Searches for exotic physics by comparing the fundamental properties of protons and antiprotons at BASE

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RIKEN

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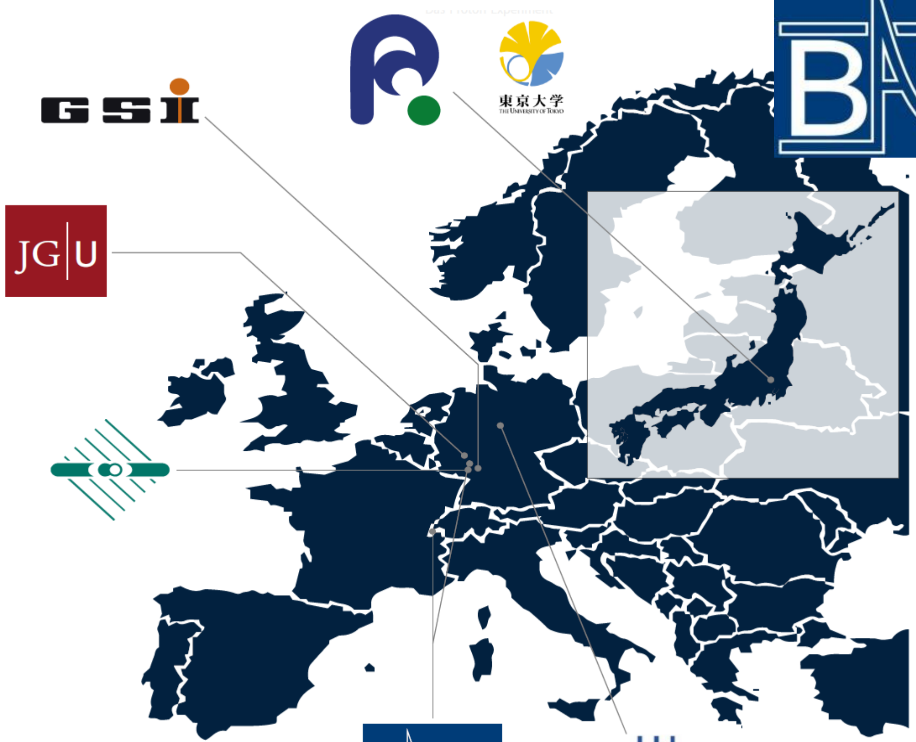
BASE Collaboration

- **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

→ **Sympathetic cooling of a trapped proton mediated by an LC circuit** , Bohman, M. et al. Nature 596, 514–518 (2021).

- **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

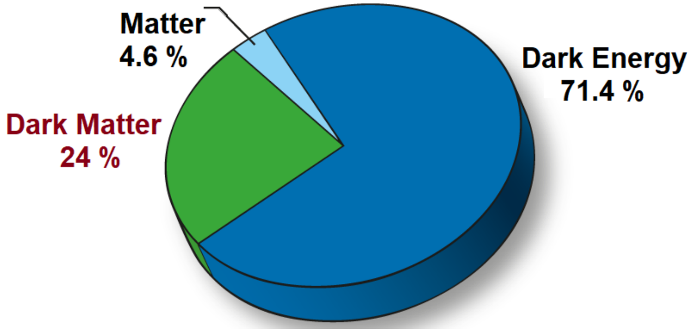
Baryon/Antybarion Symmetry Experiment

Standard Model of Particle Physics

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

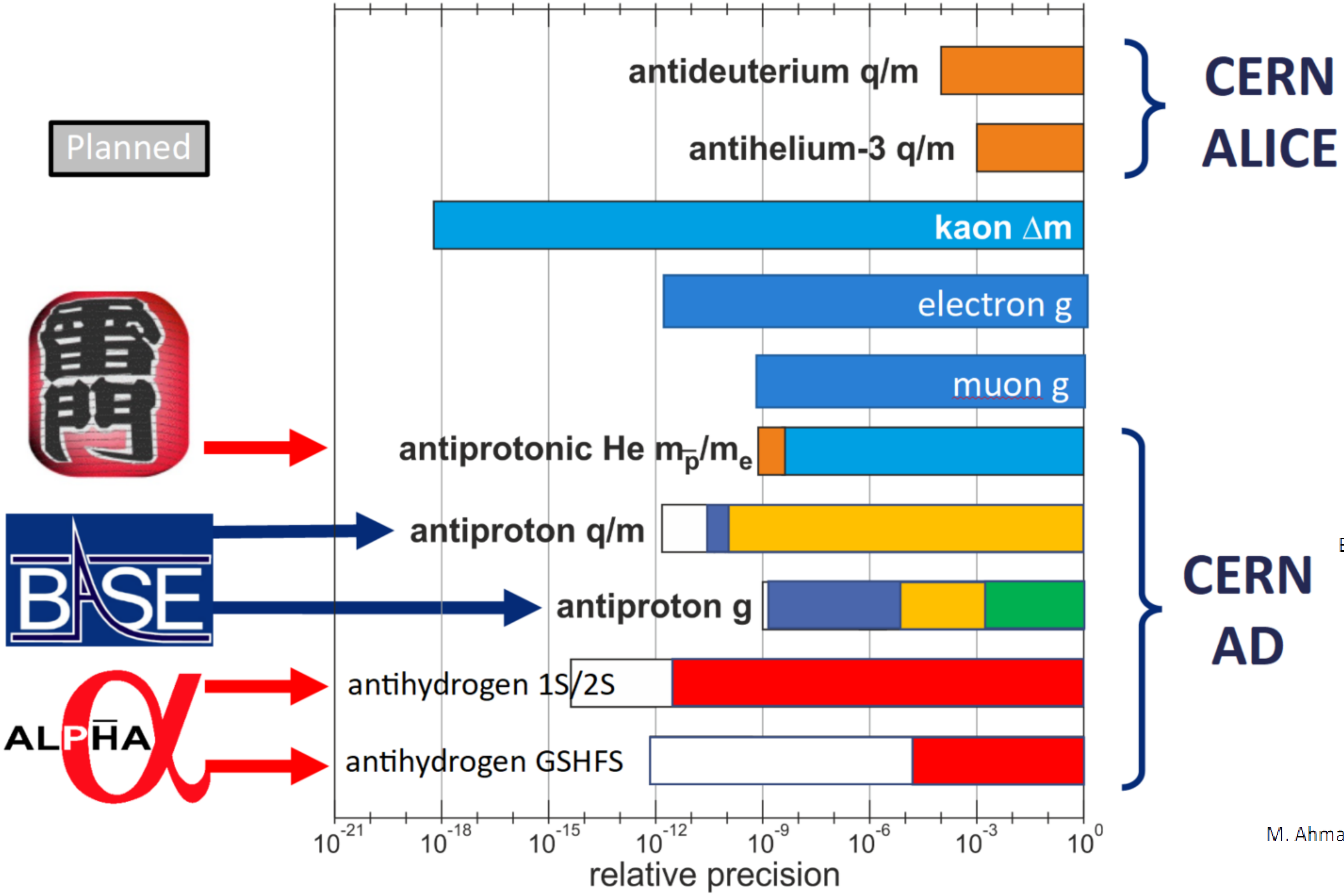
Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000

- 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**

CPT with particle/antiparticle comparisons



-> Absolute energy resolution normalized to m-scale.

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).

Slide from S. Ulmer

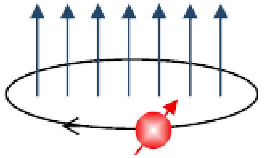
Single particle measurements in Penning Traps

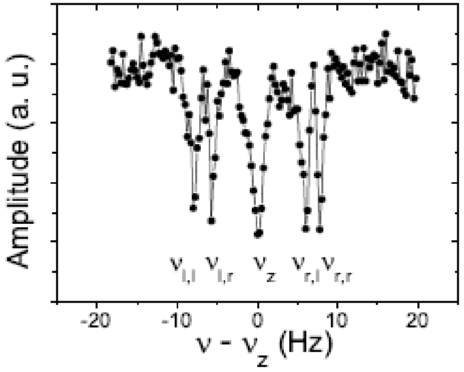
High precision mass spectroscopy

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

Cyclotron Motion

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





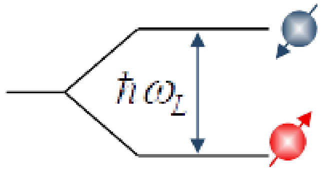
- **69 ppt comparison of the antiproton-to-proton charge-to-mass ratio**, S. Ulmer, Nature 524, 196-199 (2015)

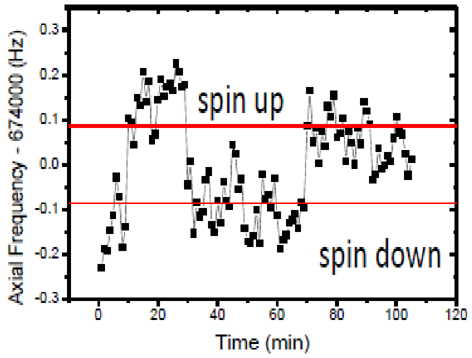
High precision magnetic moment measurements

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

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 confinment: $\vec{B} = B_0 \hat{z}$

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

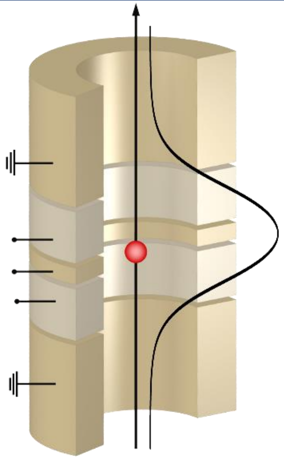
- **Invariance theorem:**

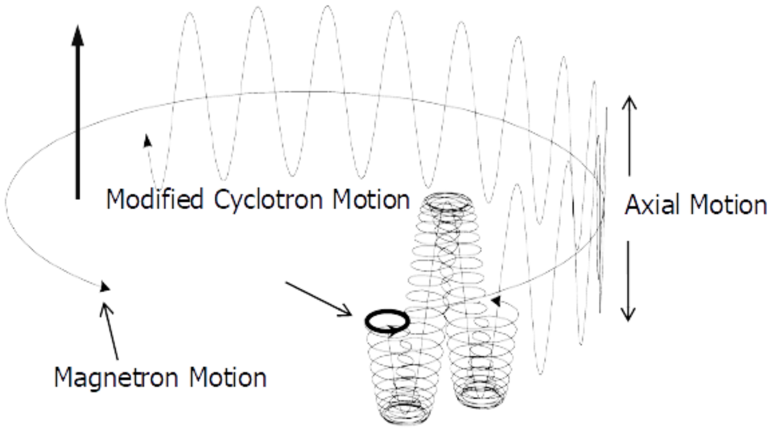
Cyclotron frequency of a particle

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

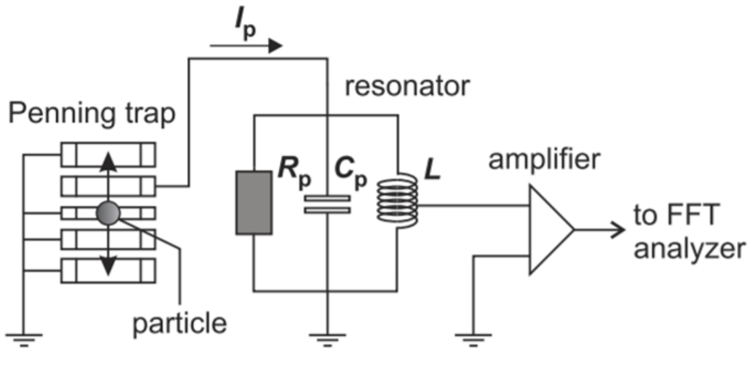
which is correct also for any small angle misalignment of the trap or quadratic imperfections of the field (G. Gabrielse)!

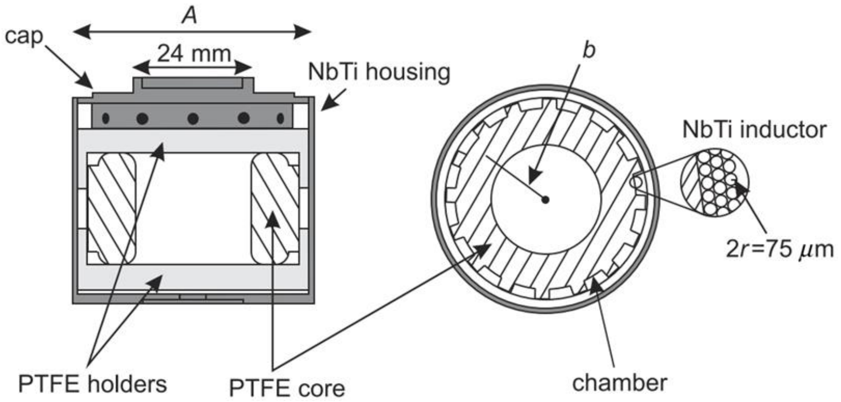
- Measurement of tiny image currents induced in trap electrodes

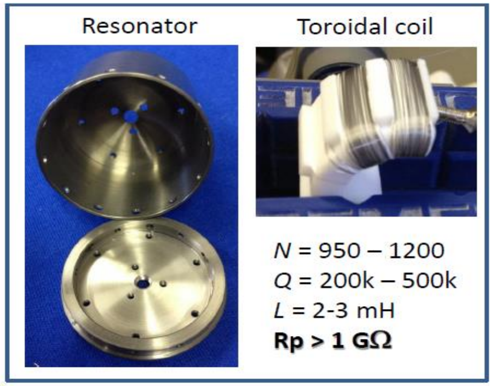




Axial	680 kHz	$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}$
Magnetron	8 kHz	$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
Modified Cyclotron	28.9 MHz	$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$



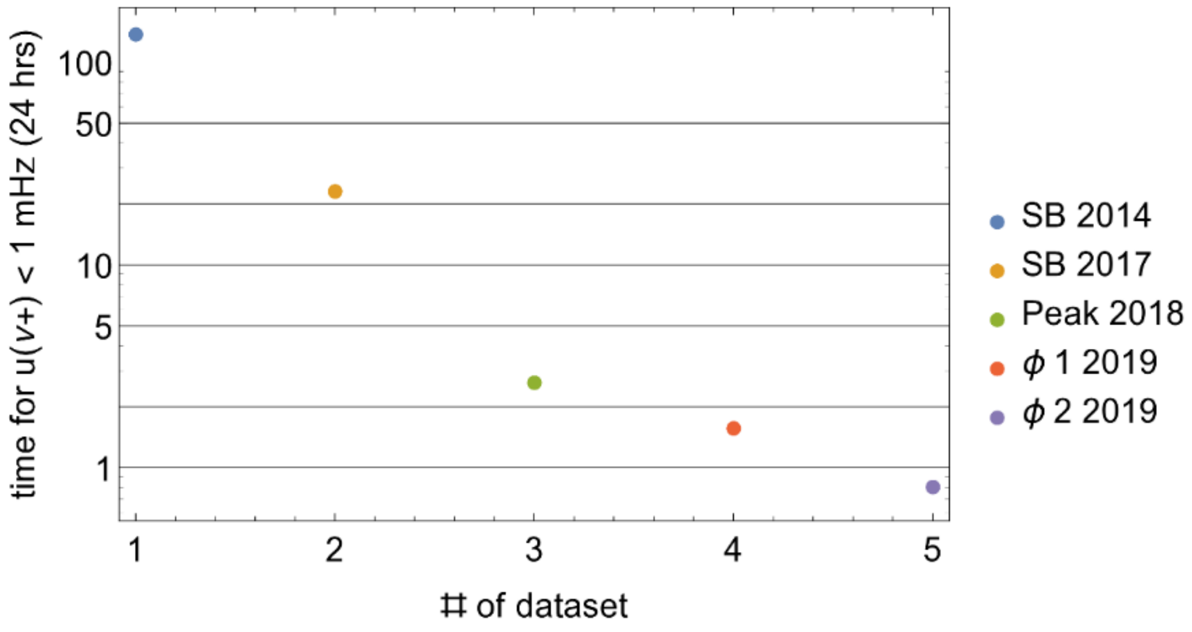


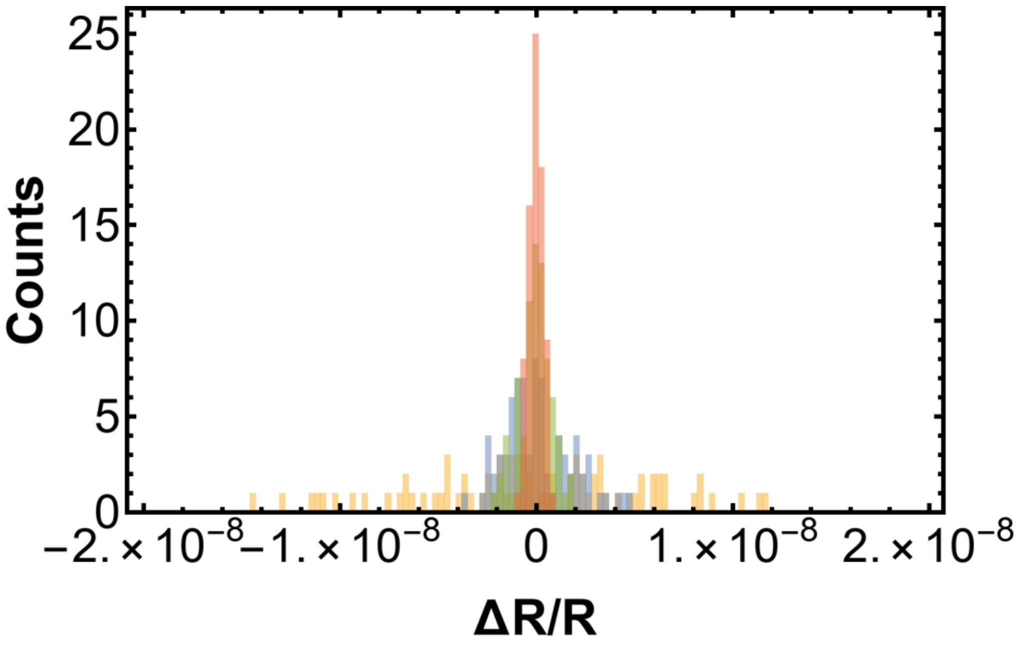


Cyclotron frequency measurement

- **„Simple" measurement, with main systematics coming from magnetic field stability**
- Classically used in the BASE experiment is the sideband method (measurement of the amplitude modulated axial mode oscillations) which is limited in 2019 to 1.6(2) p.p.b. (120 s).
- Eric A. Cornell, et al. PRL, 63(16):1674–1677, 1989.

  Sven Sturm, et al. PRL, 107(14):143003, September 2011.
- **We implemented a new phase method**, ~ averaging time, with which they reached in the best cases 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) – improvement by a factor of 5!





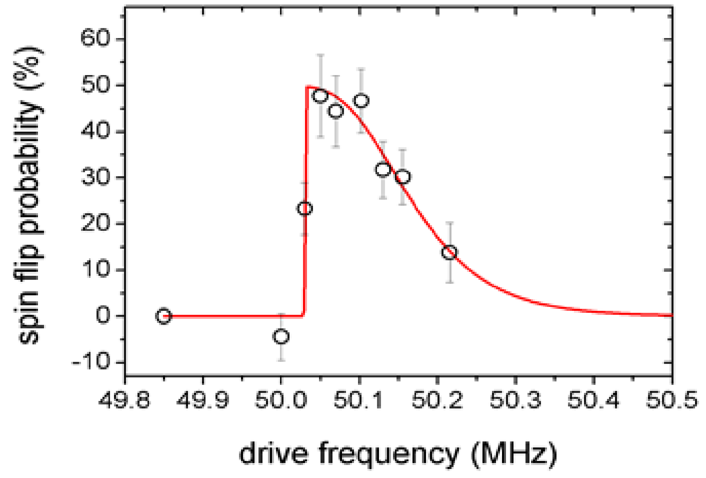
Larmor frequency

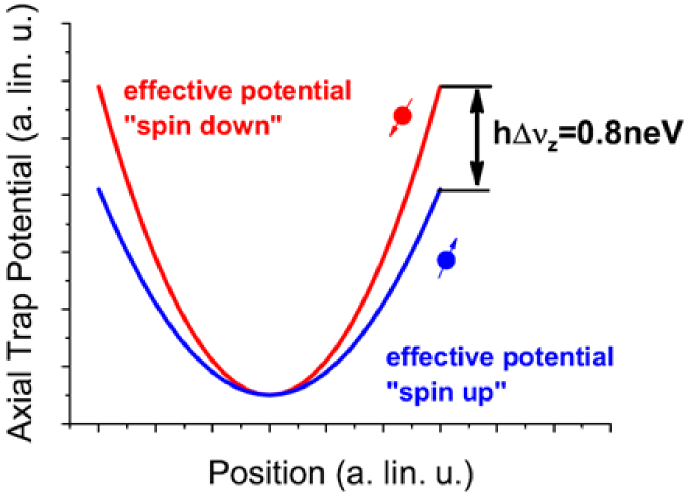
- **To resolve the Larmor Frequency one has to measure the spin flip probability as a function of drive frequency.**

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

- In order to resolve the change of the spin state we need extremly high B2 (axial 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.
- In one trap the g factor measurement is limited to ppm level.

High B2 ⟶ ν_L
Low B2 ⟶ ν_c
$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$





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

Larmor frequency – experimental problems

- Radial quantum jumps shift the axial frequency:

$$\Delta\nu_z(n_+, n_-, m_s) \;=\; \frac{h\nu_+}{4\pi^2 m_p \nu_z}\frac{B_2}{B_0}\cdot\left(n_+ + \frac{1}{2} + \frac{\nu_-}{\nu_+}\left(n_- + \frac{1}{2}\right) + \frac{g_p m_s}{2}\right)$$

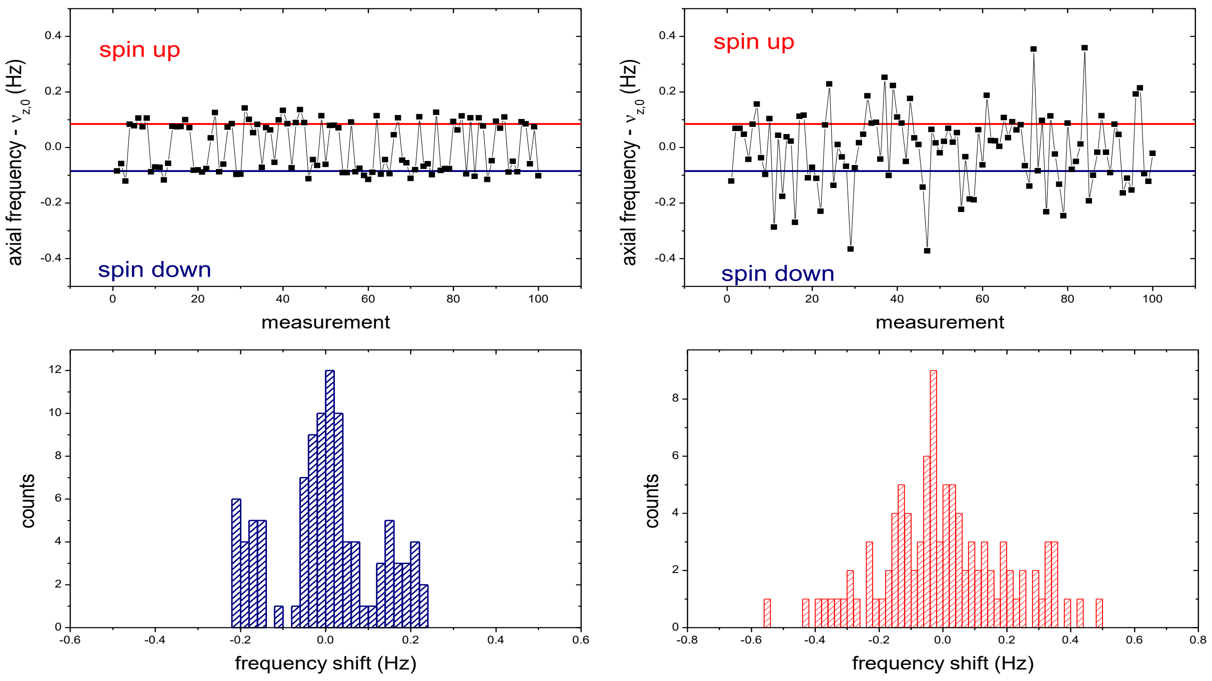
where **cyclotron quantum jump** induce about **~70mHz** (70 neV) shift, while **spin flip ~170 mHz**.

- Tiny heating of the radial mode results in significant fluctuations of the axial frequency.

- Measurement of the cyclotron frequency heats the particle!

cold particle (50mK)

hot particle (1K)

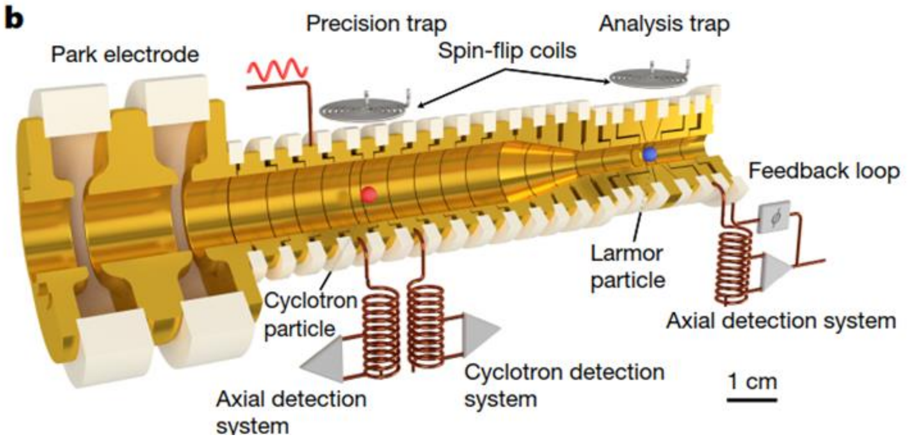


high-fidelity spin state resolution

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.

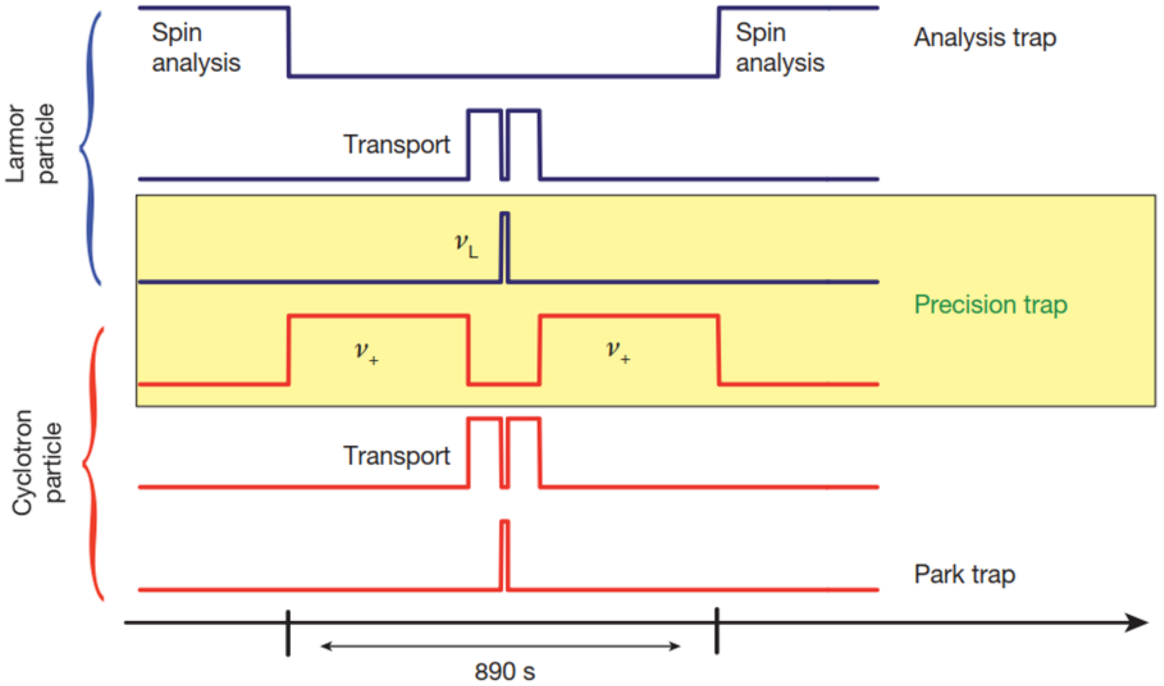


«hot» cyclotron particle which probes the magnetic field in the precision trap

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

pay: measure with two particles at different mode energies

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



Challenges:

- transport without heating
- more challenging systematics

Proton / Antiproton magnetic moment

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	calculate
Relativistic shift	0.03	0.003	measure T / calculate
Magnetic gradient	0.22	0.020	measure / calculate
Magnetic bottle	0.12	0.009	measure / calculate
Trap potential	−0.01	0.001	measure / calculate
Voltage drift	0.04	0.020	measure / calculate
Contaminants	0.00	0.280	measure / constrain
Drive temperature	0.00	0.970	measure / constrain
Spin-state analysis	0.00	0.130	measure / simulate / constrain
Total systematic shift	0.44	1.020	

The table lists the relative systematic shifts (column 2) by which the measured magnetic-moment value was corrected; column 3 is the uncertainty of the correction. Details of these systematic effects and their quantification are given in Methods.

classical trap shifts

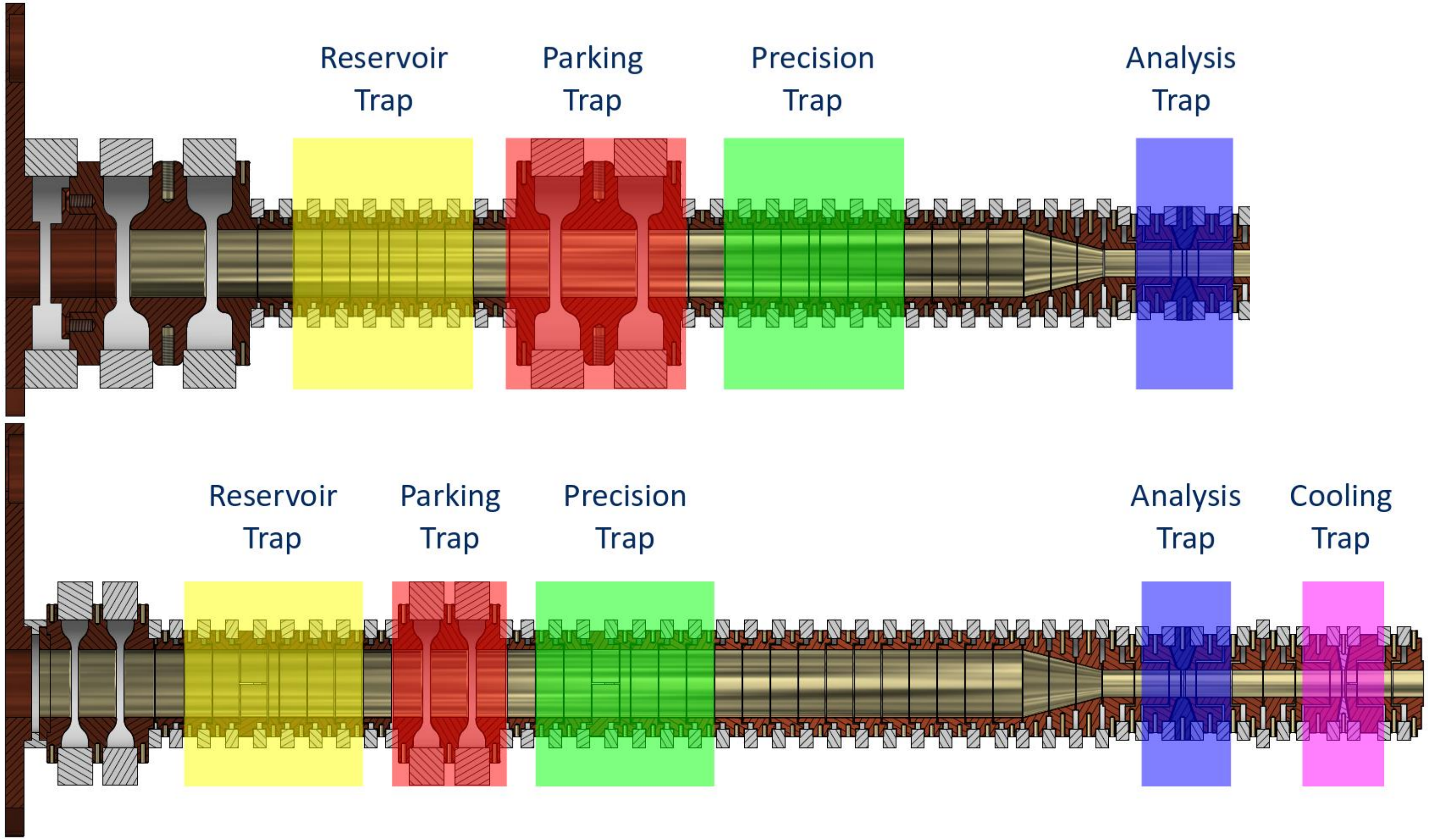
shifts induced by 2 particle approach

- **Best idea: one particle but many traps!**
- All systematics can be **reduced / eliminated** with a **cooling trap** and a **tunable magnet**.

New trap stack

2017:

2020:



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

Cooling trap

- PhD thesis of Markus Fleck
- What is a Cooling Trap?

  -> Trap dedicated to cooling 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.
- Goal: **reduce current 10 h cooling cycles to several minutes.**
- CT cyclotron detector:

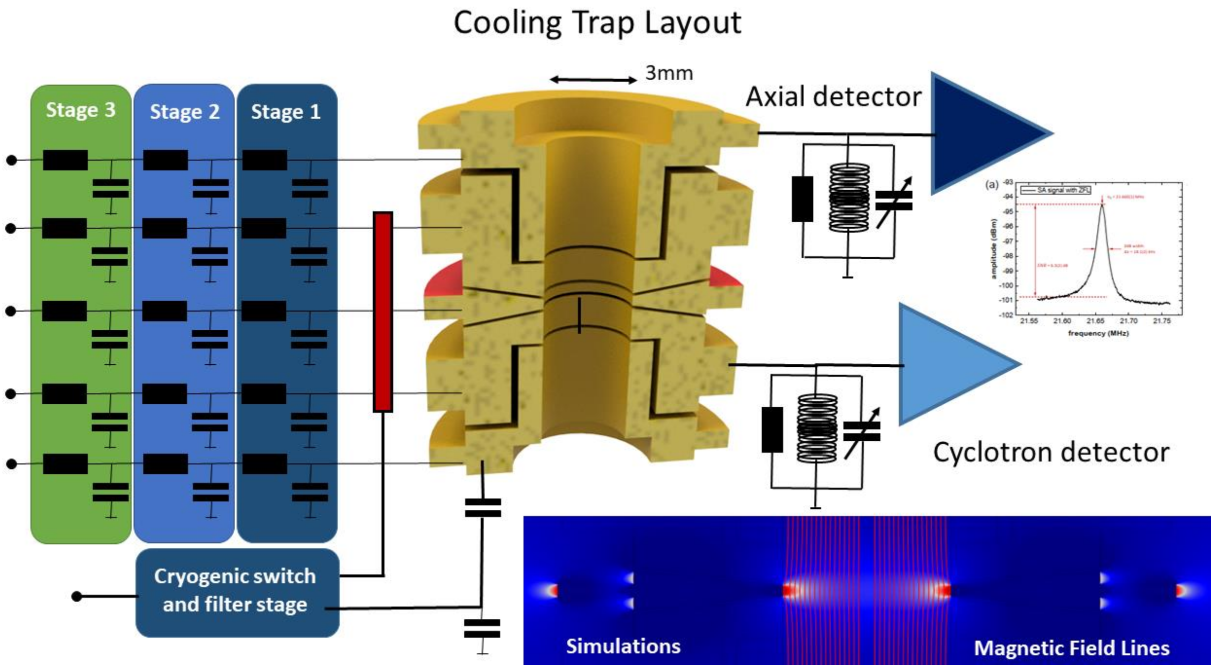
  -> Q ~ 1200 when cold, assembled in our new setup!

  -> cooling time constant ~ 12 s

  -> tuning range > 3 MHz

  -> D~5 mm

  $T = \frac{m}{q^2} * \frac{D^2}{R}$



Magnetic shimming and shielding system

- PhD thesis of Stefan Erlewein
- Idea: introduce a system of cuperconducting coils to compensate residual B2 and B1:

-> Additional 3-layer self shielding system.

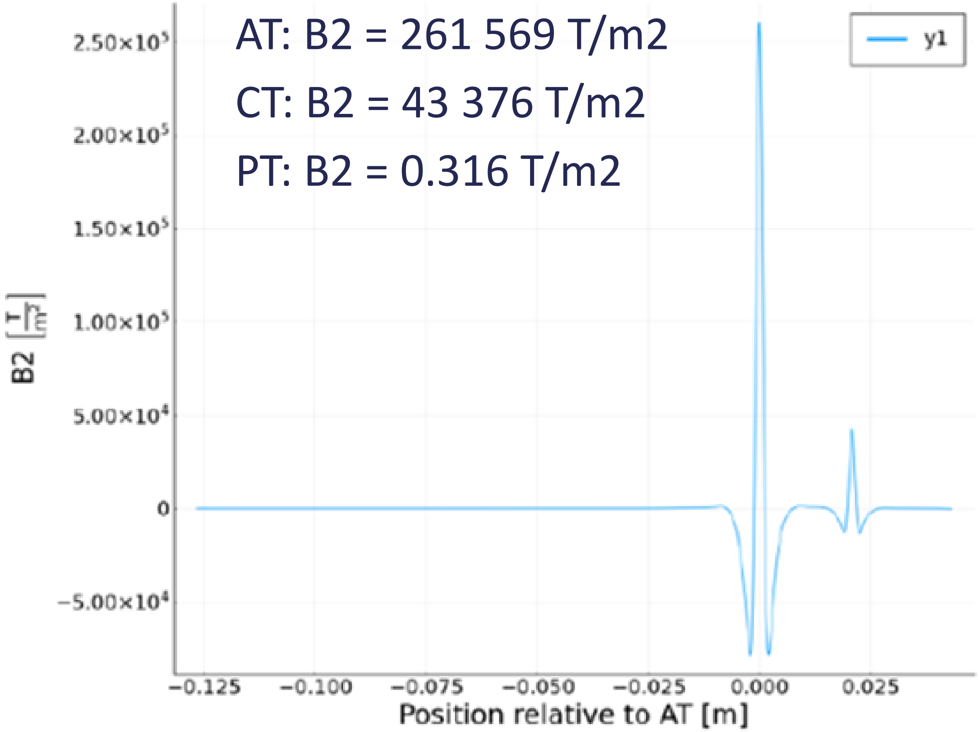
-> Use innermost SSC as B0 coil to be able to change B2 and B1 without changing ν_+.

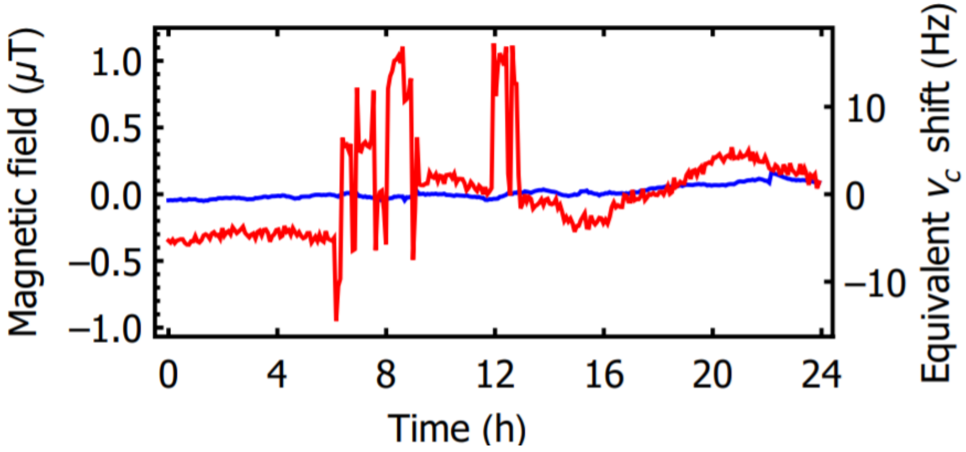
- Residual B2 comming from AT magnetic bottle:

AT: B2 = 261 569 T/m2

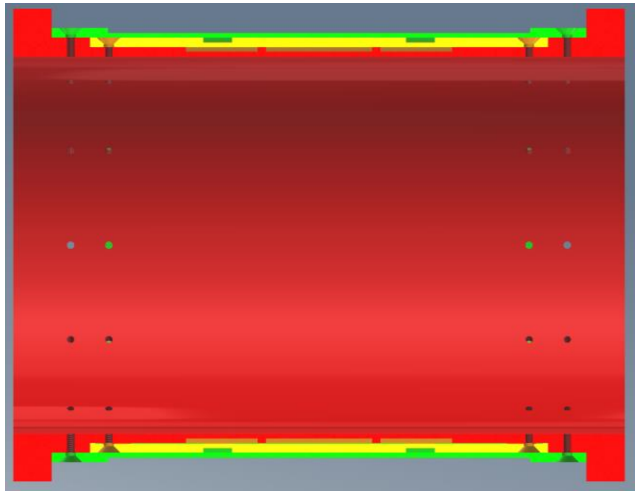
CT: B2 = 43 376 T/m2

PT: B2 = 0.316 T/m2





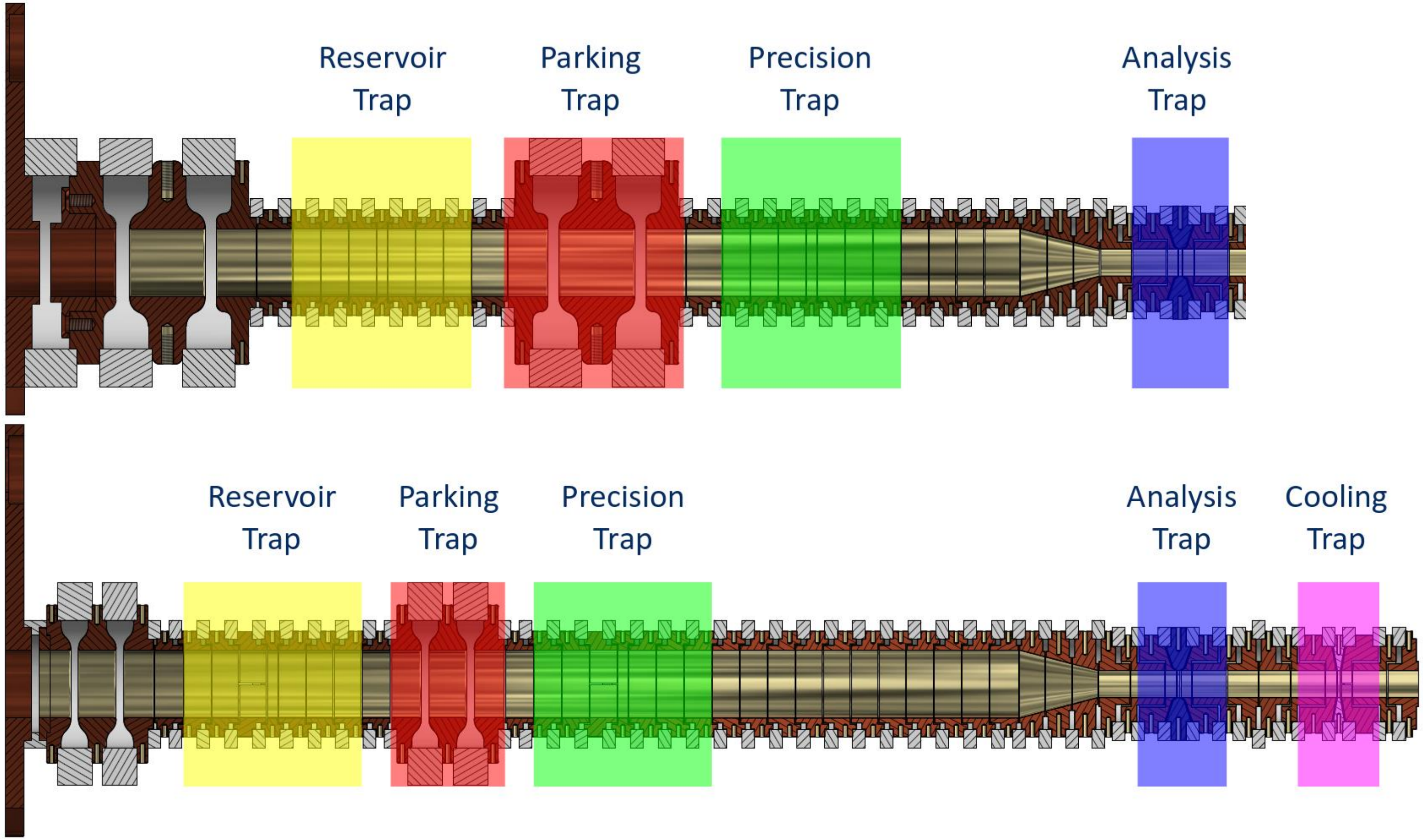
J. A. Devlin et. al., Phys. Rev. Applied 12, 044012 (2019).



New trap stack

2017:

2020:



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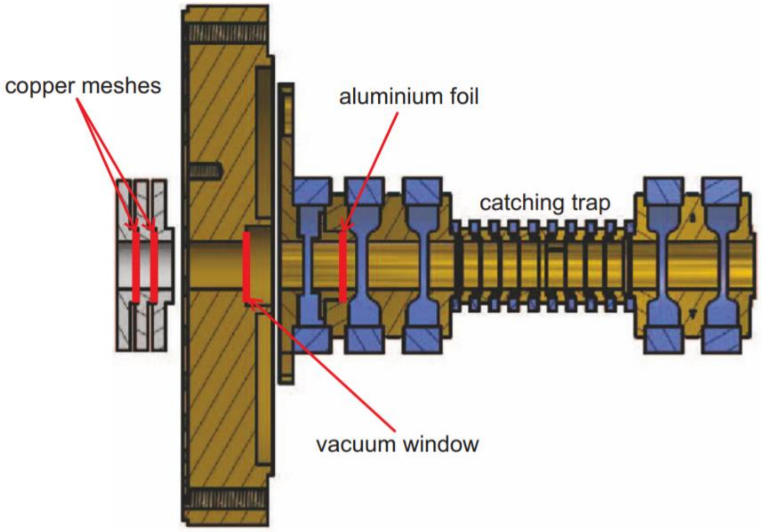
Cooling Trap: Fast cooling of the cyclotron motion.
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
-> To store antiprotons for 405 days we need pressure below 10^{-18} mbar!

New antiproton degrading system

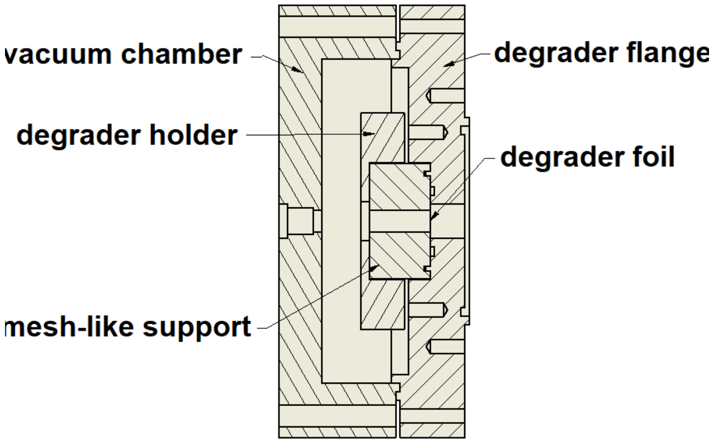
- Project of Barbara Latacz.
- Since 2018 the Antimatter Factory is operating a new **ELENA** (Extra Low ENergy Antiproton) decelerator.
- **The antiproton energy available for experiments decreased from 5.3 MeV to only 100 keV, which corresponds to the degrading foil thickness of about 1-3 µm.**
- **Challenge: 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 ???**

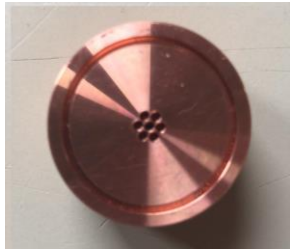
Old system:
the required window was a 25µm thick stainless-steel foil together with six stacked copper meshes and thin aluminum foil to optimise the antiproton stopping power.



New system:
Vacuum window and the degrader in one piece - 2 µm thick Mylar foil coated on both sides with 80 nm of Al.
- Beam acceptance: 7 holes with 1 mm diameter - 17.1 % ($\sigma_{x,y}$=2 mm, 5×10^6 p)

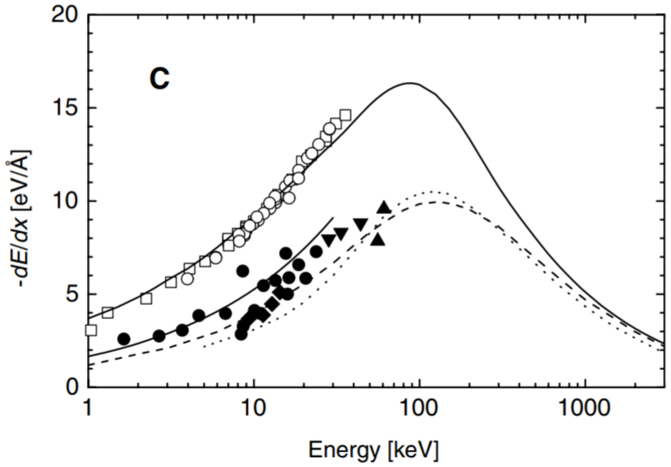
→ in the worst expected case with 0.3 % trapping probability it gives 2550 particles.



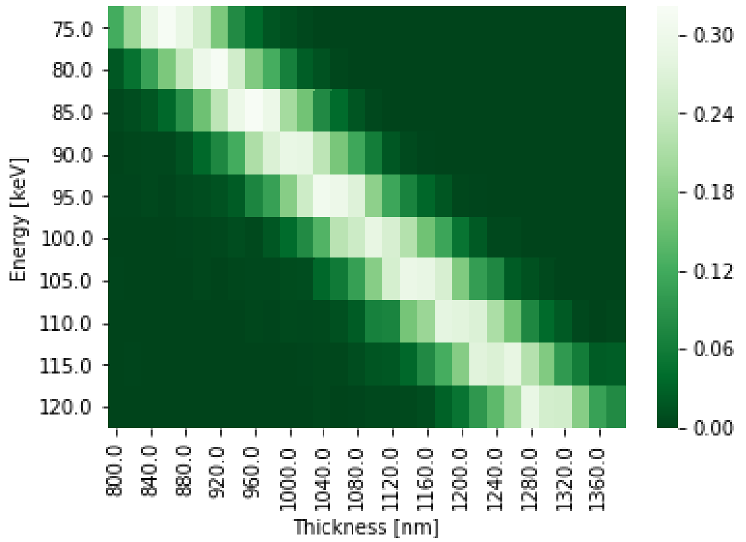


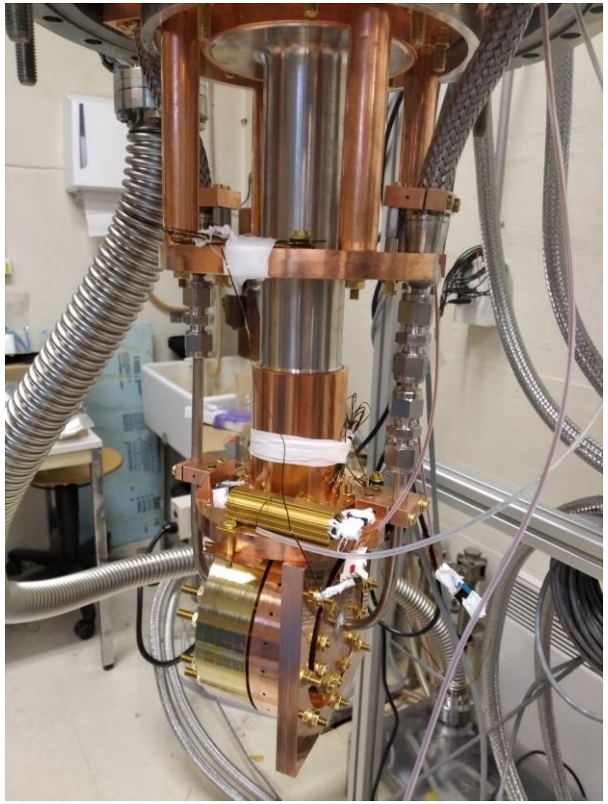
New Degrader system

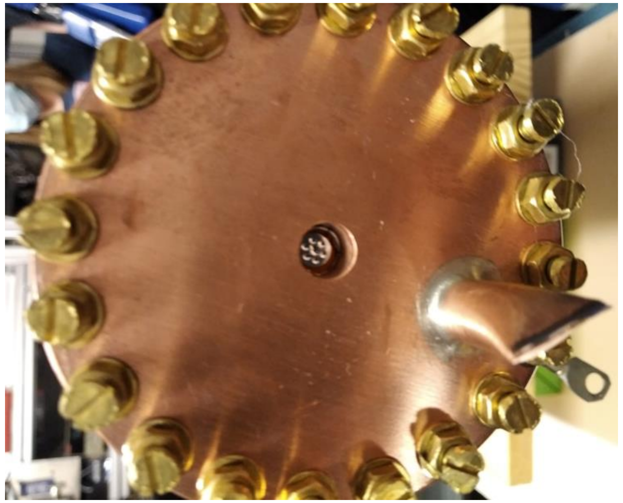
- Estimated antyproton caching efficiency:



DOI: 10.1103/PhysRevLett.88.193201



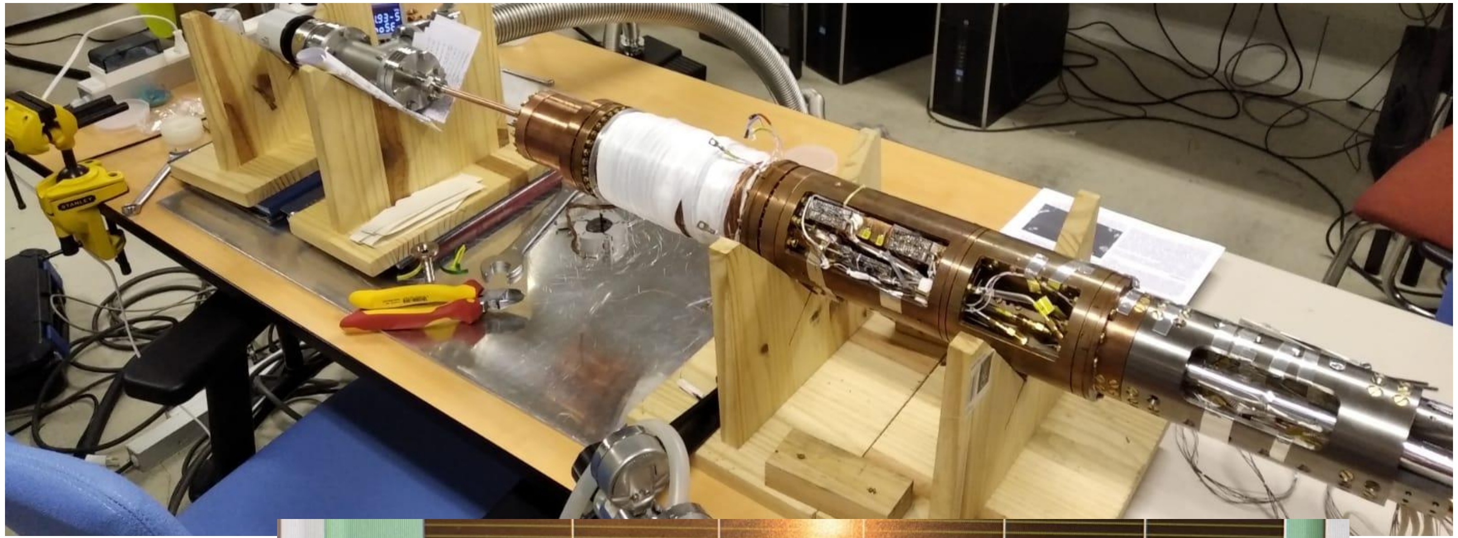


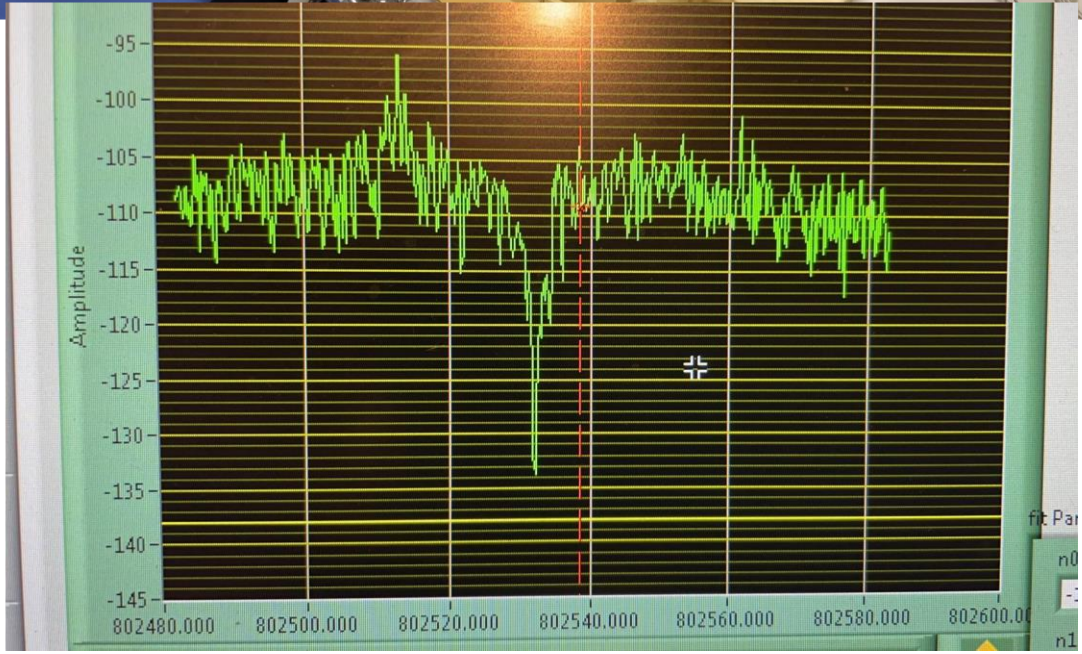


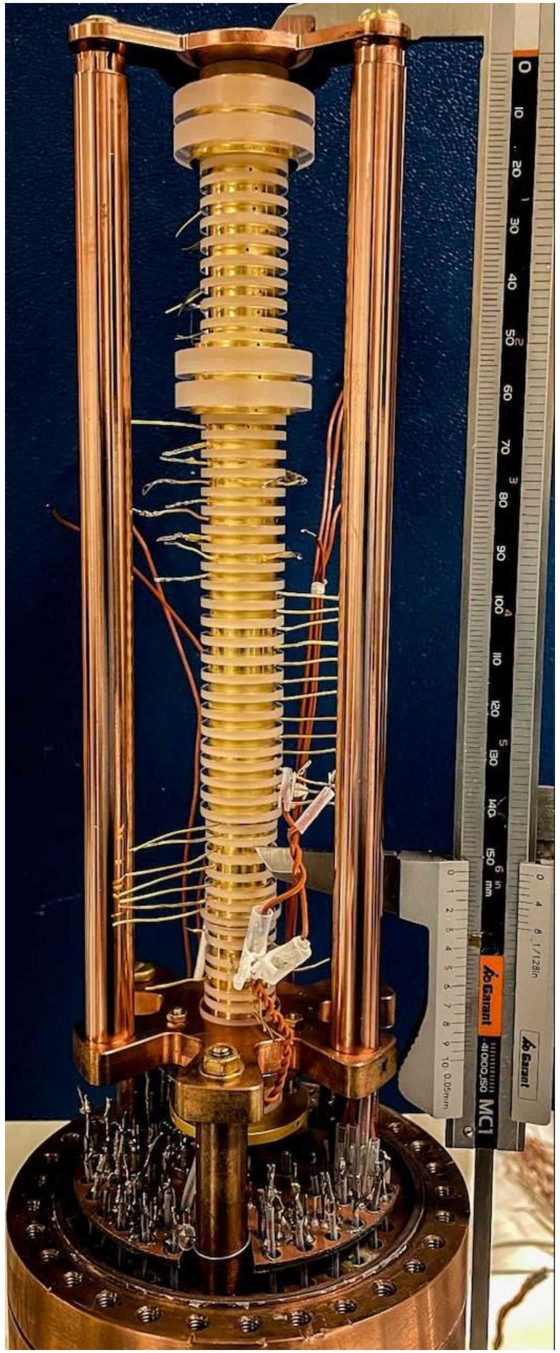
- We estimated that to be safe even if we would be open into air for 30 days, we need the system with leak < 10^{-8} mbar l/s with 1 bar pressure difference.
- **300 K: $5x10^{-9}$ mbar l/s.**
- **7 K: max around $4x10^{-11}$ mbar l/s.**
- System did not break under different endurance tests like repetitive cooling cycles, stretching in air and even in liquid nitrogen (!).

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

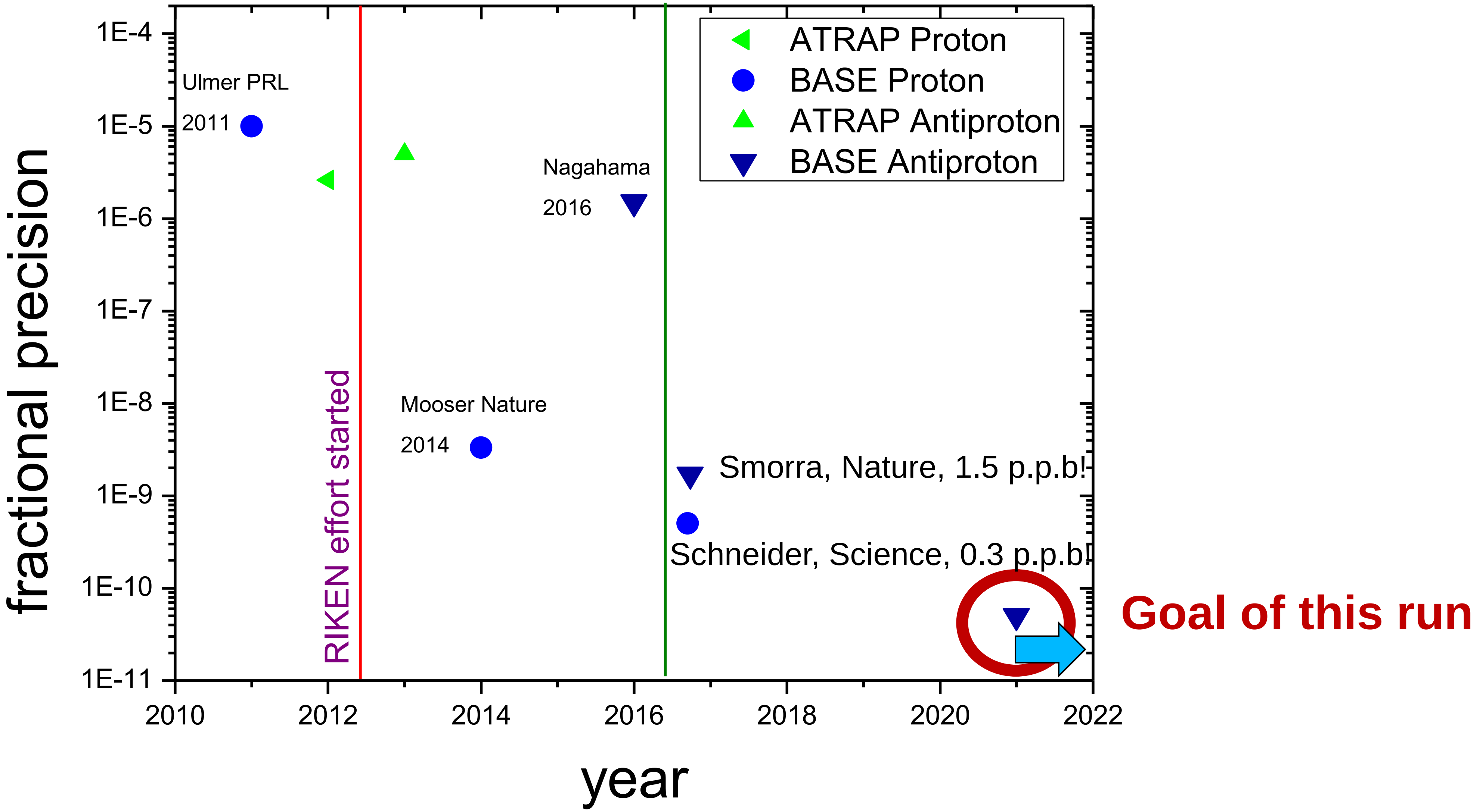
The 2021 experimental setup





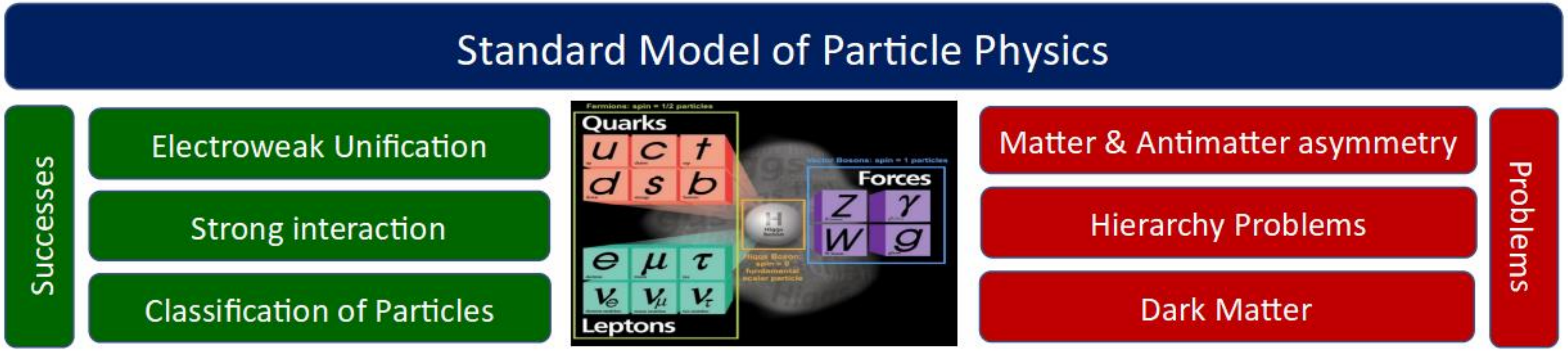


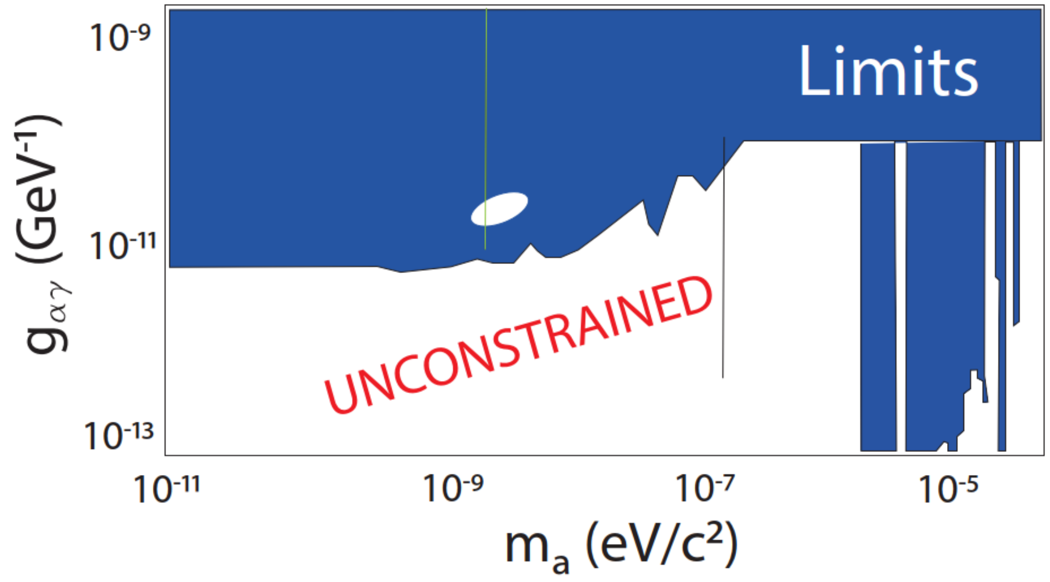
Proton / Antiproton magnetic moment



Cold dark matter searches - motivation

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

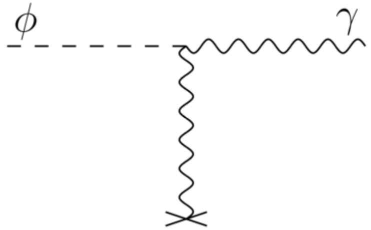




- **Axion Like Particles - ALPs:**

→ 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:

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

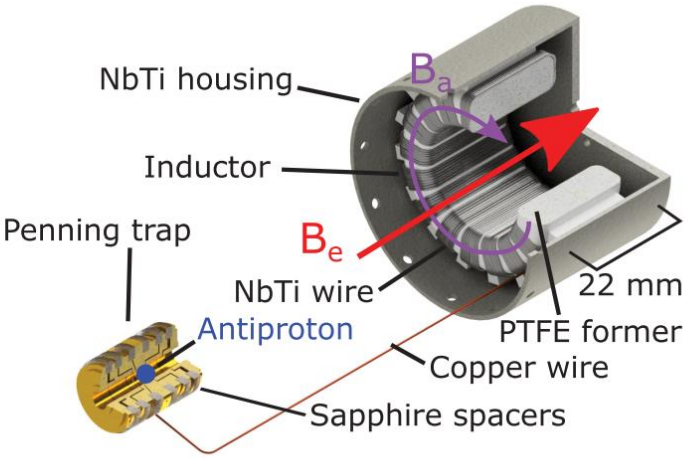
- Coupling of ALP field to **E** and **B** fields:

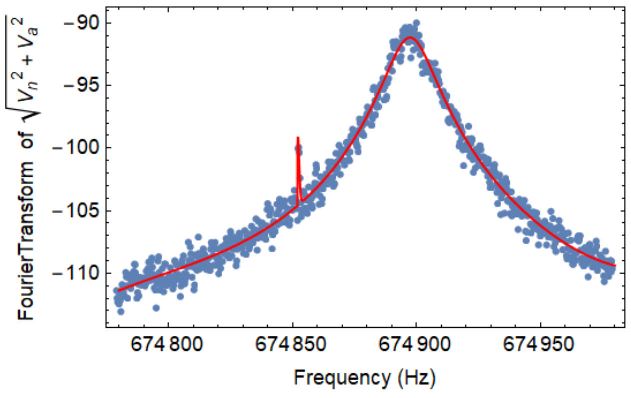
$$L_{a\gamma} = -g_{a\gamma} a(x)\mathbf{E}(x) \cdot \mathbf{B}(x)$$

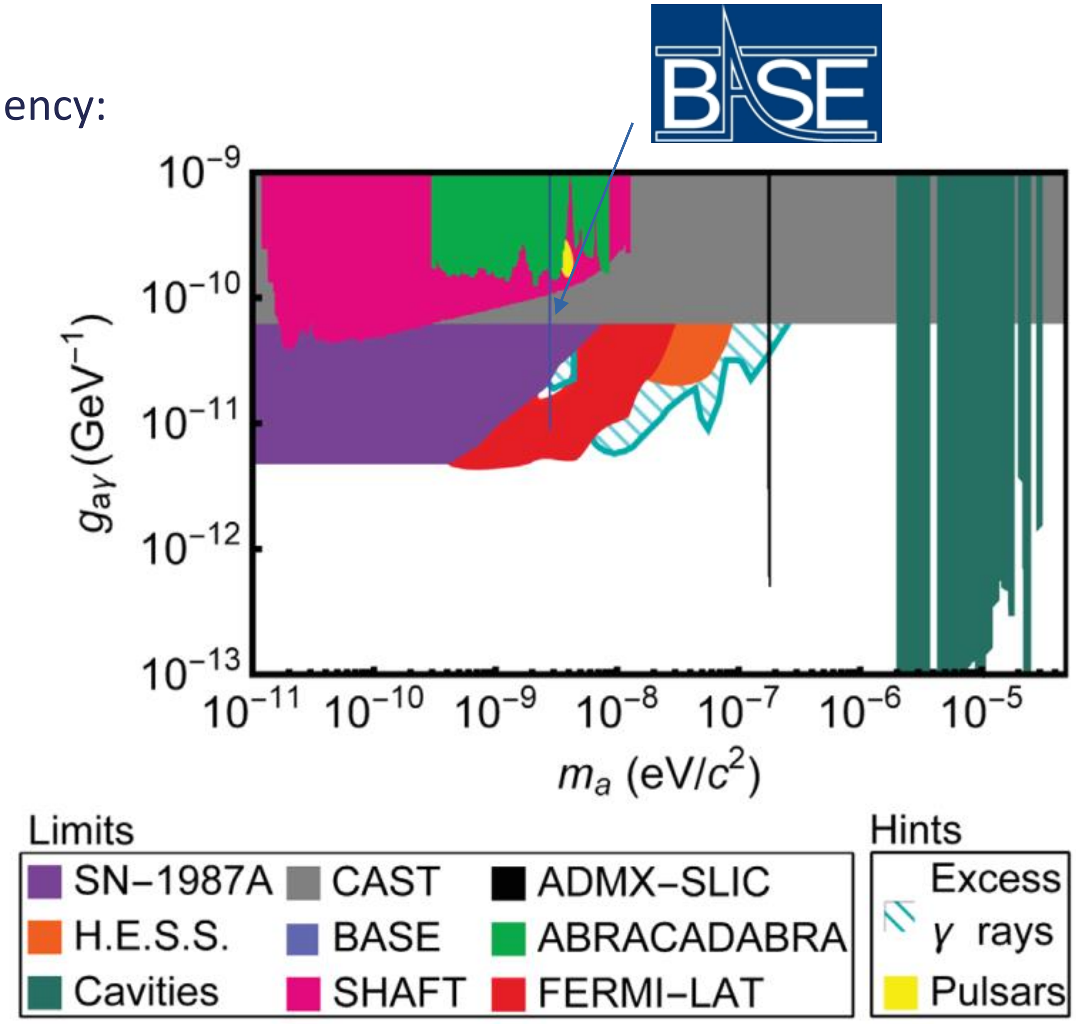
- The oscillating ALP field source oscillating magnetic field:

$$\nabla \times \mathbf{B} - \mu \frac{\partial \mathbf{E}}{\partial t} = -g_{a\gamma} \mathbf{B}_e \frac{\partial a}{\partial t}$$
$$\mathbf{B}_a = -\frac{1}{2} g_{a\gamma} r \sqrt{\rho_a \hbar c} B_e \hat{\phi}$$

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







Upgraded ALPs detection sensitivity

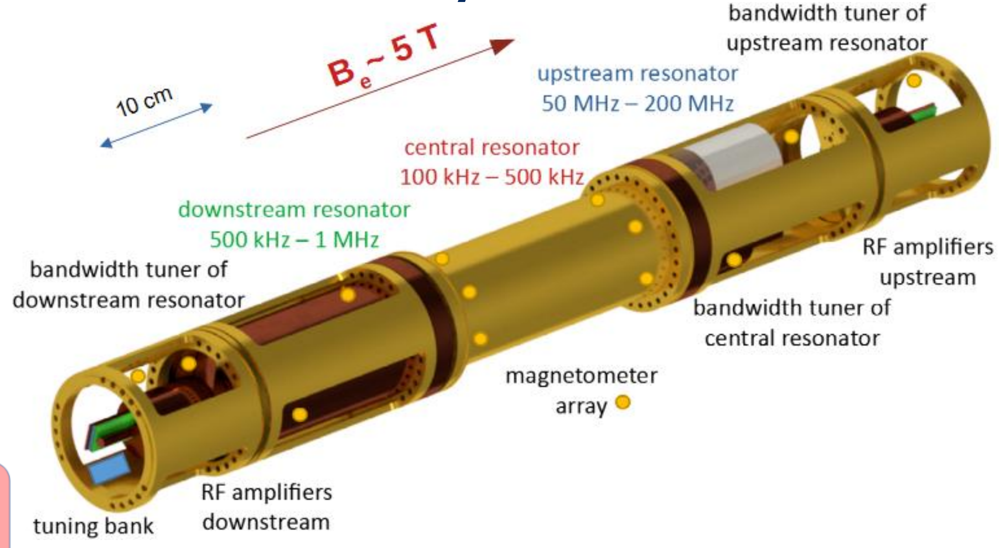
- Dedicated ALPs detection experiment:

→ improved sensitivity

Magnetic field | **Temperature** and **Quality factor** of the detector | **Measurement averaging time**

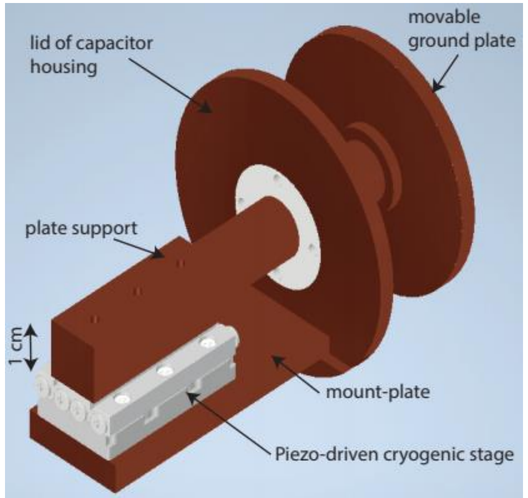
$$Limit\left(g_{a\gamma}\right) \sim \frac{1}{B_e} \cdot \frac{1}{V} \cdot \sqrt{\frac{T}{Q} \cdot \frac{e_n}{\kappa} \cdot \frac{1}{N_{av}}}$$

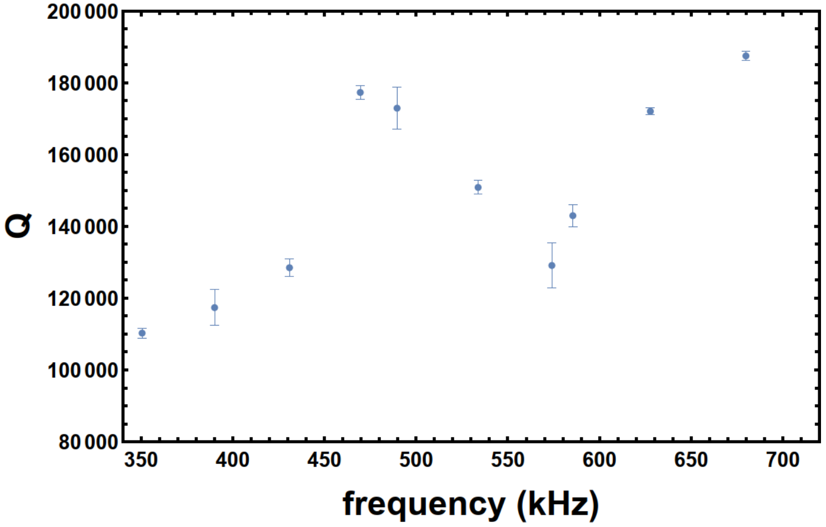
Volume of the detector | **Amplifier noise contribution** which defines the strength of the signal with respect to the noise of the amplifier

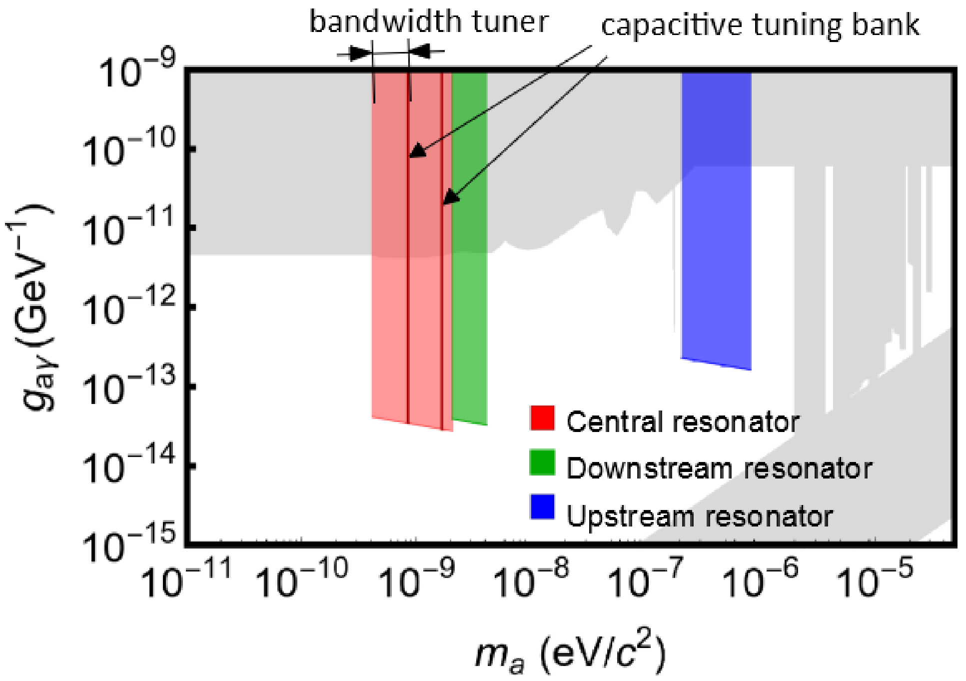


→ increased bandwidth between 500 kHz and 200 MHz with a tunable capacitance of the resonator (which does not decrease Q value!).

- Prototype - bachelor thesis of F. Voelksen







Summary

- 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

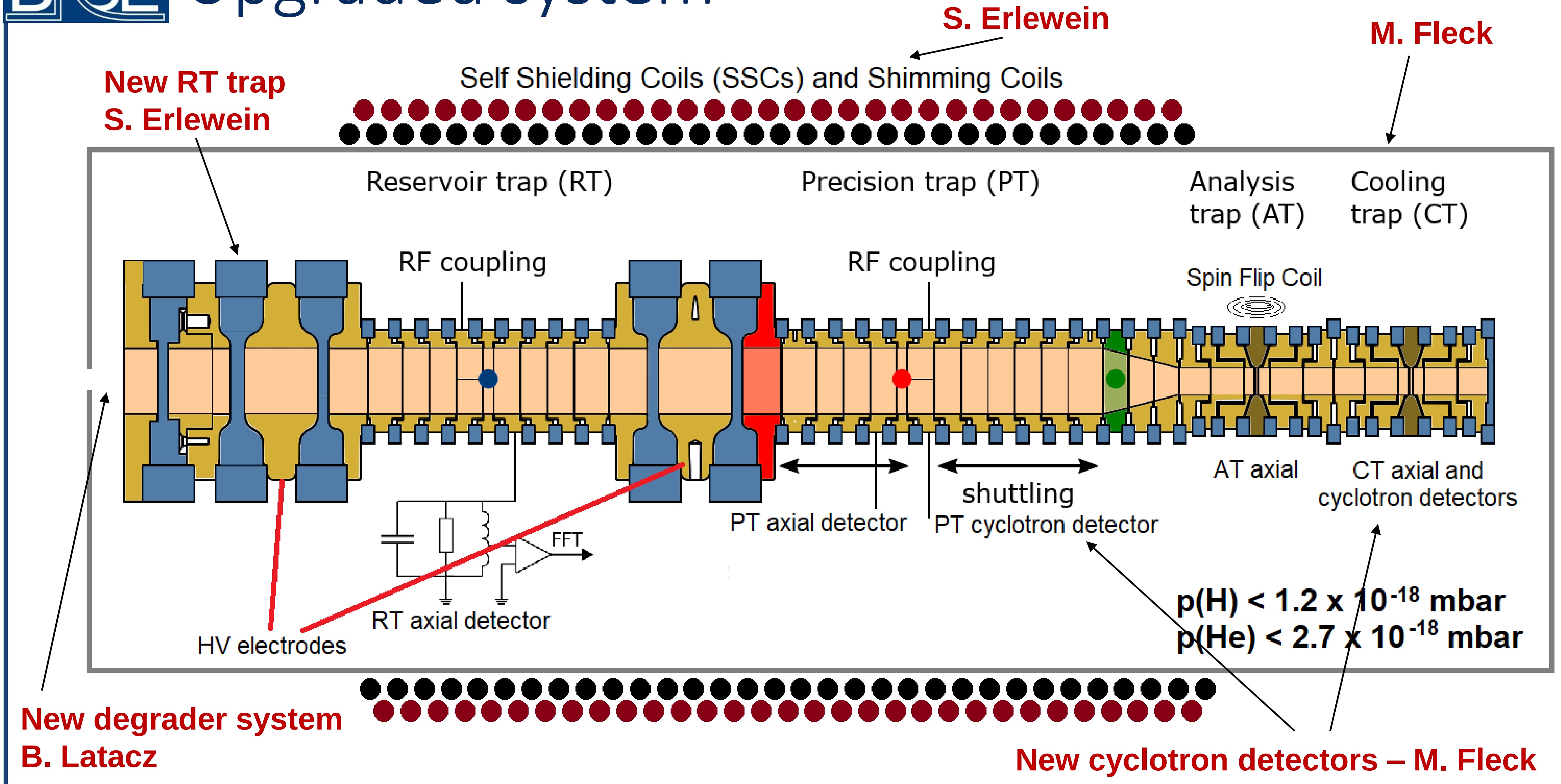
-> new cooling trap

-> new magnetic shimming and shielding system.

- In the meantime we will continue to develop dark matter searches experiments.

We can't wait for the 2021/2022 run!!!

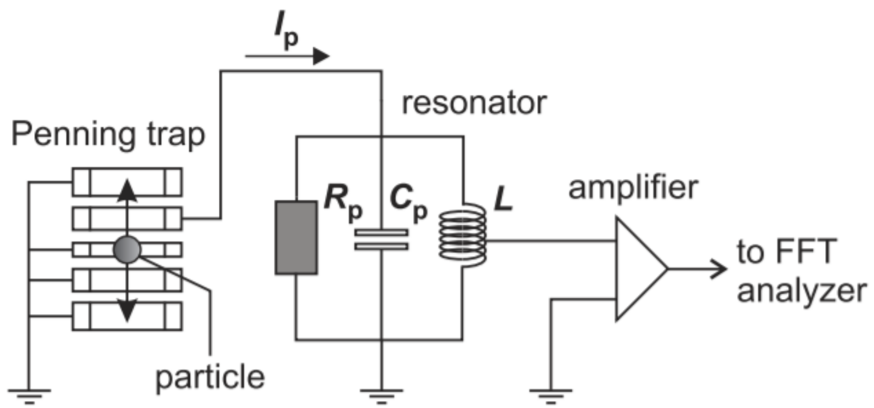
Upgraded system

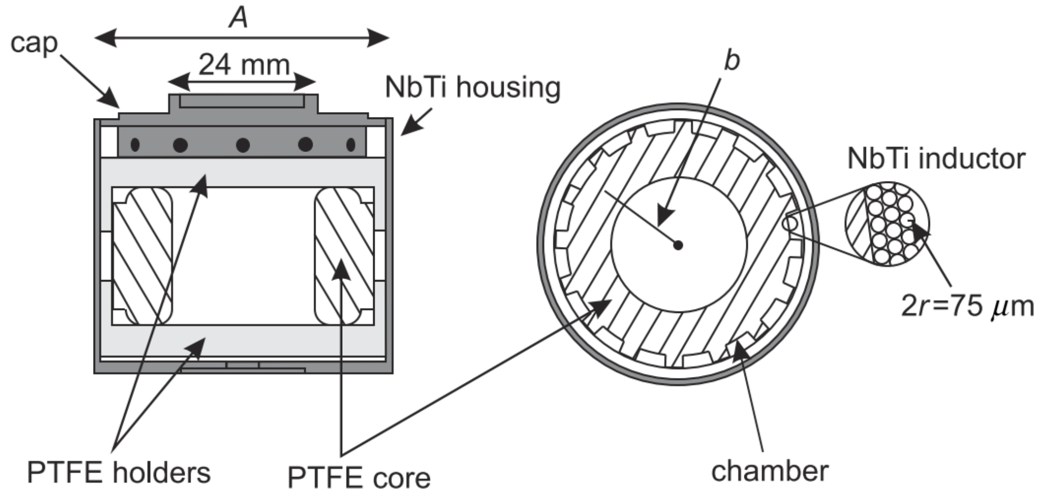


4 axial detectors! S. Ulmer, H. Nagahama. J.Devlin, B. Latacz

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

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