Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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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About me:

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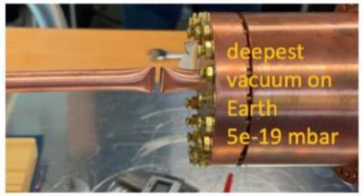
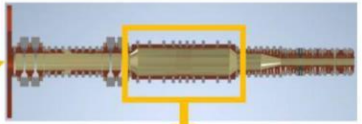
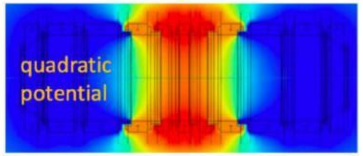


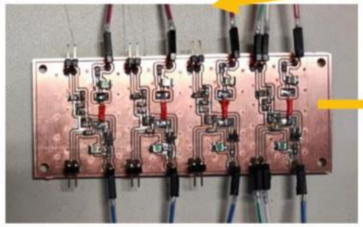
- 1998 : Born in Klaipeda, Lithuania
- 2016—2017 : International Physics Olympiads experience
- 2017—2021 : Bachelor and Master degrees at University of Cambridge
- 2021— : PhD studies at ETH Zürich, full-time at CERN, BASE experiment

PhD thesis topic: implementation of new seven-electrode precision trap

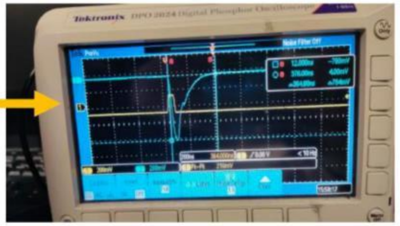
Currently working on: antiproton beam monitor amplifiers



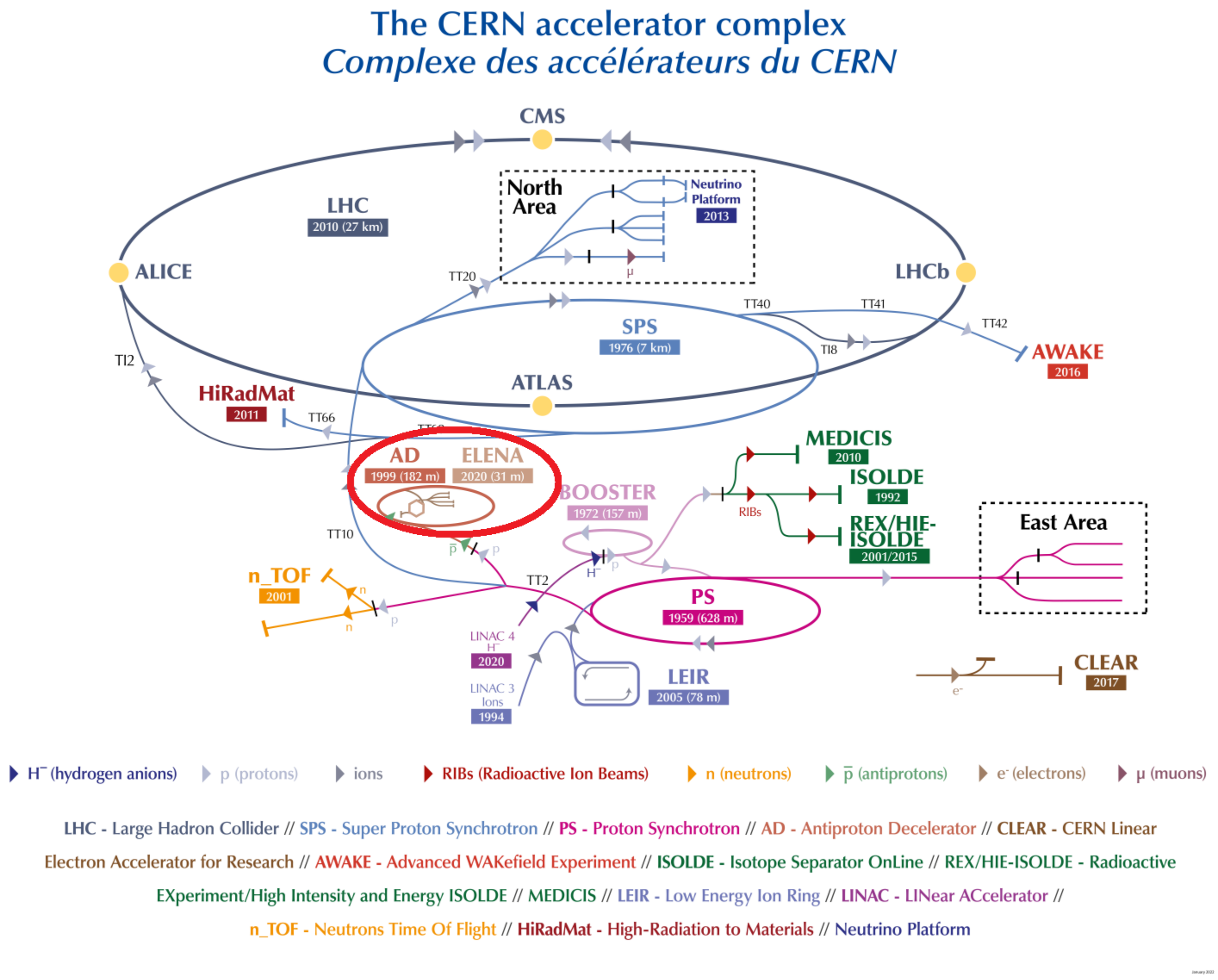




signal



Antiproton Decelerator



BASE – overview

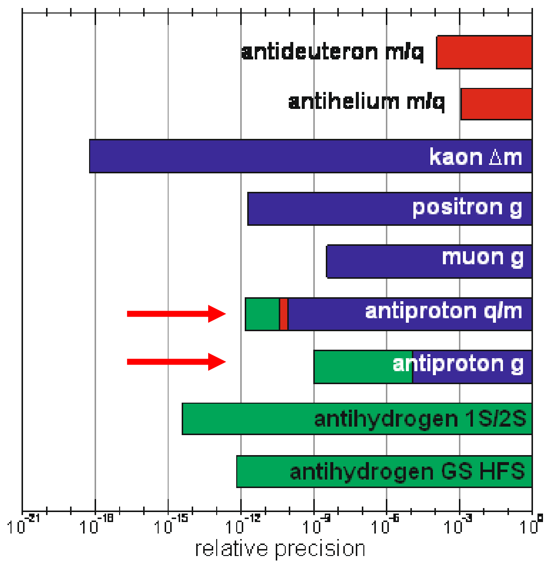
- Low energy **particle physics**:
  - Measuring fundamental constants: g-factor, q/m ratio,
  - Comparing q/m for $\bar{\mathrm{p}}$ and H^- ions (proxy for protons),
  - Comparing g-factor for $\bar{\mathrm{p}}$ and p,

  -> CPT symmetry test in the baryon sector up to the p.p.t. precision

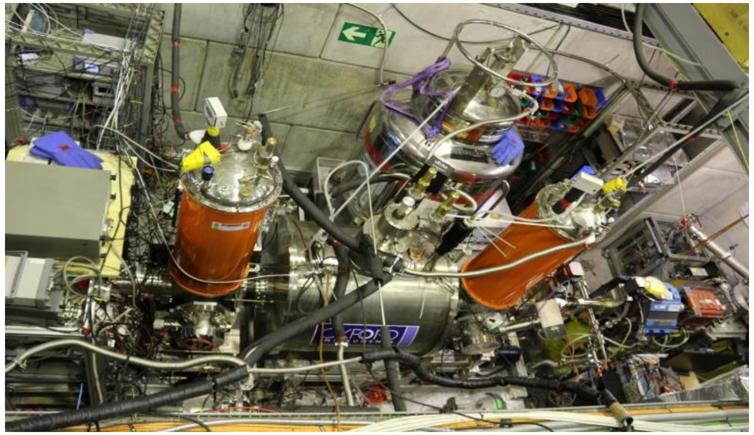
- Atomic physics:
  - Penning traps for storing ions
  - Irradiating Larmor frequency signal via the dedicated spin-flip coils and measuring the spin flip probability
    -> measuring the g-factor

- “Classical” physics:
  - Moving particles produce charge image on electrodes **-> currents**
  - Particle with resonator oscillations **-> frequency determination**

(a) Precision of selected constants



(b) Experiment setup



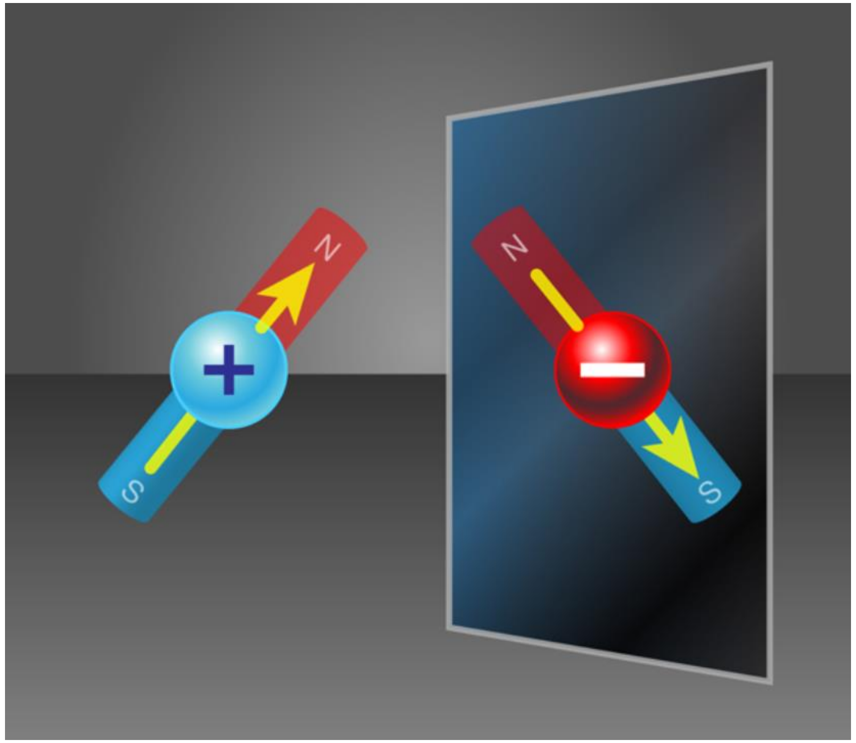
Motivation – CPT symmetry test

Consider behaviour of **common physical quantities** under the three **discrete transformations 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	$\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	$+\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	$+\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$	$-\vec{\sigma} \cdot (\vec{p}_1 \times \vec{p}_2)$

Recent upgrades and expectations

- Two particle – triple trap method is an upgrade on the measurement algorithm for the proton and/or antiproton magnetic moment. Using two particles in the 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 less than **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:

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

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:

$$\Phi(z,\rho) = C_2\, V_r\, (z^2 - \rho^2/2)$$

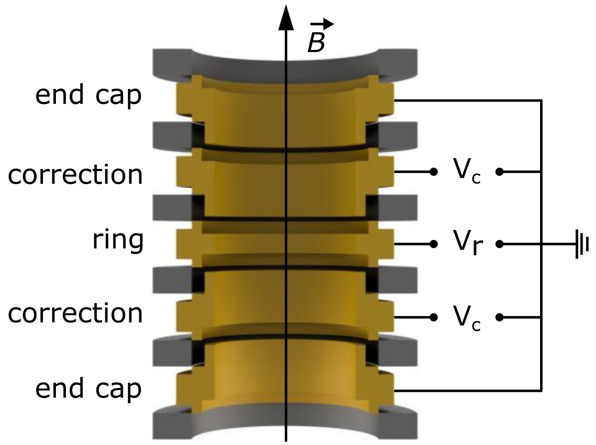
- Static uniform axial B-field

Trajectory – 3 orthogonal motions:

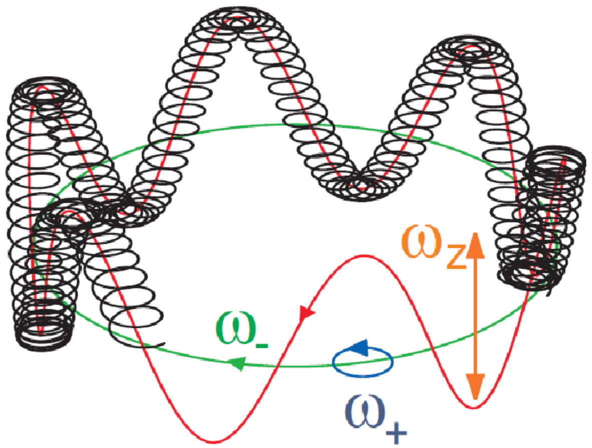
- Harmonic axial
- Circular planar modified cyclotron
- Circular planar magnetron

Axial frequency: $\omega_z = \sqrt{\frac{2qV_rC_2}{m}}$

Cyclotron frequency: $\omega_c = \frac{qB_0}{m}$



[2]



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

[3]

BASE Penning trap stack

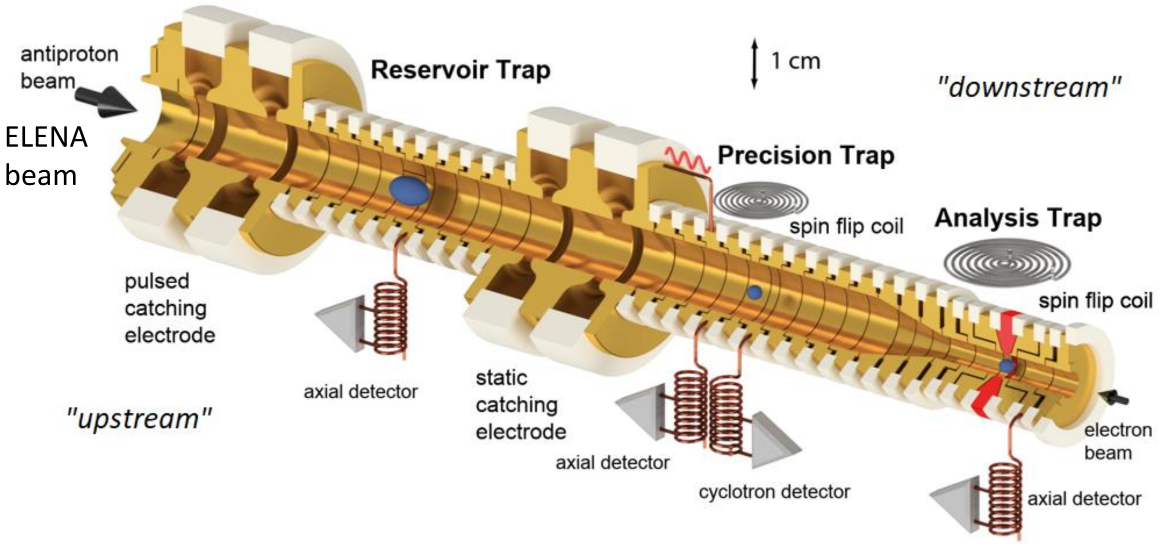
Four Penning traps are used in BASE at CERN:

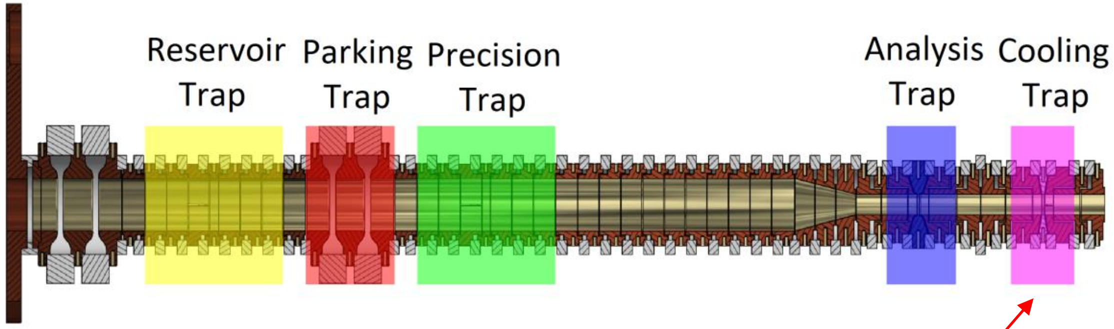
a) Reservoir Trap -> long storage of particles
-> stable 4.5 mm radius trap

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

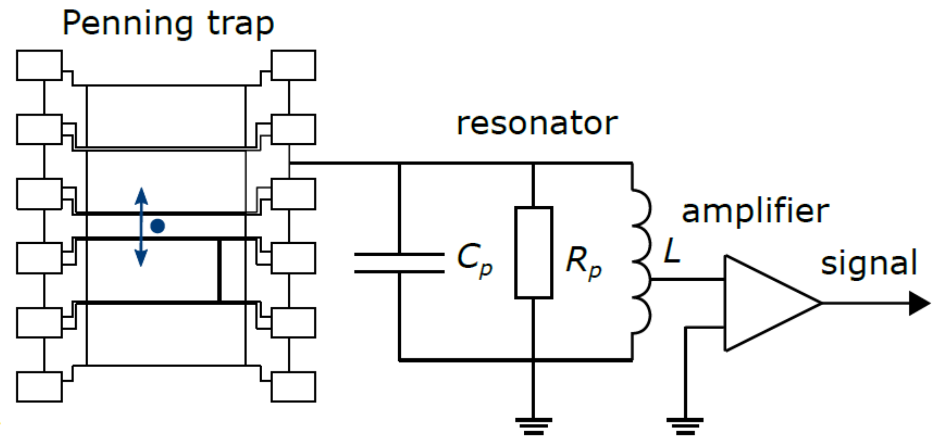
$$\Delta\nu_{z,SF} = \frac{h\nu_L}{4\pi^2 m_{\bar{p}}\nu_z}\frac{B_{2,AT}}{B_{0,AT}}$$

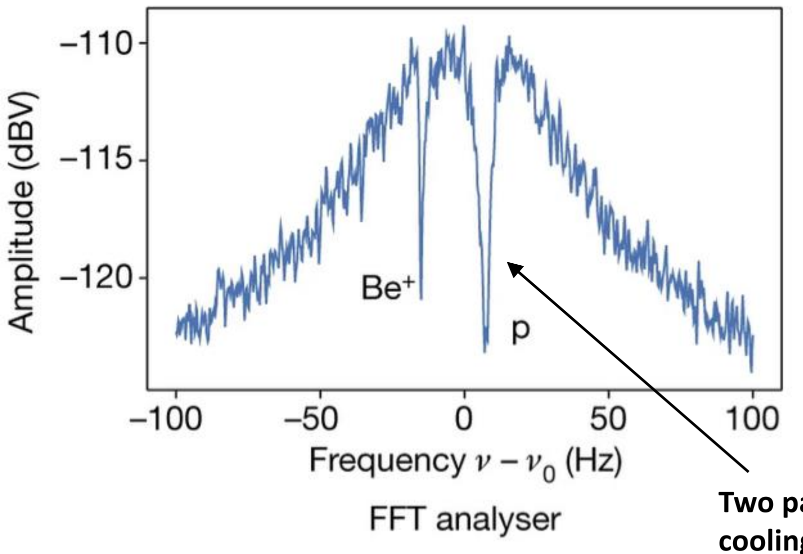
Frequency measurement technique

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 undergoes Boltzmann statistics while it is interacting with the resonator:

    -> particle in thermal equilibrium with a reservoir





Two particle sympathetic cooling (BASE Mainz)

PhD projects: New seven-electrode trap design

Advantages over the five-electrode traps:

- Better E-field harmonicity at low z ($C_4=C_6=C_8=C_{10}=0$):
  - symmetric field expansion $\Phi(z) = V_r\,(C_0 + C_2\,z^2 + C_4\,z^4 + \dots)$
- Larger (factor of ~3) stable magnetron region:
  - lower $\Delta\nu_z$ (from Duffing equations):

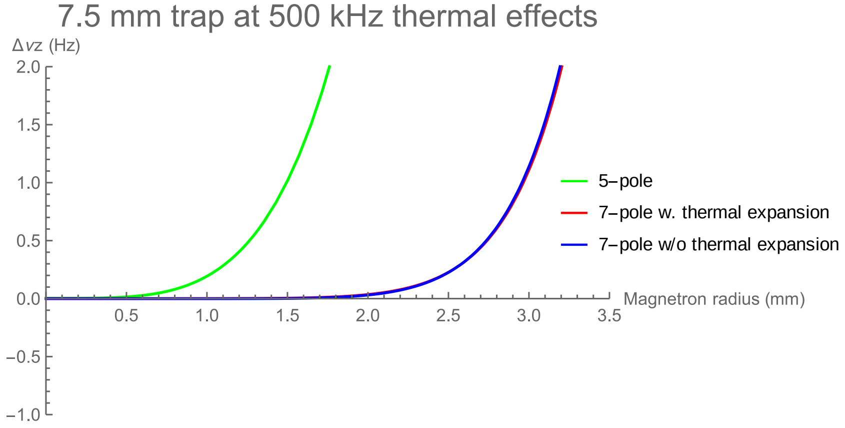
$$\Delta\nu_z = \nu_z\,(3/4\; C_4/C_2^2\,(k_B\,T_z/qV_r) + 15/16\; C_6/C_2^3\,(k_B\,T_z/qV_r)^2 + \dots)$$

  - similar frequency shift dependence in the other modes

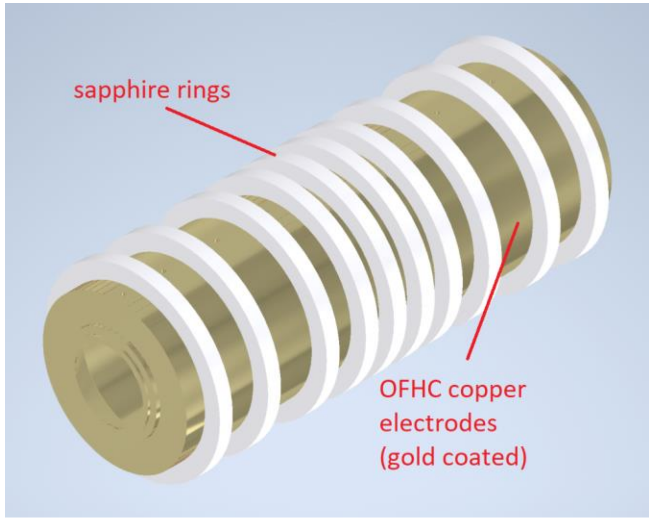
-> More precise cyclotron frequency measurement

- Already implemented in other Penning trap experiments:
  - LIONTRAP (Mainz, Germany)
  - ALPHATRAP (Heidelberg, Germany)

(a) Thermal expansion vs. harmonicity:

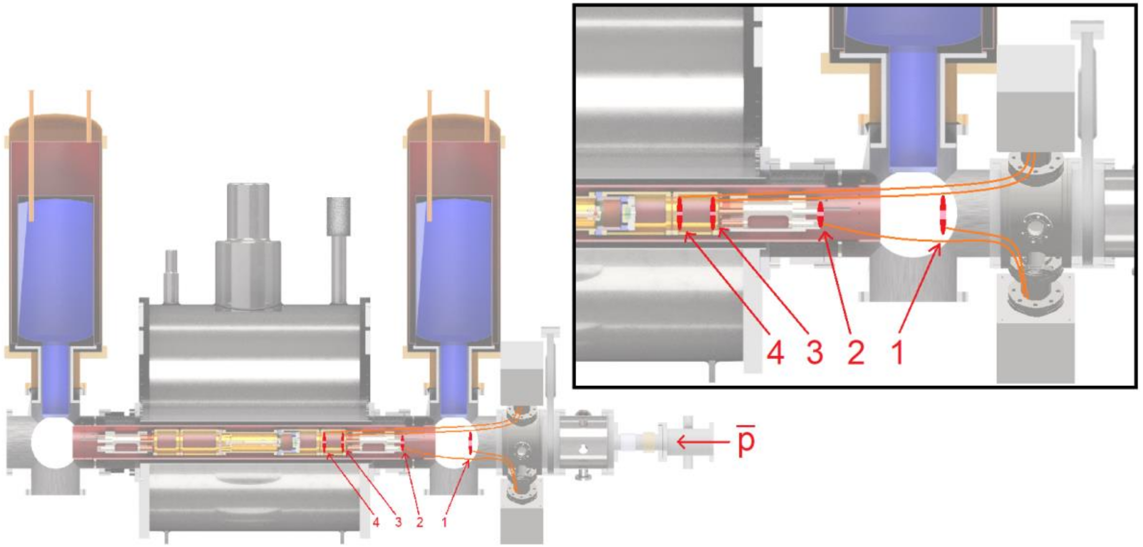


(b) New trap design:

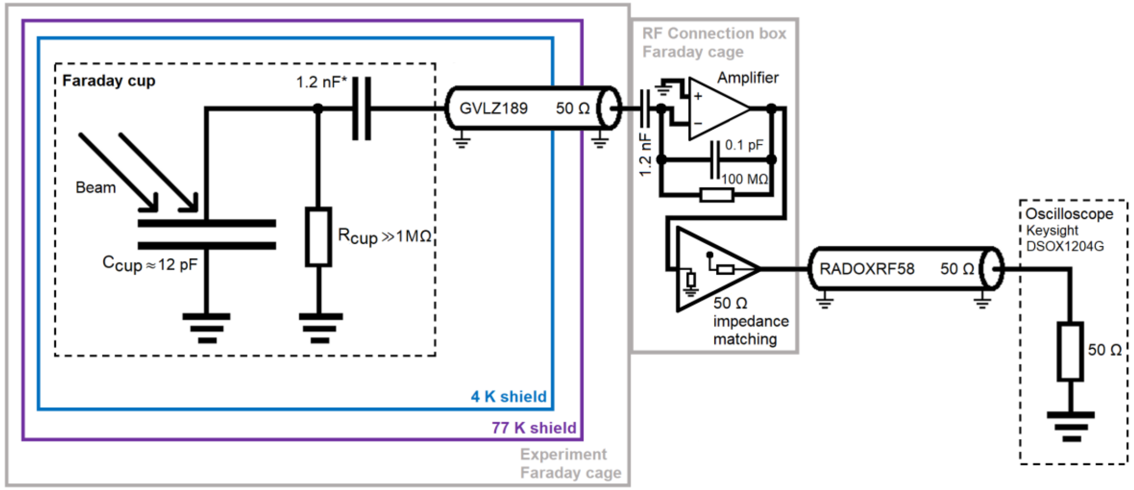


PhD projects: Antiproton beam monitors (1)

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

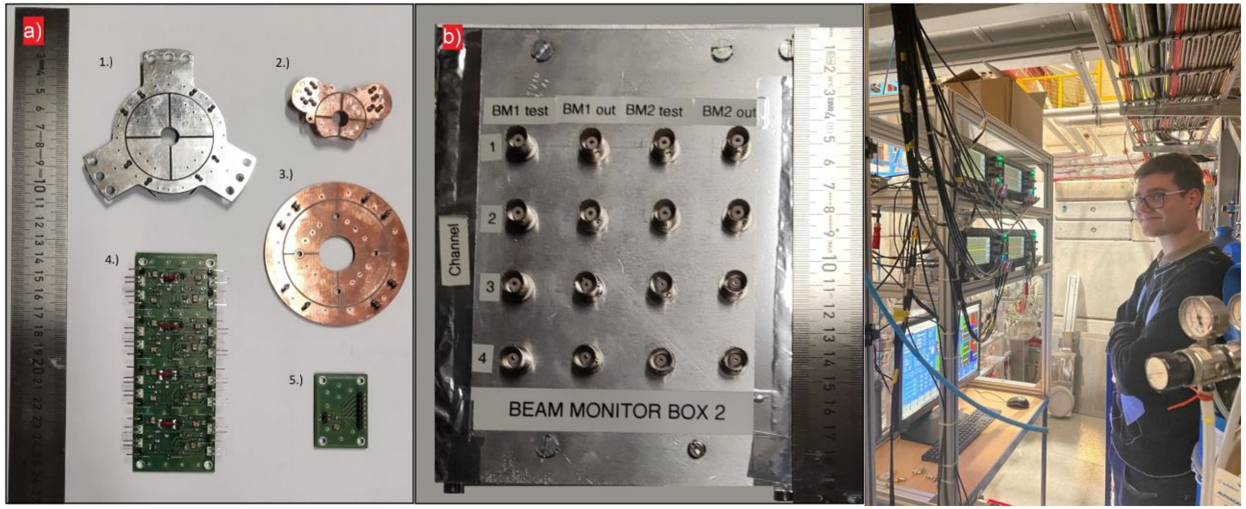


- Antiprotons are registered using Faraday cups, which consist of a capacitor, onto which the charge is distributed, and an amplification stage.

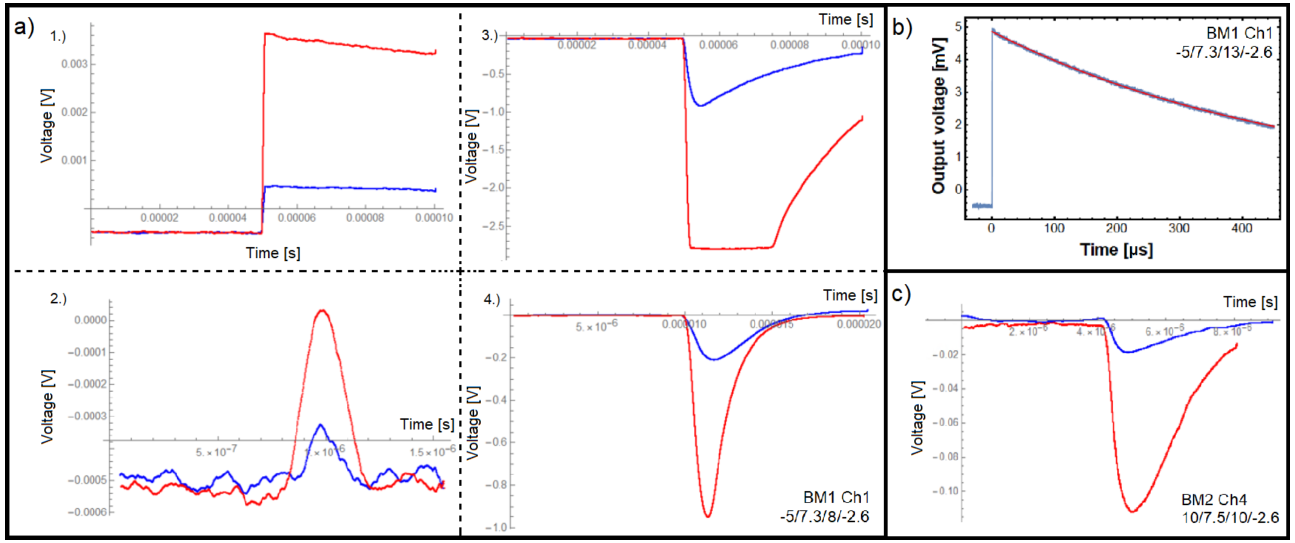


PhD projects: Antiproton beam monitors (2)

- 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.



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 publications by BASE