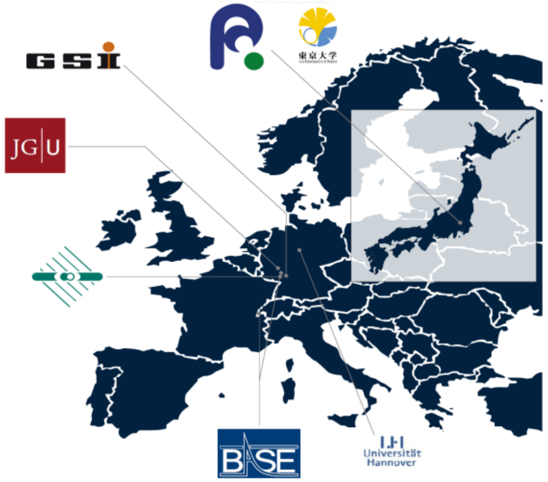


BASE

Review, Status and Future

Stefan Ulmer

RIKEN,

Ulmer Fundamental Symmetries Laboratory

(Spokesperson BASE collaboration, CERN)

2018 / 03 / 12

RIKEN

Programs for Junior Scientists

MAX-PLANCK-GESELLSCHAFT

東京大学
THE UNIVERSITY OF TOKYO

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

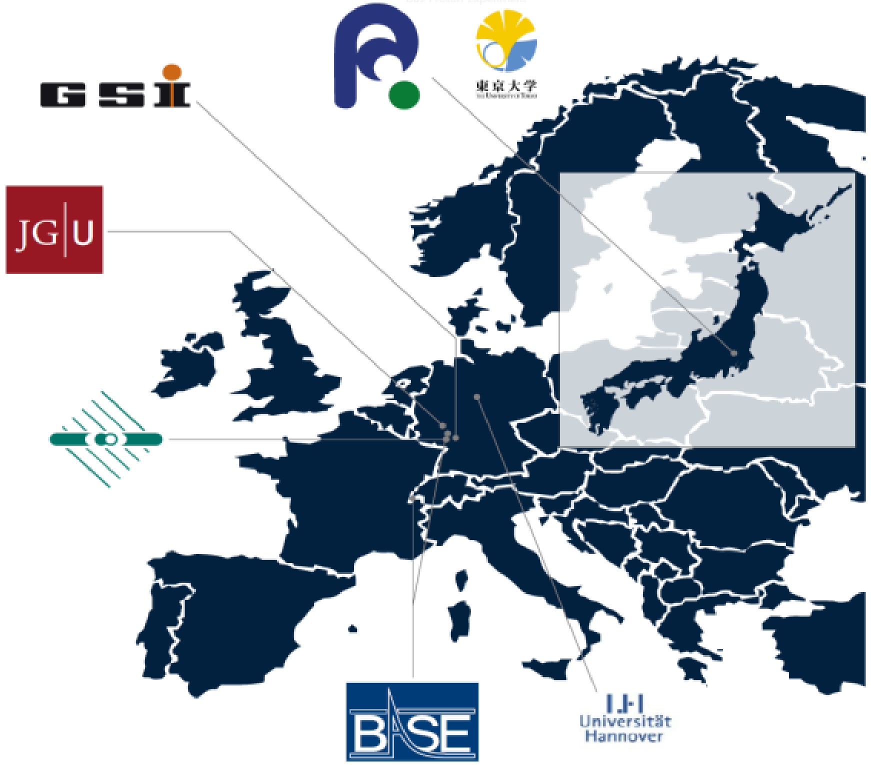
GSI

Leibniz Universität Hannover

PTB

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton (Mooser, Ulmer, Blaum, Walz, Quint).
- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (Ulmer, Smorra, Yamazaki, Blaum, Matsuda).
- **Hannover/PTB:** QLEDS-laser cooling project (Ospelkaus, Ulmer)




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

EPJ ST

Recognized by European Physical Society

Special Topics

THE BASE EXPERIMENT

BASE

edp sciences Springer

Scale: 4 P.I.s, 5 Post-Docs, 7 PhD Students

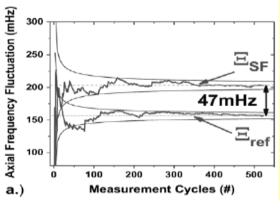
Institutes: RIKEN Ulmer IRU, RIKEN APL, Max Planck Society, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

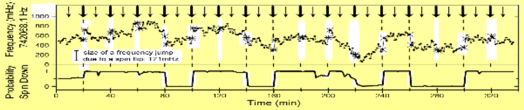
16 hands-on people working on three experiments.

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

BASE Overview

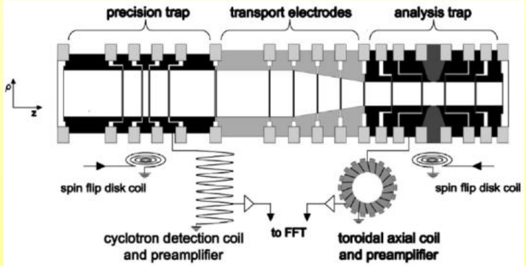
Observation of spin flips with a single trapped proton





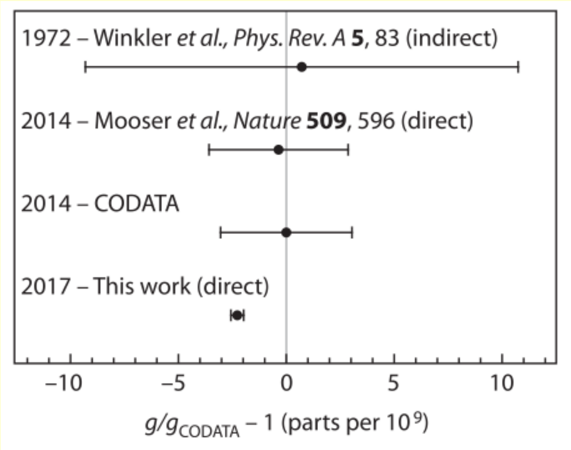
S. Ulmer, et al., **PRL 106, 253001 (2011)**
A. Mooser, et al., **PRL 110, (2013)**

Application of the double Penning-trap technique



A. Mooser, et al., **PLB 723, 78 (2013)**

Most precise proton g-factor measurment



g/2 = 2.792 847 350 (9)

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

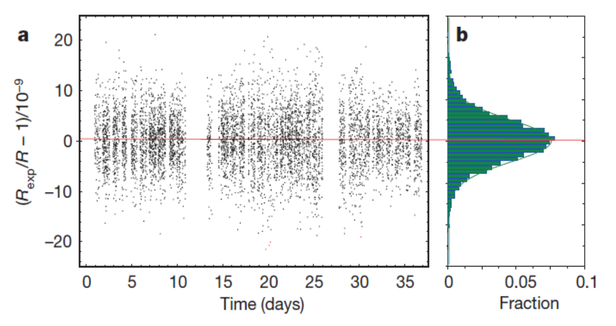
First direct high precision measurement of the proton magnetic moment.

g/2 = 2.792 847 344 62 (82)

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

Precise CPT test with baryons

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

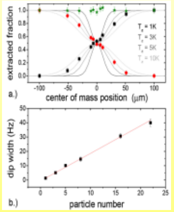


$$\boxed{1+\frac{(q/m)_{\bar{p}}}{(q/m)_{p}}=1(69)\times10^{-12}}$$

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

To be improved by another factor of 10 to 100

Reservoir trap for antiprotons

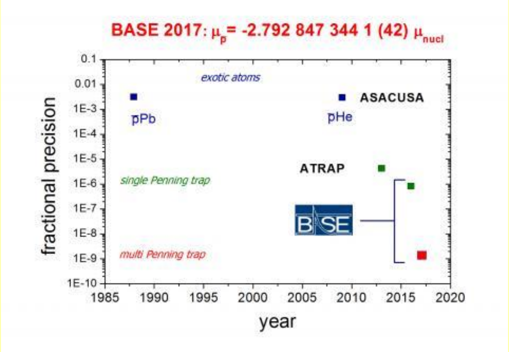


C. Smorra, et al., **Int. Journ. Mass Spec. 389, 10 (2015).**

Idea: Enable operation with antiprotons independent of accelerator run times.

Most precise antiproton g-factor measurment

H. Nagahama, et al., Nature Comms. **8, 14084 (2017)**
C. Smorra *et al.*, Nature **550**, 371 (2017)



g/2 = 2.792 846 5 (23)

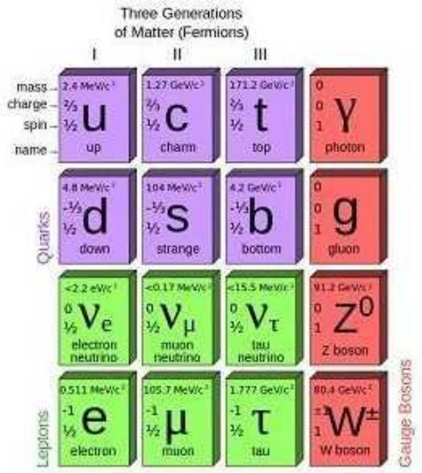
Sixfold improvement compared to previous measurement

g/2 = 2.792 847 344 1 (42)

350-fold improvement compared to previous measurement

Partly comparable work by J. DiSciacca, G. Gabrielse et al.. (ATRAP/TRAP collaboration)

Tests of the Standard Model using Antimatter



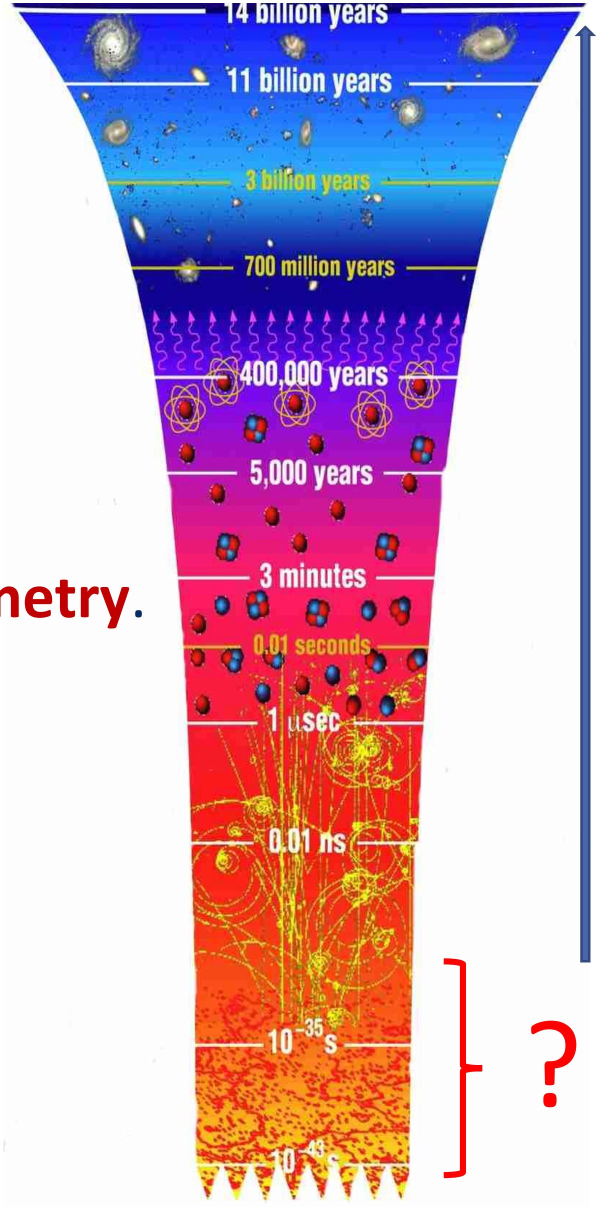
…at lowest energy and with great precision….

Standard model is the success story of modern physics: Many particle physics observations are reproduced. High predictive power for QED/BS-QED (sub-ppt). $g / 2 = 1.001\ 159\ 652\ 180\ 73\ (28)$

On the other hand: SM does **NOT** include, dark matter, neutrino oscillations, anomalies in the muon sector, **matter/ antimatter asymmetry**. known SM-CP violation -> factor of 2×10^8missing

Precise comparisons of fundamental properties of matter/antimatter conjugates provide **stringent tests of CPT invariance**, which is the “most fundamental” symmetry in the SM.

Antimatter systems constitute probes for exotic physics which exclusively couples to antimatter.

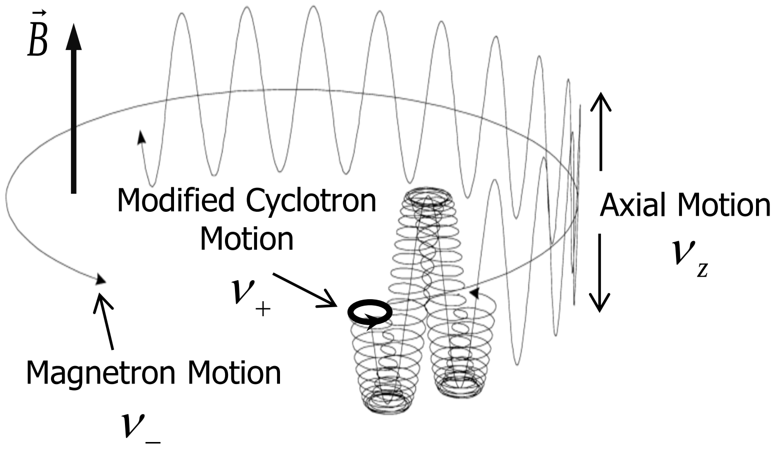


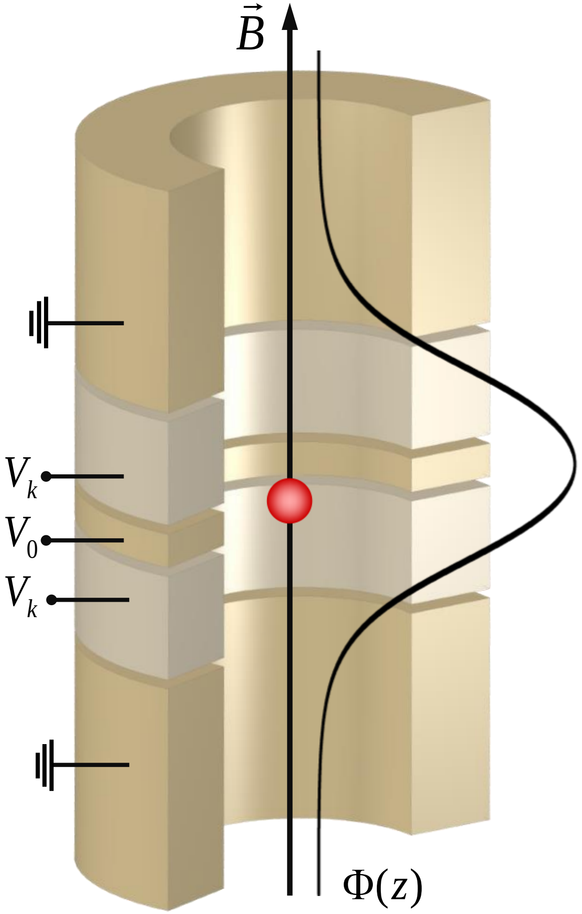
Main Tool: Penning Trap

Basically one of the **simplest systems you can think of**….

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

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

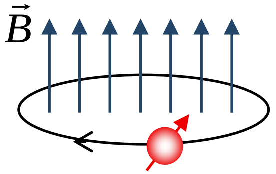
Cyclotron Frequency

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

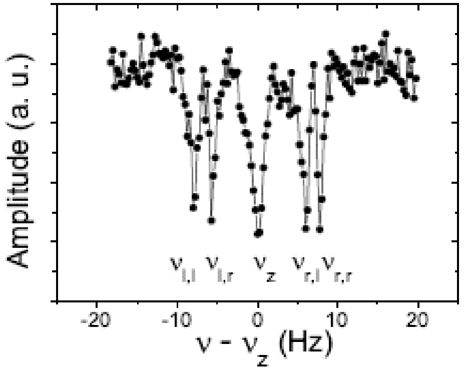
Cyclotron frequency connects measurable quantity to fundamental properties of trapped charged particle

Measurements with Single Particles in Penning Traps

Cyclotron Motion



simple



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

g: mag. Moment in units of nuclear magneton

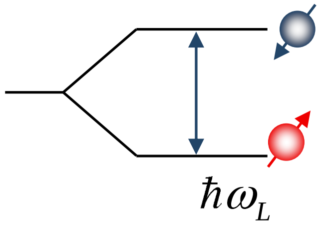
$$\boxed{\omega_c = \frac{e}{m_p} B}$$

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

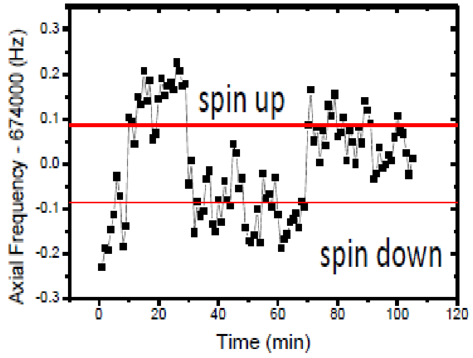
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

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

Larmor Precession



difficult

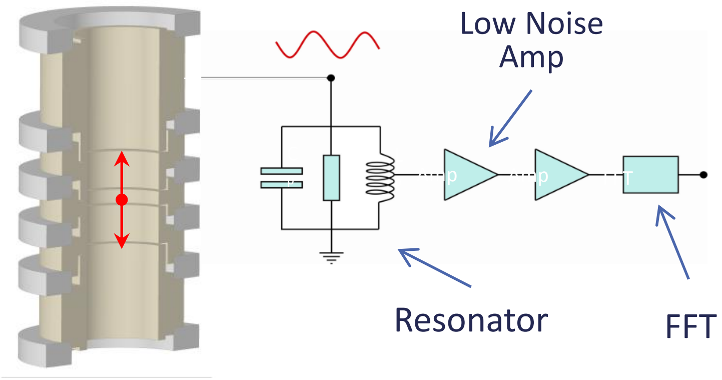


S. Ulmer *et al.*, PRL **106**, 253001 (2011)
A. Mooser *et al.*, PRL **110**, 140405 (2013)

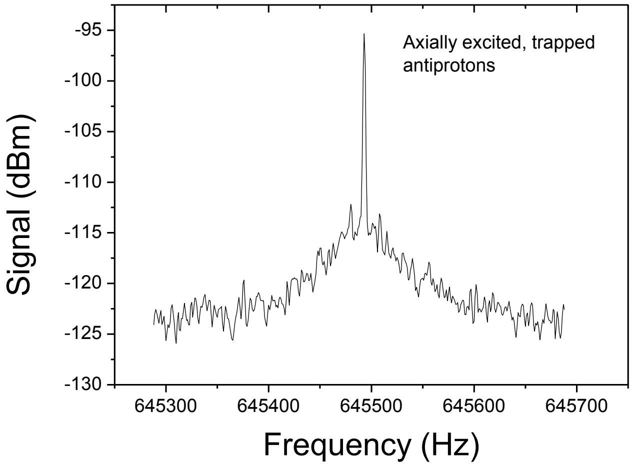
Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

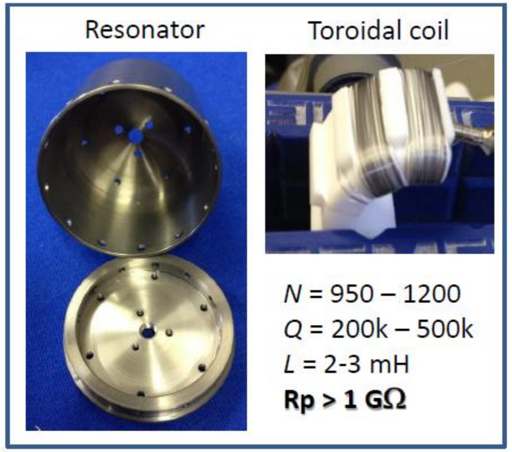
Frequency Measurements

- Measurement of tiny image currents induced in trap electrodes



currents: 1 fA

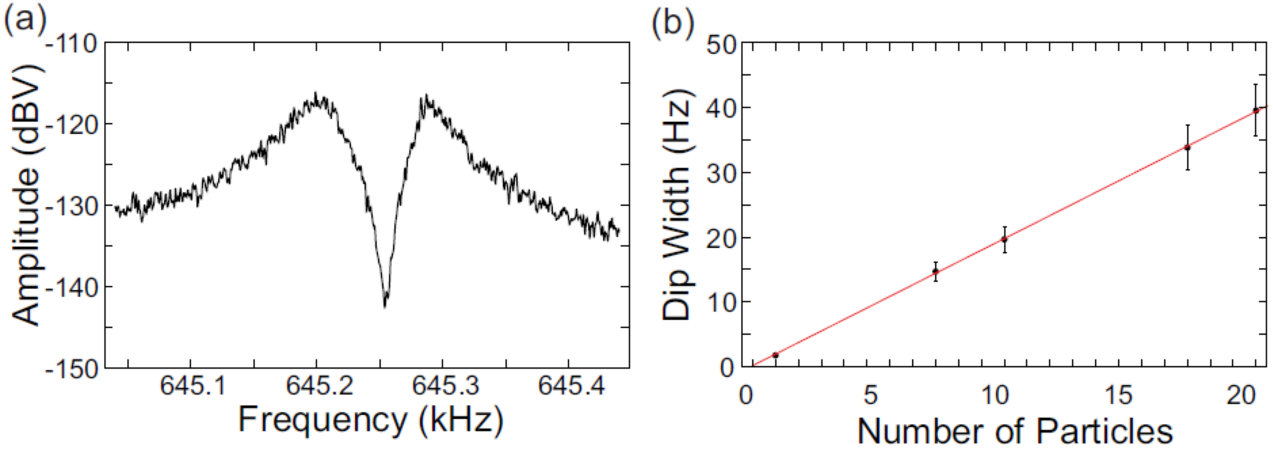




N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

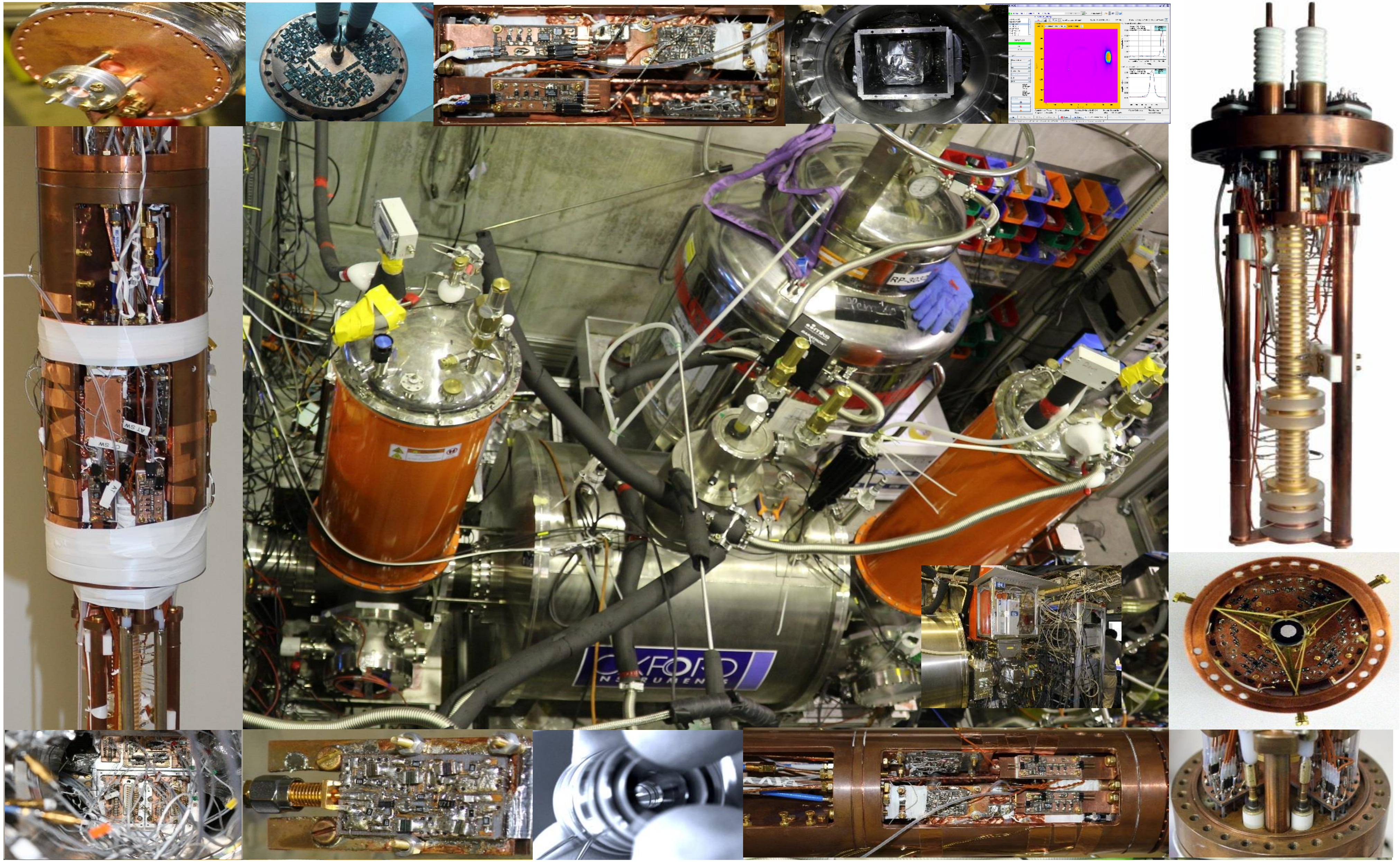
- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip -> number of particles

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$



- Measurements in thermal equilibrium -> tiny volumina / homogeneous condititions

Experiment



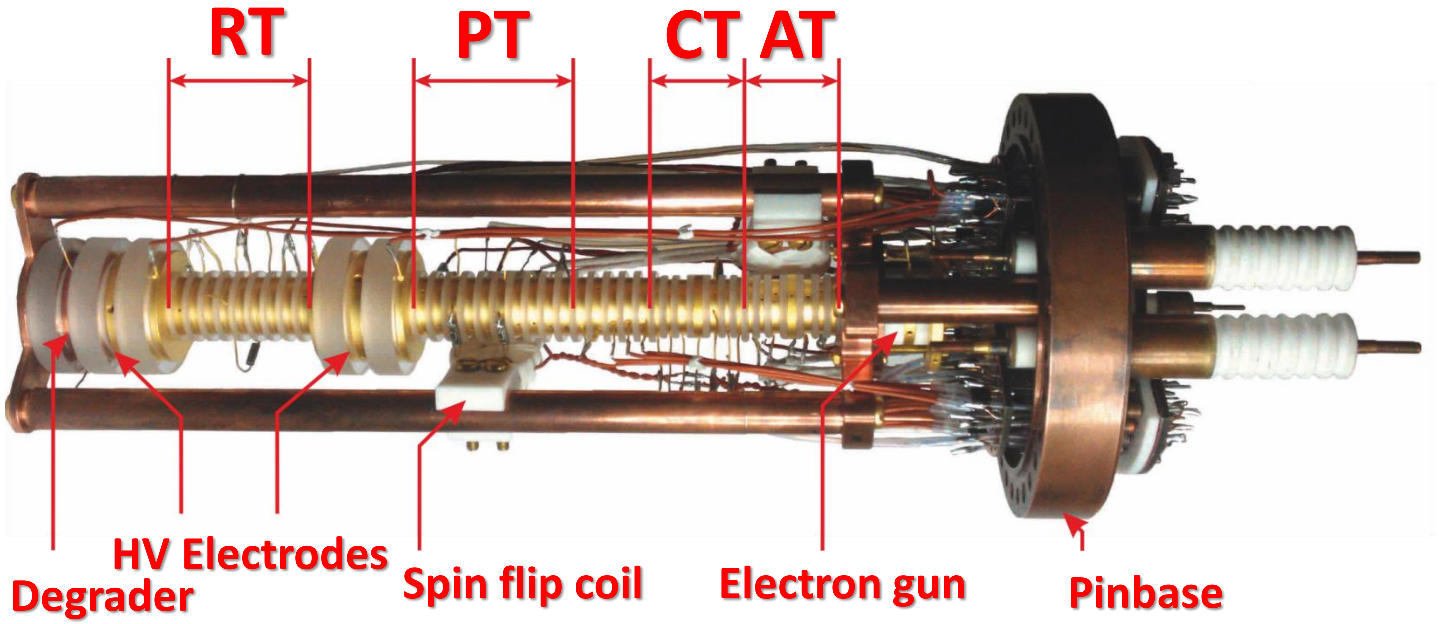
The BASE Trap System

World's first successfully running four trap system

Enables application of a variety of new methods

High-sampling rate mass spectrometer

Multi-trap multi particle methods



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

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

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

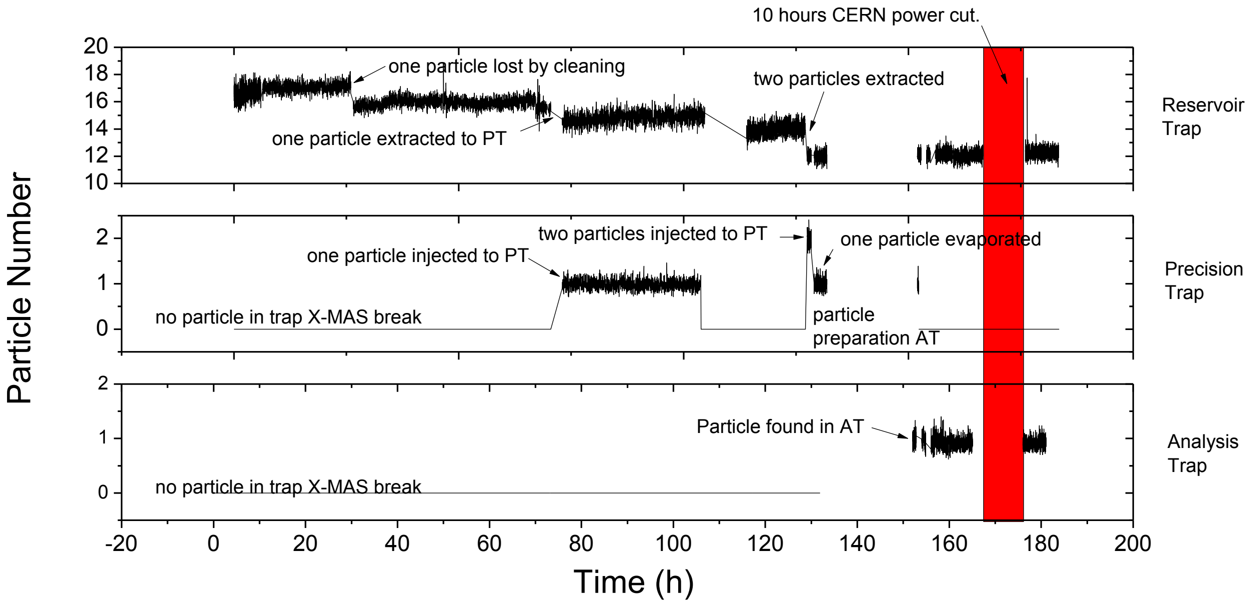
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300$ mT / mm^2

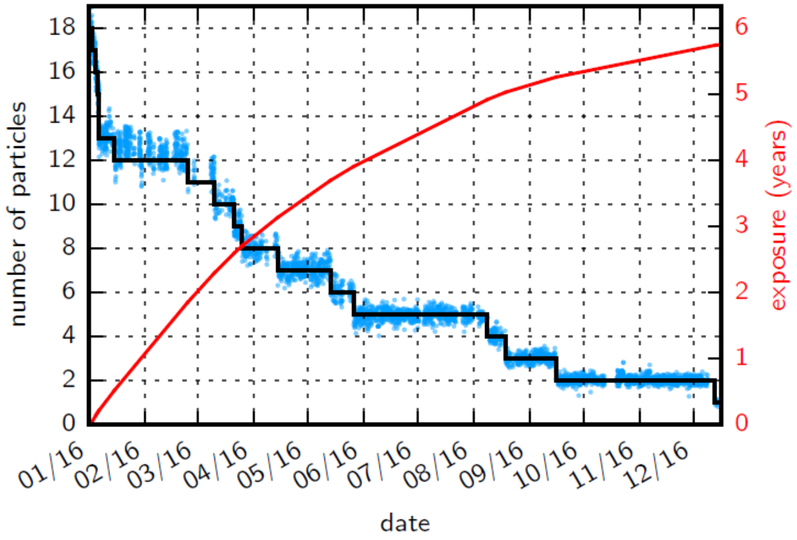
S. Ulmer et al., BASE TDR, CDS (2013).

The BASE Reservoir Trap – the Key Method

Invented by BASE – first exotic particle experiment using such a device

Doubles available experiment time and enables experiments at low background noise (accelerator OFF mode)





Experiment has been operated with antiprotons trapped in October 2015 until December 2016 for more than 400 days.

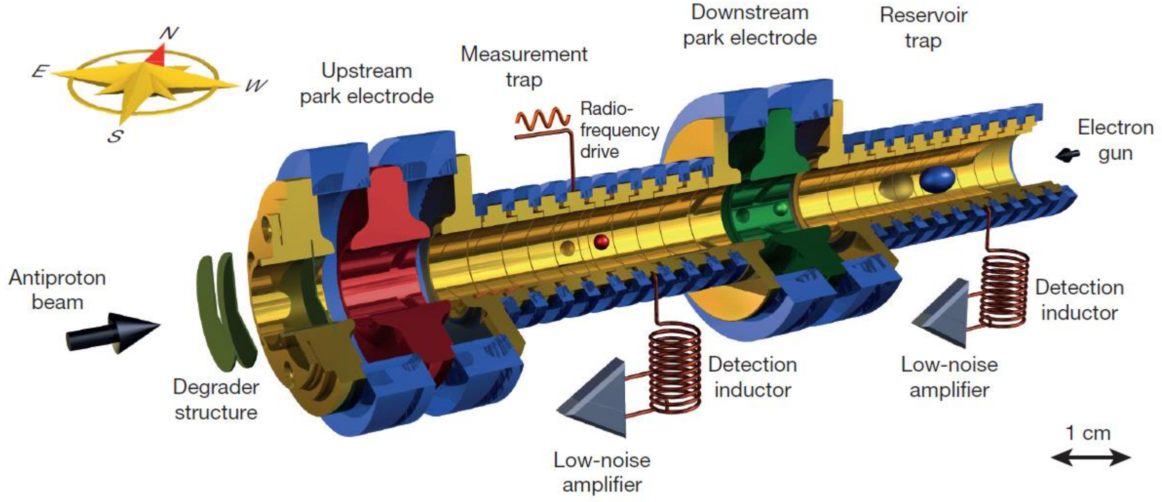
Measurement provides most stringent direct limit on lifetime of the antiproton (21.7 years (status Feb. 2018))

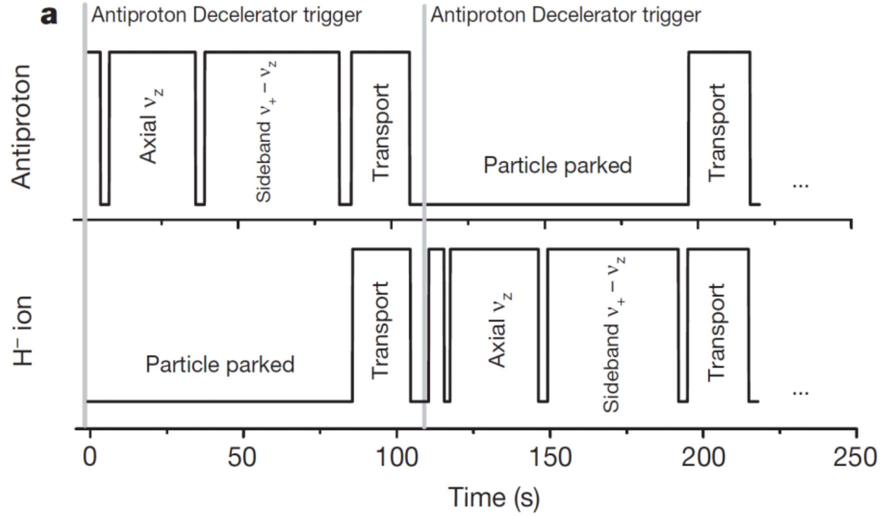
Best pressure-limit ever characterized by measurement $5*10^{-19}$ mbar

Proposed: S. Ulmer et al., BASE Letter of Intent, CDS (2012).
Realized: C. Smorra et al., Int. Journ. Mass. Spec. **389**, 10 (2015).
Improved: S. Sellner et al., New. J. Phys. **19**, 083023 (2017).

Fast Shuttling Technique

Proposed by many different authors, e.g. S. Rainville and J. Thompson (MIT PhD Theses)





Potential tweezer method enables us to prepare single particles upstream and downstream of a measurement trap and interchange the particles rapidly.

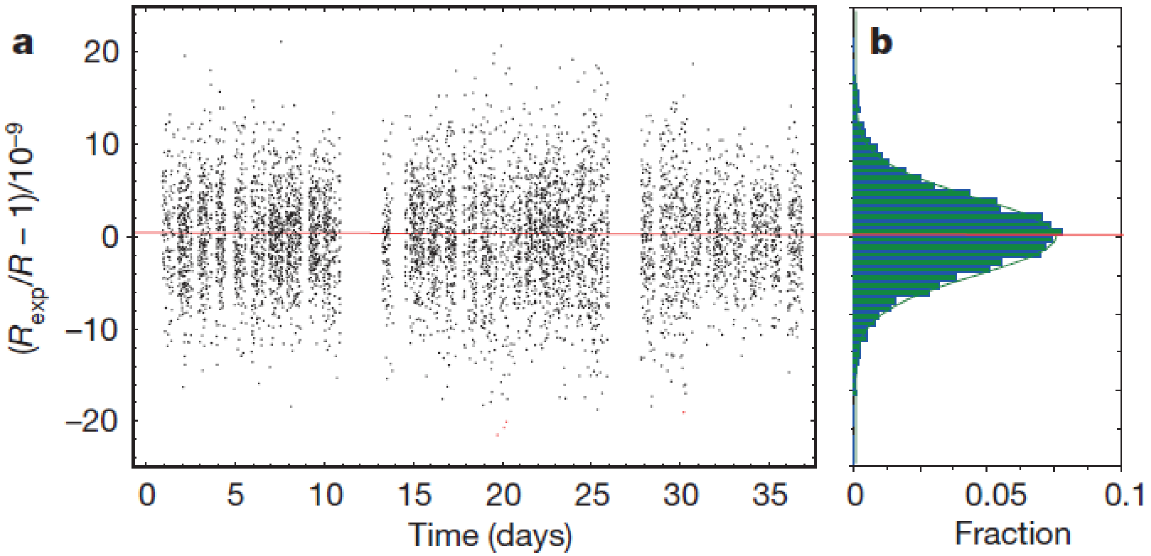
Applied scheme to perform one cyclotron frequency ratio measurement within 4 minutes, which is **50 times faster than in previous proton/antiproton Q/M comparisons** -> Higher statistics, improved precision.

Scheme can be applied to any arbitrary mass doublet and has thus the potential to improve arbitrary mass ratio measurements.

Applied this scheme to measure proton/antiproton q/m ratio using antiprotons and **hydrogen ions.**

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

Measurements: Proton-to-Antiproton Q/M-Ratio



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

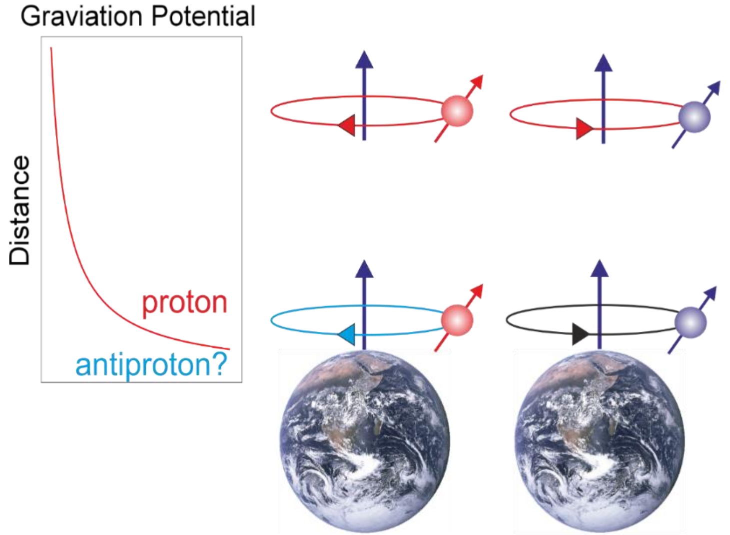
- Constrain of the gravitational anomaly for antiprotons:

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

Our 69ppt result sets a new upper limit of

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

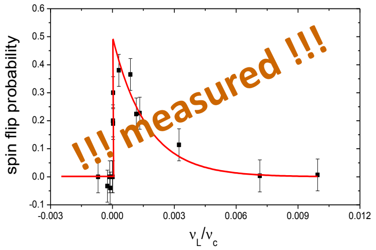
At the surface of the earth, matter and antimatter clocks appear to oscillate – within the uncertainties of the experiments – at identical frequencies.



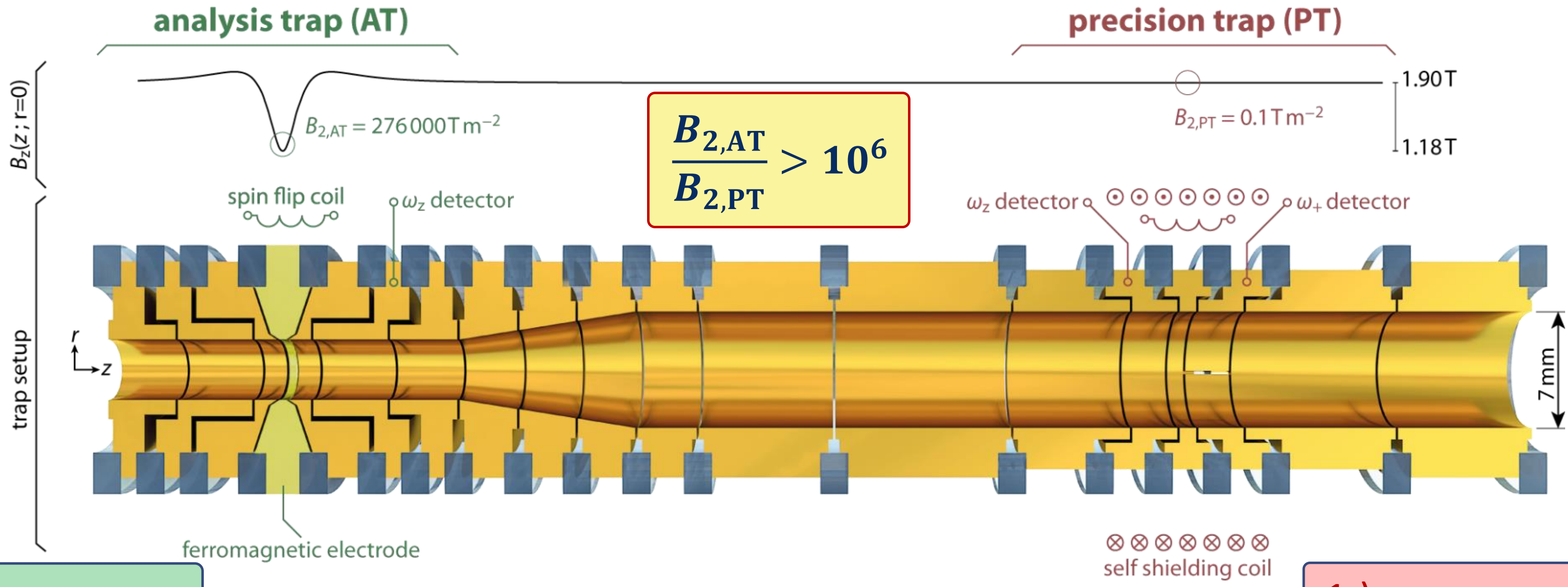
S. Ulmer et al., *Nature* **524** 196 (2015)

Magnetic Moment Measurements

Single trap

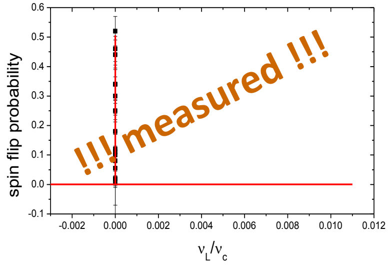


Statistical method



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

Double trap



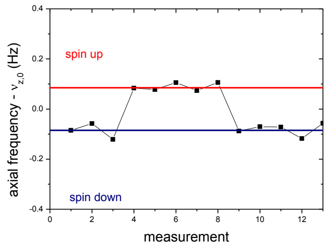
hifi method

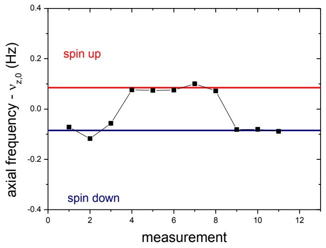
Initialize the spin state

particle transport

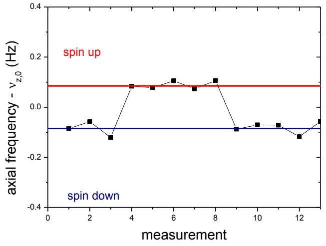
1.) measure cyclotron ν_c
2.) drive spin transition at ν_{rf}

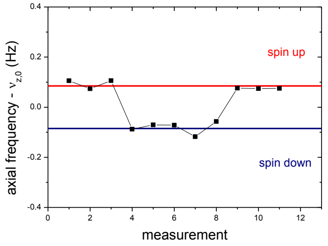
analyze the spin state





no spin-flip in PT



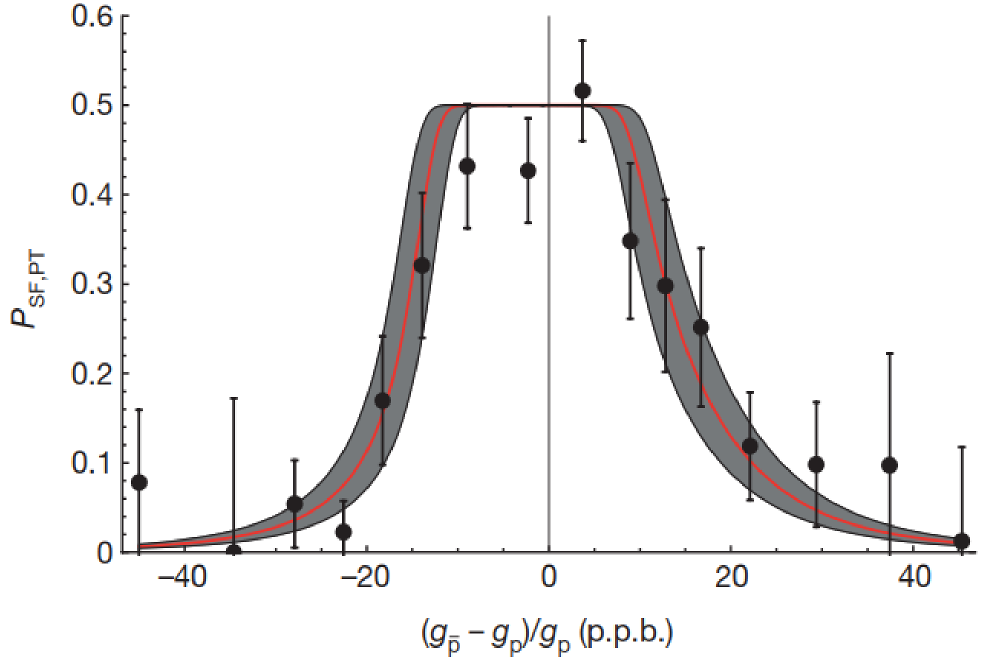


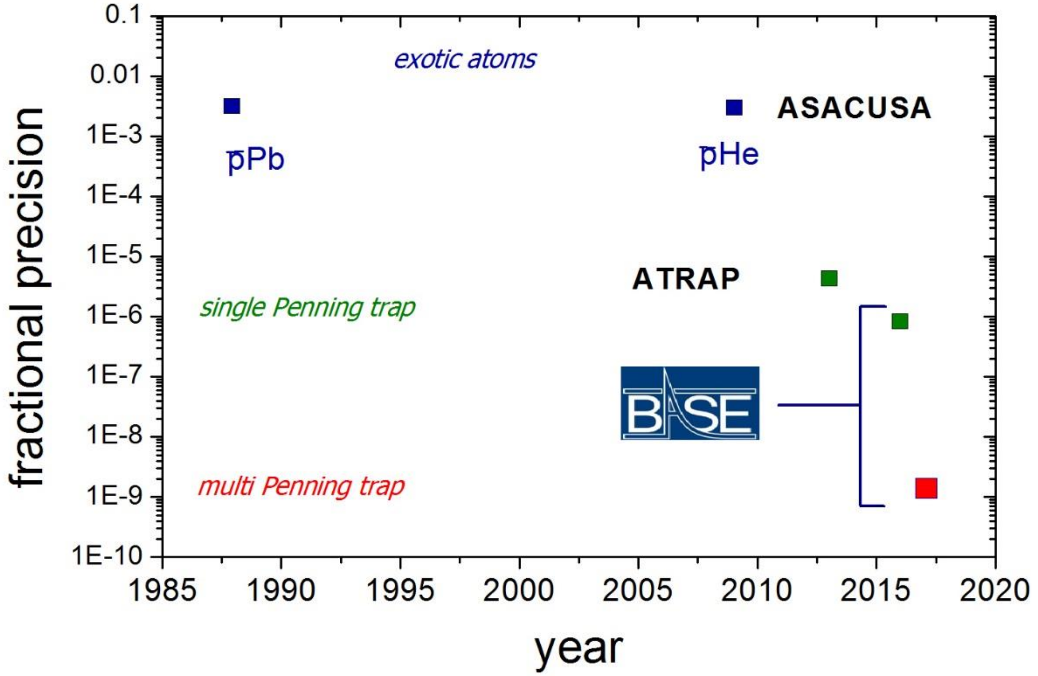
spin flipped in PT

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

The Magnetic Moment of the Antiproton

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





G. Schneider *et al.*, Science **371**, 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
RIKEN
MAX-PLANCK-GESELLSCHAFT
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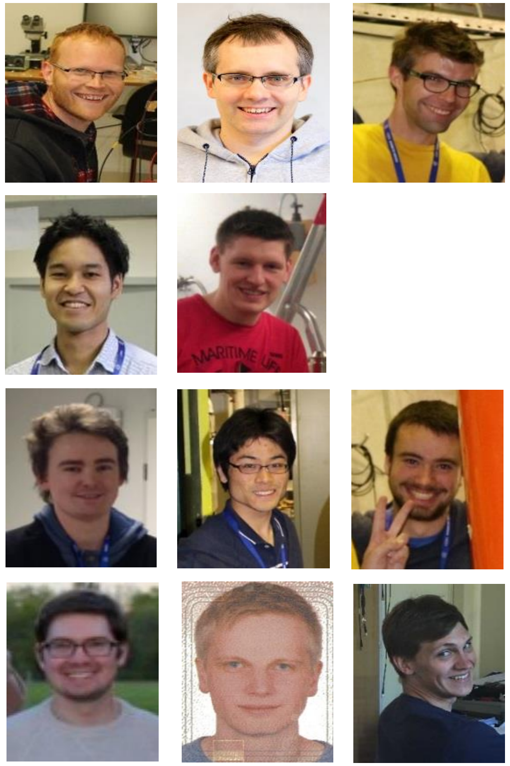
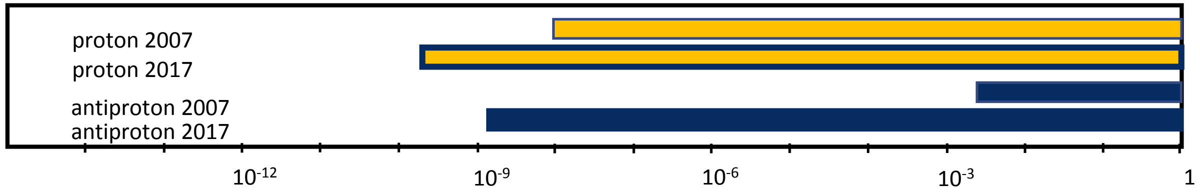
東京大学 THE UNIVERSITY OF TOKYO
GSI
Leibniz Universität Hannover
PTB

K. Blaum, Y. Yamazaki
J. Walz, W. Quint,
Y. Matsuda, C. Ospelkaus



$$\frac{g_p}{g_{\bar{p}}} - 1 = -0.000\,000\,000\,2\,(15)$$

PRECISION GOAL OF TDR HAS BEEN REACHED WITHIN 5 YEARS



??? HOW CAN WE DO BETTER ???

How can we do better ?

Limiting Mechanisms

In trap noise

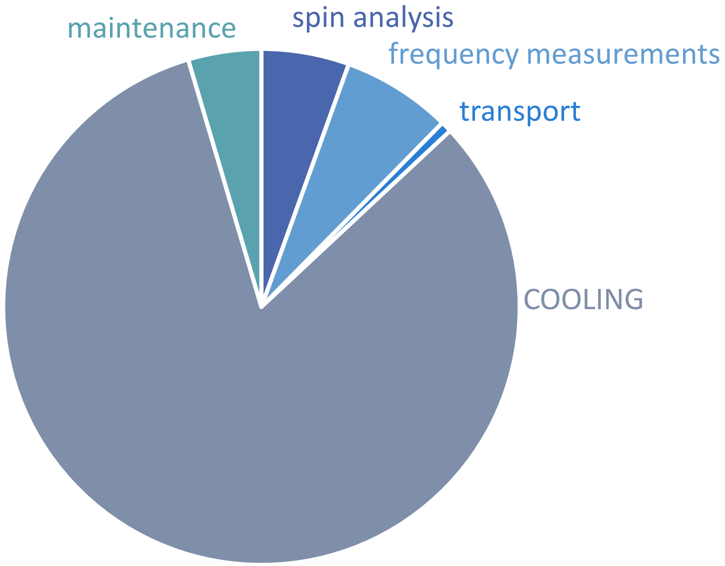
Cycle limitations (time)

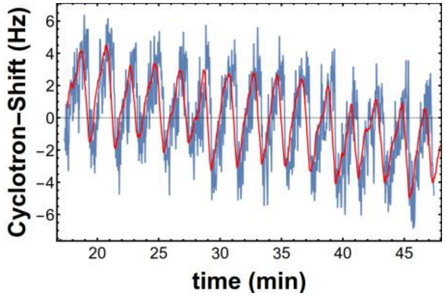
External noise sources

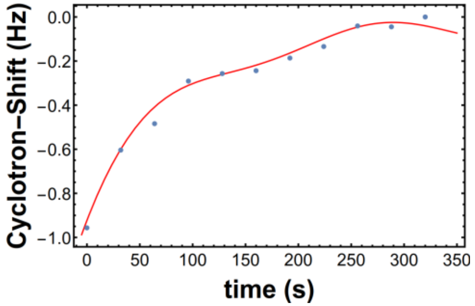
Frequency shifts induced by particle’s mode energies

measurement noise

Un-controlable fluctuations





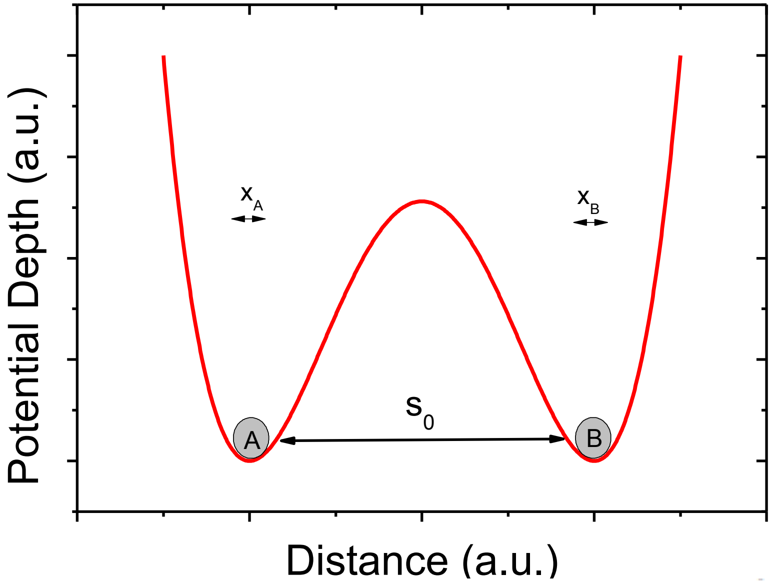


SYMPATHETIC COOLING

!!! Move Out !!!

Sympathetic Cooling of (Anti)protons

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



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

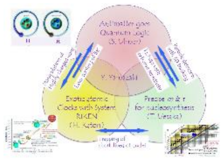
$$\approx \frac{1}{4\pi\varepsilon_0}\frac{q_aq_b}{s_0}\left(\underbrace{1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2}}_{\textbf{Static}} - \underbrace{\frac{2x_ax_b}{s_0^2}}_{\textbf{Dynamic}}\right)$$

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

Resonant Coupling:

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

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



Effective Energy Exchange

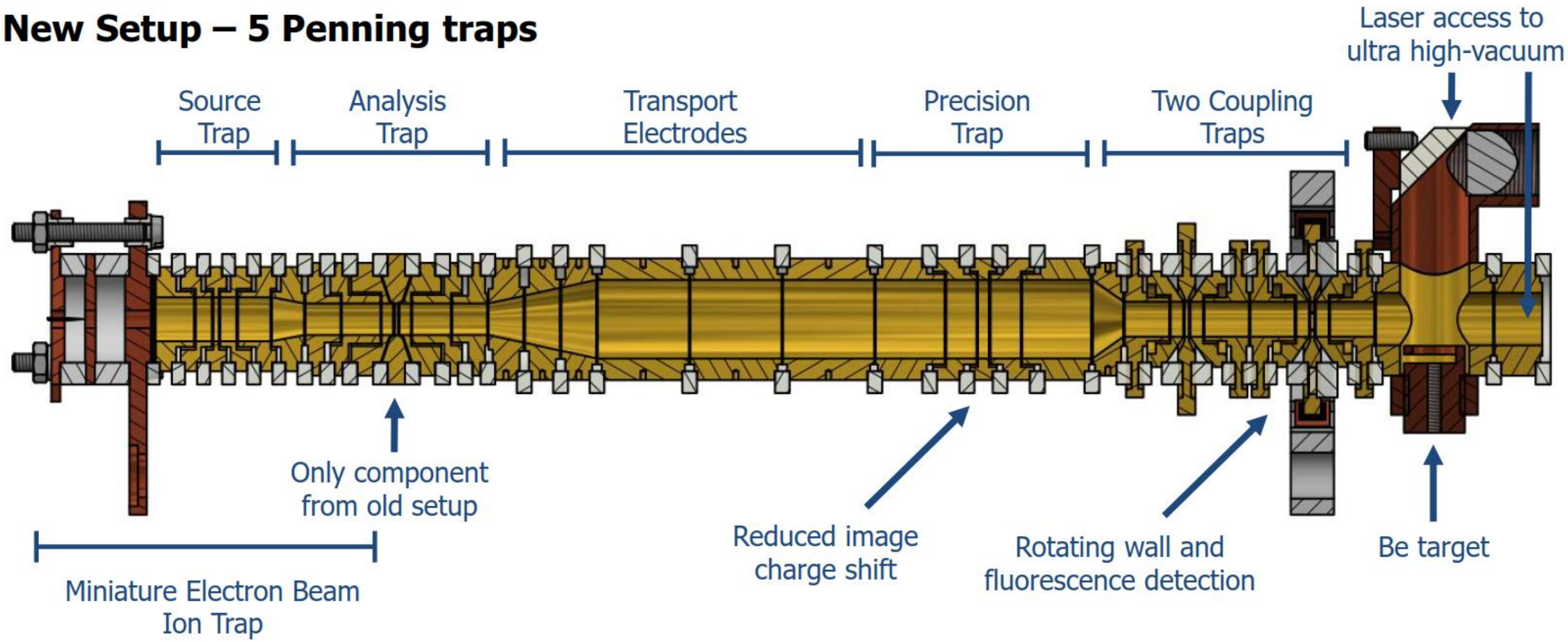
- Basic idea: laser-cool a cloud of Be-ions – bring (anti)proton to interaction – remove (axial) energy from antiproton within typical coupling time – couple sideband
- Immediate application: Quasi-deterministic cyclotron cooling of spectroscopy particle.
  - Dramatically improved spin identification fidelidy
  - Significantly improved experiment cycle time
  - Improved statistics / reduced systematics

100mK in 30s

(currently: 100mK in 20h)

see also the presentation by J.M. Cornejo

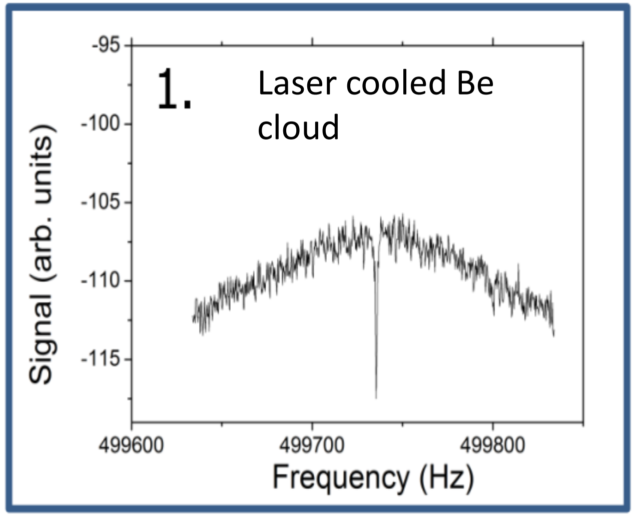
Developed at BASE-Mainz Experiment



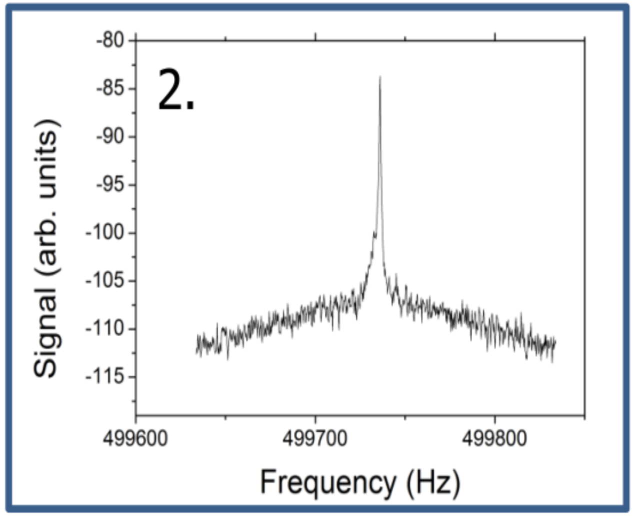
- Experiment has been constructed, currently under commissioning.
  - Be loading -> works
  - Laser access -> works
  - Particles in coupling traps -> OK

M. Bohman *et al.* , J. Mod. Opt. **14**, 04656 (2017

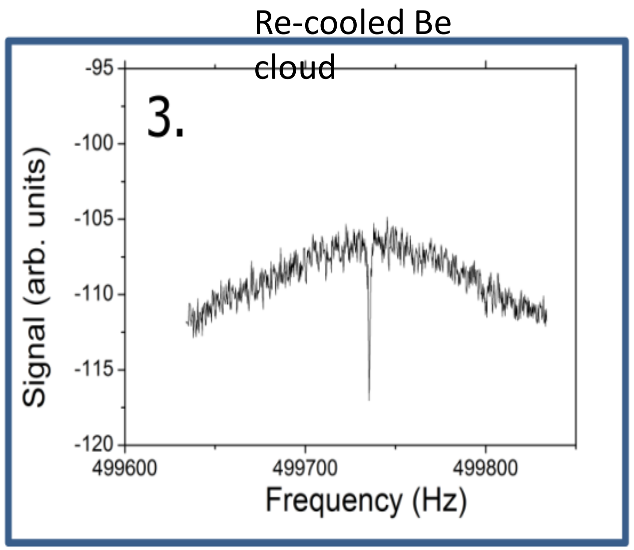
First Demonstration of Laser Manipulation in CT

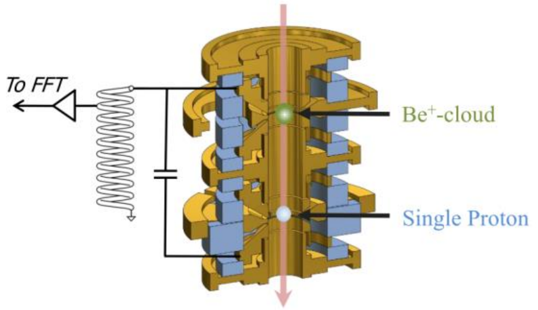


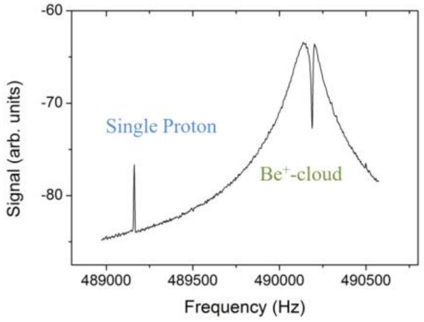
Laser excite at blue sideband



Laser cool at red sideband

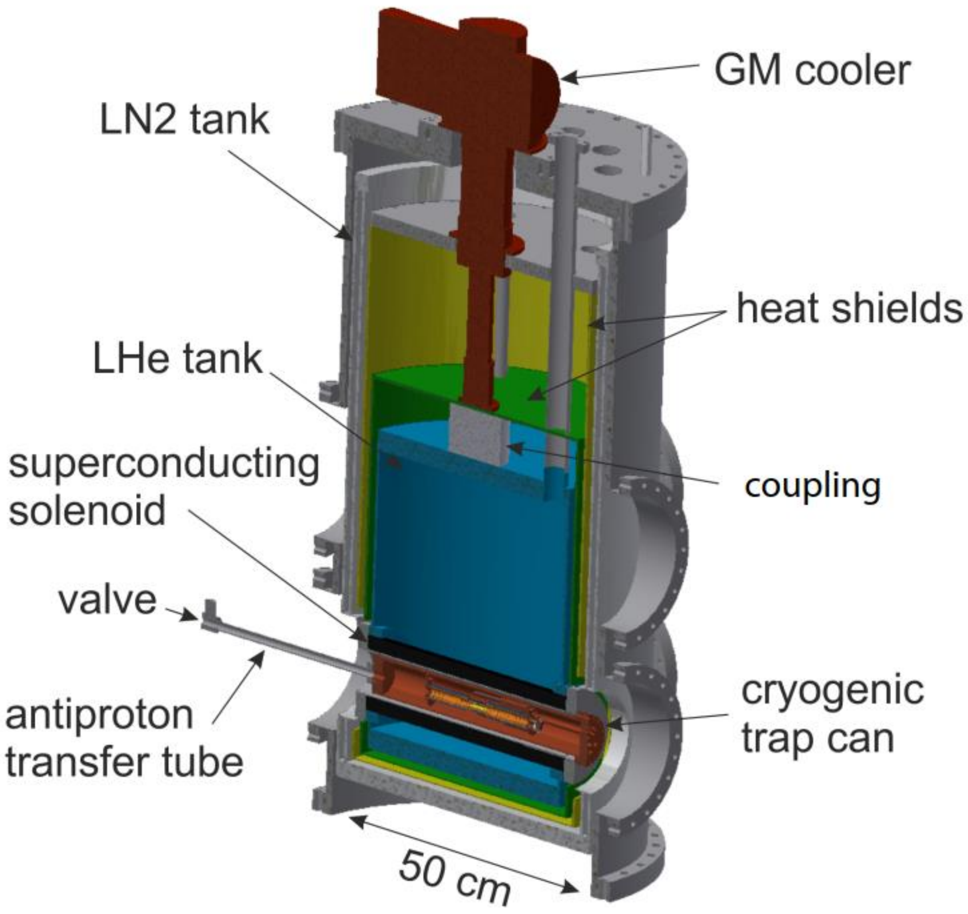






- Co-trapping of Be and single proton in the coupling trap has been demonstrated.
- Next step: demonstration of energy transfer between the particles
    - Coupling optimization
    - Temperature measurements: Work in progress.

Transportable antiproton traps for precision experiments



Transport of trapped particles: C. H. Tseng et al., Hyperfine Int. 76, 381 (1993)

Proposed Antiproton Transport: M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **88**, 214 (2004)

- Ingredients needed:
  - Trapping of antiprotons for considerable amount of time

    S. Sellner et al. (BASE collaboration), New. J. Phys. **19**, 083023 (2017).
  - Extraction of single particles from a reservoir

    C. Smorra et al. (BASE collaboration), Int. Journ. Mass. Spec. **389**, 10 (2015).
  - Ultra-adiabatic particle transfer

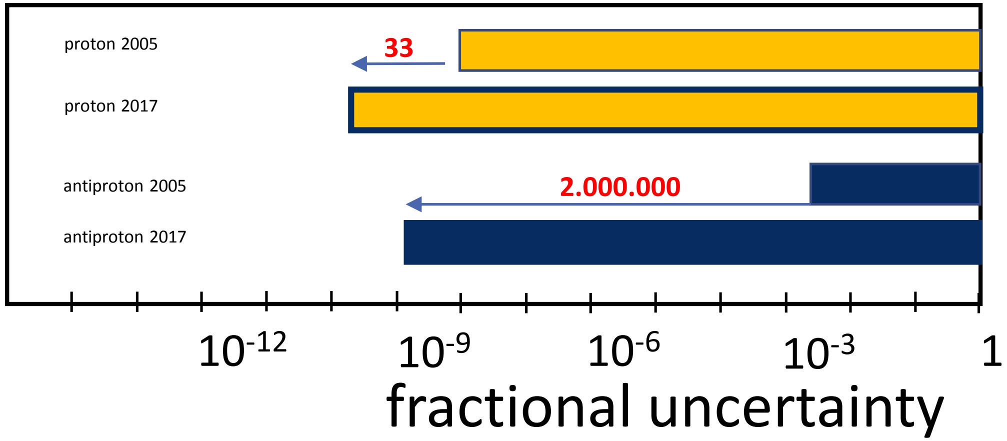
    C. Smorra et al. (BASE collaboration), Nature **550**, 371 (2018).
- Yet missing:
  - cryogenic transfer section (under development)
  - cryogenic valves (under development)

Summary

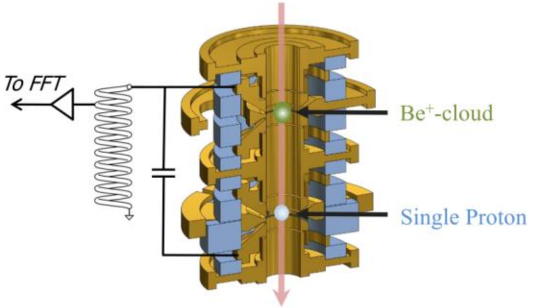
- Reported on a test of CPT invariance and WEP by comparing proton-to-antiproton charge-to-mass ratios with a fractional precision on the 69 p.p.t. level.

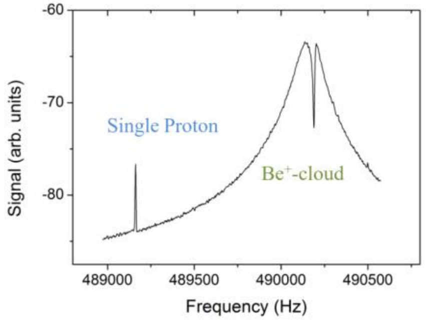
$$\frac{(q/m)_{\mathrm{\bar{p}}}}{(q/m)_{\mathrm{p}}} -1 = 1(69) \times 10^{-12}$$

- Improved proton/antiproton magnetic moment CPT test by a factor of 3000 using an elegant two particle method.



- New experiment under commissioning which will allow sympathetic cooling of antiprotons and protons.





- Design of a transport container in progress.

BASE

Thanks for your attention!

RIKEN

Programs for Junior Scientists

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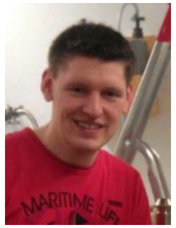
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U - Mainz


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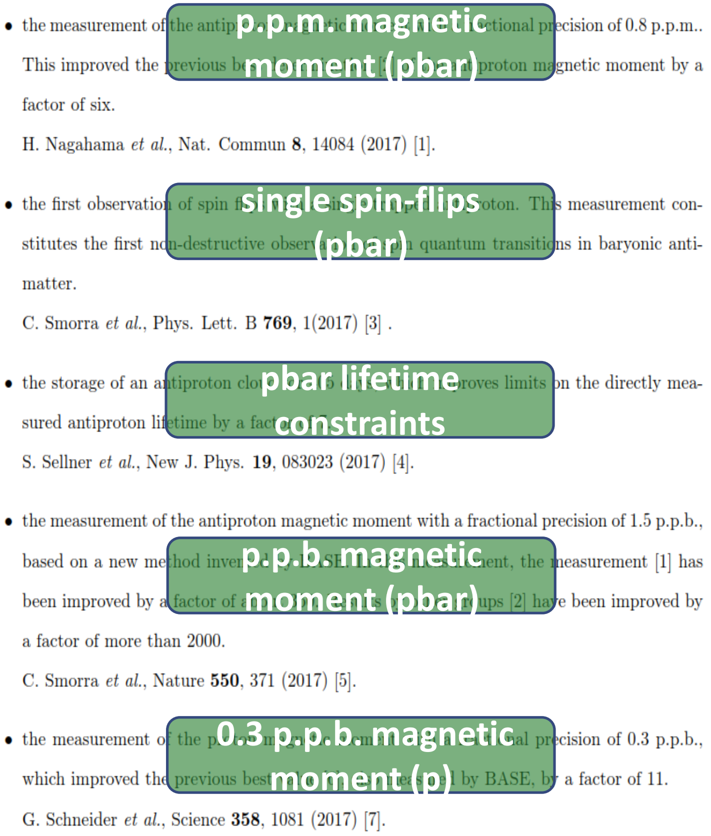
M. Wiesinger
RIKEN/MPIK


p.p.m. magnetic moment (pbar)

- the measurement of the antip[illegible]ctional precision of 0.8 p.p.m.. This improved the previous bes[illegible] proton magnetic moment by a factor of six.

  H. Nagahama *et al.*, Nat. Commun **8**, 14084 (2017) [1].

single spin-flips (pbar)

- the first observation of spin f[illegible]oton. This measurement constitutes the first non-destructive observ[illegible]n quantum transitions in baryonic antimatter.

  C. Smorra *et al.*, Phys. Lett. B **769**, 1(2017) [3] .

pbar lifetime constraints

- the storage of an antiproton clo[illegible]proves limits on the directly measured antiproton lifetime by a fact[illegible]

  S. Sellner *et al.*, New J. Phys. **19**, 083023 (2017) [4].

p.p.b. magnetic moment (pbar)

- the measurement of the antiproton magnetic moment with a fractional precision of 1.5 p.p.b., based on a new method inven[illegible]ment, the measurement [1] has been improved by a factor of a[illegible]ups [2] have been improved by a factor of more than 2000.

  C. Smorra *et al.*, Nature **550**, 371 (2017) [5].

0.3 p.p.b. magnetic moment (p)

- the measurement of the p[illegible]al precision of 0.3 p.p.b., which improved the previous best [illegible]ed by BASE, by a factor of 11.

  G. Schneider *et al.*, Science **358**, 1081 (2017) [7].