A roadmap for proton-antiproton precision measurements

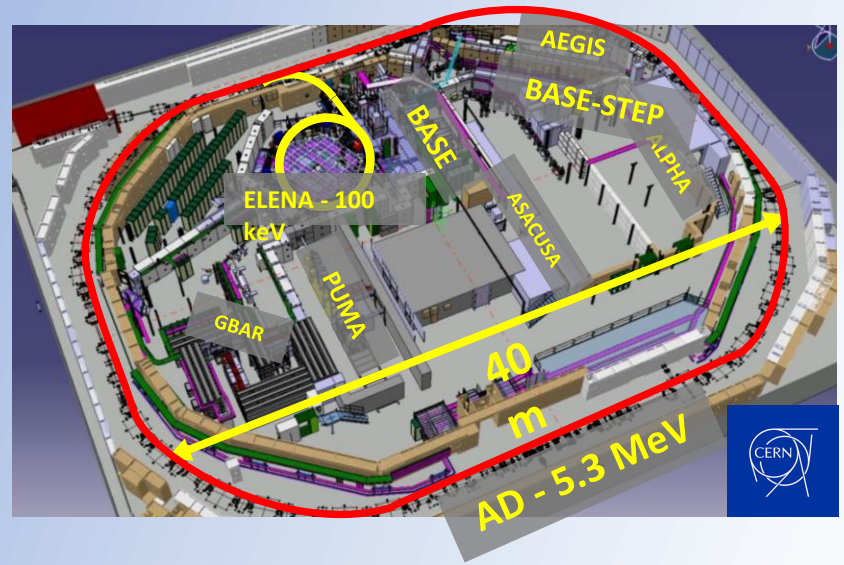
ECTI - 7th European Conference on Trapped Ions

Schloss Bückeburg - 26.09.2023

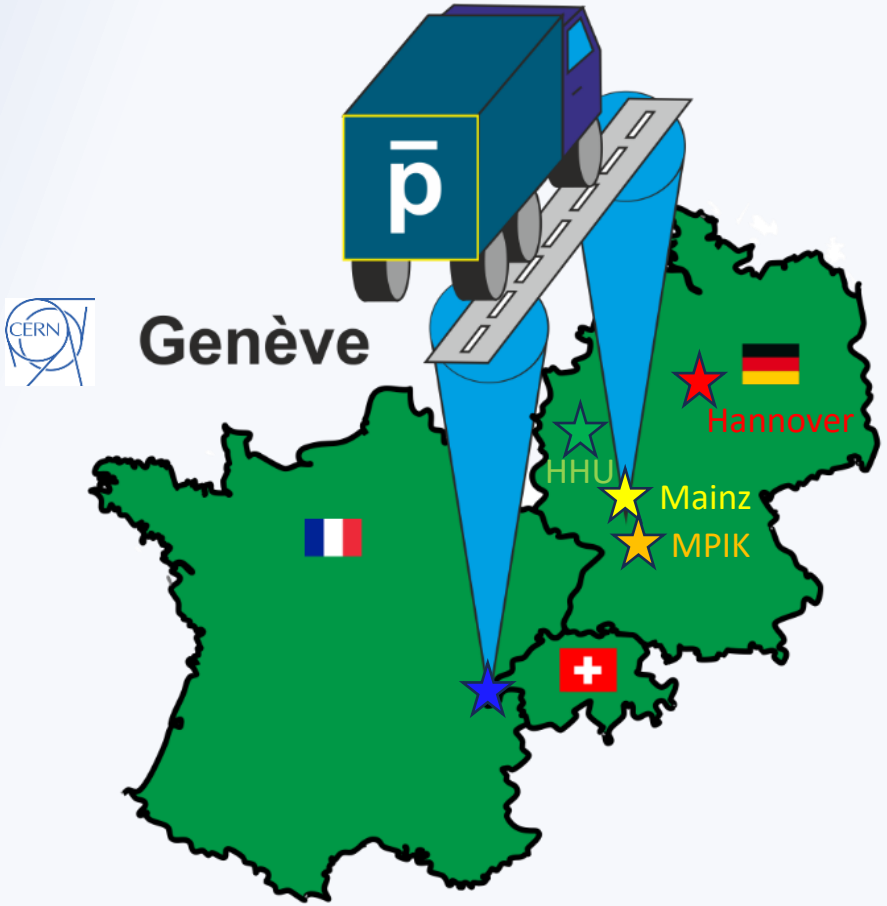
Dr. Christian Smorra on behalf of the BASE collaboration

Johannes Gutenberg University Mainz

The roadmap for antiprotons…



High precision

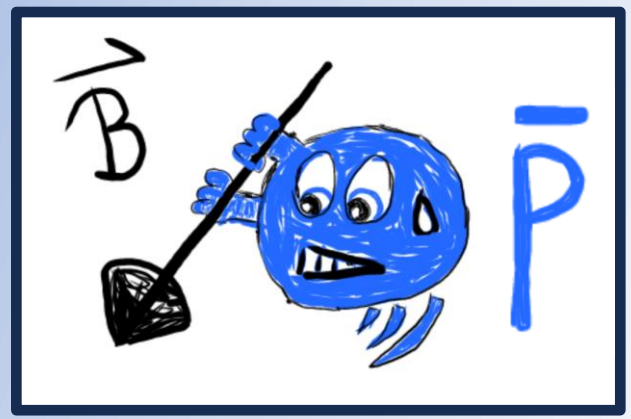


Millicharged particle search

D. Budker et al., PRX Quantum 3, 010330 (2022).
C. Smorra et al., arXiv:2304.09555 (2023).

The main actors…

The single trapped (anti-)proton in the ion cage



A coupled harmonic oscillator

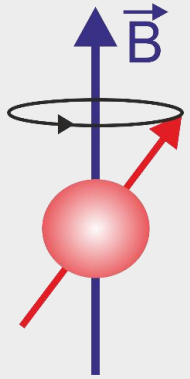
…but with trapped ions

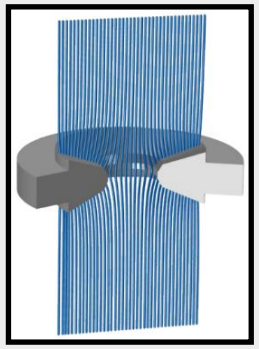
A transportable magnet

…but superconducting

Precision measurements on single trapped protons/antiprotons

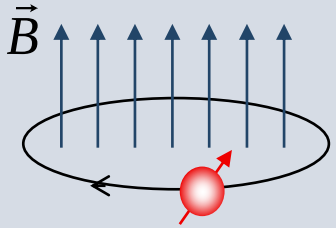
Larmor Frequency

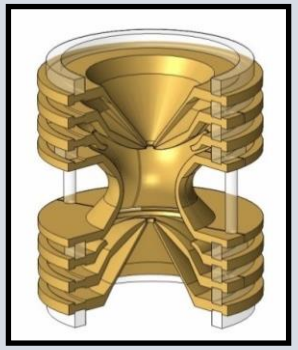




$$\omega_L = g\frac{e}{2m_p}B$$

Cyclotron Frequency





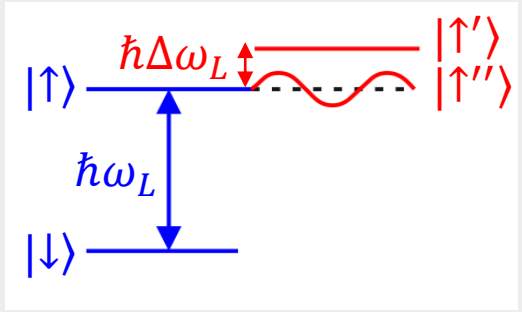
$$\omega_c = \frac{q}{m}B$$

$$\frac{\omega_{L,p/\bar{p}}}{\omega_{c,p/\bar{p}}} = \frac{g_{p/\bar{p}}}{2} = \pm\frac{\mu_{p/\bar{p}}}{\mu_N} \qquad \frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

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).

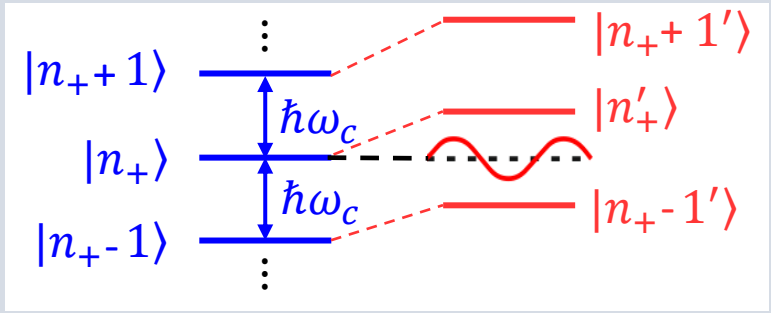
Precision measurements…with new physics?

Larmor Frequency modifications



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

Cyclotron Frequency modifications



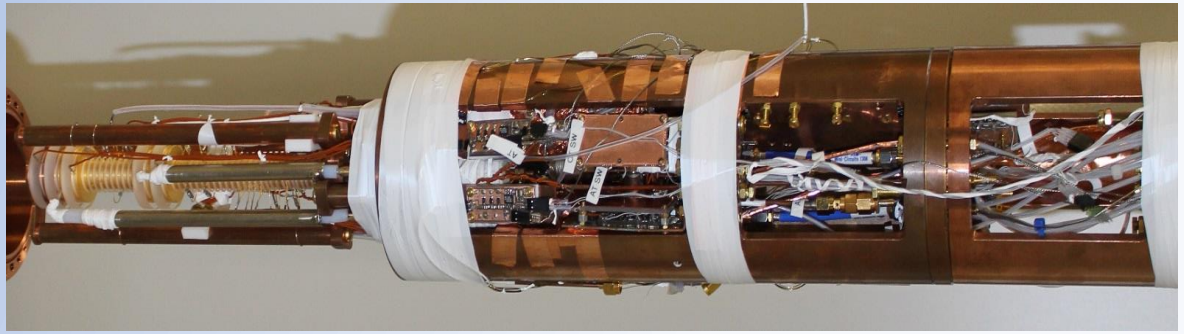
Lorentz and CPT-violation
Antiproton gravitation anomalies

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

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

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 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).

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 (about 22 mins for 100 mK)
- Nuclear spin state detection of single protons/antiprotons

C. Smorra et al., Eur. Phys. J. 225, 1-53 (2015).
S. Ulmer et al., CERN Document Server, CERN-SPSC-2023-003 (2023).

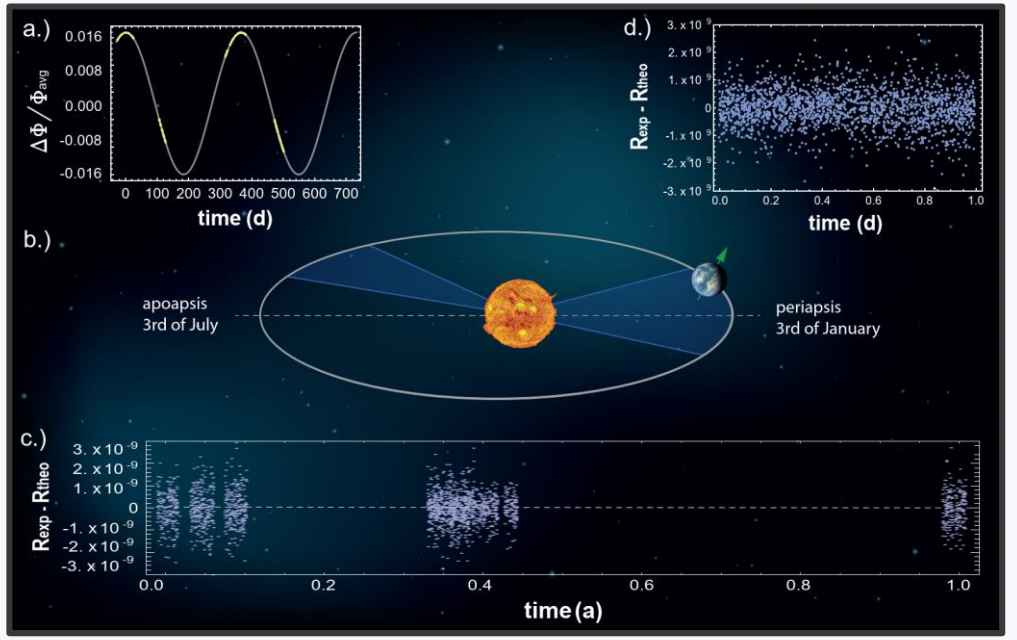
Recent results of BASE-CERN

Improved comparison of the proton/antiproton q/m ratios:

$$\left(\frac{q_{\bar{p}}}{m_{\bar{p}}}\right) / \left(\frac{q_p}{m_p}\right) = -1.000\,000\,000\,003\,(16)$$

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

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

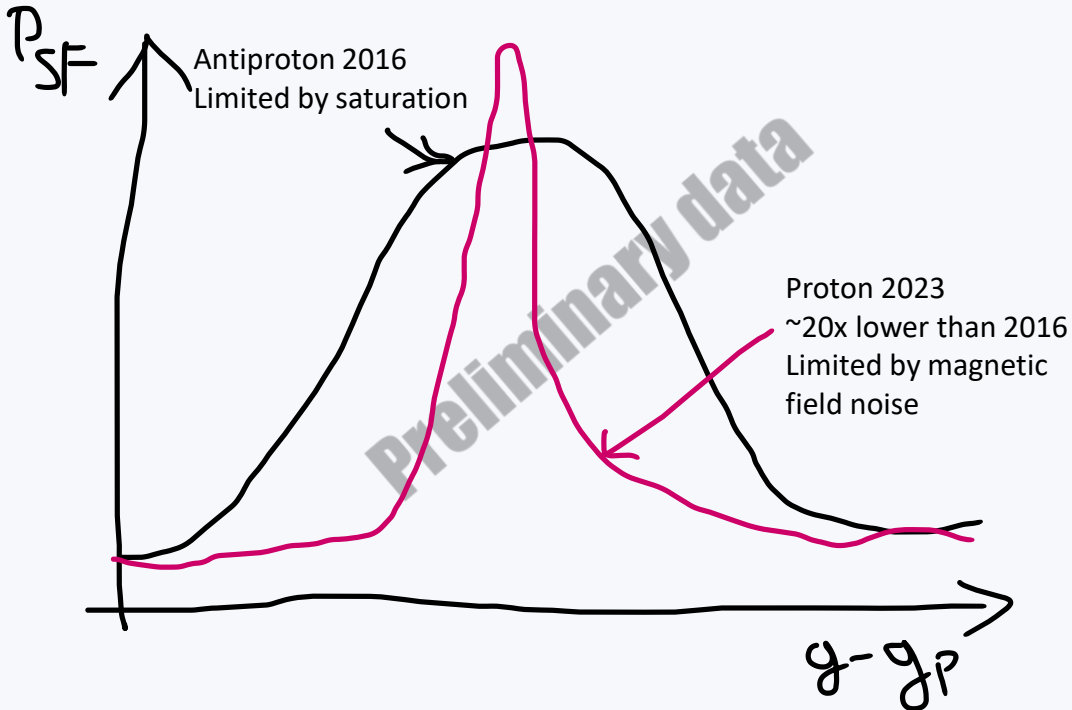


M. Borchert et al., Nature **601**, 53–57 (2022).

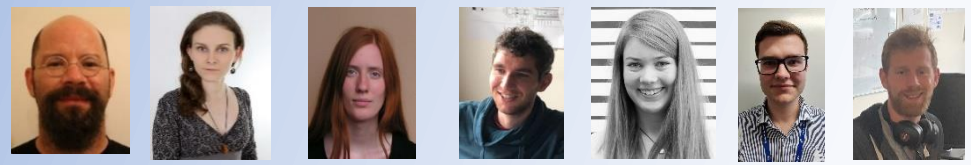
Comparison of the proton/antiproton magnetic moments:

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

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



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



… (Ulmer, Latacz et al.)

- Linewidth reduced by zeroing the quadratic magnetic field gradient
- Observation of spin transitions with a coherent component

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**

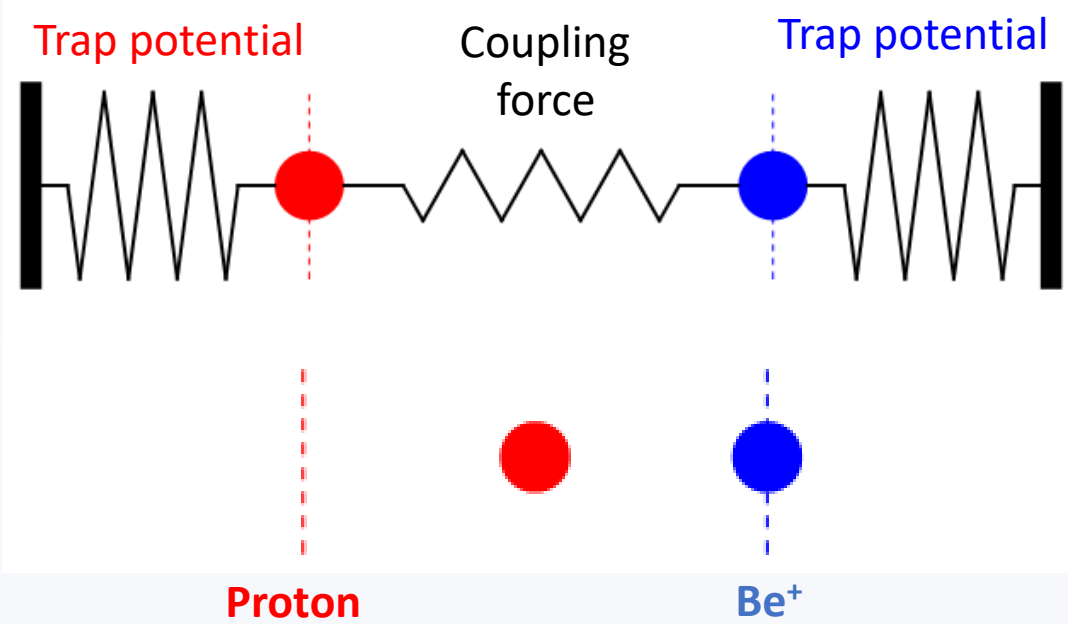
  D.J. Heinzen and D.J. Wineland, Phys. Rev. A **42**, 2977 (1990).
  - Co-trapped ions – widely applied in RF-traps

    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:

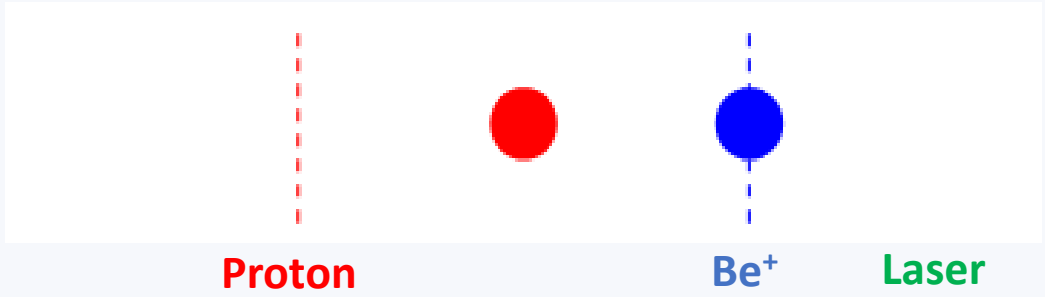
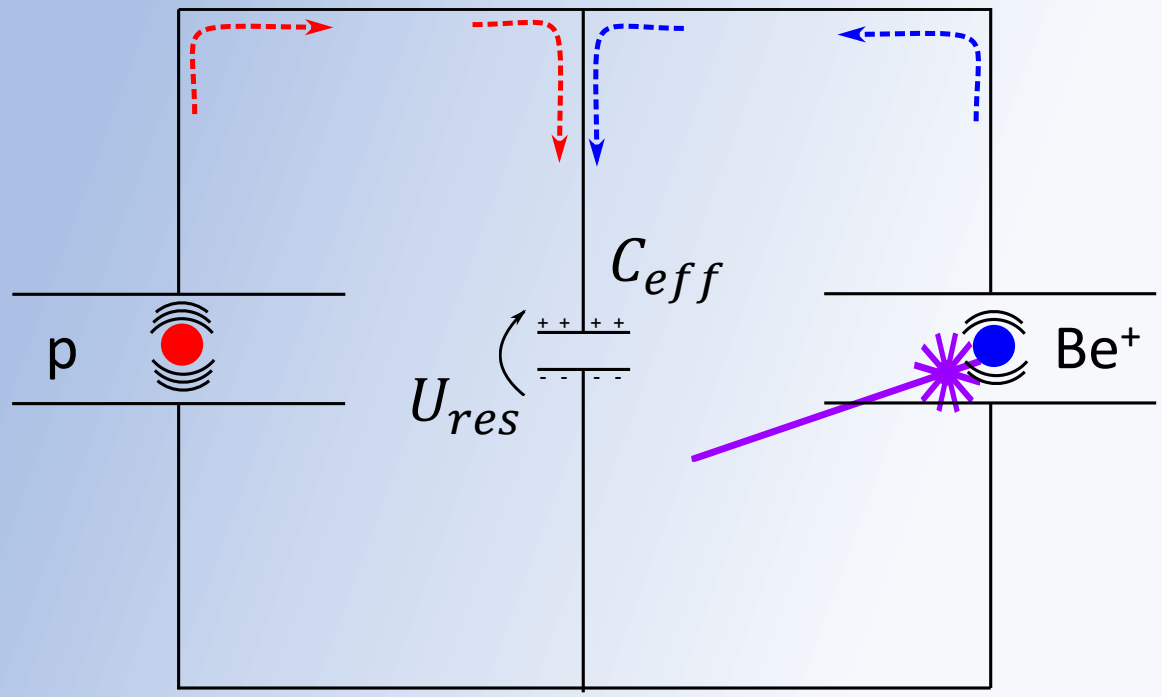
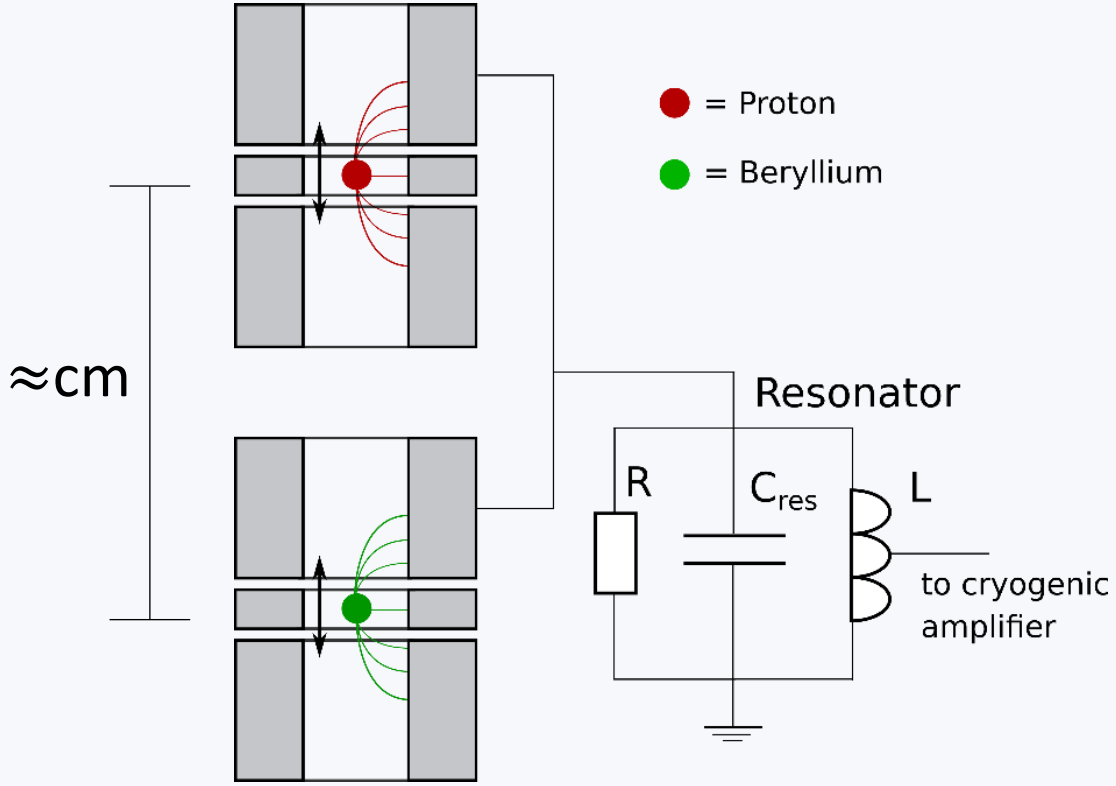


Image-current coupling in Penning traps

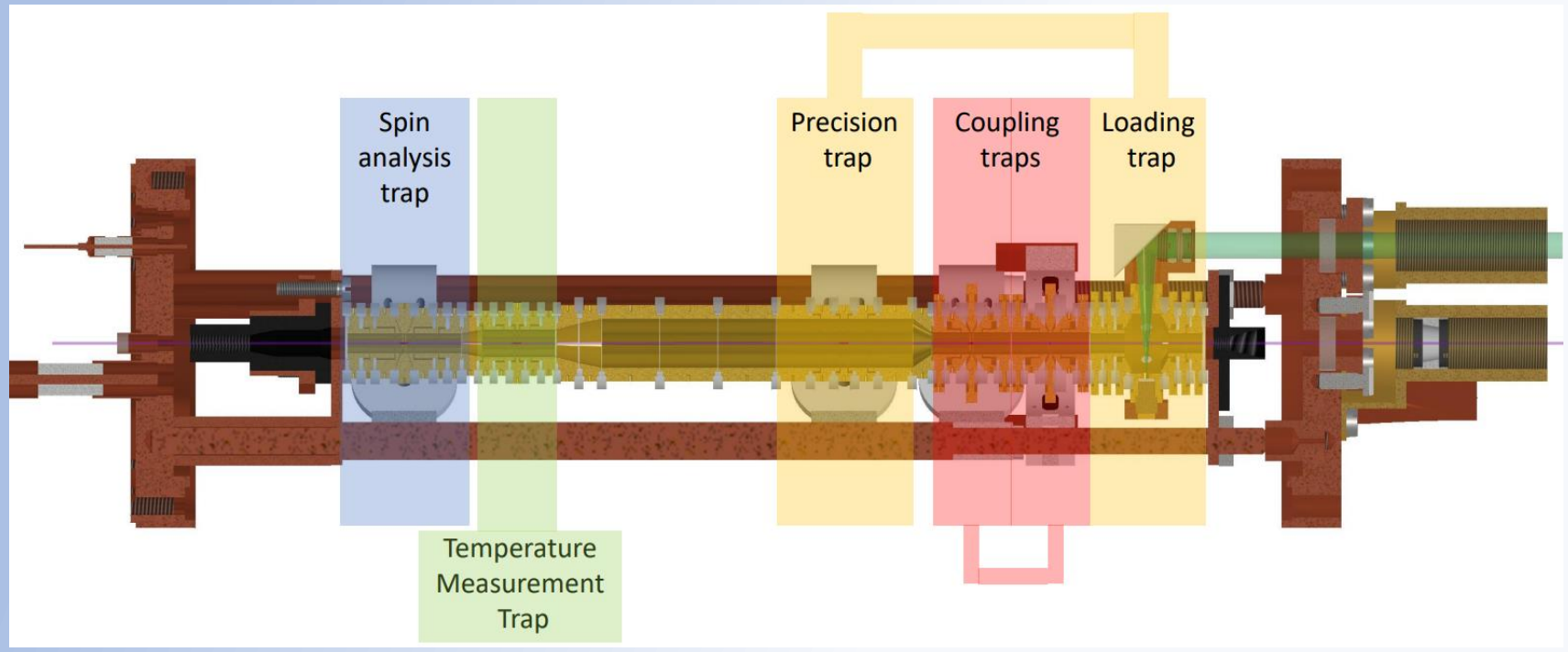


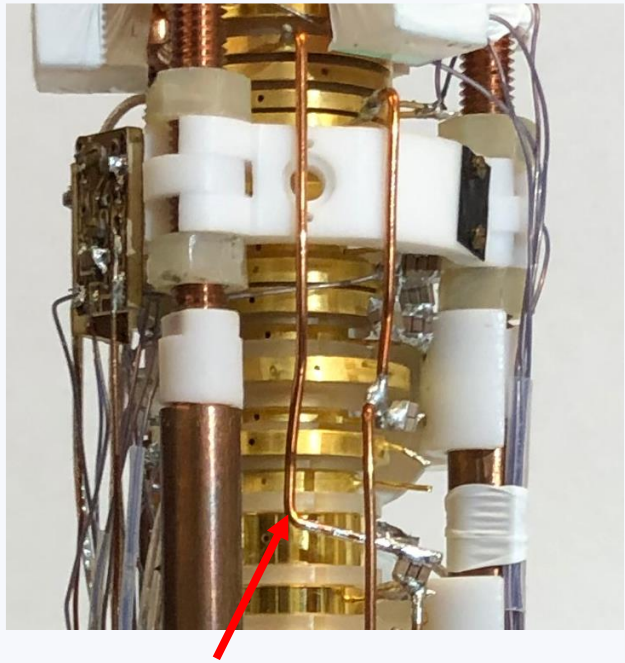


$$C_{eff} = Im\left(\frac{1}{Z_{RLC}}\right)/\omega \approx 10^{-2}\text{pF close to resonance!}$$

Compared to ≈ 5 pF for an optimized common trap electrode.

A trap system for image-current coupling





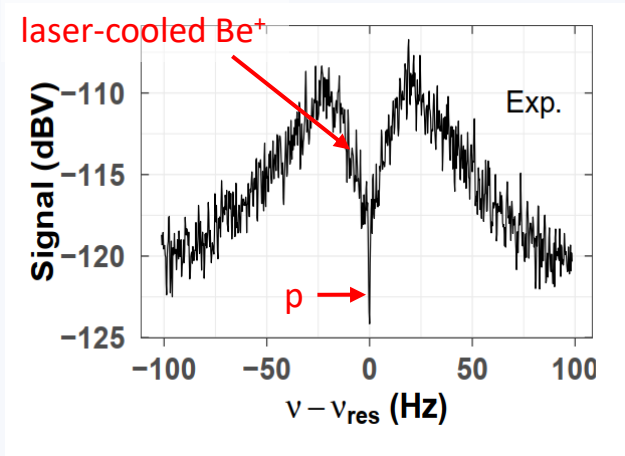
"Transmission line" for laser cooling

First demonstration of image-current coupling

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

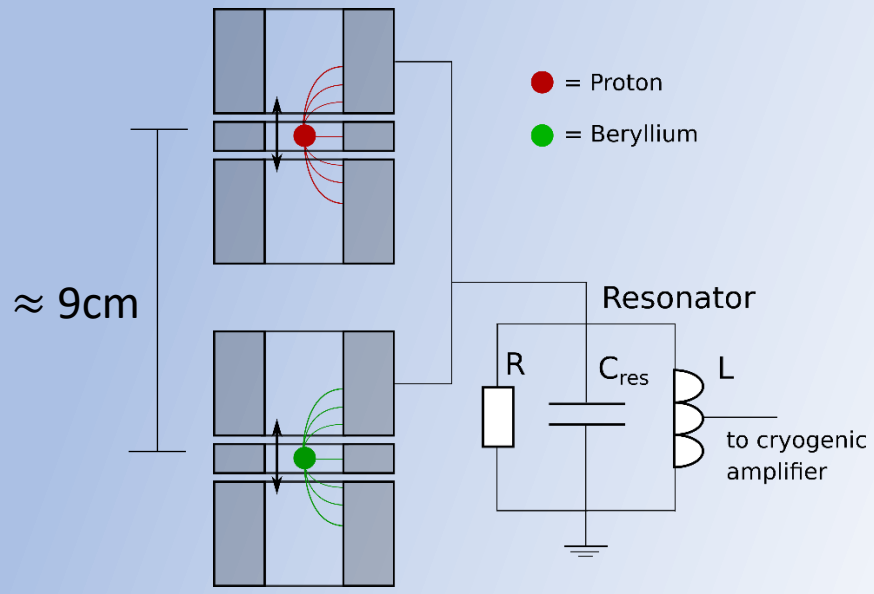
New temperature measurement trap
New loading trap
Improved image-current detectors
Silicon photomultipliers for fluorescence detection

M.Wiesinger et al., arXiv:2308.02365.

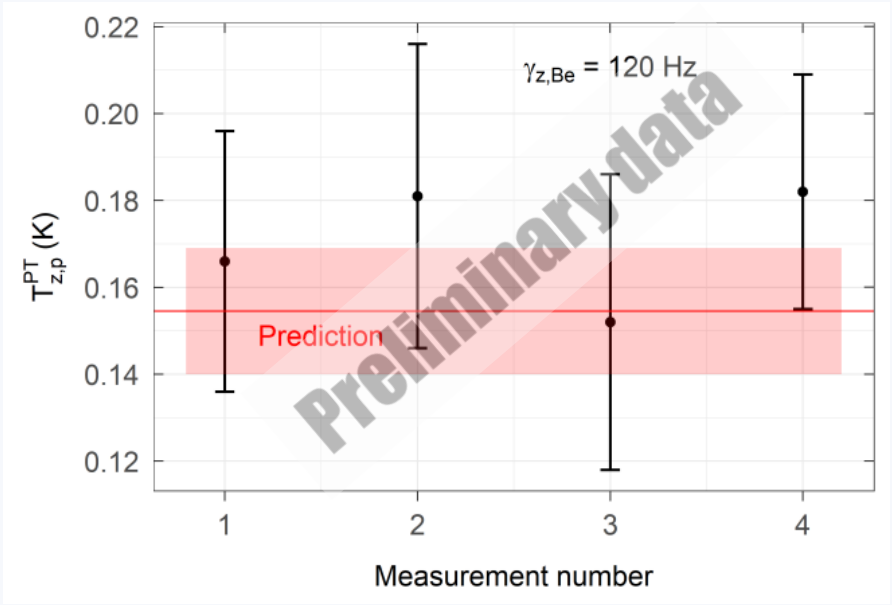


Demonstration of sympathetic cooling mediated by the LC-circuit

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 to 170 mK will be reported soon.

Simulations show that cooling to 10 mK is feasible.

C. Will et al., manuscript in preparation (2023).

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

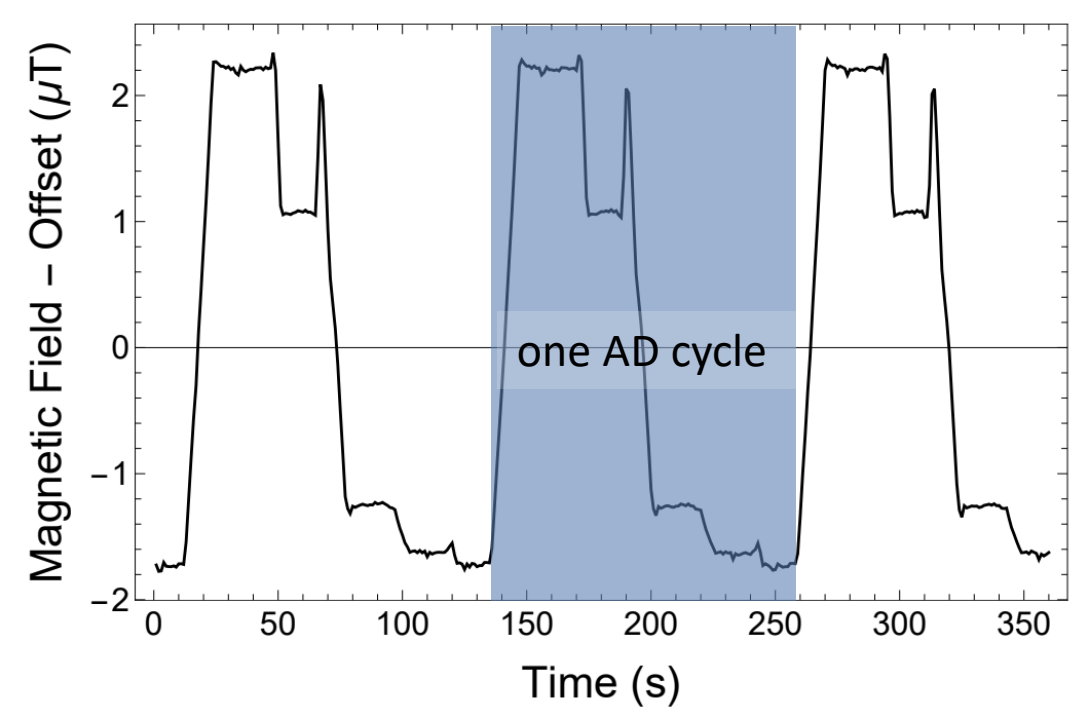
Christian Will (MPIK)

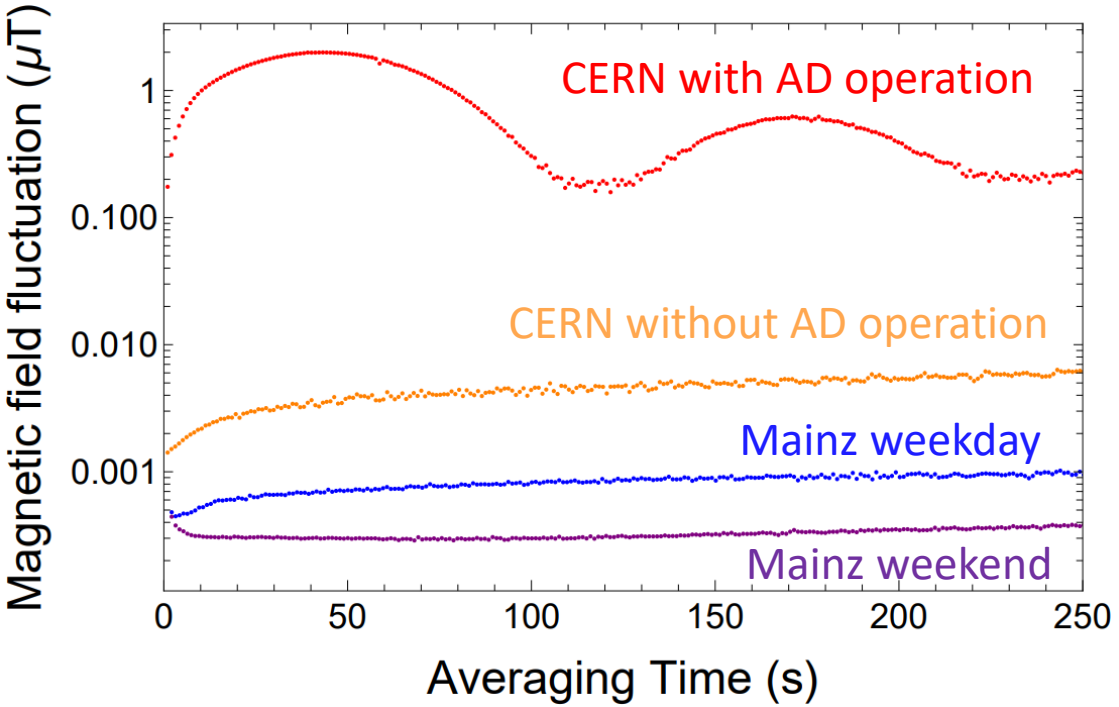
Dr. Peter Micke (MPIK/GSI)

Hüseyin Yildiz (JGU Mainz)

Limitations by magnetic field fluctuations in the AD/ELENA facility

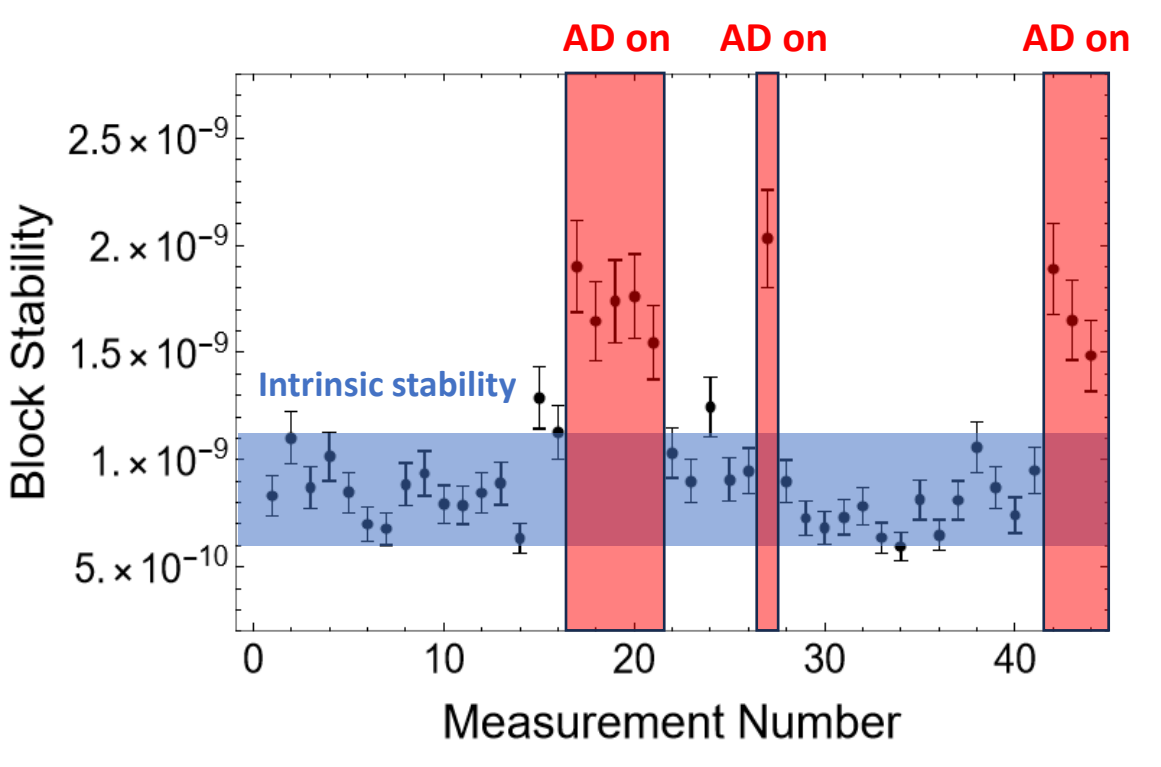
Antiproton precision measurements are conducted on the inside of a synchrotron (Antiproton decelerator)





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:

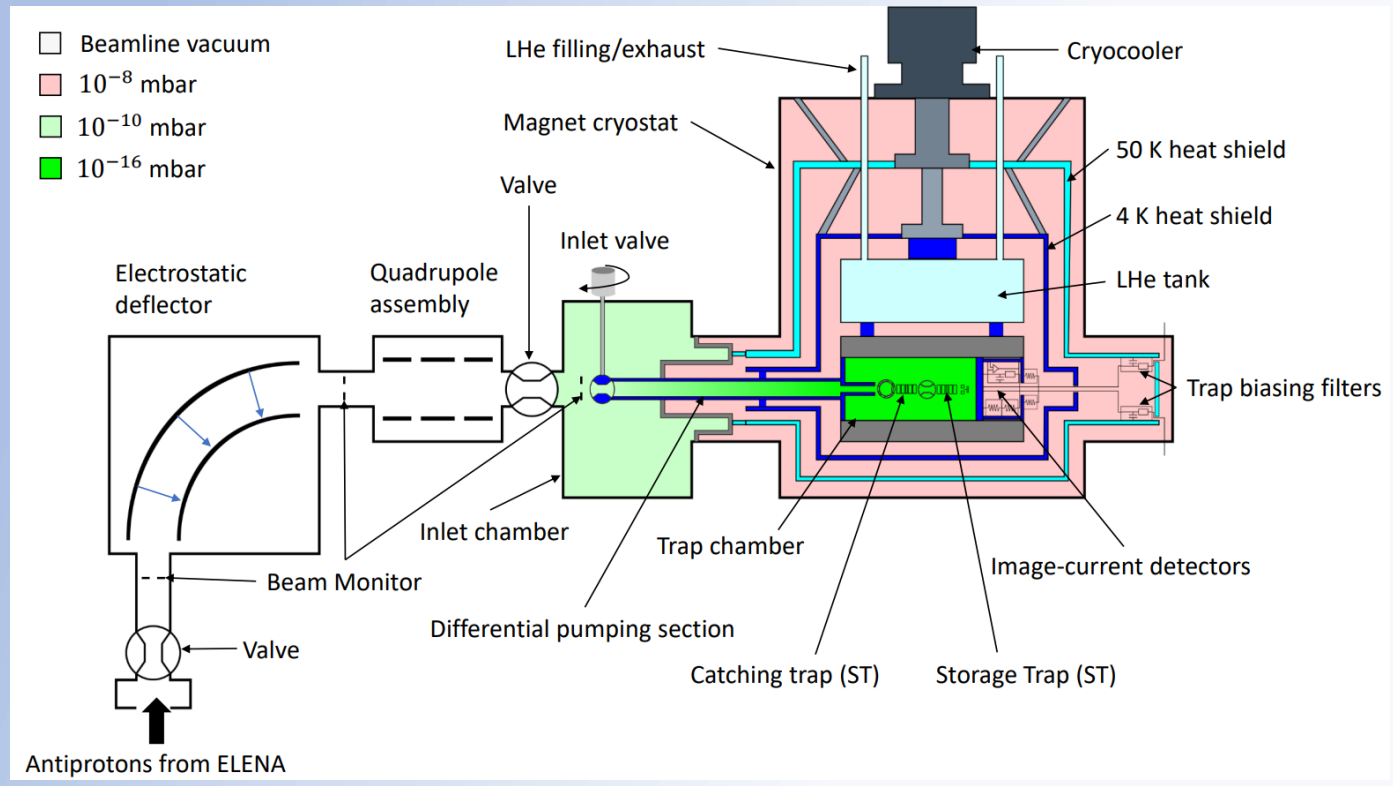
$$\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\nu_{c,2i} - \nu_{c,2i-1}}{\nu_{c,2i}}\right)^2}$$

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

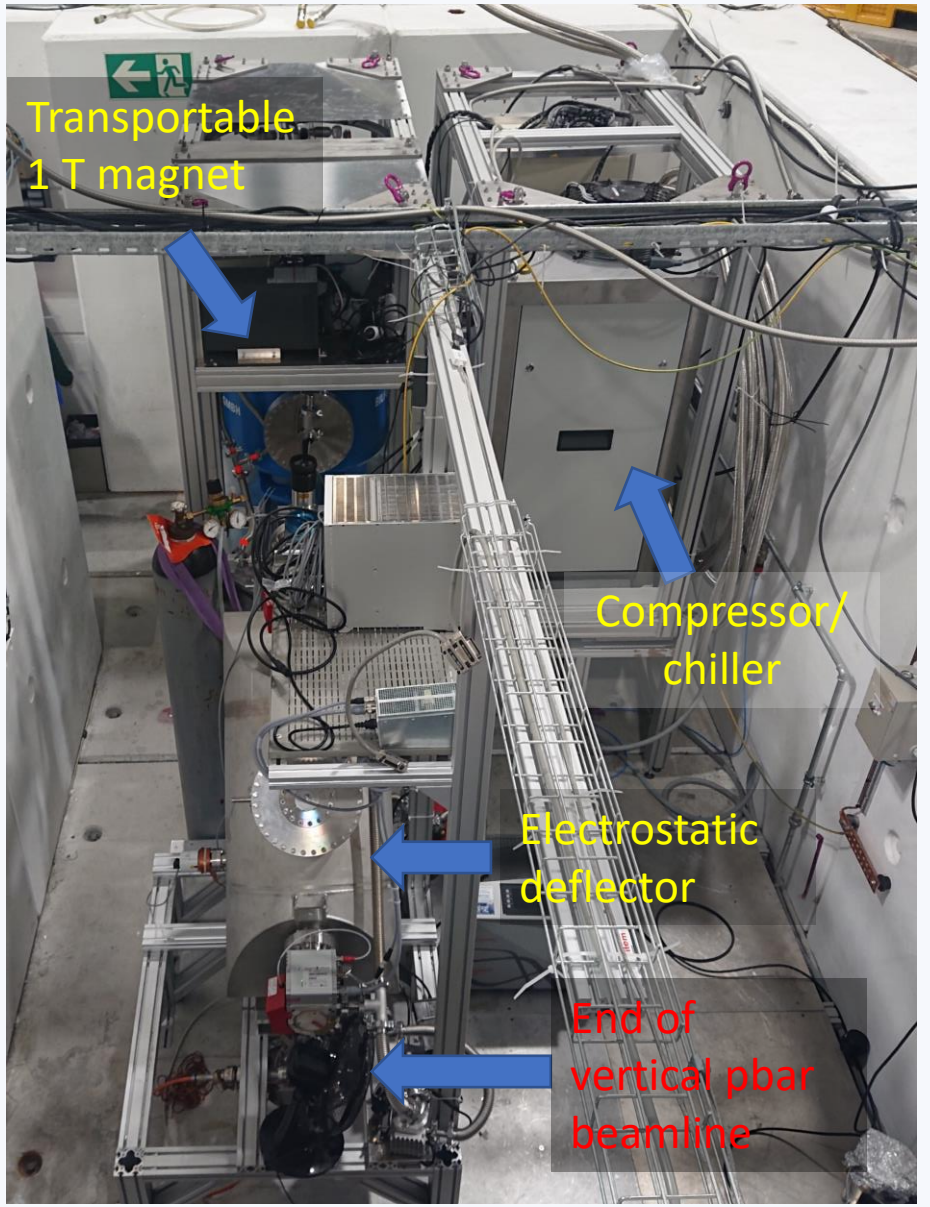


Basis is the reservoir trap system developed in BASE, but:

- 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).

BASE-STEP in the Antimatter Factory

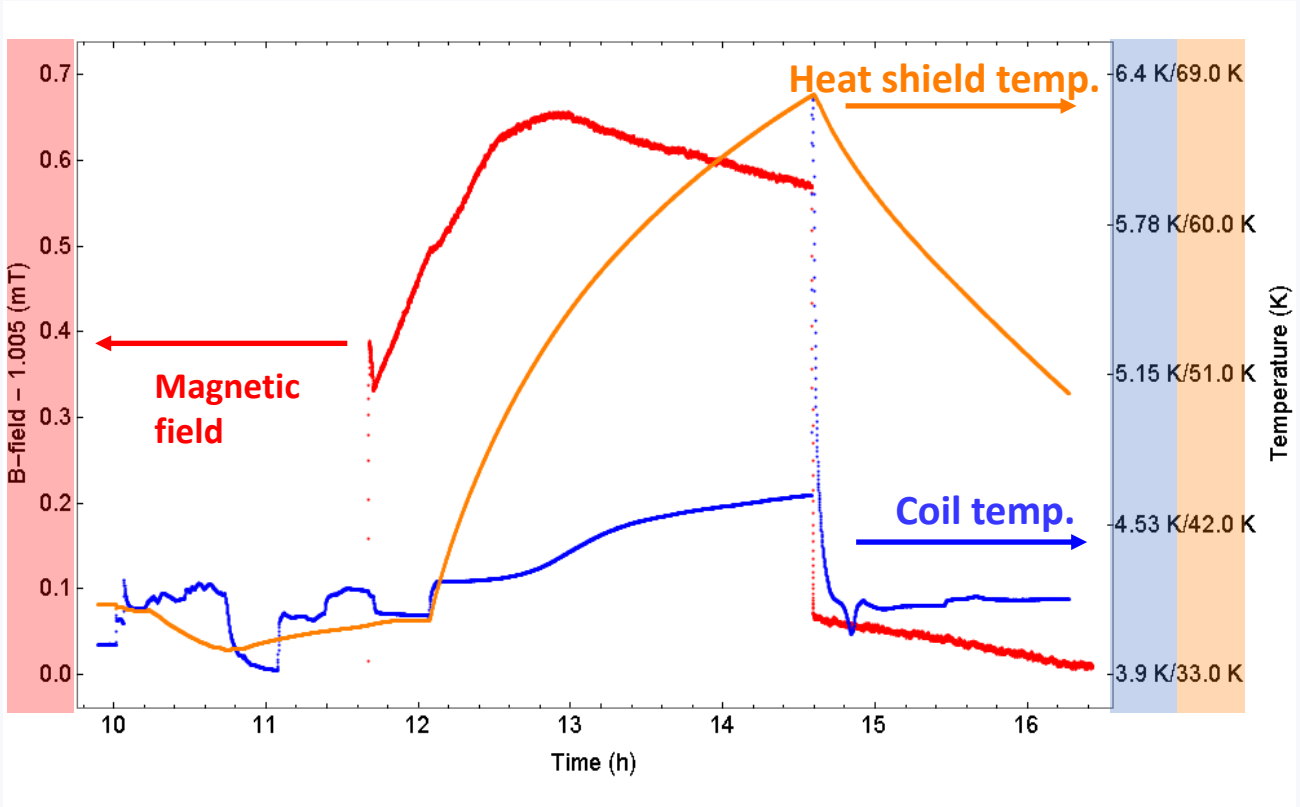


Testing of transport conditions

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.

An actual transport test (tour at CERN) will be conducted after the installation of the trap system is finished.



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 – 400 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.

European Research Council
Established by the European Commission

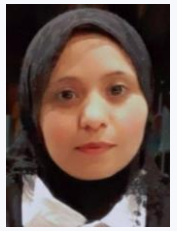
Thank you for your attention!

Upcoming:

- New 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!

BASE – STEP:



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B.M. Latacz
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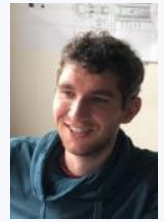

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