Precision measurements on single protons and antiprotons

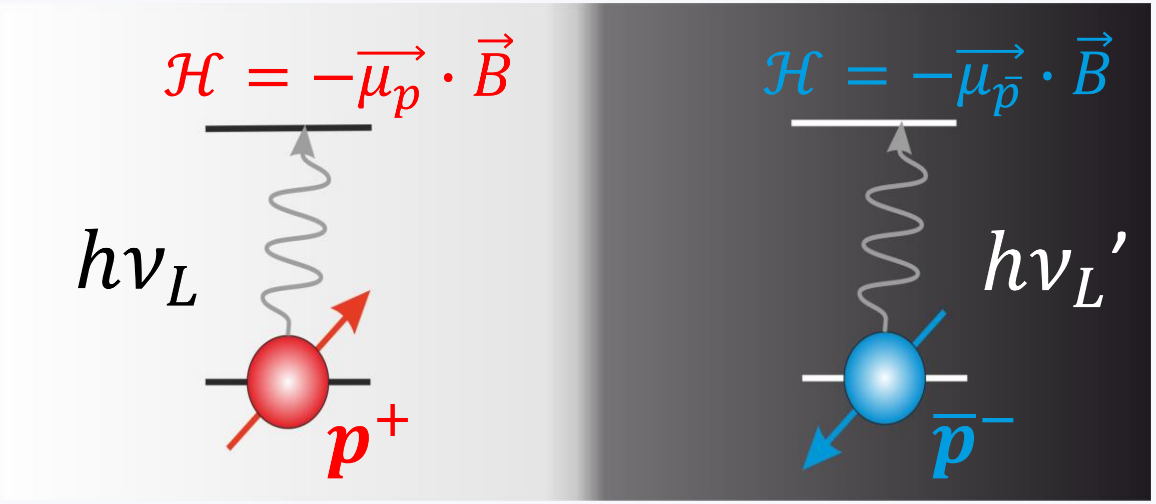
PSAS – ETH Zürich - 12.06.2024

Dr. Christian Smorra on behalf of the **BASE collaboration**

Heinrich-Heine-Universität Düsseldorf

What to learn from proton/antiproton precision measurements?

Fundamental properties of conjugate particles/antiparticles are supposed to be identical.

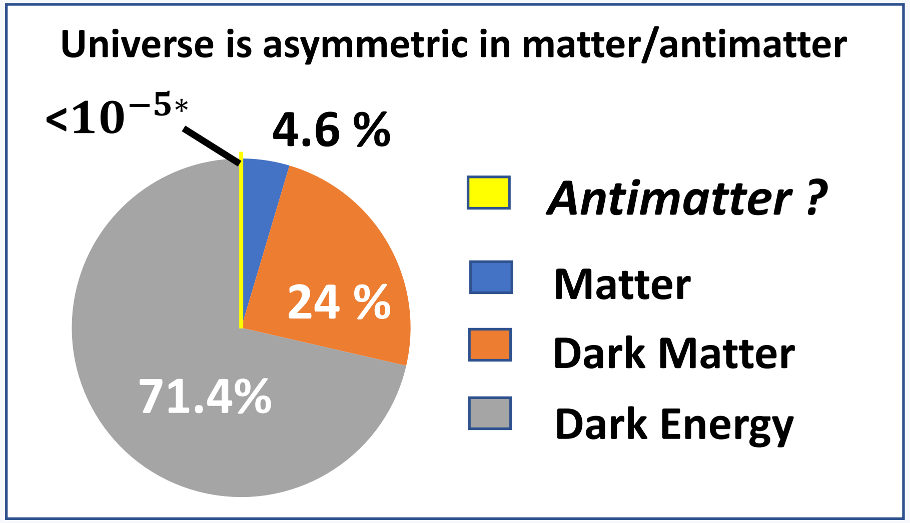


Test of fundamental symmetries:
CPT invariance is linked to Lorentz-invariance and the construction of Quantum Field Theory.

M. Charlton, S. Erikson, G. M. Shore, "Antihydrogen and Fundamental Physics", Springer Verlag, ISBN 978-3-030-51713-7 (2020).

The matter excess in the universe is not understood.
Antimatter abundance is irrelevant on cosmic scales,
e.g. composition of high-energy cosmic rays,
absence of annihilation radiation

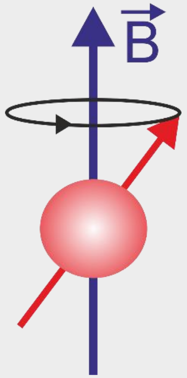
R. Kappl et al., J. Cosmology Astropart. Phys. 09, 051 (2014).
S. Dupourqué, L. Tibaldo, P. von Ballmoos, Phys. Rev. D 103, 083016 (2021).

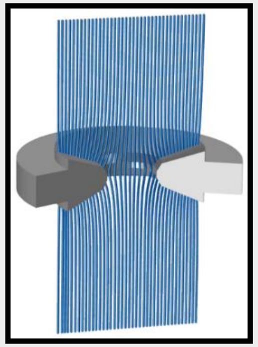


No process that is asymmetric in the production/annihilation of particles and antiparticles has been observed.

Precision measurements on single trapped protons/antiprotons

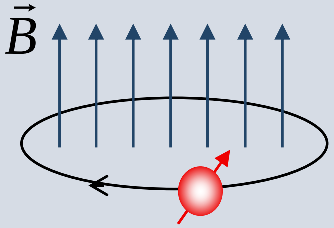
Larmor Frequency

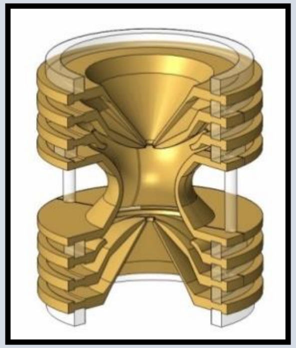




$$\omega_L = g \frac{e}{2m_p} B$$

Cyclotron Frequency





$$\omega_c = \frac{q}{m} B$$

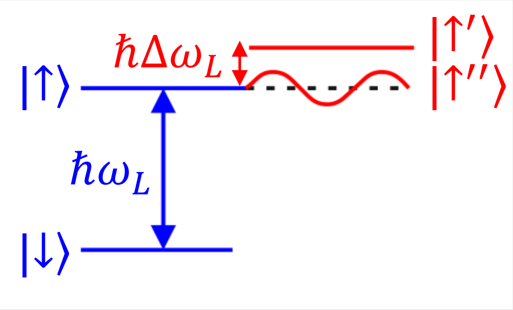
$$\frac{\omega_{L,p/\bar{p}}}{\omega_{c,p/\bar{p}}} = \frac{g_{p/\bar{p}}}{2} = \pm \frac{\mu_{p/\bar{p}}}{\mu_N}$$

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

H. G. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).

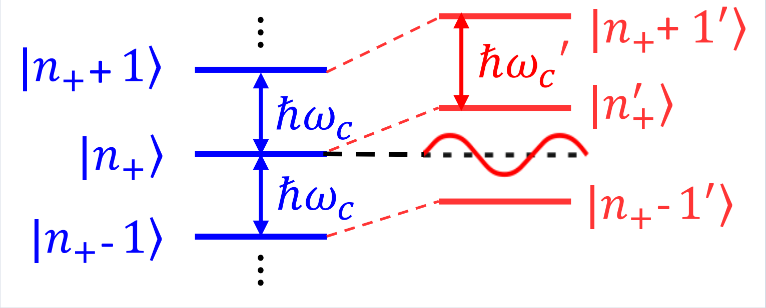
Precision measurements…but with new physics?

Larmor Frequency modifications



Lorentz- and CPT-violation
Axion wind / Axion-like particles
(Permanent electric dipole moment)

Cyclotron Frequency modifications



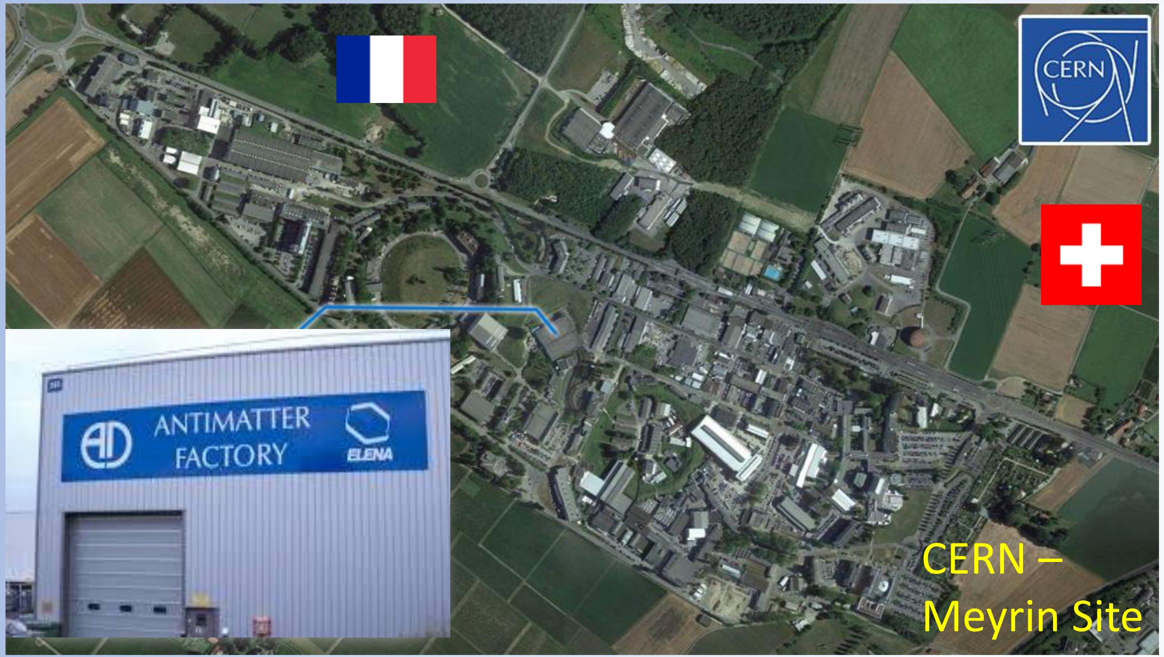
Lorentz and CPT-violation
Antiproton gravitation anomalies

$$\Delta\omega_L = \frac{\Delta g}{2}\frac{q}{m}B + \Delta\omega_{Axion}\sin(\omega_a t) + d_{EDM}\cdot\left|\vec{E}\right|/\hbar$$

$$\Delta\omega_C = \Delta\left(\frac{q}{m}\right)B + (3\alpha - 2)\frac{U_{grav}}{c^2}$$

Standard Model Extension: Y. Ding et al., Phys. Rev. D **94**, 056008 (2016).
Axions: P. Graham et al., Ann. Rev. Nucl. Part. Sci. **65**, 485 (2015).
C. Smorra, Y. Stadnik et al., Nature **575**, 310-314 (2019).
EDM: D. Budker, Y. Semertzidis et al., (in preparation).
Antimatter gravitation: R. J. Hughes et al., Phys. Rev. Lett. **66**, 854 (1991).

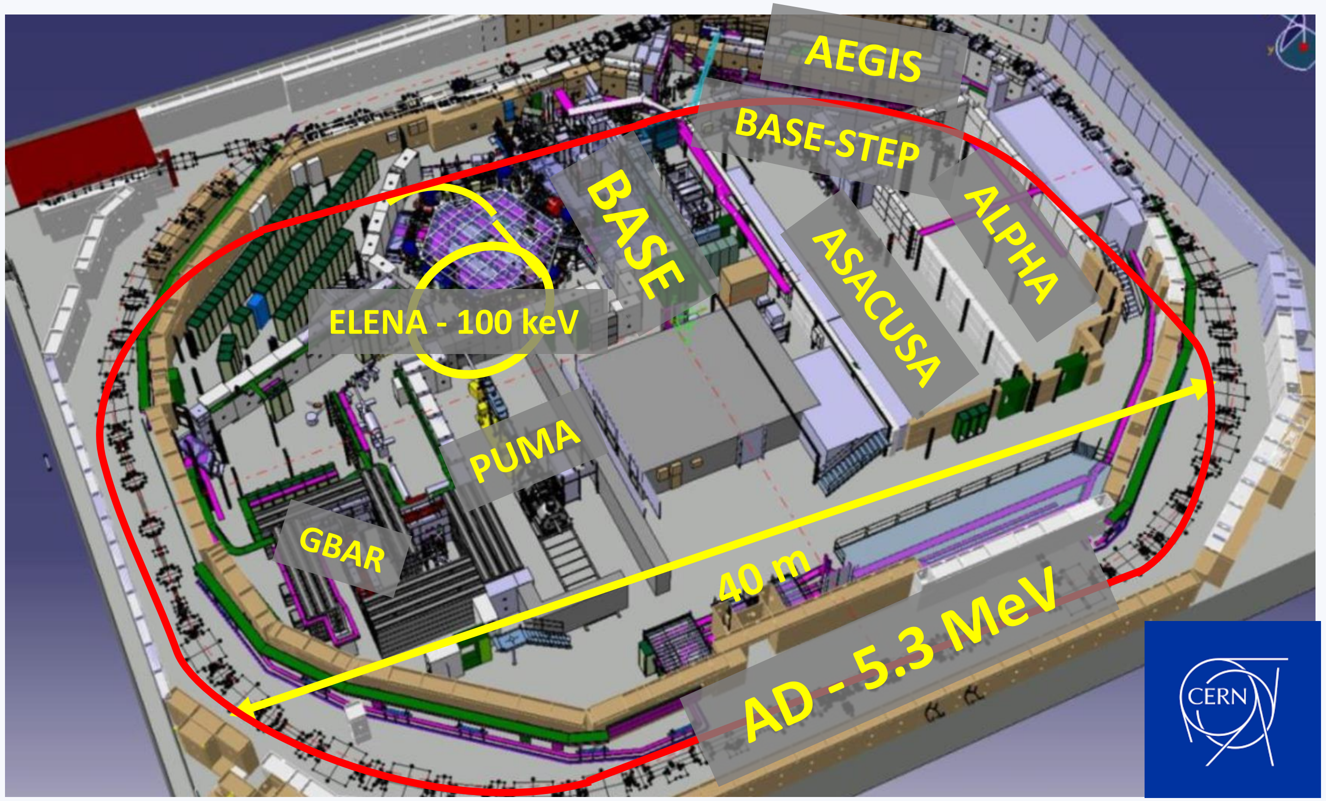
Antimatter Factory of CERN



Antimatter factory:

Deceleration of antiprotons in two synchrotrons to 100 keV

Enables low-energy experiments with antiprotons



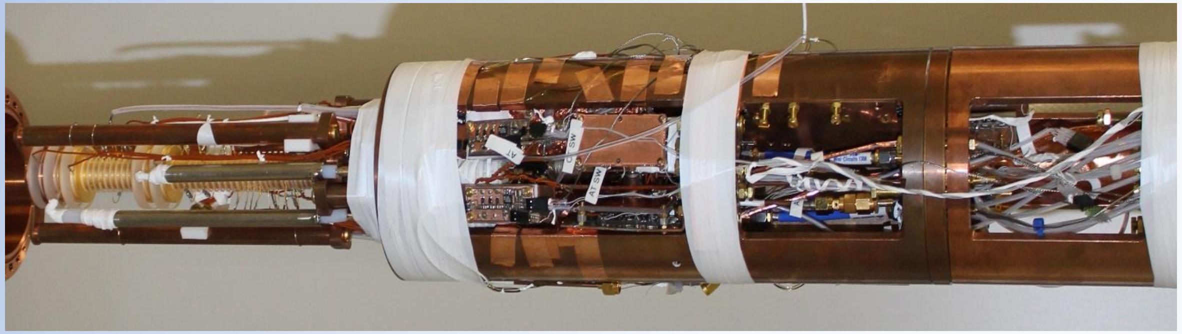
Experiment program:

Precision spectroscopy on antiprotons, antihydrogen, antiprotonic atoms

Gravitational behaviour of antimatter

Nuclear skin composition by antiproton annihilation

Antiproton precision measurements in BASE



Ingredients for high precision:

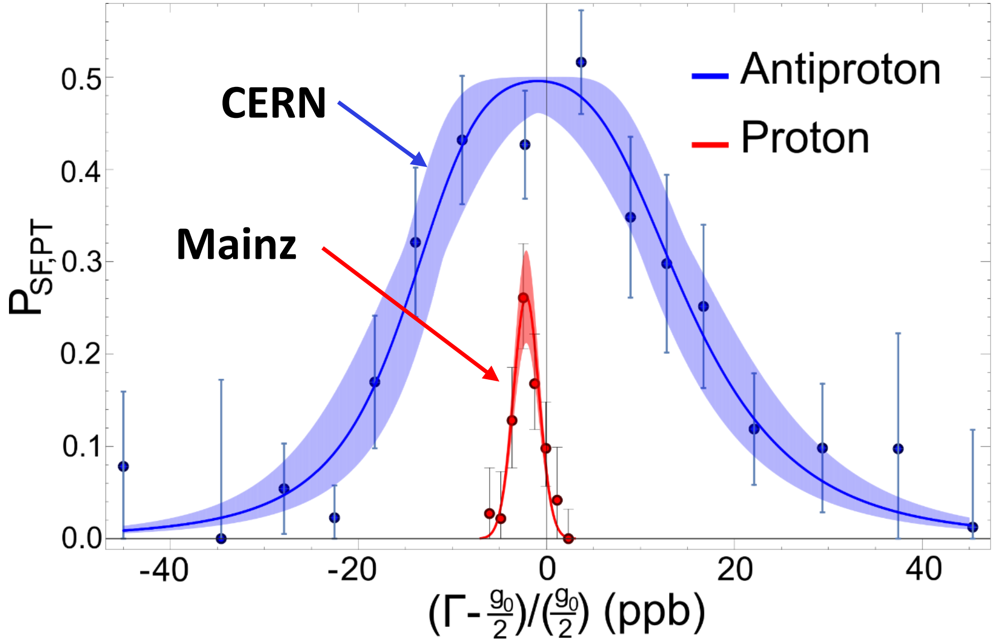
- High magnetic field stability (< 10^{-9})
- High trap voltage stability ($\sim 5 \cdot 10^{-8}$)
- Environment stabilization
- Low magnetic field noise (difficult in the AD!)

Cryogenic multi-Penning trap system:

- Long-term antiproton storage (> 1 year)
- Precision frequency measurements using non-destructive image-current detection
- Fast resistive cooling (now: ~22 mins for 100 mK)
  B. M. Latacz, M. Fleck et al., arXiv:2404.07928 (2024).
- **Nuclear spin state detection of single protons/antiprotons**

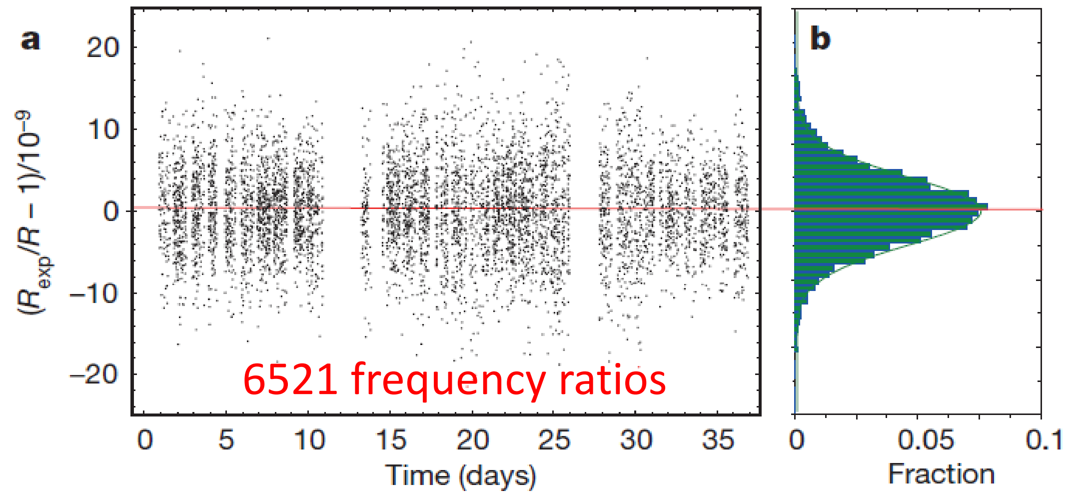
C. Smorra et al., Eur. Phys. J. 225, 1-53 (2015).

First generation of precision measurements with BASE (2014-2017)



$$\left| \frac{g_p}{2} - \frac{g_{\bar{p}}}{2} \right| < 0.3\ (8.3)\ 10^{-9}$$

C. Smorra et al., Nature **550**, 371 (2017).
G. Schneider et al., Science **358**, 1081-1084 (2017).



$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 = 1(64)(26) \times 10^{-12}$$

S. Ulmer et al., Nature **524**, 196 (2015).
G. Gabrielse, Int. J. Mass Spectr. 251, 273-280 (2006).

$$\frac{\omega_{L,p/\bar{p}}}{\omega_{c,p/\bar{p}}} = \frac{g_{p/\bar{p}}}{2} = \pm \frac{\mu_{p/\bar{p}}}{\mu_N}$$

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

Improvements towards higher precision

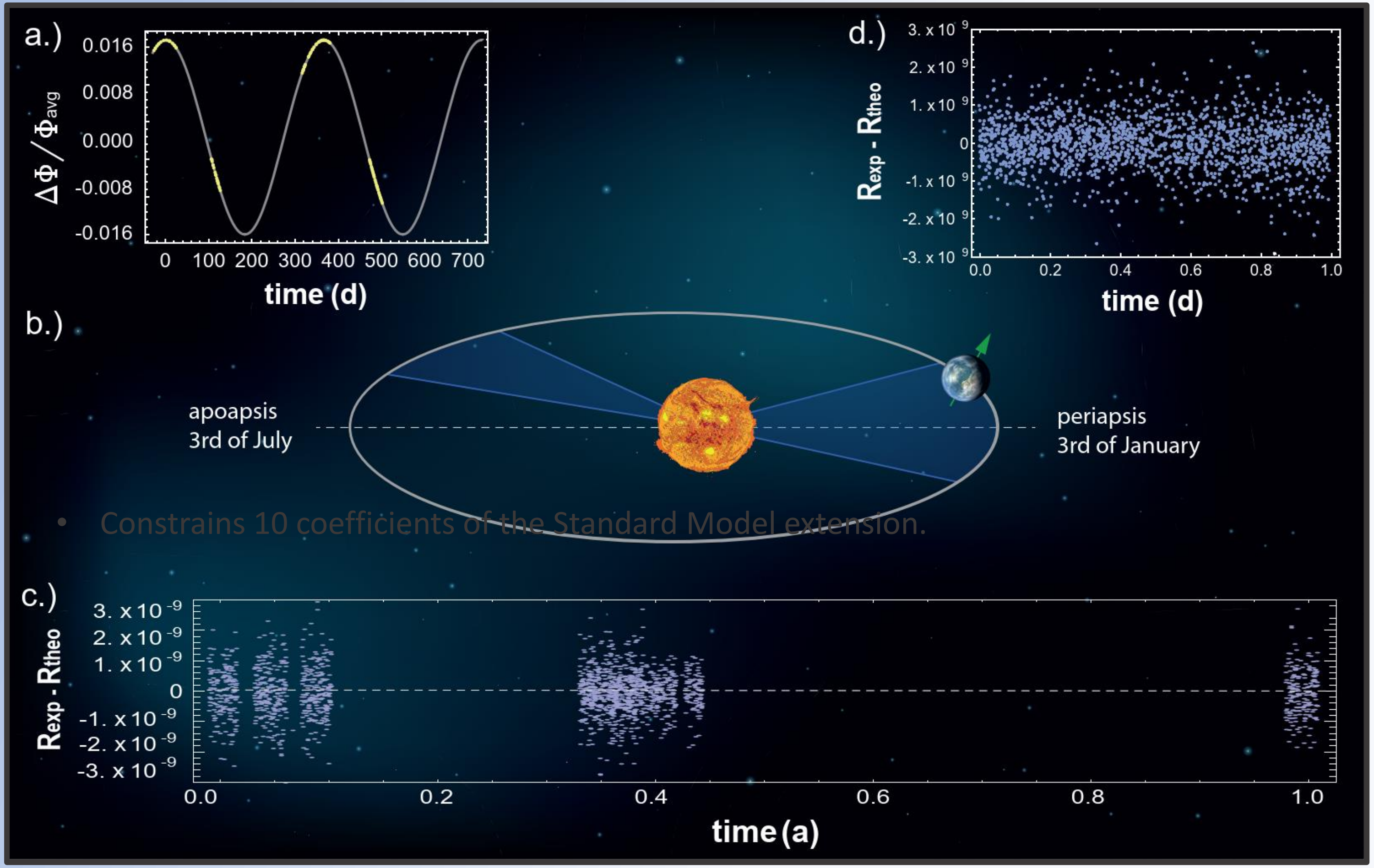
Block stability of cyclotron frequency shifts: $\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\nu_{c,2i}-\nu_{c,2i-1}}{\nu_{c,2i}}\right)^2} \sim 5.5$ ppb in 2014

- Self-shielding superconducting coil system to suppress magnetic field noise
  J.A. Devlin et al., Phys. Rev. Applied 12, 044012 (2019).
- Decoupling of vibrations from the LHe boiloff in the cryostats
  M. Borchert, PhD thesis, Leibniz Universität Hannover (2021).
- Improved thermal isolation
- Shim-coil system to tune out the magnetic field gradients
  S. Erlewein, PhD thesis, Heidelberg University (2024).

$$\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\nu_{c,2i}-\nu_{c,2i-1}}{\nu_{c,2i}}\right)^2} \sim 500 \text{ ppt}$$

Recent results of BASE-CERN

Improved comparison of the proton/antiproton q/m ratios: $\left(\frac{q_{\bar{p}}}{m_{\bar{p}}}\right) / \left(\frac{q_p}{m_p}\right) = -1.000\,000\,000\,003\,(16)$



Constrain of 10 coefficients of the Standard Model Extension:

$$|\delta\omega_c^{\bar{p}} - R_{\bar{p},p,\exp}\delta\omega_c^{p} - 2R_{\bar{p},p,\exp}\delta\omega_c^{e^-}| < 1.96\times 10^{-27}\ \text{GeV}$$

Differential test for gravitational anomalies of antiprotons:

$$\frac{\Delta R(t)}{R_{avg}} = \frac{3GM_{sun}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right)$$

Property	Limit
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

M. Borchert et al., Nature **601**, 53–57 (2022).

First Coherent Nuclear Spin Transisition Spectroscopy

- Trap homogeneity was improved: $2.7\ T/m^2 \rightarrow 0.0015(21)\ T/m^2$
- This enabled the observation of spin transitions with a coherent component
- Has never been demonstrated in a Penning trap.

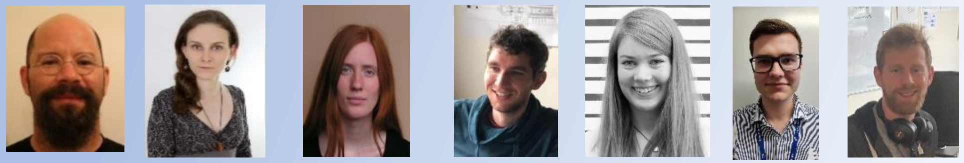
each point contains 20
protocol cycles

Preliminary data

Preliminary data

Please contact me if you need to view
the preliminary figures again.

Now: Progress on proton/antiproton g-factor measurement at CERN (2023/2024)



… (Ulmer, Latacz et al.)

Magnetic field noise limited (2023)

Saturation broadened (2016)

Preliminary data

Please contact me if you need to view the preliminary figures again.

Objective:

Compare proton and antiproton *g*-factors with 100 ppt uncertainty

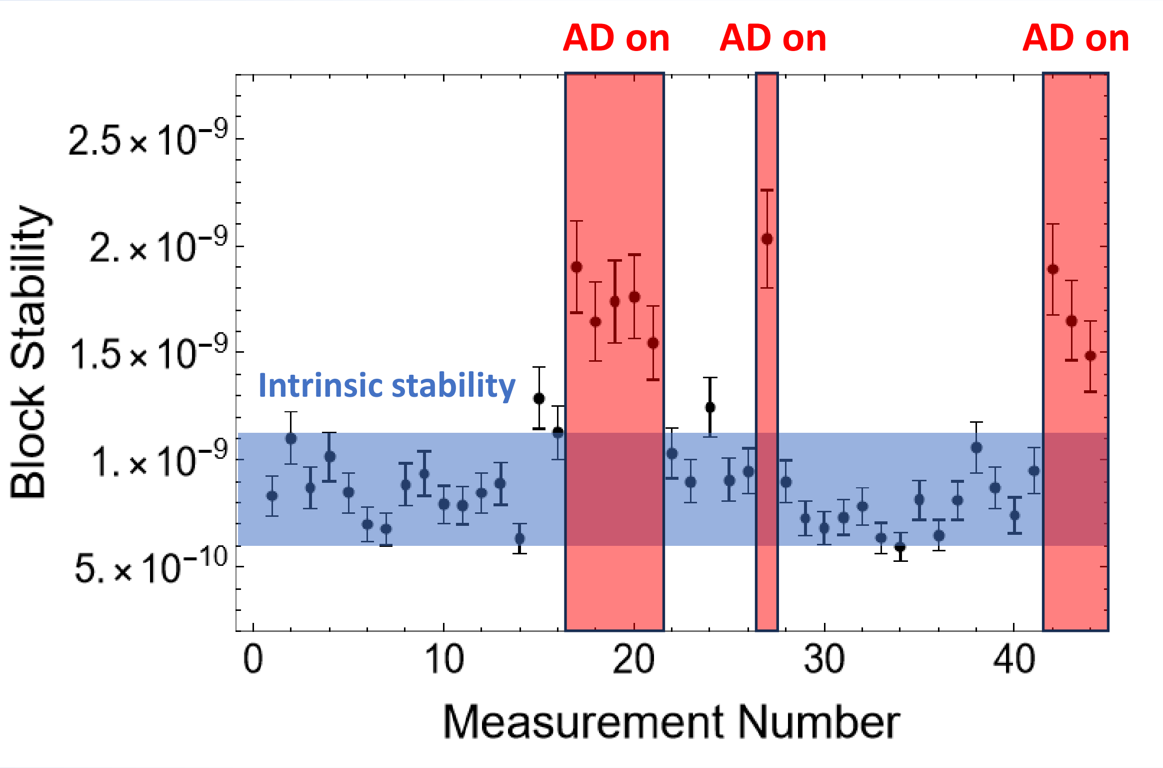
Proton data was recorded in 2023

Antiproton data was recorded starting in the Christmas break of 2023

Systematic measurements require a calm magnetic field in the AD hall

Limitations by magnetic field fluctuations in the AD/ELENA facility

Impact on frequency ratio measurements in the BASE-CERN apparatus



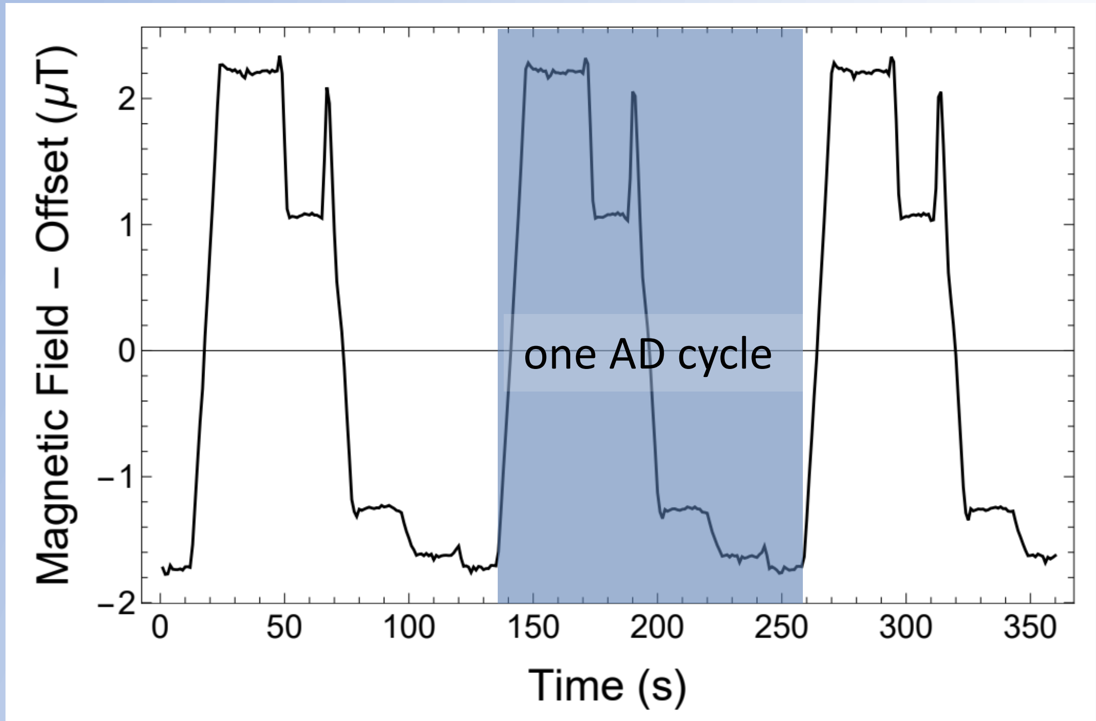
About 45 mins per block,
40 frequency measurements

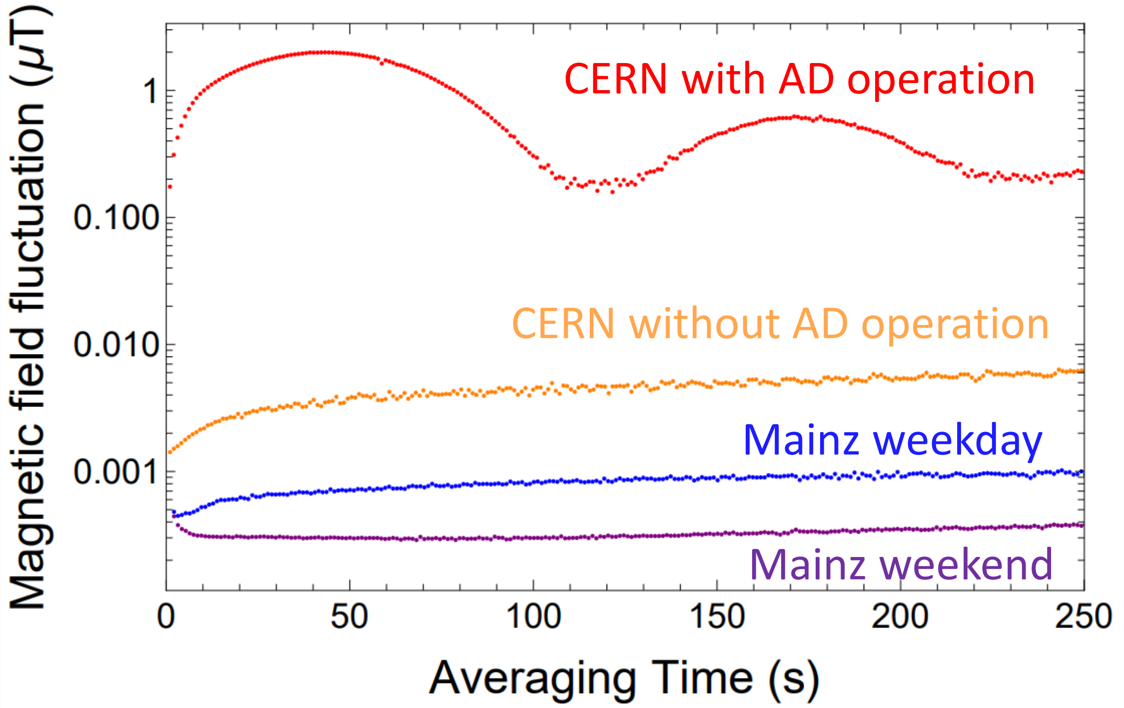
Block stability of cyclotron frequency shifts:

$$\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\nu_{c,2i} - \nu_{c,2i-1}}{\nu_{c,2i}}\right)^2}$$

Limitations by magnetic field fluctuations in the AD/ELENA facility

Antiproton precision measurements are conducted on the inside of a synchrotron (Antiproton decelerator)



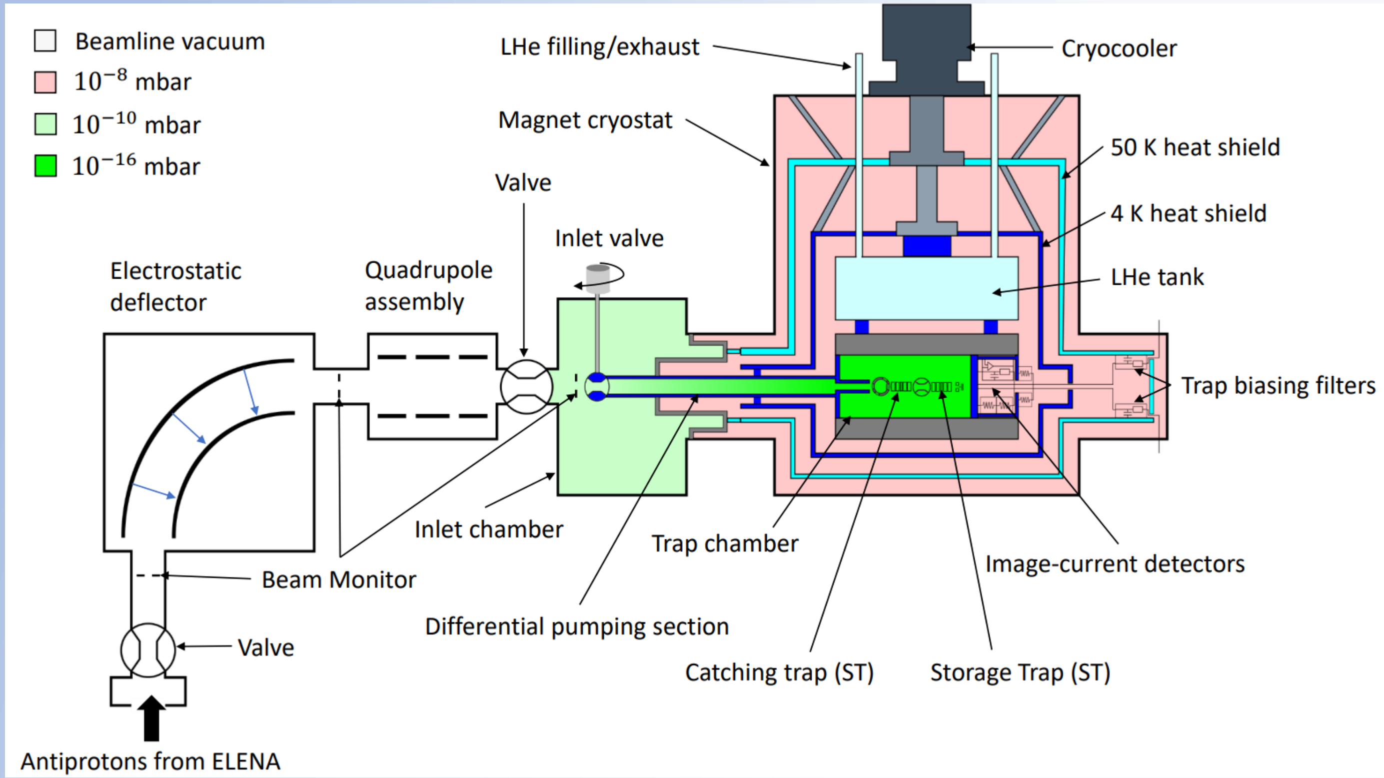


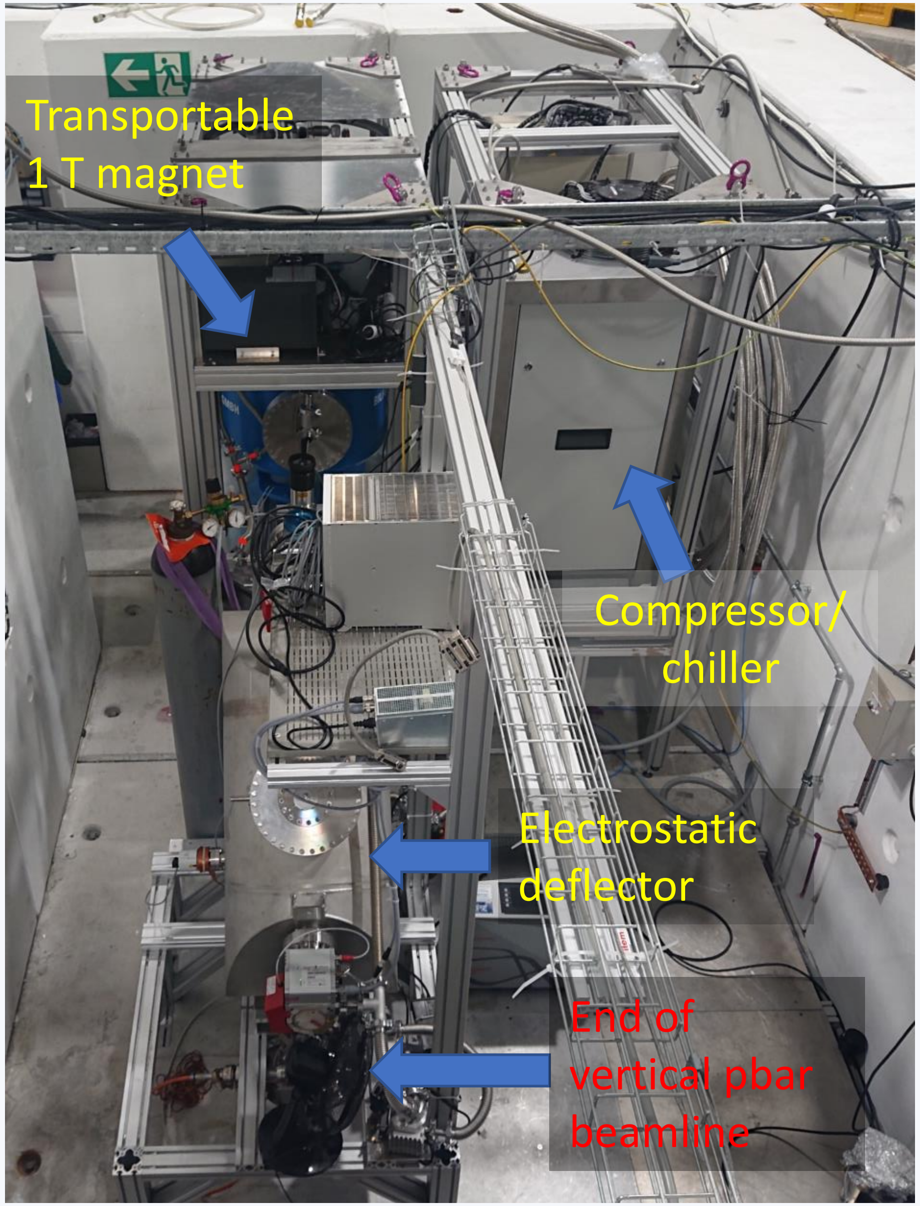
Transportable antiproton trap BASE-STEP

Transportable superconducting magnet (1.0 T) with transport frame (900 kg), movement by trailer and crane

Experimental setup of the transportable trap

Equipment to receive and transport antiprotons





Basis is the reservoir trap system developed in BASE, but:

- The trap system is inside a transportable superconducting magnet
- The trap can has an open injection/ejection channel for antiprotons

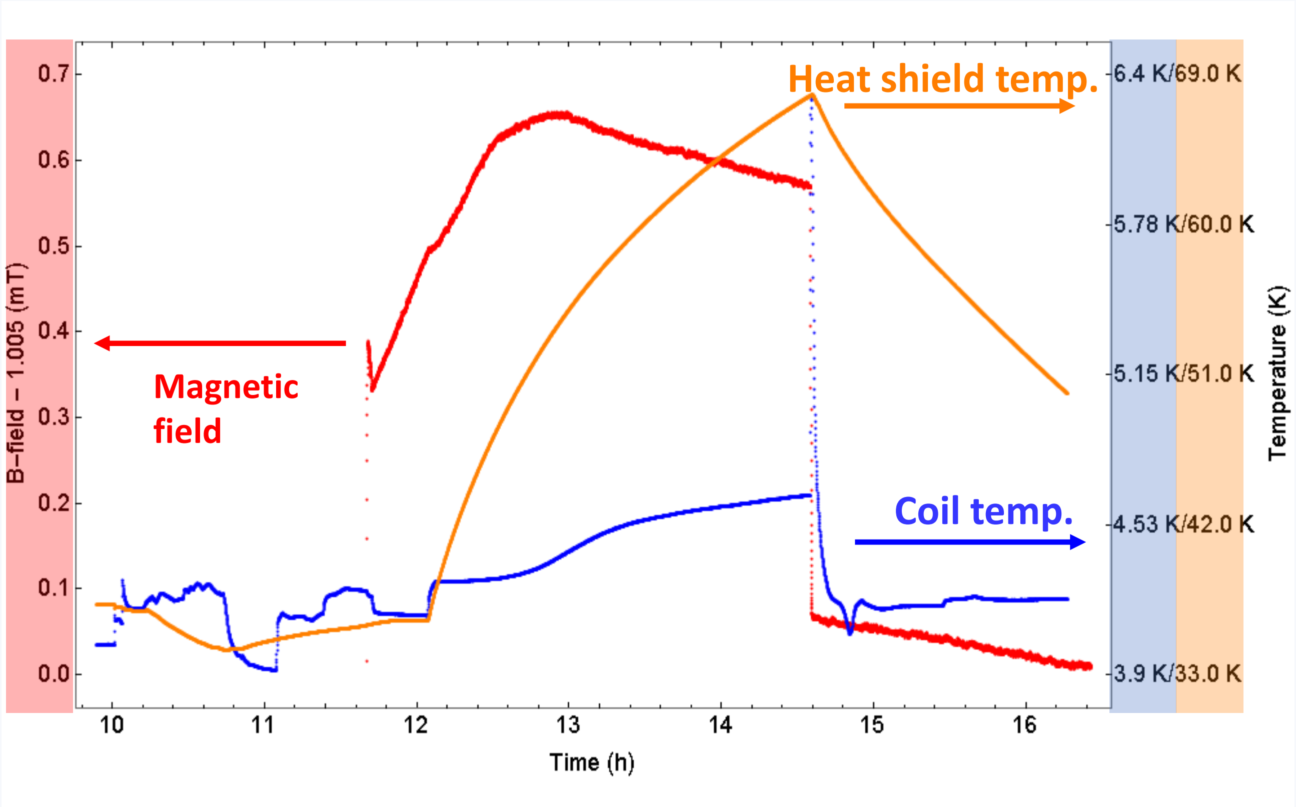
C. Smorra et al., Int. J. Mass Spectr. 389, 10-13 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).

Testing of transport conditions

Operation of the superconducting magnet without power on the cryocooler.

The magnet coil is cooled by liquid helium, and the cryocooler is restarted after 2.5 hours.

Next objective is an actual transport test at CERN of trapped protons within these 2.5 hours.



Measurements using BASE-STEP

BASE-STEP is a transportable antiproton trap, with the goal to supply other precision trap systems.

Other applications with antiprotons having low consumption rate or low reloading frequency are conceivable as application.

	BASE-CERN	State of art (other exp.)	BASE-STEP
Frequency ratio scatter	1700 ppt	50 ppt	50 ppt*
(AD shutdown)	250 ppt – 800 ppt		
Quality measurement time	Nights & weekends in shutdown periods (5 months/year) 15% duty cycle	24/7 100% duty cycle	24/7 100% duty cycle
Number of antiproton precision experiments	1	0	expandable

*by injecting antiprotons into the best state-of-art experiment.

Improvement towards better cooling

Block stability of cyclotron frequency shifts: $\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\nu_{c,2i}-\nu_{c,2i-1}}{\nu_{c,2i}}\right)^2} \sim 5.5$ ppb in 2014

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Cooling of antiprotons

Established methods

- Sympathetic electron cooling

  G. Gabrielse et al. Phys. Rev. Lett. **63**, 1360 (1989).

- Resistive cooling

  G. Gabrielse et al. Phys. Rev. Lett. **63**, 1360 (1989).
  C. Smorra et al. Eur. Phys. J. ST **224**, 3055-3108 (2015).

Temperature limit: 4.2 K

Cooling methods with lower temperature limits

- Direct laser cooling (not possible)
- Sympathetic cooling by a co-trapped laser-cooled ion (not established)

  A. Kellerbauer and J. Walz, New J. Phys. **8**, 45 (2006).
  P. Yzombard et al., Phys. Rev. Lett. **114**, 213001 (2015).

- **Sympathetic cooling using a coupled oscillator system**

  D.J. Heinzen and D.J. Wineland, Phys. Rev. A **42**, 2977 (1990).

  - Co-trapped ions – widely applied in RF-traps

    e.g.: S. M. Brewer et al., Phys. Rev. Lett. **123**, 033201 (2019)

  - Separate potential wells - demonstrated in RF-traps

    K.R. Brown et al., Nature **471**, 196 (2011).
    M. Harlander et al., Nature **471**, 200 (2011).

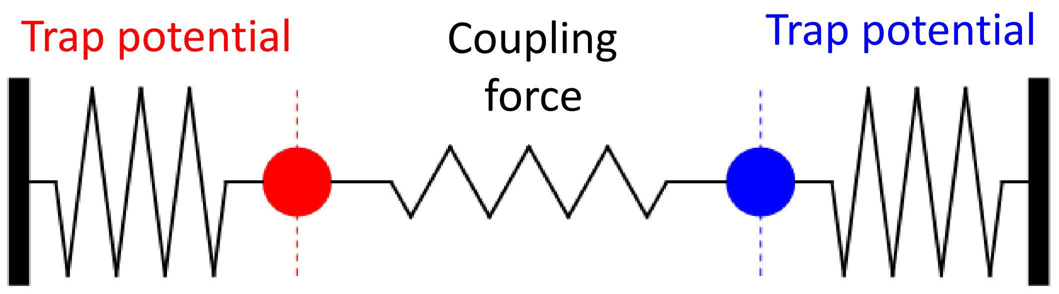
  - Coulomb coupling in Penning traps

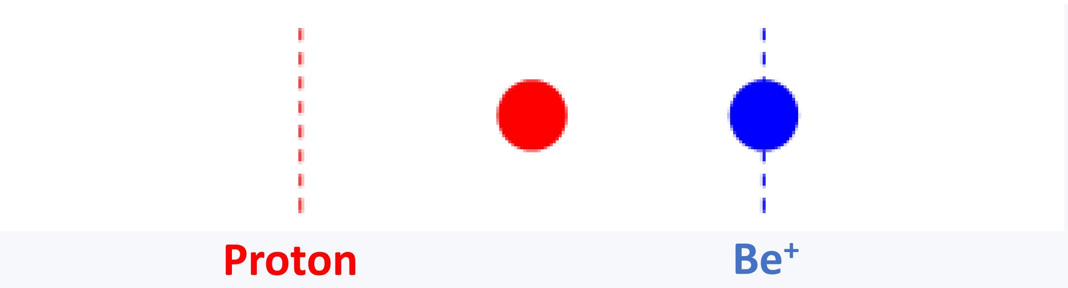
    - J. M. Cornejo et al., New J. Phys. **23** 073045 (2021).

  - **Image-current coupling in Penning traps**

    M. Bohman et al., Nature **596**, 514–518 (2021).

Form coupled harmonic oscillators:





Apply laser cooling to one oscillator:

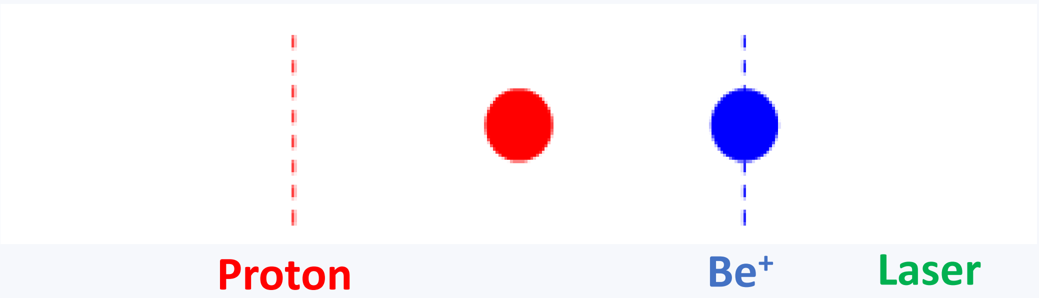
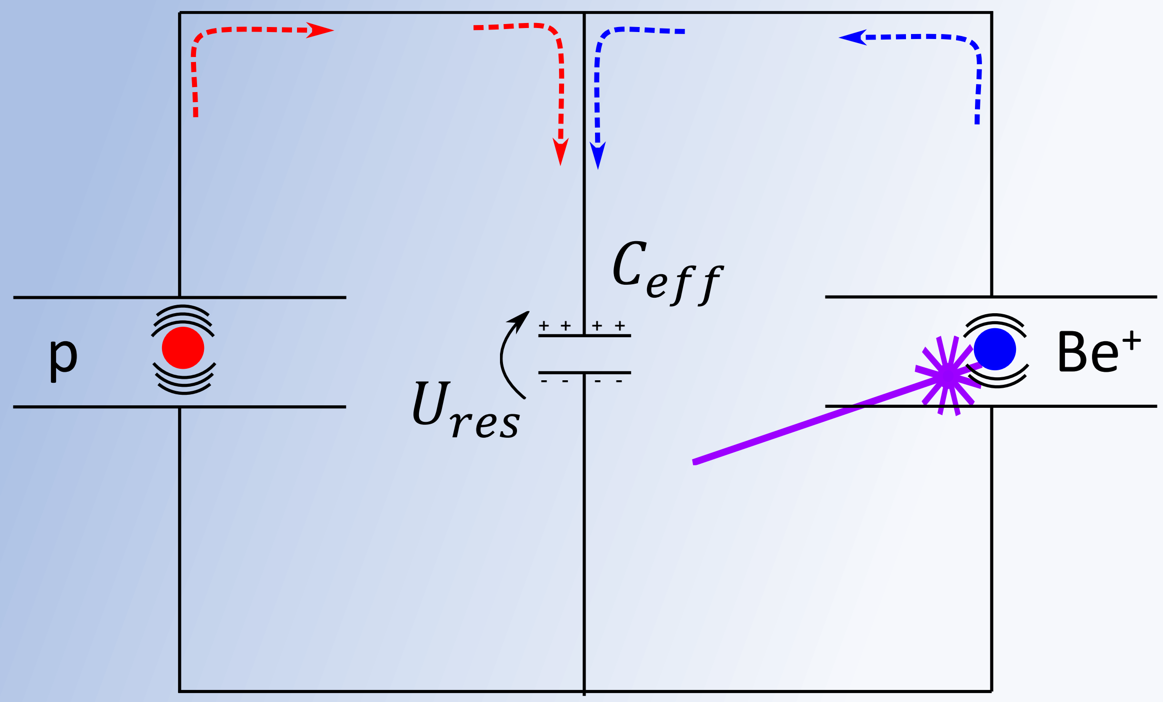
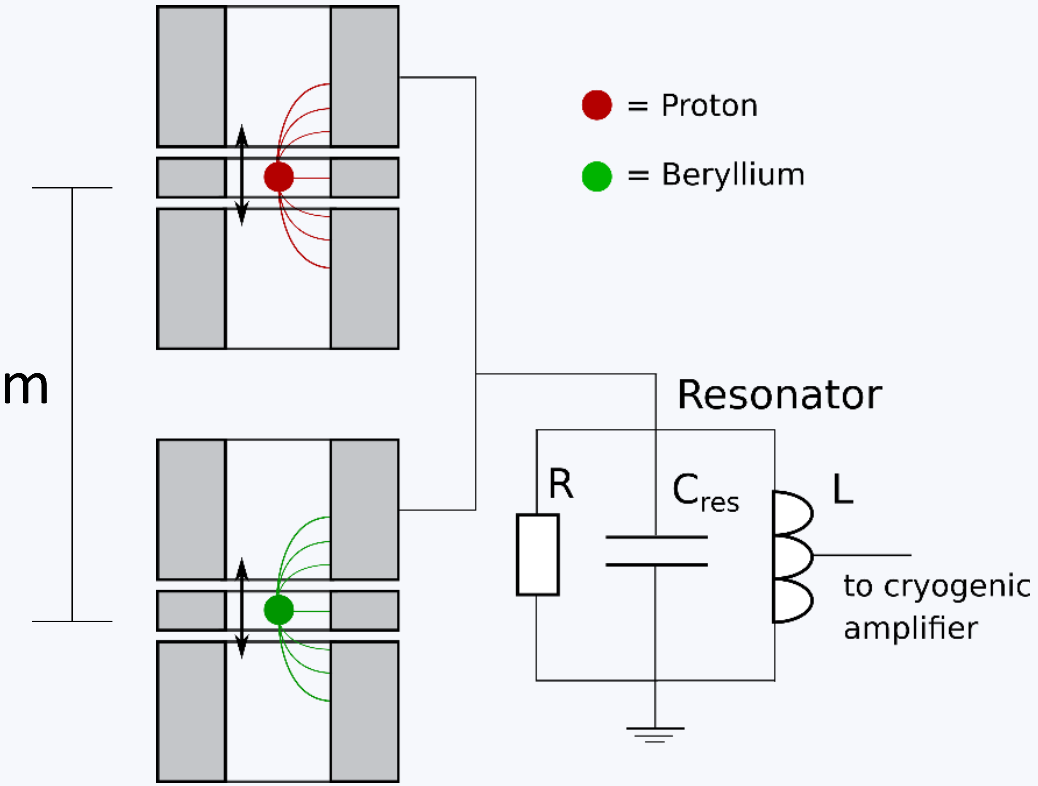


Image-current coupling in Penning traps



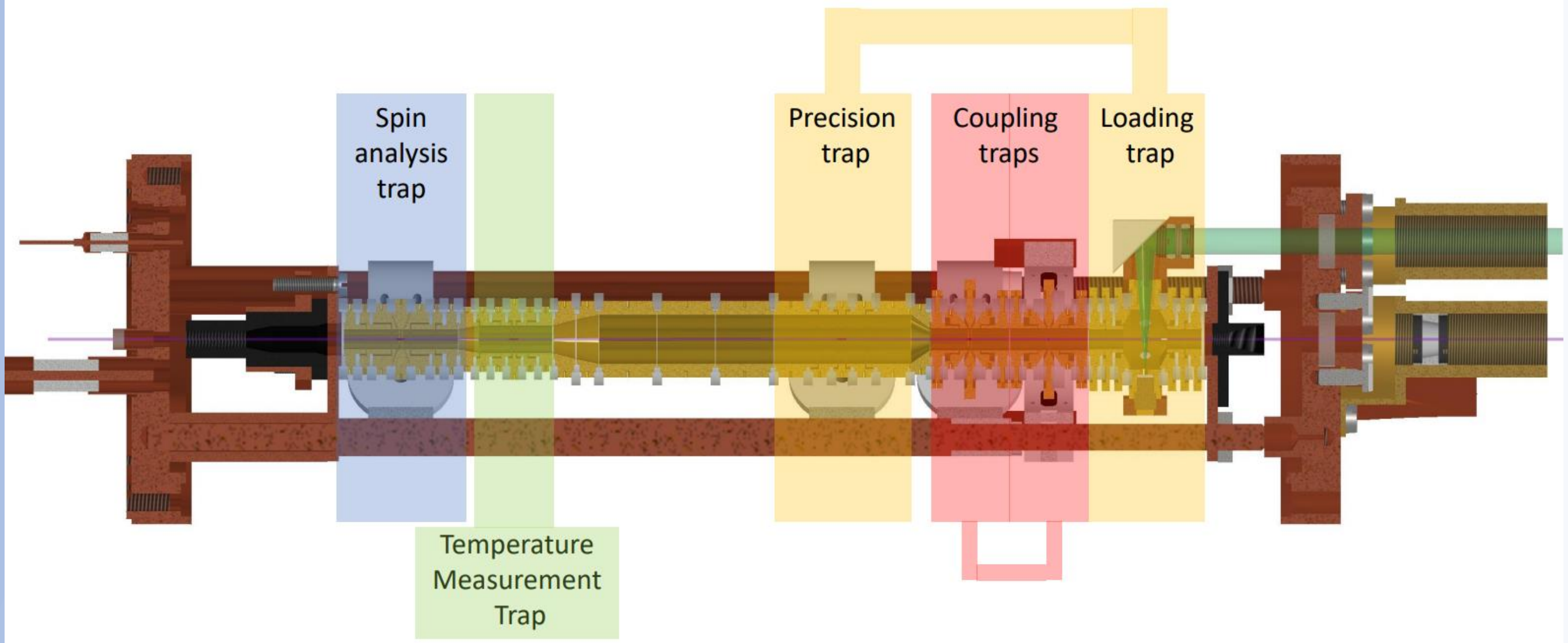
≈10 cm

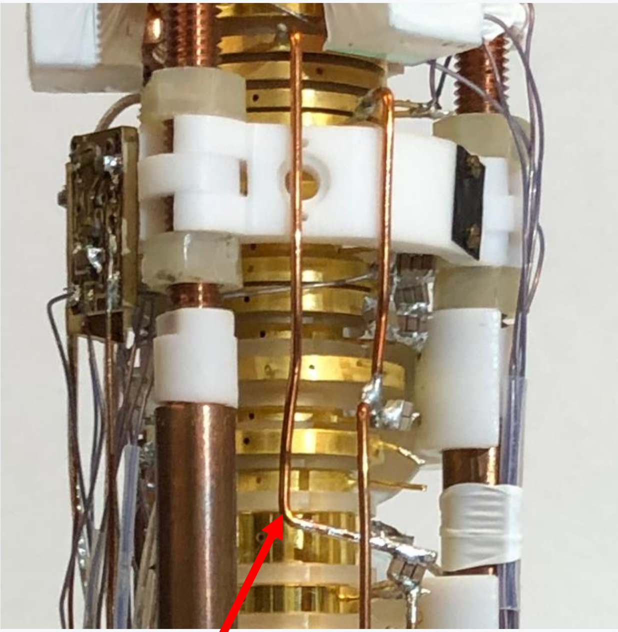


$$C_{eff} = Im\left(\frac{1}{Z_{RLC}}\right)/\omega \approx 10^{-2}\text{pF close to resonance!}$$

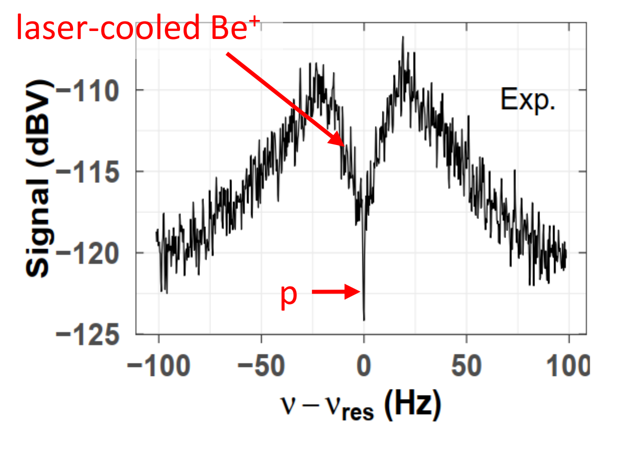
Compared to $\approx 5\,\text{pF}$ for an optimized common trap electrode.

A trap system for image-current coupling





"Transmission line" for laser cooling



Demonstration of sympathetic cooling mediated by the LC-circuit

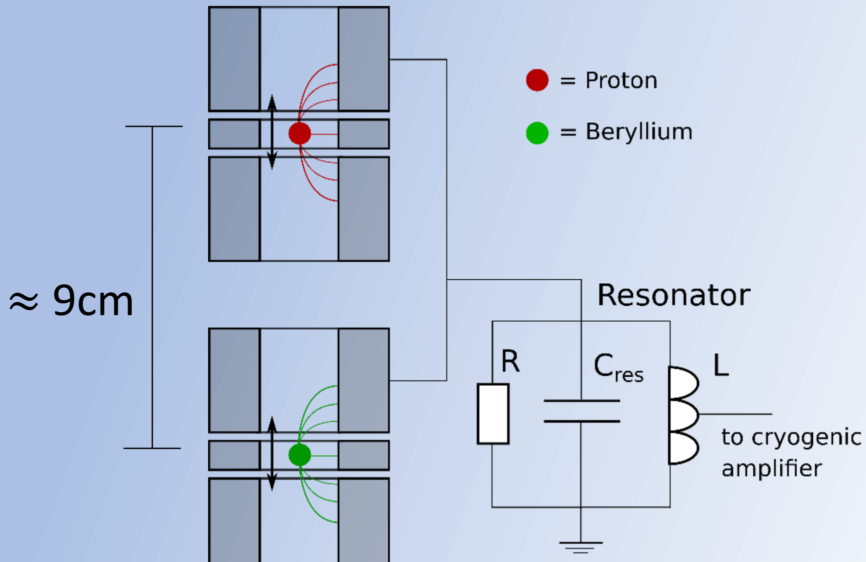
First demonstration of image-current coupling

M. Bohman et al., Nature **596**, 514–518 (2021).

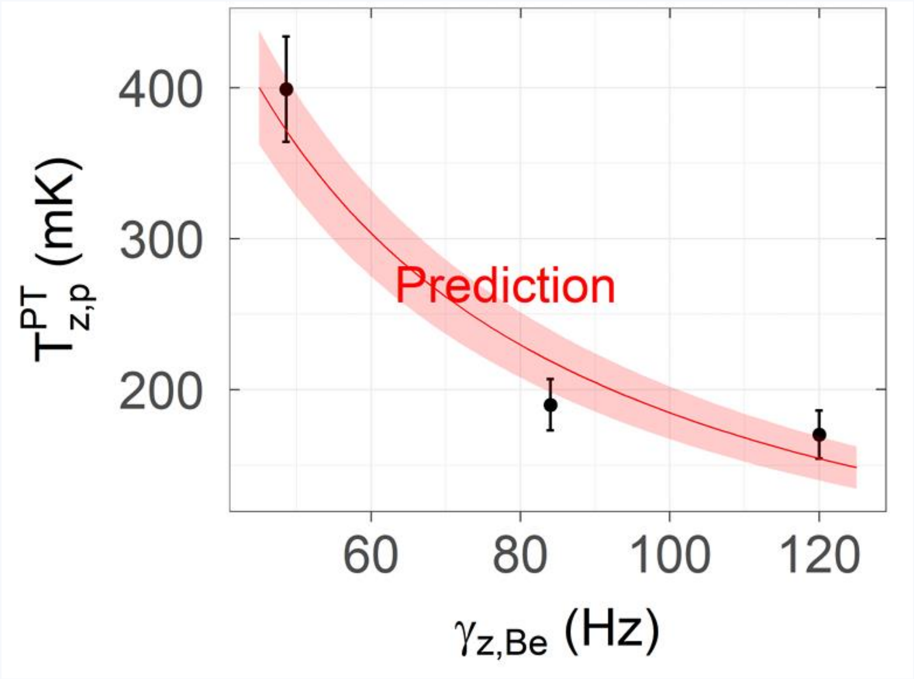
New temperature measurement trap
New loading trap
Improved image-current detectors
Silicon photomultipliers for fluorescence detection

M.Wiesinger et al., *Rev. Sci. Instrum.* 94, 123202 (2023).

Current status of cooling measurements



$$T_p = \frac{1}{1 + \frac{\gamma_{Be}}{\gamma_p}} T_{RLC}$$



Common mode of proton and Be ions interacts with the LC circuit and with environment
All other coupled proton and Be ion modes are at laser cooling temperatures

Lower temperature by using larger beryllium clouds (higher γ_{Be}).
Temperature limited by the frequency stability of the Be cloud.

Cooling of a single proton to 170 mK will be reported soon.

C. Will et al., arXiv:2310.10208 (2023).
C. Will et al., Phys. Rev. Lett., accepted (2024).

Simulations show that cooling to 10 mK is feasible.

B. Tu et al., PRX Quantum (2021), C. Will et al., New J. Physics (2022)

Christian Will (MPIK)

Dr. Peter Micke (MPIK/GSI)

Hüseyin Yildiz (JGU Mainz)

Current status: Sympathetic cooling of H_2^+

H_2^+

Preliminary data

Please contact me if you need to view the preliminary figures again.

Sympathetic image-current cooling of a molecular ion

Be^+ cloud needs better cooling to advance (axial + radial laser, RW)

Coupling without LC circuit requires ultra-stable voltages (~mV)

Separation of the ionization region and the measurement region is required to avoid patch potential changes.

Hüseyin Yildiz
(JGU Mainz)

Thank you for your attention!

Upcoming:

- New (anti-)proton g-factor data from BASE-CERN
- New temperature limit from image-current coupling
- Start-up of the BASE-STEP trap system at CERN
- Transport tests of the transportable trap system

…measurements on ultra-cold antiprotons in a magnetically calm laboratory!

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