Alpha-g

Observation of the effect of gravity on antimatter

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Antimatter gravity

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CPT symmetry and antimatter gravity in general relativity

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PACS 04.90.+e – Other topics in general relativity and gravitation
PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries
PACS 98.80.-k – Cosmology

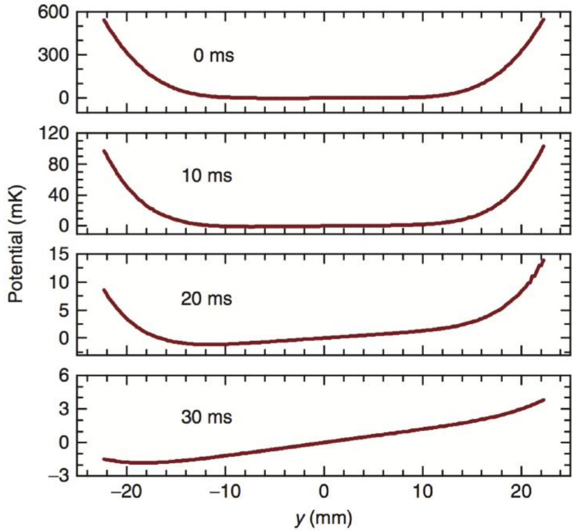
Abstract – The gravitational behavior of antimatter is still unknown. While we may be confident that antimatter is self-attractive, the interaction between matter and antimatter might be either attractive or repulsive. We investigate this issue on theoretical grounds. Starting from the CPT invariance of physical laws, we transform matter into antimatter in the equations of both electrodynamics and gravitation. In the former case, the result is the well-known change of sign of the electric charge. In the latter, we find that the gravitational interaction between matter and antimatter is a mutual repulsion, *i.e.* antigravity appears as a prediction of general relativity when CPT is applied. This result supports cosmological models attempting to explain the Universe accelerated expansion in terms of a matter-antimatter repulsive interaction.

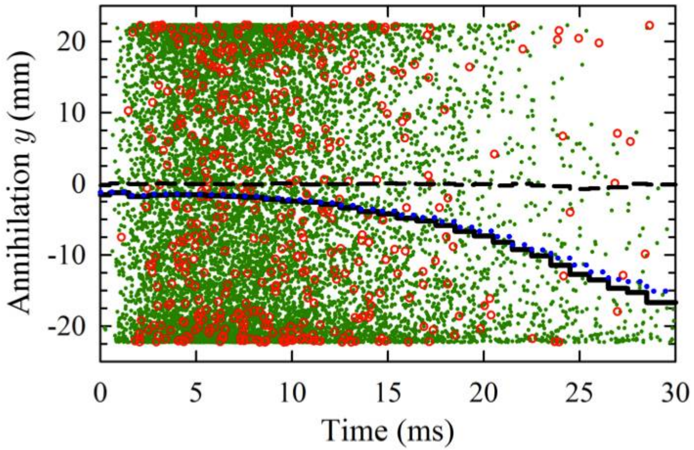
NATURE COMM 4:1785 DOI: 10.1038/ncomms2787

Previous measurement with antihydrogen in horizontal trap of ALPHA-1 (2013)

$F_{antihydrogen} = F \cdot mg$

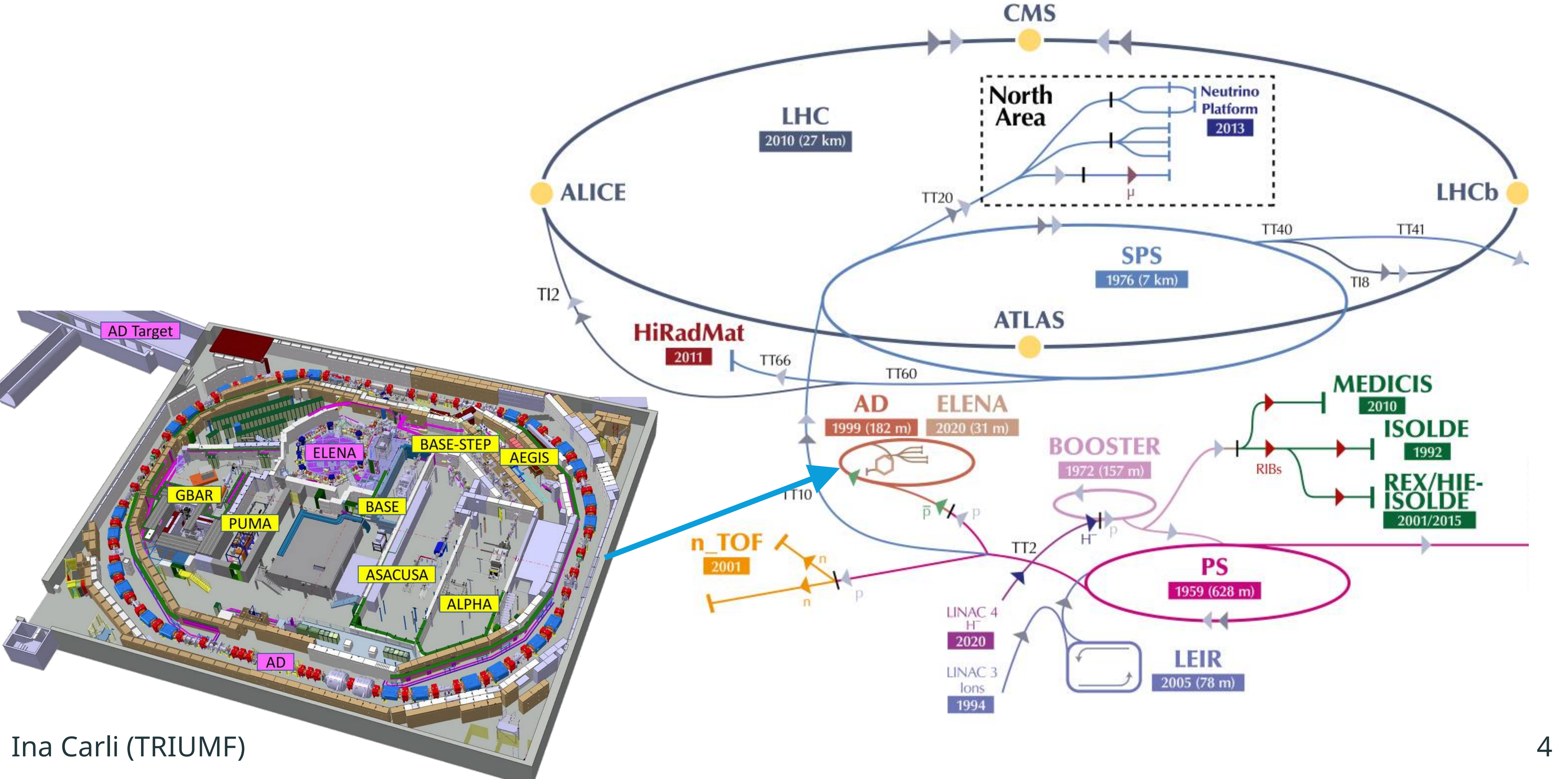
$U(y) = \mu_{antihydrogen}\, B(y) + F \cdot mgy$



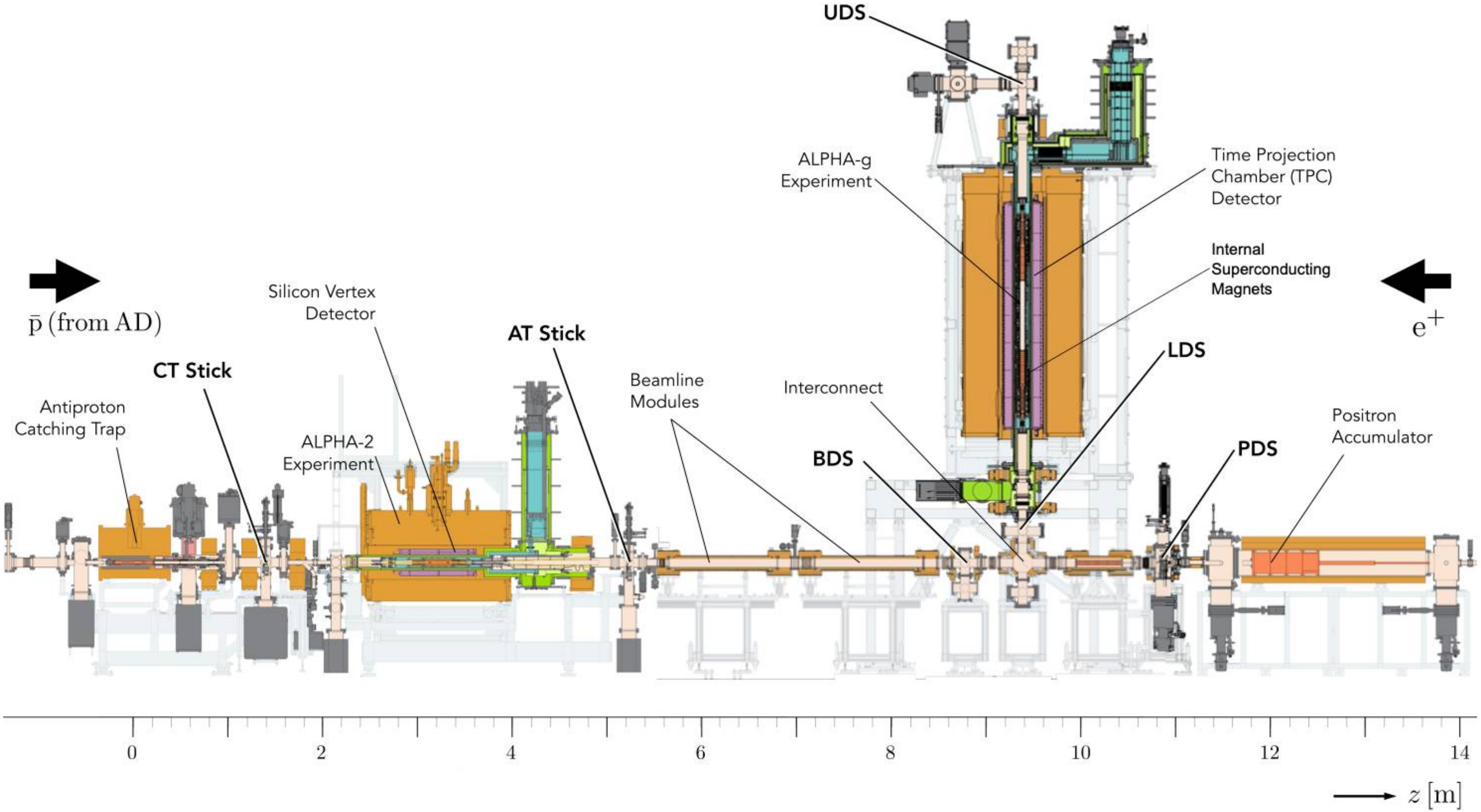


$-65 < F < 110$

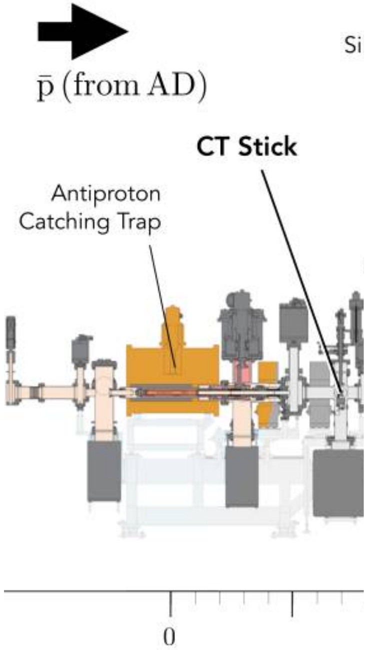
CERN's Antimatter factory



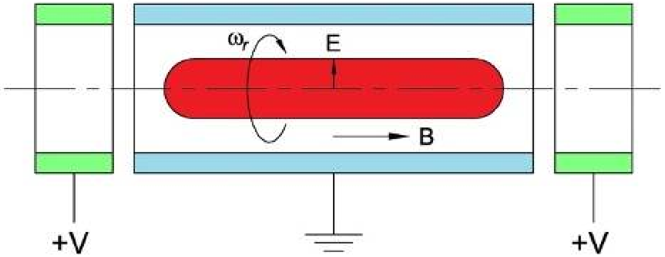
ALPHA experiment

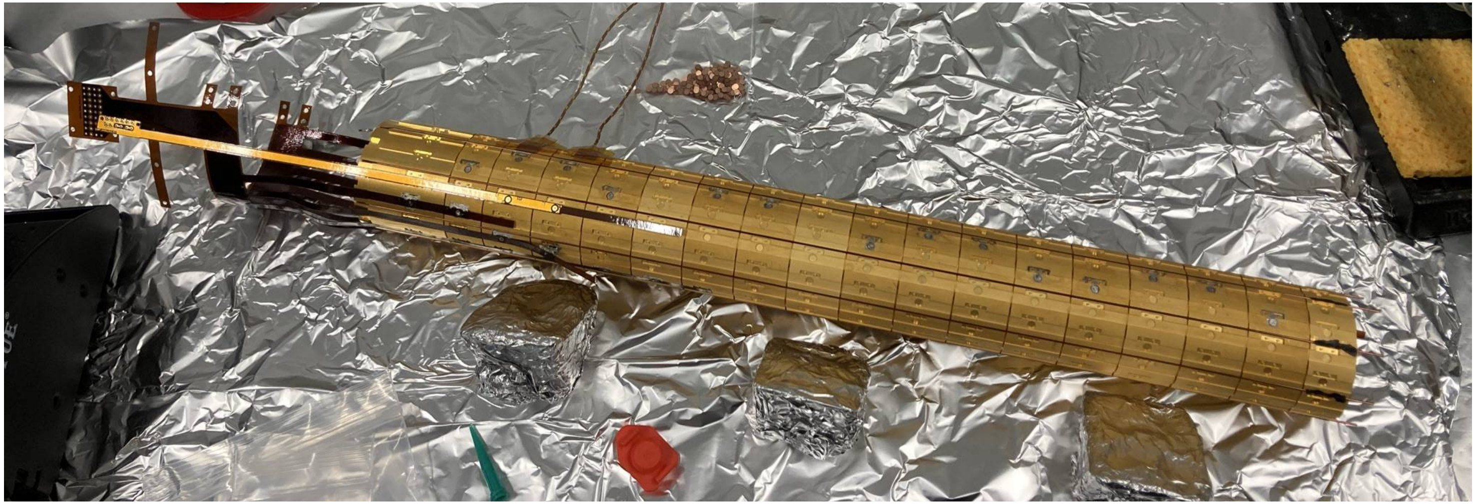


ALPHA experiment



Penning-Malmberg trap

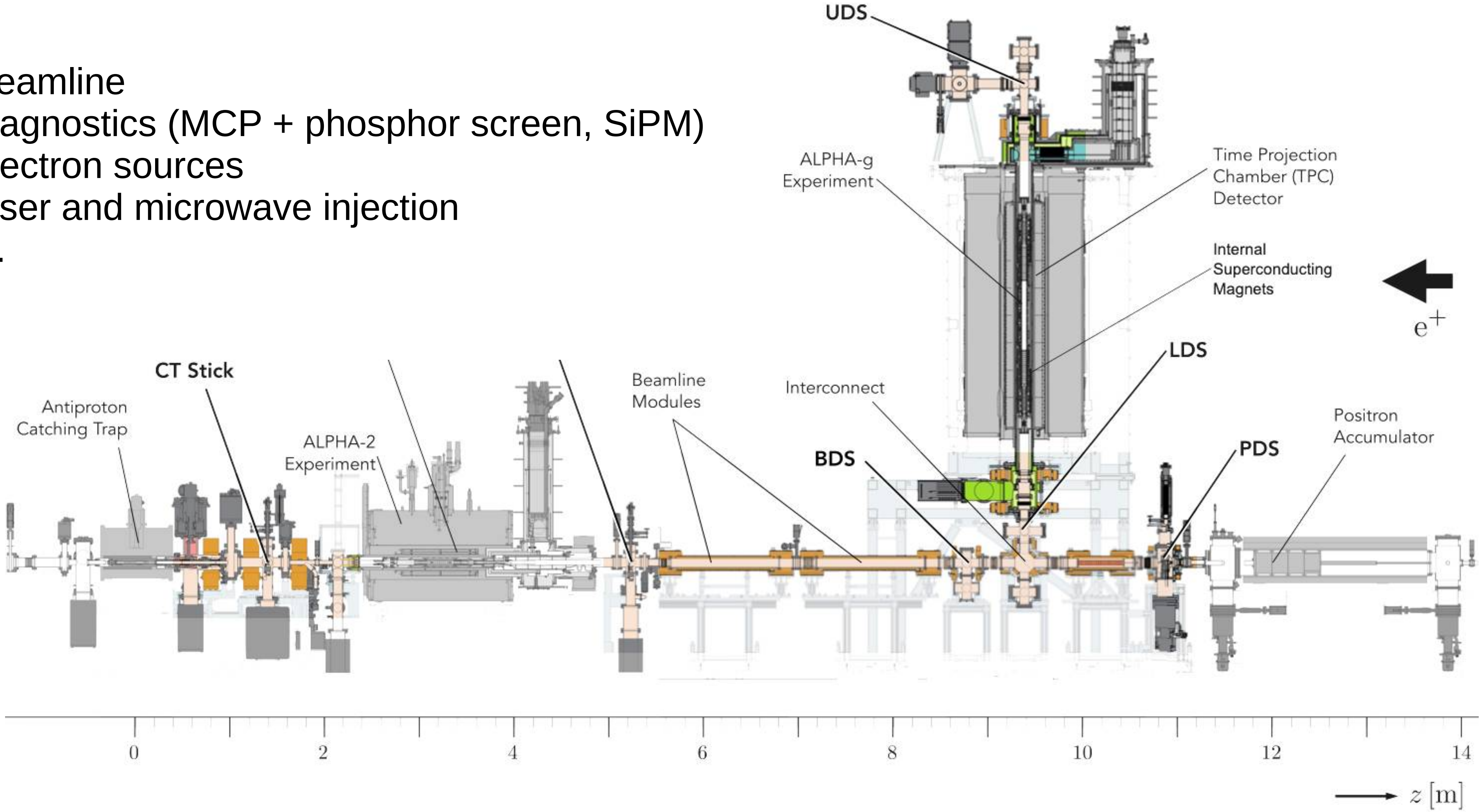




Catching trap:
- catch and prepare 200k antiprotons
- cool from 100keV to 5keV and down to ~0.1 eV or 2000K

ALPHA experiment

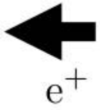
Beamline
diagnostics (MCP + phosphor screen, SiPM)
electron sources
laser and microwave injection
…



Positron source

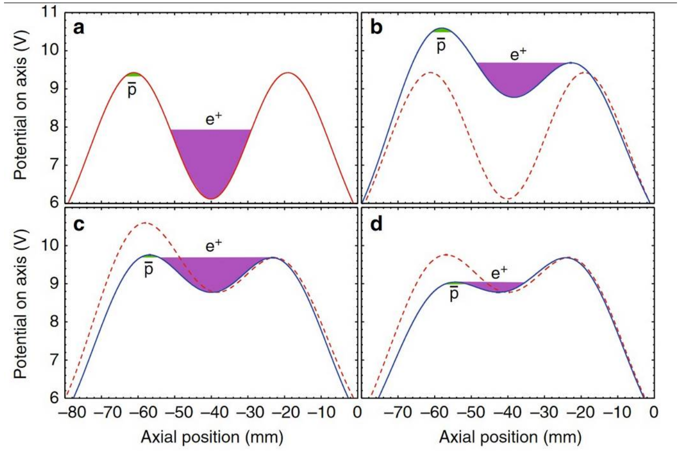
$$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^{+} + \nu_e + \gamma$$

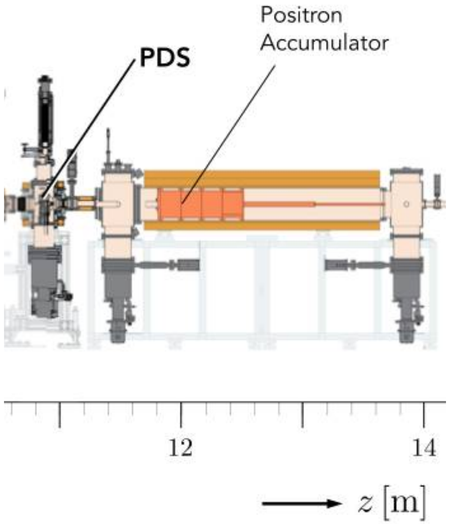
- accumulate and transfer 20M e^{+} per 100s



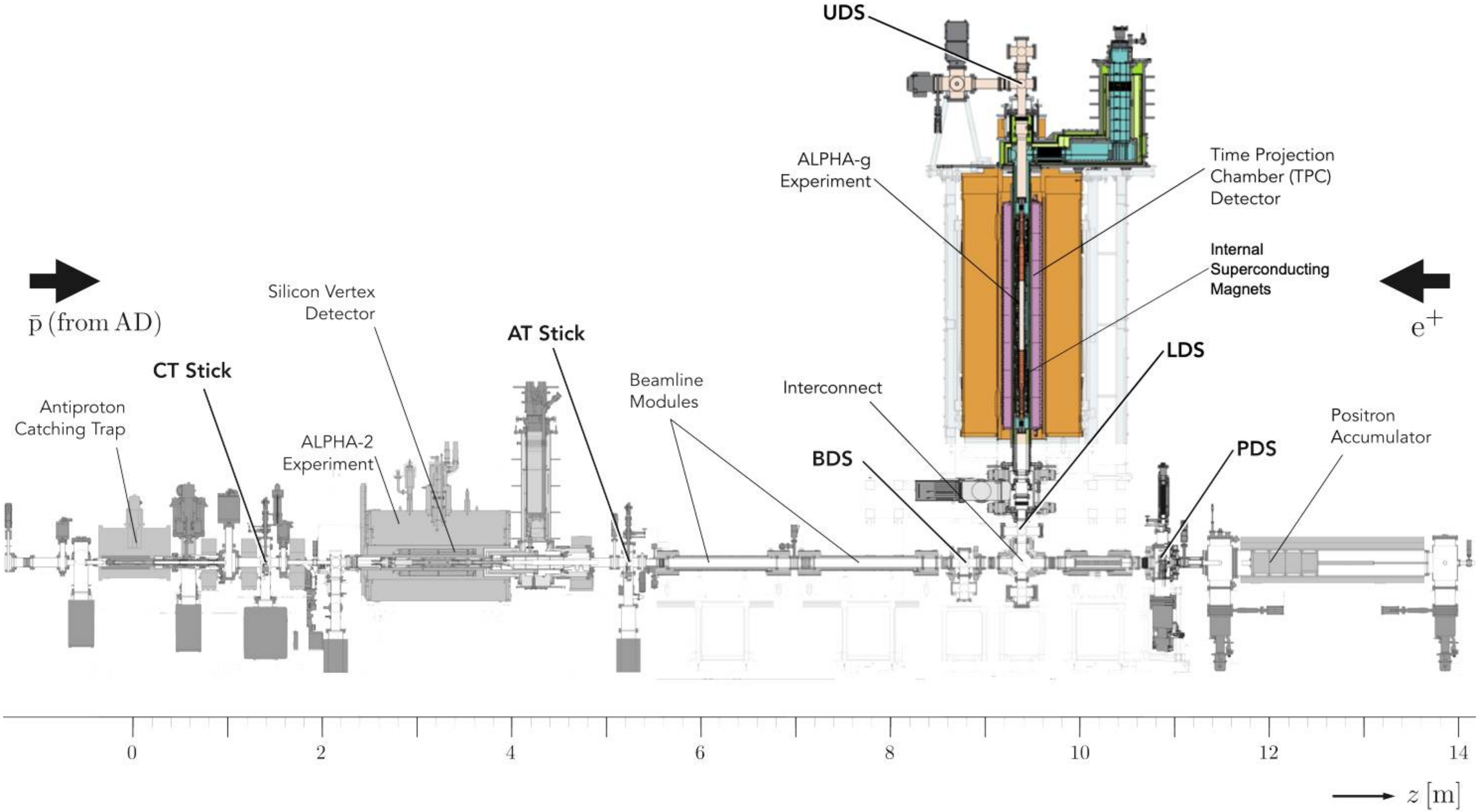
Antihydrogen creation in Penning-Malmberg trap

1-3s mixing of plasmas



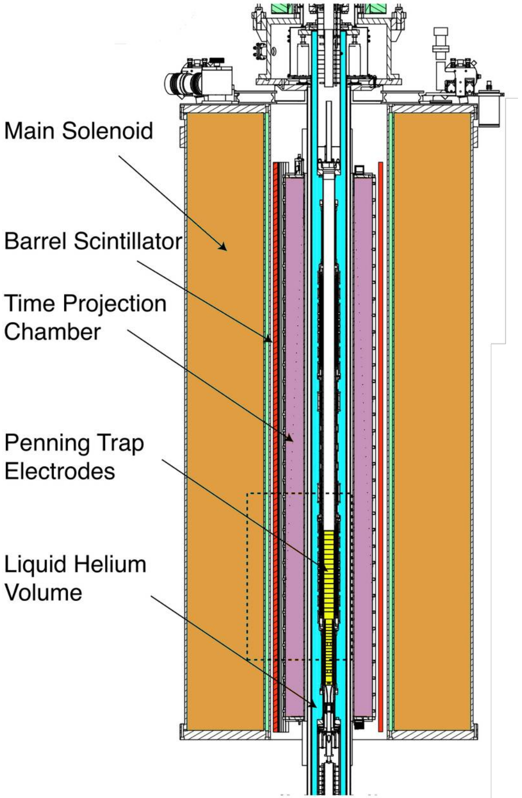


ALPHA-g

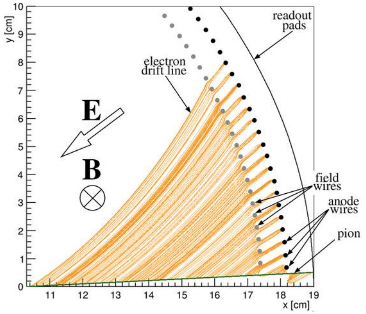


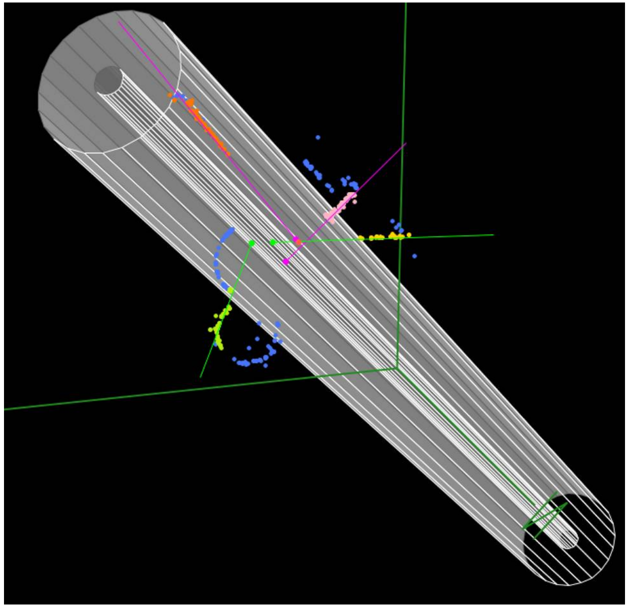
UDS
ALPHA-g Experiment
Time Projection Chamber (TPC) Detector
Internal Superconducting Magnets
p̄ (from AD)
e+
Silicon Vertex Detector
AT Stick
LDS
CT Stick
Beamline Modules
Interconnect
Antiproton Catching Trap
ALPHA-2 Experiment
BDS
PDS
Positron Accumulator
0
2
4
6
8
10
12
14
z [m]

ALPHA-g detectors



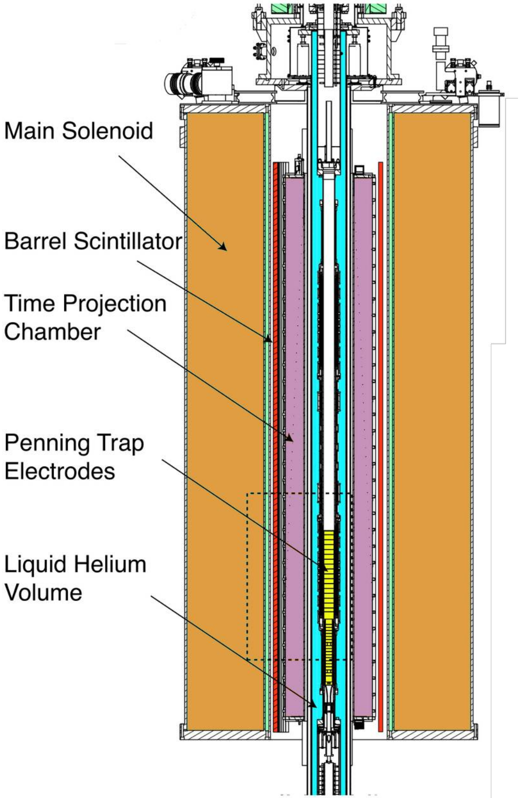
Radial Time Projection Chamber (rTPC)
- Ar+CO2 70:30
- 256 anode wires and 18k readout pads
- self triggering on wire signal
- 2cm z resolution





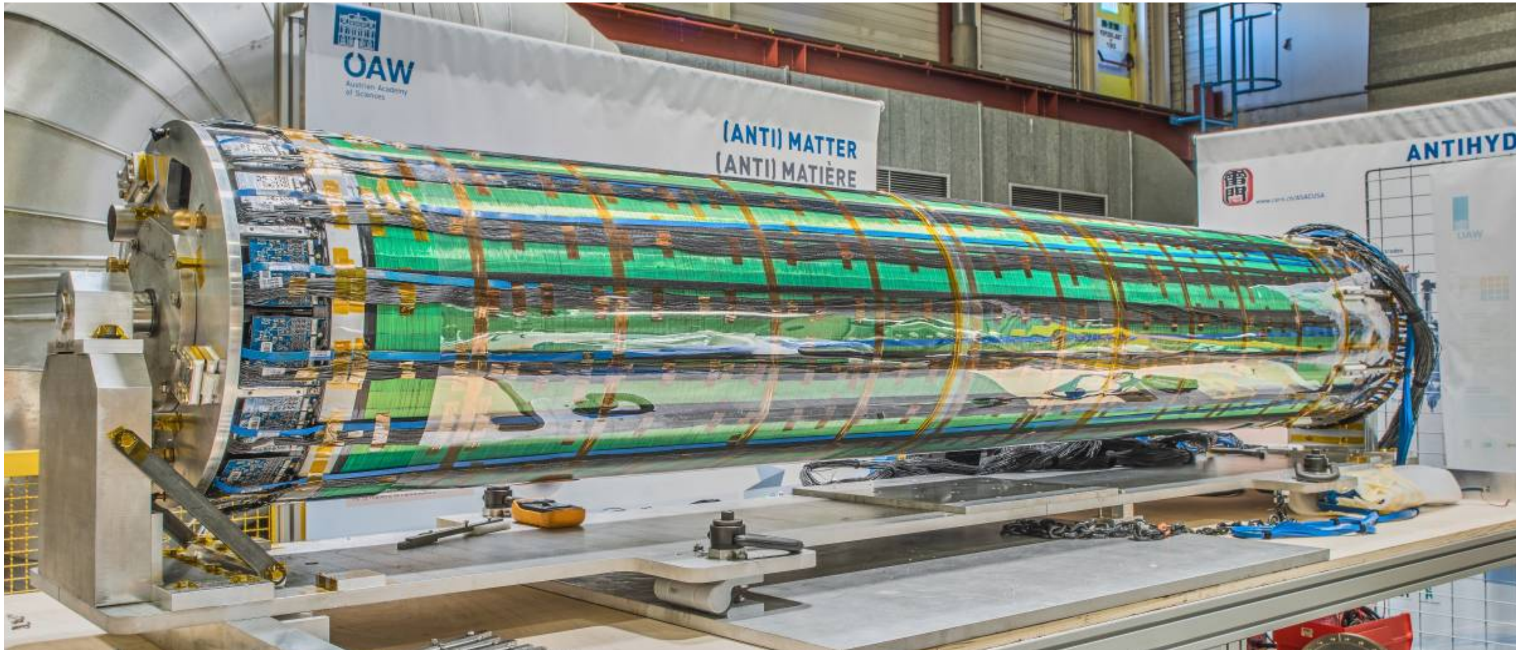
Ina Carli (TRIUMF)

ALPHA-g detectors

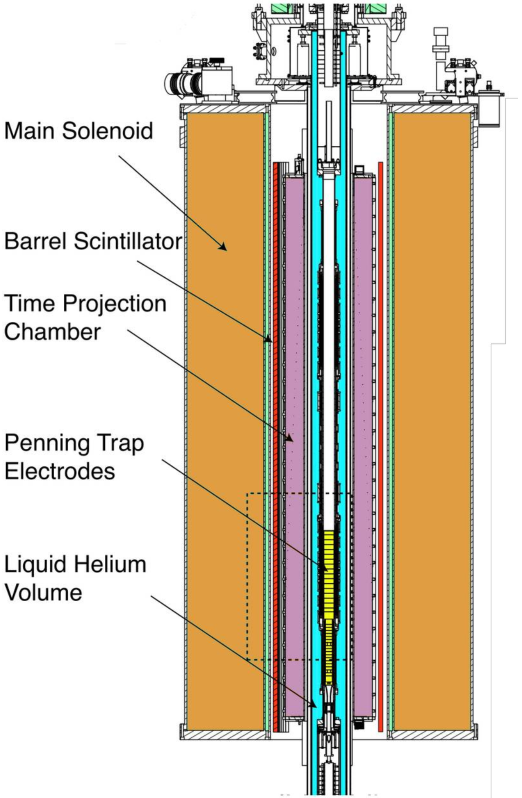


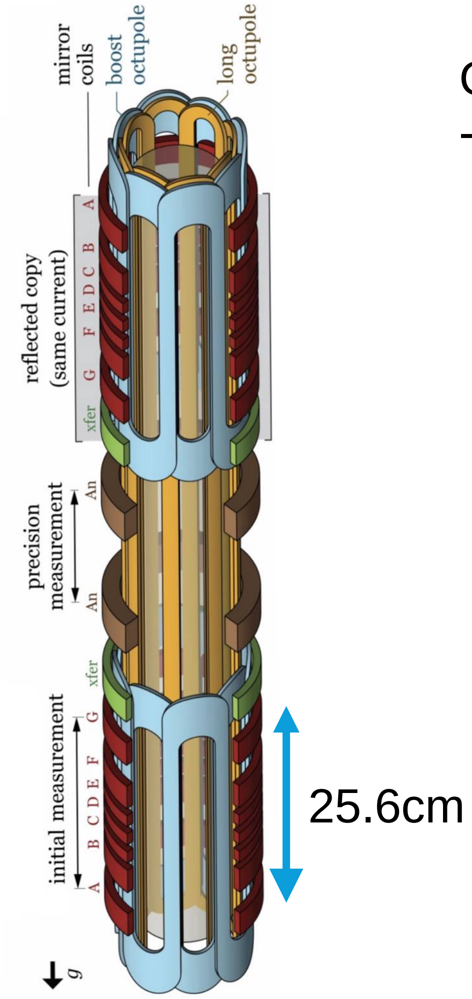
Barrel Veto
- 3m long, 64 scintillator bars with SiPM readout + TDC
- suppression of cosmics with ToF, aiming at ~200ps resolution

Reconstruction
- MVA selection with track/vertex/event variables

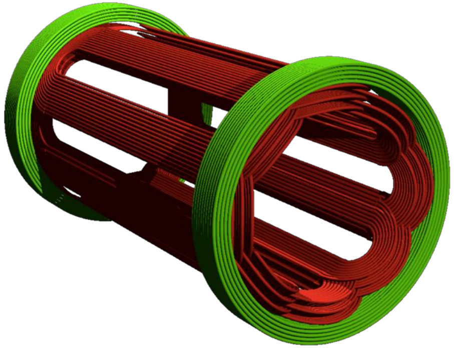


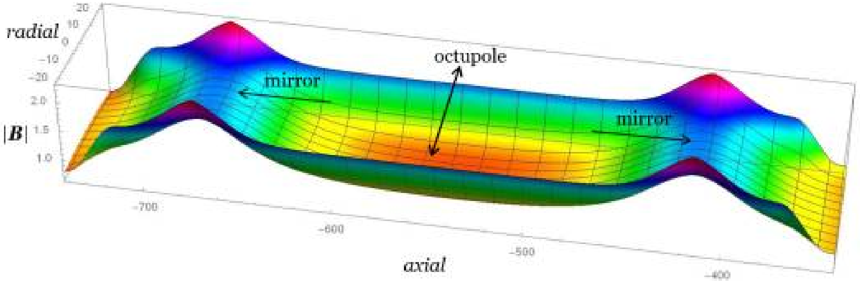
ALPHA-g neutral trap



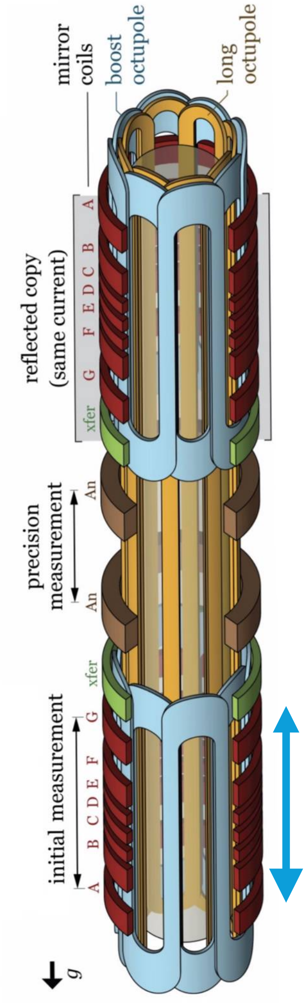


Octupole+mirrors
- trap only $\overline{\mathrm{H}}$ with E_k < ~500mK
  (velocity of ~70m/s)

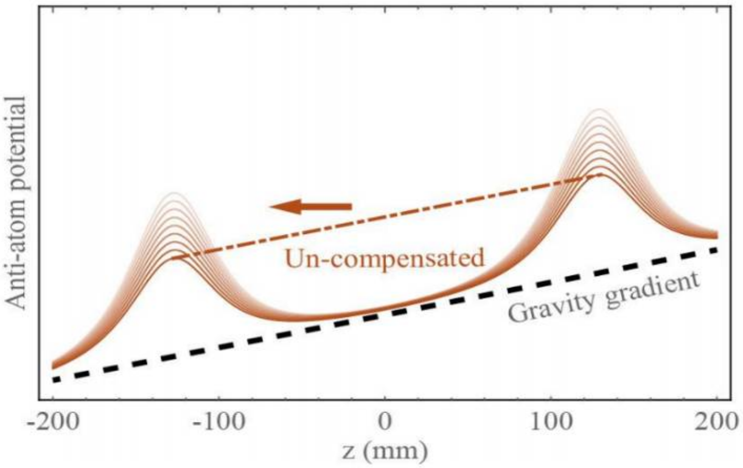


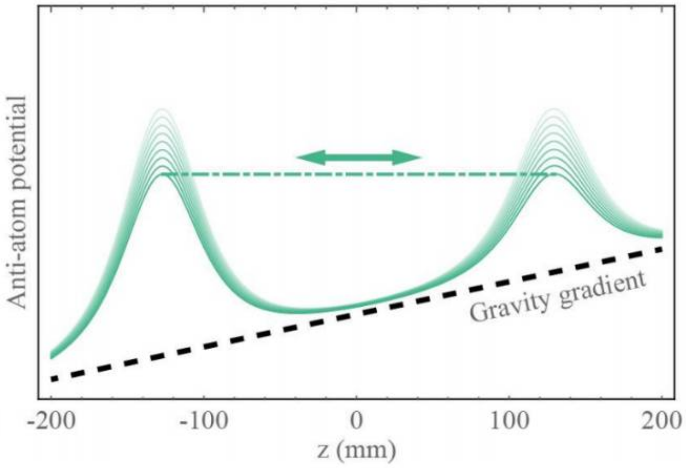


ALPHA-g up/down measurement principle



25.6cm





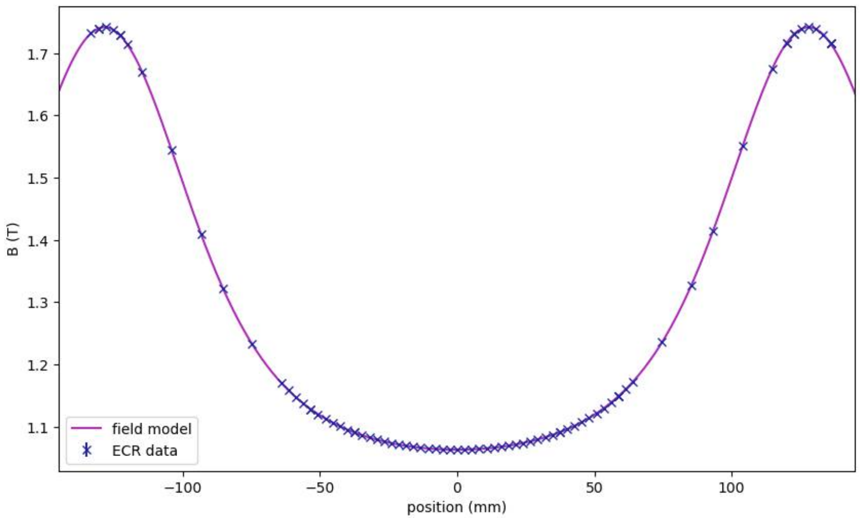
- with same mirror current: 80% annihilations down, 20% up
- apply magnetic field bias to balance out gravity

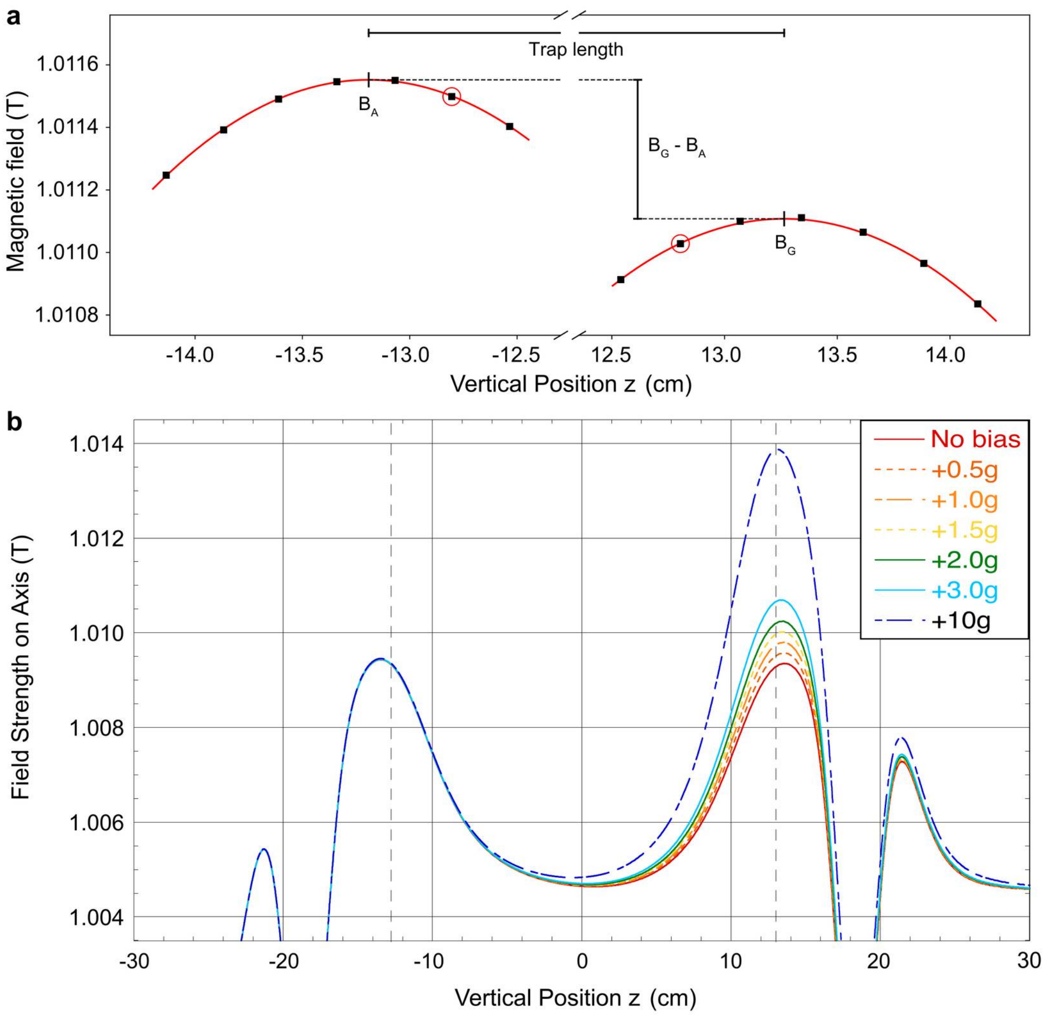
$$\text{bias} = \frac{\mu_B \left(B_G - B_A\right)}{m_H \left(z_G - z_A\right)} \qquad \Delta B_{1g} \sim 4.5\,\text{Gauss}$$

- requires sub-mA control of current difference during 20s rampdown (on 70A current)

ALPHA-g magnetic field measurements

Electron cyclotron resonance (ECR)
- load electrons, illuminate with microwaves
- on axis only





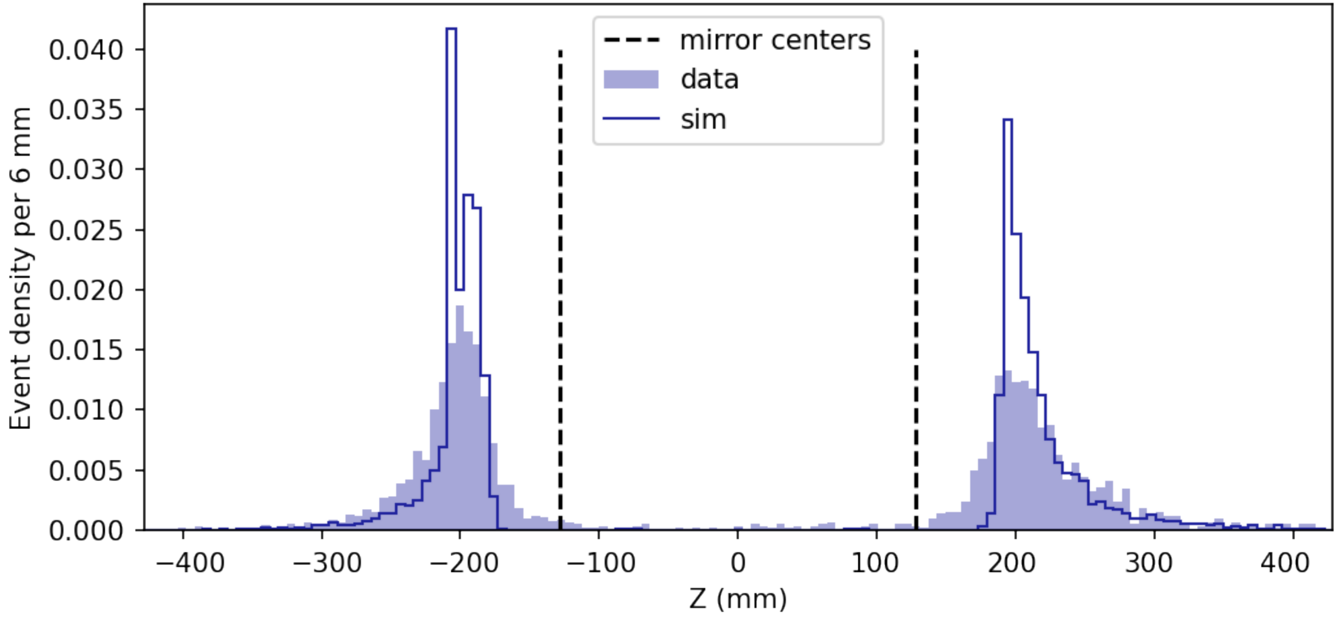
2022 gravity experiment

Nature 621 (2023) 7980, 716-722

- create and accumulate antihydrogen (~50 stacks, 4h, 100 $\bar{H}$)
- ramp down long octupole
- measure magnetic field at mirror A+G position (with bias)
- ramp down mirrors while maintaining bias and detecting annihilations
- measure magnetic bias again

    … repeat for different bias

±10g data



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- ramp down long octupole
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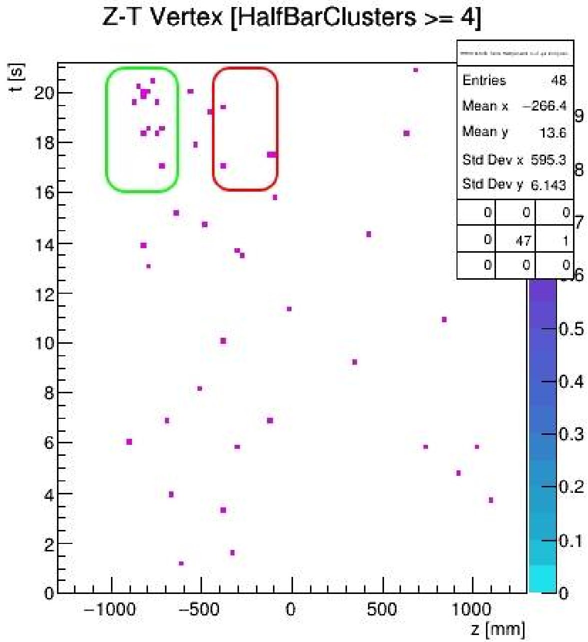
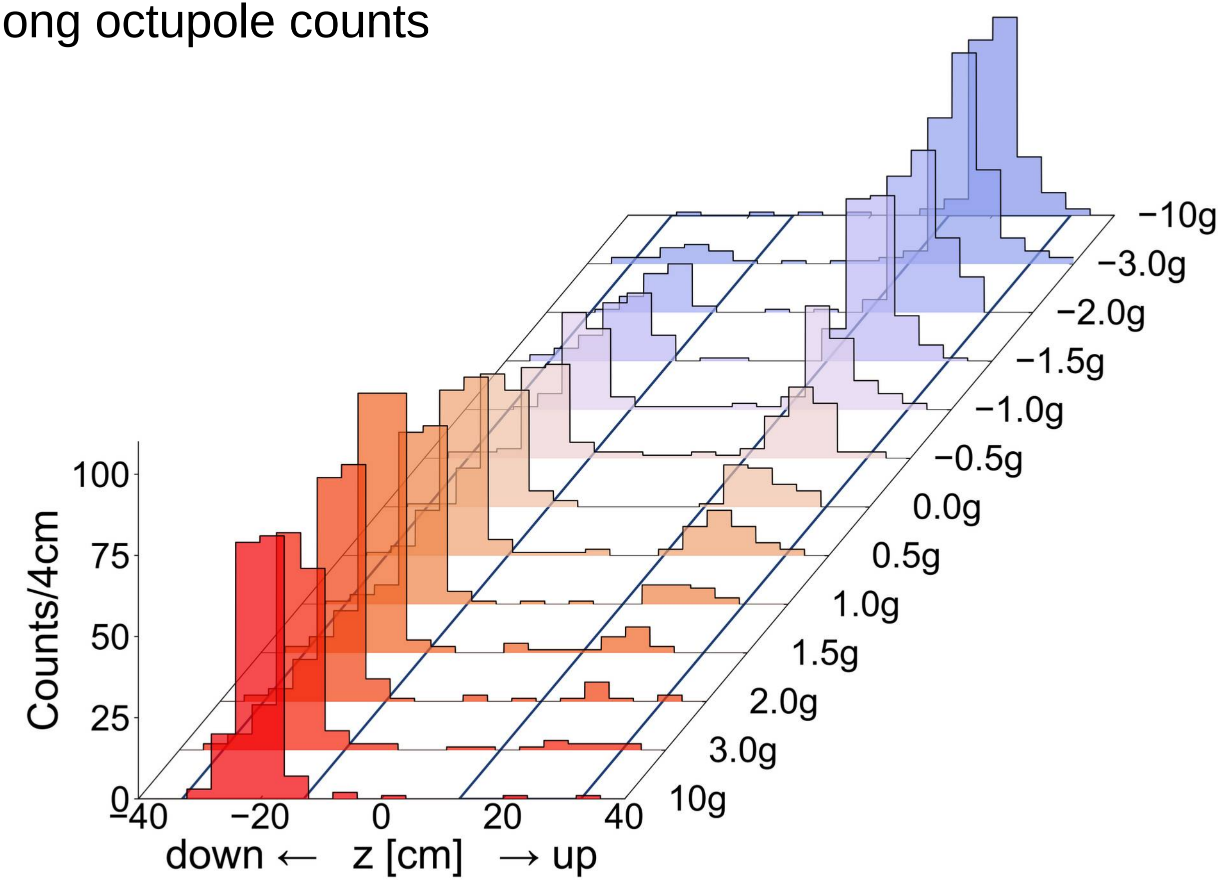
- ramp down mirrors while maintaining bias and detecting annihilations
- measure magnetic bias again

… repeat for different bias

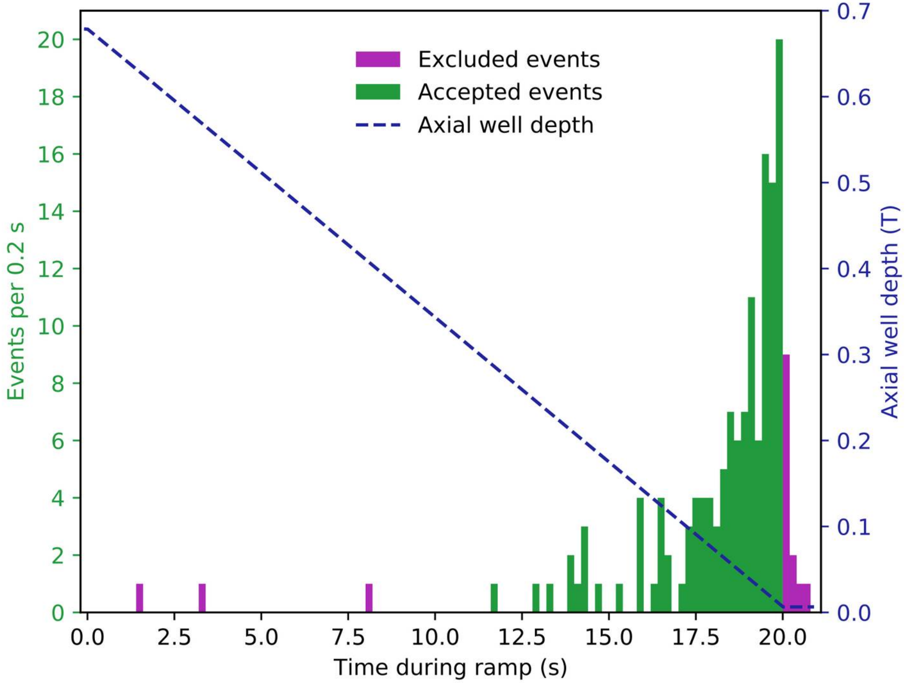
0g data, 1 run



Raw data with time cut t = [10,20]s
- before background subtraction and efficiency correction
- normalized with long octupole counts

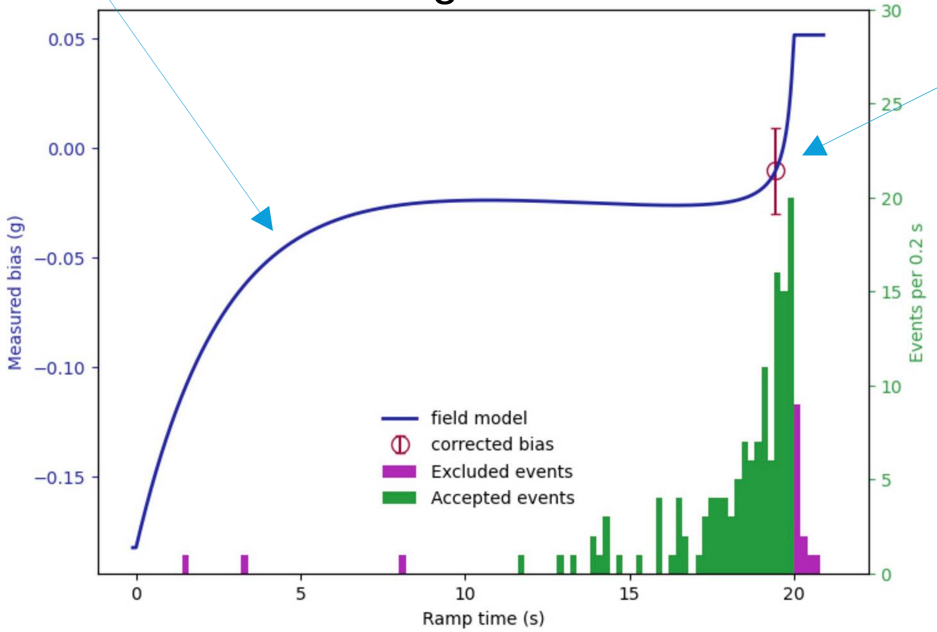


Time structure of annihilations



Simulating full magnetic field: geometry + persistent currents (up to ~10G on axis)

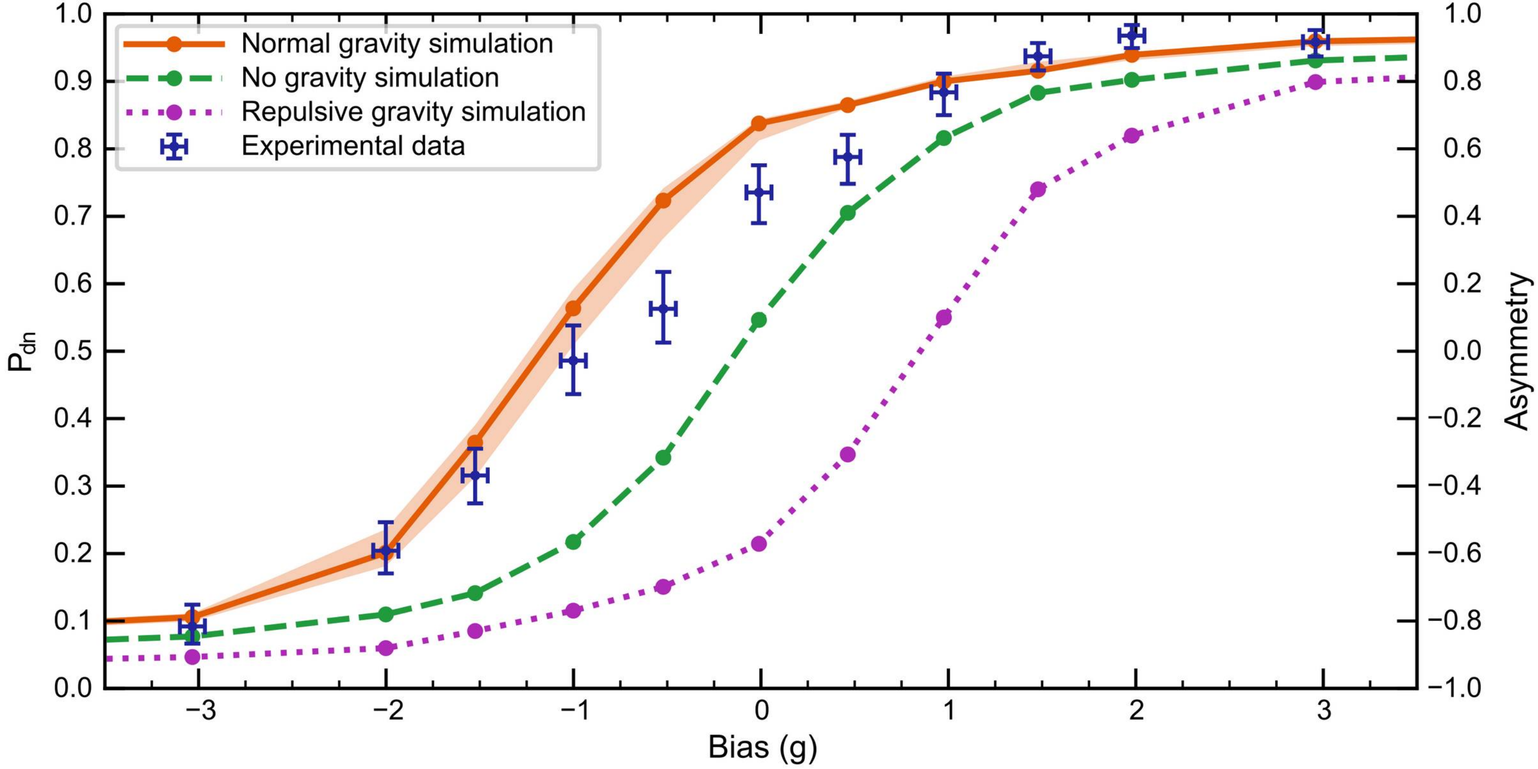
0g data



weighted mean = bias

Results

Compute probability of downward escape P_{dn}

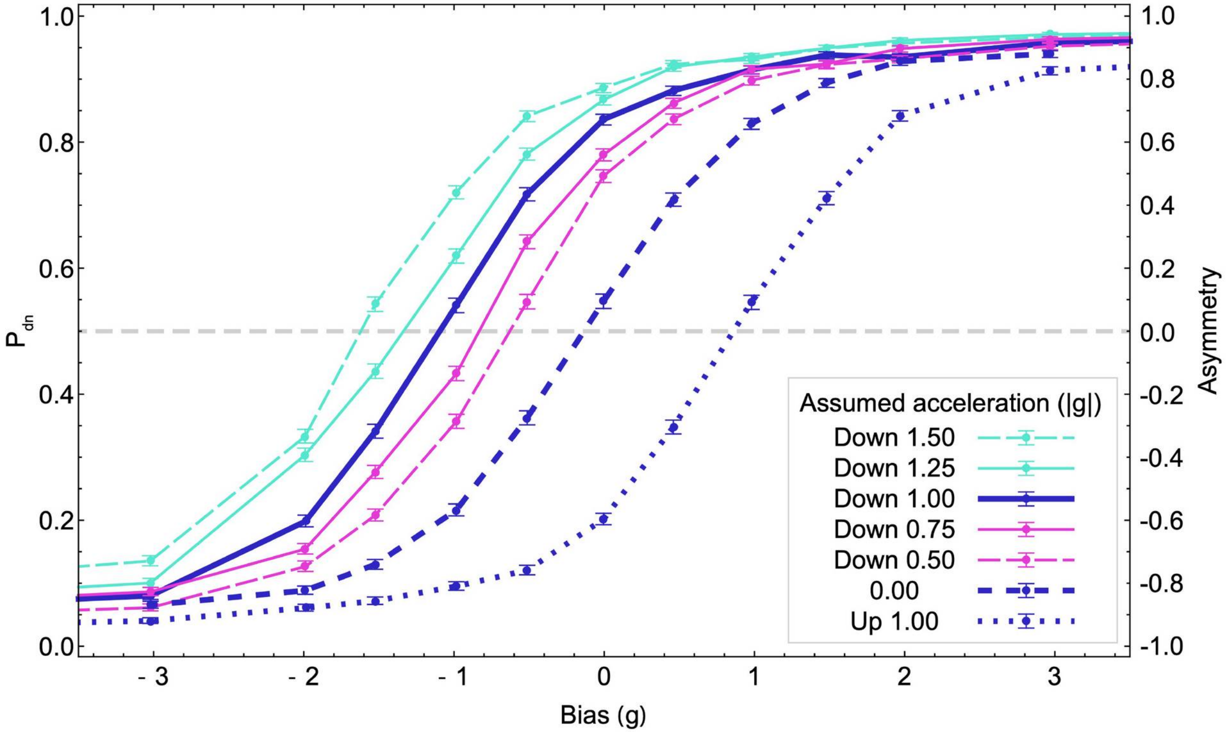


Repulsive gravity probability < 10^{-15} → excluded

No gravity probability 2.9×10^{-4}

Calculating antihydrogen g: simulations for different g, interpolate and find best fit to data

$$\bar{g} = [0.75 \pm 0.13 \ (\text{statistical} + \text{systematic}) \ \pm 0.16 \ (\text{simulation})] \, g$$



Uncertainties

Bias determination

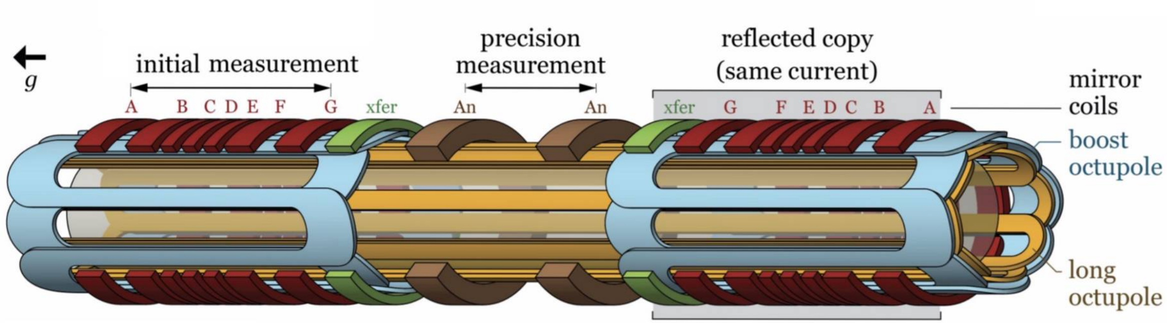
Uncertainty	Magnitude (g)
ECR spectrum width	0.07
Repeatability of $(B_G - B_A)$	0.014
Peak field size and z-location fit	0.009
Field decay asymmetry (A to G) after ramp	0.02
Bias variation in time	0.02
Field modelling	0.05

$a_{\bar{g}}$ measurement uncertainties

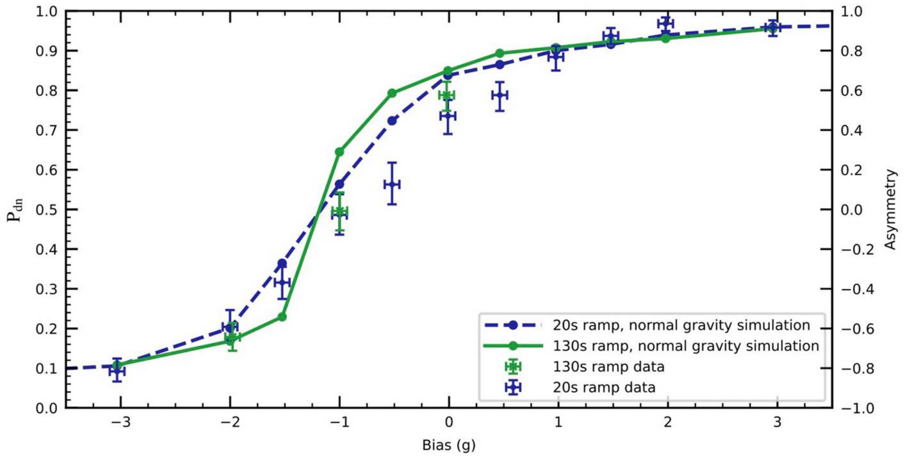
	Uncertainty	Magnitude (g)
Statistical and systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03

Future improvements

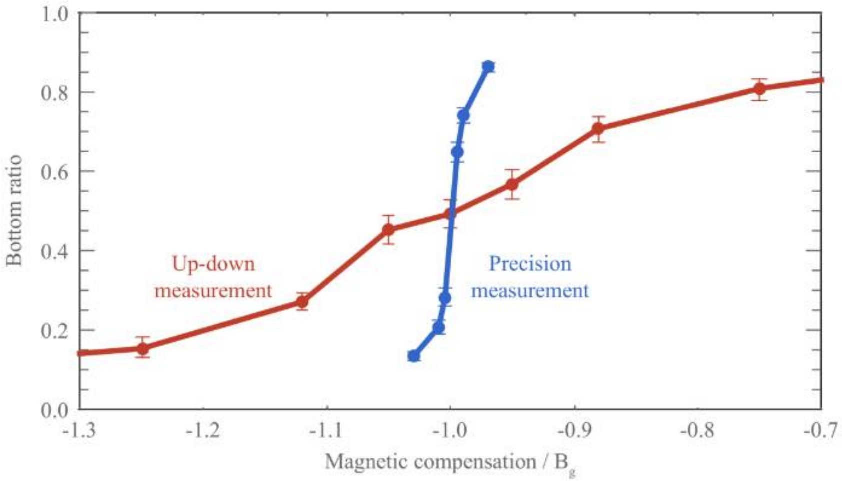
Road to 1% measurement:
- colder antihydrogen (Doppler laser cooling, adiabatic expansion)
- use precision region



130s release data

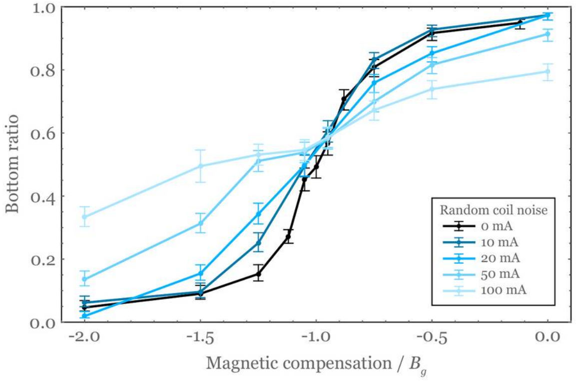


simulation

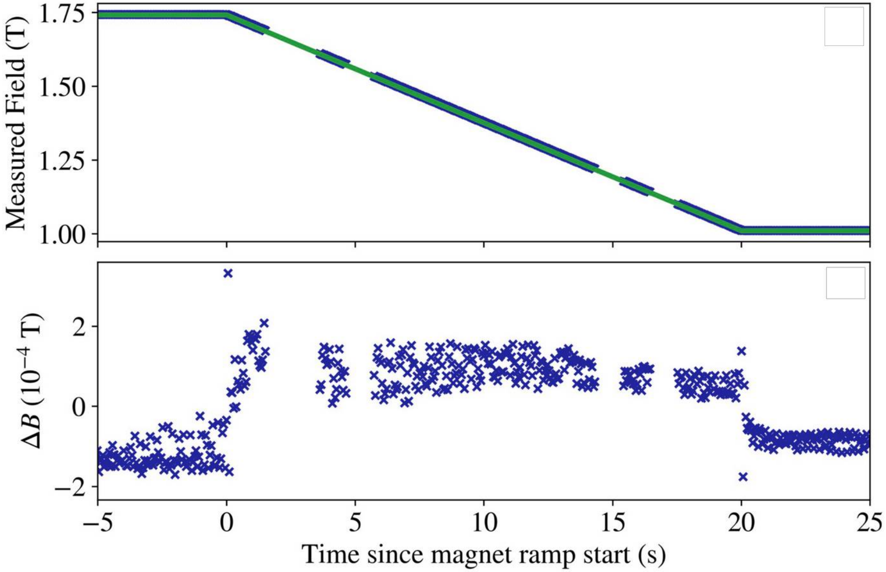


Future improvements

Road to 1% measurement:
- improve reconstruction symmetry, efficiencies, …
- background suppression (ToF, ML)



- improve current control
- new techniques to measure magnetic fields
    - magnetron motion of e^- plasma
    - off axis measurements
    - Be^+ magnetometry

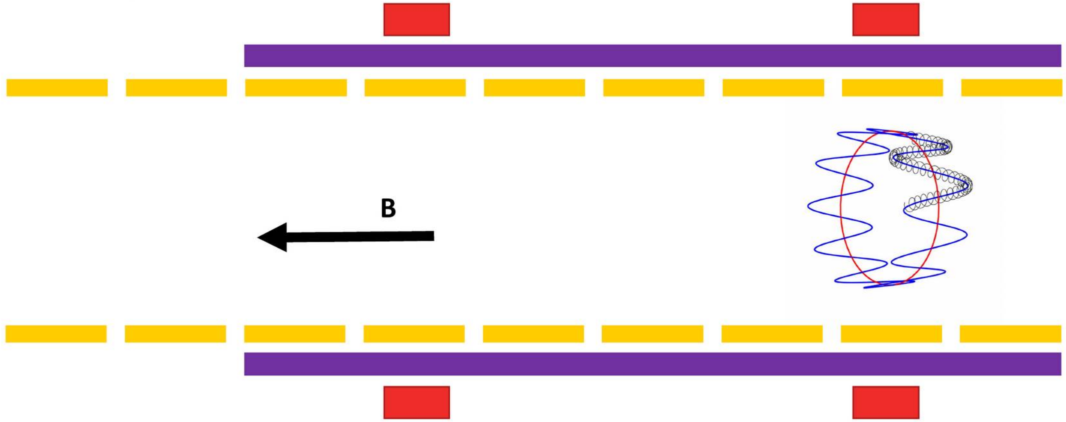


First observation of antihydrogen free fall published by ALPHA

Best fit gives

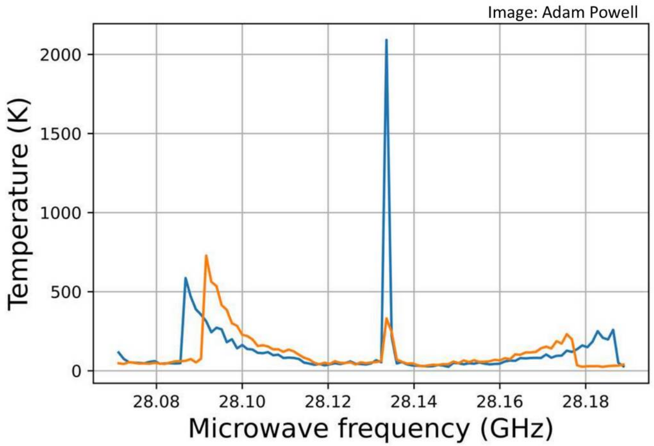
$$\bar{g} = [0.75 \pm 0.13 \text{ (statistical + systematic)} \pm 0.16 \text{ (simulation)}]\, g$$

ECR



$$f_c = \frac{q\,B}{2\,\pi\,m}$$

At 1 T $f_c \approx 28$ GHz

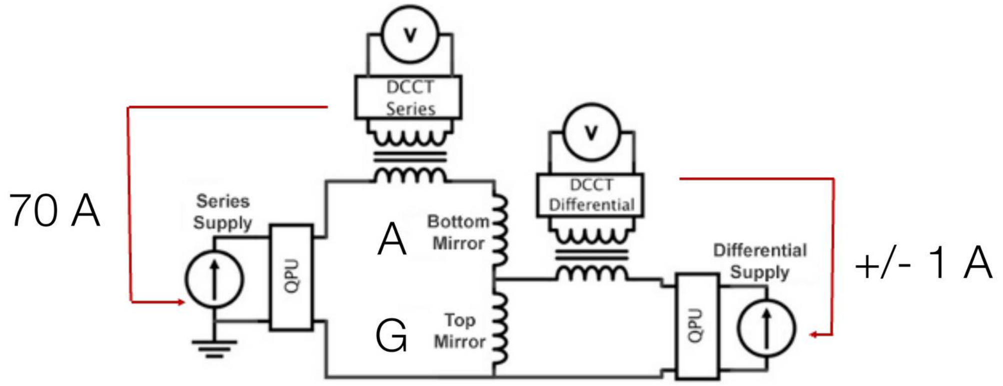


- Narrow central peak = $f_c = \frac{q\,B}{2\,\pi\,m}$
- Precision related to peak width
- Broad, asymmetric sidebands from electrons axial motion

Backup

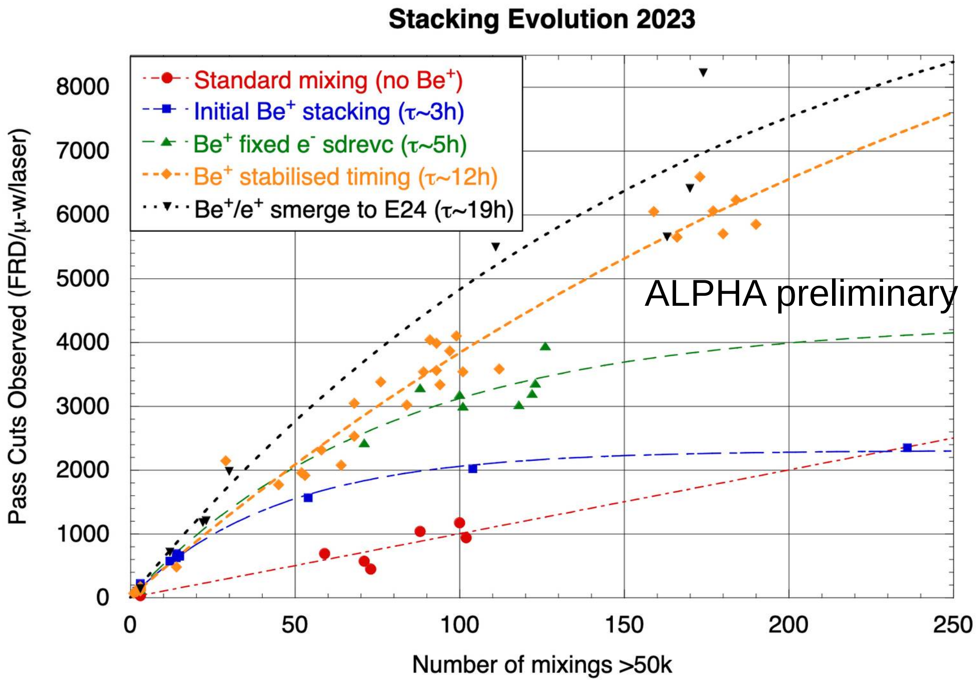
Magnet current control

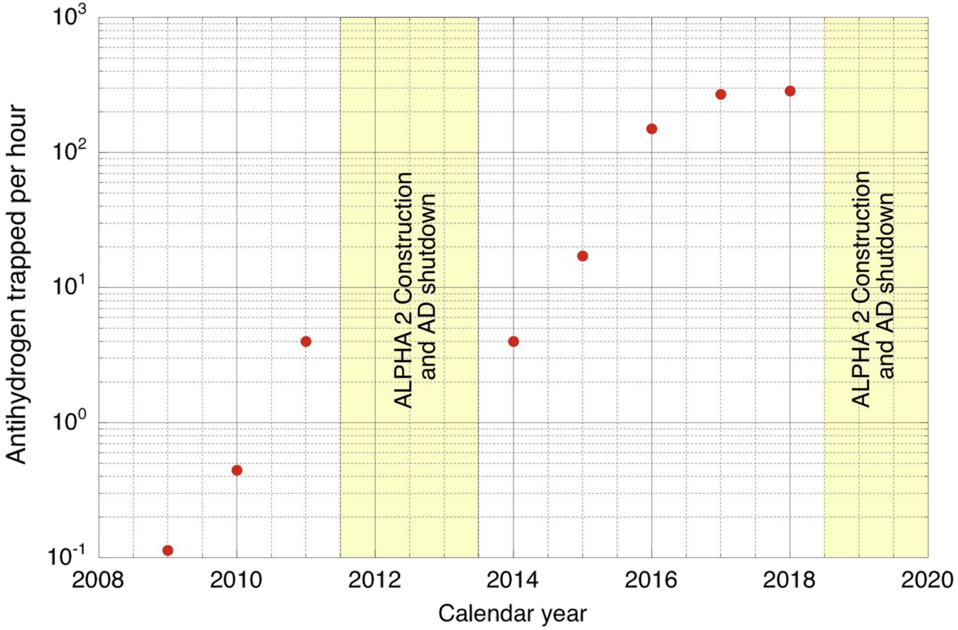
	Supply (maximum Operating Current)	Current Programming Resolution (mA)	Programming Resolution (g)	Current noise (mA rms)	Bias field from current noise (g)
Long Octupole (LOc)	Sorensen SGA 10-1200 (830 A)	37 (analog)	N/A	0.5	N/A
Bottom Octupole (OcB)	Sorensen SGA 10-1200 (830 A)	37 (analog)	N/A	0.6	N/A
Mirrors (MAG)	CAENELS FAST-PS-1K5 (70 A)	3.1 (analog)	0.06	0.7	< 0.001
Mirror G bias (MGDiff)	Kepco BOP 20-10 (3 A)	0.34 (analog)	0.007	0.4	< 0.001
External Solenoid Main Coil	2x CAENELS FAST-PS-1K5 (191 A)	0.8 (digital)	0.04	1.8	0.01
External Solenoid Shim Coil	CAENELS FAST-PS 1020-200 (5A)	0.1 (digital)	N/A	1.5	0.003



Backup

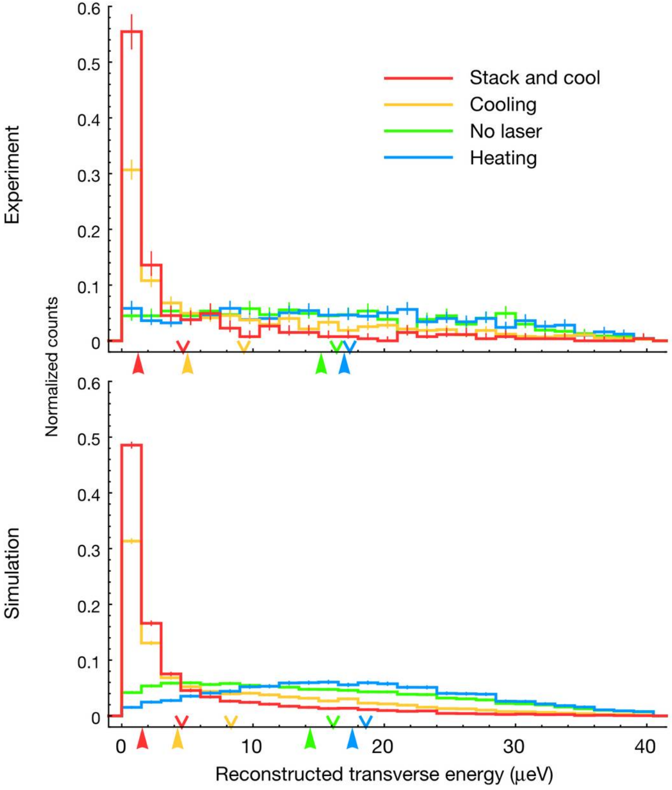
Increase $\overline{H}$ production:
- Be^+ laser cooled, sympathetic cooling of positrons
- decrease $\overline{H}$ losses in interactions with plasma

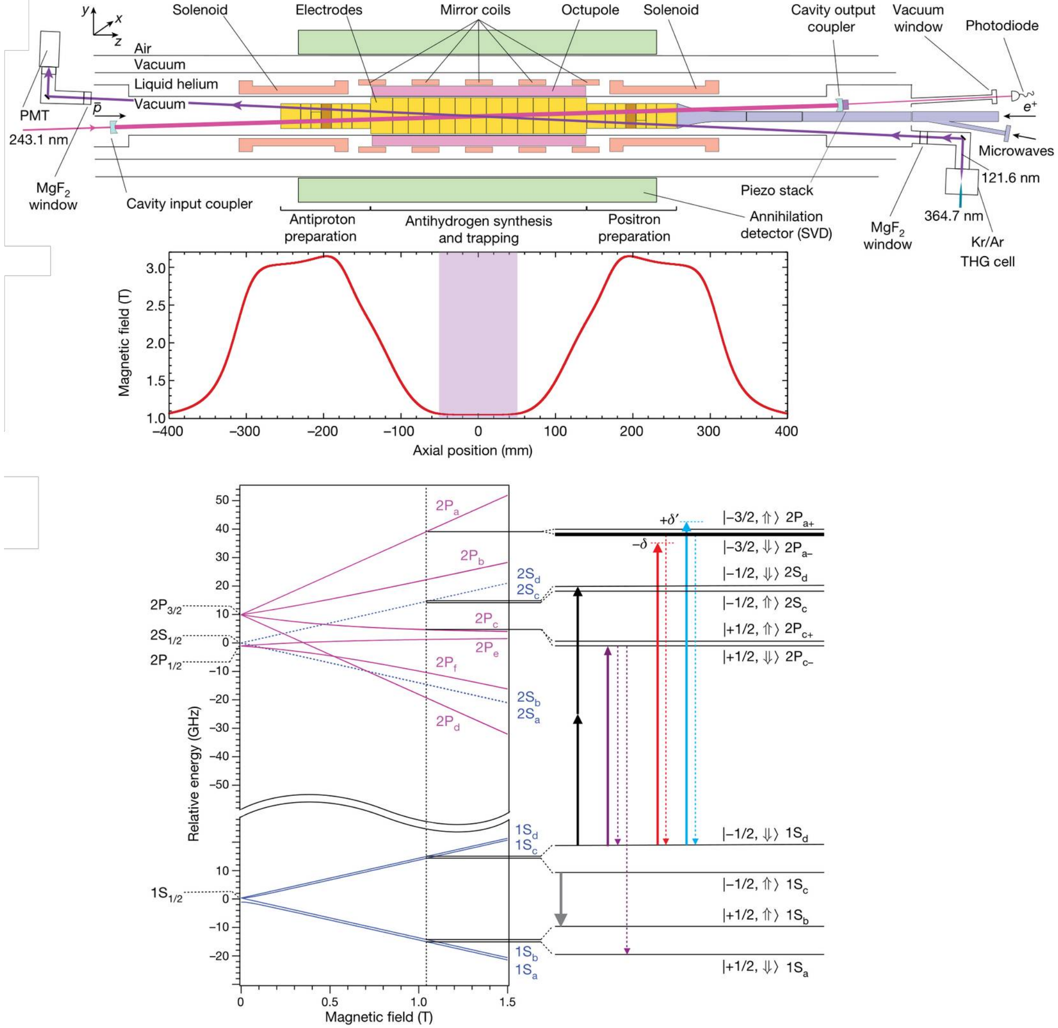




Backup

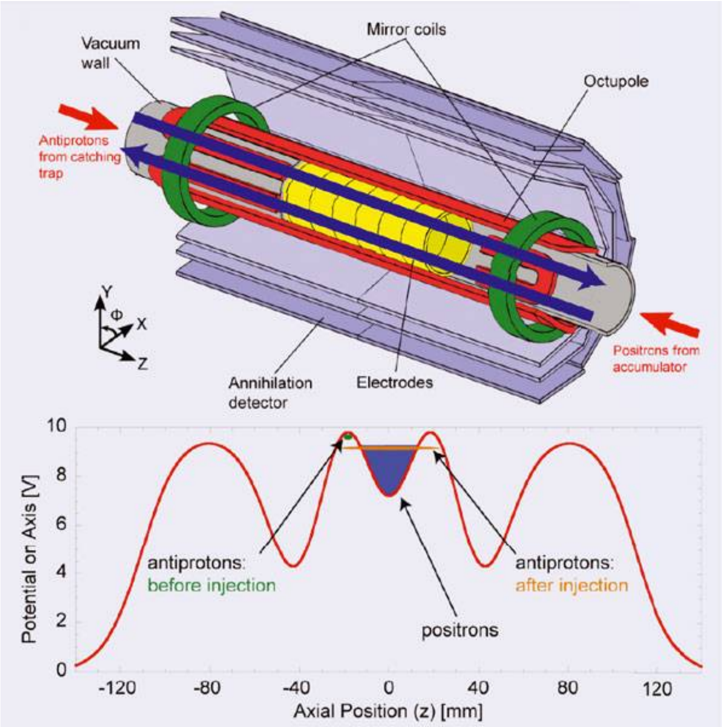
Doppler laser cooling
- demonstrated in Alpha-2



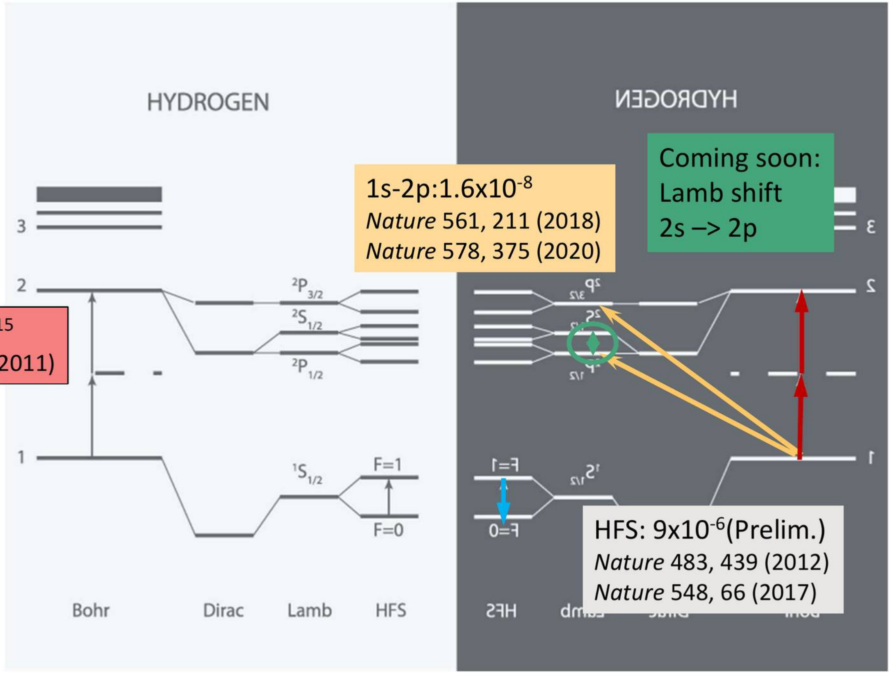


Nature 592 (2021) 7852, 35-52

Spectroscopy with Alpha-2



1s-2s: 4×10^{-15}
PRL 107, 203001 (2011)



1s-2p: 1.6×10^{-8}
Nature 561, 211 (2018)
Nature 578, 375 (2020)

Coming soon:
Lamb shift
2s –> 2p

1s-2s: 2×10^{-12}
Nature 541, 506 (2017)
Nature 557, 71 (2018)

HFS: 9×10^{-6}(Prelim.)
Nature 483, 439 (2012)
Nature 548, 66 (2017)