Towards a transportable antiproton reservoir

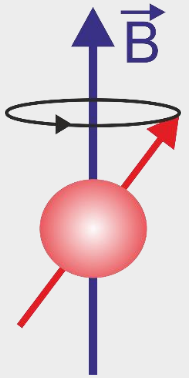
Dr. Christian Smorra on behalf of the **BASE collaboration**
Heinrich-Heine-Universität Düsseldorf

27.08.2024

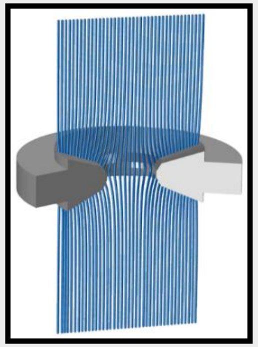
LEAP/EXA Conference - Vienna

CPT invariance tests on single trapped protons/antiprotons

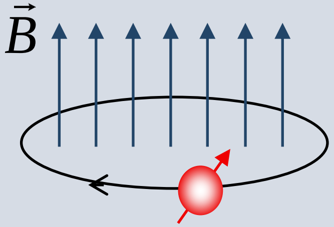
Larmor Frequency



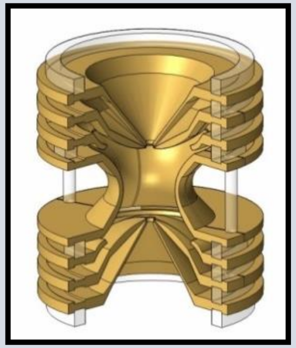
$$\omega_L = g \frac{e}{2m_p} B$$



Cyclotron Frequency



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



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

Antiproton @ BASE CERN: $\frac{g_{\bar{p}}}{2}$ = 2.792 847 344 3 (46)

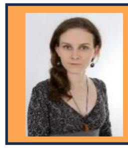
Proton @ BASE Mainz: $\frac{g_p}{2}$ = 2.792 847 344 62 (83)

Ongoing measurements by B. Latacz, S. Ulmer et al.

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

BASE 2015: $-1 + 1(69) \times 10^{-12}$

BASE 2021: $-1 + 3(16) \times 10^{-12}$



Talk by Barbara tomorrow 10h00

Concepts:
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).

Recent measurements:
S. Ulmer, C. Smorra, et al., Nature **524**, 196-200 (2015).
C. Smorra et al., Nature **550**, 371 (2017).
G. Schneider et al., Science **358**, 1081-1084 (2017).
M. Borchert et al., Nature **601**, 53–57 (2022).

Low-energy Antiprotons at CERN

The worlds only source of
low-energy antiprotons:

Antiproton Decelerator (AD)

30 million antiprotons / 2 mins
5.3 MeV kinetic energy

ELENA
(Extra Low Energy Antiproton ring)

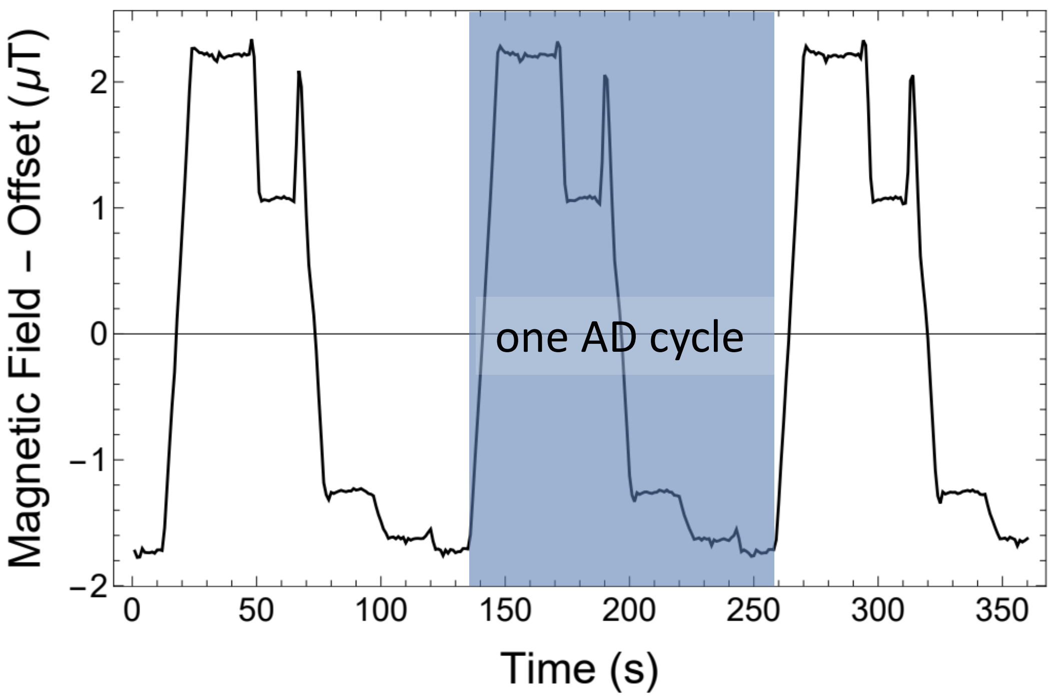
starting full operation in 2021

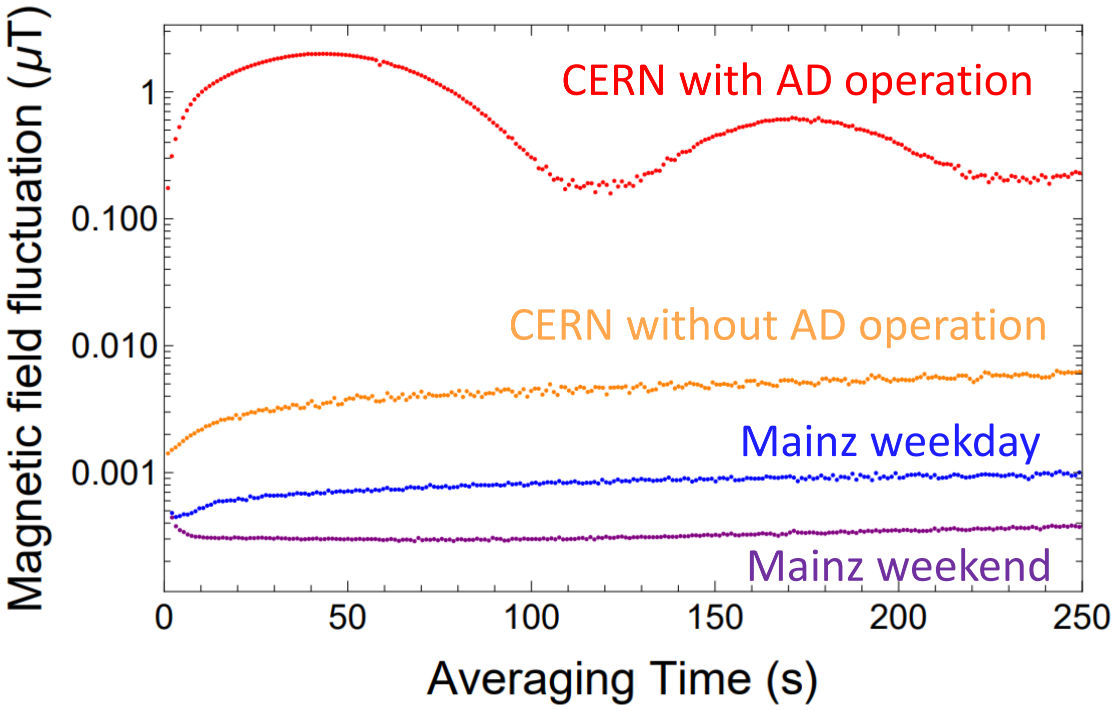
4 x 5 million antiprotons / 2 mins
100 keV kinetic energy

Magnetic field fluctuations in the AD/ELENA facility

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

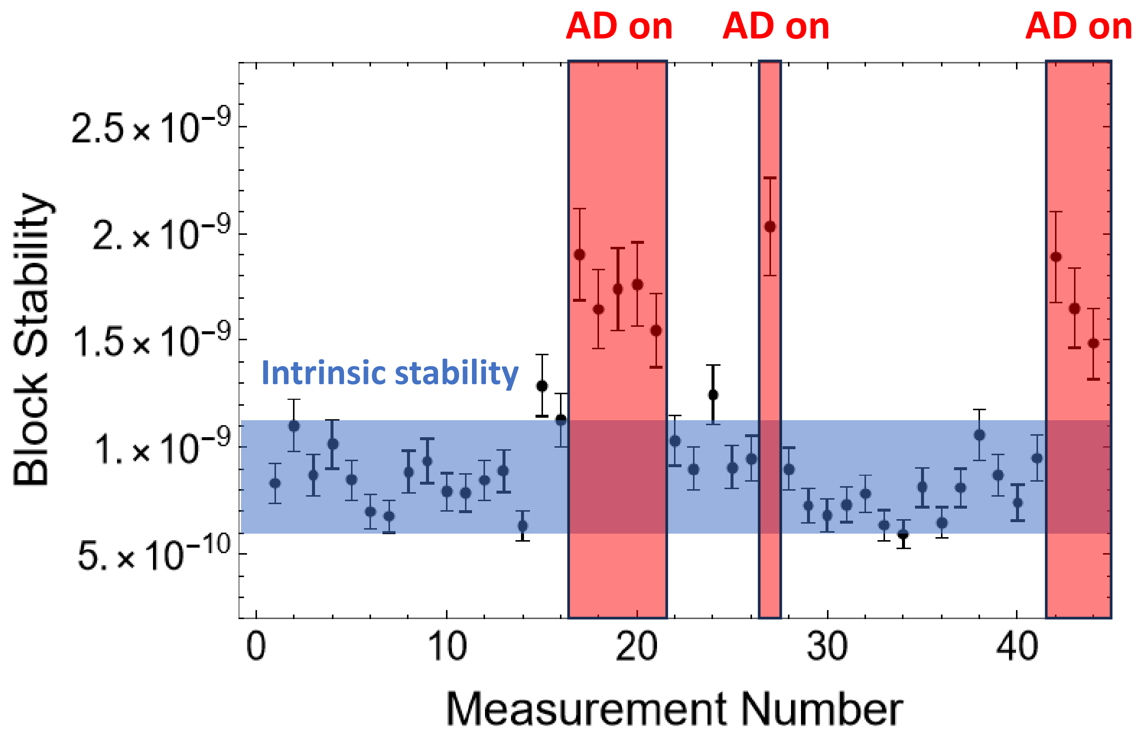
Flux-gate sensor measurements of external magnetic field fluctuations:





Magnetic field fluctuations in the AD/ELENA facility

Impact on frequency ratio measurements in the BASE-CERN apparatus

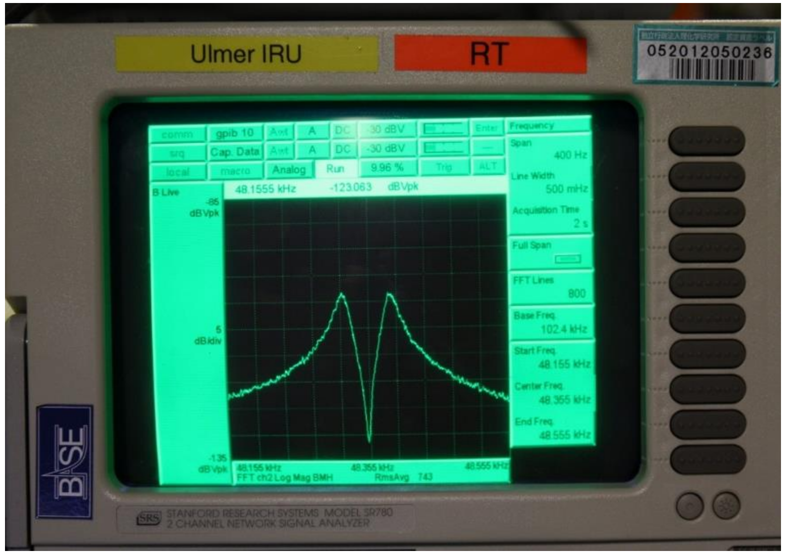


About 45 mins per block,
40 frequency measurements

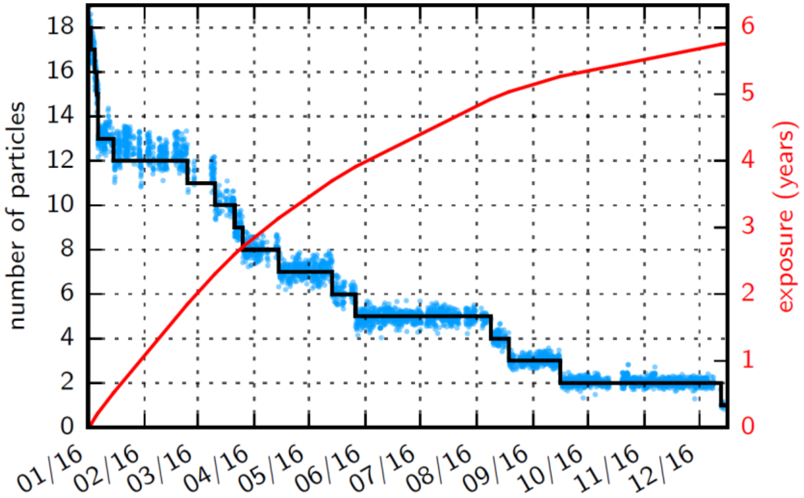
Block stability of cyclotron frequency shifts:

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

Reservoir trap in BASE-CERN (since 2014)



S. Ulmer
HHU/RIKEN



BASE-CERN:

- Long-term storage of antiprotons, > 1 year
- Precision measurements supplied by non-destructive separation of single antiprotons from the reservoir trap
- Antiprotons are not transportable
  Superconducting magnet is not made for transporting
- Antiprotons are not transferable
  Measurements are conducted in a closed cryogenic vacuum chamber

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

Benefits of a transportable antiproton reservoir

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 & BASE-HHU
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.

Experimental setup of the transportable trap

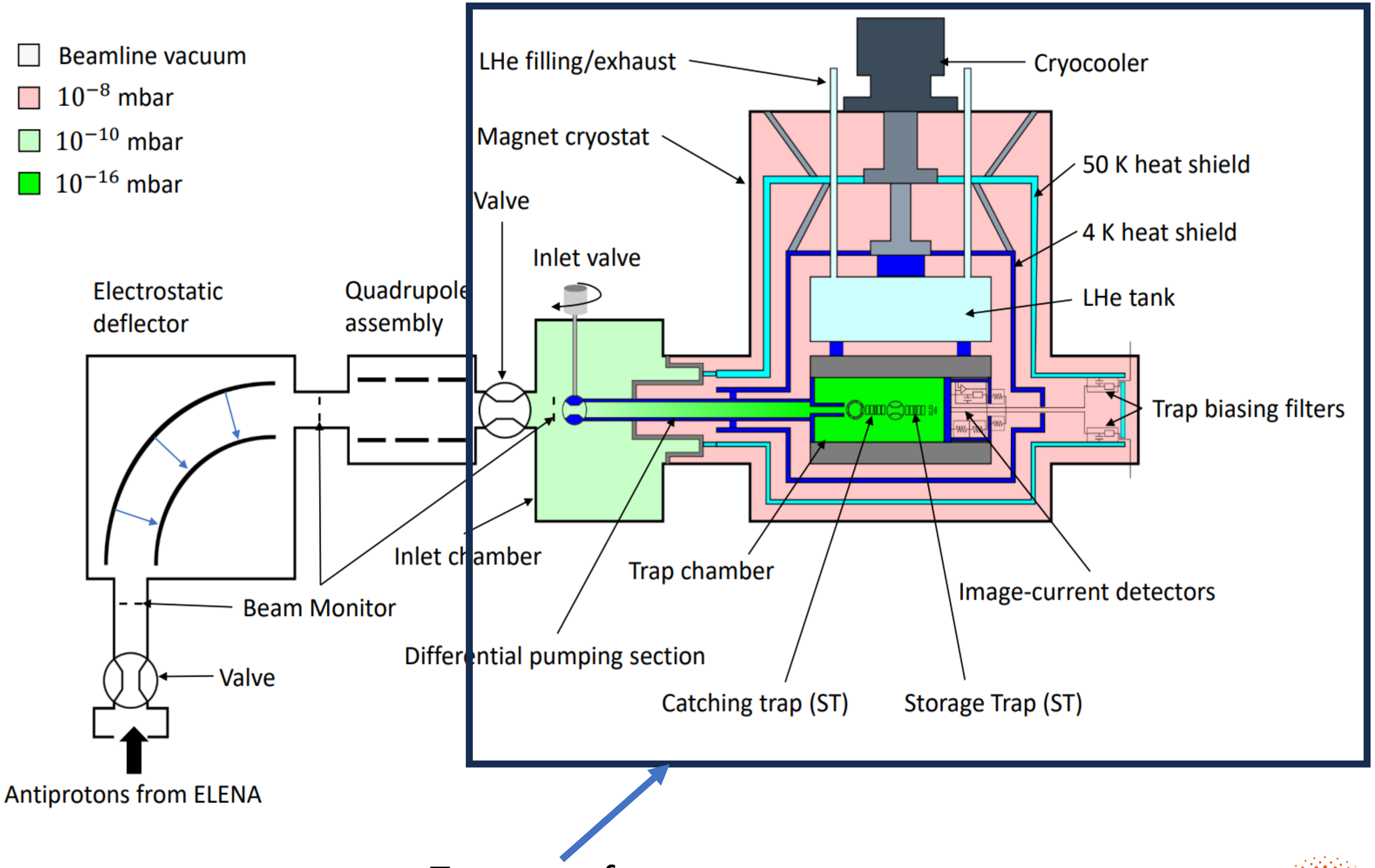
Transportability:
Withstand forces occurring on the overhead crane and transport on the road
Requirement: 0.5 g to 0.7 g (CTU Standard)

Requested: +1.0 g in all directions
Design study: ~3.0 g is the limit for elastic deformation

Cooling concept during transportation:
Dry magnet with 30 L LHe tank buffer
12 h holding time, but temperature spikes during the cooler restart

Injecton/ejection:
Differential pumping section with a cryogenic valve and several gas flow blocking mechanisms (performance under investigation)

Equipment to receive and transport antiprotons

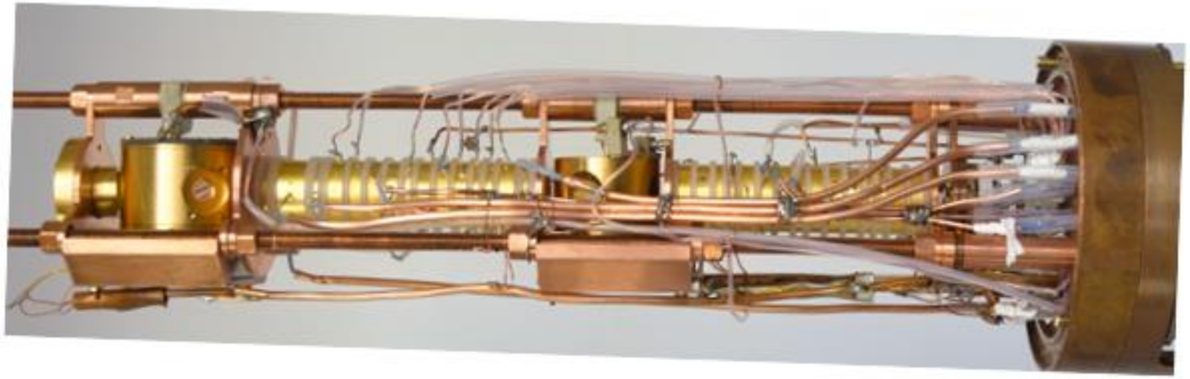


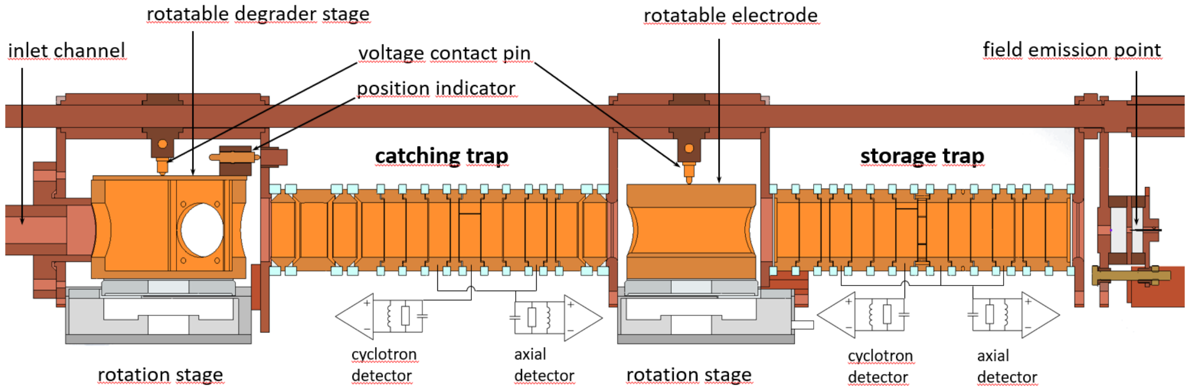
C. Smorra et al., Rev. Sci. Instrum. 94, 113201 (2023).

Transportable antiproton trap BASE-STEP

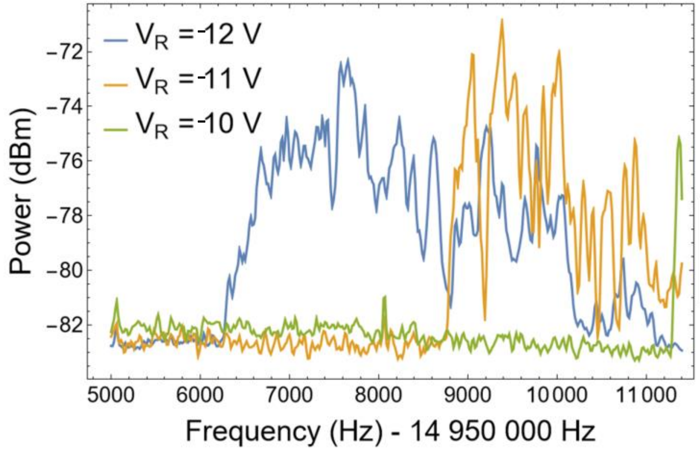
Transportable superconducting magnet (1.0 T) with transport frame (900 kg), movement by trailer and crane

Transportable superconducting Penning trap system

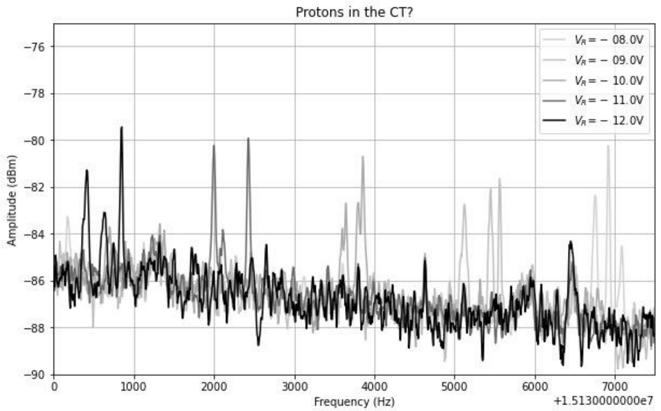




Protons in the Reservoir trap

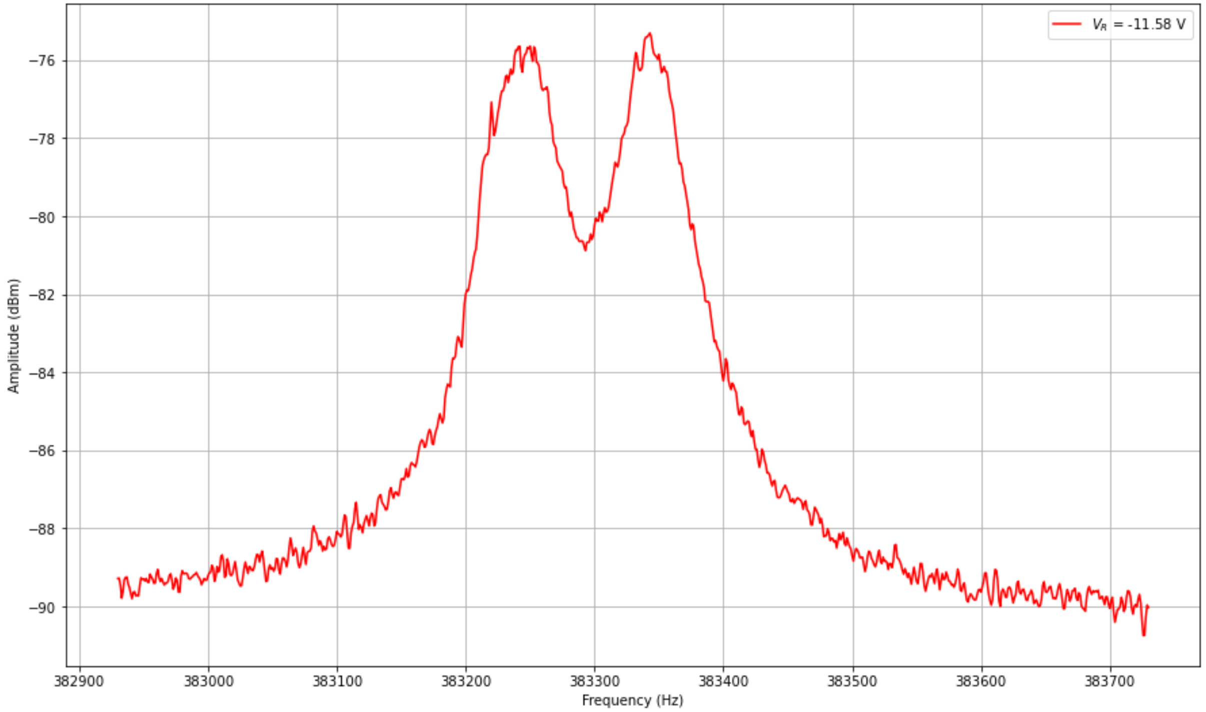


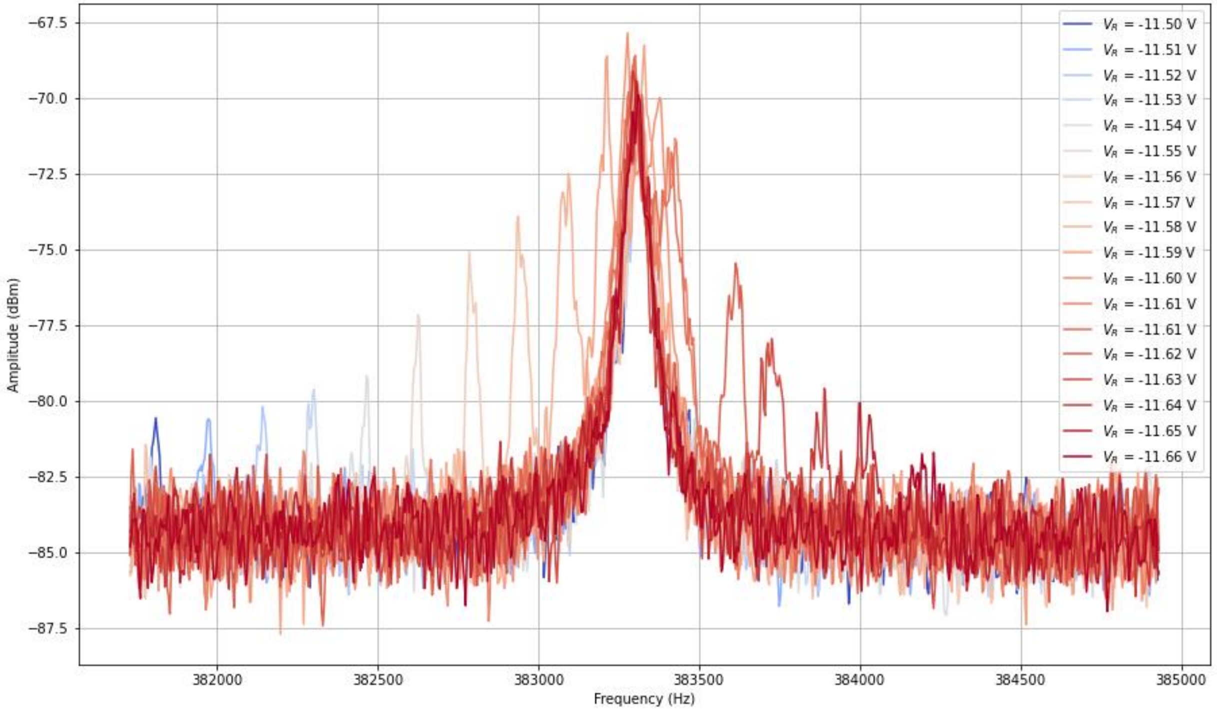
Protons in the Catching trap



- Transportable superconducting magnet (operational since May 2023)
- Transport test runs with up to 2.5 hours time
- Double trap-stack Penning trap system
  (34 electrodes, 4 detection systems)
- Trapped particles since July 2024
- Preparation of proton transport at CERN ongoing

First particle dip on the axial detector

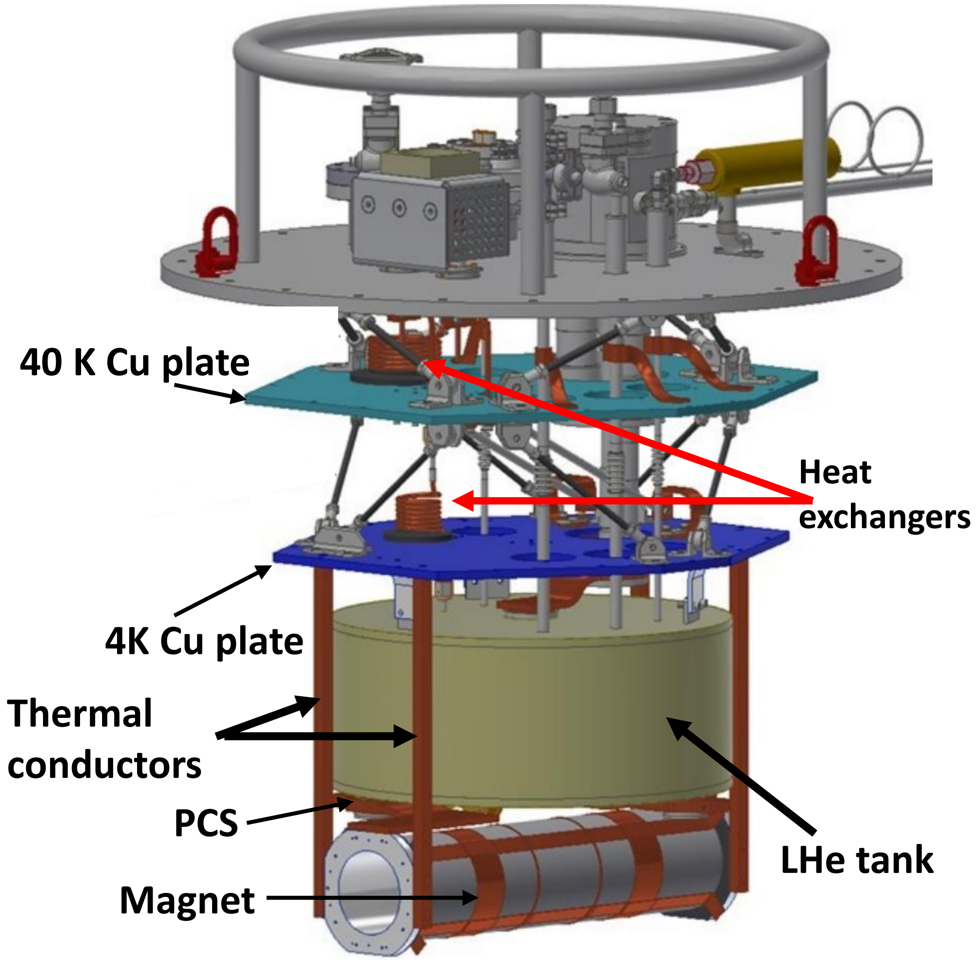


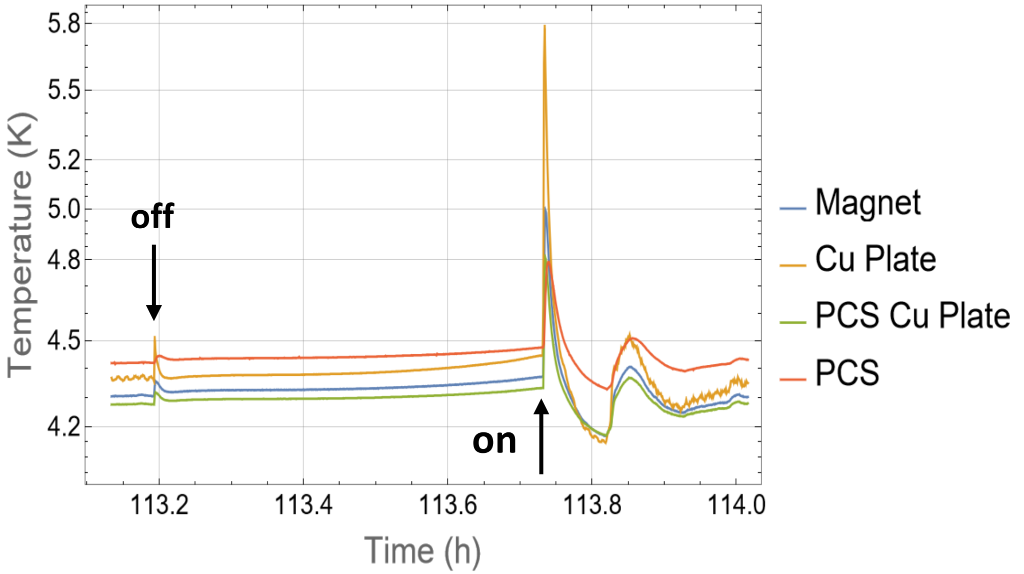


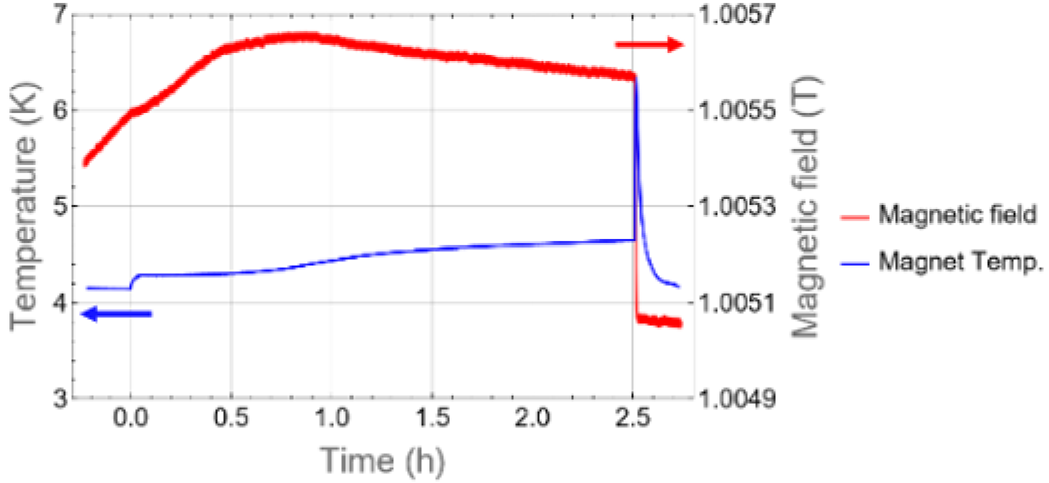
Marcel Leonhardt (HHU)

Enables particle counting by the dip width
Investigation of vacuum conditions by looking at ion recombination rates
Characterization of particle loss during transportation

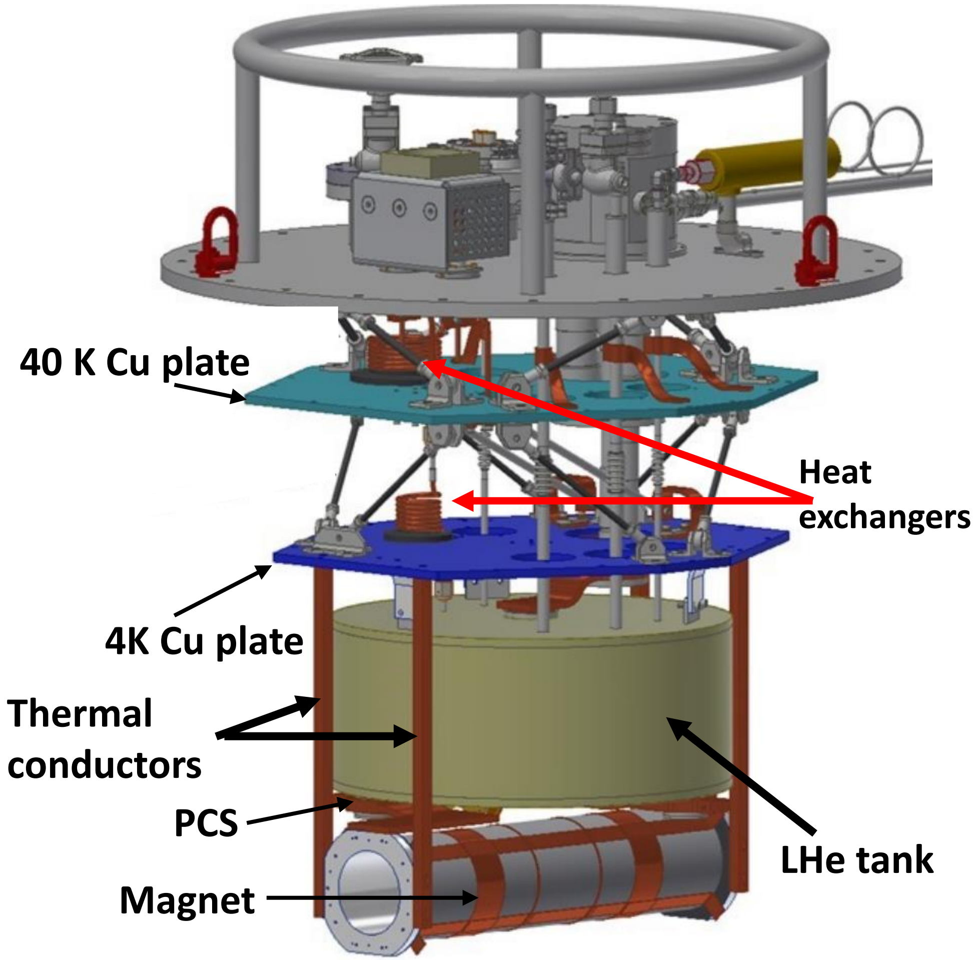
Transport mode tests

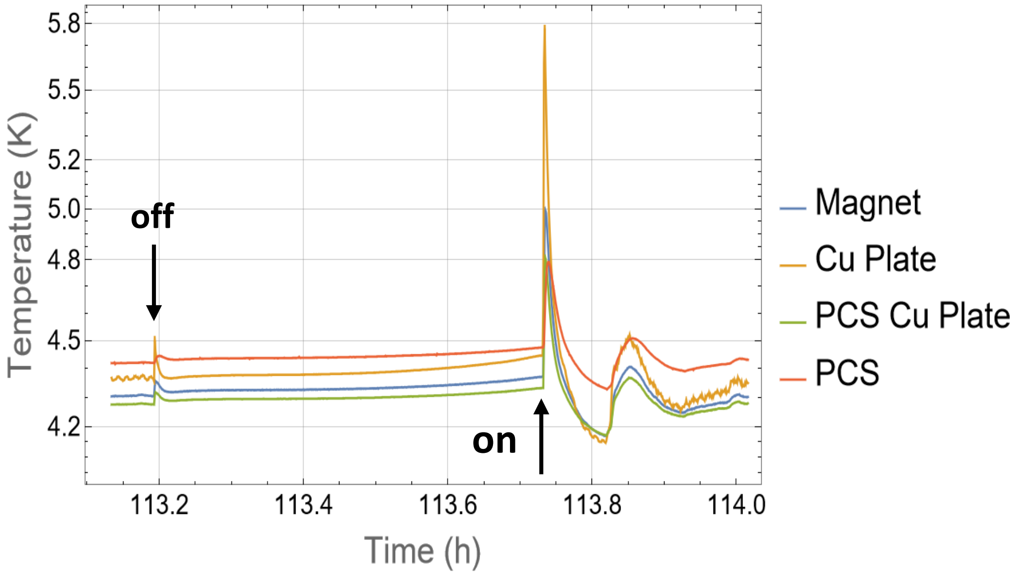


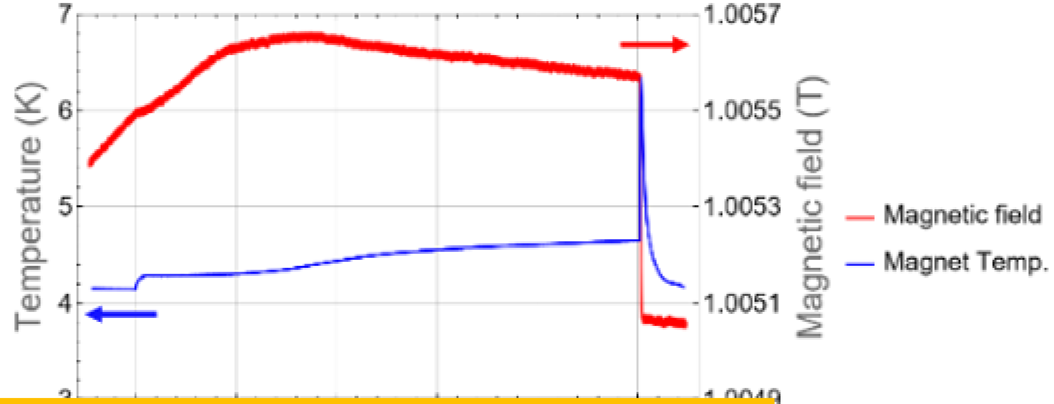




Transport mode tests



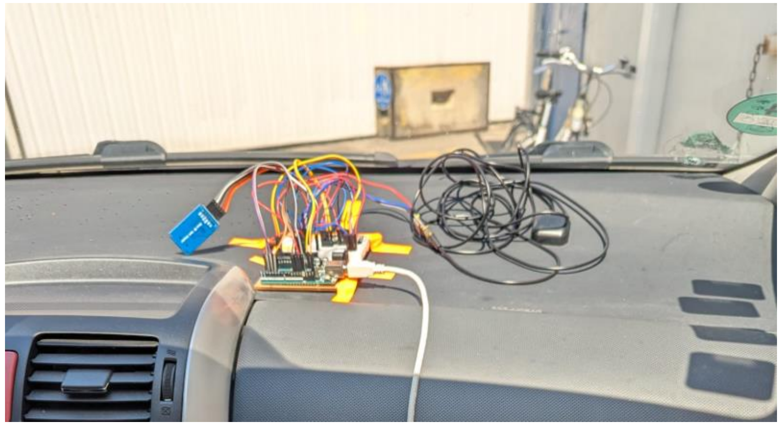


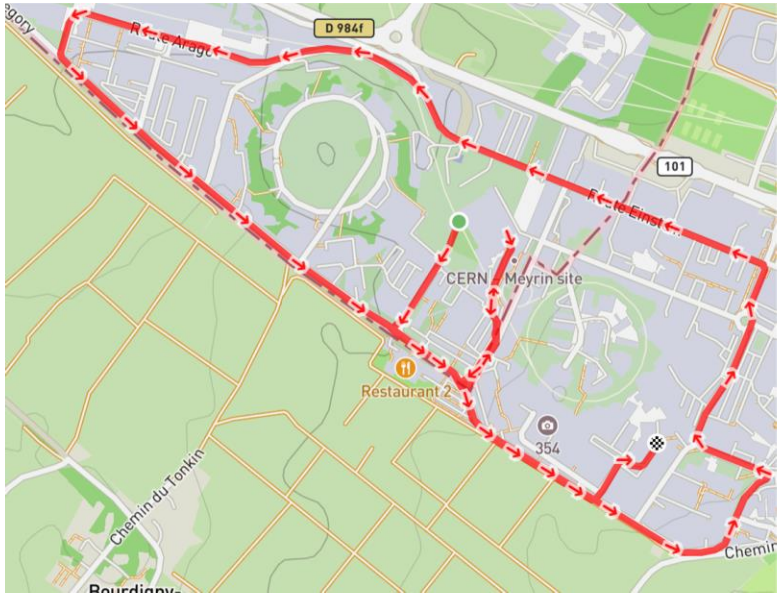


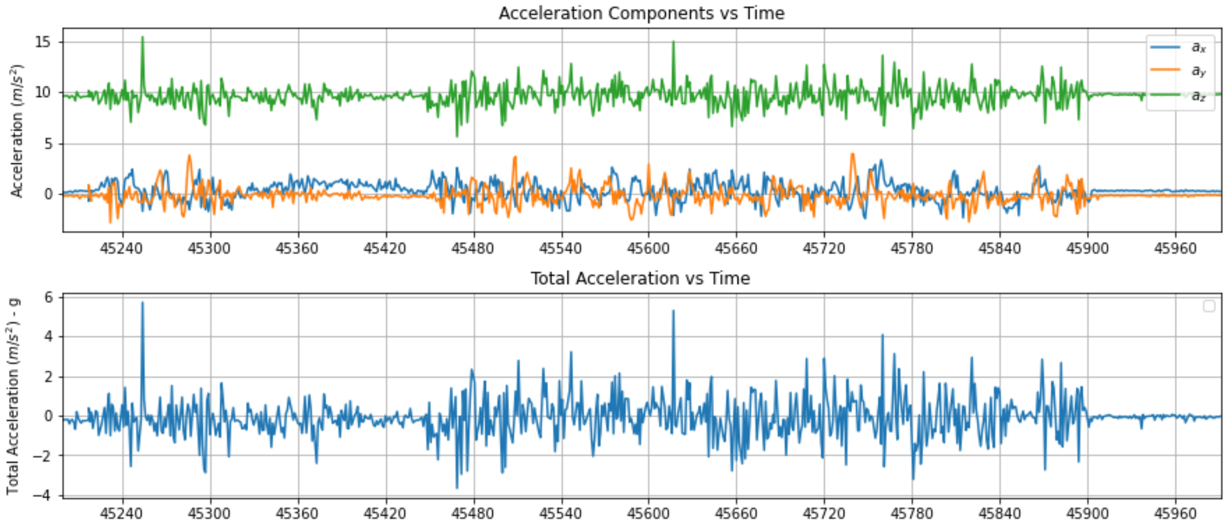
- Sufficient for transport demonstration inside CERN
- Requires power generators on the truck for long distance transports

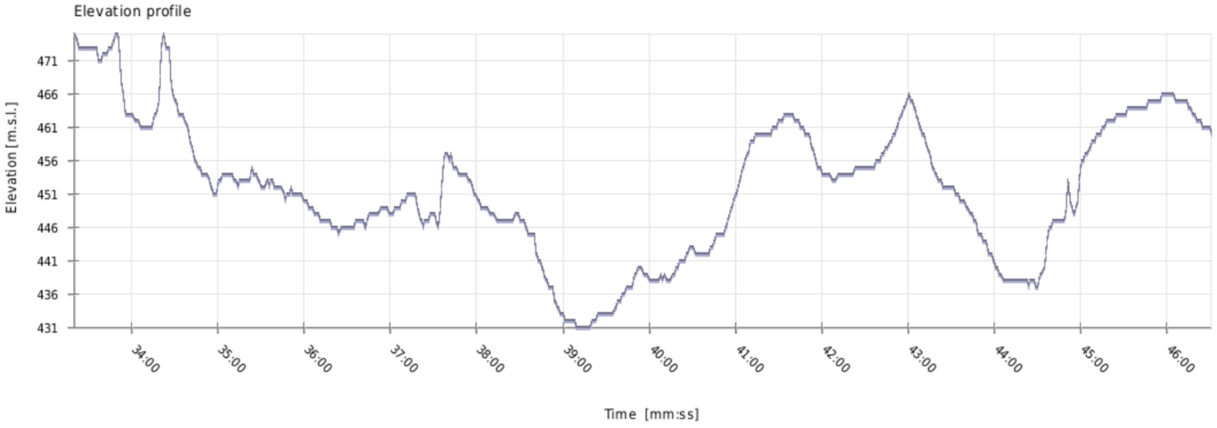
Telemetry data – test drive

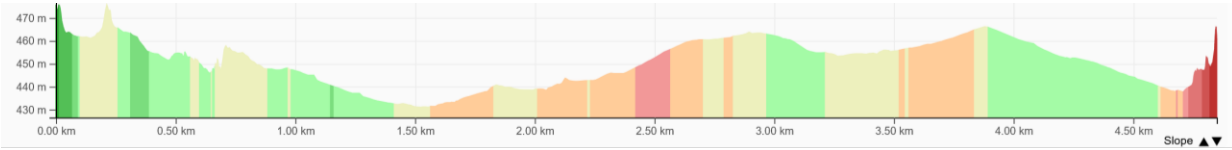
Marcel Leonhardt (HHU)





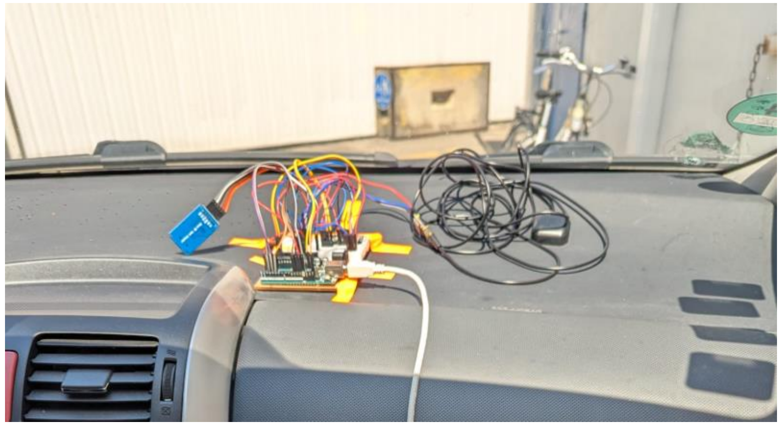


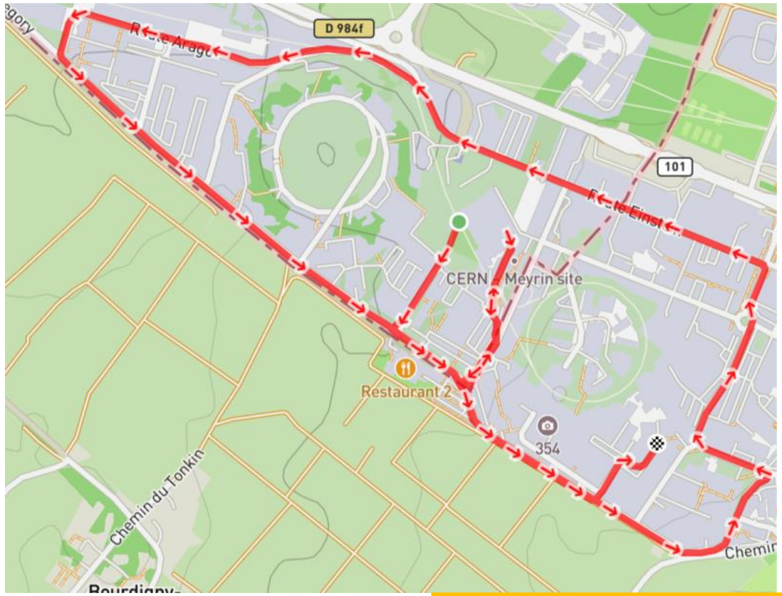


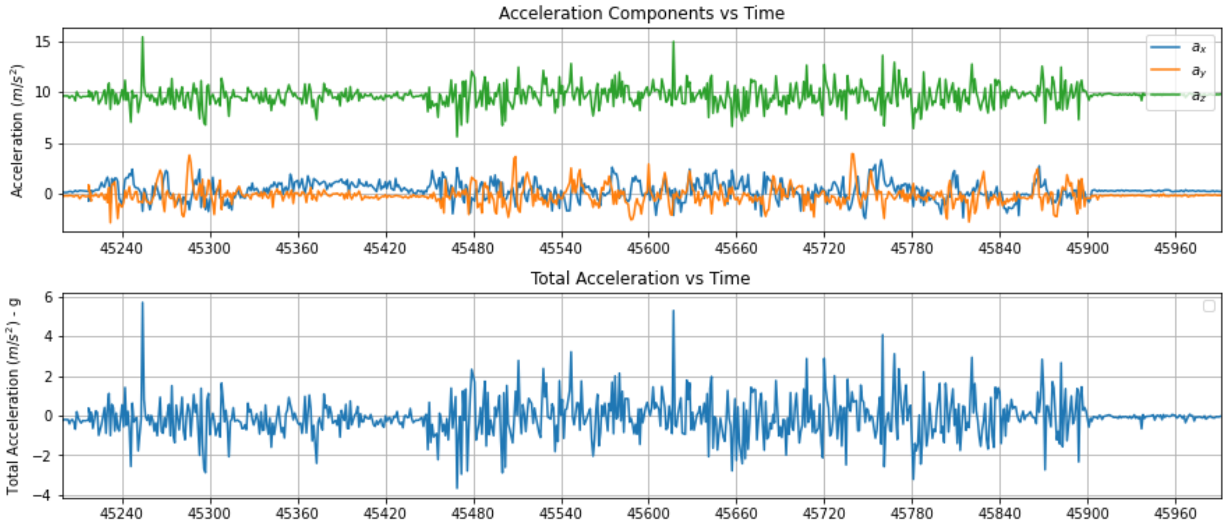


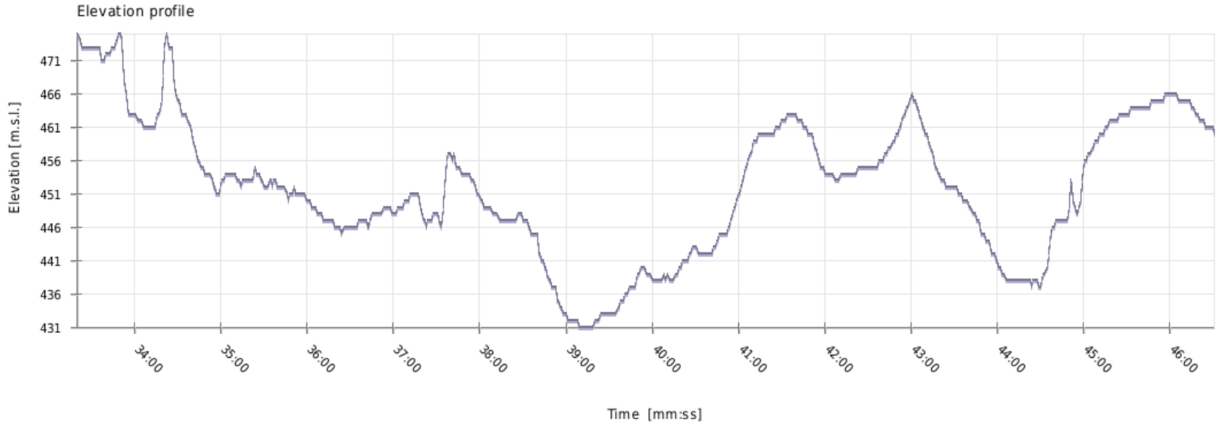
Telemetry data – test drive

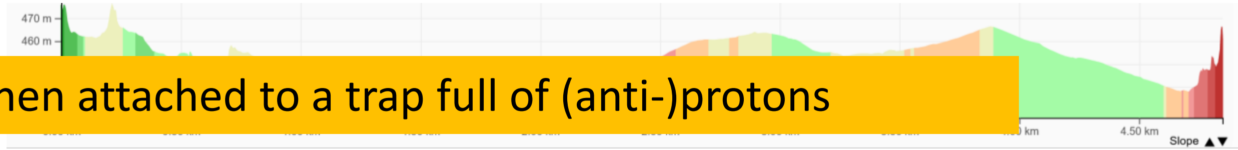
Marcel Leonhardt (HHU)











- To be repeated when attached to a trap full of (anti-)protons

Permanent magnet transportable traps

V. Gomer et al., A compact Penning trap for light ions, Appl. Phys. B 60, 89 (1995).
B.J. McMahon et al., Second-Scale 9Be+ Spin Coherence in a Compact Penning Trap, Phys. Rev. Appl. 17, 014005 (2022).

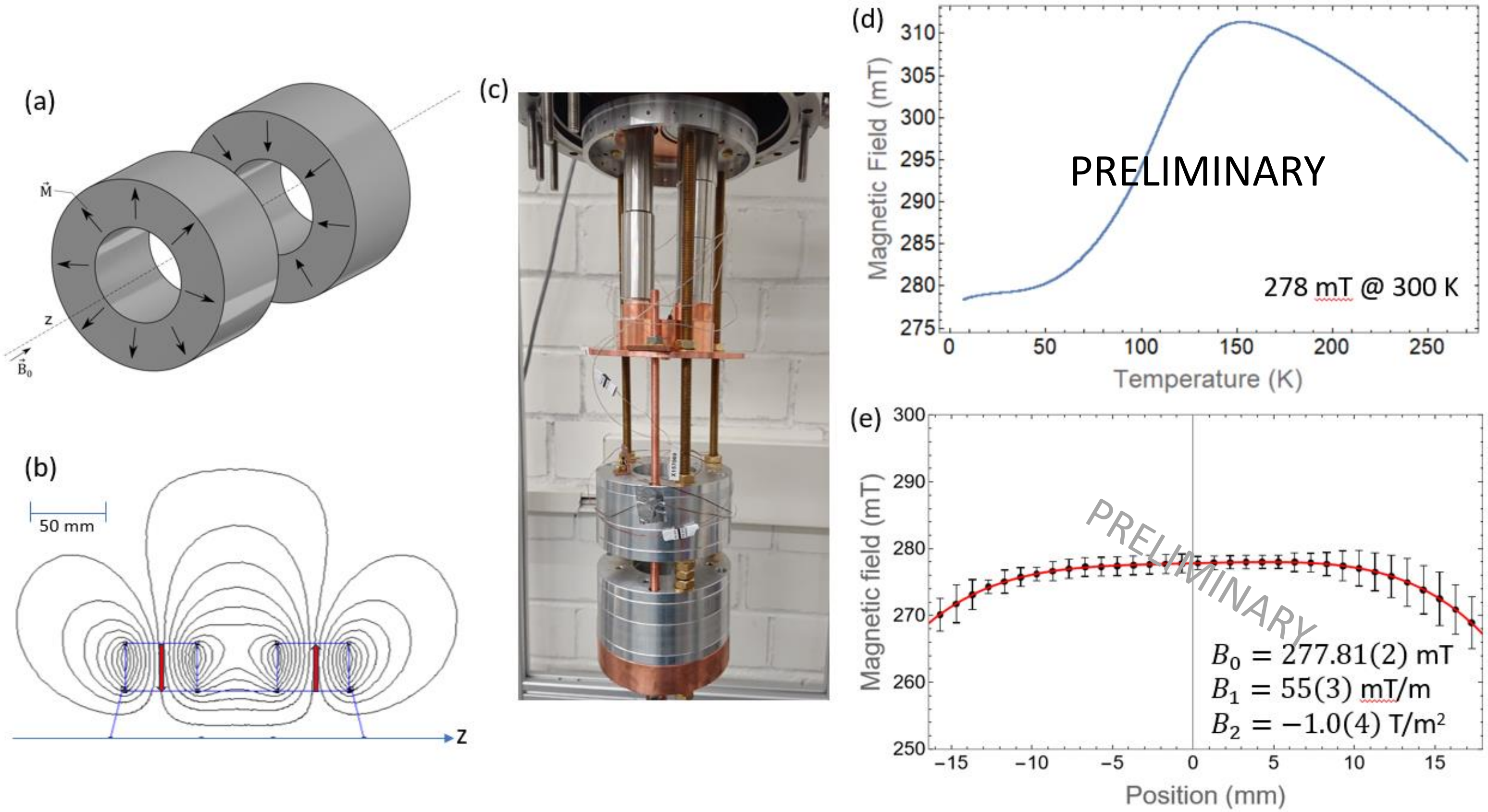
Low cost / low production time

BUT

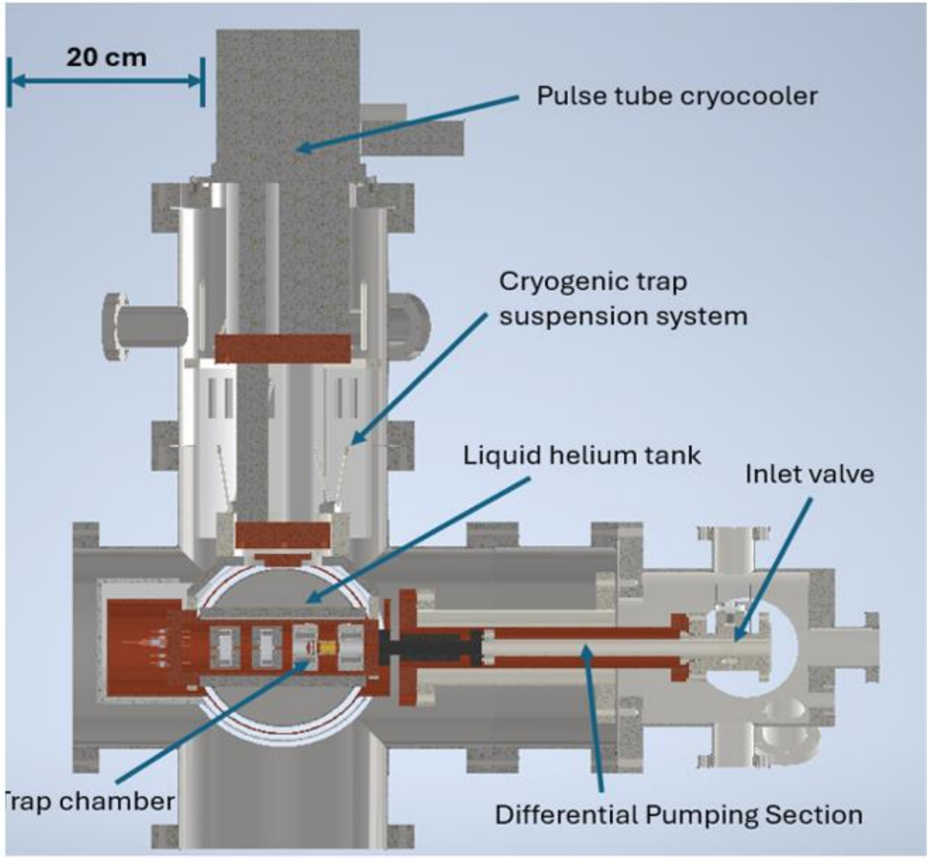
Low field / low volume

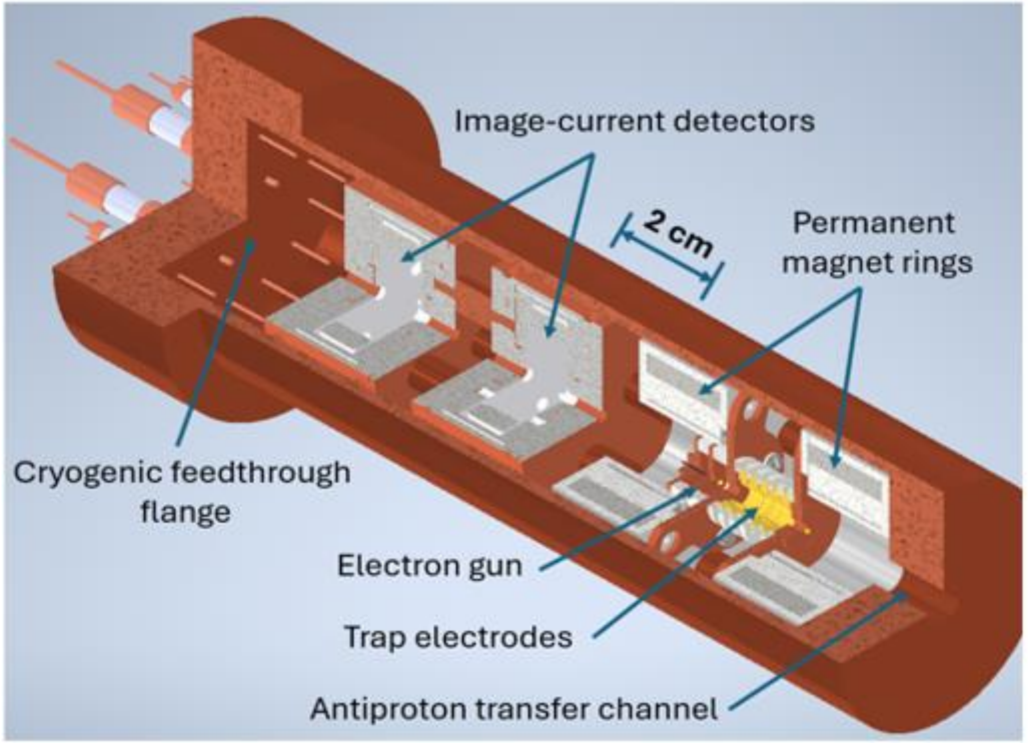
Prototype with so-called Aubert configuration an 62 mm bore has been build and tested
(Brillouin limit: 10^8 pbars/cm^3)

280 mT with $B_2 < 5$ T/m^2 was achieved. B_1 shim coil is necessary to become more homogeneous.



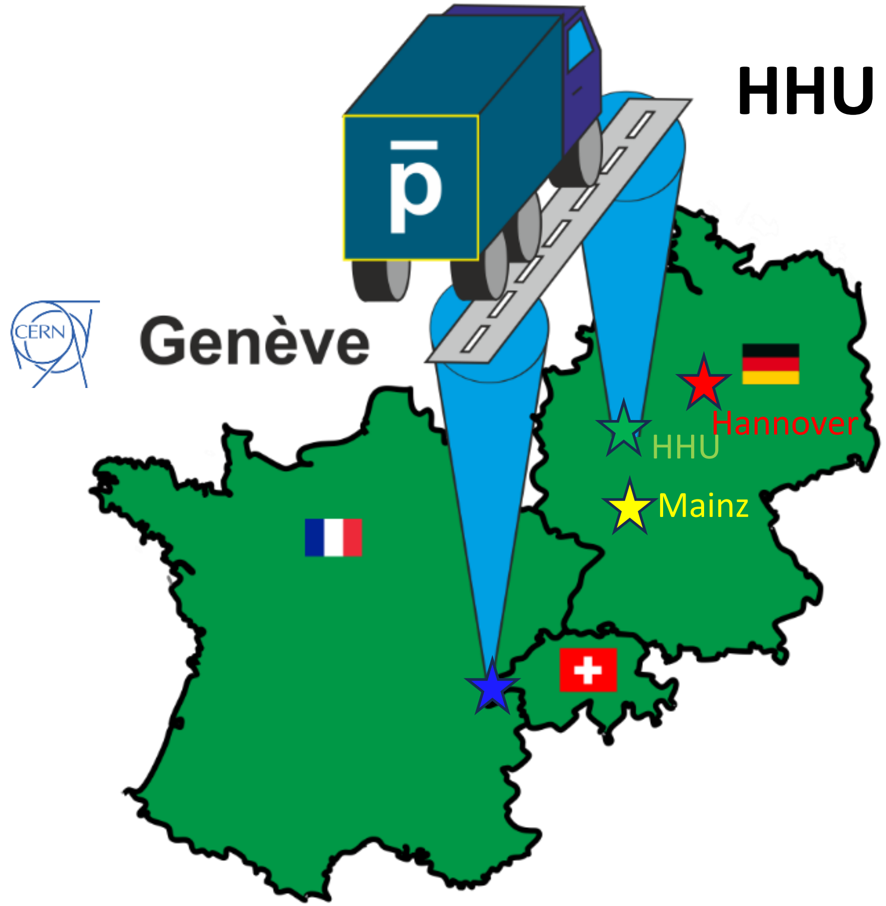
Compact general purpose transport trap





'*Perfection* is *achieved, not* when *there* is nothing more to *add, but* when *there* is *nothing left* to *take away.*' — Antoine de Saint-Exupéry

The roadmap for antiprotons…



HHU Düsseldorf

BASE-HHU:

Receiver experiment for transportable antiprotons

Implementation of the quantum-logic and sympathetic cooling technology of BASE-Mainz and BASE-Hannover

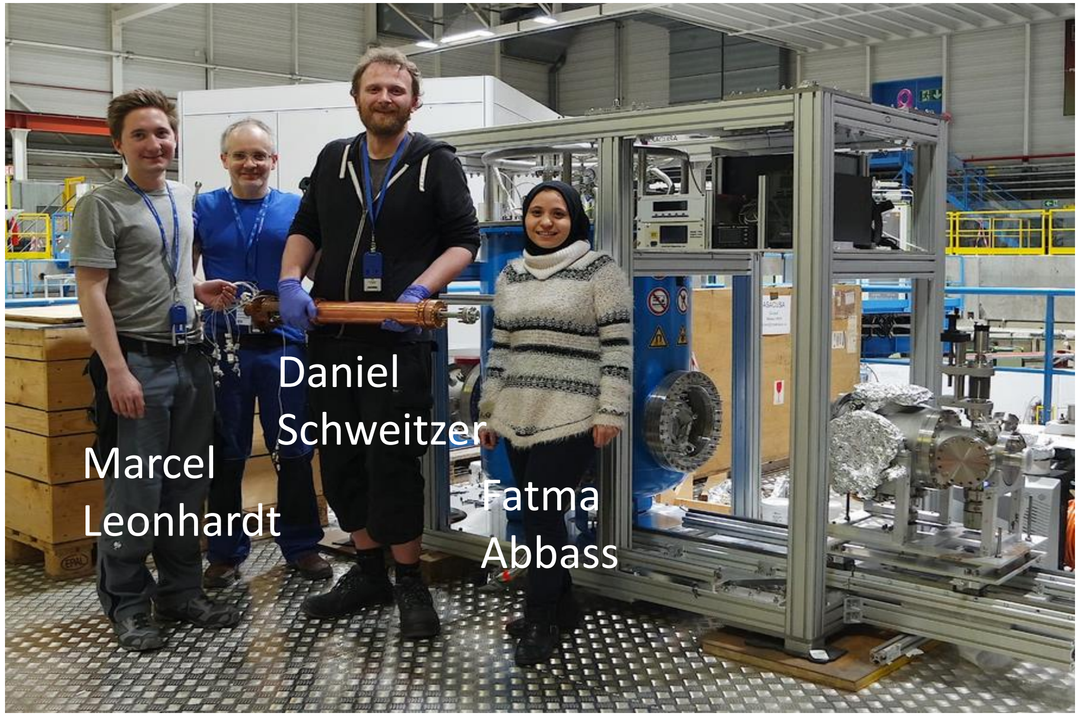
Laboratory with precision measurement conditions for the ultimate antiproton precision measurements and most sensitive CPT invariance tests

Thank you for your attention!

…many thanks for the support from CERN!

Experiment zone (F. Butin et al.), Cryolab, Beam (Y. Dutheil et al.), Safety (J. Devine)

BASE-STEP team



BASE – CERN:

S. Ulmer
HHU/RIKEN

B.M. Latacz
CERN/RIKEN

S. Erlewein
CERN/MPIK

J. Jäger
MPIK

E. Wursten
CERN/RIKEN

and I. Ahrens, B. Arndt, I. M. Beine, S. Erlewein, M. Fleck, P. Geissler, J. Jaeger, H. Klett, T. Imamura, P. Schöps, A. Siebert, F. Voelksen

BASE – Mainz:

H. Yildiz
K. Anjum
D. Rensink
R. Corell
P. Micke
J. Walz

previous work by M. Bohman, C. Will, and M. Wiesinger

and senior partners: **K. Blaum (MPIK)**, Y. Matsuda, A. Mooser, C. Ospelkaus, W. Quint, and A. Soter