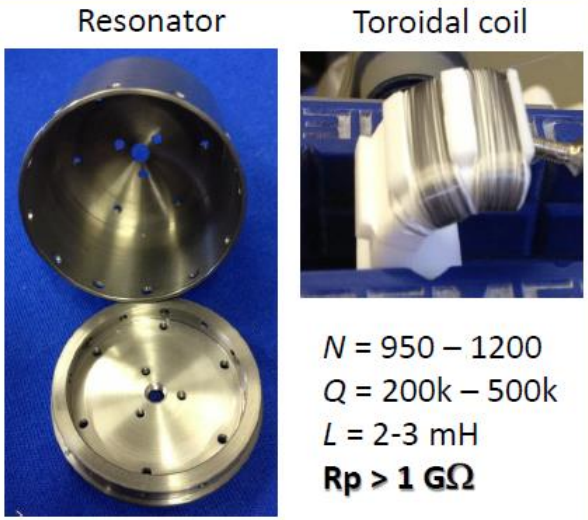
Antiproton

BASE - GERN

New Advanced Penning Trap System



Catching trap and reservoir for antiprotons.



N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

Cooling trap:

Weak magnetic bottle with cyclotron energy resolution of 5Hz/K. Small trap with improved cooling time constant.

Procedure:

Alternate fast coupling and measuring cycles. Preparation of particle with single spin flip resolution within a few minutes.

Improved detectors:

$$\sigma \propto \sqrt{\frac{1}{4\pi} * \frac{\Delta\nu}{t\sqrt{SNR}}}$$

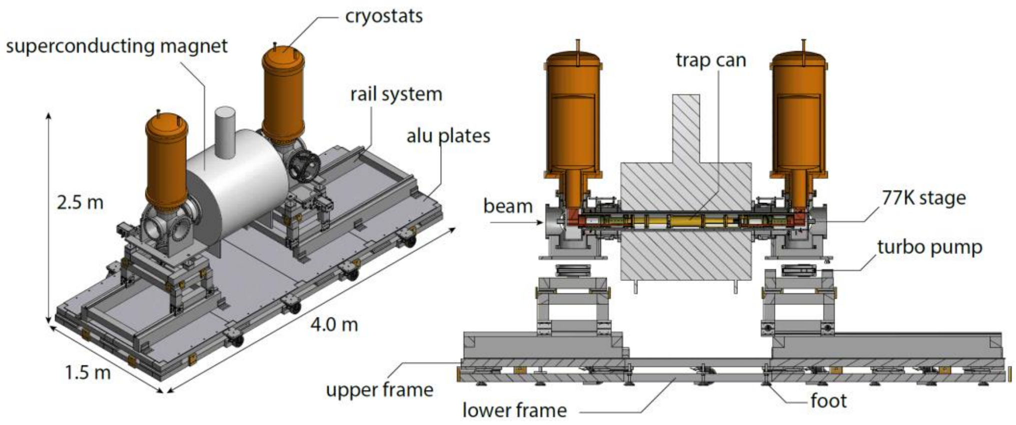
$$\frac{S}{N} = \frac{\sqrt{4\,\pi\,k\,T\,R_p}}{e_n}$$

two times faster detection

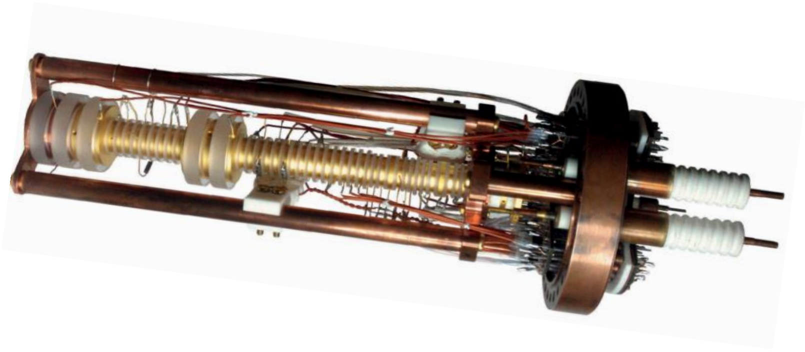
BASE-CERN Apparatus

- ***Experiment was approved in June 2013.***

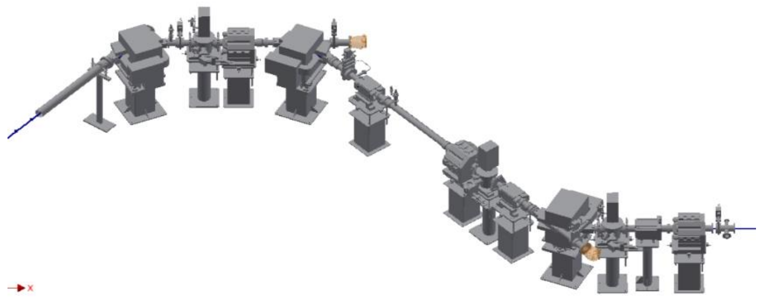
Constructed new apparatus



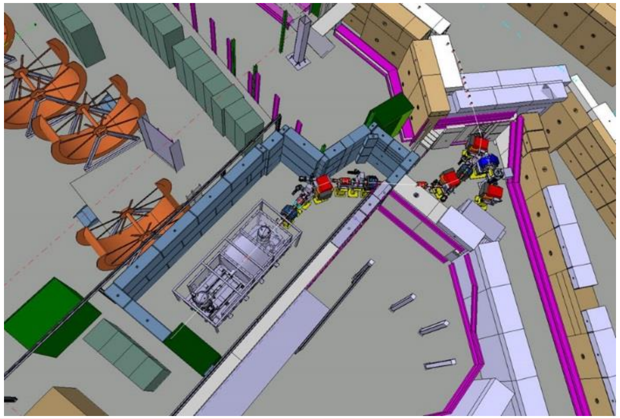
Developed advanced trapping system



Constructed antiproton transfer line



Implemented system into AD facility



Installation

...about 1 and a half year ago there was nothing...

06/2013

09/2013

12/2013

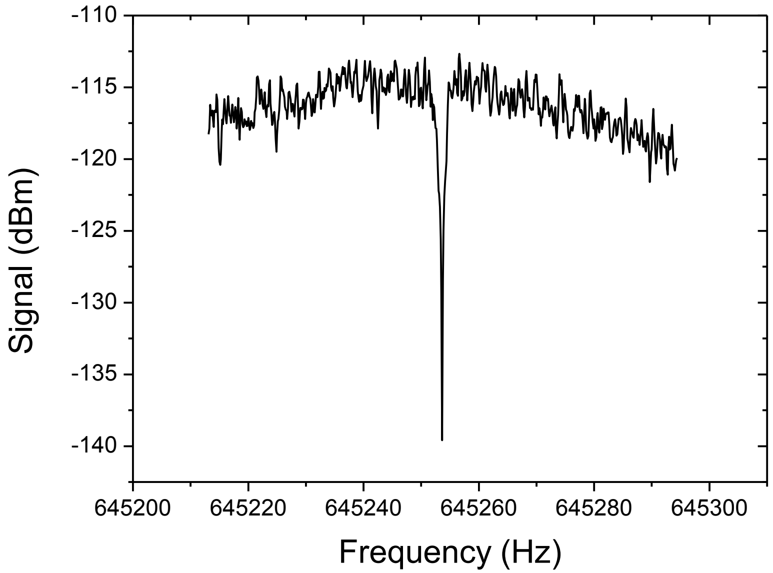
05/2014

11/2013

03/2014

Methods

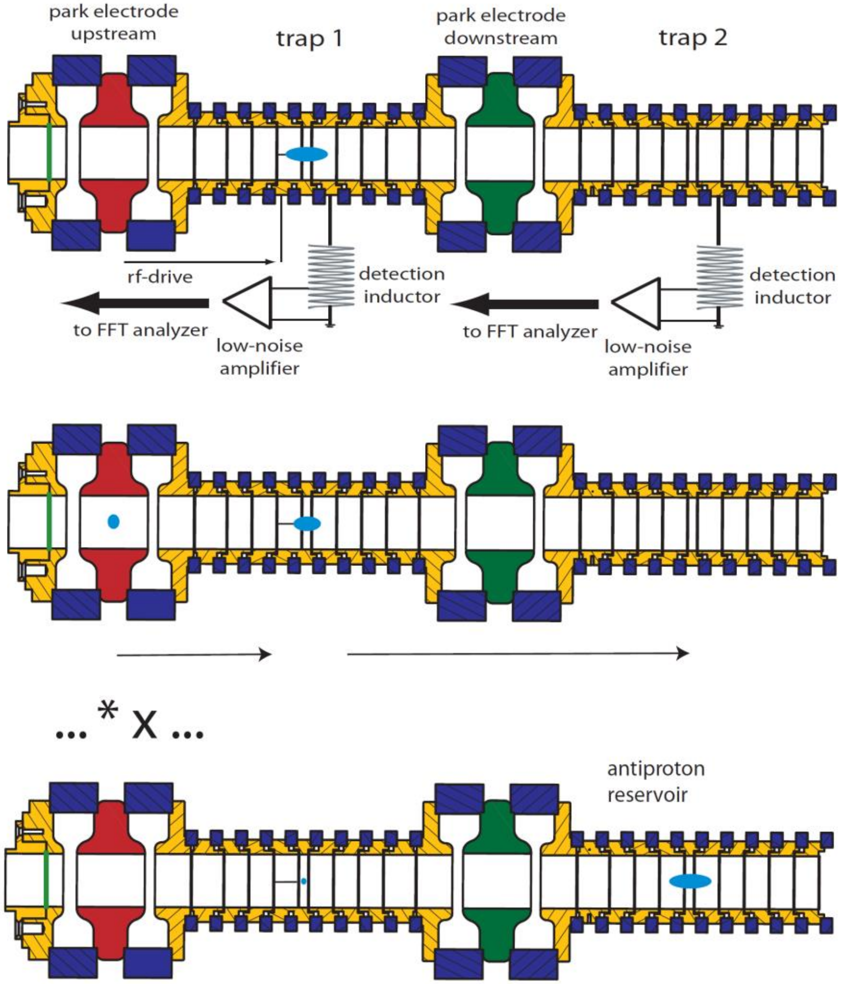
- Established meanwhile all standard techniques used in the antiproton community:
  - Catching
    - Deceleration of 5.3 MeV antiprotons using degrader foils.
    - Fast HV catching pulses to confine the slow antiprotons up to 5 keV.
  - Electron cooling
    - Electron and resistive cooling to 4 K thermal equilibrium energy ~ 320 μeV
  - Electron kick-out
  - Trap cleaning
  - Single particle preparation



Catching: G. Gabrielse et al, PRL 57, 2504 (1986)
Cooling: G. Gabrielse et al, PRL 63, 1360 (1989)
Measurement: G. Gabrielse et al, PRL 65, 1317 (1990)

The Reservoir Trap

Basic idea: serve as antiproton reservoir – survive accelerator shutdown



Initial state: antiproton cloud in trap 1

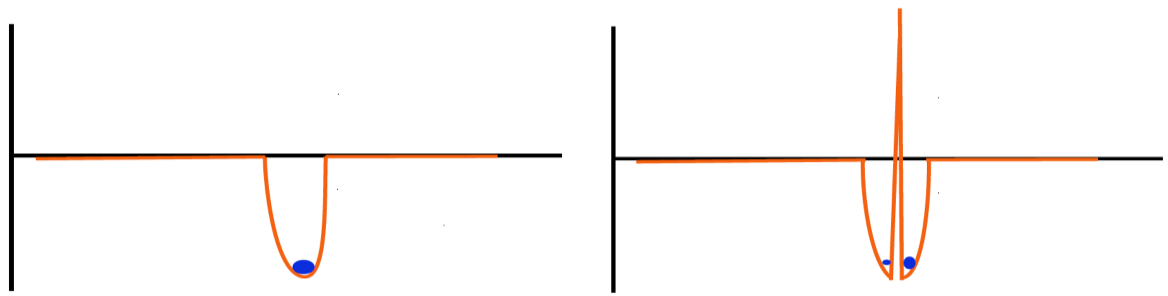
step 1: separation of particle cloud

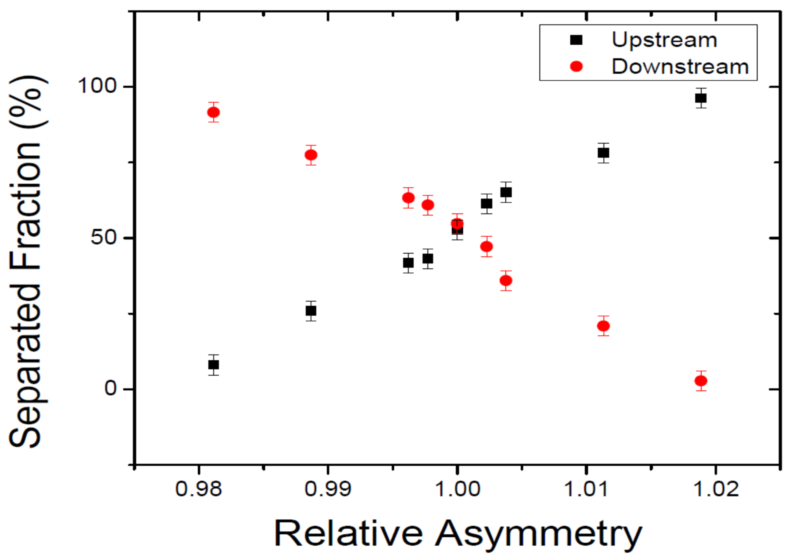
step 2: adiabatic transport to second trap

Final state: cloud ion reservoir, single particle in experiment cycle

Realization

- Found that adequate potential ramps are most efficient to perform this scheme.
- Potential-tweezer scheme:



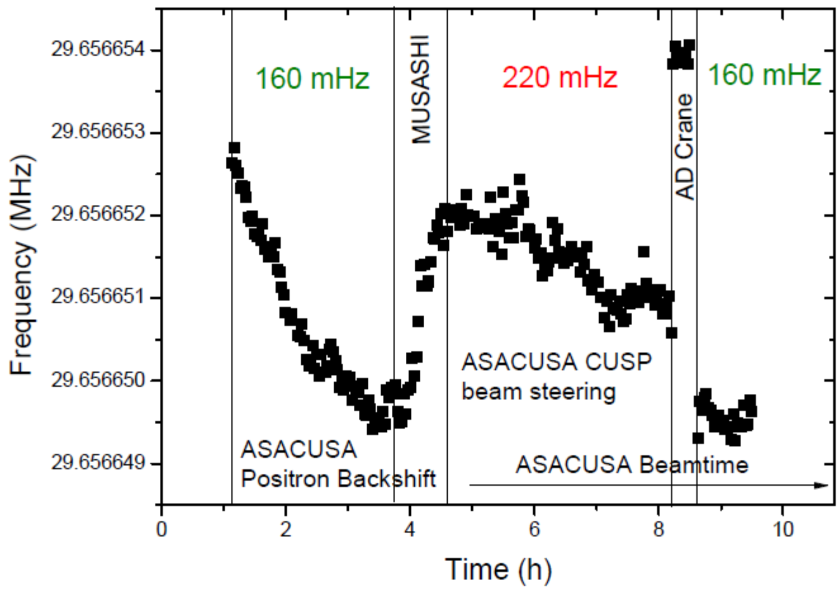


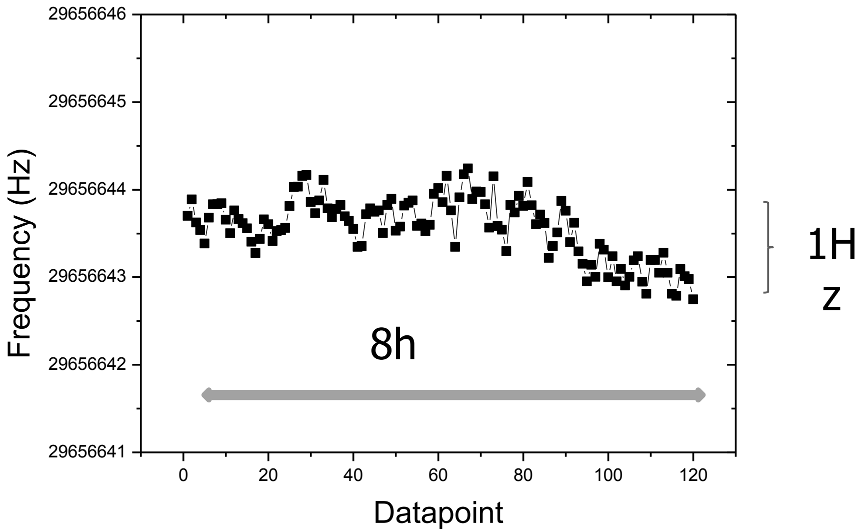
- All experiments were performed with the same cloud of particles **-> also merging of particle clouds works.**
- No particle loss during separation/merging experiments
- One separation cycle takes only 12s

Noise

- Careful electronics layout: No issues with electrical interference
- Magnetic noise is a pain:

10 nT fluctuation

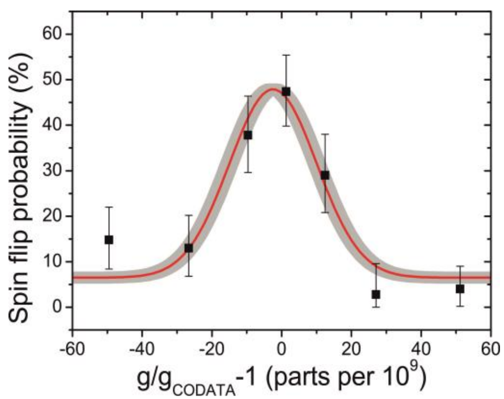




- Cyclotron frequency fluctuations of 500ppt – proves magnetic inhomogeneity problems seen in Mainz solved
- With respect to magnetic field stability 500ppt measurement feasible

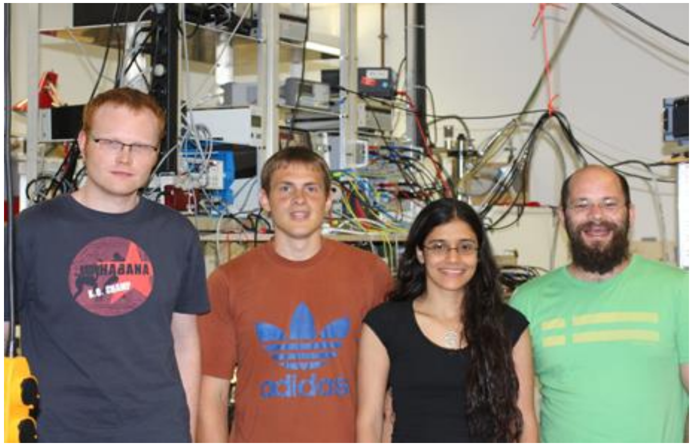
Conclusion

- Detection of single proton spin transitions
  - Demonstration of double Penning-trap technique
    - Most precise and direct high-precision measurement of proton g -factor
- BASE experiment successfully installed
  - Captured and prepared first single antiproton



CERN

Mainz



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Thank you for your attention

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