BASE

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Programs for
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ETH Zürich

Progress 2022
BASE Collaboration

Stefan Ulmer

HHU Düsseldorf and RIKEN

2023 / 02 / 07

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

PRL 106, 253001 (2011)

Selected for a Viewpoint in *Physics*

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]

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(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

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

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

EPJ ST

Recognized by European Physical Society

Special Topics

THE BASE EXPERIMENT

BASE

edp sciences Springer

CERN Courier March 2018

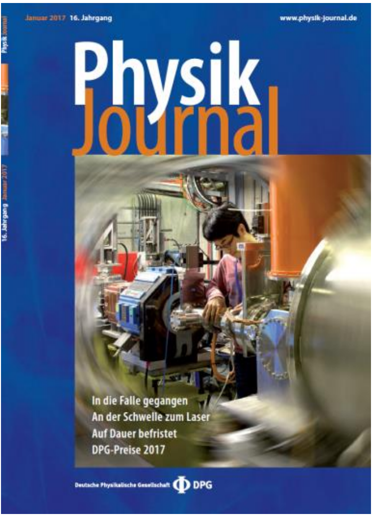
BASE

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 BASE setup at CERN's Antiproton Decelerator.

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

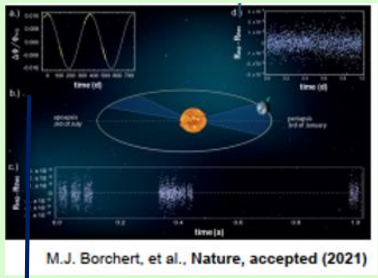
C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

Team at CERN

BASE Annual Summary 2022

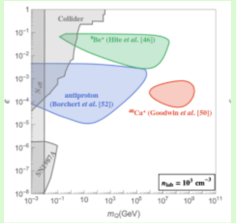
Experiment Online

Test of WEP-cc

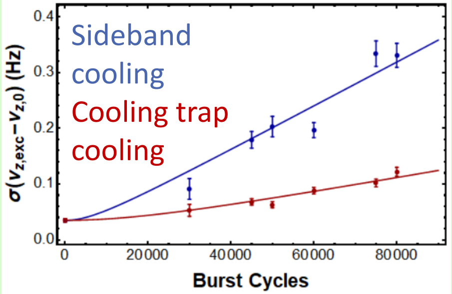


M.J. Borchert, et al., Nature, accepted (2021)

MCP Limits



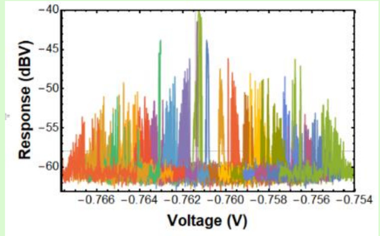
Phase Space Reduction



Commissioning of SSC System

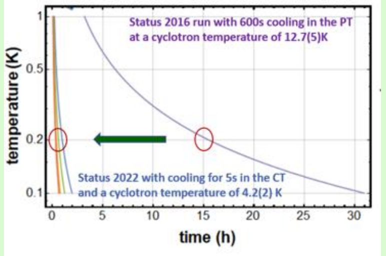
Commissioning of analysis trap

Parametric resonance optimization



Cooling Trap

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



Parallel Projects:

Development of new beam monitors / Evaluation of time series of QM measurement

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

Shutdown:

- Implementation of new spin flip coils
- Implementation of new beam monitors

- Implementation of revised RT detection electronics.

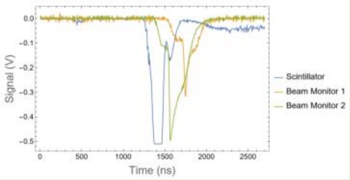
Converged to successful implementation of reliably running 4-trap system featuring all ingredients needed to perform sub-ppb magnetic moment measurement

Shutdown

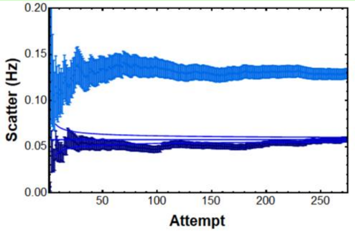
Experiment Online

Antiproton Run

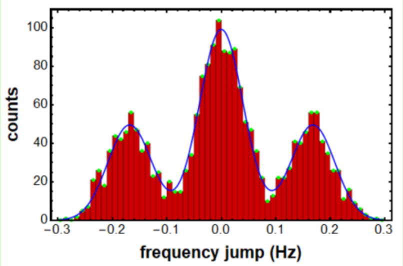
New beam monitors commissioned.
Catching in BASE not successful.
STEP line successfully commissioned



Observation of Spin Flips



Observation of Single Spin Flips



Highest detection fidelity ever observed.

Proton Run ongoing with the goal of preparing the experiment to reach sub-ppb proton moment resolution.

Ready to measure pbar moment at same resolution.

Parallel Developments:

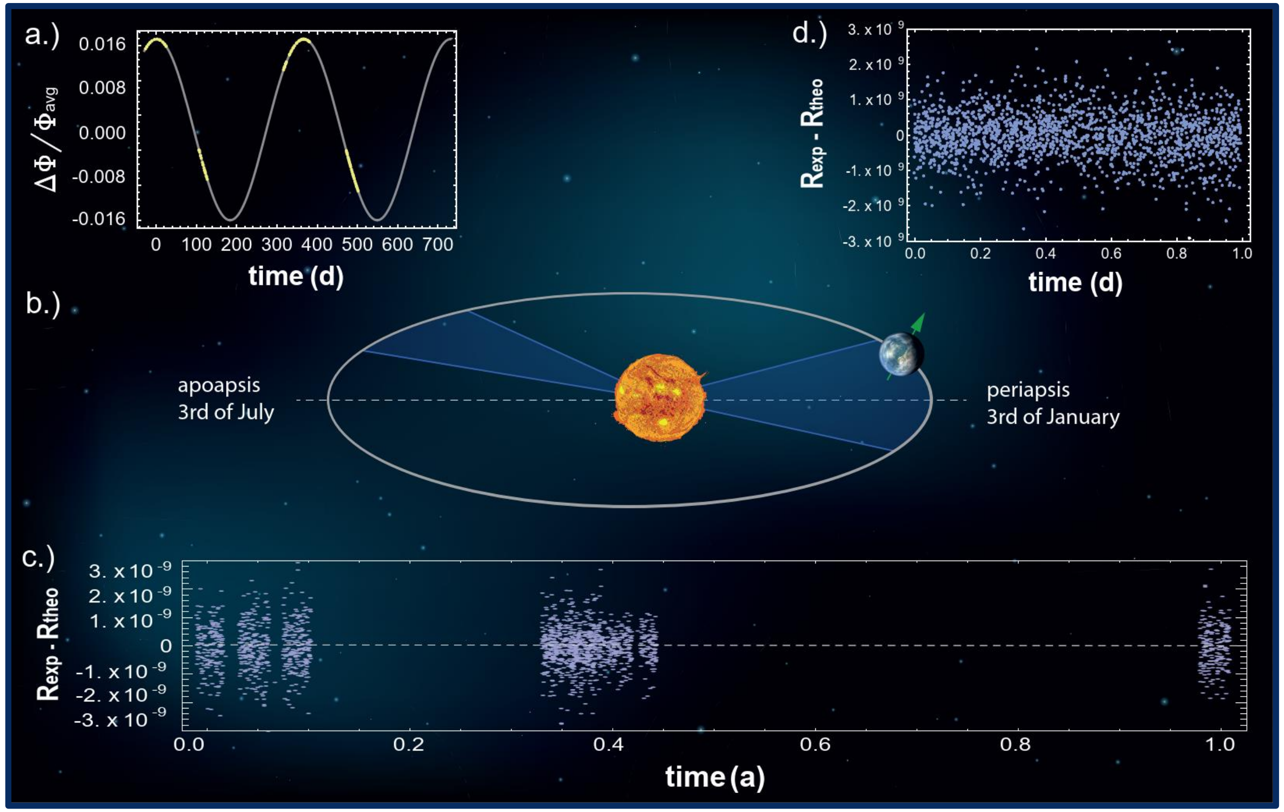
Additional beam diagnostics
Improved cooling trap detection system
Improved SSC joints

Quick Review – Article Published / QM

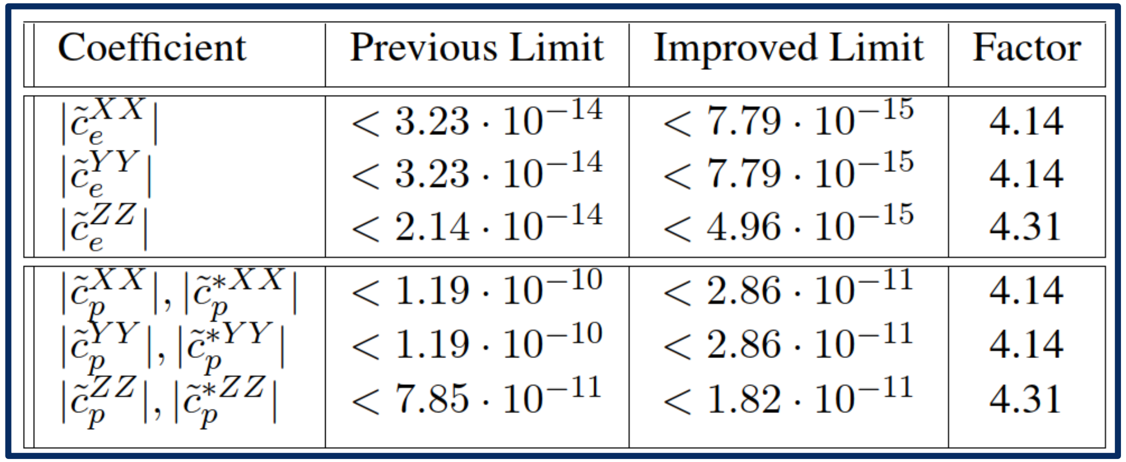
$$R_{\bar{p},p} = -1.000\,000\,000\,003\,(16)$$

- Constrain 10 coefficients of the Standard Model extension.

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



Non-minimal Standard Model Extension:



Coefficient	Previous Limit	Improved Limit	Factor
$\lvert\tilde{c}_e^{XX}\rvert$	$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}_e^{YY}\rvert$	$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}_e^{ZZ}\rvert$	$< 2.14\cdot10^{-14}$	$< 4.96\cdot10^{-15}$	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

- Differential test of the weak equivalence principle comparing a matter and an antimatter clock

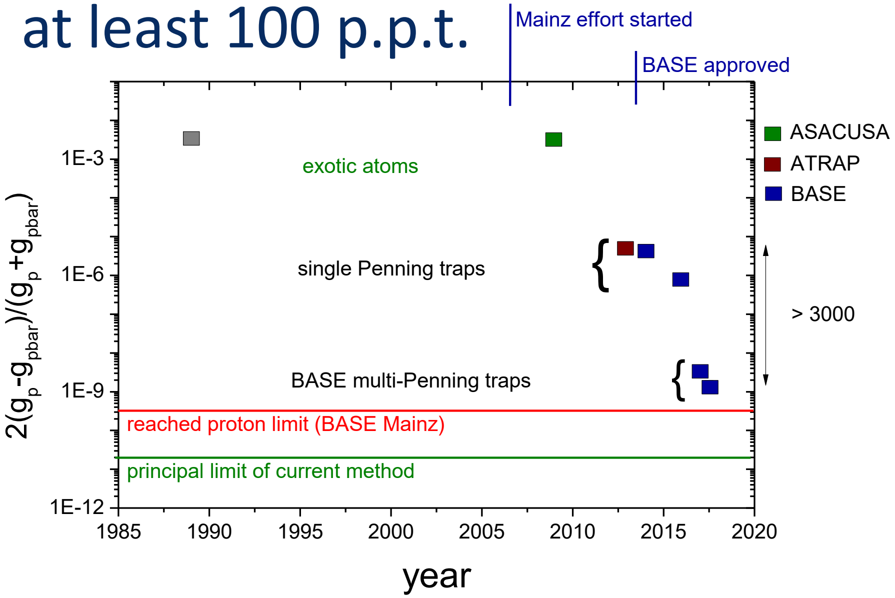
$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right)$$

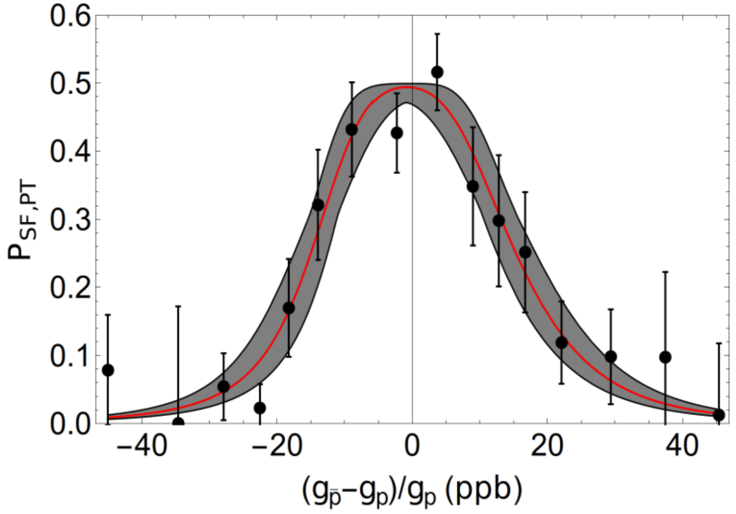
Property	Limit
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

Most Precise Test of CPT Invariance in the Baryon Sector

Goal of the Current Run

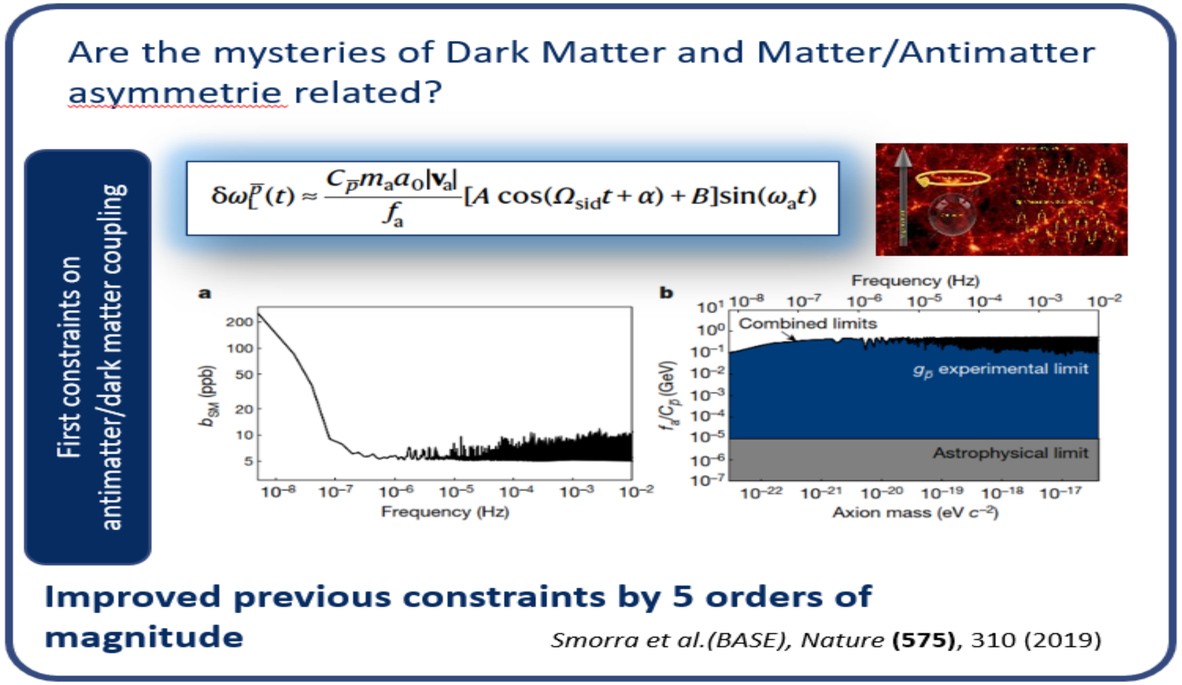
- Improved measurement of the antiproton magnetic moment with a target precision of at least 100 p.p.t.





- 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

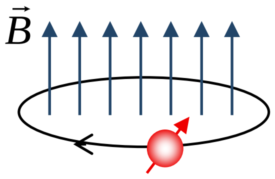
$$\delta\omega_L^{\bar p}(t) \approx \frac{C_{\bar p} m_a a_0 |\mathbf{v}_a|}{f_a}[A\cos(\Omega_{sid}t+\alpha)+B]\sin(\omega_a t)$$

Improved previous constraints by 5 orders of magnitude

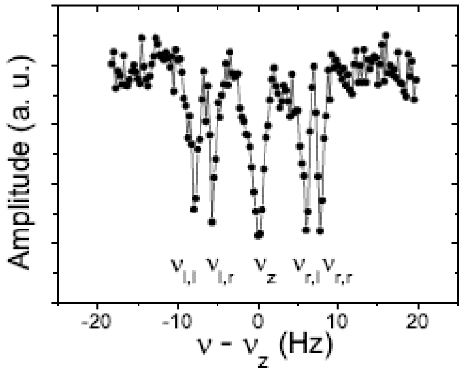
Smorra et al.(BASE), Nature **(575)**, 310 (2019)

Penning Trap Magnetic Moment Measurements

Cyclotron Motion



simple



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

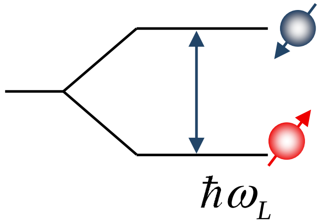
g: mag. Moment in units of nuclear magneton

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

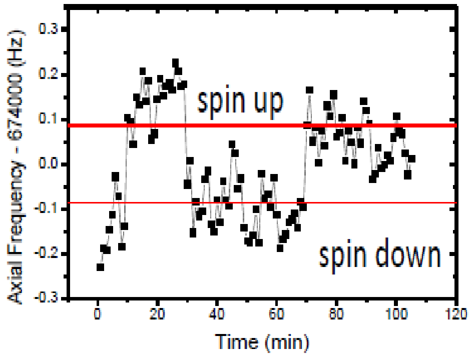
$$\boxed{\omega_L = g \frac{e}{2m_p} B}$$

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

Larmor Precession



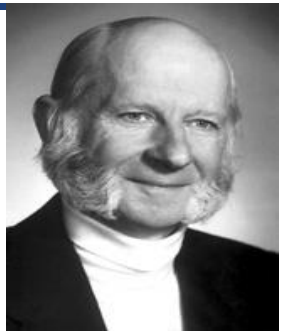
difficult



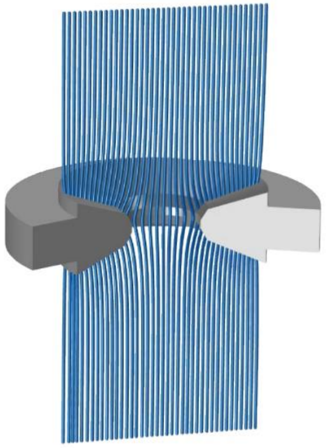
A. Mooser, S. Ulmer, *et al.* PRL 106, 253001 (2011)

Determinations of the g-factor reduces to the measurement of a frequency ratio -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

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

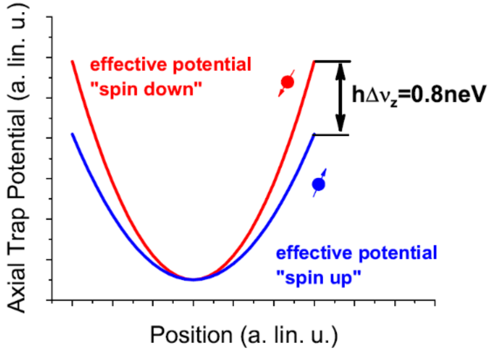
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

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

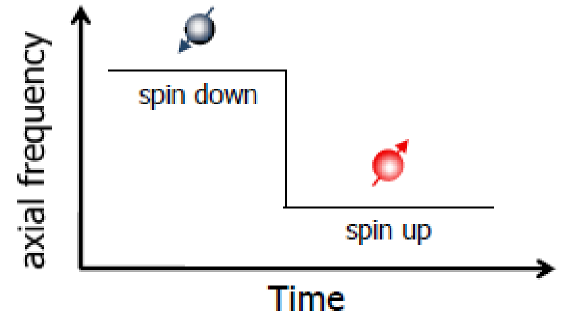


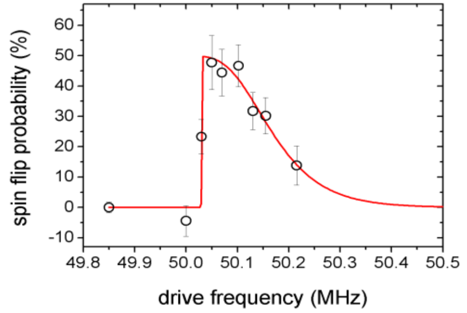
Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

Limited to p.p.m level

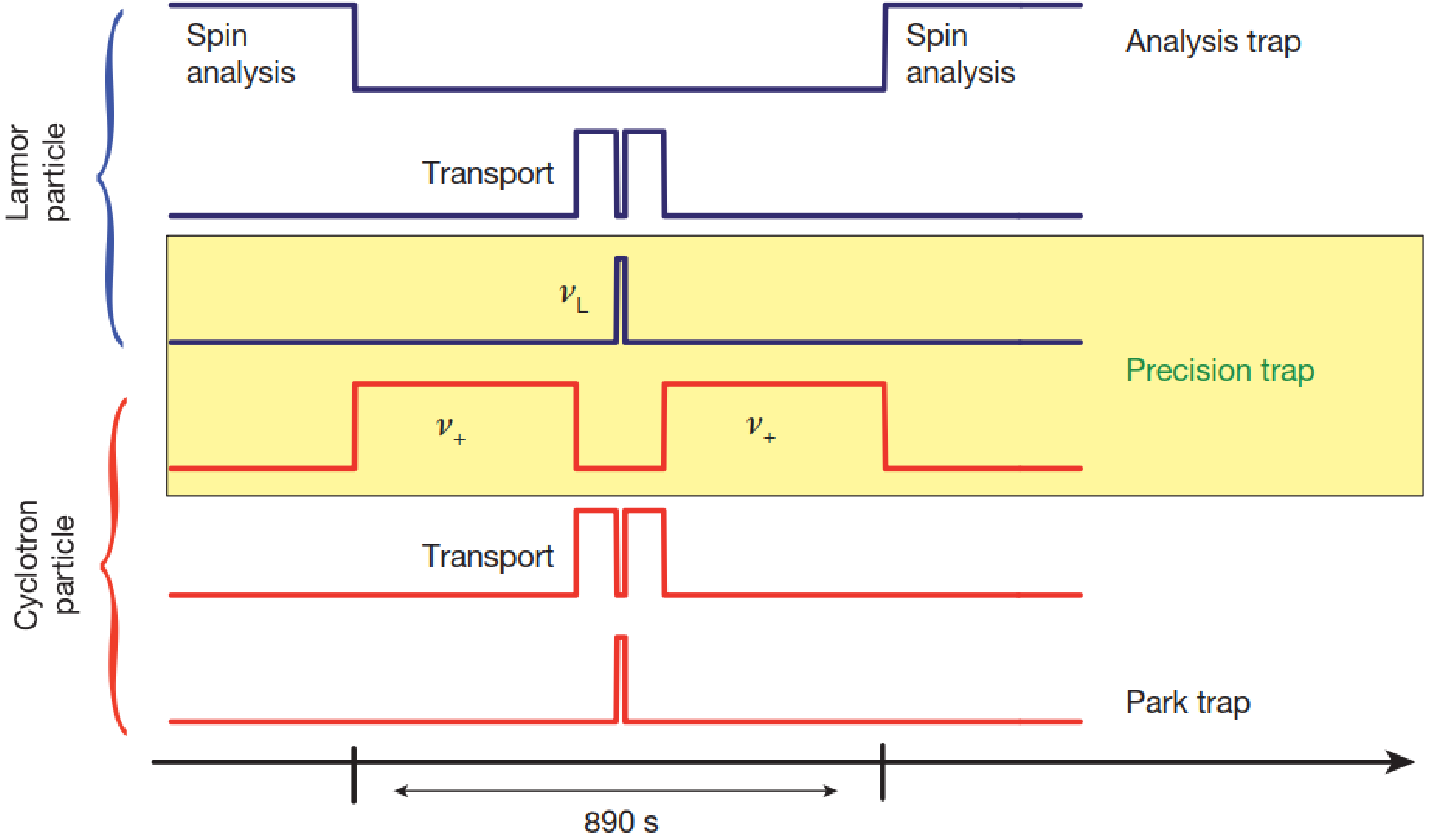




S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

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.

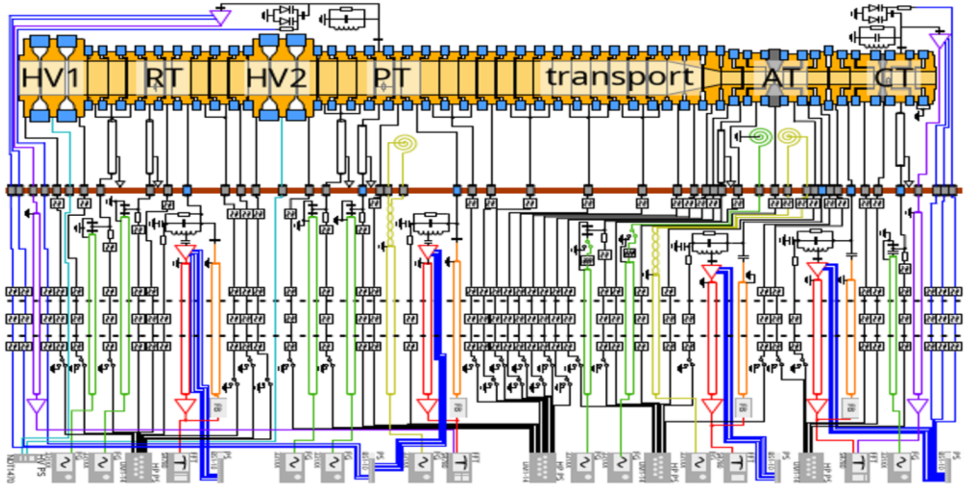
Magnetic field fluctuations and drifts during the frequency measurements in this sequence.

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

Towards an Improved Measurement

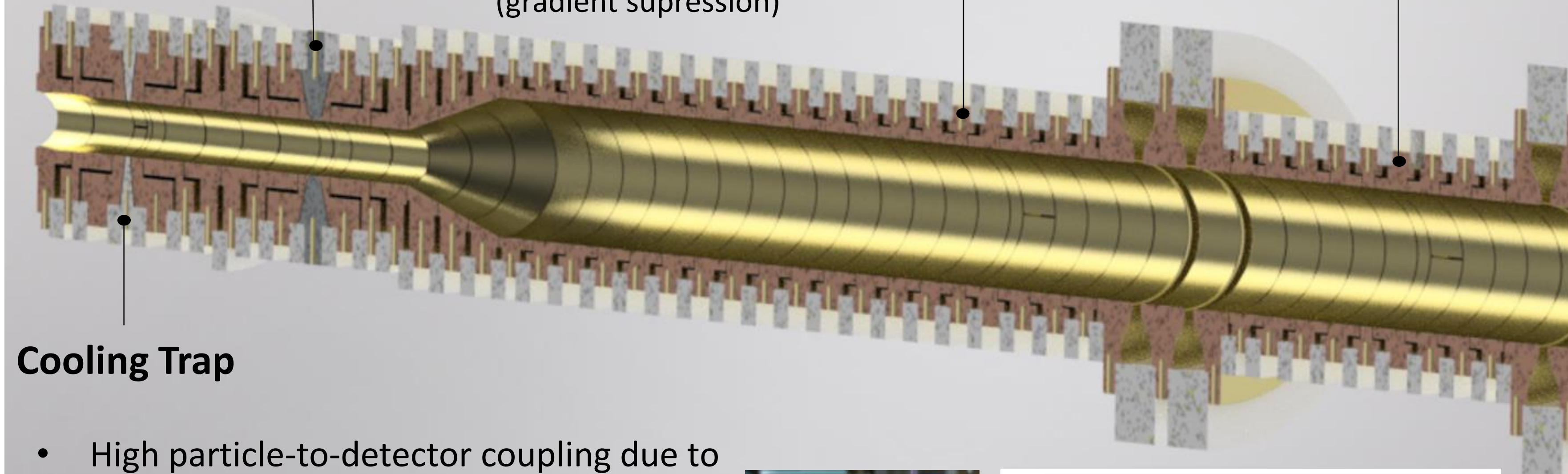
- **Systematic Limitations:**
  - Magnetic field fluctuations: 15ppb width
  - Magnetic field homogeneity: 0.980 ppb unc.
  - Measurement stability: 6ppb unc.
  - Limited data accumulation rate
  - Noise sensitivity of the spin-state detection trap
  - Transport heating rates

- **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



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

New 2022-Multi Trap Stack



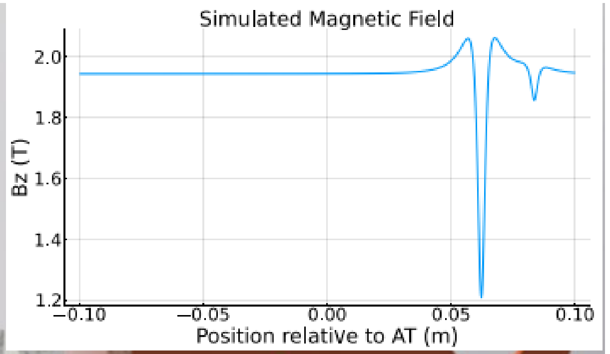
Analysis Trap
(spin state analysis)

Precision Trap
(frequency measurements)

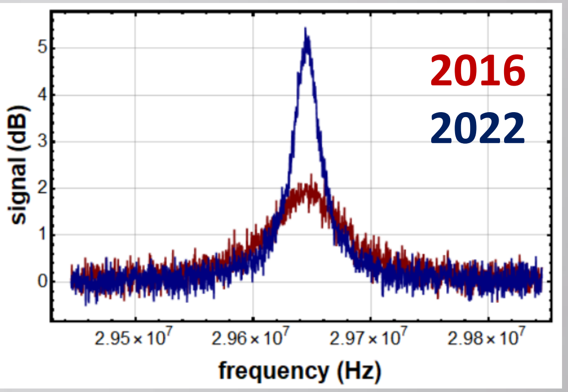
Reservoir Trap
(antiproton catching)

Elongated Transport Section
(gradient supression)

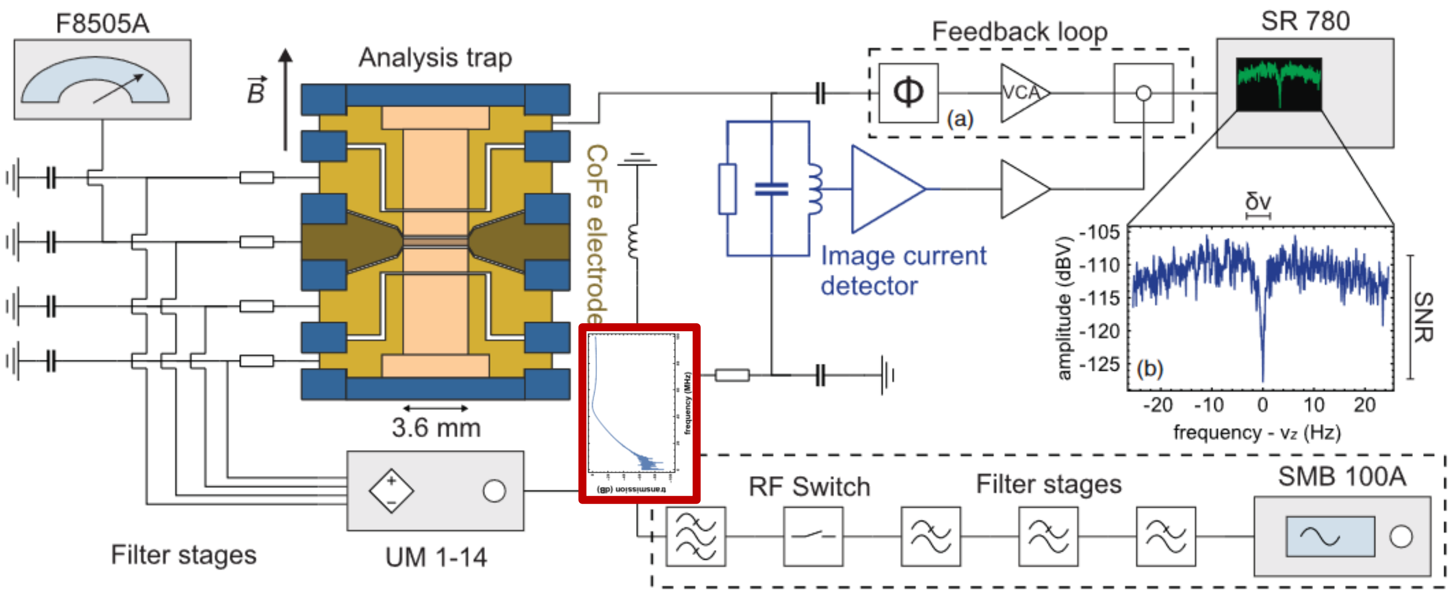
Cooling Trap



- 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**.

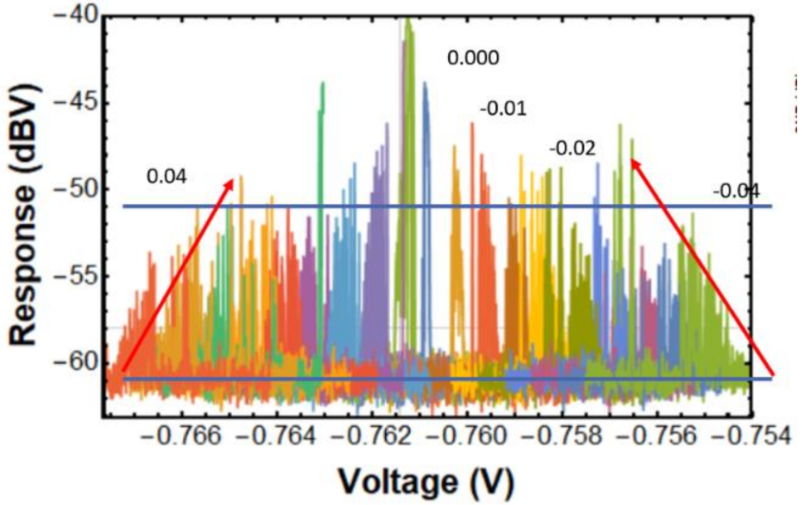


Analysis Trap Upgrades / Commissioning

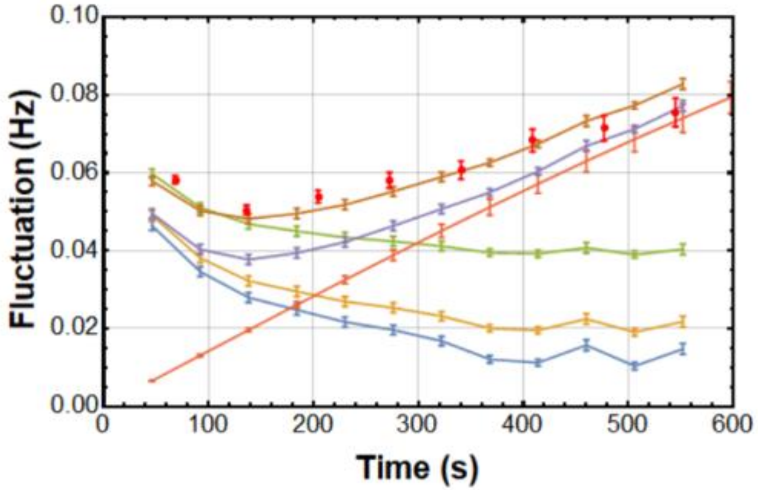


Generally better shielding of all the trap supply lines, multitude of cryogenic switches, cryogenic bandpass filters, decoupling of spin flip and radial manipulation lines.

- Commissioning of the trap by parametric resonance



- Optimization of axial frequency stability



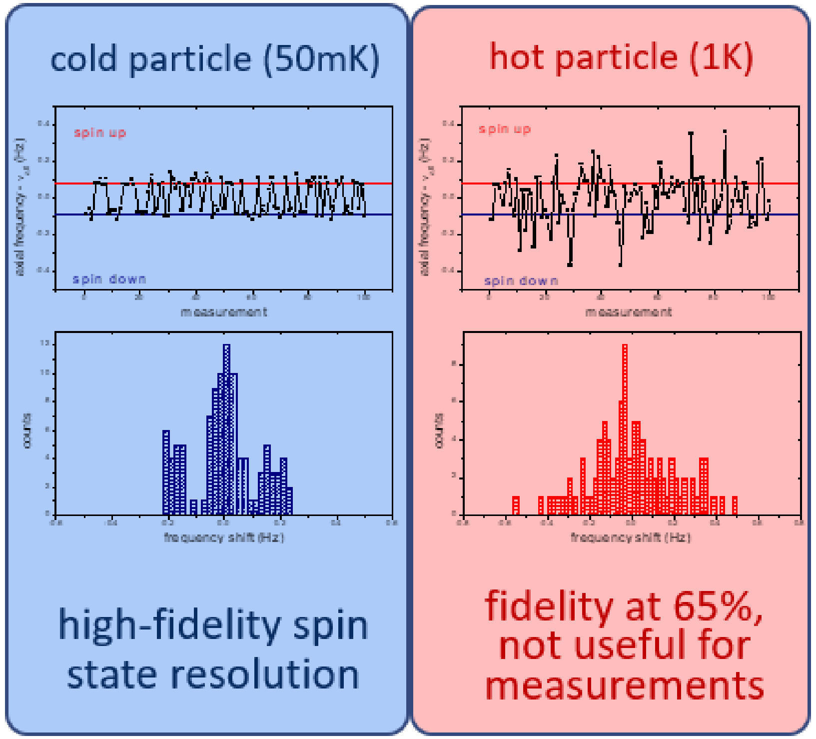
Already two times better than in previous experiments

Heating Rates

- BASE magnetic moment measurements can only be performed, once we cool particles to low cyclotron energy.

- Magnetic bottle does not only couple spin-magnetic moment to the axial frequency but also cyclotron magnetic moment. Cyclotron transitions are driven by background rf-noise, inducing heating rates:

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



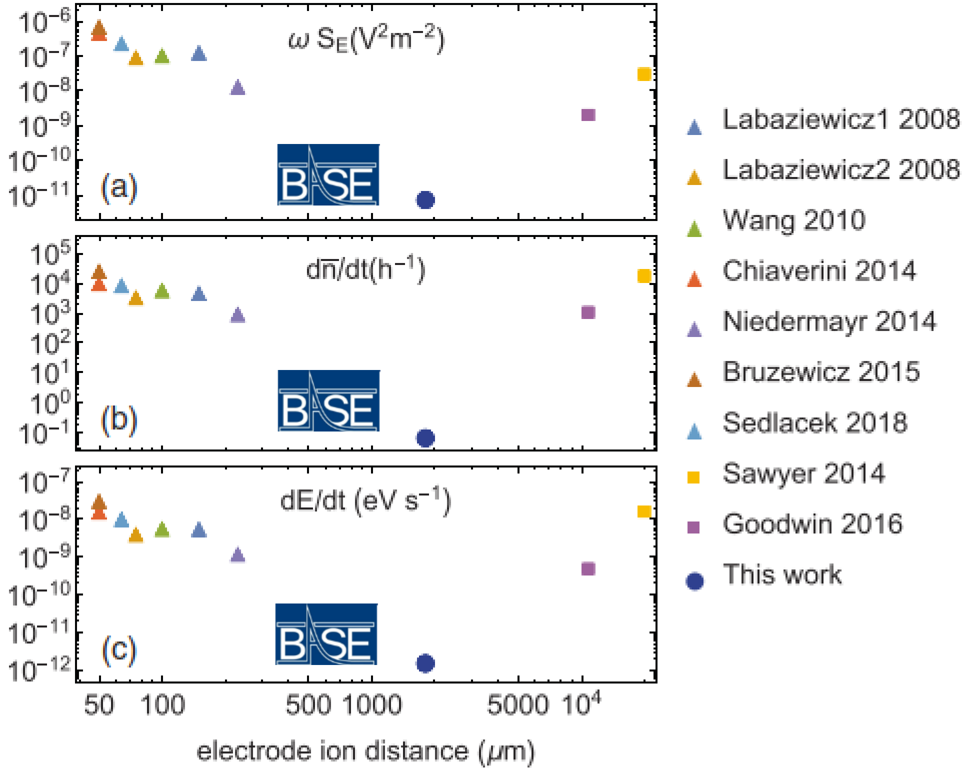
cold particle (50mK)

high-fidelity spin state resolution

hot particle (1K)

fidelity at 65%, not useful for measurements

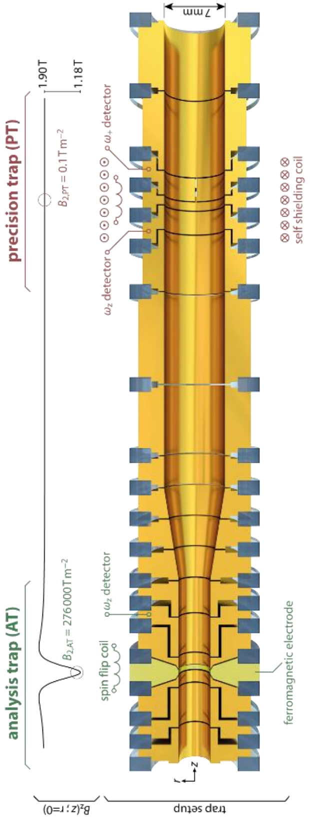
Lowest heating rates ever measured in a trap experiment



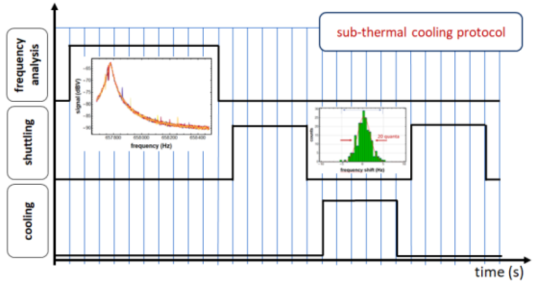
Borchert, PRL **122**, 043201 (2019), https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.122.043201

Sub-Thermal Cooling

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



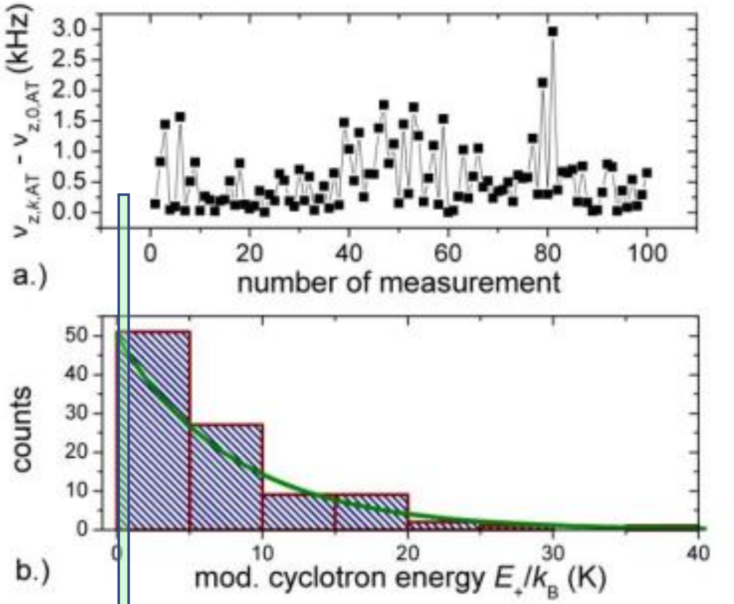
thermalize particle (10 min.)



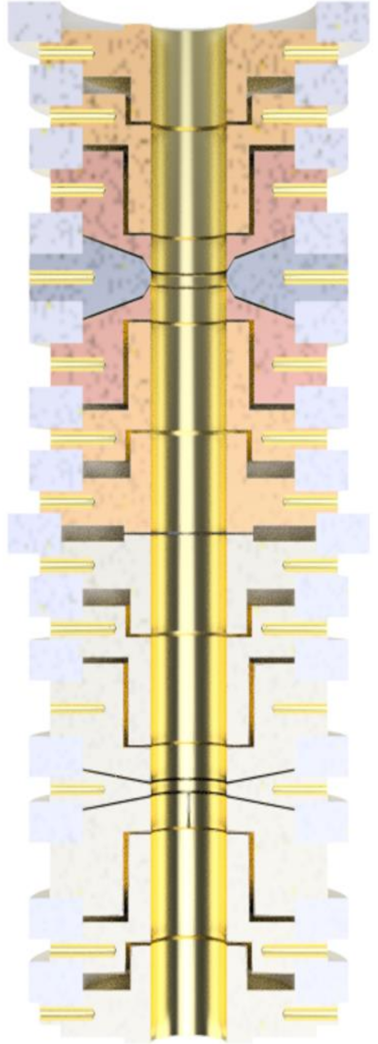
Analyze temperature using the magnetic bottle

particle below threshold
-> **MEASURE**

particle above threshold



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

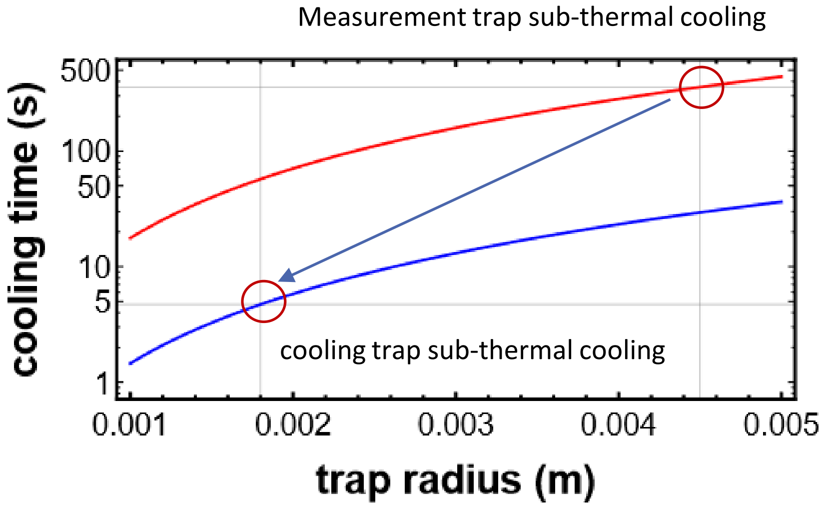


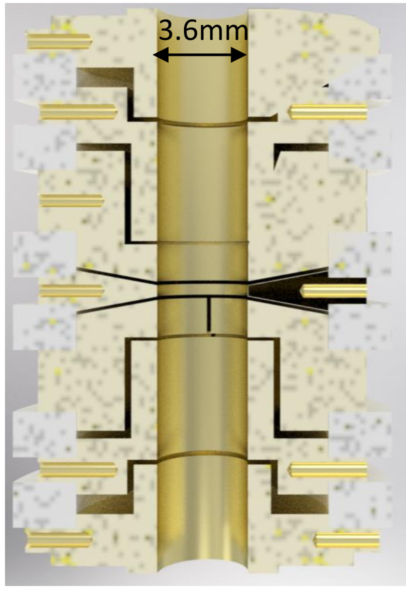
NOTE: each cyclotron frequency measurement heats the particle to about 300K

sub-thermal cooling is EXTREMELY time consuming

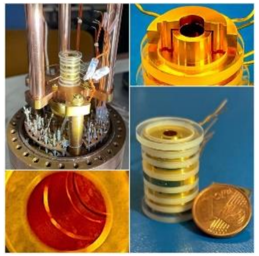
Antiproton Cooling Trap

- 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

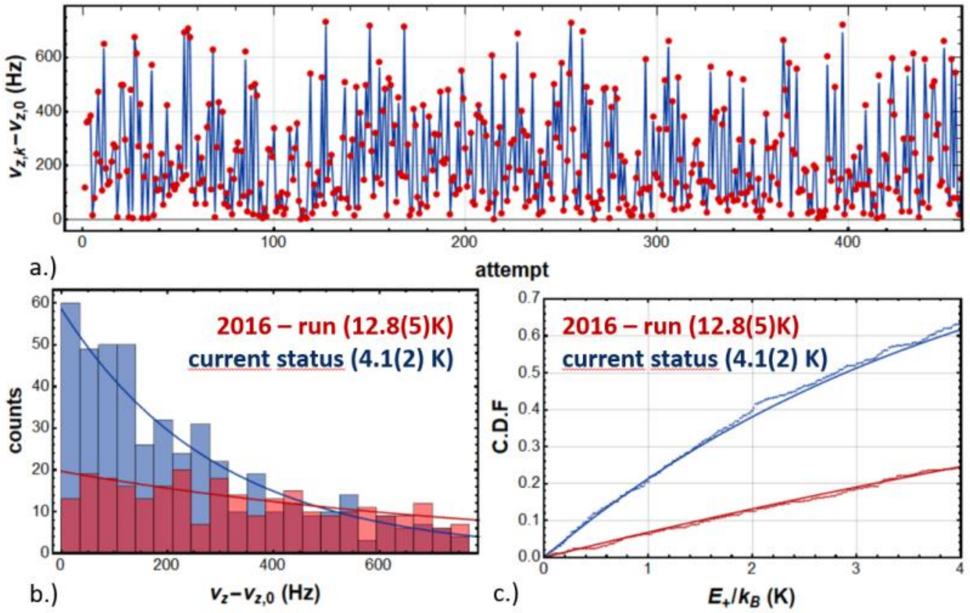


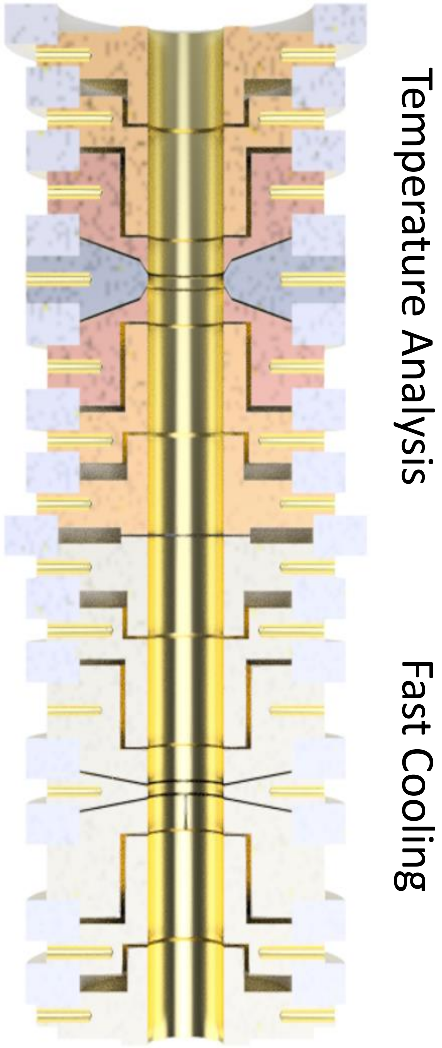
$$\tau = \frac{m}{R_p} * \left(\frac{D_{eff}}{q}\right)^2$$

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

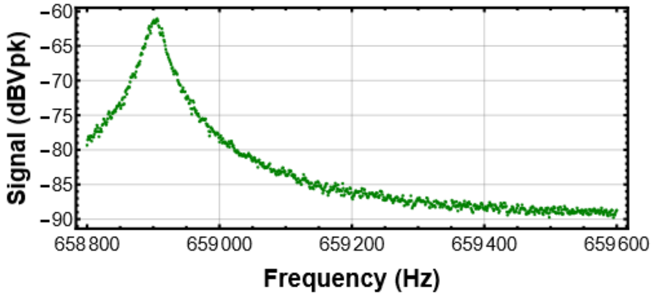
Temperature Measurement

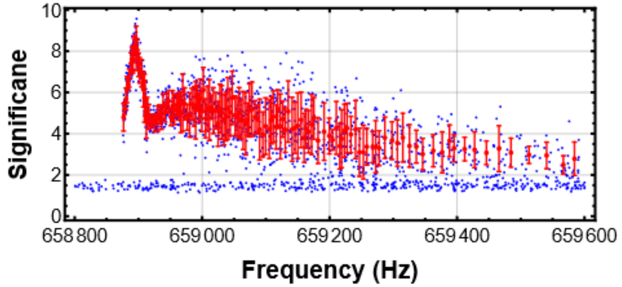
- Sequence:
  - Measure axial frequency in AT
  - Shuttle AT – CT
  - Thermalize in CT
  - Shuttle CT – AT





- **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

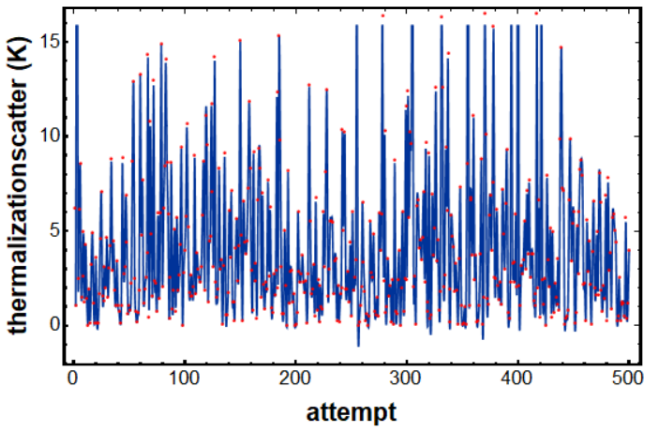


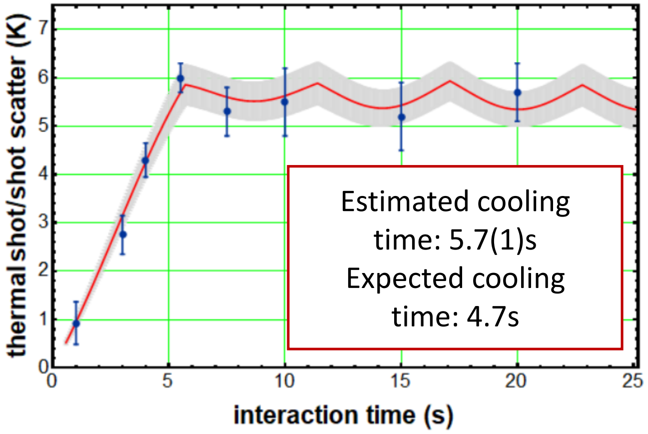


- **2016** – used particle readout time of 60s in several screenshots.
- **2022** – optimized single shot particle readout time for high identification efficiency:
  - 16s at 0.5K detection bandwidth and 95.8% detection efficiency.
  - 16s at 0.25K detection bandwidth and 99.8% detection efficiency.

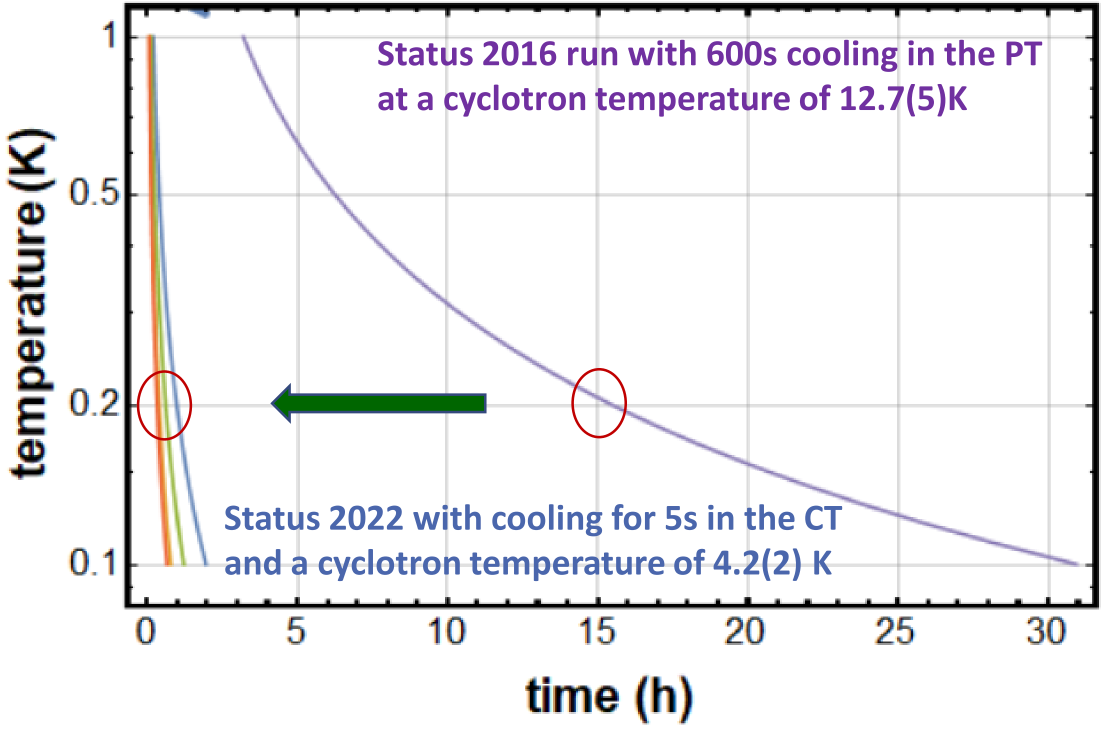
Thermalization Time Optimization

- 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

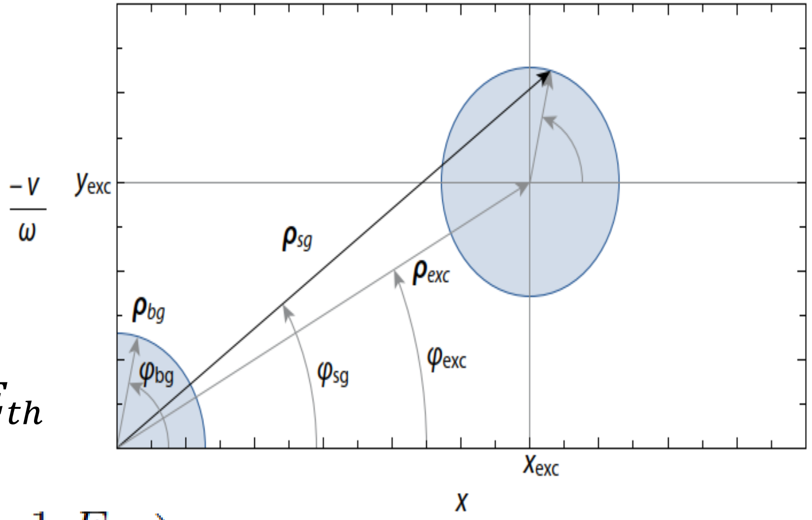
Status 2022 with cooling for 5s in the CT and a cyclotron temperature of 4.2(2) K

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)		

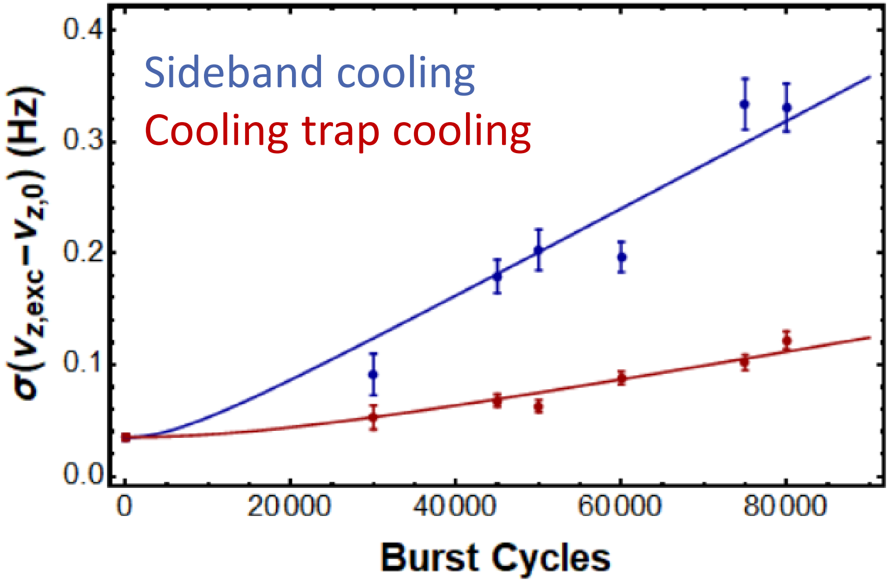
- Three-fold temperature reduction gives additional factor of three in time reduction for particle preparation at given threshold.
- **Explicitly demonstrated:** robust 200mK particle preparation in 8 minutes compared to previously 15h.

Applications – Phase Space Reduction

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



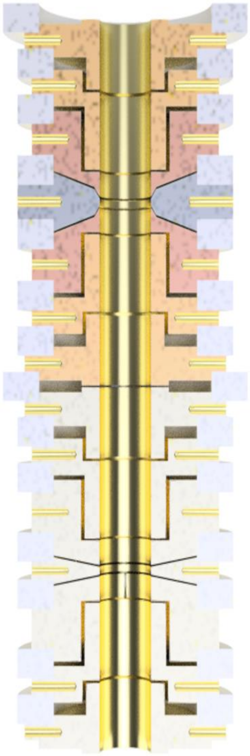
- Resonant Radius $$\rho(t) = \frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}$$
- Resulting Energy $$E(t) = \left(\frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}\right)^2 = E_{exc} + 2\sqrt{E_{th}}\sqrt{E_{exc}} + E_{th}$$
- Resulting Energy Scatter $$\sigma(E_+) = \sqrt{2E_{\mathrm{th}}E_{\mathrm{exc}}} \times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



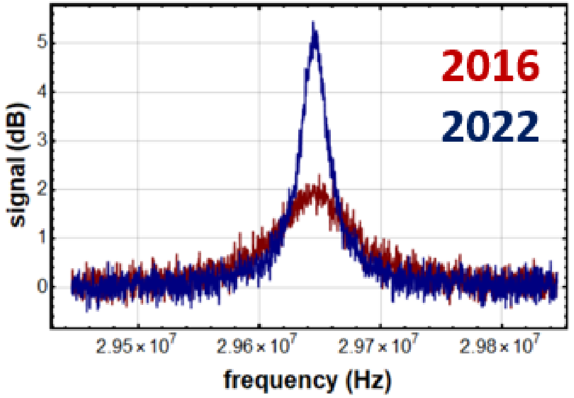
- **Enables:**
  - Measurements at lower temperature and reduced systematic shifts
  - Measurements at better defined particle energy
  - Measurements at robust signal to noise ratio
  - Measurement at higher phase resolution

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**



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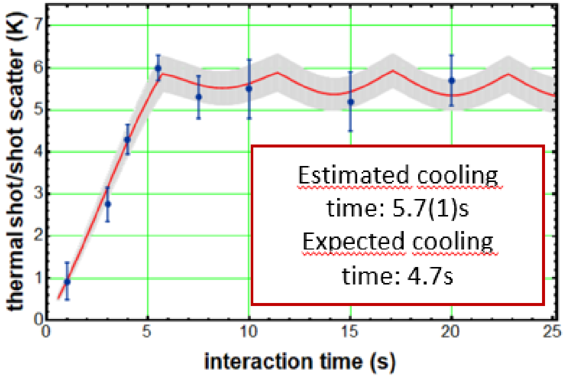
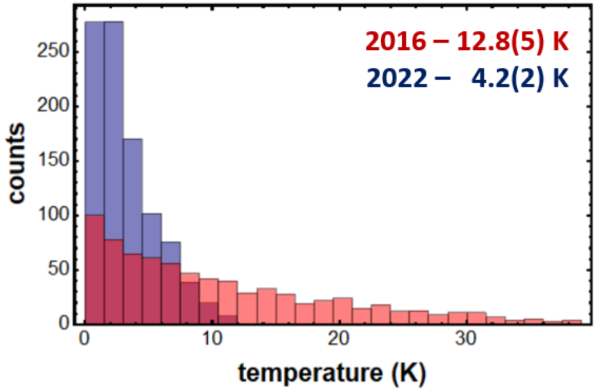
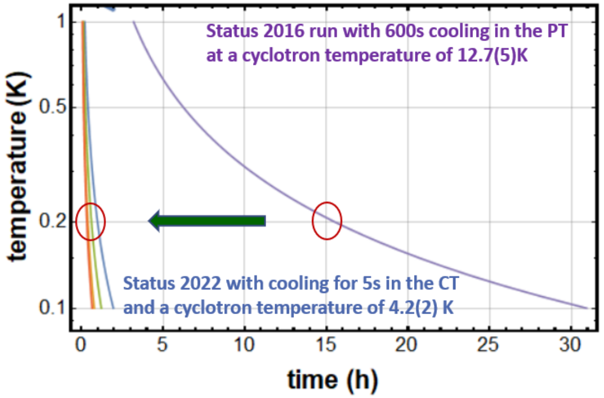


Estimated cooling time: 5.7(1)s
Expected cooling time: 4.7s

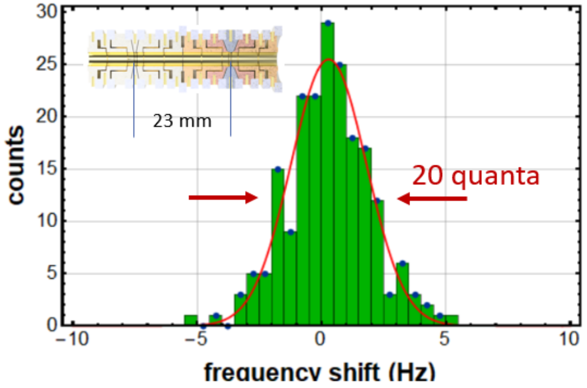


2016 – 12.8(5) K
2022 – 4.2(2) K



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



20 quanta

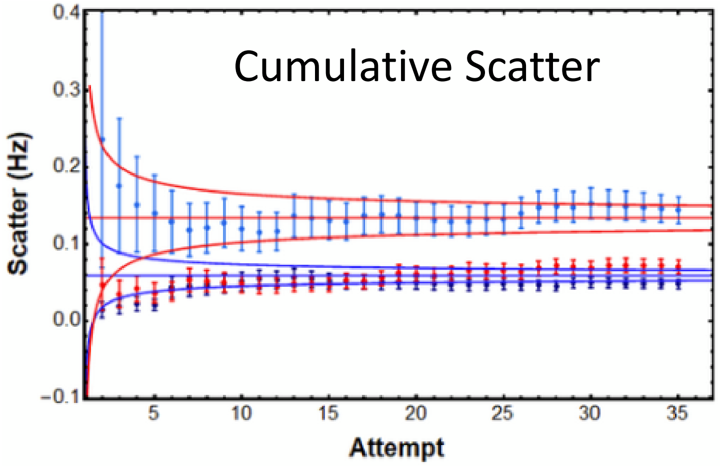
Flipping Spins

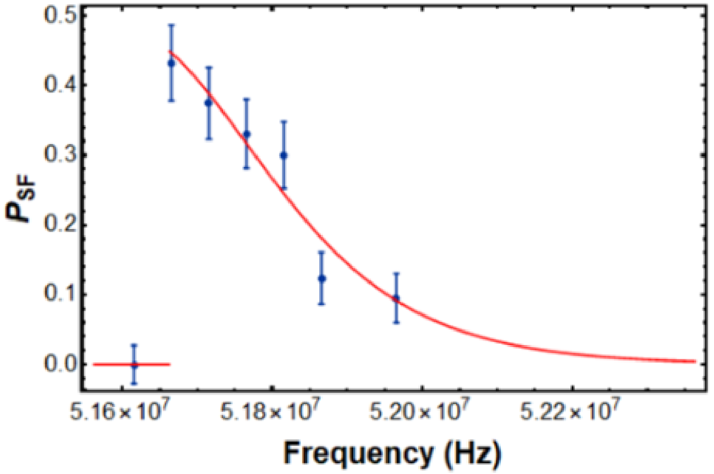
- Recording **statistical spin flips** and sampling of a Larmor resonance curve

Observed frequency scatter:

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

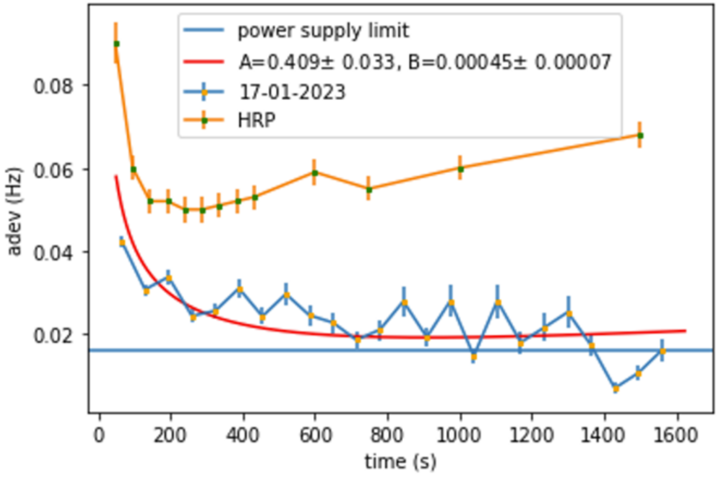
Further optimization of background noise and averaging time ->

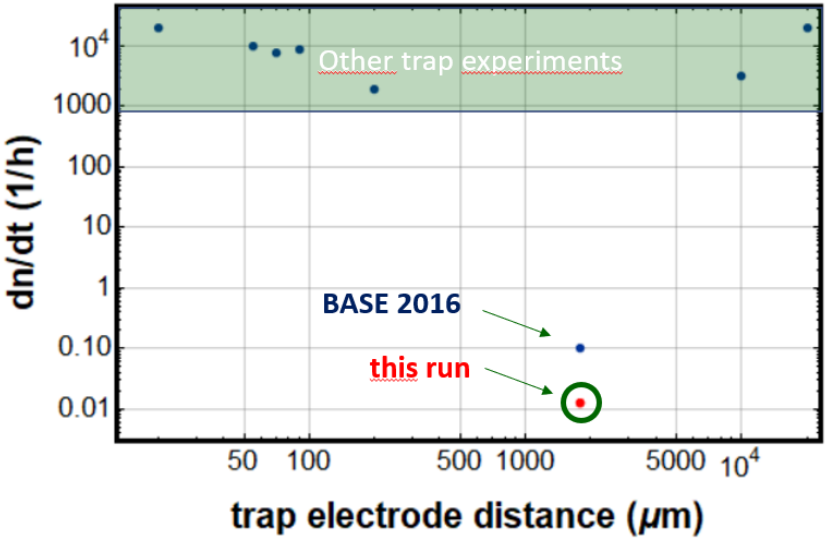


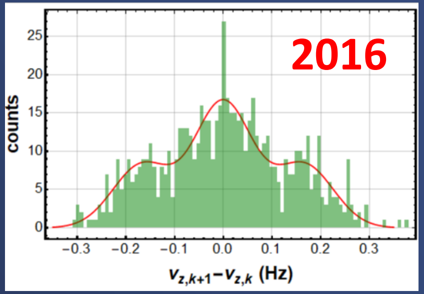


Heating rates further reduced by tweaking many parameters like

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

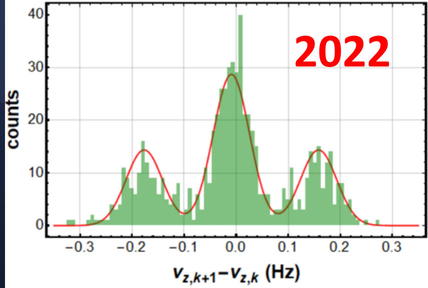


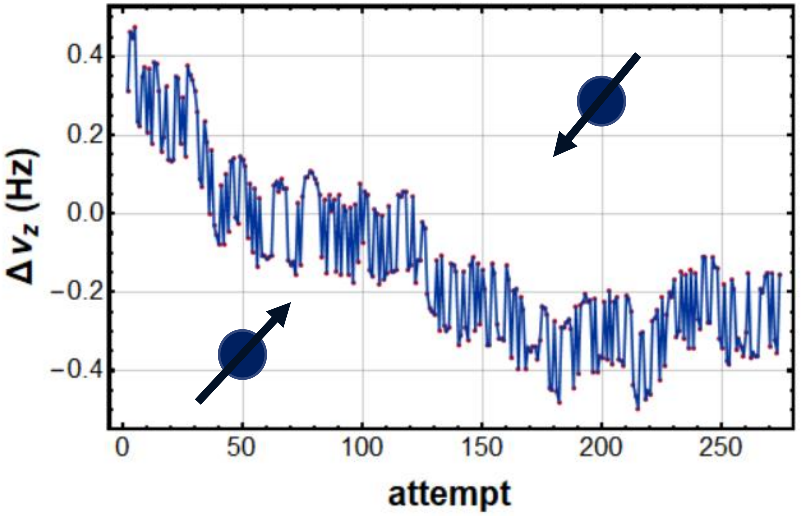


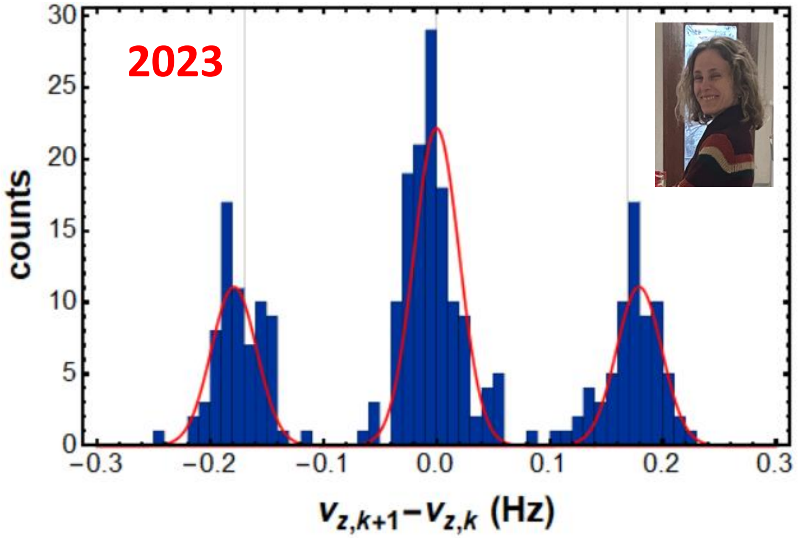


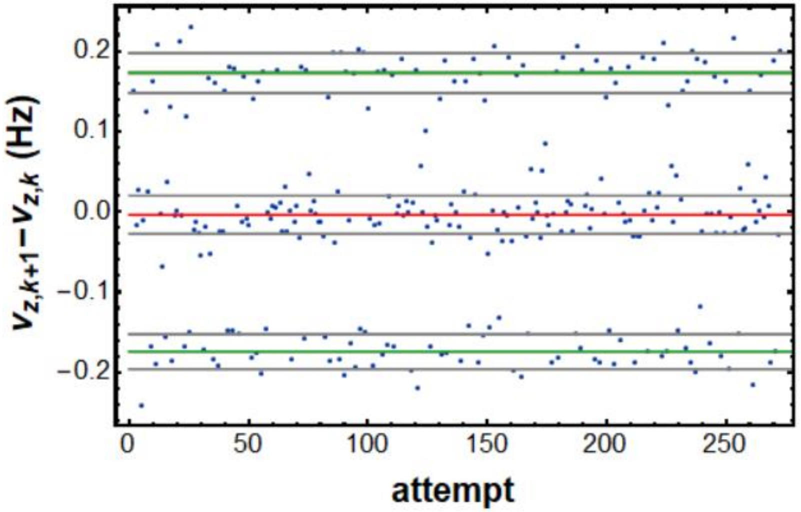
...with highest detection fidelity ever reported...:

...observation of Single Spin Flips....









Parameter	Value	Uncertainty	Width	Events
Left Distribution	-0.17403	0.00185674	0.0218117	70
Center Distribution	-0.00378045	0.00146963	0.023697	131
Right Distribution	0.172828	0.00213892	0.0249438	69
Spin Flip Prob.				1.06107

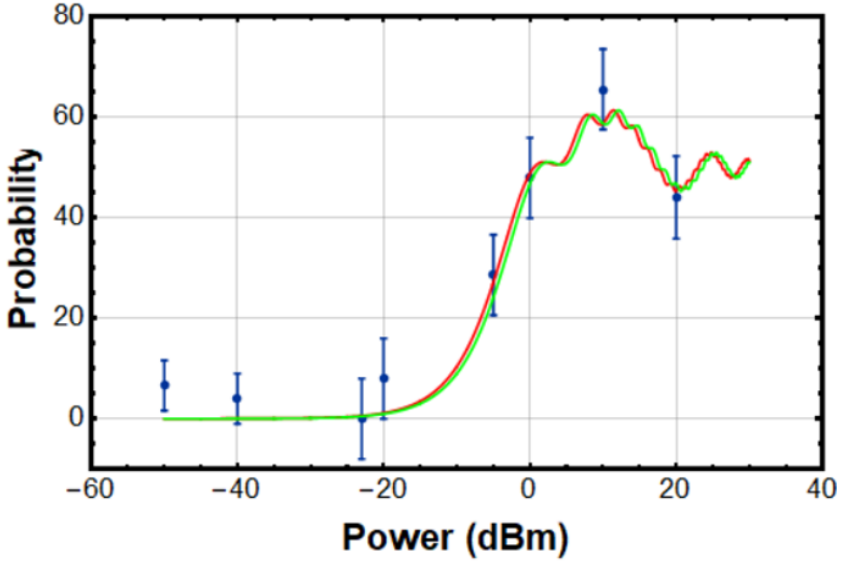
Total **game changer** in magnetic moment experiments

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

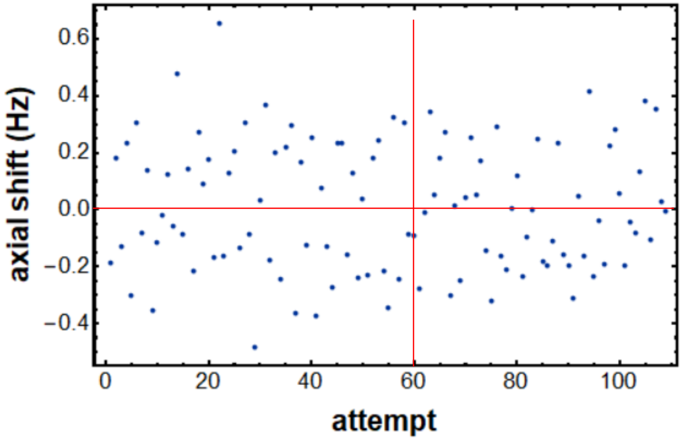
This is several 1000 times harder than observing the same for the electron/positron

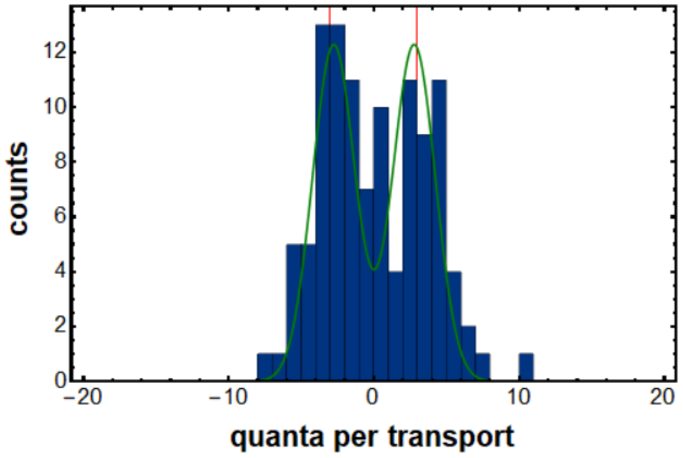
Single Spin Flips in the PT

- Key ingredient to multi-trap magnetic moment measurements:
  - Identify spin quantum state in the AT
  - Transport to PT
  - Induce spin transition in the PT
  - Transport back to AT
  - Detect in AT whether spin has flipped or not



Have executed 480 cycles with one single particle (median 80 in 2016)

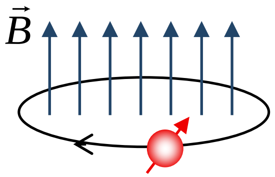




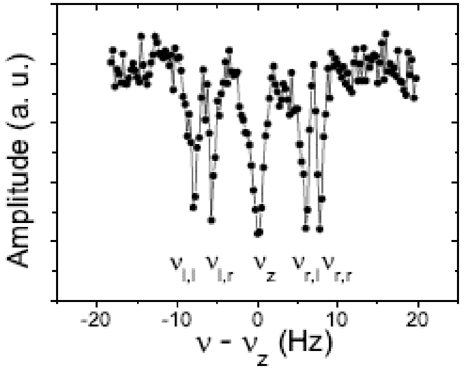
- Under these conditions:
  - No AT spin flipping required anymore
  - Reduces cycle from 17min to 5min.
  - Some stability issues under investigation at the moment.

Penning Trap Magnetic Moment Measurements

Cyclotron Motion



simple



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

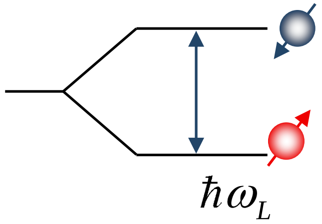
g: mag. Moment in units of nuclear magneton

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

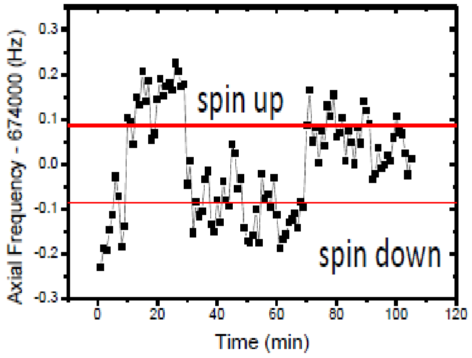
$$\omega_L = g \frac{e}{2m_p} B$$

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

Larmor Precession



difficult

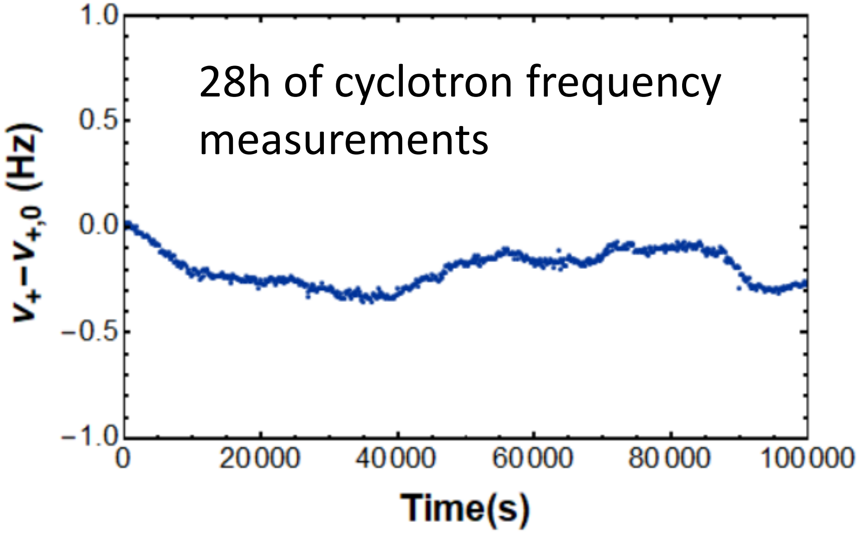


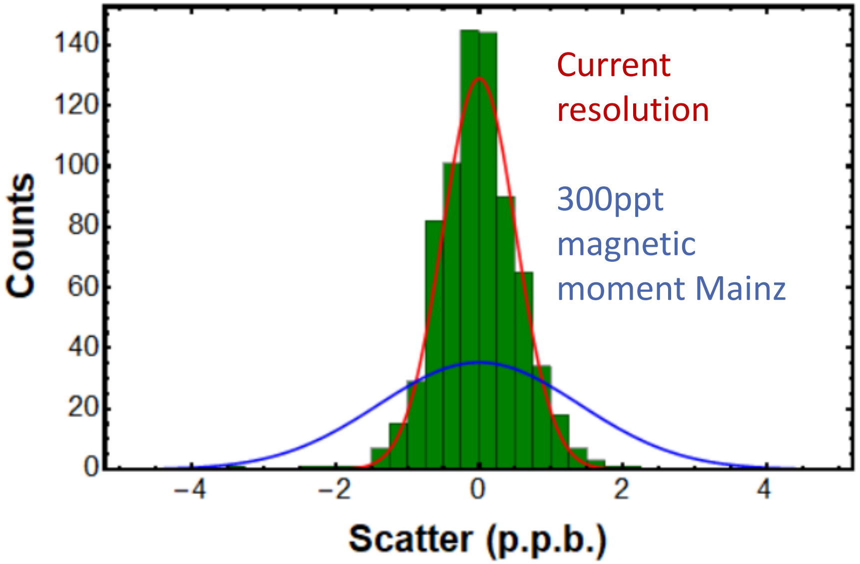
A. Mooser, S. Ulmer, *et al.* PRL 106, 253001 (2011)

Determinations of the g-factor reduces to the measurement of a frequency ratio -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

Cyclotron Frequency Measurements

- Recent cyclotron frequency measurements (recorded this weekend)


28h of cyclotron frequency measurements


Current resolution

300ppt magnetic moment Mainz

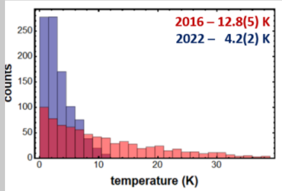
- Frequency scatter of this measurement is at a median of 520p.p.t., 3 times better than in our recently published charge-to-mass ratio measurement.
- Measured here 25 p.p.t. in 28h of measurement time -> 16p.p.t. in four days of averaging time.
- Resonance is about three times narrower than 300 p.p.t. Mainz proton magnetic moment measurement.

- In case we get our systematics under control -> potential to improve the proton moment by a factor of 3 to 5, and the pbar moment by a factor of 15 to 25.
- **Still a lot to investigate.**
  - Relaxation drifts in cyclotron frequency measurements to be understood.
  - B1 improved from 72mT/m to 16mT/m, but still considerable.
  - Some higher order pseudo-harmonic cross talk to be understood B1/C3 and C1/B3.
  - Magnetic bottle RF heating?

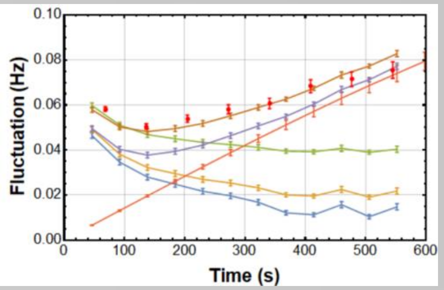
Summary of exp. achievements made in 2022

Cooling Trap | **Analysis Trap** | **Transport Section** | **Precision Trap** | **Park** | **Reservoir Trap** | **Target**

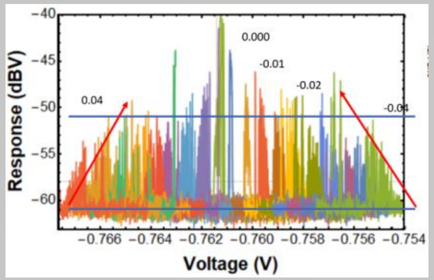
Reduced particle temperature



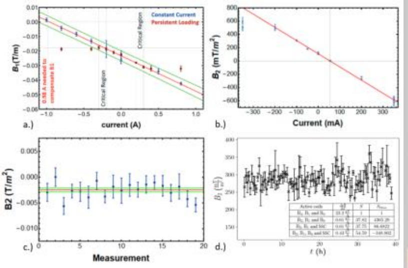
Optimized frequency averaging

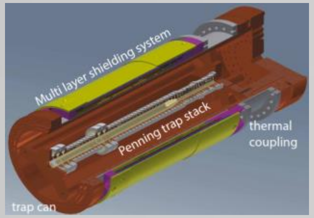


Parametric particle detection

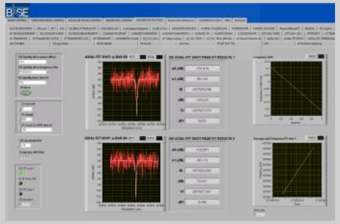


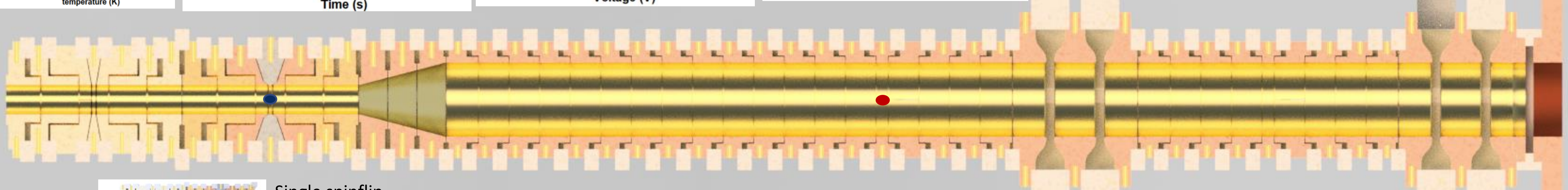
Homogenized and shielded magnetic field



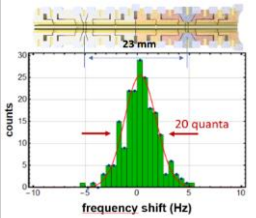


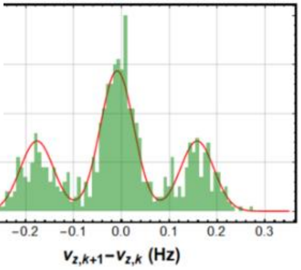
Heavy control system



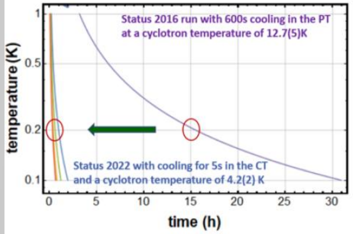


Single spinflip resolution

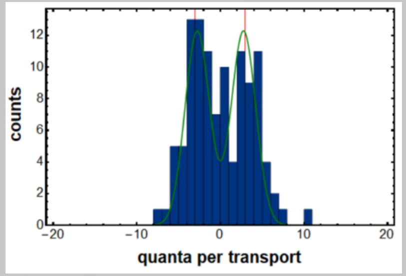




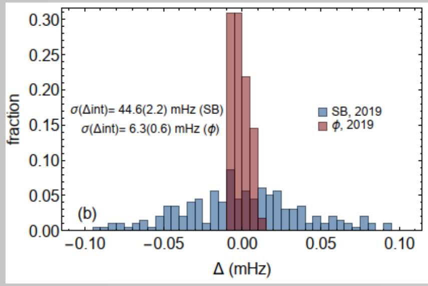
80-fold reduced prep time



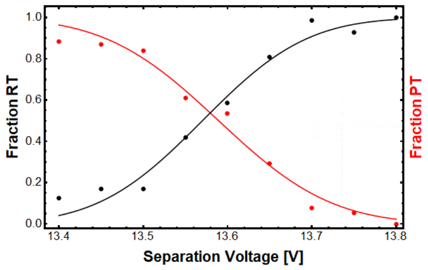
Low-quantum-noise transport



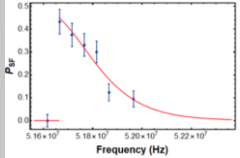
Optimized frequency measurements



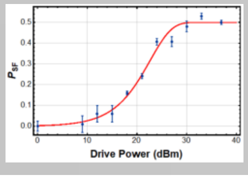
Particle extraction protocols



Larmor resonance measurement



Optimized spin flip power



Complex rf manipulation system

Prepared for improved magnetic moment measurements

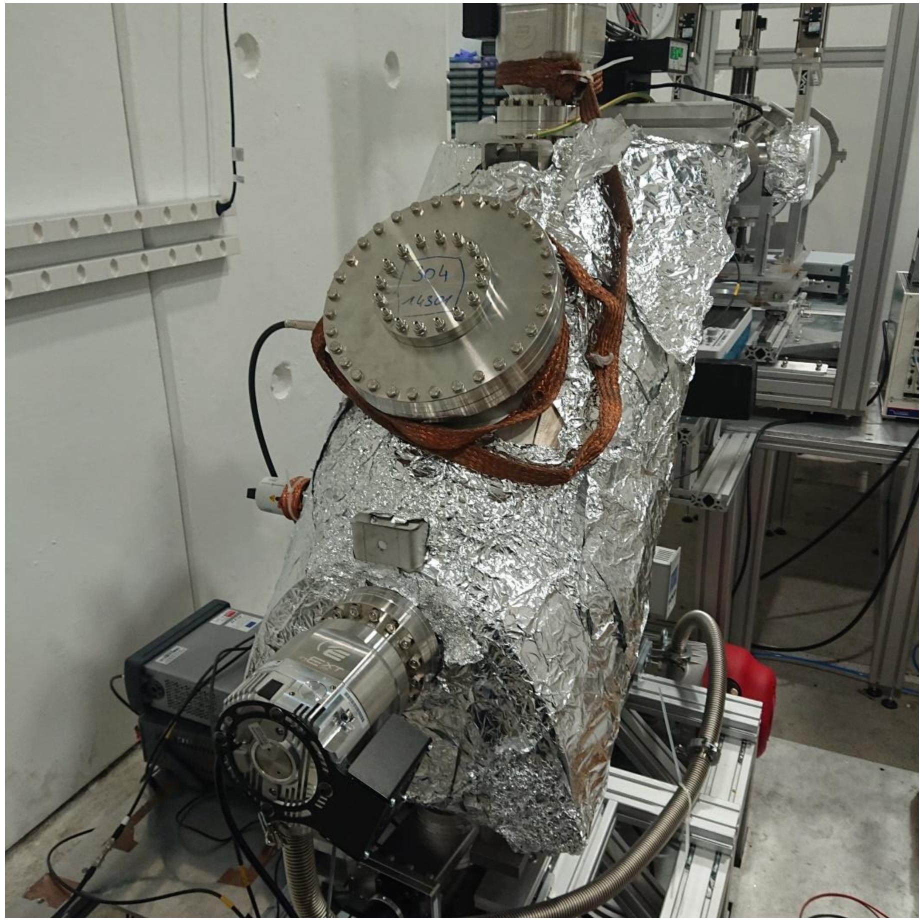
Summary and next steps

- 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.

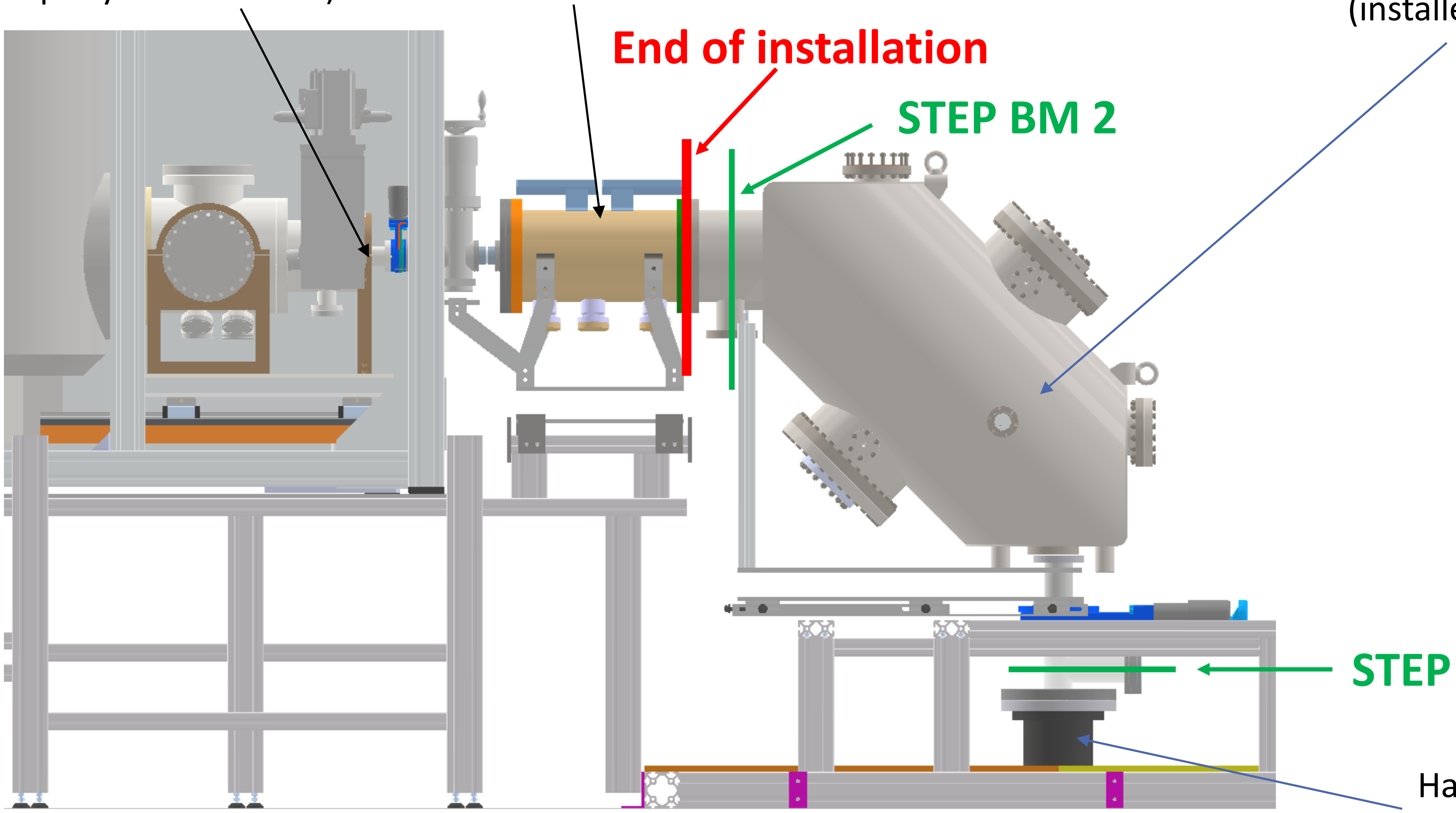
End of the physics run 2022 for STEP



Progress at CERN in 2022:

- Installation of the experiment support structures
- Installation of the vertical beamline and the deflector chamber
- Cryogenic stage for the transportable magnet is assembled and placed in the experiment area
- Commissioning of the electrostatic deflector chamber
- Operation of two beam monitors tested
- Detection of antiprotons behind the electrostatic deflector

Installation Status – 28.11.2022



Inlet chamber
(support plate not
properly dimensioned)

ZQNA chamber
(4 support plates missing)

End of installation

STEP BM 2

Deflector chamber
(installed, pumped to 2 10^{-8})

STEP BM 1

Handover point
vacuum

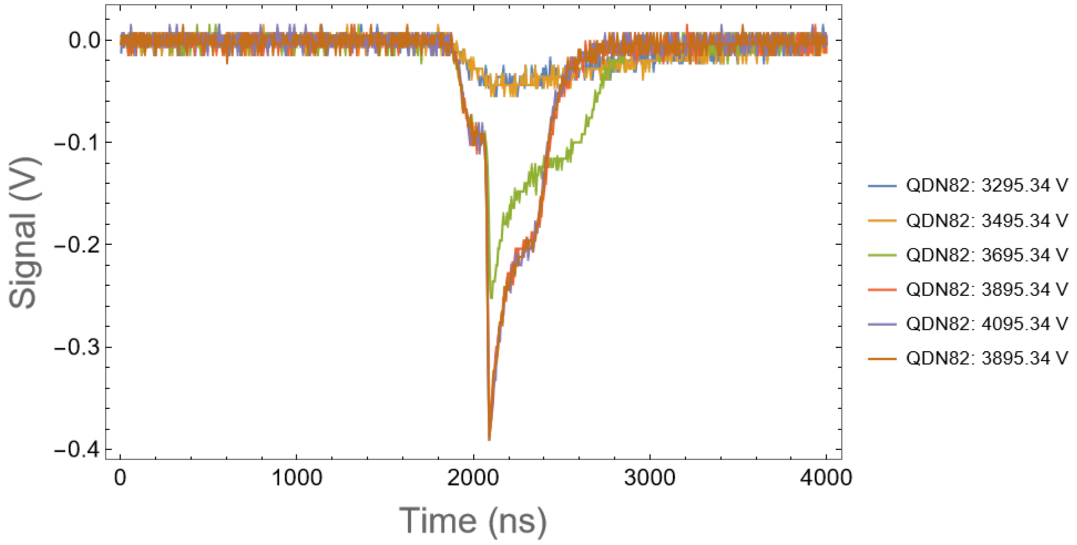
First antiprotons in the BASE-STEP zone

The 90 degree deflector and the beam monitors were commissioned with antiprotons at the end of the run 2022.

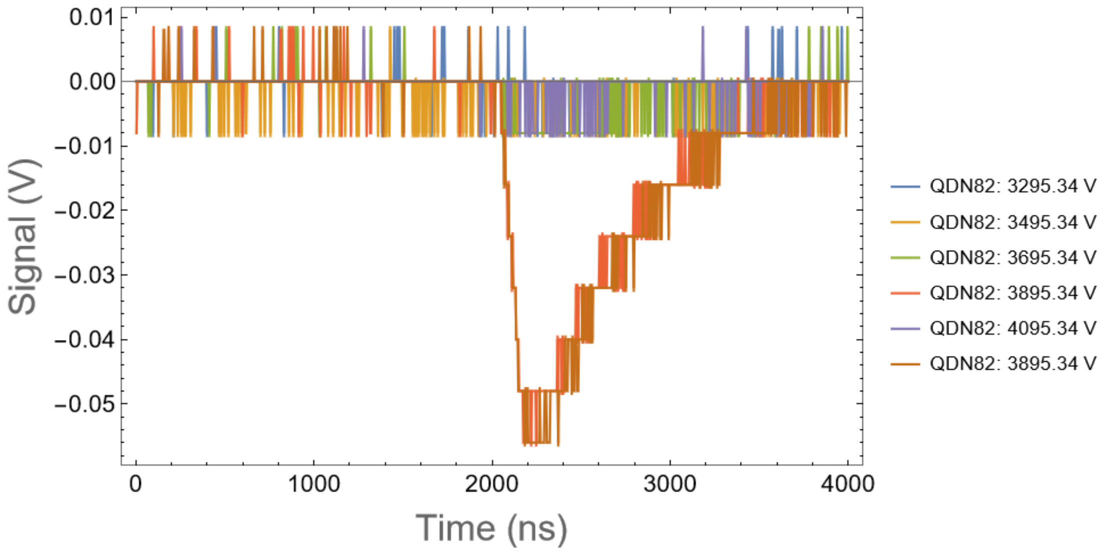
After only 2 hours of operation, we observe antiprotons on the beam monitor in front and behind the deflector chamber.

Optimization for injection into BASE-STEP will take place in 2023.

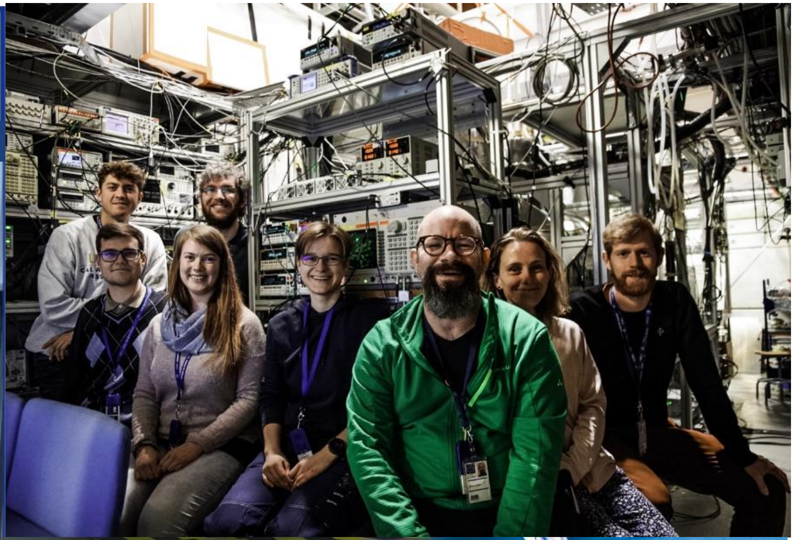
Representative response of beam monitor 1

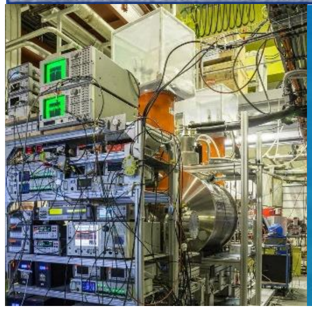


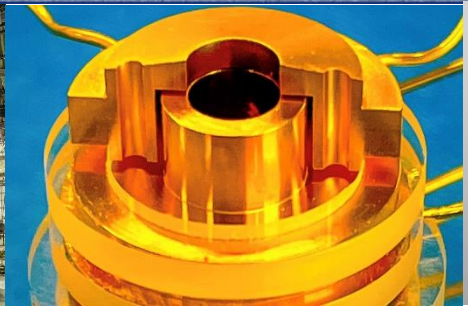
First signal on beam monitor 2

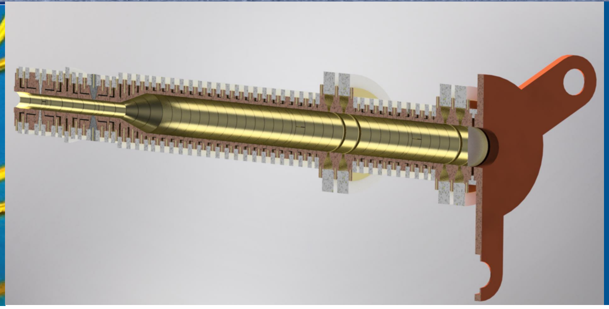


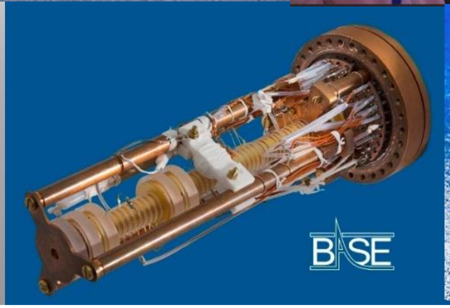
Thanks for your attention

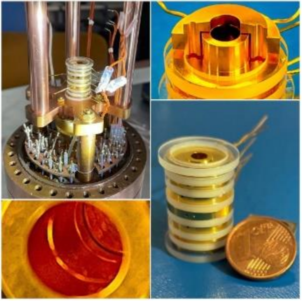




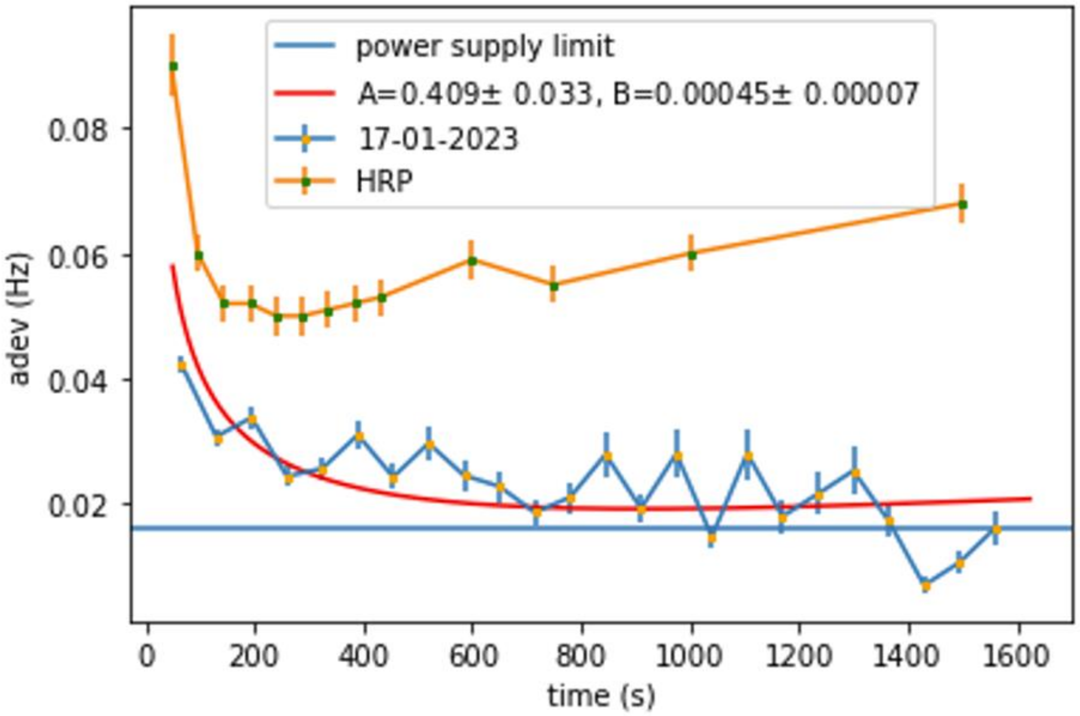


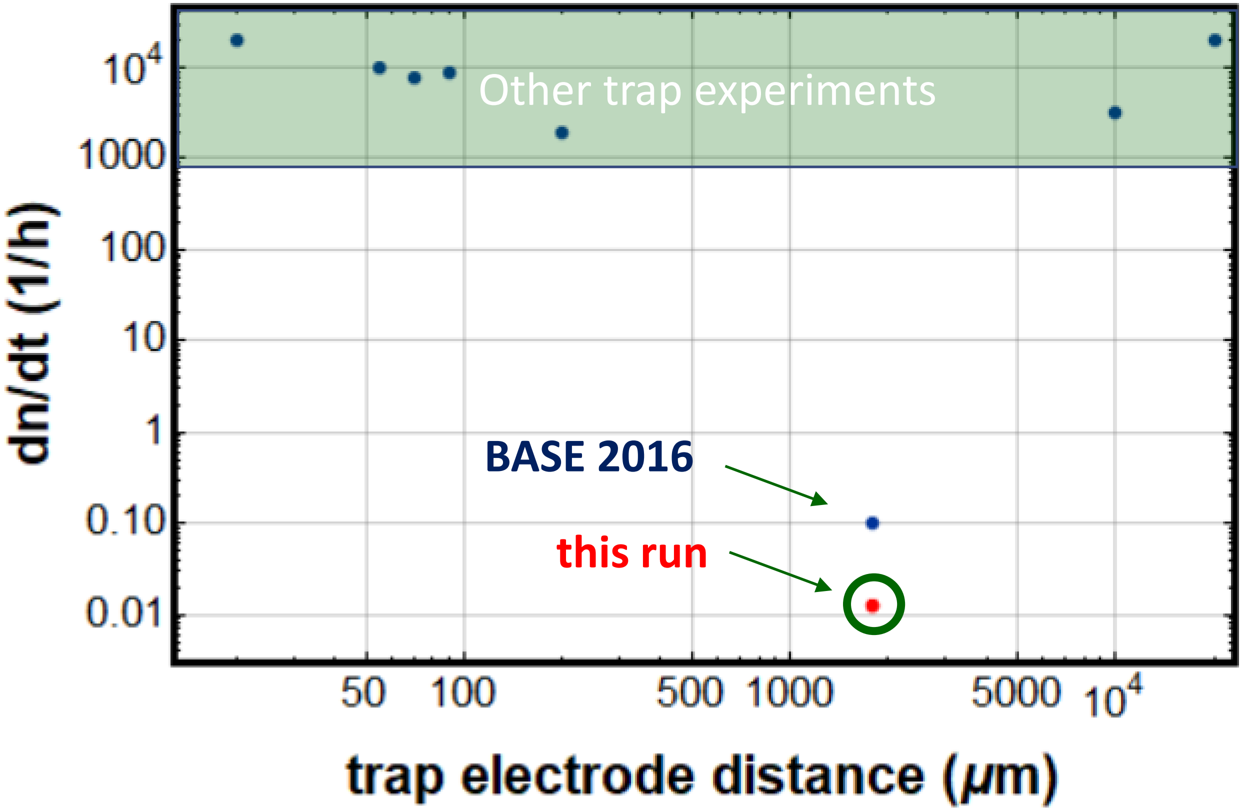






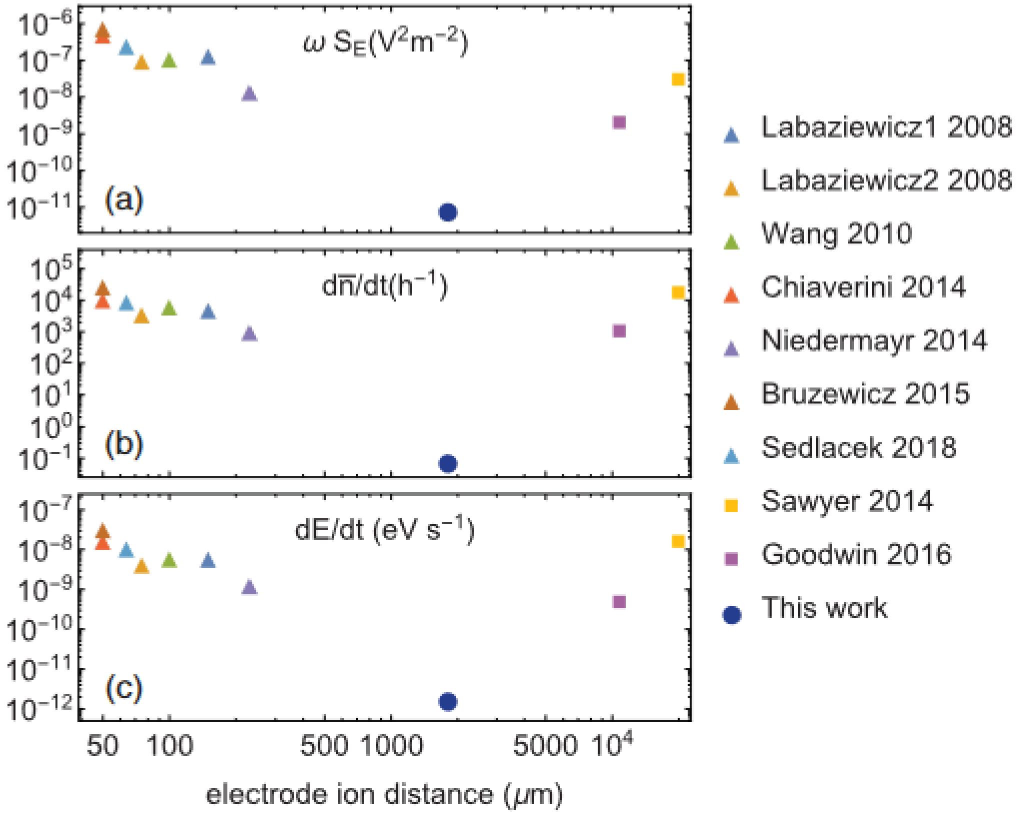
Heating Rates and Improved MCP limits

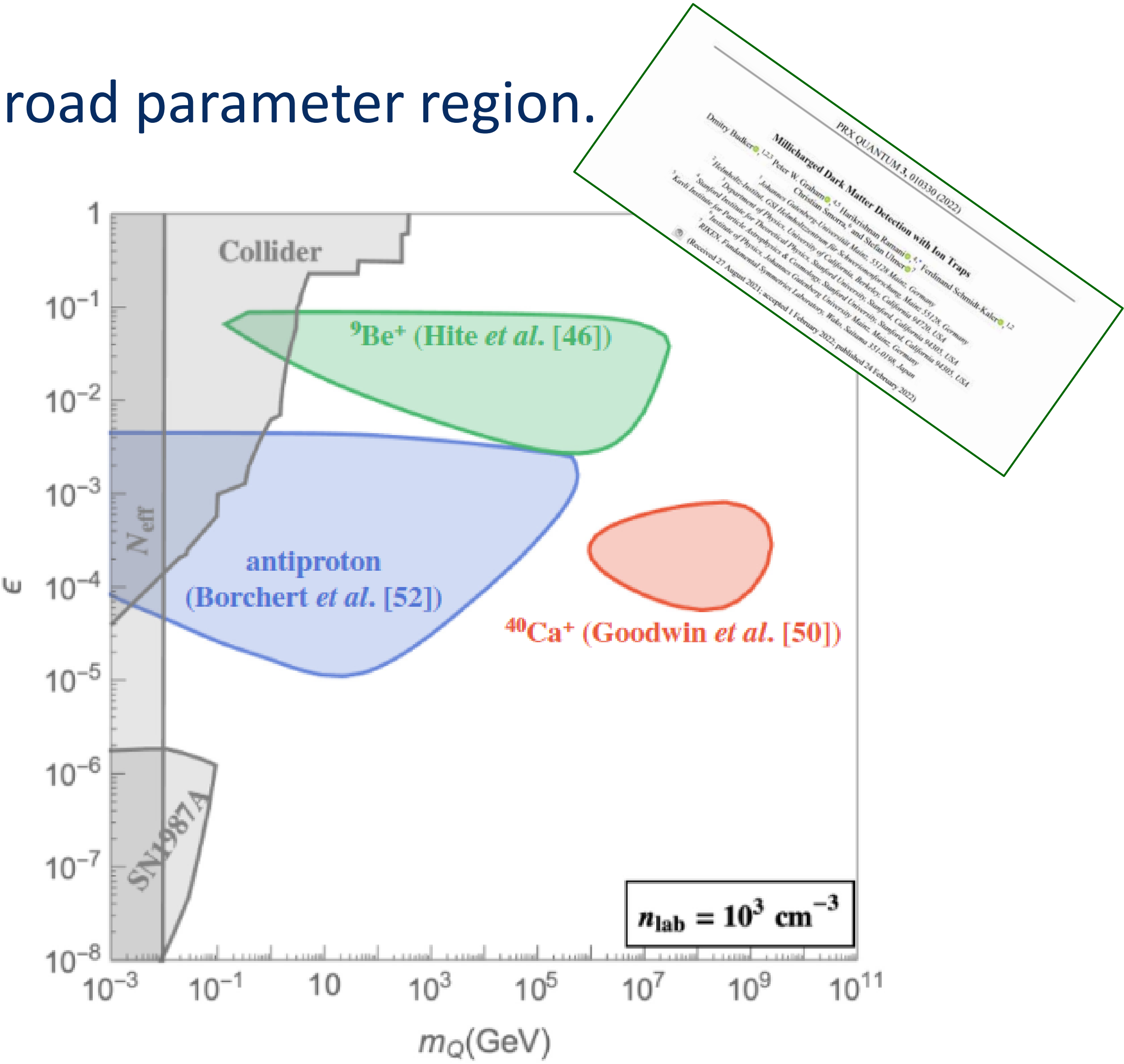




Quick Review – Article Published / MCP

- Uses heating rate measurements in the BASE-analysis trap to set limits on millicharged particles.
- Derives model dependent MCP constraints in a broad parameter region.





PRX QUANTUM 3, 010330 (2022)

Millicharged Dark Matter Detection with Ion Traps

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(Received 27 August 2021; accepted 1 February 2022; published 24 February 2022)