Searches for exotic physics with antiprotons and protons in Penning Traps at BASE

Barbara Latacz

on behalf of the BASE collaboration

RIKEN, Japan

19 / 11 / 2021

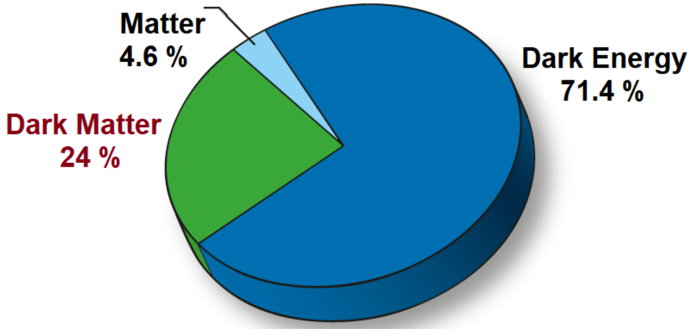
BASE Baryon/Antibaryon Symmetry Experiment

Standard Model of Particle Physics

Naive Expectation	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000

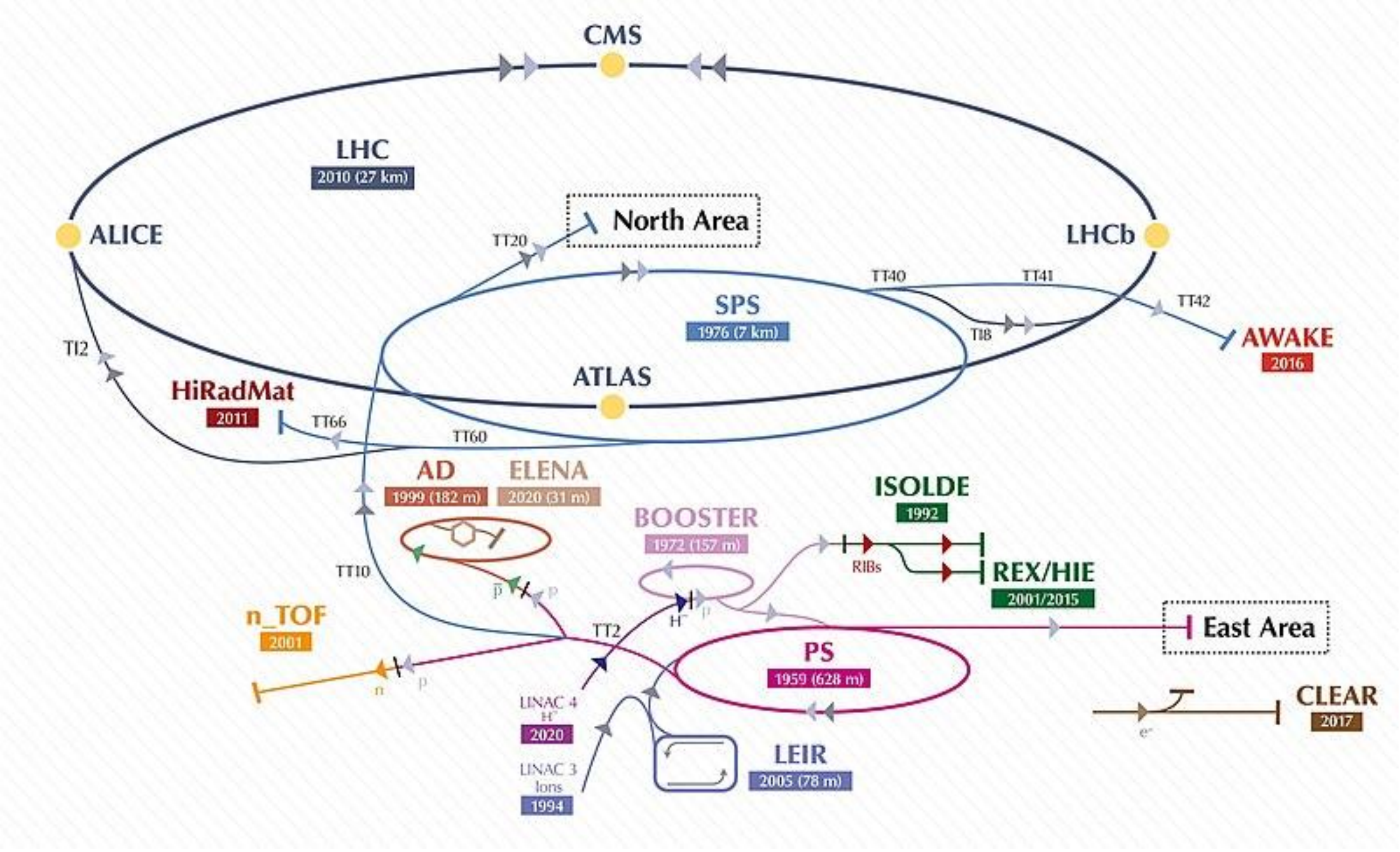
- A. Sakharov presented possible solutions in 1967 . According to his work, the matter-antimatter asymmetry could be explained by simultaneously occurring three conditions:
  - violation of baryon number;
  - C and CP symmetry violation;
  - lack of thermal equilibrium in the expanding Universe (or direct CPT violation).



CPT violation? → **Comparison of fundamental properties of matter/antimatter conjugate system**

Baryon/Antibaryon Symmetry Experiment

- **CERN-AD:** Measurement of (RIKEN):
  - → **proton/antiproton q/m ratio**
  - → **magnetic moment of the antiproton and**
  - → **cold dark matter searches**

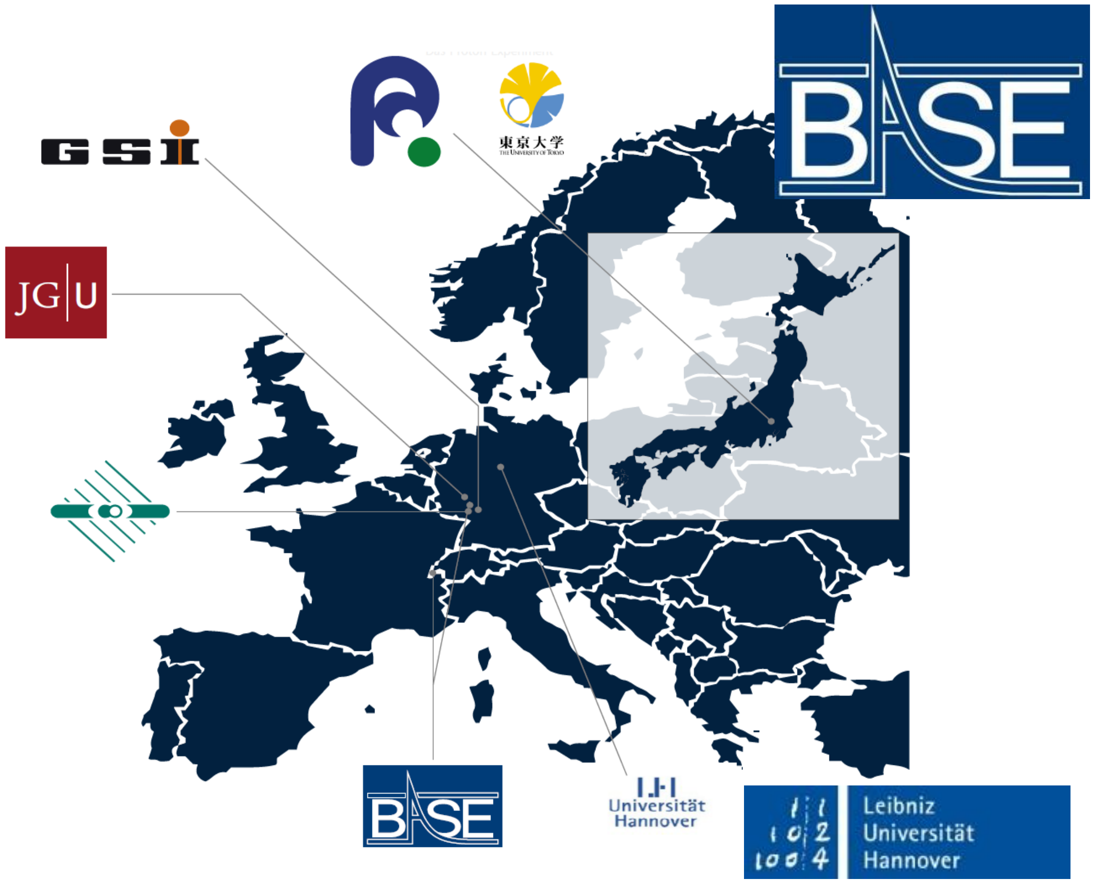


BASE Collaboration

- **CERN-AD:** Measurement of (RIKEN):
  - → proton/antiproton q/m ratio
  - → magnetic moment of the antiproton and
  - → cold dark matter searches
- ○ Core members: **Stefan Ulmer**, Jack Devlin, Barbara Latacz, Peter Micke, Elise Wursten, Matthias Borchert, Stefan Erlewein, Markus Fleck, Julia Jaeger, Gilbertas Umbrazunas, Frederik Voelksen

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies (RIKEN/MPG)
- ○ Core members: **Christian Smorra**, Fatma Abbass, Matthew Bohman, Markus Wiesinger, Daniel Popper, Christian Will

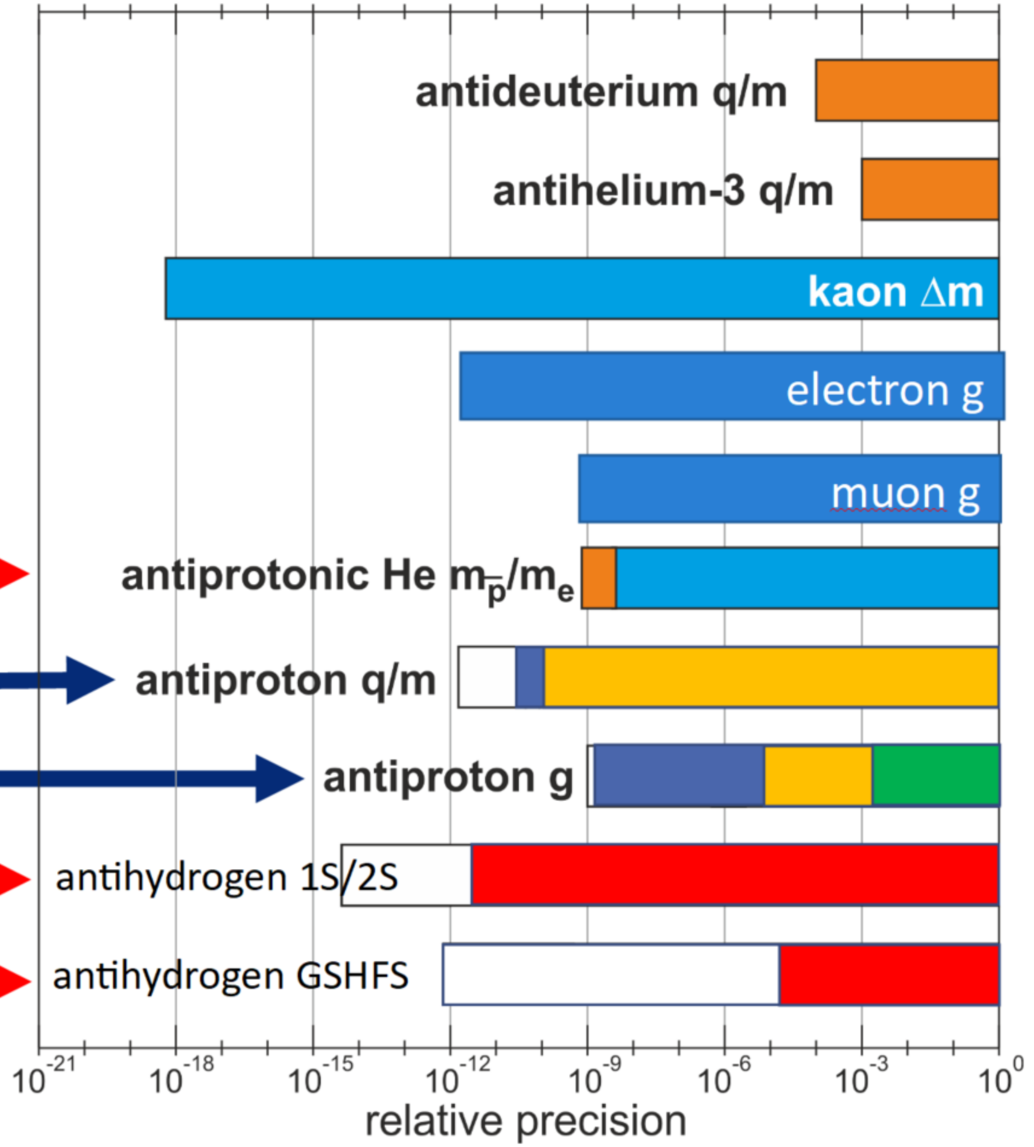
- **Hannover/PTB:** QLEDS-laser cooling project, new technologies. (RIKEN/PTB/UH)
- ○ Group leader: **Christian Ospelkaus**



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

CPT with particle/antiparticle comparisons

Planned



CERN ALICE

CERN AD

R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabriesle et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **586**, doi:10.1038/s41586-018-0017 (2018).

-> Absolute energy resolution normalized to m-scale.

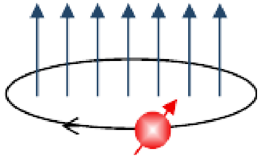
Single particle measurements in Penning Traps

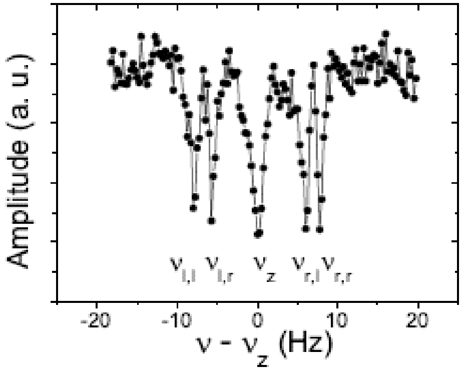
High precision mass spectroscopy

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

Cyclotron Motion

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





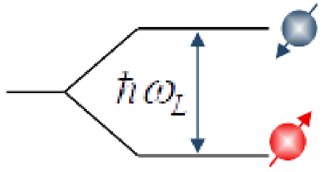
- **69 ppt comparison of the antiproton-to-proton charge-to-mass ratio**, S. Ulmer, Nature 524, 196-199 (2015). **New result comming soon!**

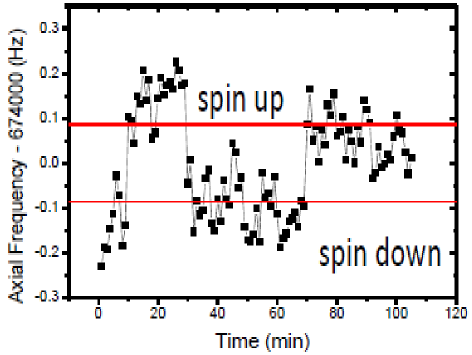
High precision magnetic moment measurements

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

Larmor Precession

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





- **1.5 p.p.b. Measurement of antiproton magnetic moment,** C. Smorra, Nature 550, 371-374 (2017)

Penning trap

- **Penning trap with:**
  -> radial confinement: $\vec{B} = B_0 \hat{z}$

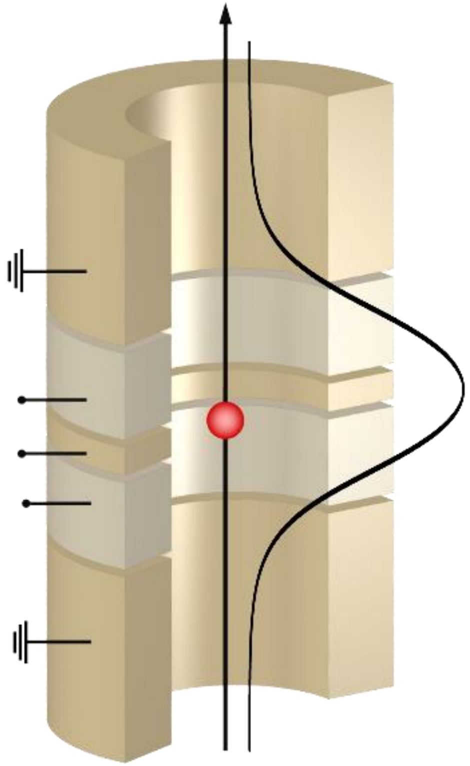
  -> axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

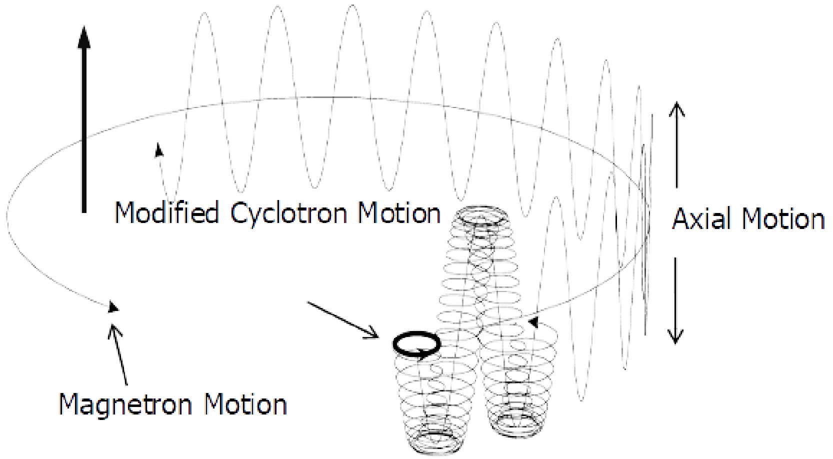
- **Invariance theorem:**

Cyclotron frequency of a particle

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2} \longleftrightarrow \nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

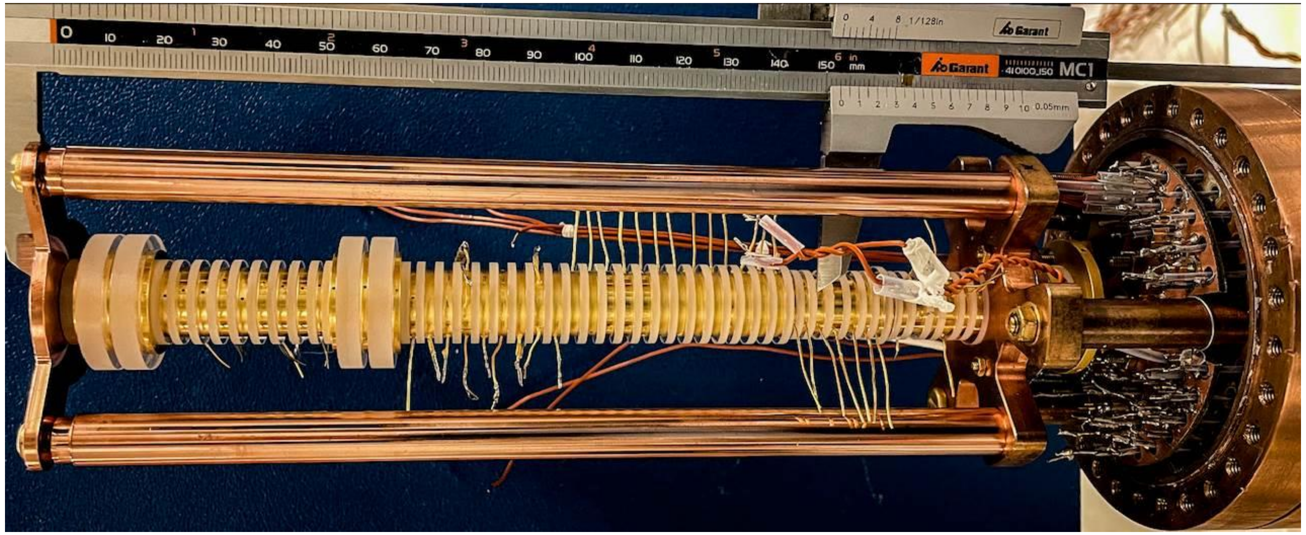
which is correct also for any small angle misalignment of the trap or quadratic imperfections of the field (G. Gabrielse)!

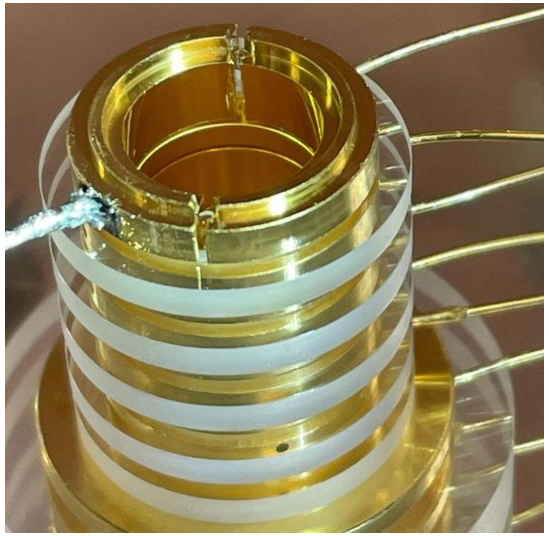


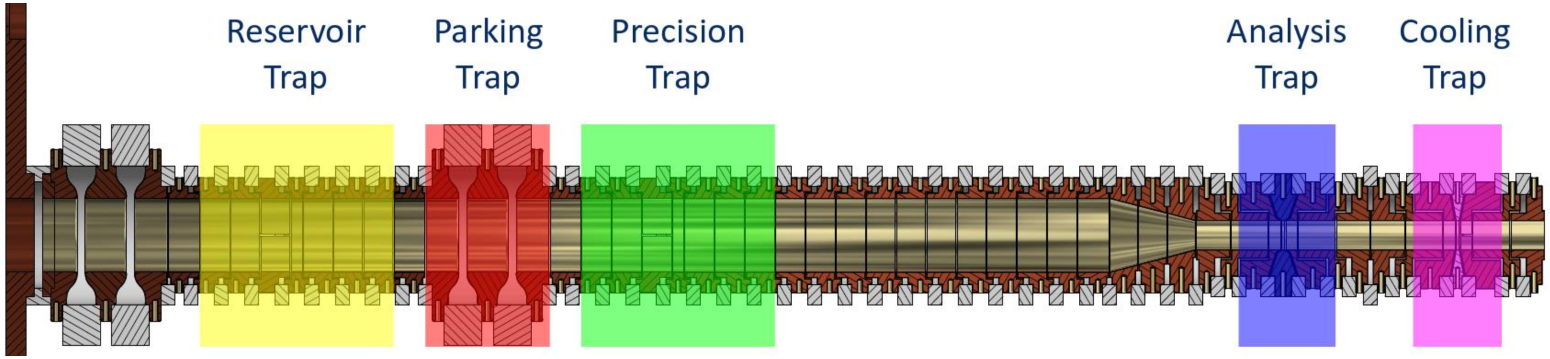


Axial	680 kHz	$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}$
Magnetron	8 kHz	$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
Modified Cyclotron	28.9 MHz	$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$

BASE Trap Stack







Reservoir Trap

Parking Trap

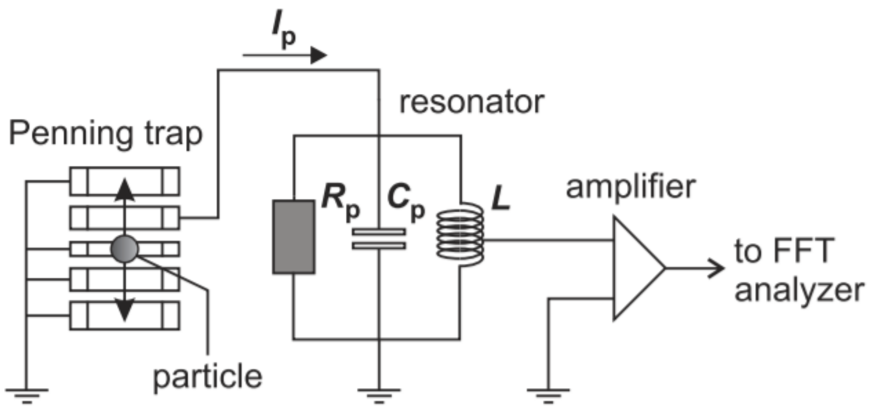
Precision Trap

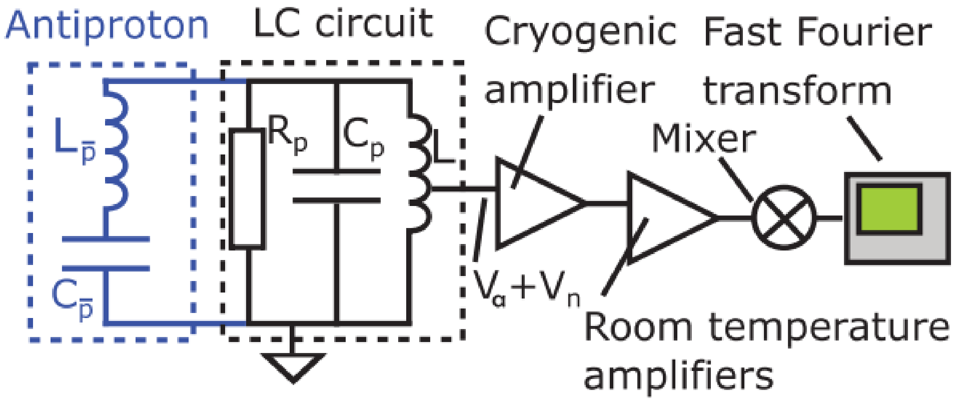
Analysis Trap

Cooling Trap

Frequency Measurements

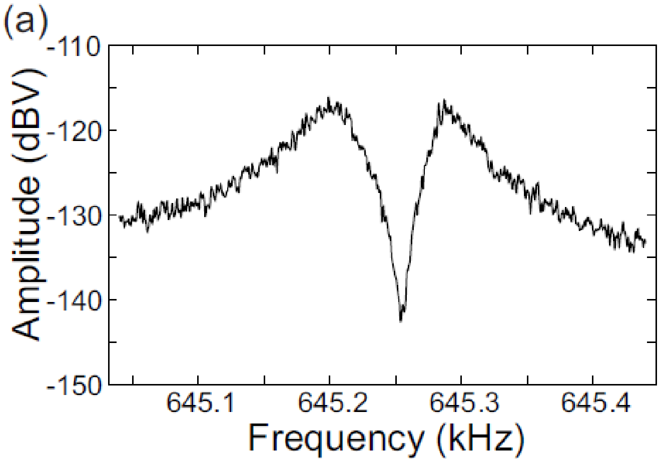
- Measurement of tiny image currents induced in trap electrodes

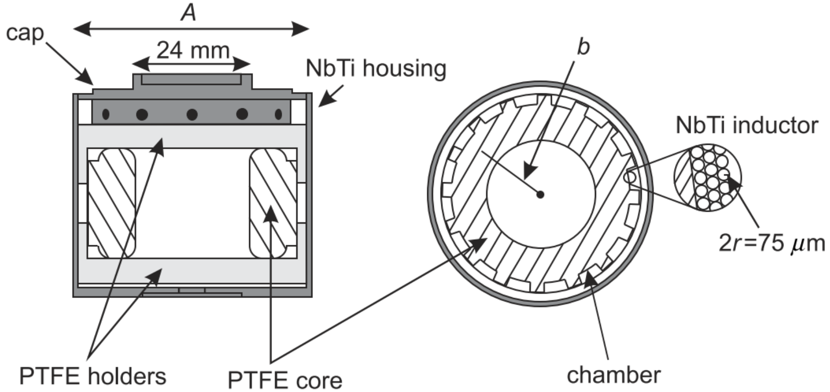




- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip -> number of particles

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^{2} \cdot N$$



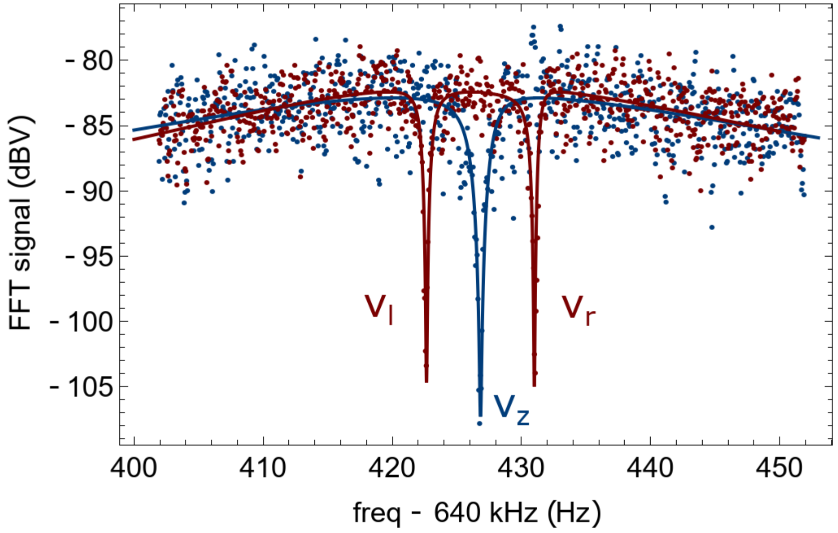


Cyclotron frequency measurement

- **„Simple" measurement, with main systematics coming from magnetic field stability**

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

- **Sideband method (5.5 ppb in 2016 scatter):**
  - -> axial dip spectrum: υ_z
  - -> sideband radio-frequency drive at $\upsilon_{rf} \approx \upsilon_+ - \upsilon_z$
  - -> double dip spectrum: $\upsilon_+ = \upsilon_{rf} + \upsilon_l + \upsilon_r - \upsilon_z$
  - -> megnetron mode: $\upsilon_- \approx \upsilon_z^2/(2\upsilon_+)$



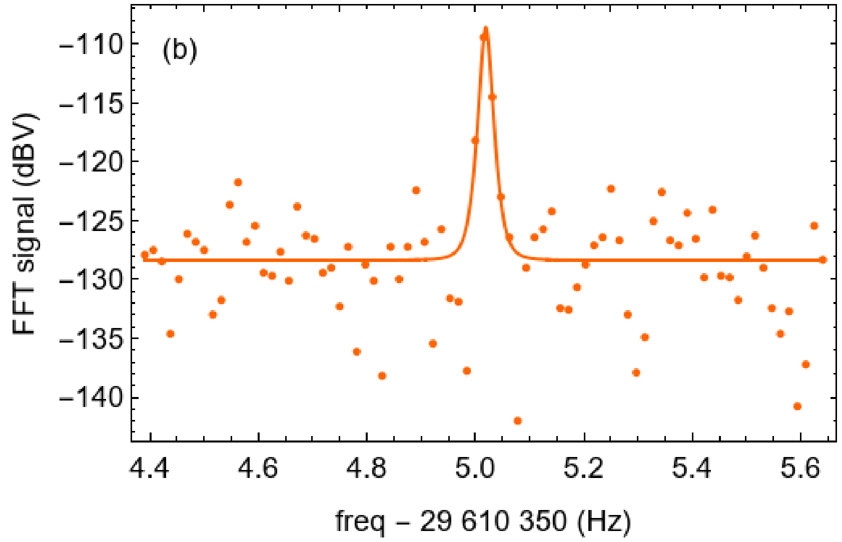
Main uncertaintity: spectrum shift.

- **Peak method:**

-> direct detection of the modified cyclotron frequency using specially designed cyclotron detector

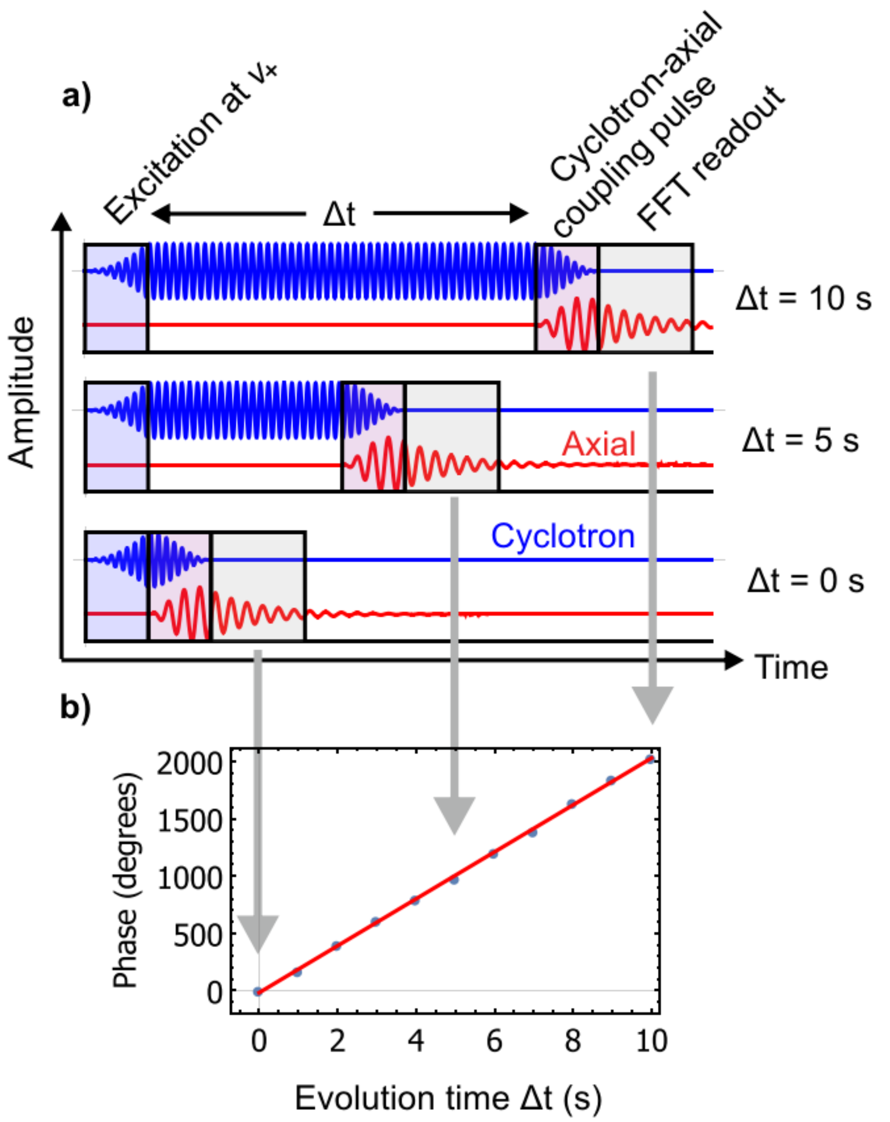
$$\Delta\nu_{+,z} = \nu^*_{+,z} - \nu_{+,z} = \mathcal{M}_{+,z}(B_2, C_4, \mathrm{SR}) \times E_+$$

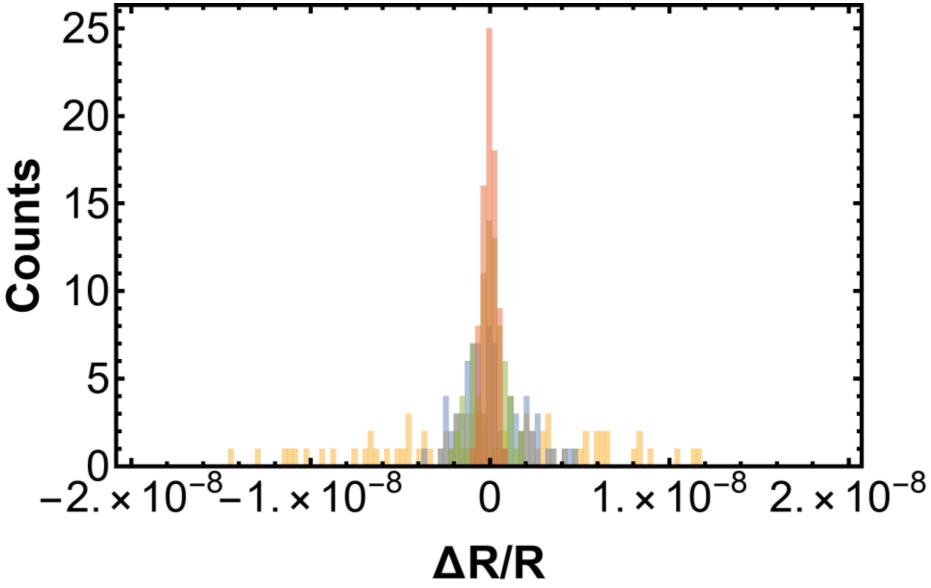
Main uncertaintity: magnetic field stability.



Cyclotron frequency measurement

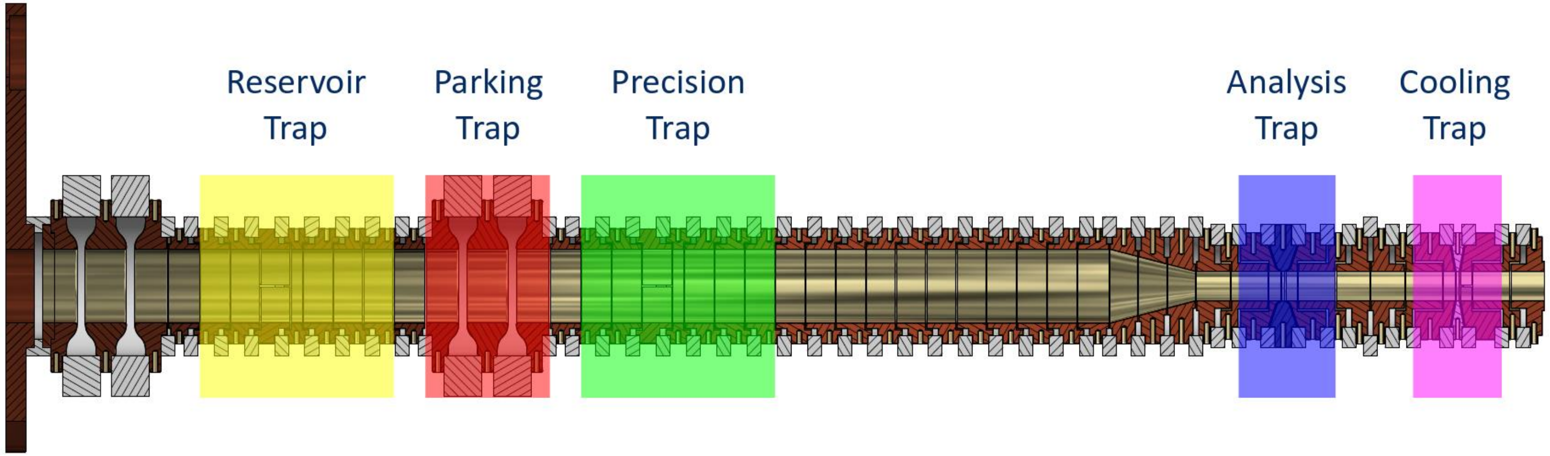
- **In 2019, we implemented a new phase method** with which we reached even the frequency scatters for protons on the order of 280(20) p.p.t. at a shot-to-shot sampling rate of 1/(265 s)
- **20 p.p.t. / 24h , but only possible during accelerator shutdown**
- Eric A. Cornell, et al. PRL, 63(16):1674–1677, 1989.
  Sven Sturm, et al. PRL, 107(14):143003, September 2011.





New trap stack

2021:



Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$.
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Cooling Trap: Fast cooling of the cyclotron motion.
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.

Magnetic shielding and shimming system

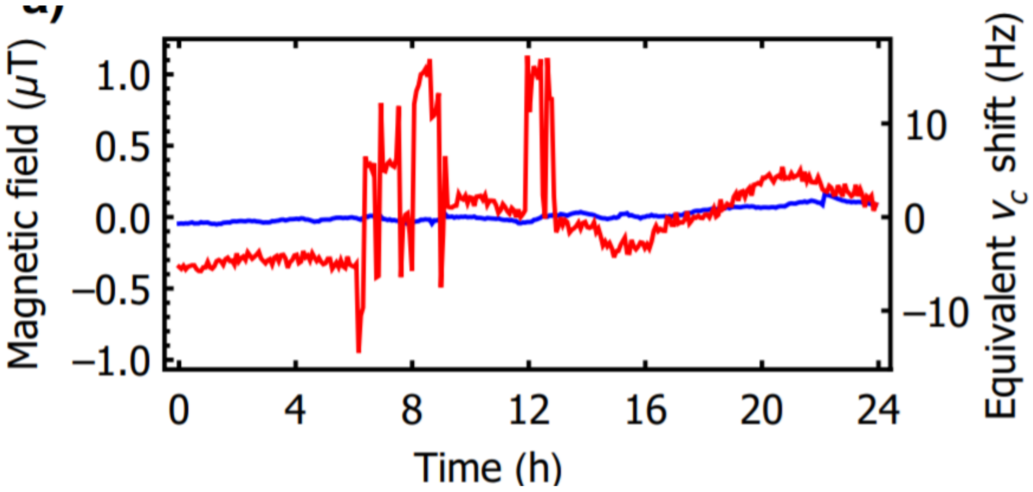
- **Magnetic shielding** -> necessary to decrease fluctuations caused by the Antiproton Decelerator and other experiments.
- In 2018 it supressed the magnetic field flactuations by up to 225(16).
- **Magnetic shimming**

  -> a system of superconducting coils to compensate residual B2 and B1:

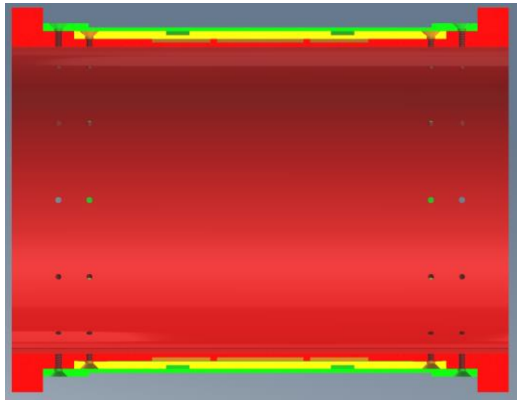
  -> B0 coil to be able to change B2 and B1 without changing v_+.
- Residual B2 originating from AT magnetic bottle:

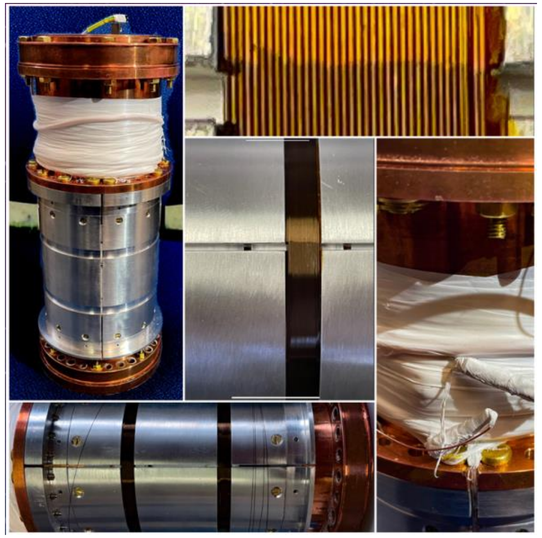
  AT: B2 = 261 569 T/m2

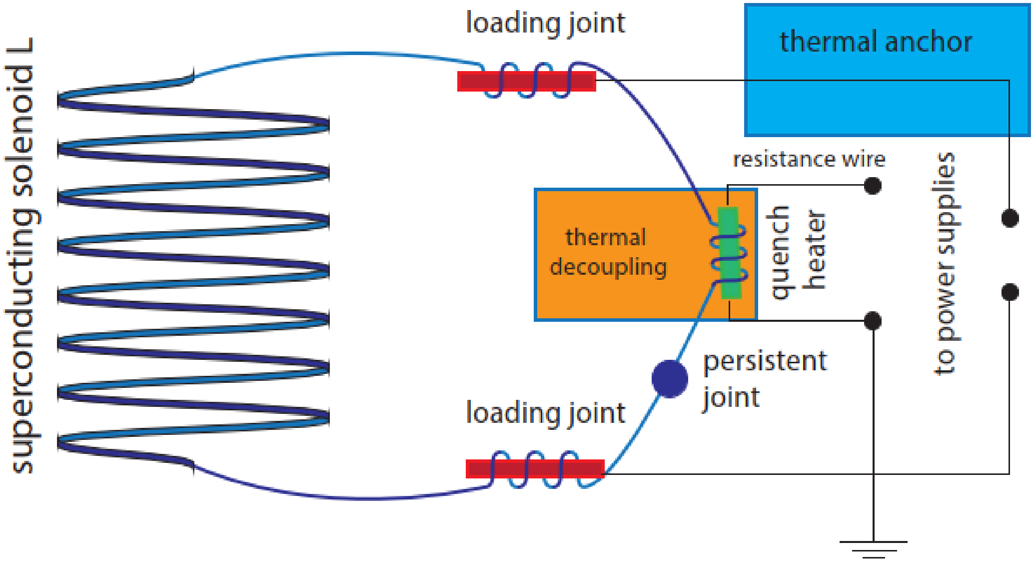
  PT: B2 = 0.316 T/m2



J. A. Devlin et. al., Phys. Rev. Applied 12, 044012 (2019).





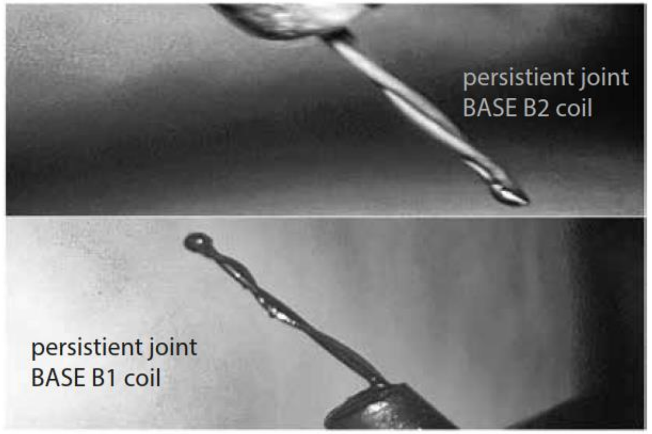


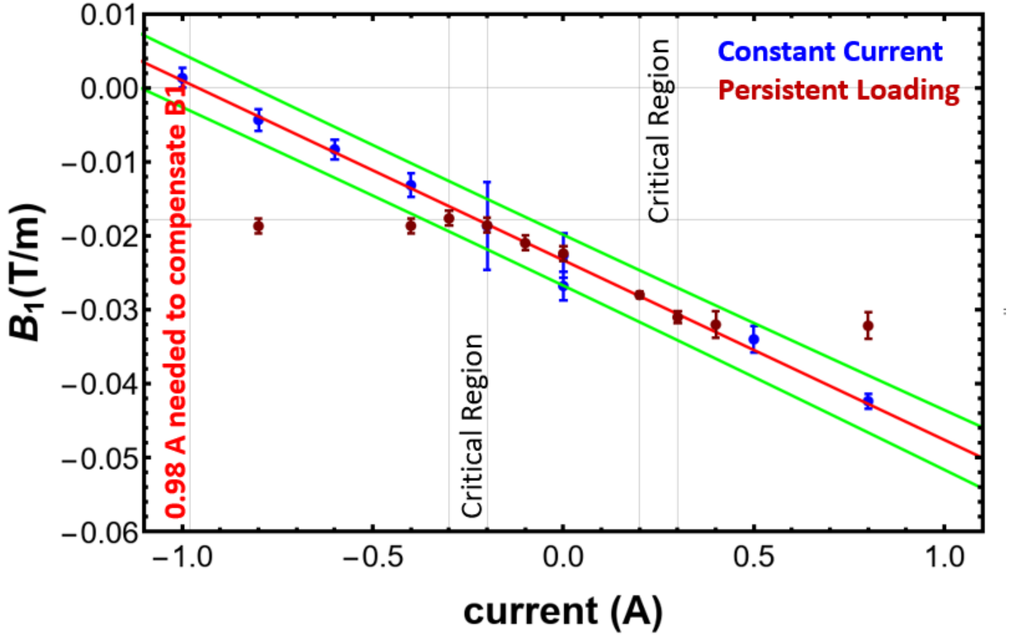
Shimming system – comparison

- Gradients improved by a factor of 2.9 (B1) and 22 (B2) -> systematic shift reduced by a factor of 22!

Coefficient	Value 2016
B0	1.945XXX
B1	71.2(4)mT/m
B2	2.7(3) T/m^2

Coefficient	Value 2021	Simulation (MF)
B0	1.945XXX	XXX
B1	24.3(2.5)mT/m	30.4 mT/m
B2	0.122 (11) T/m^2	0.3599 T/m^2





Charge to mass ratio measurements

- Charge to mass ratio for antiprotons and protons:

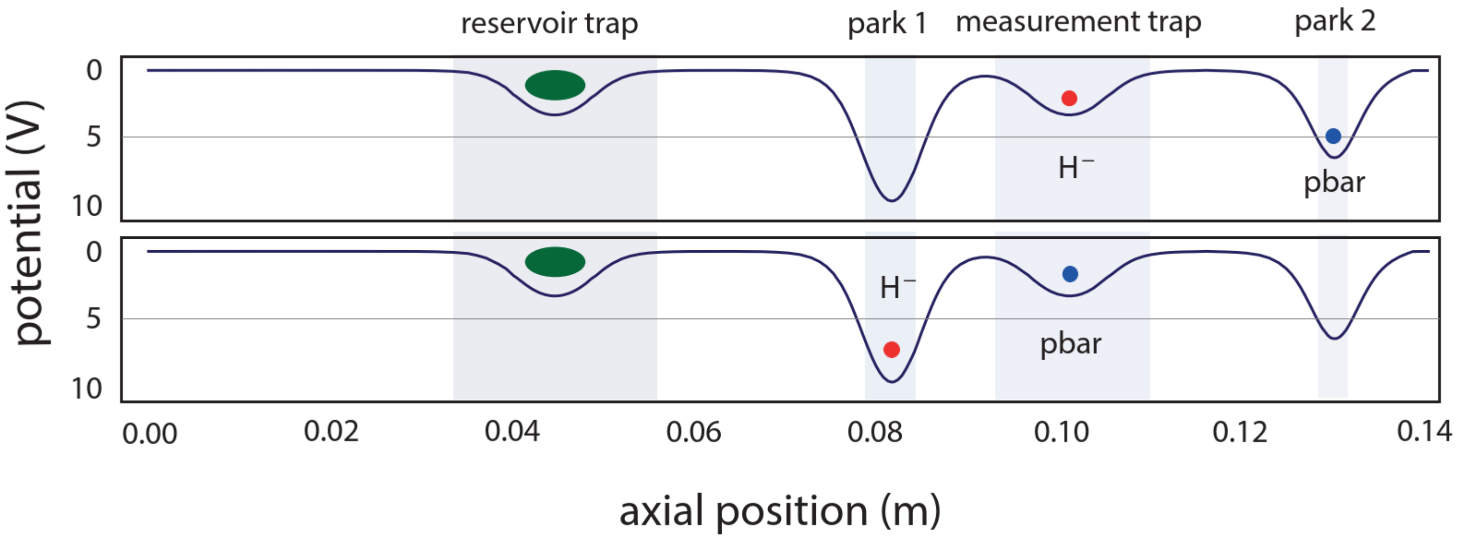
$$R = \frac{\nu_{c,pbar}}{\nu_{c,H^-}} = \frac{(q/m)_{pbar}}{(q/m)_{H^-}}$$

where

$$m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p}\right)$$

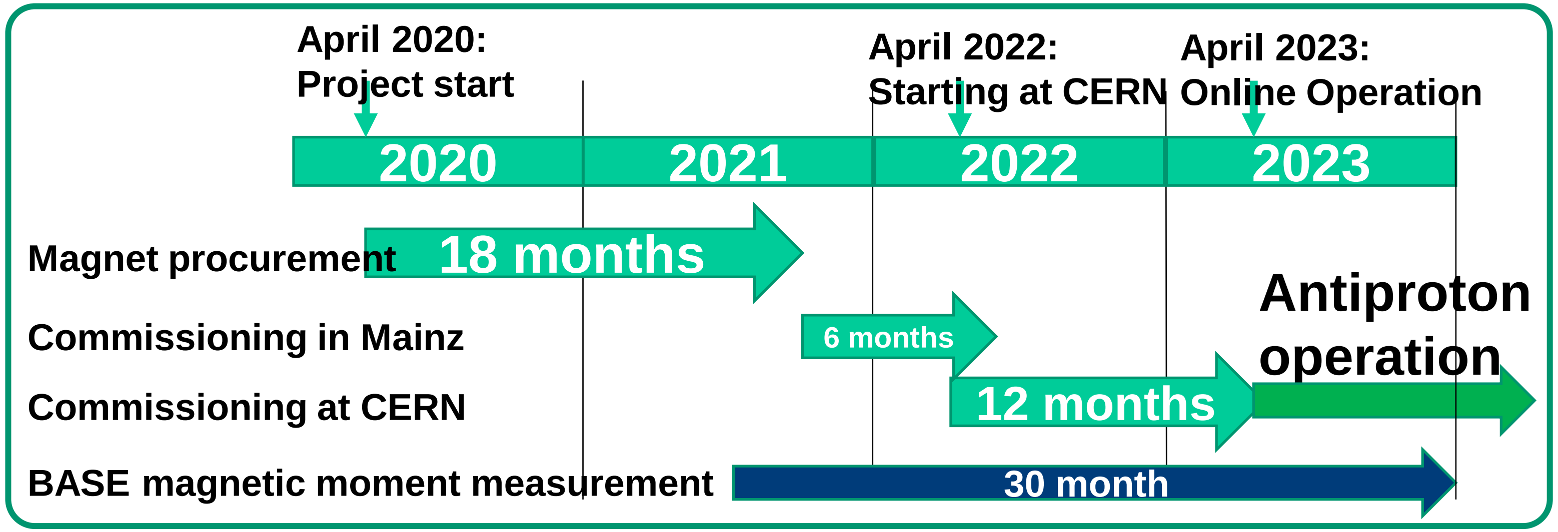
We use H^- as a proxy for a proton to avoid flipping the voltages in the trap => reduction of the systematic uncertainties by a factor of 300.

- First Measurement: S. Ulmer, et al., Nature 524, 196 (2015).



AD noise problems? - BASE STEP

- Project by Christian Smorra – ERC Univ. Mainz



April 2020:
Project start

April 2022:
Starting at CERN

April 2023:
Online Operation

2020	2021	2022	2023

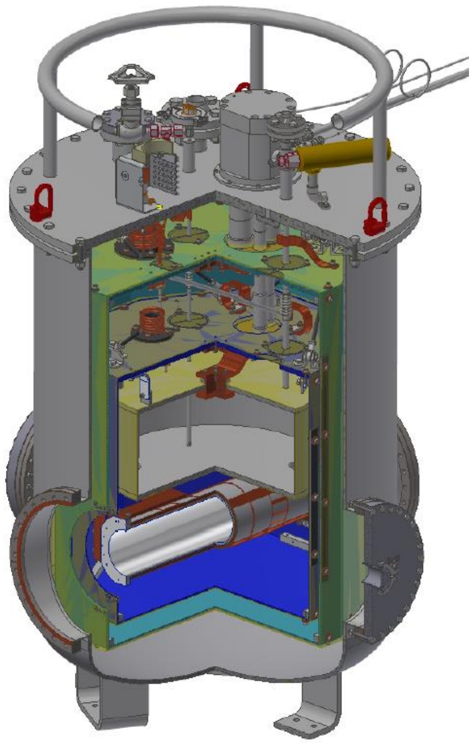
Magnet procurement – 18 months

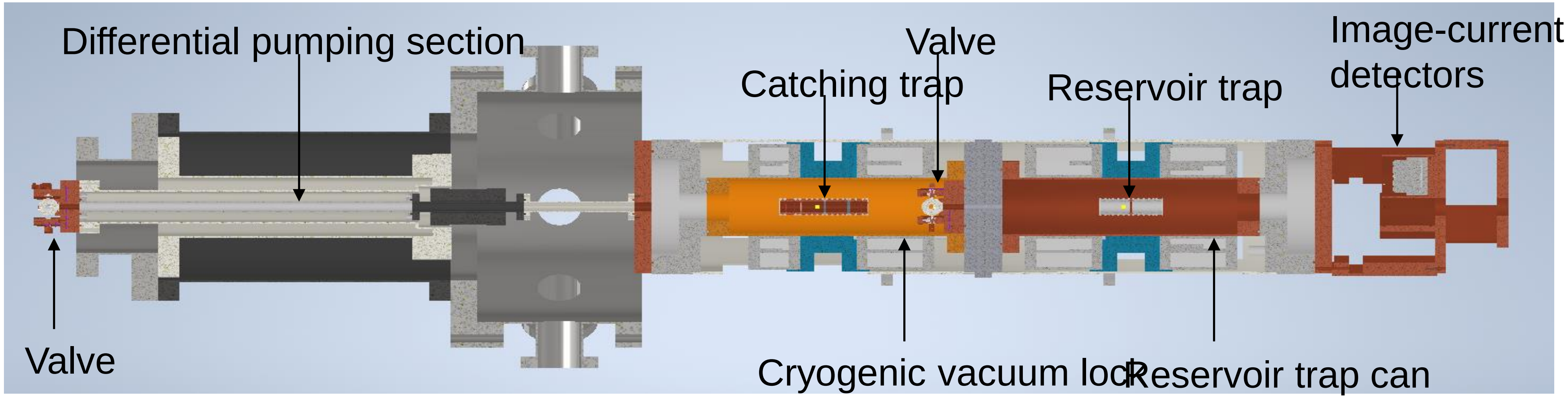
Commissioning in Mainz – 6 months

Commissioning at CERN – 12 months

Antiproton operation

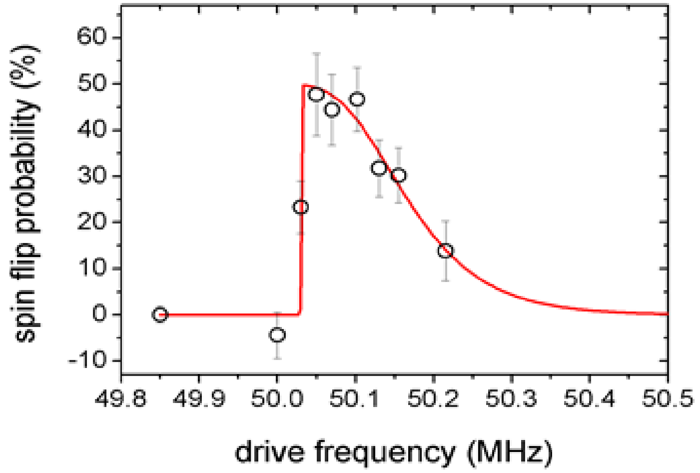
BASE magnetic moment measurement – 30 month





Larmor frequency

- **To resolve the Larmor Frequency one has to measure the spin flip probability as a function of drive frequency.**
- **First observed proton spin flip: S. Ulmer, PRL 106(25):253001.**

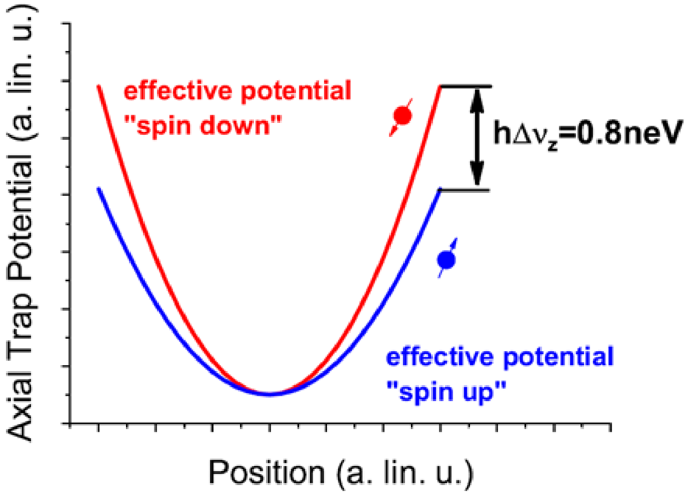


- Energy of magnetic dipole in magnetic field: $\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$
- The B2 magnetic field correction:

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

adds a spin dependent quadratic axial potential so **the Axial frequency becomes function of spin state** $(\alpha_p \approx \alpha_e - 10^{-6})$

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



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

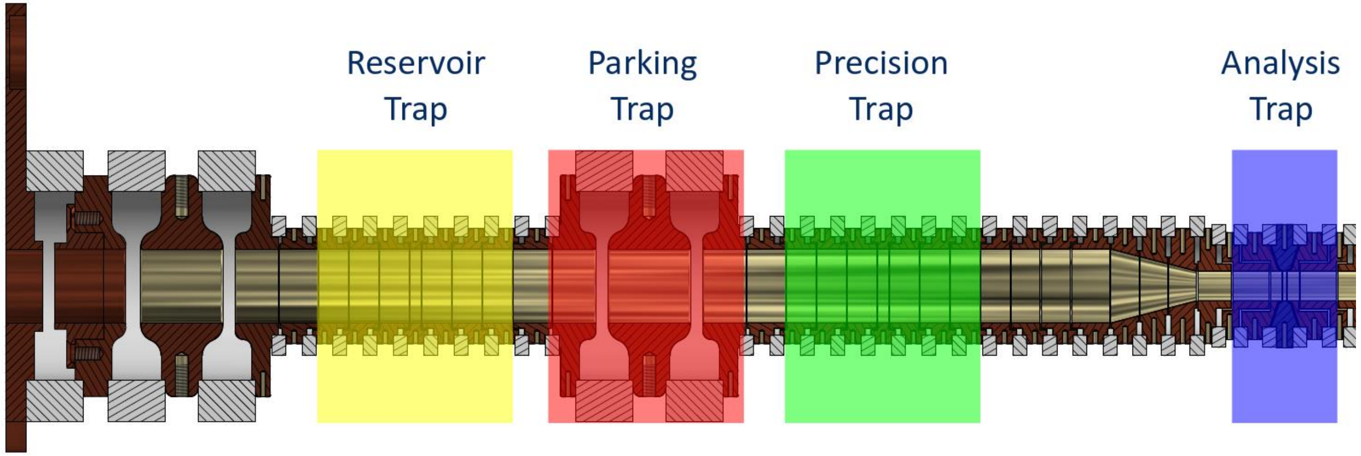
- In order to resolve the change of the spin state we need extremly high B2 (axia frequency about 700 kHz):

$$B_2 \sim 300000\, T/m^2 \Longrightarrow \Delta\nu_z \sim 170\, mHz$$

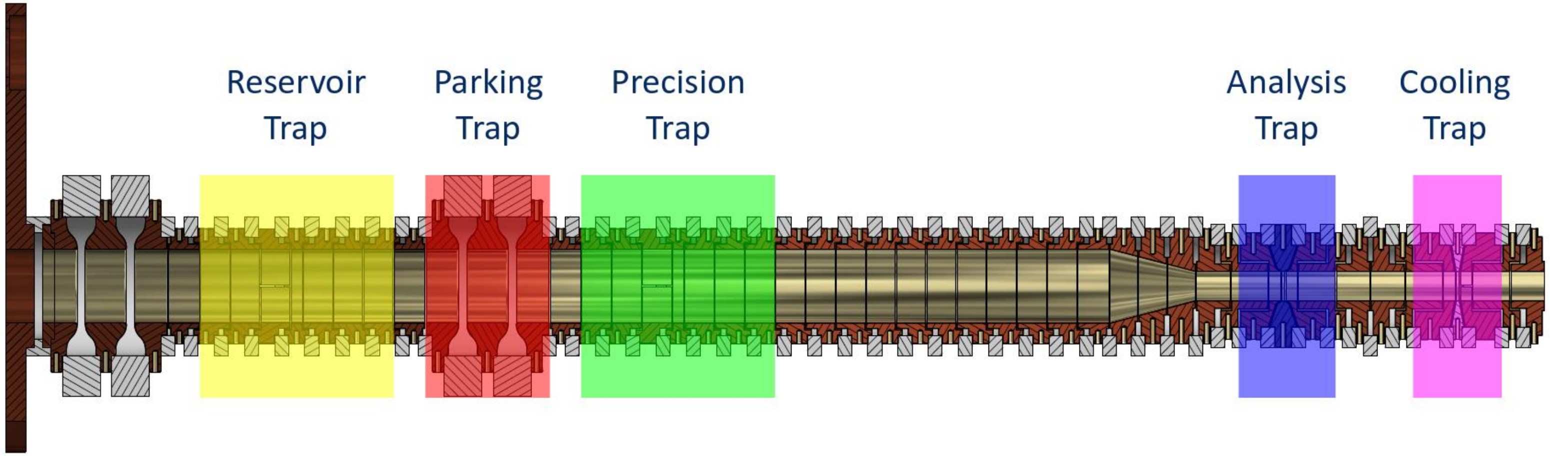
- Most extreme magnetic conditions ever applied to single particle.

New trap stack

2017:



2021:



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Larmor frequency – experimental problems

- Radial quantum jumps shift the axial frequency:

$$\Delta\nu_z(n_+,n_-,m_s) \;=$$

$$\frac{h\nu_+}{4\pi^2 m_{\mathrm{p}}\nu_z}\frac{B_2}{B_0}\cdot\left(n_+ + \frac{1}{2} + \frac{\nu_-}{\nu_+}\left(n_- + \frac{1}{2}\right) + \frac{g_{\mathrm{p}} m_s}{2}\right)$$

where **cyclotron quantum jump** induce about **~70mHz** (70 neV) shift, while **spin flip ~170 mHz**.

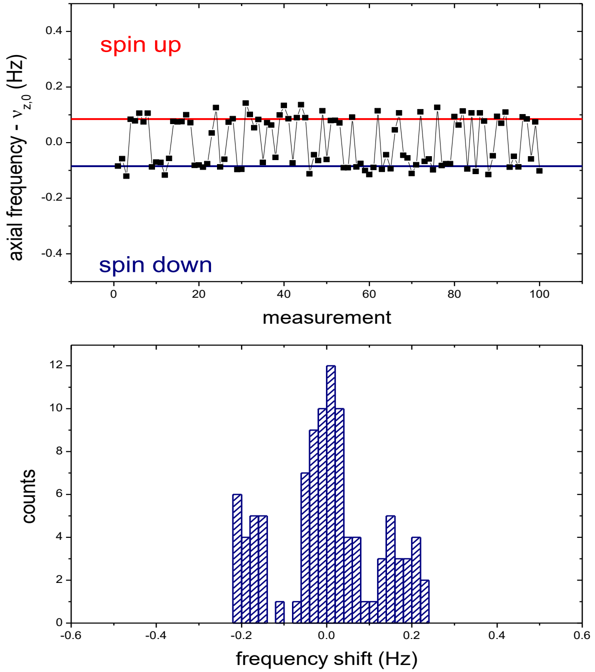
- Tiny heating of the radial mode results in significant fluctuations of the axial frequency.
- Measurement of the cyclotron frequency heats the particle!
- In one trap the g factor measurement is limited to ppm level.

High B2 → ν_L

Low B2 → ν_c

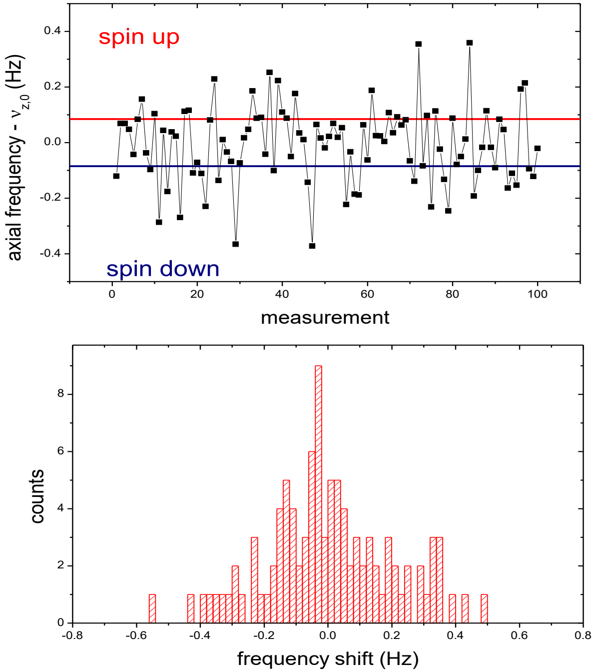
$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

cold particle (50mK)



high-fidelity spin state resolution

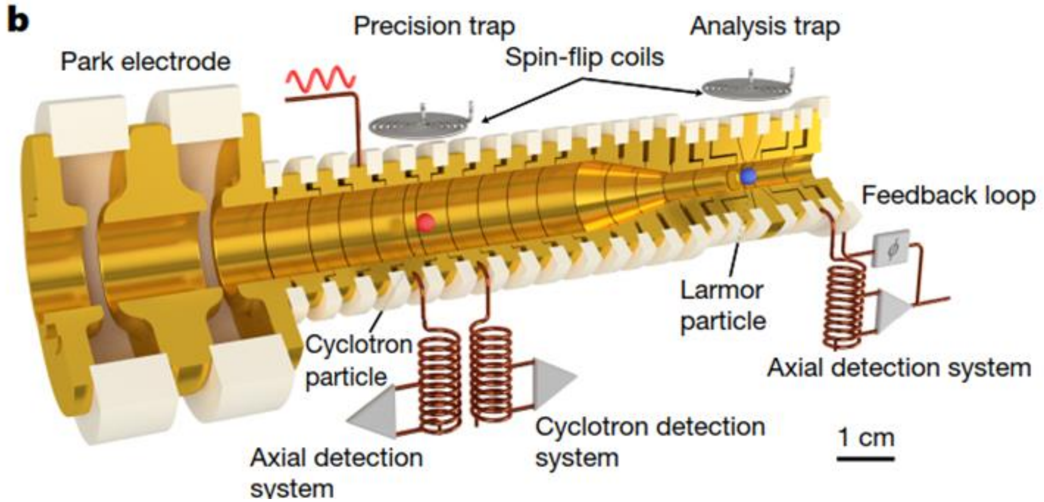
hot particle (1K)

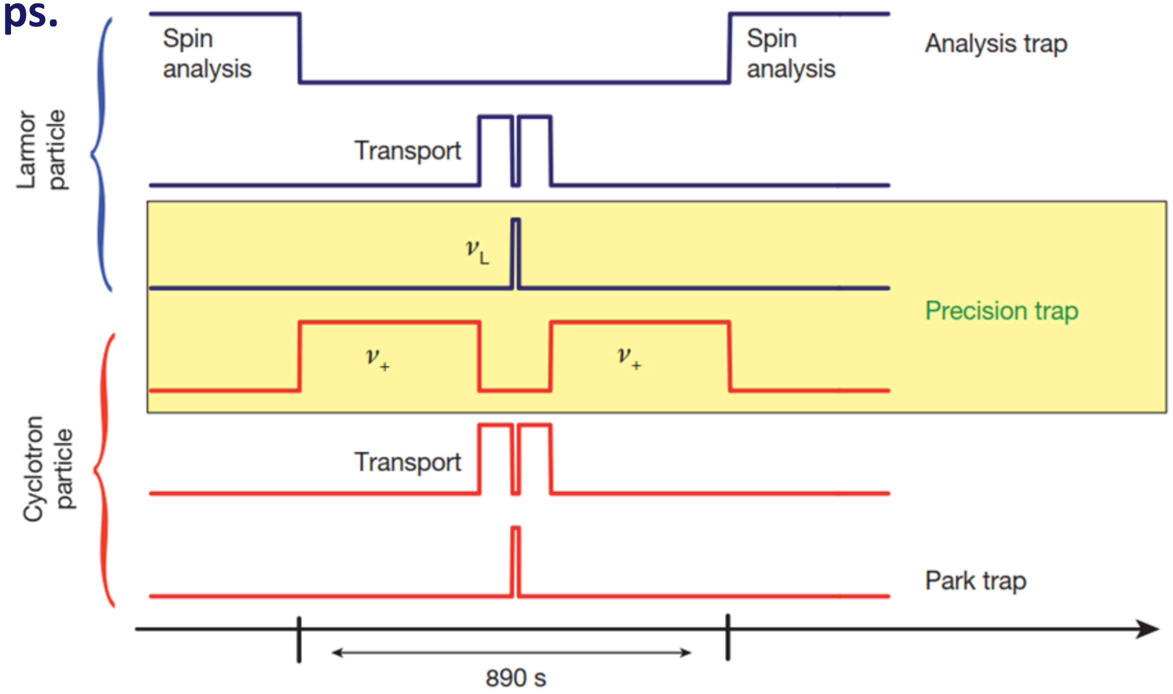


fidelity at 65%, not useful for measurements

1.5 p.p.b. -> C. Smorra, Nature 550, 371-374 (2017)

Idea: divide measurement to two particles and different traps.





«hot» cyclotron particle which probes the magnetic field in the precision trap

«cold» cyclotron particle to flip and analyze the spin-eigenstate

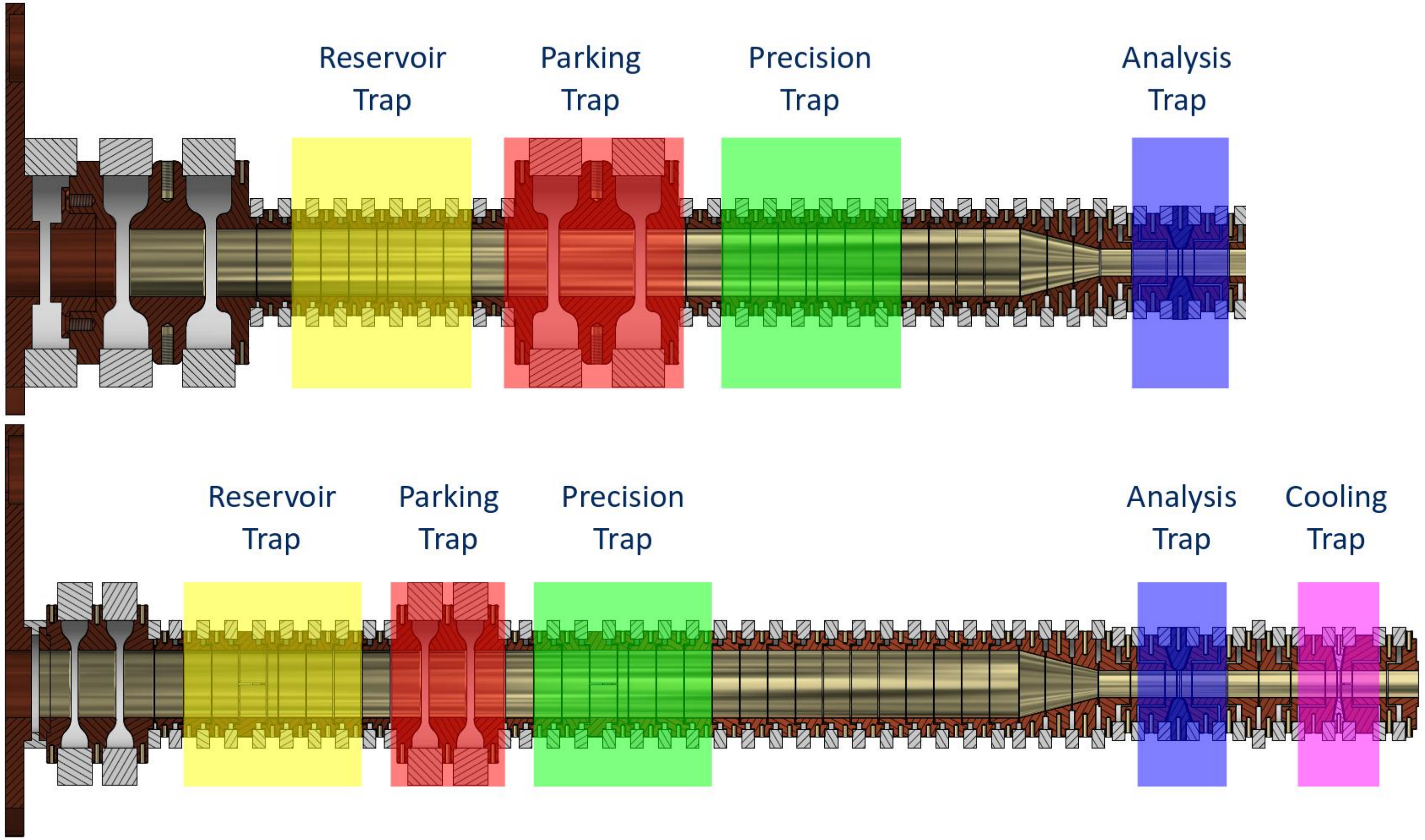
Problems: measure with two particles at different mode energies

Advantages: 60% of time usually used for sub-thermal cooling useable for measurements

New trap stack

2017:

2020:



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Cooling trap – 2021 run

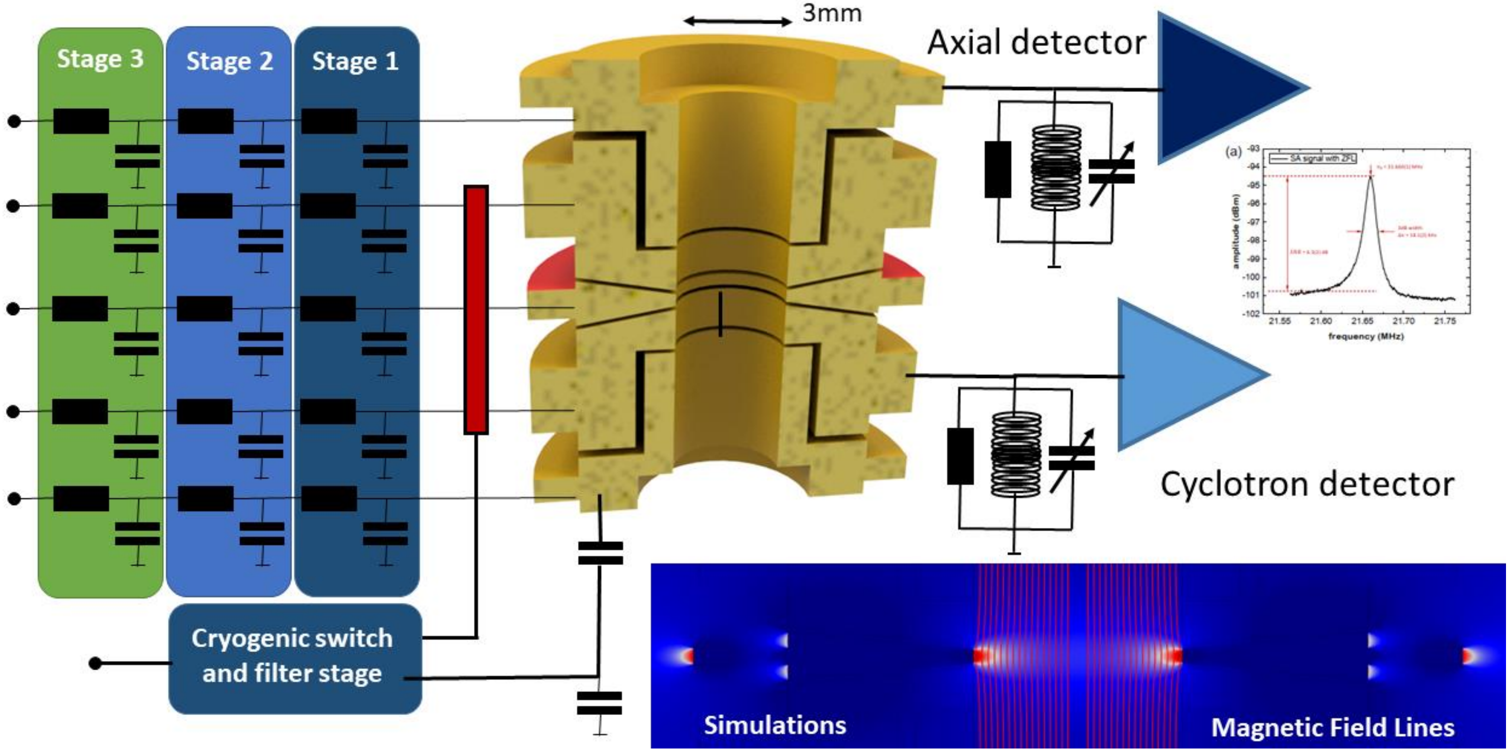
- **Goal: reduce current some 10 h cooling cycles to several minutes**
- What is a Cooling Trap?

-> Trap dedicated to cool the cyclotron mode

-> It has both cyclotron and axial detectors and a magnetic bottle to allow for both cooling and temperature evaluation.

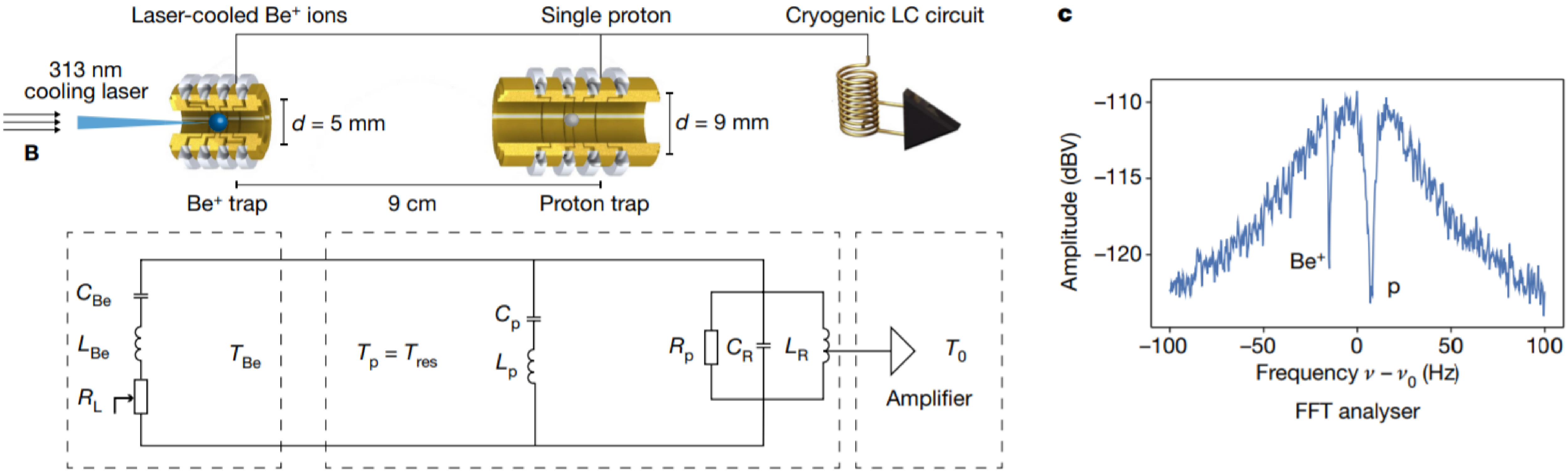
-> Redesigned cyclotron detectors for efficient cooling with wide tunning ranges.

CT cyclotron detector:
-> Q ~ 1200 when cold, assembled in our new setup!
-> cooling time constant ~ 12 s
-> tuning range > 3 MHz



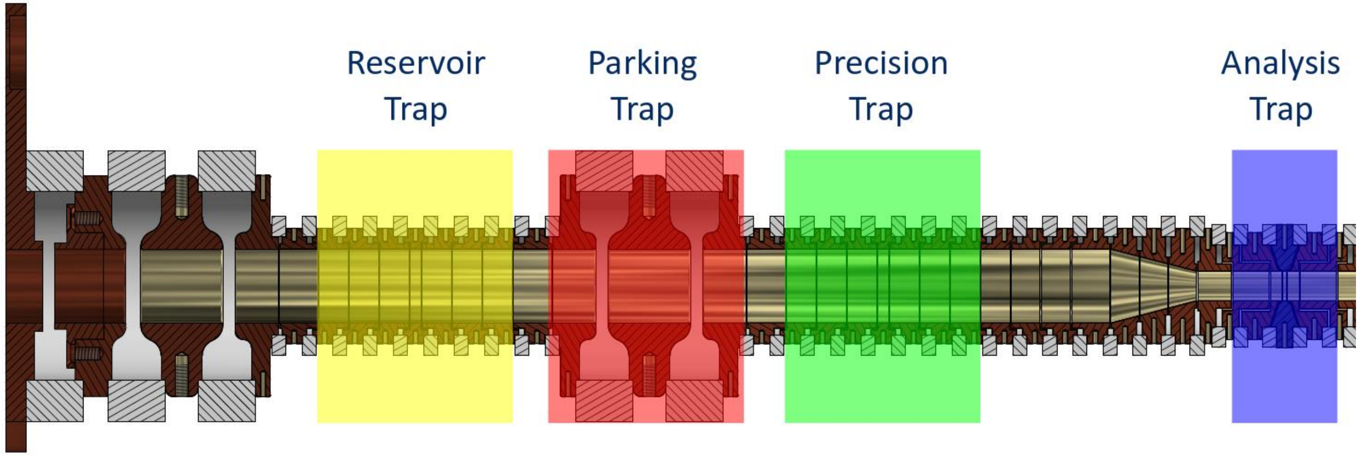
Future - Sympathetic cooling of antiprotons

- Sympathetic cooling of a trapped proton mediated by an LC circuit, M. Bohman, et al. Nature 596, 514-518 (2021).
- Already achieved: ΔT = 14.4 (0.7) K and T = 2.6 (2.5) K
- Possible according to simulations: 10 mK in 10 s.

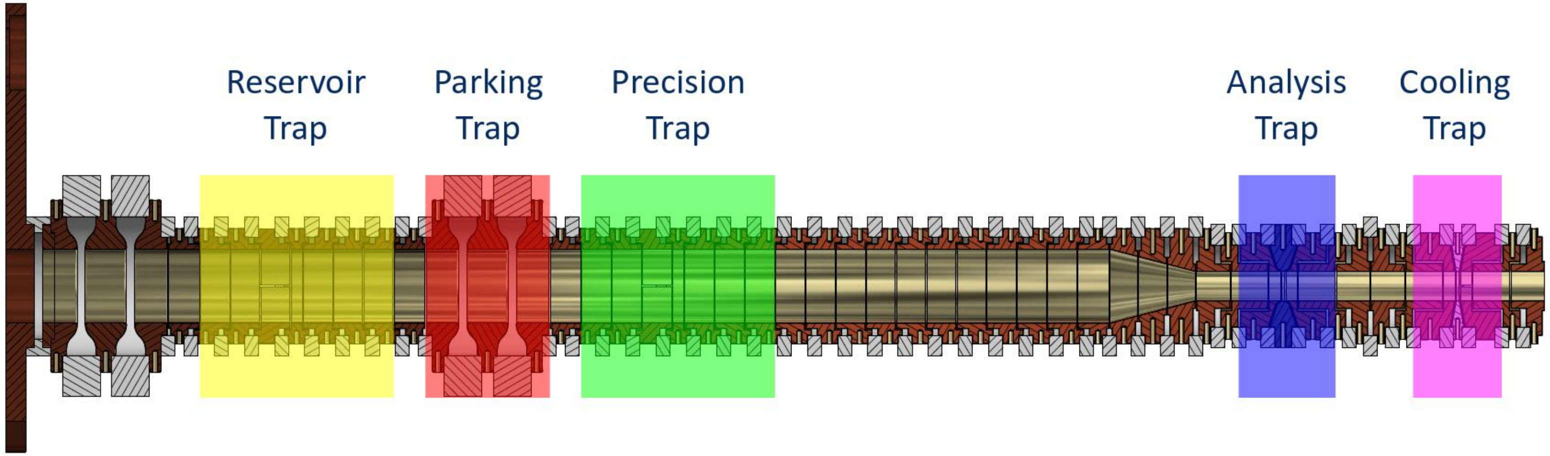


New trap stack

2017:



2020:

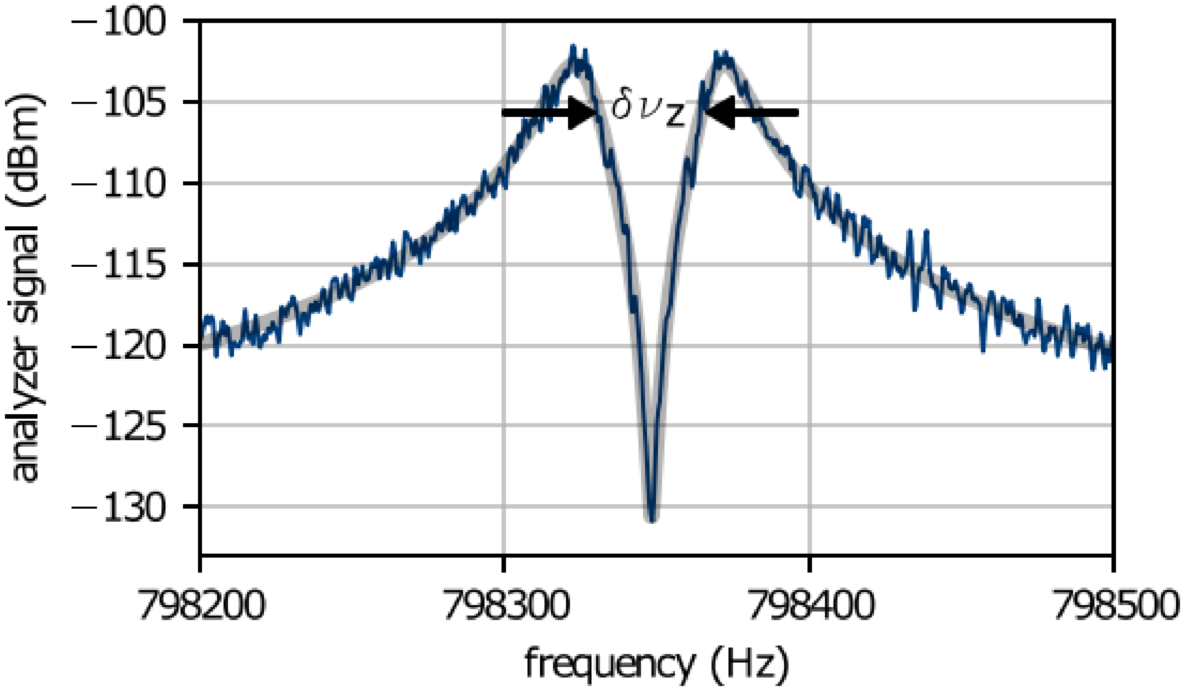


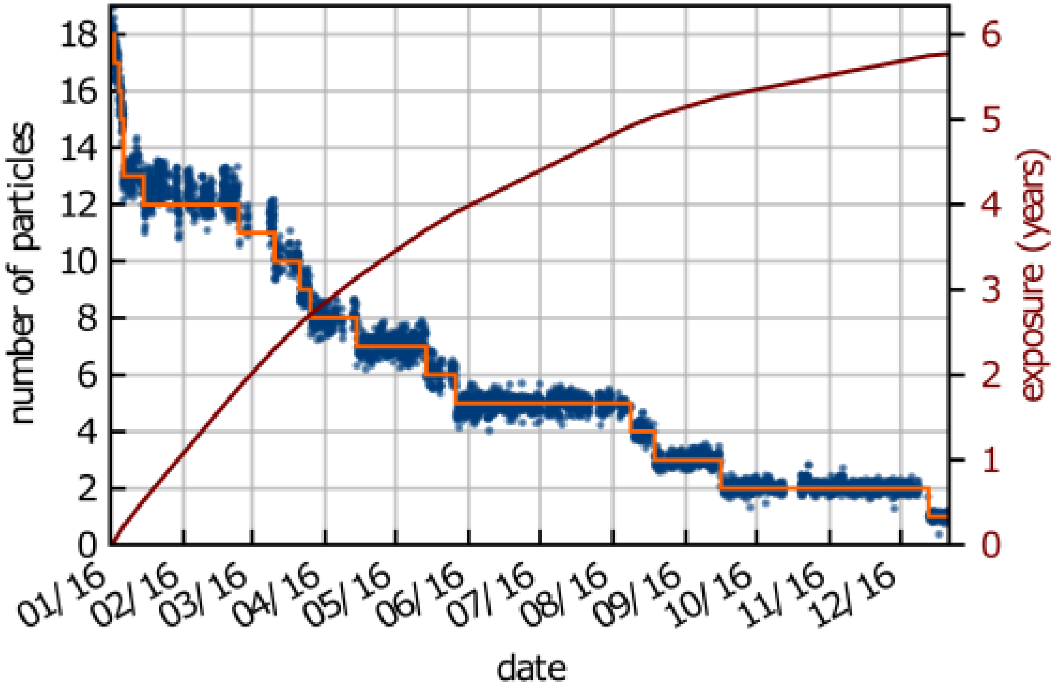
Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu\mathrm{T} / \mathrm{mm}^2$.
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ \mathrm{mT} / \mathrm{mm}^2$.
Cooling Trap: Fast cooling of the cyclotron motion.
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.

Antiproton storage

- **BASE managed to store antiprotons for 405.**
- Antiproton lifetime limit: $\tau_{\mathrm{lower},\bar{p}} = 26.15\,\mathrm{a}$
- To store antiprotons for 405 days we need pressure below 10^{-18} mbar!

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$





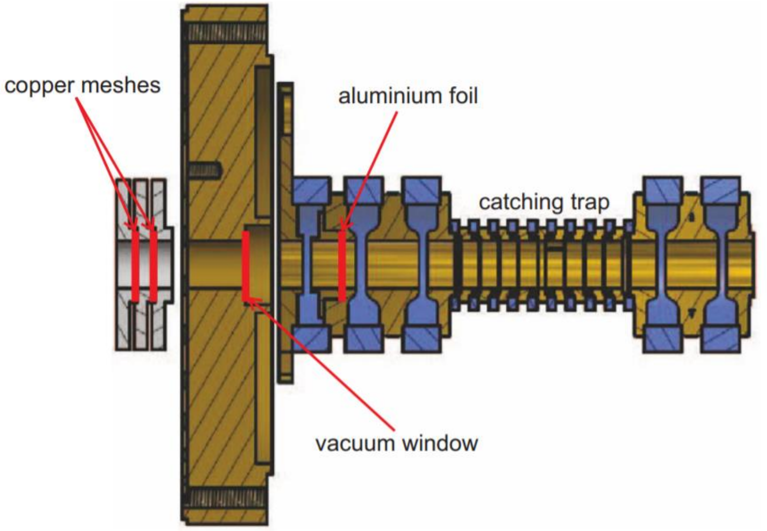
New antiproton degrading system

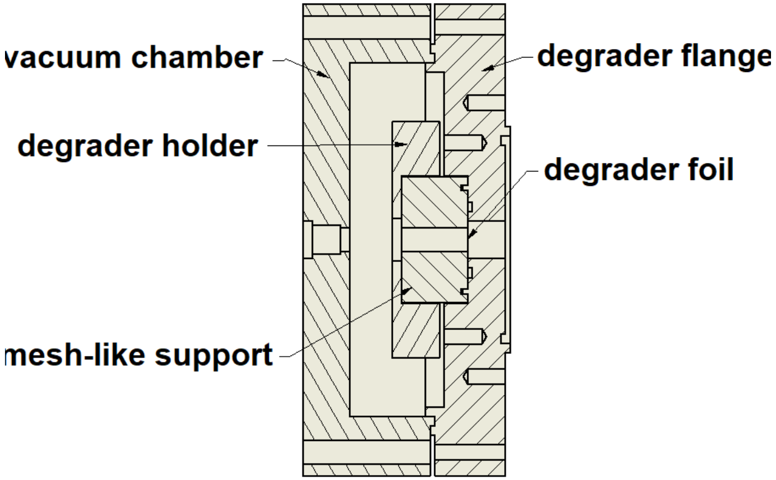
- Since 2018 the Antimatter Factory is operating a new **ELENA** (Extra Low ENergy Antiproton) decelerator.
- **The antiproton energy available for experiments decreased from 5.3 MeV to only 100 keV, which corresponds to the degrading foil thickness of about 1-3 µm.**
- **Challenge: how to close the vacuum system which has to survive 1 bar pressure difference and will keep our fantastic pressure at the levels below 10^{-18} mbar with 2 µm foil ???**

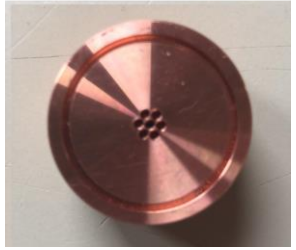
Old system:
the required window was a 25µm thick stainless-steel foil together with six stacked copper meshes and thin aluminum foil to optimise the antiproton stopping power.

New system:
Vacuum window and the degrader in one piece – 1.9 µm thick Mylar foil coated on both sides with 30 nm of Al.

- Beam acceptance: 7 holes with 1 mm diameter - 17.1 % ($\sigma_{x,y}$=2 mm, 5×10^6 p)





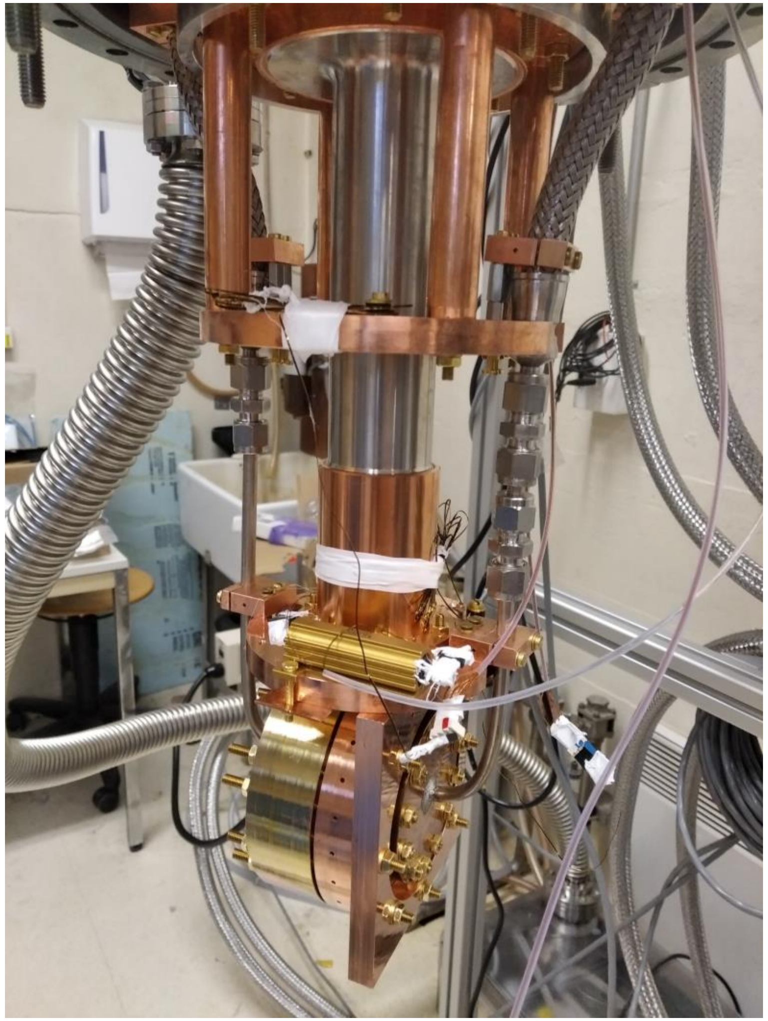


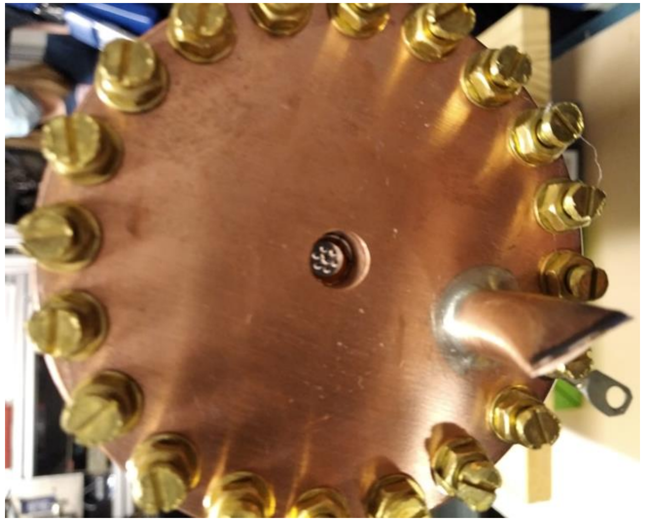
New Degrader system

- We estimated that to be safe even if we would be open into air for 30 days, we need the system with leak < 10^{-8} mbar l/s with 1 bar pressure difference.
- **300 K: 1.4×10^{-8} mbar l/s (result for 1.96 um foil)**
- **7 K: max around 4×10^{-11} mbar l/s.**
- System did not break under different endurance tests like repetitive cooling cycles, stretching in air and even in liquid nitrogen (!).

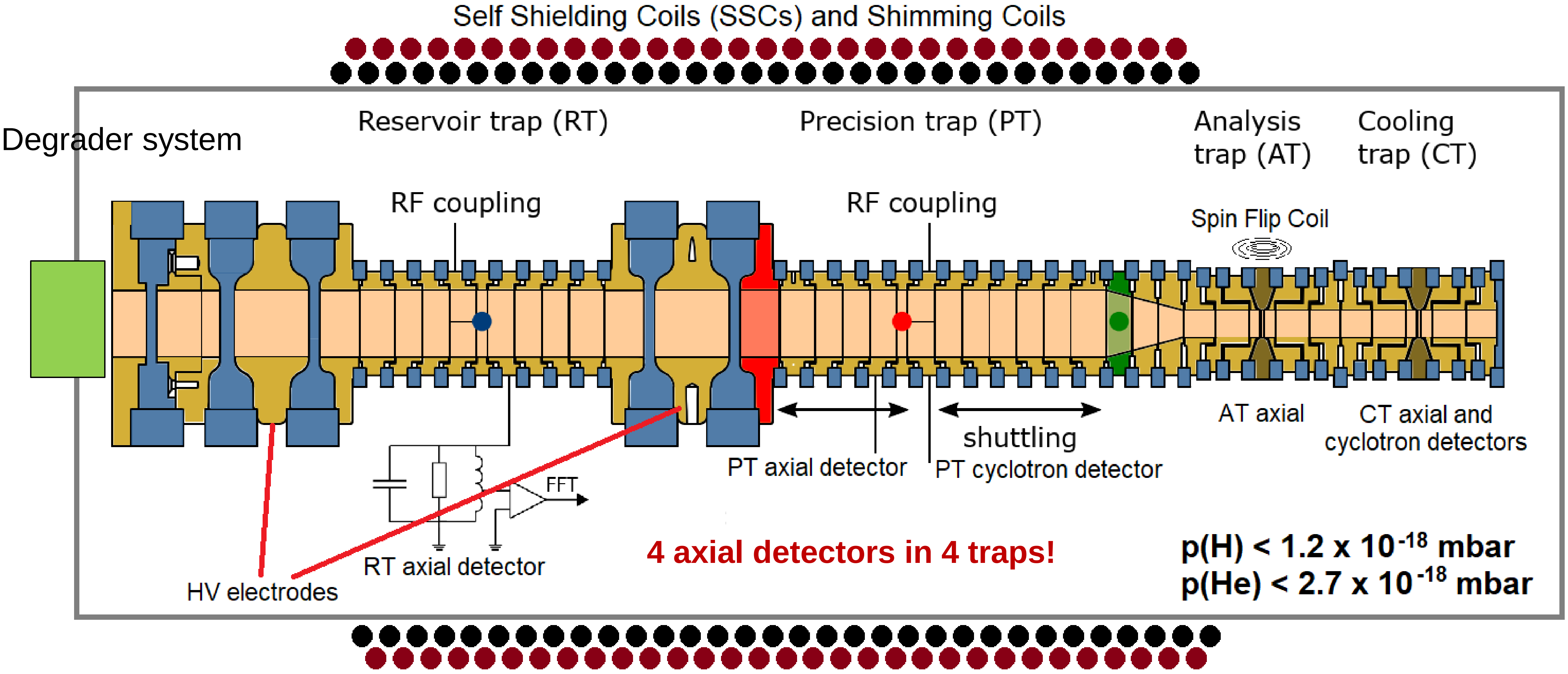
- **Currently running tests with protons allowed us not to lose any particle due to high pressure in the system, which corresponds to p< 10^{-15} mbar, even after 2.5 cooling cycles!**

- Antiproton deceleration: we can decelerate antiprotons to 5 keV….





Scheme of the trap system



4 axial detectors in 4 traps!

$p(H) < 1.2 \times 10^{-18}$ mbar
$p(He) < 2.7 \times 10^{-18}$ mbar

Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.

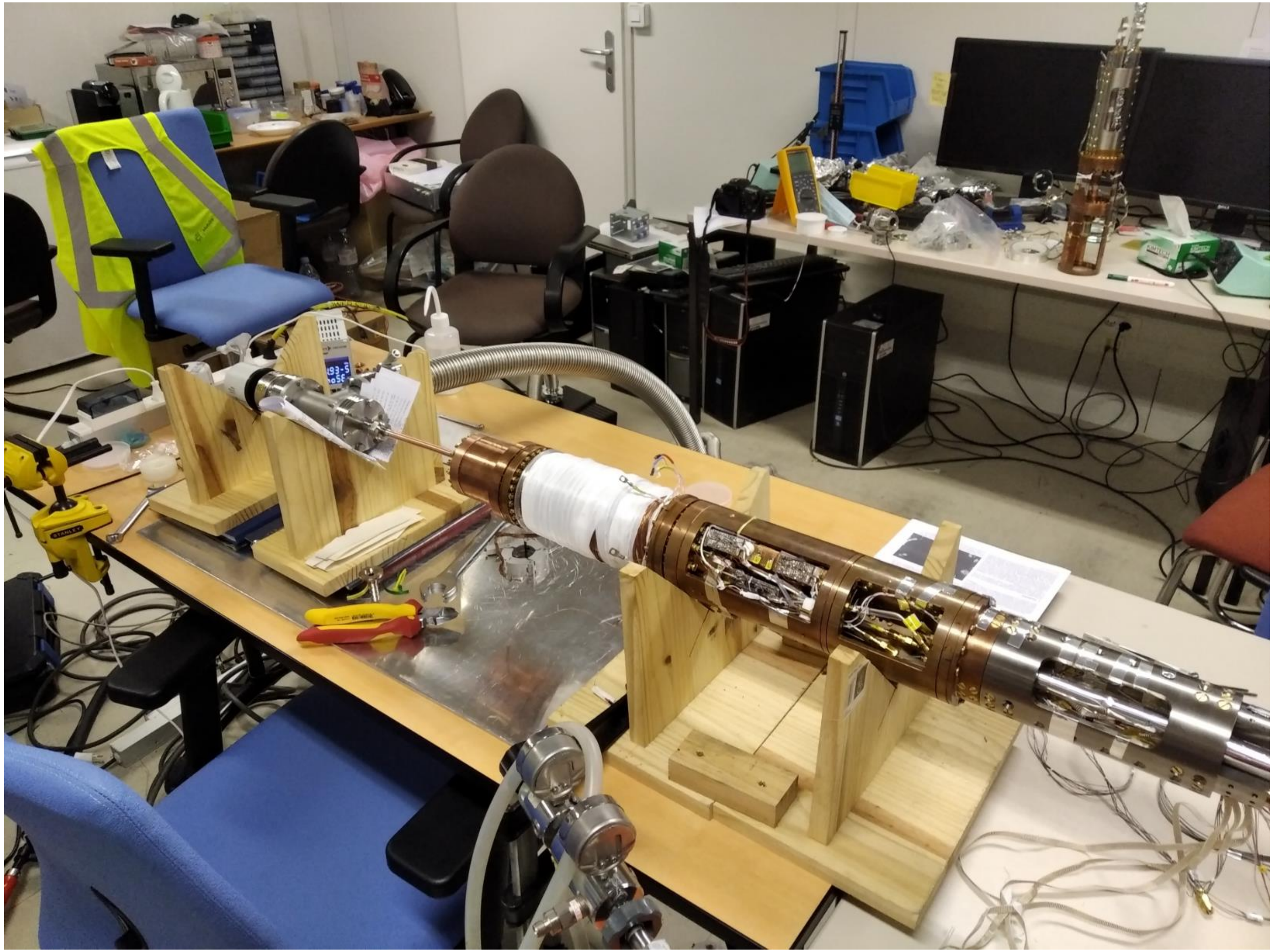
Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$.

Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$.

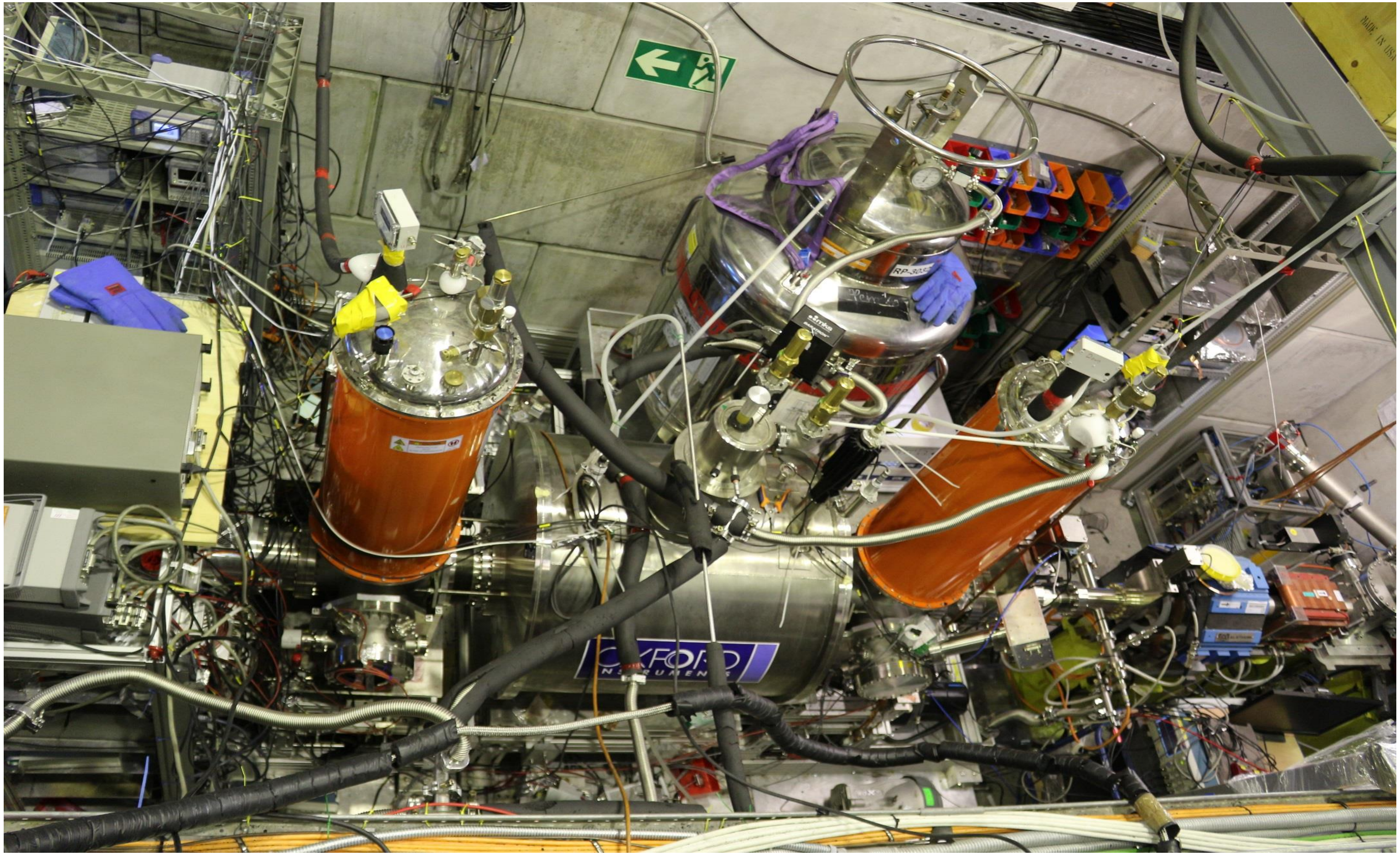
Cooling Trap: Fast cooling of the cyclotron motion.

Final assembly 2021

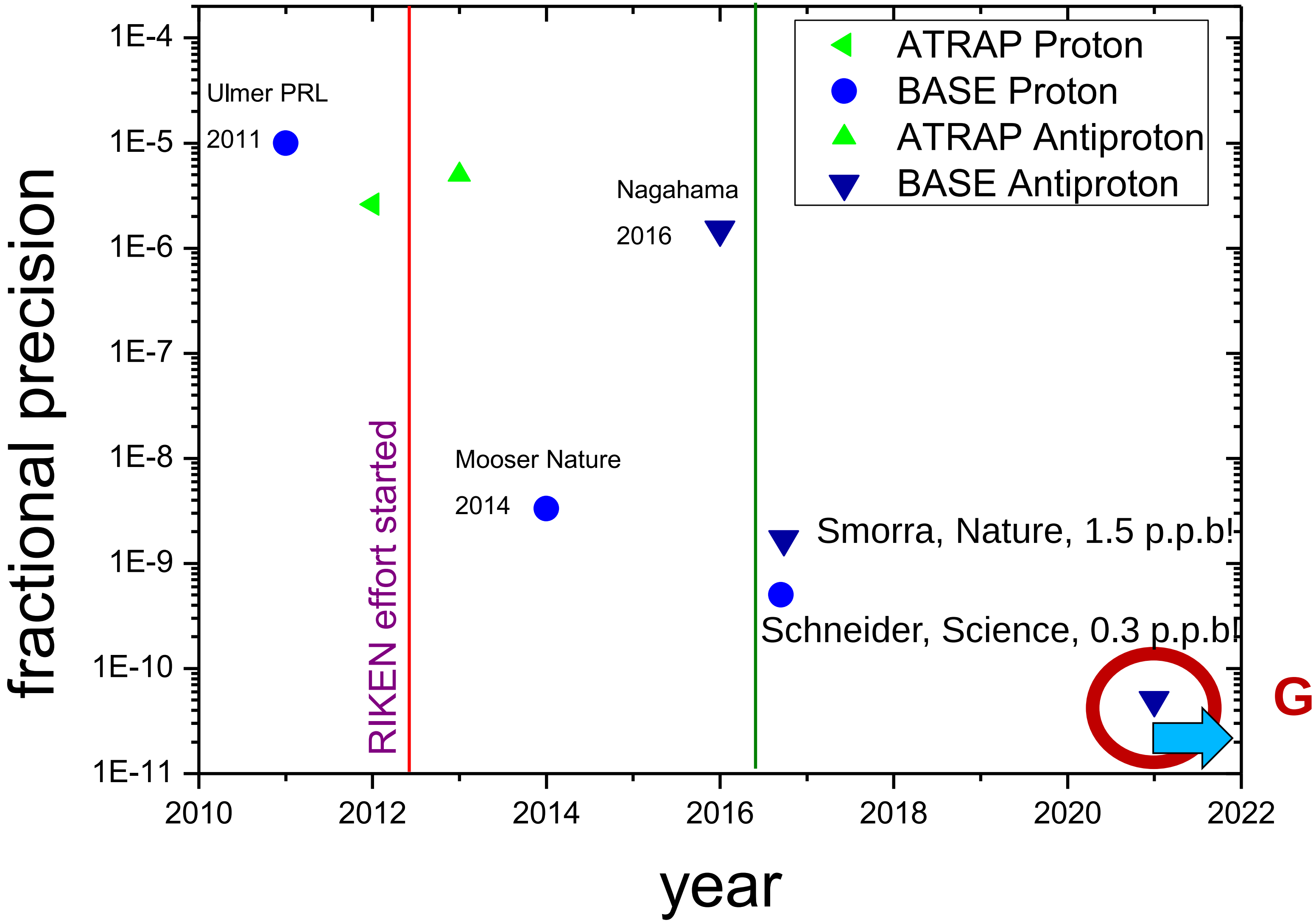
Final assembly 2021



The experiment



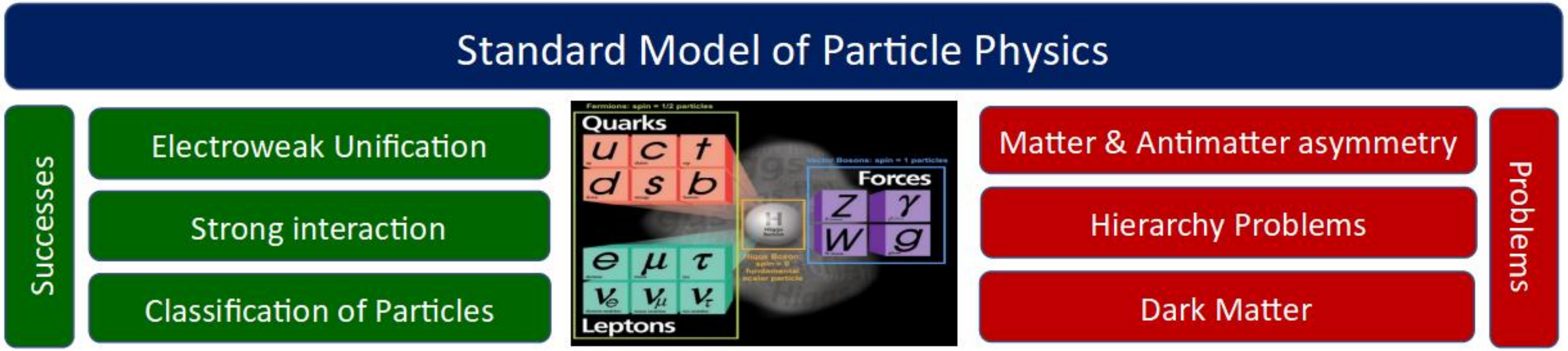
Proton / Antiproton magnetic moment



Goal of this run

Cold dark matter searches - motivation

- **We have very sensitive detectors at BASE, so why not to use it also to search for dark matter…**



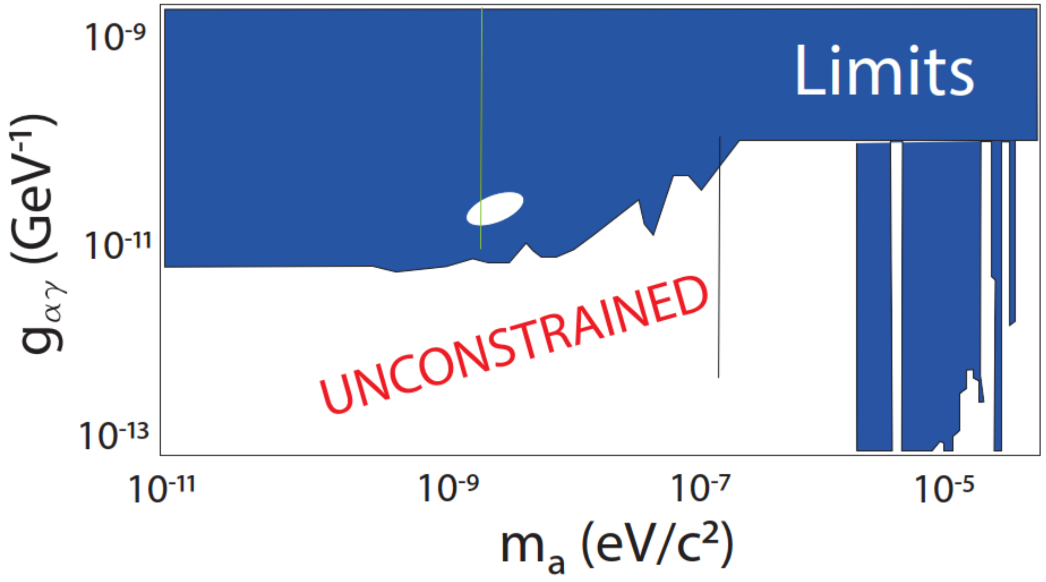
Standard Model of Particle Physics

Successes

- Electroweak Unification
- Strong interaction
- Classification of Particles

Problems

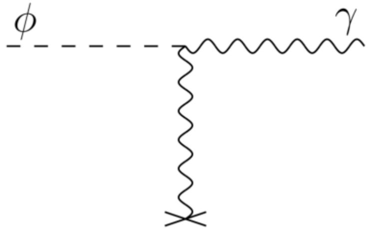
- Matter & Antimatter asymmetry
- Hierarchy Problems
- Dark Matter



- **Axion Like Particles - ALPs:**

→ pseudoscalar bosons weakly interacting with matter motivated by many beyond the standard model theories

→ coupling to photons by derivative interactions $g_{a\gamma}$ through e.g. inverse Primakoff Effect



- mass m_a << 1 eV (e− mass = 0.5 MeV!)

New Axion-like particle detection method

- **J. A. Devlin** et al. (BASE Collaboration), PRL 126, 041301 (2021).
- Any low mass ALP would form a classical field oscillating with frequency:

$$\nu_a \approx m_a c^2 / h$$

- Coupling of ALP field to **E** and **B** fields:

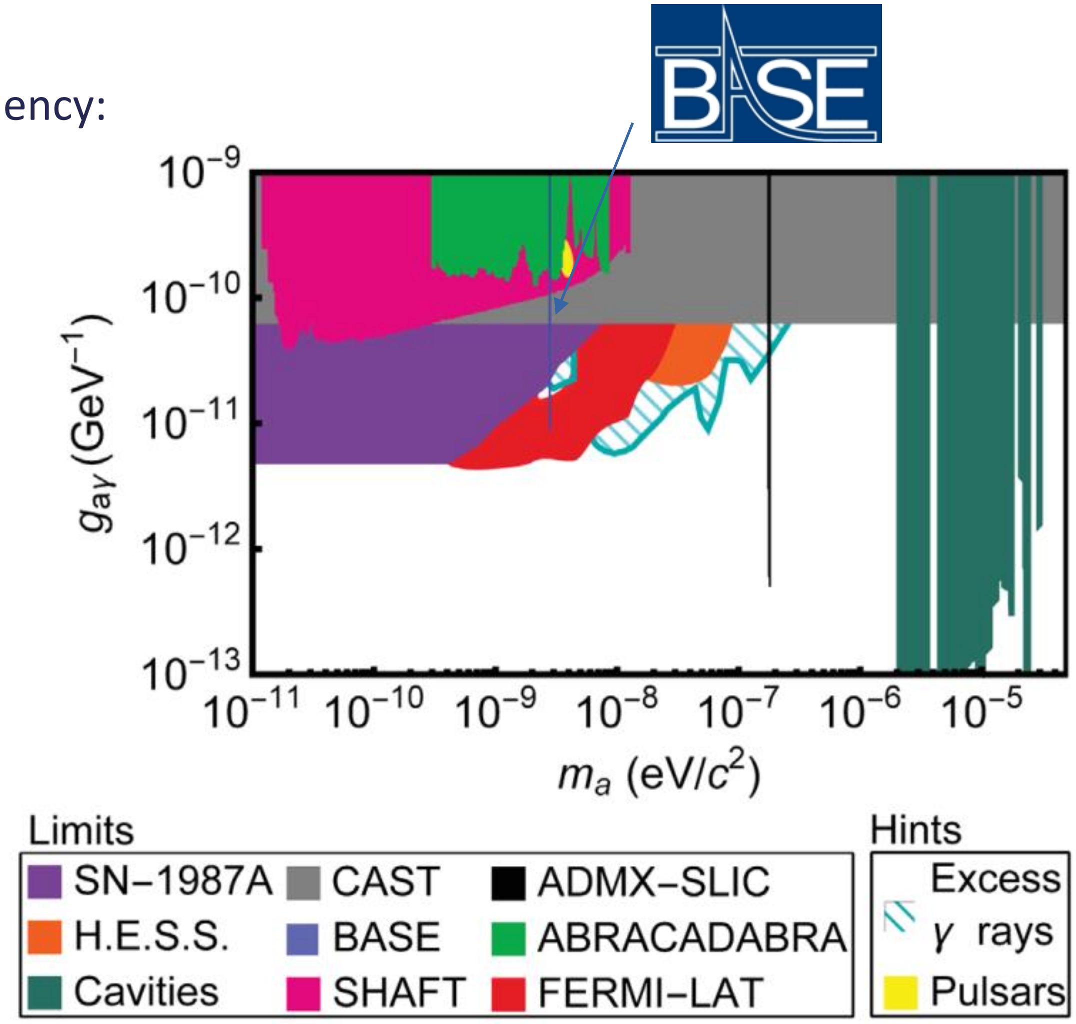
$$L_{a\gamma} = -g_{a\gamma} a(x) \mathbf{E}(x) \cdot \mathbf{B}(x)$$

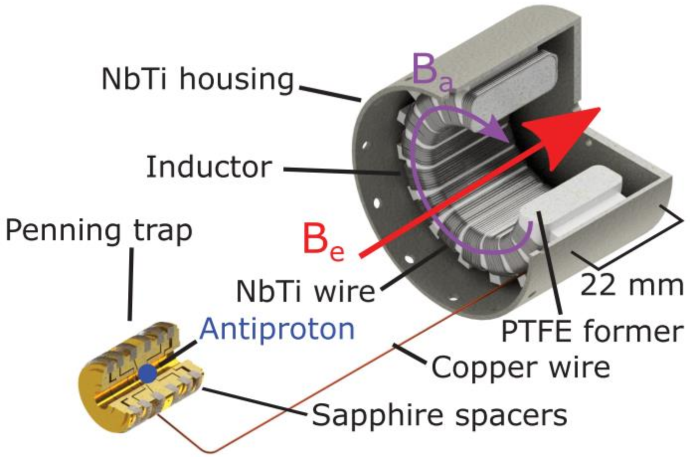
- The oscillating ALP field source oscillating magnetic field:

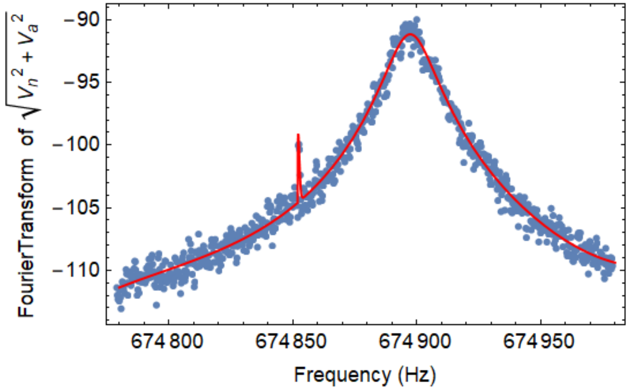
$$\nabla \times \mathbf{B} - \mu \frac{\partial \mathbf{E}}{\partial t} = -g_{a\gamma} \mathbf{B}_e \frac{\partial a}{\partial t}$$

$$\mathbf{B}_a = -\frac{1}{2} g_{a\gamma} r \sqrt{\rho_a \hbar c} B_e \hat{\phi}$$

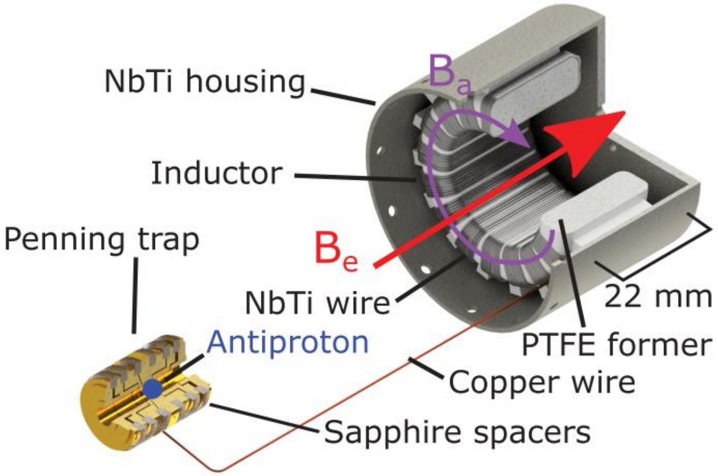
- where $\rho_a \hbar c$ is the local ALP energy density, r is the radial distance
- from the axis of the toroid.



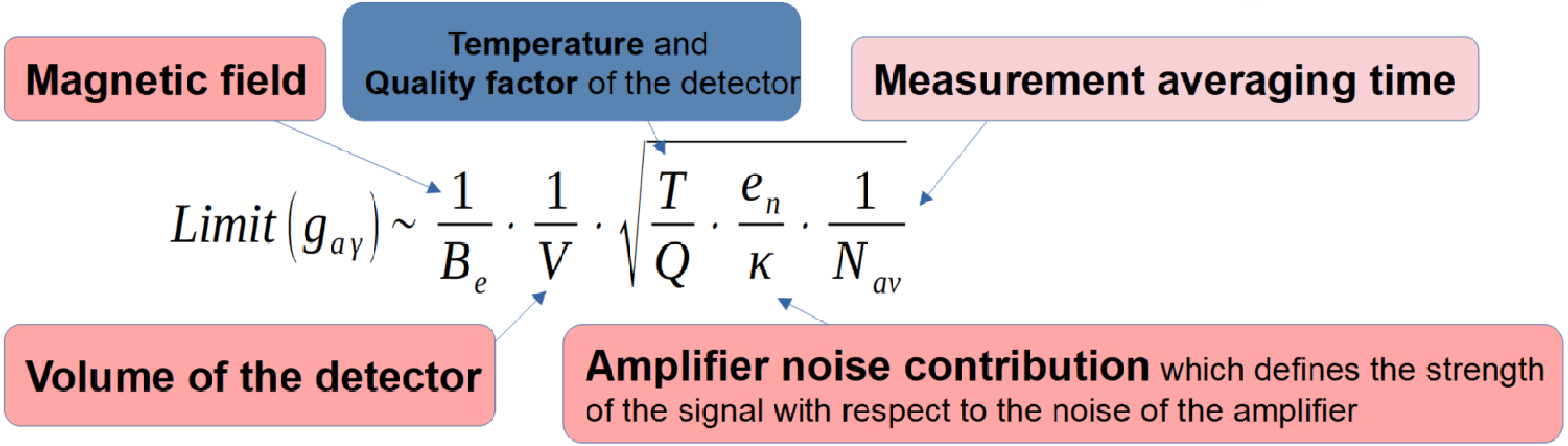




New detectors



-> **improved sensitivity**



Magnetic field

Temperature and **Quality factor** of the detector

Measurement averaging time

$$Limit\left(g_{a\gamma}\right) \sim \frac{1}{B_e} \cdot \frac{1}{V} \cdot \sqrt{\frac{T}{Q} \cdot \frac{e_n}{\kappa} \cdot \frac{1}{N_{av}}}$$

Volume of the detector

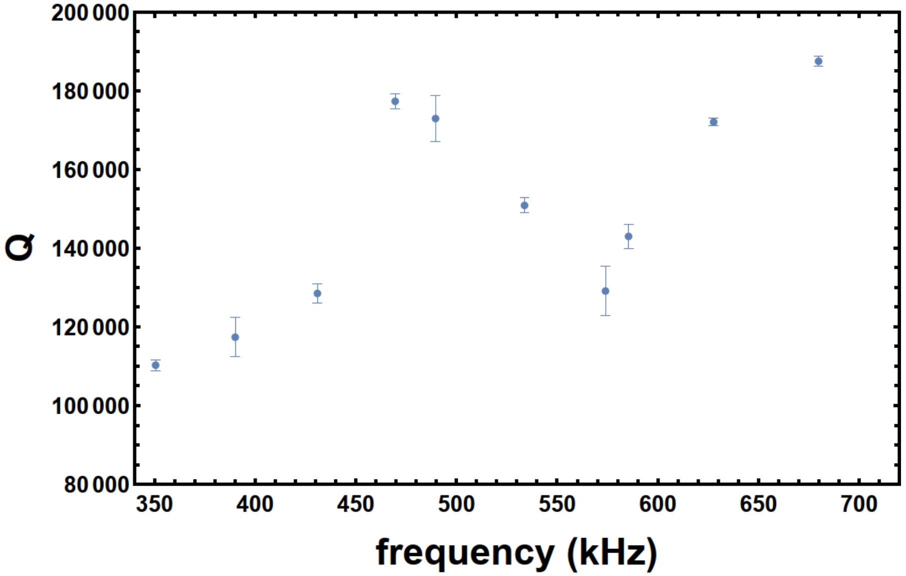
Amplifier noise contribution which defines the strength of the signal with respect to the noise of the amplifier

New detectors

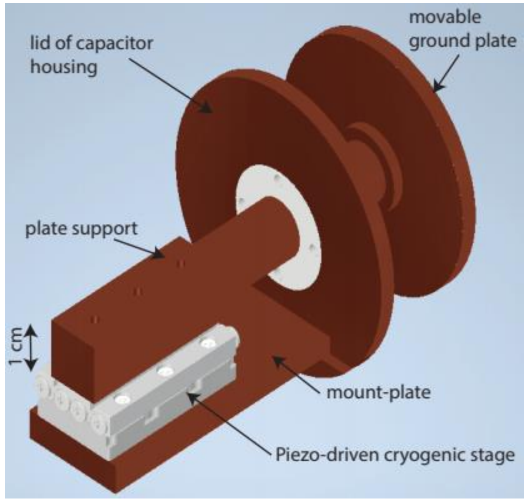
-> Goal: **increased bandwidth** between 500 kHz and 200 MHz.

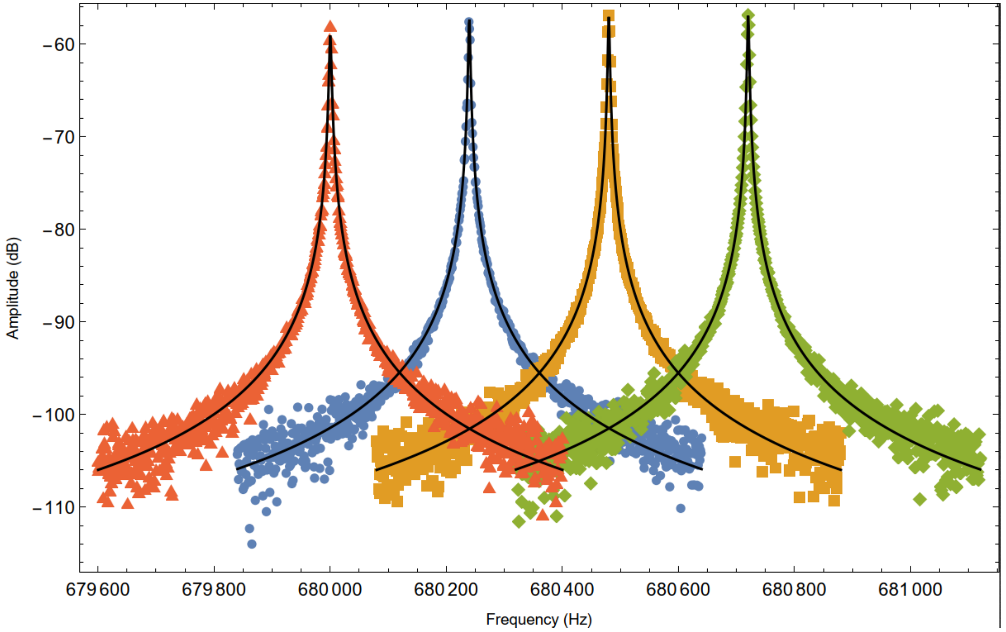
-> Solution: tunable capacitance of a resonator which does not decrease the Q value (Limit($g_{a\gamma}$)~$\sqrt{Q}$):

- big resonant frequency changes – capacitive tuning bank – static capacitors with movable connector
- fine tuning – bandwidth tuner – movable capacitor



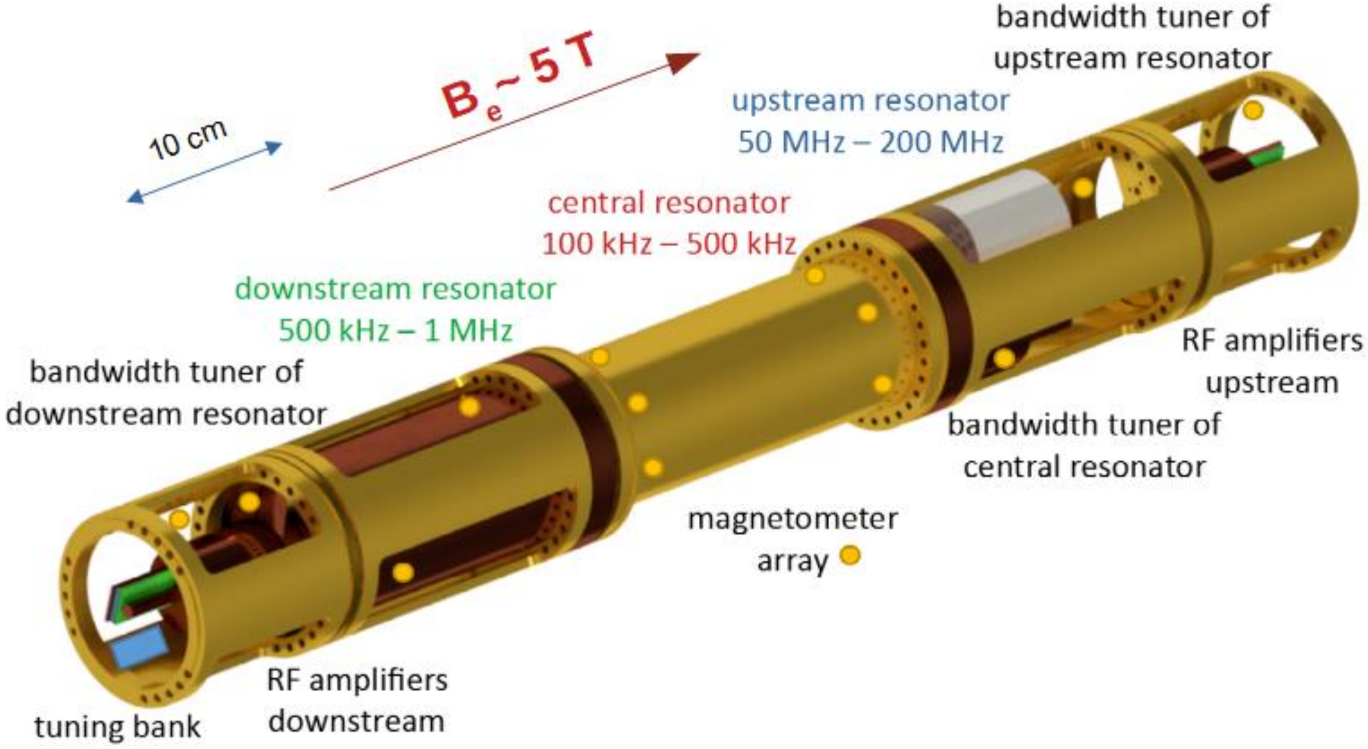
-> Prototype - bachelor thesis of F. Voelksen

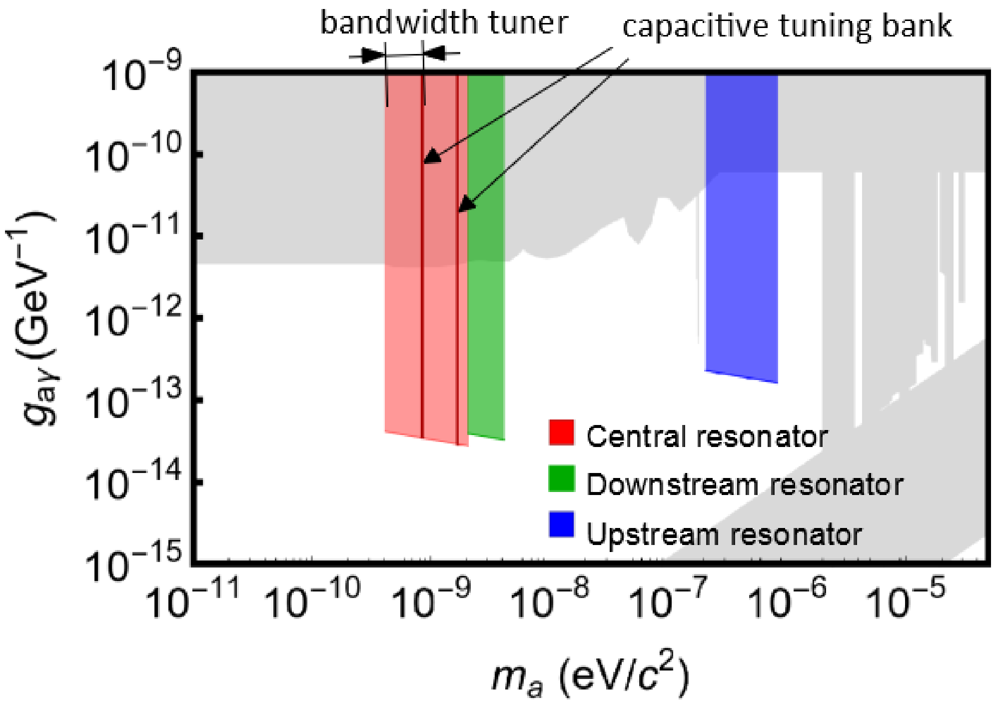




An ultra-sensitive ALP detection standard

→ **The new setup will consist of three dedicated detectors:**





Summary and outlock

- **BASE** is specialising in measurements of fundamental properties of antiparticles:

  -> **69 ppt comparison of the antiproton-to-proton charge-to-mass ratio**, S. Ulmer, Nature 524, 196-199 (2015). **New result coming soon!**

  -> **1.5 p.p.b. Measurement of antiproton magnetic moment,** C. Smorra, Nature 550, 371-374 (2017).
- We are preparing to beat the last BASE magnetic moment measurement of the antiproton at 1.5 p.p.b.

  For that we implemented a few crucial improvements:

  - -> new degrader interface for 100 keV antiproton beam
  - -> new cooling trap
  - -> new magnetic shimming and shielding system.
- BASE is the only experiment which is able to store antiprotons for a long time…
- … and soon will be the experiment that will transport antiprotons (**BASE STEP**)!
- BASE participates in searches for Cold Dark Matter. Recently we developed a **new technique to search for Axion Like Particles** which will be further improved in the future, J. A. Devlin PRL 126, 041301 (2021).

Thank you for your attention