

Road Transport of Trapped Antiprotons

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Road Transport of Trapped Antiprotons

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Low-energy antiprotons confined in ultra-high vacuum Penning traps (1) enable precision investigations of charge, parity, and time-reversal (CPT) invariance (2) to test the fundamental symmetry between matter and antimatter. These studies are driven by the search for physics beyond the Standard Model of particle physics, including efforts to explain the observed cosmological matter–antimatter asymmetry. To date, such experiments have only been possible at CERN’s Antimatter Factory (AMF) (3, 4). Magnetic-field fluctuations caused by the facility operation currently limit the sensitivity of trapped-antiproton precision measurements (5), which currently provide the most stringent matter/antimatter symmetry tests in the baryon sector (6–9). This has inspired us to develop the cryogenic, open, and transportable Penning-trap system BASE-STEP (5, 10), designed to relocate antiprotons into low-noise offline laboratories, a strategy expected to enable at least 100-fold improved CPT tests (9, 11). Here, we demonstrate the first road transport of antiprotons trapped in BASE-STEP. 92 trapped antiprotons have been transported for the first time outside of the AMF over a 7.5 km route without particle loss or measurable degradation of the trap vacuum. This achievement marks the starting point for a new era of antiproton precision measurements (8, 12) in dedicated low-noise offline laboratory environments.

Experiments that compare the properties of matter–antimatter conjugates (13, 14) test the fundamental CPT invariance (2), which is deeply intertwined with our understanding of energy, space-time, and causality (15, 16). As such, it constitutes a cornerstone of the relativistic quantum field theories of the Standard Model, and any observed difference would point to physics beyond it. Particularly compelling are experiments involving stable matter–antimatter systems, such as electrons and positrons (17, 18), protons and antiprotons (8, 21), or hydrogen and antihydrogen (19, 20). Stored in ultra-high vacuum, the intrinsic stability of these systems permits non-destructive measurements (22, 23) at exceptionally long interrogation times (11) and ultra-high fractional precision, enabling sensitivity to potential minute signatures of exotic phenomena beyond established physics (24–29).

Within the BASE collaboration, we use an advanced cryogenic Penning trap system to perform CPT invariance tests by high-precision comparisons of the fundamental properties of protons and antiprotons, such as charge-to-mass ratios q/m and magnetic moments (6, 7). These are extracted from single particle measurements of the cyclotron ν_c and spin-precession frequencies ν_L , both proportional to the magnetic field B (30). Using the BASE trap system in the AMF, we have achieved relative uncertainties at the level of 16 parts per trillion (ppt) for the charge-to-mass ratio (6, 9) and 1.6 parts per billion (ppb) (7, 8) for the magnetic moment, constraining CPT-violating effects down to sensitivities of 2×10^{-27} GeV (9). However, these measurements are ultimately limited by fluctuations of B at the experiment location in the AMF, which directly contribute to the measurement uncertainty (5). Our efforts to mitigate these limitations have included the development of the reservoir trap technique (31, 32), enabling precision measurements when the AMF is offline, typically for 2–3 months per year (9). Combined with improved magnetic shielding (33), this strategy has boosted the frequency stability and enabled our latest results (11), further improvements toward ppt-measurements require long term systematic studies extending well beyond annual shutdown periods and consequently years of data taking (34). Other Penning trap systems in magnetic noise-free environments achieved g-factor difference measurements with 5.6×10^{-13} relative uncertainty (35), high-precision magnetic moment measurements (36) and 10^{-12} level uncertainties in q/m measurements (37, 38) on much shorter time scales. In contrast, while we demonstrated the methods required for measurements at higher precision (11, 39), progress in our experiments remains constrained by the ambient magnetic noise in the AMF.

As a key technology to overcome these limitations, we have constructed the transportable antiproton trap system BASE-STEP (5), to decouple our measurements from the dominant source of magnetic noise. Although transporting antiprotons has been mentioned and proposed earlier in different contexts, for example in refs. (40–42), only the recent limits of the BASE antiproton measurements made its implementa-

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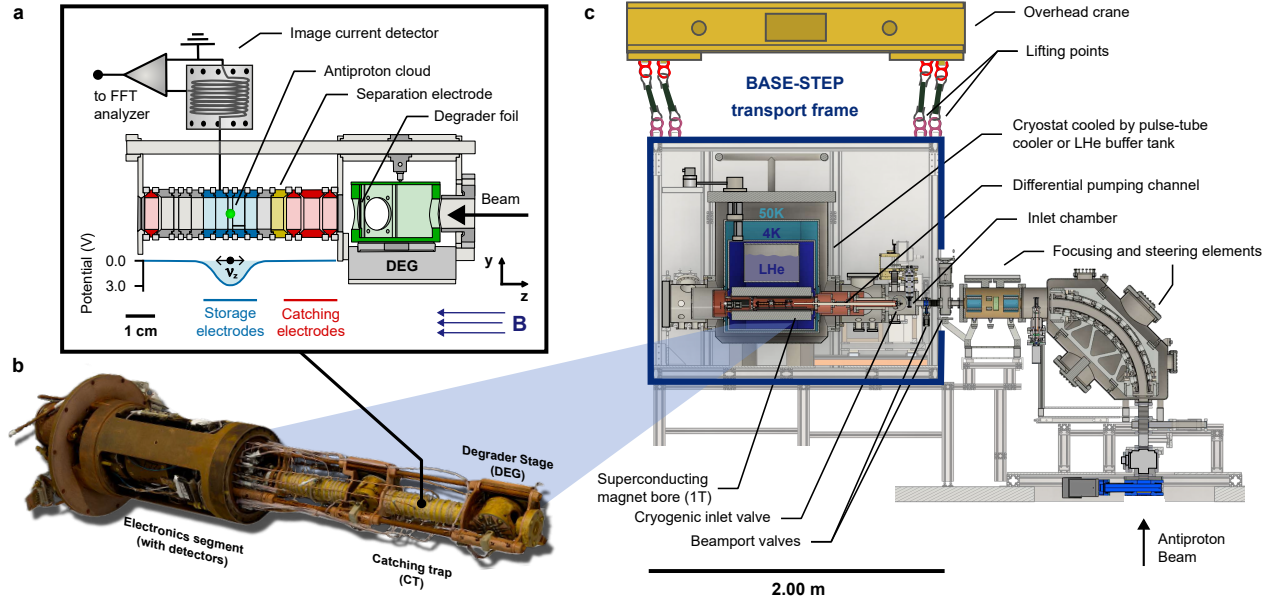


Fig. 1. | The BASE-STEP Apparatus. **a**, Overview of the BASE-STEP catching trap used in this study. The positions of the high-voltage catching electrodes (red) for antiproton injection and extraction are indicated together with the storage electrodes (blue) used to prepare and monitor the antiproton reservoir. Antiprotons are injected through the rotatable degrader stage (DEG), confined within the central storage electrodes, and non-destructively monitored using an image-current detector. **b**, Cryogenic inset of the experiment in the bore of a 1 T superconducting magnet, showing the catching trap (CT), the degrader stage, and the electronics segment housing the image-current detectors. **c**, Schematic of the injection setup showing the antiproton transfer beamline and the transport frame. Antiprotons are injected with 100 keV kinetic energy guided by several steering and focusing elements, the inlet chamber, and the differential pumping channel that suppresses the residual gas flow into the trap chamber. The beamline is connected to the transport frame housing the magnet cryostat through beamport valves. Closing these valves enables the BASE-STEP apparatus to be detached from the beamline and lifted out of the AMF hall by crane.

tion necessary as next logical step towards higher precision. Other projects working towards antiproton transport include PUMA (43) and the work proposed in (44), both exploiting antiproton annihilation for probing nuclear skin compositions of radionuclides (41) or producing isomeric ions for metrology applications (45), respectively. However, only two transport studies with electrons (42) and protons (10) have been reported so far. These confirm the feasibility of relocating Penning-trap systems, but leave unresolved whether the extreme vacuum conditions required for antiproton storage can be maintained during and after transport. Here, we demonstrate for the first time the successful relocation of antiprotons using BASE-STEP (5), transporting the device by truck across the Meyrin site of CERN.

The BASE-STEP Apparatus. The design of the BASE-STEP apparatus (see Fig. 1) and the development of the transport routine is described in Refs. (5, 10). Here, we summarize the key components and procedures relevant to antiproton transport. The Penning trap confines charged particles through the superposition of a magnetic field and an electrostatic quadrupole potential (5, 30, 46). In our setup, this configuration is realized by a custom-built, transportable superconducting magnet with an adjustable magnetic field B of up to 1 T, and a stack of cylindrical electrodes positioned within its 4 K cold bore. For this study, antiprotons are confined in the catching trap (CT), shown schematically in Fig. 1a. The central storage electrodes form a compensated, orthogonal, open-endcap Penning trap (47), where trapped particles oscillate harmonically along the magnetic field lines with the

axial frequency set by the central ring electrode voltage V_R . In the radial plane, the particles undergo a superposition of two circular motions at the modified cyclotron ν_+ and magnetron ν_- frequencies, both depending in addition to V_R on B . Image currents induced by the axial motion enable non-destructive detection and monitoring of the trapped antiprotons (22, 48, 49). The image-current detector consists of a superconducting LC circuit (23) at a resonance frequency of 453 kHz, and requires frequency matching of ν_z by setting $V_R \approx 3.911$ V. For readout, the LC circuit is coupled to a low-noise amplifier placed in the cryogenic electronic segment interfacing the trap stack (see Fig. 1b). The superconducting magnet and its cryogenic inset are operated at approximately 4.3 K using a hybrid cooling system based on a cryocooler and a liquid helium reservoir (Fig. 1c). The trap system, the magnet, and the beamline-to-trap vacuum interface, which consists of the inlet chamber, a newly developed cryogenic inlet valve, and the differential pumping section (see Fig. 1c and Methods for details), are enclosed in the BASE-STEP transport frame. The complete assembly has a weight of approximately 850 kg and can be lifted by an overhead crane.

Antiproton Injection. Antiprotons are delivered from the AD/ELENA complex of CERN (3) and injected into the trap through electrostatic steering and focusing elements (Fig. 1c). Upon entering the apparatus with a kinetic energy of 100 keV, they enter through the beamline-to-trap vacuum interface into the cryogenic trap chamber. In the subsequent degrader stage (DEG), the antiprotons propagate

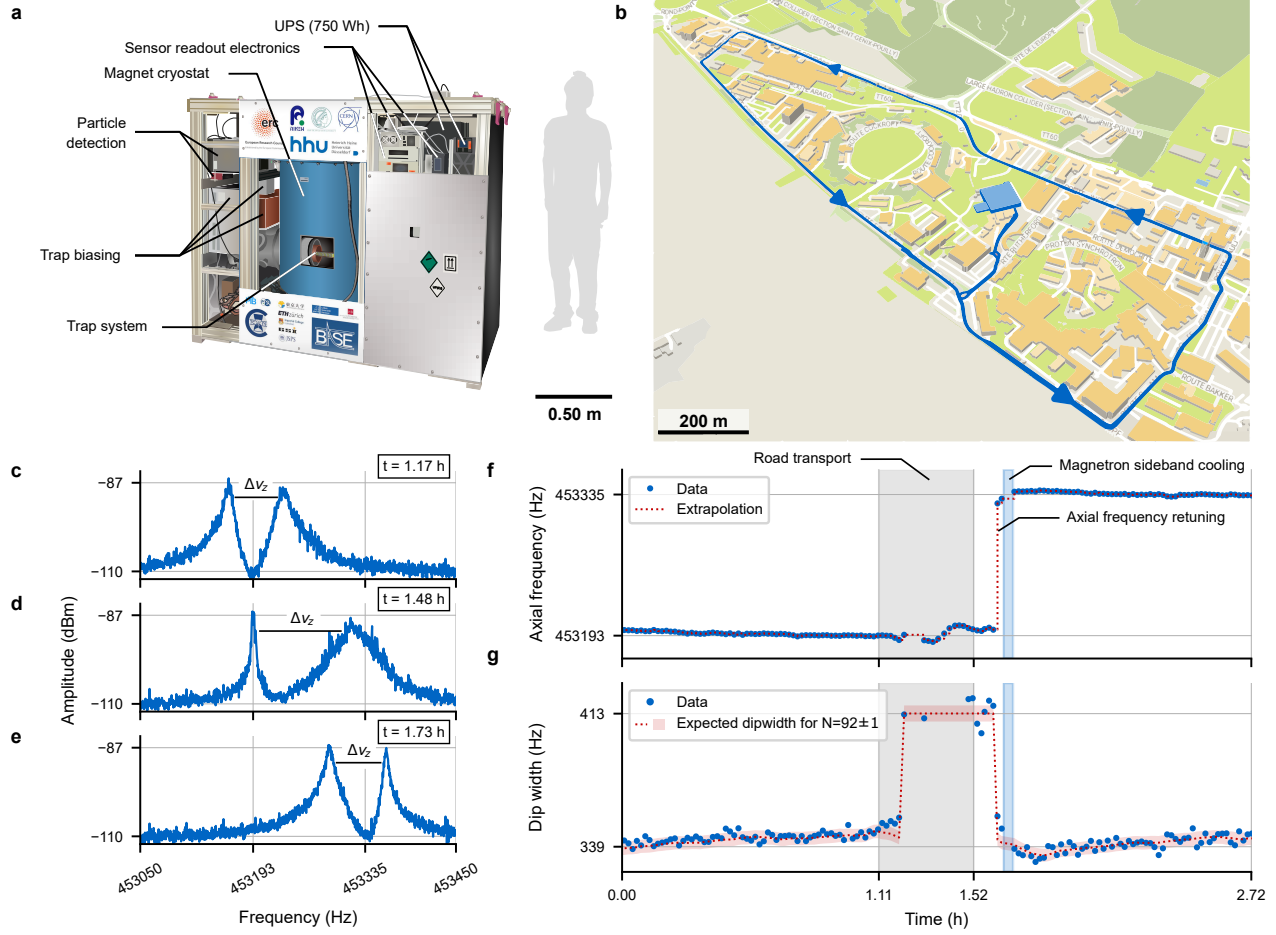


Fig. 2. | Transport and monitoring of the antiproton reservoir. **a**, Schematic of the transport frame containing the magnet cryostat with the trap system inside. The frame also houses UPS batteries, trap-biasing and amplifier power supplies, as well as particle detection and sensor readout electronics. The dimensions of the apparatus are illustrated with a person shown for scale. **b**, Road map of CERN's Meyrin site, including GPS position data recorded during road transport. Map reproduced from [OpenStreetMap](#). **c–e**, FFT spectra of the image-current signal recorded on the truck, showing the thermal noise of the superconducting LC circuit shorted by the trapped antiproton cloud. Timestamps correspond to: **c**, before the resonator shift; **d**, after the resonator shift; and **e**, after the axial frequency was retuned to the resonator. **f–g**, Axial frequency and dip width extracted from the recorded spectra. The road transport period and magnetron sideband cooling are highlighted by coloured vertical bars. The expected dip width for lossless transport, based on calibration data recorded during stationary operation and including corrections for detuning-induced systematic broadening, is overlaid on the measured data.

through a $1.8 \mu\text{m}$ -thick PET degrader foil, reducing the energy of the transmitted particles to the keV range (50, 51). Antiprotons in the low-energy tail of the resulting distribution are captured at $B = 993 \text{ mT}$ by injection into the three high-voltage electrodes adjacent to the degrader stage. Afterwards, the trapping potential is increased so that most co-trapped contaminant anions become unstable while antiprotons have a higher q/m and remain confined (46). Subsequently, the captured particles are transferred to the central region of the CT and we remove co-trapped electrons and remaining negative contaminant ions including H^- by driving their axial or cyclotron modes and ramping to a shallow trap potential (30).

After cleaning, the trap voltage is adjusted to frequency match the axial mode of the antiprotons to the resonant frequency of the image-current detector. To this end, we cool the antiproton axial mode resistively and a quadrupolar RF-drive is applied at $\nu_z + \nu_-$ to reduce the magnetron radius and to center the particles in the trap via sideband coupling (52). This technique is called magnetron sideband cooling. Once

the antiprotons reach thermal equilibrium with the detection system, their interaction produces a dip in the detector's noise spectrum. The number N of trapped antiprotons can then be determined non-destructively, using the 3 dB-width $\Delta\nu_z$ of the dip signature. For a fully thermalized ion cloud, where the trapped particles short the detection circuit noise, the dip signal-to-noise ratio equals that of the detector and was measured to be $25(2) \text{ dB}$. For small particle numbers, the dip width is given as (22)

$$\Delta\nu_z = \frac{1}{2\pi} \frac{Nq^2 R_p}{mD_z^2}. \quad (1)$$

Here, $R_p \approx 263 \text{ M}\Omega$ is the measured effective parallel resistance of the detector and $D_z \approx 13.3 \text{ mm}$ is a trap-specific length. Using the catching scheme described above and detailed in Methods, we reproducibly load approximately 90 antiprotons per executed injection/preparation protocol.

Antiproton Transport. For the transport, we loaded $N = 92$ antiprotons into the trap. After capture, the magnet has been

ramped down to the transport field $B = 136$ mT, decreasing the energy stored in the magnet coil. As a result, the risk and severity of magnet quenching during transport are reduced (10). To free the transport frame for lifting, we close the two beamport valves, remove the vacuum section in between, and disconnect the compressor of the cryocooler. In the configuration shown in Fig. 2a, with external cooling and power disconnected, the transport frame operates in the so-called autonomous transport mode (see ref. (10) and Methods for details). Uninterruptible power supply (UPS) batteries provide power for the precision voltage source to bias the trap electrodes and supply sensor readout and detector electronics, while liquid helium provides cooling. We have tested autonomous operation several times, reaching up to 4 h of operation without loss of the antiproton reservoir.

In autonomous mode, the apparatus was transferred by overhead crane onto a truck positioned in the AMF cargo loading bay, using the same loading and handling procedure established for proton transport. Upon departure from the AMF, the onboard GPS collected real-time position data, producing the trajectory shown in Fig. 2b. Whereas the proton transport followed a shorter route, we moved the system along an extended 3.5 km loop across the CERN Meyrin site, completing two laps in regular traffic.

Detector noise spectra of the antiproton reservoir were acquired at 1 minute intervals throughout the journey (Fig. 2c–e). From these data, the axial frequency and the dip width can be extracted (Fig. 2f–g), allowing for continuous monitoring of the trapped antiprotons. During the first round, the resonator frequency shifted by 122 Hz, likely due to vibration-induced deformation of the detection wire attached to the trap, changing the circuit capacitance by approximately 20 fF. This results in a dispersive particle signal (Fig. 2d) with a systematic dip width broadening, but leaves the axial frequency unaffected. Although limited data quality during transport allowed extraction of only a few dip-width points, the antiprotons have been continuously tracked. We also observe a slow axial frequency drift during the entire road transport, attributed to temperature variations in the high-precision voltage source that supplies the trap electrodes and defines the axial frequency of the trapped antiprotons. In total, the apparatus traveled 7.5 km in 24 minutes, reaching a maximum velocity of 40.8 km h^{-1} . Counting from start, after 1.52 h the system returned to the AMF loading bay, where the trap voltage was adjusted to retune the axial frequency to the detector (Fig. 2e), followed by magnetron sideband cooling. The apparatus was then reinstalled at the BASE-STEP beamline and reconnected to power and cooling, completing 2.72 h of autonomous operation.

During the entire transport procedure, all parameters have remained within design specifications: the magnet temperature peaked at 6.2 K (below the critical temperature of >8 K), and the maximum acceleration was 7.3 m s^{-2} , within the 1 g cryostat tolerance. Spectra measured over 24-hour intervals before and after transport yield dip widths of $334.08(8)$ Hz and $333.92(6)$ Hz, respectively. Their difference is more than an order of magnitude smaller than the $3.633(16)$ Hz signal

expected from the loss of a single antiproton, as determined by the calibrated single-particle dip width (see Methods). We therefore exclude such a loss during transport and demonstrate that transport-related vacuum effects do not induce antiproton annihilation in our system over the tested timescales.

Storage Lifetime and Vacuum Performance. To constrain the residual gas pressure in the CT and assess any impact from autonomous operation and transport, we analyze spectra collected over 33 d, extracting the number of antiprotons stored as a function of time, as shown in Fig. 3. Throughout the entire data set, including four runs in autonomous mode totaling 12.3 h, we observe no antiproton annihilation attributable to residual gas interactions. A single particle loss occurred 26 d after injection during trap voltage manipulation ramps performed on the reservoir. Although hermetically sealed cryogenic systems can reach pressures below 1×10^{-18} mbar (48, 49), the open CT geometry for particle ejection leads to residual gas influx of helium and hydrogen. The absence of annihilation events yields an integrated equivalent single-particle storage time of $T_{\bar{p}} = 8.28$ a. Using a Poisson process decay model and annihilation cross-sections reported earlier (48, 49, 53), we obtain a lower limit on the antiproton storage lifetime in our transportable trap system of $\tau_{\bar{p}, \text{lower}} = 7.27$ a at 68% confidence level, with corresponding upper limits on residual gas partial pressures of

$$\begin{aligned} p_{\text{H}} &< 9.6 \times 10^{-19} \text{ mbar}, \\ p_{\text{He}} &< 2.2 \times 10^{-18} \text{ mbar}. \end{aligned} \quad (2)$$

BASE-STEP has been designed to achieve pressures below 1×10^{-16} mbar to ensure antiproton storage over several months (5); the pressure levels achieved during the present transport campaign substantially surpass this design target.

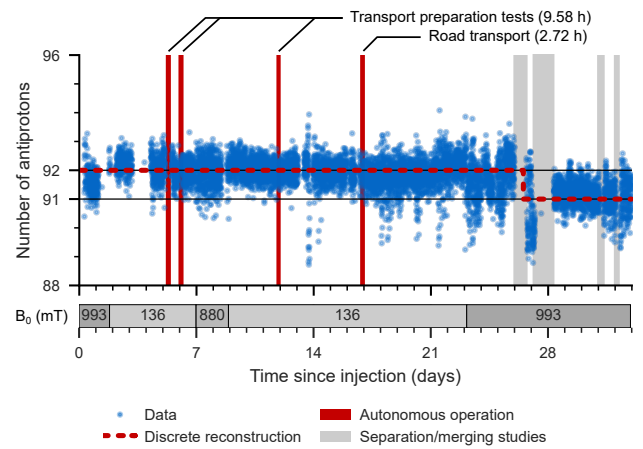


Fig. 3. | Antiproton storage for over one month in the BASE-STEP apparatus. Measured particle number, inferred from the axial dip width, as a function of storage time since antiproton injection on 7 March 2026. Periods of autonomous operation and of particle separation and merging studies are highlighted by colored vertical bars. The magnetic field at the CT trap center is indicated along the x-axis. The red dotted line shows the discrete antiproton number reconstruction obtained by averaging the dip-width data over 24 h intervals and rounding to the nearest integer particle number. On day 26, one antiproton was lost during separation studies (see text for details).

Controlled Transport Reservoir Manipulation. With stable reservoir operation established, we demonstrate controlled antiproton extraction and merging, essential for offline operation. In future implementations, antiprotons will be injected from the transport trap described here into a receiver trap via a transfer beamline, which has been optimized before by using ions produced by a separate ion source. To ensure a successful transfer, only small fractions of the reservoir, ranging from single particles to $\sim 10\%$, will be extracted, transferred, and subsequently merged in the receiver experiment to form a new reservoir. To demonstrate the required control of separation and merging, we apply the sequences sketched in Fig. 4a, adapted from the BASE trap system (32), to the transported reservoir. During separation, carefully ramping the central ring electrode to an inverted voltage divides the cloud into two fractions. A potential offset applied to one of the correction electrodes results in an electric field that displaces the reservoir’s axial center of mass, thereby controlling the extraction yield, defined as the ratio of separated to initial particle number. The separated fraction is transported to the separation electrode (Fig. 1a) at the end of the trap stack, while the remaining particles are retained in the trap center. The fractions are then recombined by gradually merging the trapping potentials.

By comparing the dip widths before separation, after separation, and after merging, we determine both the extraction yield as a function of center-of-mass position (Fig. 4b) and associated losses. Magnetron heating during the voltage ramps is negligible for asymmetric splits, but becomes significant for nearly equal fractions. In those cases, we apply magnetron sideband cooling. Using this procedure, we achieve controlled separation down to a single antiproton, while preserving the integrity of the reservoir, with only one antiproton lost under near-equal splitting conditions. Consequently, we can control the amount of ejected particles, which is essential to establish an antiproton reservoir that can supply offline experiments.

Conclusion. In summary, we resolve the central, previously untested question to enable offline antiproton experiments: we show that antiprotons can be relocated without compromising the extreme vacuum conditions required for their storage. We demonstrate a lossless transport of antiprotons across CERN within the explored regime, establishing the feasibility of offline operation with antiprotons.

Pressure constraints from more than one month of storage time remain below 2.2×10^{-18} mbar, to our knowledge, the lowest pressure ever reported for an open cryogenic Penning-trap system. This record performance establishes the BASE-STEP trap-vacuum interface as a blueprint for future offline apparatus, enabling operation over months or even years after antiproton delivery. Beyond vacuum performance, the experimental workflow has matured into a routine procedure, with repeated transport trials on the same reservoir demonstrating robust near-lossless handling. Further advances in our demonstrated methods are the reliable antiproton injection and full control of separation and merge procedures down to single-antiparticle preparation.

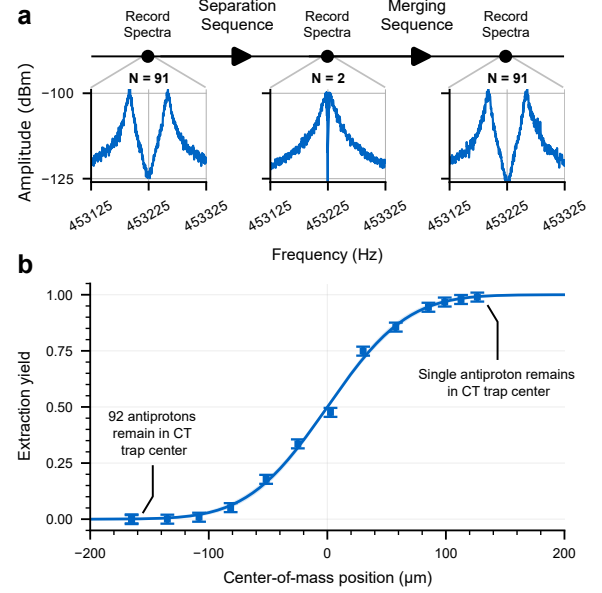


Fig. 4. | Antiproton extraction and merging. **a**, Measurement sequence used to separate antiprotons from the transported reservoir and subsequently merge them back in. Particle numbers are tracked via the dip widths in the image-current detector spectra before separation, after separation, and after merging. **b**, Extraction yield as a function of reservoir center-of-mass position during separation. A yield of 1 corresponds to complete extraction to the separation electrode, while a yield of 0 indicates no extraction from the reservoir. Positive (negative) center-of-mass positions denote displacements towards (away from) the separation electrode. The error bars represent one standard deviation (1σ) uncertainties. The solid line is a model fit based on analytical calculations of the axial energy distribution using 1D Boltzmann statistics (32).

As a next crucial step, we are planning to demonstrate the controlled antiproton transfer to receiver experiments installed for example at CERN and Heinrich Heine University in Düsseldorf, Germany. Highly-efficient transfer between trap systems via electrostatic (54) and magnetic beamlines (55) has already been demonstrated and must now be implemented for our systems. To account for potential transfer losses, we intend to increase the antiproton reservoir size. We expect that antiproton clouds up to 1000 particles can be stabilized by sideband cooling. However, large ion clouds become increasingly sensitive to torque-driven radial expansion (56). Therefore, for the transport of larger clouds, the trap system will be upgraded with a rotating-wall drive (57, 58). Furthermore, we will proceed with the development of long-distance truck transport using a dedicated mobile power and cooling system, conceptually similar to ref. (43).

These advances will complete the transition to antiproton precision experiments beyond their production site, enabling at least 100-fold improvements in measurements of fundamental antiproton properties and higher-precision CPT invariance tests (7, 9, 11). Finally, transportable trap technology can be extended to other charged particles, providing a foundation for high-precision measurements across a broader range of exotic ions (59, 60) and charged antimatter systems (61, 62).

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AUTHOR CONTRIBUTIONS

The transport concept and strategy was conceptualized, developed and implemented by C.S. and S.U. Ideas and methods were provided by S.U.(lead), C.S.(lead), M.L., J.M., F.A., K.K.A., S.E., B.M.L., and D.S. The initial apparatus was prepared by F.A., D.S., and C.S., and upgraded for the antiproton transport by M.L.(lead), C.S.(lead), J.M.(lead), F.A., K.K.A., R.P.C., N.D., S.E., L.K., B.M.L., R.R., D.S., F.V., and S.U. Data acquisition and experiment operation was carried out by M.L.(lead), C.S.(lead), J.M.(lead), K.K.A., S.E., B.M.L., R.R., and S.U. Data analysis was performed by M.L.(lead), C.S., and K.K.A. Funding and resources were provided by C.S.(lead), S.U.(lead), K.B., and J.W. C.S. and S.U. supervised, and C.S. managed the project. The manuscript was written by M.L., C.S. and S.U., all co-authors discussed and approved the content. This article comprises content of the PhD theses of M.L., K.K.A., and S.E.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

DATA AVAILABILITY

The data sets will be made available on reasonable request.

CODE AVAILABILITY

Analysis codes will be made available on reasonable request. Correspondence and requests for materials should be addressed to C.S. Christian.Smorra@cern.ch or S.U. Stefan.Ulmer@cern.ch.

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References

- Gabrielse, G. *et al.* First capture of antiprotons in a Penning trap: a kiloelectronvolt source. *Physical Review Letters* **57**, 2504–2507 (1986). URL <https://doi.org/10.1103/PhysRevLett.57.2504>.
- Lüders, G. Proof of the TCP theorem. *Annals of Physics* **281**, 1004–1018 (2000). URL <https://doi.org/10.1006/aphy.2000.6027>.
- Maury, S. *et al.* ELENA: the extra low energy anti-proton facility at CERN. *Hyperfine Interactions* **229**, 105–115 (2014). URL <https://doi.org/10.1007/s10751-014-1067-y>.
- Bartmann, W. *et al.* The ELENA facility. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **376**, 20170266 (2018). URL <https://doi.org/10.1098/rsta.2017.0266>.
- Smorra, C. *et al.* BASE-STEP: A transportable antiproton reservoir for fundamental interaction studies. *Review of Scientific Instruments* **94**, 113201 (2023). URL <https://doi.org/10.1063/5.0155492>.
- Ulmer, S. *et al.* High-precision comparison of the antiproton-to-proton charge-to-mass ratio. *Nature* **524**, 196–199 (2015). URL <https://doi.org/10.1038/nature14861>.
- Smorra, C. *et al.* A parts-per-billion measurement of the antiproton magnetic moment. *Nature* **550**, 371–374 (2017). URL <https://doi.org/10.1038/nature24048>.
- Schneider, G. *et al.* Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision. *Science* **358**, 1081–1084 (2017). URL <https://doi.org/10.1126/science.aan0207>.
- Borchert, M. J. *et al.* A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio. *Nature* **601**, 53–57 (2022). URL <https://doi.org/10.1038/s41586-021-04203-w>.
- Leonhardt, M. *et al.* Proton transport from the antimatter factory of CERN. *Nature* **641**, 871–875 (2025). URL <https://doi.org/10.1038/s41586-025-08926-y>.
- Latacz, B. M. *et al.* Coherent spectroscopy with a single antiproton spin. *Nature* **644**, 64–68 (2025). URL <https://doi.org/10.1038/s41586-025-09323-1>.
- Cornejo, J. M. *et al.* Quantum logic inspired techniques for spacetime-symmetry tests with (anti-)protons. *New Journal of Physics* **23**, 073045 (2021). URL <https://doi.org/10.1088/1367-2630/ac136e>.
- Hori, M. and Walz, J. Physics at CERN's antiproton decelerator. *Progress in Particle and Nuclear Physics* **72**, 206–253 (2013). URL <https://doi.org/10.1016/j.pnpnp.2013.02.004>.
- Charlton, M. and Eriksson, S. and Shore, G. M. *Antihydrogen and Fundamental Physics*. Springer Cham, Switzerland (2020). URL <https://doi.org/10.1007/978-3-030-51713-7>.
- Greenberg, O. W. CPT violation implies violation of Lorentz invariance. *Physical Review Letters* **89**, 231602 (2002). URL <https://doi.org/10.1103/PhysRevLett.89.231602>.
- Lehnert, R. CPT symmetry and its violation. *Symmetry* **8**, 114 (2016). URL <https://doi.org/10.3390/sym8110114>.
- Fan, X. *et al.* Measurement of the electron magnetic moment. *Physical Review Letters* **130**, 071801 (2023). URL <https://doi.org/10.1103/PhysRevLett.130.071801>.
- Van Dyck Jr, R. S. and Schwinberg, P. B. and Dehmelt, H. G. New high-precision comparison of electron and positron g factors. *Physical Review Letters* **59**, 26–29 (1987). URL <https://doi.org/10.1103/PhysRevLett.59.26>.
- Parthey, C. G. *et al.* Improved measurement of the hydrogen 1S–2S transition frequency. *Physical Review Letters* **107**, 203001 (2011). URL <https://doi.org/10.1103/PhysRevLett.107.203001>.
- Ahmadi, M. *et al.* Characterization of the 1S–2S transition in antihydrogen. *Nature* **557**, 71–75 (2018). URL <https://doi.org/10.1038/s41586-018-0017-2>.
- Borchert, M. J. *et al.* Measurement of ultralow heating rates of a single antiproton in a cryogenic Penning trap. *Physical Review Letters* **122**, 043201 (2019). URL <https://doi.org/10.1103/PhysRevLett.122.043201>.
- Wineland, D. J. and Dehmelt, H. G. Principles of the stored ion calorimeter. *Journal of Applied Physics* **46**, 919–930 (1975). URL <https://doi.org/10.1063/1.321602>.
- Nagahama, H. *et al.* Highly sensitive superconducting circuits at ~ 700 kHz with tunable quality factors for image-current detection of single trapped antiprotons. *Review of Scientific Instruments* **87**, 113305 (2016). URL <https://doi.org/10.1063/1.4967493>.
- Hori, M. *et al.* Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to-electron mass ratio. *Science* **354**, 610–614 (2016). URL <https://doi.org/10.1126/science.aaf6702>.
- Ficek, F. *et al.* Constraints on exotic spin-dependent interactions between matter and antimatter from antiprotonic helium spectroscopy. *Physical Review Letters* **120**, 183002 (2018). URL <https://doi.org/10.1103/PhysRevLett.120.183002>.
- Safronova, M. S. *et al.* Search for new physics with atoms and molecules. *Reviews of Modern Physics* **90**, 025008 (2018). URL <https://doi.org/10.1103/RevModPhys.90.025008>.
- Smorra, C. *et al.* Direct limits on the interaction of antiprotons with axion-like dark matter. *Nature* **575**, 310–314 (2019). URL <https://doi.org/10.1038/s41586-019-1727-9>.
- Alighanbari, S. *et al.* Precise test of quantum electrodynamics and determination of fundamental constants with HD⁺ ions. *Nature* **581**, 152–158 (2020). URL <https://doi.org/10.1038/s41586-020-2261-5>.
- Budker, D. *et al.* Millicharged dark matter detection with ion traps. *PRX Quantum* **3**, 010330 (2022). URL <https://doi.org/10.1103/PRXQuantum.3.010330>.
- Smorra, C. *et al.* BASE–The Baryon Antibaryon Symmetry Experiment. *The European Physical Journal Special Topics* **224**, 3055–3108 (2015). URL <https://doi.org/10.1140/epjst/e2015-02607-4>.
- Ulmer, S. *et al.* Direct high-precision measurement of the g-factor of a single antiproton stored in a cryogenic Penning trap. CERN-SPSC-2012-019, SPSC-I-241, CERN, Geneva (2012). URL <https://cds.cern.ch/record/1455847>.
- Smorra, C. *et al.* A reservoir trap for antiprotons. *International Journal of Mass Spectrometry* **389**, 10–13 (2015). URL <https://doi.org/10.1016/j.ijms.2015.08.007>.
- Devlin, J. A. *et al.* Superconducting solenoid system with adjustable shielding factor for precision measurements of the properties of the antiproton. *Phys. Rev. Applied* **12**, 044012 (2019). URL <https://doi.org/10.1103/PhysRevApplied.12.044012>.
- Ulmer, S. *et al.* BASE – Annual report 2024. CERN-SPSC-2025-006, SPSC-SR-361, CERN, Geneva (2025). URL <https://cds.cern.ch/record/2923879>.
- Sailer, T. *et al.* Measurement of the bound-electron g-factor difference in coupled ions. *Nature* **606**, 479–483 (2022). URL <https://doi.org/10.1038/s41586-022-04807-w>.
- Schneider, A. *et al.* Direct measurement of the ³He⁺ magnetic moments. *Nature* **606**, 878–883 (2022). URL <https://doi.org/10.1038/s41586-022-04761-7>.
- Schweiger, C. *et al.* Penning-trap measurement of the Q value of electron capture in ¹⁶³Ho for the determination of the electron neutrino mass. *Nature Physics* **20**, 921–927 (2024). URL <https://doi.org/10.1038/s41567-024-02461-9>.
- Kromer, K. *et al.* Atomic mass determination of uranium-238. *Phys. Rev. C*, **109**, L021301, (2024). URL <https://link.aps.org/doi/10.1103/PhysRevC.109.L021301>.
- Borchert, M. J., Challenging the Standard Model by high precision comparisons of the fundamental properties of antiprotons and protons, PhD thesis, Gottfried Wilhelm Leibniz Universität Hannover, Hannover (2021). URL <https://doi.org/10.15488/11564>.
- Dehmelt, H. Economic synthesis and precision spectroscopy of anti-molecular hydrogen ions in Paul trap. *Physica Scripta* **T59**, 423–423 (1995). URL <https://doi.org/10.1088/0031-8949/1995/t59/060>.
- Wada, M. & Yamazaki, Y. Technical developments toward antiprotonic atoms for nuclear structure studies of radioactive nuclei. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **214**, 196–200 (2004). URL <https://doi.org/10.1016/j.nimb.2003.08.019>.
- Tseng, C. H. & Gabrielse, G. Portable trap carries particles 5000 kilometers. *Hyperfine Interactions* **76**, 381–386 (1993). URL <https://doi.org/10.1007/BF02316739>.
- Aumann, T. *et al.* PUMA, antiproton unstable matter annihilation - PUMA collaboration. *Eur. Phys. J. A* **58**, 88 (2022). URL <https://doi.org/10.1140/epja/s10050-022-00713-x>.
- Caravita, R. *et al.* Progress report of the AeGIS experiment 2025. CERN-SPSC-2026-004, SPSC-SR-374, CERN, Geneva (2026). URL <https://cds.cern.ch/record/2954126>.
- Alfaro, S. *et al.* Towards metrology with highly charged isomeric ions from antiproton annihilation. *J. Phys. B: At. Mol. Opt. Phys.* **58**, 215002 (2025). URL <https://doi.org/10.1088/1361-6455/ae19af>.
- Brown, L. S. & Gabrielse, G. Geonium theory: Physics of a single electron or ion in a Penning trap. *Reviews of Modern Physics* **58**, 233–311 (1986). URL <https://doi.org/10.1103/RevModPhys.58.233>.
- Gabrielse, G., Haarsma, L. & Rolston, S. L. Open-endcap Penning traps for high precision experiments. *International Journal of Mass Spectrometry and Ion Processes* **88**, 319–332 (1989). URL [https://doi.org/10.1016/0168-1176\(89\)85027-X](https://doi.org/10.1016/0168-1176(89)85027-X).
- Sellner, S. *et al.* Improved limit on the directly measured antiproton lifetime. *New Journal of Physics* **19**, 083023 (2017). URL <https://doi.org/10.1088%2F1367-2630%2Faa7e73>.
- Jäger, J. I. Progress on antiproton cooling and an improved direct limit on the antiproton lifetime. PhD thesis, Heidelberg University, Heidelberg (2025). URL <https://doi.org/10.11588/heidok.00037815>.
- Latacz, B. M. *et al.* Ultra-thin polymer foil cryogenic window for antiproton deceleration

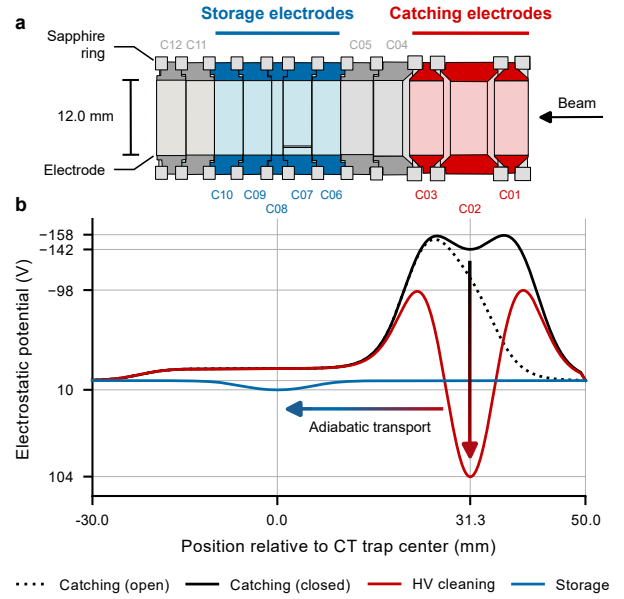
- and storage. *Review of Scientific Instruments* **94** (2023). URL <https://doi.org/10.1063/5.0167262>.
51. Nordlund, K. and Hori, M. and Sundholm, D. Large nuclear scattering effects in antiproton transmission through polymer and metal-coated foils. *Physical Review A* **106** (2022). URL <https://doi.org/10.1103/PhysRevA.106.012803>.
 52. Cornell, E. A., Weisskoff, R. M., Boyce, K. R. & Pritchard, D. E. Mode coupling in a Penning trap: π pulses and a classical avoided crossing. *Phys. Rev. A* **41**, 312–315 (1990). URL <https://doi.org/10.1103/PhysRevA.41.312>.
 53. Fei, X. Trapping low energy antiprotons in an ion trap. PhD thesis, Harvard University (1990). URL https://cfp.physics.northwestern.edu/documents/1990_Fei_Xiang_Thesis.pdf.
 54. Kluge, H.-J. and Bollen, G. ISOLTRAP: A tandem Penning trap mass spectrometer for radioactive isotopes. *Hyperfine Interactions* **81**, 15–26 (1993). URL <https://doi.org/10.1007/BF00567247>.
 55. Baker, C. J. *et al.* Design and performance of a novel low energy multispecies beamline for an antihydrogen experiment. *Physical Review Accelerators and Beams* **26** (2023). URL <https://doi.org/10.1103/PhysRevAccelBeams.26.040101>.
 56. Mitchell, T. B. *et al.* Mode and transport studies of laser-cooled ion plasmas in a Penning trap. *AIP Conference Proceedings* **457**, 309–318 (1999). URL <https://doi.org/10.1063/1.57470>.
 57. Huang, X.-P. *et al.* Steady-state confinement of non-neutral plasmas by rotating electric fields. *Physical Review Letters* **78**, 875–878 (1997). URL <https://doi.org/10.1103/PhysRevLett.78.875>.
 58. Fajans, J. and Surko, C. M. Plasma and trap-based techniques for science with antimatter. *Physics of Plasmas* **27**, 030601 (2020). URL <https://doi.org/10.1063/1.5131273>.
 59. Kluge, H.-J. *et al.* Chapter 7 HITRAP: A facility at GSI for highly charged ions. In Salomonson, S. & Lindroth, E. (eds.) *Current Trends in Atomic Physics*, vol. 53 of *Advances in Quantum Chemistry*, 83–98 (Academic Press, 2008). URL [https://doi.org/10.1016/S0065-3276\(07\)53007-8](https://doi.org/10.1016/S0065-3276(07)53007-8).
 60. Sturm, S. *et al.* The ALPHATRAPP experiment. *The European Physical Journal Special Topics* **227**, 1425–1491 (2019). URL <https://doi.org/10.1140/epjst/e2018-800225-2>.
 61. Pérez, P. *et al.* The GBAR antimatter gravity experiment. *Hyperfine Interactions* **233**, 21–27 (2015). URL <https://doi.org/10.1007/s10751-015-1154-8>.
 62. Myers, E. G. CPT tests with the antihydrogen molecular ion. *Physical Review A* **98**, 010101 (2018). URL <https://doi.org/10.1103/PhysRevA.98.010101>.

Methods

A. Antiproton Catching and Cleaning Procedure. The BASE-STEP catching trap (CT) is constructed of 15 cylindrical electrodes arranged in a coaxial stack (Fig. A1a). Sapphire rings ensure electrical insulation and mechanical alignment. Antiprotons emerging from the degrader foil follow the magnetic field lines ($B = 993$ mT) into the trap, where three high-voltage electrodes (C01–C03) on the degrader side capture them. These electrodes form a nested axial potential well floated to -142 V with a depth of 16 V (Fig. A1b). For capture, we pulse the beam-side electrode C01 from 0 V to -158 V within 30 ns using a high-voltage switch. This pulse closes the potential well centered on C02 and traps antiprotons from the low-energy tail of the degraded beam.

After capture, co-trapped electrons – secondary particles forced out of the degrader – sympathetically cool the antiprotons (63). We then ramp the C02 voltage to increase the trapping potential to 200 V, which destabilizes most contaminant negative ions while preserving antiproton confinement due to their higher q/m . We subsequently transport the particles to the central region of the CT. To this end, we configure electrodes C01–C03 to form a 20 V well and shift the axial potential adiabatically through the stack (typical electrode ramp time: 1 s). We finally confine the particles in a compensated, orthogonal five-electrode Penning trap formed by the central ring electrode C08, correction electrodes C07 and C09, and grounded endcaps starting at C06 and C10.

For non-destructive antiproton detection, we remove residual contaminants that would otherwise distort particle motion via space-charge effects and prevent formation of a stable axial

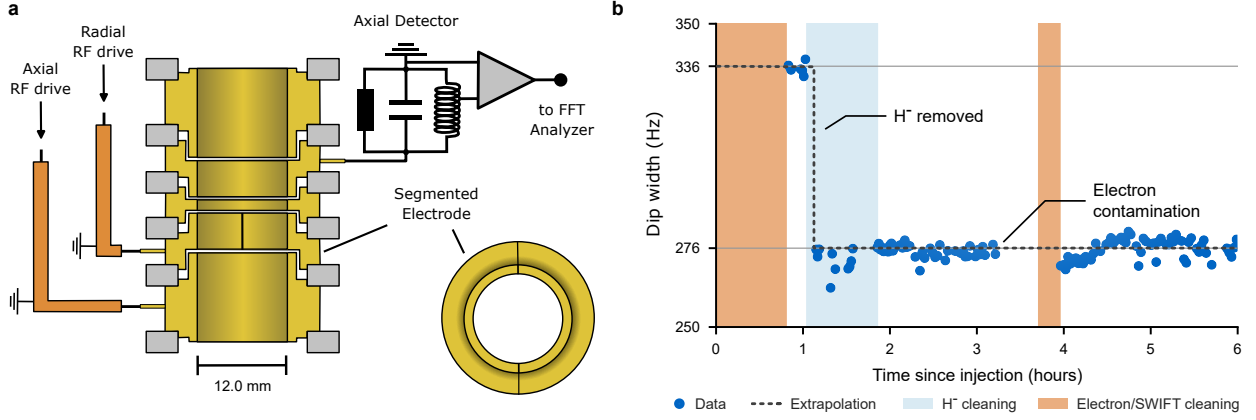


Extended Data Fig. A1. | Antiproton catching potentials. **a**, Cross-sectional illustration of the BASE-STEP CT showing all electrodes biased during the catching procedure. Each electrode is labeled (C01–C12), numbered along the antiproton beam direction (C01 at entrance). The storage electrodes (blue) and the high-voltage catching electrodes (red) are highlighted. **b**, Sequence of on-axis potentials applied during the antiproton catching procedure.

dip signal. The dominant residual species are electrons and H^- ions, which cannot be eliminated by high-voltage cleaning due to their similar or higher q/m .

We remove co-trapped electrons by applying an axial dipolar drive at 9.59 MHz to an endcap electrode (Fig. A2a). By reducing the trap depth to 1 V, we tune the electron axial frequency into resonance with the applied drive. We then further reduce the trap depth to 0.5 V, evaporating the excited electrons. We repeat this sequence until no electrons remain. The drive is sufficiently detuned from the motional frequencies of antiprotons and H^- ions to avoid unintended excitation. Following injection, we repeat electron cleaning as needed to remove beta-decay-induced electron contamination from activated surfaces (Fig. A2b). We then tune the particle cloud into resonance with the axial detector (453 kHz) and apply magnetron sideband cooling. As described in the main text, at thermal equilibrium, the particle–detector interaction produces a characteristic dip in the detector noise spectrum. Next, we remove heavier residual ions that persist after the initial high-voltage ramp using a stored waveform inverse Fourier transform (SWIFT) excitation (64) applied to the endcap electrode. The drive spans 20 kHz to 380 kHz, exciting their axial motion. By subsequently reducing the trap depth to 0.5 V and repeating the sequence, we obtain a reservoir containing only antiprotons and H^- ions.

Antiprotons and H^- ions exhibit nearly identical axial frequencies (separated by ~ 250 Hz) and indistinguishable dip widths per particle, such that both species contribute to a combined dip signal. At the applied catching parameters, we typically obtain a mixed particle cloud consisting of approximately 80% antiprotons and 20% H^- ions. To discriminate between them, we exploit the difference in modified cy-



Extended Data Fig. A2. | Antiproton reservoir cleaning. **a**, Shielded excitation lines deliver RF drives for axial excitation to an endcap electrode and for radial excitation to a segmented correction electrode. **b**, Co-trapped electrons and negative ions, including H^- , are removed by resonantly exciting their axial (electron/SWIFT cleaning) or cyclotron (H^- cleaning) motion and ramping the trap potential to a shallow depth. Removal of H^- leads to a reduction in dip width (1 h after injection), whereas electron contamination perturbs the dip-width measurement and produces a gap in the recorded data (3.3 h).

clotron frequency, which amounts to approximately 16 kHz at $B = 993$ mT. Using a single trapped proton as a magnetic field probe prior to injection, we determine

$$\nu_{+,p} = 15.140 \text{ MHz}, \quad \nu_{+,H^-} = 15.124 \text{ MHz}. \quad (3)$$

We selectively remove H^- ions by applying a radial dipolar RF drive to a segmented correction electrode (Fig. A2a). A frequency sweep from 15.130 MHz to 15.120 MHz resonantly excites the H^- modified cyclotron motion, increasing its radius until radial confinement is lost, while leaving antiprotons unaffected. We verify successful removal by monitoring the dip width before and after excitation (Fig. A2b). We repeat the sweep until the dip width no longer decreases (typically after one sweep, at least three are applied for robustness), yielding a clean antiproton reservoir.

Given the procedure described above, we currently prepare antiproton reservoirs containing approximately 90 antiprotons per beam injection.

B. Particle number calibration. The particle number N as shown in Eq. 1 is determined from the linear dependence of the axial resonator dip width $\Delta\nu_z$ on the number of trapped particles. The relation can be simplified to

$$\Delta\nu_z = \Delta\nu_{z,1} N, \quad (4)$$

where $\Delta\nu_{z,1}$ denotes the single-particle dip width. This proportionality enables extraction of N from measured spectra once a calibration of $\Delta\nu_{z,1}$ has been established. Calibration measurements use proton and antiproton clouds of different sizes. We prepare clouds containing approximately 20 particles in the CT, as larger particle numbers require longer averaging times for precise counting. The clouds are then reduced stepwise to a single particle by controlled evaporation. At each step, we record the spectra and fit the dip lineshape (22) to determine $\Delta\nu_z$. The final single-particle signal provides a reference for $\Delta\nu_{z,1}$, allowing assignment of particle numbers to intermediate cloud sizes. Linear fits of $\Delta\nu_z(N)$ yield the

calibration functions. Proton and antiproton data are treated equivalently as their $\Delta\nu_{z,1}$ is identical. The dip width depends on the magnetic field, as the effective parallel resistance R_p of the superconducting resonator varies with field strength. Following a magnetic-field ramp from 136 mT to 993 mT, we observe a reduction in dip width (Fig. B1a), consistent with a decrease in R_p at higher magnetic fields (65). The single-particle dip width scales linearly with R_p :

$$\Delta\nu_{z,1} = \frac{1}{2\pi} \frac{q^2}{mD_z^2} R_p. \quad (5)$$

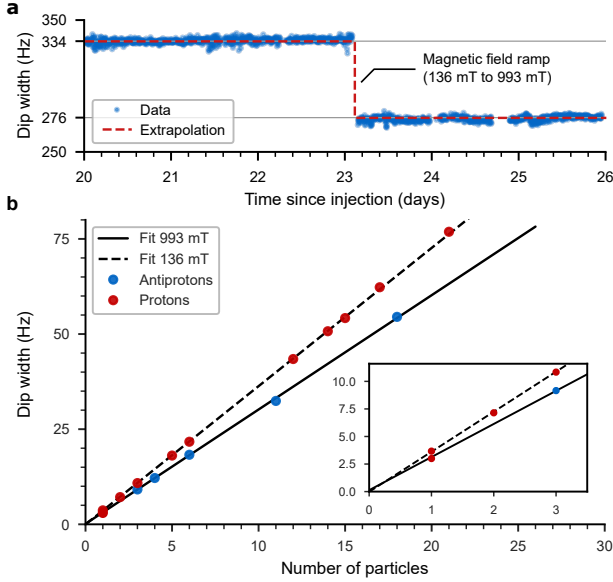
We therefore perform separate calibration measurements for each magnetic field. Linear fits of $\Delta\nu_z(N)$ for 136 mT and 993 mT (Fig. B1b) yield

$$\begin{aligned} \Delta\nu_z(993 \text{ mT}) &= 3.004(24) \text{ Hz} \cdot N + 0.129(166) \text{ Hz}, \\ \Delta\nu_z(136 \text{ mT}) &= 3.633(16) \text{ Hz} \cdot N - 0.017(105) \text{ Hz}, \end{aligned} \quad (6)$$

where the intercepts are consistent with zero within uncertainty. The calibration data shown has been obtained from a proton cloud with $N = 21$ at 136 mT and an antiproton cloud with $N = 18$ at 993 mT. The single-proton reference point at 993 mT, obtained after complete evaporation, serves as an independent cross-check of the antiproton single-particle dip width at that field.

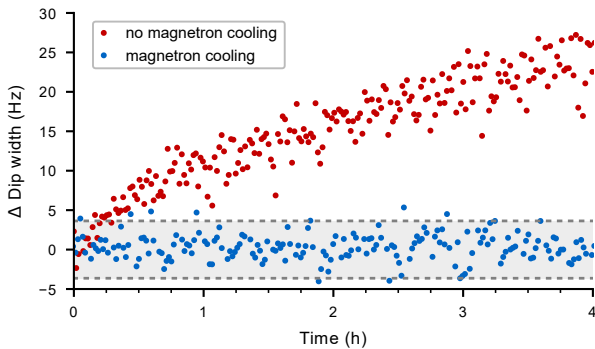
For 880 mT, where no direct calibration measurement is available, the dip width per particle is inferred from the measured detector R_p . Using the proportionality $\Delta\nu_{z,1} \propto R_p$ and comparison to calibrated field settings, we obtain $\Delta\nu_{z,1}(880 \text{ mT}) \approx 3.07(4) \text{ Hz}$.

To monitor the antiproton number in the transport reservoir over time, we implement an automated measurement sequence recording image-current spectra with an averaging time of 64 s. The stored antiproton cloud undergoes slow radial expansion, an effect that has been observed and studied in detail in other traps (56, 66). In general, cylinder-symmetry breaking components of the electric field apply a torque to the trapped ion cloud driving the radial expansion.



Extended Data Fig. B1. | Dip width calibration. **a**, Measured dip width of the transport reservoir as a function of storage time following antiproton injection. A distinct change in dip width is observed after ramping the magnetic field (23 d after injection). **b**, Evaporation measurements used for particle-number calibration, showing dip width versus particle number. Red (blue) points correspond to (anti)proton data, black lines indicate linear fits defining the calibration functions at 136 mT and 993 mT.

Here, these arise potentially from a small tilt between the electric and magnetic field axes, patch potentials or leakage currents on the segmented electrodes. The radial expansion results in a shift of the axial frequency and also in an increased dip width due to the residual potential imperfections in the trap, see Fig. B2. Compared to our proton tests where the radial expansion has not been observable on a time scale of 4 hours (10), our trap currently exhibits a higher torque and requires regular magnetron cooling cycles to reset the radial expansion and enable an accurate particle number extraction.



Extended Data Fig. B2. | Antiproton dip stabilization. Deviation of the measured dip width from the expected value for $N=92$ antiprotons over two overlaid 4 h data sets, with consecutive measurements taken at 64 s averaging time. In one data set, no magnetron sideband cooling was applied, resulting in an increasing deviation over time. In the other, magnetron sideband cooling was applied for 64 s after every six measurements, keeping the dip-width deviation centered within the ± 1 antiproton range indicated by the grey shaded area.

To suppress this systematic effect, we apply magnetron sideband cooling in 6-minute intervals, which keeps the cloud

centered in the trap. The residual drift corresponds to a particle-number offset of only 0.1(2) antiprotons for a cloud of $N = 92$. Additional systematic increases of the dip width occur if the tuning ratio and frequency detuning between particles and resonator deviate from their optimum values. However, these have been optimized so that their contribution to the particle number is not significant. For substantially larger clouds containing more than 1000 antiprotons, however, we expect these effects to introduce significant uncertainties. In this regime, the application of a rotating-wall drive becomes desirable for reliable particle-number determination.

Over a period of 33 d, we have acquired more than 26000 spectra and extracted the dip width from each spectrum by fitting the appropriate line shape (22) to them. For our evaluation, we average the dip width over 24 h intervals and apply the magnetic-field-dependent calibration functions, and round to the next integer number to determine the particle number. In this way, the statistical deviation from the integer number is small and systematic shifts of order 0.1 particle numbers do not affect the extracted particle number.

During the first four days, non-optimized trap parameters resulted in dip width broadening, leading to a systematic overestimation of the particle number. Therefore, these data require an additional correction. After determining the particle number with optimized settings, we repeated measurements at 136 mT and 993 mT under identical non-optimized conditions and compared them to spectra recorded with optimized settings. For these settings, we obtain correction factors of $k = \Delta\nu_{z,\text{true}}/\Delta\nu_{z,\text{measured}}$,

$$\begin{aligned} k(993 \text{ mT}) &= 0.9779(11), \\ k(136 \text{ mT}) &= 0.99395(54). \end{aligned} \quad (7)$$

The evaluation procedure in this section yields the time evolution of the antiproton number shown in Fig. 3 of the main text.

C. Storage time and trap vacuum pressure. As noted in the main text, only a single antiproton has been lost over the full 33 d storage period. The loss has occurred during voltage ramp sequences applied to the reservoir as part of manipulation studies. Because these ramp sequences permitted only intermittent monitoring of the reservoir, the exact time of particle loss cannot be determined precisely. Based on the available spectrum data, we assign an uncertainty of 3 h to the loss time.

Event	Date	Time
Injection	07.03.2026	11:18
Particle loss	03.04.2026	01:19 $\pm$ 3 h
Last data point	09.04.2026	10:56

Extended Data Tab. 1. | Antiproton reservoir event timeline. Key reservoir events with corresponding dates and times. The uncertainty in the particle-loss time is given in the time column. Times are reported in 24-hour format.

Using the event timeline in Tab. 1 we obtain a total antiproton storage duration of 32 d 22 h 38 min. This corresponds to 26 d 13 h 01 min $\pm$ 3 h for $N = 92$ and 06 d 09 h 37 min $\mp$ 3 h for $N = 91$. By weighting the storage time with the particle

number and summing the contributions for $N = 92$ and $N = 91$, we obtain an integrated equivalent single-particle storage time of $T_{\bar{p}} = 8.28025(34)$ a.

We model antiproton annihilation as a Poisson process, $f(n; \lambda) = \lambda^n e^{-\lambda} / n!$, with expectation value $\lambda = T_{\bar{p}} / \tau_{\bar{p}, \text{lower}}$. Assuming zero observed annihilation events ($n = 0$), the lower bound on the antiproton lifetime at a given confidence level (CL) is obtained from the probability of observing zero events:

$$\text{CL} = 1 - \epsilon = 1 - f(0; \lambda), \quad (8)$$

with

$$f(0; \lambda) = \exp\left(-\frac{T_{\bar{p}}}{\tau_{\bar{p}, \text{lower}}}\right). \quad (9)$$

This yields a lower limit on the antiproton storage lifetime under our experimental conditions of $\tau_{\bar{p}, \text{lower}} = 7.27$ a at a 68% confidence level.

The pressure limits reported in the main text are based on following approach: The conversion of the storage lifetime into an upper limit for the partial pressure of one residual gas component is performed by calculating the reaction rate based on the cross-section of the annihilation reaction:

$$R = \frac{1}{\tau} = \frac{v_{\text{rel}}}{\lambda} = \sigma n_{\text{gas}} v_{\text{rel}} \quad (10)$$

where λ is the mean free path of the particle in the residual gas, v_{rel} the relative velocity between the particle and the gas molecules, σ the reaction cross section, and n_{gas} the density of the residual gas. This density is then converted into the pressure p using the ideal gas law:

$$p_{\text{gas}} = n_{\text{gas}} k_B T_{\text{gas}} = \frac{k_B T_{\text{gas}}}{\tau \sigma v_{\text{rel}}}. \quad (11)$$

The temperature of the residual gas inside the trap chamber is measured by the thermometer on the magnet coil body which has a strong thermal connection to the walls of the trap chamber and is typically at $T_{\text{gas}} = 4.3$ K. We assume here that the residual gas is only composed of hydrogen molecules and helium atoms, and that all other gases freeze out in the DPS or trap chamber before reaching the trap center. Since the residual gas composition is not known, the upper limit on the total pressure in the trap chamber is set by the highest partial pressure limit and the assumption that this component makes up 100% of the residual gas pressure.

The remaining task is now to insert the annihilation cross section and the relative velocity. The frequently-used cross section formulas for the annihilation reaction with hydrogen (32, 43, 48, 49) trace back to studies about protonium formation (53, 67–69), and approximate the reaction as being with atomic hydrogen. We use the cross-section derived in ref. (68) as:

$$\sigma = 3\pi a_0^2 \sqrt{E_0/E} = 6\pi a_0^2 \sqrt{\frac{E_0}{m_{\bar{p}}}} \frac{1}{v_{\text{rel}}}, \quad (12)$$

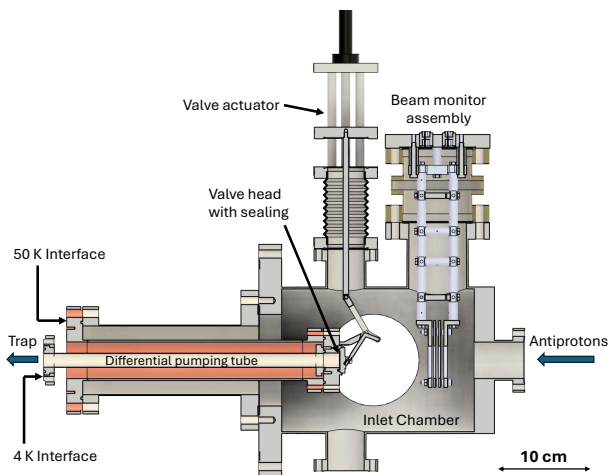
where a_0 is the Bohr radius and $E_0 = 27.2$ eV twice the binding energy of the hydrogen atom. Notably, the $1/v_{\text{rel}}$

scaling makes the reaction rate and consequently the pressure limits independent of v_{rel} and therefore also of the effective noise-temperature of the detection circuit that defines the trapped particle velocity. The same applies for the annihilation cross section of helium, where the Langevin cross section is used (53), so that a determination of v_{rel} becomes unnecessary to report the pressure limits in the main text.

We additionally consider a conservative scenario in which the antiproton loss is attributed to annihilation with residual gas rather than to the voltage ramps applied during separation and merging. Under this assumption, a likelihood analysis yields a lower bound on the storage lifetime of $\tau_{\bar{p}, \text{lower}} = 3.6$ a at the 68% confidence level, with a maximum likelihood estimate of 8.3 a. The corresponding pressure constraint relaxes to an upper limit of 4.4×10^{-18} mbar, with a maximum likelihood value of 1.9×10^{-18} mbar, which remains below the upper limit quoted in the main text under the assumption of no annihilation events. Even this conservative bound of 4.4×10^{-18} mbar represents, to our knowledge, the lowest pressure reported to date for an open cryogenic Penning-trap system and exceeds the minimum operational requirements by more than an order of magnitude. However, given the temporal coincidence of the loss event with the ramp sequence, together with comparable loss behavior observed for other antiproton clouds under similar manipulation conditions in the same apparatus, a chance annihilation event due to residual gas is highly unlikely.

D. Inlet valve and vacuum interface. The injection beamline is operated at local pressures from 6×10^{-9} mbar to 3×10^{-8} mbar, determined by the outgassing, conductance, and pumping speed along the line. The inlet chamber pressure is held below 1×10^{-9} mbar using a non-evaporative getter (NEG) pump during trap operation and transport, and a turbomolecular pump (TMP) in addition while the valves to the injection beamline are open. The differential pumping section is described in Ref. (5) and connects the vacuum of the inlet chamber and the trap chamber for the antiproton transfer with a conductance of 0.16 L/s. It also manages the thermal conductance of the vacuum chamber from room temperature to 4 K via a set of concentric tubes. The inlet valve located at the entrance of the differential pumping channel is connected via a copper tube to the 50 K heatshield of the magnet. It is supposed to be only opened for the antiproton transfer and closed during storage and transport operations. This reduces the residual gas flow into the trap chamber and increases the monolayer formation time. The inlet valve used in Refs. (5, 10) has been exchanged for a newly developed version shown in Fig. D1. It improves the sealing, mechanics, and heat load compared to the previous version. In particular, the valve head presses on a PTFE gasket when closing and is supposed to have a lower leak rate than the previously installed metal-on-metal sealed version.

E. Transport setup. Fig. E1 summarizes the electronic setup integrated within the transport frame (see Fig. 2a) for



Extended Data Fig. D1. | Upgraded cryogenic valve. Schematic of the vacuum interface between the beamline and the trap, showing the differential pumping channel and the inlet chamber. The cryogenic inlet valve, and the beam monitor can be moved in and out of the beam path using linear actuation stages.

autonomous operation. The antiproton cloud is confined within the central ring electrode (C08) of the CT. Axial confinement is provided by biasing the ring and adjacent correction electrodes with a high-precision voltage supply. All remaining electrodes are grounded through relays at the room-temperature interface.

The antiproton cloud is monitored via the noise spectrum of the image-current detector using a sound-card-based FFT system. The cryogenic amplifier is powered by a precision DC supply, whereas the room-temperature amplifiers operate from battery power. Magnetron sideband cooling is implemented through a waveform generator connected to the radial excitation line of the CT. The transport frame further incorporates a LHe heater element on the LHe tank to increase the gas flow for cooling of the magnet heat shields by heat transfer to the cold gas in heat exchanger elements on the exhaust line. Before transport, the TMP gate valve on the inlet chamber is closed, whereas the NEG-pump valve remains open to maintain vacuum conditions in the inlet chamber. Consequently, continuous power is supplied to the NEG-pump valve to prevent automatic closure during transport.

All transport electronics except the room-temperature amplifiers are powered by a dedicated UPS, with a total transport power consumption of approximately 170 W (Tab. 2). The UPS has a capacity of approximately 750 Wh, providing around 4.5 h of operation after the BASE-STEP apparatus has been disconnected from external power. All voltage supplies, waveform generators, the sound card, sensor readout devices, and a telemetry logger are connected to the transport control PC, a frame-mounted mini-PC. It continuously monitors the particle signal, cryostat temperatures, telemetry sensors, LHe level and vacuum pressures. The PC additionally controls electrode voltages and RF drives for magnetron sideband cooling during transport. After disconnection from external infrastructure, remote access to the transport control PC is established via a wireless network.

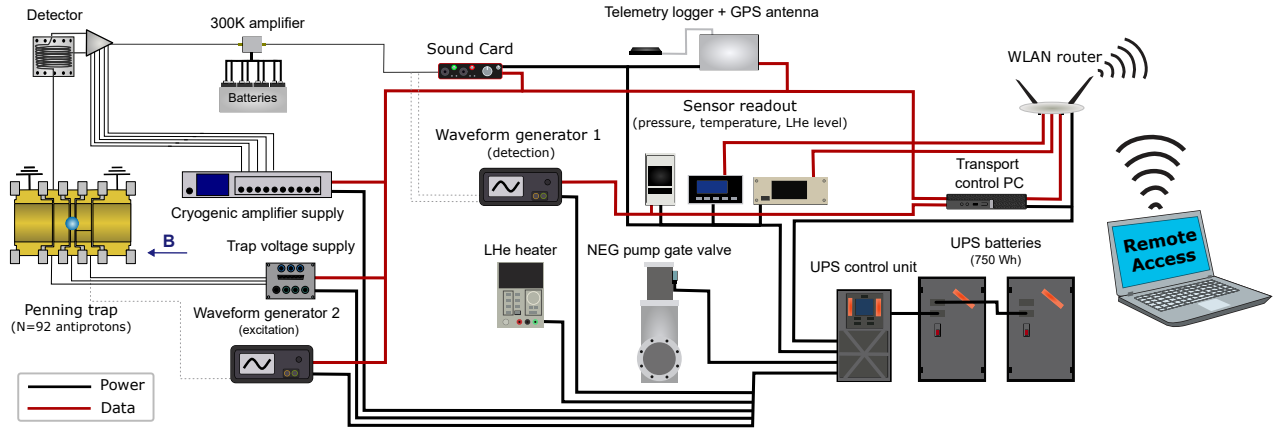
Power (W)	Device
46.5	Transport control PC
24.2	Waveform generator 1 (detection)
20.0	Liquid helium heater
19.9	Waveform generator 2 (excitation)
13.8	Liquid helium levelmeter
11.7	Trap voltage supply
10.5	Cryogenic amplifier power supply
05.8	NEG pump gate valve
04.9	Pressure sensor readout
04.5	Soundcard FFT spectrum analyzer
03.0	Temperature sensor readout
01.4	Wireless router
00.3	Telemetry logger
166.5	Total

Extended Data Tab. 2. | Power consumption. The average power consumption in transport configuration broken down by devices from highest consumption to lowest.

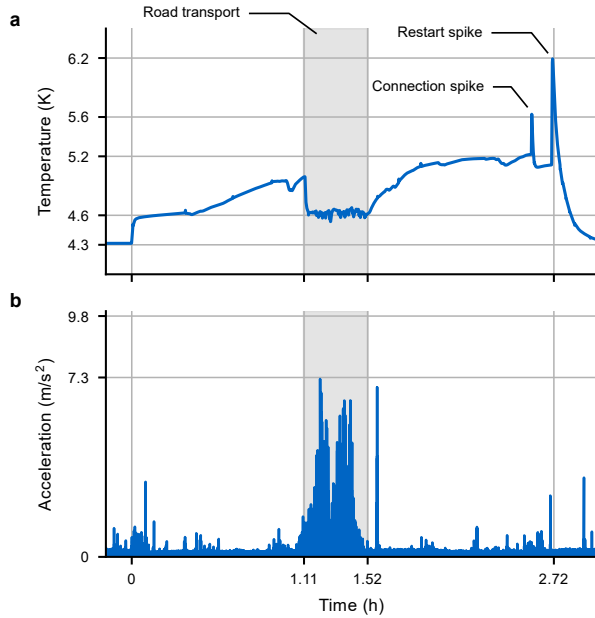
F. Additional transport data. With the cryocooler switched off, the magnet temperature (Fig. F1a) gradually increases. Once inactive, the pulse tubes act as a thermal conduction path to the magnet, which remains thermally linked to the cryocooler. Consequently, the magnet temperature increases from 4.3 K to an equilibrium value of approximately 5.2 K. During the 2 h 43 min transport sequence, approximately 11 L of liquid helium evaporate, corresponding to nearly half of the initial LHe buffer reservoir.

The overall temperature evolution during antiproton transport is consistent with that observed during the proton transport rehearsal (10). During road transport (1.11 h to 1.52 h), accelerations of the transport frame (Fig. F1b), including vibration-induced peaks, generate turbulence in the LHe buffer tank. This enhances magnet cooling and maintains the temperature near 4.6 K throughout truck transport. Transport has been performed using a medium-duty truck equipped with air suspension and an automatic transmission. To reduce mechanical shocks and high-frequency vibrations, a 5 t steel plate has been installed in the truck bed to soften the effective suspension response during transport.

Transient temperature spikes are observed at 2.57 h and 2.72 h of autonomous operation. The first spike occurs during connection of the cryocooler flexlines. During disconnection, a pressure differential develops between the flexlines and the transport-frame-mounted cooling system, with higher pressure in the flexlines. Upon reconnection, helium gas flows into the cryocooler cold head, transiently heating the 4 K stage and causing a temporary increase in magnet temperature. The second spike occurs upon cryocooler restart at the end of transport. During inactivity, helium gas within the cryocooler warms, such that initial compressor operation transfers heat into the 4 K stage before steady-state cooling resumes. Following restart of the cooler, the magnet temperature returns to its initial operating temperature.



Extended Data Fig. E1. | Transport mode setup. Overview of the devices used in the autonomous transport mode and their respective power and data connections. The BASE-STEP apparatus can be remotely controlled and monitored via a laptop or smartphone.



Extended Data Fig. F1. | Transport sensor data. **a**, Magnet temperature and **b**, total acceleration measured during autonomous operation. The zero on the horizontal axis marks the shutdown time of the cryocooler. The gray bar indicates the time interval corresponding to the road transport.

Approximately 50% of the UPS battery capacity has been consumed during transport. During stationary periods, the UPS is temporarily reconnected to external power to preserve battery capacity. Vacuum conditions remain stable throughout transport. Pressure spikes reaching the 10^{-7} mbar level are observed in the cryostat vacuum chamber and are attributed to gas release from the multilayer insulation surrounding the thermal stages of the magnet. In contrast, the inlet-chamber pressure remains below the gauge detection threshold of 1×10^{-9} mbar, with only occasional vibration-induced outgassing spikes below 3×10^{-9} mbar.

Extended References

63. Gabrielse, G. *et al.* Cooling and slowing of trapped antiprotons below 100 mV. *Physical Review Letters* **63**, 1360–1363 (1989). URL <https://doi.org/10.1103/PhysRevLett.63.1360>.
64. Guan, S. & Marshall, A. G. Stored waveform inverse Fourier transform (SWIFT) ion excitation in trapped-ion mass spectrometry: Theory and applications. *International Journal of Mass Spectrometry and Ion Processes* **157**, 5–37 (1996). URL [https://doi.org/10.1016/S0168-1176\(96\)04461-8](https://doi.org/10.1016/S0168-1176(96)04461-8).
65. Ulmer, S. *et al.* The quality factor of a superconducting rf resonator in a magnetic field. *Review of Scientific Instruments* **80**, 123302 (2009). URL <https://doi.org/10.1063/1.3271537>.
66. Will, C. *et al.* Image-current mediated sympathetic laser cooling of a single proton in a Penning trap down to 170 mK axial temperature. *Physical Review Letters* **133**, 023002 (2024). URL <https://doi.org/10.1103/PhysRevLett.133.023002>.
67. Morgan, D. L. and Hughes, V. W. Atom-antiatom interactions. *Physical Review A* **7**, 1811–1825 (1973). URL <https://doi.org/10.1103/PhysRevA.7.1811>.
68. Bracci, L. and Fiorentini, G. and Pitzurra, O. Protonium formation in flight. *Physics Letters B* **85**, 280–284 (1979). URL [https://doi.org/10.1016/0370-2693\(79\)90597-5](https://doi.org/10.1016/0370-2693(79)90597-5).
69. Morgan, D. L. Atomic processes in antiproton-matter interactions. *Hyperfine Interactions* **44**, 399–411 (1989). URL <https://doi.org/10.1007/BF02398689>.