Annual Report 2014

Stefan Ulmer

on behalf of the BASE Collaboration

RIKEN

SPSC-Meeting 2015 / 01 / 13

BASE - Collaboration

- **Main goal: Measure magnetic moments of the proton and the antiproton with high precision.**

- **BASE-Mainz:** Measurement of the magnetic moment of the proton, implementation of sympathetic cooling of protons

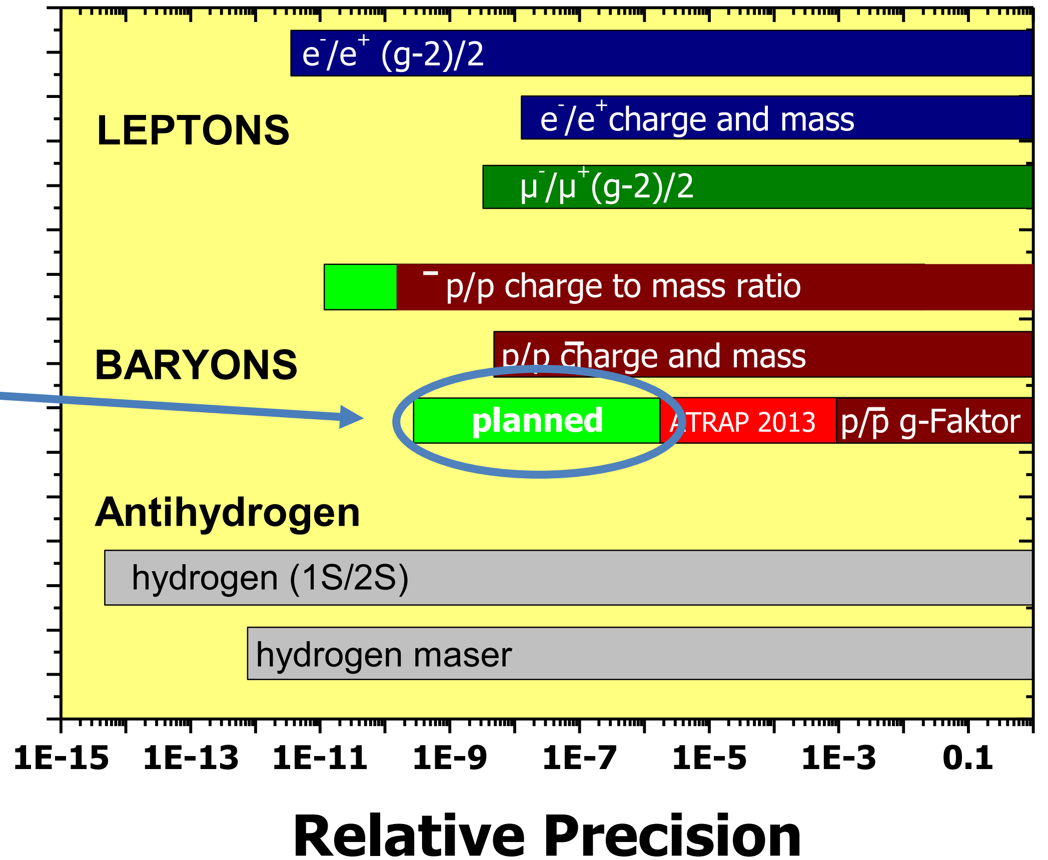
- **BASE-CERN:** Measurement of the magnetic moment of the antiproton

- **BASE-Hannover:** Implementation of quantum logic readout of spin state

Project was approved in June 2013

Test of CPT invariance

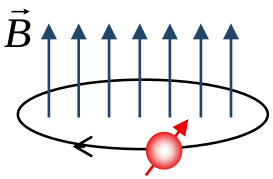
- CPT invariance is the most fundamental symmetry in the Standard Model.
- Strategy: Compare properties of matter and antimatter conjugates with high precision.



Basic Principle

Experiments performed with single particles in Penning traps

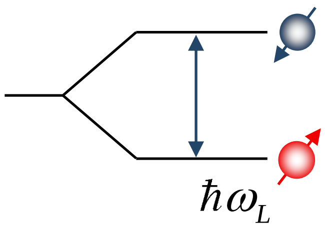
Cyclotron Motion



$$\vec{\mu} = g\frac{e}{2m_p}\vec{S}$$

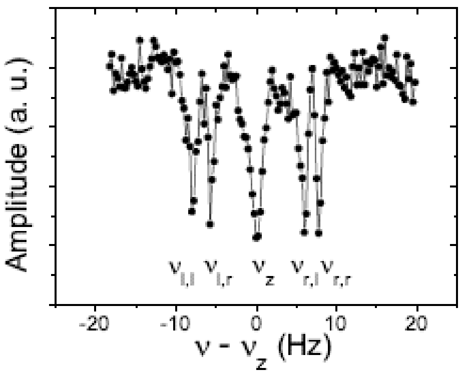
g: mag. Moment in units of nuclear magneton

Larmor Precession



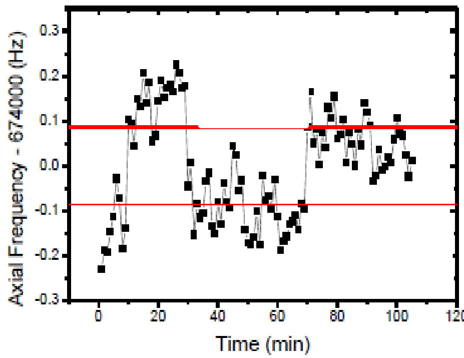
$$\omega_c = \frac{e}{m_p}B$$

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



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

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

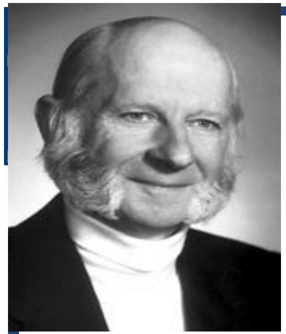


S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

simple

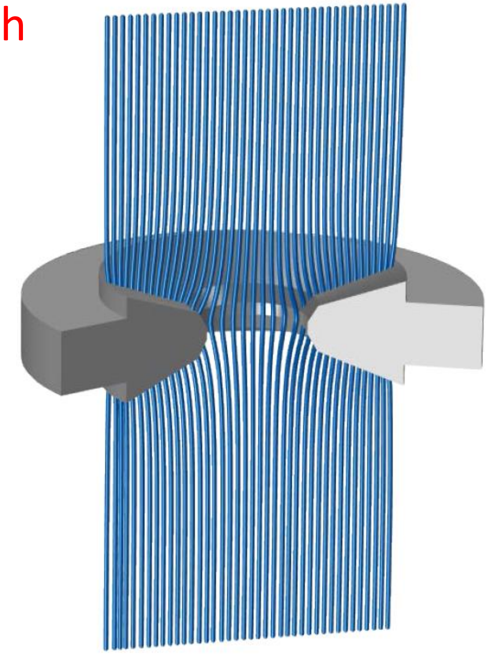
difficult

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 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

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

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

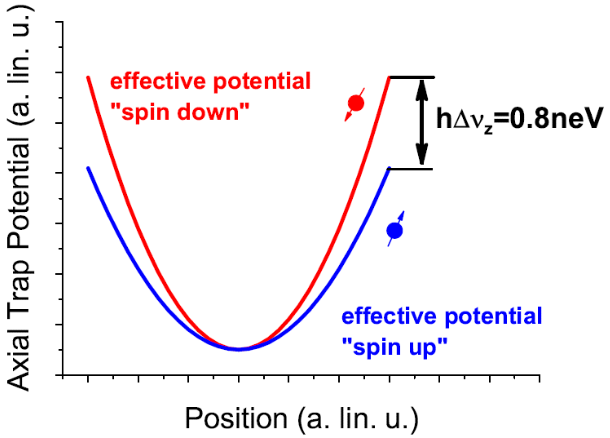
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

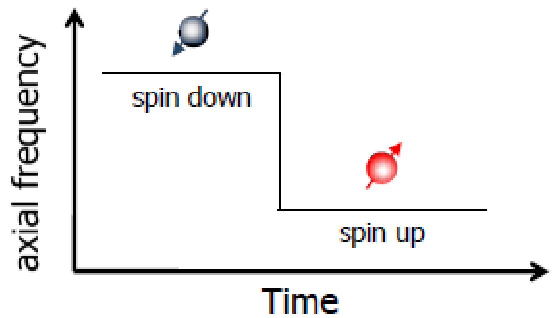
- Most extreme magnetic conditions ever applied to single particle.

$$\Delta\nu_z = 170\ mHz$$

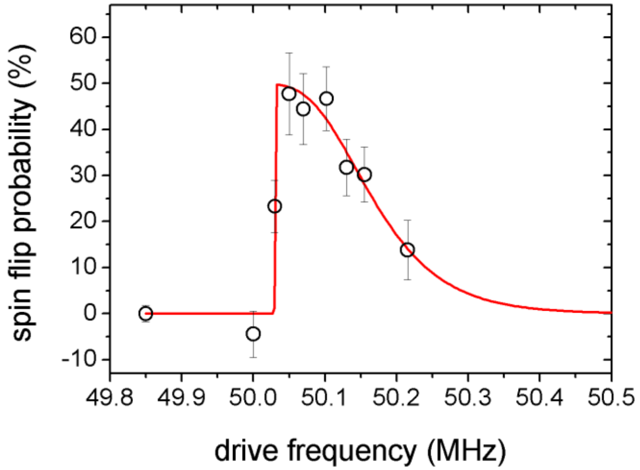


Larmor Frequency Measurement

- Spin is detected and analyzed via an axial frequency measurement



- Larmor Frequency is measured by repetition and evaluating the spin flip probability
- Together with cyclotron frequency measurement:



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

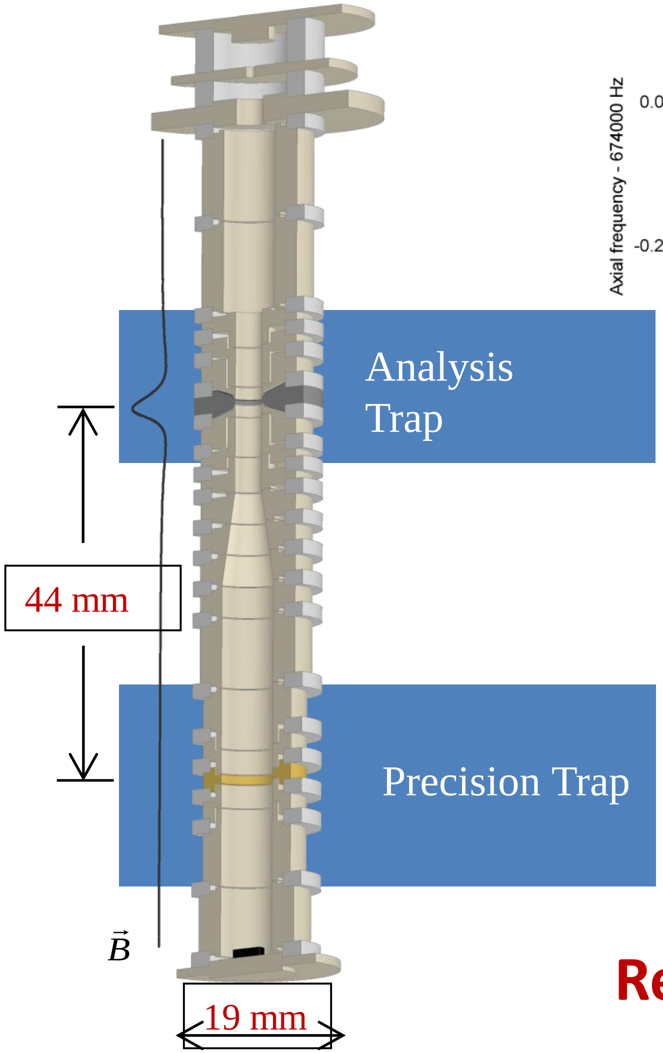
g/2 = 2.792 848 (24) Rodegheri et al., NJP 14, 063011, (2012)

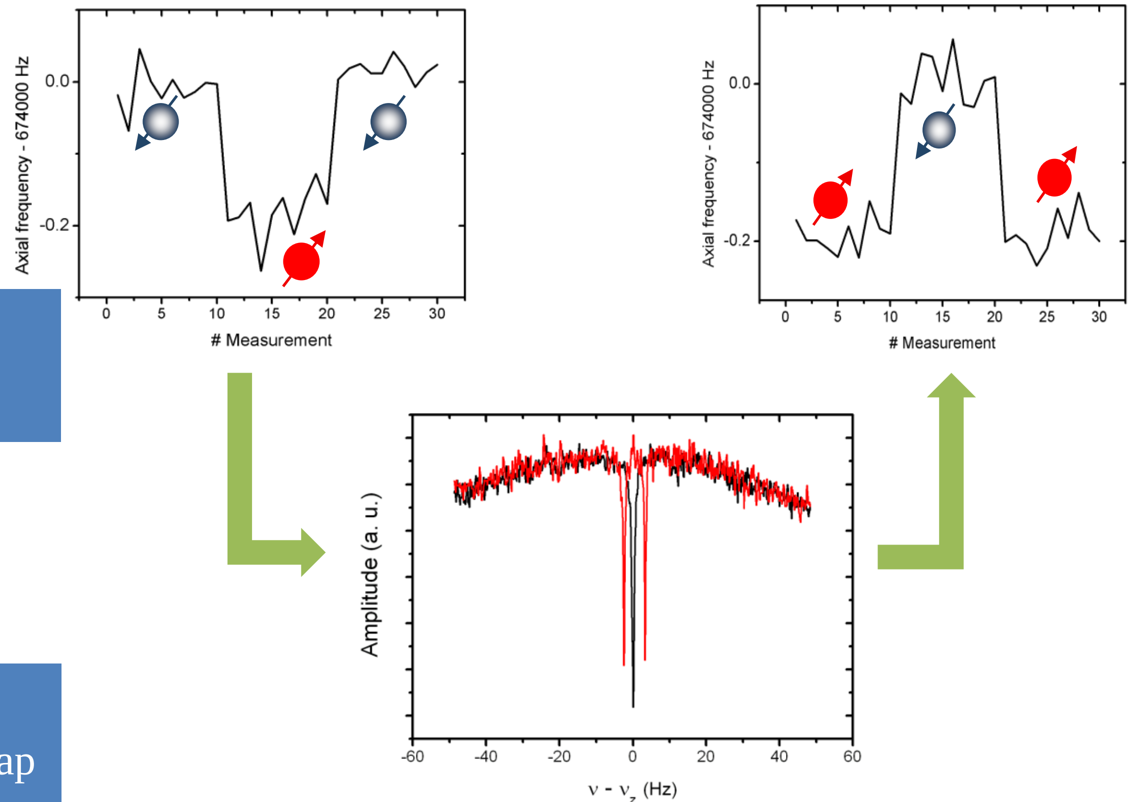
g/2 = 2.792 846 (7) di Sciacca et al., PRL 108, 153001 (2012)

Limited to the ppm level due to the strong magnetic bottle.

Double-Trap Method

Idea: Separate spin state analysis and precision frequency measurements.



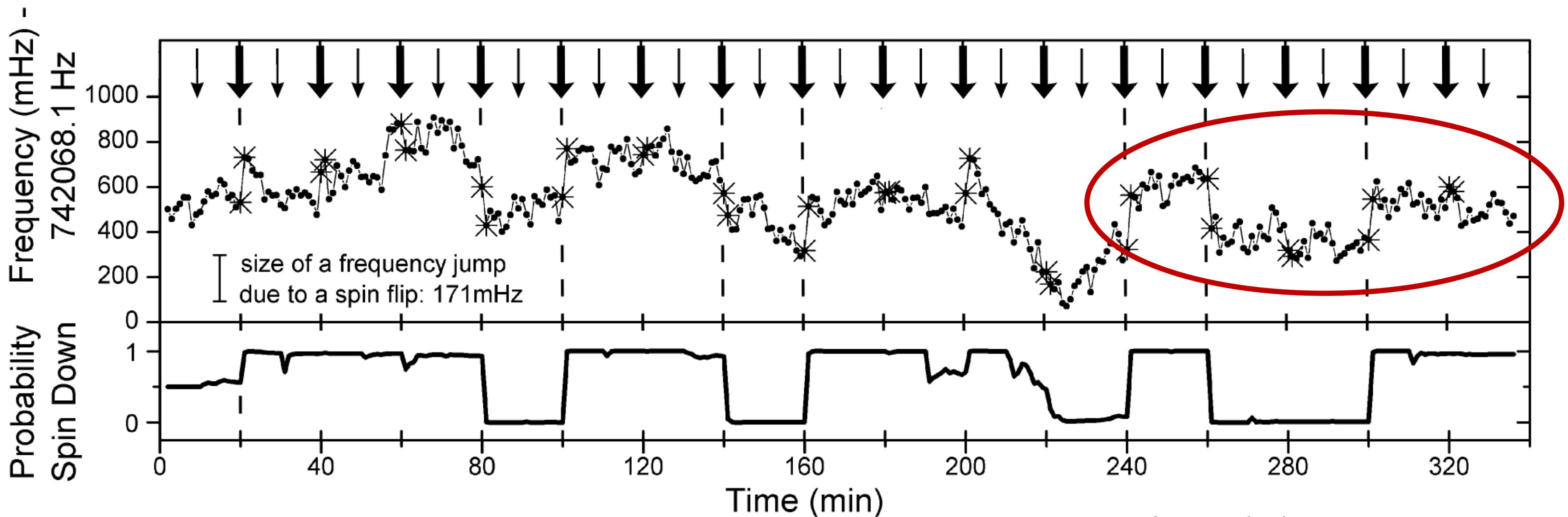


Requires clear identification of the spin state

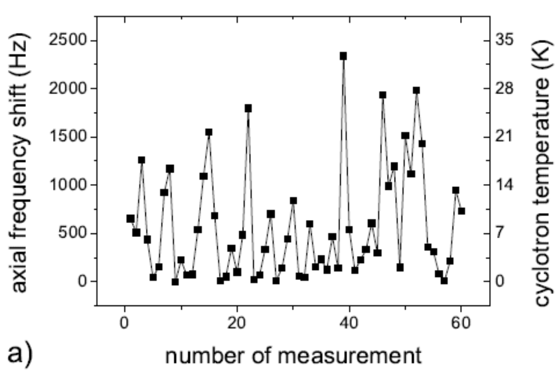
H. Häffner, Phys. Rev. Lett.85, 5308 (2000)

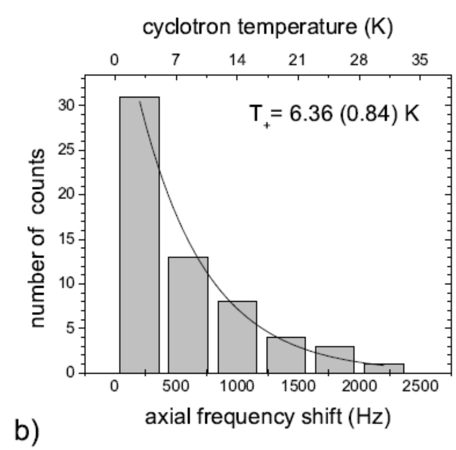
Single Spin Flips and Double Trap Method

- Improvement of apparatus, trap wiring, quality of detection systems (lower noise, faster measuring cycles):



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



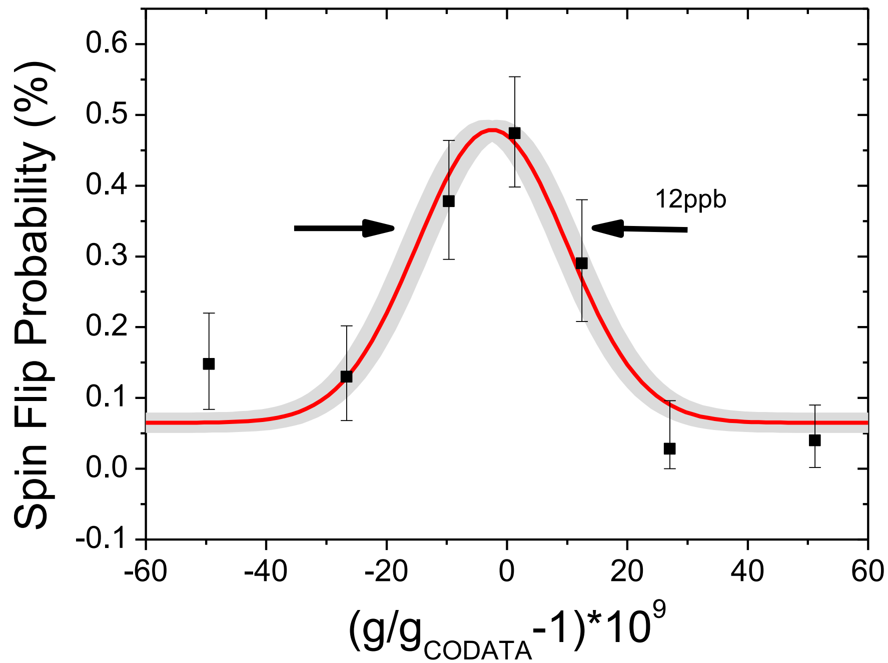


Heating rate: 10 cyclotron jumps in 1h

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

The Magnetic Moment of the Proton

- Sweeping excitation frequency -> g factor resonance



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)**

Line width:
due to saturation and residual B_2
In precision trap.

g/2 = 2.792847350 (7) (6)

- First direct high precision measurement of the proton magnetic moment.
- Improves 42 year old MASER value by factor of 3.
- Value in agreement with accepted CODATA value, but 2.5 times more precise

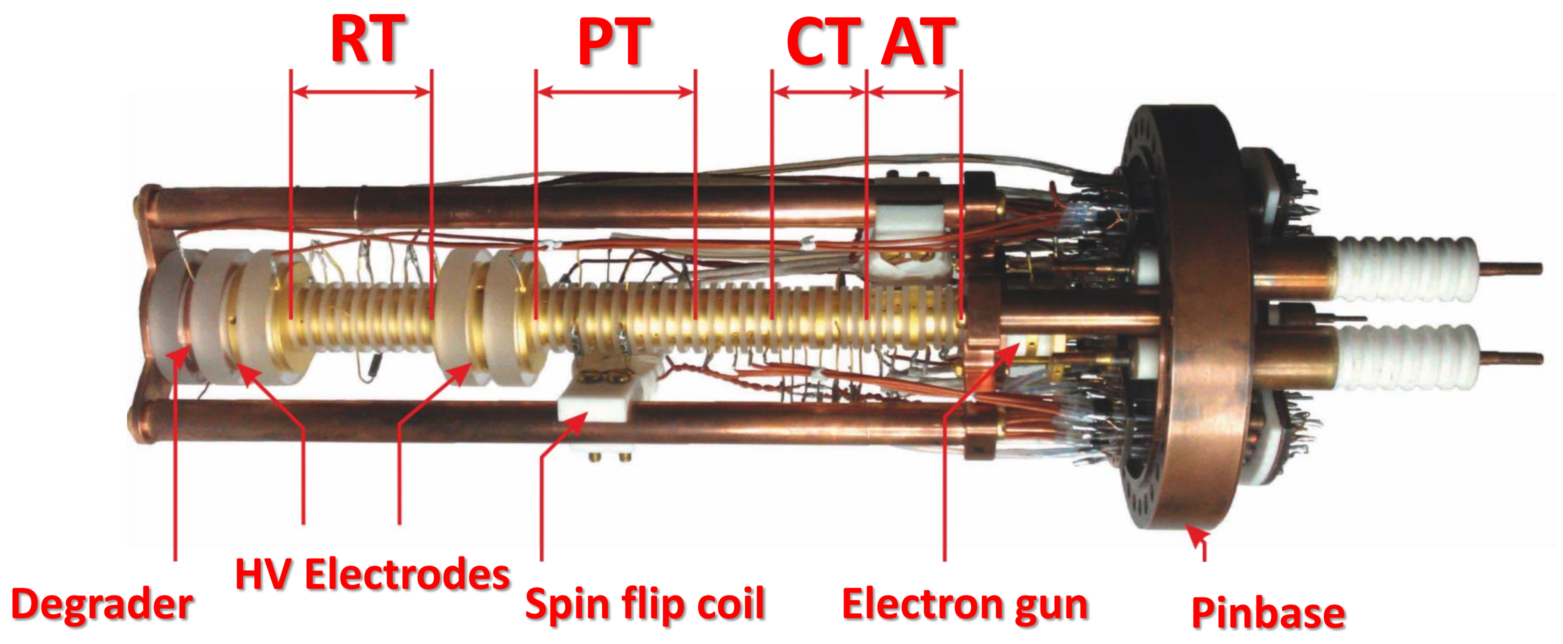
Mainz Setup Revisited

- Status:
  - Experiment is sensitive to rms noise amplitudes at the level of a few pV.
    - Long preparation cycles of particles with single spin flip resolution (2 to 3 hours per datapoint, 500 points needed).
    - Precision is currently limited by stray magnetic field caused by the strong AT magnetic bottle in the center of the PT.

issues addressed in BASE Penning trap design

BASE at CERN

BASE Trap System



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)**

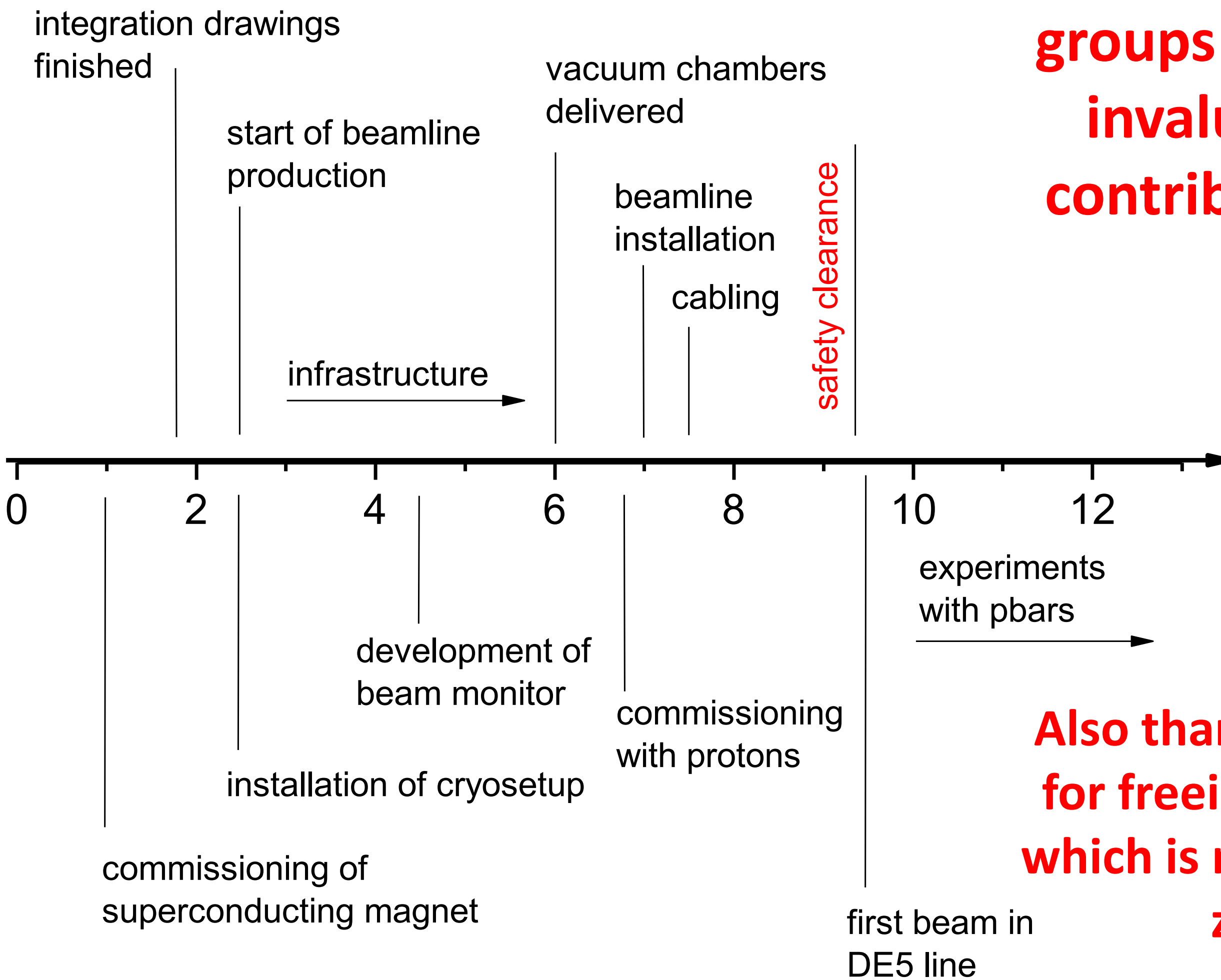
Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**

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

Integration of BASE

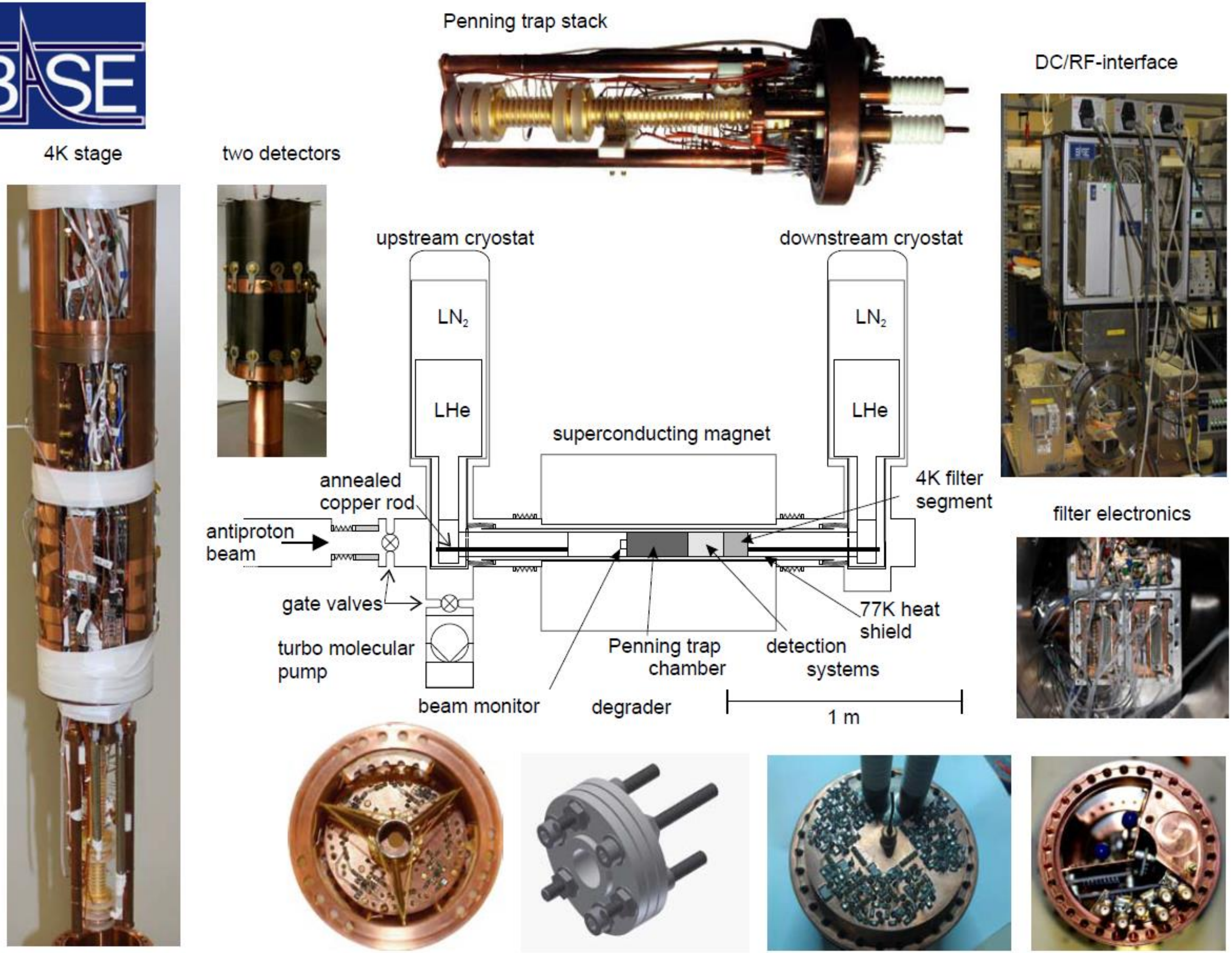
- Timeline 2014

Thanks to all CERN groups for the invaluable contributions



Also thanks to ATRAP for freeing the space which is now the BASE zone.

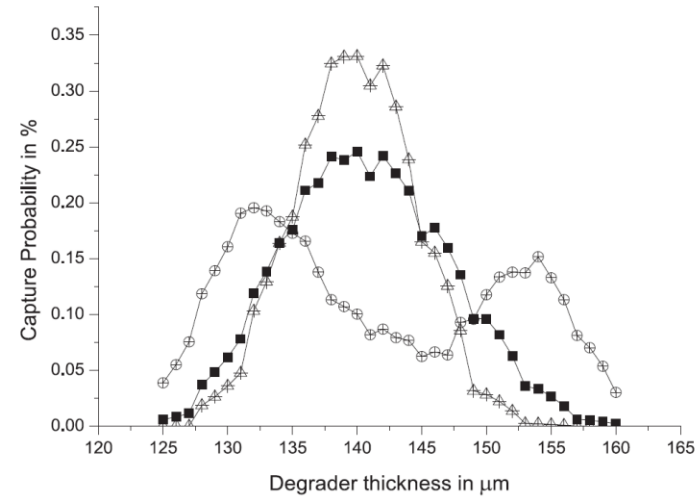
RIKEN (85%) and Max Planck Society (15%) paid about 800,- kCHF to CERN.



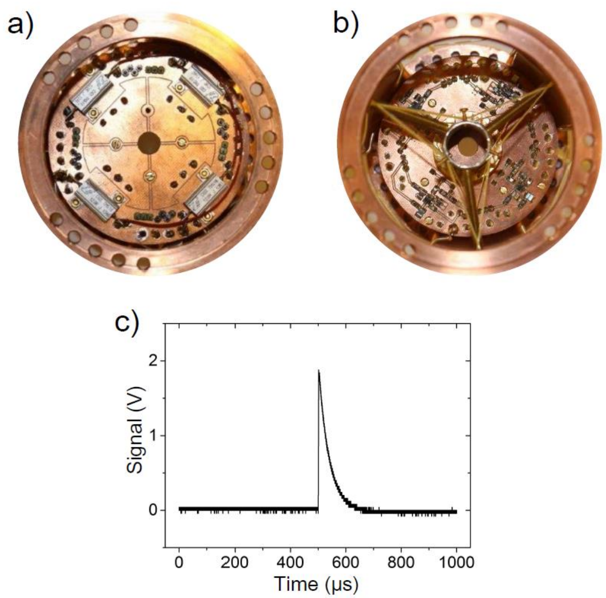
Penning trap stack
DC/RF-interface
4K stage
two detectors
upstream cryostat
downstream cryostat
LN_2
LN_2
LHe
LHe
superconducting magnet
annealed copper rod
4K filter segment
filter electronics
antiproton beam
gate valves
turbo molecular pump
77K heat shield
Penning trap chamber
detection systems
beam monitor
degrader
1 m

Degrader / Beam Monitor

- Degrader is a construction of rotated meshes (2.5um each)
- Low effective transmission (1e-4) but very robust with high energy acceptance.



C. Smorra et al., manuscript in preparation



- Four Faraday cups around central transmission circle
  - Cryogenic
  - Si-CMOS technology (low noise, sensitive)
  - Power-consumption of 2mW.
  - Cheap, after prototyping: about 80CHF per monitor.

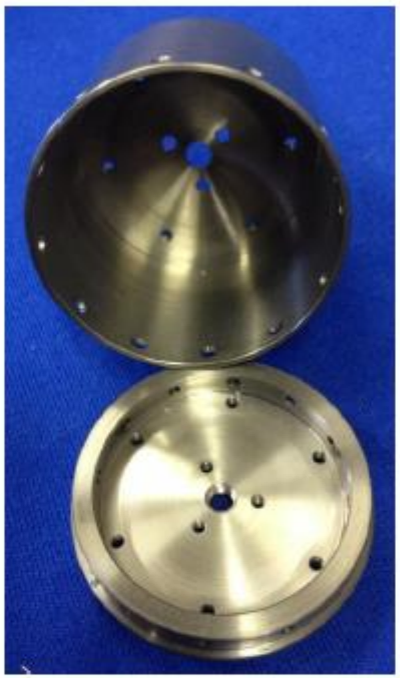
A. Mooser et al., manuscript in preparation

Improved Detection Systems

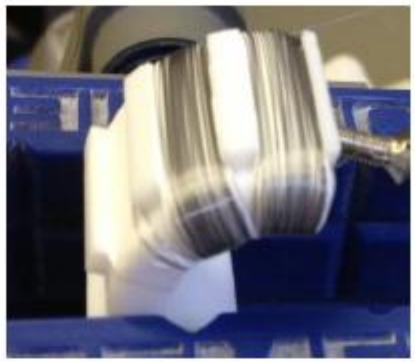
- Frequency resolution: $\sigma \propto \sqrt{\frac{1}{4\pi} * \frac{\Delta\nu}{t\sqrt{SNR}}}$

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

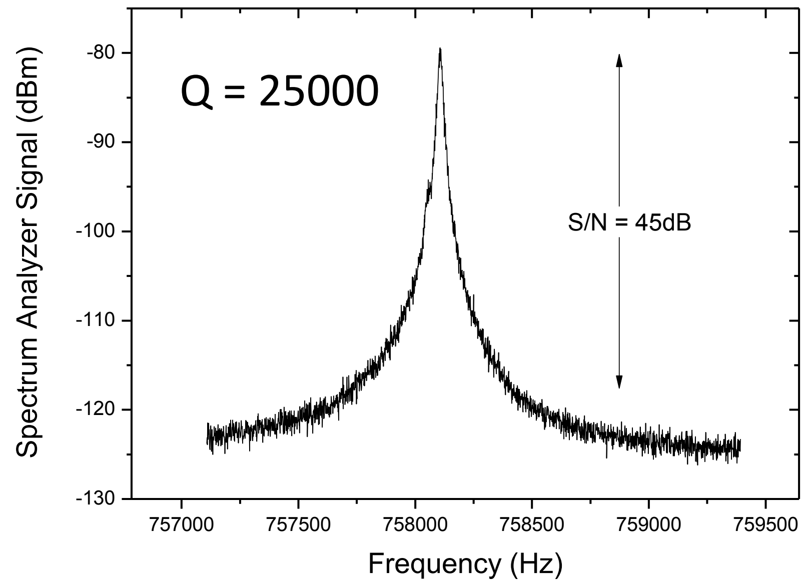
Resonator



Toroidal coil



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



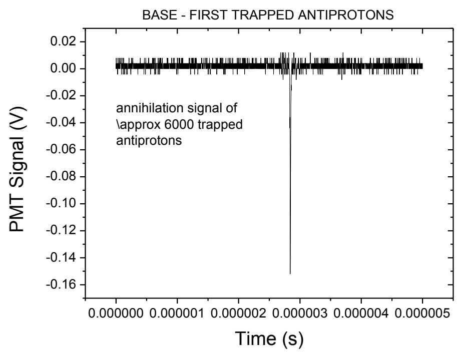
(Unloaded Q = 550000, technical limit)

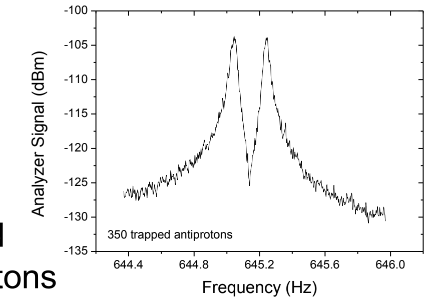
- Frequency measurements in BASE-CERN are faster than at the BASE-Mainz experiment

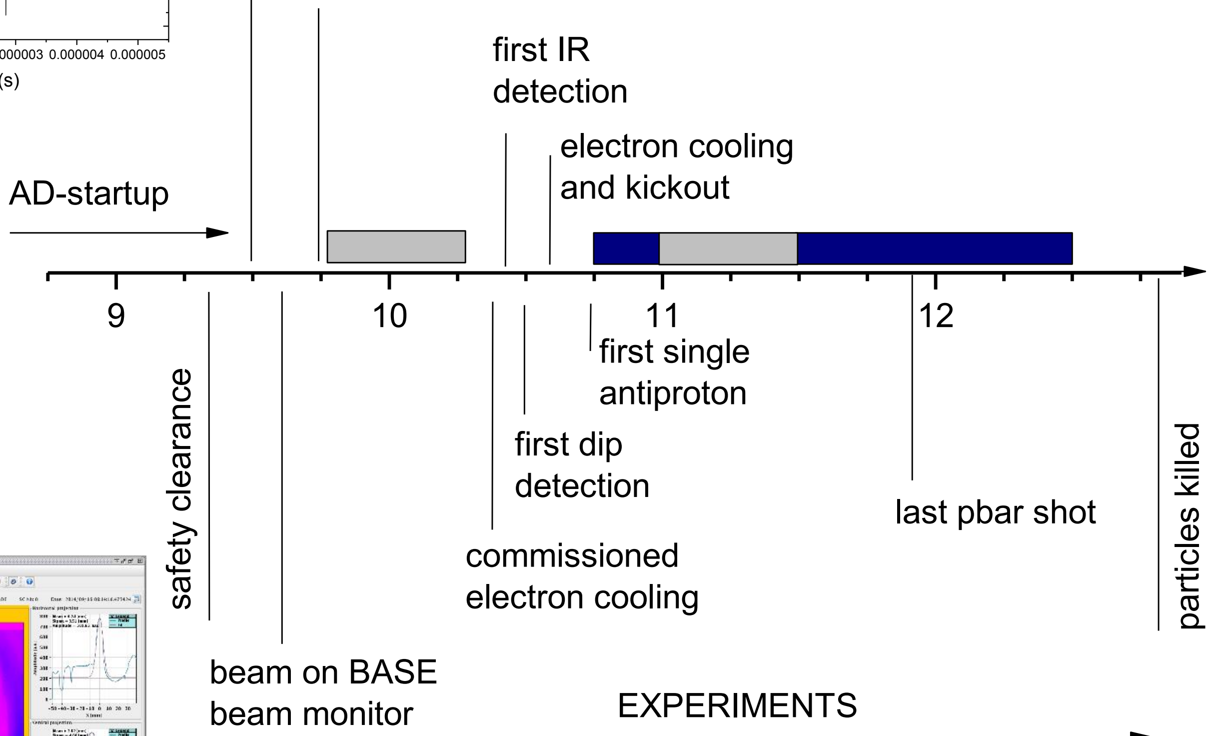
S. Ulmer et al., manuscript in preparation

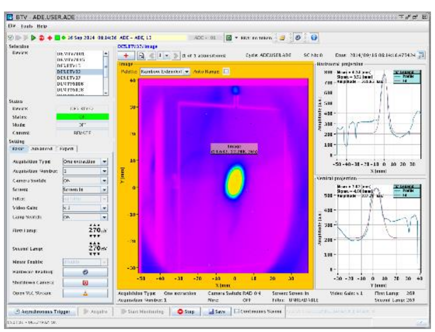
Beamtime 2014

First Steps





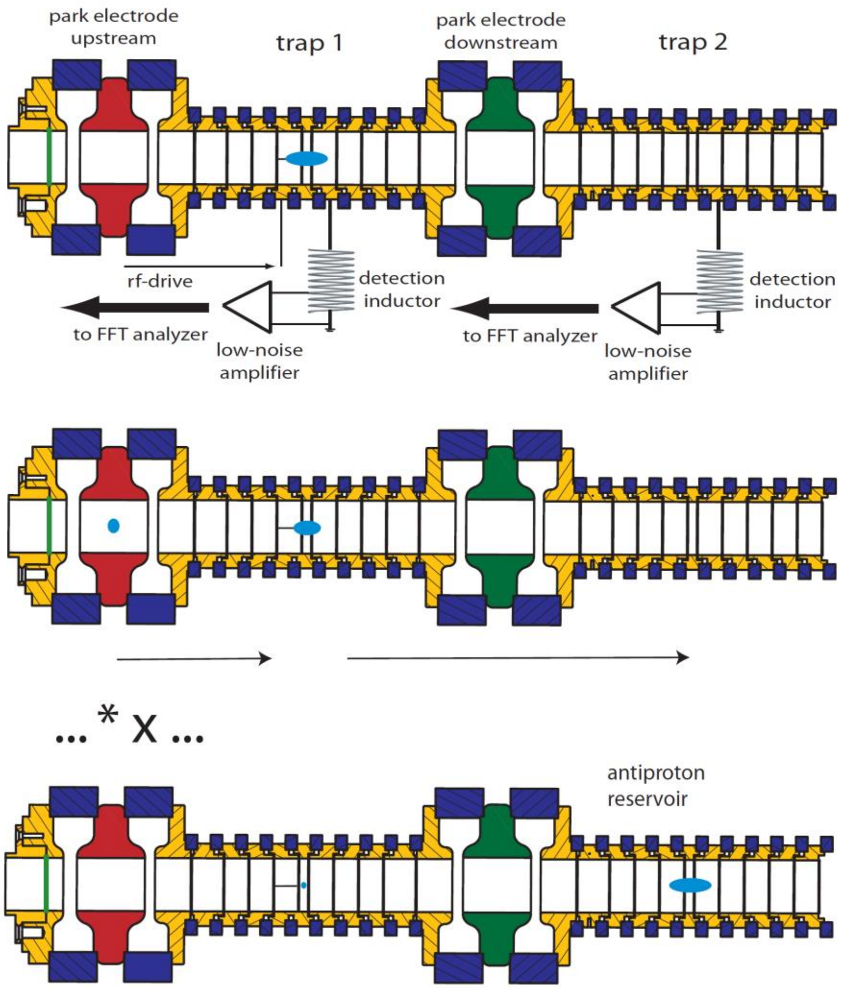




Catching: G. Gabrielse et al, PRL 57, 2504 (1986)
Cooling: G. Gabrielse et al, PRL 63, 1360 (1989)
Measurement: G. Gabrielse et al, PRL 65, 1317 (1990)

The Reservoir Trap

Basic idea: serve as antiproton reservoir – survive accelerator shutdown



Initial state: antiproton cloud in trap 1

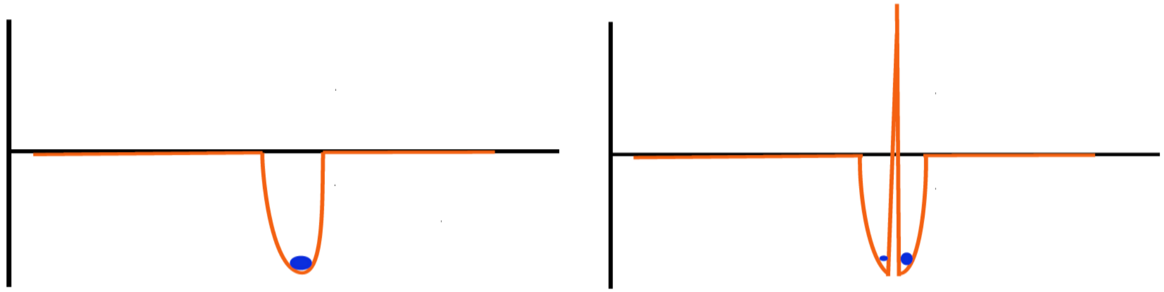
step 1: separation of particle cloud

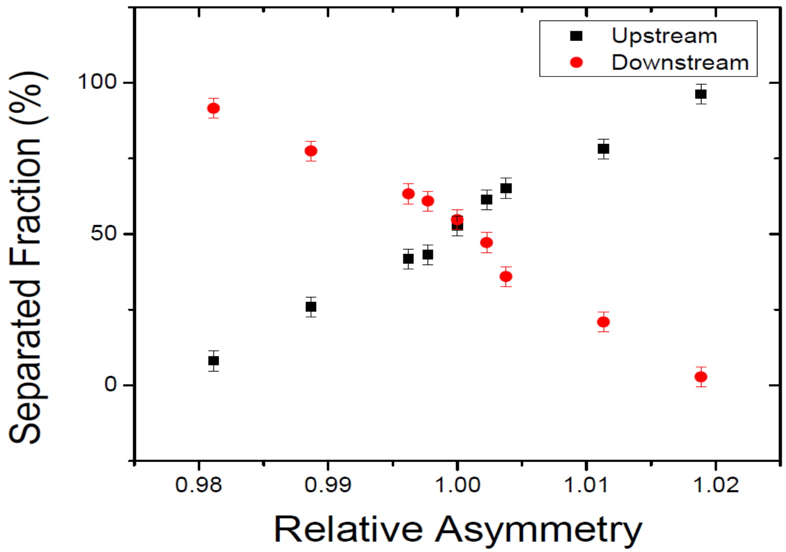
step 2: adiabatic transport to second trap

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:

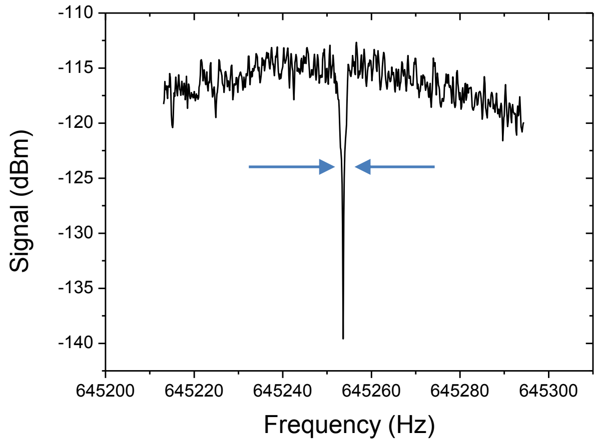


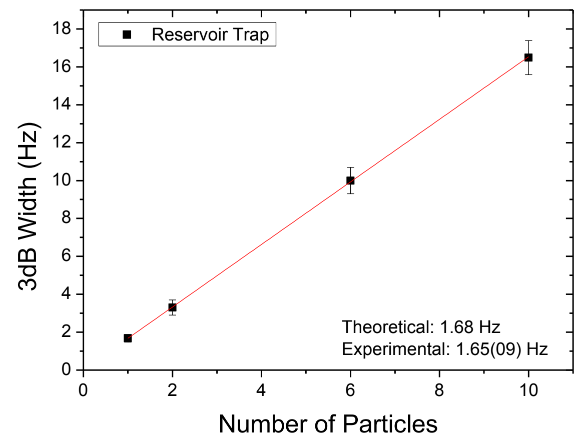


- All experiments were performed with the same cloud of particles **-> also merging of particle clouds works.**
- No particle loss during separation/merging experiments
- One separation cycle takes only 12s

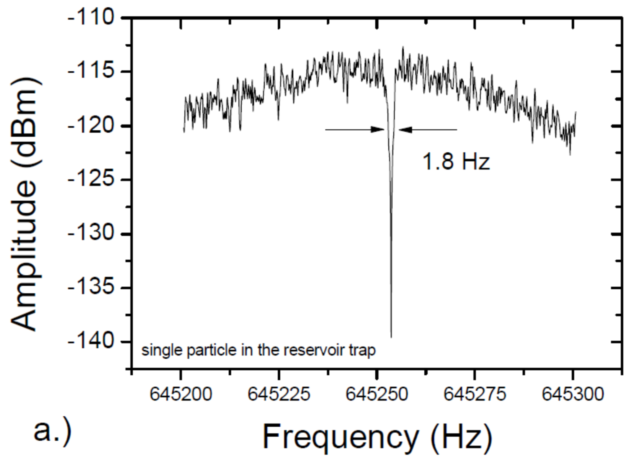
Single Particle Experiments

- Count particles by measuring line-with of the dip.

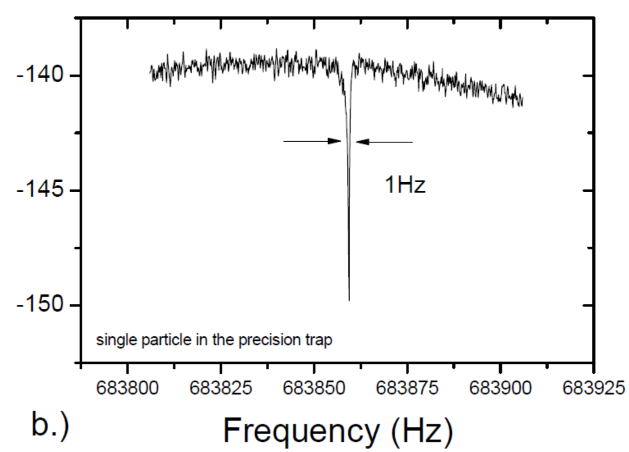




- Shuttling of particles:



a.)



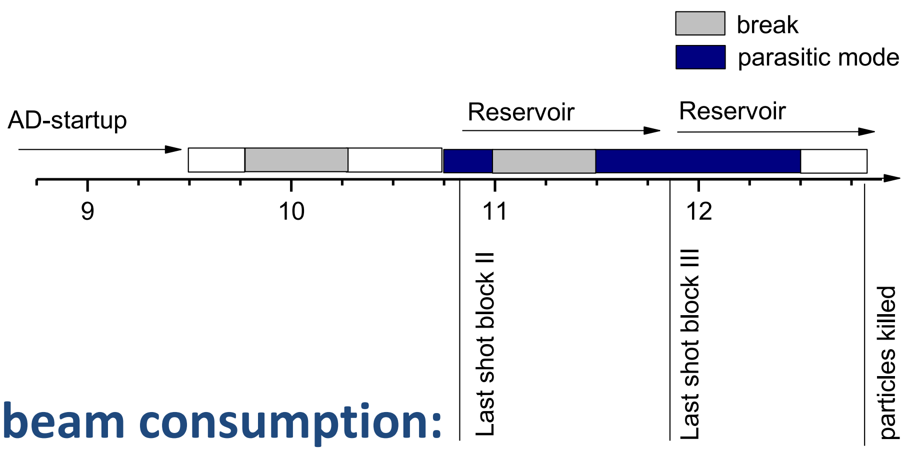
b.)

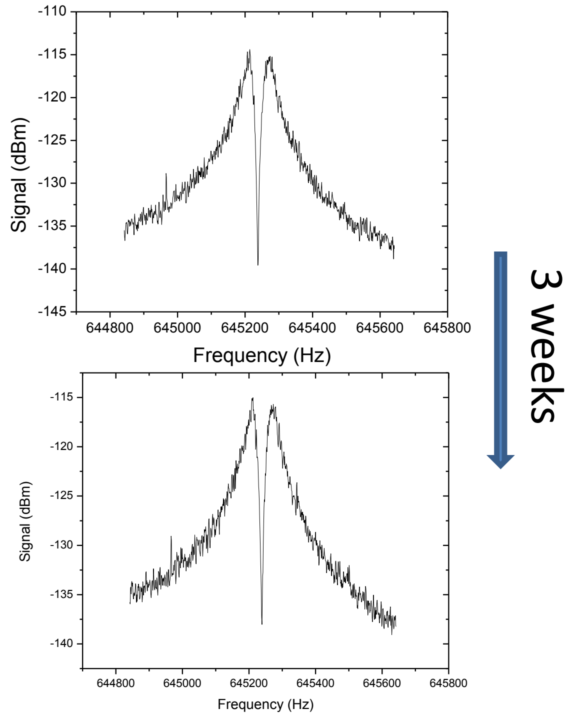
- Shuttling from RT -> PT takes 10s.

Further Comments on the Reservoir

Our system survives:

- 10 hours power cuts (power consumption of trap is 100W, can be reduced further).
- Is cryo-pumped at insulation vacuum of 1e-9 (no power for pumping).
- Never observed particle losses due to annihilation.





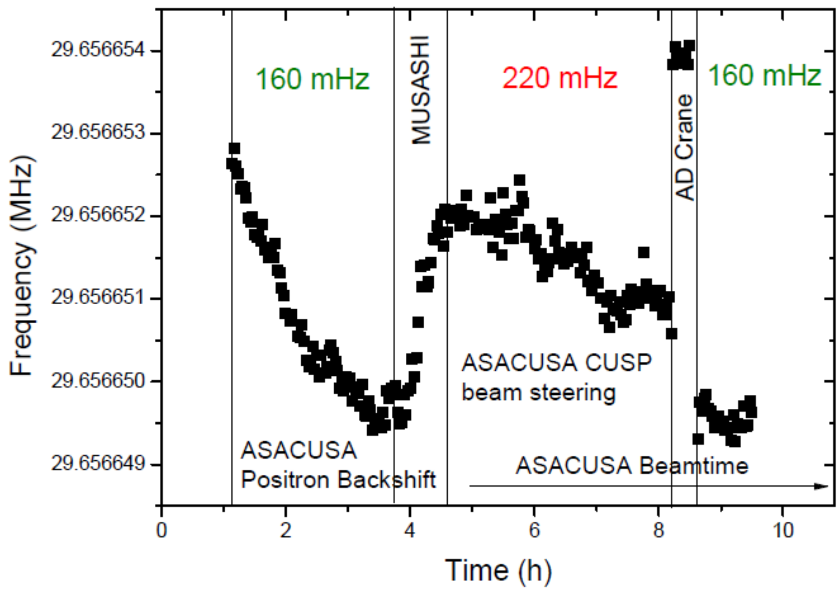
- **BASE beam consumption:**
  - One week to trap antiprotons: effectively 6 shifts
  - One week for electron cooling and resonant detection: 4 full shifts, 3 shared
  - Three shifts taking only a few shots
  - Two additional full shifts for systematic studies.

BASE consumed only 12 full shifts, in total maybe 15 shifts

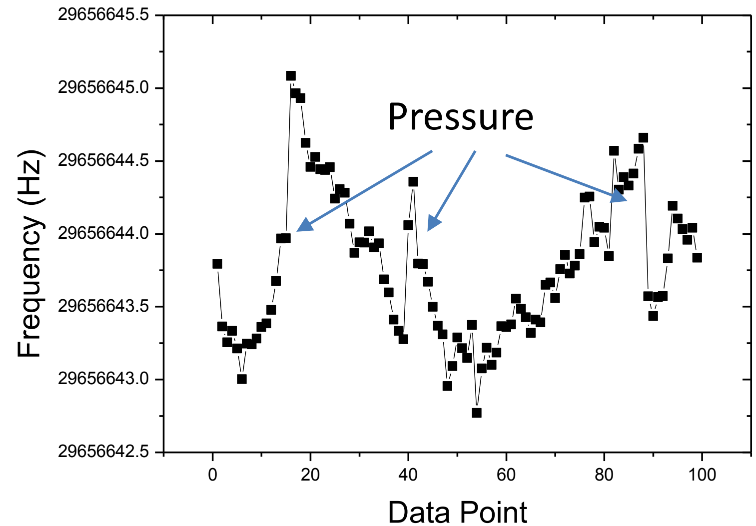
Noise

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

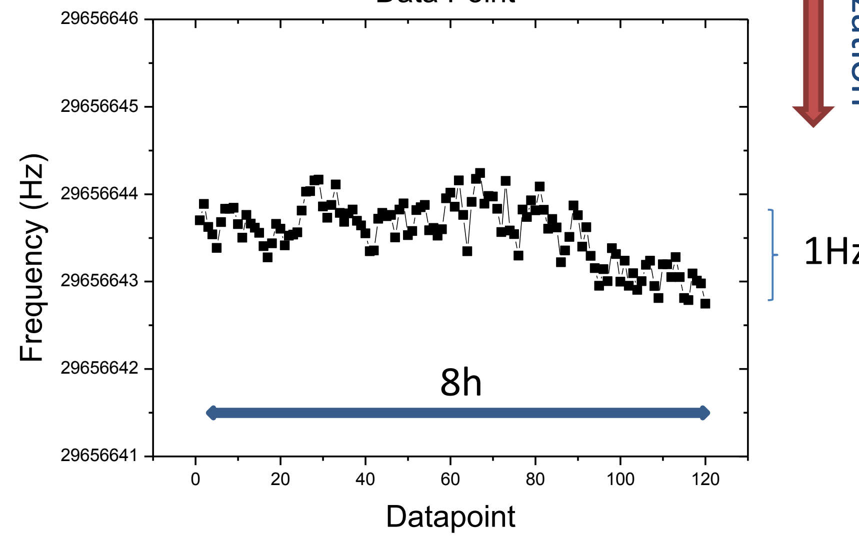
10 nT fluctuation



- Profited from Mainz experiment -> technology exchange takes typically 10 hours



Pressure Stabilization



Frequency stability allows for sub ppb g-factor measurement

Planned in 2015

- Developments:
  - Implementation of new magnet with shielding factor of 200
  - Implementation of a set of self-shielding coils (another shielding factor of 200)

-> Significant improvement of magnetic field stability

- Commission spin flip setup with protons

- Prepare experiment for double-trap measurements with protons and **apply the scheme to antiprotons.**

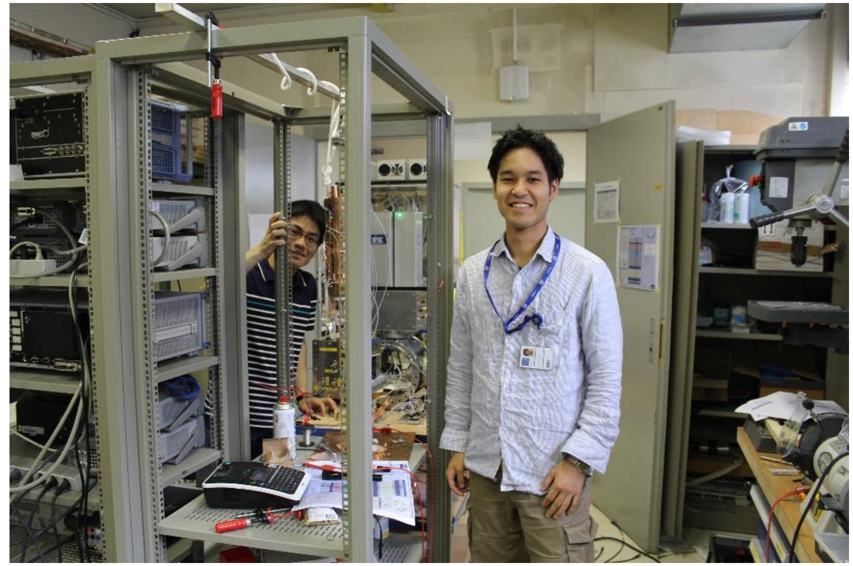
Summary

- BASE measured the magnetic moment of the proton with a fractional precision of 3.3ppb.
- In beamtime 2014 BASE commissioned an entirely new 4-Penning trap experiment.
  - Demonstrated:
    - Catching of antiprotons
    - Electron cooling of antiprotons
    - Single particle preparation

  …within two weeks.
- Commissioned the reservoir trap and implemented methods to extract single particles from the reservoir.
- Took data with single particles to characterize the noisy AD environment.
- Took effectively only 15 full AD shifts.
- Will prepare experiment to run our first single antiproton spin flip experiments in beamtime 2015.

BASE

Thanks very much for your attention



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K. Blaum, W. Quint, J. Walz, Y. Yamazaki

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