Progress towards an improved measurement of the proton and antiproton magnetic moments

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Baryon-Antibaryon Symmetry Experiment at CERN

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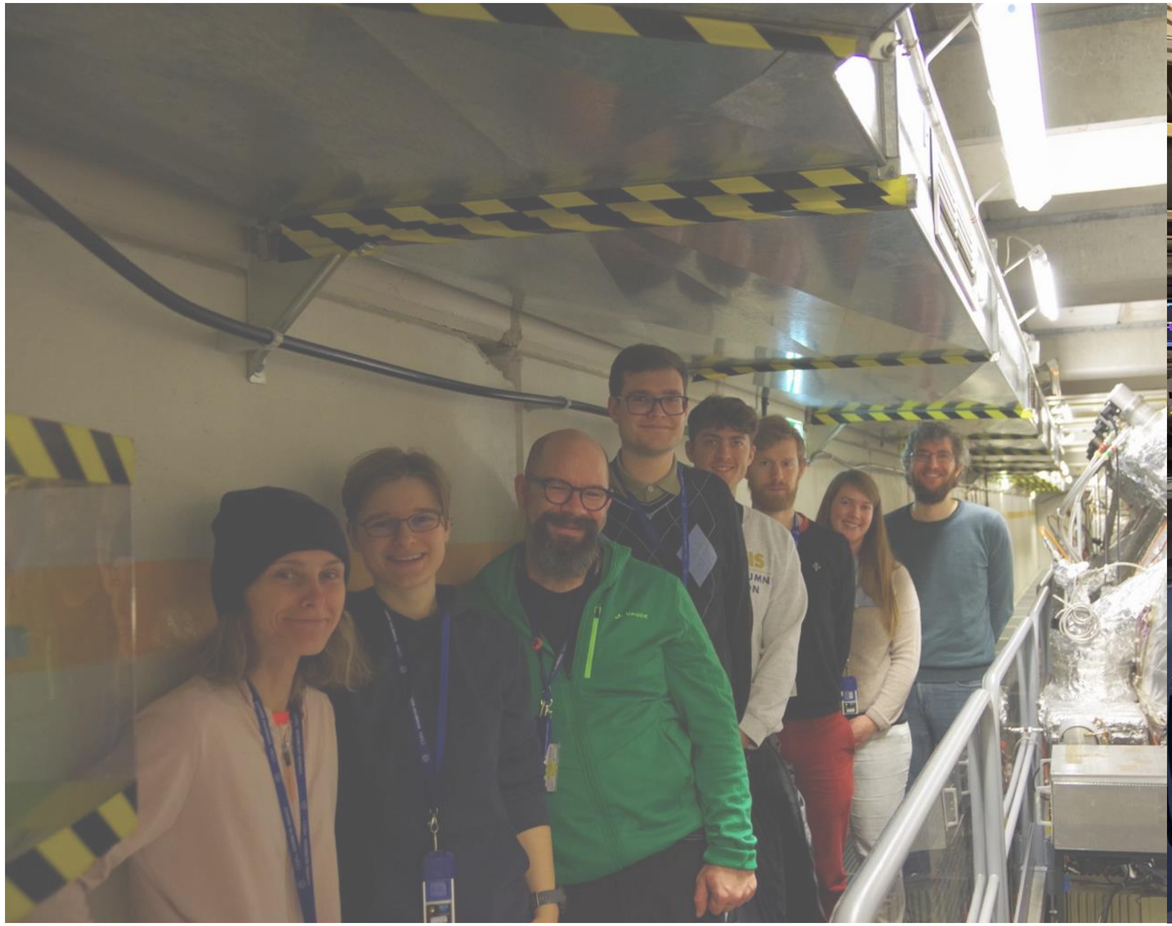
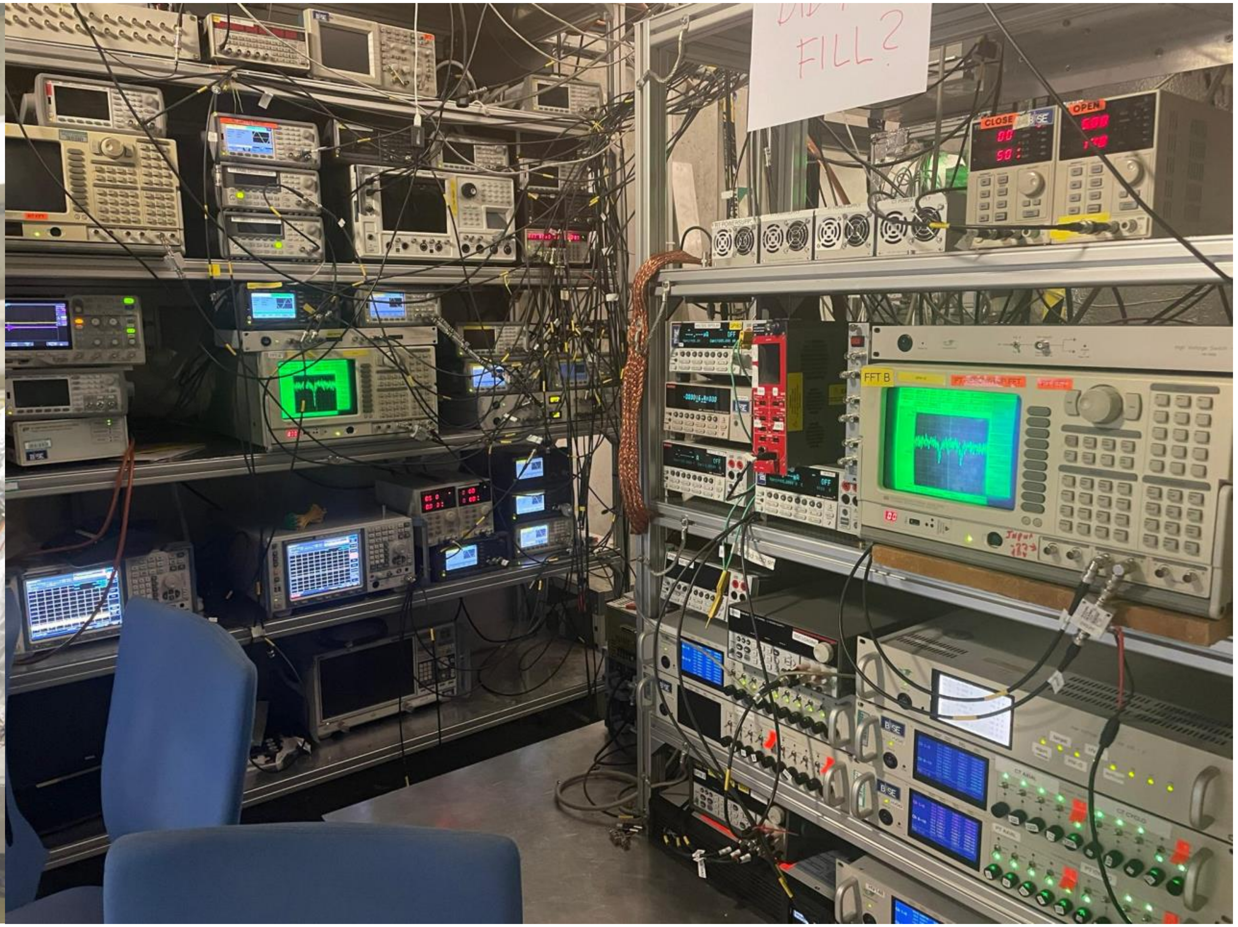
Winter School, Leukerbad

BASE collaboration at CERN



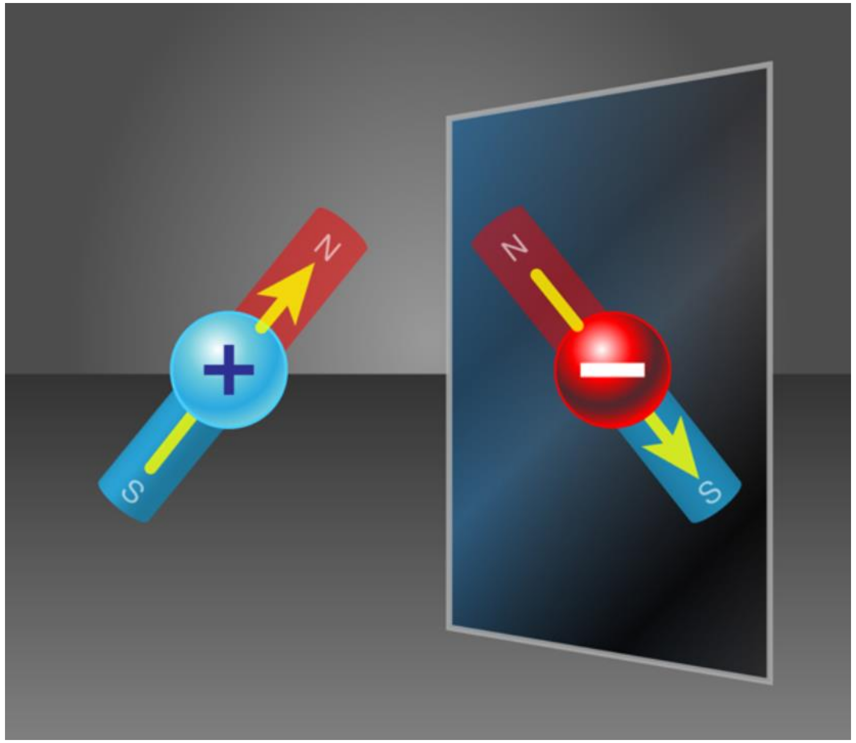
BASE collaborators, Antiproton Decelerator, 2022



BASE Experimental Area, 2023

Motivation (1)

- An upgrade on the measurement technique in the Baryon-Antibaryon Symmetry Experiment was developed for measuring the proton and/or antiproton magnetic moment. Using two particles in a trap stack simultaneously, a single repetitive measurement cycle time can be decreased significantly.
- Combined with the recent apparatus upgrade, a newly installed cooling trap, this opens prospects towards the measurements of the proton/antiproton **magnetic moments** with a **100 ppt** fractional precision (current values: 300 ppt for proton, 1500 ppt for antiproton).
- Comparing the newly measured proton and antiproton g-factors, we aim at a **15-fold** improved test of the **CPT invariance** in the baryon sector.
- A prospect for more precise and fast cyclotron frequency determination is foreseen when the phase-sensitive methods will be implemented and integrated to the experiment.



[1]

CPT invariance predicts:

$$q_p = -q_{\bar{p}},$$
$$m_p = m_{\bar{p}},$$
$$\mu_p = -\mu_{\bar{p}}.$$

Motivation (2)

- Consider behaviour of **common physical quantities** under the three **discrete transformation P, C and T**:

Quantity	Notation	P	C	T
Position	$\vec{x}$	$-\vec{x}$	$+\vec{x}$	$+\vec{x}$
Velocity	$\vec{v} = \mathrm{d}\vec{x}/\mathrm{d}t$	$-\vec{v}$	$+\vec{v}$	$-\vec{v}$
Linear momentum	$\vec{p} = m\vec{v}$	$-\vec{p}$	$+\vec{p}$	$-\vec{p}$
Angular momentum	$\vec{L} = \vec{r} \times \vec{p}$	$+\vec{L}$	$+\vec{L}$	$-\vec{L}$
Spin	$\vec{S}$ or $\vec{\sigma}$	$+\vec{\sigma}$	$+\vec{\sigma}$	$-\vec{\sigma}$
Helicity	$h = \vec{\sigma} \cdot \vec{p}/\lvert p \rvert$	$-h$	$+h$	$+h$
Electric Field	$\vec{E}$	$-\vec{E}$	$-\vec{E}$	$+\vec{E}$
Magnetic Field	$\vec{B}$	$+\vec{B}$	$-\vec{B}$	$-\vec{B}$
Electric Dipole Moment	$\vec{\sigma} \cdot \vec{E}$	$-\vec{\sigma} \cdot \vec{E}$	$-\vec{\sigma} \cdot \vec{E}$	$-\vec{\sigma} \cdot \vec{E}$
Magnetic Dipole Moment	$\vec{\sigma} \cdot \vec{B}$	$+\vec{\sigma} \cdot \vec{B}$	$-\vec{\sigma} \cdot \vec{B}$	$+\vec{\sigma} \cdot \vec{B}$
Longitudinal Polarization	$\vec{\sigma} \cdot \vec{p}$	$-\vec{\sigma} \cdot \vec{p}$	$+\vec{\sigma} \cdot \vec{p}$	$+\vec{\sigma} \cdot \vec{p}$
Transverse Polarization	$\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	$+\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	$+\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	$-\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$

Penning traps

Penning traps are used:

- to trap charged particles,
- to manipulate charged particles:
  - to park, move along the axis,
  - to excite axially/radially,
  - to “cool” axially/radially,
  - to split a cloud of particles,
  - …
- to measure the cyclotron frequency.

Physics topics include:

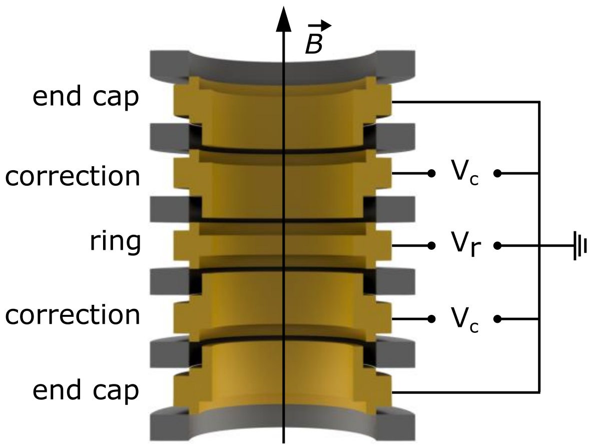
-> ion spectra
-> quantum computers
-> atomic clocks
-> **fundamental properties: g-factor, q/m ratio**

Trapping condition – E&B fields:

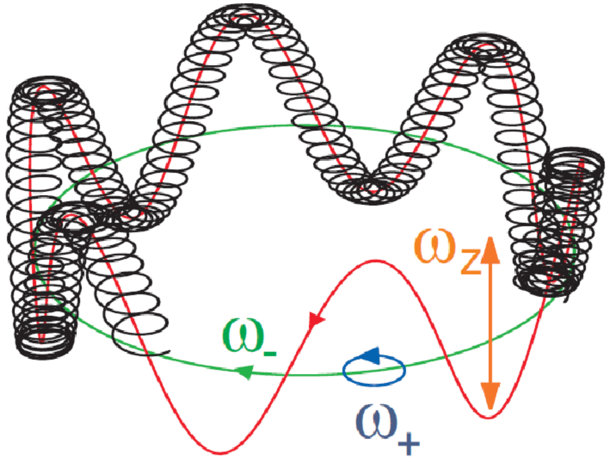
- Static quadratic electric potential
- Static uniform axial B-field

Trajectory – 3 orthogonal motions:

- Harmonic axial
- Circular planar modified cyclotron
- Circular planar magnetron



[2]



[3]

f_z = 650 000 Hz
f_+ = 29 000 000 Hz
f_- = 7 000 Hz

BASE Penning trap stack

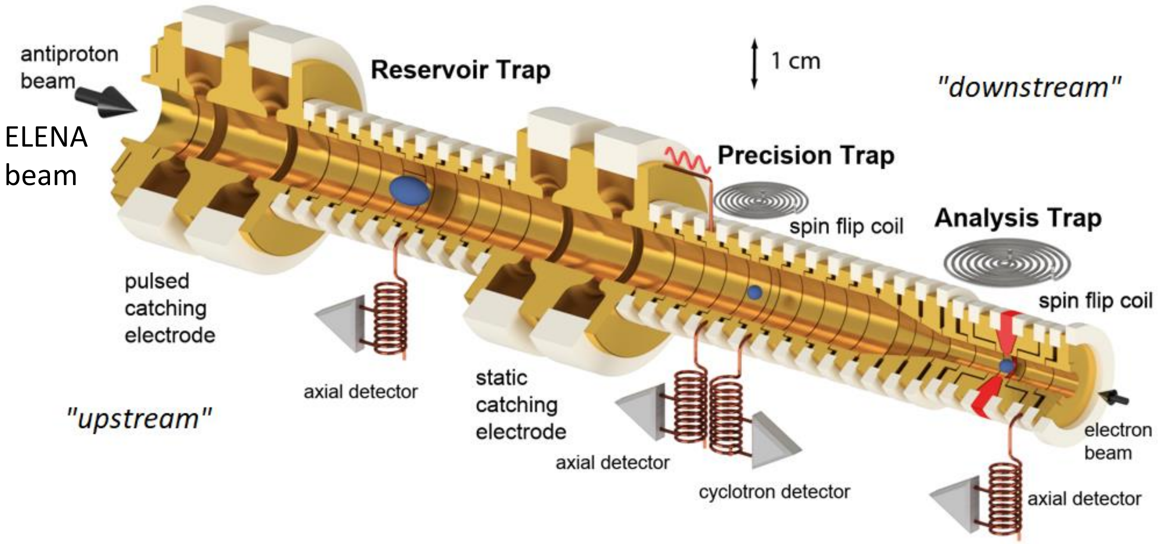
Four Penning traps are used in BASE at CERN:

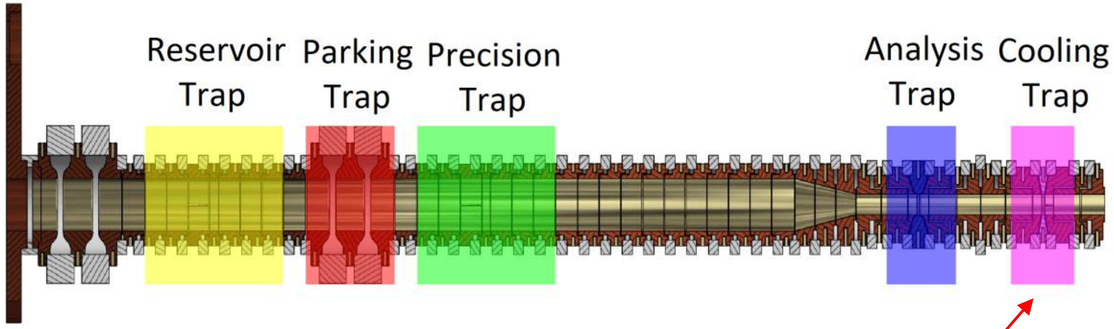
a) Reservoir Trap -> long storage of particles
-> stable 4.5 mm radius trap

b) **Precision Trap** -> frequency measurements
-> stable magnetic field

c) **Analysis Trap** -> spin-state determination
-> large magnetic "bottle"

d) Cooling Trap -> low orbit particle preparation
-> magnetic "bottle" term
-> new cyclotron detector





Recently implemented dedicated Cooling Trap

Two-trap method:

- Particle is initialized with low cyclotron orbit in the PT,
- Particle cyclotron frequency is measured in the PT,
- Particle spin is flipped in the PT,
- Transports: PT -> AT -> PT,
- Particle spin-state measured in the AT
  - -> **~172(8) mHz** axial frequency difference for ↑ and ↓ states

$$\Delta\nu_{z,SF} = \frac{h\nu_L}{4\pi^2 m_{\bar{p}}\nu_z}\frac{B_{2,AT}}{B_{0,AT}}$$

Magnetic moment measurement setup

Measurement setup and cycle used in the 2016 proton campaign:

1. The proton is thermalized in the PT by the interaction with the cyclotron detector;

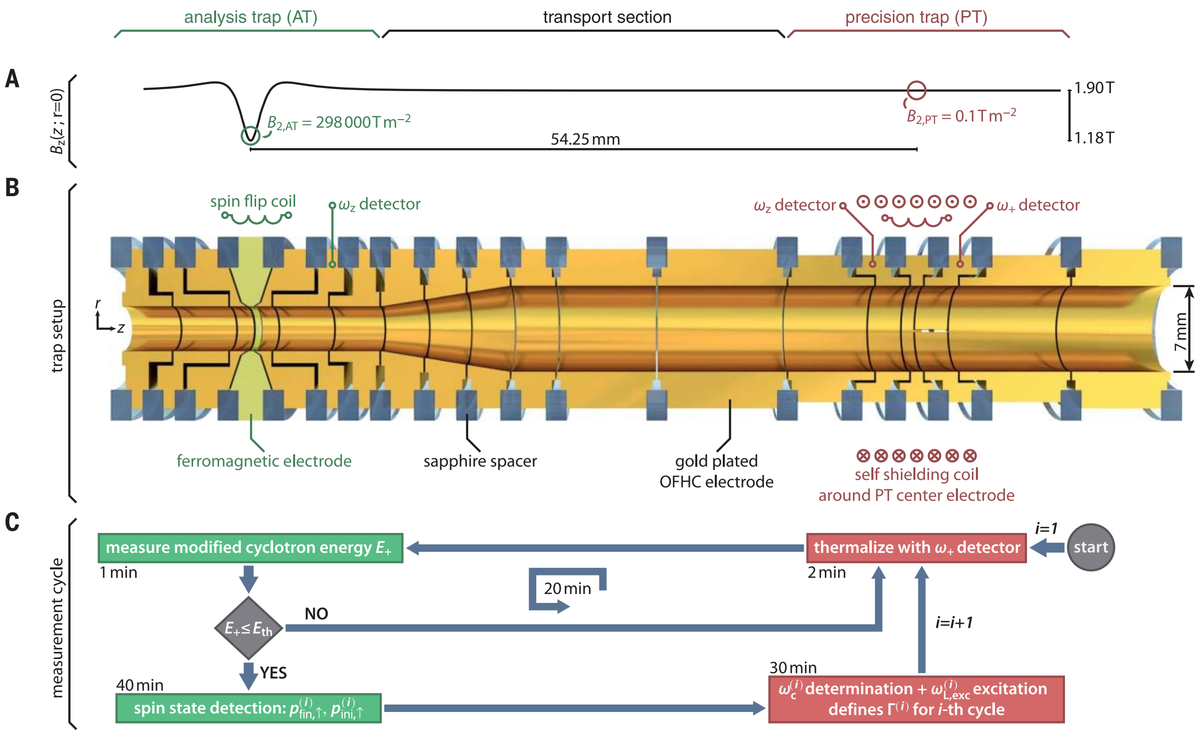
2. The proton modified cyclotron mode energy, which translates to an axial frequency shift (due to large B_2), is measured in the AT;

3. The cyclotron-cold particle preparation cycle is running until the proton prepared is colder than the pre-defined threshold value;

4. Then the spin state detection sequence is running in the AT, which continuously cycles FFT data collection, axial frequency determination and AT Larmor frequency irradiation, trying to register a frequency shift consistent with the spin-flip. This cycle stops when the spin state is determined with high fidelity. From this data one can tell if there was a spin flip in the PT before.

5. The particle is transported to the PT, where the cyclotron frequency is measured by axial-cyclotron sideband coupling. Once the cyclotron frequency is known, the calculated Larmor frequency irradiation is applied.

6. The sideband method increases the particle modified cyclotron mode energy, so the next cooling cycle starts.



Larmor-to-cyclotron frequency ratio is a direct measure of the proton/antiproton magnetic moment:

$$\frac{\mu_p}{\mu_N} = \frac{g_p}{2} = \frac{\nu_L}{\nu_c}, \quad \frac{\mu_{\bar{p}}}{\mu_N} = -\frac{g_{\bar{p}}}{2} = -\frac{\nu_L}{\nu_c}$$

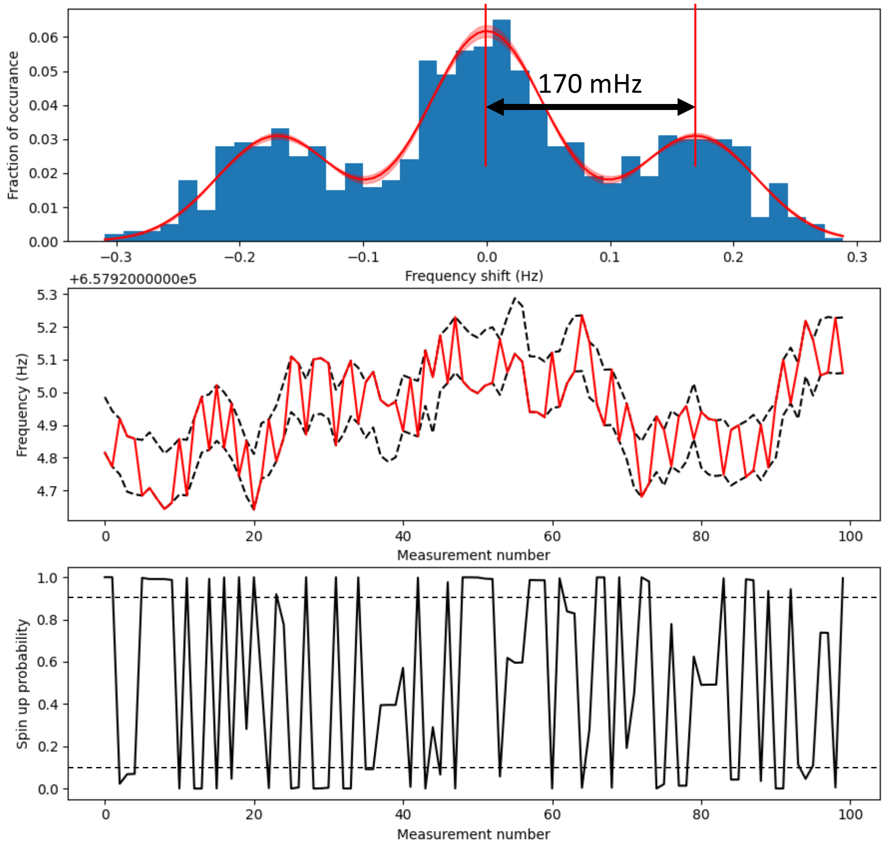
nuclear magneton

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

Frequency scatter rates in the AT

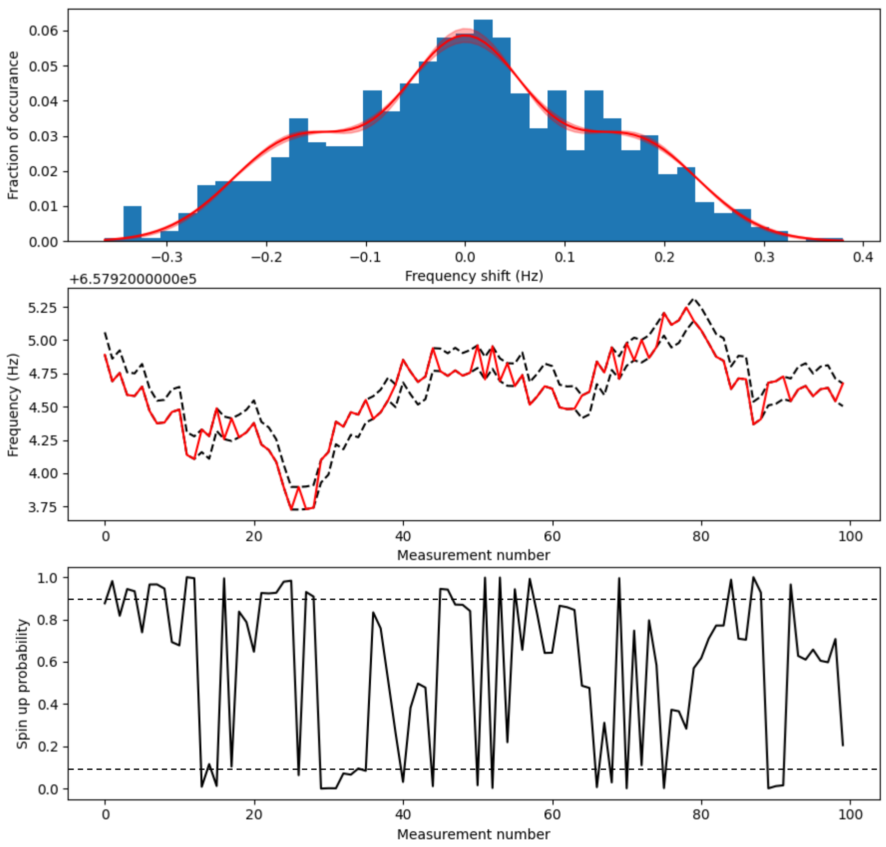
- rms = 48(1) mHz
- rms = 65(3) mHz

Better spin flip resolution



-> higher state resolution fidelity
-> lower error rate

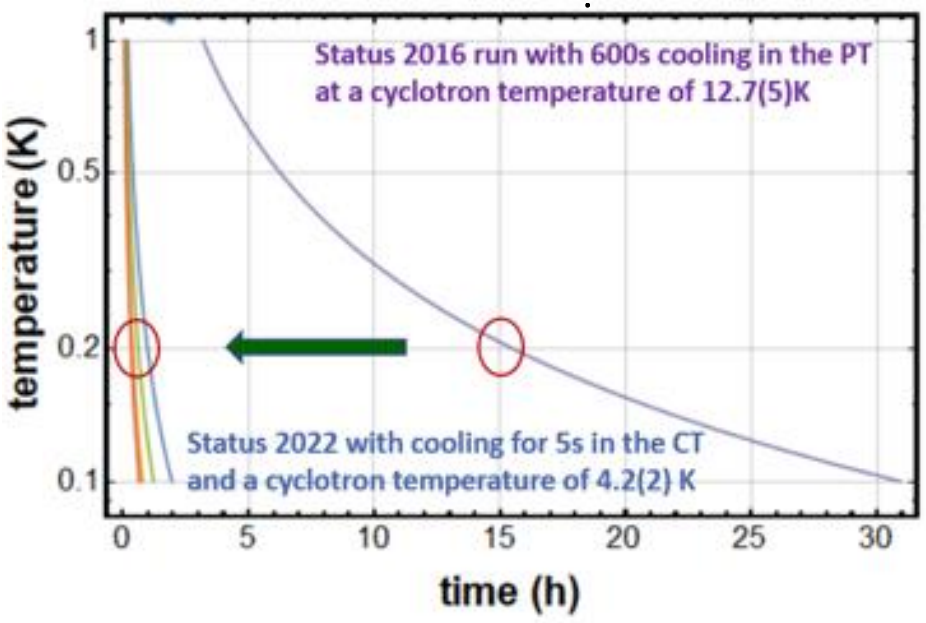
Worse spin flip resolution



-> lower state resolution fidelity
-> higher error rate

Latest improvements and Cooling trap

- New Cooling Trap:
  - cold particle preparation faster as shorter effective electrode distance and lower resonator temperature (related to quality factor).
- We recently observed PT spin flips with 93% state detection fidelity.
- Triple trap – two particle method does not require to cool the Larmor particle every cycle:
  - the cyclotron frequency is measured with the cyclotron particle, for which we do not require to be below the low energy threshold;
  - savings in one cycle time.
- Headroom to improve the measurement by…



Uncertainty comparison

- μ_p/μ_N 300 ppt

Parameter	Relative shift on $g/2$ (ppt)	Error (ppt)
Trapping potential	0	9
Magnetic inhomogeneity	8	4
Relativistic shift	−44	26
Image current	1	1
Image charge	−98	3
Fitting	0	80
Total	−133	123

Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision by G. Schneider et al. (2017)

- $\mu_{\bar{p}}/\mu_N$ 1500 ppt

Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)
Image-charge shift	0.05	0.001
Relativistic shift	0.03	0.003
Magnetic gradient	0.22	0.020
Magnetic bottle	0.12	0.009
Trap potential	−0.01	0.001
Voltage drift	0.04	0.020
Contaminants	0.00	0.280
Drive temperature	0.00	0.970
Spin-state analysis	0.00	0.130
Total systematic shift	0.44	1.020

$B_{2,PT}$:
Previous: 2.8 T/m^2
2023: 0.0005 T/m^2

only in TTM

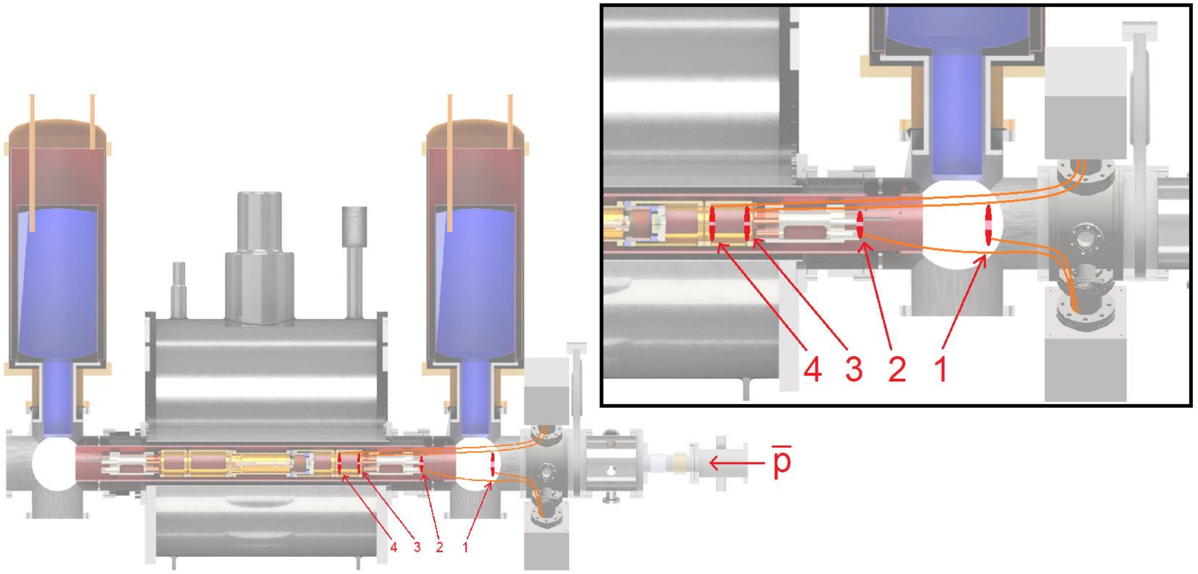
Cycle time:
Previous: 45 mins
2023: 11 min

limiting uncertainty

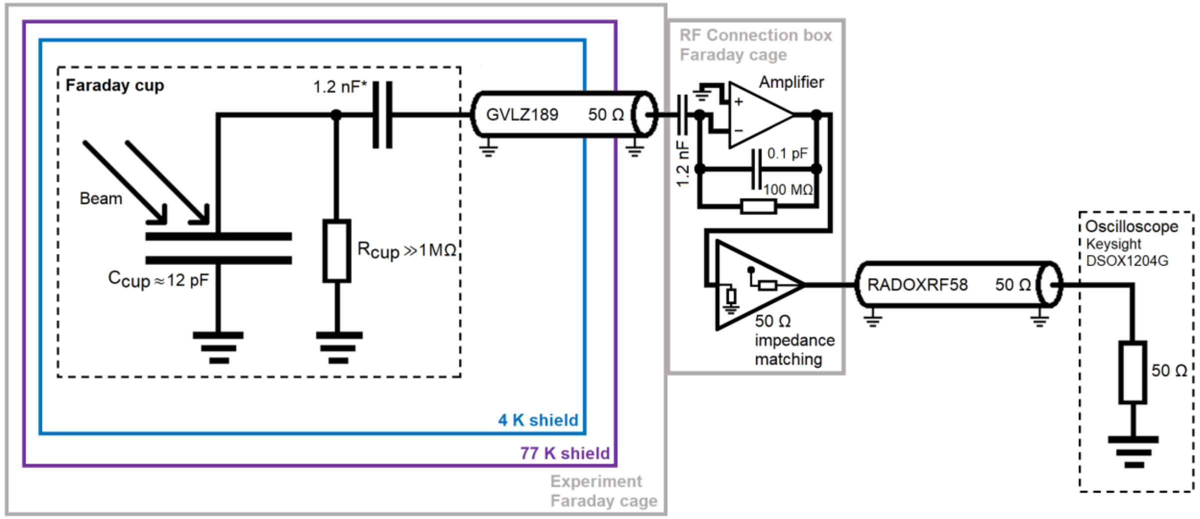
A parts-per-billion measurement of the antiproton magnetic moment by C. Smorra et al. (2017)

Antiproton beam monitors (1)

- Four new antiproton beam monitors were installed in 2022 (marked 1-4), to have better antiproton beam tracking along the experiment axis.

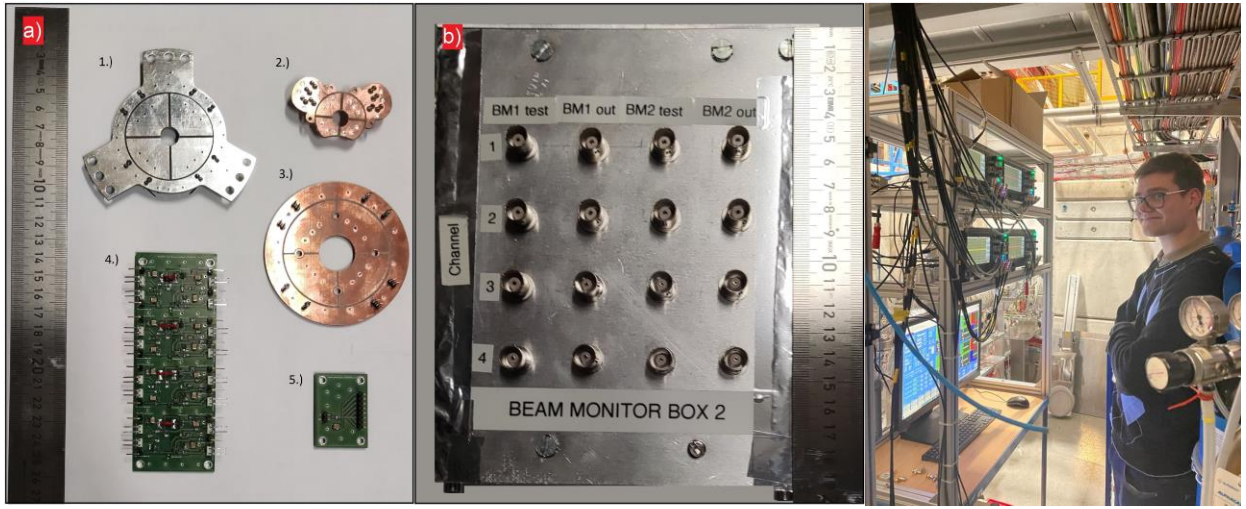


- Antiprotons are registered using Faraday cups, which consist of a capacitor, onto which the charge is distributed, and an amplification stage.

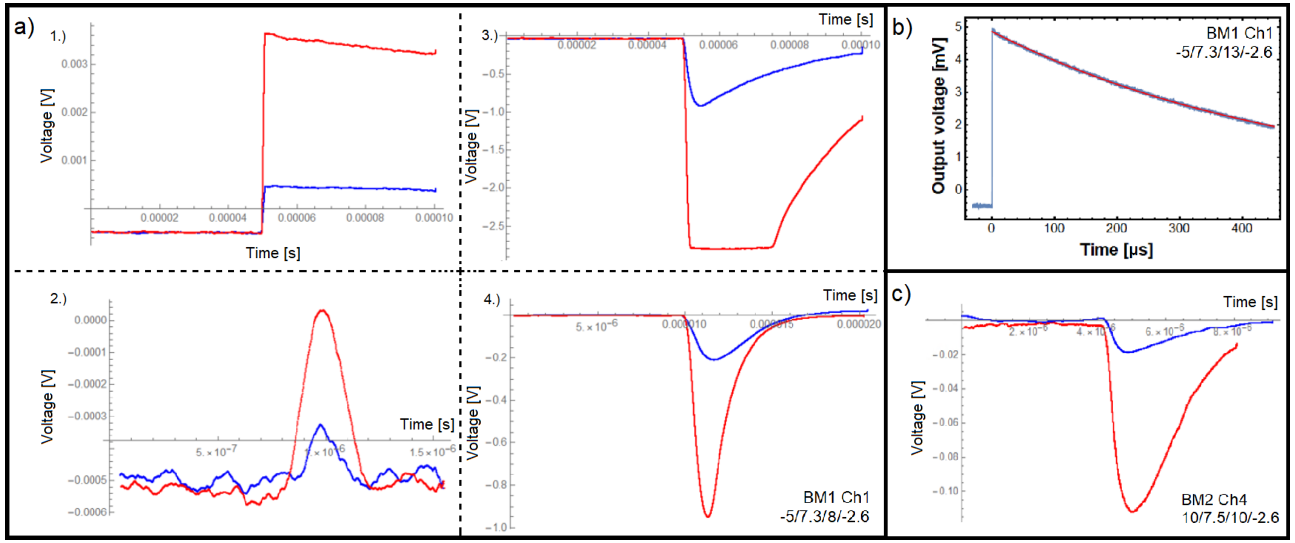


Antiproton beam monitors (2)

- Beam monitors and amplifier PCBs;
- Faraday cage for amplifying and connecting the hot lines to the coaxial outputs;
- Data readout rack: four oscilloscopes.



- Signals of the antiproton annihilation and H- ion deposition + charge liberation from the board;
- Different signal shape depends on the oscilloscope input resistance and whether the amplifier stage is used or not.



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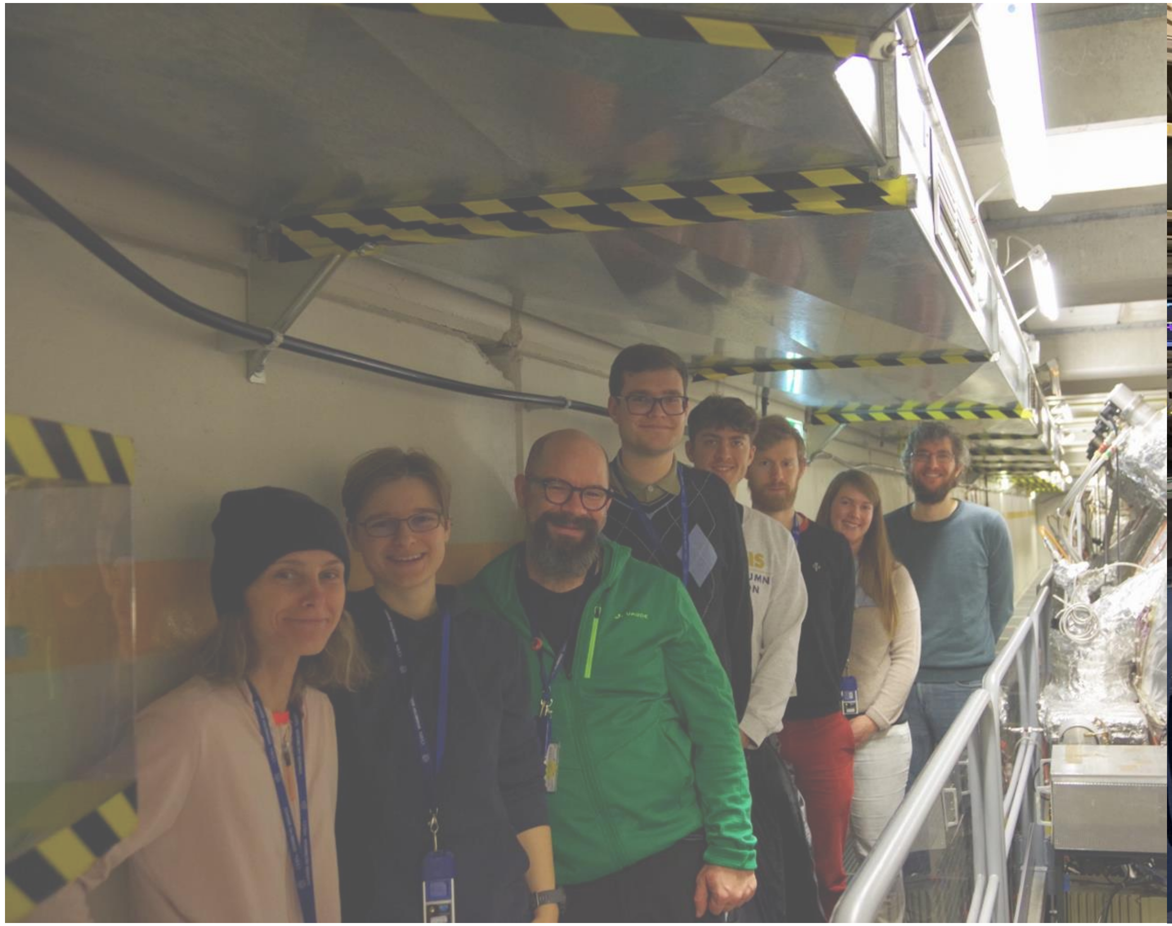
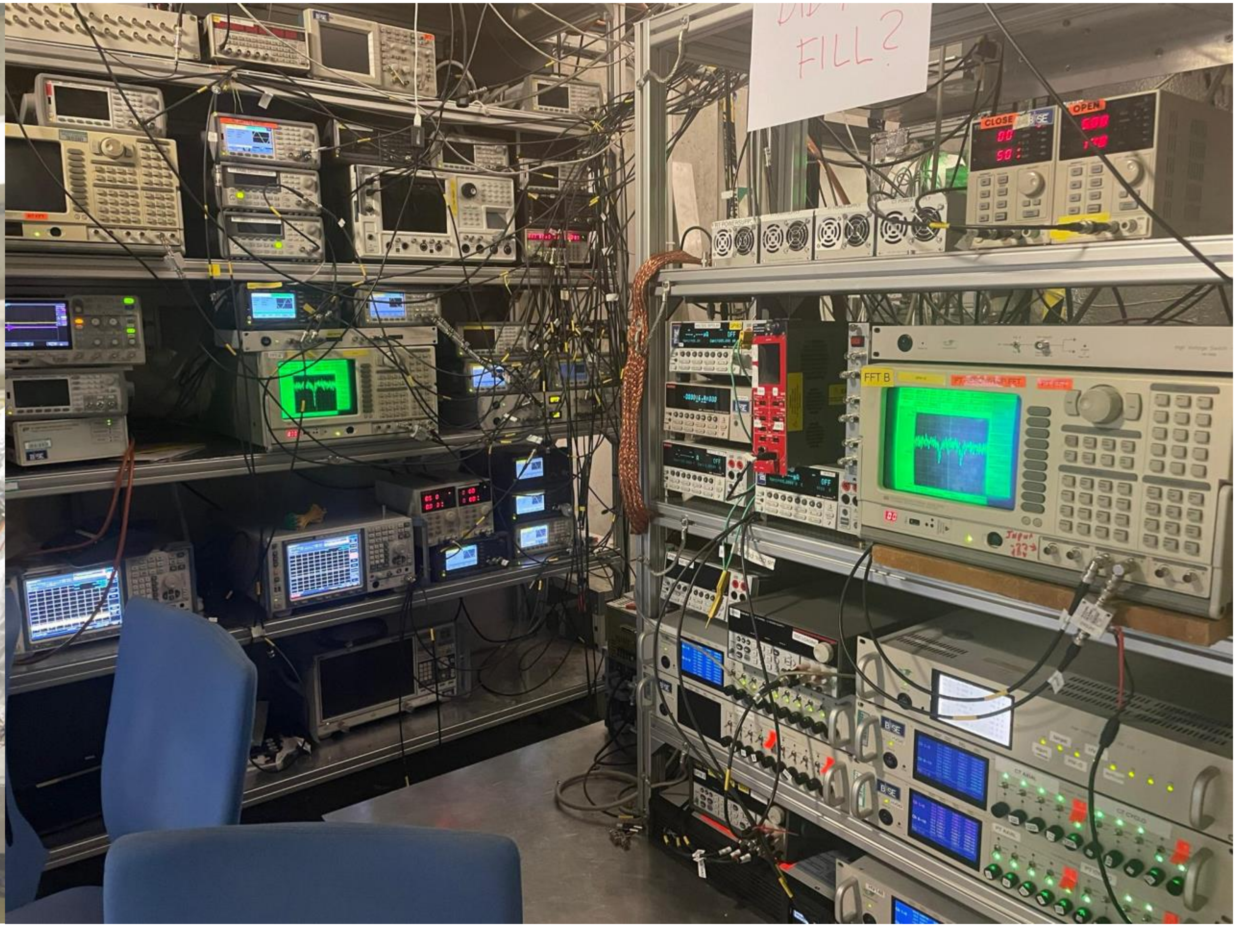


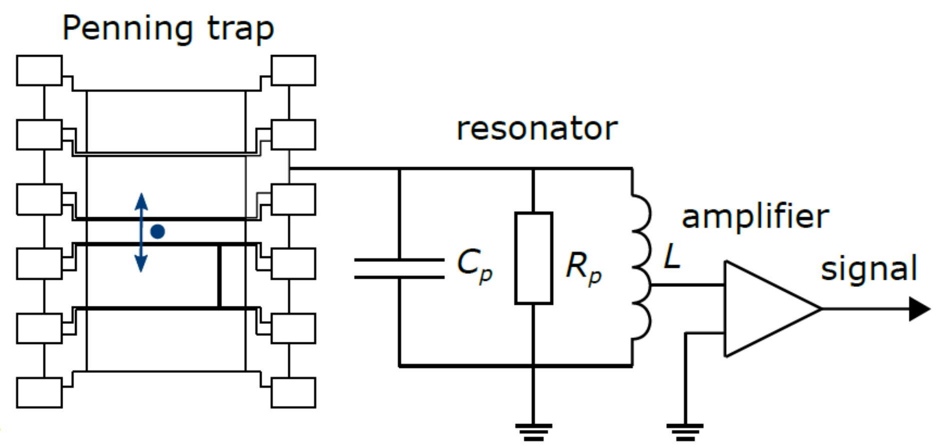


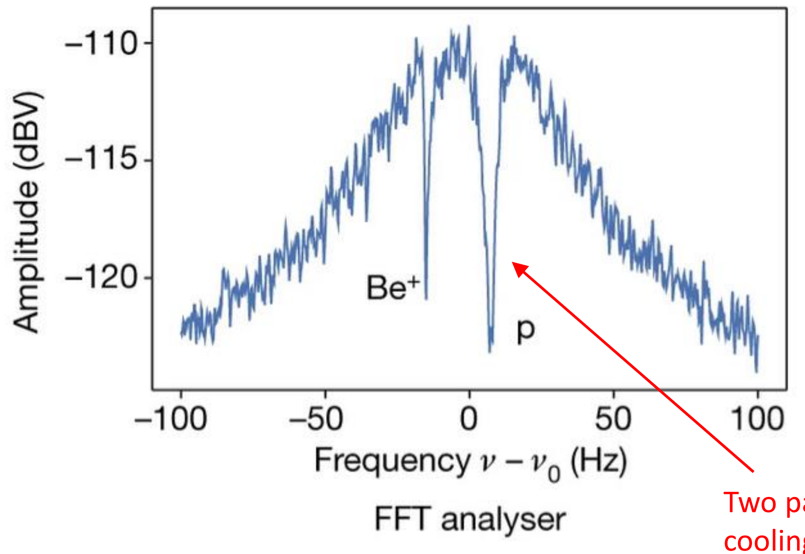
App. 1: Frequency measurement technique

1. A charged particle induces image charge on the electrodes.
2. An oscillating charge induces current.
3. The full circuit consists of particle-electrode system and in parallel connected resonator.
4. The resonator Nyquist-Johnson noise is measured at the FFT analyser.
5. The oscillating particle effectively shorts the resonator Nyquist-Johnson noise at its oscillation frequency.
6. This can be seen as a dip in the noise FFT profile.

- The temperature of the particle changes while it is interacting with the resonator.

  -> Boltzmann statistics (particle in thermal equilibrium with a reservoir)

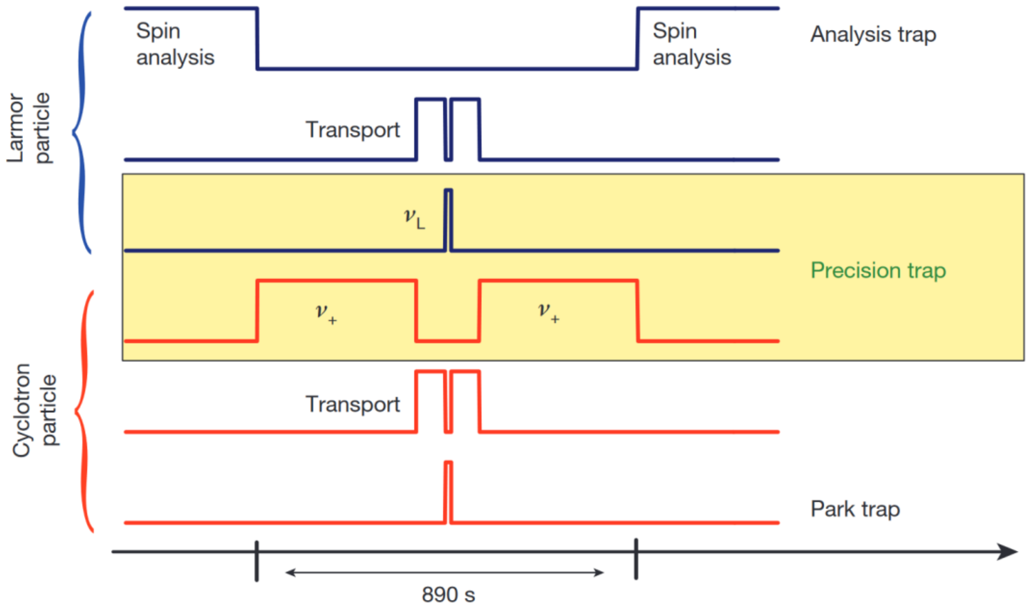




Two particle sympathetic cooling (BASE Mainz)

App. 2: Two-particle triple-trap method

- In the two-trap method the particle cyclotron energy is increased when the sideband coupling is active:
  - ➢ need to re-prepare a colder particle every cycle.
- TTM already implemented in the 2016-2017 antiproton magnetic moment measurement campaign:
  - ➢ headroom for an improved proton magnetic moment in 2023.



App. 3: Key publications by BASE

Title	Journal	Year	Quantity	Value	Fractional precision
A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio by M. J. Borchert et al.	Nature	2022	$\left(\frac{q}{m}\right)_{\bar{p}} / \left(\frac{q}{m}\right)_{p}$	-1.000000000003(16)	16 ppt
Sympathetic cooling of a trapped proton mediated by an LC circuit by M. Bohman et al.	Nature	2021	–	–	–
Direct limits on the interaction of antiprotons with axion-like dark matter by C. Smorra et al.	Nature	2019	–	–	–
Measurement of ultralow heating rates of a single antiproton in a cryogenic Penning trap by M. J. Borchert et al.	Phys. Rev. Lett.	2019	–	–	–
Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision by G. Schneider et al.	Science	2017	$\boldsymbol{\mu_p/\mu_N}$	**2.79284734462(82)**	**300 ppt**
A parts-per-billion measurement of the antiproton magnetic moment by C. Smorra et al.	Nature	2017	$\mu_{\bar{p}}/\mu_N$	-2.7928473441(42)	1500 ppt TTM
Observation of individual spin quantum transitions of a single antiproton by C. Smorra et al.	Phys. Lett. B	2017	–	–	–

References

[1] American Physical Society: Alan Stonebraker

[2] Matthias Borchert PhD thesis, University of Hannover, Germany

[3] Onsets of nuclear deformation from measurments with the ISOLTRAP mass spectrometer by S. Naimi, 2010

… and key publications by BASE