Progress Report 2021
BASE Collaboration

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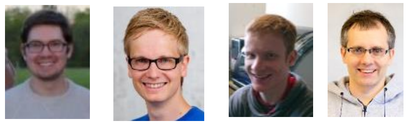
RIKEN

2022 / 01 / 18

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

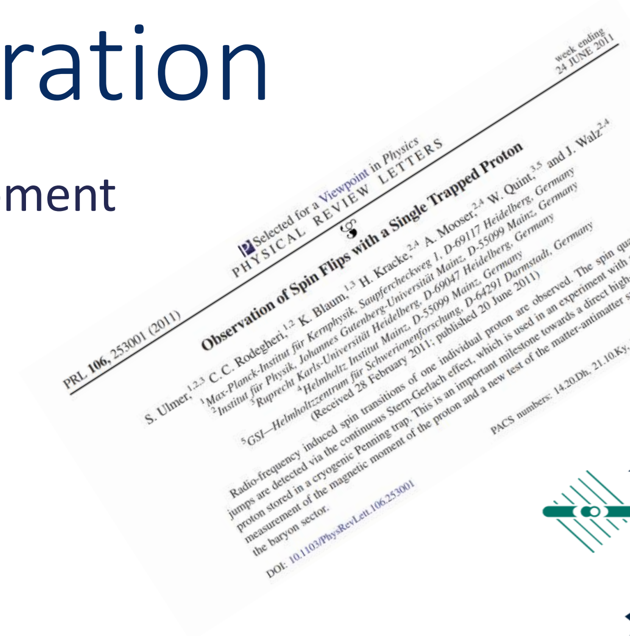
BASE – Collaboration

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



- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio

- **Hannover/PTB:** 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]

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[2] *Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
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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

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

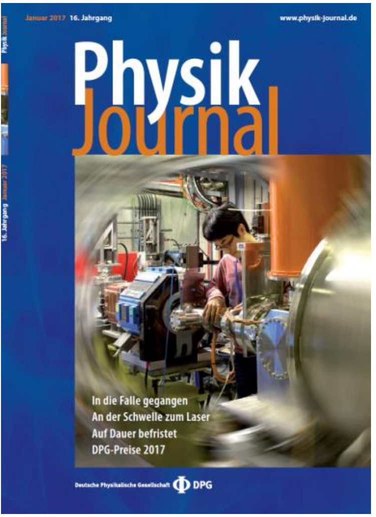
BASE

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.

Non-destructive physics



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

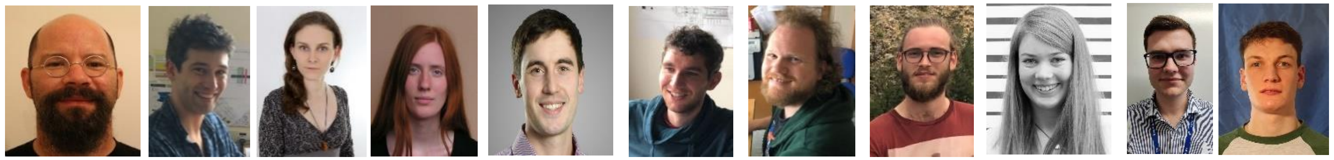
Physik Journal

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)

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

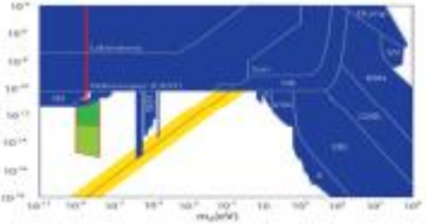


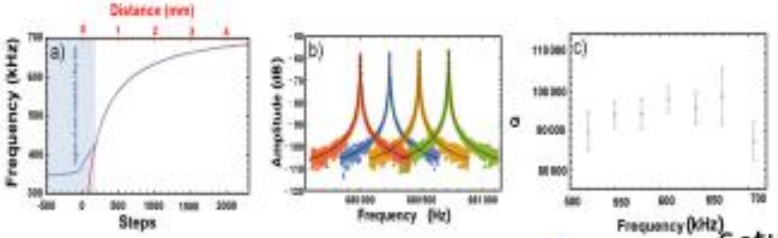
Team at CERN

Data evaluation and manuscript writing of new Q/M measurement

Development of tuneable axion detector

Constraints on axion photon coupling using an LC based haloscope



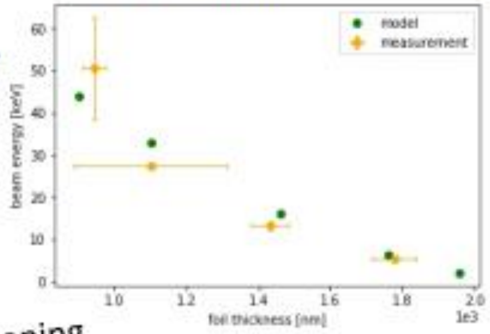


J. A. Devlin, et al., **PRL, accepted (2021)**

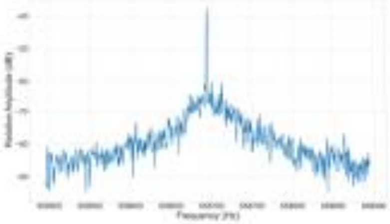
2021

Development of new background magnetometry

Characterization of degrader foils



Commissioning of 4 trap system



Single particle AT signal

Setup and commissioning of cryogenic experiment

Jan

Feb

Mar

Apr

May

June

July

Aug.

Sep.

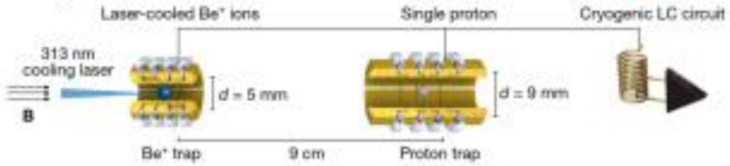
Oct.

Nov.

Dec.

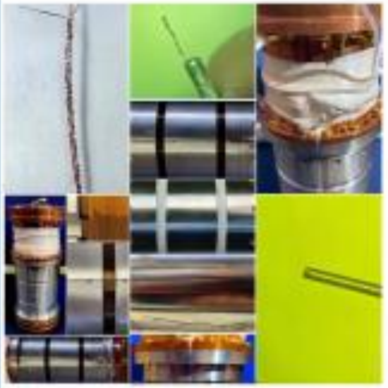
Jan.

Sympathetic cooling of protons.



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

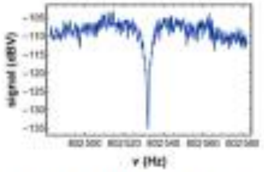
16 ppt measurement of the proton/antiproton QM ratio and test of the clock WEP



Development of shim coil system

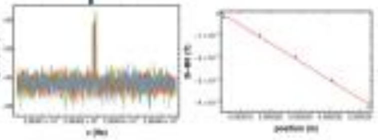
Development of new detection electonics

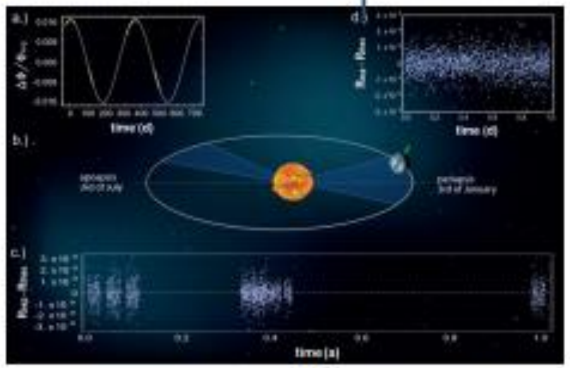
Setup an wiring of experiment electronics



First particles 2021

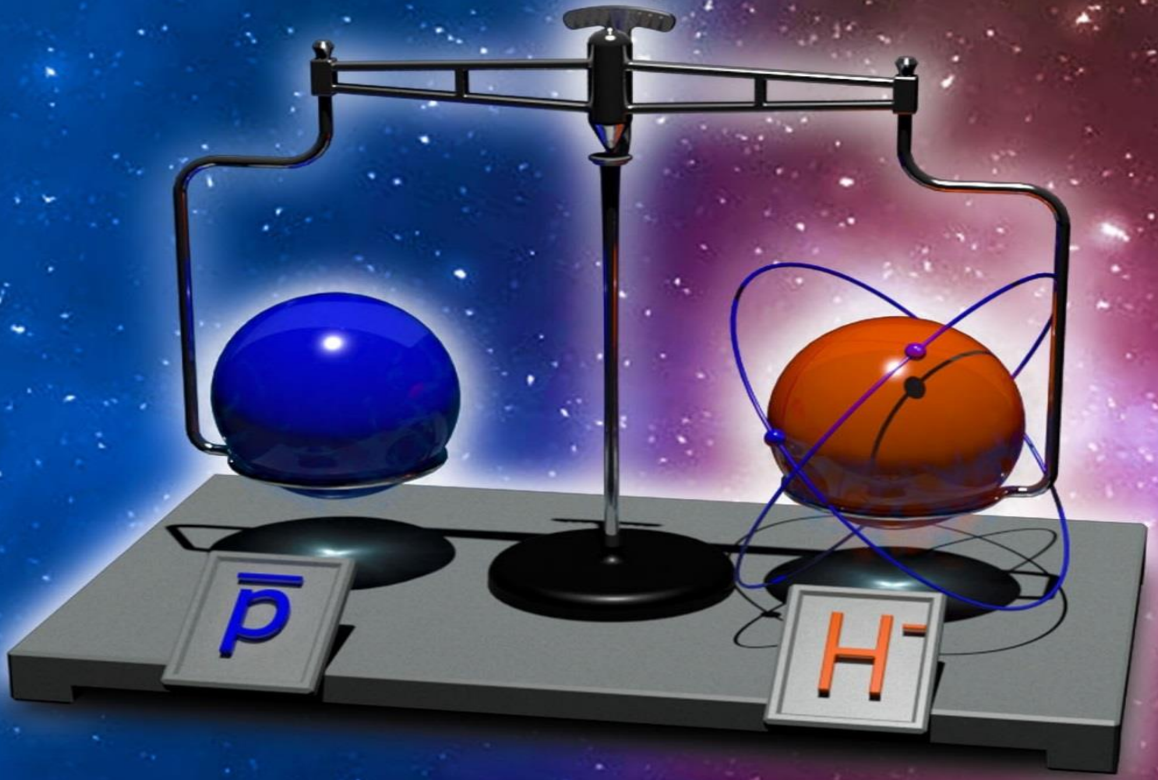
Commissioning of B-field tuning





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

High-Precision Comparison of the

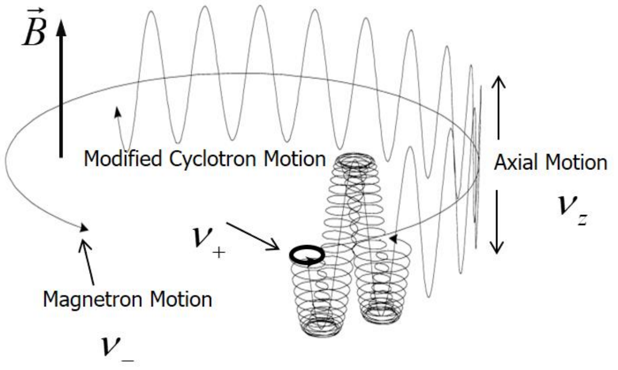


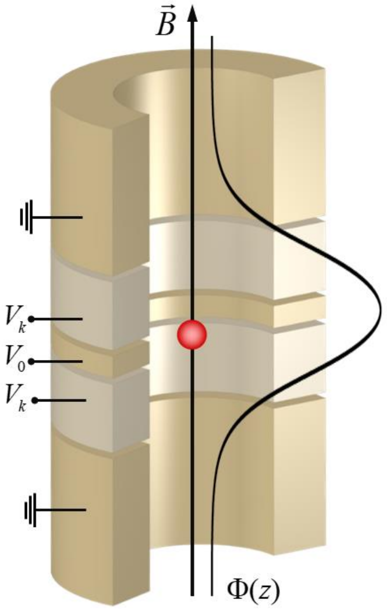
Antiproton-to-Proton Charge-to-Mass Ratio

Q/M Measurements in Precision Penning Traps

radial confinement: $\vec{B} = B_0\hat{z}$

axial confinement: $\Phi(\rho,z) = V_0 c_2\left(z^2 - \frac{\rho^2}{2}\right)$





Invariance Theorem

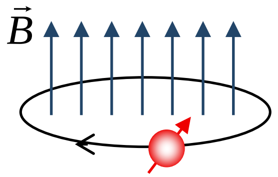
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies

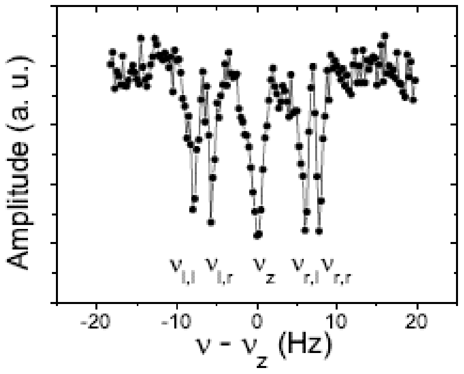
$$\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}}B$$

exact for misalignment and second order corrections. Other corrections need to be calibrated / constrained.

Cyclotron Motion



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



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

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

The Sound of the Antiproton Charge/Mass Ratio

- „The real voyage of discovery consists not in seeking new landscapes, but in having new eyes **(…and using different sensors)**.” (M. Proust)

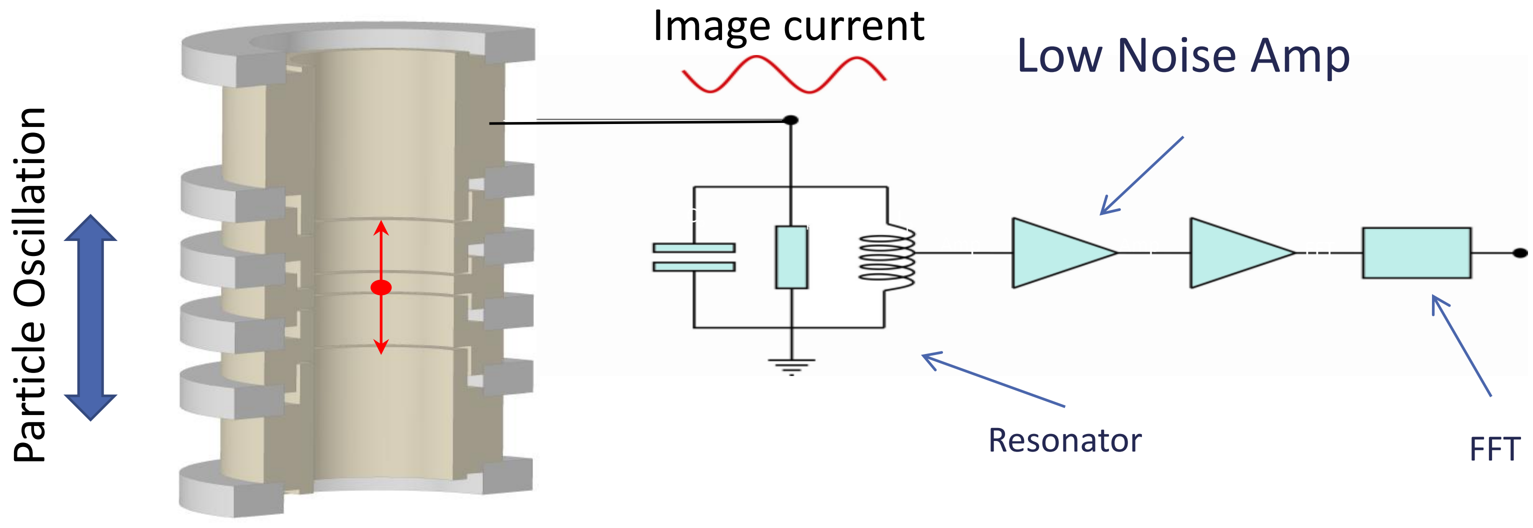
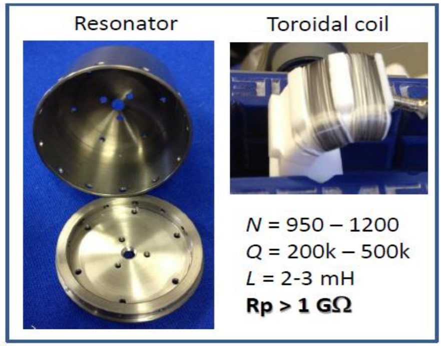

Particle Oscillation

Image current

Low Noise Amp

Resonator

FFT

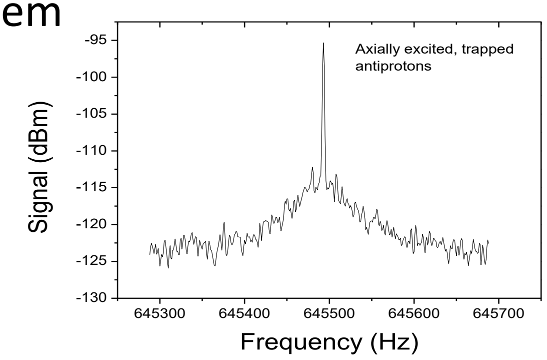


N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

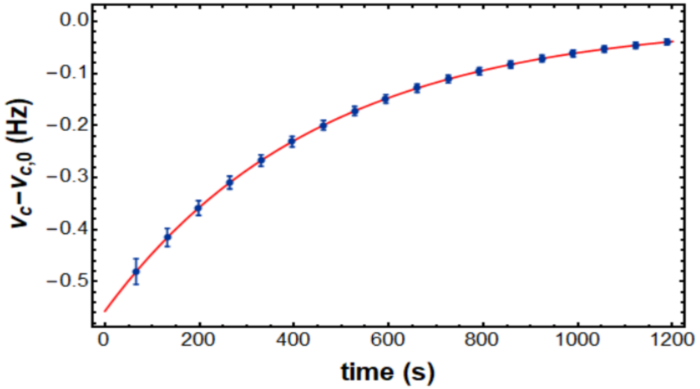
Inductor compensates system capacitance

$$I_{p,x} \sim \frac{q}{D_{eff}}(2\pi\nu_x)x$$

$$I_{p,x} \sim 0.1\ fA\ /(MHz\ \mu m)$$



- Special Relativity
  - Resistive cooling changes oscillation frequency

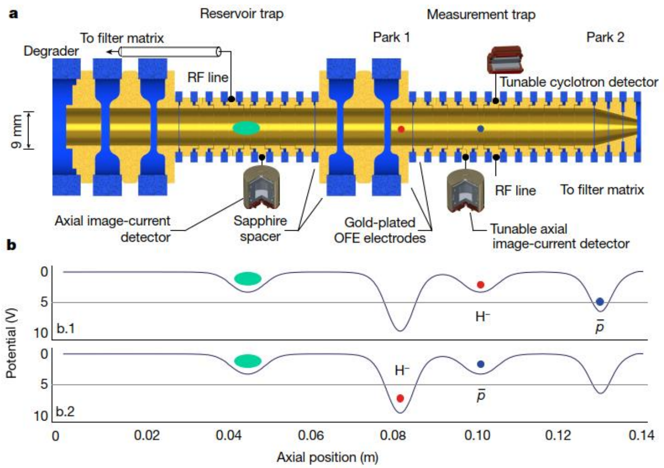


$$\nu_c = \frac{1}{2\pi}\left(\frac{q}{m}\sqrt{1-\left(\frac{v}{c}\right)^2}\,B_0\right)$$

  - Special relativity changes pitch

In charge-to-mass ratio comparisons we are «listening» to the sound of protons and antiprotons

Previous Measurement and Improvements



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

$$\boxed{m_{\mathrm{H}^-} = m_{\mathrm{p}}\left(1 + 2\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}} - \frac{E_{\mathrm{b}}}{m_{\mathrm{p}}} - \frac{E_{\mathrm{a}}}{m_{\mathrm{p}}} + \frac{\alpha_{\mathrm{pol,H}^-} B_0^2}{m_{\mathrm{p}}}\right)}$$

Effect	Magnitude	
m_e/m_p	0.001 089 234 042 95 (5)	MPIK
$-E_b/m_p$	0.000 000 014 493 061 …	MPQ
$-E_a/m_p$	0.000 000 000 803 81 (2)	Lykke

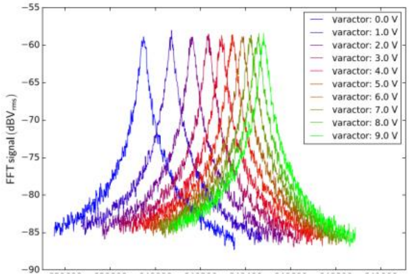
Result of 6500 proton/antiproton Q/M comparisons:

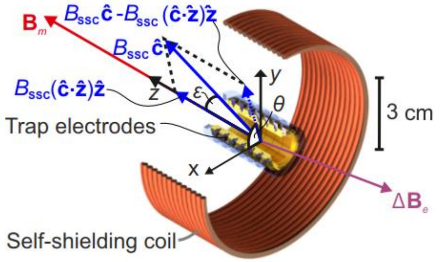
$R_{\mathrm{exp,c}}$ = 1.001 089 218 755 (69)

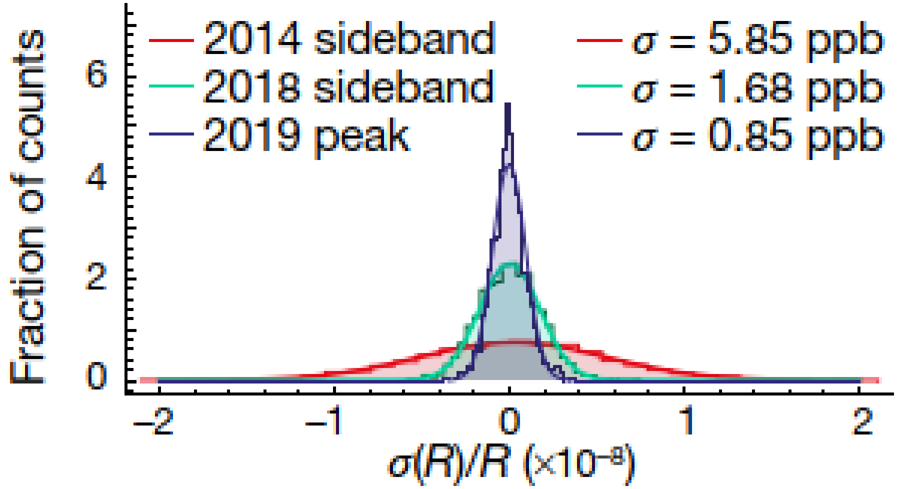
$$\boxed{\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}} + 1 = 1(69) \times 10^{-12}}$$

Improvements compared to previous run:

- Tuneable superconducting detector
  - Enables measurements at constant trapping potential
- Improved magnetic field homogeneity
- Improved magnetic shielding







Inspired by work of TRAP collaboration (G. Gabrielse et al., PRL **82**, 3199(1999).)

Systematic Studies

- 16 parts in a trillion at 30MHz cyclotron frequency correspond to an absolute frequency resolution of 480uHz. This is an absolute resolution similar to resolutions achieved in the best clock experiments.
- Also corresponds to a required magnetic field similarity of 31pT to be allowed to solve:

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

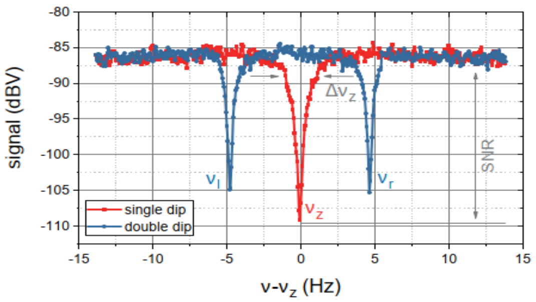
- BASE magnet homogeneity

Parameter	2018-1/2-SB	2018-3-PK/2019-1-SB
B_0	$1.944\,862(2)\,\mathrm{T}$	$1.944\,866(2)\,\mathrm{T}$
B_1	$0.00415(5)\,\mathrm{T/m}$	$0.00156(4)\,\mathrm{T/m}$
B_2	$-0.267(2)\,\mathrm{T/m^2}$	$-0.0894(6)\,\mathrm{T/m^2}$

- Need to characterize particle amplitudes and positions at the 10nm scale of drifts (compare identical particles)

Applied two different measurement methods

Sideband technique

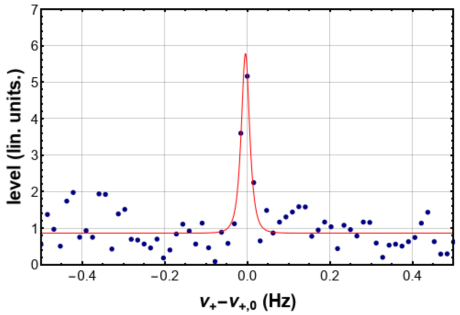


- Thermal equilibrium measurements, largely insensitive to «trap systematics», but sensitive to lineshape effects

Scatter of 1.6(2) p.p.b. per shot

Limited by intrinsic measurement scatter

Peak technique



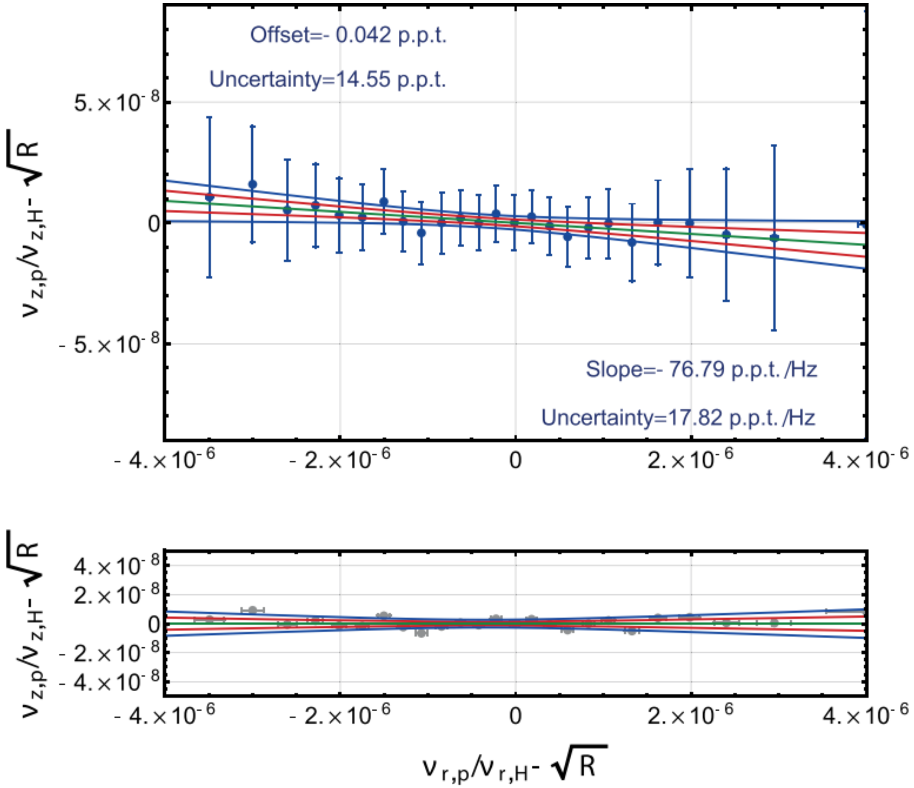
- High energy measurements, largely insensitive to lineshape effects, but sensitive to trap systematics.

Scatter of 0.85(5) p.p.b. per shot

Limited by magnet properties

Dominant Systematic Limitations

- Lineshape Shift



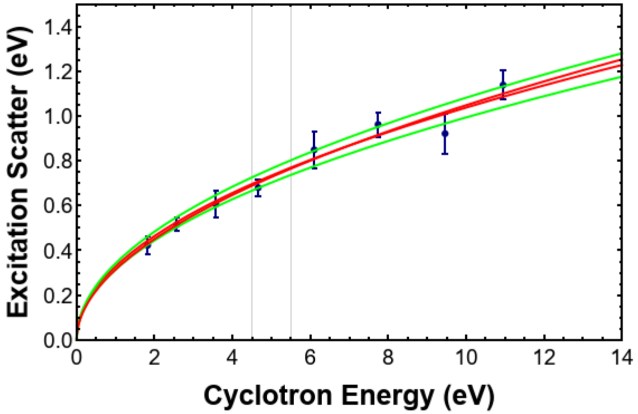
- Scaling of particle frequency with respect to frequency center of the detection resonator leads to frequency dependent shift of the measured frequency ratio.

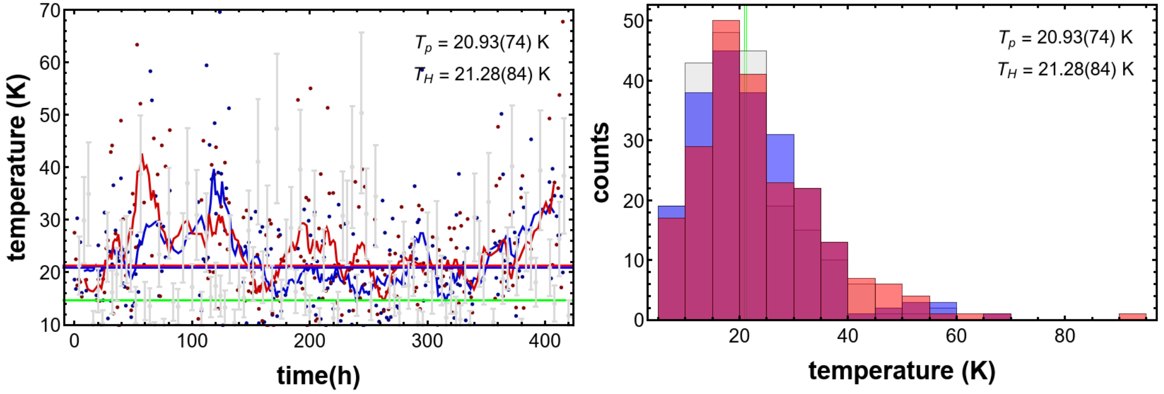
Strong suppression in PEAK measurements

- Temperature Shifts

Temperature difference of the single particle detectors at the different working points (23ppt/K).

$$E(t) = \left(\frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}\right)^2 = E_{exc} + 2\sqrt{E_{th}}\sqrt{E_{exc}} + E_{th}$$

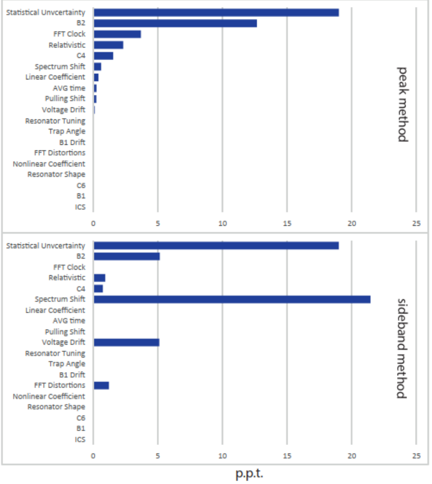




Continuously measured in PEAK measurements

Systematic Effects and Result

Effect	2018-1-SB	2018-2-SB	2018-3-PK	2019-1-SB
B_1-shift	0.03(2)	0.01(2)	< (0.01)	< (0.01)
B_2-shift	20.27(14.86)	8.38(14.86)	10.79(12.66)	3.75 (5.16)
C_4-shift	(1.12)	(1.13)	(1.54)	(0.76)
C_6-shift	< (0.01)	< (0.01)	< (0.01)	< (0.01)
Relativistic	1.20(92)	0.47(90)	1.90(2.32)	0.65(94)
Image charge shift	0.05(0)	0.05(0)	0.05(0)	0.05(0)
Trap misalignment	0.06(0)	0.06(0)	0.05(0)	0.05(0)
Voltage Drifts	−3.35(5.12)	−3.77(5.12)	−0.11(11)	−5.03(5.12)
Spectrum Shift	0.37(20.65)	16.89(46.49)	0.74(61)	−8.61(21.45)
FFT-Distortions	(1.57)	(3.48)	(0.03)	(1.23)
Resonator-Shape	0.02(3)	0.02(2)	< (0.01)	0.01(2)
B_1-drift offset	< (0.11)	< (0.11)	< (0.04)	< (0.04)
Resonator Tuning	< (0.16)	< (0.16)	< (0.06)	< (0.06)
Averaging Time	–	–	−2.87(25)	–
FFT Clock	–	–	(3.69)	–
Pulling Shift	–	–	2.86(24)	–
Linear Coefficient Shift	–	–	0.16(40)	–
Nonlinear Shift	–	–	0.03(2)	–
Systematic Shift	18.65(26.04)	22.11(49.22)	13.60(13.50)	−9.13(22.71)
$R_{exp} - R_{theo}$	13.02(27.12)	−5.04(46.57)	7.99(18.57)	18.34(18.89)
$R_{exp,c} - R_{theo}$	−5.63(37.60)	−27.15(67.76)	−5.61(22.66)	27.47(29.54)



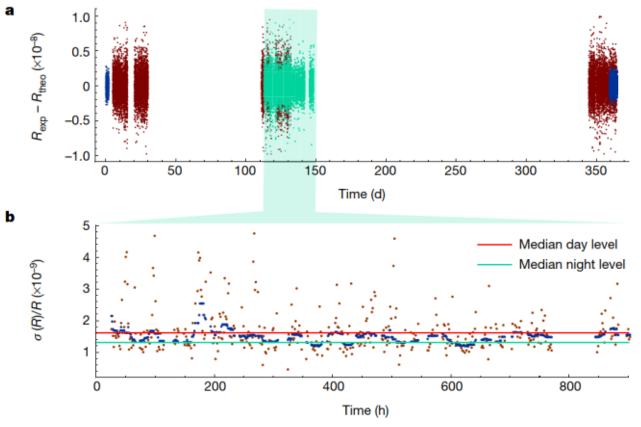


Table 1 | Summary of measured results

Campaign	R_{exp}	$\sigma(R)_{stat}$	$\sigma(R)_{sys}$
2018-1-SB	1.001089218748	27×10^{-12}	26×10^{-12}
2018-2-SB	1.001089218727	47×10^{-12}	49×10^{-12}
2018-3-PK	1.001089218748	19×10^{-12}	14×10^{-12}
2019-1-SB	1.001089218781	19×10^{-12}	23×10^{-12}

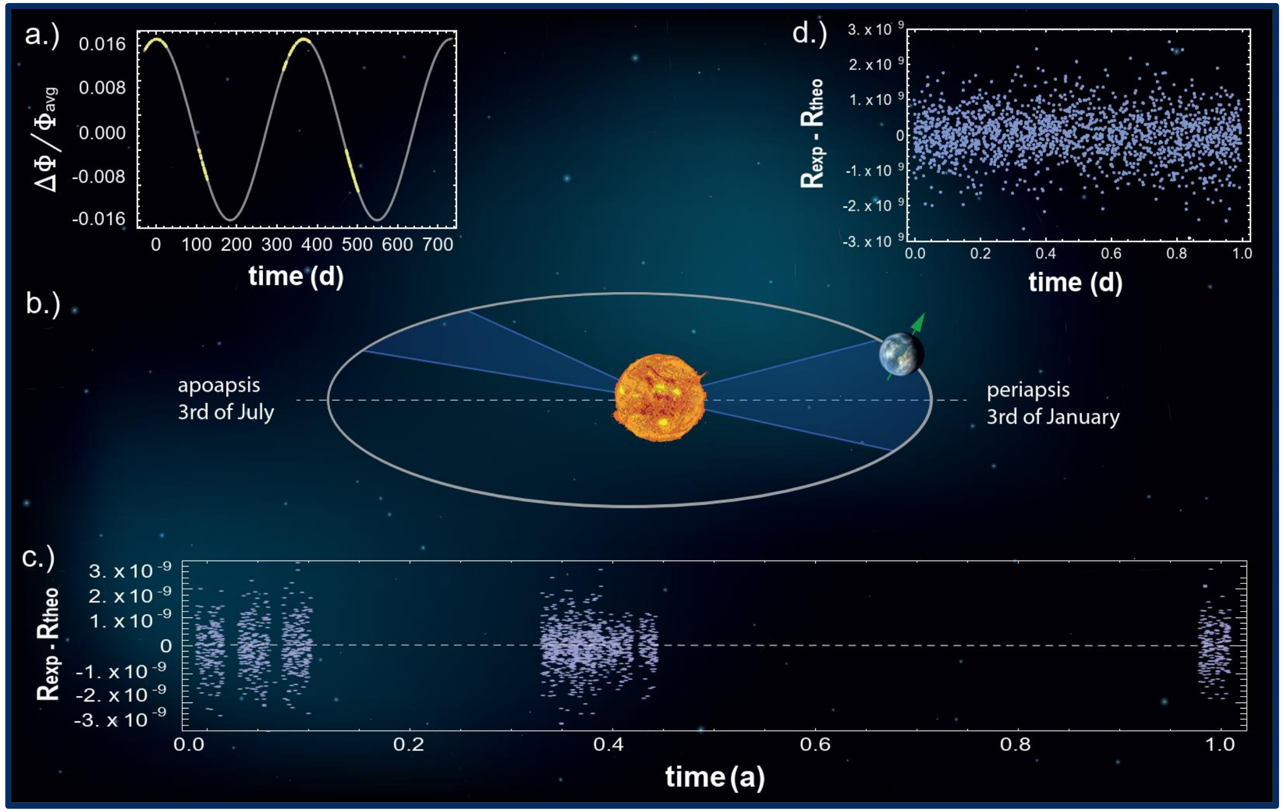
$$R_{\bar{p},\mathrm{H}^-} = 1.001\,089\,218\,757\,(16)$$

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

Interpretation

- 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

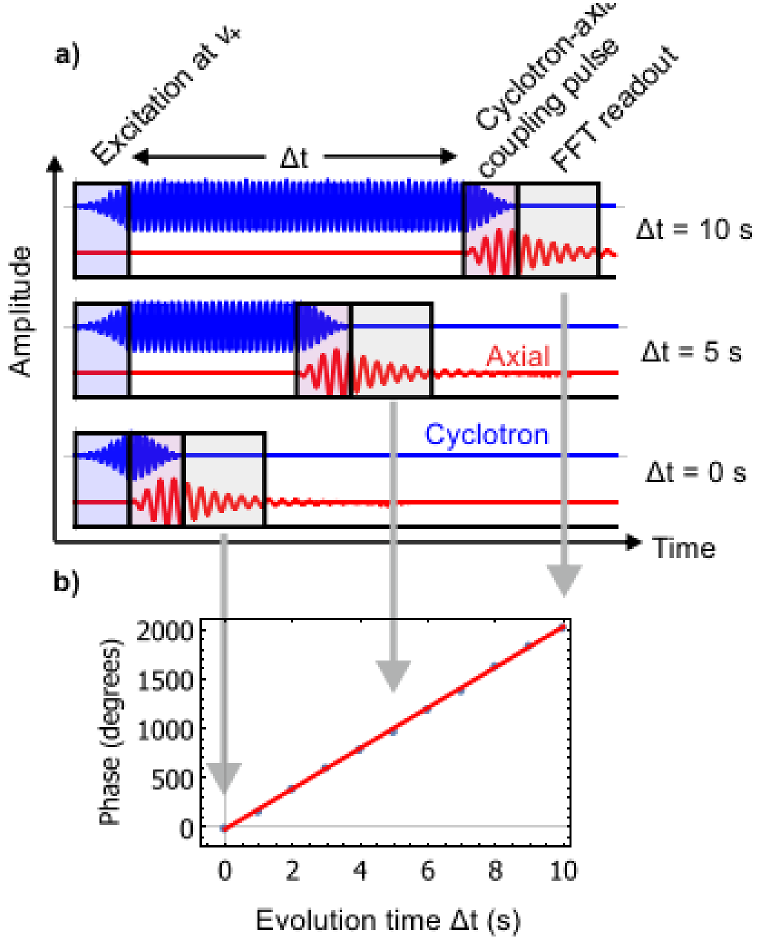
$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right)$$

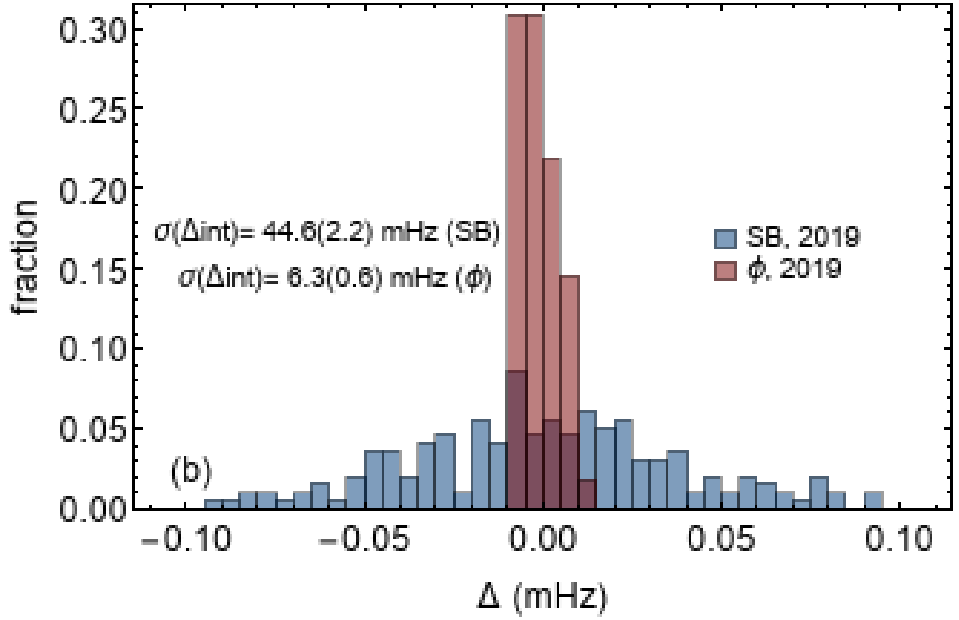
Property	**Limit**
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

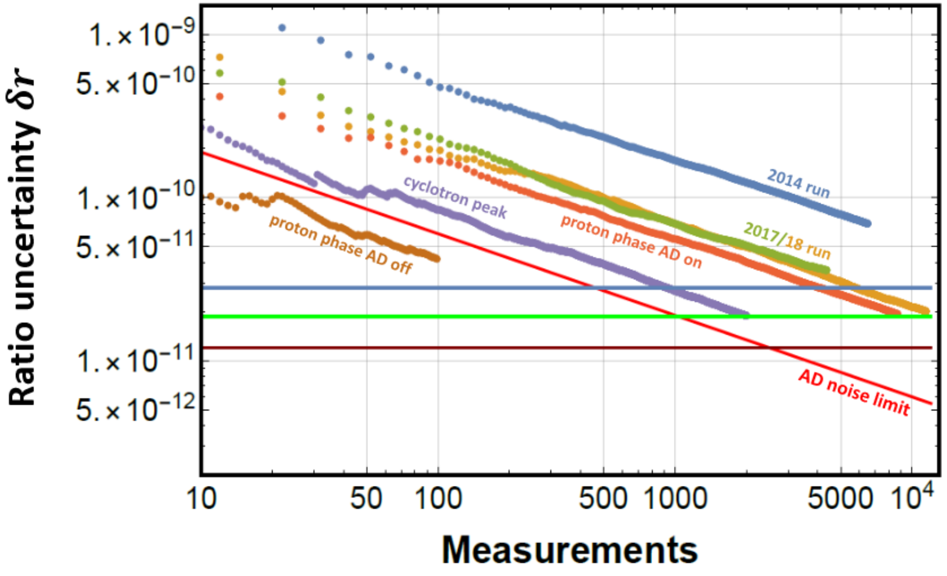
Broad band time base analysis under evaluation

Outlook

- Using phase sensitive methods







20 p.p.t. / 24h , but only possible during accelerator shutdown

The transportable trap BASE-STEP

Goal:

- Relocate antiproton measurements into a calm magnetic environment in a transportable trap system

Gain:

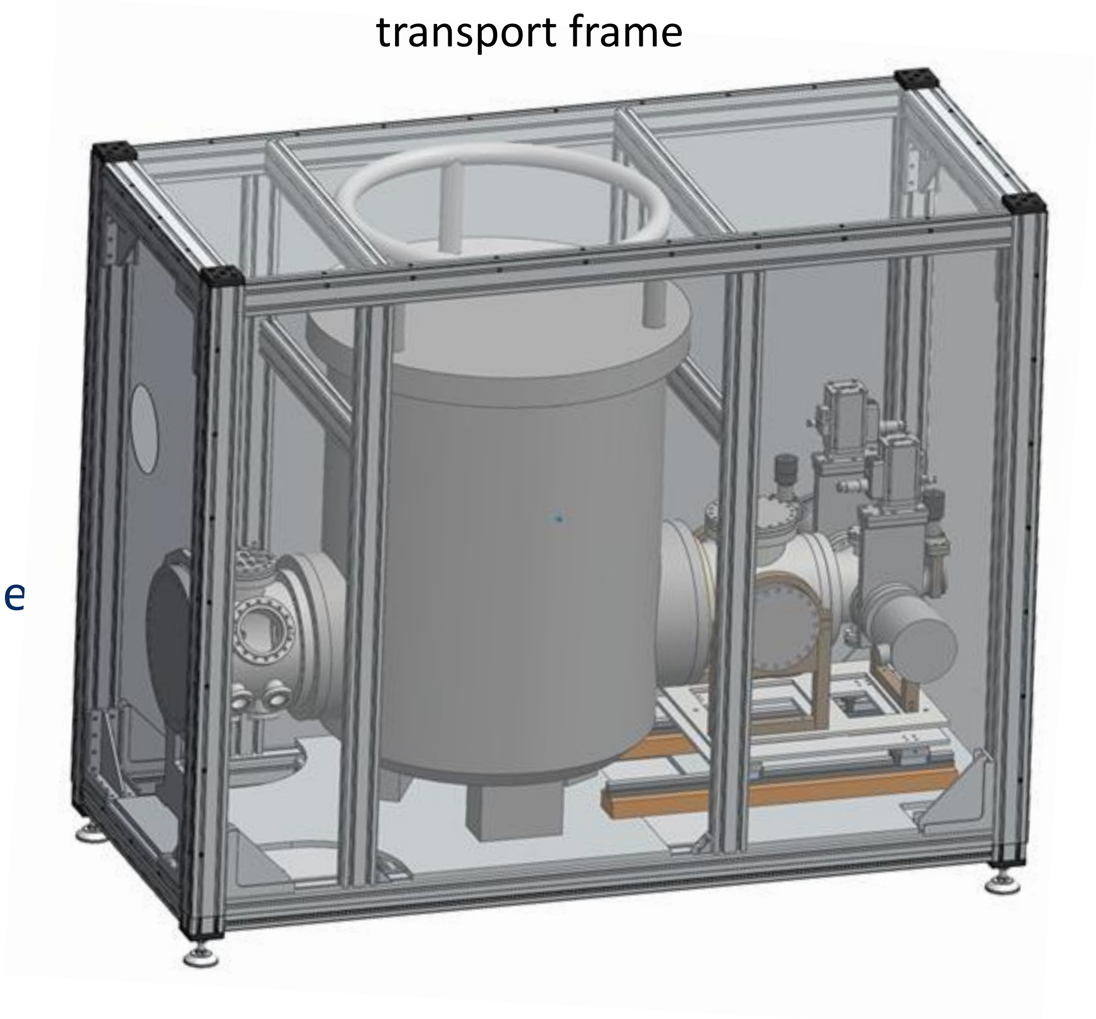
- Precision measurements with antiprotons on the 10^{-12} level

Design goals:

- Transportable reservoir trap with up to 100 to 10000 antiprotons
- Supplies non-destructive single-particle experiments with the reservoir trap technique

- Compact trap system (2 m x 0.87 m x 1.65 m)
- Transportable superconducting magnet with mechanical support suitable for transportation.
- Hybrid cooling system: One cryocooler (10 kW power) + 8 h LHe buffer

BASE-STEP magnet with transport frame



Progress and Status of BASE-STEP

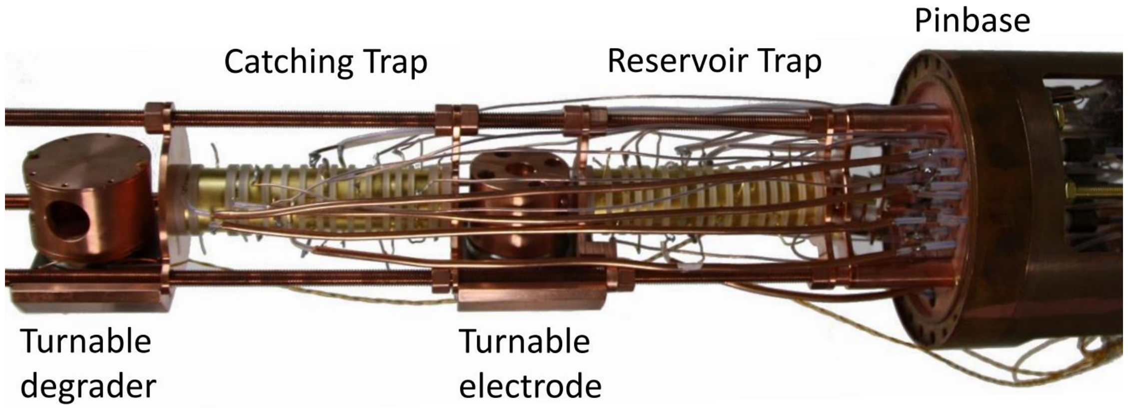
Progress in 2021:

- Antiproton injection simulations and beamline design finished
- Recommendation of BASE-STEP by the SPSC committee and approval by the CERN research board
- Improved technical design of the trap system and the cryogenic valves
- Cryogenic trap inlay was produced and assembled
- Four image-current detectors were produced and characterized
- Experiment zone for BASE-STEP was prepared, thanks to CERN

Goals in 2022:

- Delivery of the superconducting magnet (May 2022)
- Preparation of the experiment zone and antiproton injection line
- First cooldown of the transportable trap system
- Online operation with ELENA possible earliest in August 2022

BASE-STEP Trap System



Experiment area layout

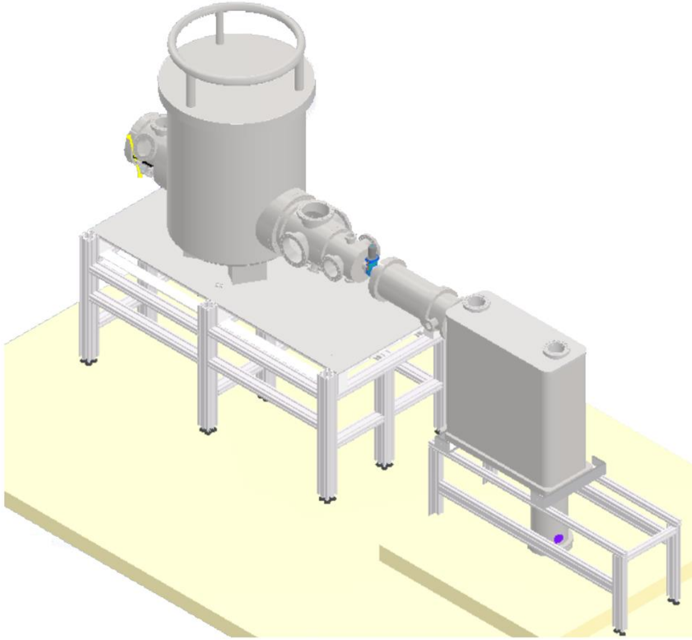
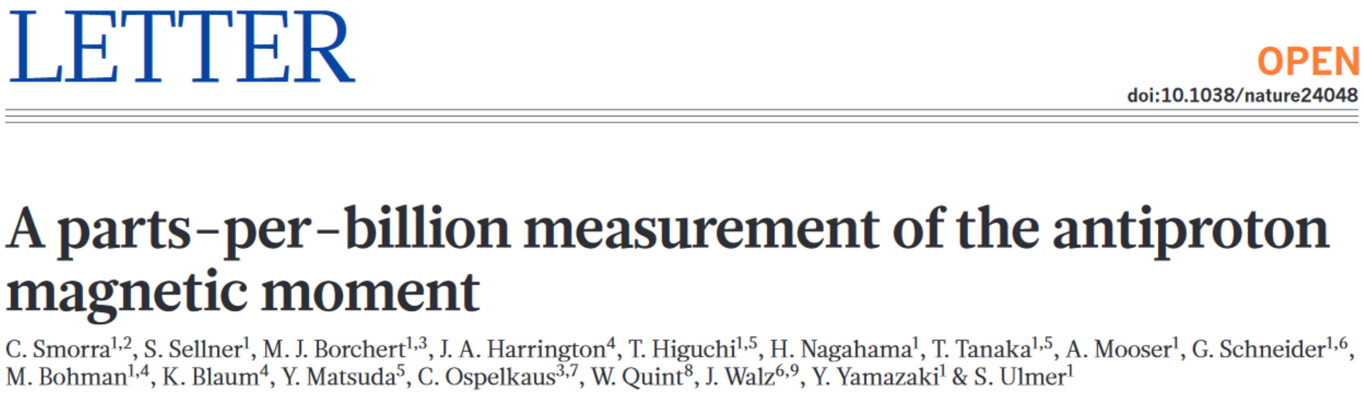


Image-current detectors

GOAL: Get prepared for late 2022 antiproton run

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics



LETTER

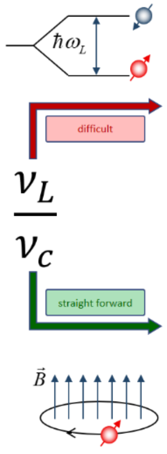
OPEN

doi:10.1038/nature24048

A parts-per-billion measurement of the antiproton magnetic moment

C. Smorra[1,2], S. Sellner[1], M. J. Borchert[1,3], J. A. Harrington[4], T. Higuchi[1,5], H. Nagahama[1], T. Tanaka[1,5], A. Mooser[1], G. Schneider[1,6], M. Bohman[1,4], K. Blaum[4], Y. Matsuda[5], C. Ospelkaus[3,7], W. Quint[8], J. Walz[6,9], Y. Yamazaki[1] & S. Ulmer[1]

$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\,\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$



Continuous Stern Gerlach Effect

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

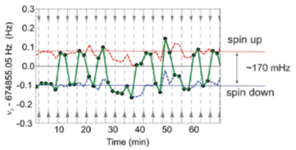
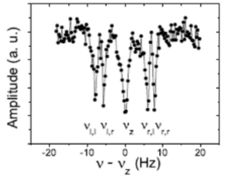
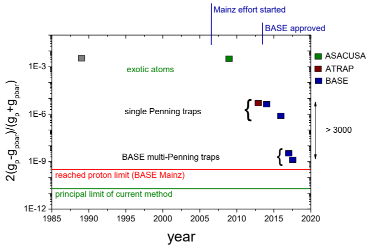


Image Current Measurements



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



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

CERN Courier

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.

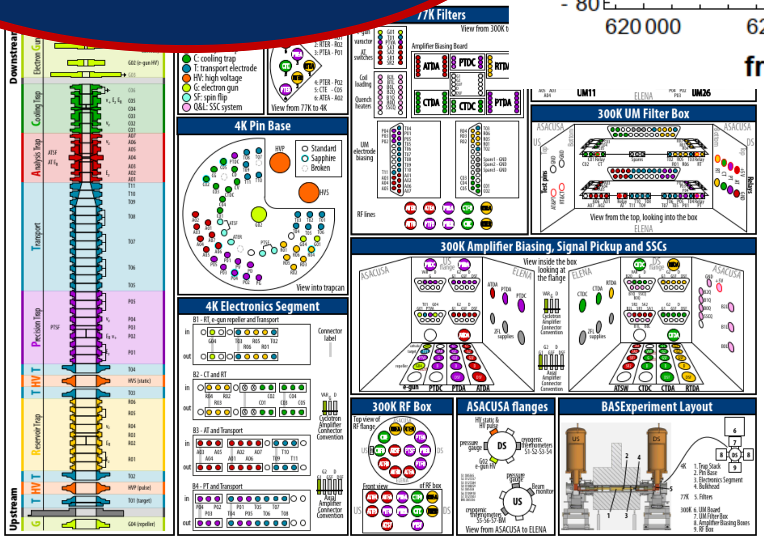
The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement 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.

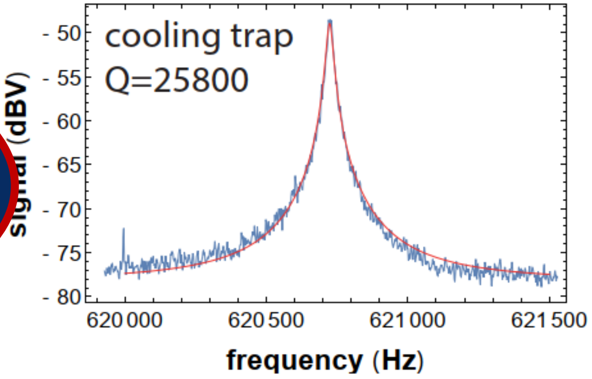
CERN COURIER, 3 / 2018.

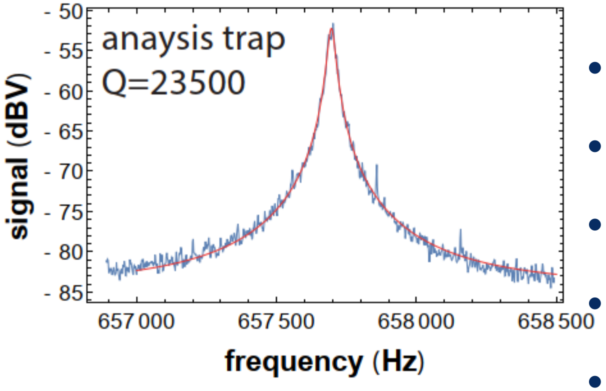
Developments for the new experiment

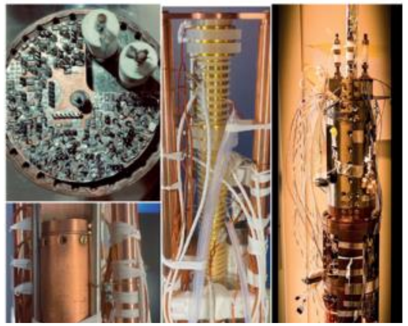
First full 4-trap stack operated in BASE

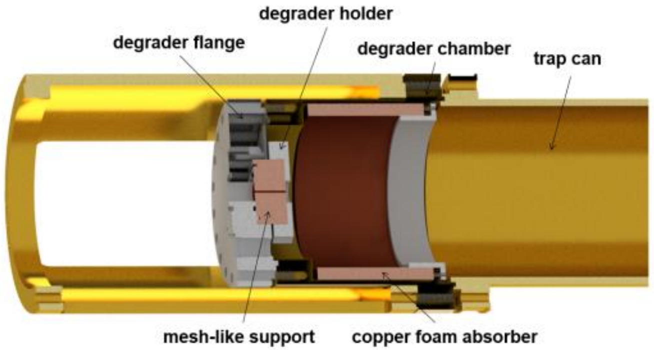


Property	Value 2021	Value 2019
Resonance Frequency	29.64 MHz	29.64 MHz
Tuning range	4.3 MHz	1.5 MHz
Inductance	1.52 μH	1.68 μH
Capacitance	2.72 pF	2.63 pF
Free Q @ 5 K	1250(150)	196(8)
Detection Resistance @ 5 K	376 kΩ	61 kΩ









- Many components developed 2020 and 2021.
- New trap system
- New electronics layout
- New axial detectors
- New degarder interface
- New cryoswitch system
- New magnet shim system
- New e-gun
- Upgraded software system
- Upgraded zone layout

Although everything else looks promising, problems with antiproton catching in 2021 (stray fields, misalignment, diagnostics, etc.).

Systematic Limitations of Previous Experiment

Published error budget

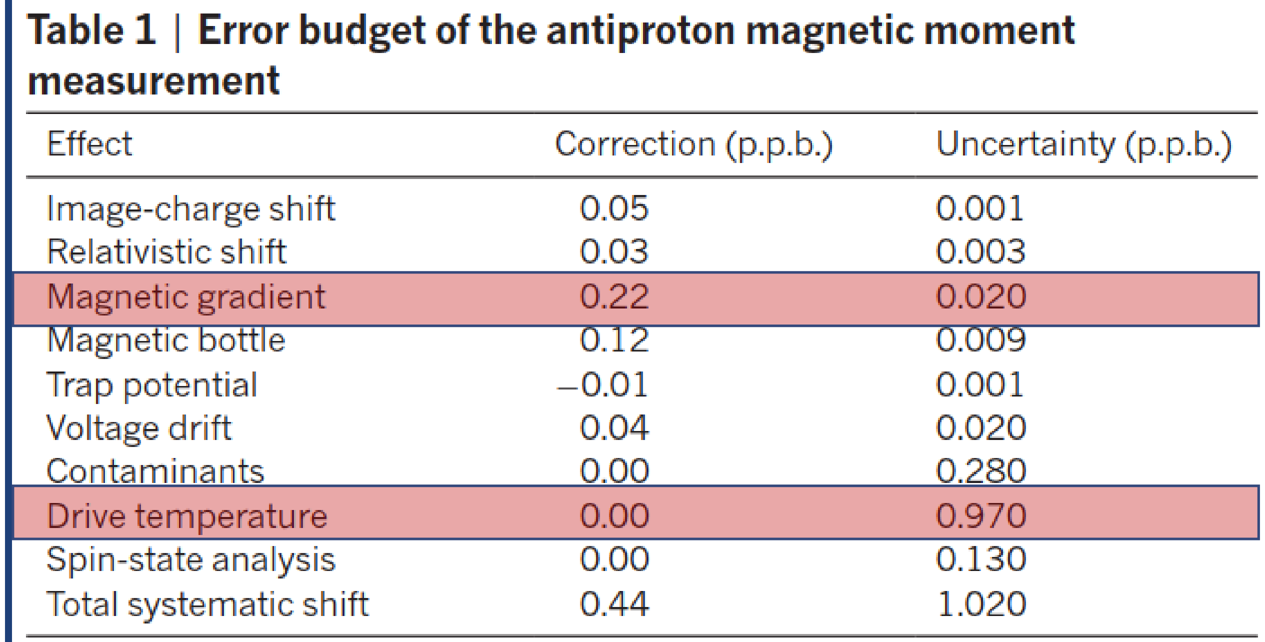
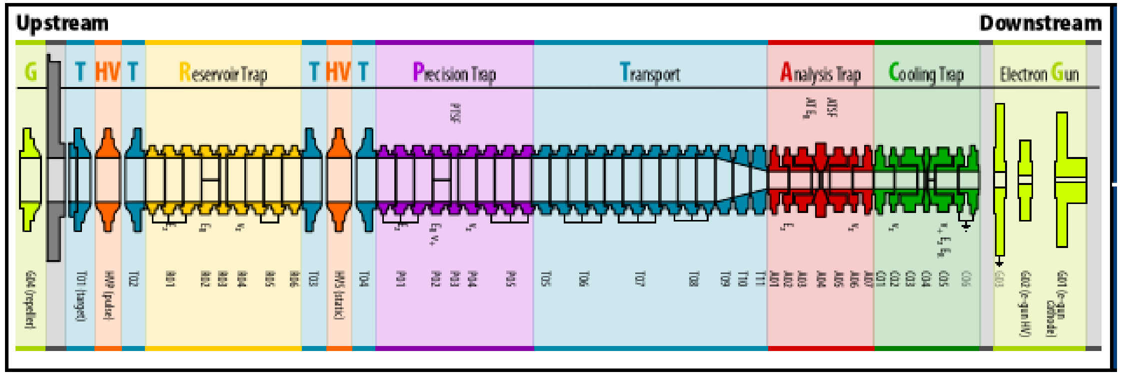


Table 1 | Error budget of the antiproton magnetic moment measurement

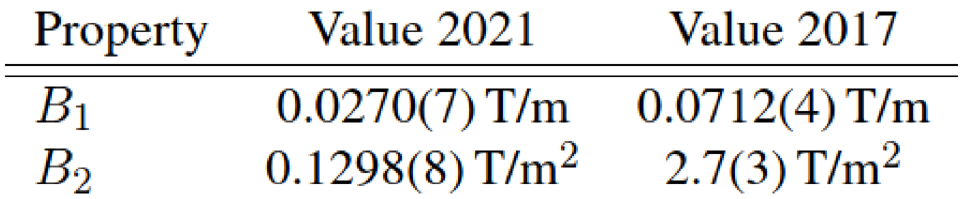
Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)
Image-charge shift	0.05	0.001
Relativistic shift	0.03	0.003
Magnetic gradient	0.22	0.020
Magnetic bottle	0.12	0.009
Trap potential	−0.01	0.001
Voltage drift	0.04	0.020
Contaminants	0.00	0.280
Drive temperature	0.00	0.970
Spin-state analysis	0.00	0.130
Total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



Property	Value 2021	Value 2017
B_1	0.0270(7) T/m	0.0712(4) T/m
B_2	0.1298(8) T/m^2	2.7(3) T/m^2

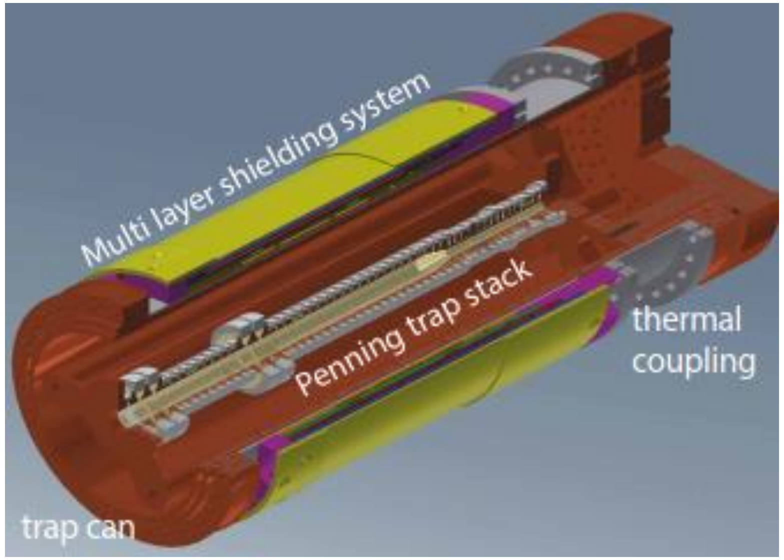
B1 improved by factor of 3.

B2 improved by factor of 20.

g-factor target precision of order 100 p.p.t. seems to be in reach (so far no show stoppers identified).

Dominant Systematic Trap – Uncertainty

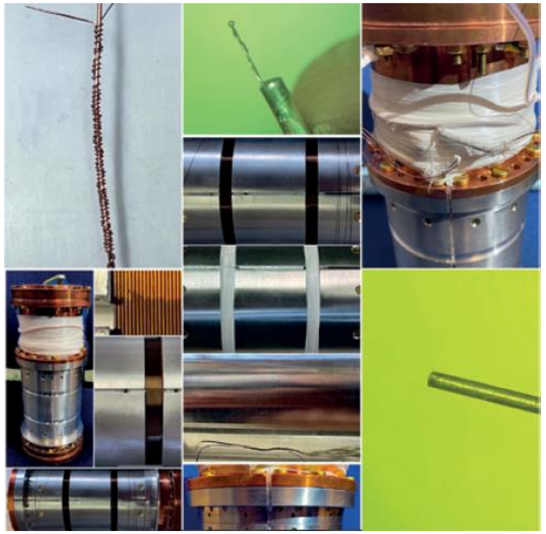
Designed and developed
in the BASE
development laboratory



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

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

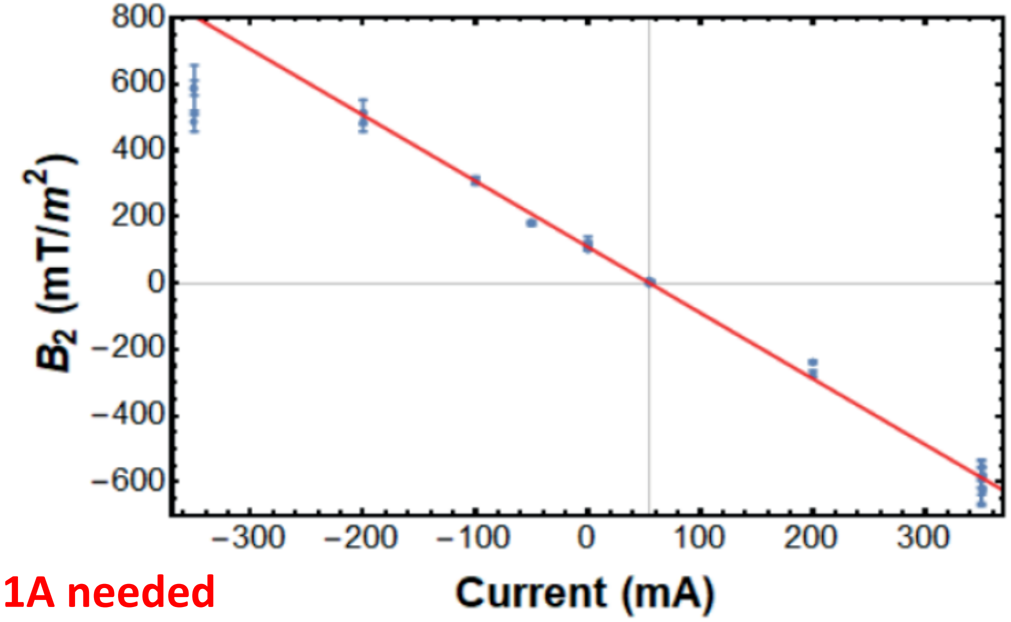
Need to get rid of this scaling in future runs -> local tuning magnets need to be implemented.



System running successfully in persistent mode.

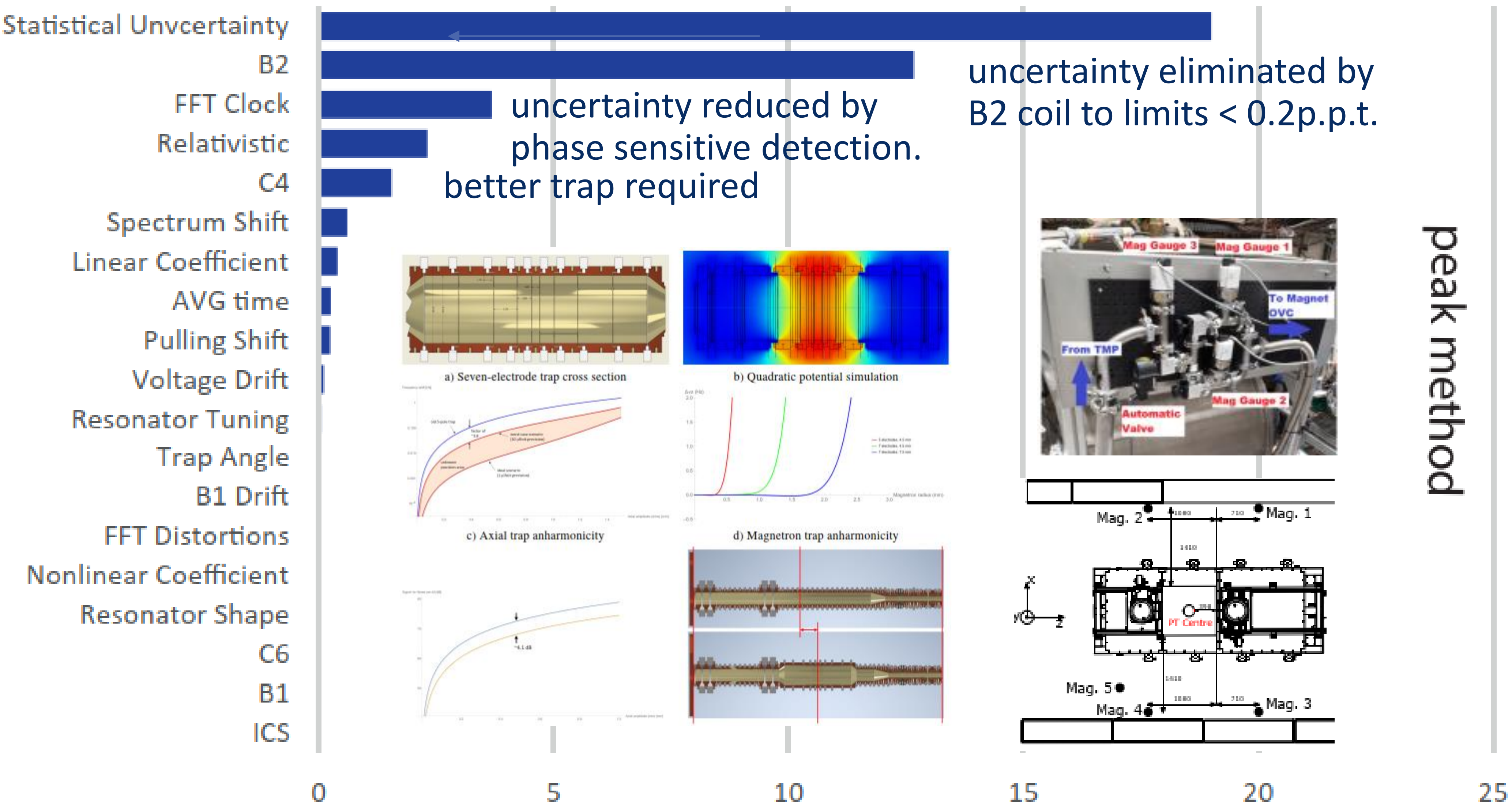
Able to tune the B2 coefficient to 0 within uncertainties of 0.00006mT/m^2

Reduces the dominant systematic uncertainty of Q/M ratio measurements by a factor of 90.



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

Explicit Error Budget



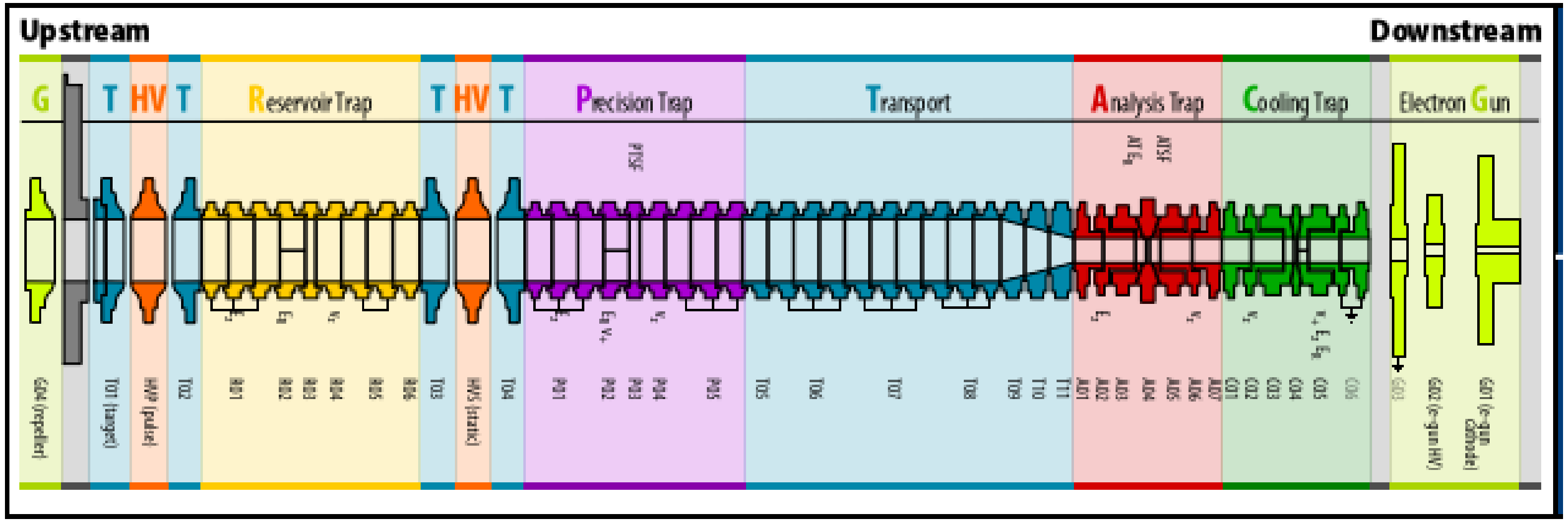
uncertainty reduced by
phase sensitive detection.

better trap required

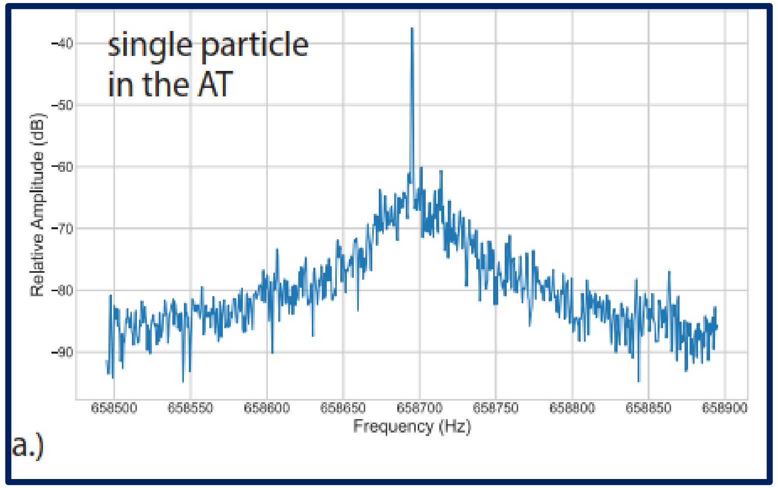
uncertainty eliminated by
B2 coil to limits < 0.2p.p.t.

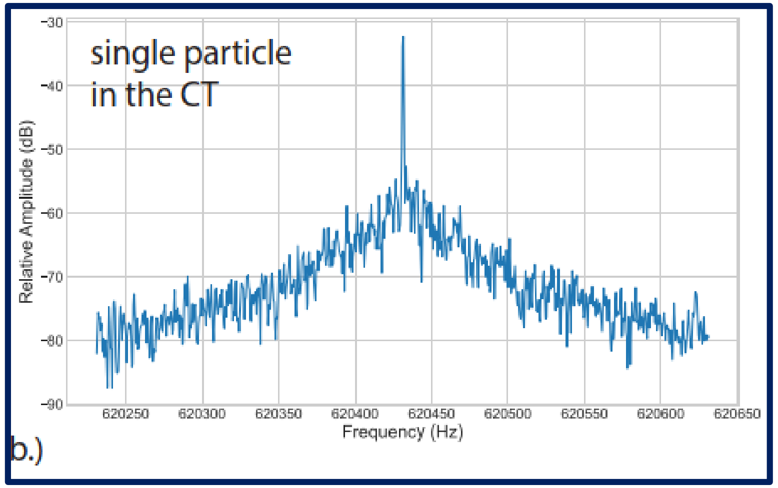
peak method

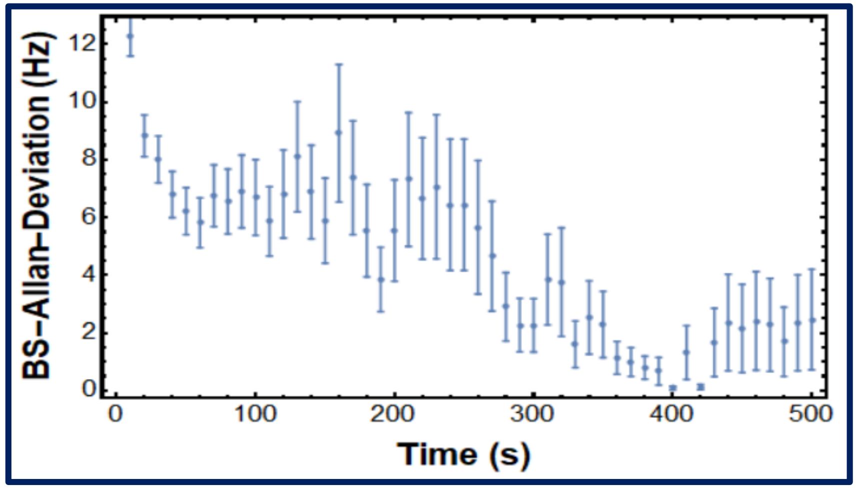
Current Status



- RT detector SNR limited
- Very successful commissioning of precision trap.
- Transport through trapstack established.
- Detected single particles in all four traps
- Further commissioning in progress.







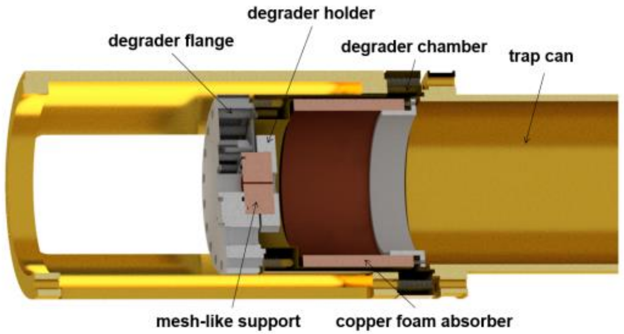
Small traps look in principle promising, but currently some frequency stability issues that have yet to be understood

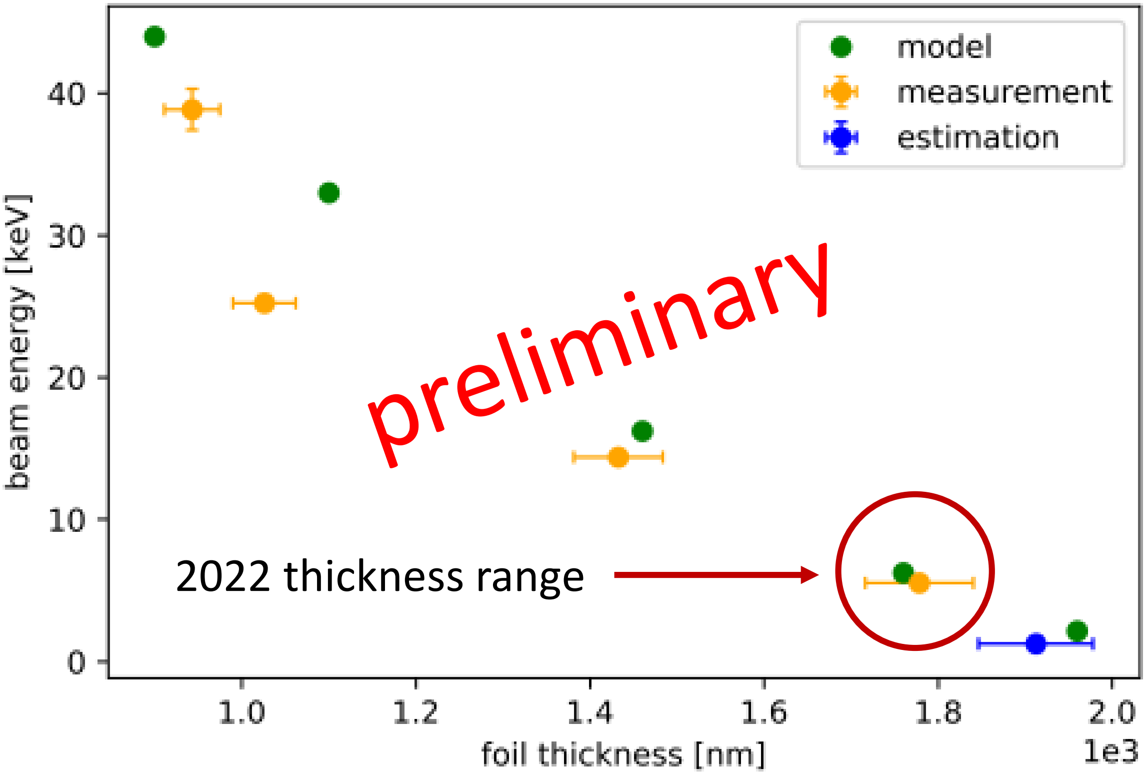
Studies of Antiproton Transmission Through Mylar

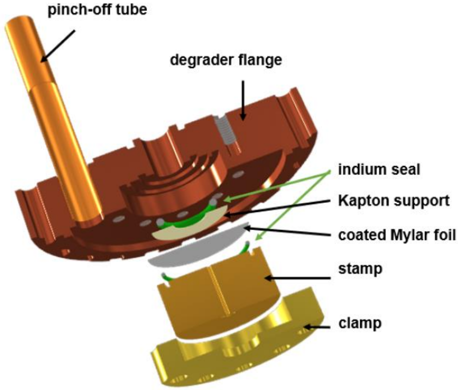
Did transmission measurements through different Mylar foils, to define ideal degrader geometry for the next run.
Unfortunately no antiprotons caught in 2021 (misalignment / obstacles / lack of time for upgrades)

Current understanding:

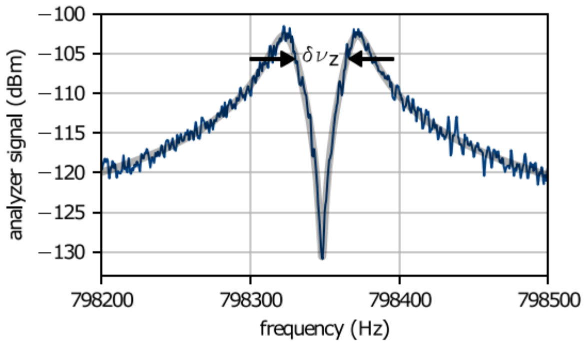
Likely chosen a slightly too conservative design for the antiproton injection.







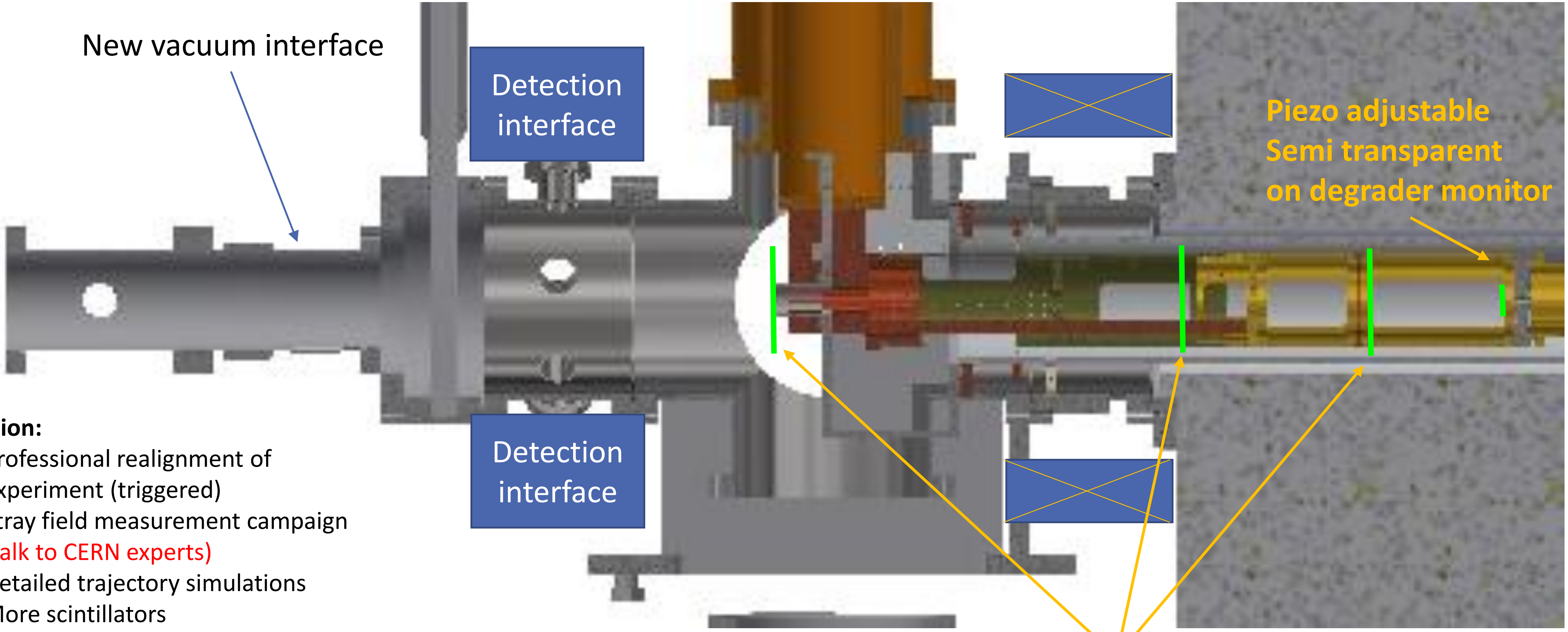
Design can be easily modified, we just didn't have enough time in the 2021 run.



Ideal foil for next run determined.
On trap operation will be tested during the shutdown.

Good news: trapping time indicates vacuum < $5*10^{-17}$ mbar

Upgraded Beamline Diagnostics / Under Development



Remote GV control

Injection solenoid

(not just a solenoid)

New vacuum interface

Detection interface

Detection interface

Piezo adjustable Semi transparent on degrader monitor

Faraday cup / aperture assemblies

Addition:

- Professional realignment of experiment (triggered)
- Stray field measurement campaign (talk to CERN experts)
- Detailed trajectory simulations
- More scintillators
- HV switch upgrade
- Optics
- More (working) scintillators

Recent Achievements – Sympathetic Cooling

- Magnetic moment measurements are limited by particle temperature and would be considerably accelerated by inventing a method beyond resistive cooling

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

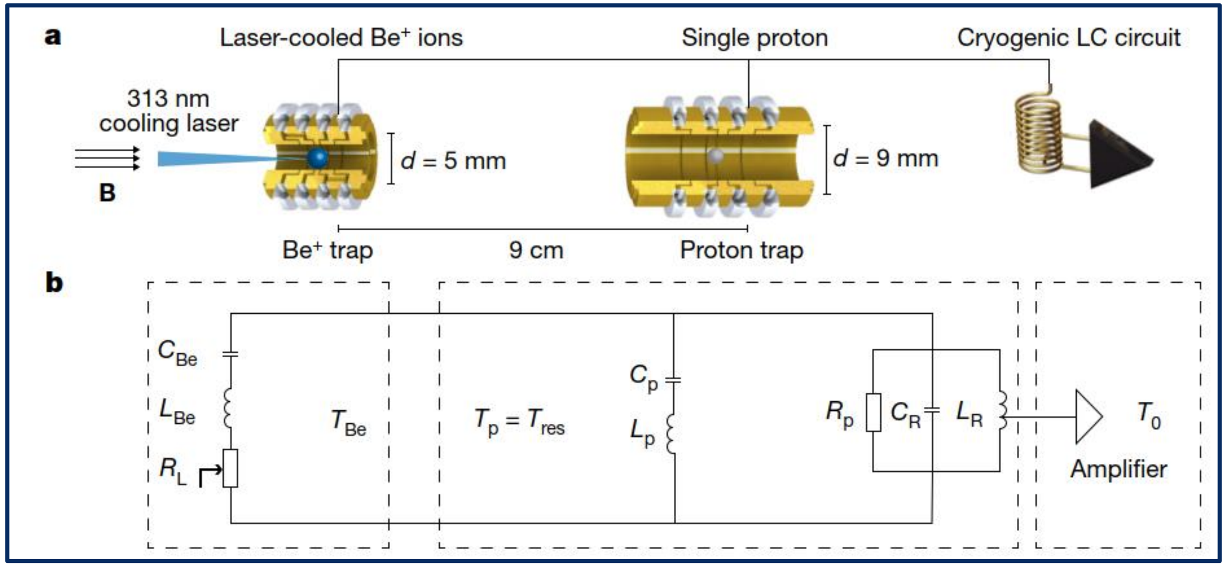
One of the particle types: Laser cooled species
Transfer particle temperatures from one trap to the other.

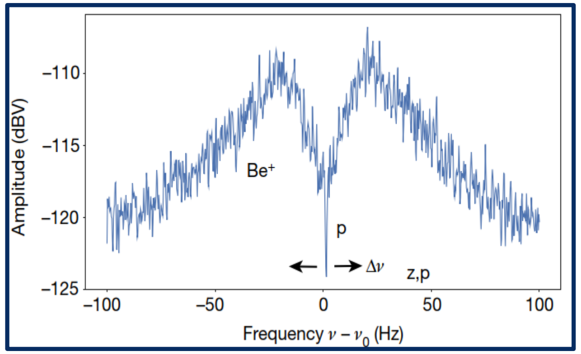
First proof of principle demonstration successful!!!

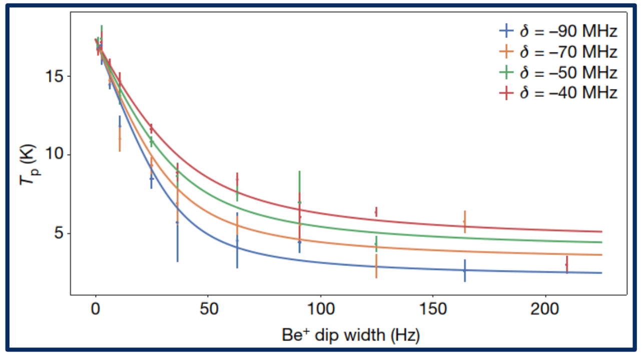
Demonstrated proton temperature reduction by about a factor of 8. (17.8(3.6)K -> 2.8(2.5)K)

New trap geometries under development for more efficient cooling.

Simulations: Optimized procedures will enable 20 mK temperatures in 10 s.





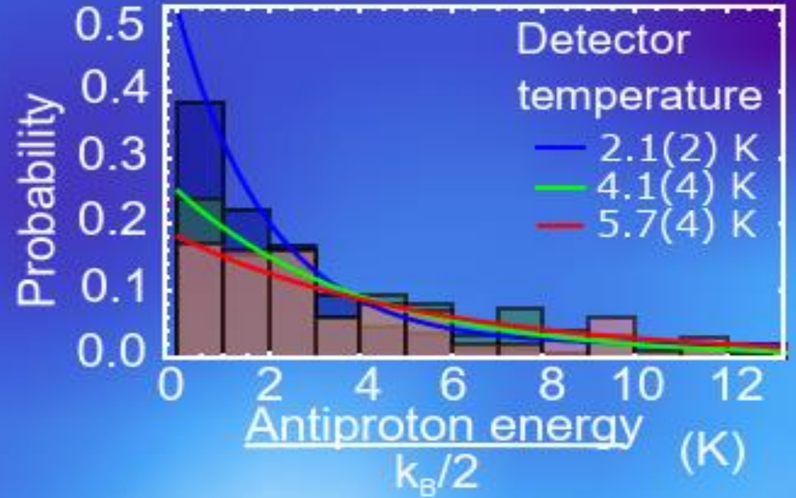


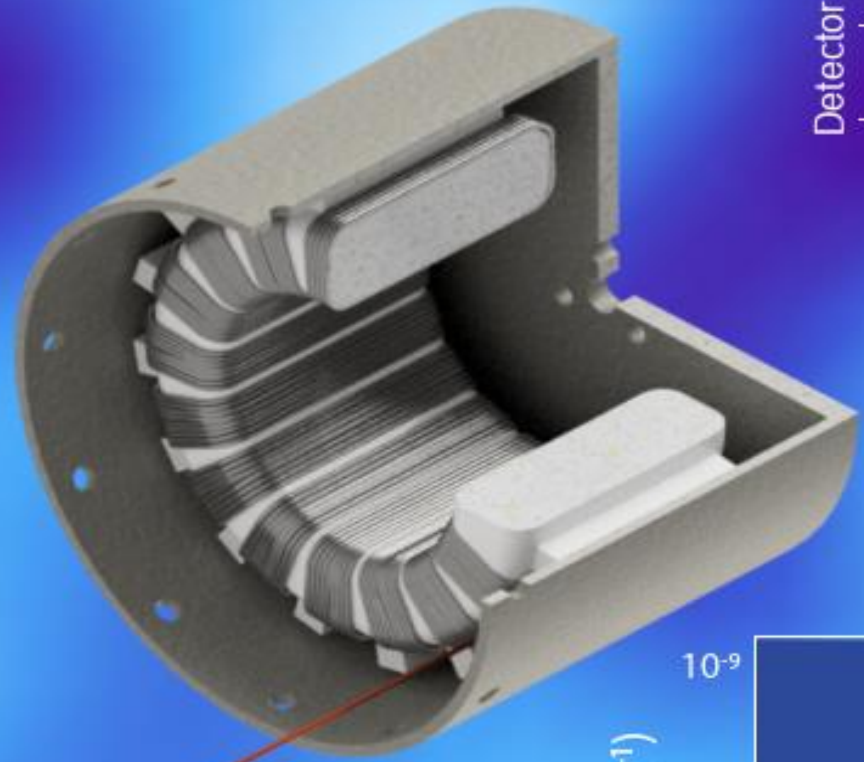
Bohman et al., Nature **596**, 514 (2021)
Will et al., arXiv 2112.04818 (2021)

Nice playground, a lot of work ahead

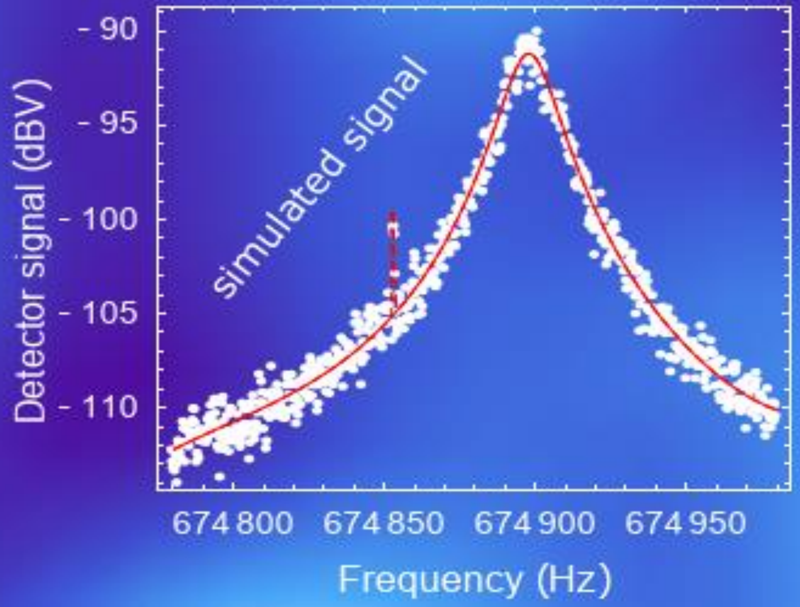
BASE CDM

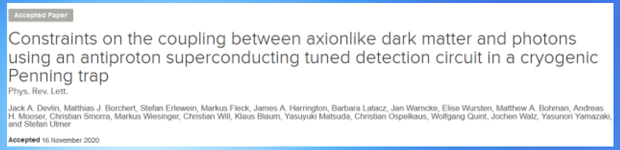
AXION SEARCH





calibrated with a trapped antiproton





Accepted Paper

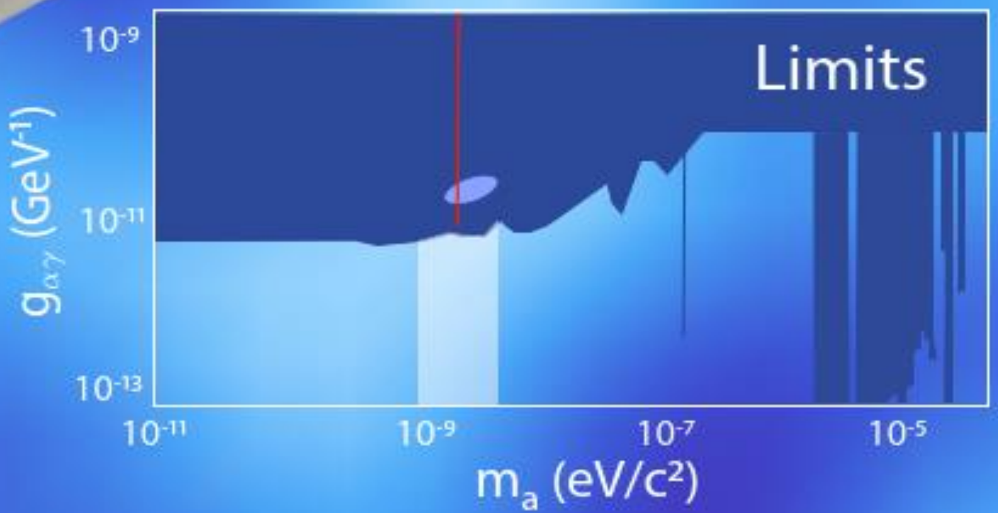
Constraints on the coupling between axionlike dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap

Phys. Rev. Lett.

Jack A. Devlin, Matthias J. Borchert, Stefan Erlewein, Markus Fleck, James A. Harrington, Barbara Latacz, Jan Warncke, Elise Wursten, Matthew A. Bohman, Andreas H. Mooser, Christian Smorra, Markus Wiesinger, Christian Will, Klaus Blaum, Yasuyuki Matsuda, Christian Ospelkaus, Wolfgang Quint, Jochen Walz, Yasunori Yamazaki, and Stefan Ulmer

Accepted 16 November 2020

https://journals.aps.org/prl/accepted/15071Y2dJe514a63281b1498fe4274156d3788acc

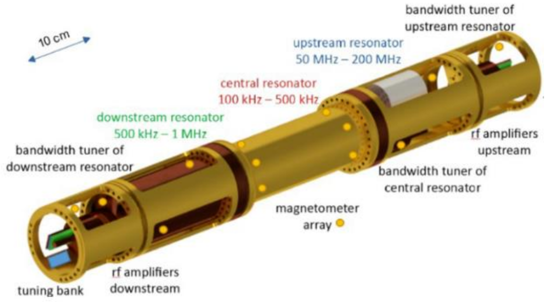


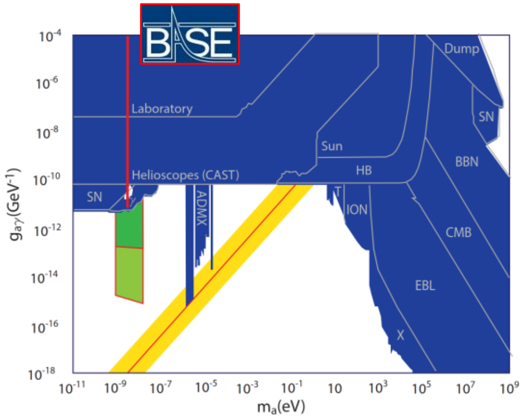
Detector Development

- With a purpose-built experiment we should be able to improve sensitivity considerably

$$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_{a\gamma}\sqrt{\nu_a \rho_a \hbar c_0} * \sqrt{\frac{f(Q)}{4k_B g(T_z)}}\sqrt{(\boldsymbol{r_2}-\boldsymbol{r_1})}(\boldsymbol{r_2}+\boldsymbol{r_1})^{3/2}\boldsymbol{B_e}$$

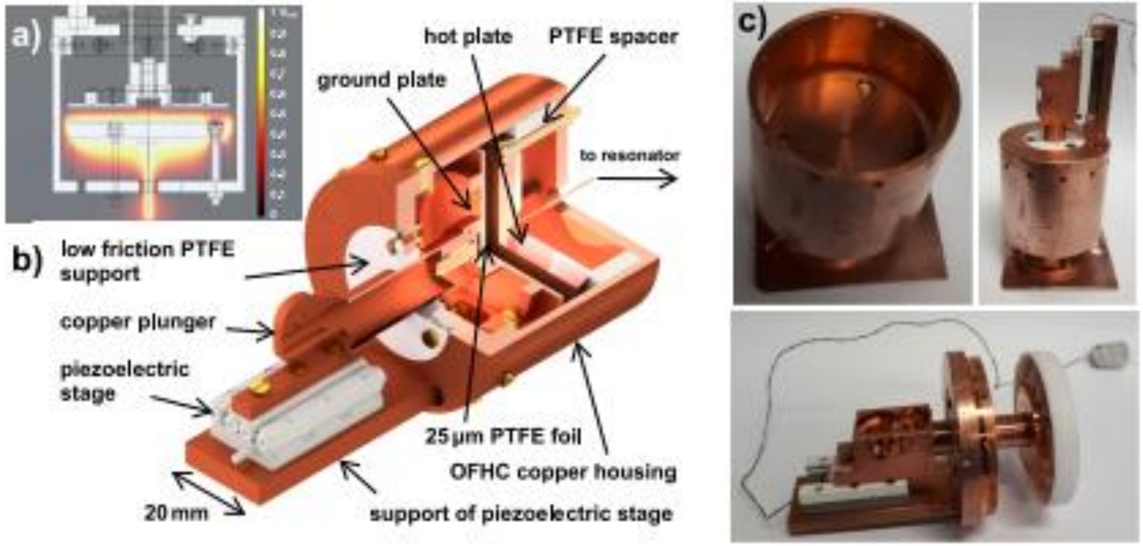
- Planned setup of new experiment BASE CDM



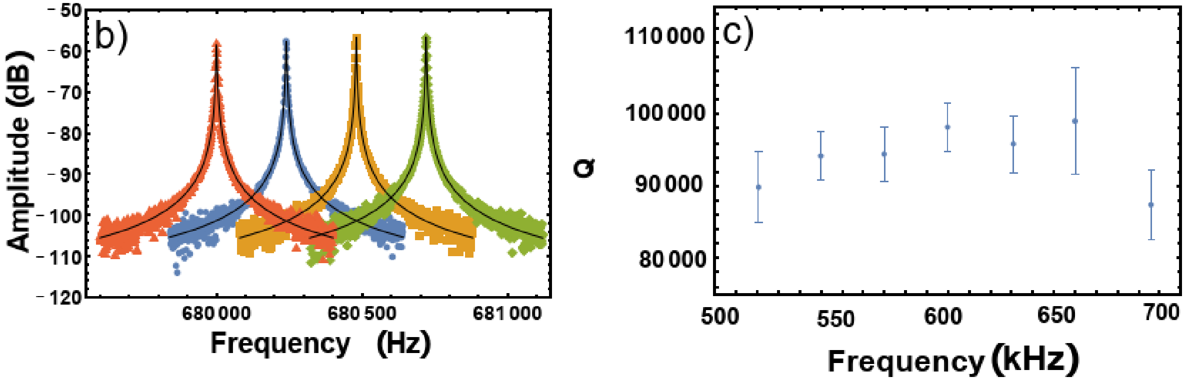


- Uses entire magnet volume. Sample whenever no pbars available.

Devlin et al., BASE, Phys. Rev. Lett. 126, 041301



First superconducting detector with such a high tuning range at such a high sensitivity

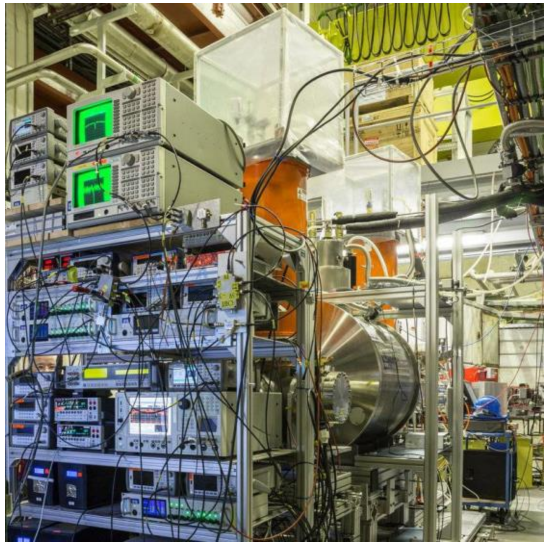


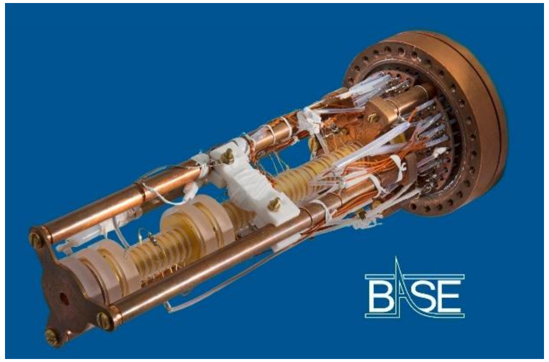
Will improve bandwidth of previous experiment by more than a factor of 1000.

Summary

- Very productive year for BASE
  - 16 ppt measurement of the antiproton-to-proton charge-to-mass ratio.
  - Demonstration of sympathetic cooling of a single trapped proton.
  - Rapid progress on developments of BASE-STEP and BASE-CDM.
  - Much improved experiment online with considerably improved trapping system that will enable magnetic moment measurements at the 100 p.p.t. level.
- Problems
  - Pbar trapping in the 2021 antiproton run was unsuccessful -> refined beamline, more beam monitors, injection coil, modified degrader setup.
  - B1 coil of the new tuning system requires an upgrade.
  - Optimization of small traps seems unusually difficult (work in progress).
- Other
  - Thanks very much to the AD-operators team, for excellent work with ELENA, strong support with any kind of problems, and pro-active approaches !
  - Congrats to ALPHA demonstrating laser-cooling of trapped antihydrogen!

Thanks for your attention





Support needed by CERN for BASE-STEP

- Office space for three team members of BASE-STEP working at CERN in Bat. 545.
- The antiproton injection beamline of BASE-STEP needs an ELENA ZQNA quadrupole unit. We discussed with W. Bartmann and it is possible to borrow in principle the deflector unit, but intellectual property rights need to be clarified.