Progress 2023
BASE Collaboration

Stefan Ulmer, Christian Smorra, Barbara Latacz
HHU Düsseldorf, RIKEN, and CERN

2024 / 02 / 06

BASE uses single particles in advanced Penning trap systems, to study the fundamental properties of protons and antiprotons with high precision.

BASE – Collaboration

- **BASE-Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies.

- **BASE-CERN:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio
- **BASE-STEP:** transportable antiproton trap
- **BASE-Hannover:** QLEDS-laser cooling project, new technologies

Selected for a Viewpoint in *Physics*
PRL **106,** 253001 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Observation of Spin Flips with a Single Trapped Proton

S. Ulmer,[1,2,3] C. C. Rodegheri,[1,2] K. Blaum,[1,3] H. Kracke,[2,4] A. Mooser,[2,4] W. Quint,[3,5] and J. Walz[2,4]

[1]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*
[2]*Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[3]*Ruprecht Karls-Universität Heidelberg, D-69047 Heidelberg, Germany*
[4]*Helmholtz Institut Mainz, D-55099 Mainz, Germany*
[5]*GSI—Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*
(Received 28 February 2011; published 20 June 2011)

Radio-frequency induced spin transitions of one individual proton are observed. The spin quantum jumps are detected via the continuous Stern-Gerlach effect, which is used in an experiment with a single proton stored in a cryogenic Penning trap. This is an important milestone towards a direct high-precision measurement of the magnetic moment of the proton and a new test of the matter-antimatter symmetry in the baryon sector.

DOI: 10.1103/PhysRevLett.106.253001 PACS numbers: 14.20.Dh, 21.10.Ky, 37.10.Rs, 37.10.Ty

The European Physical Journal volume 224 · number 1 · February 2015

EPJ ST

Recognized by European Physical Society

Special Topics

THE BASE EXPERIMENT

CERN Courier March 2018

BASE

Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.

The enigma of why the universe contains more matter than antimatter has been with us for more than half a century. While charge–parity (CP) violation can, in principle, account for the existence of such an imbalance, the observed matter excess is about nine orders of magnitude larger than what is expected from known CP-violating sources within the Standard Model (SM). This striking discrepancy inspires searches for additional mechanisms for the universe's baryon asymmetry, among which are experiments that test fundamental charge–parity–time (CPT) invariance by comparing matter and antimatter with great precision. Any measured difference between the two would constitute a dramatic sign of new physics. Moreover, experiments with antimatter systems provide unique tests of hypothetical processes beyond the SM that cannot be uncovered with ordinary matter systems.

The Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in addition to several other collaborations at the Antiproton Decelerator (AD), probes the universe through exclusive antimatter "microscopes" with ever higher resolution. In 2017, following many years of effort at CERN and the University of Mainz in Germany, the BASE team measured the magnetic moment of the antiproton with a precision 350 times better than by any other experiment before, reaching a relative precision of 1.5 parts per billion (figure 1). The result followed the development of a multi-Penning-trap system and a novel two-particle measurement method and, for a short period, represented the first time that antimatter had been measured more precisely than matter.

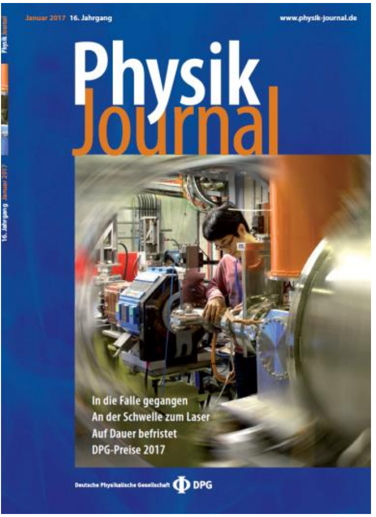
The BASE setup at CERN's Antiproton Decelerator.

Non-destructive physics

The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive observation of electronic transitions in atoms or ions led to the development of optical frequency standards that achieve fractional precisions on the 10^{-18} level. Another example, allowing one of the most precise tests of CPT invariance to date, is the comparison of the electron and positron *g*-factors. Based on quantum non-demolition detection of the spin state, such studies during the 1980s reached a fractional accuracy on the parts-per-trillion level.

The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement methods from the electron/positron to the proton/antiproton system constitutes a considerable challenge owing to the

The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.



Januar 2017 16. Jahrgang www.physik-journal.de

Physik Journal

In die Falle gegangen
An der Schwelle zum Laser
Auf Dauer befristet
DPG-Preise 2017

Deutsche Physikalische Gesellschaft DPG

Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig, ETH Zuerich

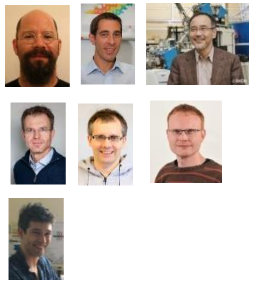
Team at CERN

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

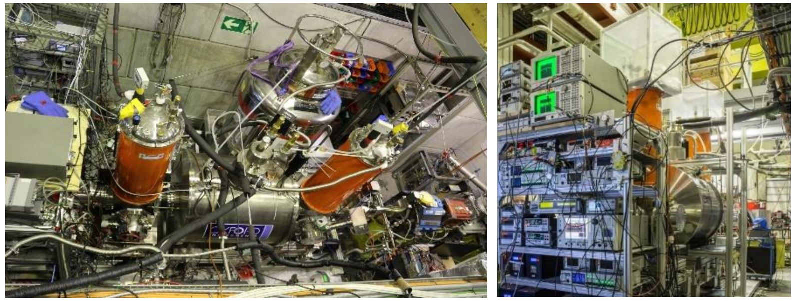
BASE Tracking Record and Current Efforts

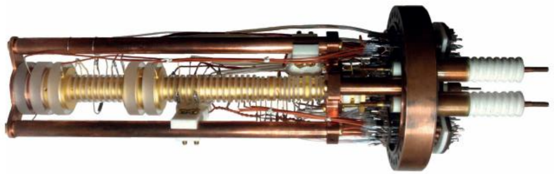
- BASE-CERN
- BASE-Mainz
- BASE-Logic
- BASE-STEP
- BASE-CDM
- BASE-Lepton

- Exotics
- He moment

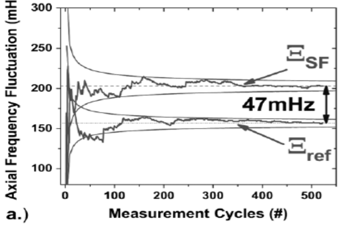


- **General:** Use ultra-high precision methods to measure fundamental constants and study fundamental symmetries with highest fractional accuracy
- **Main tools:** advanced Penning trap systems



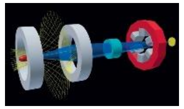


2011



S. Ulmer, et al., **PRL 106, 253001 (2011)**

2012



2013

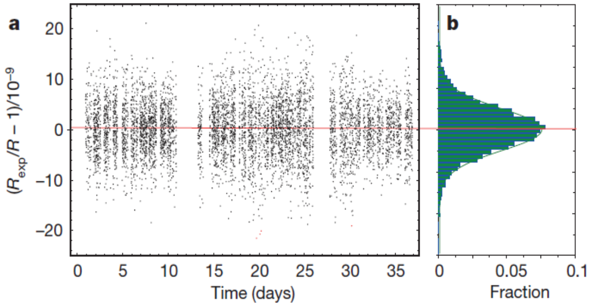
3ppb proton moment

A. Mooser, S. Ulmer, et al., **Nature 509, 596 (2014)**

2014

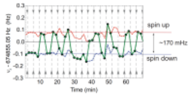
2015

$$1+\frac{(q/m)_{\bar{p}}}{(q/m)_{p}}=1(69)\times10^{-12}$$



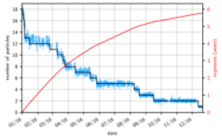
S. Ulmer, et al., **Nature 524, 196 (2015)**

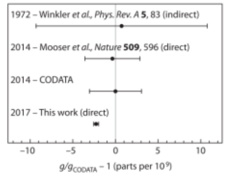
2016

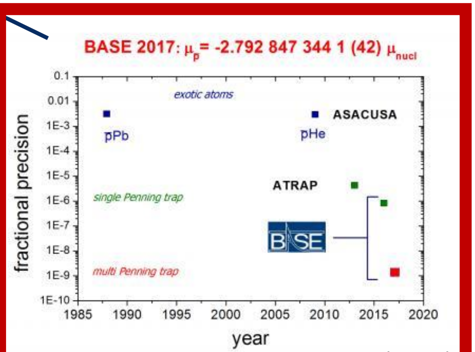


2017

pbar moment, proton moment, pbar lifetime, proton mass

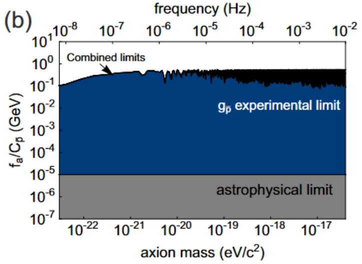




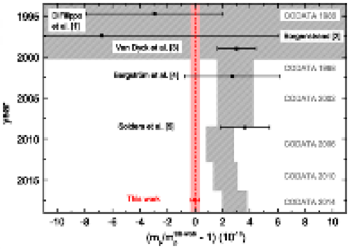


C. Smorra *et al.*, Nature **550**, 371 (2017)

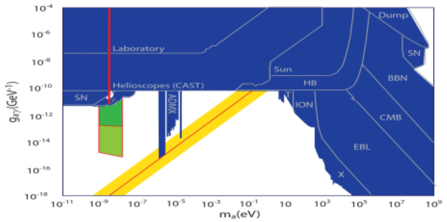
2019



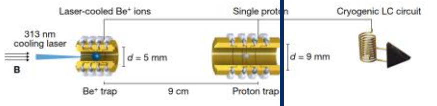
BASE, Nature **575**, 310 (2019)



2021

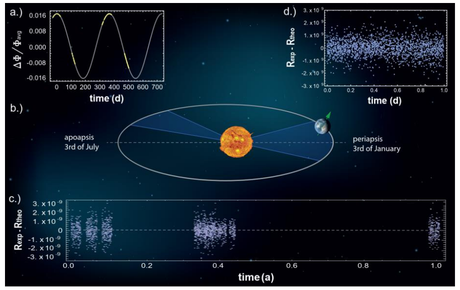


J. A. Devlin, et al., **PRL, accepted (2021)**



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

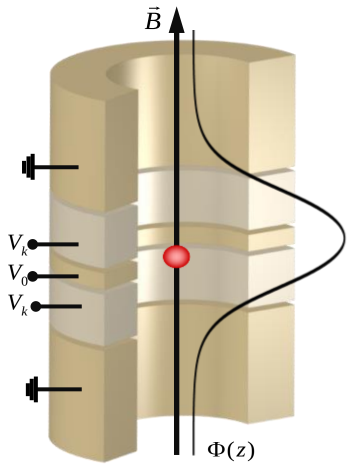
2022

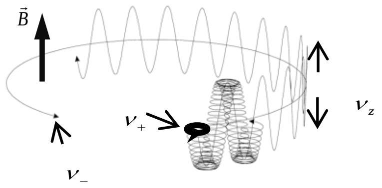


S. Ulmer, et al., **Nature, accepted (2021)**

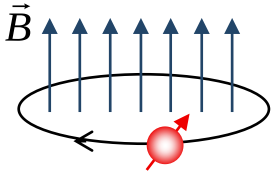
Current effort: Improve the precision in the antiproton magnetic moment

Measurements in Precision Penning Traps

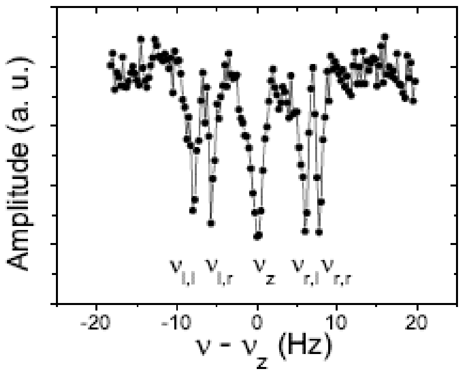




Cyclotron Motion



simple



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

g: mag. Moment in units of nuclear magneton

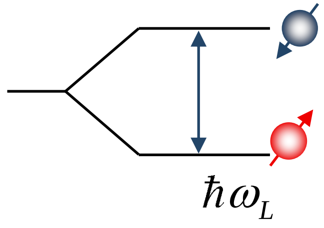
$$\omega_c = \frac{e}{m_p} B$$

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

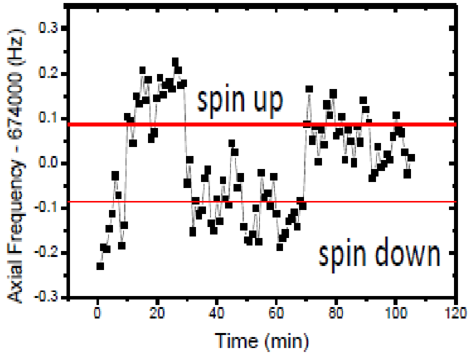
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession



difficult



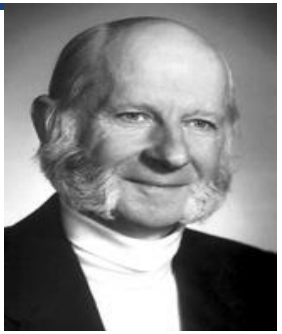
A. Mooser, S. Ulmer, *et al.* PRL 106, 253001 (2011)

Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

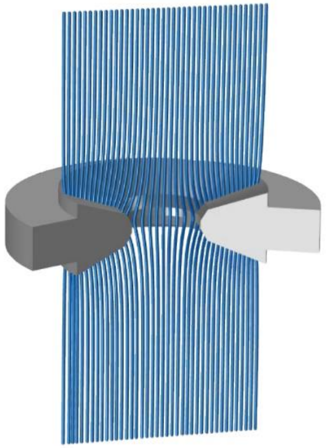
High Precision Mass Spectrometry

High Precision Magnetic Moment Measurements

Spin-Quantum-Transition Spectroscopy



Measurement based on continuous Stern Gerlach effect.



Energy of magnetic dipole in magnetic field

$$\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$$

Leading order magnetic field correction

$$B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$$

This term adds a spin dependent quadratic axial potential
-> Axial frequency becomes a function of the spin state

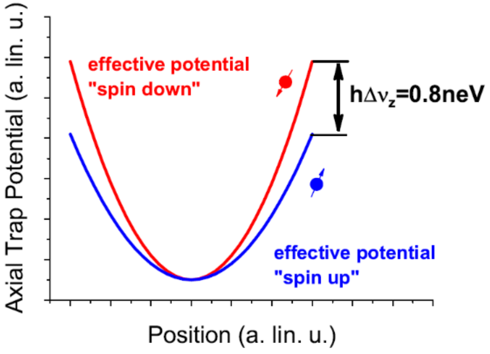
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

- Most extreme magnetic conditions ever applied to single particle.

$$\Delta\nu_z \sim 170\ mHz$$

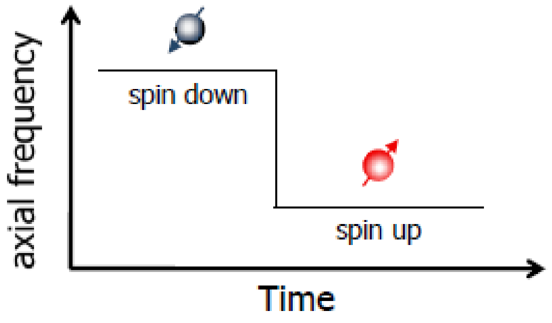


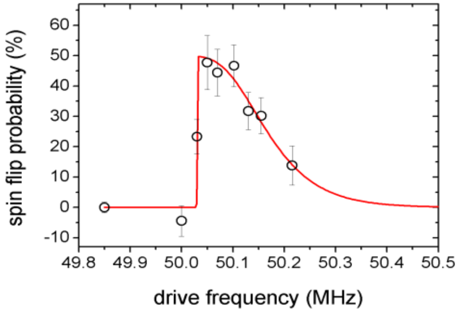
Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

Limited to p.p.m level

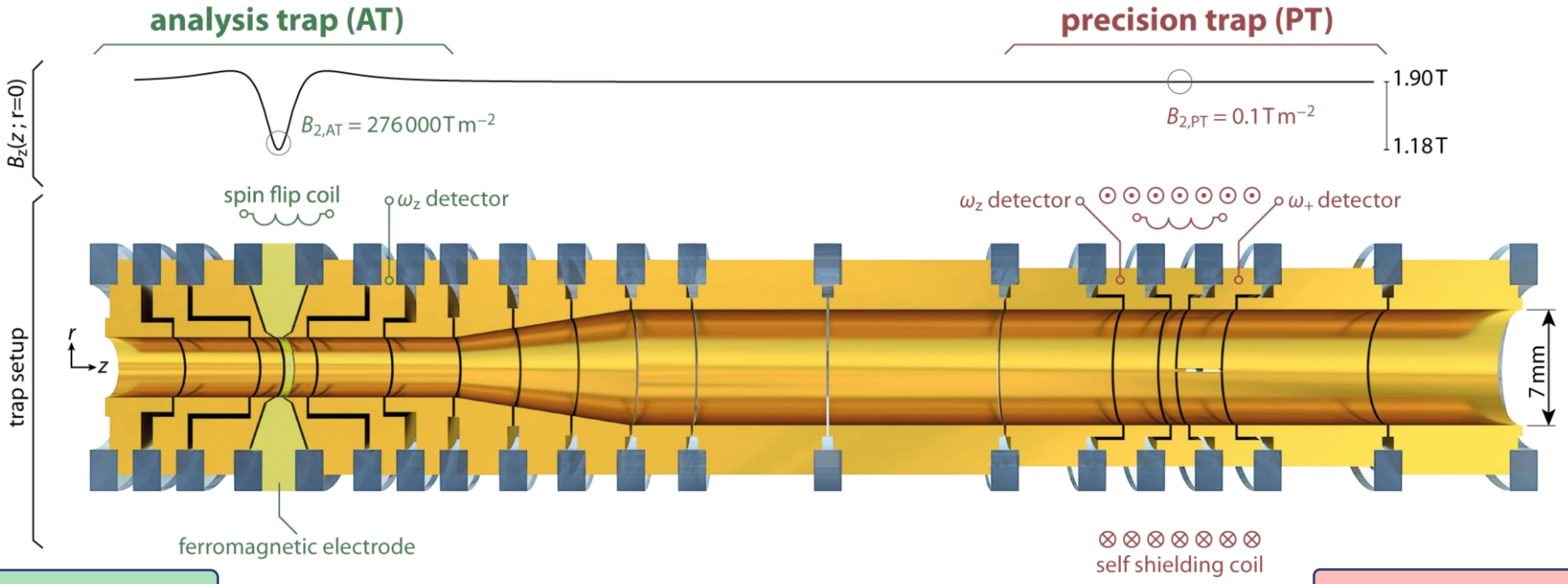


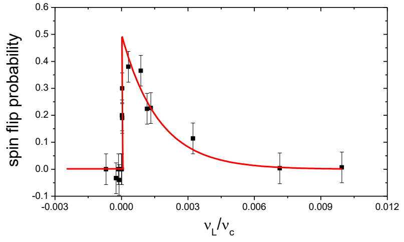


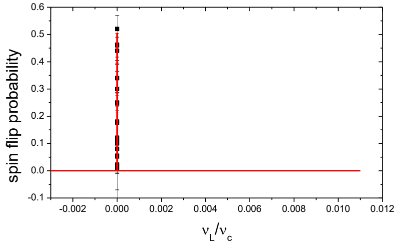
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

The Multi Penning-Trap Methods

Invented by **H. Haeffner**, in group of **G. Werth** also highly relevant in electron mass measurements and tests of BS QED (Blaum / Sturm et al.)







Initialize the spin state

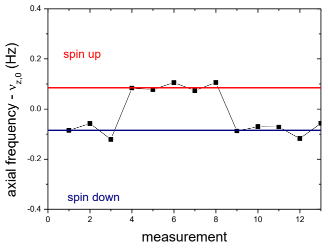
particle transport

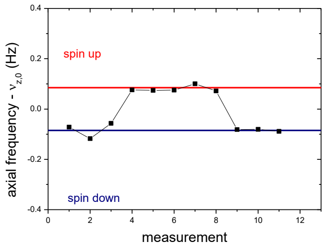
1.) measure cyclotron ν_c

2.) drive spin transition at ν_{rf}

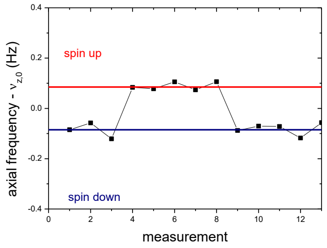
analyze the spin state

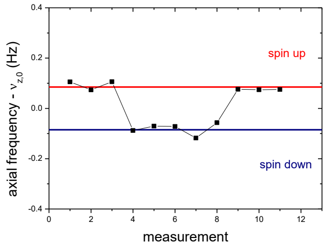
no spin-flip in PT

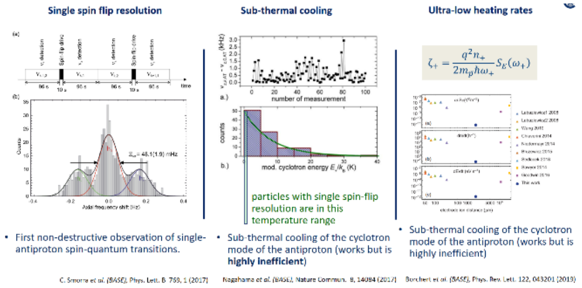




spin flipped in PT







Single spin flip resolution

- First non-destructive observation of single-antiproton spin-quantum transitions.

C. Smorra et al. (BASE), Phys. Lett. B 769, 1 (2017)

Sub-thermal cooling

particles with single spin-flip resolution are in this temperature range

- Sub-thermal cooling of the cyclotron mode of the antiproton (works but is **highly inefficient**)

Nagahama et al. (BASE), Nature Commun. 8, 14084 (2017)

Ultra-low heating rates

$$\zeta_+ = \frac{q^2 n_+}{2 m_p \hbar \omega_+} S_E(\omega_+)$$

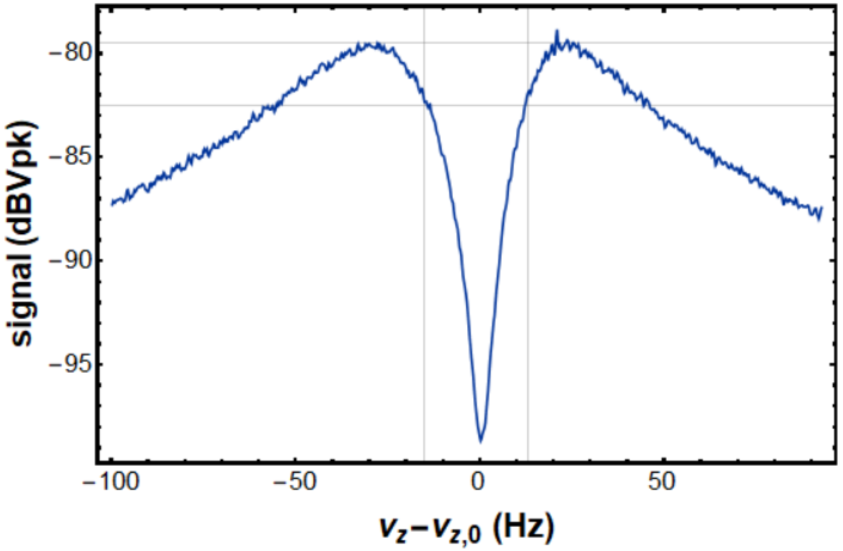
- Sub-thermal cooling of the cyclotron mode of the antiproton (works but is highly inefficient)

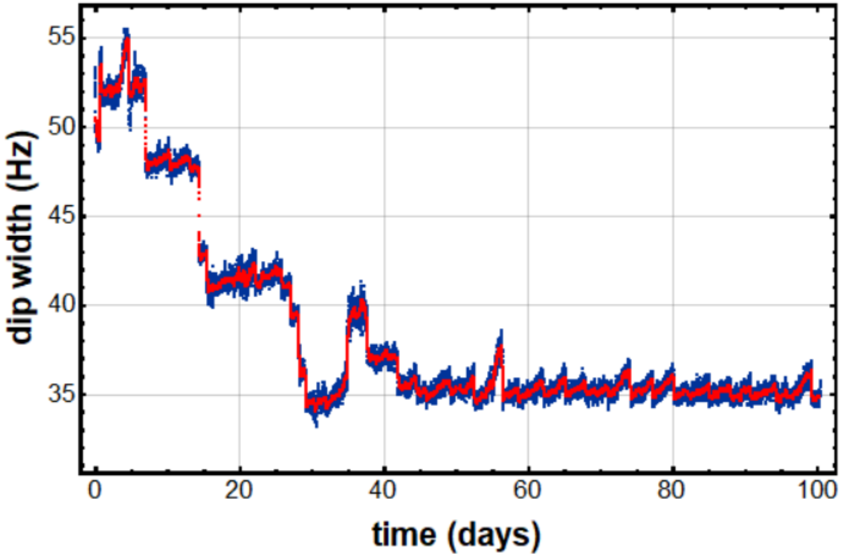
Borchert et al. (BASE), Phys. Rev. Lett. 122, 043201 (2019)

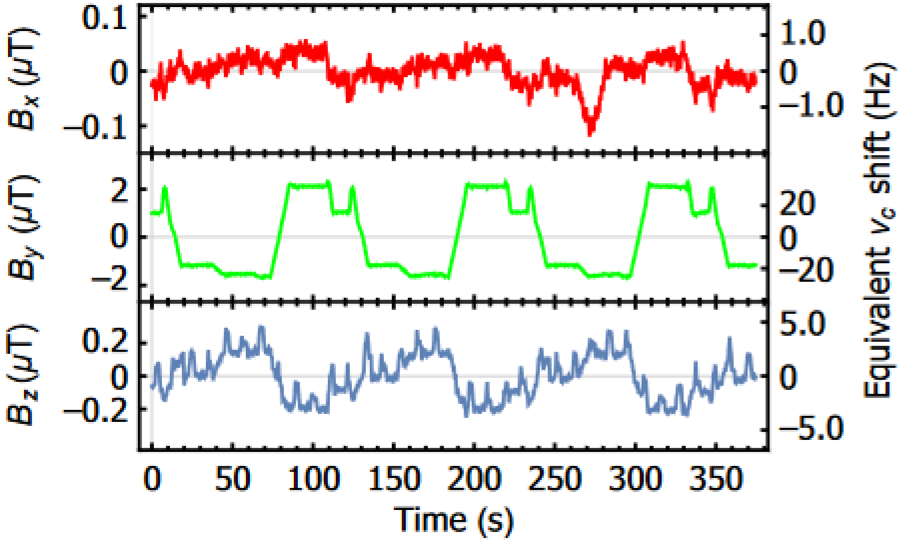
measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap

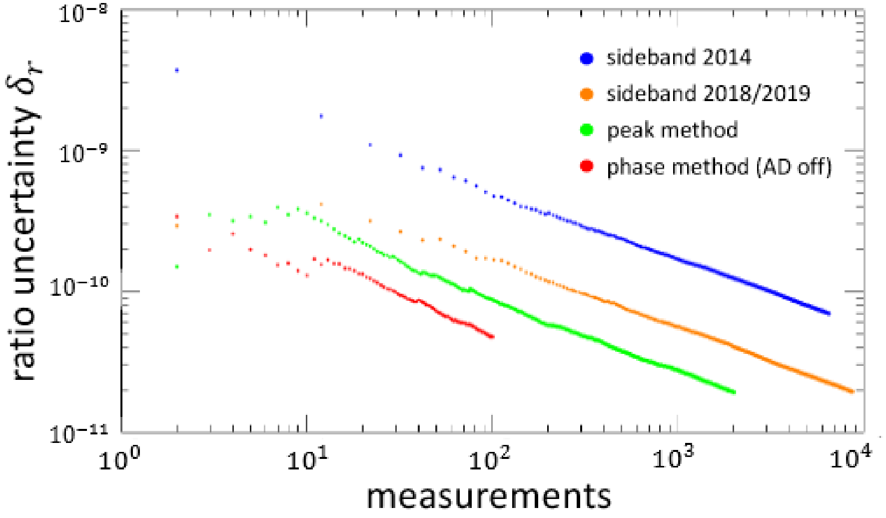
Reservoir Status – 2024-01

- **Collaboration still running with antiprotons trapped on the 27th of October 2023.** Typical commissioning losses. No particle loss since 15th of December 2023.









- It is absolutely necessary to operate BASE during shutdown, since accelerator is «too loud» to reach precisions at the p.p.t. level.
- BASE-STEP (ERC Smorra)

We are explicitly requesting 4 months per year of «calm» magnetic field conditions in the facility (no accelerator operation).

BASE Annual Summary 2023

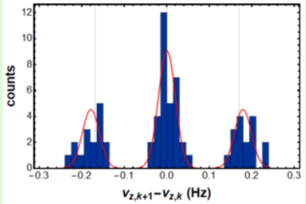
Experiment Online throughout entire year 2023

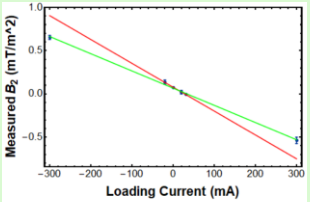
Proton Moment Run

Antiproton Run

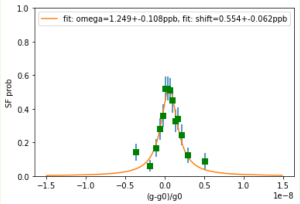
- Fidelity Optimization
- Magnetic Optimization
- Coherent Spin Flip Methods
- Proton Magnetic Moment Sampling
- Systematic Studies for Proton Moment Measurement
- Injection Studies
- Fidelity Optimization
- Antiproton Magnetic Moment Sampling

Mulit-Trap Implementation





Proton moment resonance



2023/07/15
Start of AD/ELENA physics operation

2023/09/14
Start of BASE Antiproton Run

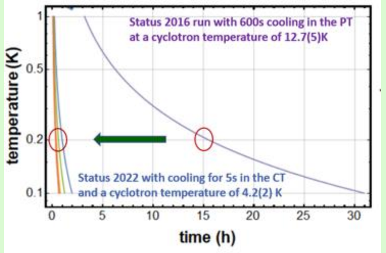
Jan. Feb. Mar. Apr. May June July Aug. Sep. Oct. Nov. Dec. Jan.

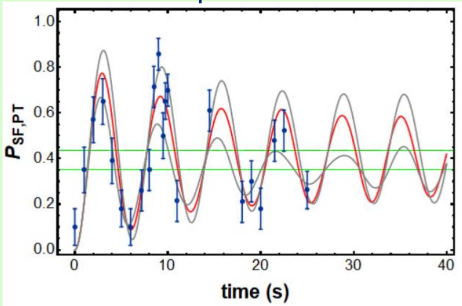
2023/12/27
High-Fidelity detection of Antiproton Spinflips

2023/10/27
Antiproton Catching

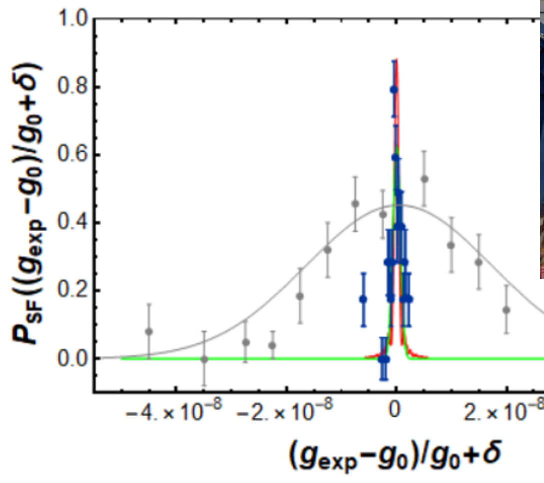
Result of first coherent proton moment measurement

Cooling Trap

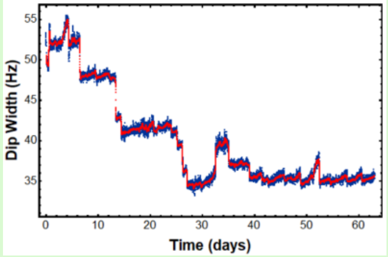




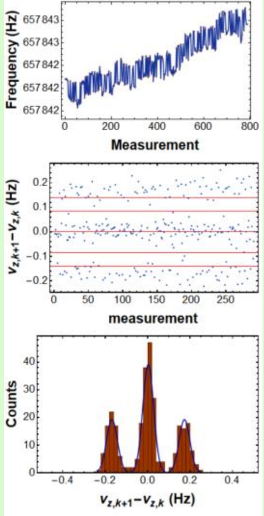
Improves sub-thermal cooling cycles by more than factor of 60



Transport of BASE STEP



Antiproton Reservoir Operation

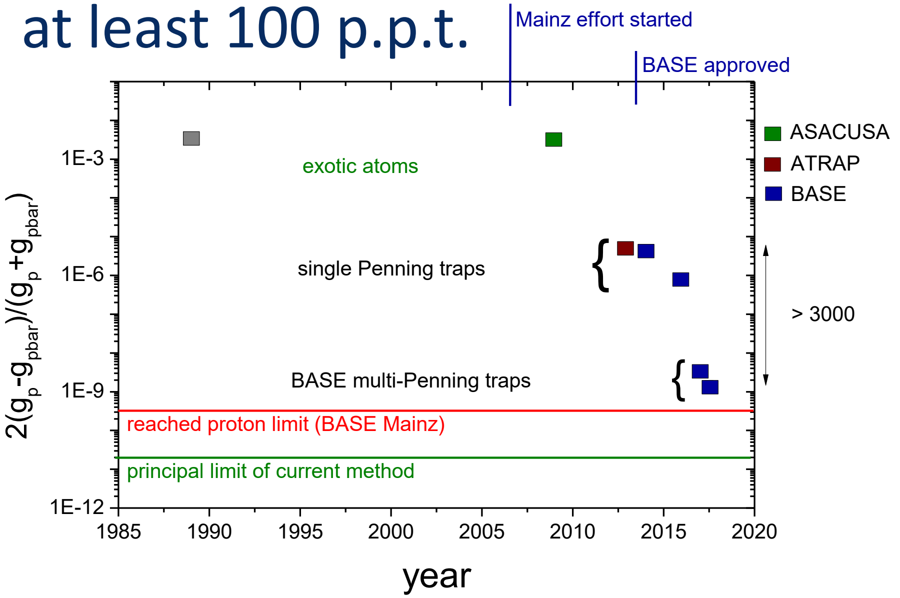


Parallel Projects:

Evaluation of time series of QM measurement / Other Projects

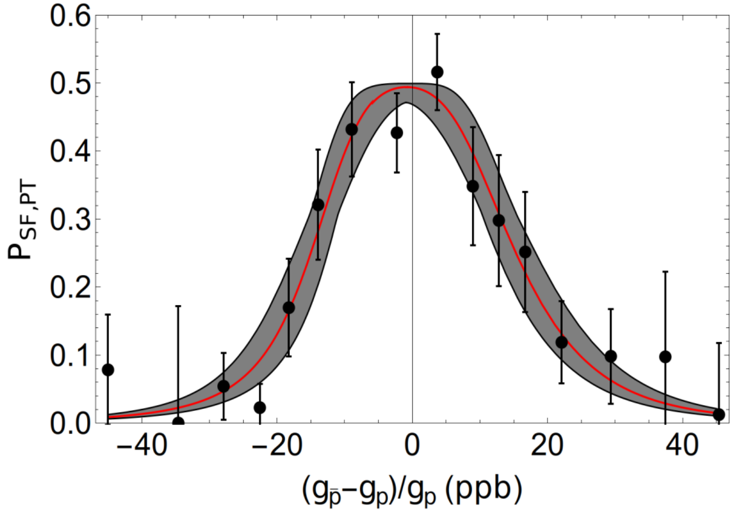
Goal of the Current Run

- Improved measurement of the antiproton magnetic moment with a target precision of at least 100 p.p.t.



- BASE has measured the antiproton magnetic moment with a fractional accuracy of 1.5 p.p.b.

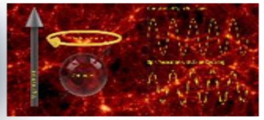
$$\frac{g_{\bar p}}{2} = 2.792\,847\,344\,1\,(42)$$

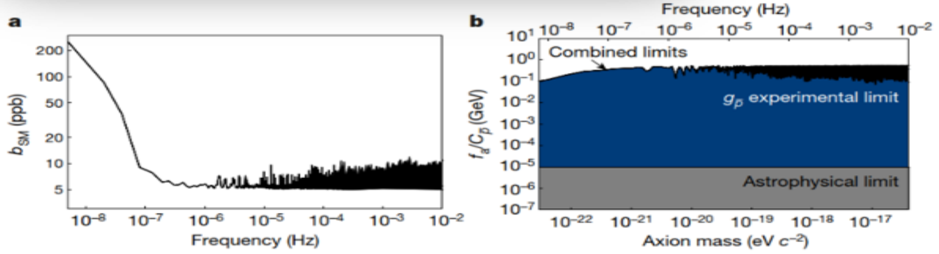


Are the mysteries of Dark Matter and Matter/Antimatter asymmetrie related?

First constraints on antimatter/dark matter coupling

$$\delta\omega_L^{\bar p}(t) \approx \frac{C_{\bar p} m_a a_0 |\mathbf{v}_a|}{f_a}[A\cos(\Omega_{\mathrm{sid}}t+\alpha)+B]\sin(\omega_a t)$$



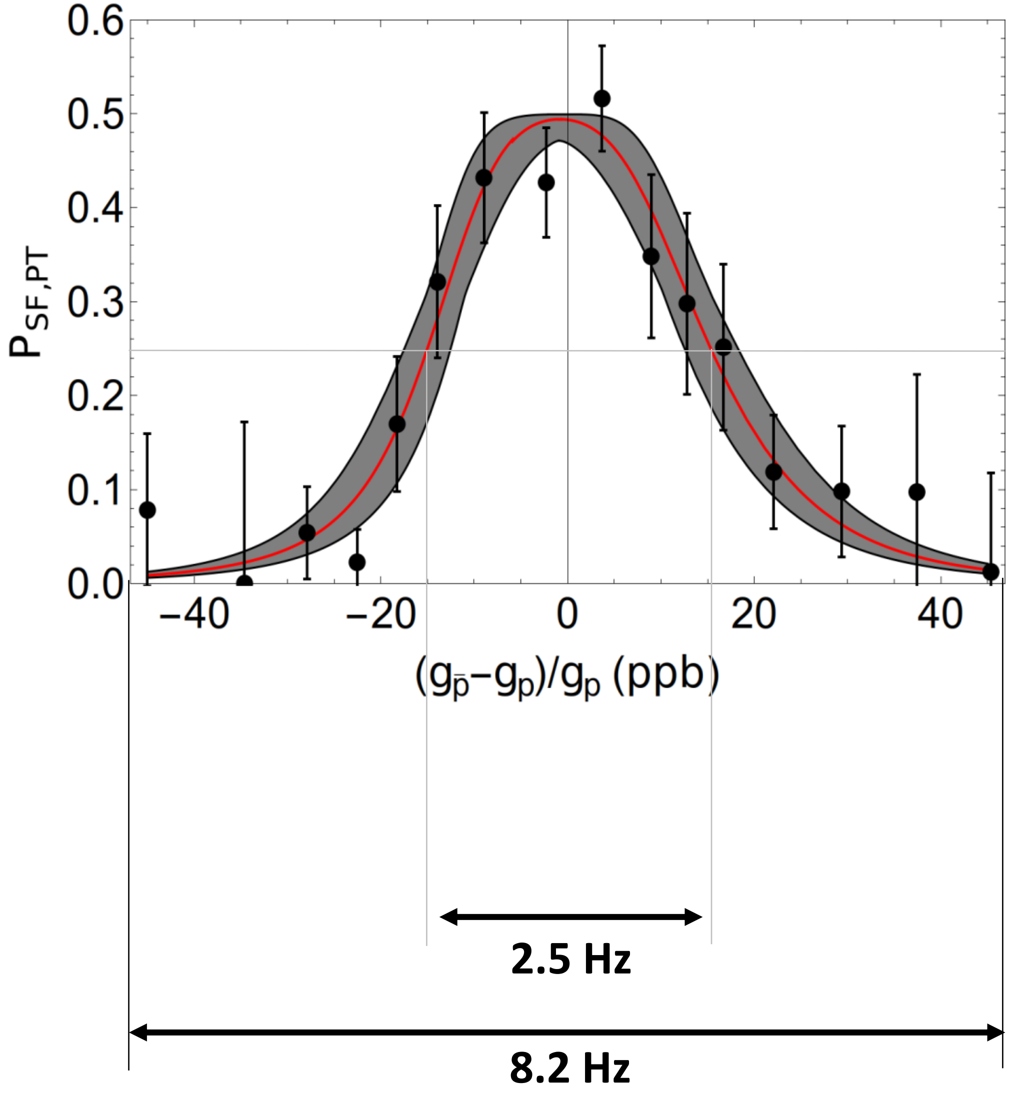


Improved previous constraints by 5 orders of magnitude

Smorra et al.(BASE), Nature **(575)**, 310 (2019)

Understanding the Limits

- Measurement improved previous experiments by a factor of >3000, but:
  - The width of this resonance is deliberately saturated to counteract accelerator imposed frequency flutuations
  - The resonance is incoherent with a maximum spin inversion of 50%. **Reason:** Particle detector interaction in inhomogeneous magnetic field leads to thermal phase noise with correlation time constant of 30ms and line width parameter of 600mHz
  - High spin state detection fidelity only achieved by sub-thermal cooling to $E_+ < 8.6\ \mu\text{eV}\ (100\ \text{mK})$, which required >10h
  - Limits due to magnetic field fluctuation in the accelerator hall.
  - Limits due to heating rates at the level of 1 cyclotron quantum transition in 10 minutes.



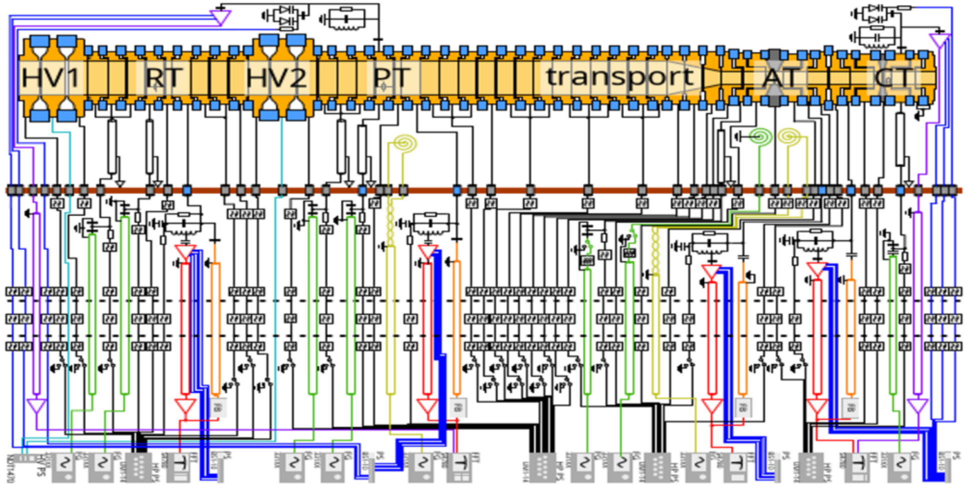
Still proud of this measurement, but also clear that there is headroom

Towards an Improved Measurement

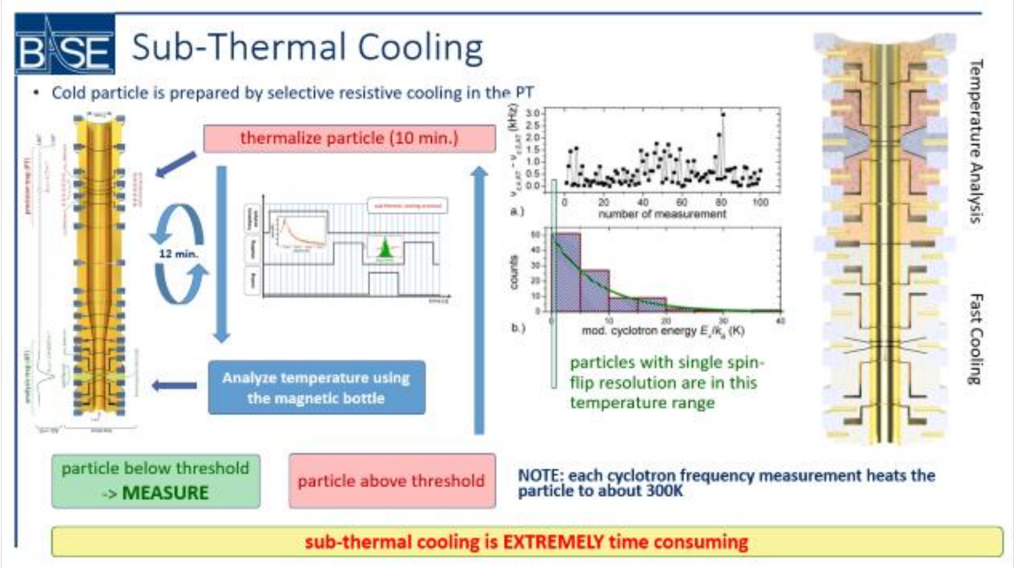
- **Systematic Limitations:**
  - Magnetic field fluctuations: 15ppb width
  - Magnetic field homogeneity: 0.980 ppb unc.
  - Measurement stability: 6ppb unc.
  - Limited data accumulation rate
  - Noise sensitivity of the spin-state detection trap
  - Transport heating rates

Goal: Develop a running 4-Penning-trap system which includes all these features.

- **Reaction:**
  - Better magnetic shielding: factor 50 to 250
  - Multi-coil shimming system: eliminates
  - Improved frequency measurement methods
  - Cooling trap for faster prep. cycles
  - Improved cryogenic filter systems
  - Improved particle shuttling techniques



Important Steps made in 2022



Sub-Thermal Cooling

- Cold particle is prepared by selective resistive cooling in the PT

thermalize particle (10 min.)

Analyze temperature using the magnetic bottle

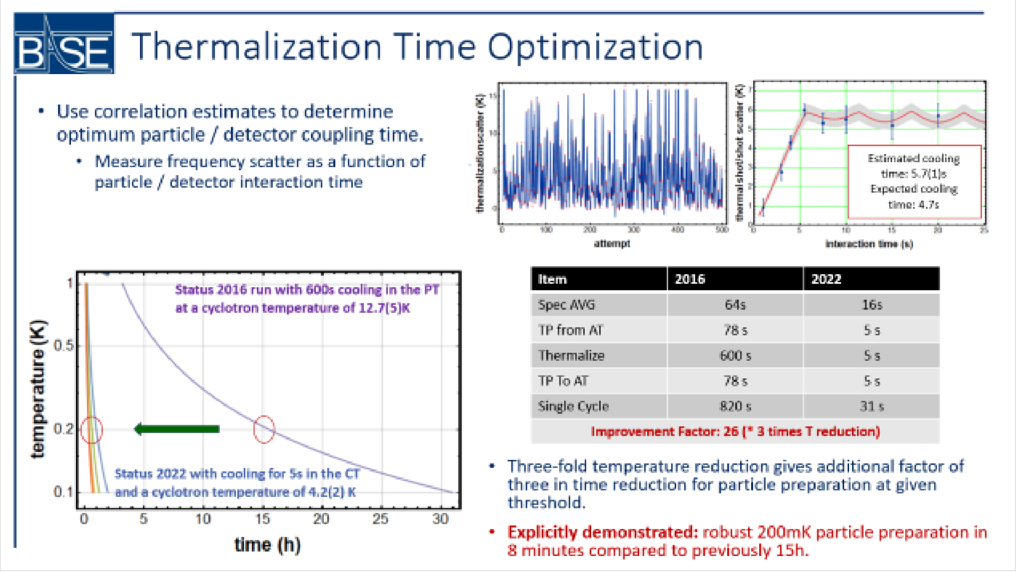
particle below threshold -> **MEASURE**

particle above threshold

particles with single spin-flip resolution are in this temperature range

NOTE: each cyclotron frequency measurement heats the particle to about 300K

sub-thermal cooling is EXTREMELY time consuming



Thermalization Time Optimization

- Use correlation estimates to determine optimum particle / detector coupling time.
  - Measure frequency scatter as a function of particle / detector interaction time

Estimated cooling time: 5.7(1)s
Expected cooling time: 4.7s

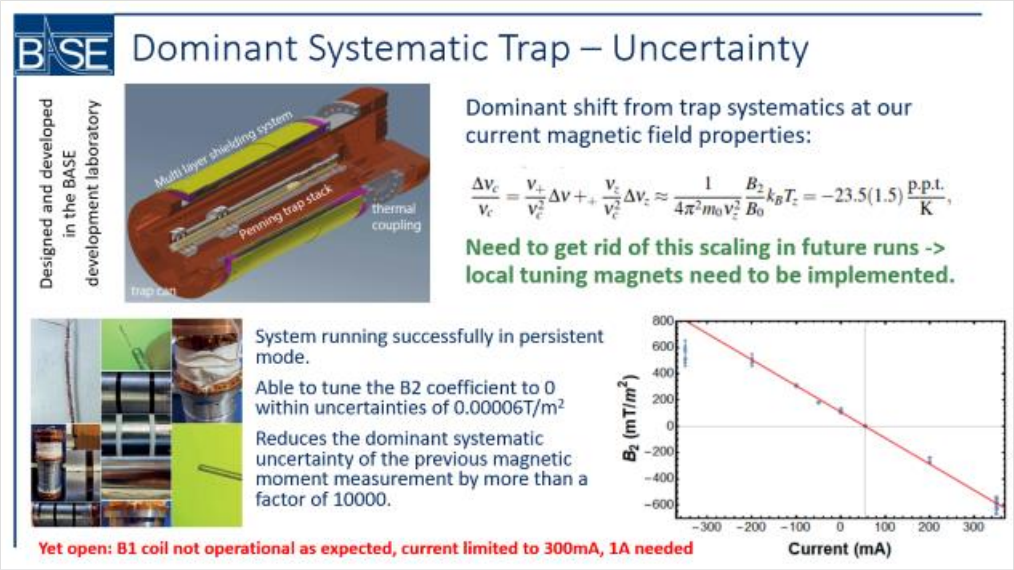
Status 2016 run with 600s cooling in the PT at a cyclotron temperature of 12.7(5)K

Status 2022 with cooling for 5s in the CT and a cyclotron temperature of 4.2(2) K

Item	2016	2022
Spec AVG	64s	16s
TP from AT	78 s	5 s
Thermalize	600 s	5 s
TP To AT	78 s	5 s
Single Cycle	820 s	31 s
Improvement Factor: 26 (* 3 times T reduction)		

- Three-fold temperature reduction gives additional factor of three in time reduction for particle preparation at given threshold.
- **Explicitly demonstrated:** robust 200mK particle preparation in 8 minutes compared to previously 15h.

Cooling: Factor of 100 achieved!!!



Dominant Systematic Trap – Uncertainty

Designed and developed in the BASE development laboratory

Dominant shift from trap systematics at our current magnetic field properties:

$$\frac{\Delta\nu_c}{\nu_c} = \frac{\nu_+}{\nu_c^2}\Delta\nu_+ + \frac{\nu_z}{\nu_c^2}\Delta\nu_z \approx \frac{1}{4\pi^2 m_0 \nu_z^2}\frac{B_2}{B_0}k_B T_z = -23.5(1.5)\,\frac{\text{p.p.t.}}{\text{K}},$$

Need to get rid of this scaling in future runs -> local tuning magnets need to be implemented.

System running successfully in persistent mode.

Able to tune the B2 coefficient to 0 within uncertainties of 0.00006T/m^2

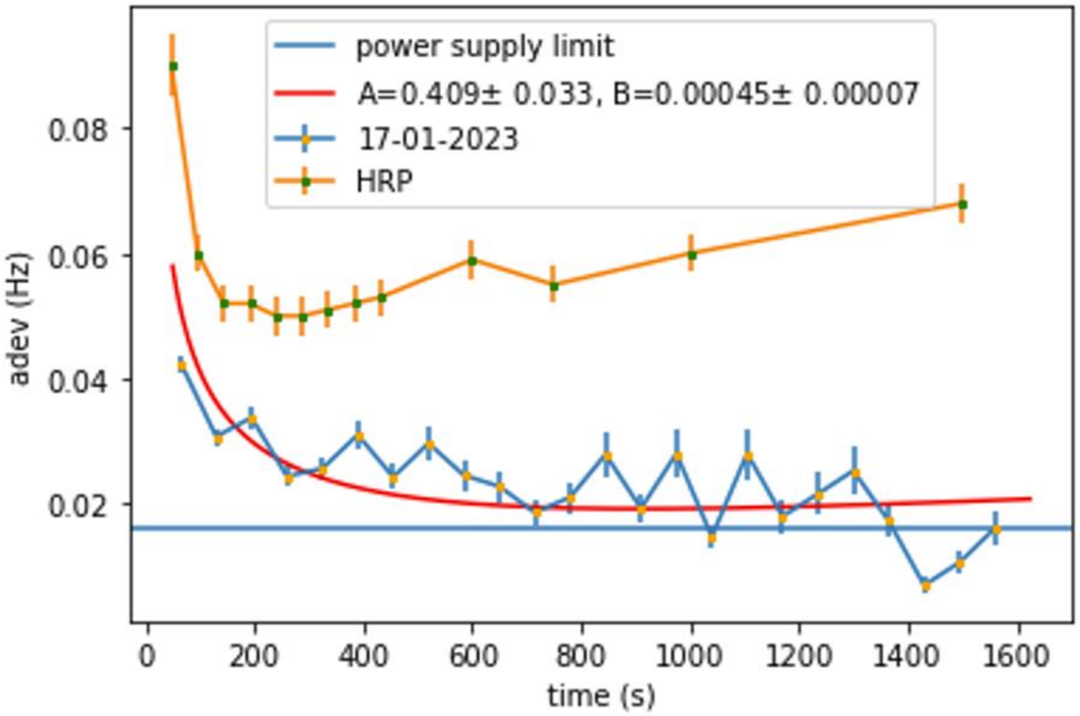
Reduces the dominant systematic uncertainty of the previous magnetic moment measurement by more than a factor of 10000.

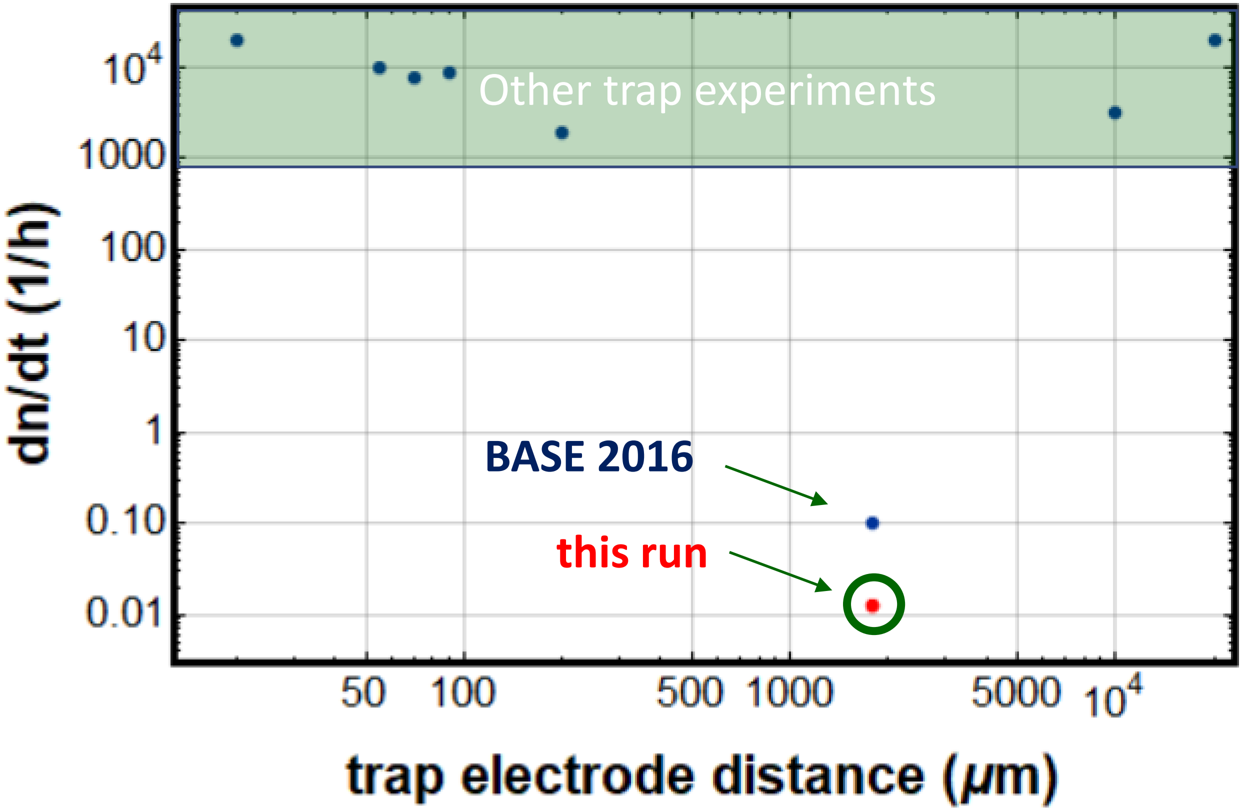
Yet open: B1 coil not operational as expected, current limited to 300mA, 1A needed

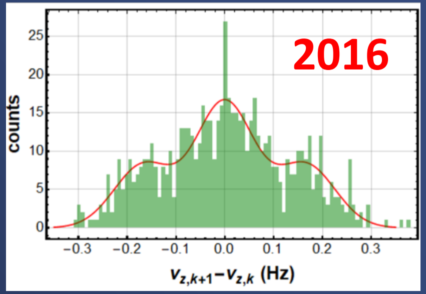
Parameter	Value 2023	Value 2017
$B_1\ (T/m)$	$0.0108(3)\ T/m$	$0.0712(4)\ T/m$
$B_2\ (T/m^2)$	$0.0015(21)\ T/m^2$	$2.7(3)\ T/m^2$

Homogeneity: Factor of >1000 achieved!!!

Heating Rates and Improved MCP limits

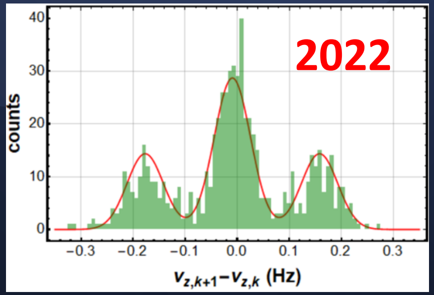


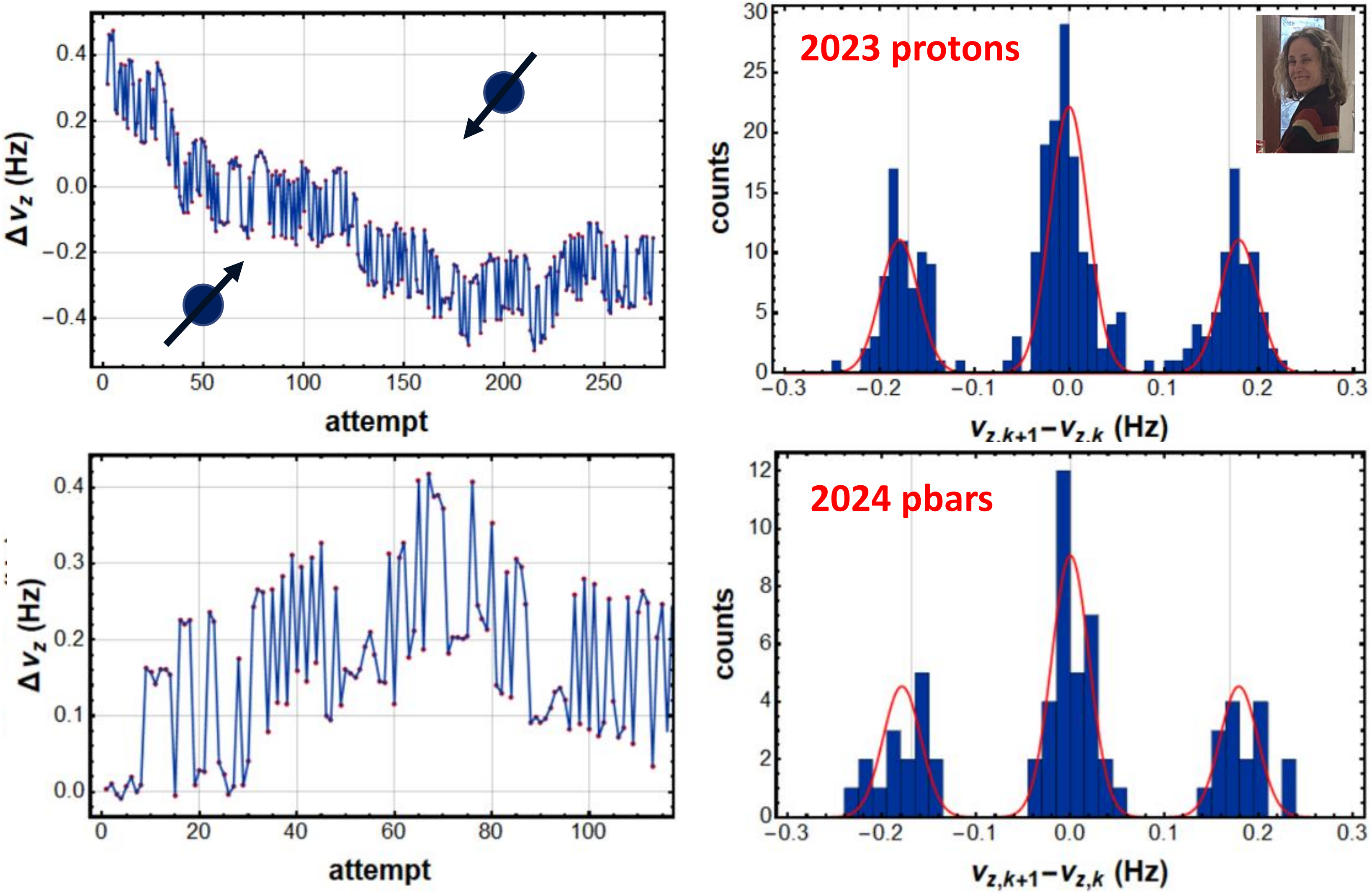




…with highest detection fidelity ever reported…:

…observation of Single Spin Flips….





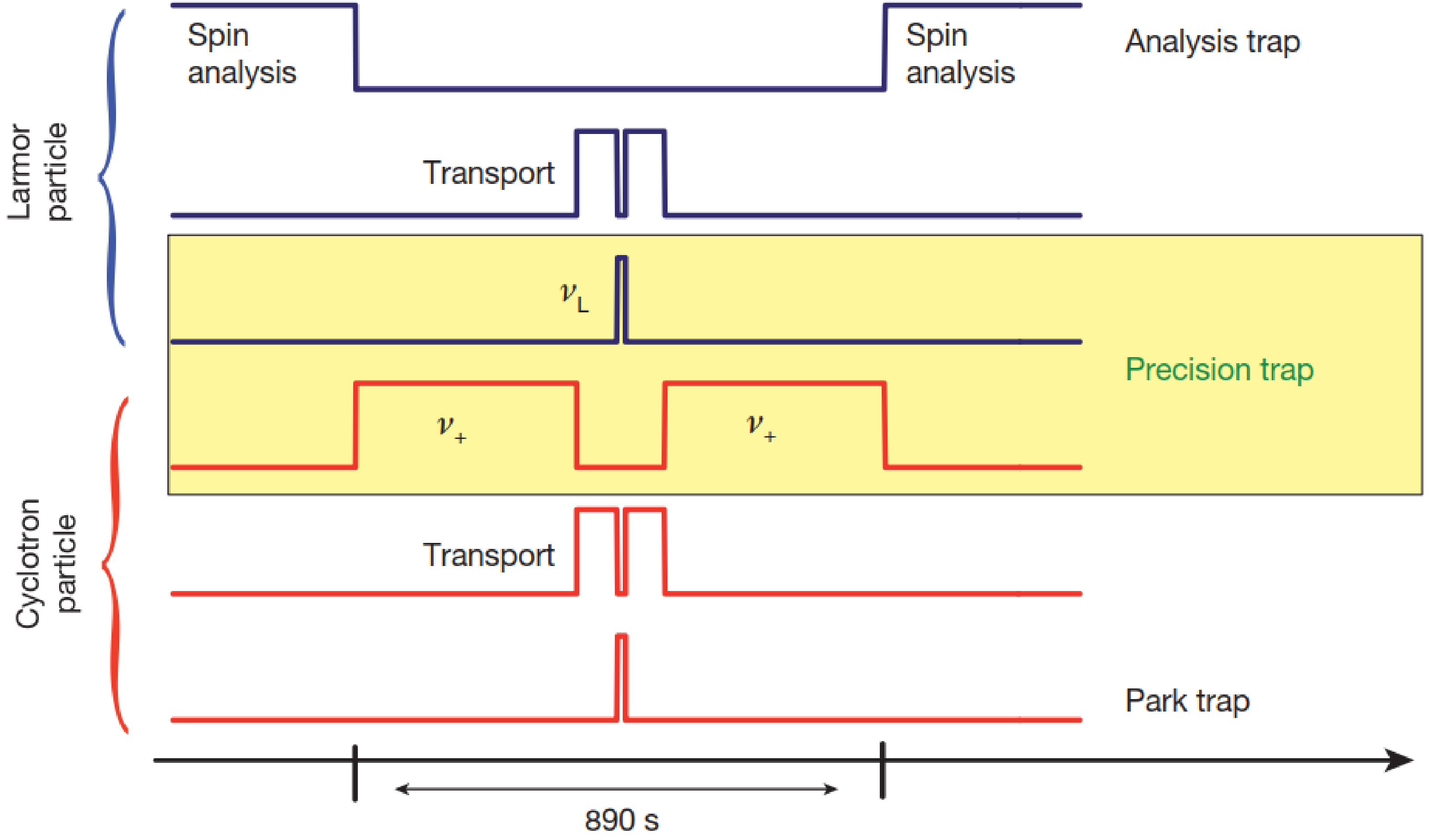
total **game changer** in magnetic moment experiments, error-rate improved by a factor of >5000.

- no threshold detection required.
- Saves considerable amount of particle identification time.

This is several 1000 times harder than observing the same for the electron/positron

Experiment Sequence

- This experiment is only possible with a particle **at a radial temperature <200mK**, which needs to be prepared with a cooling device at cryogenic temperatures. This cooling is eating up a considerable amount of the experiment time budget (previously 15h per preparation cycle).



Limited detection fidelity due to energy fluctuations in the radial modes.

80s to keep particle at low radial temperature - Optimization

Temperature fluctuations during spin flip drive.

Magnetic field fluctuations and drifts during the frequency measurements in this sequence.

- Managed to apply this sequence for about 80 cycles until new particle had to be prepared.

First Coherent Spin Transisition Spectroscopy

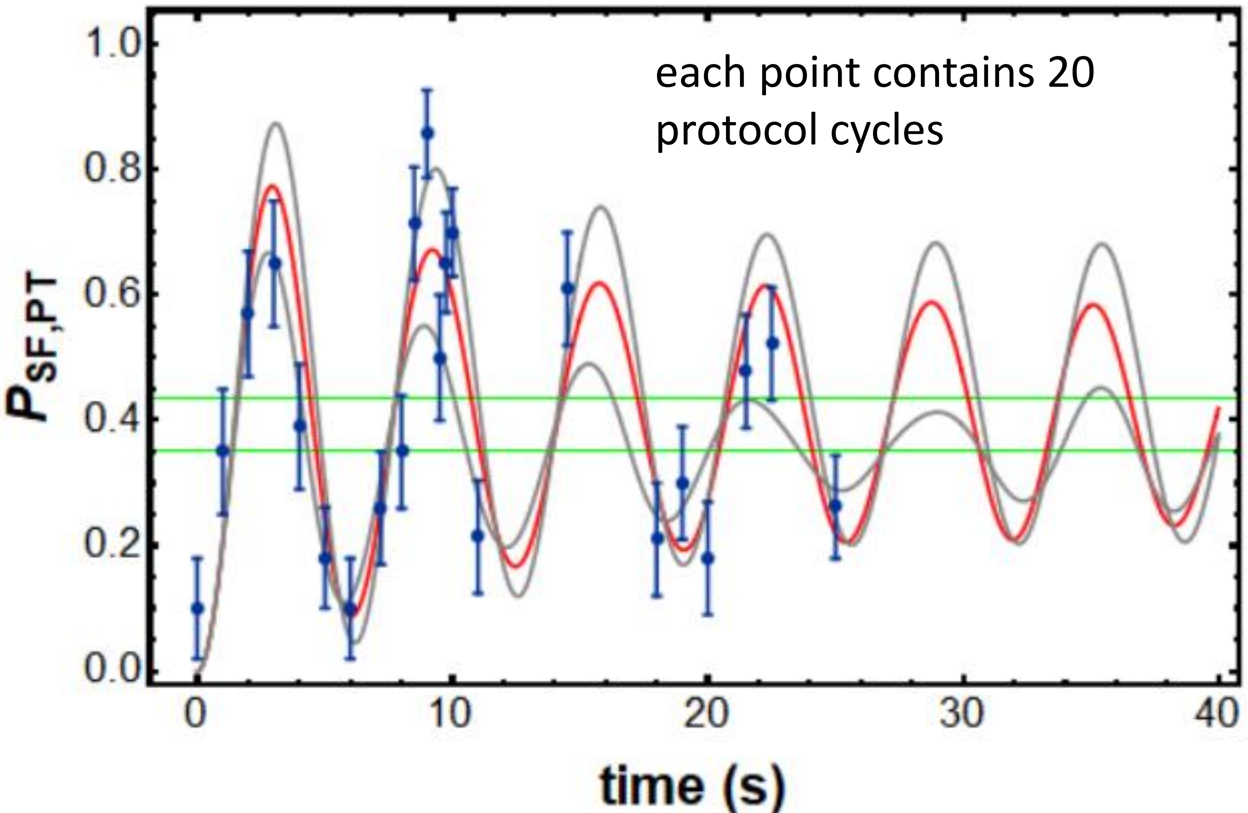
- Has never been demonstrated in a Penning trap.

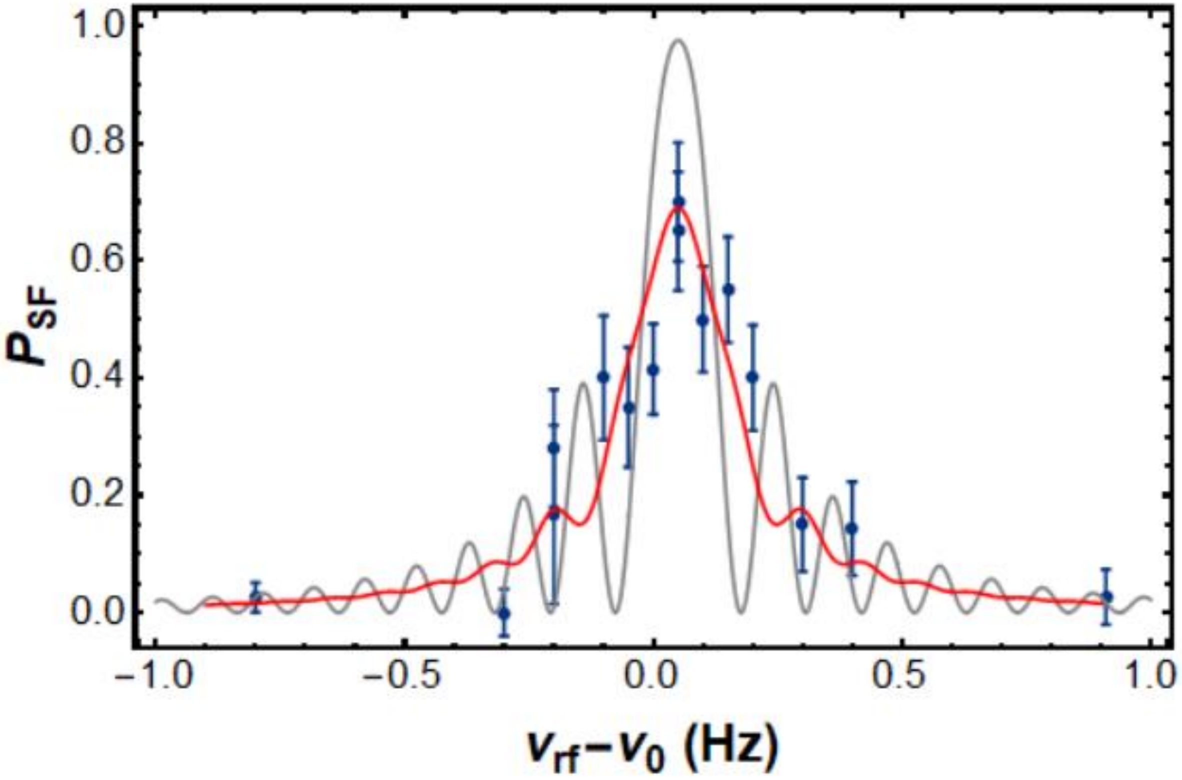
Initialize Spin State → Measure B fiel (PT) → Shuttle ATPTPTHV → PT Spinflip

6 min | X*3 min | 10s | 30s

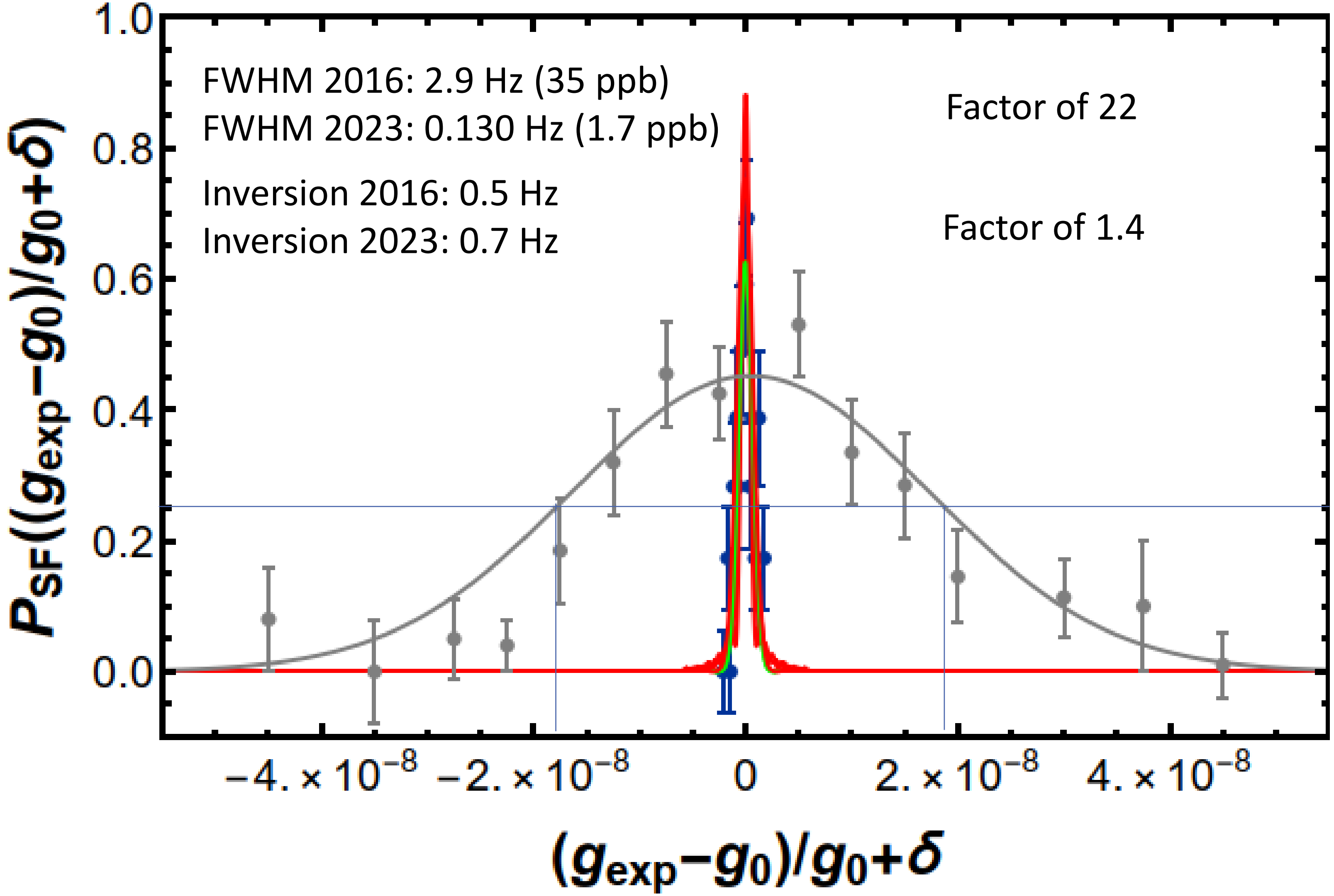
Shuttle PTATHVPT → Cool → Detect Spinstate → Conclude

10s | 20s | 180s | 15 min total


each point contains 20 protocol cycles



Frequency Sweep at Maximum Inversion

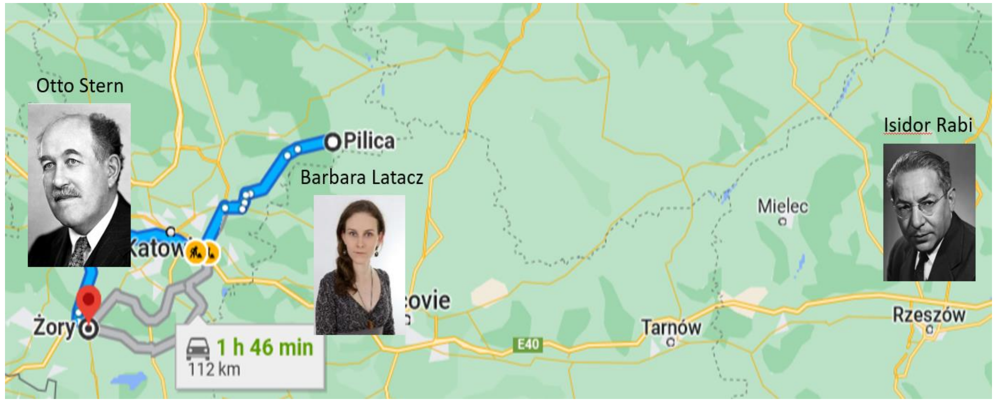


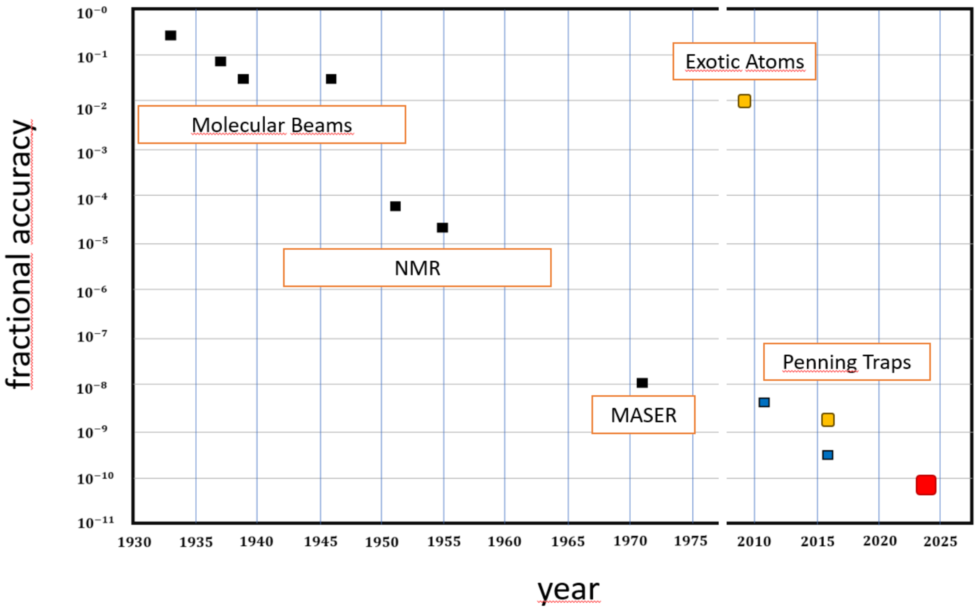
- **Status:**
  - The line-witdhs of our current measurements are the same level as the uncertainty of the line-center determination of the measurements conducted in 2016.
  - Currently, the data rate is about 10 times higher than in 2016, one of the current resonances is sampled in 48h, compared to 3 months of resonance sampling in 2016.

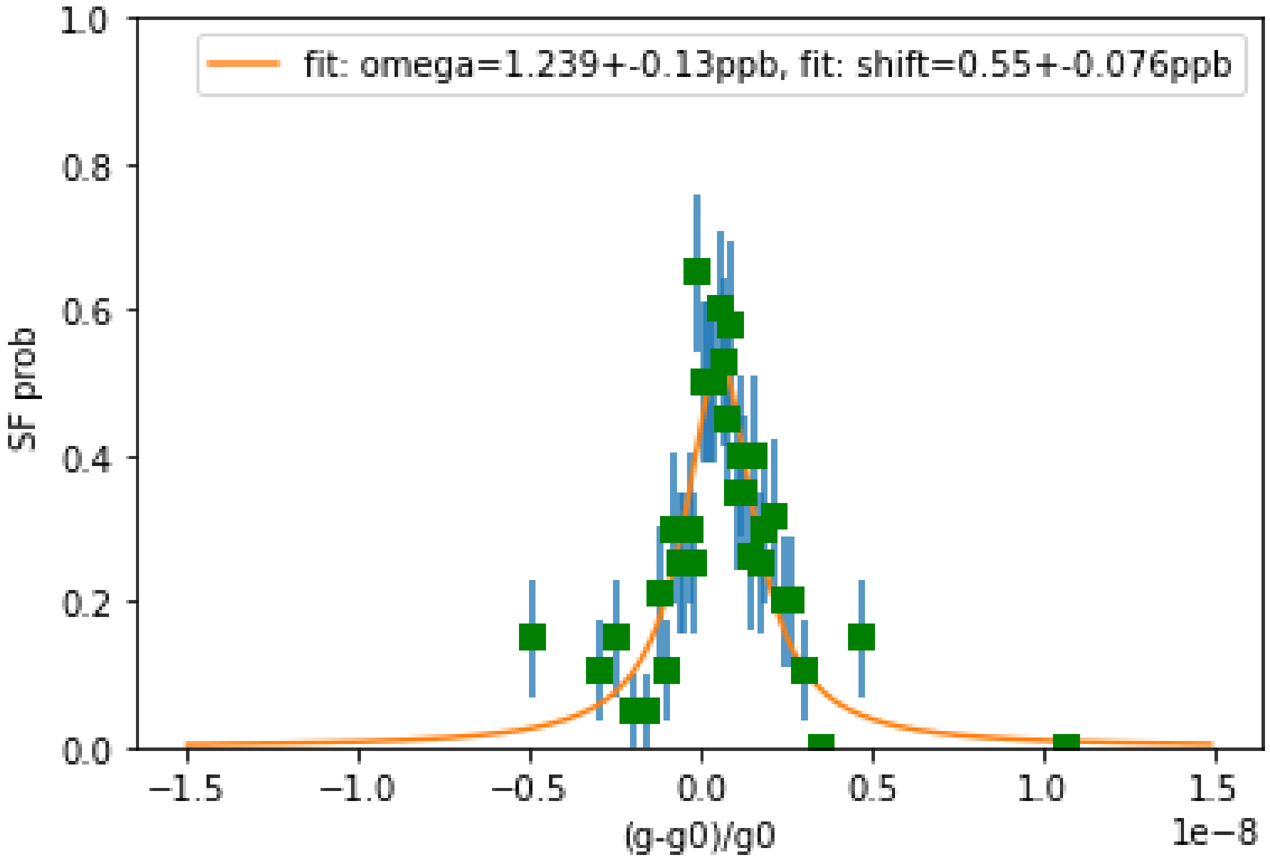
A lot of systematic studies needed to get the position of the line-center under control.

Proton Magnetic Moment Measurement

- Measurement carried out May to July with systematics in July/August, lucky that we made it thanks to late start of the AD







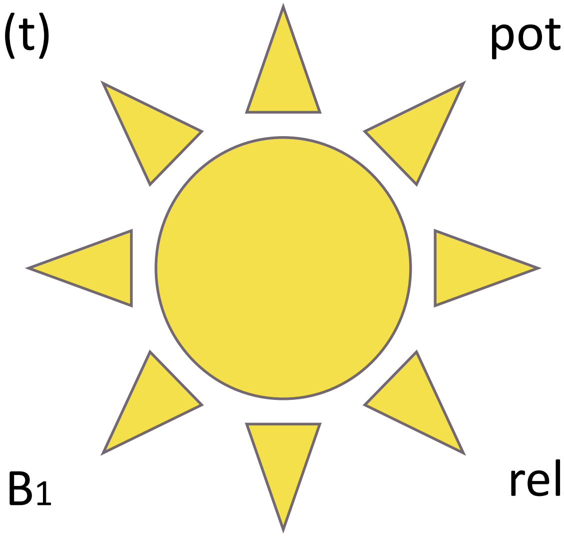
Systematics Under Evaluation

Systematic Frequency Shifts

Question: How well does the invariance theorem meet our assumptions, and how large are the deviations?

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

- **misalignment of B-axis and E-axis cancels out**
- **Elliptic disturbances in trapping potential cancel out.**



tilted trap

drifts B(t)

potential

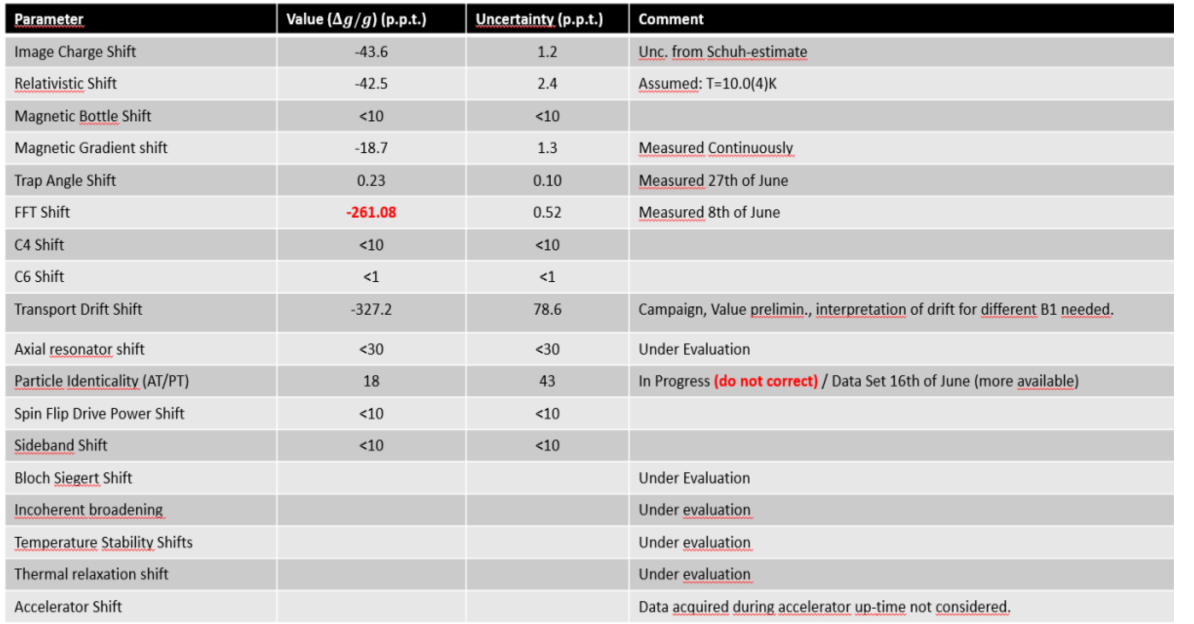
contaminants

B2 and B1

shift in B1

relativistic shifts

image charge / current

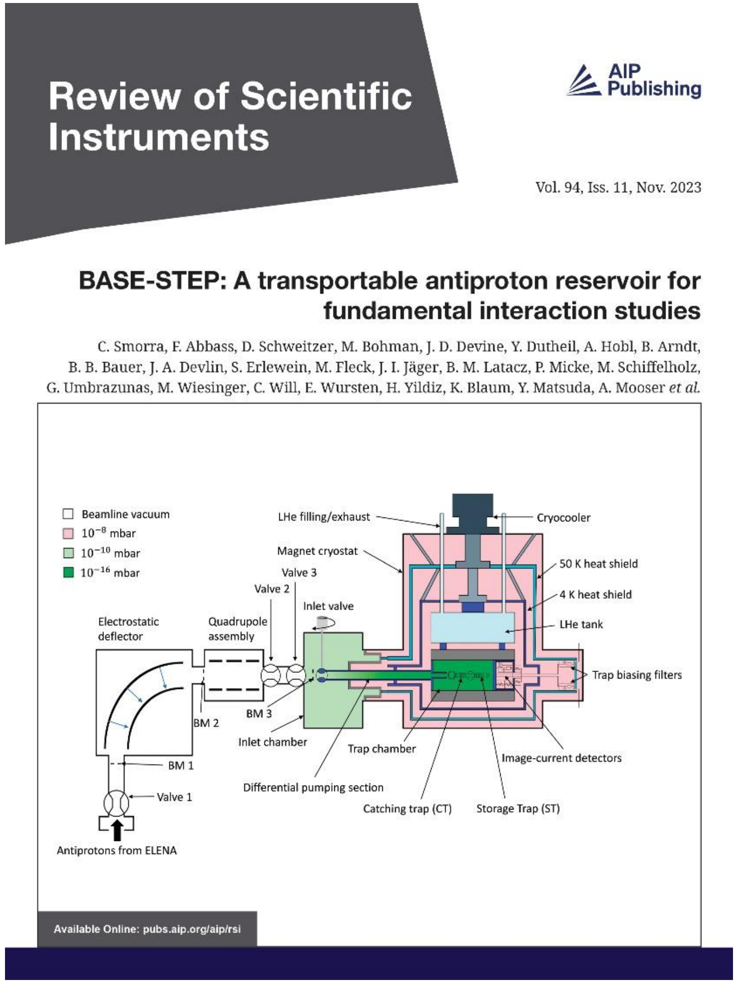


Parameter	Value ($\Delta g/g$) (p.p.t.)	Uncertainty (p.p.t.)	Comment
Image Charge Shift	-43.6	1.2	Unc. from Schuh-estimate
Relativistic Shift	-42.5	2.4	Assumed: T=10.0(4)K
Magnetic Bottle Shift	<10	<10	
Magnetic Gradient shift	-18.7	1.3	Measured Continuously
Trap Angle Shift	0.23	0.10	Measured 27th of June
FFT Shift	**-261.08**	0.52	Measured 8th of June
C4 Shift	<10	<10	
C6 Shift	<1	<1	
Transport Drift Shift	-327.2	78.6	Campaign, Value prelimin., interpretation of drift for different B1 needed.
Axial resonator shift	<30	<30	Under Evaluation
Particle Identicality (AT/PT)	18	43	In Progress **(do not correct)** / Data Set 16th of June (more available)
Spin Flip Drive Power Shift	<10	<10	
Sideband Shift	<10	<10	
Bloch Siegert Shift			Under Evaluation
Incoherent broadening			Under evaluation
Temperature Stability Shifts			Under evaluation
Thermal relaxation shift			Under evaluation
Accelerator Shift			Data acquired during accelerator up-time not considered.

Currently, these systematic studies are still ongoing.

L.S. Brown and G. Gabrielse, Rev. Mod. Phys.

BASE-STEP Review 2023



Review of Scientific Instruments

AIP Publishing

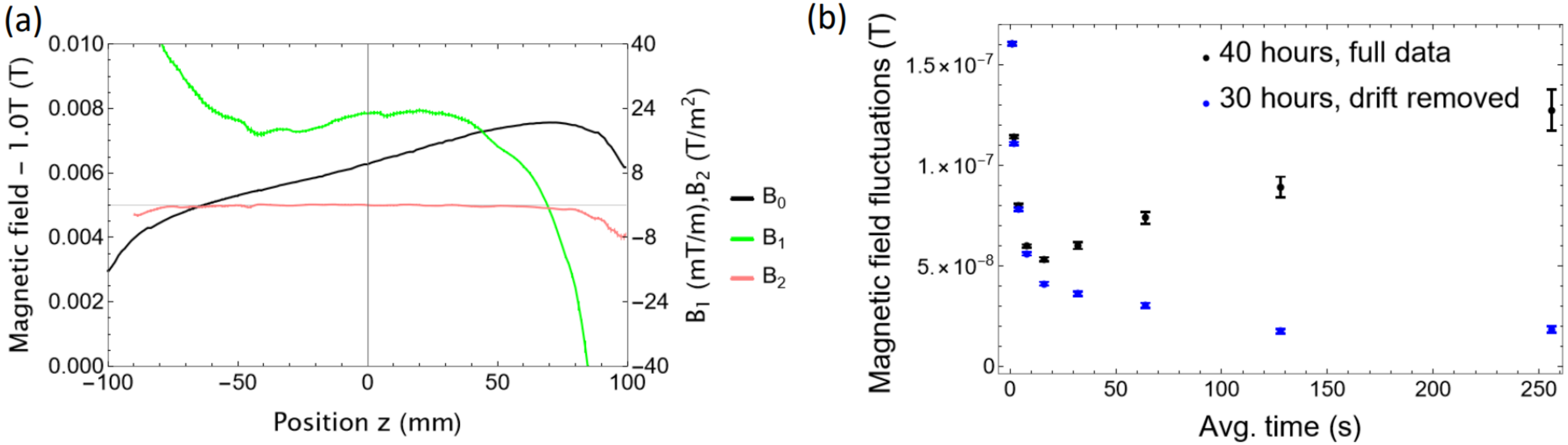
Vol. 94, Iss. 11, Nov. 2023

BASE-STEP: A transportable antiproton reservoir for fundamental interaction studies

C. Smorra, F. Abbass, D. Schweitzer, M. Bohman, J. D. Devine, Y. Dutheil, A. Hobl, B. Arndt, B. B. Bauer, J. A. Devlin, S. Erlewein, M. Fleck, J. I. Jäger, B. M. Latacz, P. Micke, M. Schiffelholz, G. Umbrazunas, M. Wiesinger, C. Will, E. Wursten, H. Yildiz, K. Blaum, Y. Matsuda, A. Mooser *et al.*

March	Delivery of the superconducting magnet
April	Installation work and commissioning of the magnet in the BASE-STEP zone
May – July:	Magnet characterization measurements, including boil-off tests for the transport of the magnet
August-October	Installation and cryogenic test of the trap system
November	Additional boil-off measurements to improve the transport time
In parallel:	Work on the beamline installation/vacuum/bake out Work on the BASE beam monitor (wire grid detector) Development of the transport routine (safety studies) Transport tests (concrete block with shock clock, craning with vibration sensors)

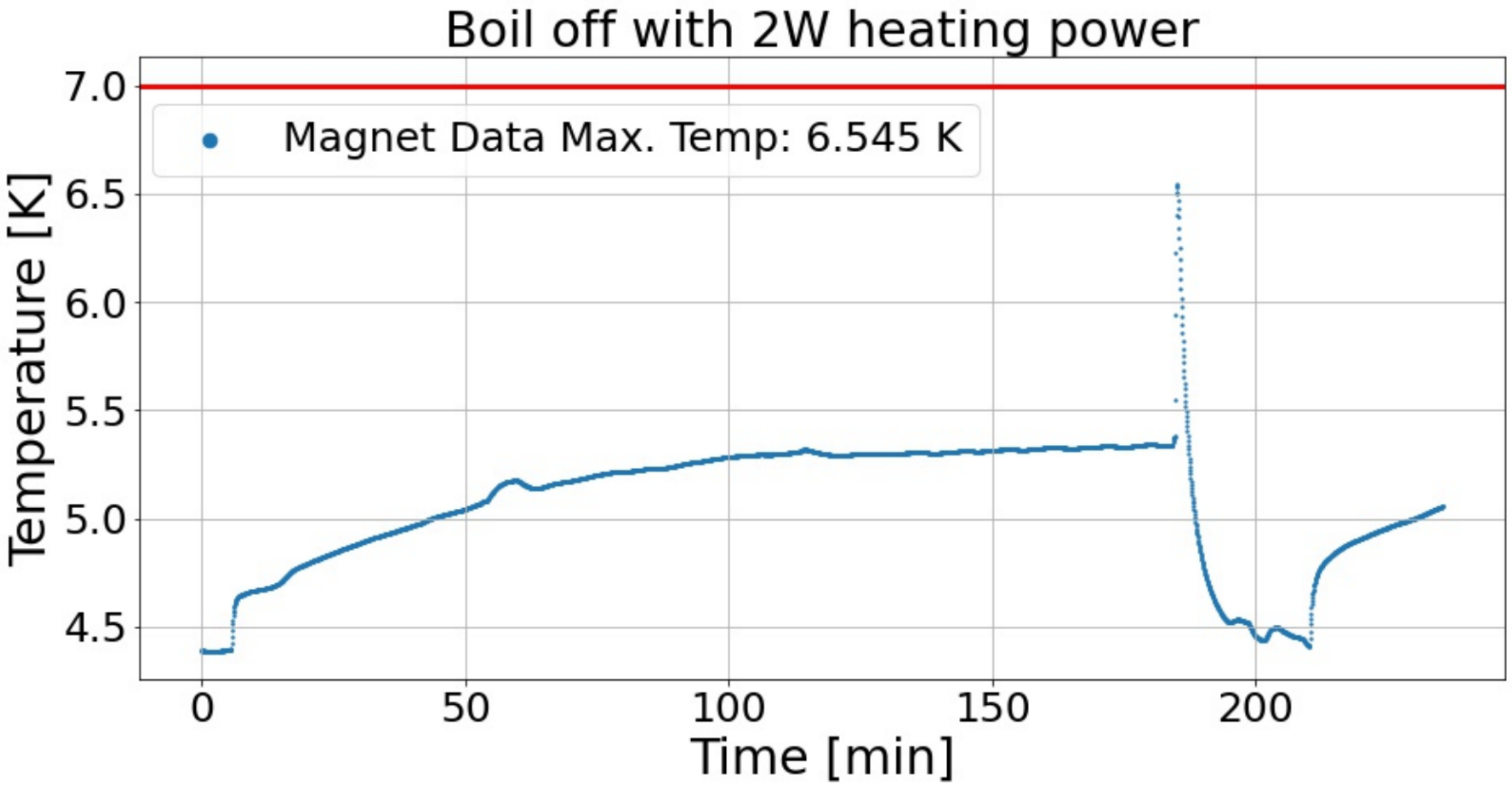
Magnetic field characterization

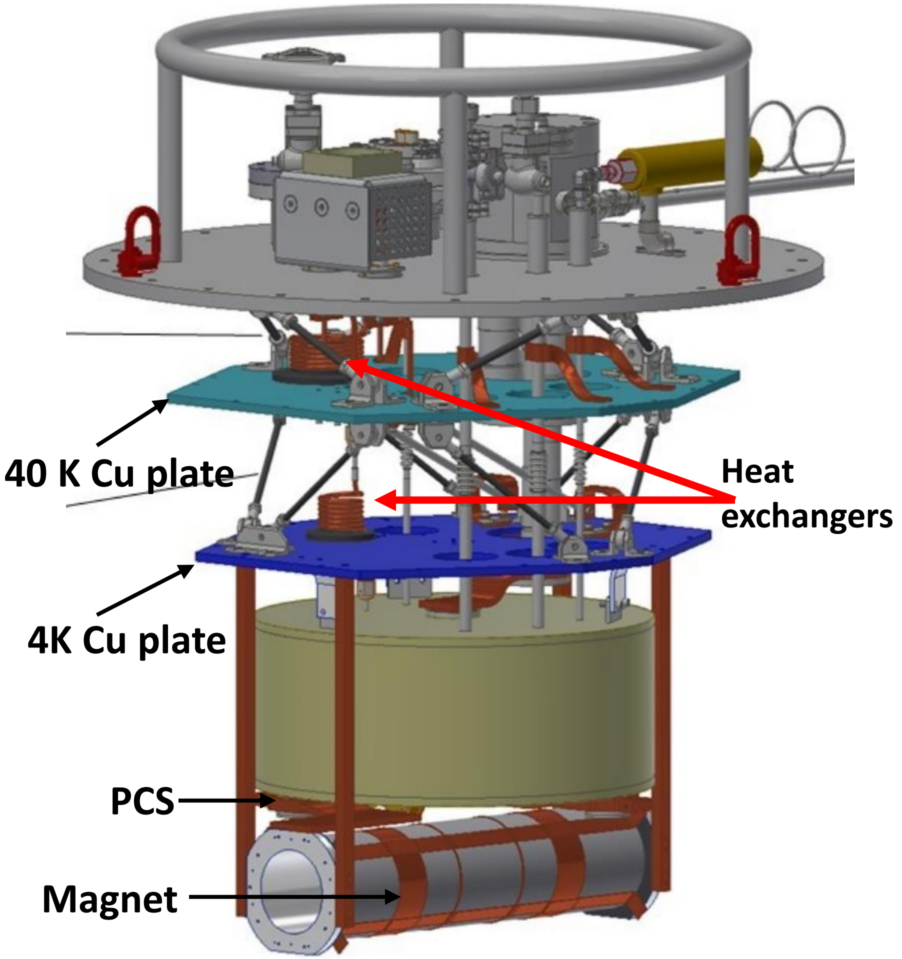


The coil system of the magnet works as desired!

In addition: Shielding factor of the magnet was measured with a Hall probe:
About 1/100 suppression of AD ramps near the magnet center due to the carbon steel vacuum chamber.

Transport time test with helium boil-off



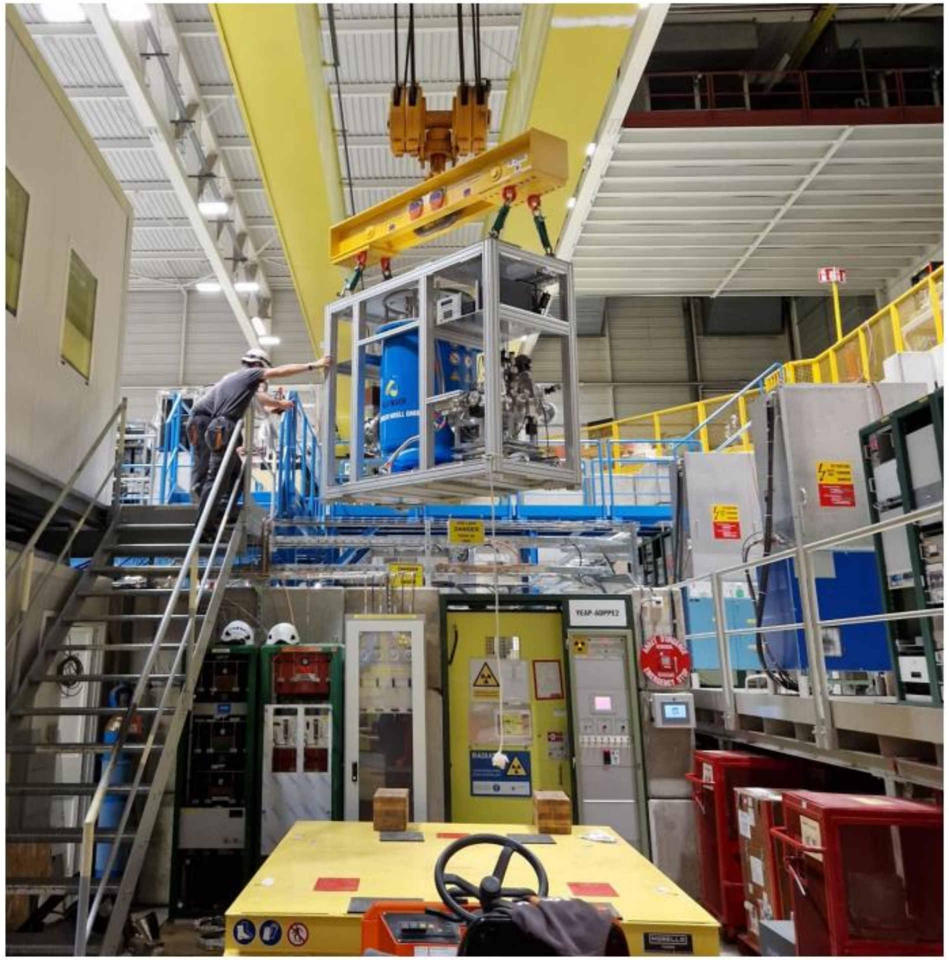


Increase the helium boil-off rate using a resistor on the liquid helium tank

Use the heat exchange line as exhaust to cool the heat shields/cryo cooler interface with the cold gas

The limit should be in the range of 4h to 6h, limited by the volume of the helium tank.

Development of the transport procedure



Cleared: Structural safety study for craning and driving

In progress: Structural safety study for towing on the truck

Cleared: Permission for chemical transport (helium gas/liquid helium)

Cleared: Radioprotection clearance for transport inside CERN

Open: RP clearance / legislation for transport on public roads

Plans for 2024

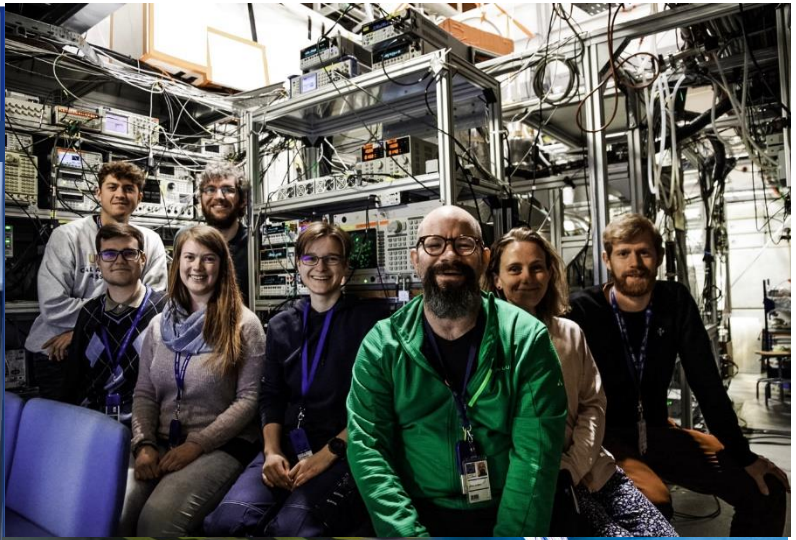
- Before start of the antiproton run
  - Finish this resonance including all systematics. Data sampling in January, systematic studies in February.
  - Afterwards – coherent methods with antiprotons.
  - Ramsey? Would look promising, because we should get for short pi/2 pulses at high power much more robust results and full inversion.
  - Combine then Ramsey with Phase methods.
  - STEP - GOAL: Trapped protons in April 2024, inlet vacuum 10^-9 or better
- During beamtime:
  - Servoed shielding.
  - First thing is to further optimize the AT. Operate the AT in 7-pole mode and do endcap based potential compensation, I hope for much higher SNR here. If this will work out, do a spin flip campaign for higher radial temperatures, to work towards a double trap measurement of the g-factor.
  - Particle shimming of the superconducting magnet, try to compensate the B1 gradient and to increase the gradient.
  - Invest additional time into the CT. We were unsuccessfully on this project in May 2022 and stopped after about 4 weeks and went for the current CT scheme, still there is a lot of potential for improvement, if we bring the axial detection signal alive. This would allow us to cool cyclotron in a kind of magnetron cooling scheme and would provide CPS cold spinflip particles in a minute. Based on that we can to real double trap schemes, which would make our g-factor systematics much better.
  - try to do adiabatic rapid passage and combine this optionally with cyclotron measurements to constrain the antiproton EDM.
  - After this measurement we should prepare for beam-taking and perform injection studies. Study systematically the robustness of catching. Load then a composite cloud of H- and pbars, then we will see…
  - STEP - GOAL: Transport trapped antiprotons!!!
- After beamtime
  - Then: H- experiments and improved pbar experiments, together with another improved measurement of the proton moment. His all will likely cover another year, but let’s see….no need to decide today.

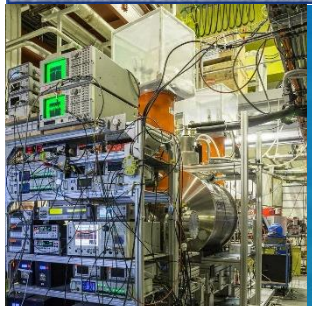
Summary and next steps

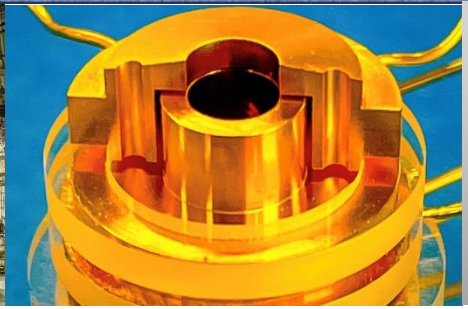
- Excellent progress towards a measurement of the proton/antiproton magnetic moment, with a considerably improved apparatus, which is fully operational.
- All experimental upgrades successful, implemented an instrument with «world record magnetic moment resolution», with excellent frequency stability, and compensated systematics.
- Issues with antiproton catching, to be resolved during YETS and in the next run.

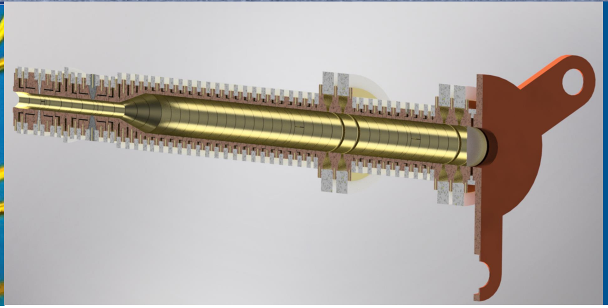
- **Next steps:**
    - Further investigate PT spin flipping.
    - Investigate residual systematics.
    - Measure the proton magnetic moment at improved fractional accuracy.
    - Measure the antiproton magnetic moment at imporved fractional accuracy.

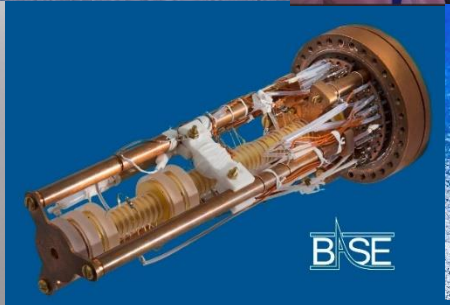
Thanks for your attention

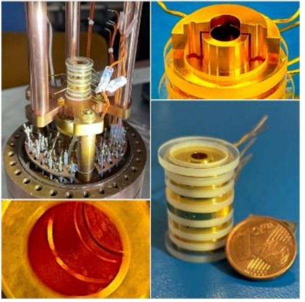












Cryogenic operation of the trap system

- Thermal construction: as expected
  - 3.9 K in dry mode without trap system
  - 3.9 K – 4.3 K in liquid mode without trap system (thermoacustic oscillations)
  - 4.8 K in dry mode with trap system
  - 4.4 K in liquid mode

- Detection systems: 3 of 4 functional
  - 1 detection wire needs repair
  - Q values of 2 axial detectors need to be improved

- Field emission point was misaligned
  - Cryogenic tests of a new electron gun are ongoing

Plans for BASE-STEP 2024

1) Be ready for the next cooldown when the AD crane comes back into operation

2) Cold head tests in the e-lab to test the e-gun with magnetic field (observe current on the target electrode)

3) Refurbish the detection systems (Figure out what the limitation is, make new coils/amplifiers, improve trap wiring

4) Improve the inlet chamber vacuum, target: 10^-10 mbar

   Last year: 10^-8 mbar, 10^-7 mbar cryogenic without pump

   Bakeout, proper cleaning, analysis of the outgassing rates of the surfaces in the inlet chamber, activate getter pump

GOAL: Trapped protons in April 2024, inlet vacuum 10^-9 or better

Plans for BASE-STEP 2024

Plans until beam stop (Nov. 2024)

Measurements with protons/ions:

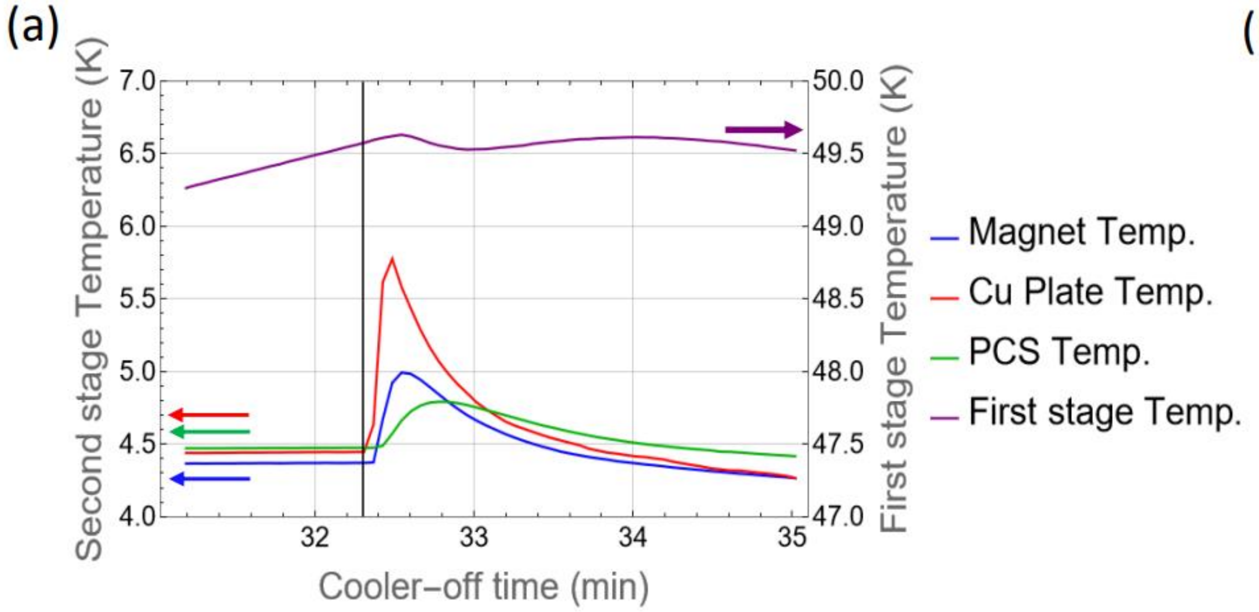
- Measure the trap vacuum
- Explore the performance of the STEP magnet for precision measurements
- Simultaneous proton/antiproton cyclotron frequency measurements
- Particle counting with simultaneous axial/cyclotron detection

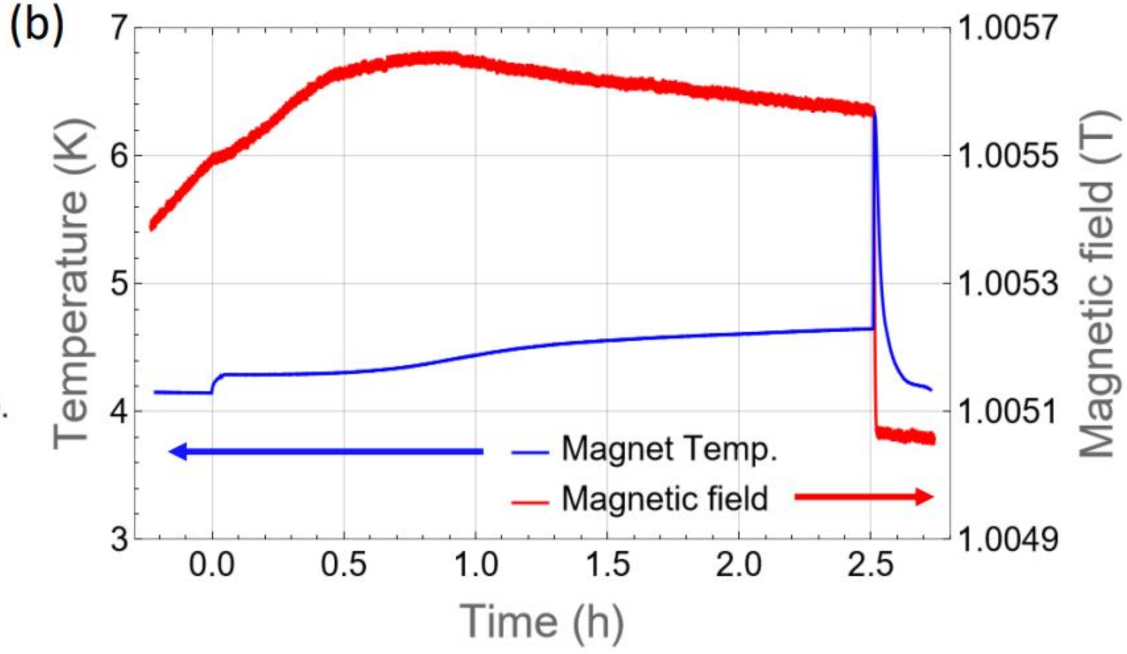
Work on injecting antiprotons:

- Improve the deflector chamber vacuum
- Prepare the beam monitors
- Install alignment equipment, and optimize the magnet position

Characterization of transport time

During transport, the cryocooler of the magnet is stopped (e.g. while craning) and restarted at its destination.
Gaps in power are bridged by the liquid helium tank.
Liquid helium holding time is 12 hours without additional heat load and cryocooler off.





Cryocooler spikes that occur when restarting the cryocooler are limiting the transport time.
Temperature limit for the magnet coil: 7.0 K at the nominal current of 33.4 A.

Best demonstration so far with magnetic field: 2.5 hours without power / no additional heat load

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.

Systematic Limitations of 2017 Measurement

Uncertainty Budget of 2017 Measurement:

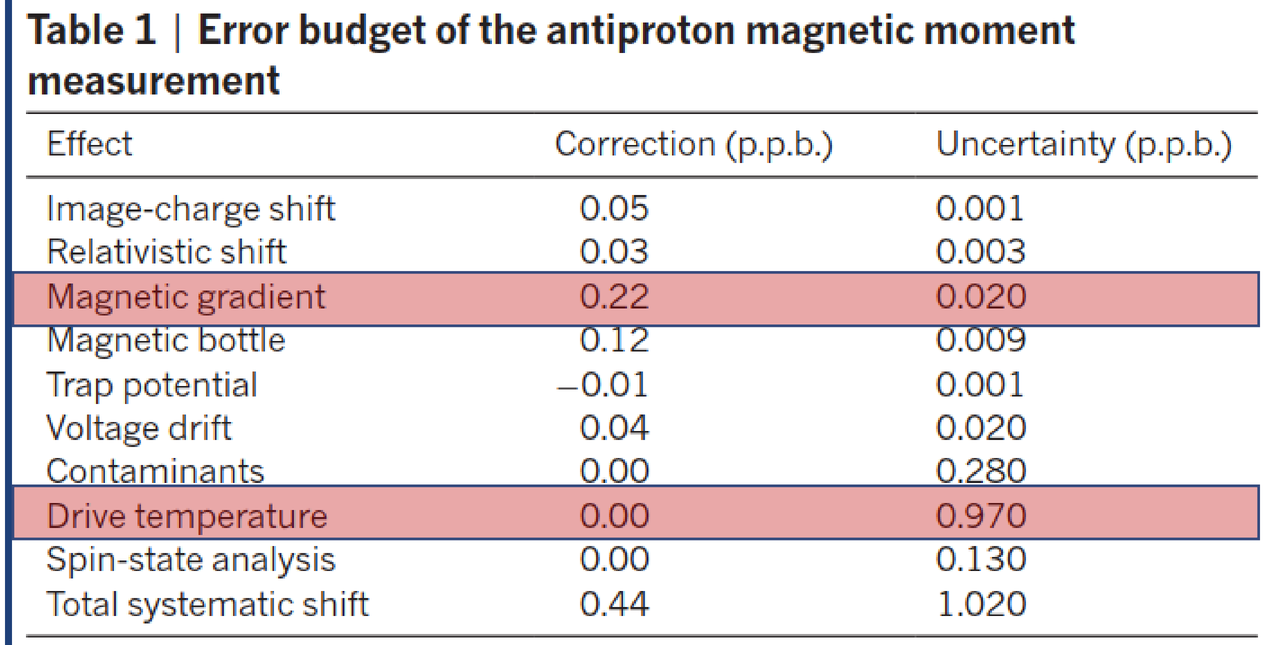
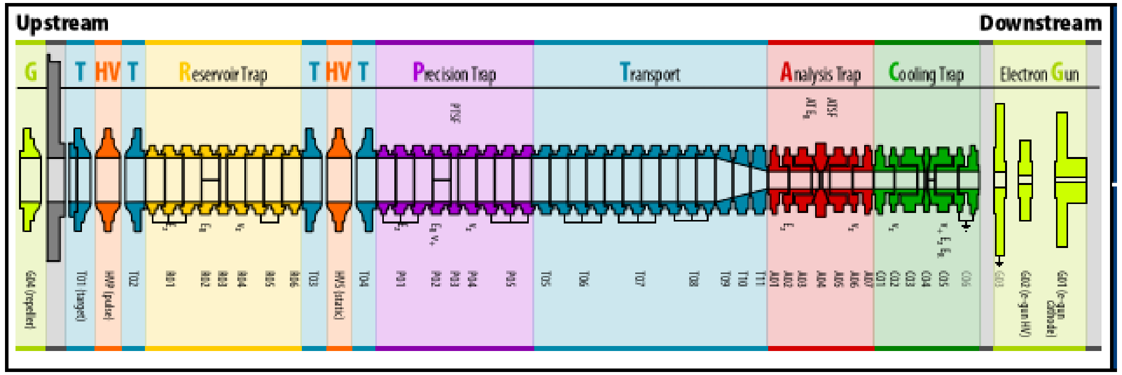


Table 1 | Error budget of the antiproton magnetic moment measurement

Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)
Image-charge shift	0.05	0.001
Relativistic shift	0.03	0.003
Magnetic gradient	0.22	0.020
Magnetic bottle	0.12	0.009
Trap potential	−0.01	0.001
Voltage drift	0.04	0.020
Contaminants	0.00	0.280
Drive temperature	0.00	0.970
Spin-state analysis	0.00	0.130
Total systematic shift	0.44	1.020

Limited by magnetic bottle strength of 2.7(3) T/m^2

New trap layout with increased distance between analysis trap and precision trap.



Recent magnetic field measurements:

Parameter	Value 2023	Value 2017
$B_1\ (T/m)$	$0.0108(3)\ T/m$	$0.0712(4)\ T/m$
$B_2\ (T/m^2)$	$0.0015(21)\ T/m^2$	$2.7(3)\ T/m^2$

B1 improved by factor of 7.

B2 improved by factor of >1000.

→

g-factor precision goal of order 100 p.p.t. at much higher sampling rate in reach (so far no show stoppers identified).

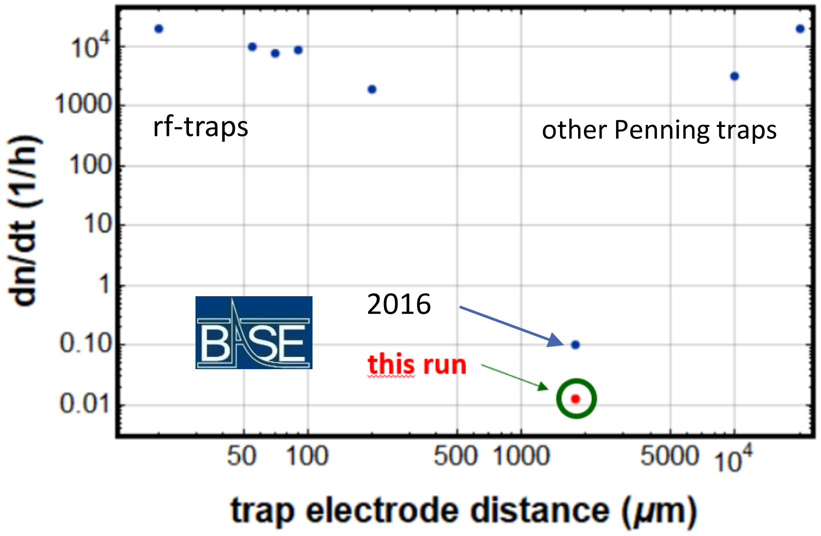
The «Perfect» g-Factor Measurement

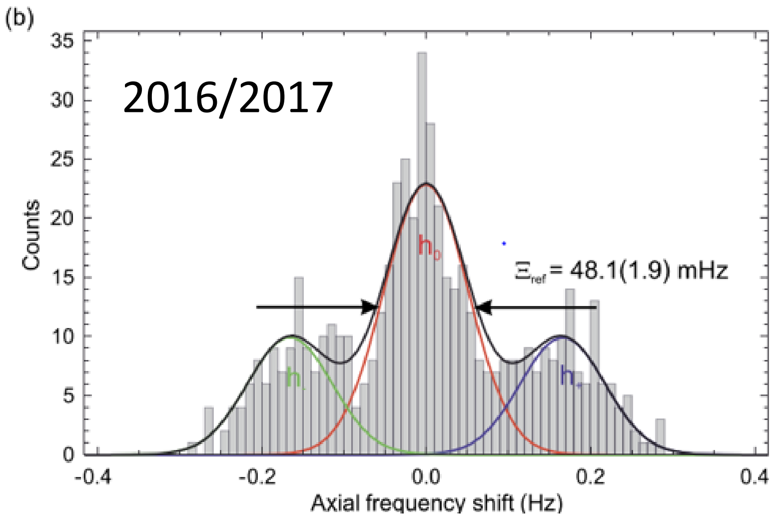
- Measurement improved previous experiments by a factor of >3000, but:
  - The width of this resonance is deliberately saturated to counteract accelerator imposed frequency flutuations
  - The resonance is incoherent with a maximum spin inversion of 50%.
    - **Reason:** Particle detector interaction in inhomogeneous magnetic field leads to thermal phase noise with correlation time constant of 30ms and line width parameter of 600mHz
  - High spin state detection fidelity only achieved by sub-thermal cooling to $E_+ < 8.6\ \mu\mathrm{eV}\ (100\ \mathrm{mK})$, which required >10h
  - Limits due to magnetic field fluctuation in the accelerator hall.

- Better shielding of accelerator imposed frequency fluctuations, or reservoir based measurements during AD/ELENA downtime
- Implement coherent spin quantum transition spectroscopy with a single anti-nuclear spin.
  - **Solution:** Much more homogeneous magnetic field at lower temperature of the axial detection system.
- Improve heating rates in the spin detection trap and implement faster Maxwell deamon state preparation.
- Mulit layer coil systems, faster frequency measurements at higher resolution.

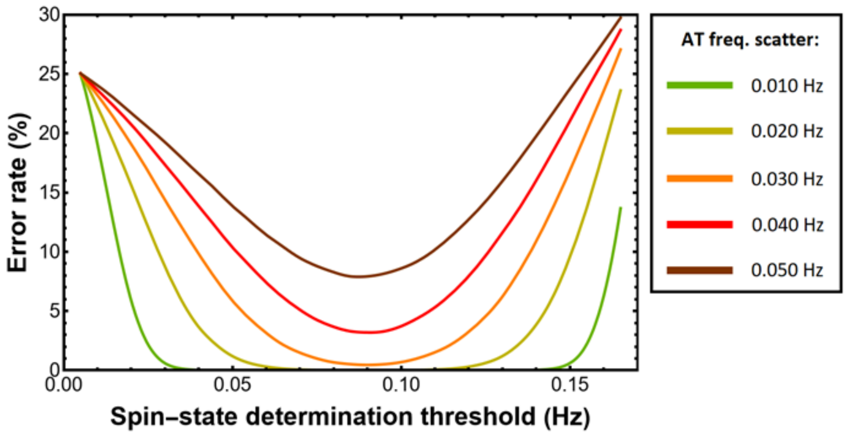
The single spin flip 2023

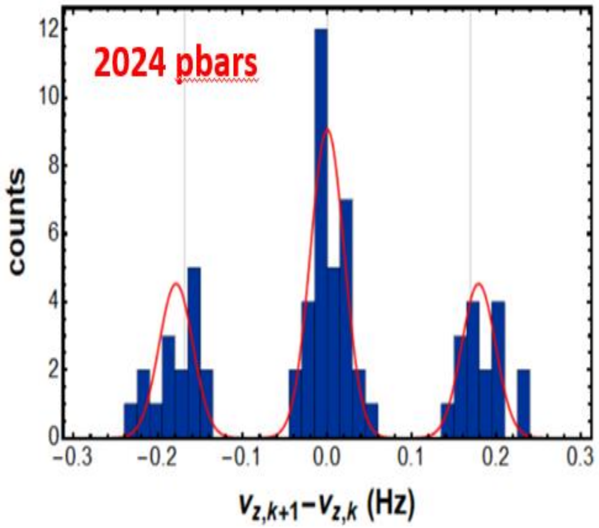
- **Current experiment:**
  - considerably improved particle cooling, thus much higher sampling rate
  - Double trap measurement cycles demonstrated -> reduced systematics
  - Ultra homogeneous magnetic field
  - Ultra stable experiment magnet
  - Coherent quantum spectroscopy methods and phase methods available.





- **Successful detection of spin transitions with 99.95% detection fidelity**
  - Much faster experiment cycles possible.
  - Threshold initialization not required anymore.





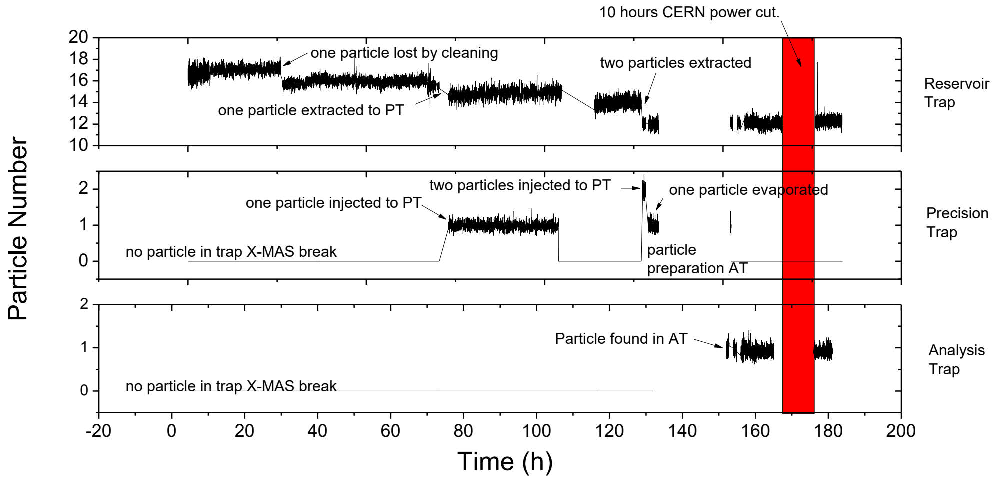
Very optimistic to improve the antiproton moment measurement by >factor of 10

Possibilities: Direct measurement of 3He2+ / 10 fold improved limits on MCP / 20neV absolute energy resolution

BASE Specialties – The Antiproton Reservoir Trap

405 day of antiproton-cloud trapping demonstrated

- We have
  - A vacuum of 5e-19 mbars
    - best characterized vacuum on earth,
    - comparable to pressures in the interstellar medium
  - Antiproton storage times of several 10 years.
  - Not more than 5000 atoms in a vacuum volume of 1.2l
  - Order 100 to 1000 trapped antiprotons
  - A local inversion of the baryon asymmetry

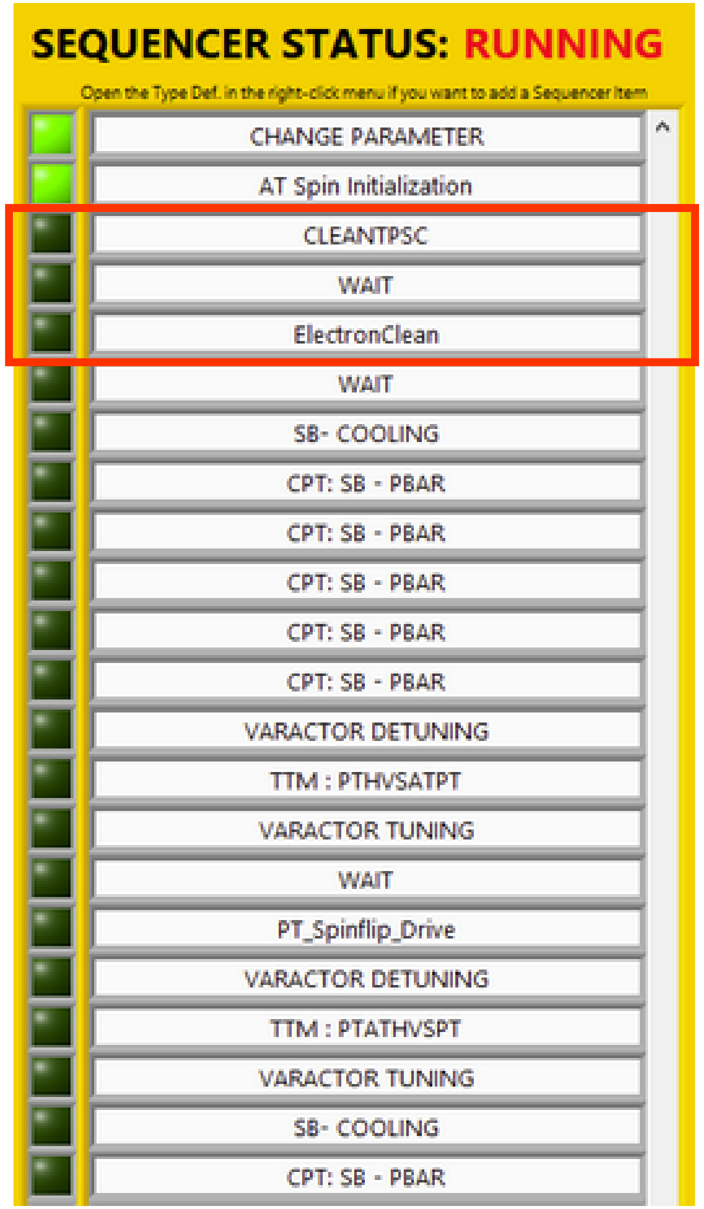


BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryons in local trap volume	$1.65*10^{-7}$
Antibaryon in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^8$**
Ratio Inversion	**$3.8*10^{12}$**

- Pbar consumption (excl. steering and trap loading):
  - Since 2014: 68 particles lost
  - Since 2014: 34 particles lost due to exp. Mistakes
- Average loss rate is at 1 particle in 2.5 months.
- **Direct lifetime limits: t > 26.5a** (80-fold impr.)

With this instrument: Investigate properties of antimatter very precisely

Antiproton Magnetic Moment Measurement

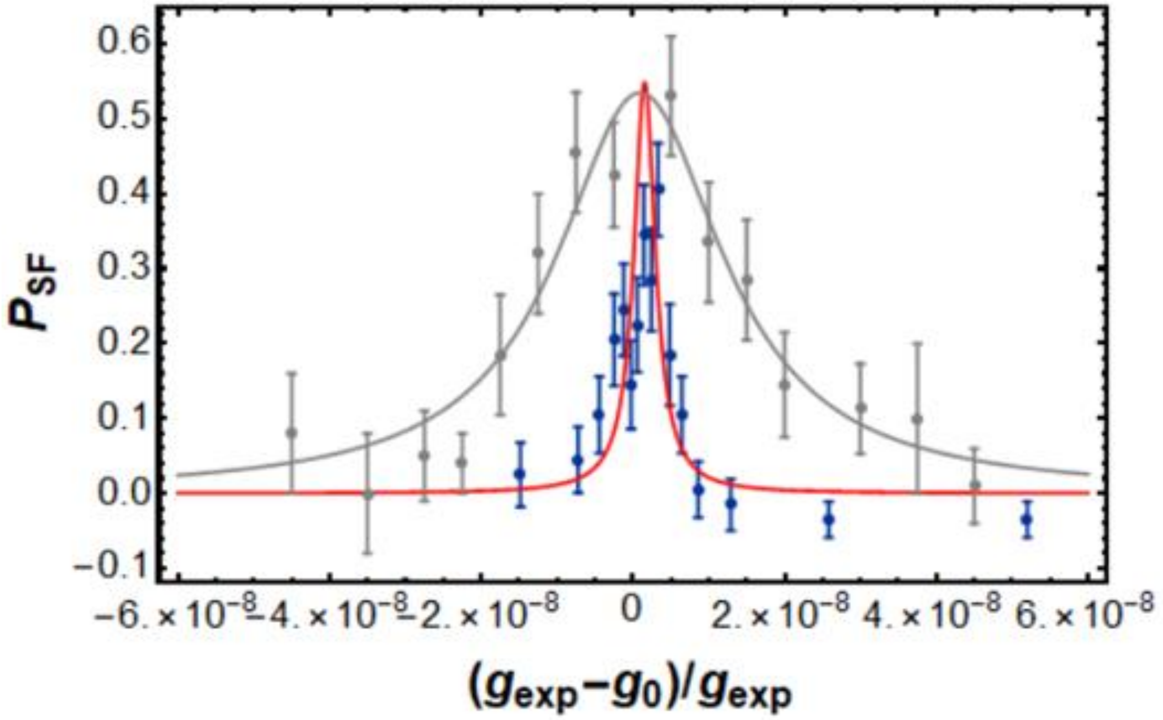


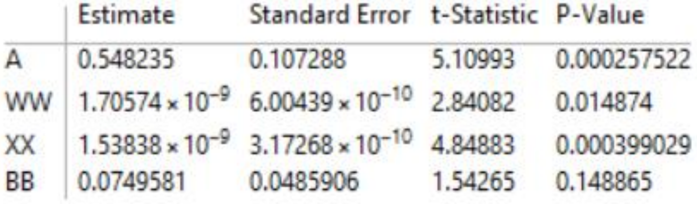
SEQUENCER STATUS: RUNNING

Open the Type Def. in the right-click menu if you want to add a Sequencer Item

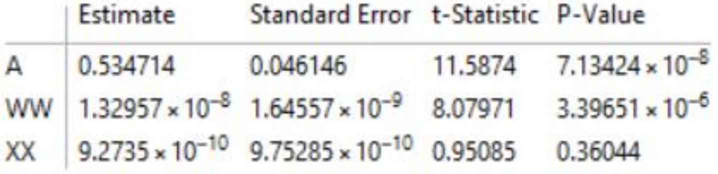
- CHANGE PARAMETER
- AT Spin Initialization
- CLEANTPSC
- WAIT
- ElectronClean
- WAIT
- SB- COOLING
- CPT: SB - PBAR
- CPT: SB - PBAR
- CPT: SB - PBAR
- CPT: SB - PBAR
- CPT: SB - PBAR
- VARACTOR DETUNING
- TTM : PTHVSATPT
- VARACTOR TUNING
- WAIT
- PT_Spinflip_Drive
- VARACTOR DETUNING
- TTM : PTATHVSPT
- VARACTOR TUNING
- SB- COOLING
- CPT: SB - PBAR

Electron cleaning due to beta decay required





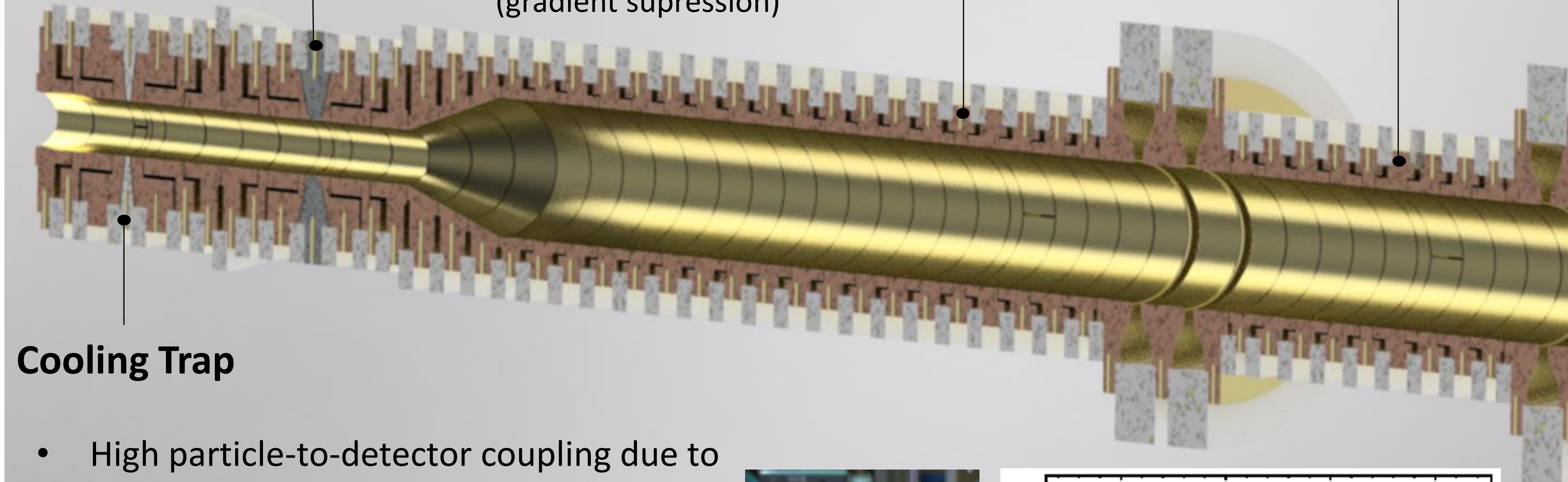
	Estimate	Standard Error	t-Statistic	P-Value
A	0.548235	0.107288	5.10993	0.000257522
WW	1.70574×10^{-9}	6.00439×10^{-10}	2.84082	0.014874
XX	1.53838×10^{-9}	3.17268×10^{-10}	4.84883	0.000399029
BB	0.0749581	0.0485906	1.54265	0.148865



	Estimate	Standard Error	t-Statistic	P-Value
A	0.534714	0.046146	11.5874	7.13424×10^{-8}
WW	1.32957×10^{-8}	1.64557×10^{-9}	8.07971	3.39651×10^{-6}
XX	9.2735×10^{-10}	9.75285×10^{-10}	0.95085	0.36044

Data sampling currently ongoing. Hope for improvement by at least a factor of 10.

New 2022-Multi Trap Stack



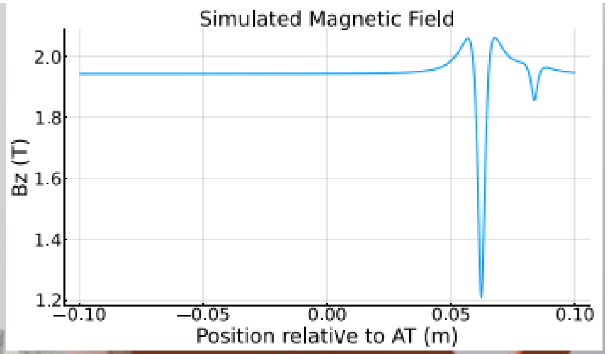
Analysis Trap
(spin state analysis)

Precision Trap
(frequency measurements)

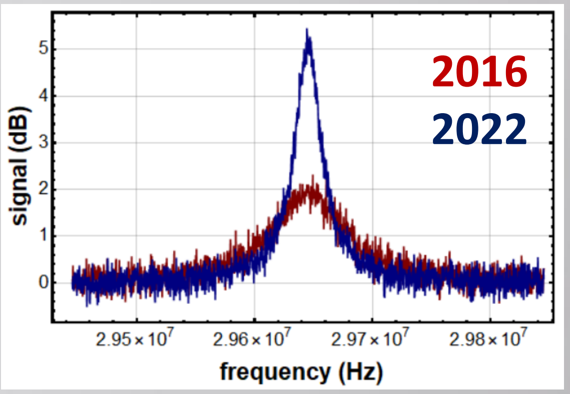
Reservoir Trap
(antiproton catching)

Elongated Transport Section
(gradient supression)

Cooling Trap

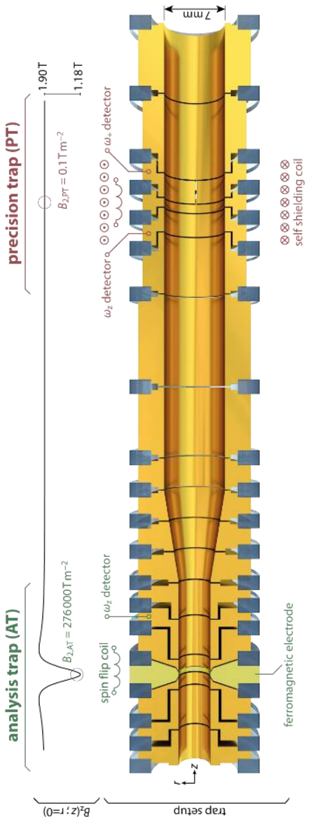


- High particle-to-detector coupling due to small electrode geometry. **Reduces cooling time constant by a factor of 25!!!**
- New highly shielded and highly optimized high performance resonant detection resistor for **more efficient cooling** and **reduced temperature**.

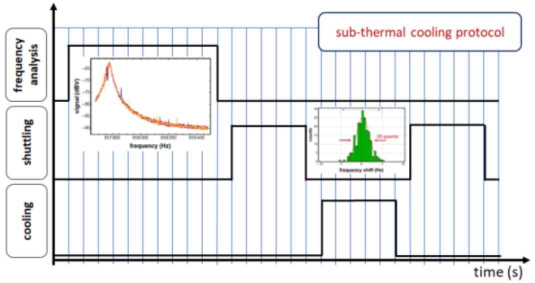


Sub-Thermal Cooling

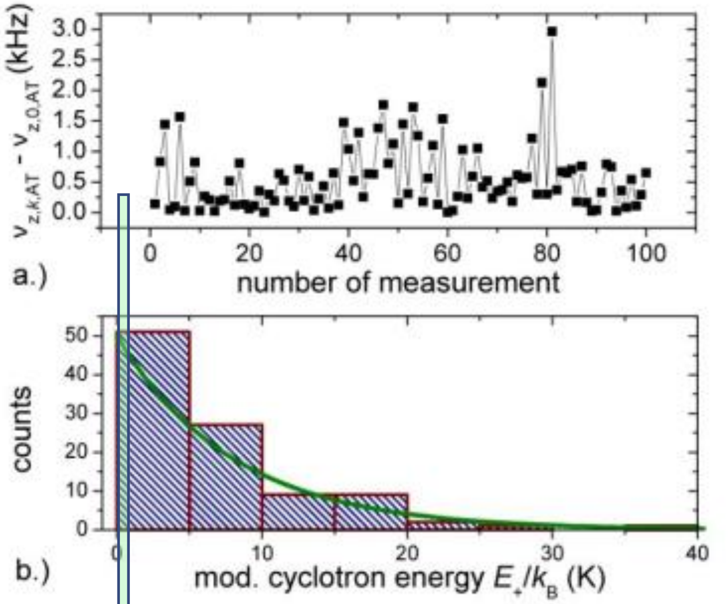
- Cold particle is prepared by selective resistive cooling in the PT



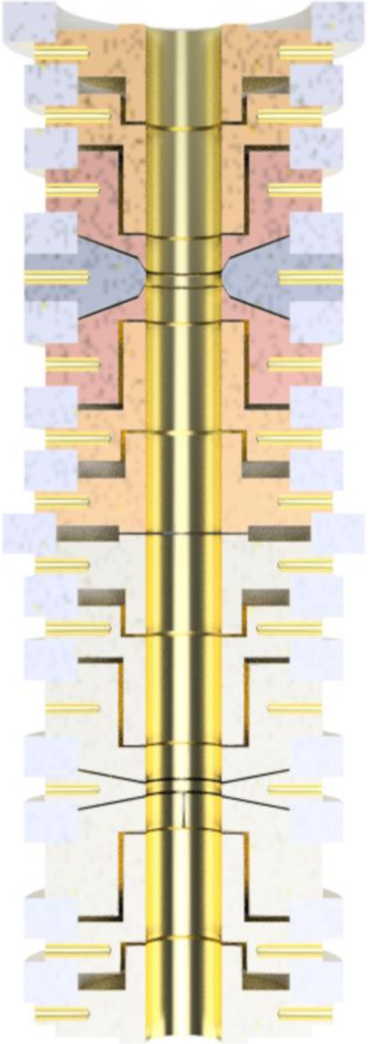
thermalize particle (10 min.)



Analyze temperature using the magnetic bottle



particles with single spin-flip resolution are in this temperature range



particle below threshold
-> **MEASURE**

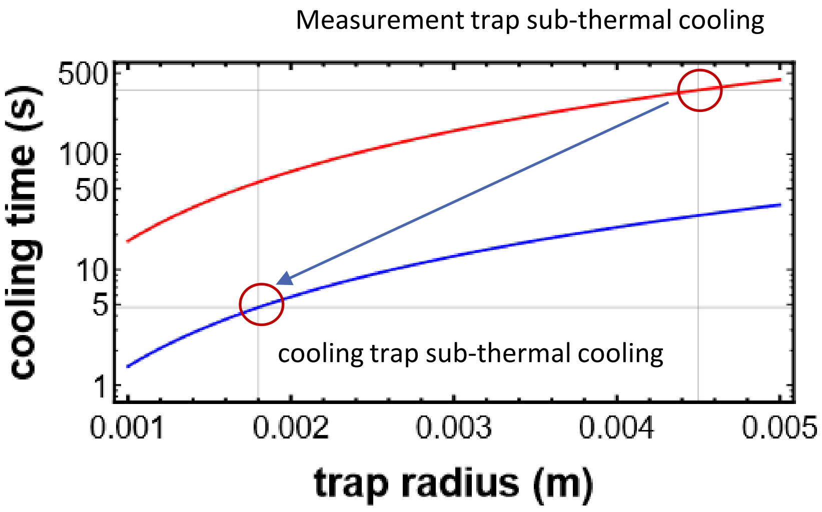
particle above threshold

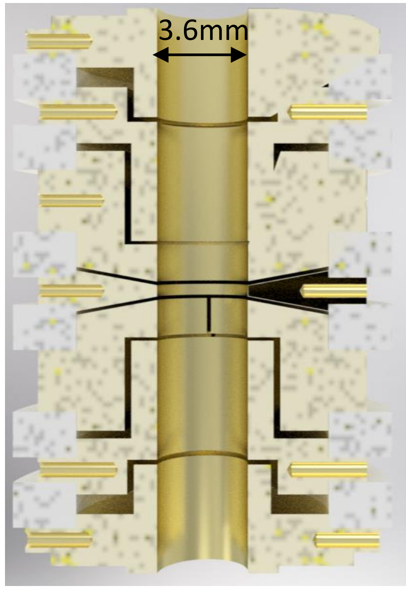
NOTE: each cyclotron frequency measurement heats the particle to about 300K

sub-thermal cooling is EXTREMELY time consuming

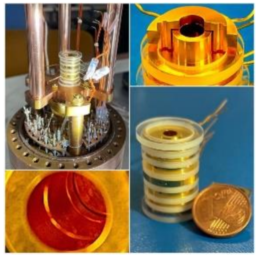
Antiproton Cooling Trap

- Implementation of a dedicated cooling trap with strong particle detector coupling, reduced detector temperature, high-performance detection resistor.
- Optimize transport and readout time in single-particle temperature measurements.





Parameter	2016 measurement (PT)	2022 measurement (CT)
detector temperature	**12.8 K**	**4.2 K**
detection Q	450	1250
R_p	75.000 Ω	360.000 Ω
pickup length (D_{eff})	21.5 mm	4.8 mm
thermalization time τ	600 s	4.2 s

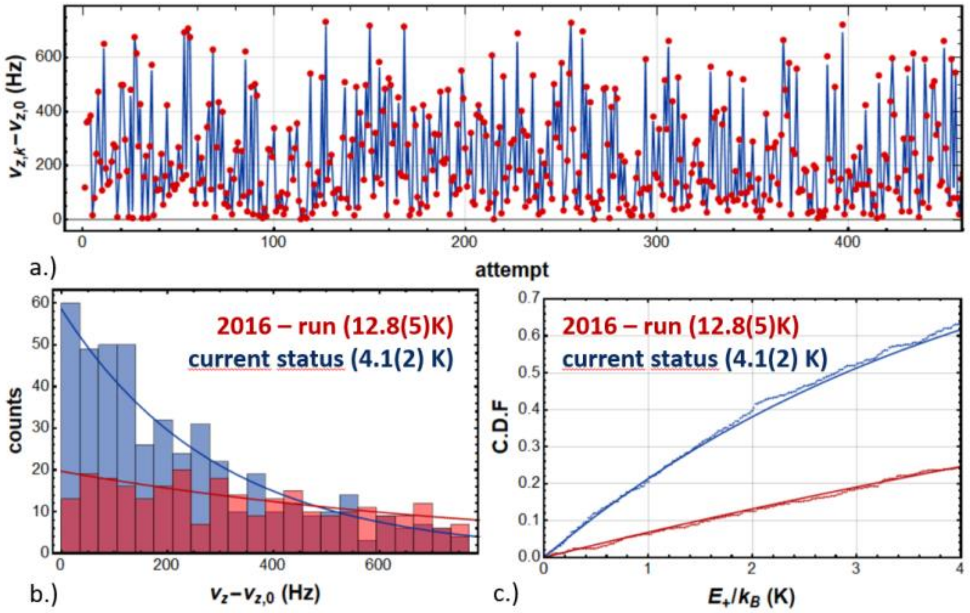


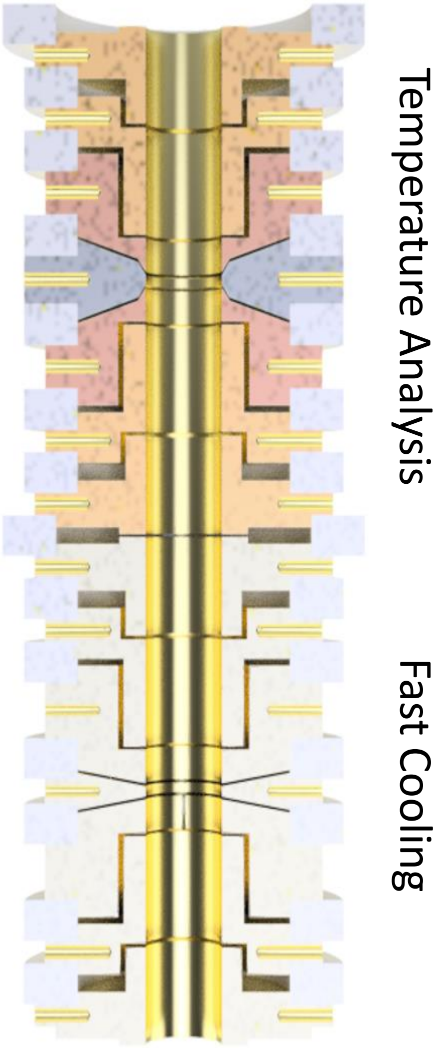
$$\tau = \frac{m}{R_p} * \left(\frac{D_{eff}}{q}\right)^2$$

Plan: More rapid cold particle preparation by stronger particle/detector coupling (smaller trap design) and improved detector performance (thermalization resistor/temperature)

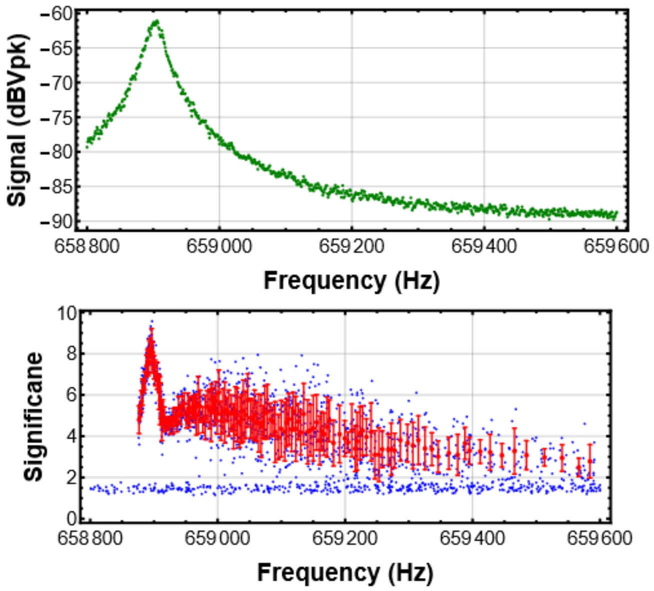
Temperature Measurement

- Sequence:
    - Measure axial frequency in AT
    - Shuttle AT – CT
    - Thermalize in CT
    - Shuttle CT – AT





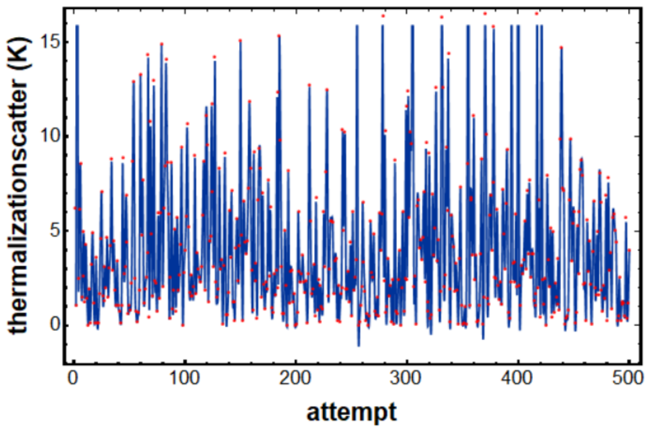
- **Conclusion:**
    - The 2022 temperature performance of the cooling resistor increased by a factor of 3.
    - Decreases amount of required cooling attempts for low temperature threshold by a factor of 3

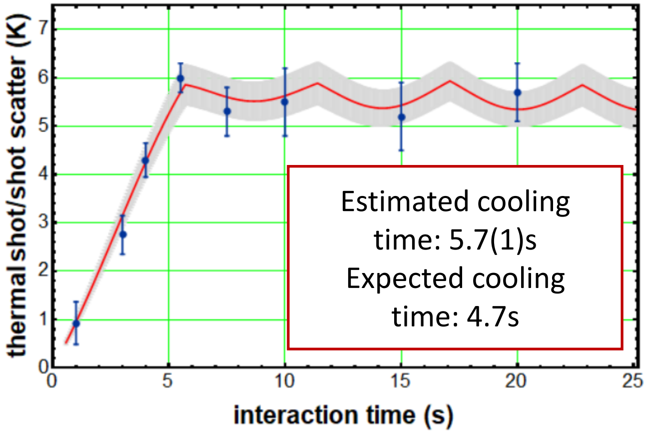


- **2016** – used particle readout time of 60s in several screenshots.
- **2022** – optimized single shot particle readout time for high identification efficiency:
    - 16s at 0.5K detection bandwidth and 95.8% detection efficiency.
    - 16s at 0.25K detection bandwidth and 99.8% detection efficiency.

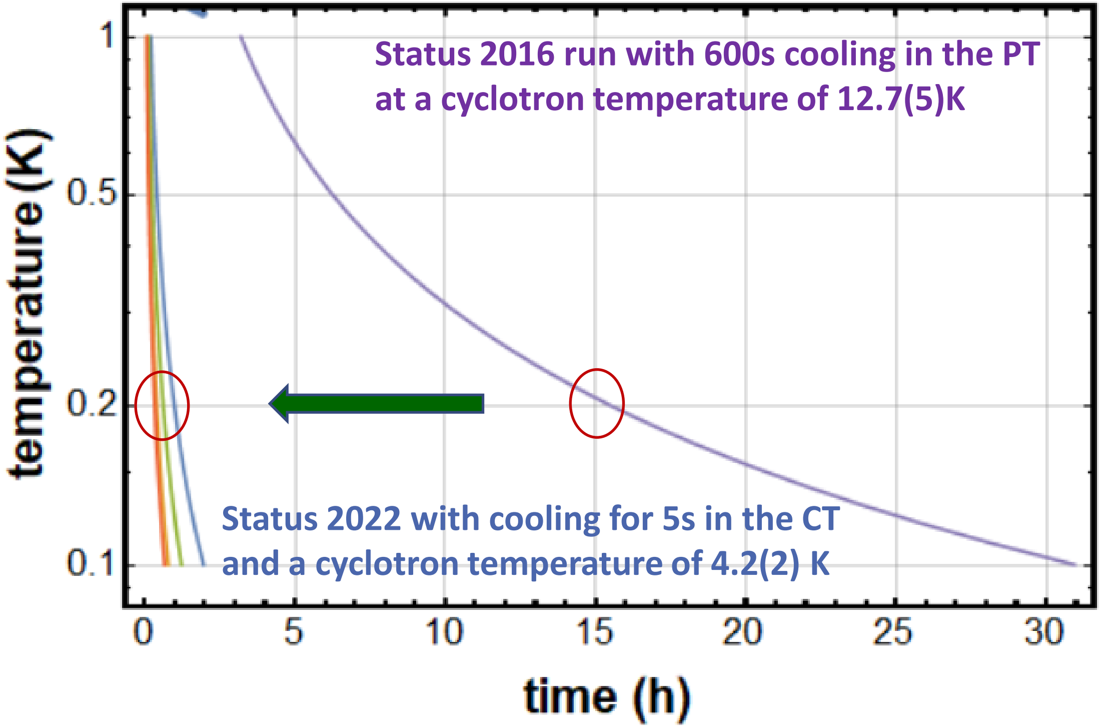
Thermalization Time Optimization

- Use correlation estimates to determine optimum particle / detector coupling time.
  - Measure frequency scatter as a function of particle / detector interaction time





Estimated cooling time: 5.7(1)s
Expected cooling time: 4.7s



Status 2016 run with 600s cooling in the PT at a cyclotron temperature of 12.7(5)K

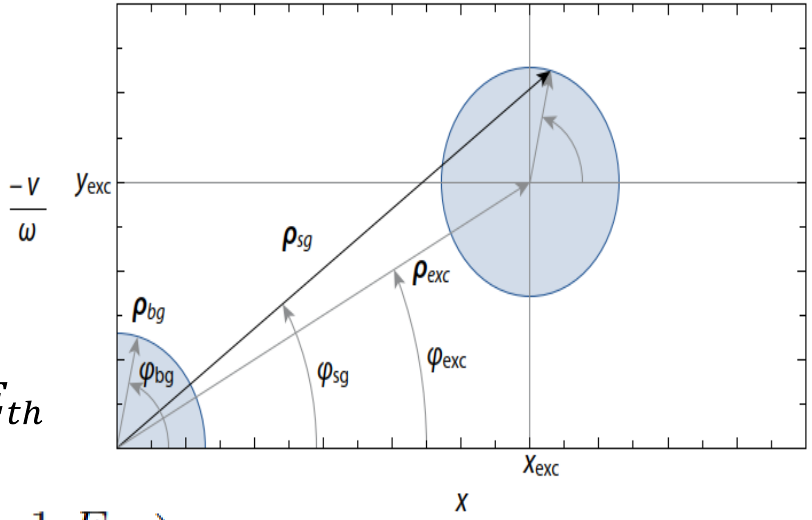
Status 2022 with cooling for 5s in the CT and a cyclotron temperature of 4.2(2) K

Item	2016	2022
Spec AVG	64s	16s
TP from AT	78 s	5 s
Thermalize	600 s	5 s
TP To AT	78 s	5 s
Single Cycle	820 s	31 s
Improvement Factor: 26 (* 3 times T reduction)		

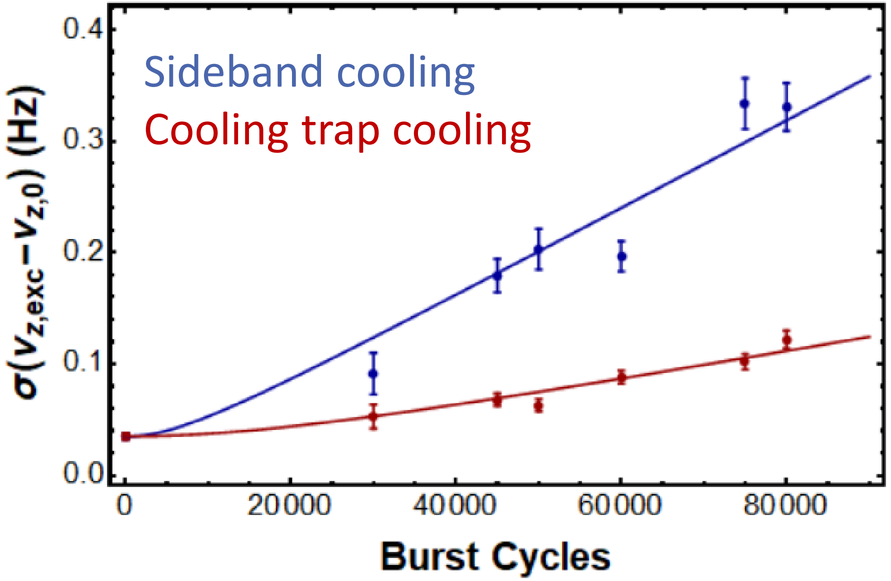
- Three-fold temperature reduction gives additional factor of three in time reduction for particle preparation at given threshold.
- **Explicitly demonstrated:** robust 200mK particle preparation in 8 minutes compared to previously 15h.

Applications – Phase Space Reduction

- Thermal initial conditions of a particle determine energy resolution and phase resolution of particle excitation



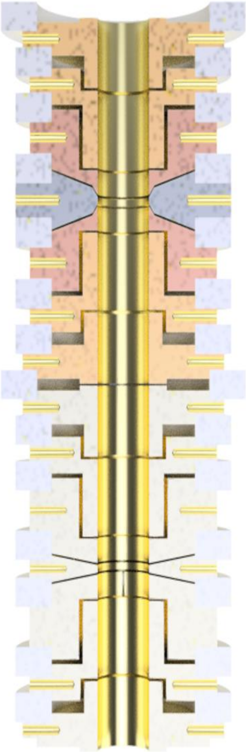
- Resonant Radius $$\rho(t) = \frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}$$
- Resulting Energy $$E(t) = \left(\frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}\right)^2 = E_{exc} + 2\sqrt{E_{th}}\sqrt{E_{exc}} + E_{th}$$
- Resulting Energy Scatter $$\sigma(E_+) = \sqrt{2E_{\mathrm{th}}E_{\mathrm{exc}}} \times \sqrt{1 + \frac{1}{2}\frac{E_{\mathrm{th}}}{E_{\mathrm{exc}}}} \approx \sqrt{2E_{\mathrm{th}}E_{\mathrm{exc}}}\left(1 + \frac{1}{4}\frac{E_{\mathrm{th}}}{E_{\mathrm{exc}}}\right)$$



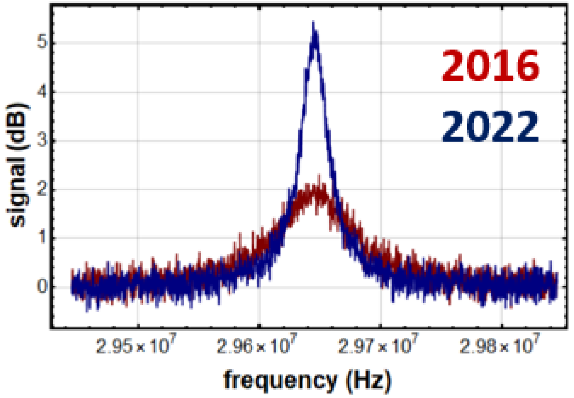
- **Enables:**
  - Measurements at lower temperature and reduced systematic shifts
  - Measurements at better defined particle energy
  - Measurements at robust signal to noise ratio
  - Measurement at higher phase resolution

Full potential for future frequency measurments under investigation

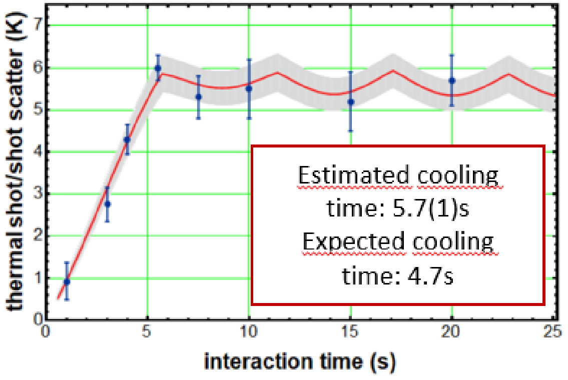
Summary – CT Performance



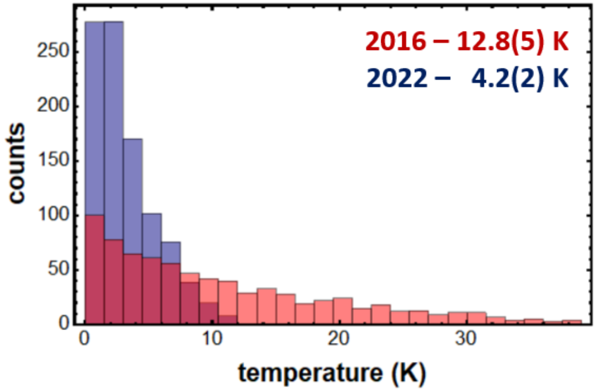
Parameter	2016 measurement (PT)	2022 measurement (CT)
detector temperature	**12.8 K**	**4.2 K**
detection Q	450	1250
R_p	75.000 Ω	360.000 Ω
pickup length (D_{eff})	21.5 mm	4.8 mm
thermalization time τ	370 s (P4)	4.2 s (C5)
Transport time	2 x 78 s	2 x 4.6 s
Readout time	64 s	16 s
200 mK preparation	**15 h**	**8 min**



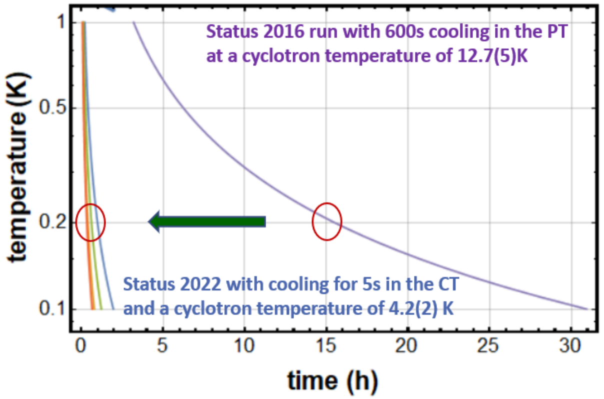
Item	2016	2022
Spec AVG	64s	16s
TP from AT	78 s	5 s
Thermalize	600 s	5 s
TP To AT	78 s	5 s
Single Cycle	820 s	31 s
Improvement Factor: 26		



Estimated cooling time: 5.7(1)s
Expected cooling time: 4.7s

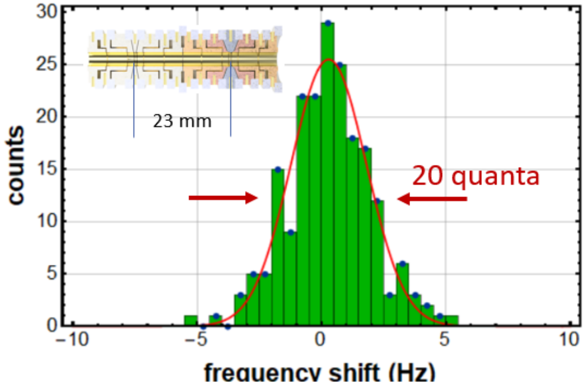


2016 – 12.8(5) K
2022 – 4.2(2) K



Status 2016 run with 600s cooling in the PT at a cyclotron temperature of 12.7(5)K

Status 2022 with cooling for 5s in the CT and a cyclotron temperature of 4.2(2) K



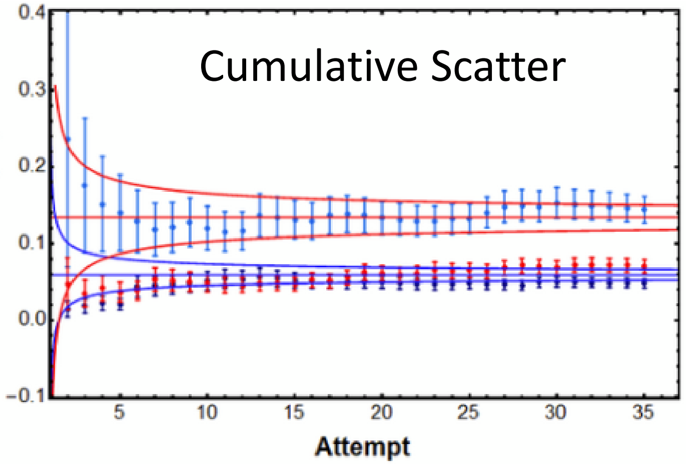
Flipping Spins

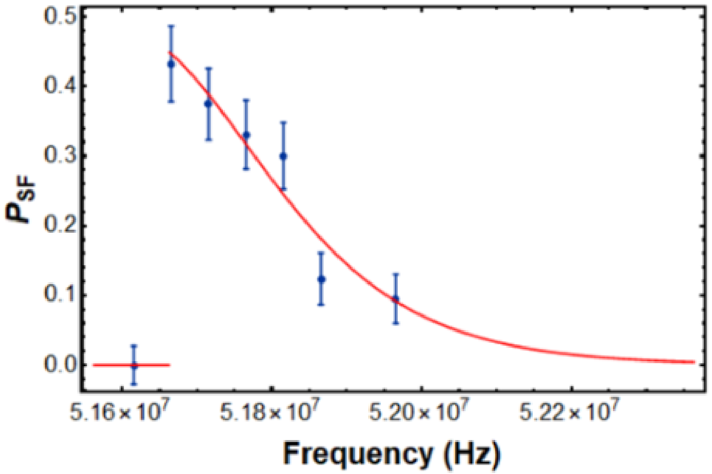
- Recording **statistical spin flips** and sampling of a Larmor resonance curve

Observed frequency scatter:

$$\Xi = \sqrt{\Xi_B^2 + P_{SF}\Delta\nu_{z,SF}^2}$$

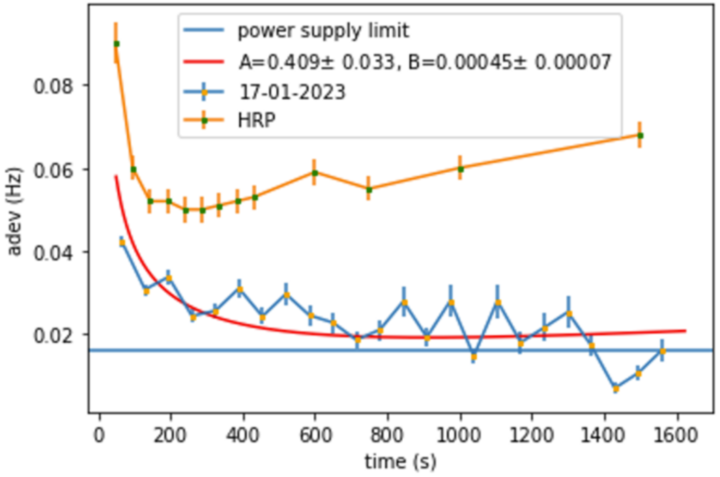
Further optimization of background noise and averaging time ->

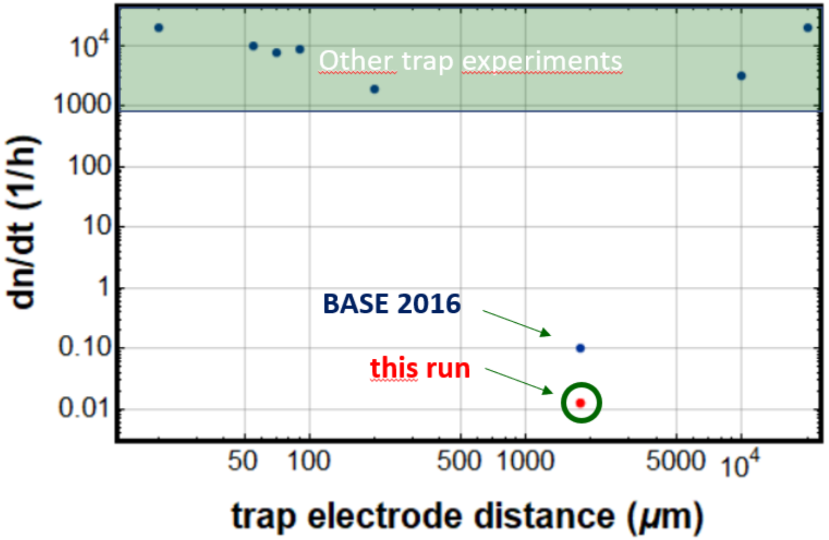




Heating rates further reduced by tweaking many parameters like

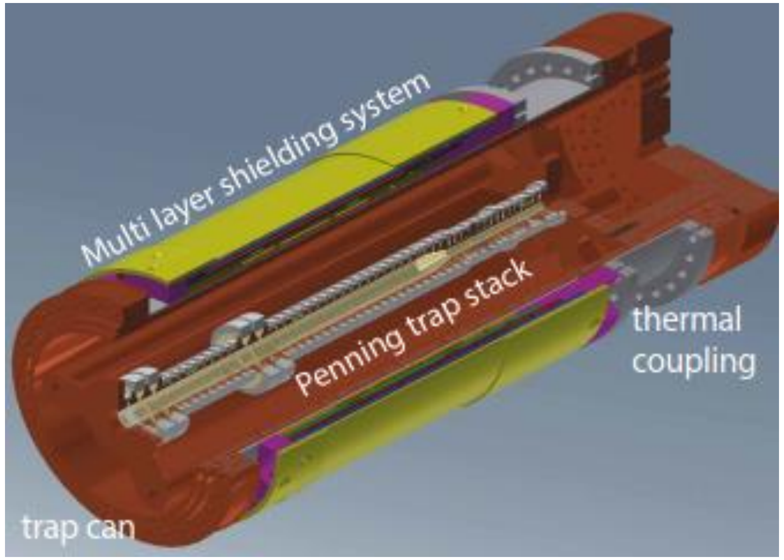
- Particle temperature
- Rf-noise amplitudes
- Detection signal-to-noise ratio
- Detection signal width





Dominant Systematic Trap – Uncertainty

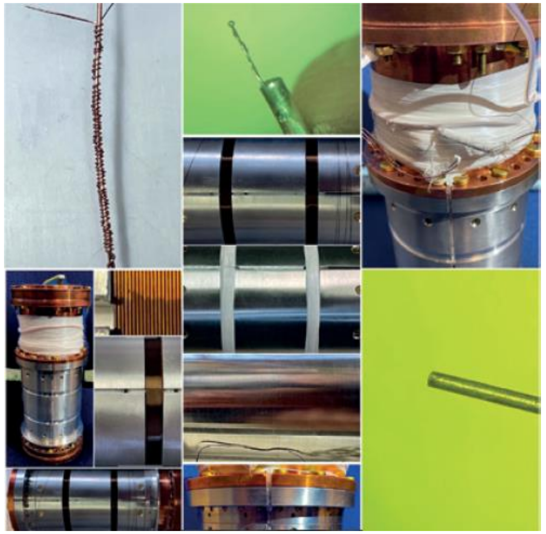
Designed and developed
in the BASE
development laboratory



Dominant shift from trap systematics at our current magnetic field properties:

$$\frac{\Delta\nu_c}{\nu_c} = \frac{\nu_+}{\nu_c^2}\Delta\nu +_{+} \frac{\nu_z}{\nu_c^2}\Delta\nu_z \approx \frac{1}{4\pi^2 m_0 \nu_z^2}\frac{B_2}{B_0}k_B T_z = -23.5(1.5)\,\frac{\text{p.p.t.}}{\text{K}},$$

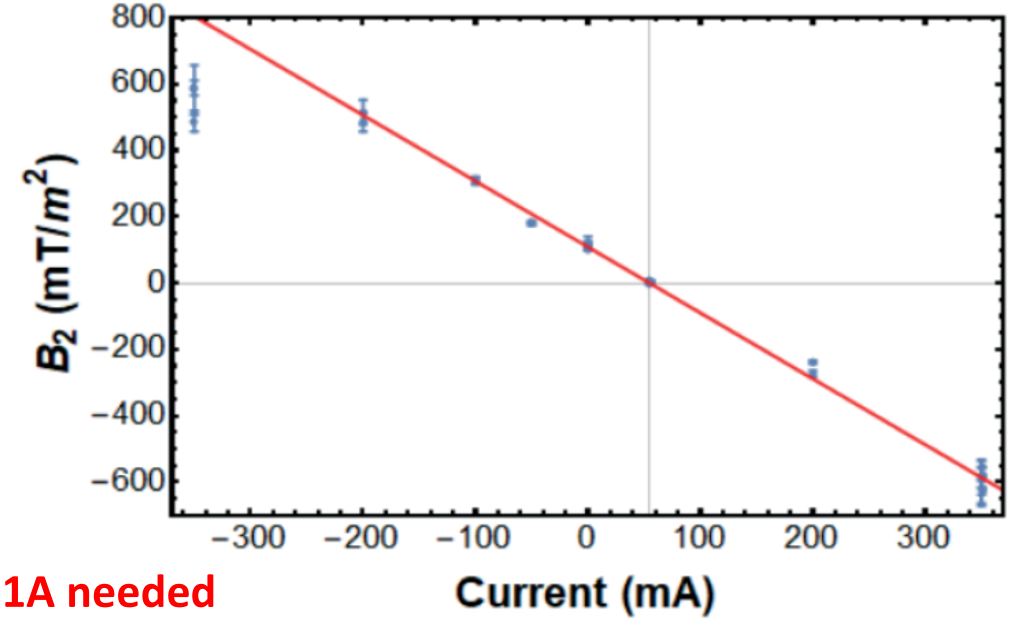
Need to get rid of this scaling in future runs -> local tuning magnets need to be implemented.



System running successfully in persistent mode.

Able to tune the B2 coefficient to 0 within uncertainties of 0.00006T/m^2

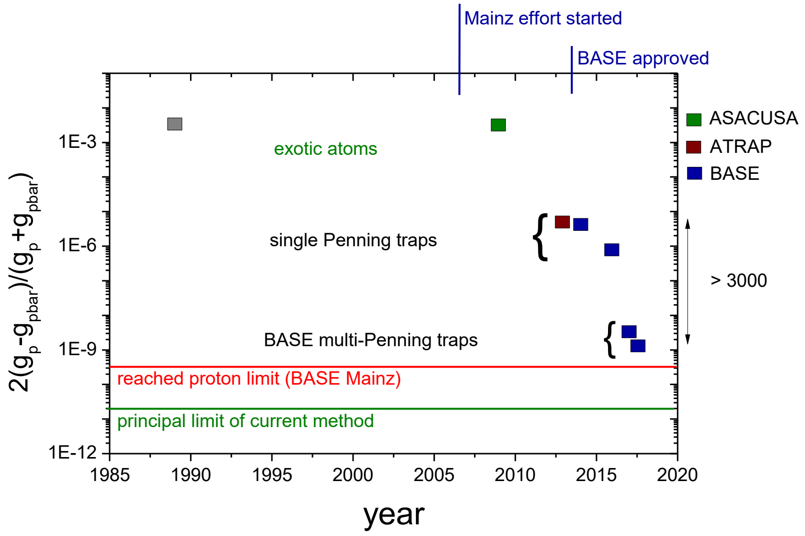
Reduces the dominant systematic uncertainty of the previous magnetic moment measurement by more than a factor of 10000.

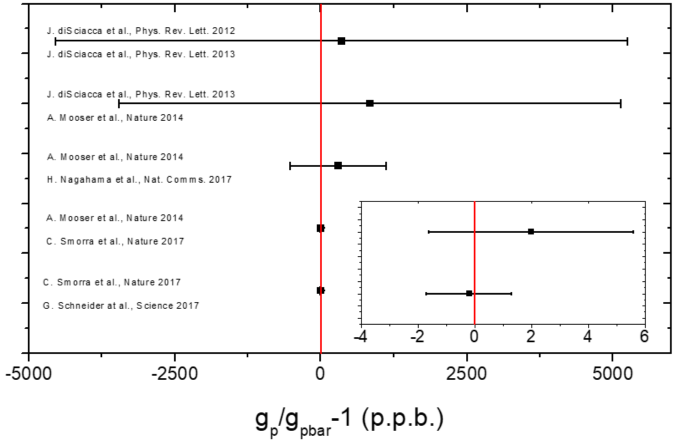


Yet open: B1 coil not operational as expected, current limited to 300mA, 1A needed

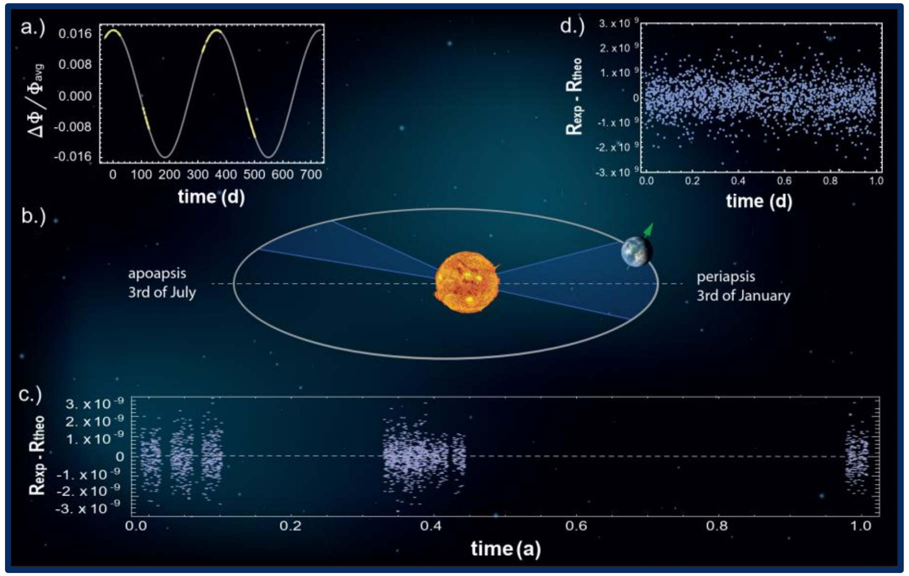
BASE Experiments with Antiprotons

Most precise measurements of proton and antiproton magnetic moments (world leading and unique)



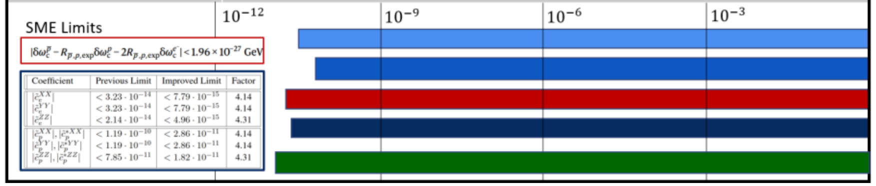


Most precise test of matter/antimatter symmetry in the baryon sector



$$\boxed{\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = -1.000\,000\,000\,003\;(16)}$$

Campaign	R_{exp}	$\sigma(R)_{stat}$	$\sigma(R)_{sys}$
2018-1-SB	1.001089218748	$27 * 10^{-12}$	$27 * 10^{-12}$
2018-2-SB	1.001089218727	$47 * 10^{-12}$	$49 * 10^{-12}$
2018-3-PK	1.001089218748	$19 * 10^{-12}$	$14 * 10^{-12}$
2018-1-SB	1.001089218781	$19 * 10^{-12}$	$23 * 10^{-12}$
Result	1.001 089 218 757 (16)		



SME Limits

$$|\delta\omega_c^{\bar{p}} - R_{\bar{p},p,\mathrm{exp}}\delta\omega_c^{p} - 2R_{\bar{p},p,\mathrm{exp}}\delta\omega_c^{e^-}| < 1.96\times10^{-27}\ \mathrm{GeV}$$

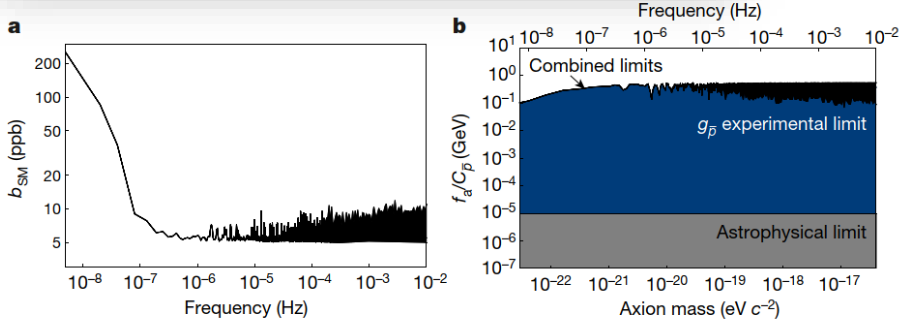
Coefficient	Previous Limit	Improved Limit	Factor
$\lvert\tilde{c}_{\bar{p}}^{XX}\rvert$	$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}_{\bar{p}}^{YY}\rvert$	$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}_{\bar{p}}^{ZZ}\rvert$	$< 2.14\cdot10^{-14}$	$< 4.96\cdot10^{-15}$	4.31
$\lvert\tilde{c}_{p}^{XX}\rvert, \lvert\tilde{c}_{p}^{*XX}\rvert$	$< 1.19\cdot10^{-10}$	$< 2.86\cdot10^{-11}$	4.14
$\lvert\tilde{c}_{p}^{YY}\rvert, \lvert\tilde{c}_{p}^{*YY}\rvert$	$< 1.19\cdot10^{-10}$	$< 2.86\cdot10^{-11}$	4.14
$\lvert\tilde{c}_{p}^{ZZ}\rvert, \lvert\tilde{c}_{p}^{*ZZ}\rvert$	$< 7.85\cdot10^{-11}$	$< 1.82\cdot10^{-11}$	4.31

First dark matter search with antiproton-magnetic moment antenna

$$\delta\omega_{\rm L}^{\bar{p}}(t) \approx \frac{C_{\bar{p}} m_{\rm a} a_0 |\mathbf{v}_{\rm a}|}{f_{\rm a}}[A\cos(\Omega_{\rm sid}t+\alpha)+B]\sin(\omega_{\rm a}t)$$

5 o.o.m. improved limits compared to sattelites

(world leading/unique)



First constraints on antimatter/dark matter coupling