Recent experimental results and techniques deployed on the CERN Antiproton Decelerator (AD) complex

Stefan Haider

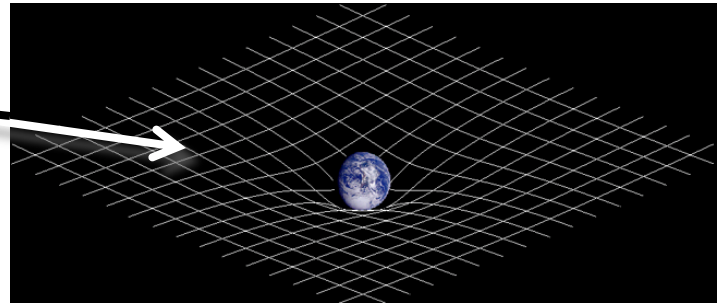
Overview

- Motivation on $\overline{p}$ – physics
- AD Hall
- AD experiments
  - ACE
  - ALPHA
  - ASACUSA
  - ATRAP
  - AEgIS
- Conclusion

Why compare matter and anti-matter?

- Baryon asymmetries in the universe? Where is the antimatter gone?
- With gravity measurements we can test the Weak Equivalence Principle

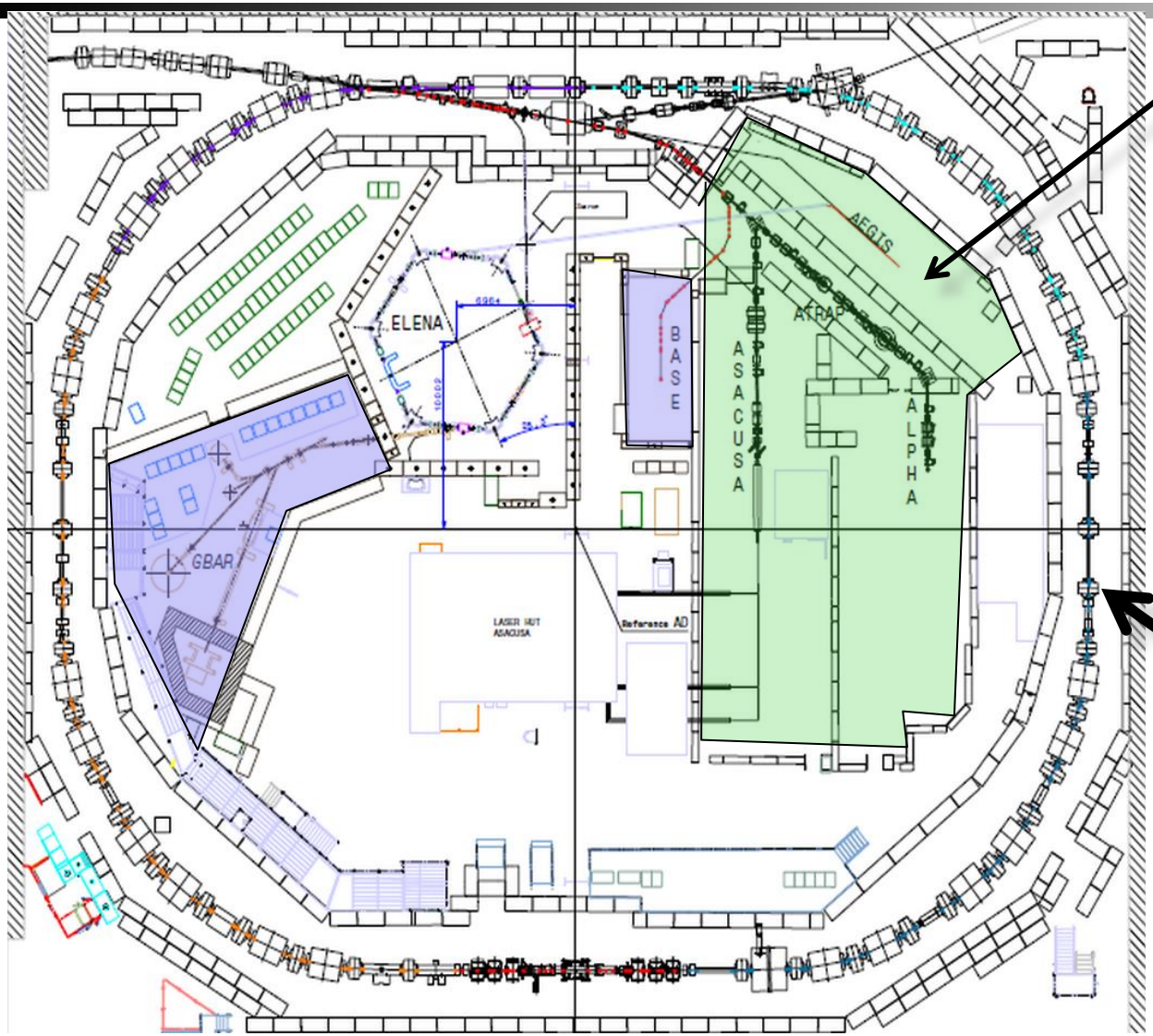
THIS
Is true for matter



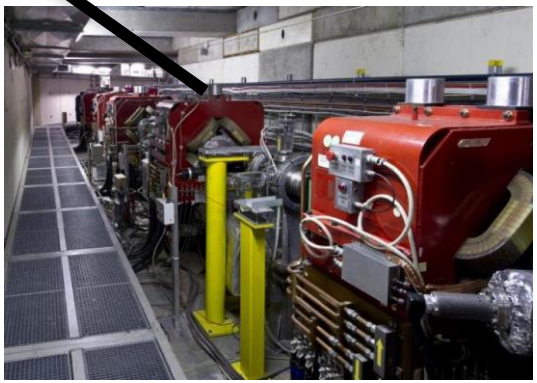
But is it true for anti-matter too?

- Offers extremely sensitive tests of CPT symmetry

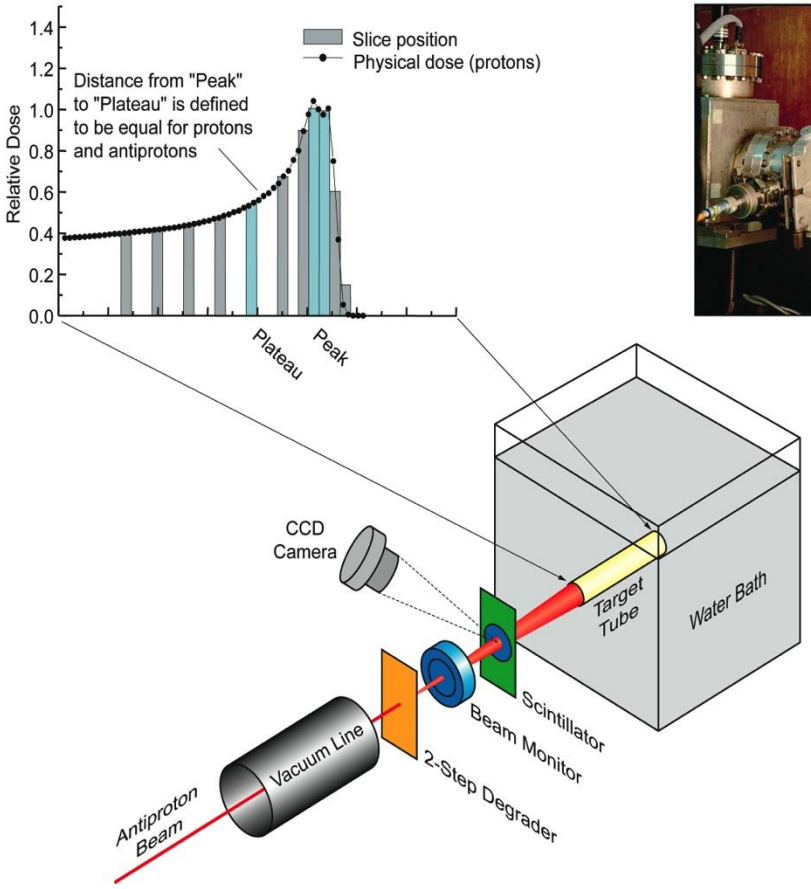
AD Hall (future layout with Elena)

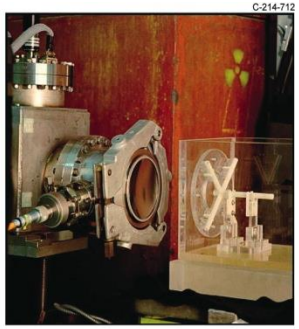


- **Present experiments (2013):**
  - ACE
  - AEgIS
  - ALPHA
  - ASACUSA
  - ATRAP
- **Future experiments:**
  - BASE
  - GBAR



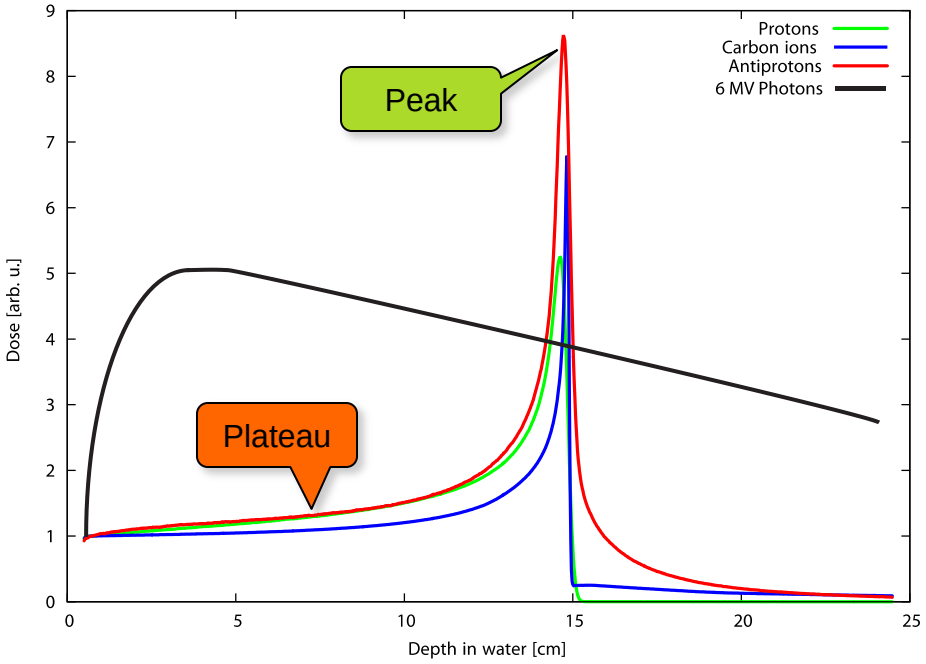
ACE (Antiproton Cell Experiment)



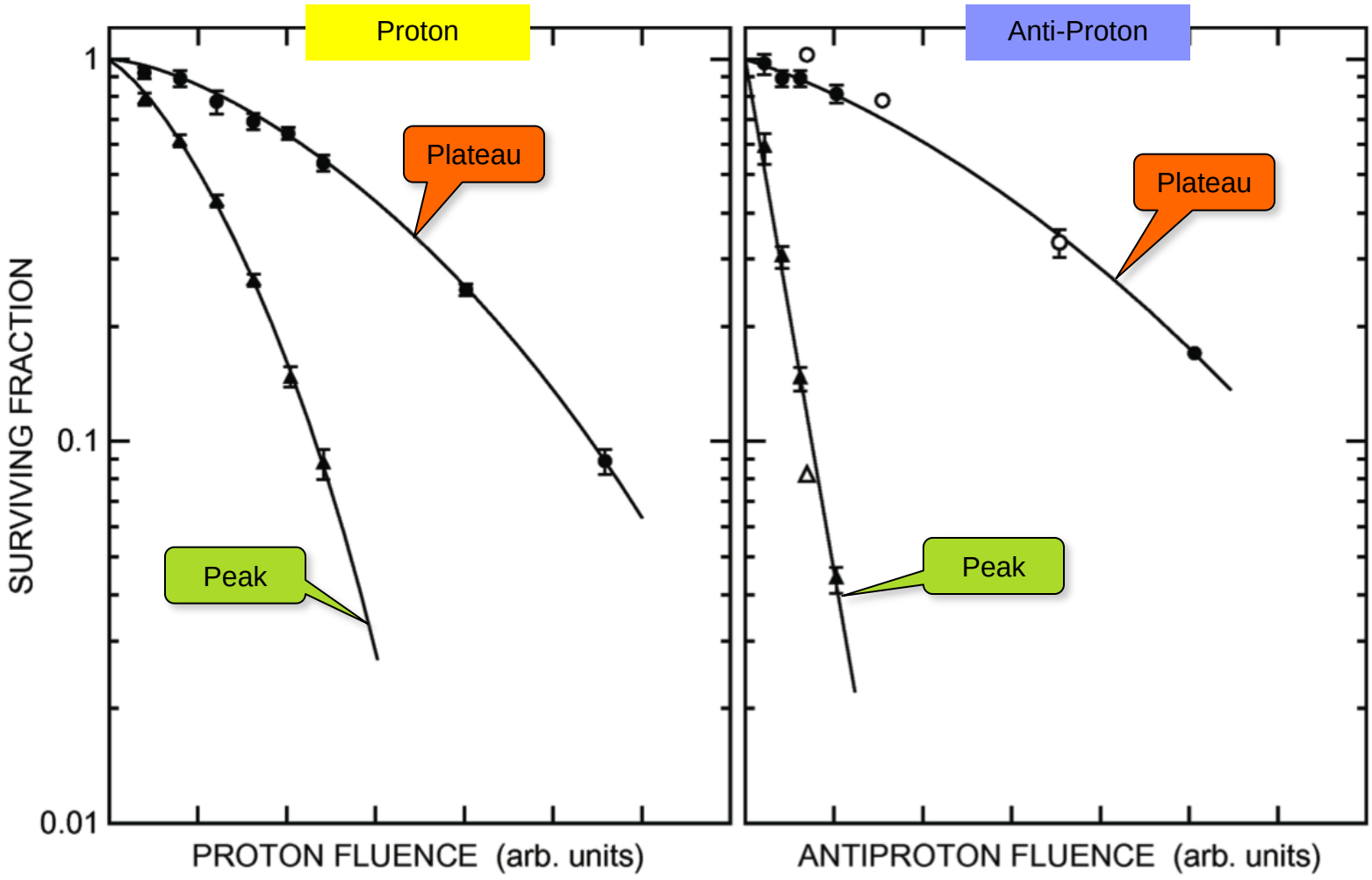


INGREDIENTS:

- **V-79 Chinese Hamster cells embedded in gelatin**
- **Antiproton beam from AD (126 MeV)**



Survival fraction of cancer cell irradiated with Protons and Antiprotons

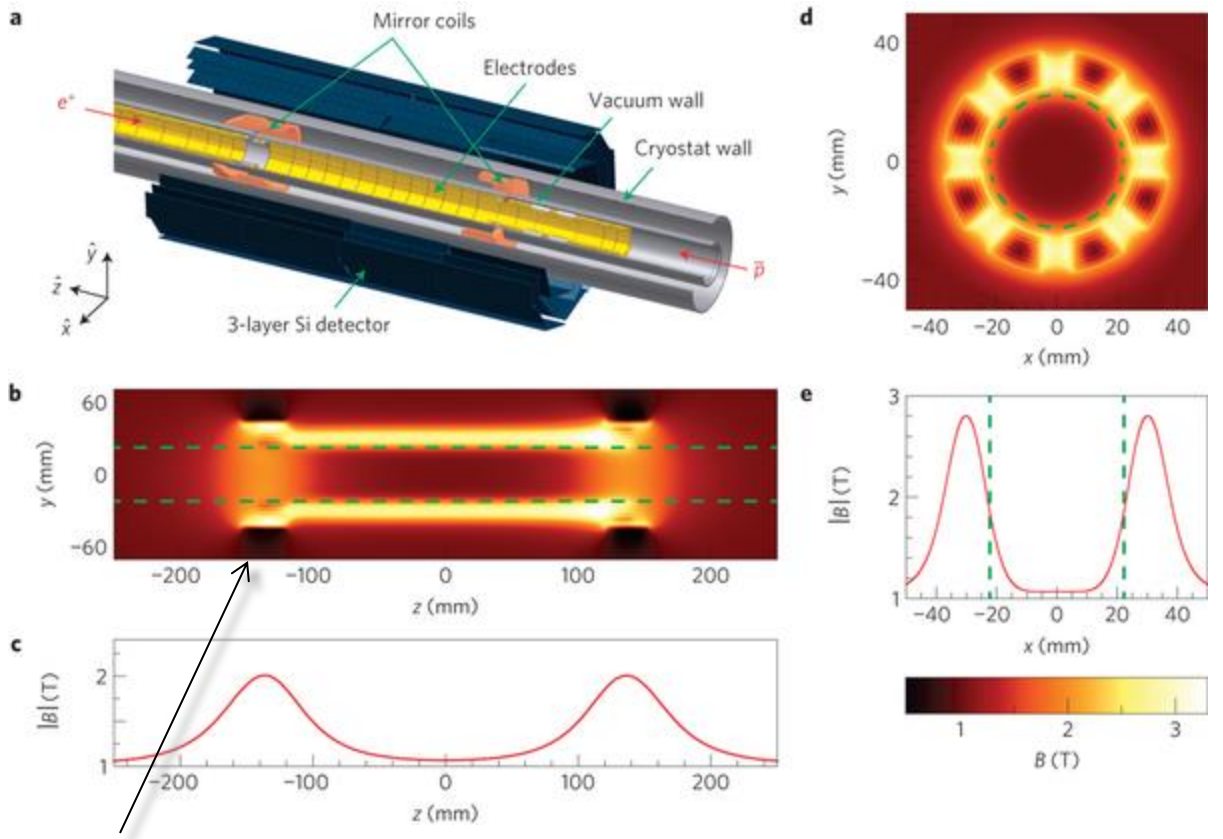


ALPHA (Antihydrogen Laser PHysics Apparatus)

- Trapping of Antihydrogen atoms
- Perform micro wave spectroscopy
- Perform laser spectroscopy (future)

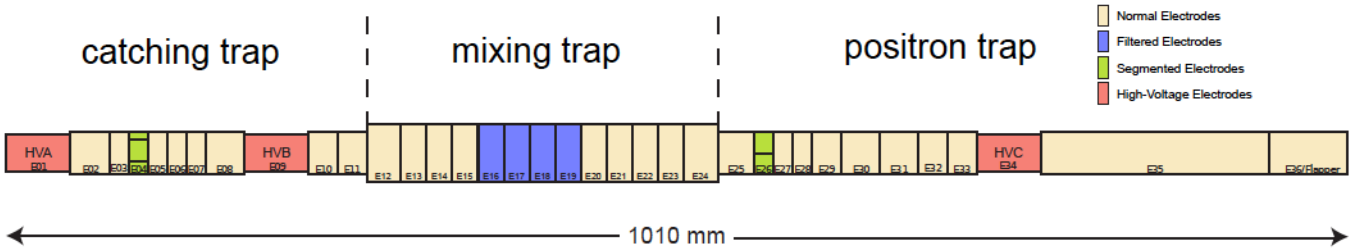
Magnetic trap configuration

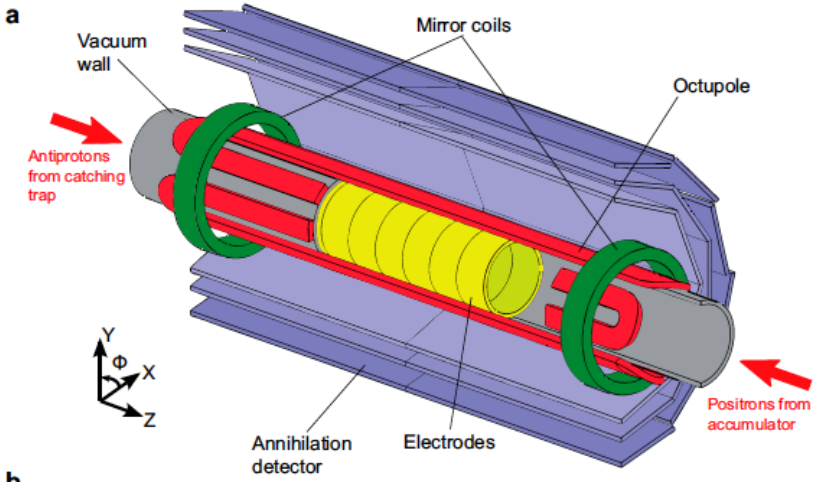
1T external field

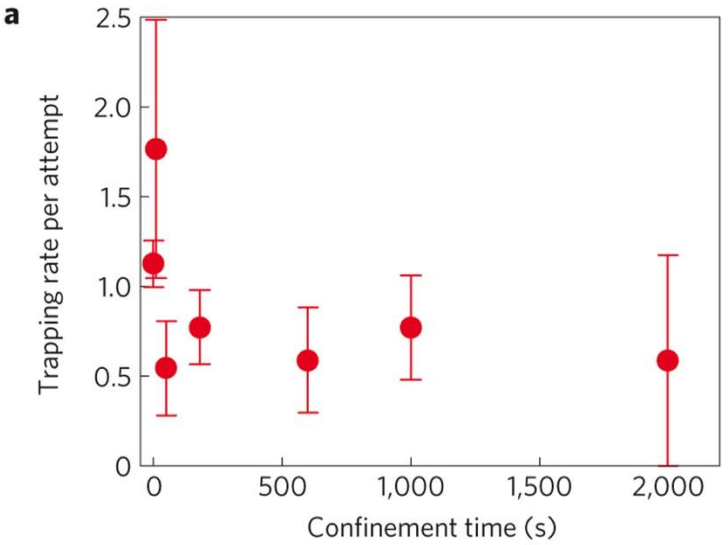


octupole magnet for radial confinement.

mirror coils for axial confinement



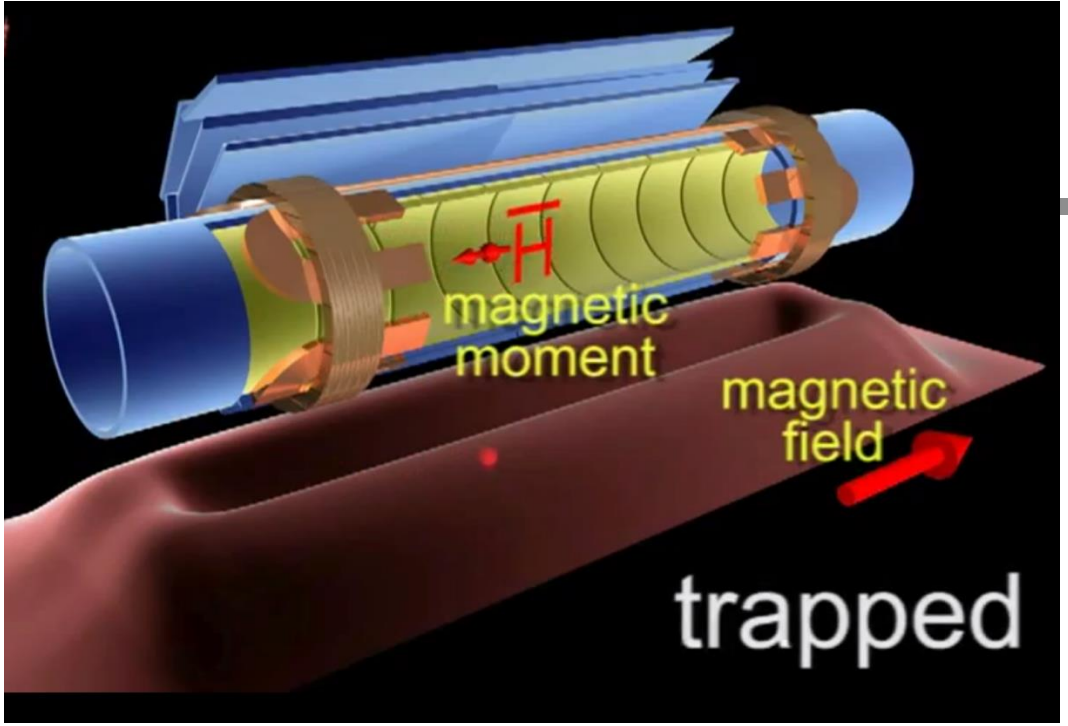


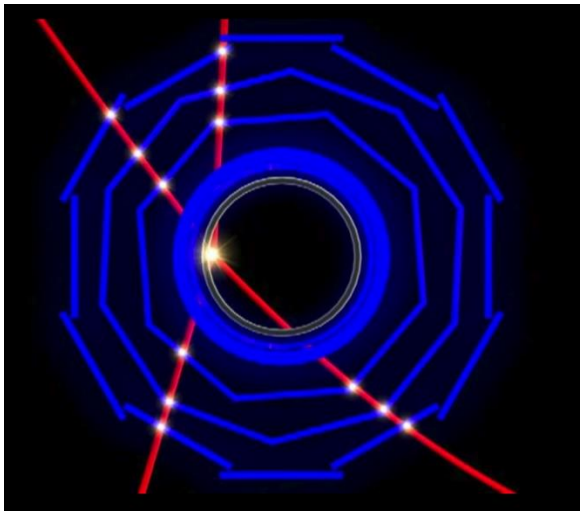


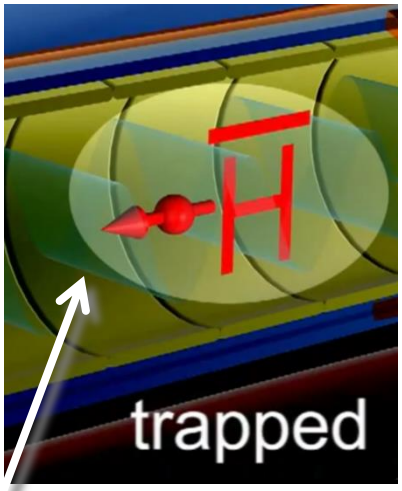
$$\bar{p} + e^+ + e^+ \rightarrow \bar{\mathrm{H}} + e^+$$

- 3×10^4 p and 2×10^6 e+ in nested Penning traps located within the bias field of the Ioffe trap
- 1000 H-bars produced but only a few were cold enough to be trapped (T<1K)
- Quench magnet within milliseconds to release the trapped atoms and record their annihilation signature

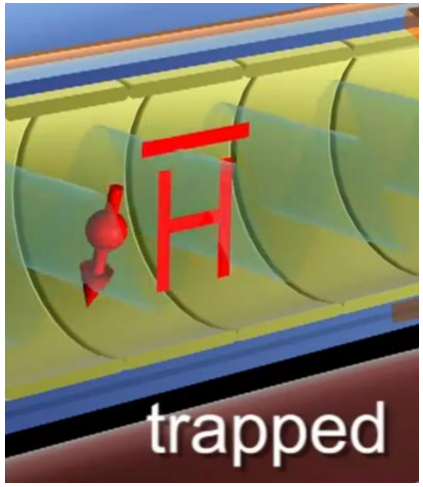
Microwave spectroscopy

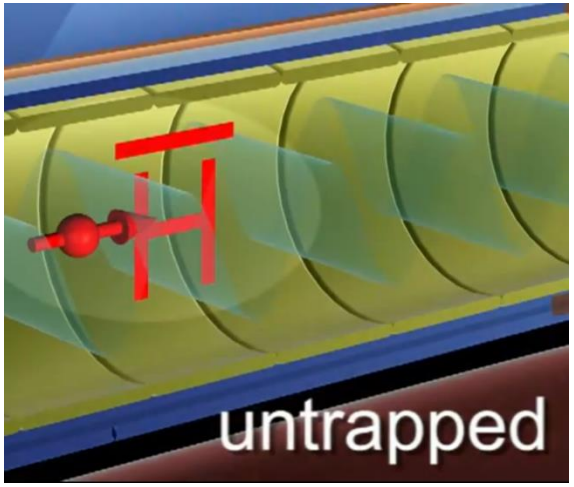






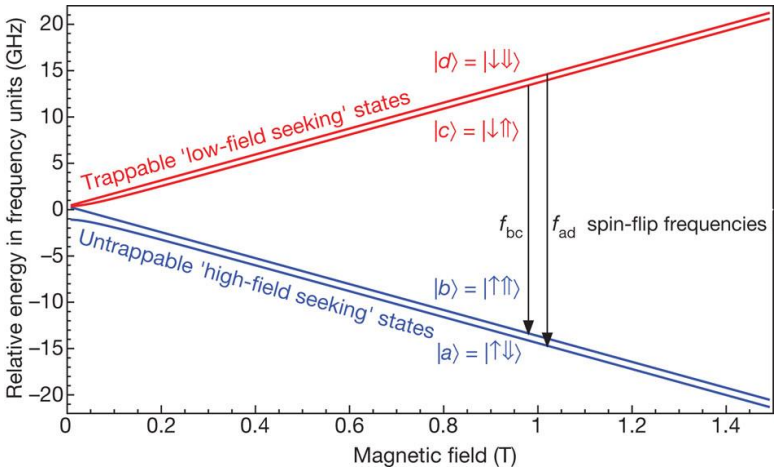
29 GHz Microwave



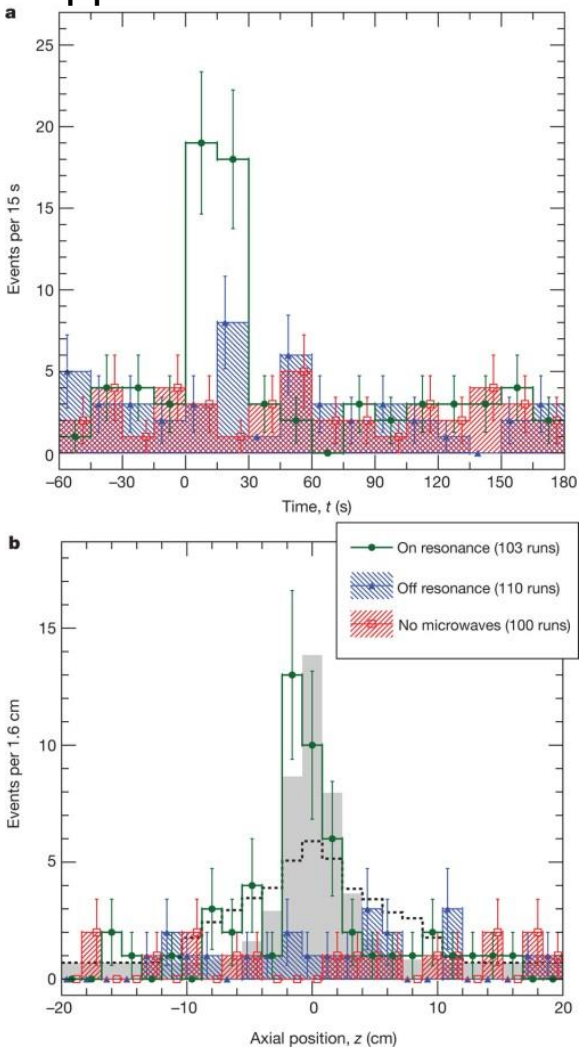


ALPHA microwave spectroscopy

Hyperfine energy levels.



Appearance mode data.

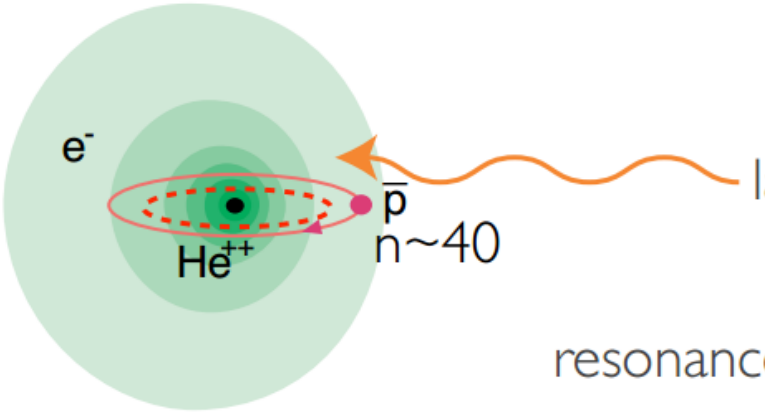


ASACUSA (Antiproton Spectroscopy And Collisions Using Slow Antiprotons)

- decelerated the 5.3-MeV p-bar arriving from AD to E ~ 60 keV with a high (~ 25%) efficiency
- Projected onto a Helium gas target in order to form $\overline{p}\mathrm{He}^{+}_{(n,\ell)}$. Measure the antiproton to electron mass ratio
- Second program: p-bar trapped to form a continuous beam for measuring the ionizing cross section of p-bar on gas targets.

$\bar{p}$He laser spectroscopy contributes to m_p/m_e

$$\bar{p} + \mathrm{He} \rightarrow \bar{p}\mathrm{He}^{+}_{(n,\ell)} + e^{-}$$



laser pulse changes the $\bar{p}$ orbit

resonance detection via $\bar{p}$ annihilation

Frequency

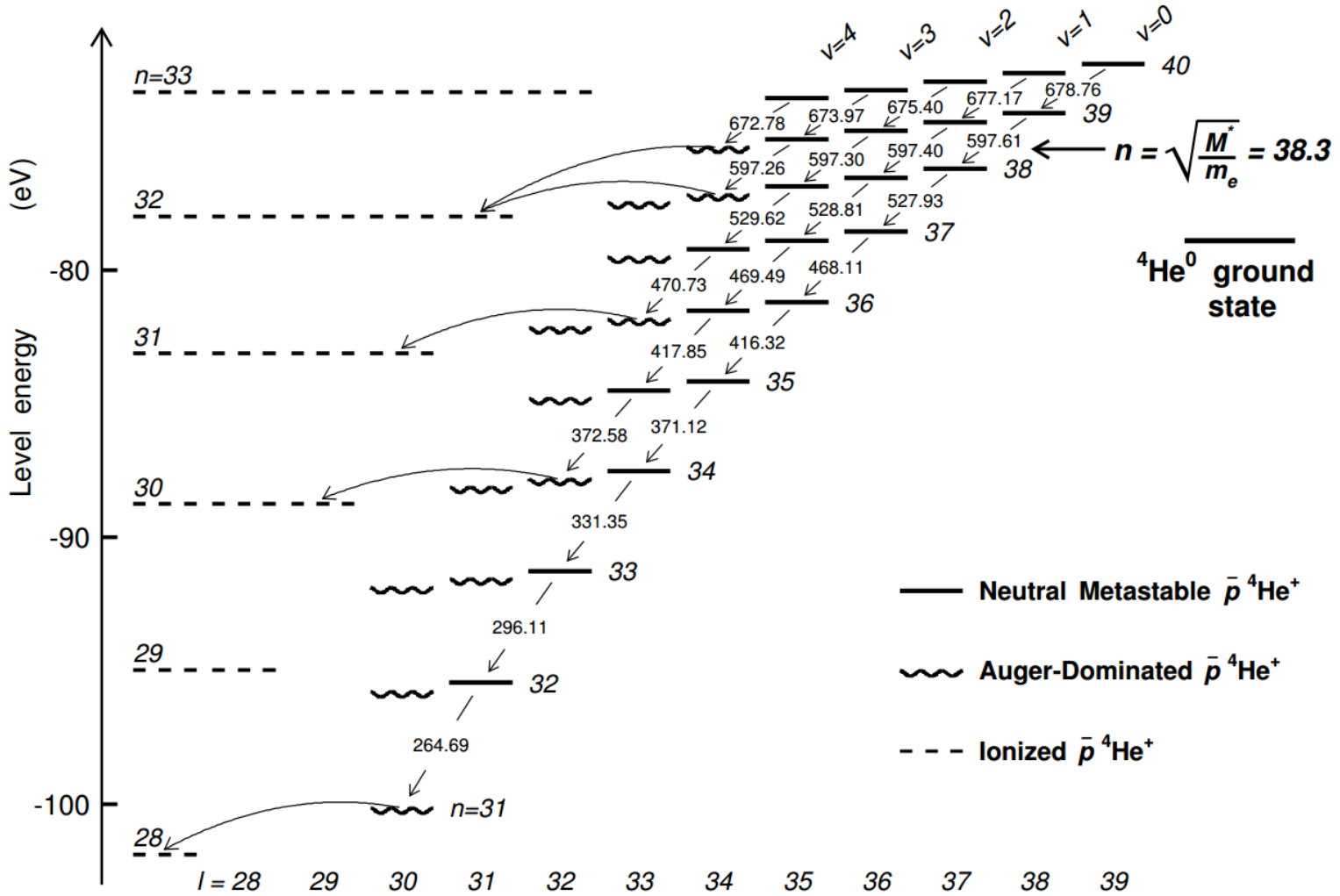
$$\nu_{n,\ell\rightarrow n',\ell'} = Rc\frac{m^{*}_{\bar{p}}}{m_e}Z^{2}_{\mathrm{eff}}\left(\frac{1}{n'^{2}} - \frac{1}{n^{2}}\right) + QED$$

$\bar{p}$ (p) - e mass ratio

Theory

Korobov

Asacusa $\overline{p}\mathrm{He}^{+}_{(n,\ell)}$ laser spectroscopy



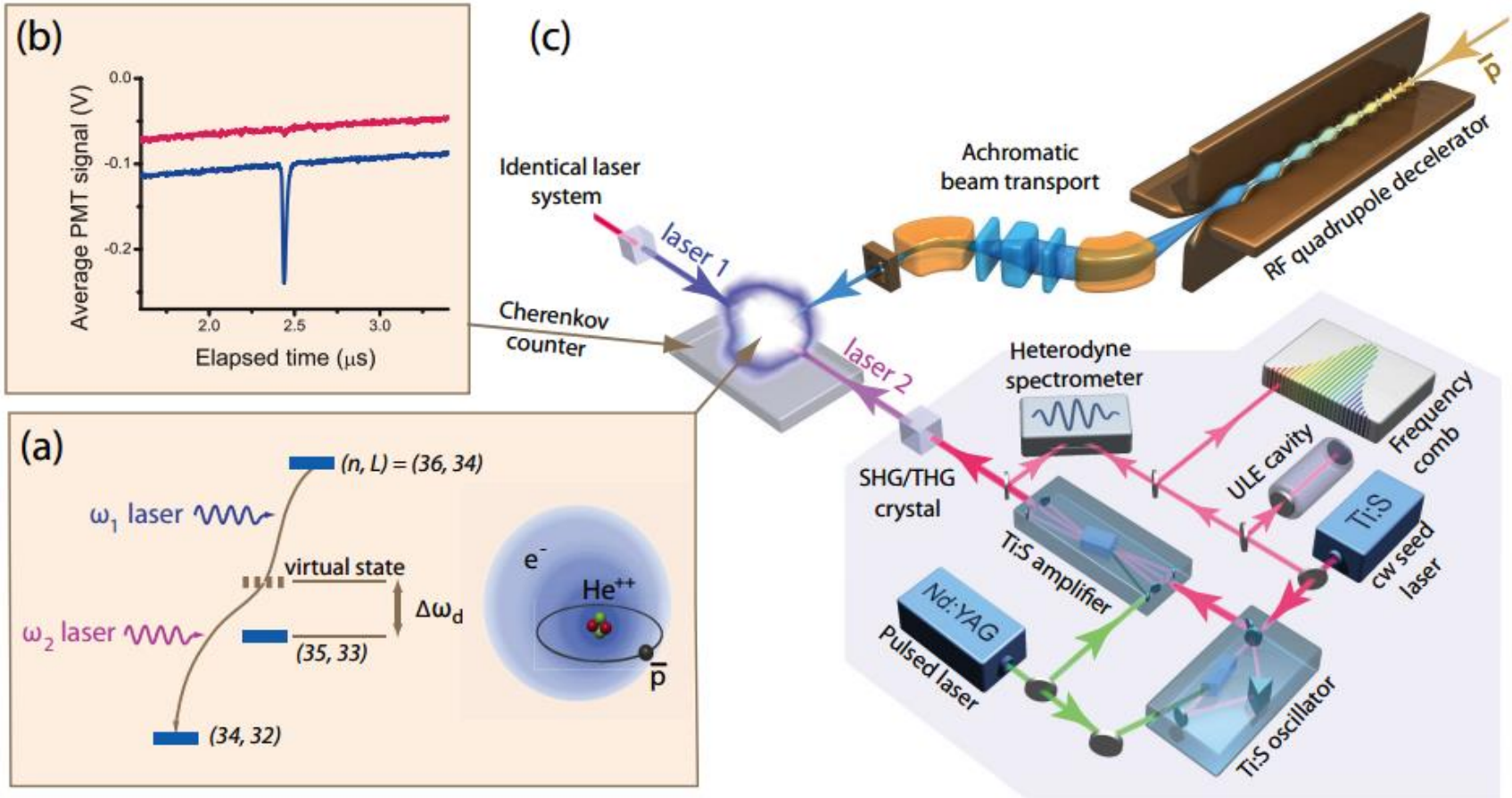
ASACUSA Antiprotonic-Helium production

$$\overline{p} + \mathrm{He} \rightarrow \overline{p}\mathrm{He}^{+}_{(n,\ell)} + e^{-}$$

- P-bar is absorbed by Helium nucleus within pico seconds
- With single photon spectroscopy observe the resonance btw laser and atom by count rate of $\pi+\pi-$ in Cherenkov detector as a function of the laser frequency
- Two photon spectroscopy with two head-on (counter propagating beams) lasers minimizes Doppler broadening effect. (first order effect)
- 2 photon transitions of the type

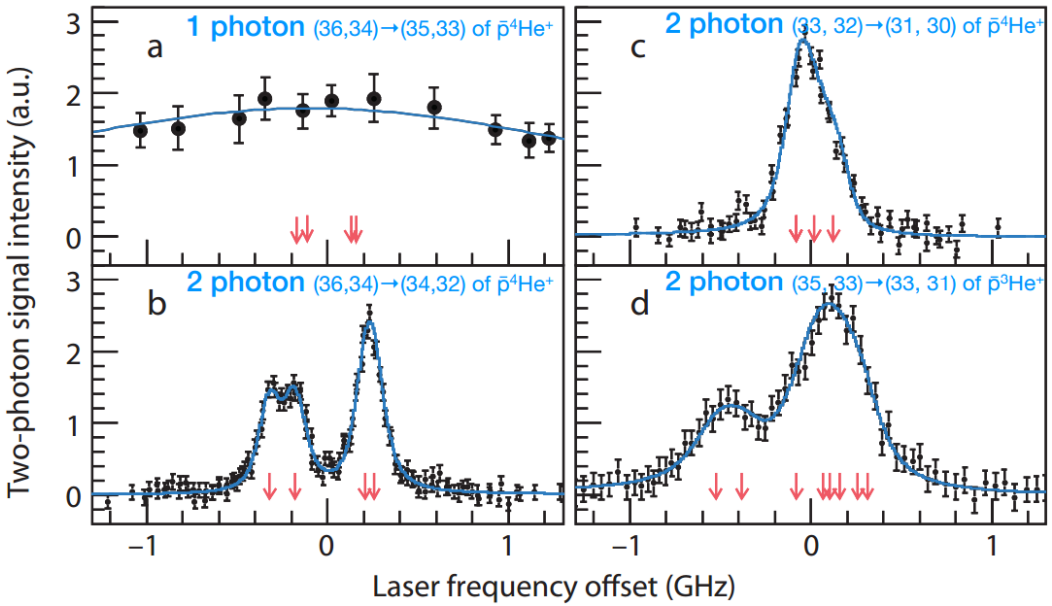
  (n,l) → (n-2, l-2) induced.
- P-bar is exited by the first laser beam, to a virtual state, - which must be close to a not-allowed state. Due to overlapping wave functions of this virtual state, the transition probability for the two photon transition increases by $>10^5$!
- High power lasers with high spectral purity and low phase noise are needed.

ASACUSA experimental setup



ASACUSA laser spectroscopy results

T~15K



M. Hori et al., Nature 475, 484 (2011).

- Comparing calculations and experimental data
  - $m_{pbar} / m_e = 1836.1526736(23)$

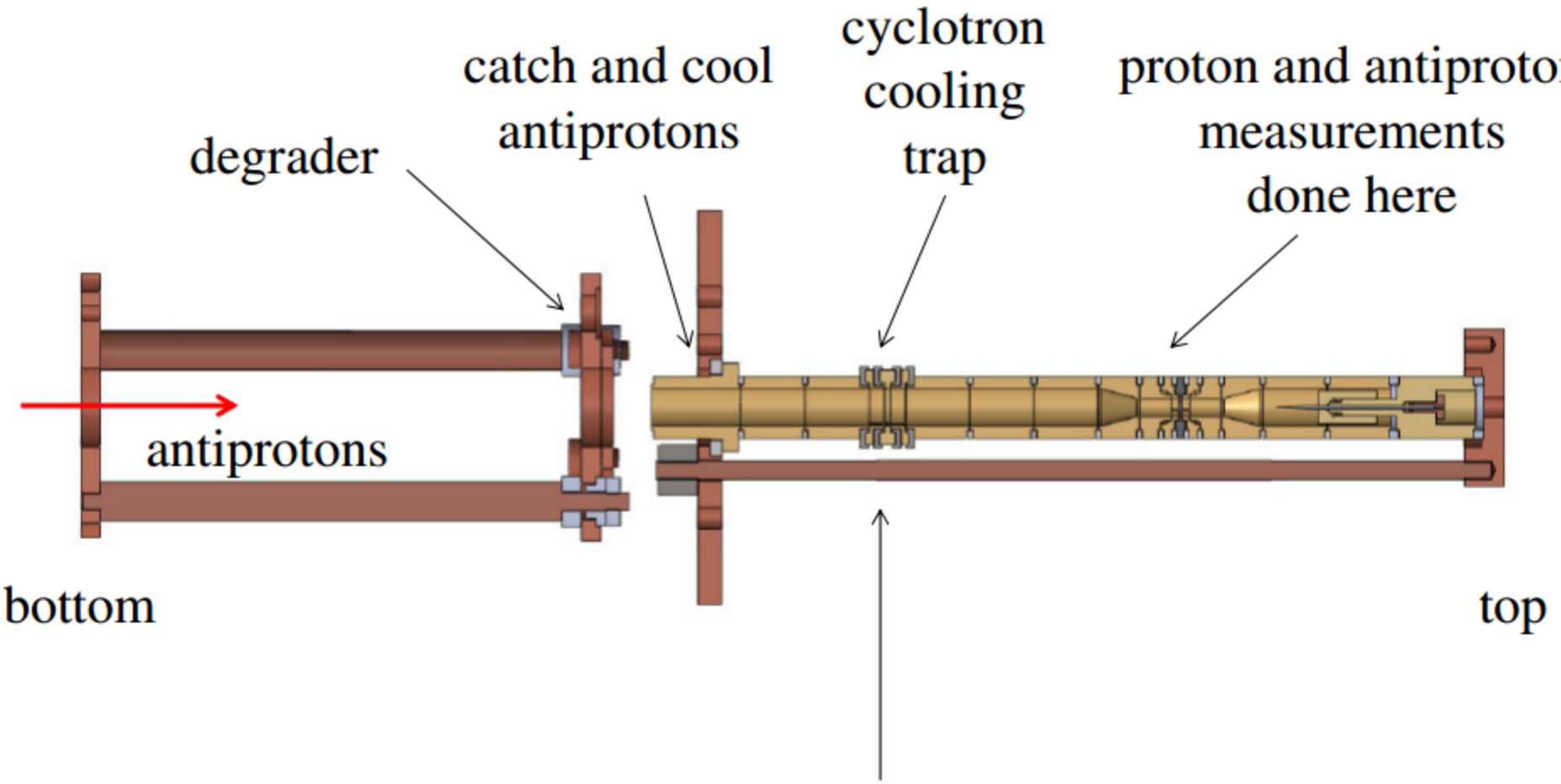
2012 Accomplishments

$\bar{p}$He	▸ $m_{\bar{p}}/m_e$ in CODATA 2010 ▸ 1-photon spectroscopy of "cold" $\bar{p}He^+$ completed (x5-10 better than the 2006 results) ▸ First attempt at 2-photon spectroscopy of "cold" $\bar{p}$He - higher than ever precision
CUSP ($\bar{H}$)	▸ Autoresonance scheme for $\bar{p}$ injection into the e^+ cloud ▸ e^+ intensity x20 with a solid Ne moderator and longer N_2 gas cells. ▸ $\bar{H}$ beam production was tested elongating the $\bar{H}$ formation period. Data analysis is in progress. ▸ $\bar{H}$ beam detectors developed
$\bar{p}$ $\sigma_{annhilation}$	▸ observation of $\bar{p}$-A annihilation at 130 keV (published in EPJ+)

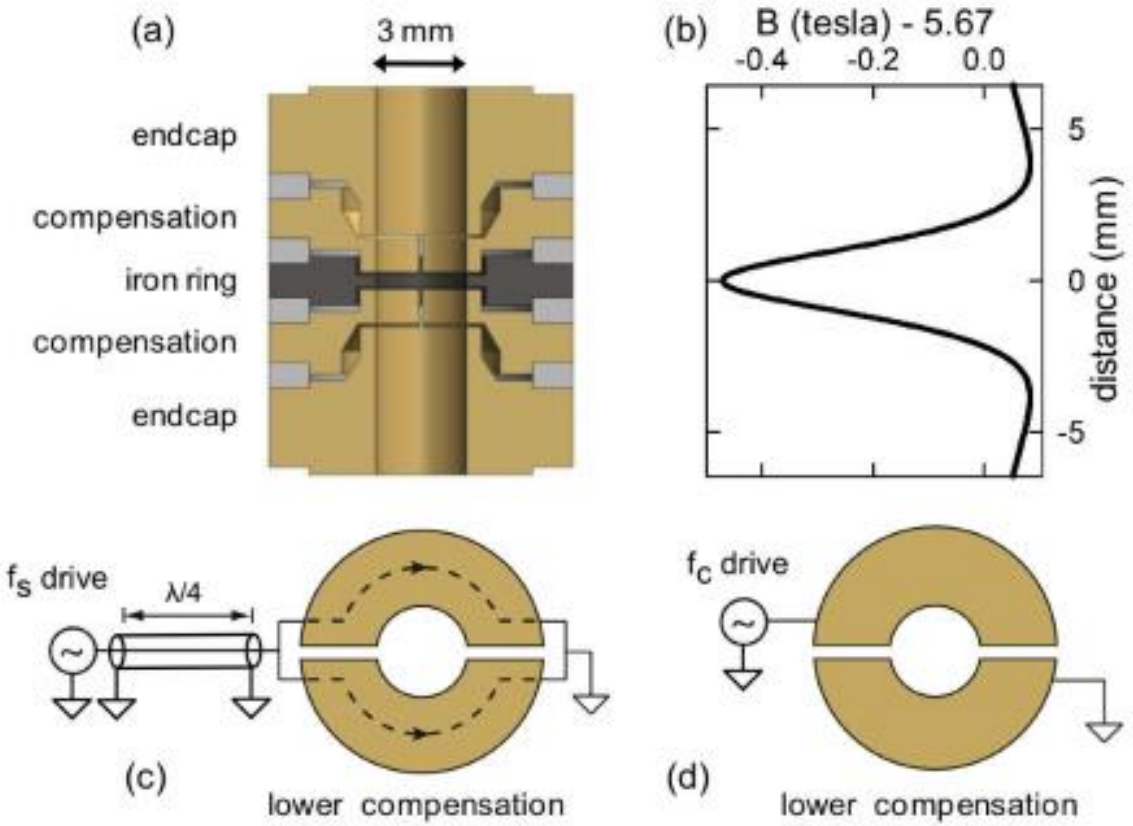
ATRAP Antihydrogen TRAP

- Anti-Hydrogen production
- Antiproton and proton magnetic moment measurement

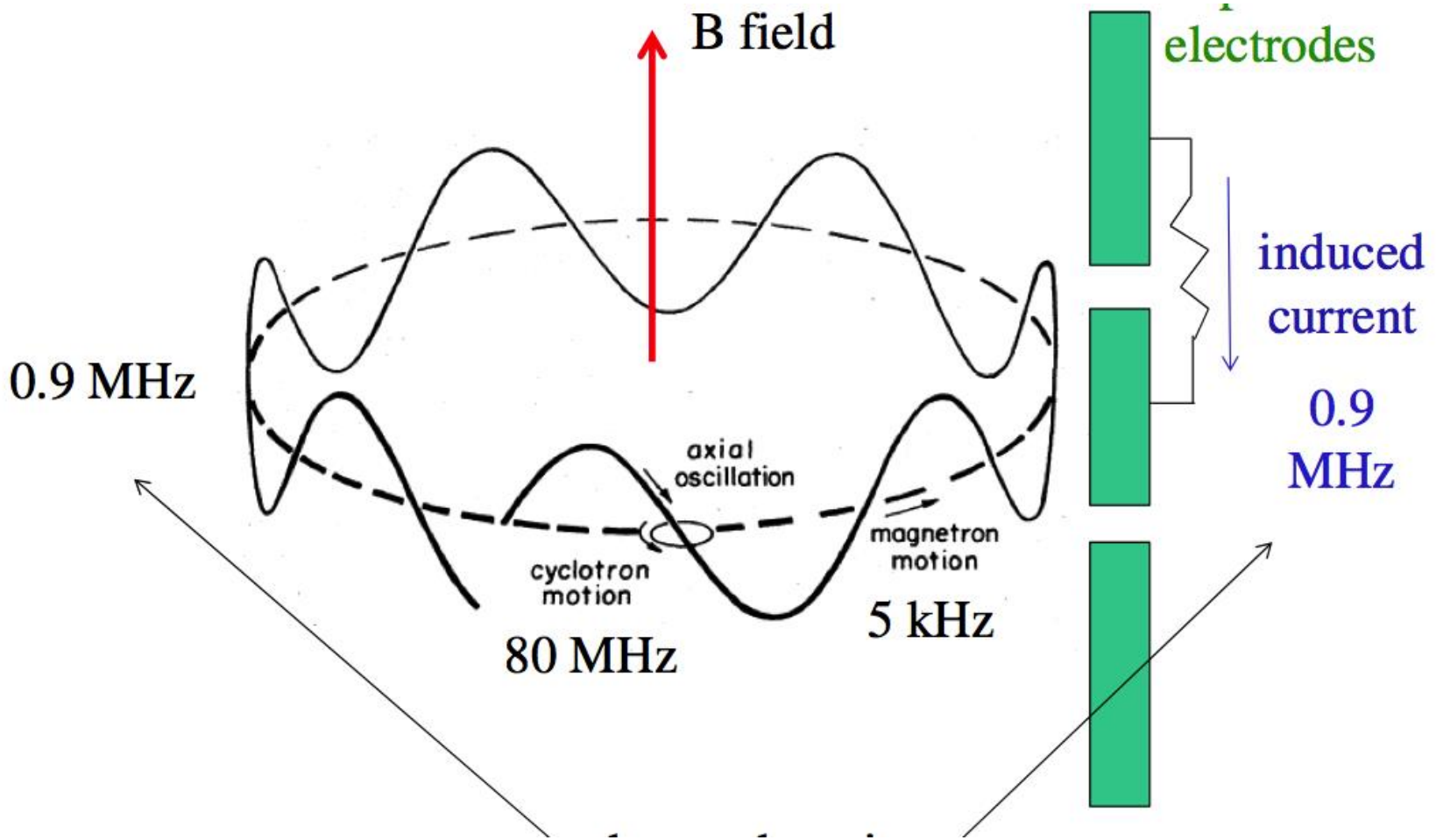
Three Antiproton Traps



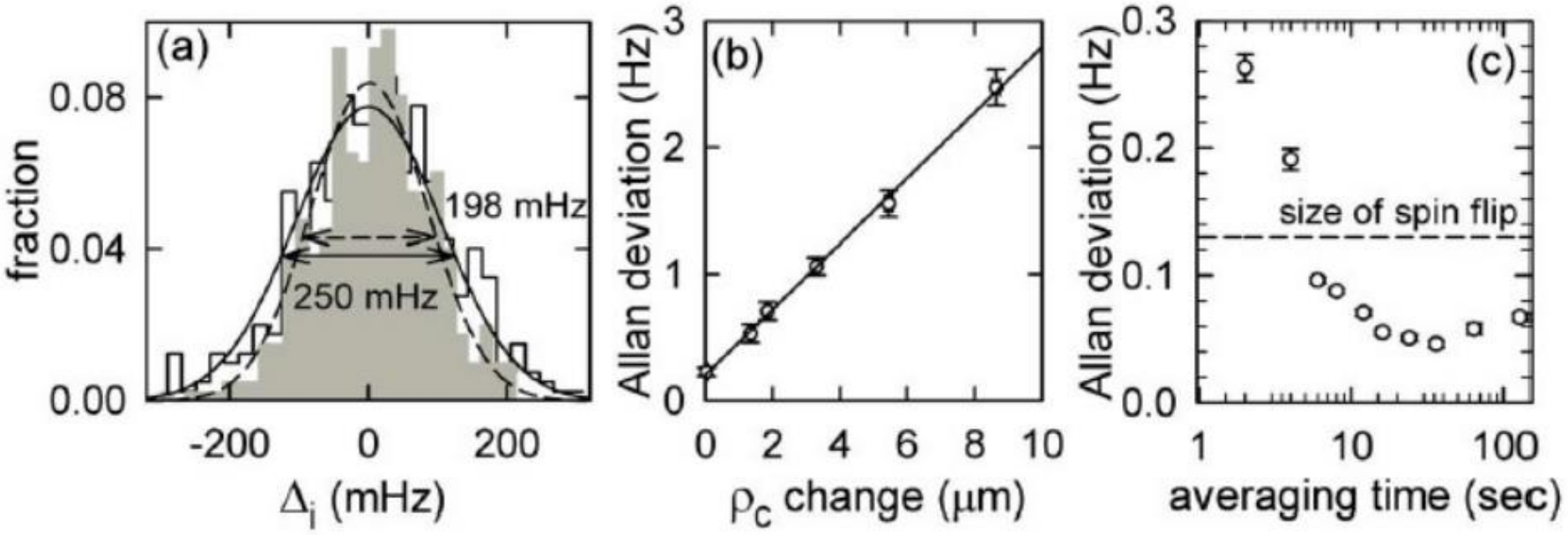
Atrap


(a)
3 mm
endcap
compensation
iron ring
compensation
endcap
(b)
B (tesla) - 5.67
-0.4
-0.2
0.0
5
0
-5
distance (mm)
f_s drive
λ/4
(c)
lower compensation
f_c drive
(d)
lower compensation

Trap 1 anti-proton



Spin-Flips Increase Allan Deviation



- Continuous Stern Gerlach split-up of the anti-proton in an inhomogenous magnetic field
- Change of Eigen frequency is a very small effect
- Considerable experimental challenge

Resonance Lines to Determine the "Two" Frequencies

square of extra width

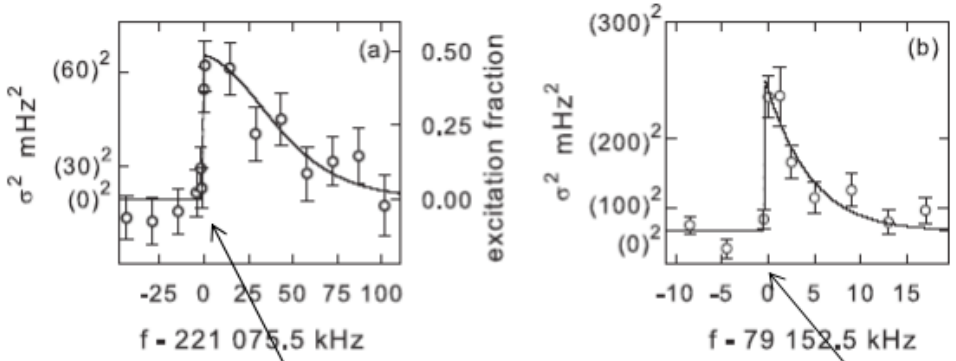


FIG. 4. (a) The spin line. (b)The cyclotron line.

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

$$f_c^2 = f_+^2 + f_z^2 + f_-^2$$

Brown-Gabrielse Invariance Theorem

Gabrielse

First One-Particle Measurement of the Antiproton Magnetic moment

$$\mu_{\overline{\mathrm{p}}}/\mu_N = -2.792\,845 \pm 0.000\,012 \quad [4.4\ \mathrm{ppm}]$$

680 times lower than previous

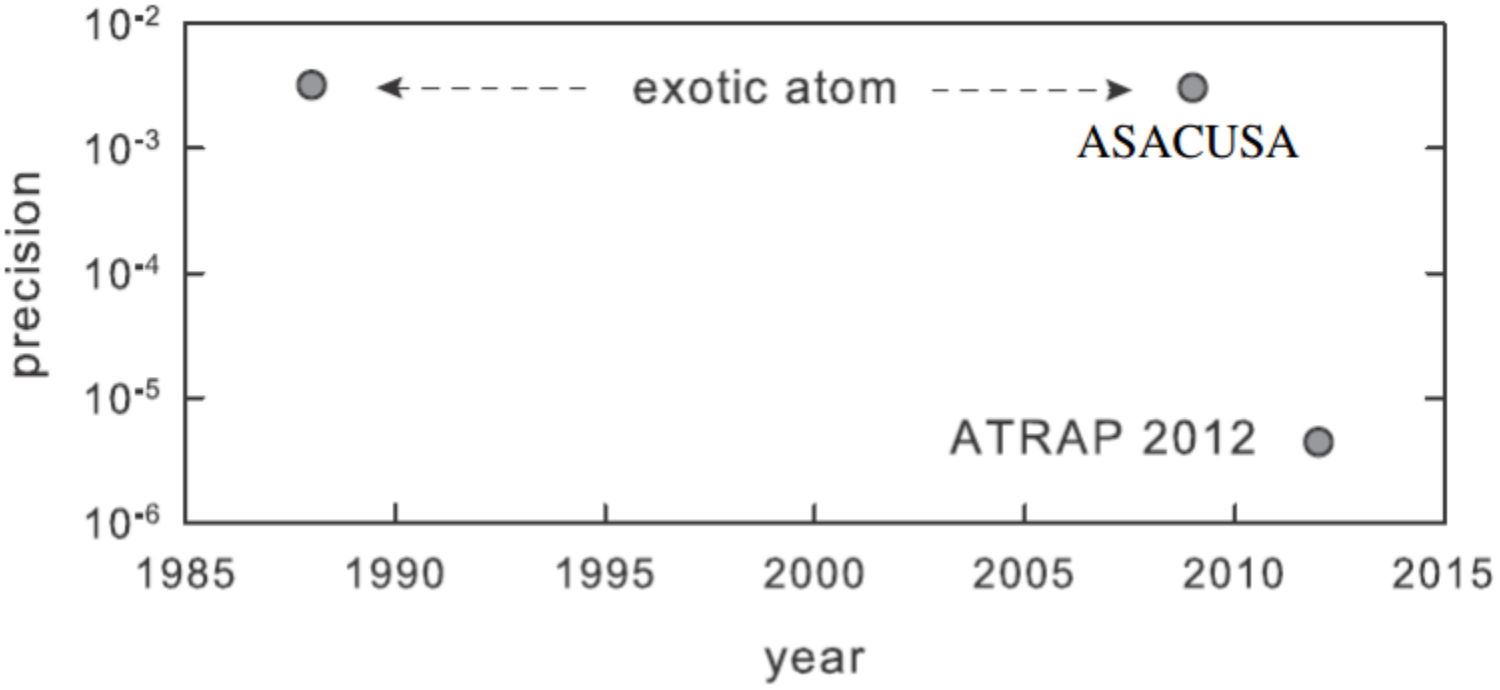
$$\mu_{\overline{\mathrm{p}}}/\mu_p = -1.000\,000 \pm 0.000\,005 \quad [5.0\ \mathrm{ppm}]$$
$$\mu_{\overline{\mathrm{p}}}/\mu_p = -0.999\,999\,2 \pm 0.000\,004\,4 \quad [4.4\ \mathrm{ppm}]$$

Resonance	Source	ppm
spin	resonance frequency	2.7
spin	magnetron broadening	1.3
cyclotron	resonance frequency	3.2
cyclotron	magnetron broadening	0.7
total		4.4

TABLE I. Significant uncertainties in ppm.

Mu_N nuclear magneton

Anti-proton Magnetic Moment



AEgIS (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy)

- Primary goal:
  - Measurement of gravitational acceleration **g** for antihydrogen with 1% accuracy

- Secondary goals:
  - Spectroscopy of antihydrogen
  - Study of Rydberg atoms
  - Positronium physics: formation, excitation, spectroscopy

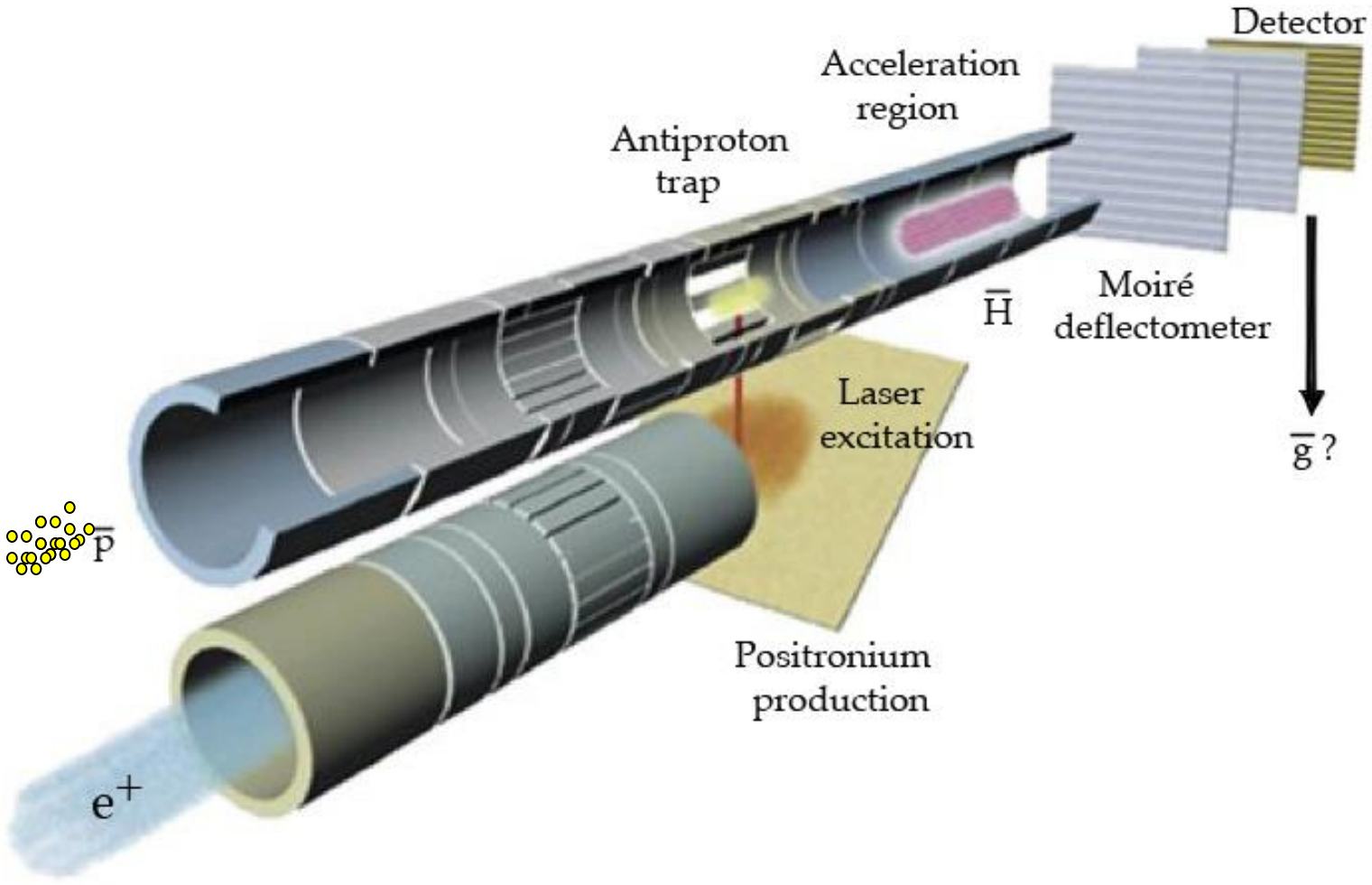
AEgIS Experimental Strategy

- Produce ultra cold antiprotons
- Form positronium by interaction of positrons with a porous target (pulsed)
- Laser excite Ps to get Rydberg Ps (pulsed)
- Form Rydberg cold antihydrogen (pulsed) by $Ps^* + \overline{p} \rightarrow \overline{H}^* + e^-$
- Stark accelerate the antihydrogen with inhomogeneous electric fields → Pulsed production of a cold beam of antihydrogen

- Measure the gravitational acceleration in a classical moiré deflectometer

AEgIS

(Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy)



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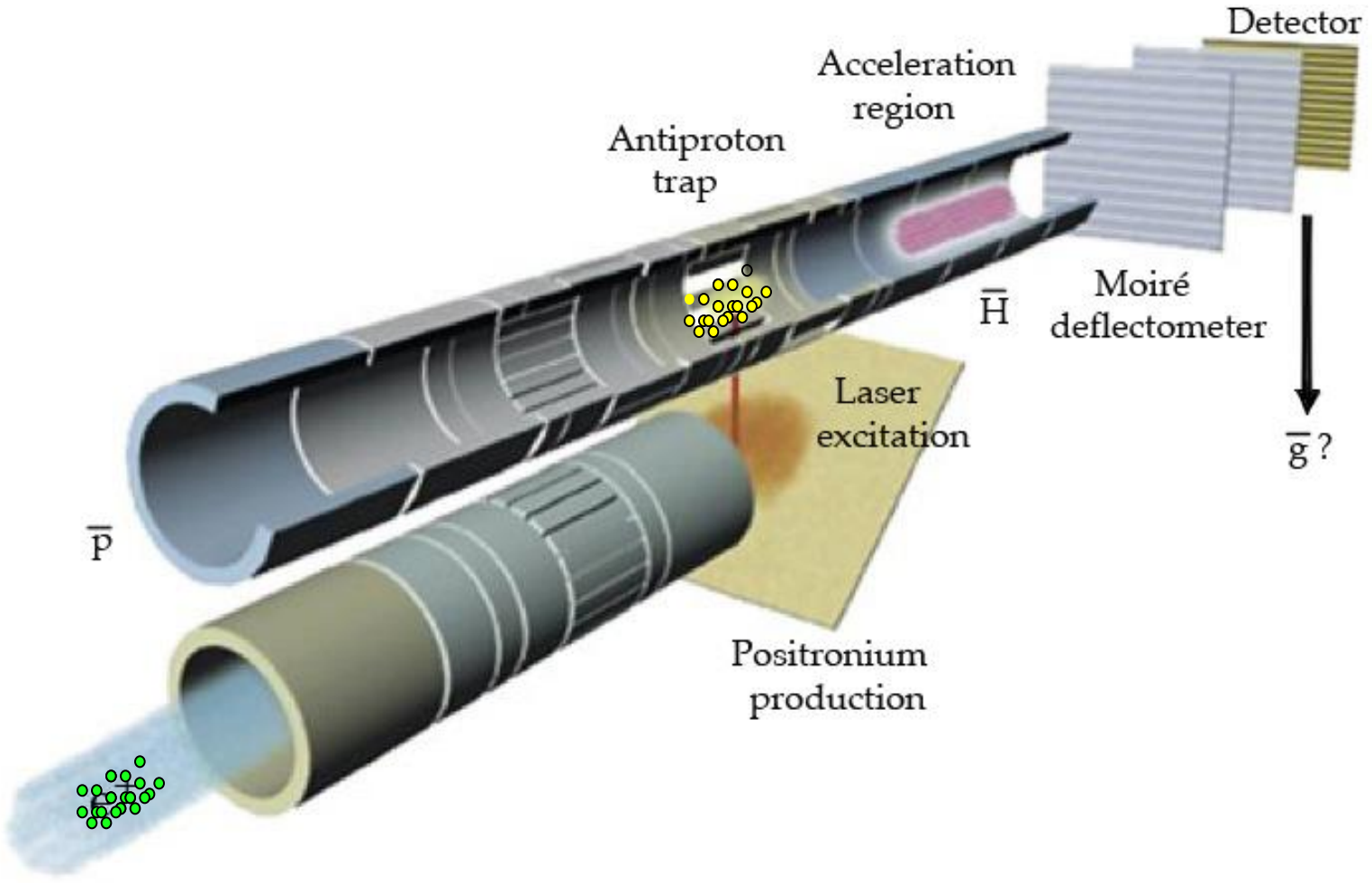

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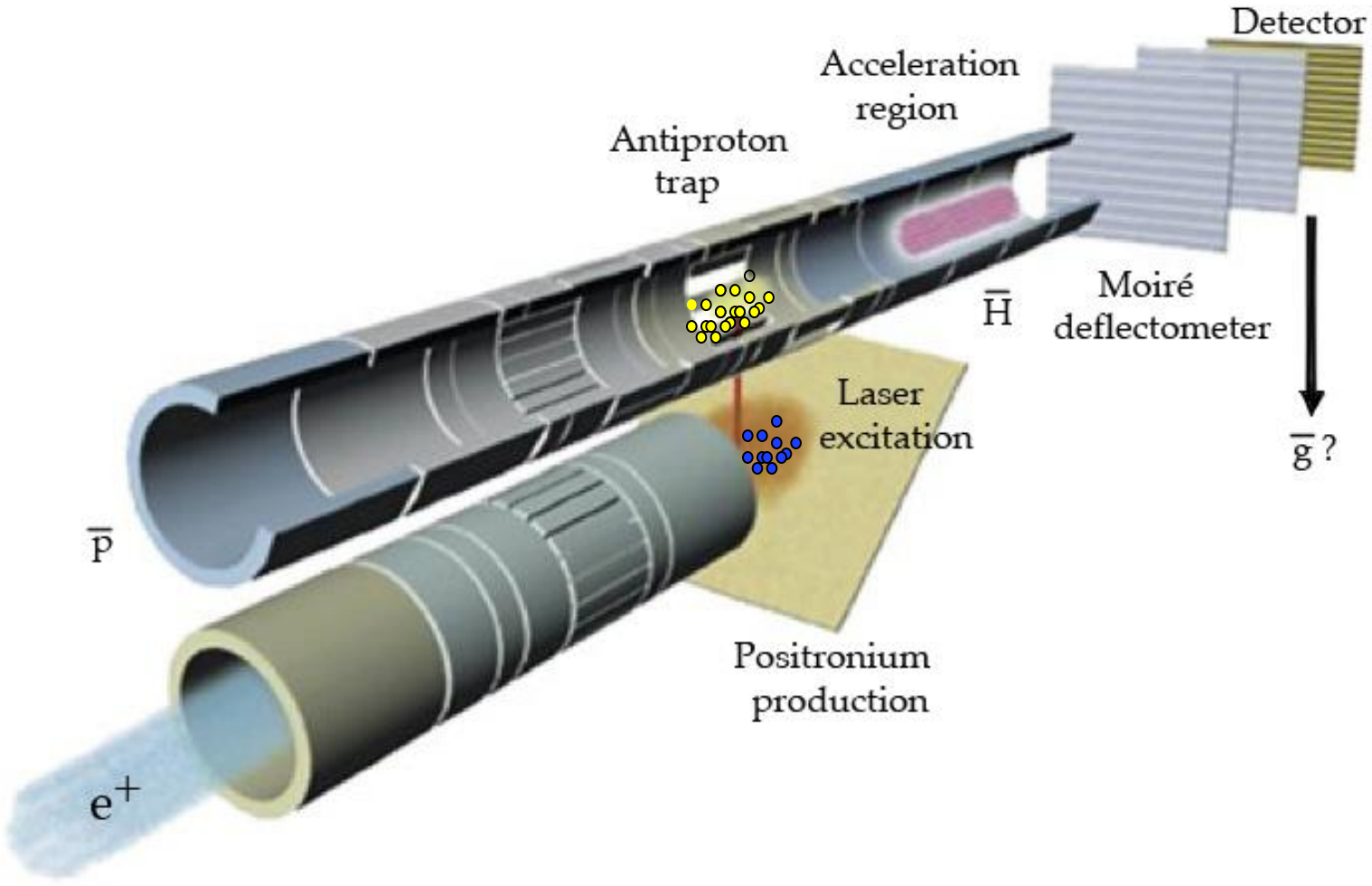

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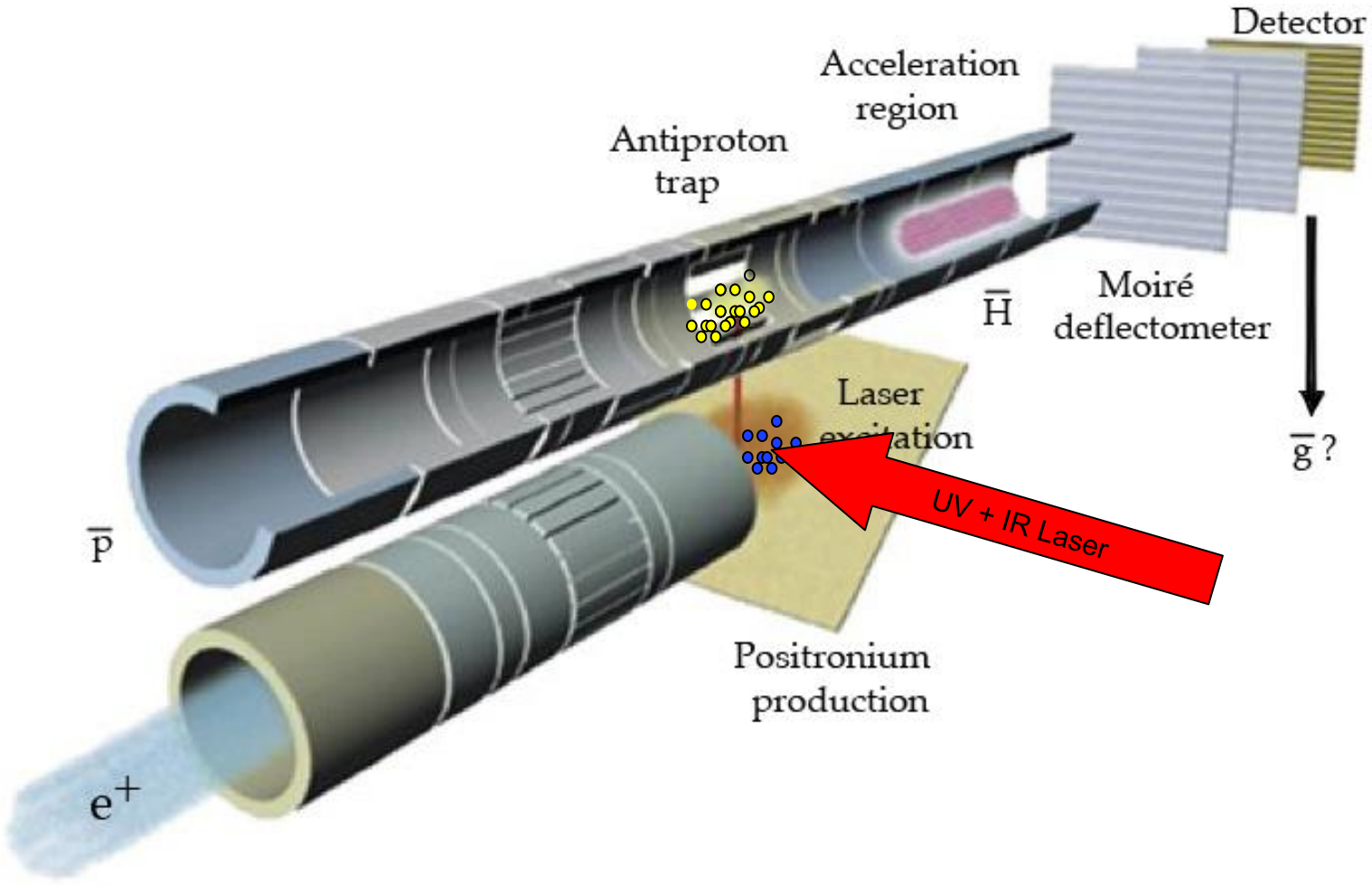

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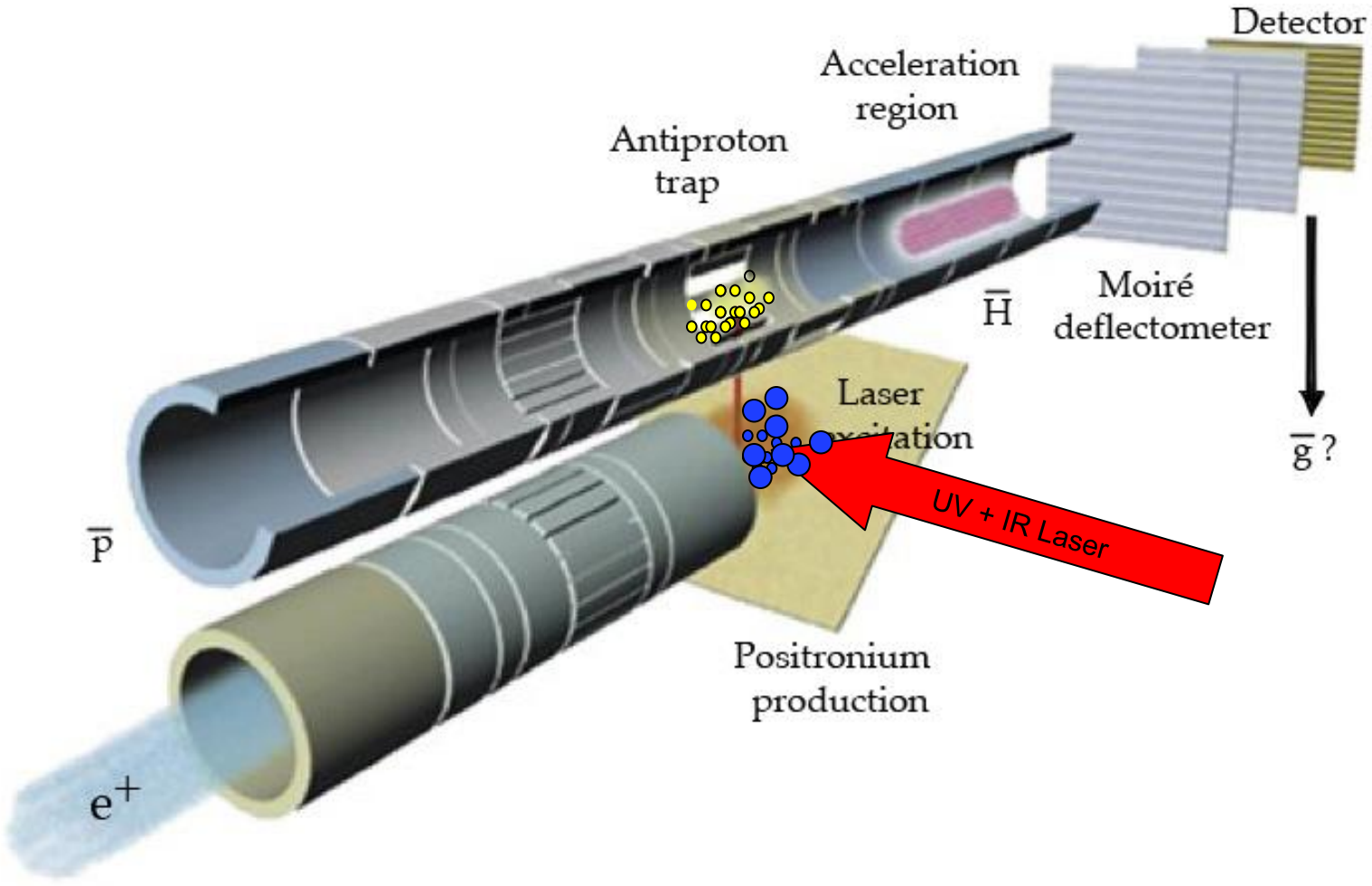

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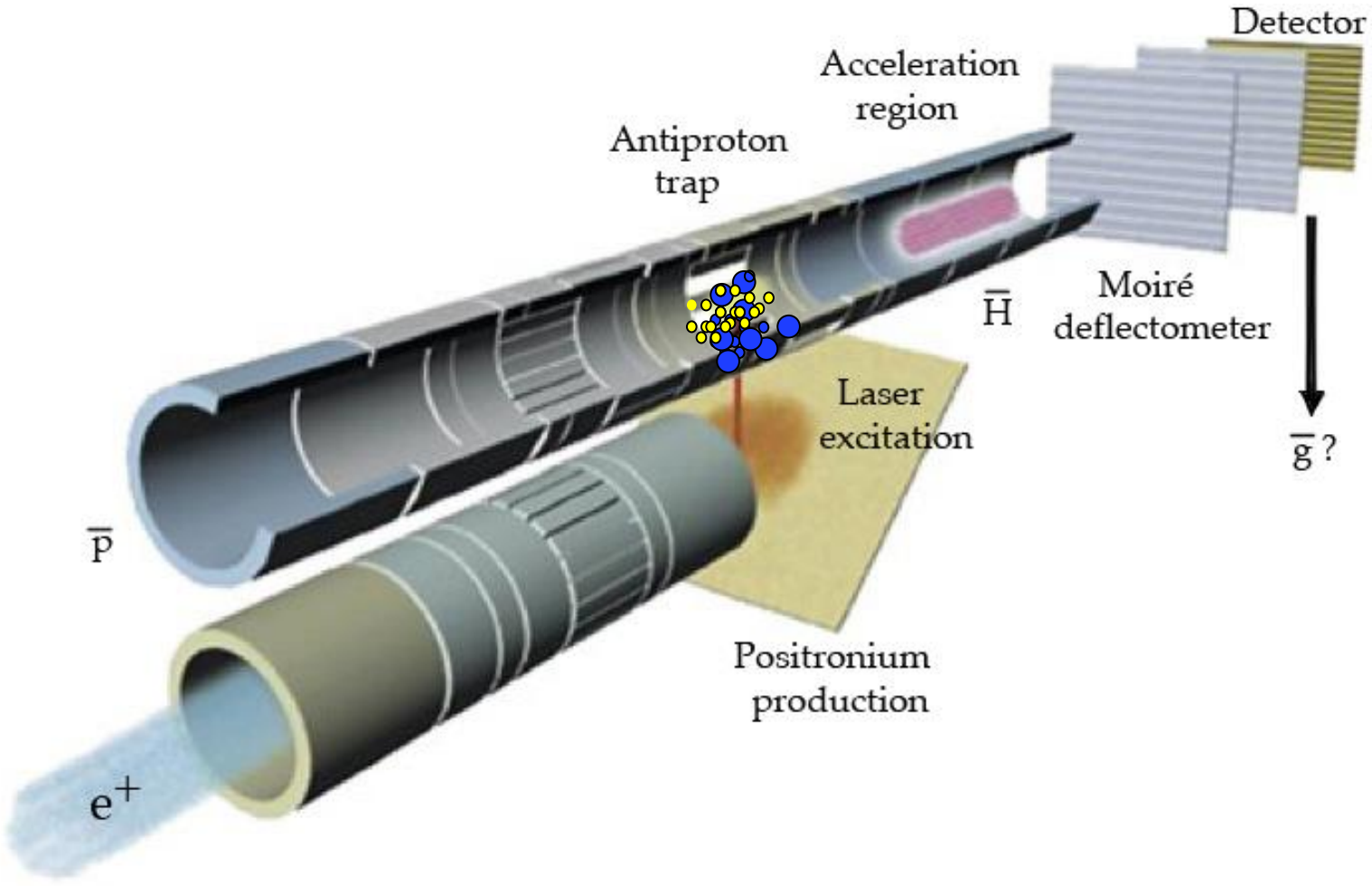

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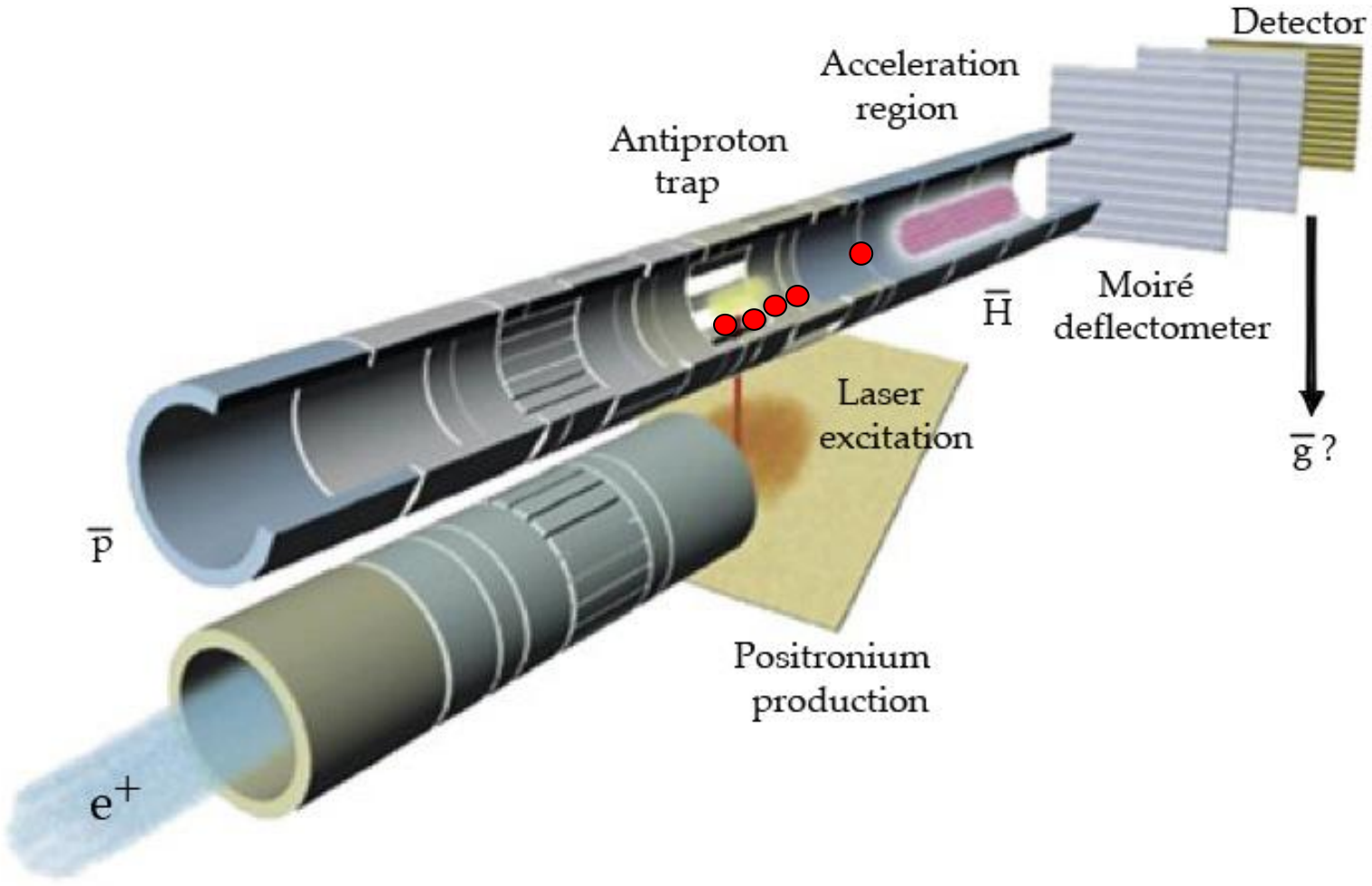

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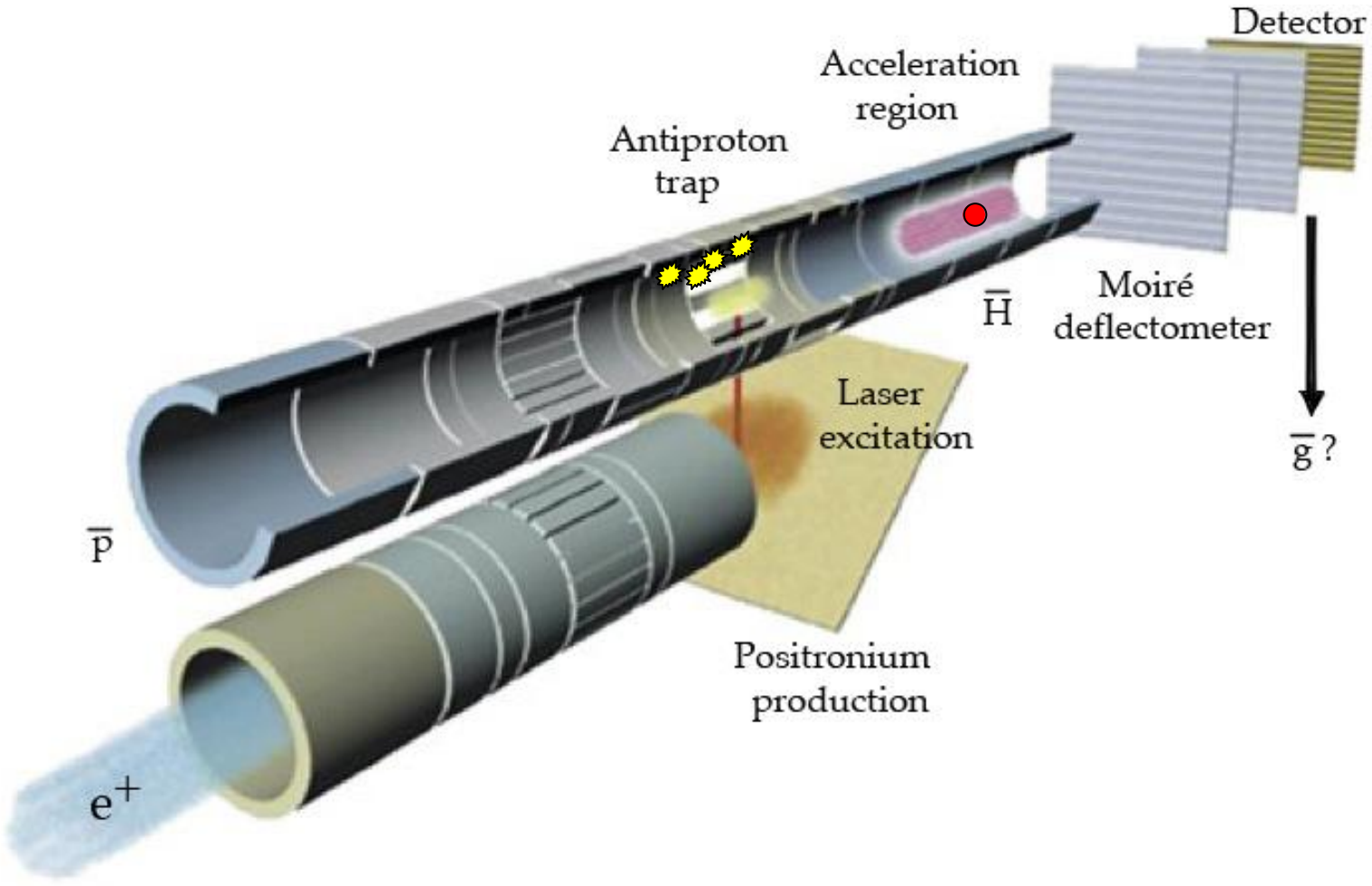

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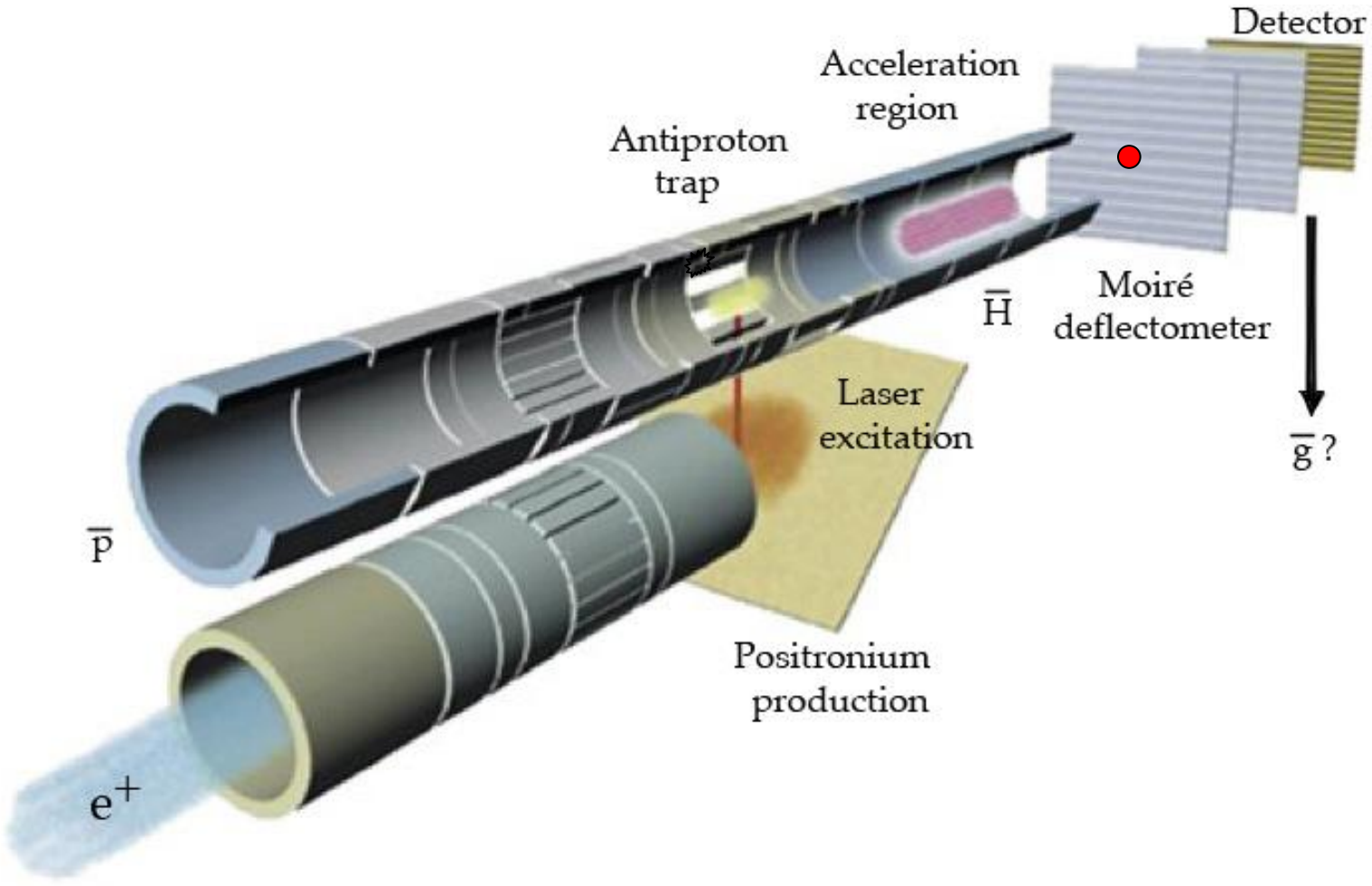

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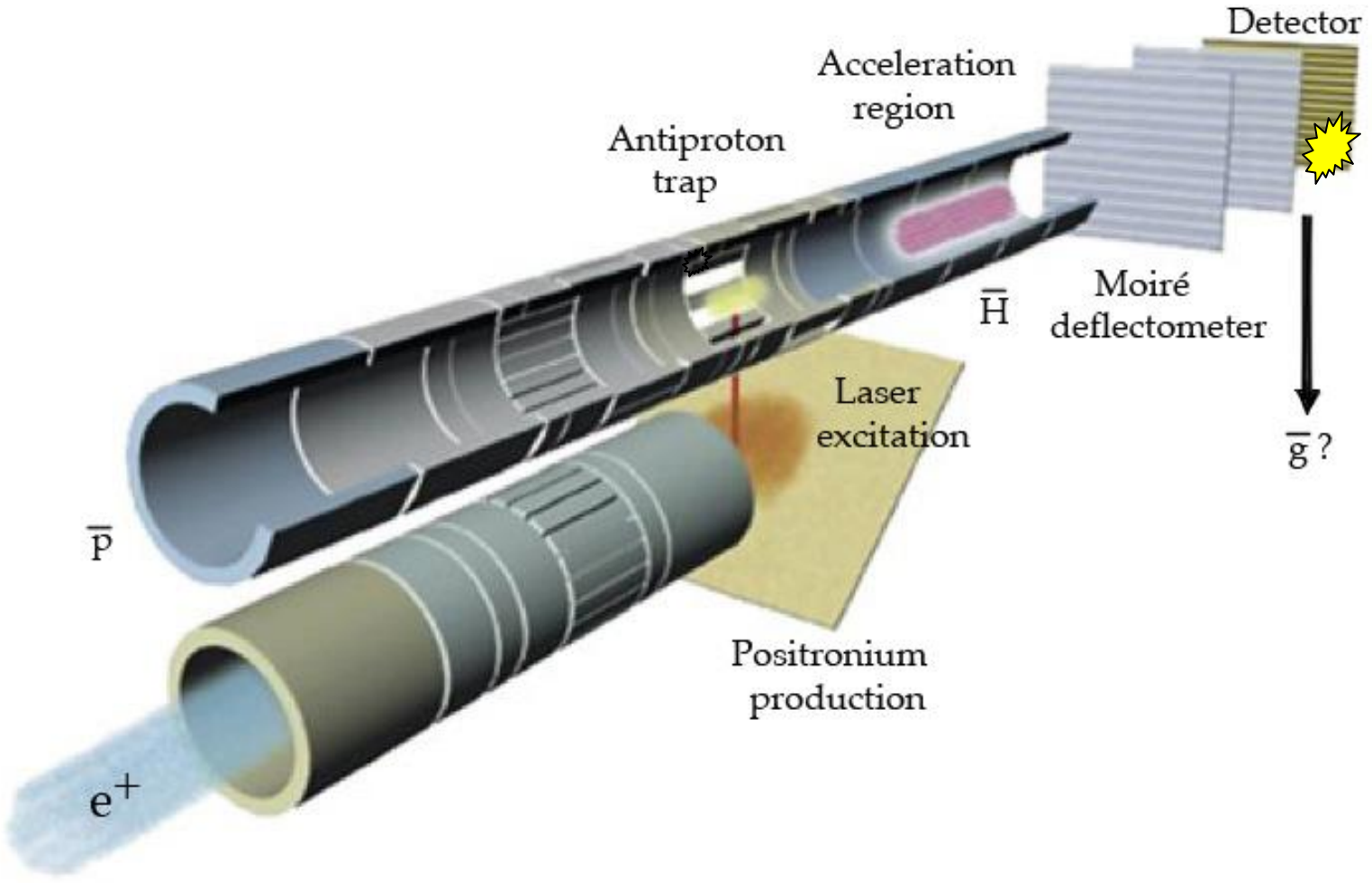
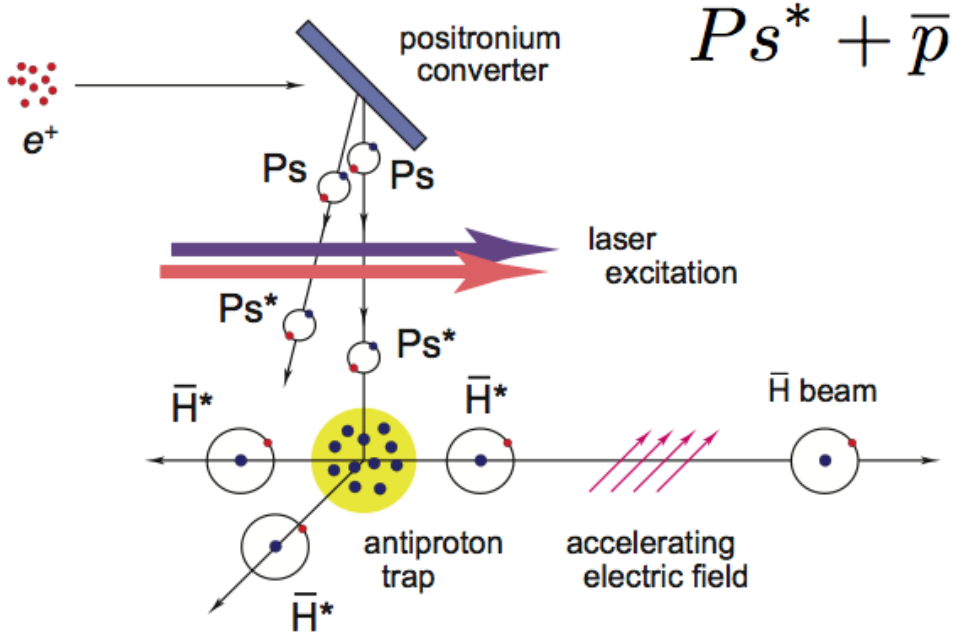
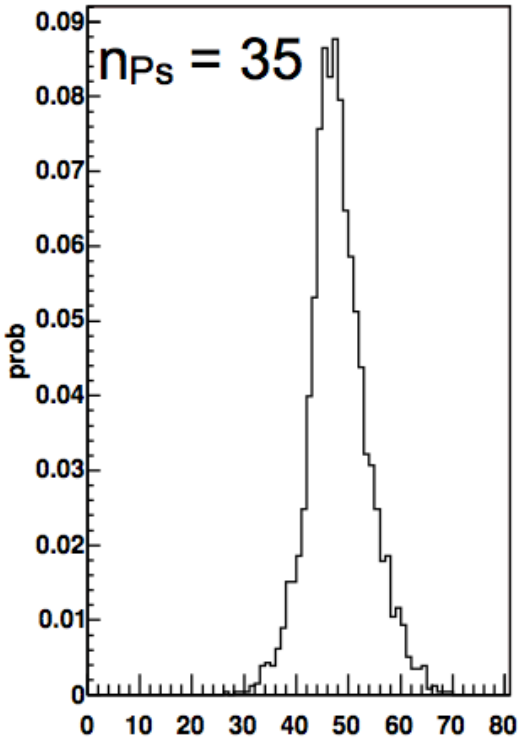


Antihydrogen formation

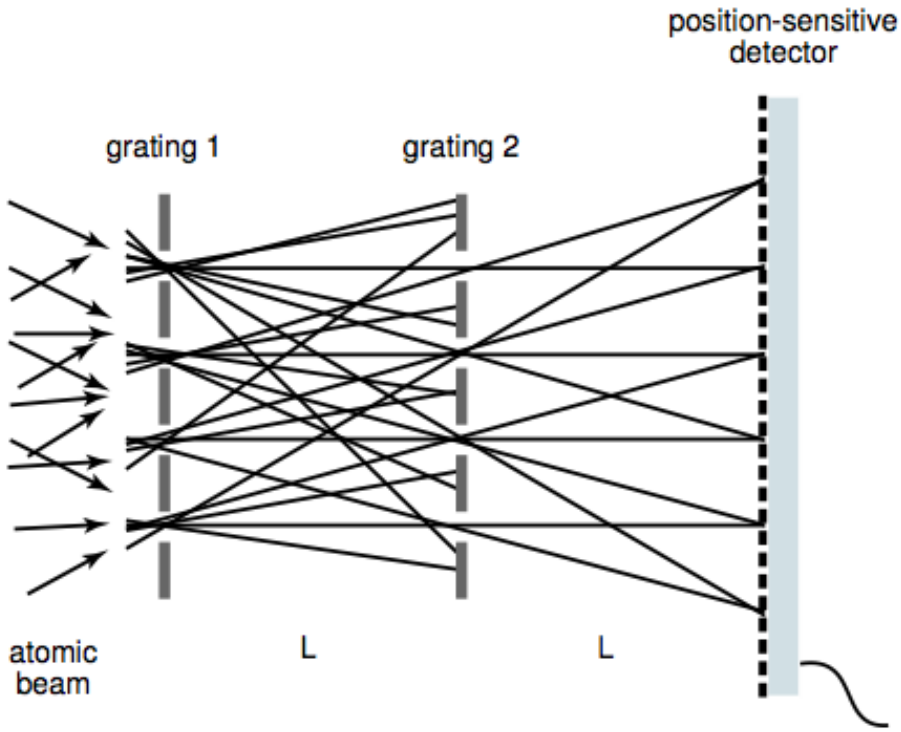


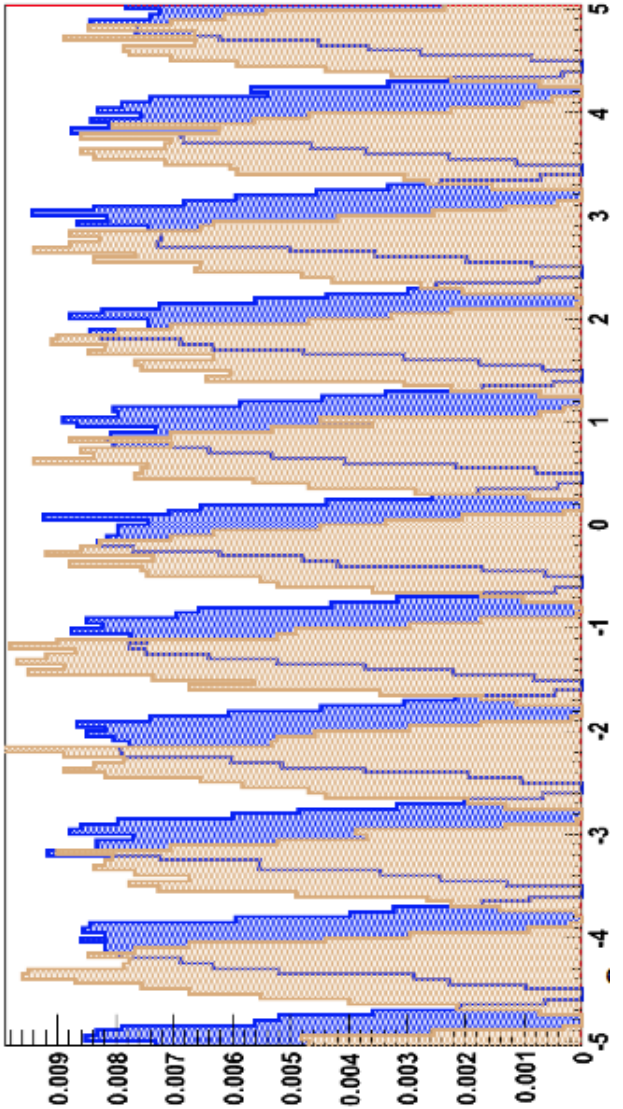
$$Ps^* + \bar{p} \rightarrow \overline{H}^* + e^-$$



- Positronium charge exchange technique:
  - Large cross-section, scales as n^4
  - Narrow and defined final state distribution

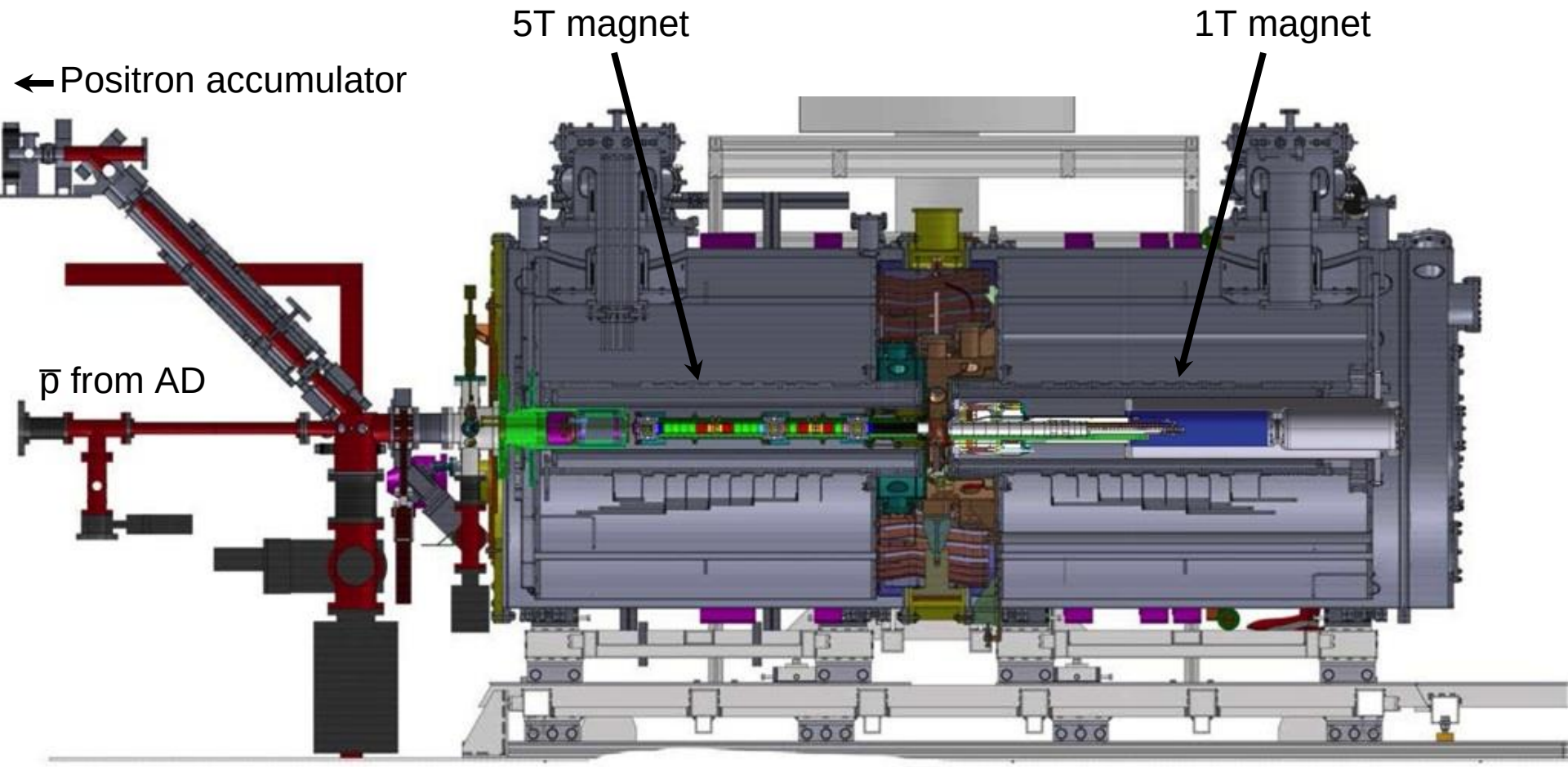
Moiré Deflectometer



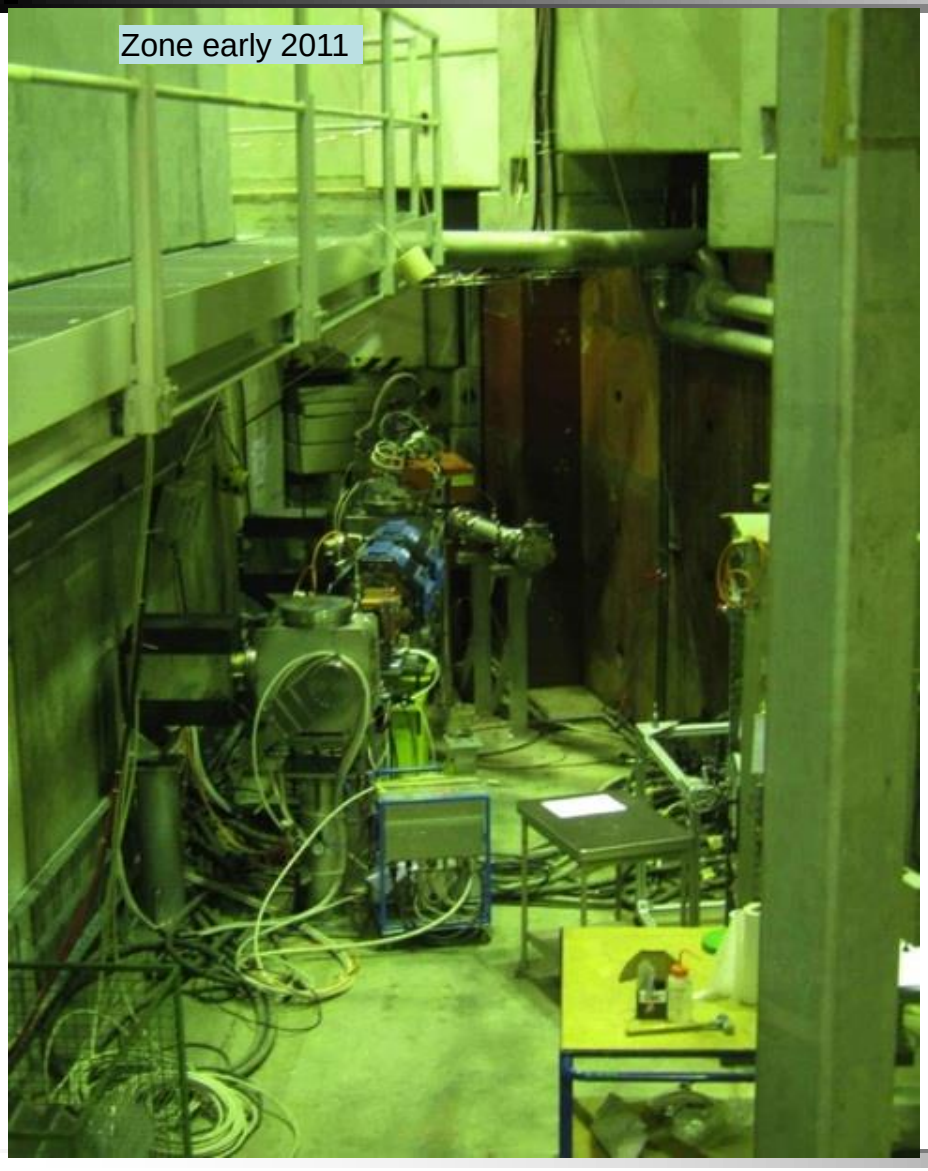


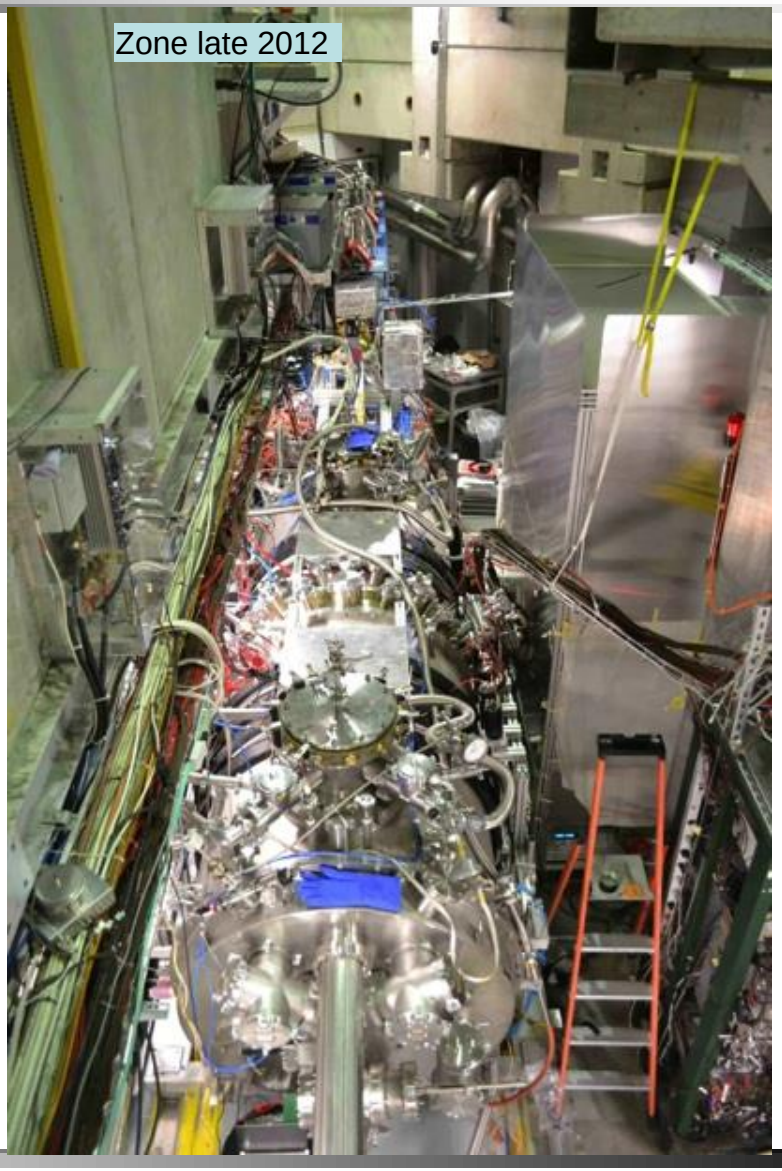
- Classical deflectometer (shadow mask)
- Third grating replaced by position-sensitive detector

Experimental Apparatus

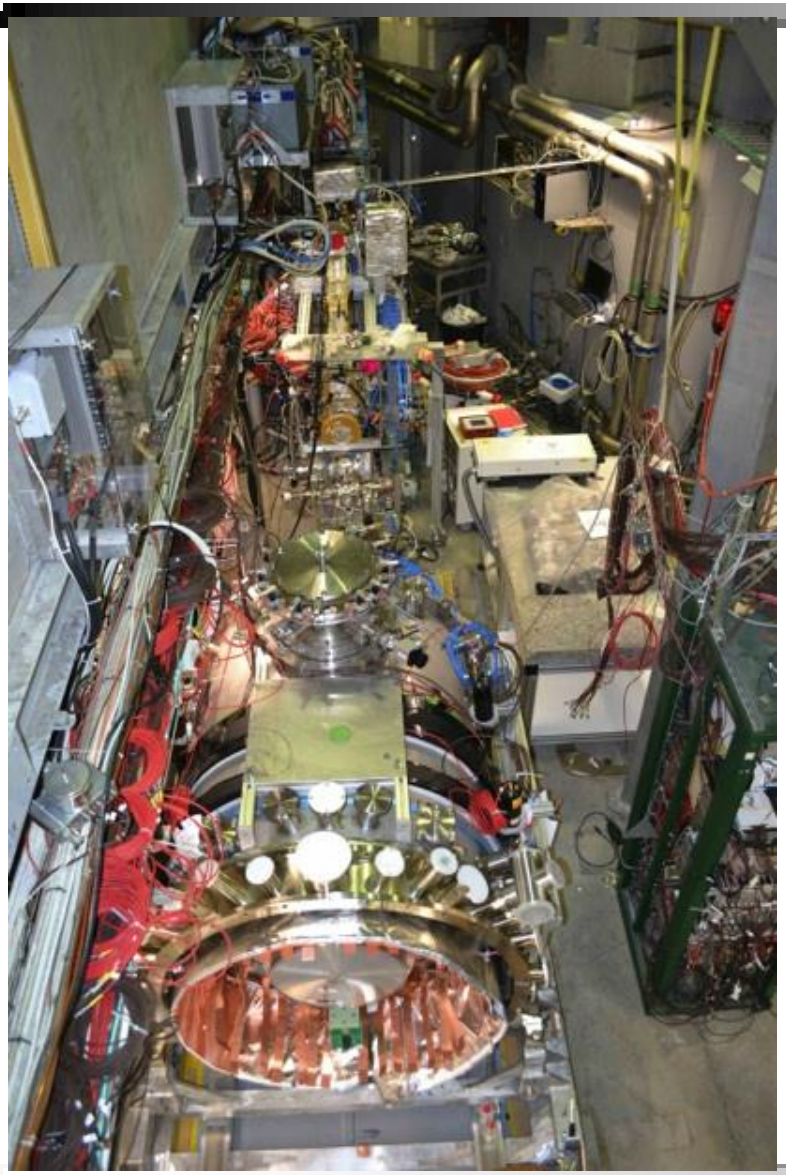


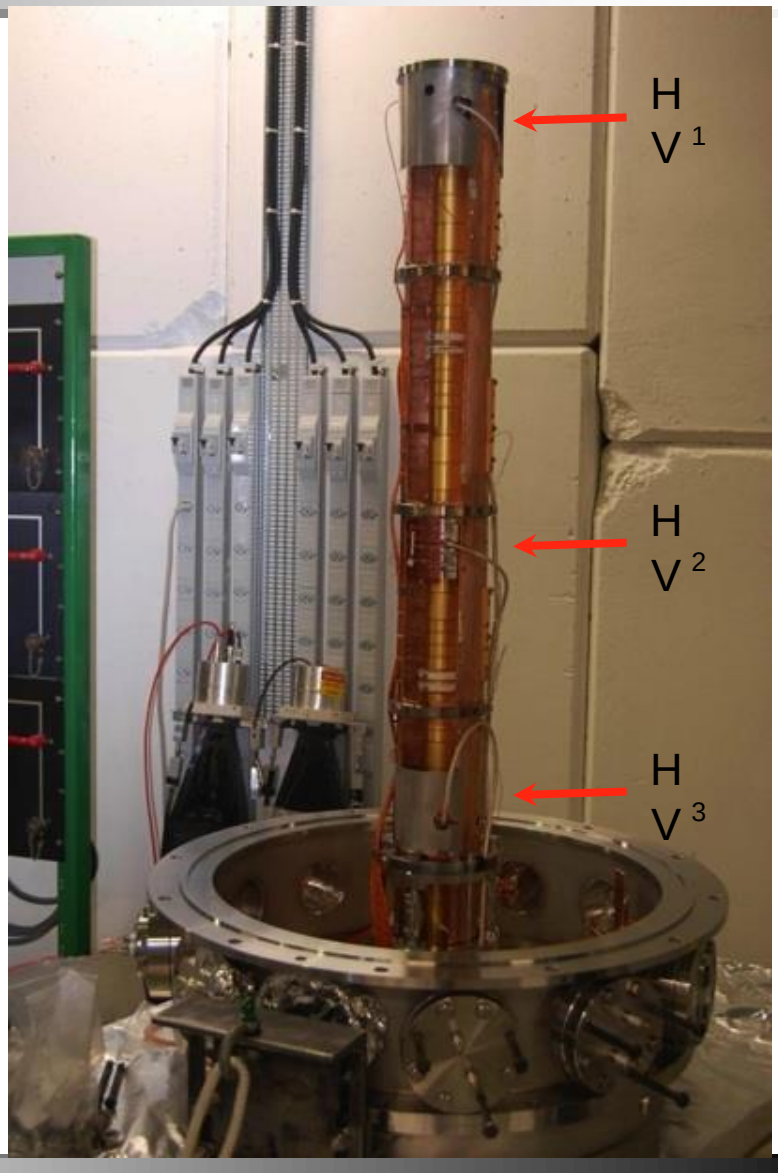
Experimental Installation



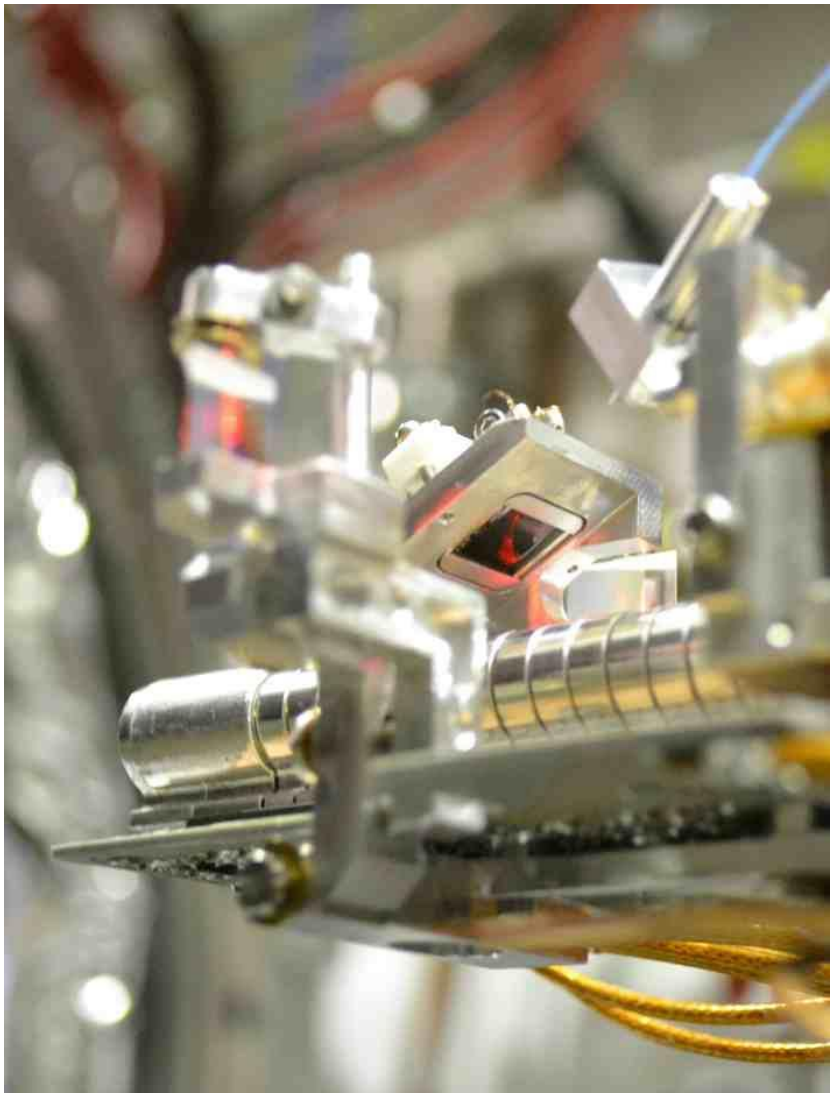


5T Catching Traps

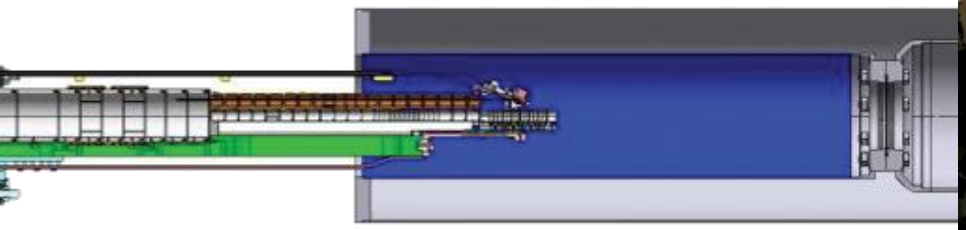


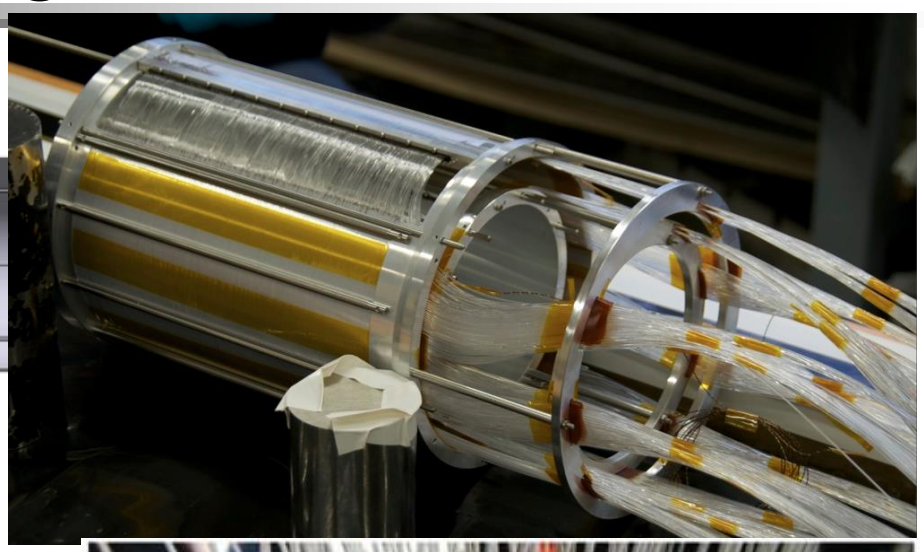


1T Formation Traps



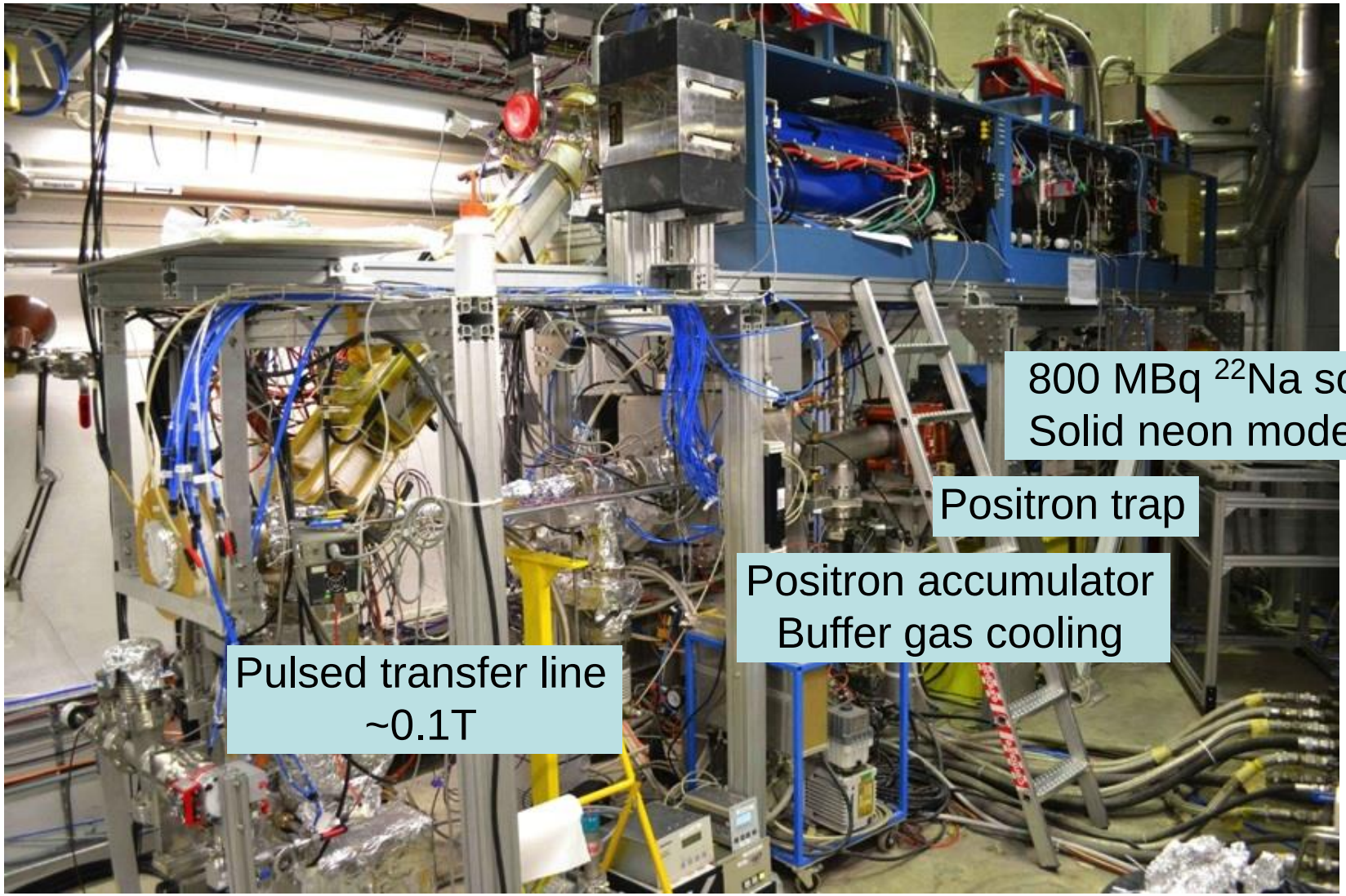
Central Antihydrogen Detector



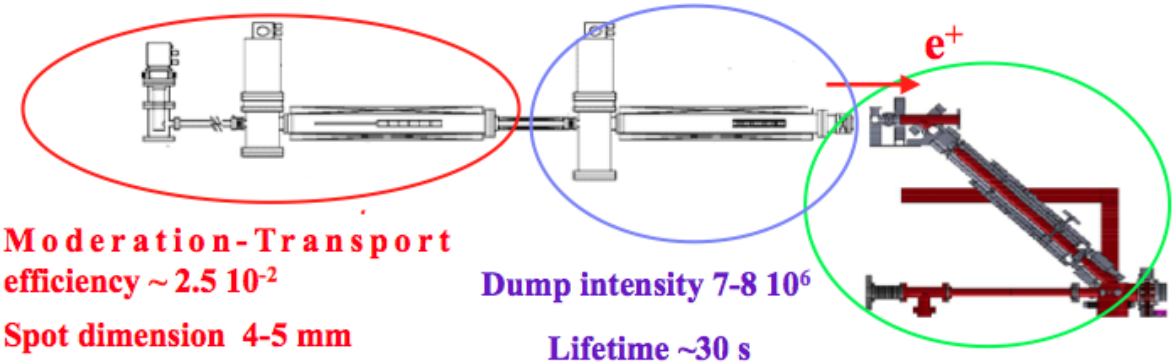


- Scintillating fibre detector operating at 4K
- 800 channels readout by SiPM
- 200 MHz readout detecting hit pattern

Positron System



Positron System



Moderation-Transport efficiency ~ 2.5 10^{-2}

Spot dimension 4-5 mm

Trapping-dumping efficiency ~ 0.14

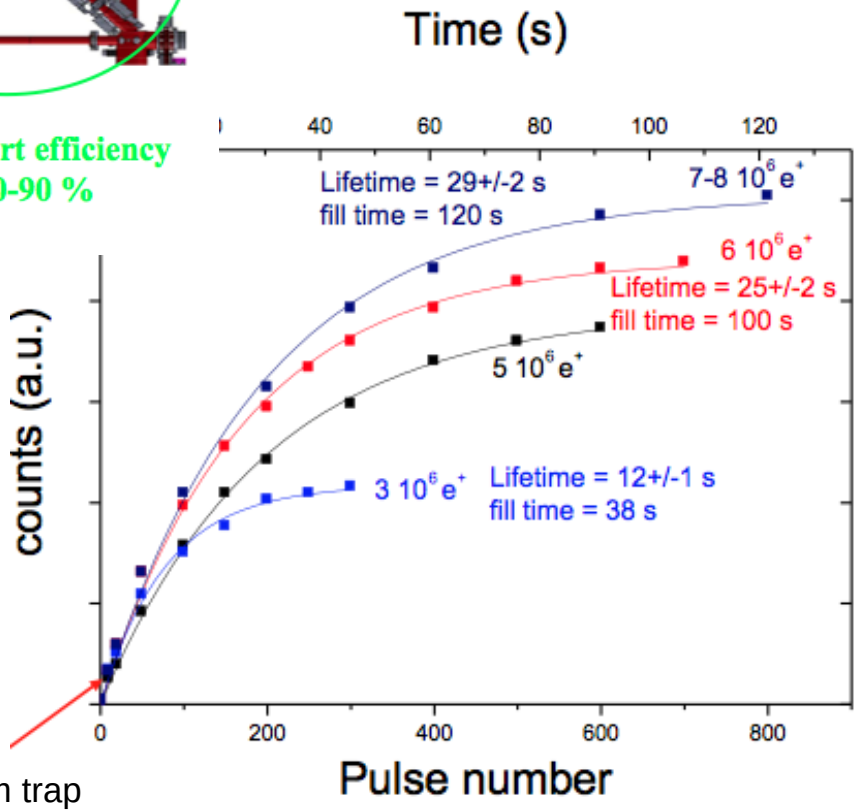
Spot dimension 1-2 mm

Dump intensity 7-8 10^6

Lifetime ~30 s

Fill time ~120 s

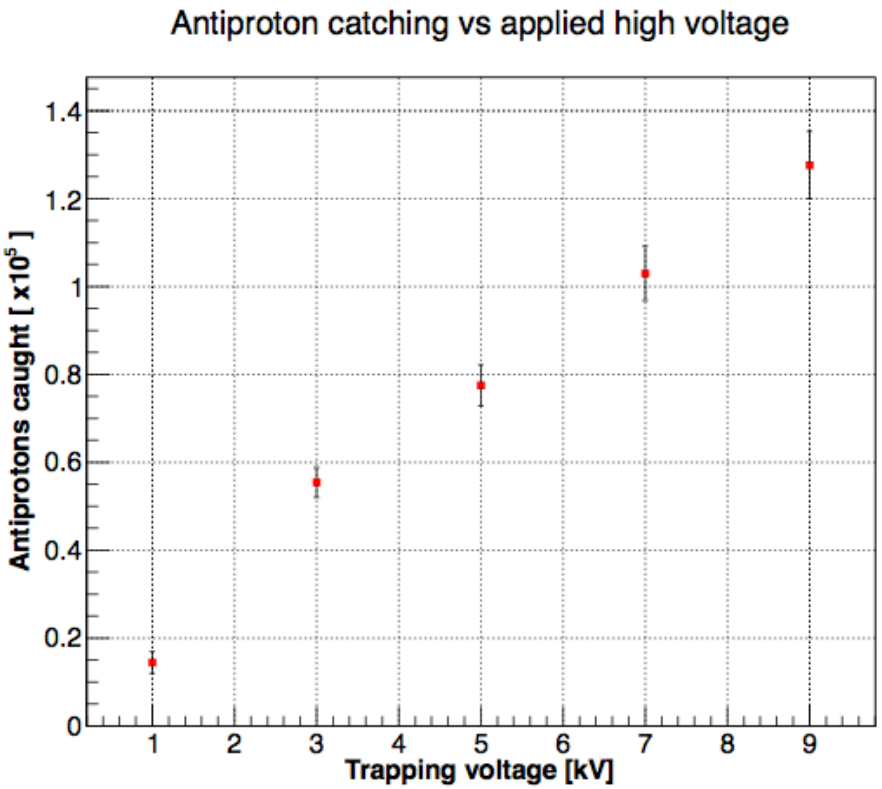
Transport efficiency ~80-90 %

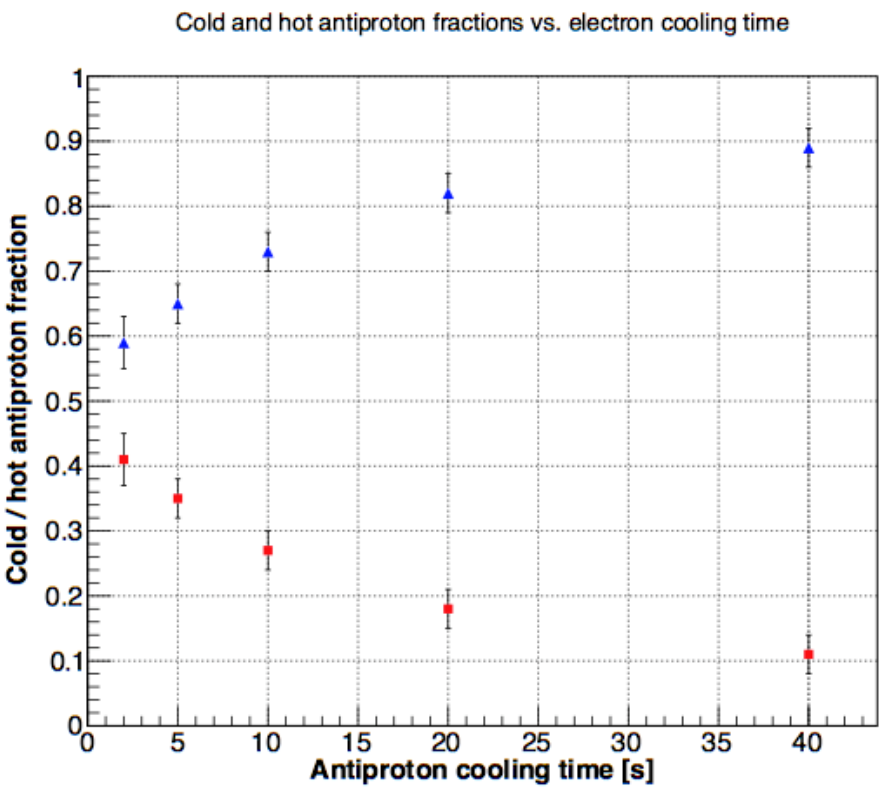


- Ongoing work to increase rates and efficiencies

5-6 x 10^4 e^+ from trap

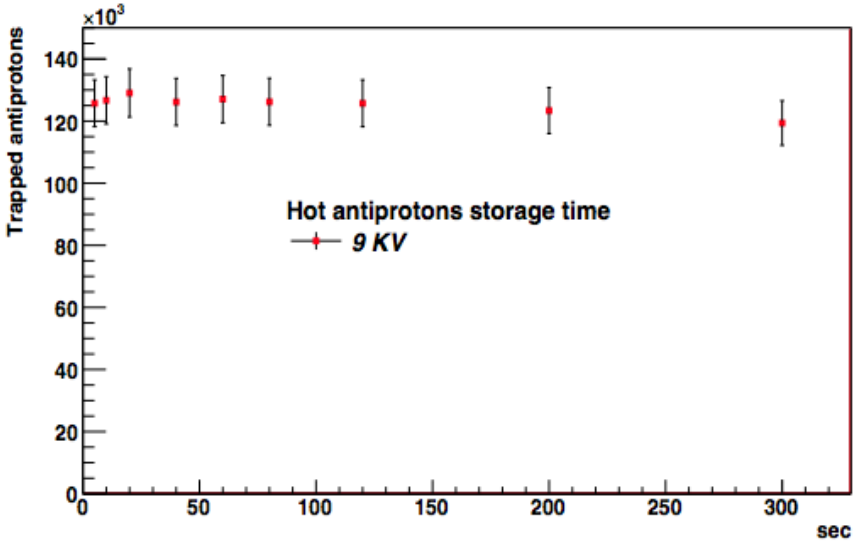
Commissioning Results

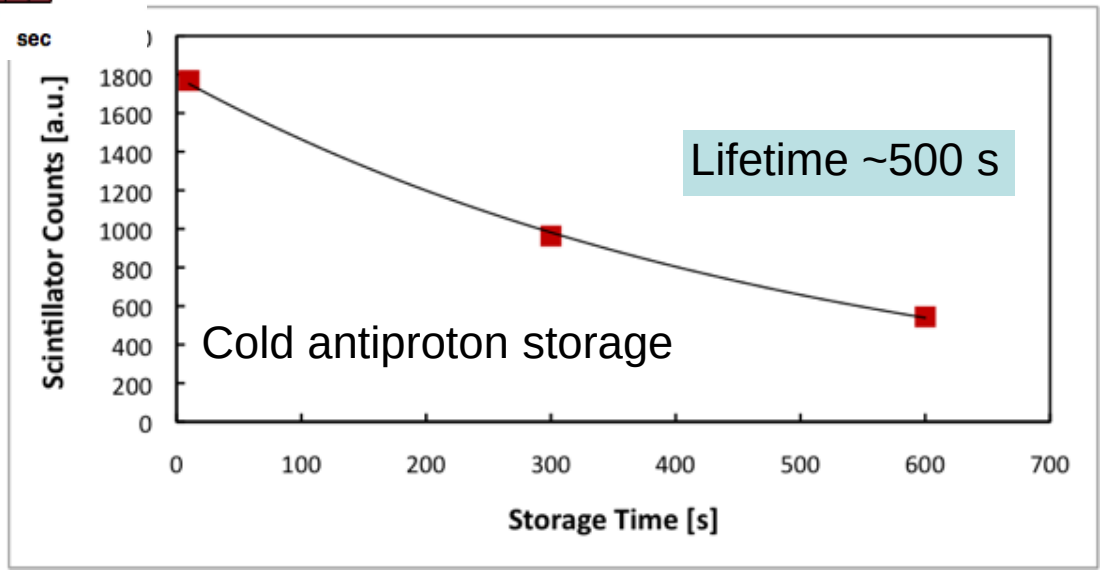




- Trapping, cooling

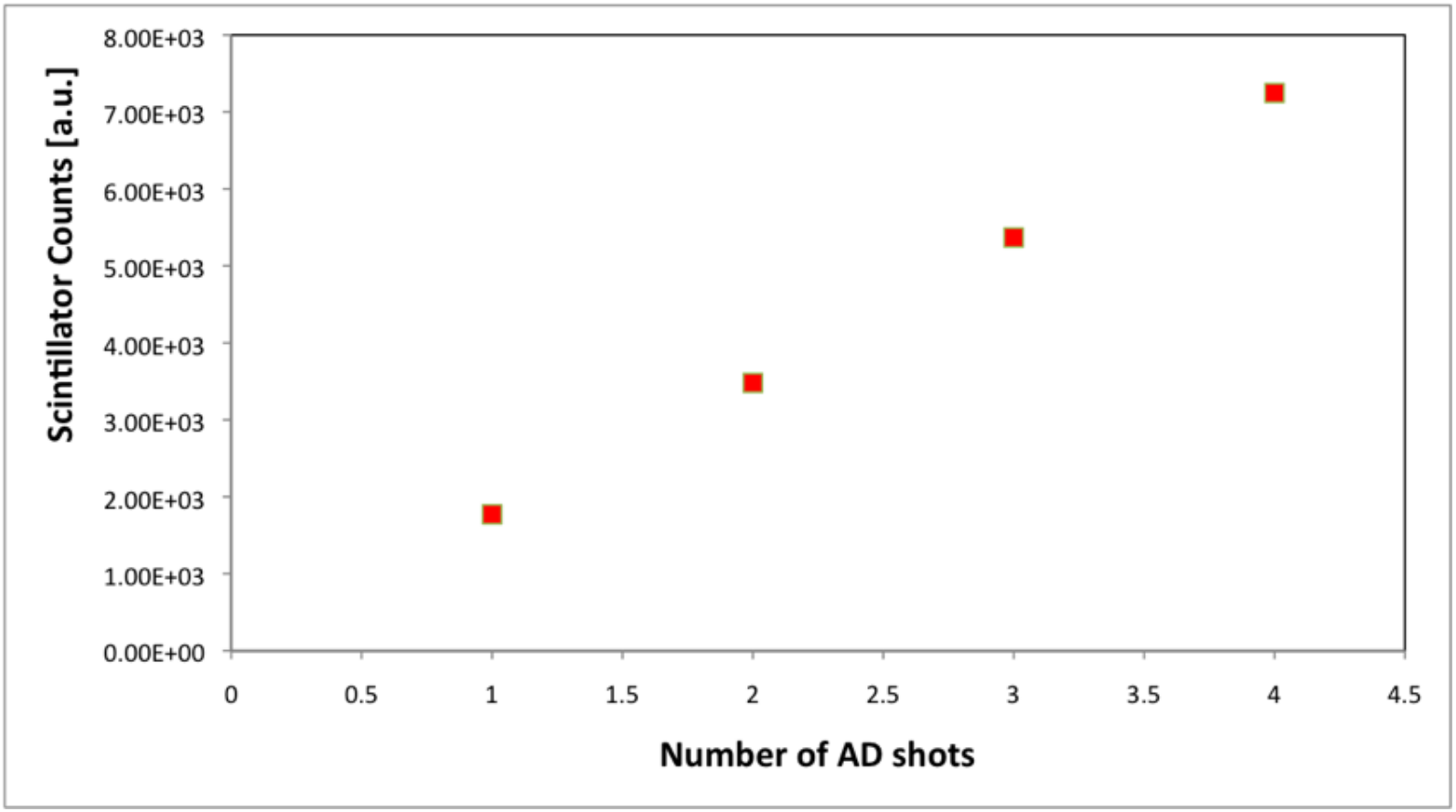
Commissioning Results





- Storing

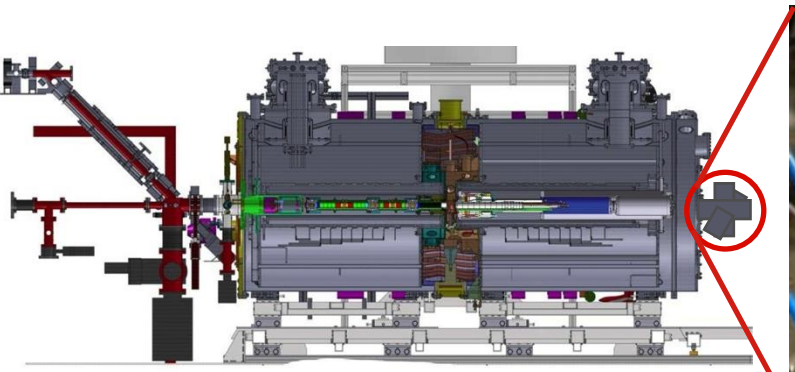
Commissioning Results

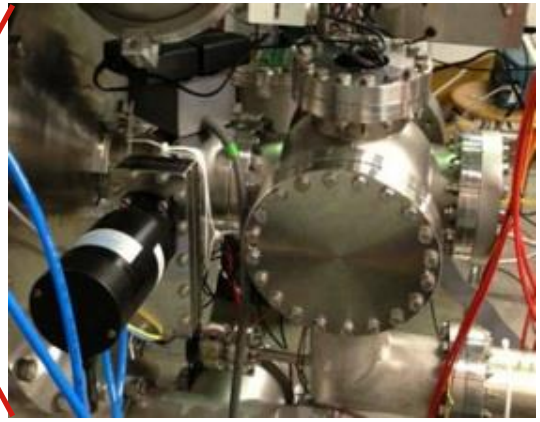


- Manipulations

Detector Tests

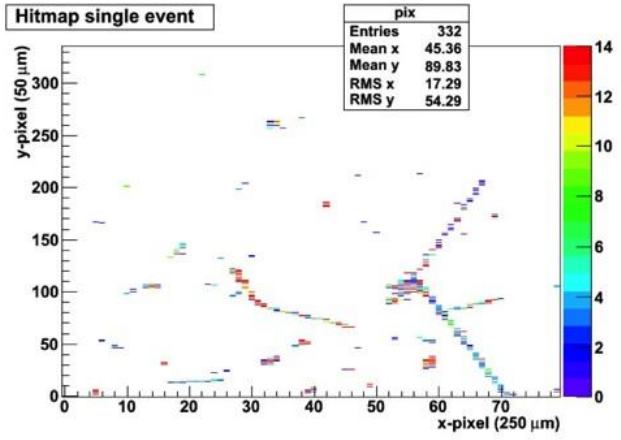
Parasitic tests:



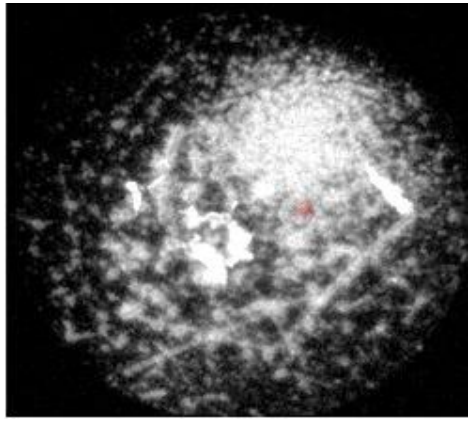


Explore different candidate technologies for the (downstream) antihydrogen detector

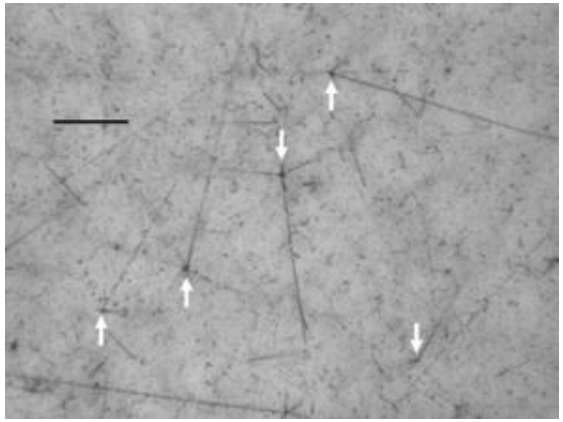
Silicon detectors (strip, pixel)



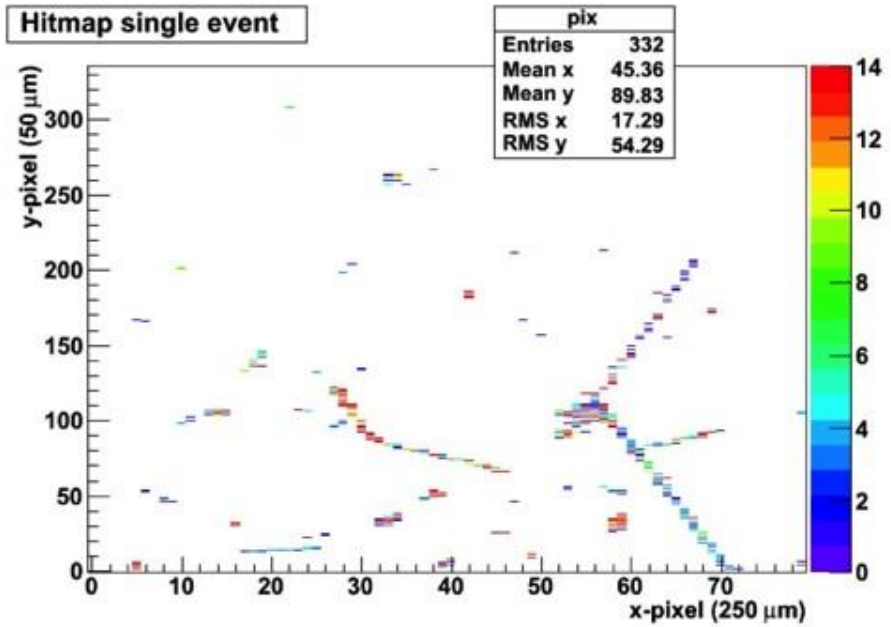
MCP

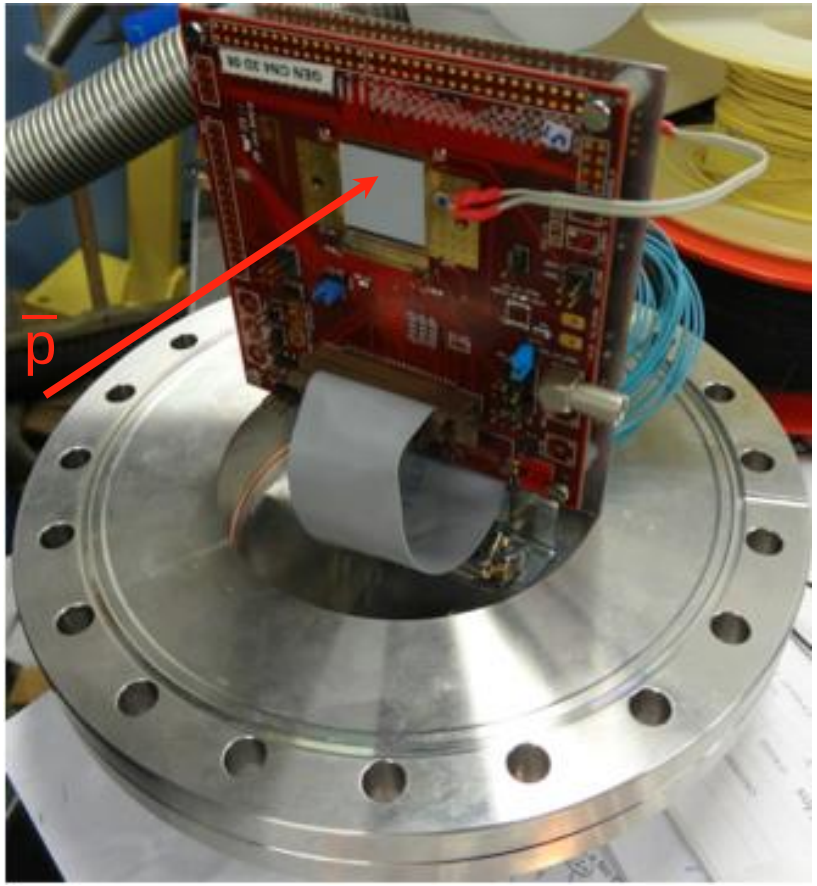


Emulsions



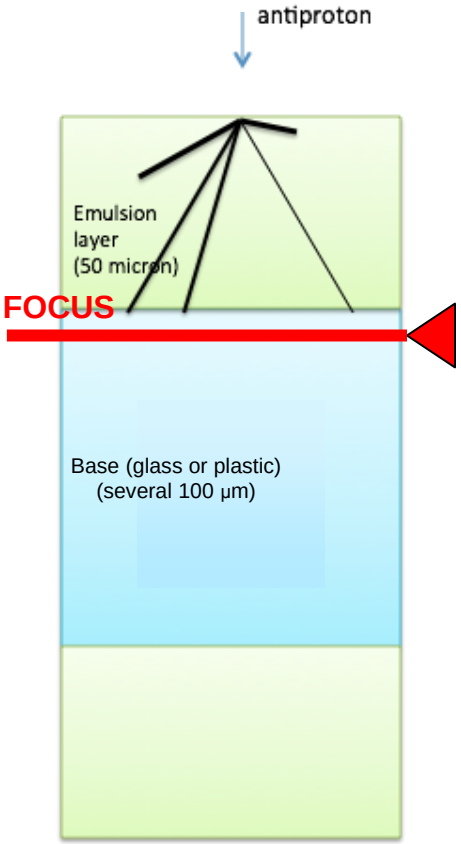
Silicon Detectors

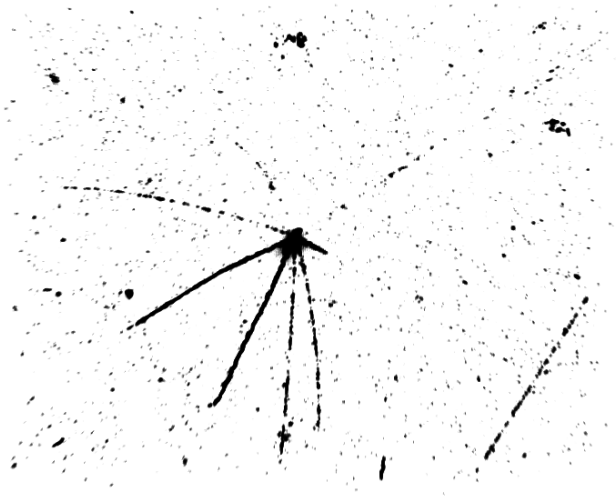




- 3D pixel sensor designed for the ATLAS upgrade
- Also tested: strip sensor, Mimotera

Emulsions



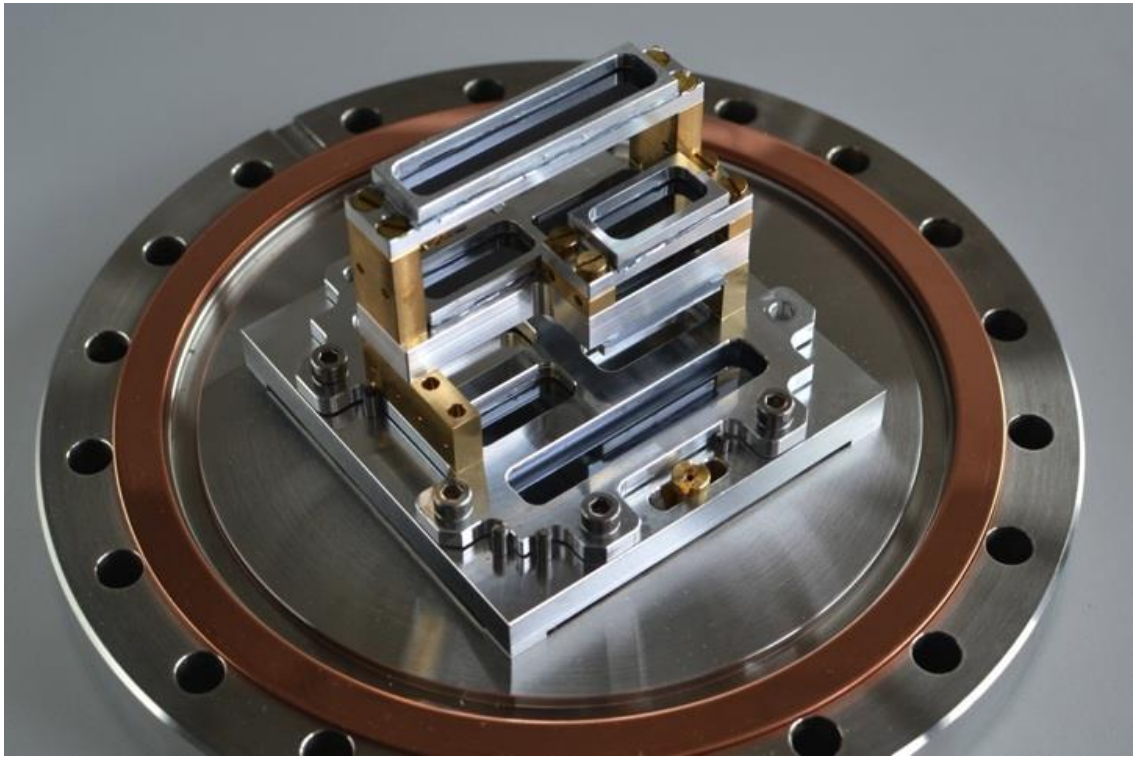


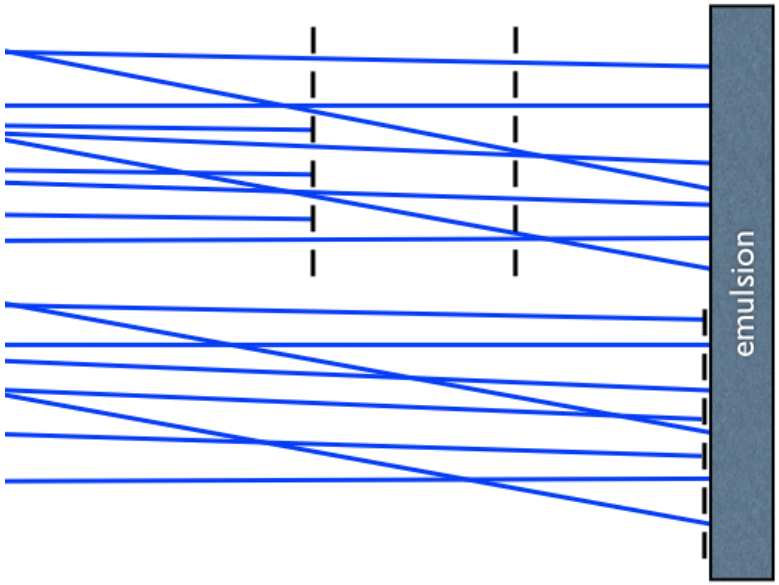
- Exposure of emulsion
- Development in dark room
- Scanning on automated microscopes

- Offline track and vertex finding algorithms
- 1 μm vertex resolution

First Test of moiré Deflectometer

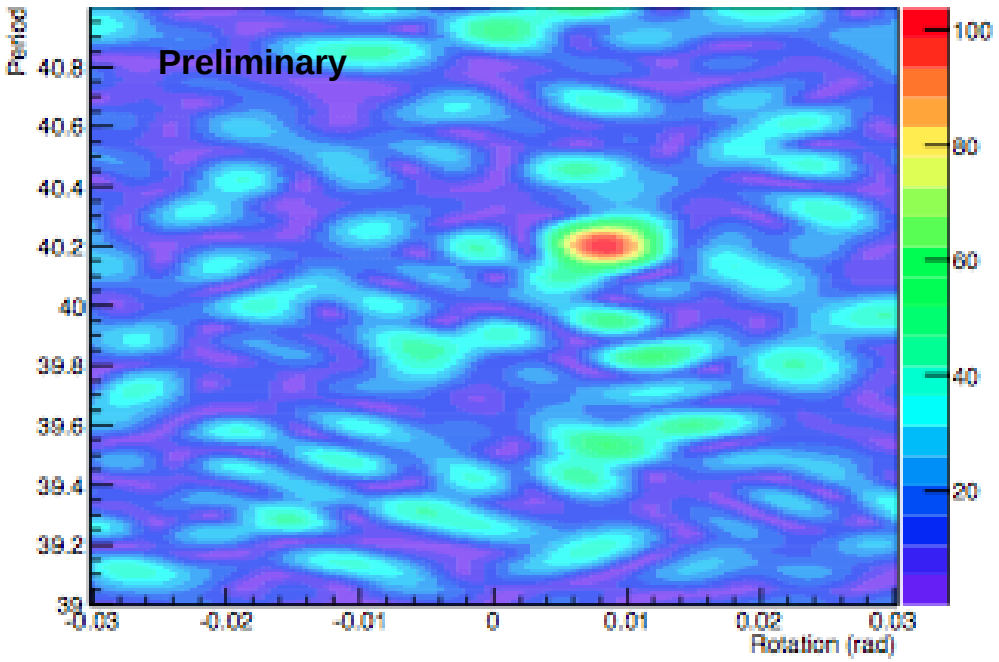
- ~100 keV antiprotons
- 7 hour exposure
- Bare emulsion behind deflectometer





First Test of moiré Deflectometer

- Antiproton fringes observed
- Alignment of gratings using light and single grating
- Promising results!



Publication forthcoming!

Overview of AD physics

	Magn. Moment μ		Spectroscopy		Gravity		Other (med, σ, ..)	
			optical	microwave				
ACE							✓	✓
AEgIS			✓	✓		✓		
ALPHA			✓	✓ ?	?	?		
ASACUSA	✓	?		✓			✓	✓
ATRAP	✓	✓	✓					
BASE		✓						
GBAR						✓		

< 2013

> 2013

Conclusions

- The AD facility has proven to be THE place for precision physics
- All experiments prepare for the return of anti-protons in Q2 2014
- Gravity measurements are in preparation now and should settle the long lasting question on the influence of gravity and anti-matter

- Many thanks to the AD team for an outstanding performance of the machine