BASE – 2015 Antiproton Run

Stefan Ulmer

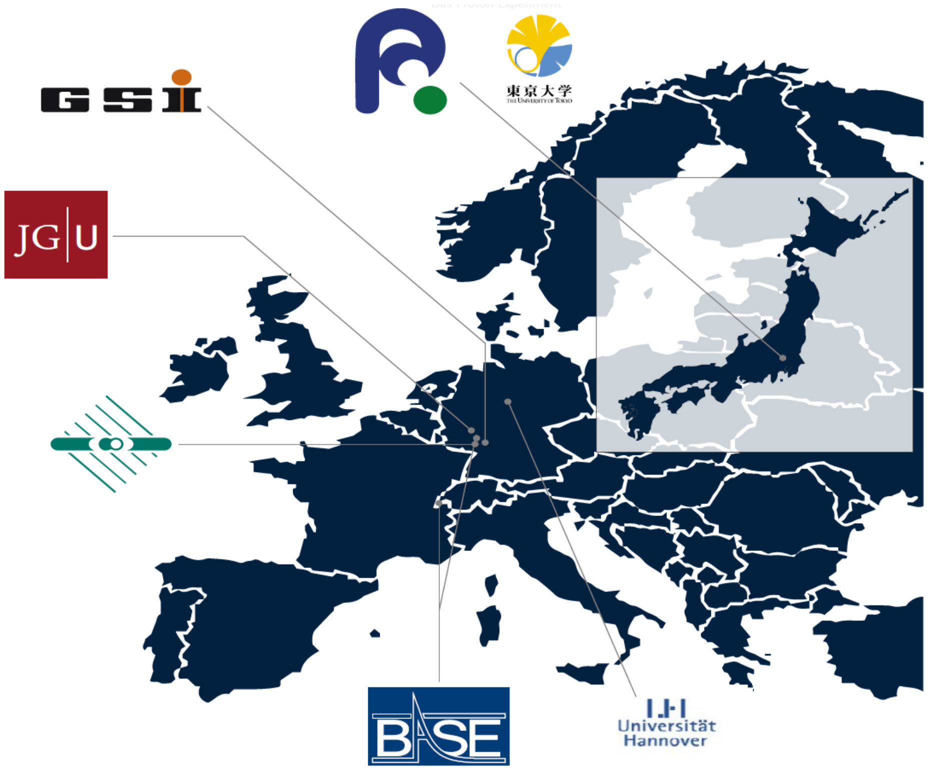
RIKEN

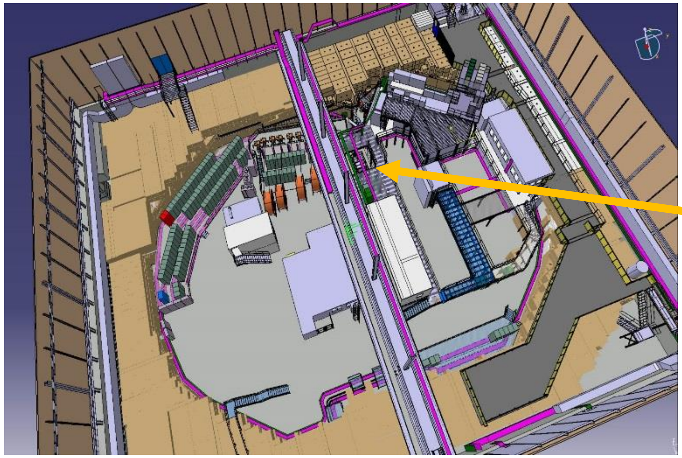
on behalf of the

BASE Collaboration

BASE – Collaboration

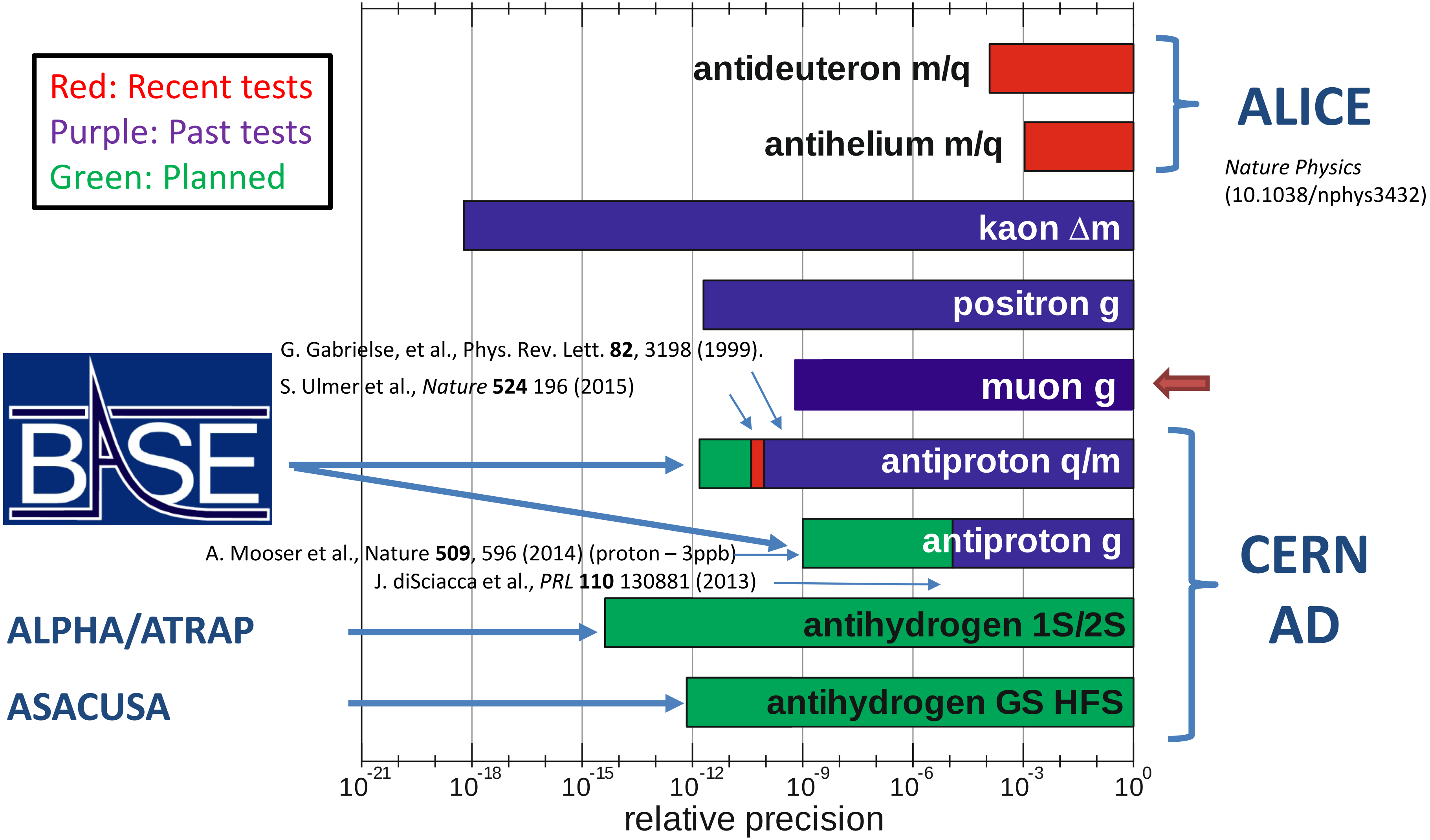
- **Mainz:** Measurement of the magnetic moment of the proton (Ulmer, Blaum, Walz, Quint)
- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (Ulmer, Yamazaki, Blaum, Matsuda)
- **Hannover:** Implementation of Laser based Penning trap techniques.





Project was approved in 2013, took first beam in 2014.

Testing CPT Invariance



Red: Recent tests
Purple: Past tests
Green: Planned

ALICE

Nature Physics (10.1038/nphys3432)

G. Gabrielse, et al., Phys. Rev. Lett. **82**, 3198 (1999).

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

A. Mooser et al., Nature **509**, 596 (2014) (proton – 3ppb)

J. diSciacca et al., *PRL* **110** 130881 (2013)

ALPHA/ATRAP

ASACUSA

CERN AD

CPT test with fractional precision of 10^{-18} available… why continue measuring?

Concept of CPT violation

- Basic idea: Add CPT violating term to a Hamiltonian based on Standard Model and treat as a perturbation theory

  => Absolute energy change ΔE will be derived

$$H' = H_{SM} + \Delta V \quad \Rightarrow \quad < \psi^* | \Delta V | \psi >= \Delta E$$

System based on SM

CPT violating term

different C's

$$\mathcal{L}_p = \frac{\lambda}{M} \langle T \rangle \bar{\psi} \Gamma (i\partial)^k \psi$$

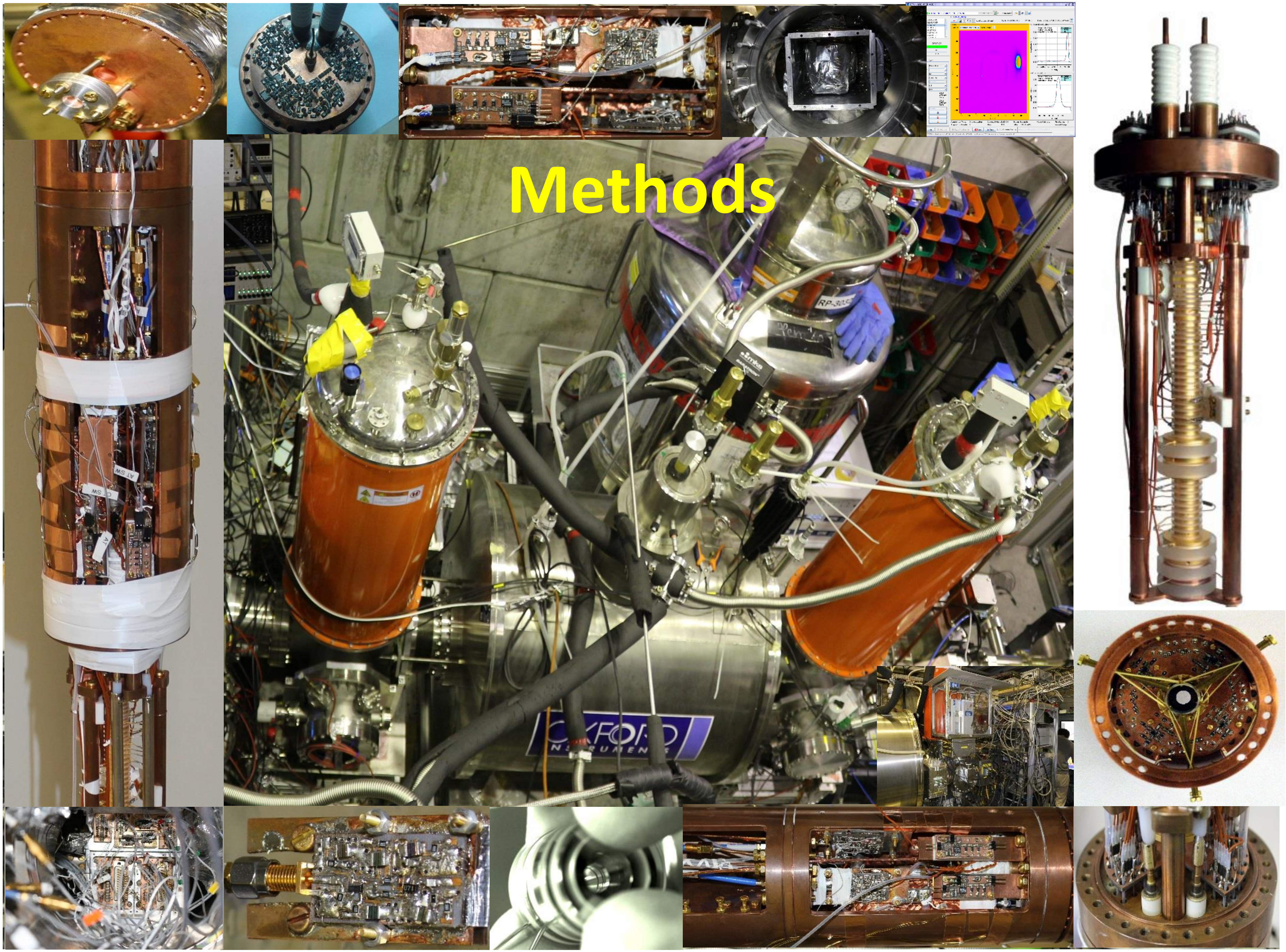
Kostelecky et al.

- Absolute energy resolution (normalized to m-scale) is appropriate measure to characterize sensitivity of an experiment with respect to CPT violation.
- Single particle measurements in Penning traps give high energy resolution.

	Relative precision	**Energy resolution**
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV
p-p̄ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV
p-p̄ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV

BASE aims to improve with 10^{-9} relative precision

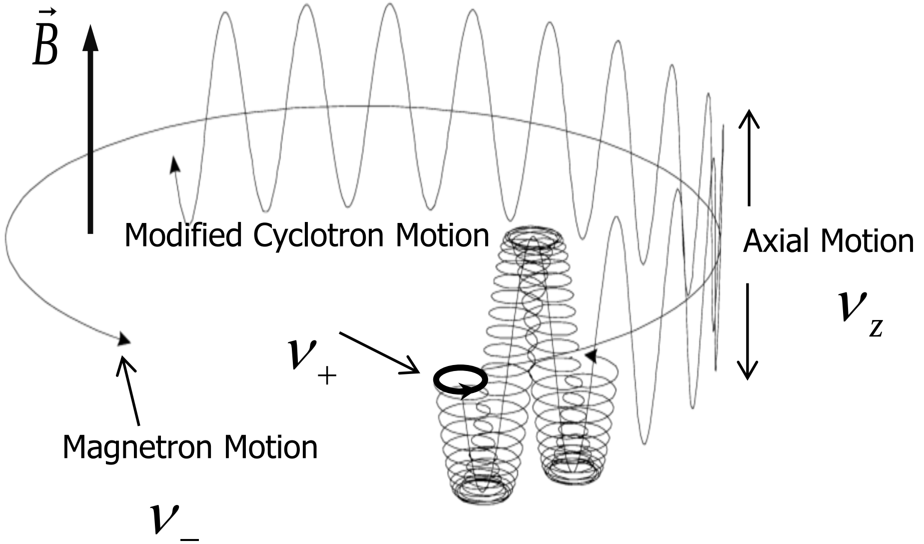
Methods

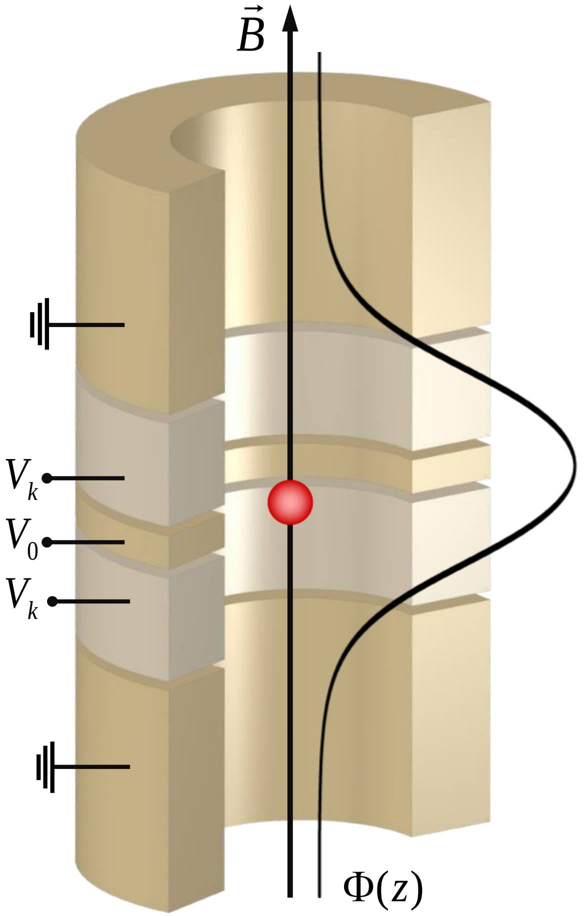


Main Tool: Penning Trap

radial confinement: $\vec{B} = B_0 \hat{z}$

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





Axial	$\nu_z = 680\,\mathrm{kHz}$
Magnetron	$\nu_- = 8\,\mathrm{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\mathrm{MHz}$

Invariance-Relation

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

Cyclotron Frequency

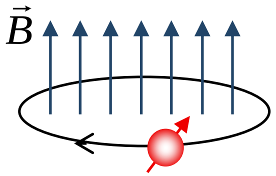
$$\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

L. S. Brown and G. Gabrielse, Phys. Rev. A **25**, 2423 (1982).

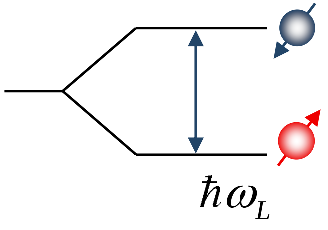
Measurements

Experiments performed with single particles in Penning traps

Cyclotron Motion



Larmor Precession



g: mag. Moment in units of nuclear magneton

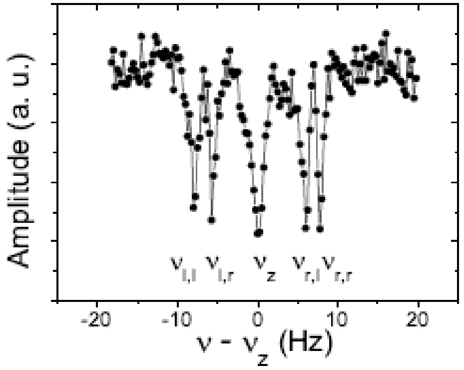
$$\omega_c = \frac{e}{m_p} B$$

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

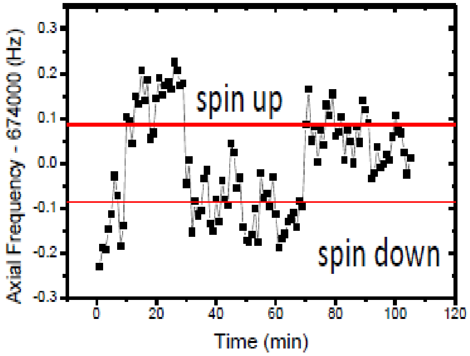
simple

difficult

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



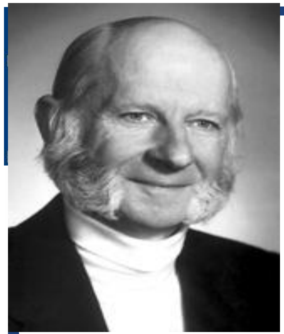
S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)



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

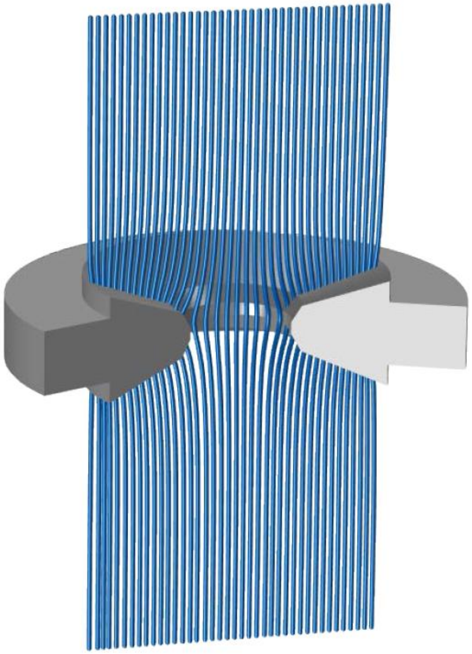
Image current detection / q/m measurement

Determination of the g-factor reduces to measurement of a frequency ratio -> in principle **a very simple** experiment –> **full control, no theoretical corrections**



Larmor Frequency Measurement

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

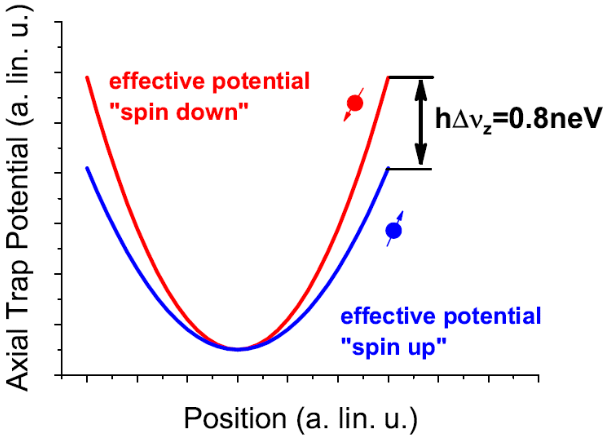
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

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

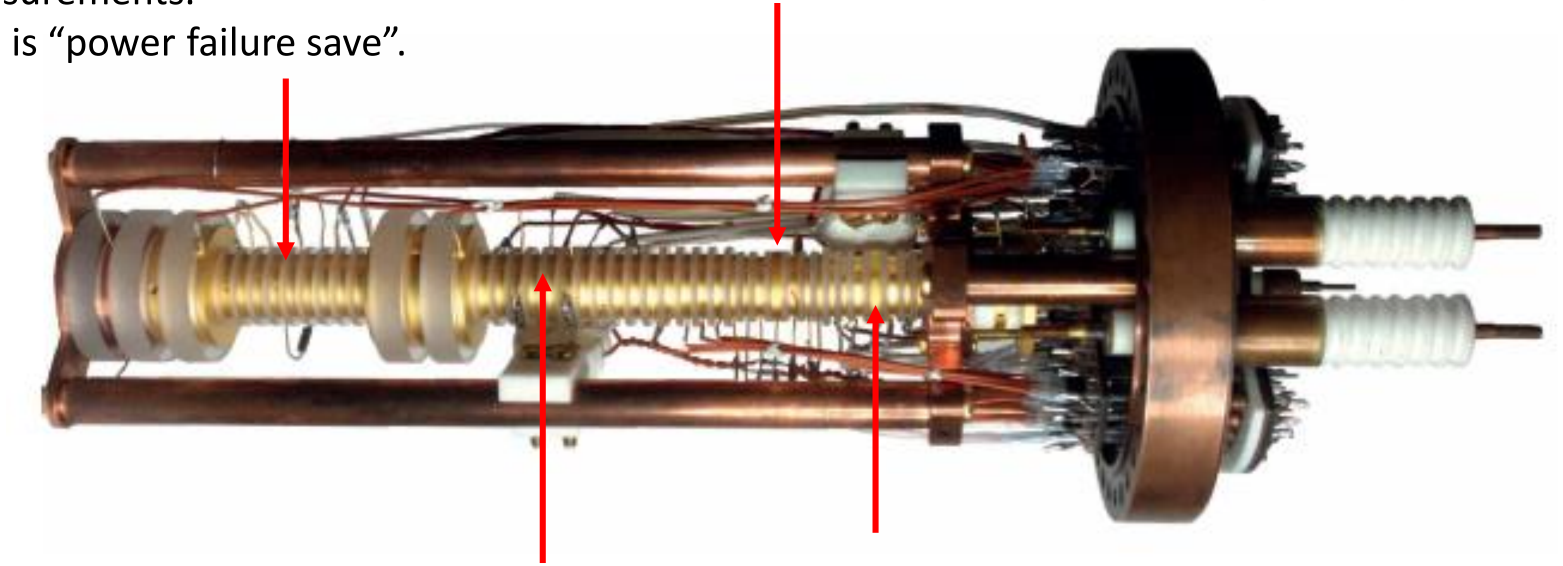


Integration

All methods are implemented in a 4-Penning trap system

Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
Trap is "power failure save".

Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**



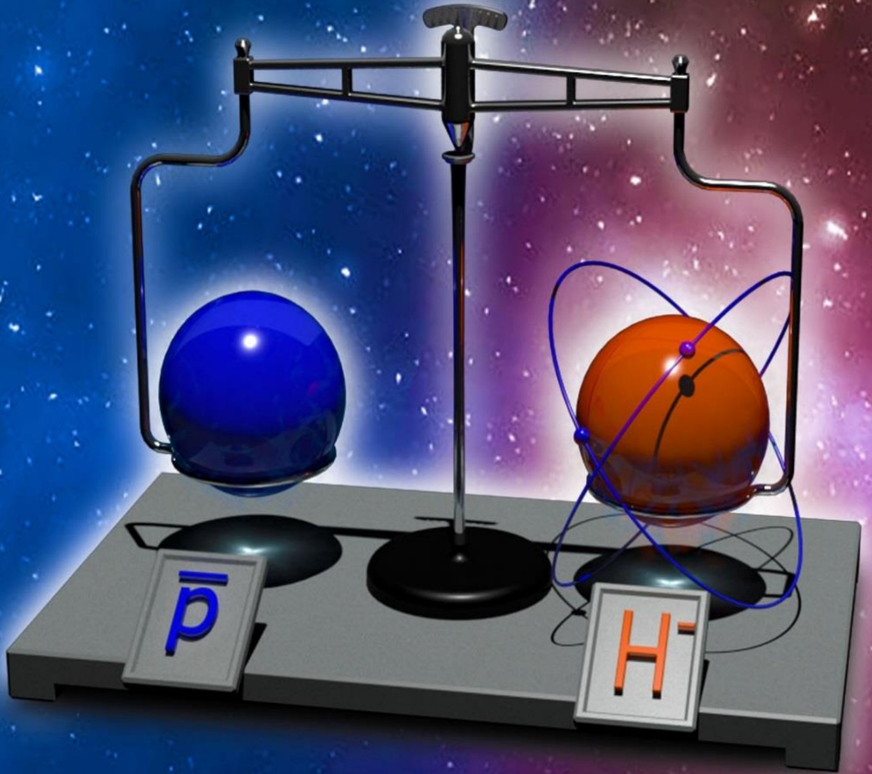
Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$ **(10 x improved)**

Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$

Charge-to-Mass-Ratio measurements

g-factor measurements

High-Precision Comparison of the



Antiproton-to-Proton Charge-to-Mass Ratio

Basic principle

Inspired by TRAP measurement, >16 years ago: Measure free cyclotron frequencies of antiproton and H$^-$ ion.

G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky, and
W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

antiproton

H$^-$ ion

*using proton=>opposite charge=>position in the trap changes

- 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

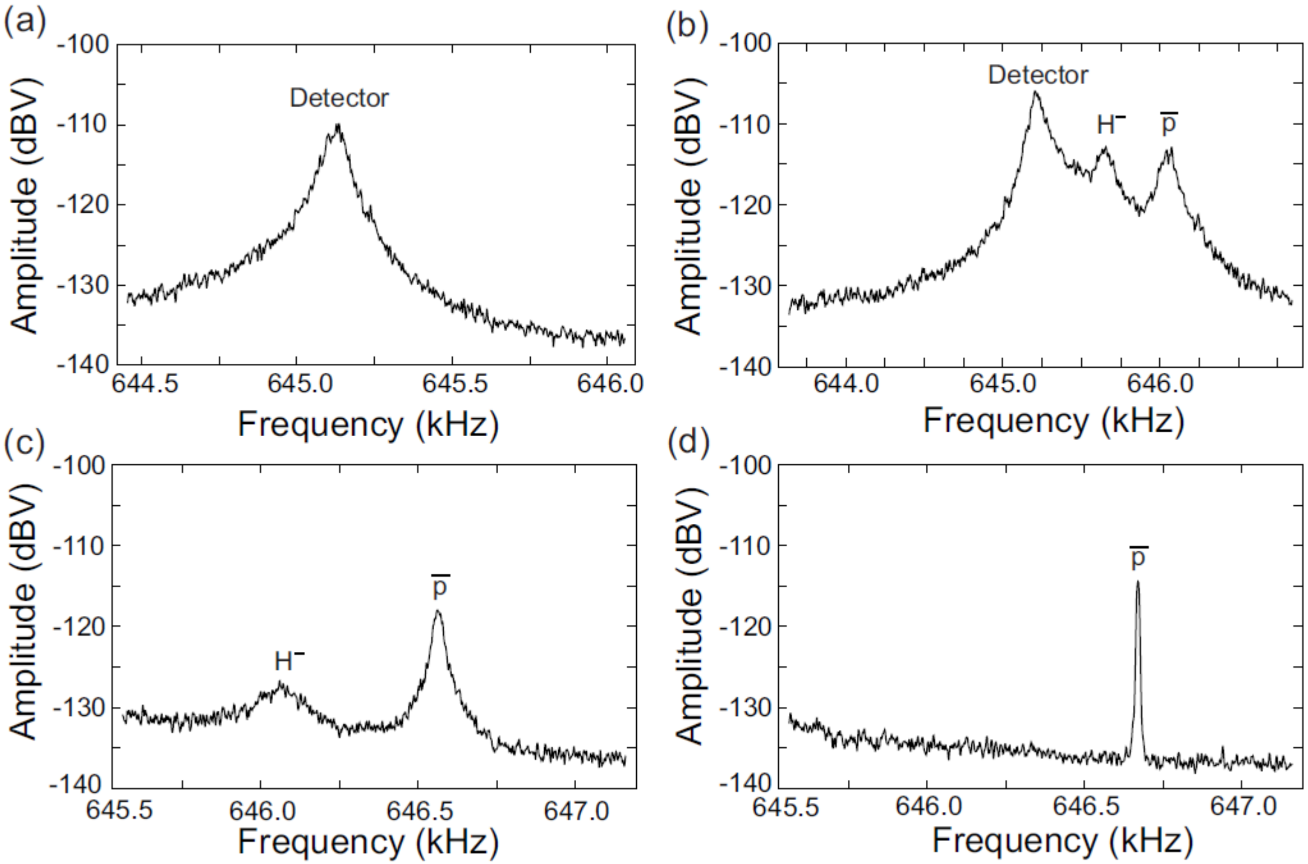
$$R = \frac{\nu_{c\bar{p}}}{\nu_{cH^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \mathrm{x} \cancel{\frac{B/2\pi}{B/2\pi}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

Magnetic field cancels out!

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

$$R_{theo} = 1.0010892187542(2)$$

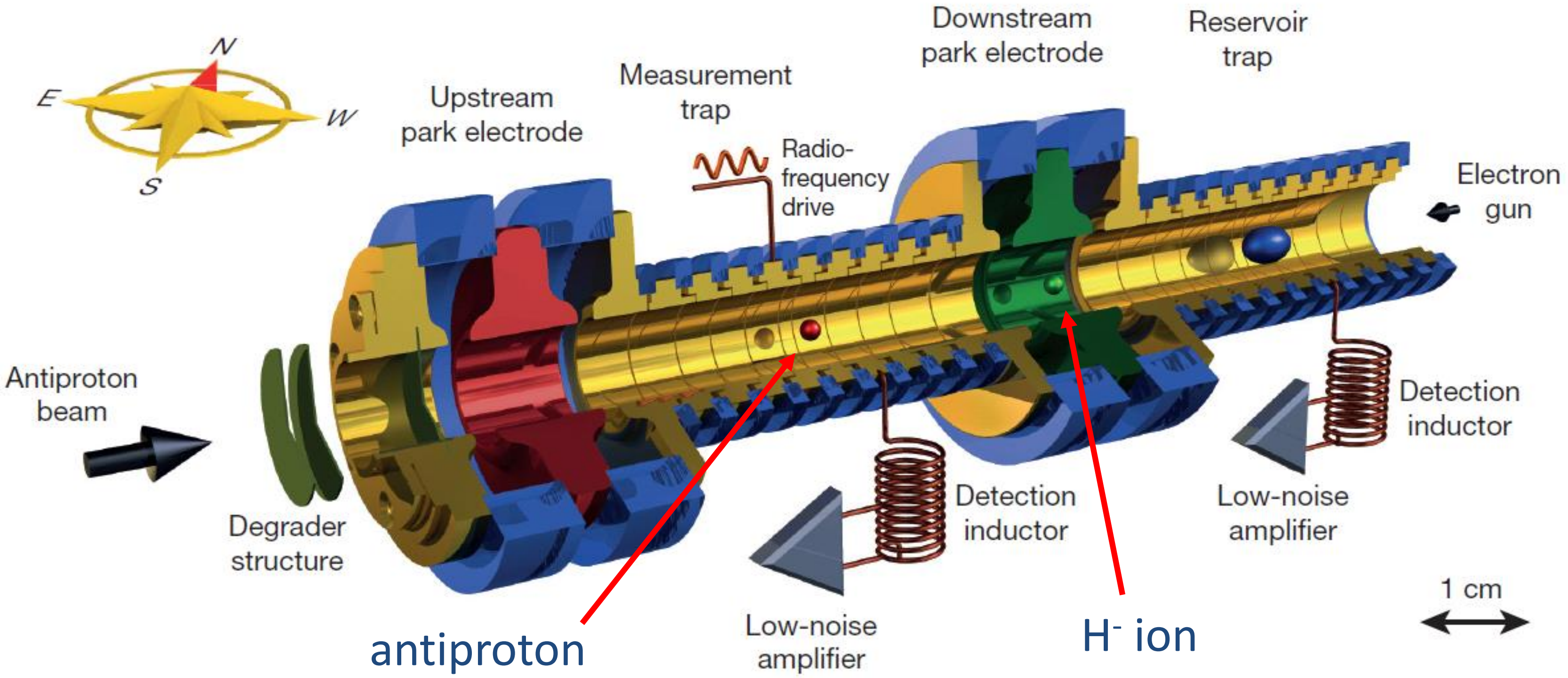
H⁻ ions for free



- details of H^- trapping have yet to be understood.
- typical yield H^-/pbar = 1/3.
- managed to prepare a clean composite cloud of H^- and antiprotons.

Techniques

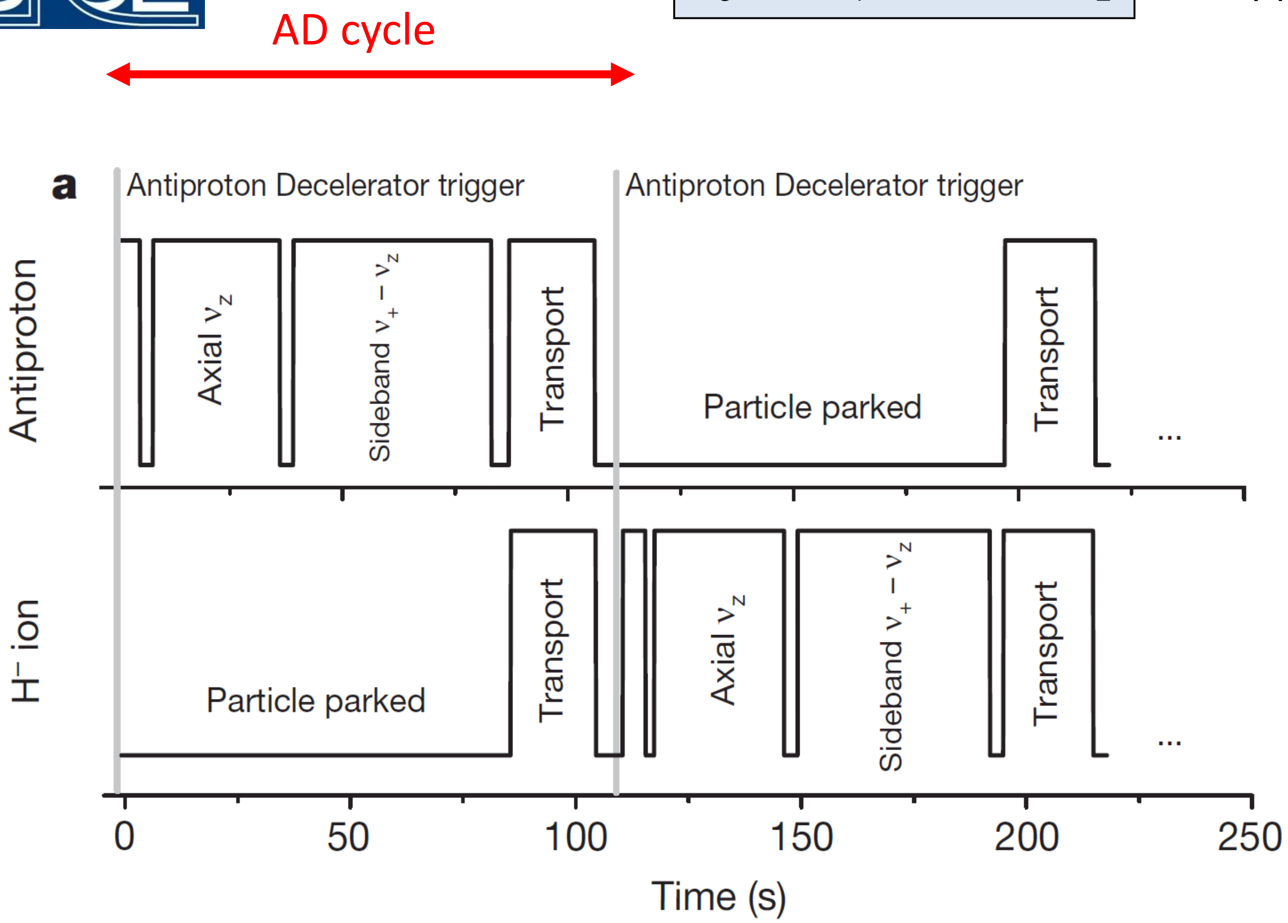
Based on reservoir extraction technique and methods to prepare negative hydrogen ions we prepared an interesting set of initial conditions

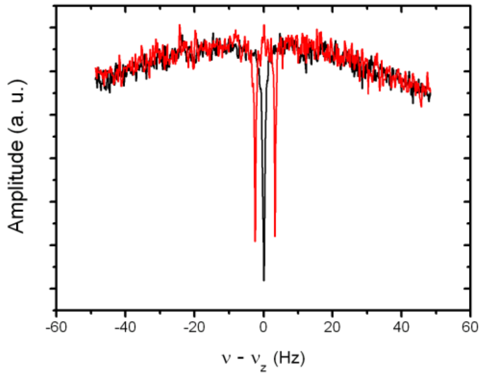


Comparison of proton/antiproton cyclotron frequencies: achieved in a not fully optimized single night test measurement a precision of 400 ppt

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

L. S. Brown and G. Gabrielse,
Phys. Rev. A **25**, 2423 (1982).





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

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

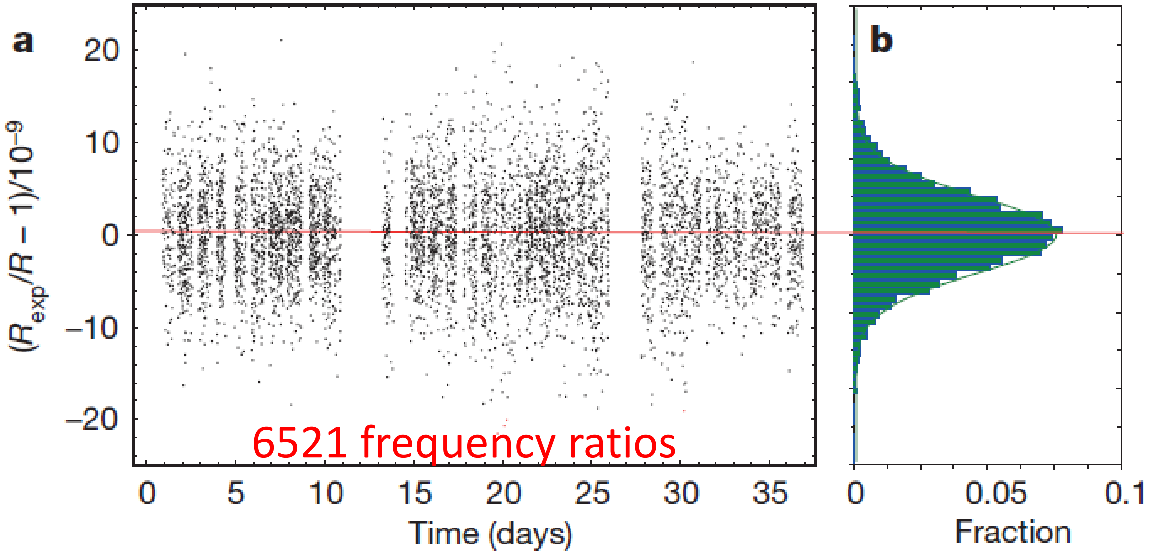
$$\nu_l + \nu_r = \nu_z + \nu_{rf} - \nu_\pm$$

Measurement cycle is triggered by the antiproton injection into the AD

One BASE charge-to-mass ratio measurement takes two AD cycles

First high-precision mass spectrometer which applies this technique

Result



- Experimental result:

$$R_{exp} = 1.001\ 089\ 218\ 872\ (64)$$

- Cyclotron frequency ratios for $\bar{\mathrm{p}}$-to-$\bar{\mathrm{p}}$ and H^--to-H^- R_{id} are also evaluated

$$R_{id} - 1 = -3(79) \times 10^{-12}$$ ← Consistent with 1

- Corrected result: **$R_{exp,c} = 1.001\ 089\ 218\ 755\ (64)\ (26)$**

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

- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

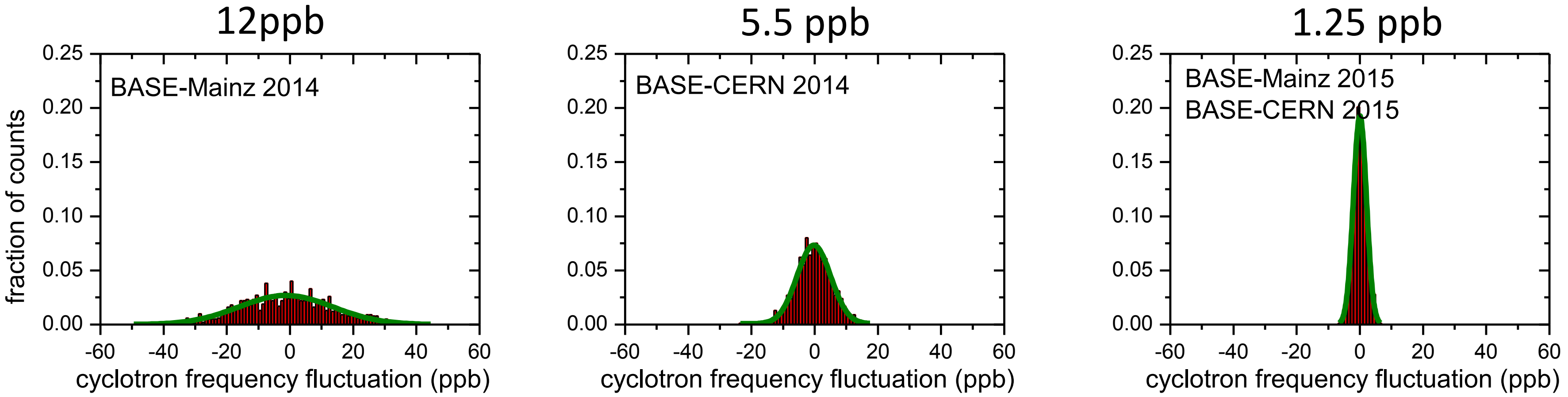
Progress – BT 2015

New magnet implemented:

Set of many shim coils enables improved tuning of B-field in the measurement trap (systematic correction reduced by factor of 10).

Implementation of a self-shielded solenoid around the measurement trap

G. Gabrielse *et al.*, J. Appl Phys. 63, 5014 (1988)

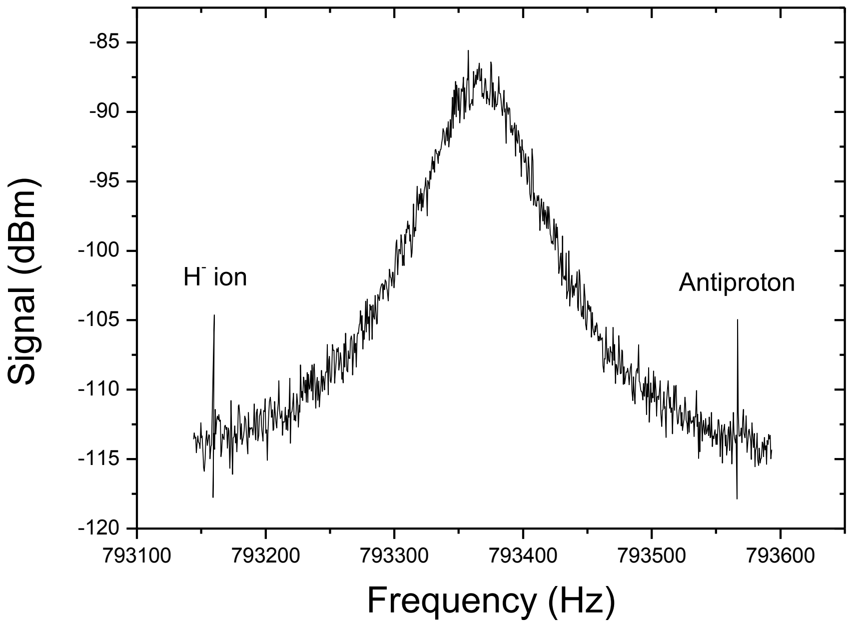


RMS fluctuation of magnetic field improved by factor of 4.

With conditions of beamtime 2014 **-> Q/M comparison at level 10 ppt possible.**

Simultaneously trapped particles

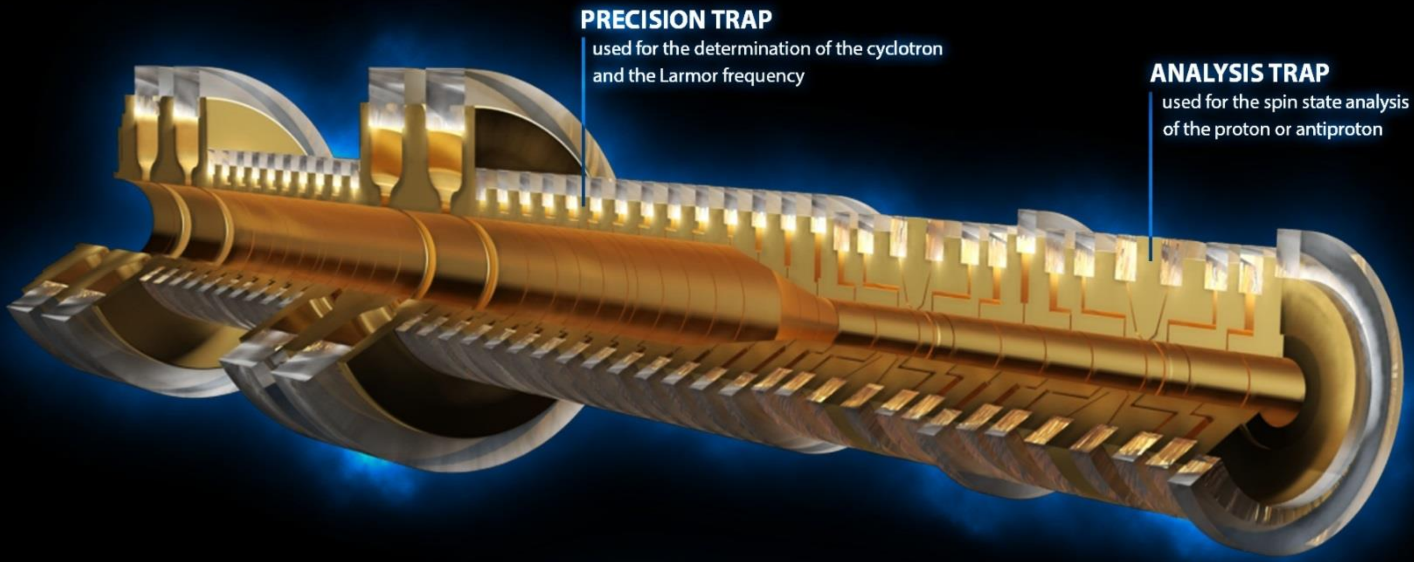
- **Dave Pritchard scheme:** Perform simultaneous measurement on antiproton and hydrogen ion -> improved precision of q/m ratio



- During a measurement the particles will experience exactly the same magnetic field fluctuations -> ppt level.
- Systematics due to particle / particle interaction.
- BASE detector is good enough to do that -> planned.

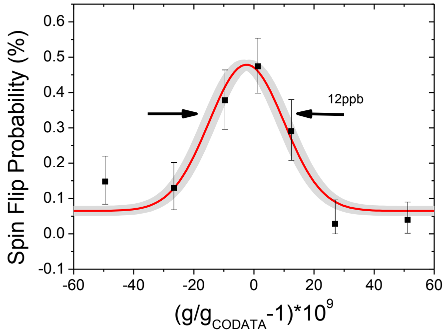
S. Rainville et al., Nature **438**, 1096 (2005).

Beamtime 2015



PRECISION TRAP
used for the determination of the cyclotron and the Larmor frequency

ANALYSIS TRAP
used for the spin state analysis of the proton or antiproton



g/2 = 2.792847350 (7) (6)

3.3 p.p.b.

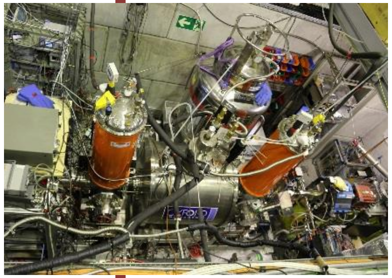
A. Mooser et al., Nature **509**, 596 (2014)

Focused on preparation of pbar magnetic moment measurement

$$\frac{\mu_{\bar{p}}}{\mu_p}$$

BASE Progress 2015

Installation and commissioning of new superconducting magnet



Development of new detection systems

Antiproton Run

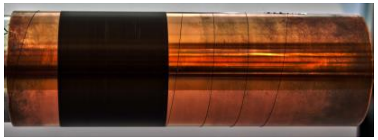
Parasitic mode after 5 days of beam

Commissioning of multi-trap methods

1 4 7 10

- Mechanical implementation
- Modification of experiment geometry
- Cooling
- Shimming
- Tuning
- Characterization

Work on self shielding solenoid



Proton experiments

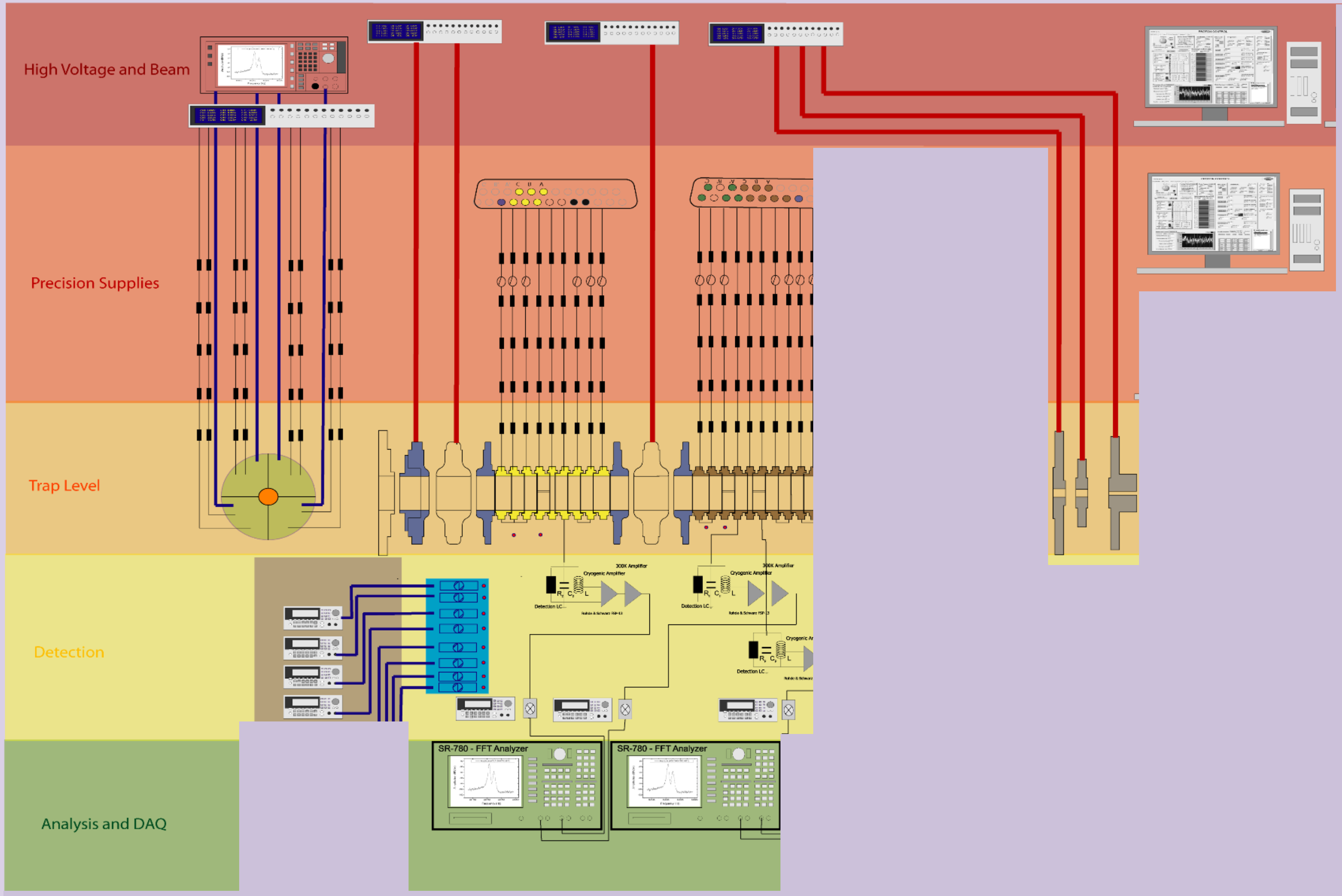
several iteration / cooling cycles needed

Commissioning of experiment, catching, kickout, reservoir extraction…

Experiments

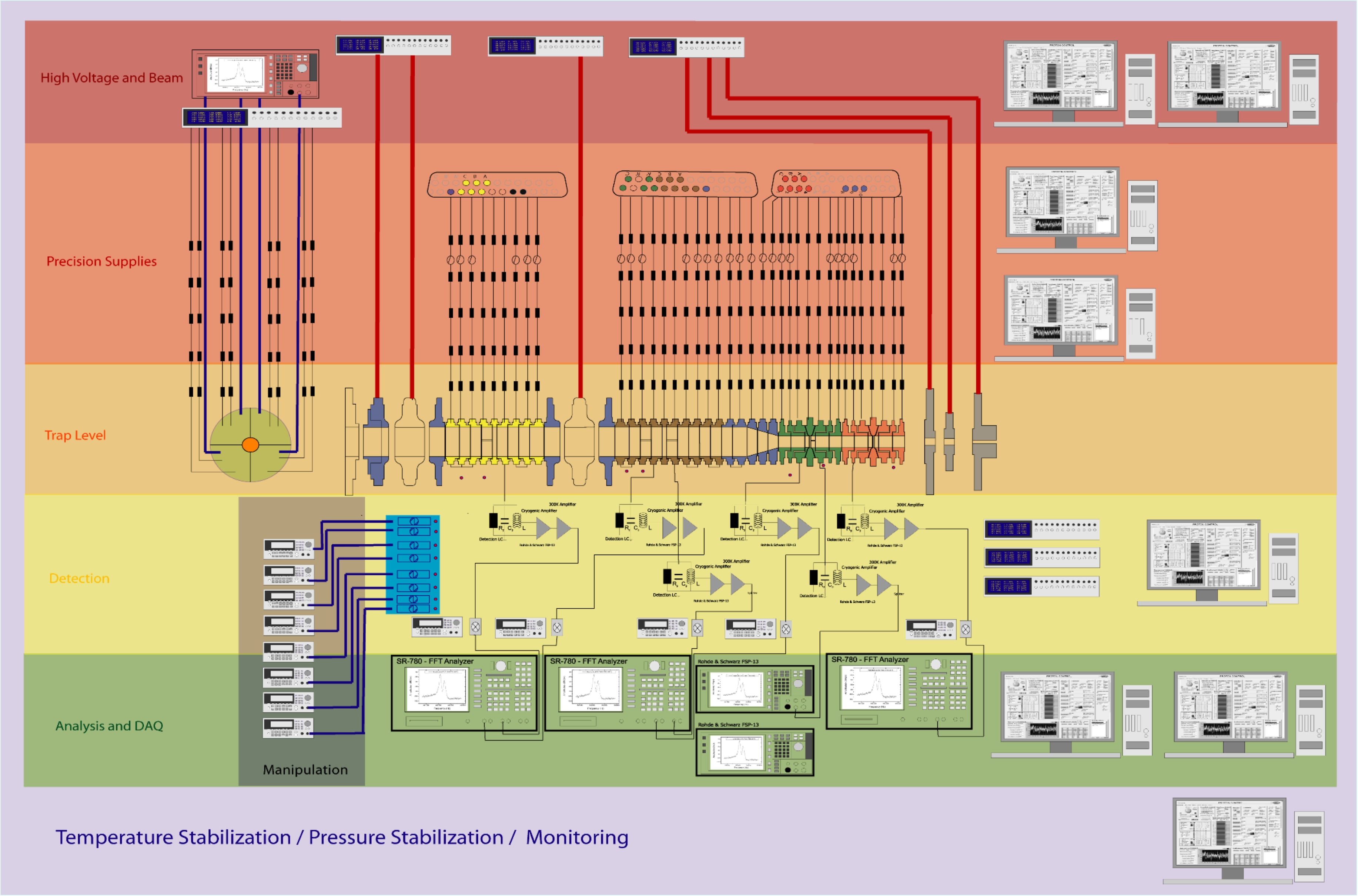
2015 BASE consumed 7 full and 5 shared shifts / still running

BASE 2014



Aim of 2015 run: **implement g-factor measurement** -> doubled hardware requirements

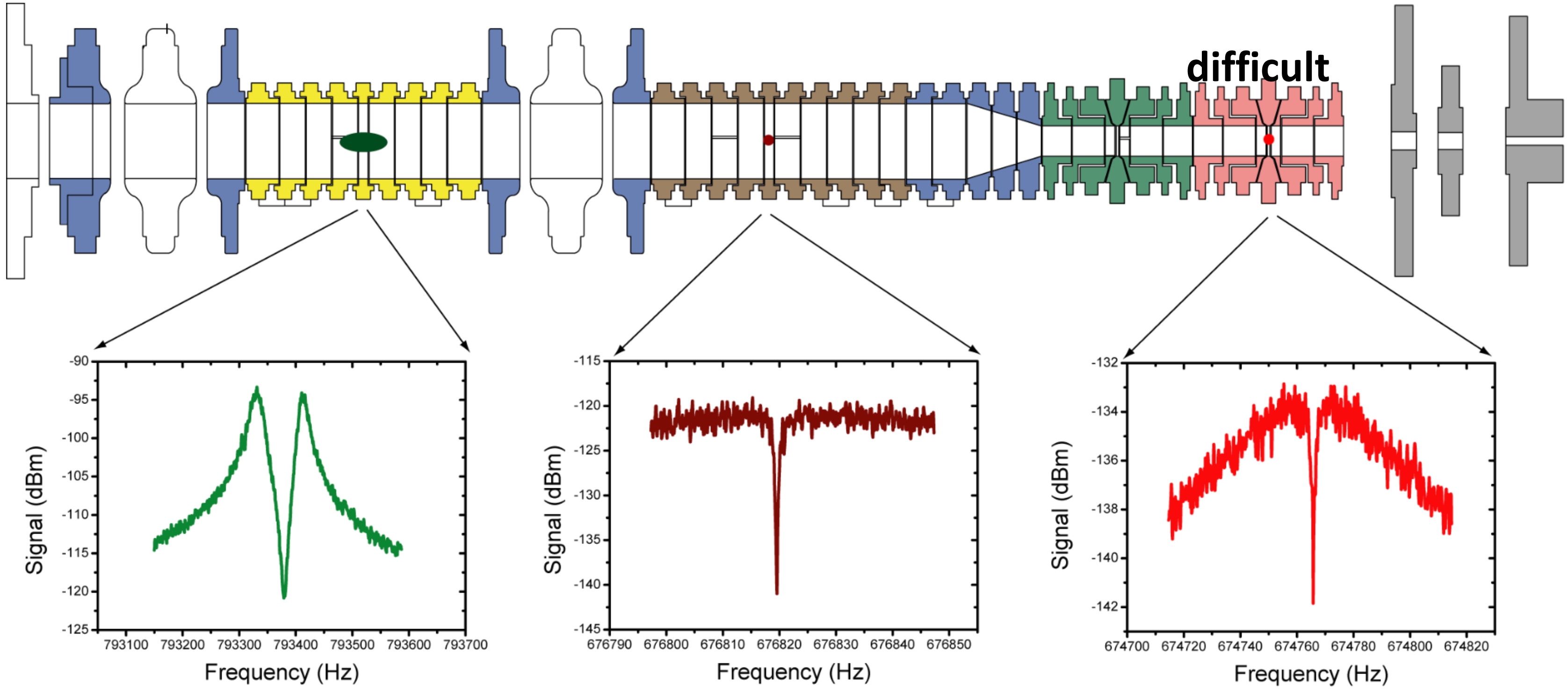
BASE 2015


High Voltage and Beam
Precision Supplies
Trap Level
Detection
Analysis and DAQ
Manipulation
300K Amplifier
Cryogenic Amplifier
Detection LC
R_p
C_p
L
Rohde & Schwarz FSP-13
Splitter
SR-780 - FFT Analyzer
SR-780 - FFT Analyzer
Rohde & Schwarz FSP-13
Rohde & Schwarz FSP-13
SR-780 - FFT Analyzer
Temperature Stabilization / Pressure Stabilization / Monitoring

Antiproton Magnetic Moment

Beamtime 2015: Shuttling along entire trap stack (20cm/5s) established.

Current situation:



50 antiprotons in reservoir trap

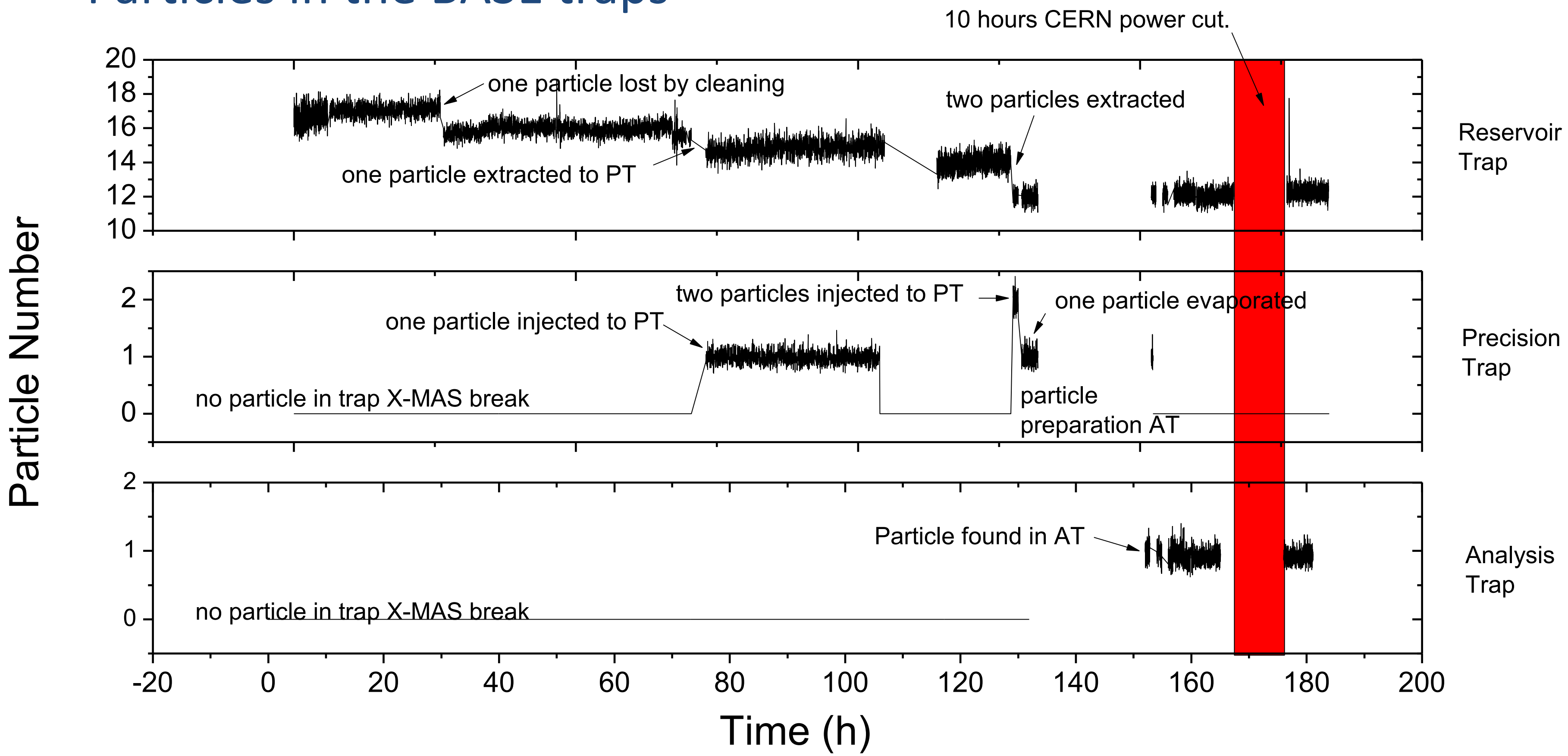
Single antiproton in precision trap

Single antiproton in analysis trap

C. Smorra et al., *The BASE Experiment*, EPJ-Special Topics **224**, 3055 (2015)

Extraction and Shuttling

- Particles in the BASE traps



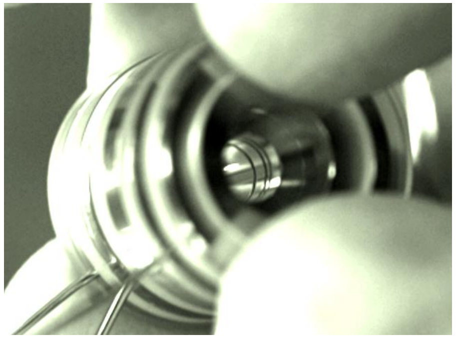
- Consume typically 1 particle per month.

C. Smorra et al., A reservoir trap for antiprotons, Int. Journ. Mass. Spec. 389, 10 (2015).

Analysis trap

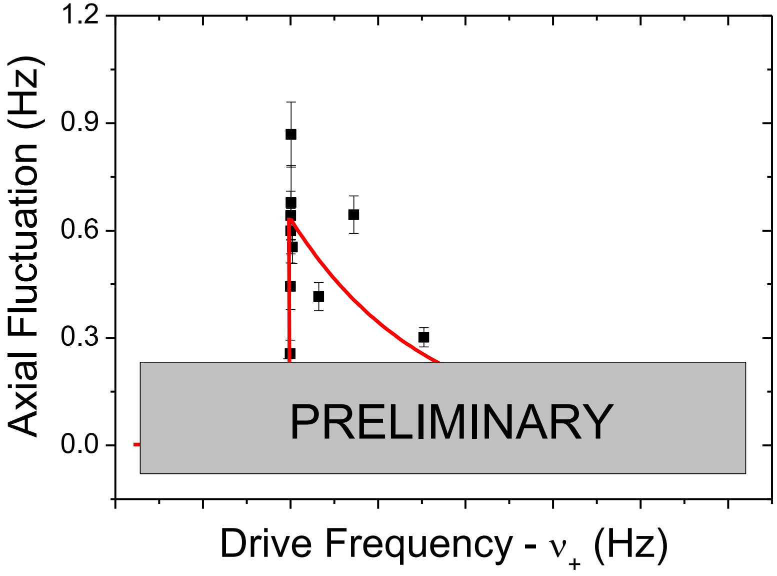
Probably (anti)proton spin flip traps are the most challenging precision Penning traps which have been built so far (3mm diameter).

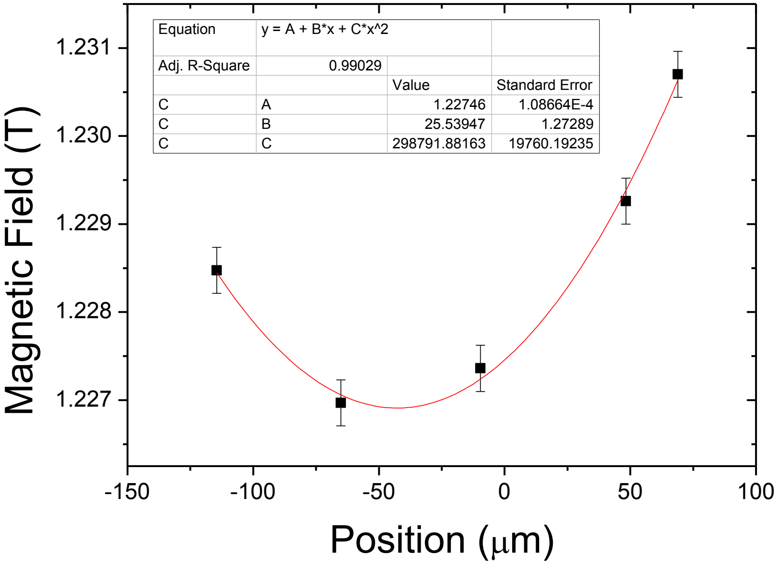
Major amount of 2015 run was used to characterize and stabilize this trap.



Careful characterization of the bottle required.

Shift particle along the trap -> measure cyclotron frequency



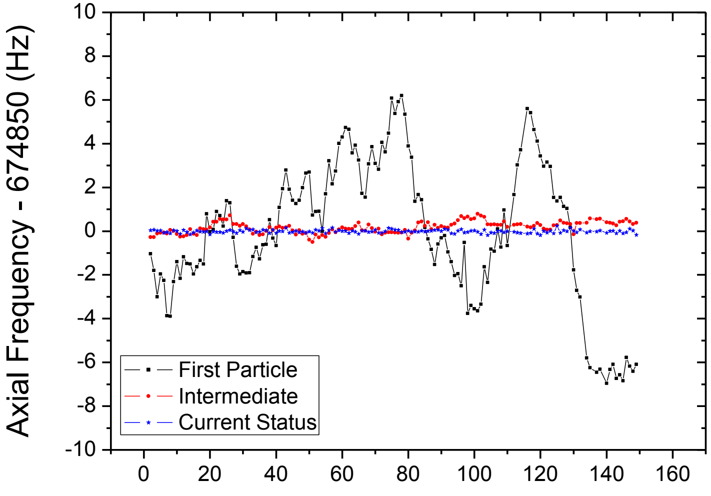


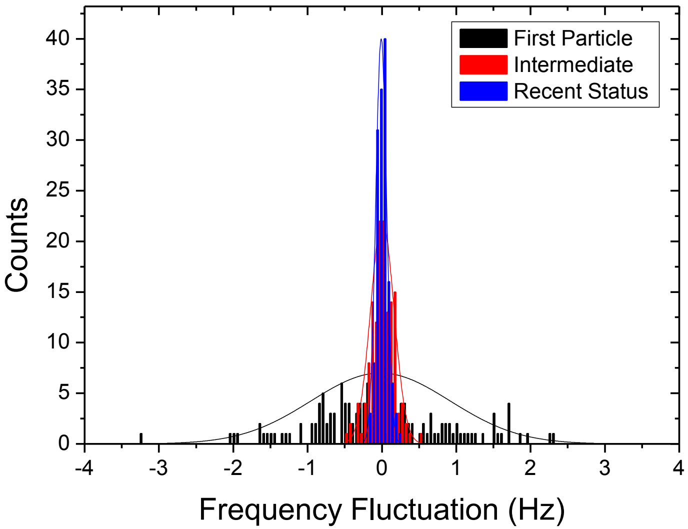
Equation	y = A + B*x + C*x^2		
Adj. R-Square	0.99029		
		Value	Standard Error
C	A	1.22746	1.08664E-4
C	B	25.53947	1.27289
C	C	298791.88163	19760.19235

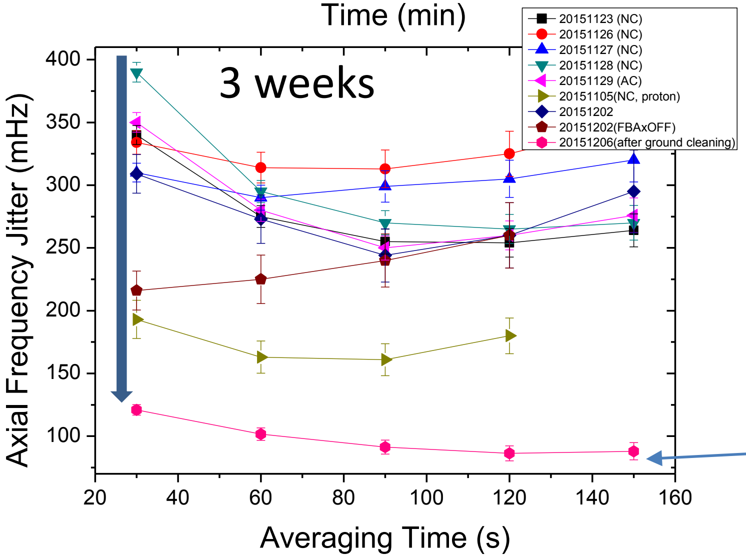
BASE magnetic bottle: 298(19) T/m^2

Progress Analysis Trap 2015

In the magnetic bottle: need to resolve spin flip induced axial frequency jumps of 200mHz:







- Trap cleaning
- Ground loops
- RF tricks
- Feedback cooling

Cyclotron heating rate:

< 1 quantum transition in 240s

In this case: Single spin flip resolution

Statistical Detection of Spin Flips

Measure axial frequency stability:

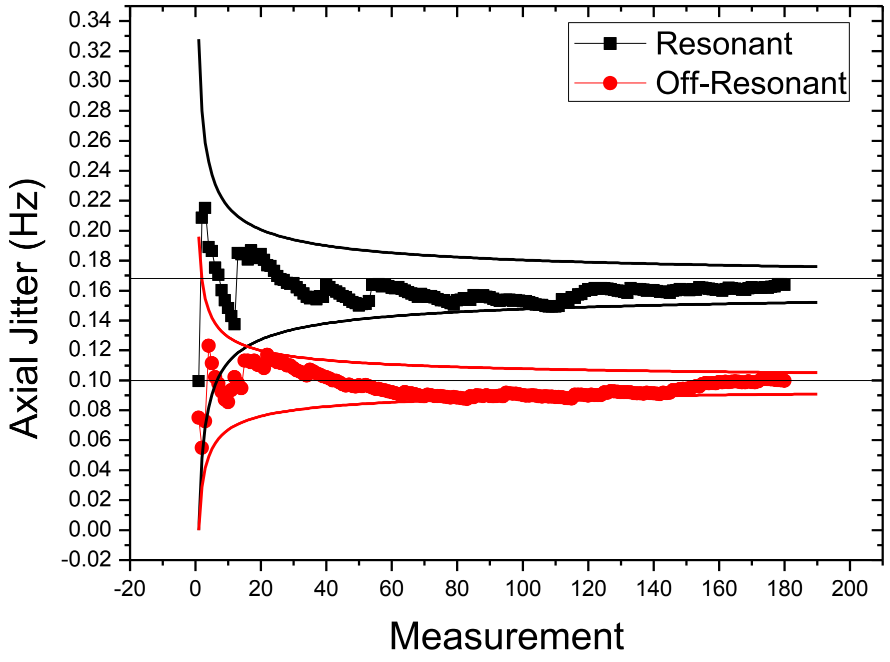
1.) reference measurement with detuned drive on,

2.) measurement with resonant drive on.

Spin flips add up

$$\Xi_{SF} = \sqrt{\Xi_{ref}^{2} + P_{SF}\Delta\nu_{z,SF}^{2}}$$

S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, J. Walz , Phys. Rev. Lett 106, 253001 (2011)



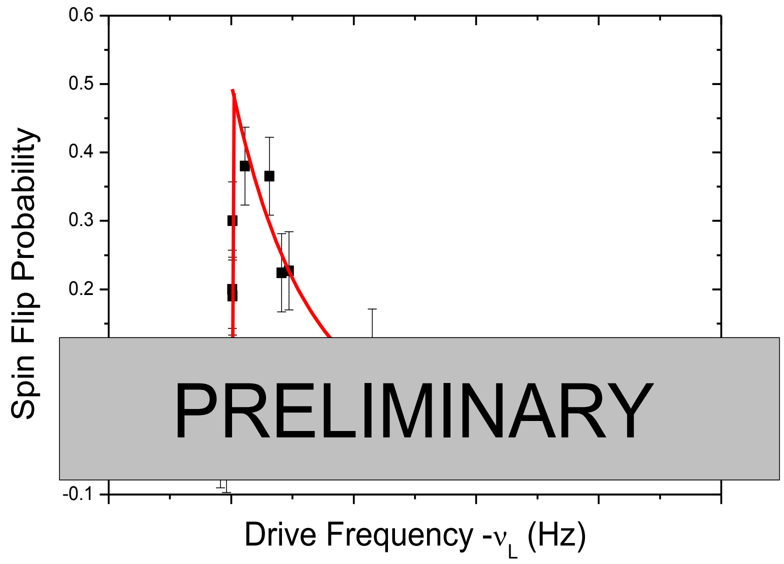
Cumulative measurement:

Black – frequency stability with superimposed spin flips.

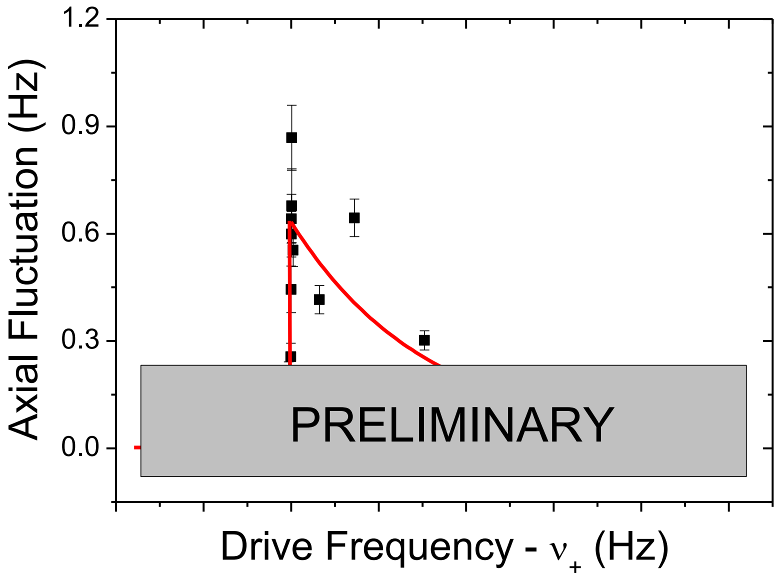
Red – background stability

Resonances

- Larmor



- Cyclotron

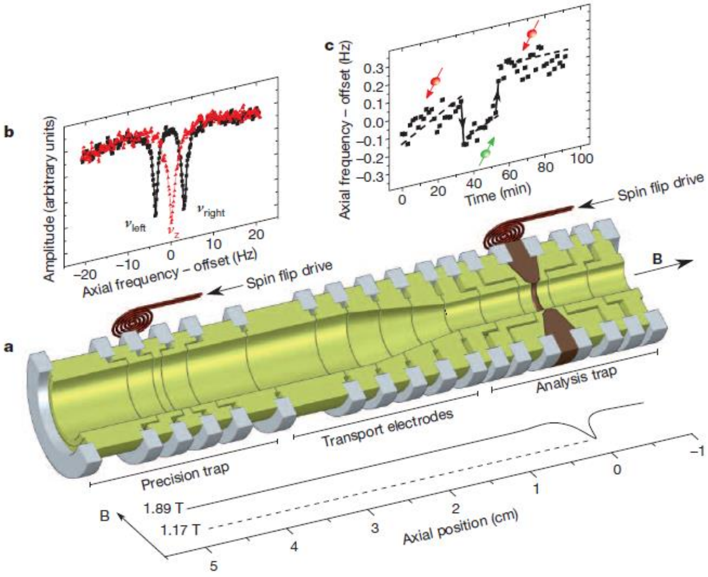


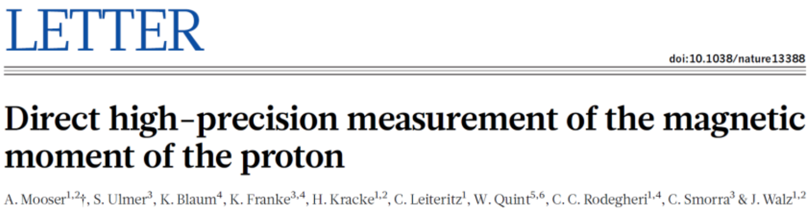
Work in progress

Beamtime 2016

GOAL:

- Apply double trap scheme to the antiproton





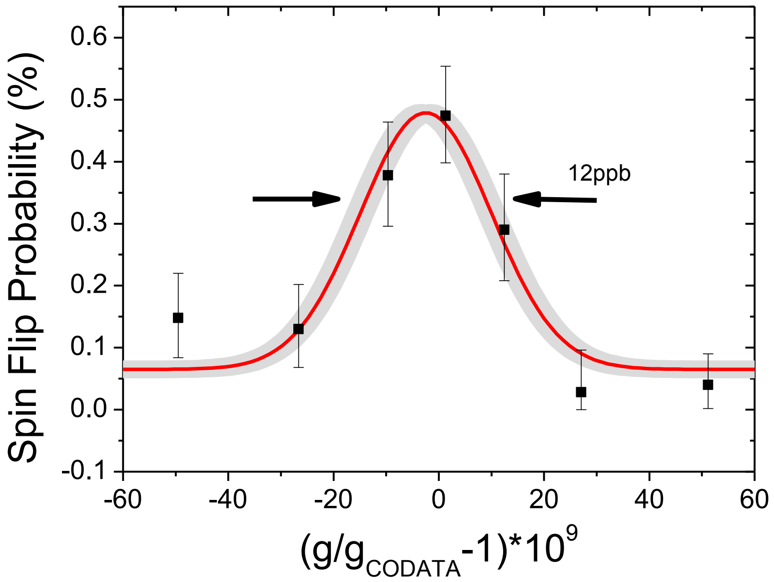
LETTER

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]

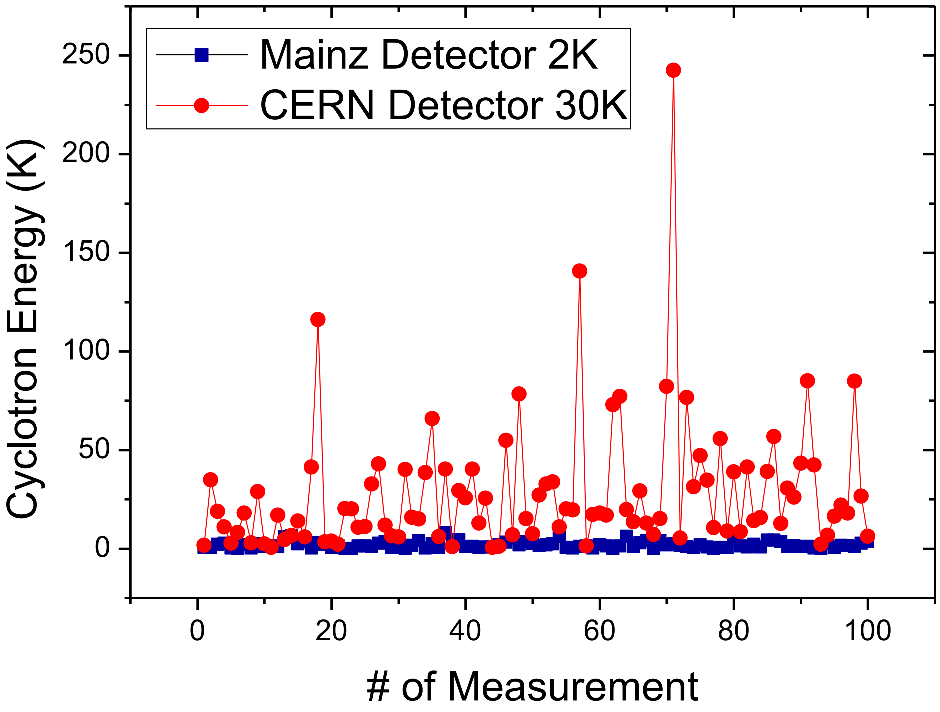
A. Mooser, S. Ulmer, K. Blaum, K. Franke, H. Kracke, C. Leiteritz, W. Quint, C. Smorra, J.Walz, **Nature 509, 596 (2014)**

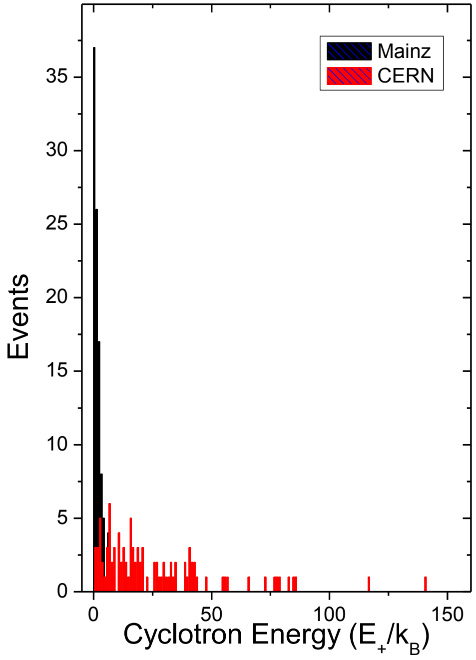


g/2 = 2.792847350 (7) (6)

Problems / in Progress

- 30K / 29MHz noise has to be understood/fixed

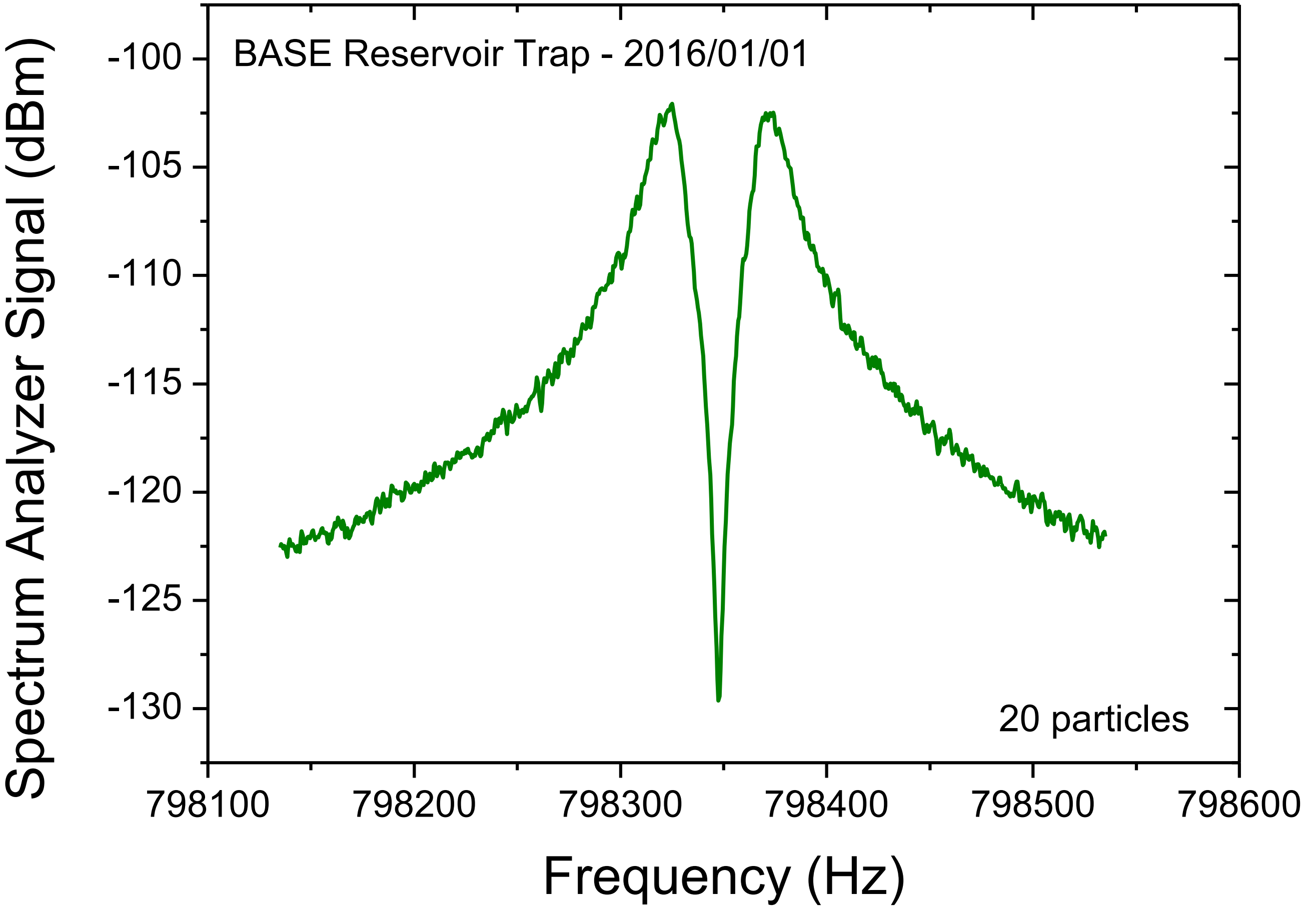




- 30K / 29MHz noise has to be understood/fixed

Status of Reservoir

Status 2016/01/01: Still 20 antiprotons in the BASE reservoir trap.



Reservoir concept works and is useful !

Typical consumption: 1 particle per month

BASE - Overview Article

Goals of BASE / Experimental Setup / Results / Future Goals


The European Physical Journal volume 224 · number 1 · February 2015

EPJ ST

Recognized by European Physical Society

Special Topics

THE BASE EXPERIMENT

Dedicated to determine the fundamental properties of the proton and the antiproton with highest precision


THE EUROPEAN
PHYSICAL JOURNAL ST

Special Topics

is a continuation of Journal de Physique IV

BASE – The Baryon Antibaryon
Symmetry Experiment

C. Smorra, K. Blaum, L. Bojtar,
M. Borchert, K.A. Franke, T. Higuchi,
N. Leefer, H. Nagahama, Y. Matsuda,
A. Mooser, M. Niemann, C. Ospelkaus,
W. Quint, G. Schneider, S. Sellner,
T. Tanaka, S. Van Gorp, J. Walz,
Y. Yamazaki and S. Ulmer

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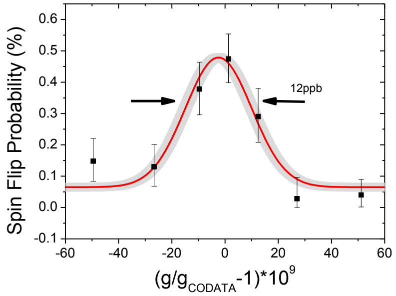
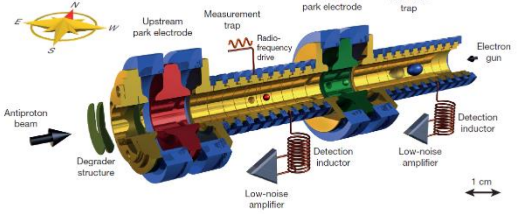
edp sciences Società Italiana di Fisica Springer

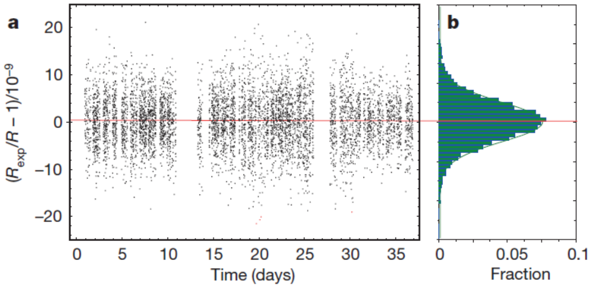
PAGE TITRE EPJST-224-14-15-16-2015.indd 2 05/10/15 19:23

C. Smorra et al., *The BASE Experiment*, EPJ-Special Topics **224**, 3055 (2015)

Summary







- Compared antiproton/proton charge-to-mass ratio with fractional precision of 69 ppt.
- Implemented entire 4 trap system and detected signals in all traps.
- Reached 70mHz axial frequency stability.
- Detected first antiproton spin flips in BASE.
- Recorded a first Larmor resonance with BASE.

experiments are on-going

BASE

Thanks for your attention !!!

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GSI

PTB

Leibniz Universität Hannover

K. Blaum, Y. Matsuda,
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J. Walz, Y. Yamazaki

Questions to the Committee

- Once all experiments are running, we already have problems with smooth helium supply to all the experiments. GBAR will start soon. What are CERN’s plans to address this problem?

Systematic Corrections

- Major systematic correction due to shift of particle in the magnetic B1 gradient caused by spin-flip bottle.
  - Particle shift and magnetic gradient can be determined precisely

dR_{B1} = -114(26) p.p.t.

  - Slight re-adjustment of the trapping potential: dR_{C4} = -3(1) p.p.t.

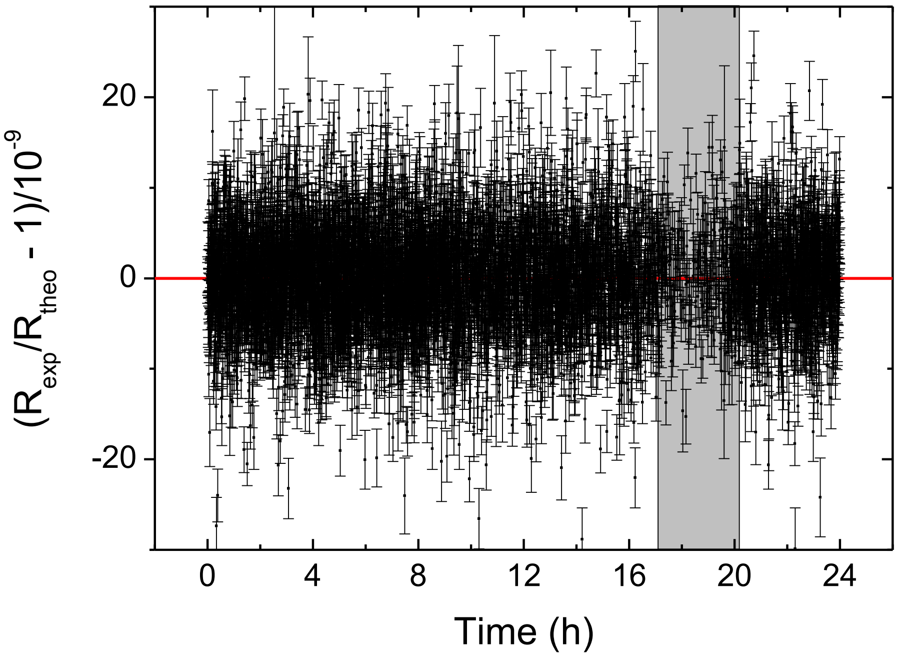
final experimental result: **$R_{exp,c}$ = 1.001 089 218 755 (64) (26)**

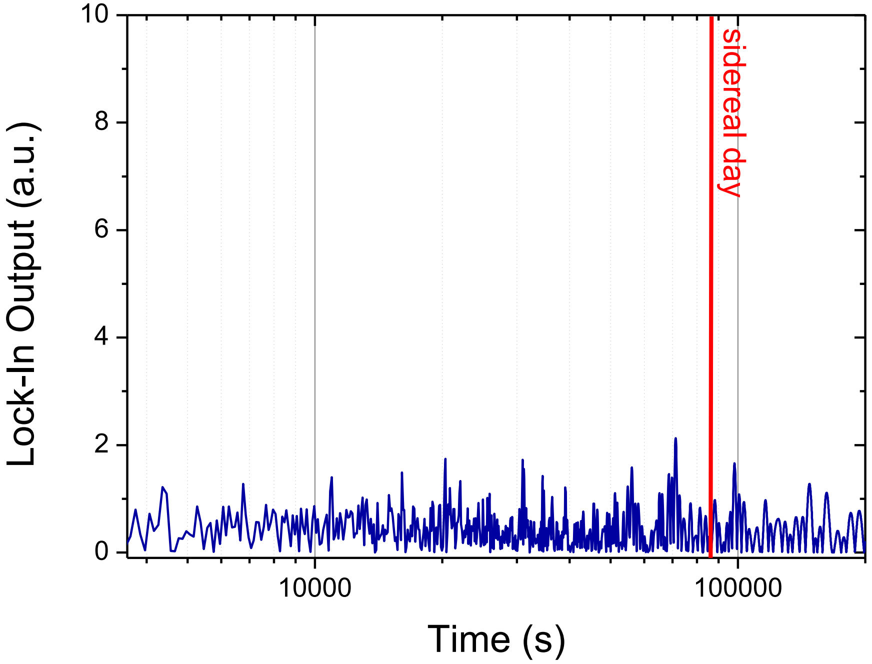
$$\boxed{\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}} - 1 = 1(69) \times 10^{-12}}$$

- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

Diurnal Variations

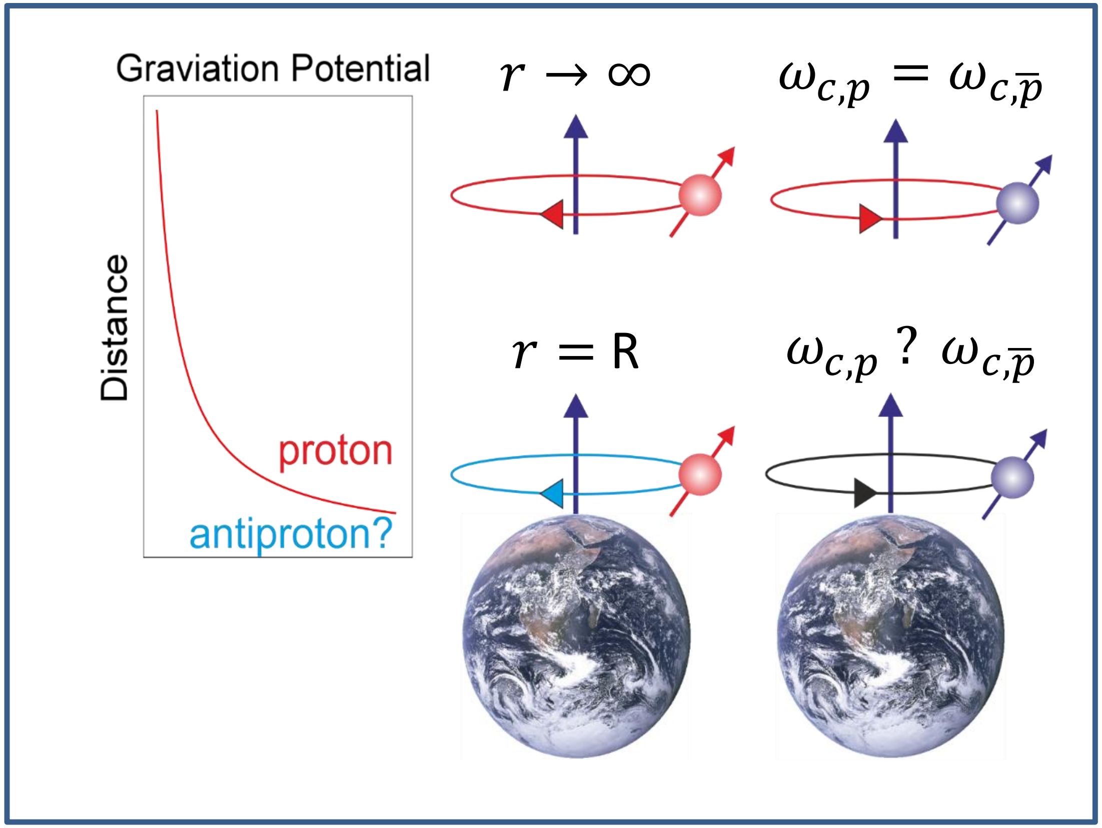
- Understanding: cosmological background field couples to particles -> Sidereal variations could be observed.





- Set limit of sidereal (diurnal) variations in proton/antiproton charge-to-mass ratios to < 0.72 ppb/day

Antiproton gravitational redshift



- Constrain of the gravitation 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

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

Assuming CPT Invariance, we can compare the proton/antiproton gravitational redshift.

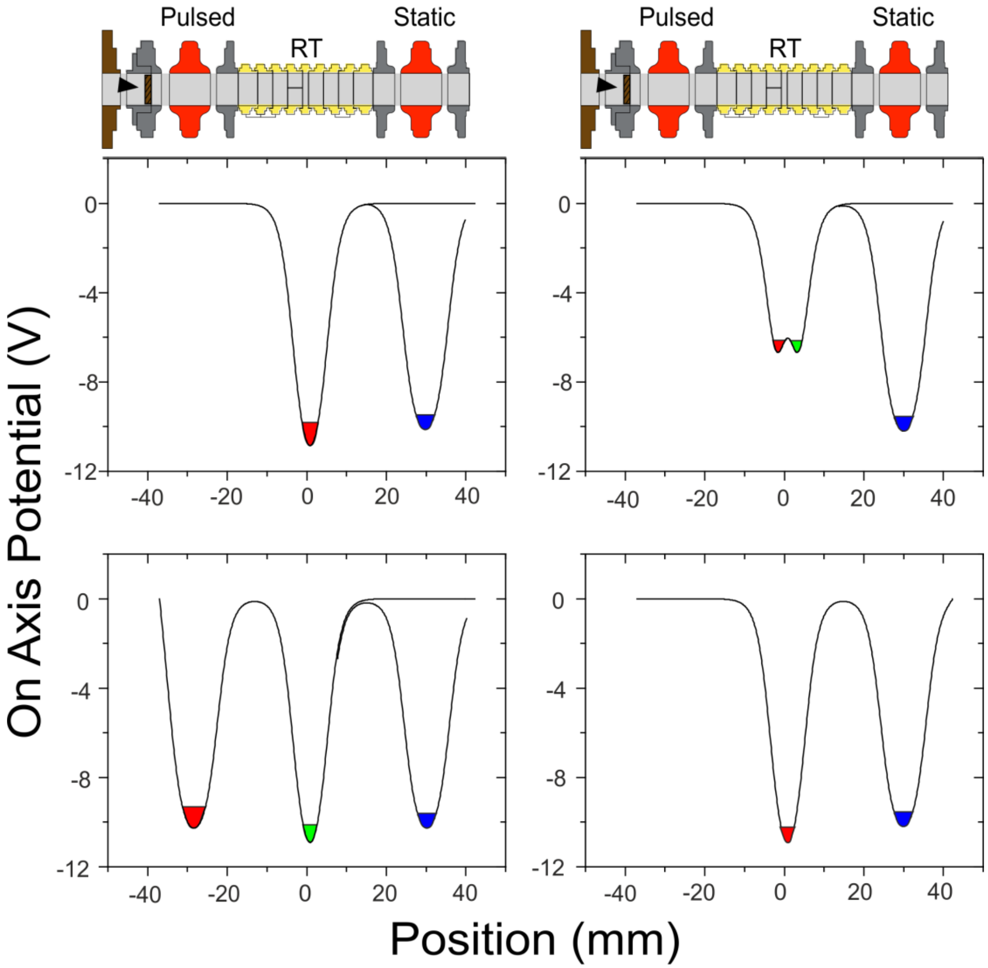
R. J. Hughes, & M. H. Holzscheiter, Phys. Rev. Lett. 66, 854-857 (1991).
R. J. Hughes, Contemporary Physics, 34:4, 177-191 (1993).

Comparison TRAP / BASE

- We profited from ideas of the TRAP collaboration which reported in 1999 on a 90 ppt measurement.
- Both experiments compare the antiproton to H$^-$ cyclotron frequencies

TRAP	**BASE**
• Direct cyclotron frequency measurement	• Sideband cyclotron frequency measurement
• Higher temperature (>10meV)	• In thermal equilibrium with detector (8K)
• co-trapped particles	• fast shuttling
• Particle exchange -> hours	• Particle exchange -> seconds
• B-drifts corrected by external sensors	• B-field in trap center less homogeneous

Reservoir Trap Method



Apply slow potential ramps to separate the trapped particles

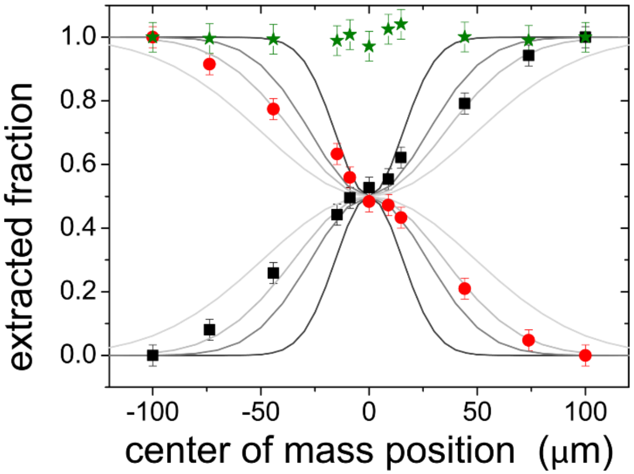
Park one fraction in a HV-electrode, count particles in the other.

Not satisfied with the result?
Merge the particle clouds by reversing potential ramps.
Try again.

Time budget 120 s:
Separate and park (15 s)
Count particles (45 s)
Exchange (15 s)
Count particles (45 s)

Asymmetric separation

- Superimpose a constant electric field over the Penning trap potential

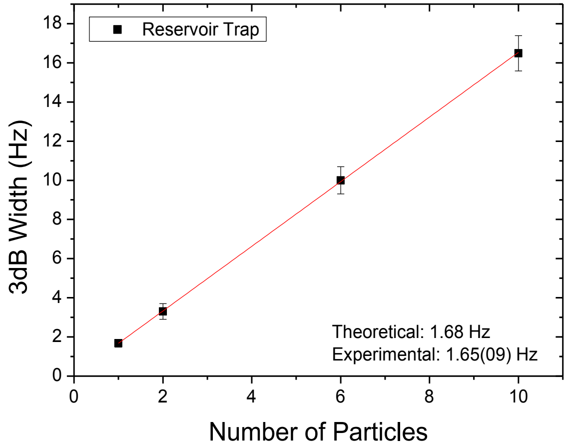


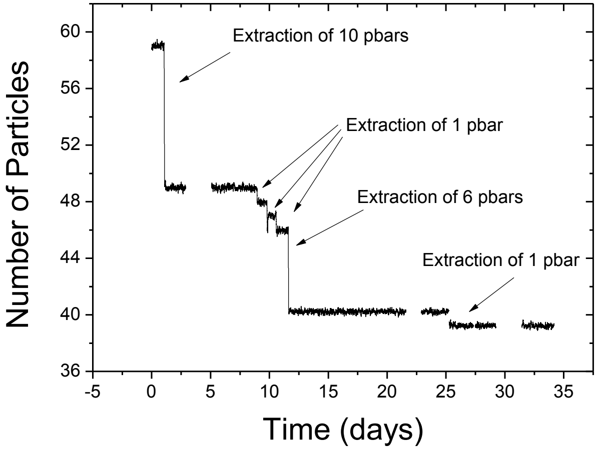
Measurement with an antiproton cloud

200 particle/50 cycles
No particle loss

C. Smorra, et al., Int. J. Mass Spectrom. (2015), http://dx.doi.org/10.1016/j.ijms.2015.08.007

- Count particles by measuring line-width of the particle dip.



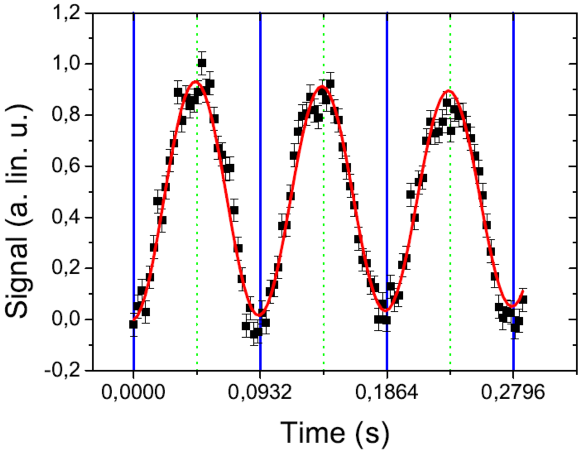


- Pressure “world record” – 5e-18 mbars

Cyclotron Frequency

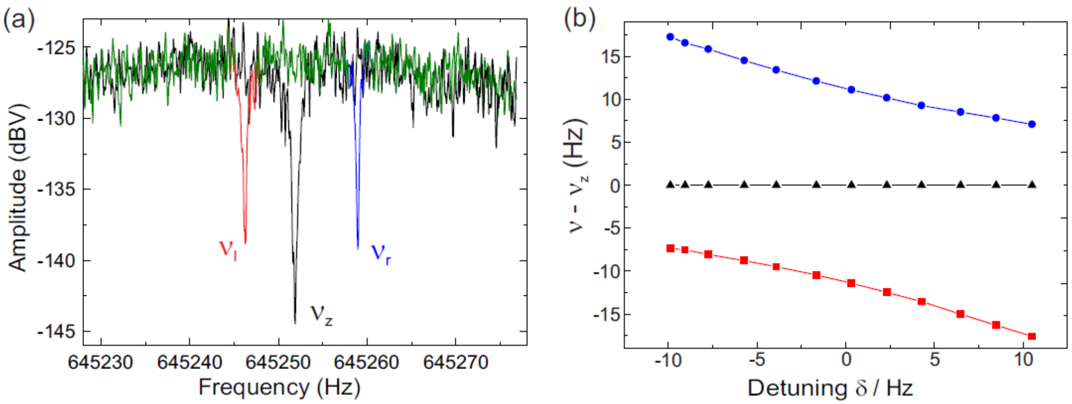
Effectively: Amplitude modulation of particle motion

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



Classical "Dressed states"

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



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

cyclotron frequency measurement at ~1ppb

The Challenge

Typical axial frequency: 700 kHz

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := 0.4\ \cdot \mu Hz \cdot B_2$$

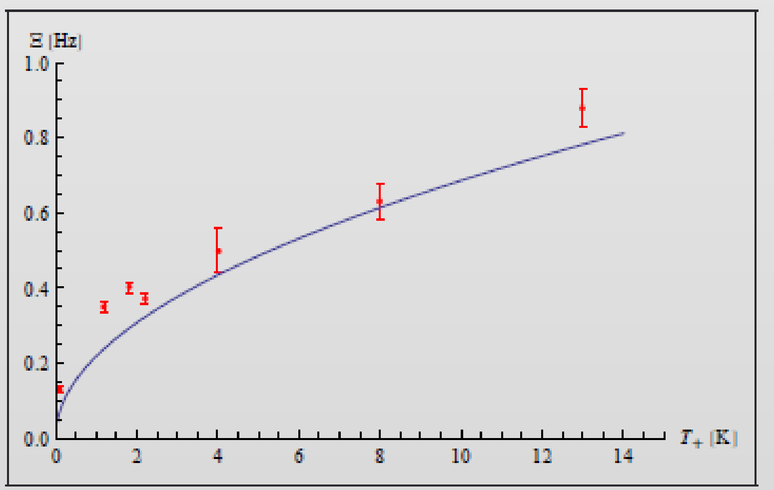
We use: $B_2 = 300000\ T/m^2$

170 mHz out of 740 kHz

Magnetic bottle coupling: $$\Delta\nu_z = \frac{1}{4\pi^2 m \nu_z}\frac{B_2}{B_0}(dE_+ + dE_-)$$ -> 1 Hz/µeV

One cyclotron quantum jump (70 neV) shifts axial frequency by 70mHz

Tiny heating of the axial mode results in significant fluctuation of the axial oscillation frequency. **-> Three cyclotron quanta (0.2 µeV) -> fidelity to 50%**



Frequency fluctuation as function of T_+

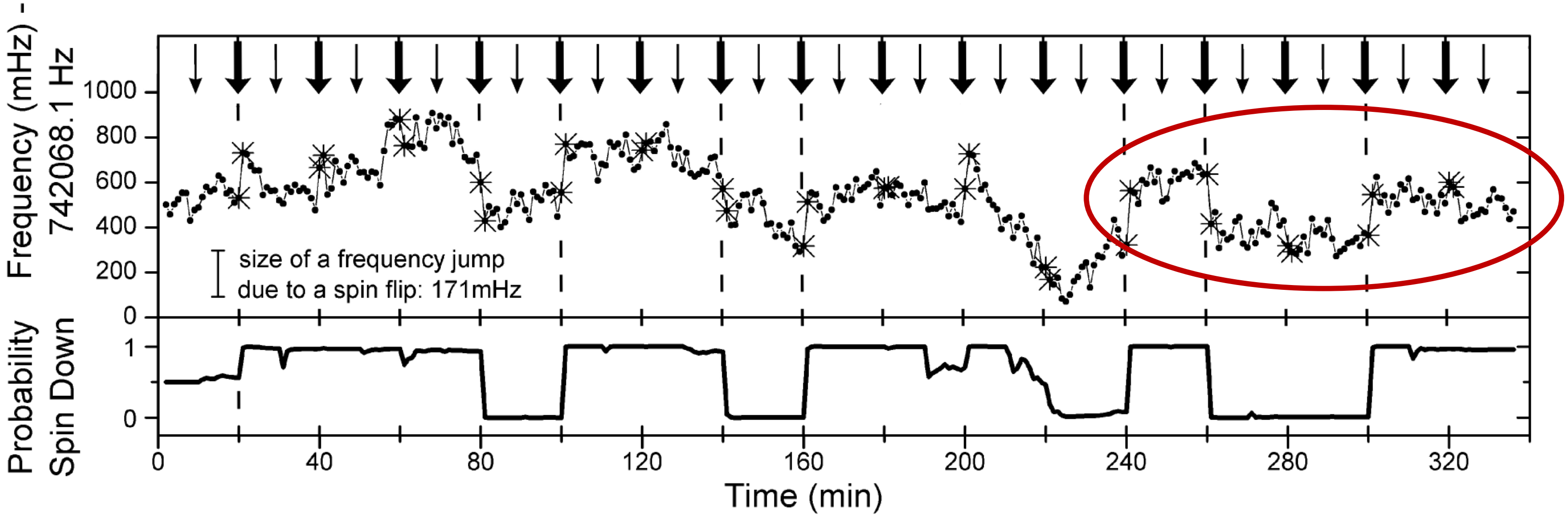
$$R_{n\to n\pm1} = \frac{q^2}{2m_p\hbar\omega}\left(n+\frac{1}{2}\pm\frac{1}{2}\right)\underbrace{\int_{\mathbb{R}} \mathrm{d}t'\, \mathrm{e}^{\pm i\omega t}\left\langle E^{(1)}(t)E^{(1)}(t+t')\right\rangle}_{S(\pm\omega)}$$

Important message: heating rates scale with the cyclotron quantum number!!!

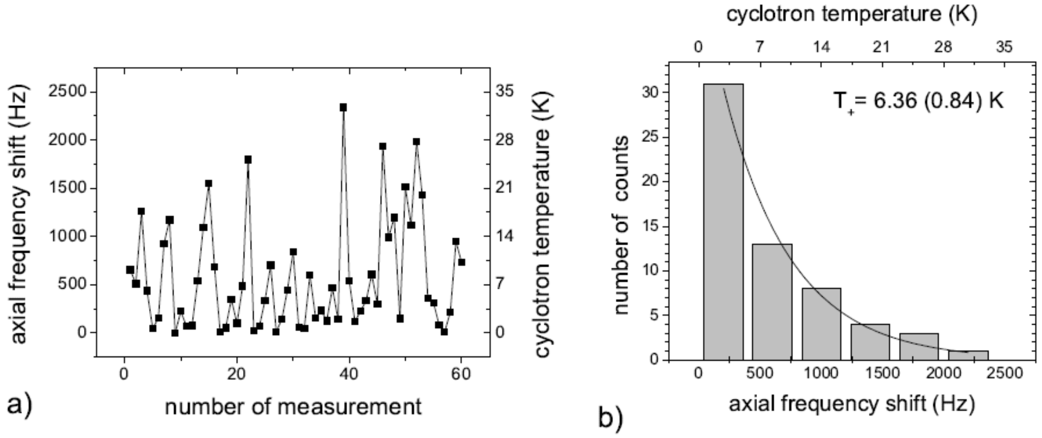
Our heating rates correspond to noise on electrodes of some pV/Hz$^{1/2}$.

Single Spin Flips and Double Trap Method

- 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)



Heating rate: 10 cyclotron quantum jumps in 1h !

preparation procedure for single particle with single spin flip resolution takes 2 hours

Context – g-factor measurement