Model based extreme vacuum pressure measurements at BASE

Barbara Latacz

on behalf of the BASE collaboration

RIKEN

06 / 04 / 2022

PBC Technologies mini-workshop on Vacuum, Coating and Surface Technologies

MAX-PLANCK-GESELLSCHAFT

東京大学 THE UNIVERSITY OF TOKYO

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Leibniz Universität Hannover

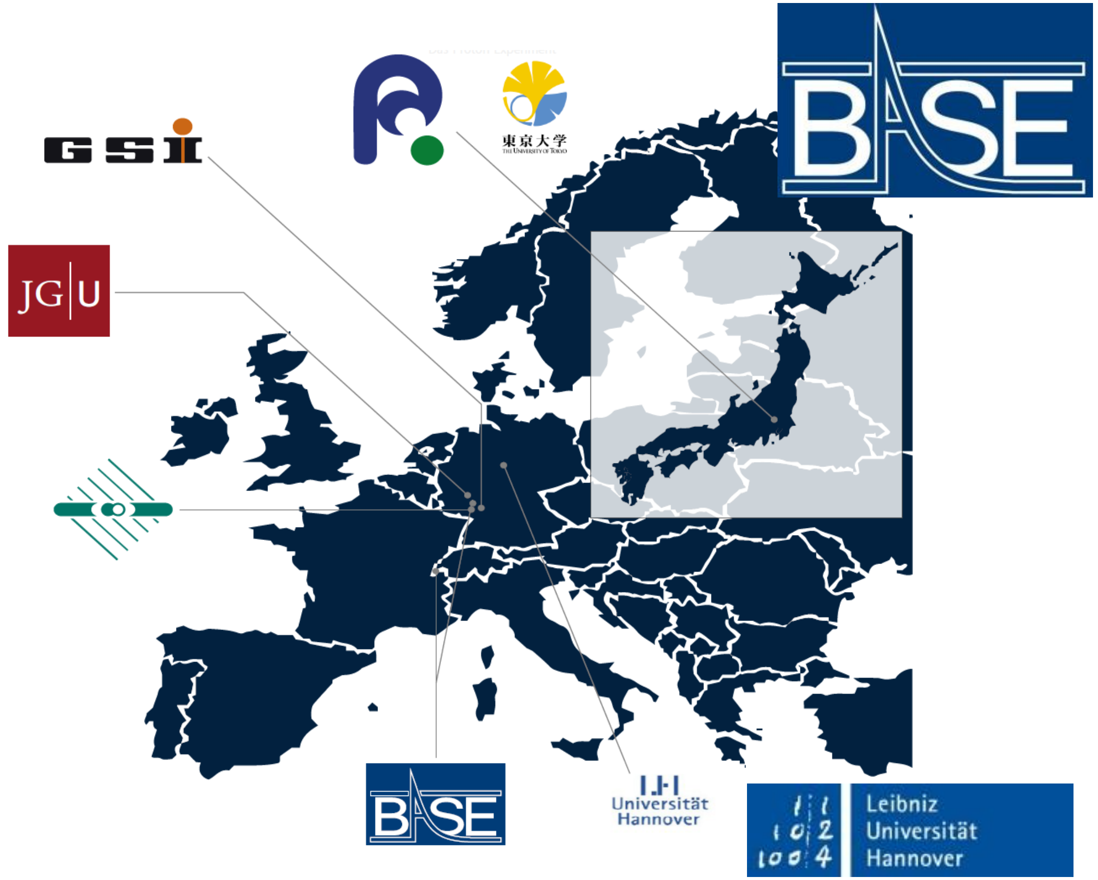
ETH Zürich

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
- ○ **A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio,** Nature 601.7891 (2022): 53-57.
- ○ **BASE-STEP:** transport of antiprotons outside AD

Christian Smorra, Fatma Abbass, Daniel Popper



- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies (RIKEN/MPG)

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

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

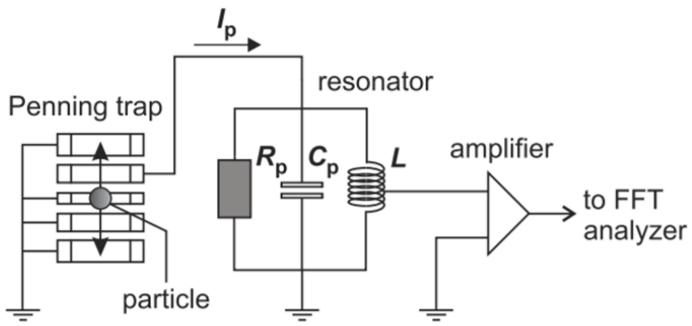
Penning trap

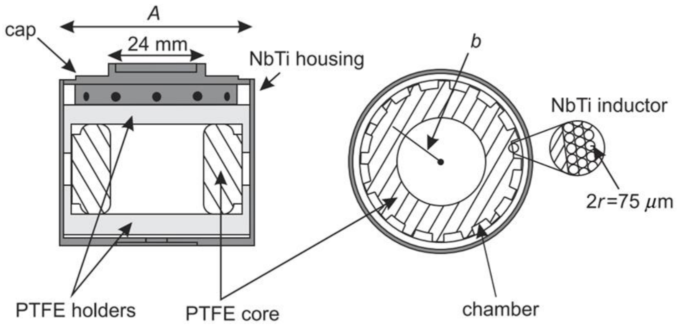
- **Penning trap with:**

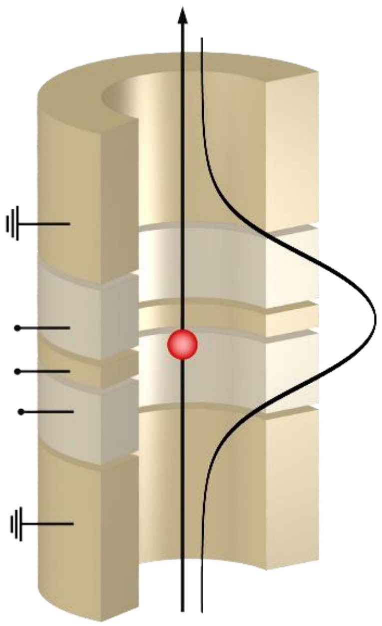
  -> radial confinement: $\vec{B} = B_0 \hat{z}$

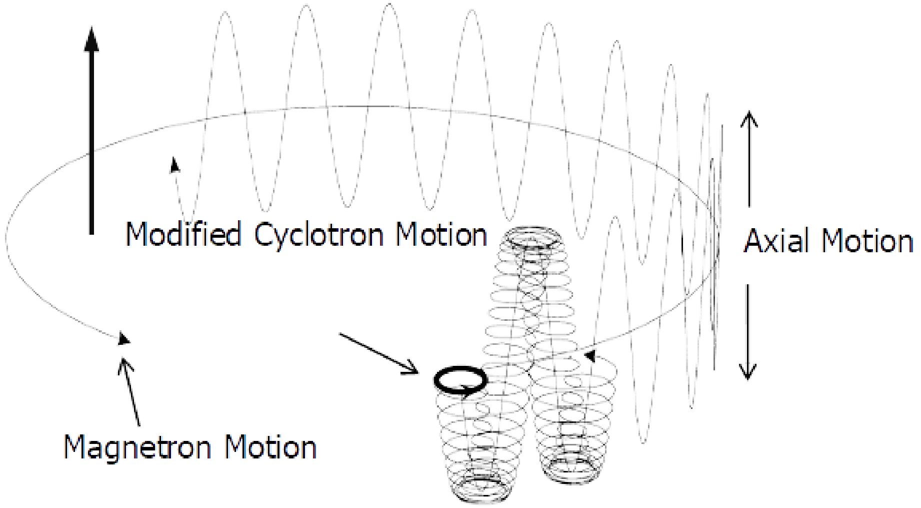
  -> axial confifement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

- **Measurement of fA image currents induced in trap electrodes by the superconducting thoroidal resonators:**







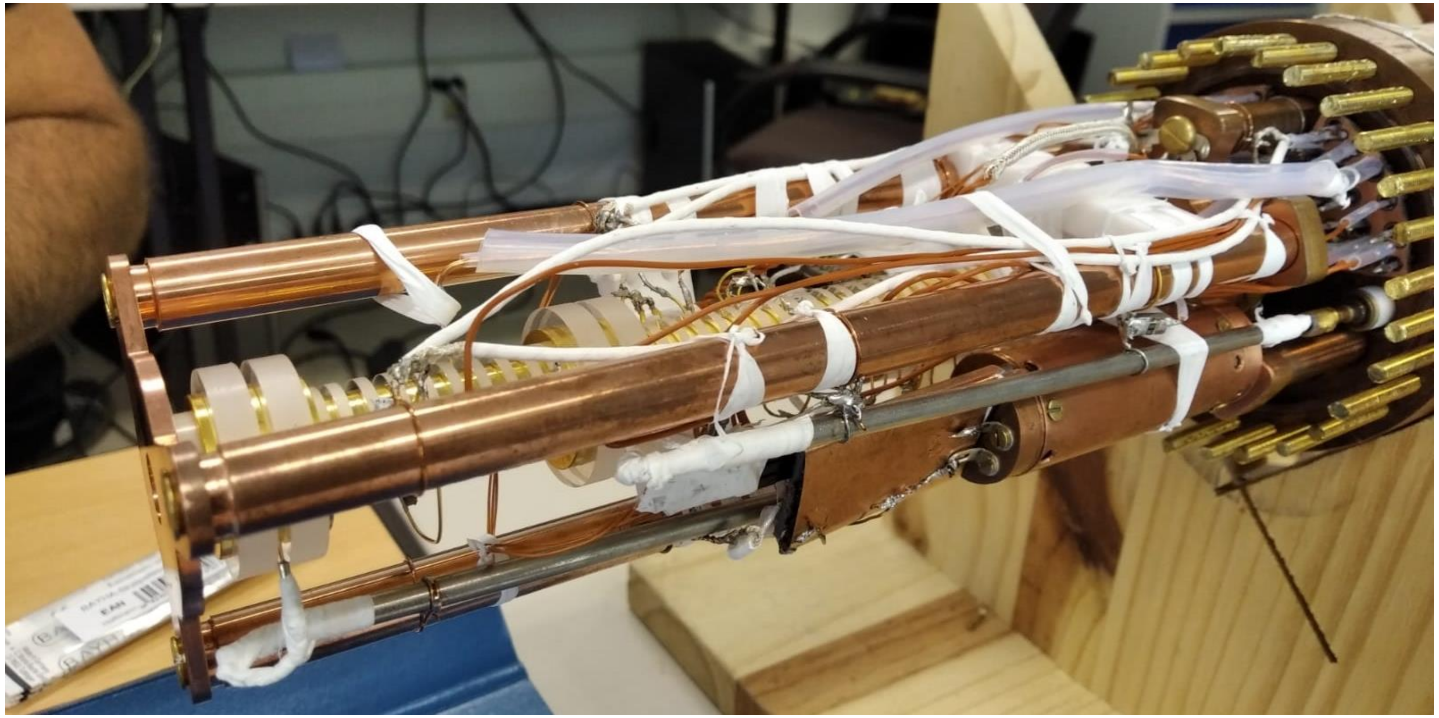


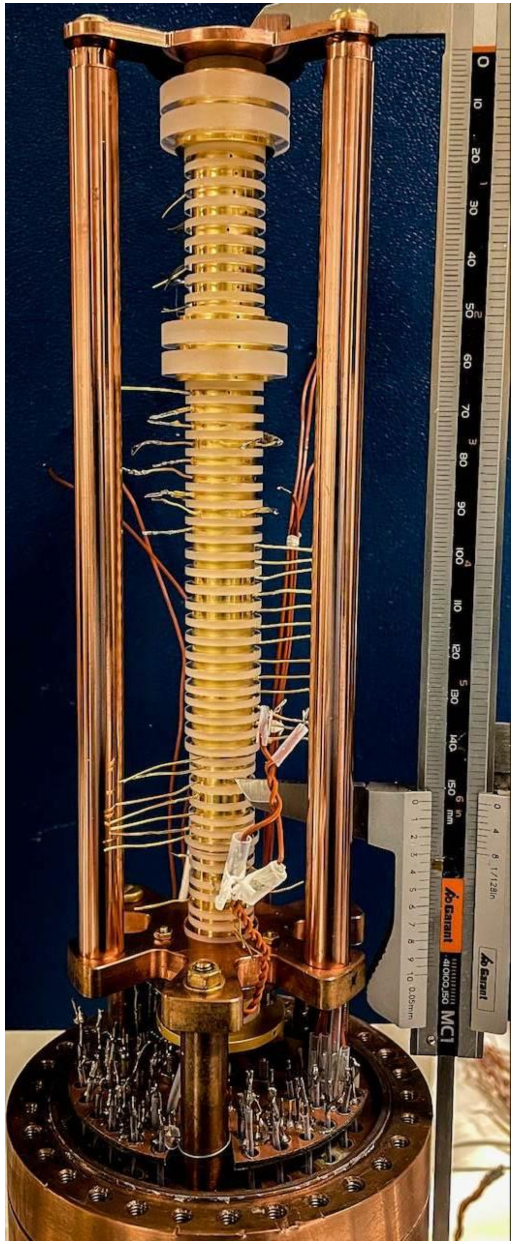
Axial	**649.140 kHz**	$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}$
Magnetron	7.106 kHz	$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
Cyclotron	29.640788 MHz	$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$

Vacuum at BASE

- Our record: 2018/2019 with $\boldsymbol{p_H < 0.46 \times 10^{-18}}$ **mbar** and $\boldsymbol{p_{He} < 1.04 \times 10^{-18}}$ **mbar**.

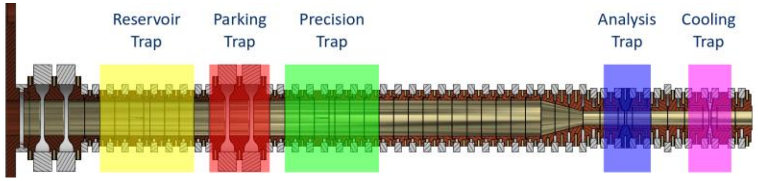
How do we measure this?
How do we achieve this?

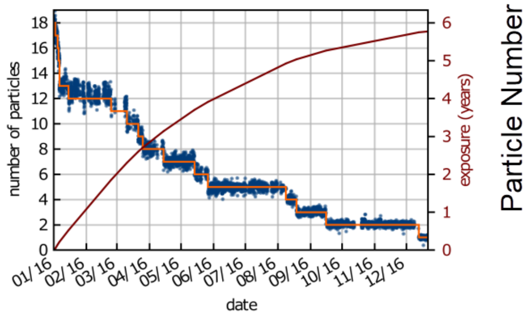


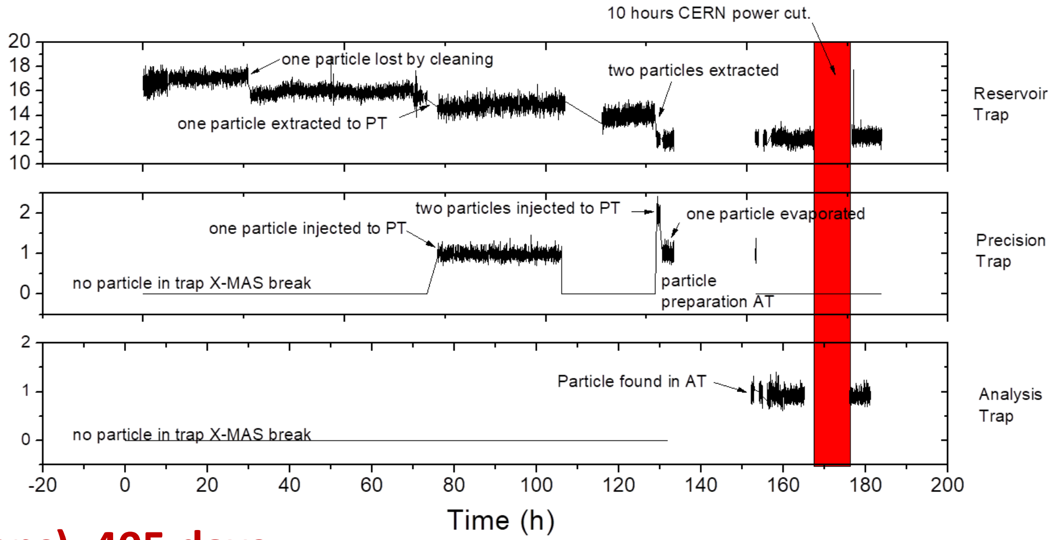


Antiproton pressure gauge

- **We know when and how many particles are in the reservoir trap.**







- **The record for storing antimatter without passive losses (antiprotons): 405 days.**
- S. X. Sellner, et al. New J. Phys. 19(8):083023, August 2017.

- Fei, „Trapping low Energy antiprotons in an ion trap," Ph.D. dissertation, Harvard University, 1990.
- Antiprotons/protons interact with residua gas via charge exchange reactions:

$$\sigma \sim q^2$$

where q is a charge of stored ion.

Under un assumption of simple idea gas laws we can derive formulas to estimate pressure in the system:

$$\boldsymbol{P_H[mbar] = 5.92 \times 10^{-16} T[K]/\tau[day]}$$

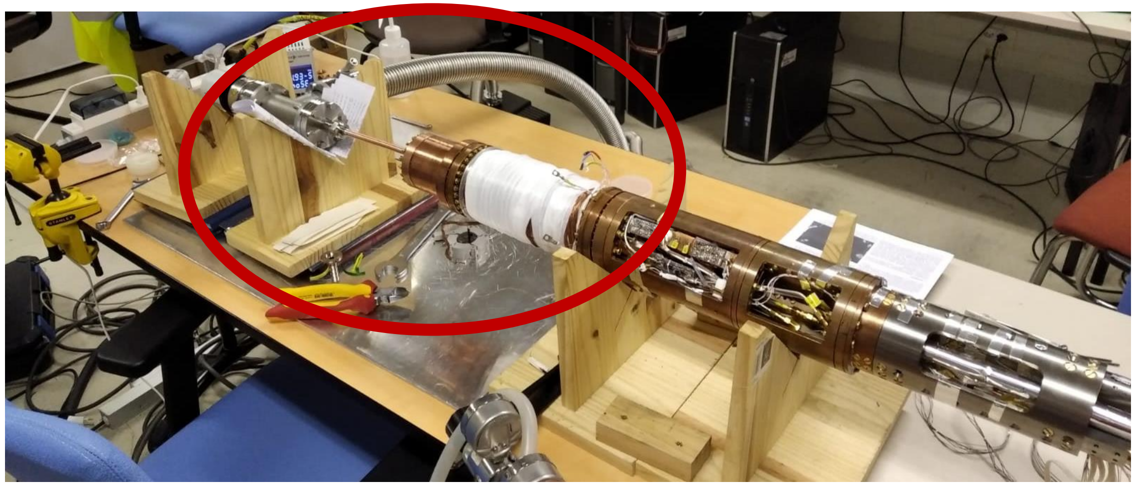
$$\boldsymbol{P_{He}[mbar] = 1.34 \times 10^{-15} T[K]/\tau[day]}$$

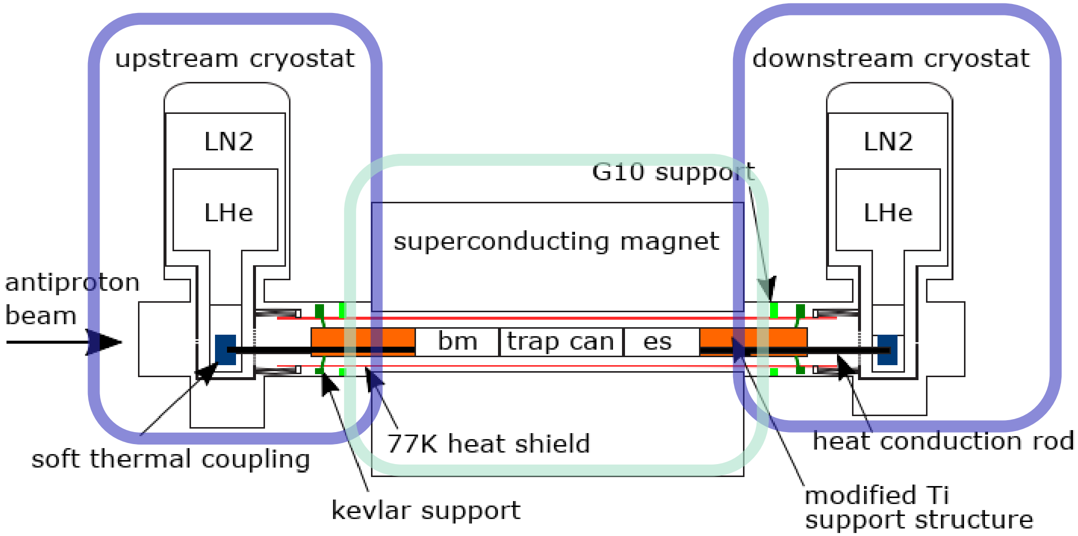
τ $-$ *time without any particle loss*

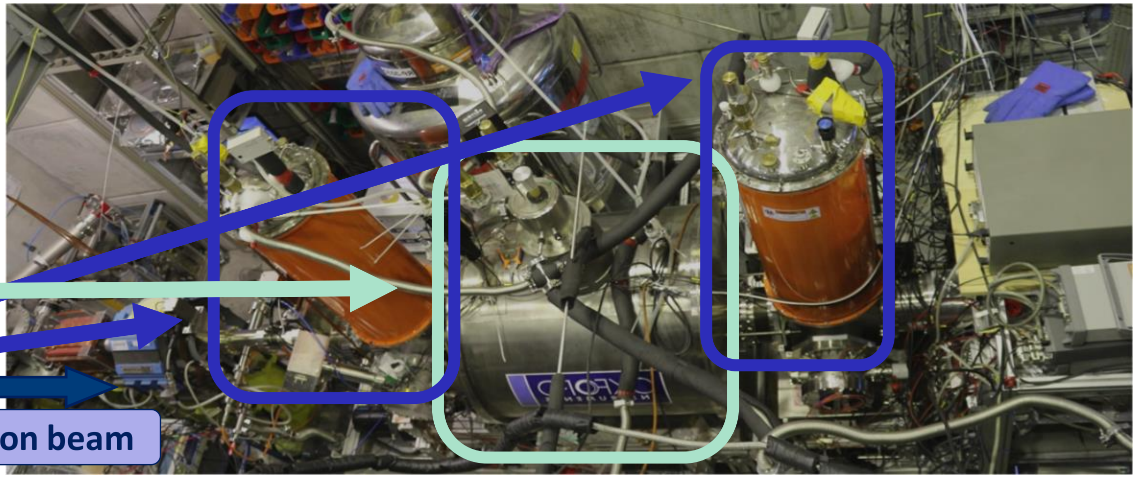
-> To perform experiments we need to reach pressure below 10^{-17} mbar.

Experimental Apparatus

- **Procedure to close the experiment:**
  - Bake the system at 100 deg for 24 h while pumping to reach about 10^{-8} mbar pressure.
  - Pinch off.
  - Close the experiment inside the magnet in the vacuum which reaches $1x10^{-8}$ mbar.
  - Cool with LN and LHe







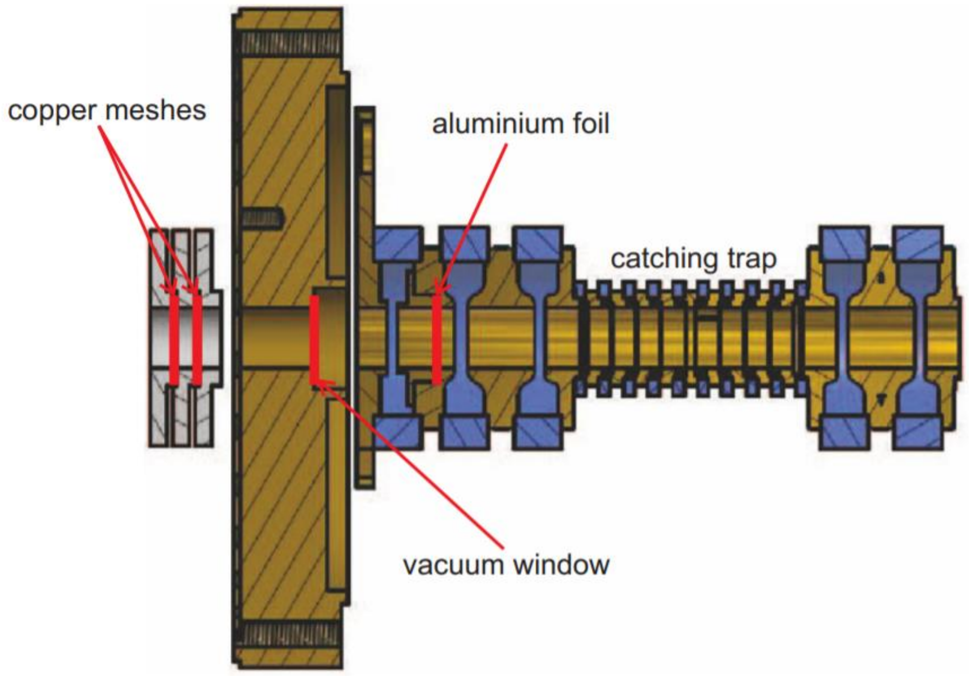
Superconducting Magnet

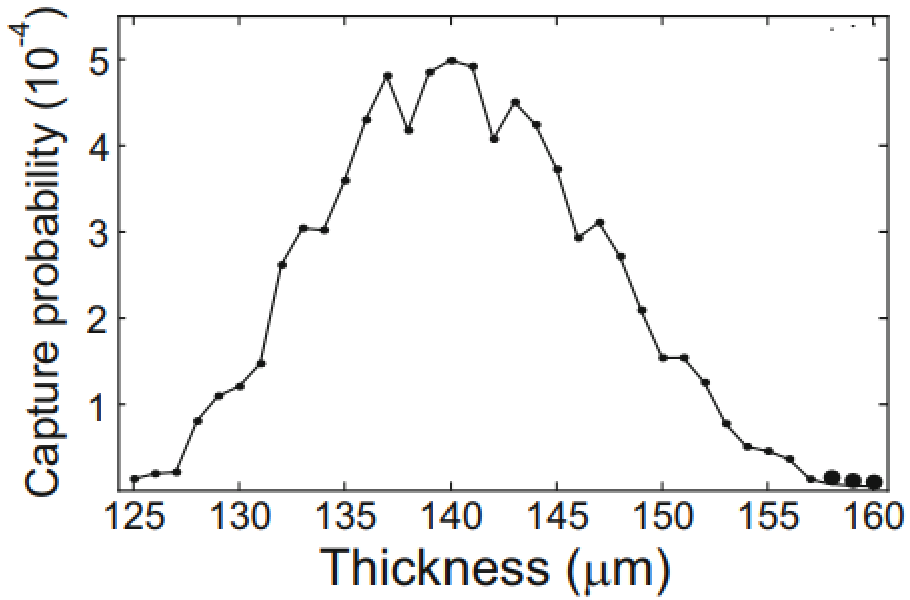
Cryostats for LN2 and LHe

Antiproton beam

2012-2019 trap can vacuum system

- **Vacuum window and the window for particles at the same time.**
- AD antiproton beam has an energy of 5.3 MeV which corresponds to the degrading thickness of about 150 µm of aluminium.
- Multi-layer degrading system:
    - 25µm thick stainless-steel foil soldered to the flange
    - six stacked copper meshes
    - thin aluminum foil to optimise the antiproton stopping power.





For E<1 keV

- **With this system BASE trapped antiprotons for 405 days** (destroyed on purpose).
- 2018/2019 system: $\boldsymbol{p_H < 0.46 \times 10^{-18}}$ **mbar** and $\boldsymbol{p_{He} < 1.04 \times 10^{-18}}$ **mbar**.

2021/2022 trap can vacuum system

- Since 2021 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 ???**

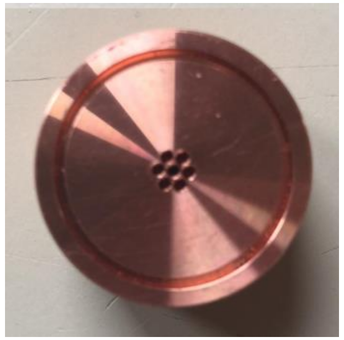
- The leak through the foil of thickness *d* and area *A*, under the pressure difference of Δp is equal to

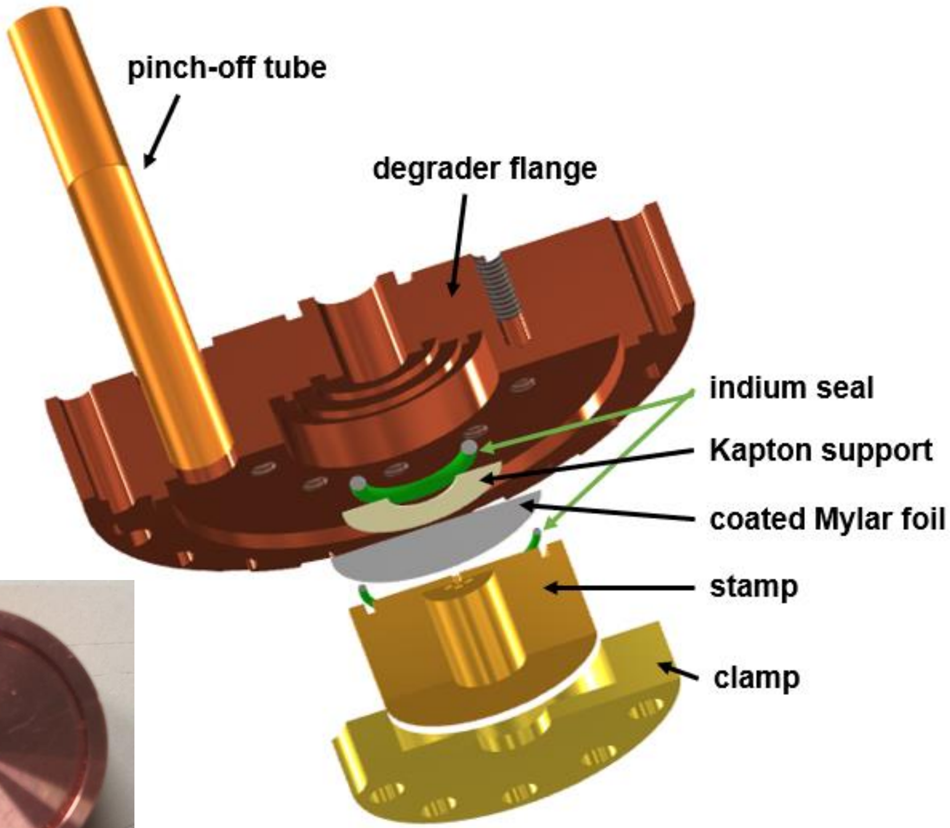
$$L_{foil}(A, d, \Delta p) = K_{foil} \times \frac{A}{d} \times \Delta p$$

where K_{foil} is the permeation constant of the foil.

- 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 -> permeation constant of 10^{-14} m^2/s.

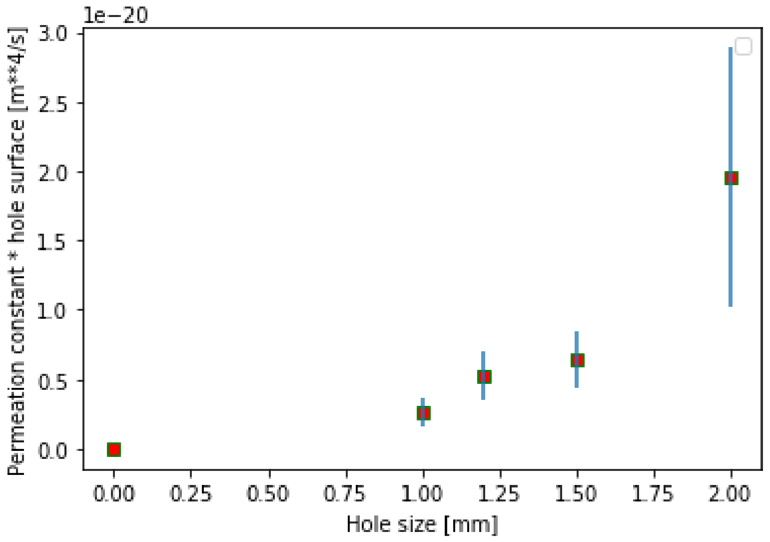
- Coating Mylar on both sides with Aluminium decreases the permeation constant by two orsers of magnitude to required level.

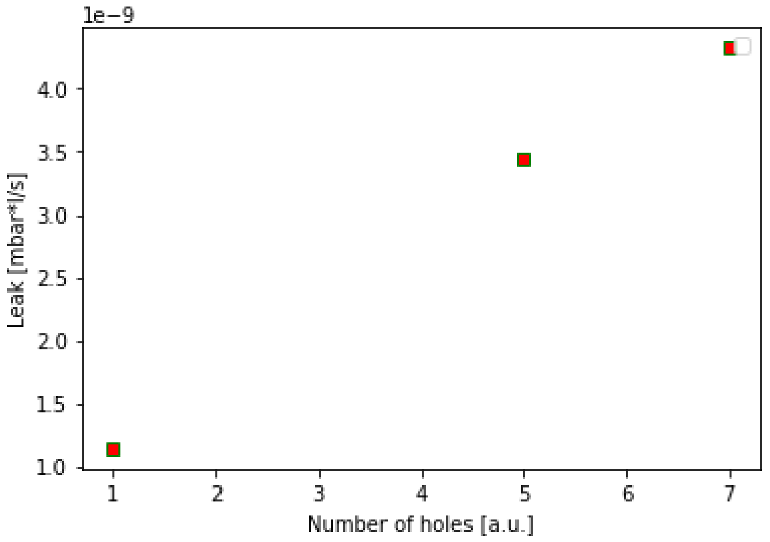


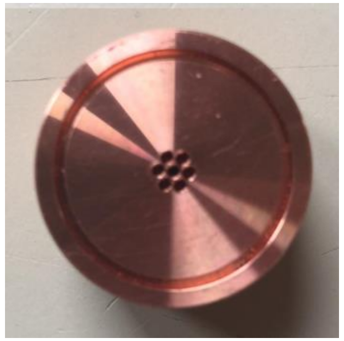


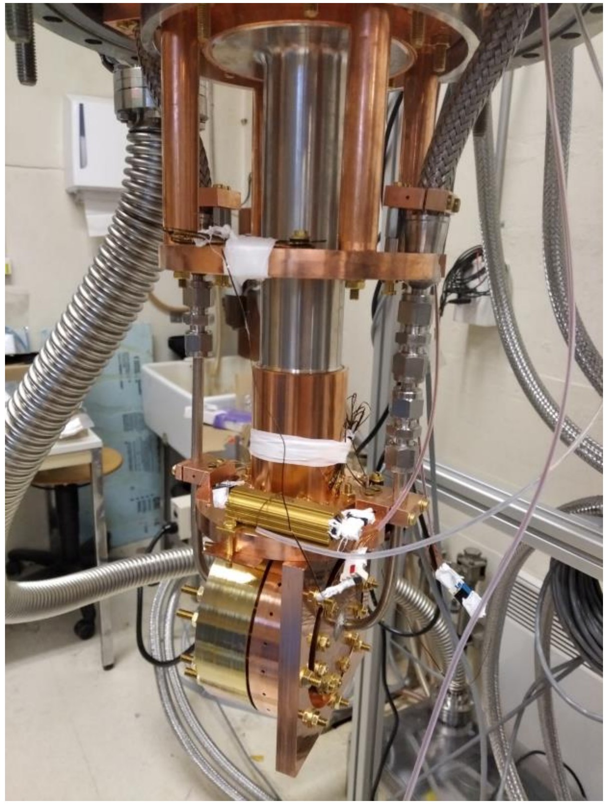
Window - Stamp Optimisation

- Optimisation of the stamp/window „shape”:









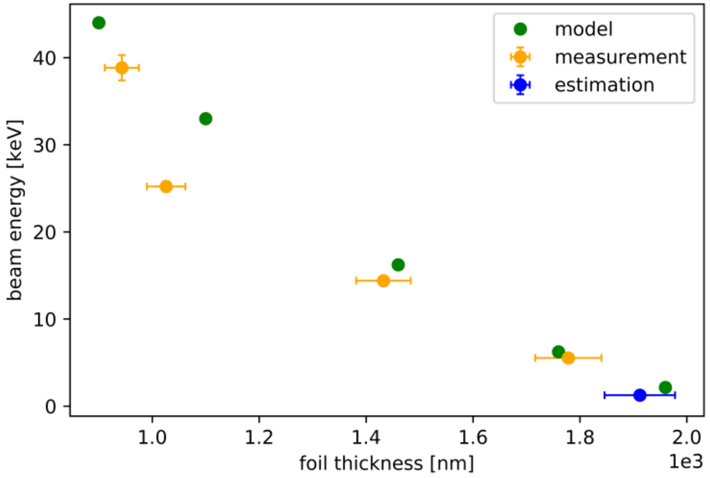
-> **Beam acceptance: 7 holes with 1 mm diameter - 17.1 %** ($\sigma_{x,y}$=2 mm, 5x10^6 p).

- System did not break under different endurance tests like repetitive cooling cycles, stretching in air and even in liquid nitrogen (!).

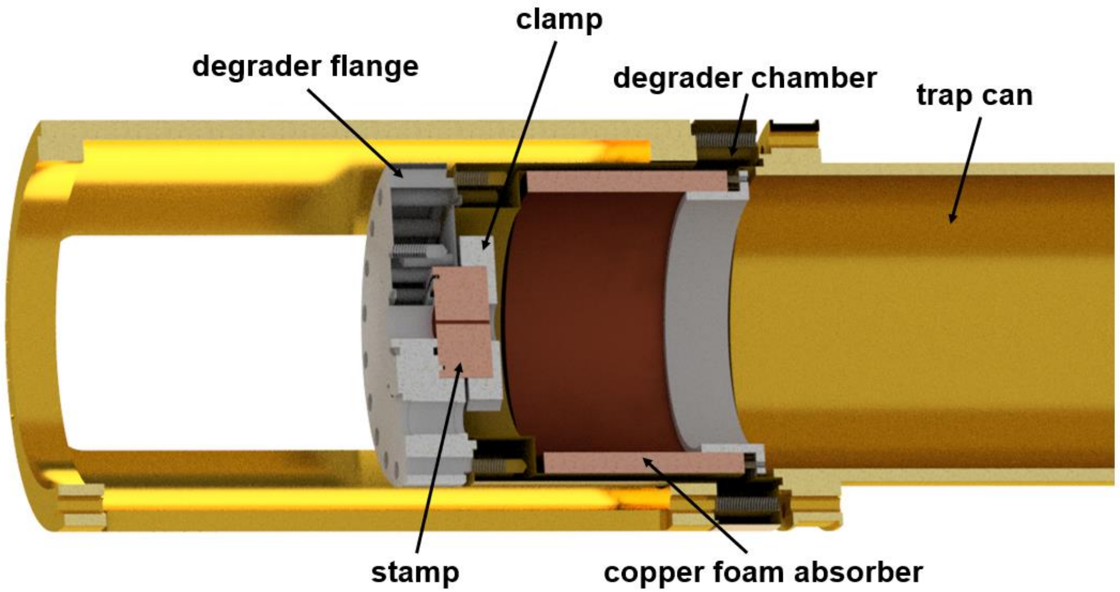
New Degrader system

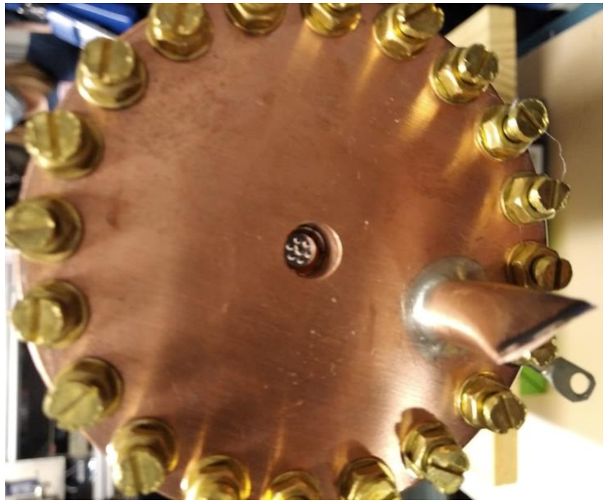
- Measurement results for our new system with 1 bar pressure difference:

Temperature	2160 nm	1760 nm
300 K	5×10^{-9} mbar l/s	1.5×10^{-8} mbar l/s
7 K	$<4 \times 10^{-11}$ mbar l/s	$<1 \times 10^{-9}$ mbar l/s



- New system:
  - Vacuum window and the degrader in one piece –thickness between 1960 nm to 1760 nm
- We did not lose any particle since closing the experiment with 1960 nm foil, which was 187 days ago.
- Rougly estimated pressure: $p_H < 1.3 \times 10^{-17}$ mbar and $p_{He} < 2.9 \times 10^{-17}$ mbar.





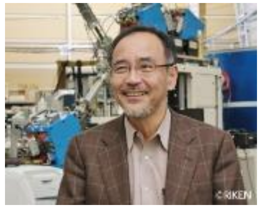
Summary

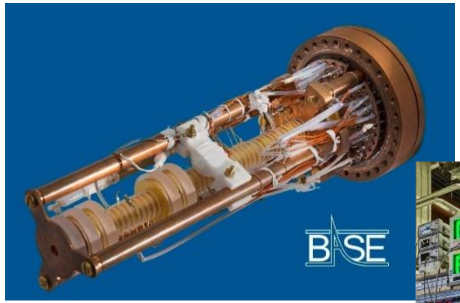
- The BASE experiment reached the lowest, measureable pressure in the vacuum system at the level of:

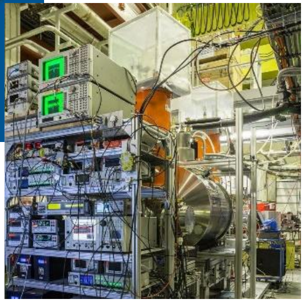
$$\boldsymbol{p_H < 0.46 \times 10^{-18}}\ \textbf{mbar and}\ \boldsymbol{p_{He} < 1.04 \times 10^{-18}}\ \textbf{mbar.}$$

- This allows BASE to store antiprotons for hundreds years.
- In 2020 we sucessfully redesign the BASE vacuum.
- We did not loose any particle for now 187 days using 1.96 μm thick cryogenic vacuum window, which allowed to constrain the partial pressures to $\boldsymbol{p_H < 1.3 \times 10^{-17}}$ **mbar** and $\boldsymbol{p_{He} < 2.9 \times 10^{-17}}$ **mbar.**
- In the next run we want to switch to 1.76 μm which should be an equally good solution from the vacuum perspective, and more robust solution for catching antiprotons.

Thank you for your attention!







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**

- **A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio**
  M. J. Borchert, Nature 601.7891 (2022): 53-57.

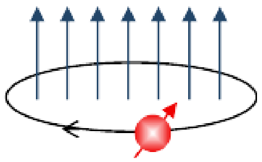
Single particle measurements in Penning Traps

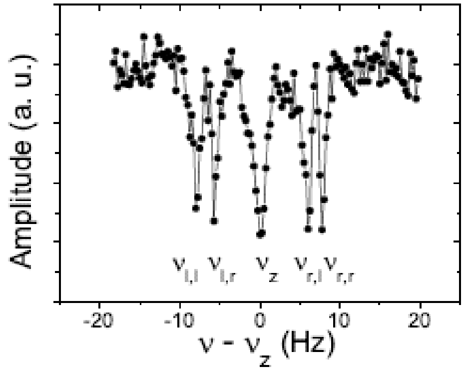
High precision mass spectroscopy

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

Cyclotron Motion

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





- **A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio**

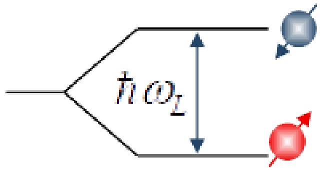
M. J. Borchert, Nature 601.7891 (2022): 53-57.

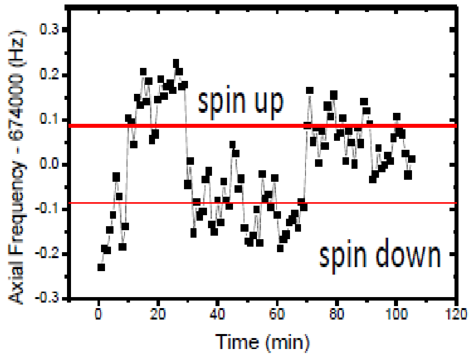
High precision magnetic moment measurements

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

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)

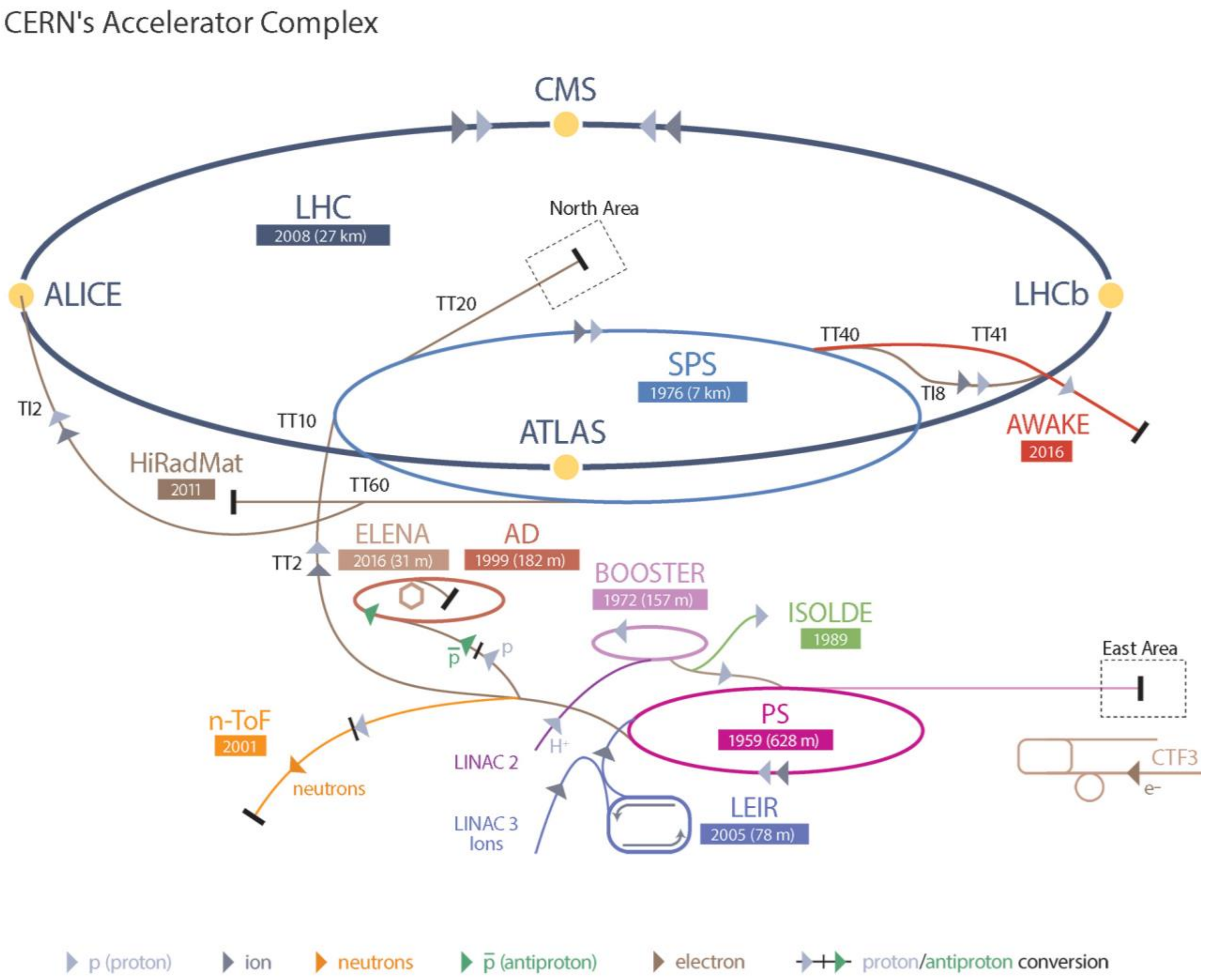
Antiproton source

- **BASE:**
  -> single protons and antiprotons.

- **Antiproton Decelerator**
  - 5.3 MeV antiproton beam
  - 7×10^7 antiprotons sent to one experiment
  - Currently an injector for ELENA

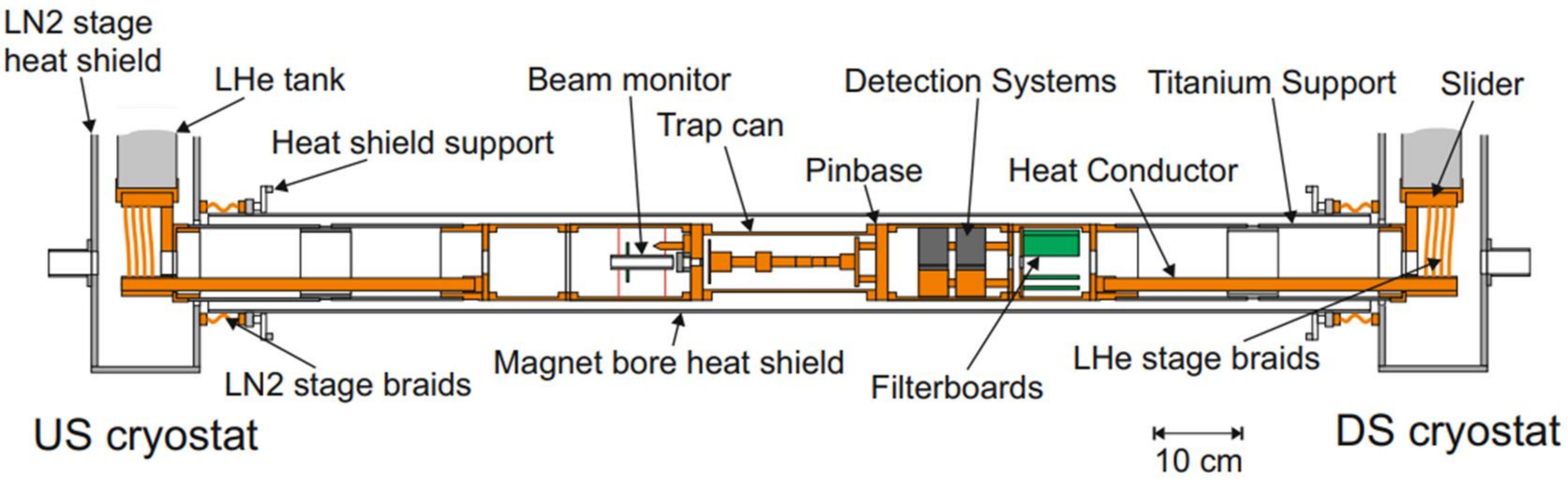
- **The Extra Low Energy Antiproton ring (ELENA)**
  - 100 keV antiproton beam
  - 7×10^7 antiprotons distributed over 4 experiments
  - available for all AD experiments since 2021

- ***To switch to ELENA we had to redesign our vacuum system*.**



Details of the experiment assembly

- This nice slide from Julia with a magnet
- Then that we need to close the chamber with a degrader foil



Antiproton pressure gauge

- Antiproton storage for a year needs a pressure below $\sim 10^{-17}$ mbar.
- X. Fei, „Trapping low Energy antiprotons in an ion trap," Ph.D. dissertation, Harvard University, Department of Physics, 1990.
- Cross-section for antyproton – hydrogen interaction valid for $E \ll 1$ eV:

$$\sigma(H) = 3\pi a_0^2 \sqrt{E_0/E}$$

where
a_0 is the Bohr radius
$E_0 = 27.2$ eV is twice the hydrogen binding energy
E is the kinetic energy of the antyproton in the center-of-mass system

- Antiproton annihilation rate is $R = n\sigma v_{rel}$, where n is the number density of the gas.
- Since the lifetime is $\tau = 1/R$

$$n[1/cm^3] = \frac{1}{\left(6\pi a_0^2 \tau \sqrt{\frac{E_0}{m}}\right)} = 3.72 \times 10^8/\tau[sec]$$

- **Based on this resoning we can derive „simple" formulas:**

$$\boldsymbol{P_H[mbar] = 5.92 \times 10^{-16} T[K]/\tau[day]}$$

$$\boldsymbol{P_{He}[mbar] = 1.34 \times 10^{-15} T[K]/\tau[day]}$$