The Baryon Antibaryon Symmetry Experiment (BASE)

RIKEN

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Y. Yamazaki, and S. Ulmer

10.06.2013 - LEAP Conference - Uppsala 2013

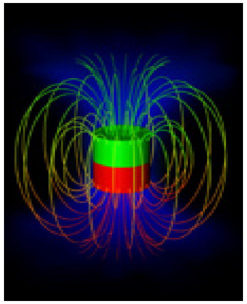
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Max-Planck-Institut für Kernphysik

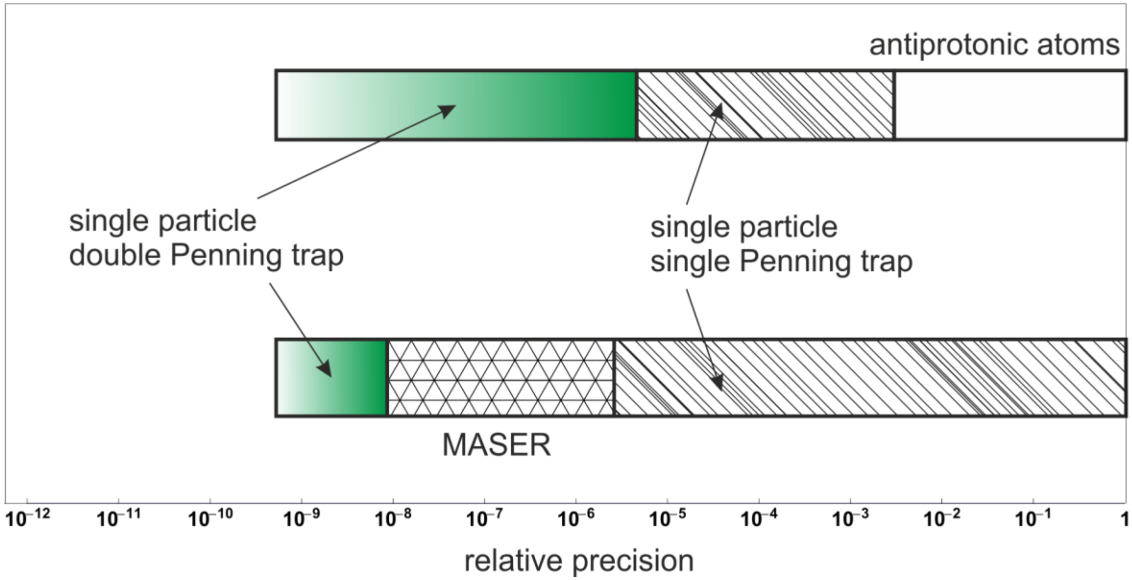
GSI

Motivation

High-precision test of the CPT invariance
by comparing the proton and antiproton magnetic moments:



$$\vec{\mu}_{p/\bar{p}} = g_{p/\bar{p}} \frac{q_{p/\bar{p}}}{2m_{p/\bar{p}}} \vec{S}$$



$$g_{\bar{p}} = 5.585690(24)$$

$$g_p = 5.585694713(46)$$

P. F. Winkler *et al.*, Phys. Rev. A **5**, p. 83 (1972).
J. DiSciacca *et al.*, Phys. Rev. Lett. **110**, 130801 (2013).

Outline

Motivation of the double-trap method

- Experimental principle of g-factor measurements
- Spin-state detection of a single proton/antiproton
- Double-Penning trap method

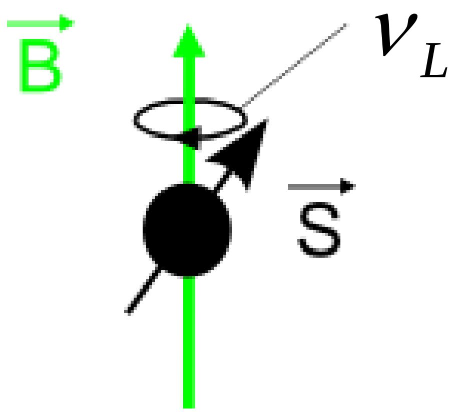
BASE

- Design of the new apparatus
- Status of the implementation in the AD

Experimental principle

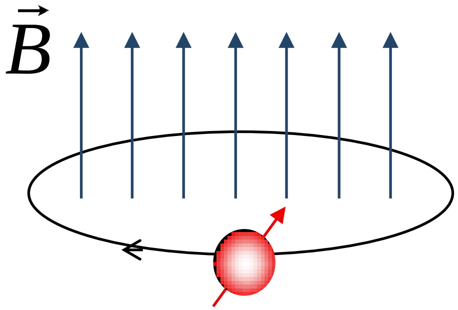
$$\frac{\mu_{p/\bar{p}}}{\mu_N} = \pm \frac{g_{p/\bar{p}}}{2} = \pm \frac{\nu_L}{\nu_C}$$

Spin precession



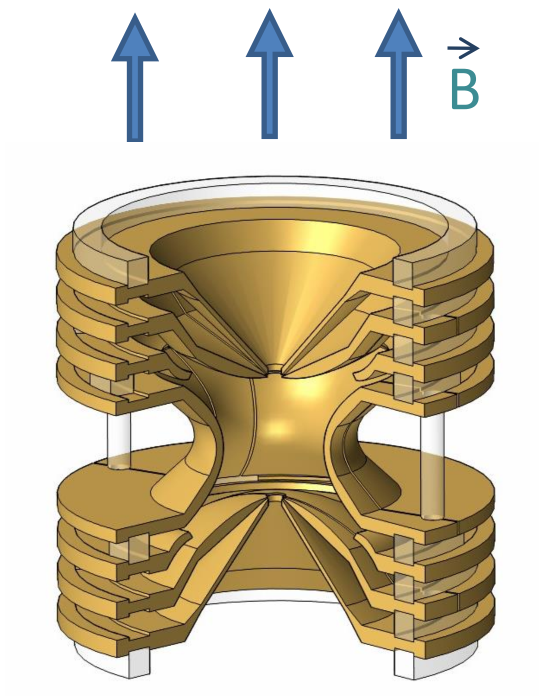
$$\nu_L = \frac{1}{2\pi} \frac{g}{2} \frac{q \cdot B}{m}$$

Cyclotron Motion

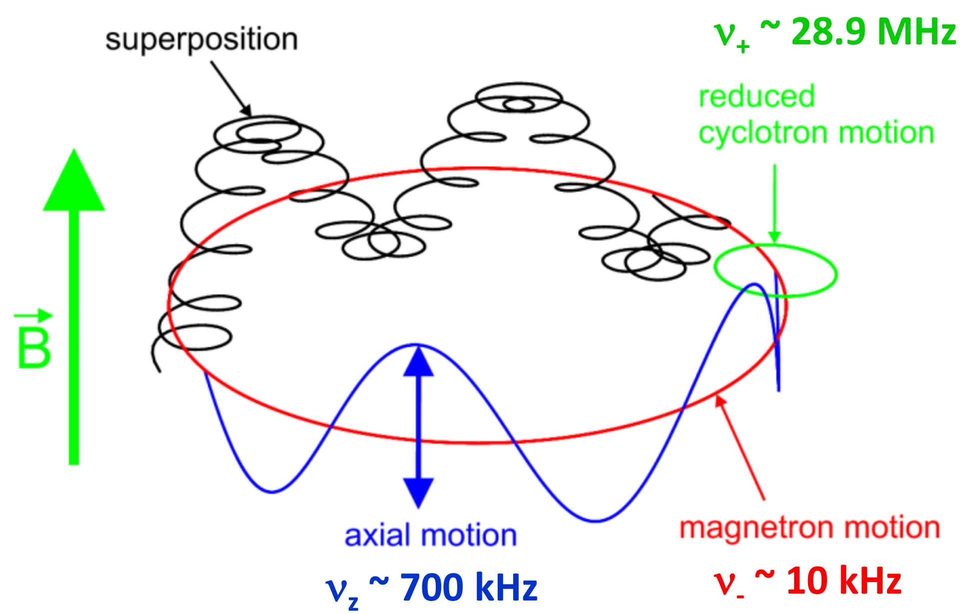


$$\nu_c = \frac{1}{2\pi} \frac{q \cdot B}{m}$$

The Penning trap



Motion in a Penning Trap

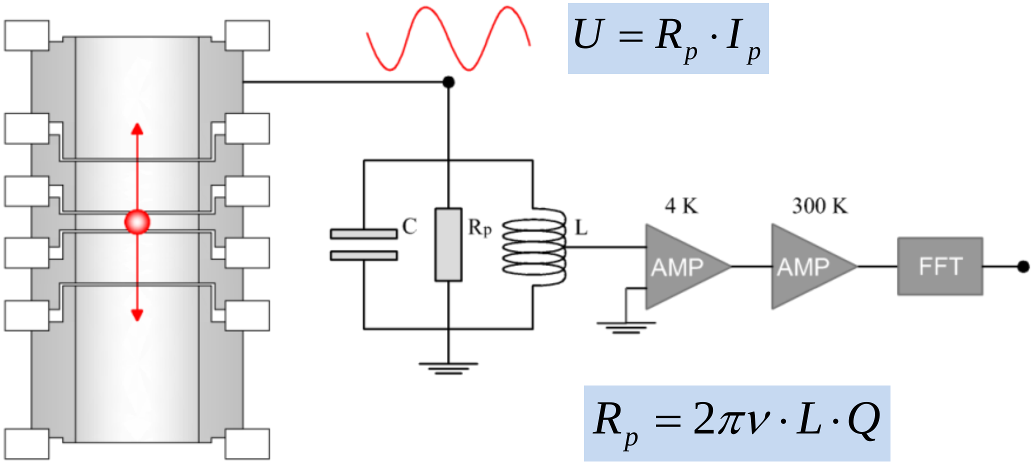


- Strong homogeneous magnetic field
- Weak electric quadrupole field

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

L.S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986).

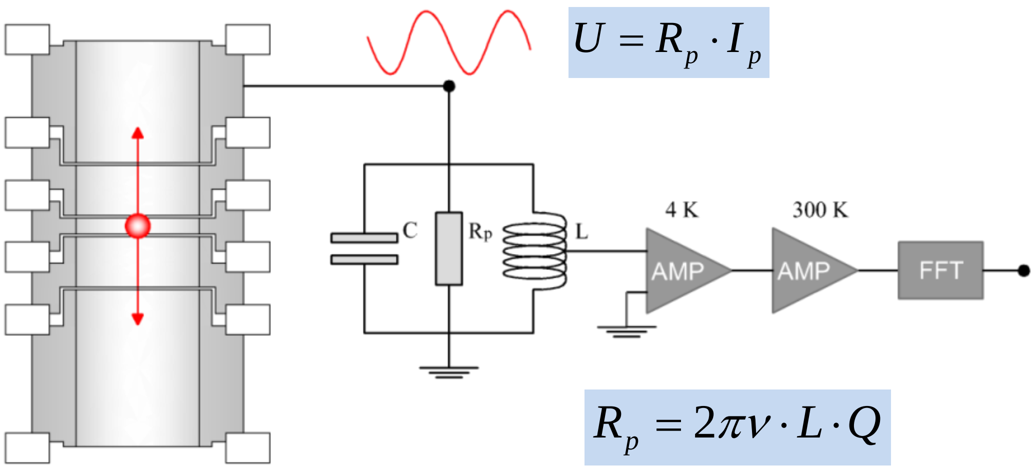
Image-current detection



$$U = R_p \cdot I_p$$

$$R_p = 2\pi\nu \cdot L \cdot Q$$

Image-current detection



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Detection of the axial frequency

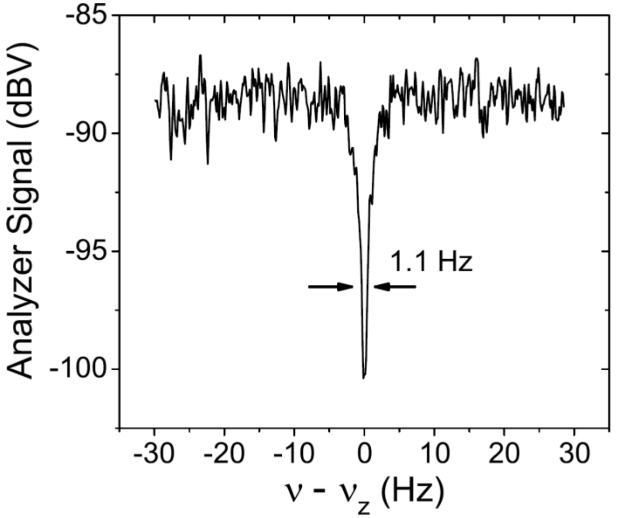
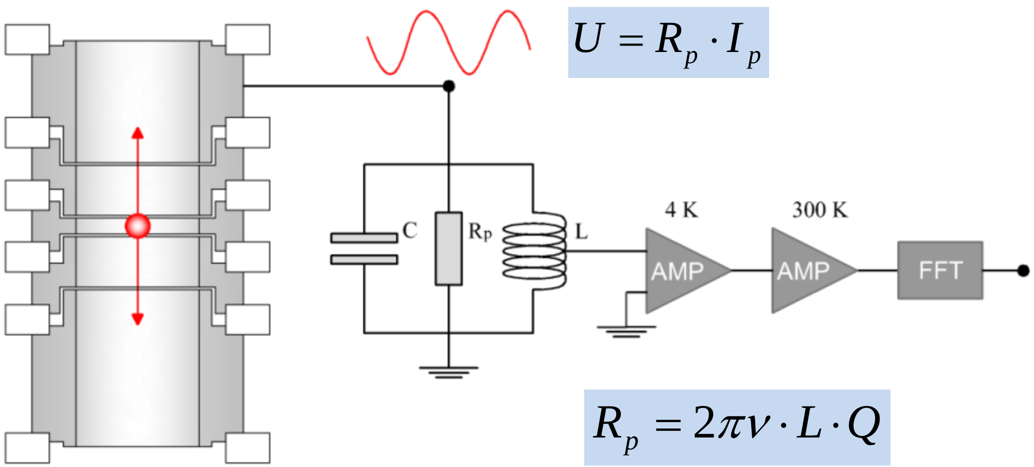


Image-current detection



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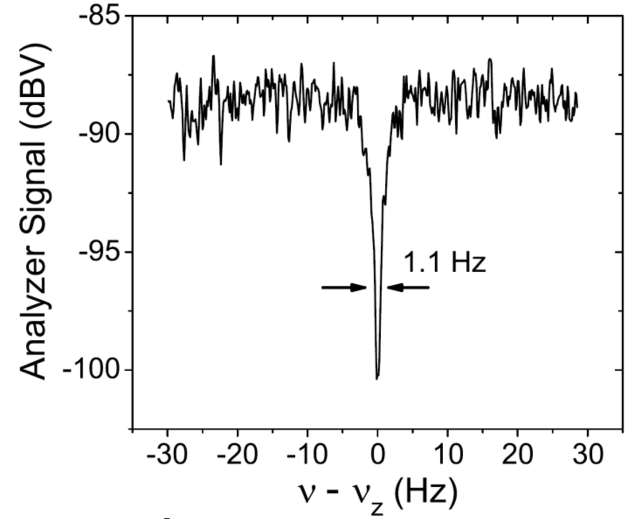
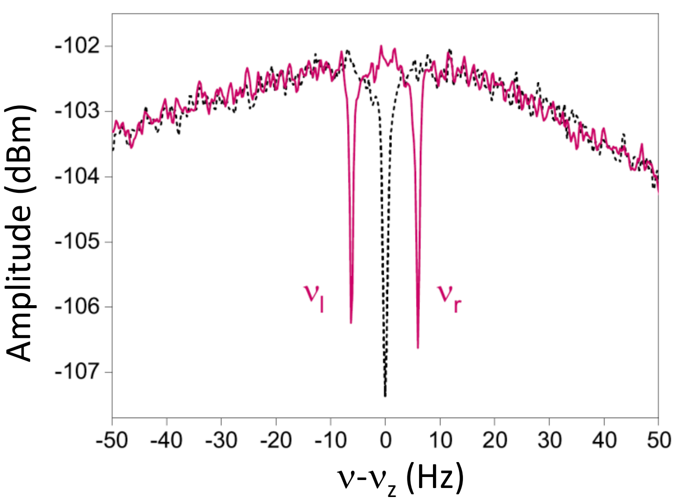


Sideband coupling to detect ν_+ and ν_-



Irradiation of a coupling rf-signal at $(\nu_+ - \nu_z)$ or $(\nu_z + \nu_-)$

Amplitude modulation of the axial motion

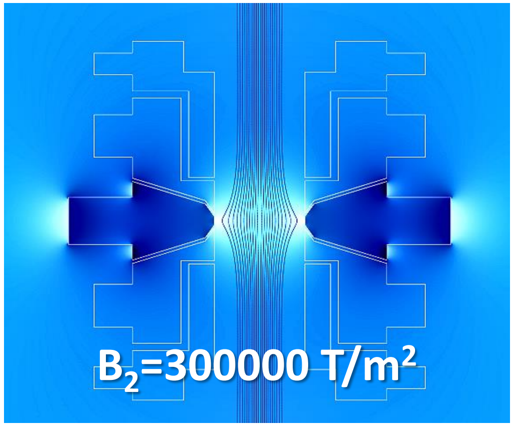
Measurement of the axial and sideband frequencies

Extraction of the free cyclotron frequency

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

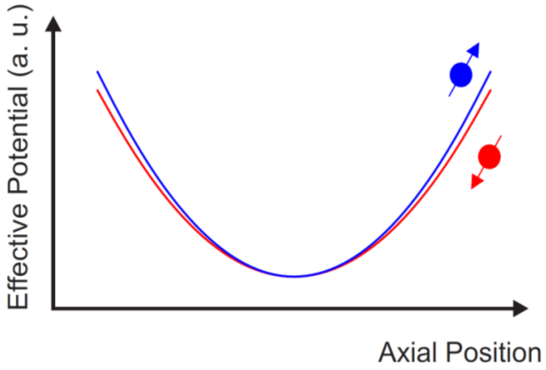
Continuous Stern-Gerlach Effect

Spin-state detection by coupling of the magnetic moment to the axial motion



Magnetic potential: $$\Phi_M = -\vec{\mu}_{p/\bar{p}} \cdot \vec{B}$$

Add a magnetic field perturbation: $$B_z = B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)$$



Continuous Stern-Gerlach Effect

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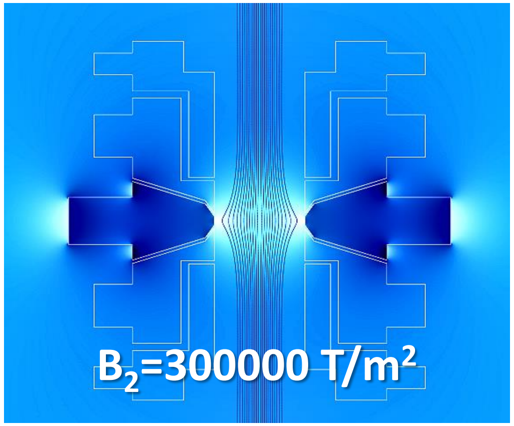

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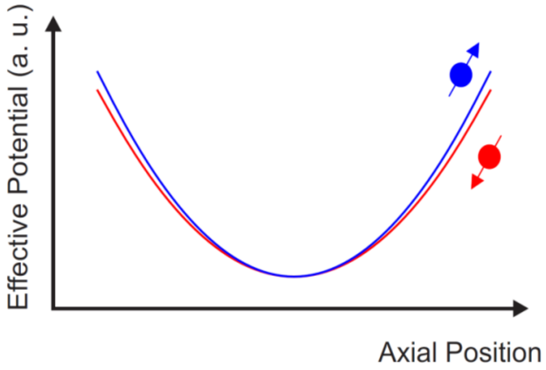
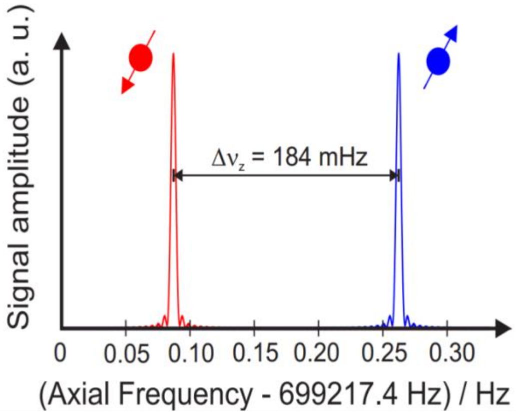


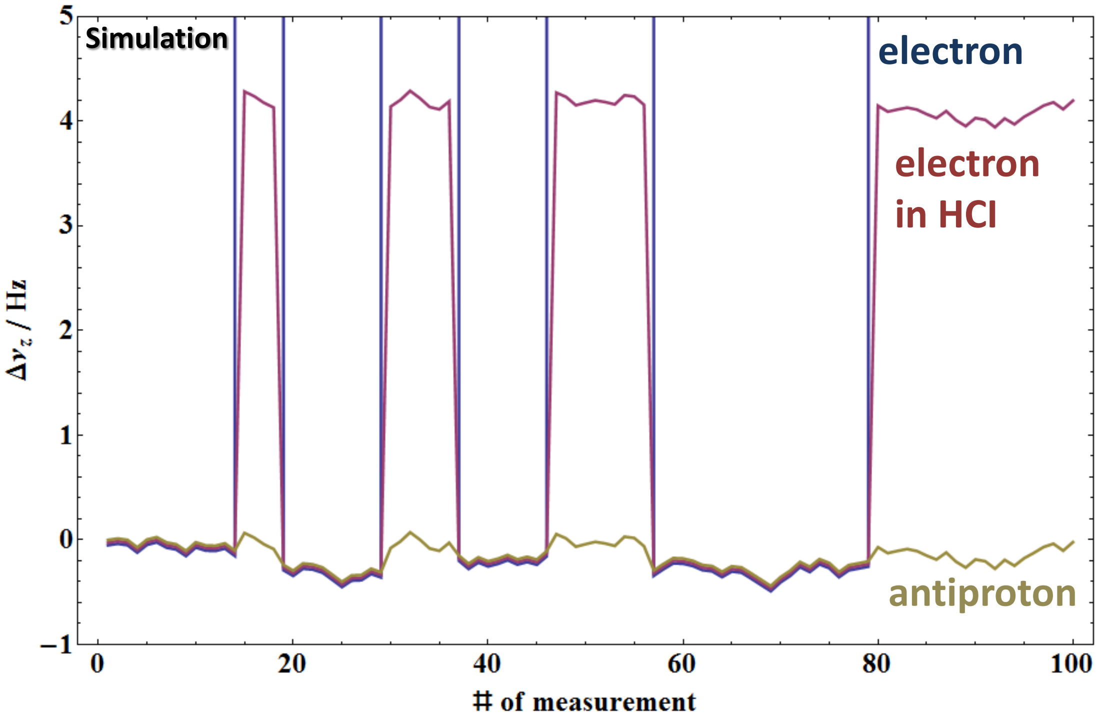
The axial frequency becomes spin-state dependent:



$$\frac{\Delta\nu_z}{\nu_z} \approx \frac{1}{4\pi^2}\frac{\mu}{m}\frac{B_2}{\nu_z^2}$$

Larmor frequency measurement

- A sequence of axial frequency measurements
- Drive the spin-flip with an rf-signal
- Extract the spin-flip probability as function of the drive frequency



Axial frequency difference:

$$\Delta \nu_z \approx \frac{1}{4\pi^2} \frac{\mu}{m} \frac{B_2}{\nu_z}$$

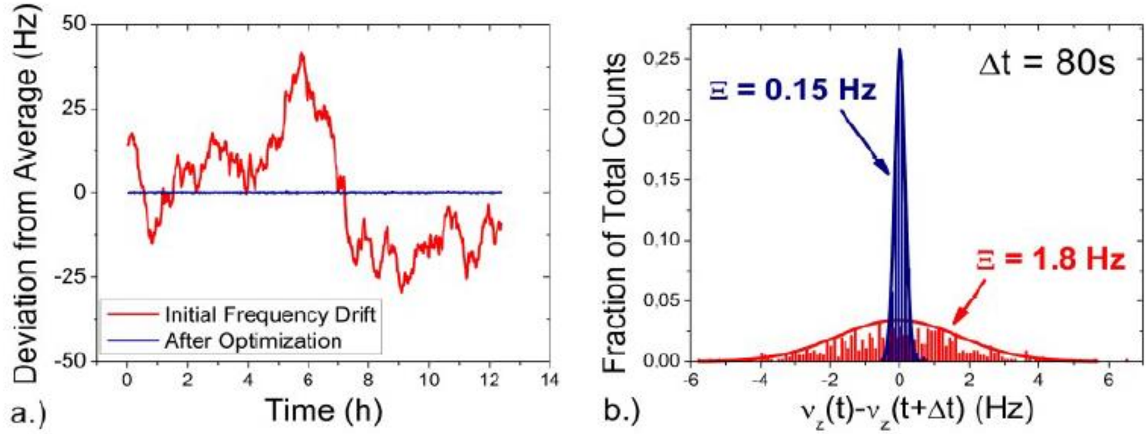
B_2=300000 T/m^2

Electron:	228 kHz
Electron in $^{28}Si^{13+}$:	4.4 Hz
Proton/antiproton:	0.18 Hz

It’s not that simple

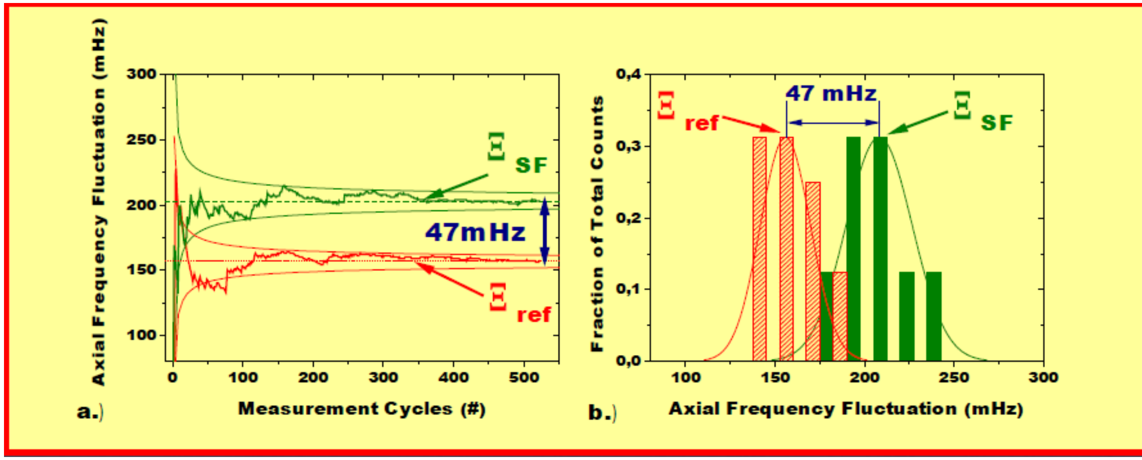
Magnetic bottle coupling: $\Delta\nu_z = \frac{1}{4\pi^2 m\nu_z}\frac{B_2}{B_0}(dE_+ + dE_-)$ -> 1Hz/µeV

Axial frequency fluctuations:



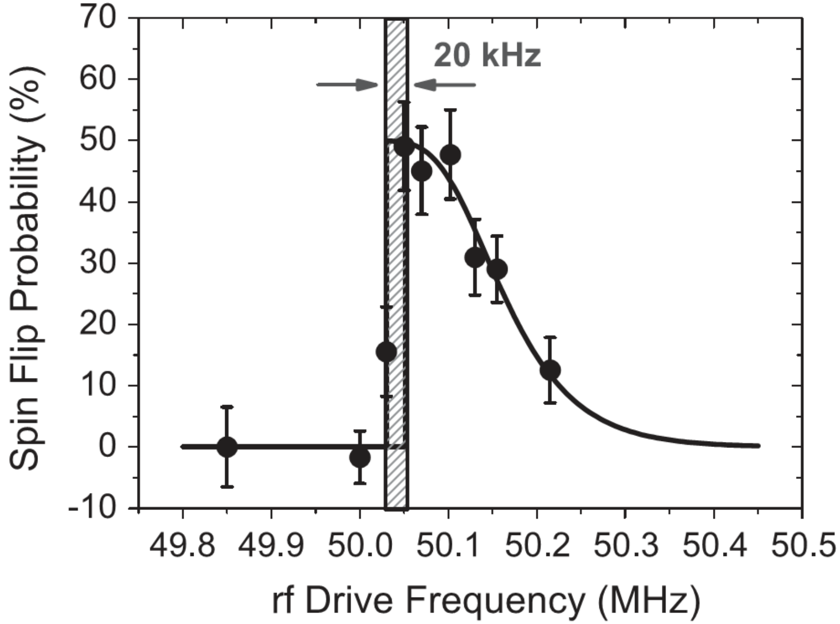
Statistical detection of spin-flips:

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



Measurement of the Larmor frequency

Measurement of the Larmor-frequency with the statistical detection method:



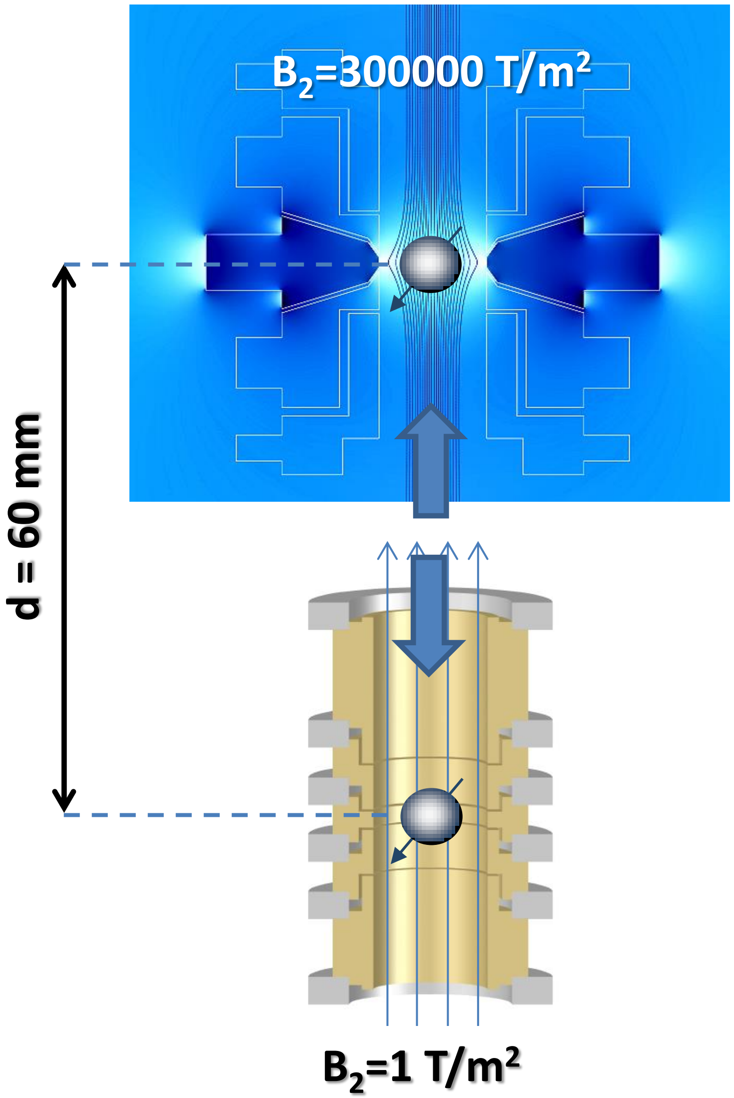
$$\nu_L = \nu_{L,0}\left(1 + \frac{B_2}{B_0}\cdot\langle z^2\rangle\right)$$

Lineshape is a convolution of the unperturbed Rabi-resonance and Boltzmann-distributed axial energy.

This limits the resolution of the frequency measurement on the 10^{-6} level!

C.C. Rodegheri *et al.*, New J. Phys. **14**, 063011 (2012).
J. DiSciacca *et al.*, Phys. Rev. Lett. **108,** 153001 (2012).

The Double Trap Method



Spatial separation of the frequency measurement and the spin-state detection

- Drive the spin until the spin-state is known

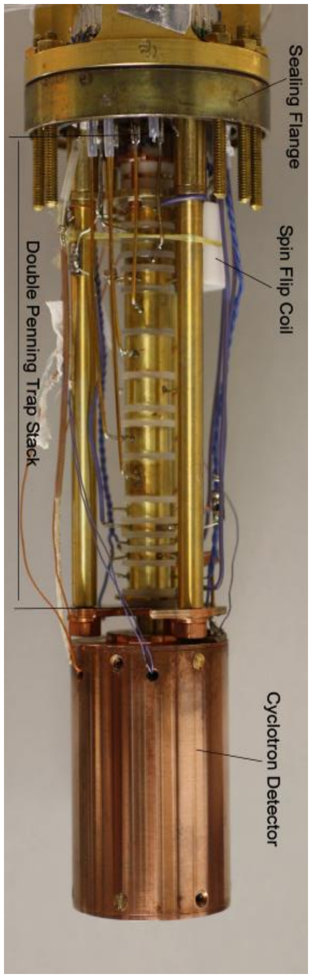
Requires that the spin-state is known!

- Transport the particle to the precision trap
- Measure ν_c and drive the spin flip for the Larmor resonance
- Transport the particle to the analysis trap
- Determine the spin state

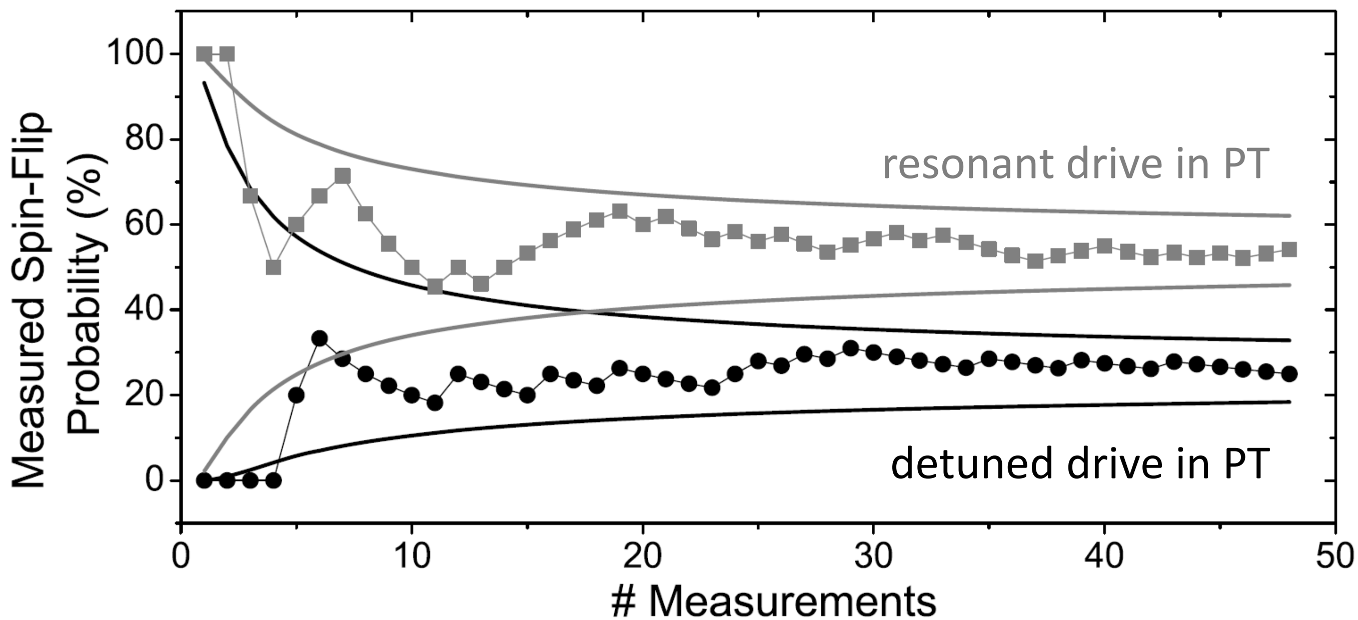
Simple idea, BUT…
Single spin-flip resolution is required!

Outlook: g-factor proton Mainz

Double Penning trap system – Mainz University



Application of the double-trap scheme with a single proton

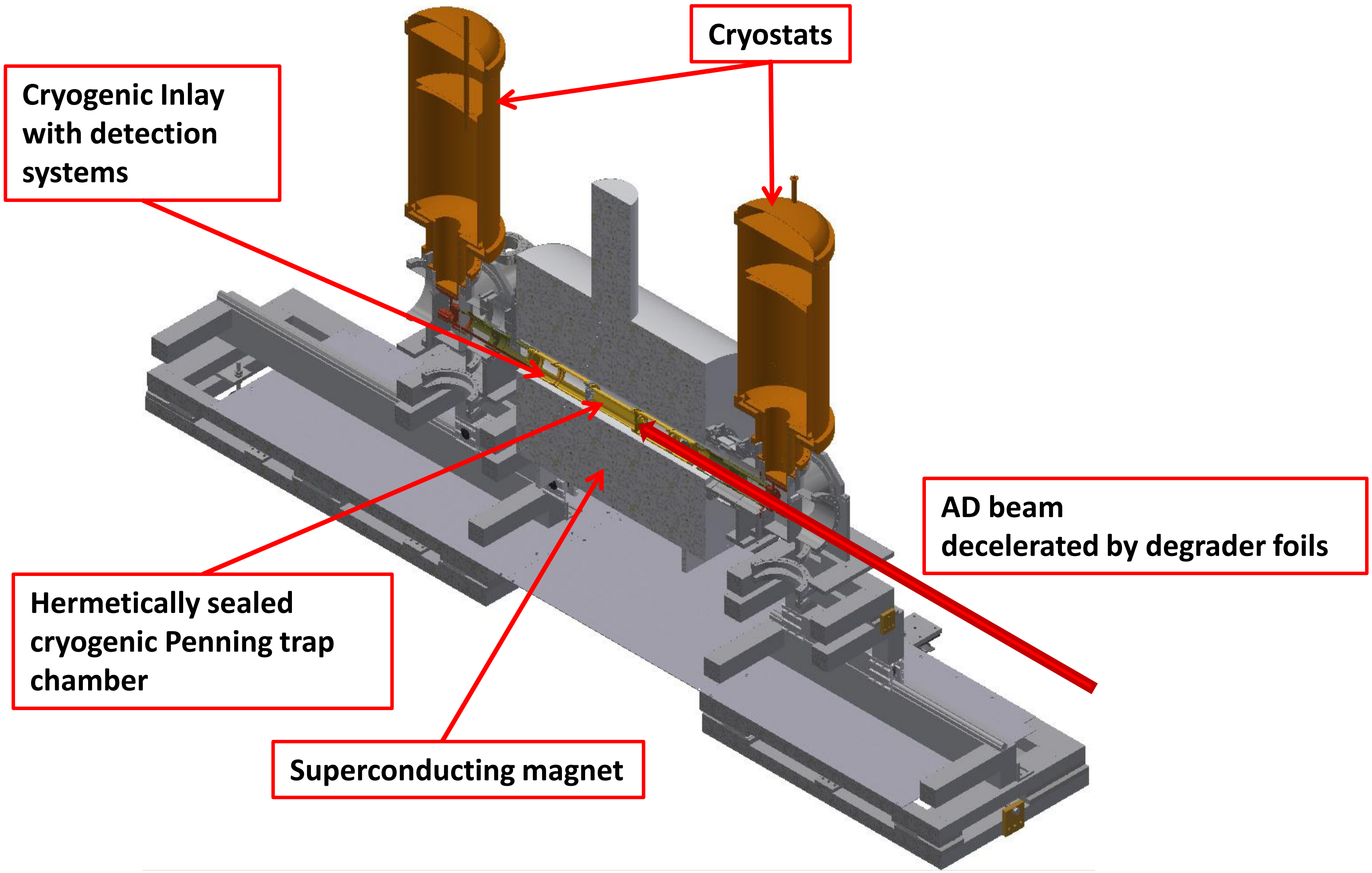


More on this hot topic on **Friday 10.40 h** by **Andreas Mooser!**

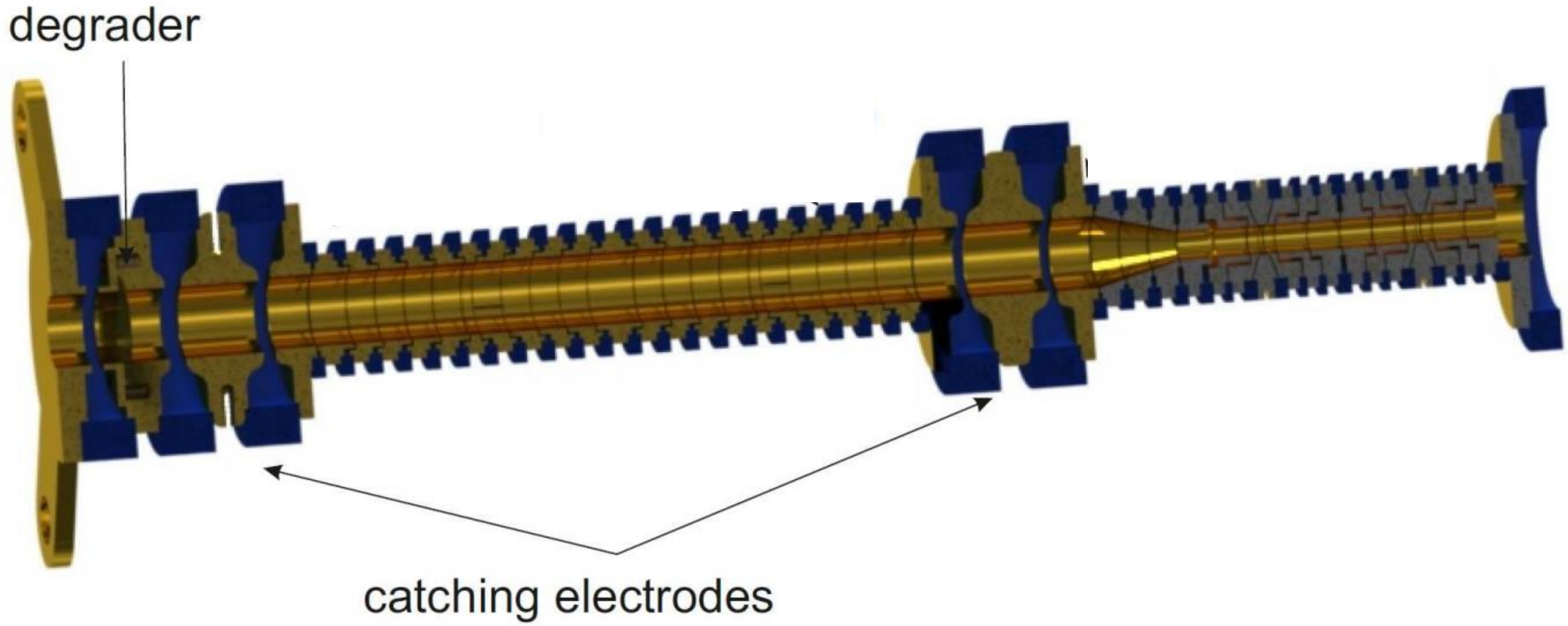
A. Mooser *et al.*, Phys. Lett. B **723**, 78–81 (2013).

The BASE apparatus

Setup of a new experiment in the AD hall to apply the double-trap method to the antiproton

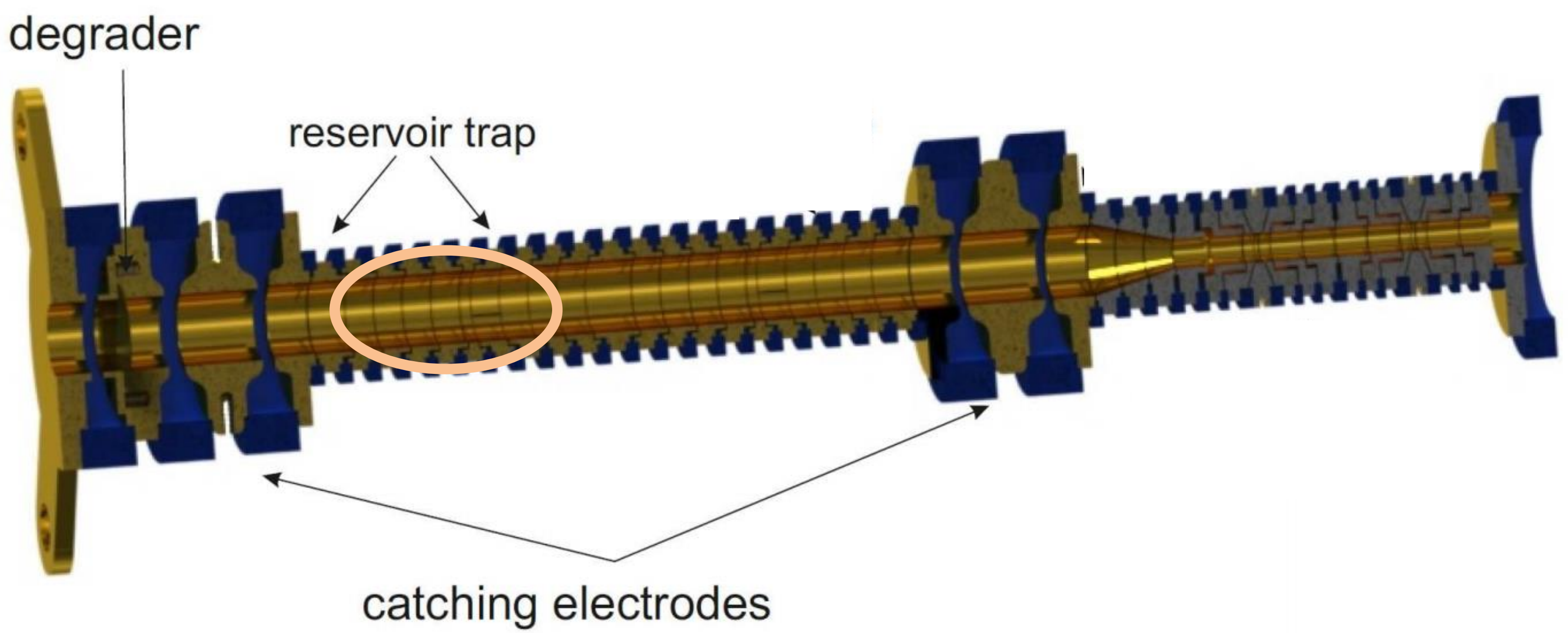


The BASE Penning trap stack



The BASE Penning trap stack

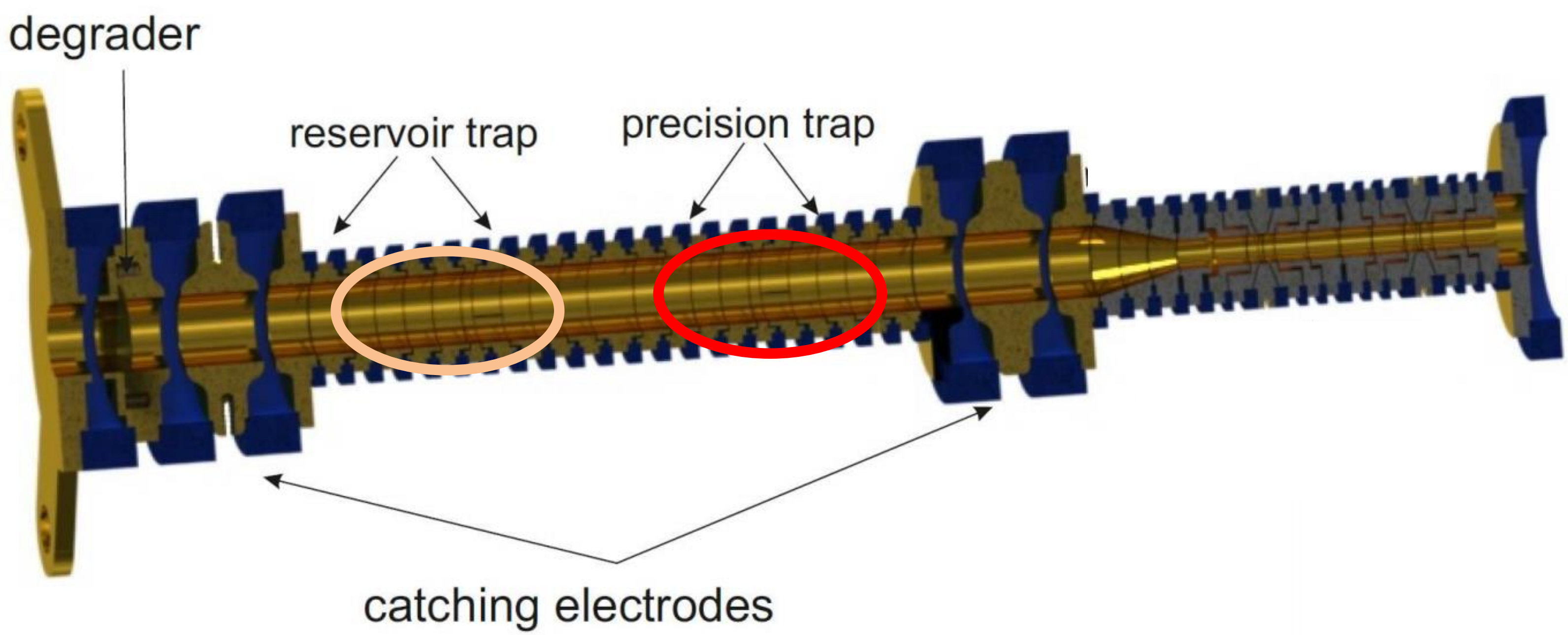
Storage of an Antiproton cloud



The BASE Penning trap stack

Cyclotron frequency measurement
Application of the spin-flip drive

Storage of an Antiproton cloud



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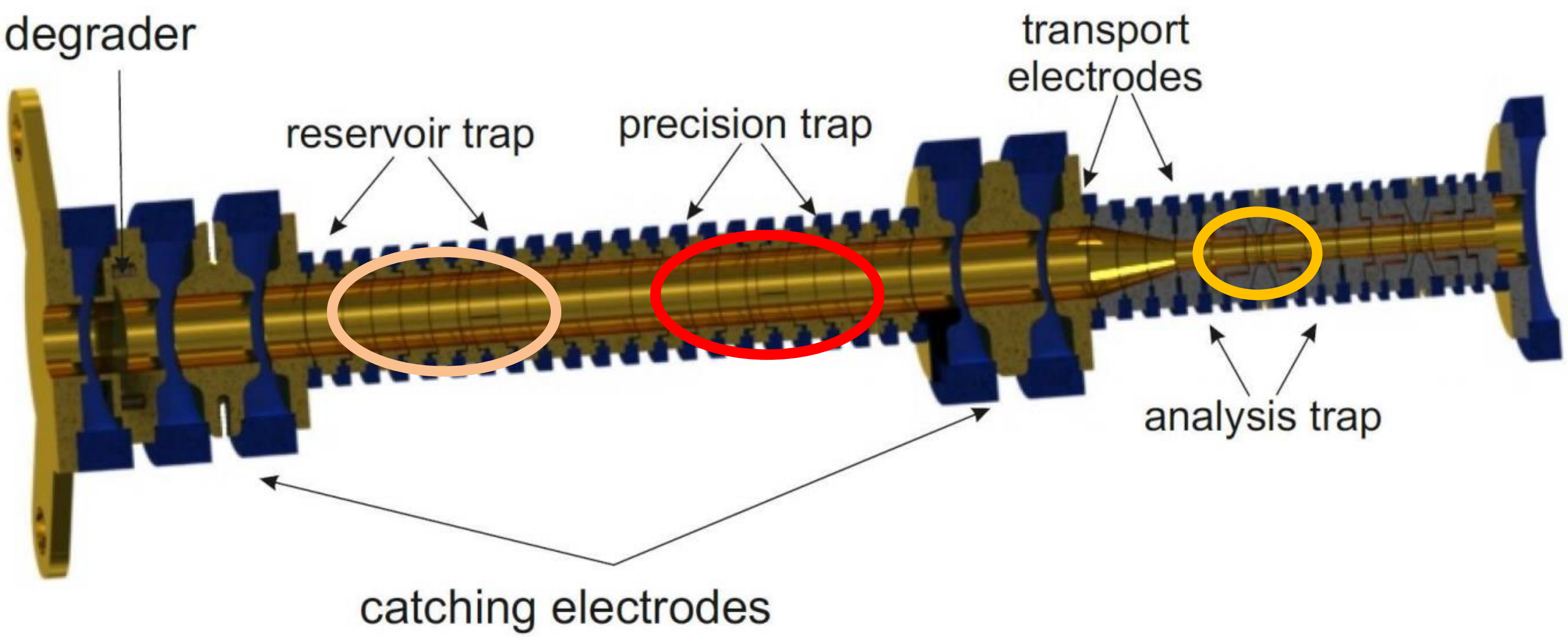
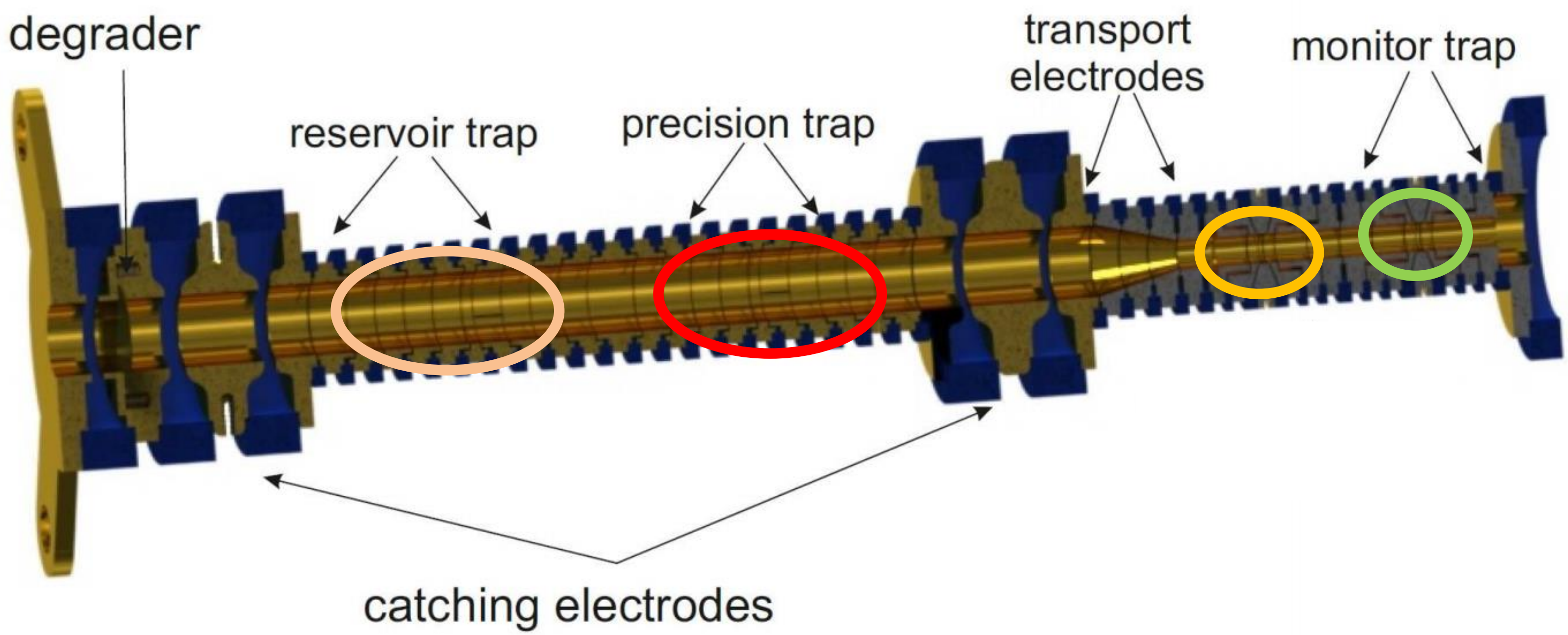


Spin-state detection

The BASE Penning trap stack

Cyclotron frequency measurement
Application of the spin-flip drive

Storage of an Antiproton cloud

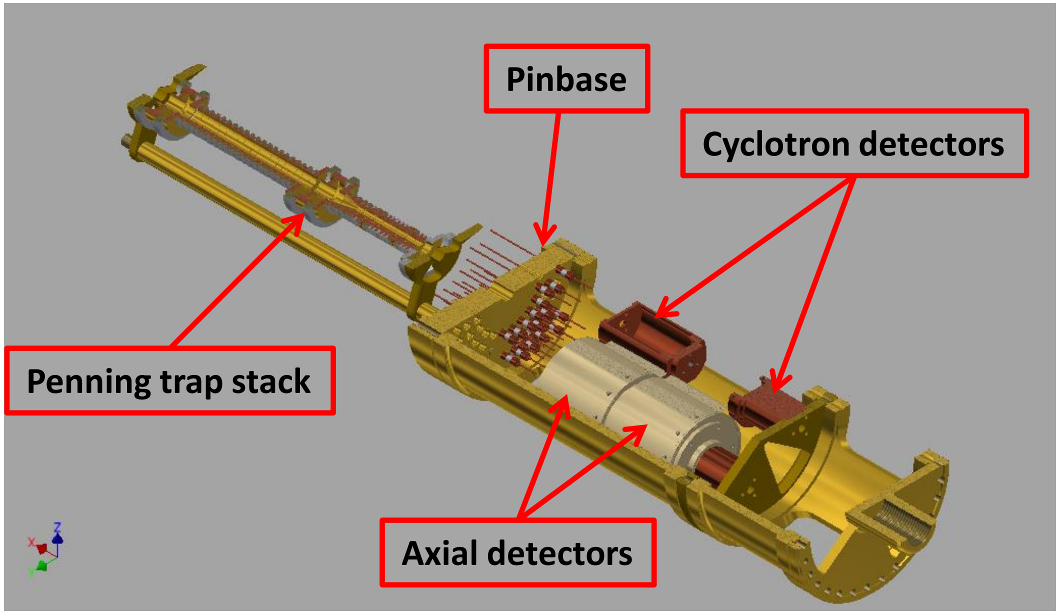


Spin-state detection

Magnetic field monitoring

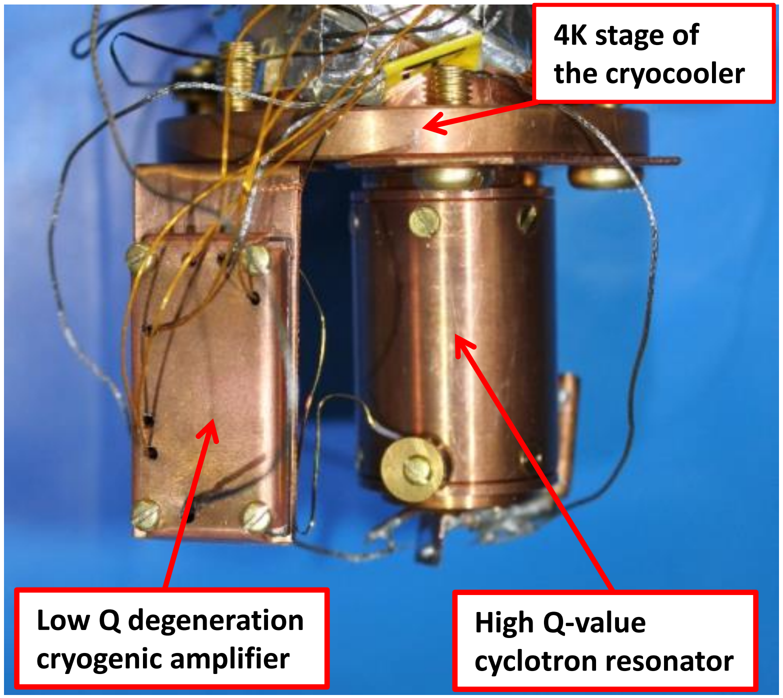
The BASE detection systems

Currently: development of the detection systems



Cyclotron detectors commissioned and tested:

Q – 1500 - 3500

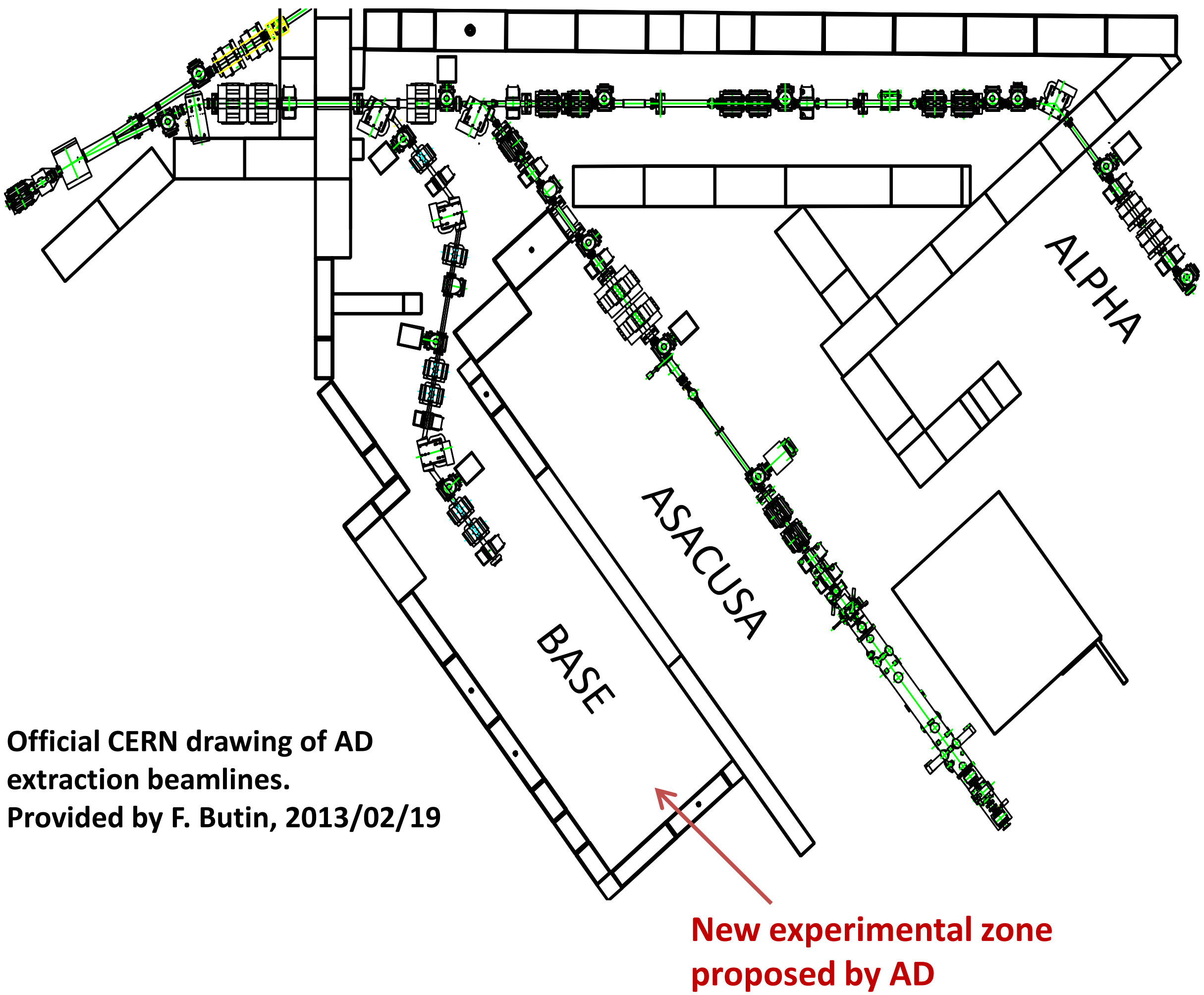


- Four axial detection systems
  NbTi resonators with NbTi coil

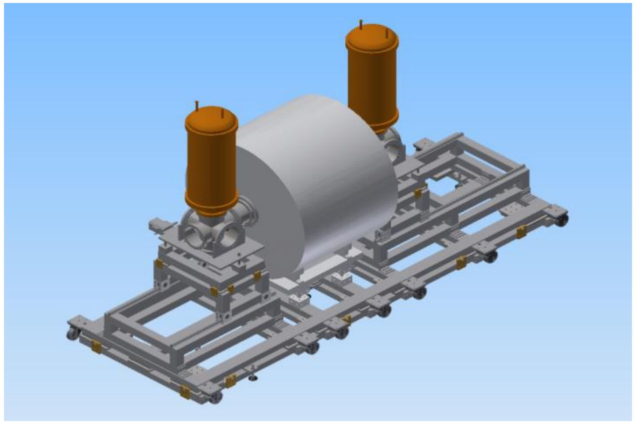
- Two cyclotron detection systems
  Copper resonator with copper coil

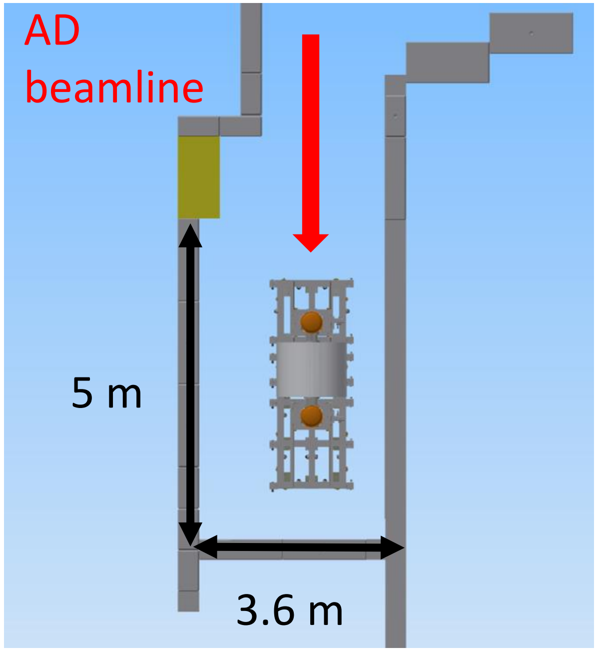
Implementation of BASE in the AD

BASE approved by the CERN research board
Installation of BASE in the AD during LS1



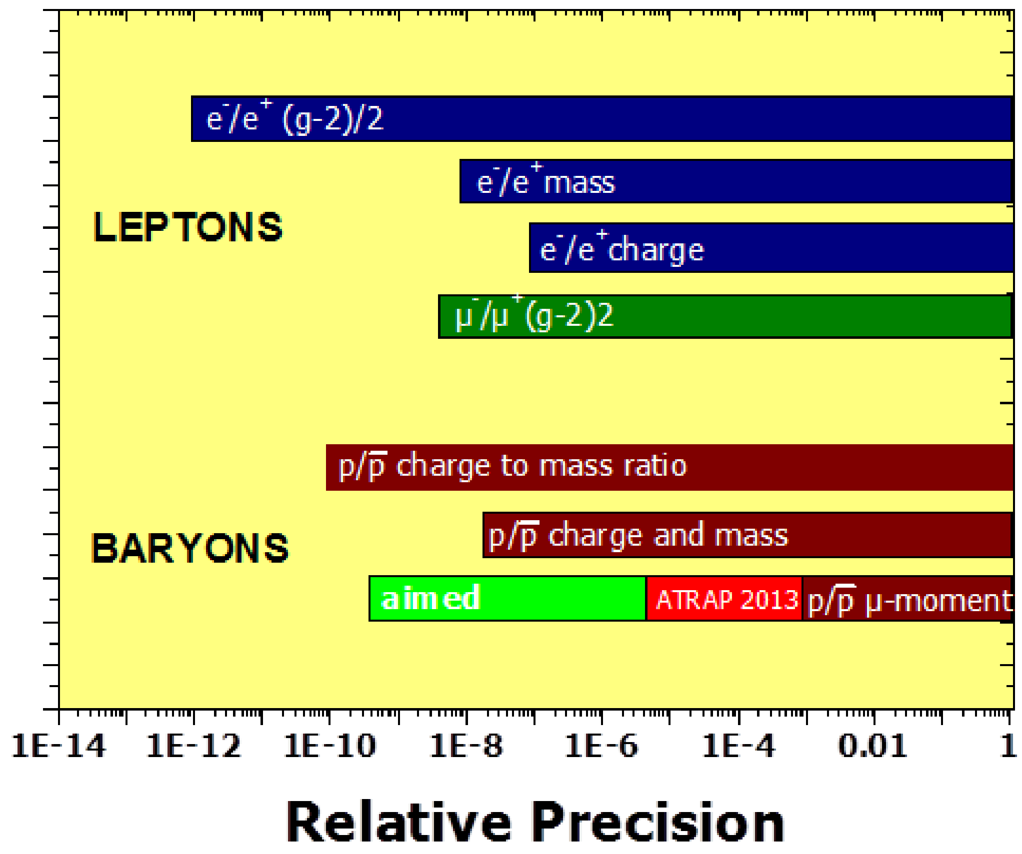
Official CERN drawing of AD extraction beamlines.
Provided by F. Butin, 2013/02/19





Conclusions

- BASE aims for a measurement of the antiproton magnetic moment with ppb precision
- Statistical spin-state detection resulted in a ppm measurement of the proton magnetic moment
- Single spin-flip resolution was achieved
- The double-trap method was applied for the first time to a proton
- Installation of BASE in the AD is in progress



Funding

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Thank you for your attention!