CHALLENGES AND APPROACHES OF UNVEILING THE NATURE OF ANTIMATTER AT CERN

(WITH A PARTICULAR FOCUS ON THE AEGIS EXPERIMENT)

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on behalf of the AEgIS collaboration

6th International Conference on New Frontiers in Physics (ICNFP2017)
17th - 29th of August 2017, Kolymbari, Crete, Greece

ANTIMATTER

Sometime in the early universe…

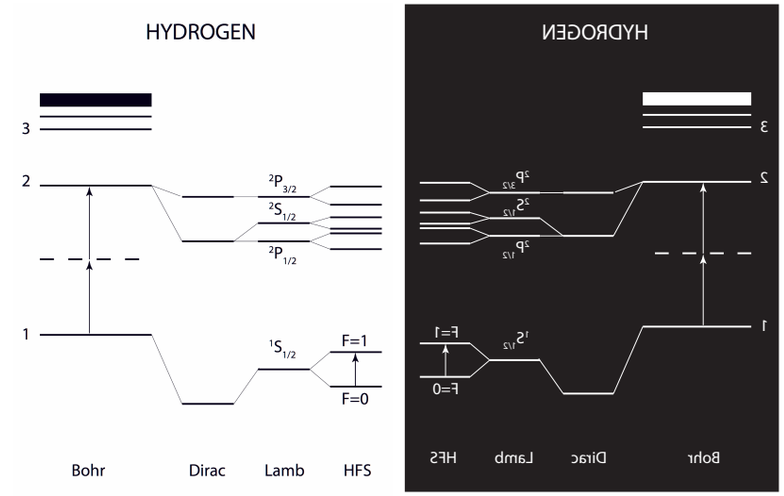
Why are we here?

ANTIMATTER

1) Test of fundamental CPT symmetry

Matter and antimatter should have equal properties (masses, lifetimes, |charge|, g-factors,…)

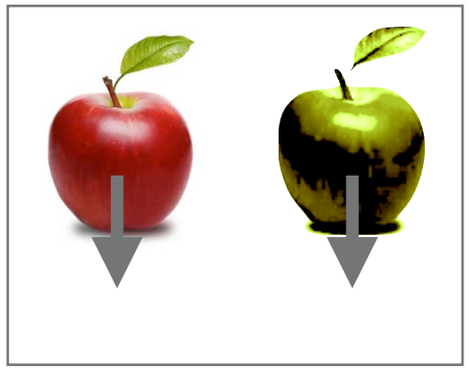
- ➤ Compare spectral lines of hydrogen and antihydrogen
- ➤ Study antiprotons and antiprotonic helium



2) Test of the Weak Equivalence Principle with antimatter

Inertial mass and gravitational mass are identical

- ➤ Compare the free fall of hydrogen and antihydrogen



Any observed difference would hint at new physics

APPROACH

Perform $\bar{H}$ measurements either with:

Trapped antihydrogen

- Require strong magnetic field gradient (broadened level lines)
- Only the coldest anti-atoms can be trapped

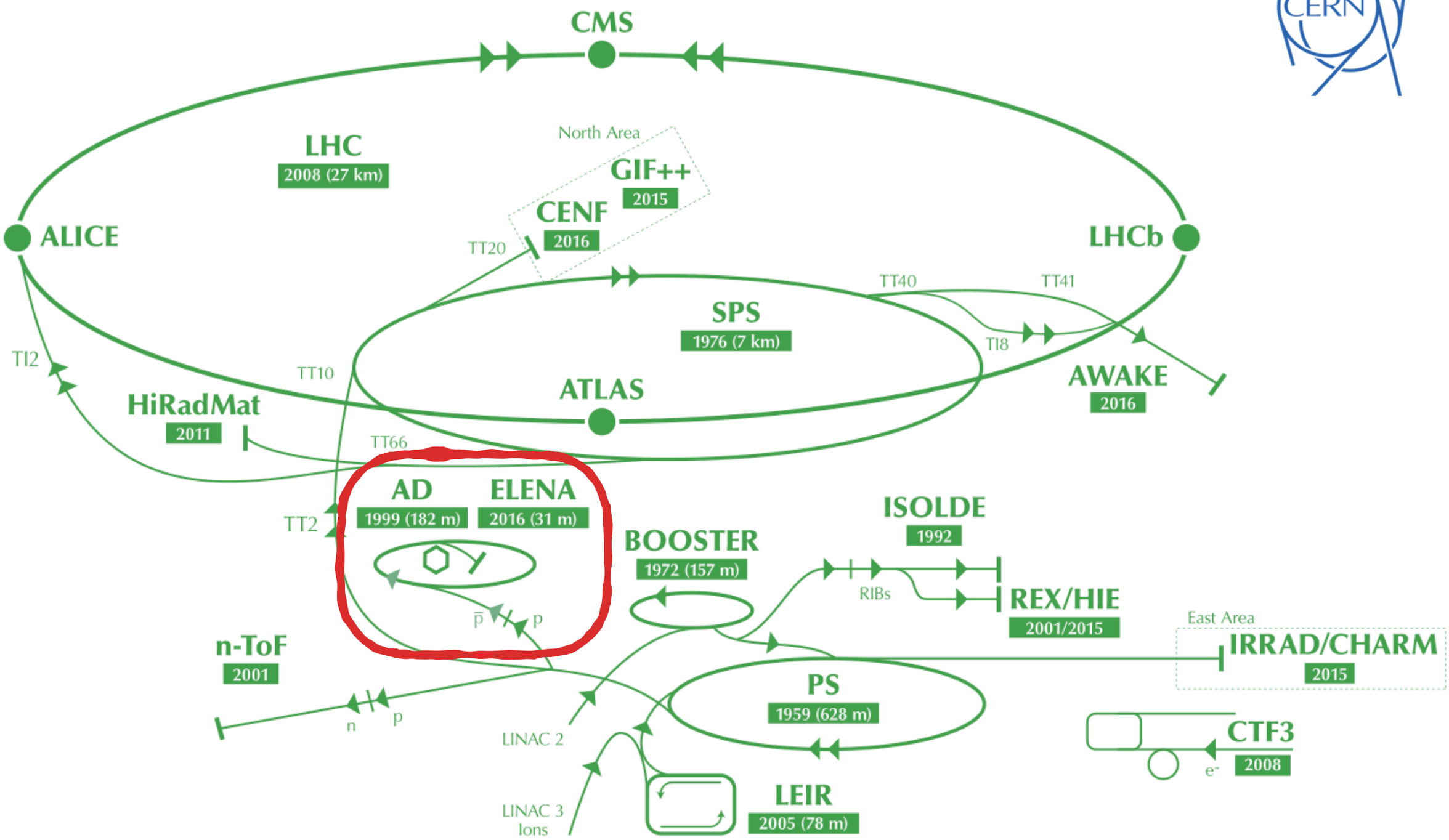
or with:

A beam of cold antihydrogen

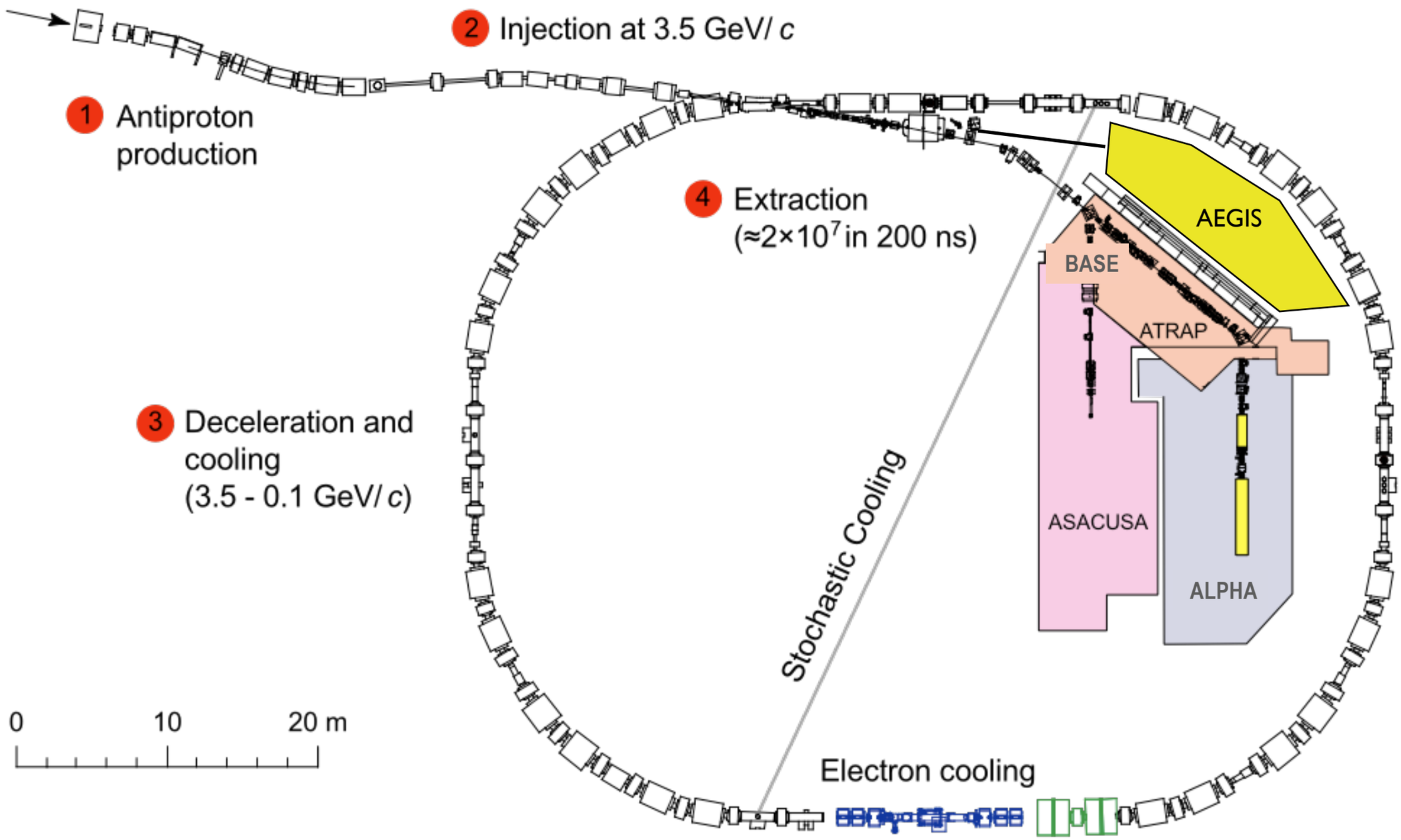
- Stark acceleration of Rydberg atoms (very sensitive to inhomogeneous electric field)
- In-flight spectroscopy; anti-atoms of higher energy are also useful

General problem: Low number of particles!
Need particles as cold as possible for precision

CERN ACCELERATOR COMPLEX



THE ANTIPROTON DECELERATOR

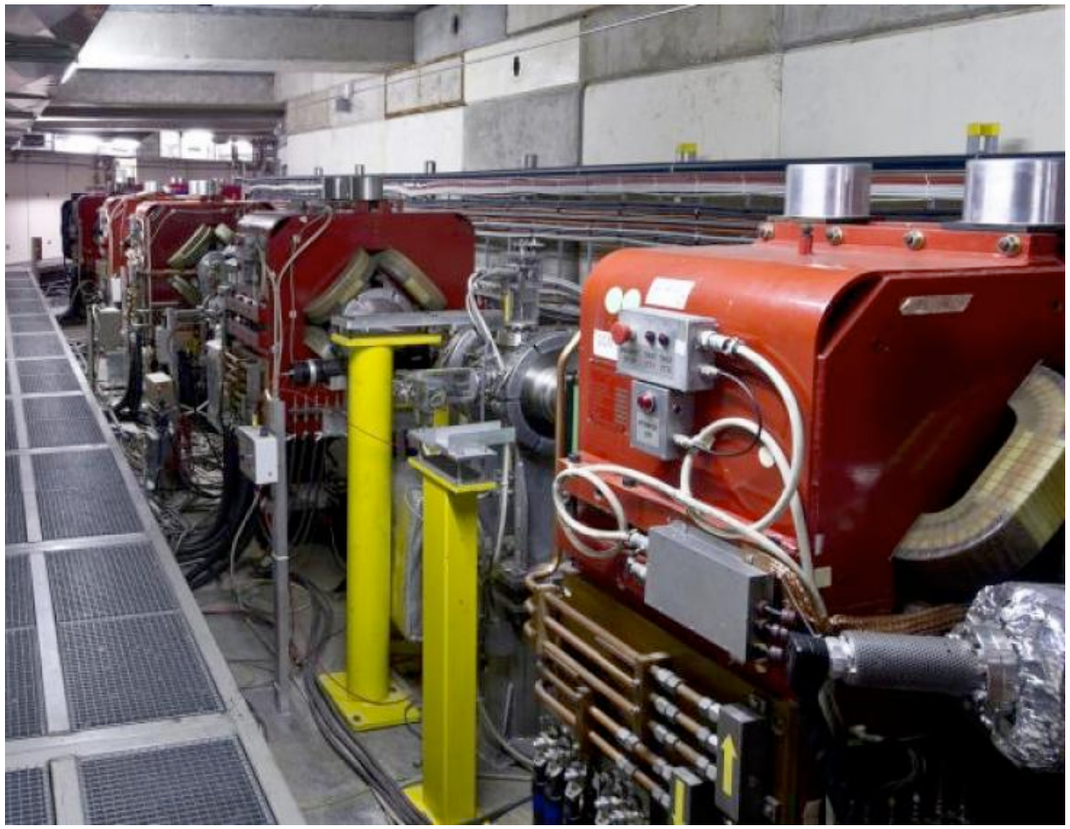


Roughly 3×10^7 antiprotons of 5.3 MeV are extracted every ~120 seconds and sent to a particular experiment.

THE ANTIMATTER FACTORY

Currently five experiments in the Antimatter Factory

- AEGIS
- ALPHA
- ASACUSA
- ATRAP
- BASE
- GBAR *(future)*



AD

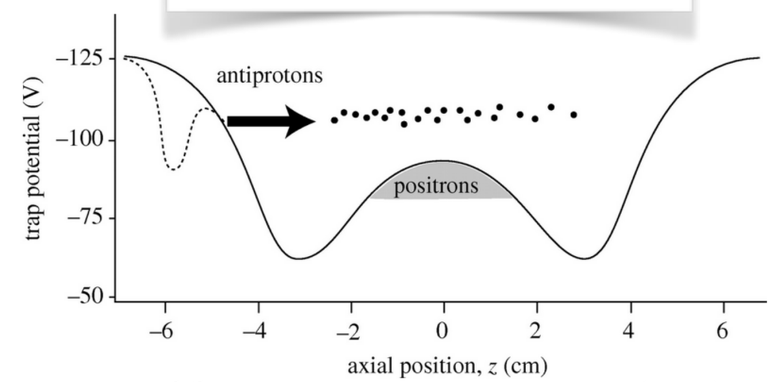
AD hall

ANTIHYDROGEN PRODUCTION

1) Three-body recombination ("mixing")

- Populations mixed in a trap
- High expected rate, $\sigma = 10^{-7}$ cm^2 @1K, n>>10
- Long-duration process

$$\overline{p} + e^+ + e^+ \rightarrow \overline{H} + e^+$$

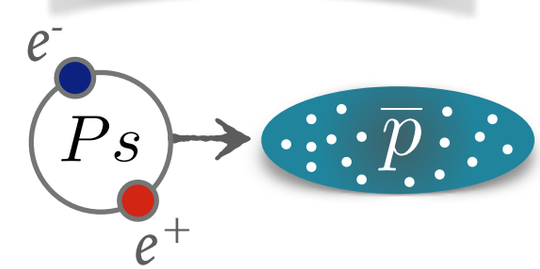


Phil. Trans. R. Soc. A 368 3671-3682 (2010)

2) Charge exchange

- Positronium introduced to trapped $\overline{p}$ cloud
- $\sigma = a_0 n^4_{Ps}$, $\sigma = 10^{-9}$ cm^2 @1K, n given by n_{Ps}, temperature given by the antiproton
- Small solid angle ⇒ low rate
- More narrow and well-defined quantum state distribution
- Demonstrated by ATRAP with Cesium (PRL 93 (2004) 263401)

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



Advantages:
Pulsed production (time of flight)
Potentially colder than via mixing

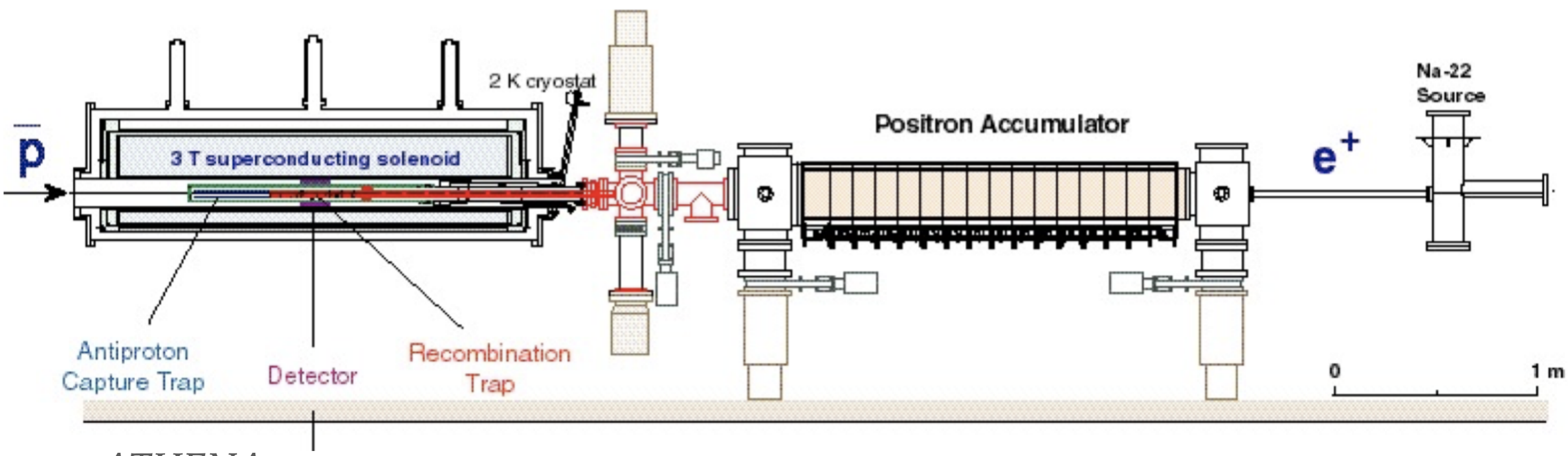
A TYPICAL ANTIHYDROGEN EXPERIMENT

Needed for antihydrogen:

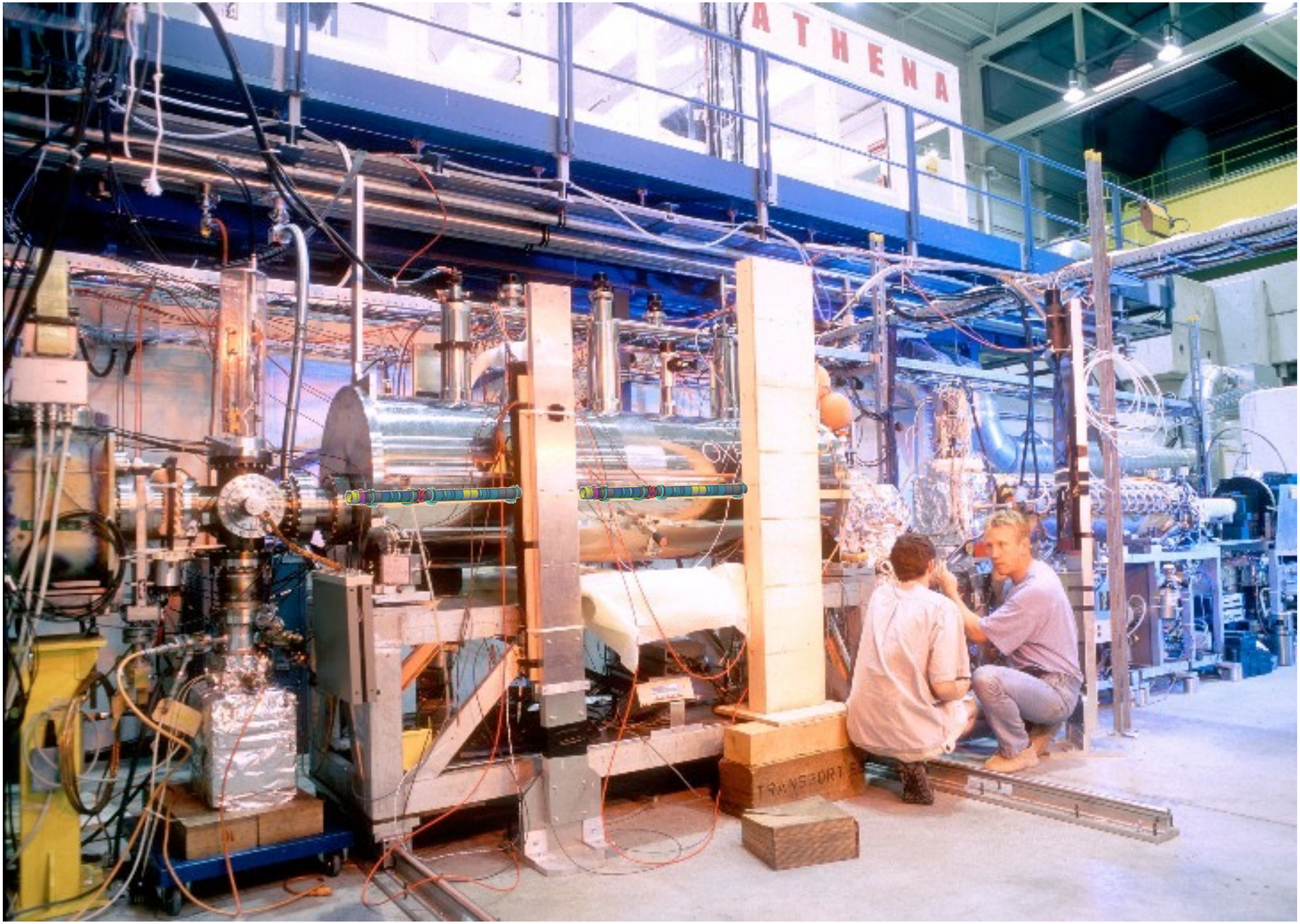
Antiprotons:		**Positrons:**	
Production:	GeV	Production:	MeV
Deceleration:	MeV	Deceleration/accumulation:	eV
Capture:	keV		
Cooling:	meV		

Needed for manipulations:

Ultra High Vacuum (UHV)
Cryogenic: T~10K
Magnetic field: 1-5T
Electrical field: ~10kV

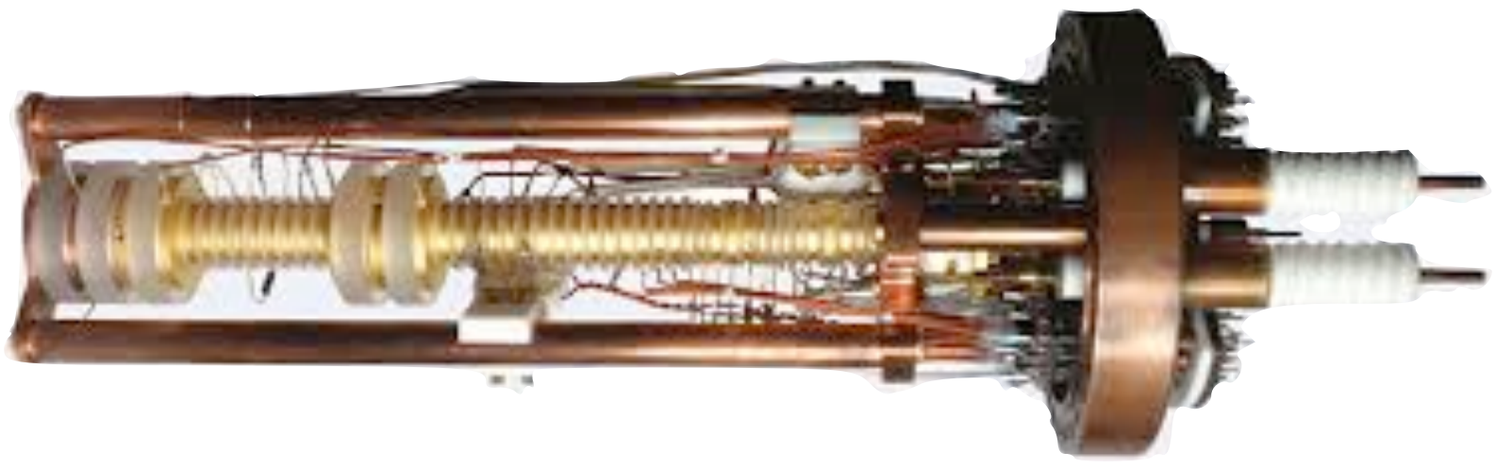


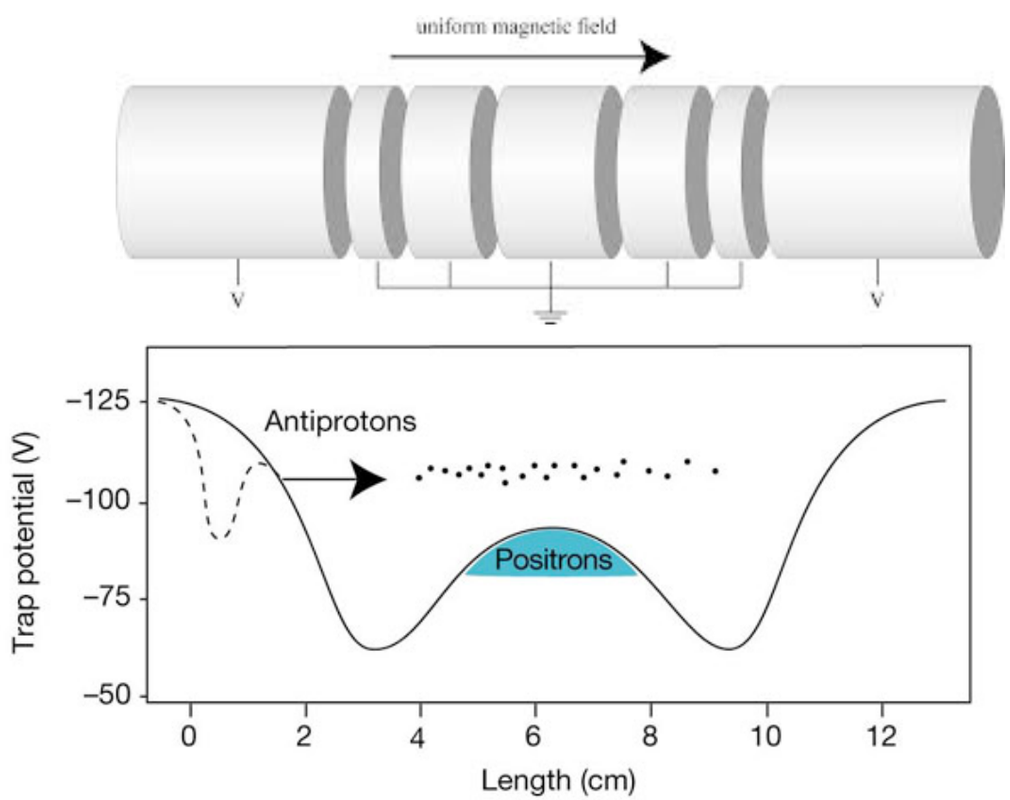
ATHENA


ATHENA

PENNING TRAP

– the workhorse of experiments in the AD facility



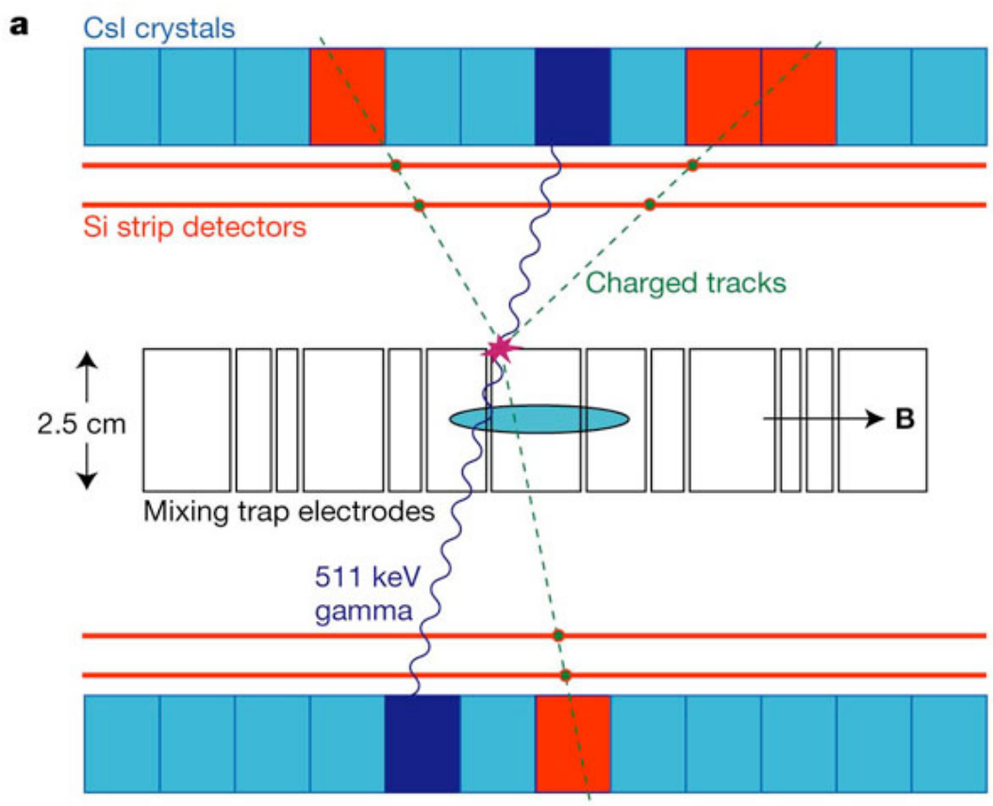


FIRST COLD ANTIHYDROGEN

@AD in 2002

by ATHENA (Nature 419(2002) 456)
ATRAP (PRL 89 (2002) 213401)

Important step: must be cold for precision

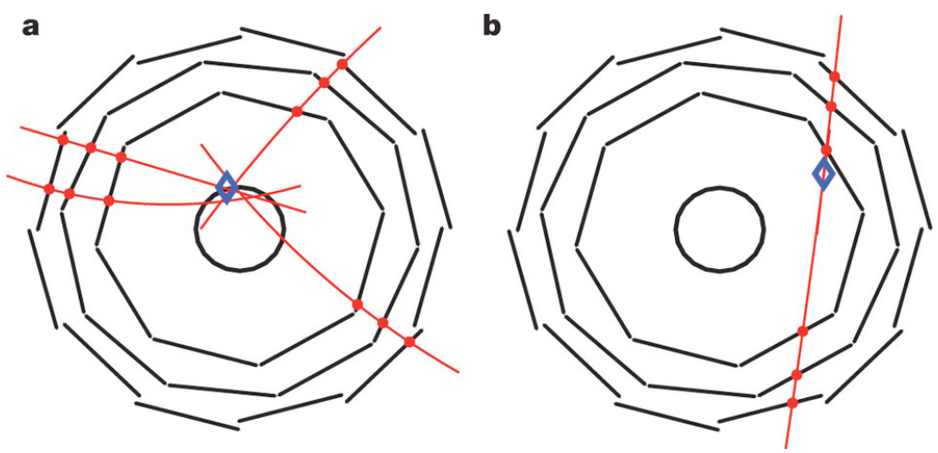


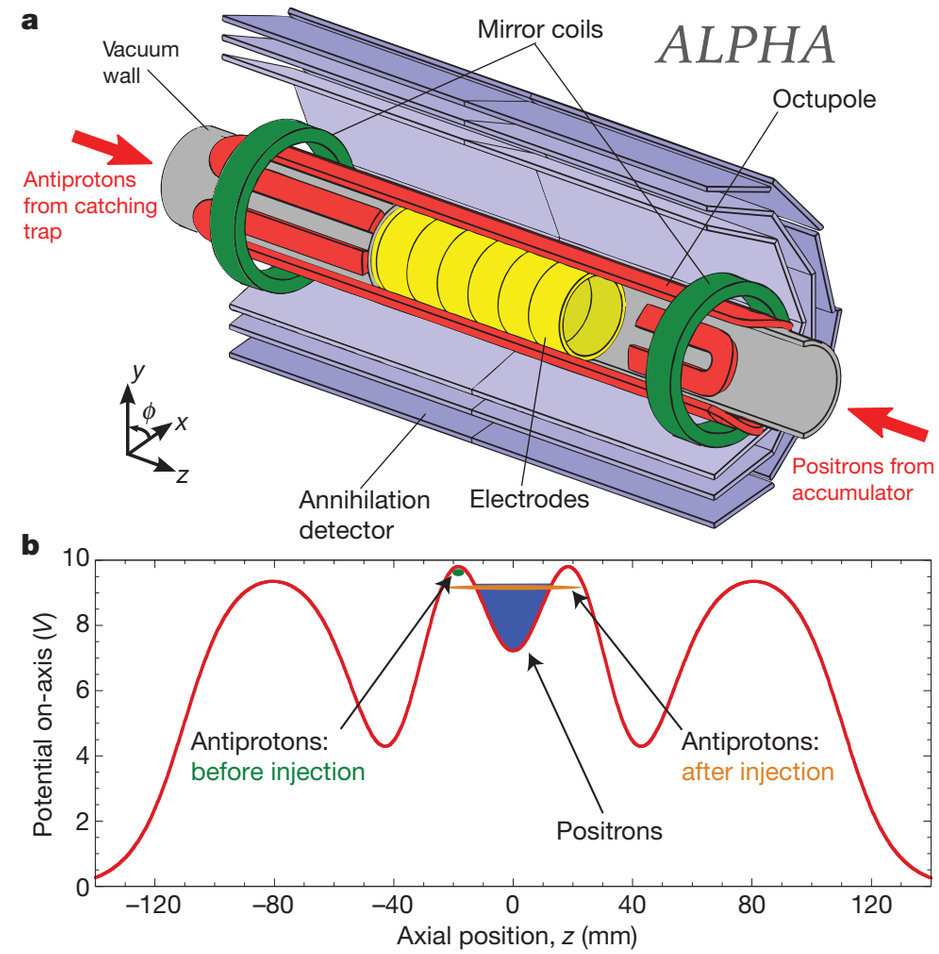
TRAPPING OF ANTIHYDROGEN

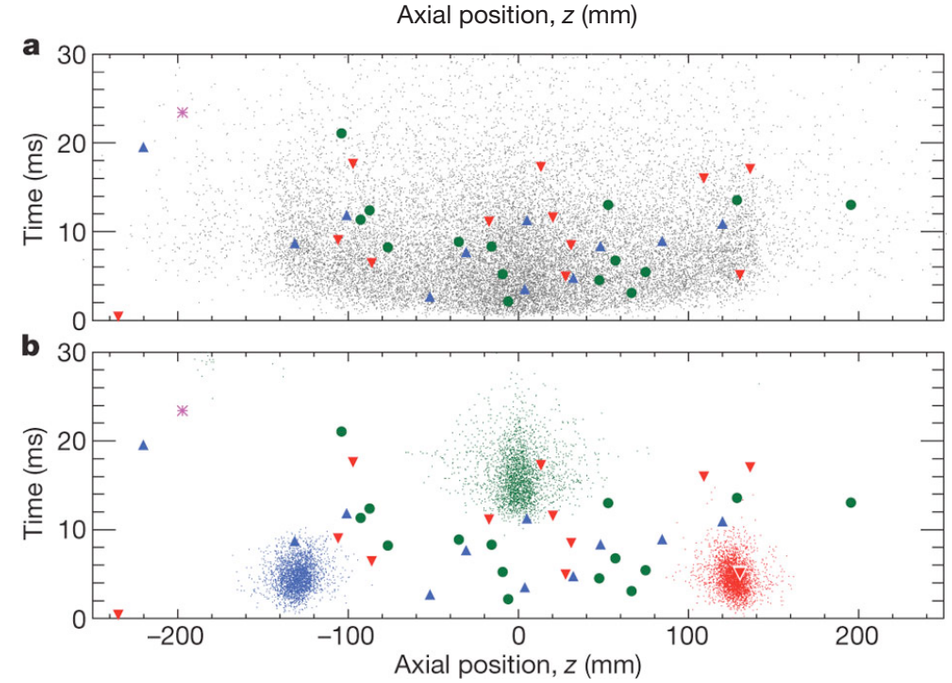
@AD in 2010

First detection of trapped antihydrogen by ALPHA
(Nature 468 (2010) 673)

- Magnetic field gradient for confinement
- Depth typically 50μeV (can trap 0.5K $\bar{H}$)





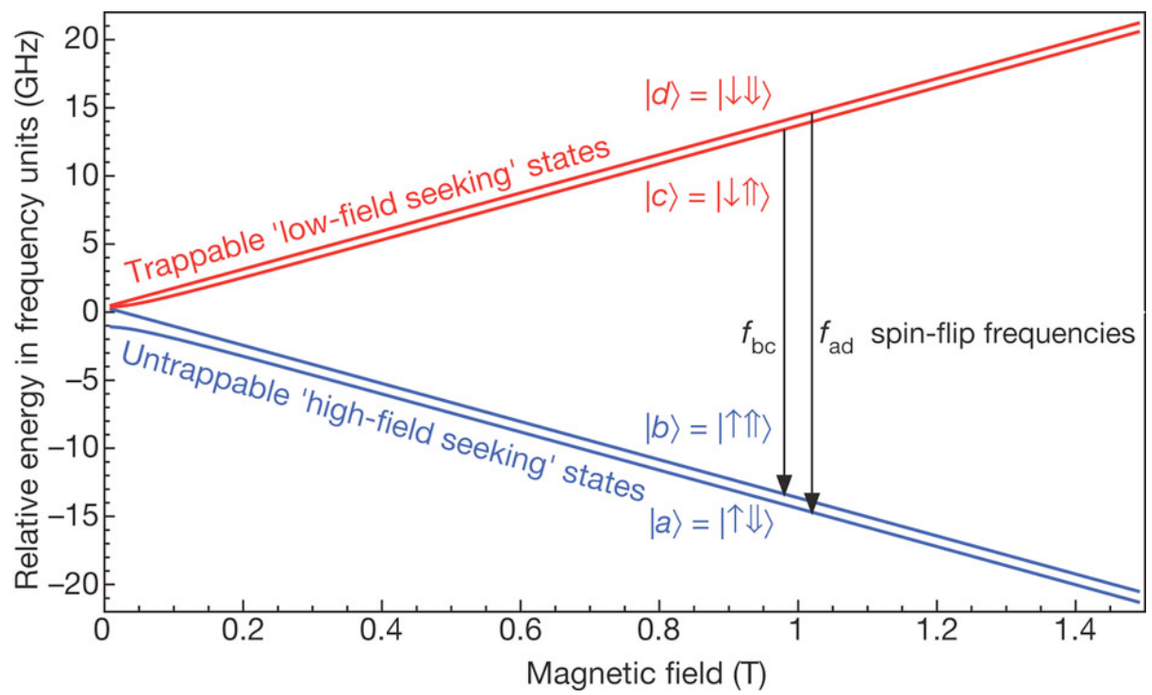


MICROWAVE SPECTROSCOPY

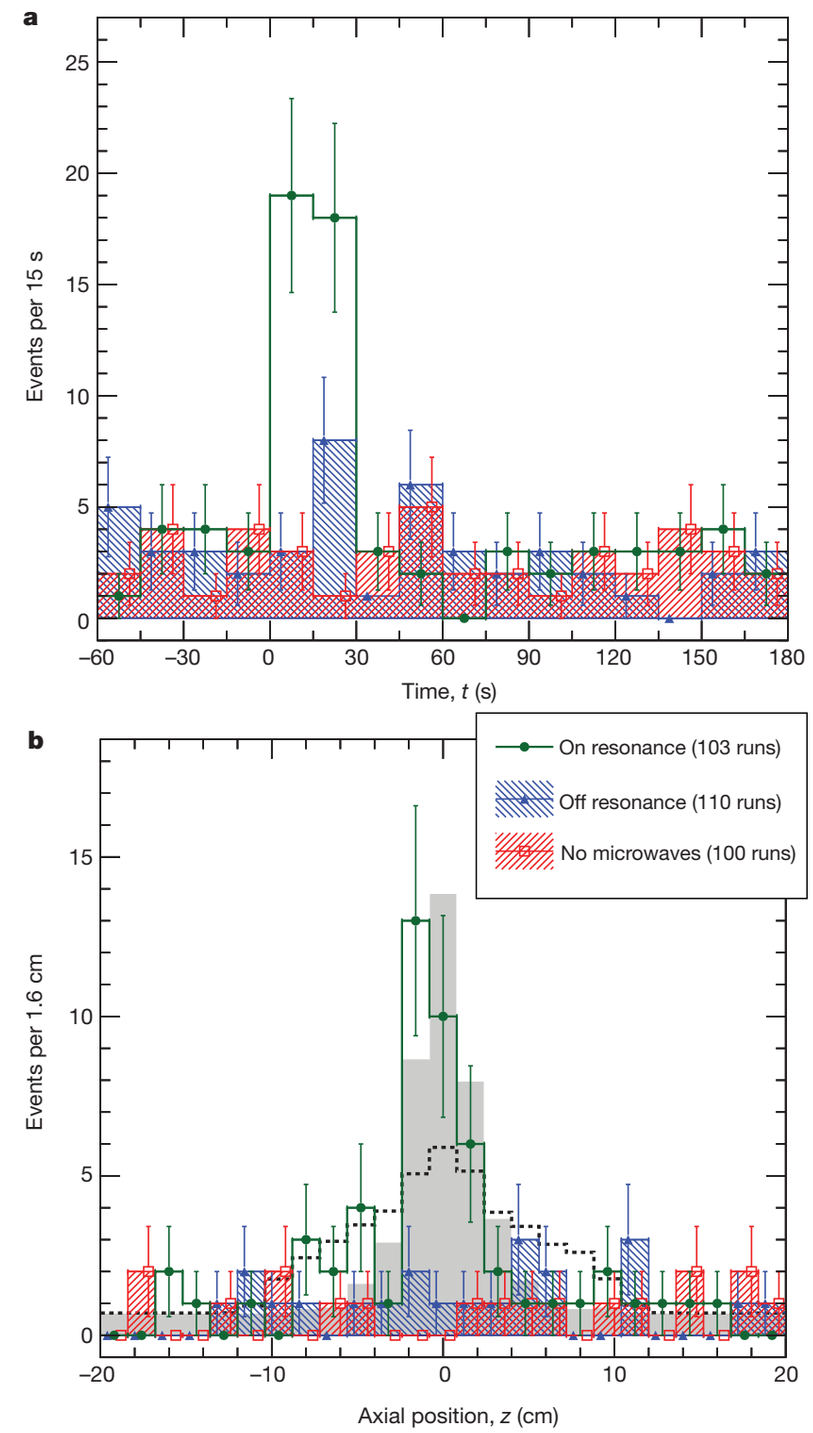
@AD in 2012 *by* ALPHA (Nature 483 (2012) 439)

$\uparrow\downarrow e^+$

$\Uparrow\Downarrow \bar{p}$



Annihilations when on-resonance/off-resonance/no microwaves injected

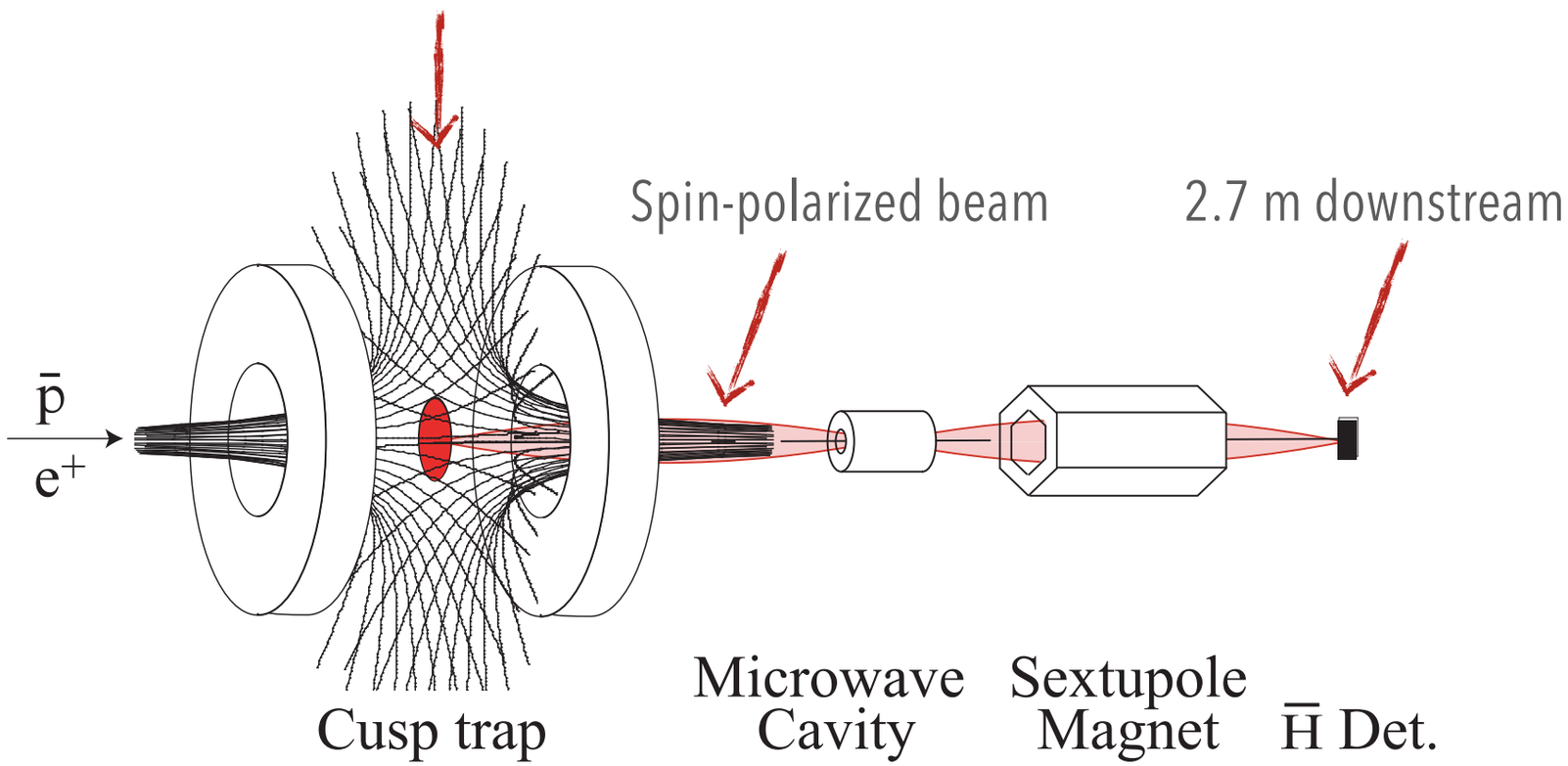


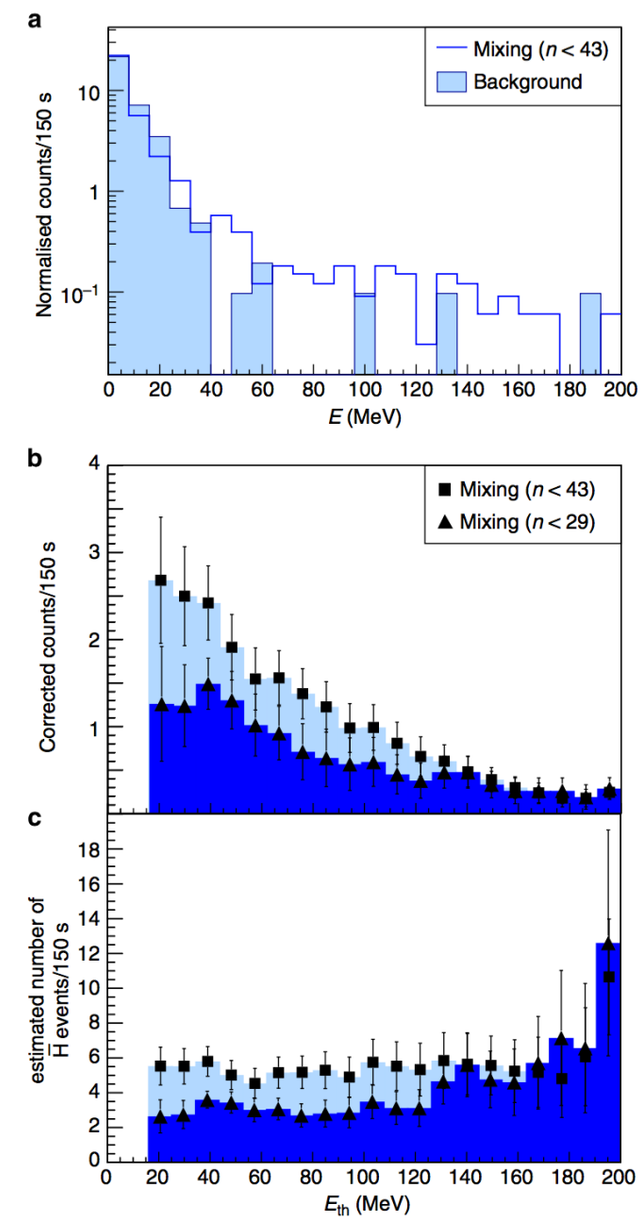
- Injecting microwaves to induce positron spin-flips
- Look for annihilations during the injection ("appearance mode") as well as reduction in signal when trap is opened ("disappearance mode")

BEAM FOR IN-FLIGHT HFS

@AD in 2014 *by* ASACUSA (Nature Com. 5 (2014) 3089)

Defocusing of high-field seeking states





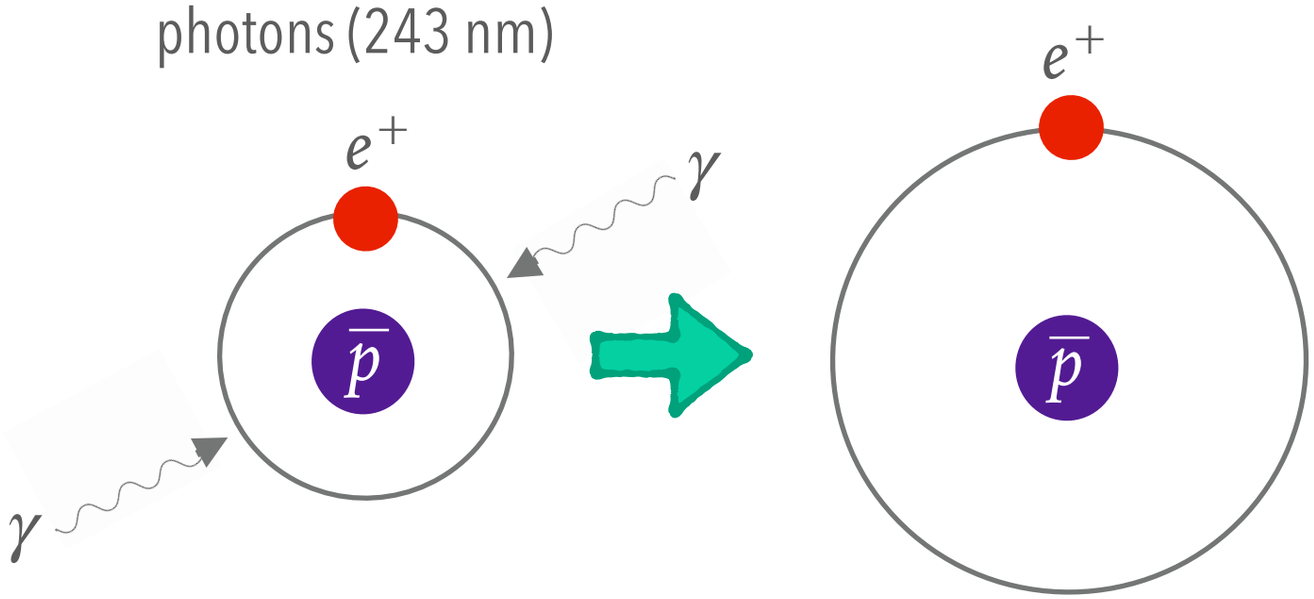
- Rate of a few atoms/hour
- Most still in Rydberg states (n>29)

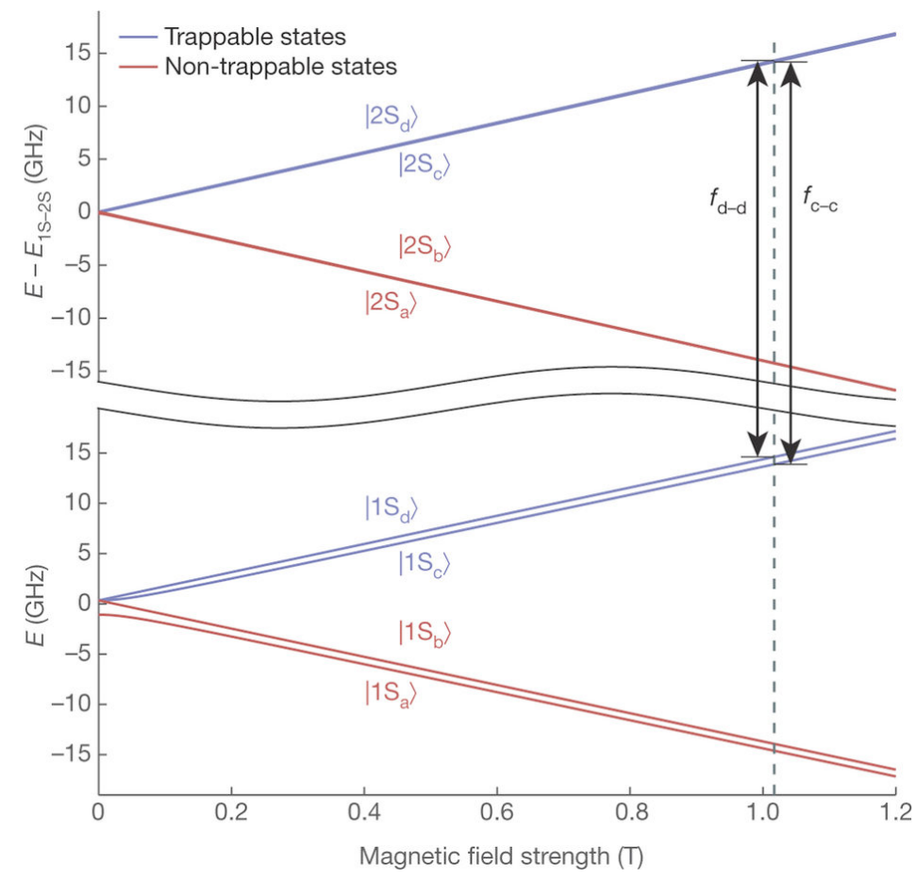
LASER SPECTROSCOPY

@AD in 2016 *by* ALPHA (Nature 541 (2017) 506)

First observation of the 1S-2S transition in antihydrogen

- Laser excitation of ground-state antihydrogen via two photons (243 nm)





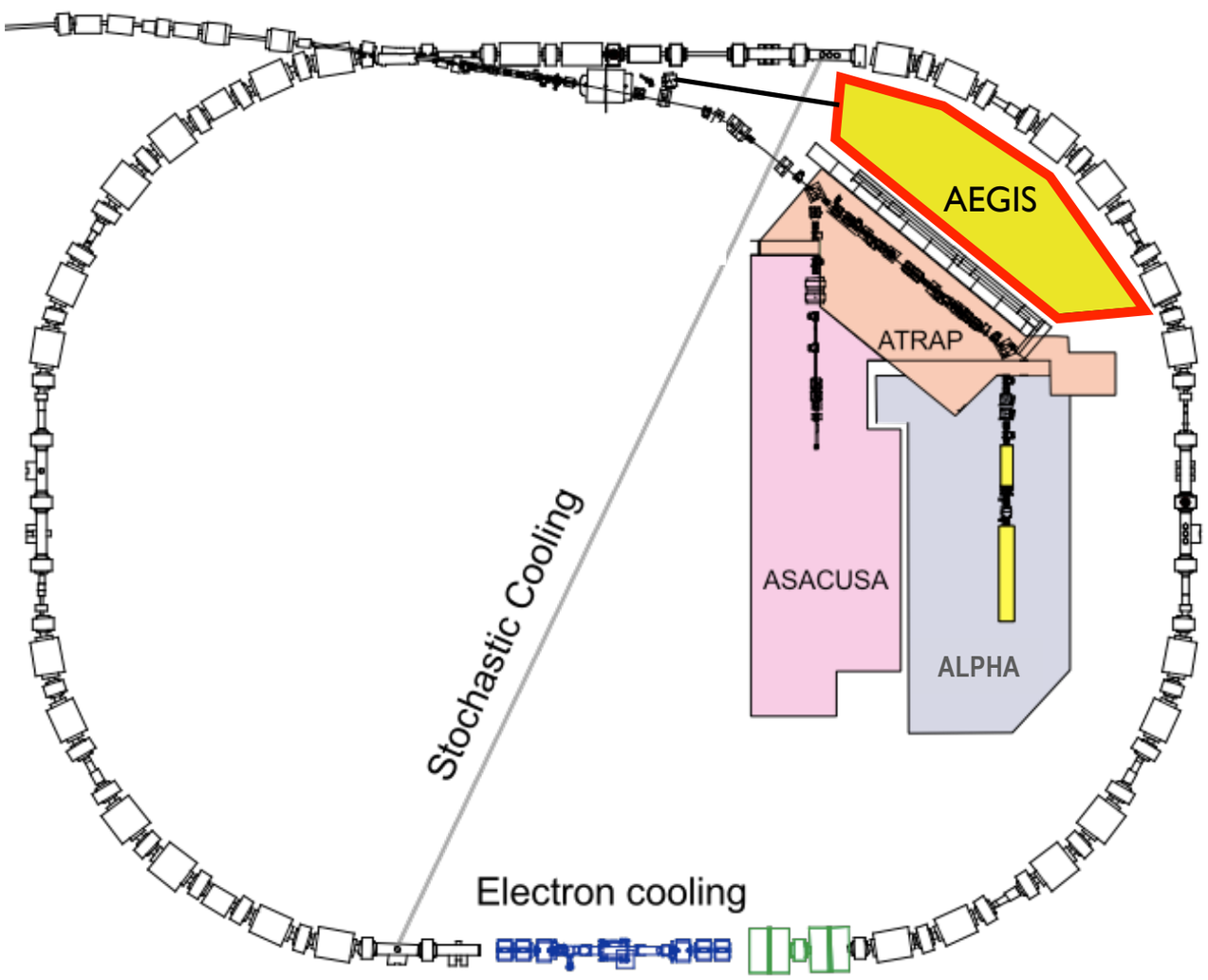
Comparing frequencies of this transition for hydrogen and antihydrogen:

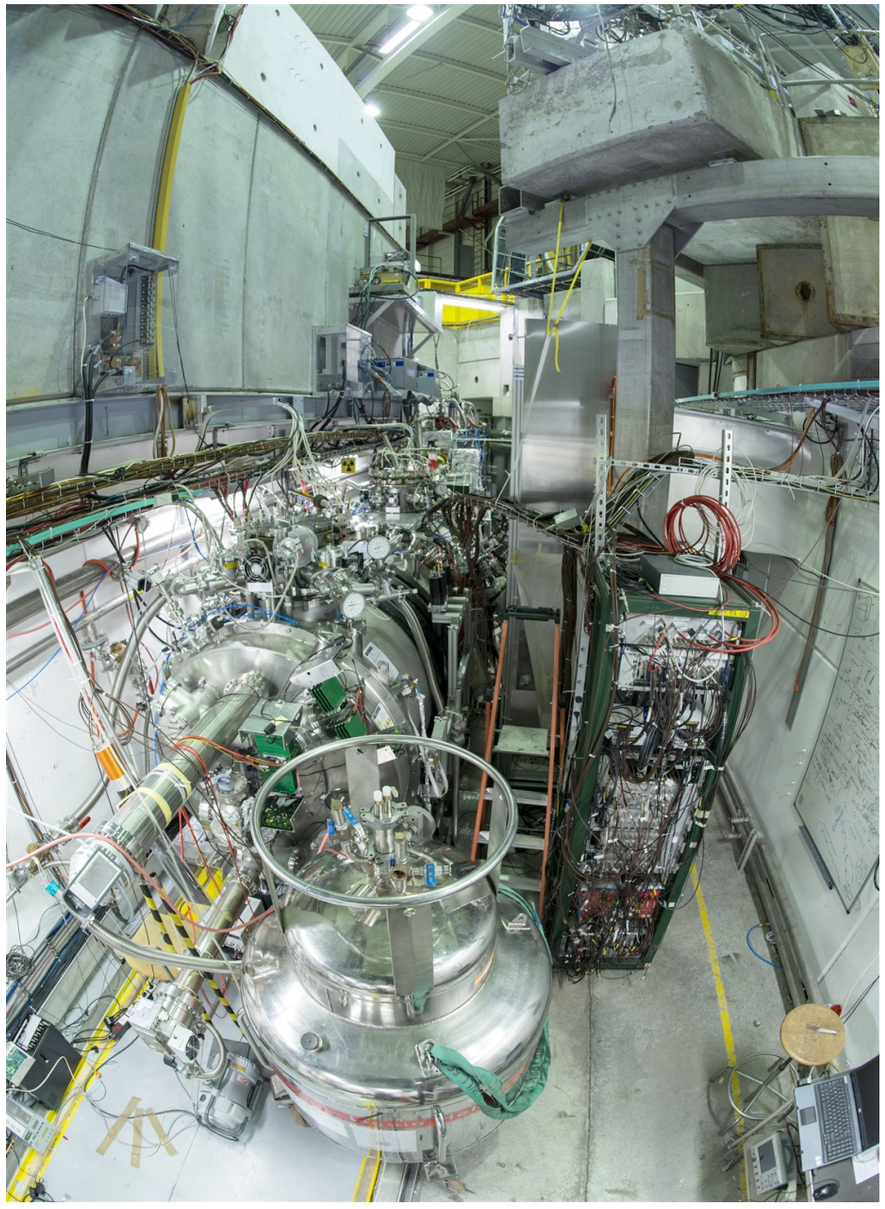
Consistent with CPT invariance to ~2×10^{-10}

The most precise measurement performed on an anti-atom

THE AEGIS EXPERIMENT

Antimatter **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy

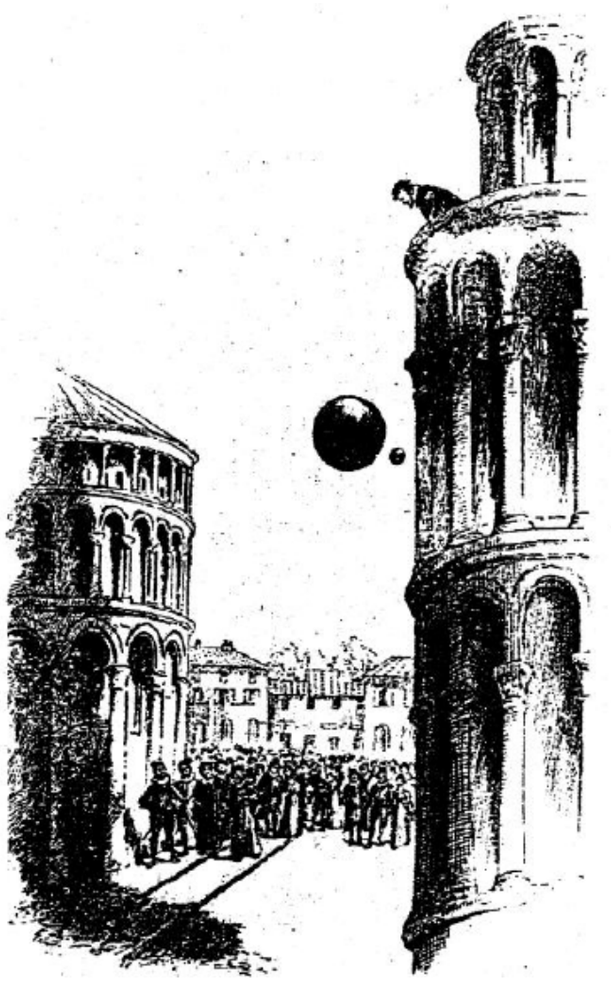


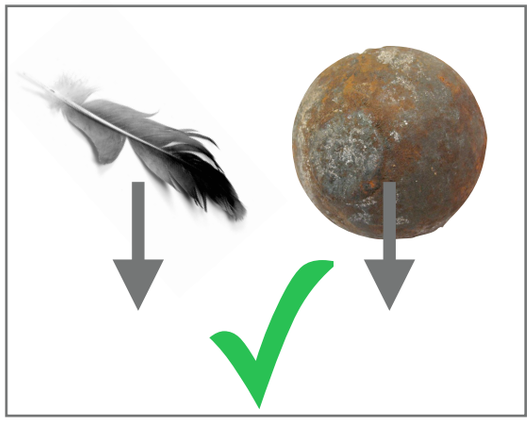


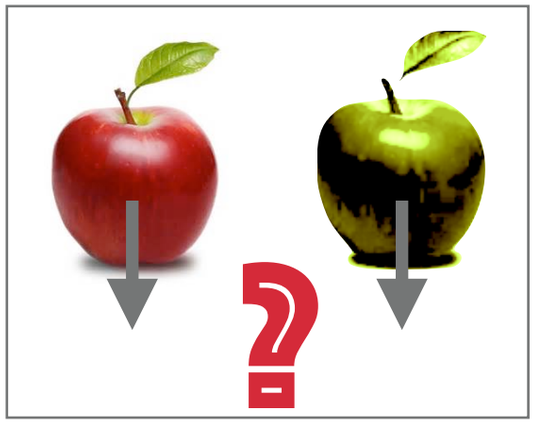
THE AEGIS EXPERIMENT

Antimatter **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy

Probing universality of free fall (the Weak Equivalence Principle)

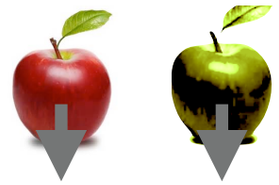






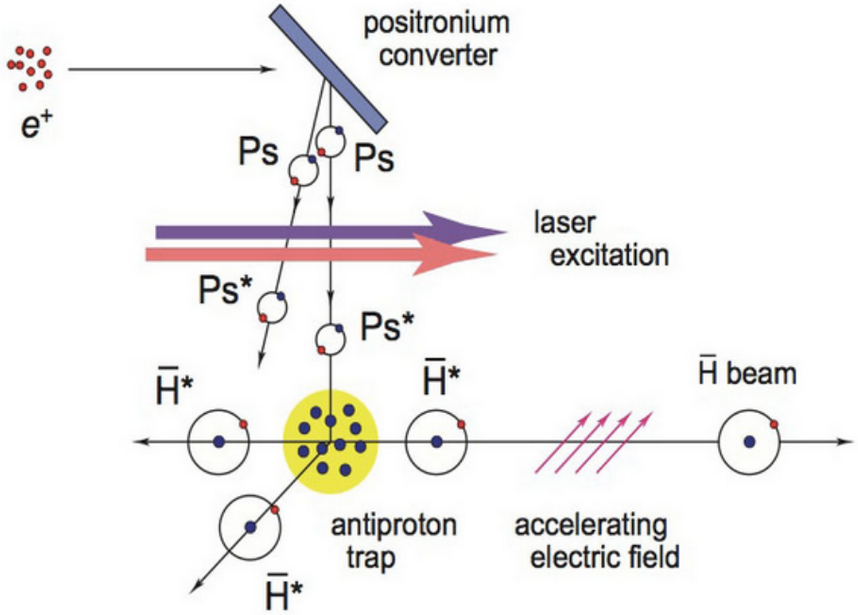
First precise direct test of gravitational interaction between matter and antimatter

THE AEGIS EXPERIMENT

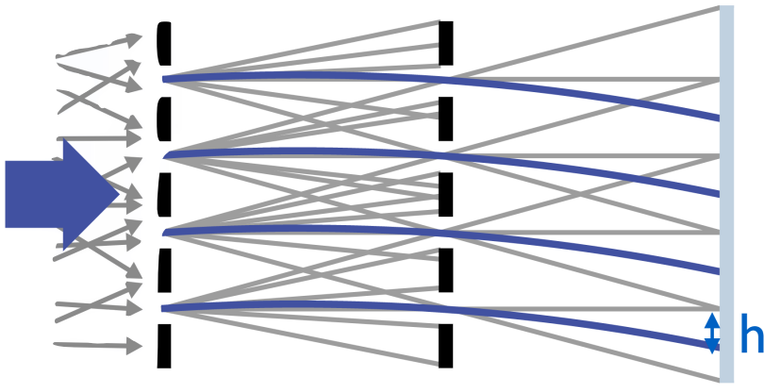


- Antihydrogen produced via charge exchange with Ps
- Cold pulsed beam of antihydrogen by Stark acceleration
- Beam deflection measured with a moiré deflectometer

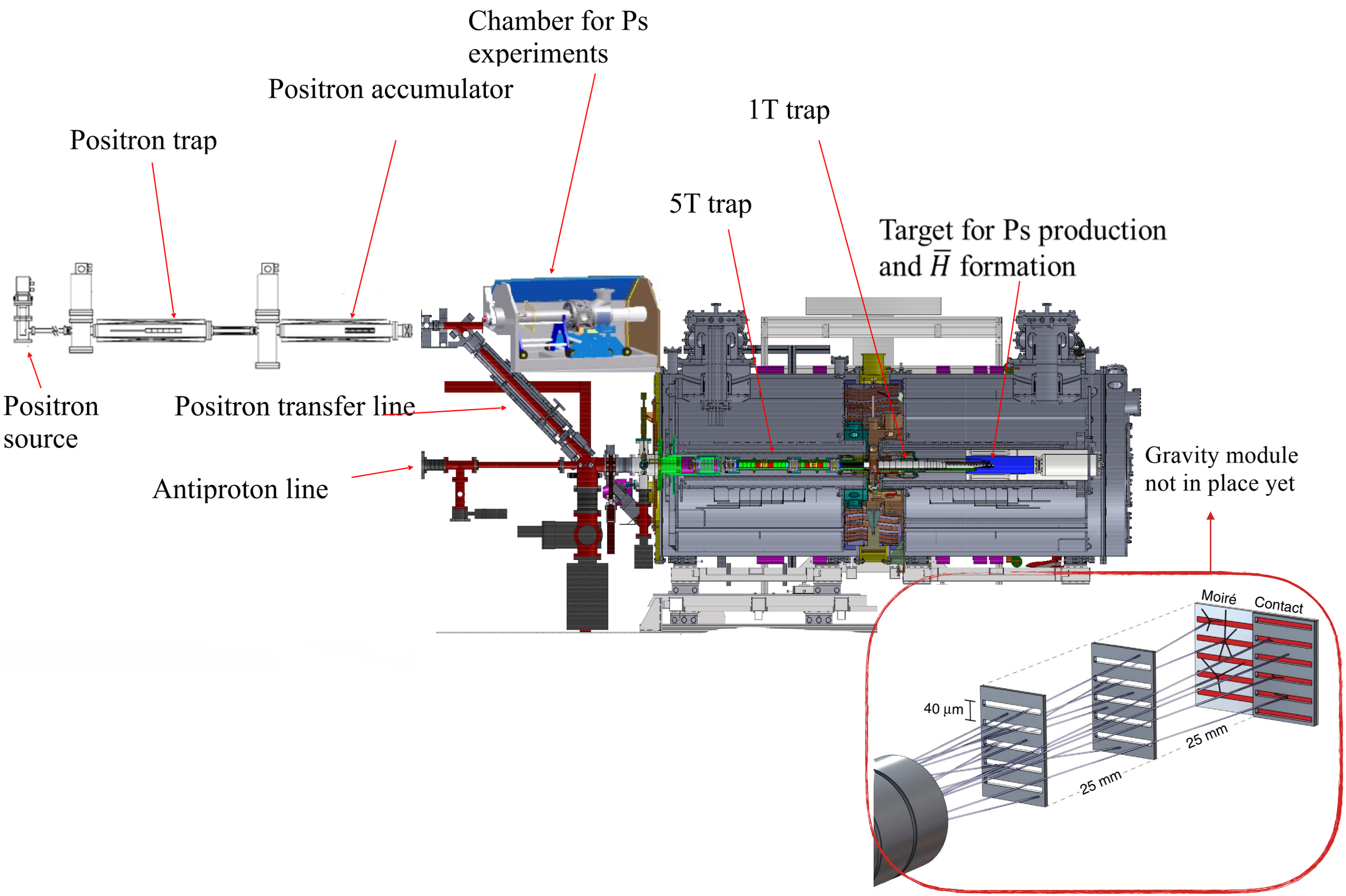
Different from other experiments in the AD hall

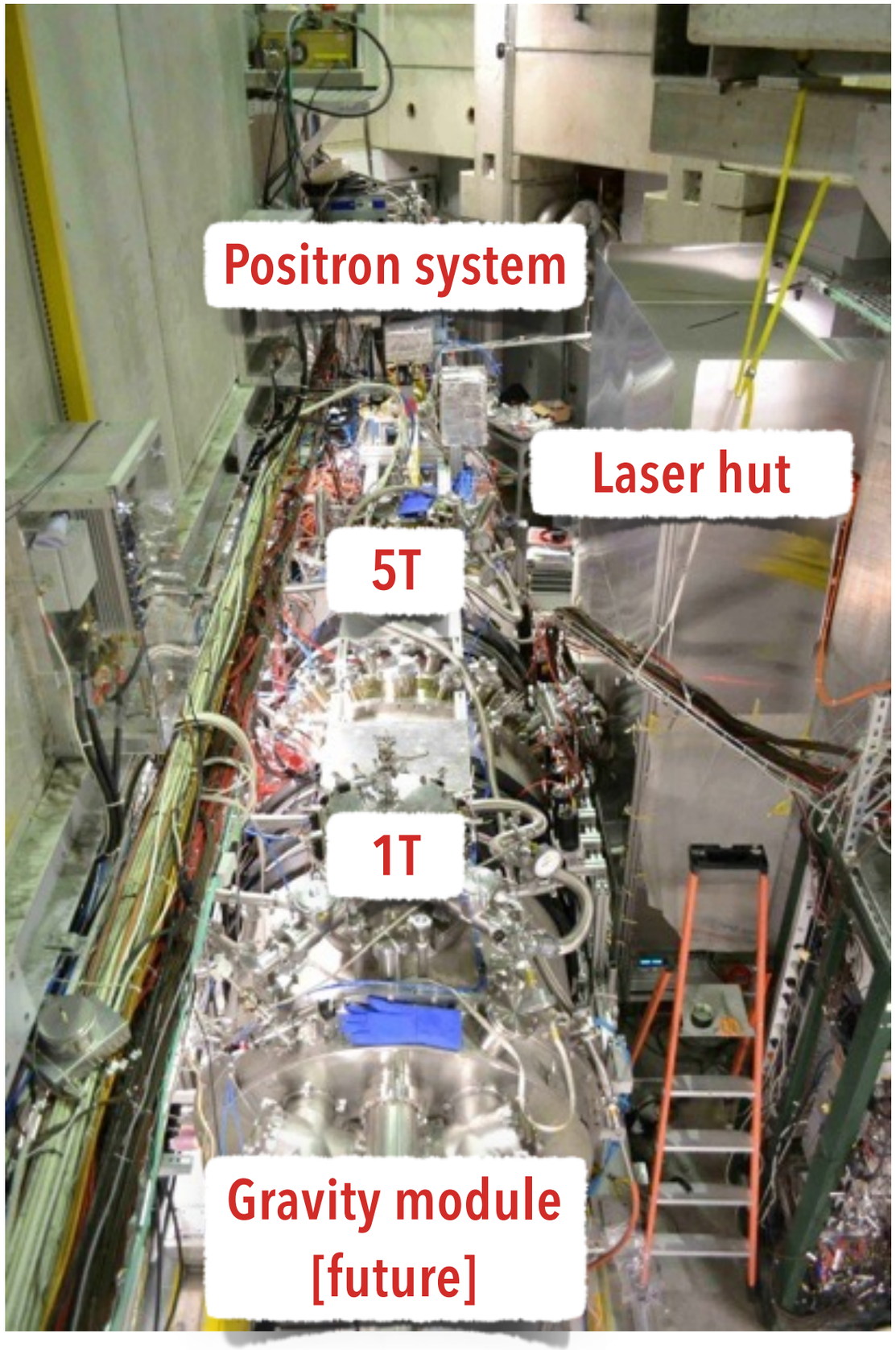


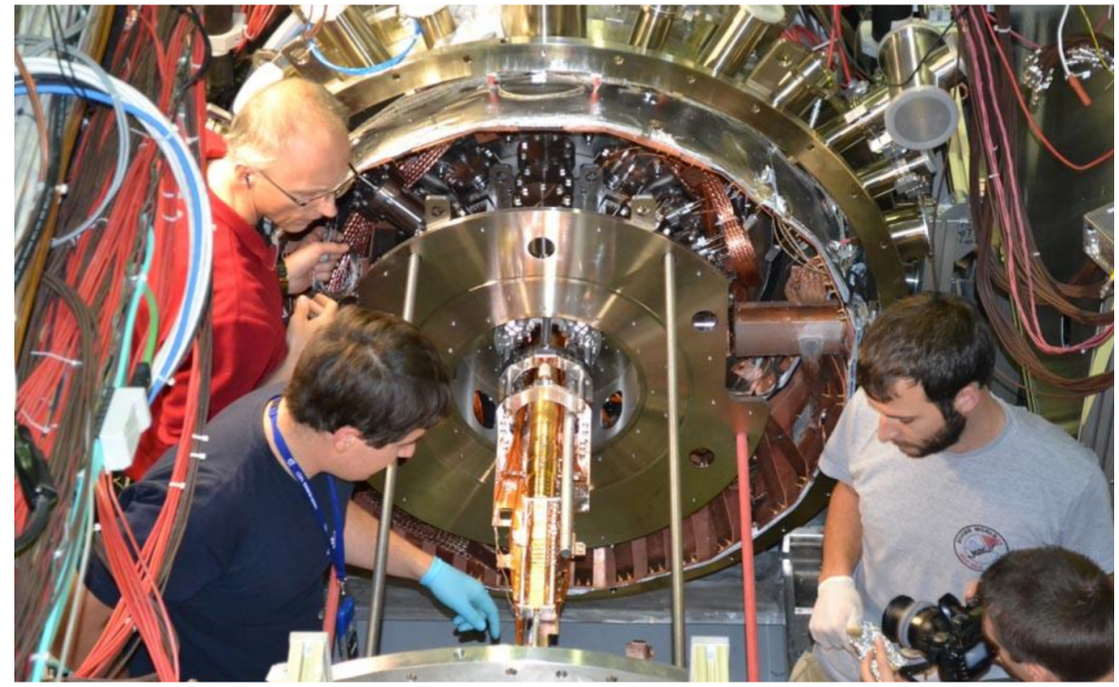
AEgIS, NIMB (2008) 266 (3) 351-356

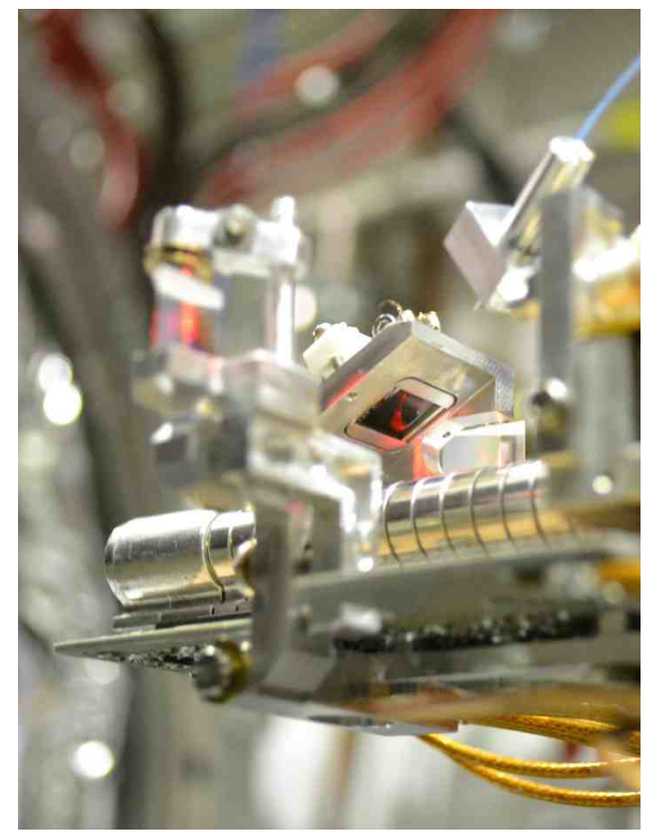


AEgIS, Nature Communications 5 (2014) 4538


Chamber for Ps experiments
Positron accumulator
Positron trap
1T trap
5T trap
Target for Ps production and $\bar{H}$ formation
Positron source
Positron transfer line
Antiproton line
Gravity module not in place yet
Moiré
Contact
40 µm
25 mm
25 mm







$\bar{H}$ production region

OVERALL STATUS

Achievements towards the gravity measurement:

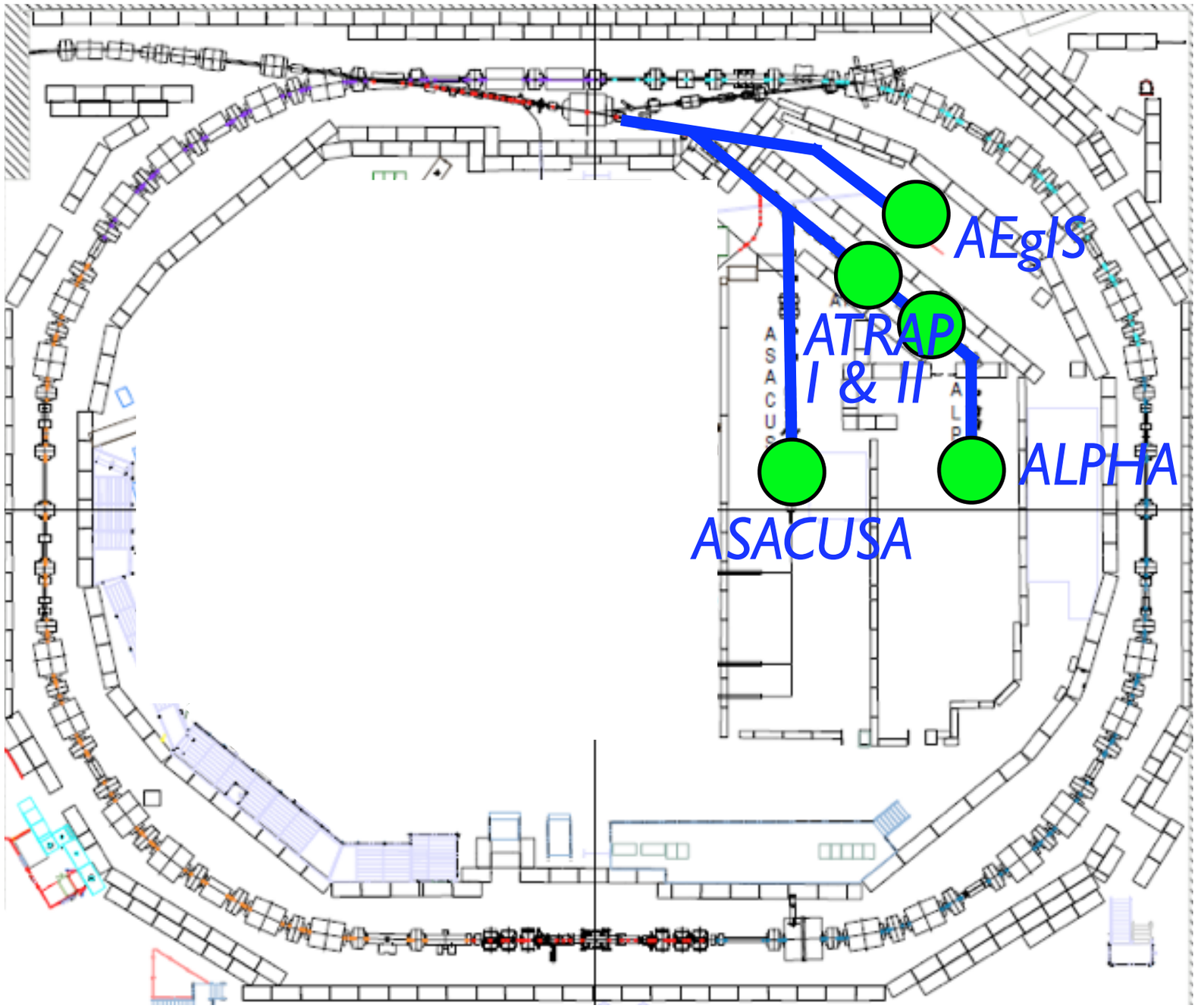
- Catching and cooling of large number of antiprotons
- Transfer of the antiproton plasma in the production region
- Production, transfer and storage of an high number of positrons
- Studies of Ps formation and laser excitation to Rydberg levels
- Positronium production in the 1T

Under development:

- Rydberg excitation of Ps in the 1T
- Antihydrogen formation
- Synthesis of a forward anti-hydrogen beam
- Detectors for gravity measurement
- Transmission targets for improved antihydrogen production
- Techniques for cooling antiprotons

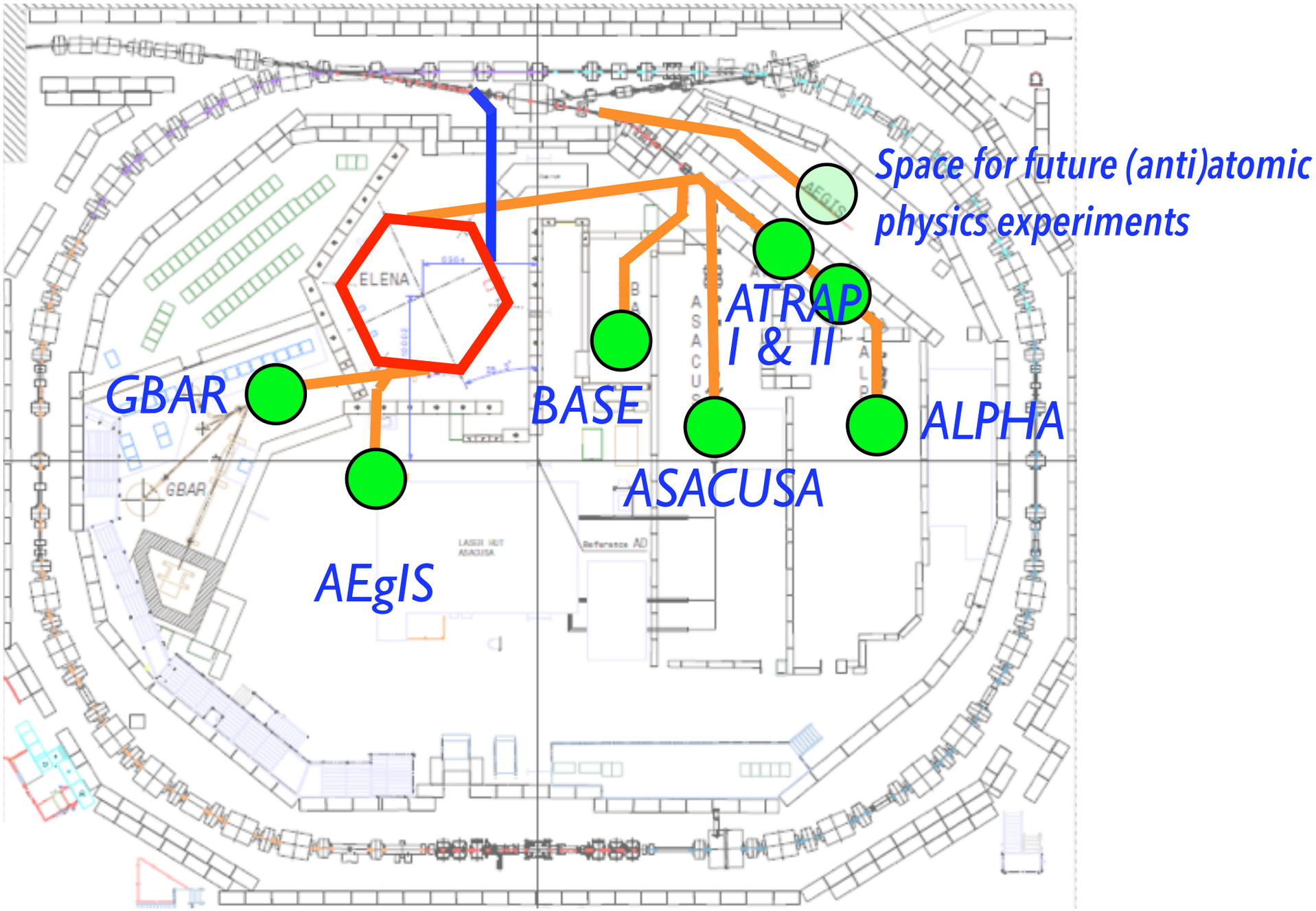
ELENA

Two main challenges: colder / more antiprotons



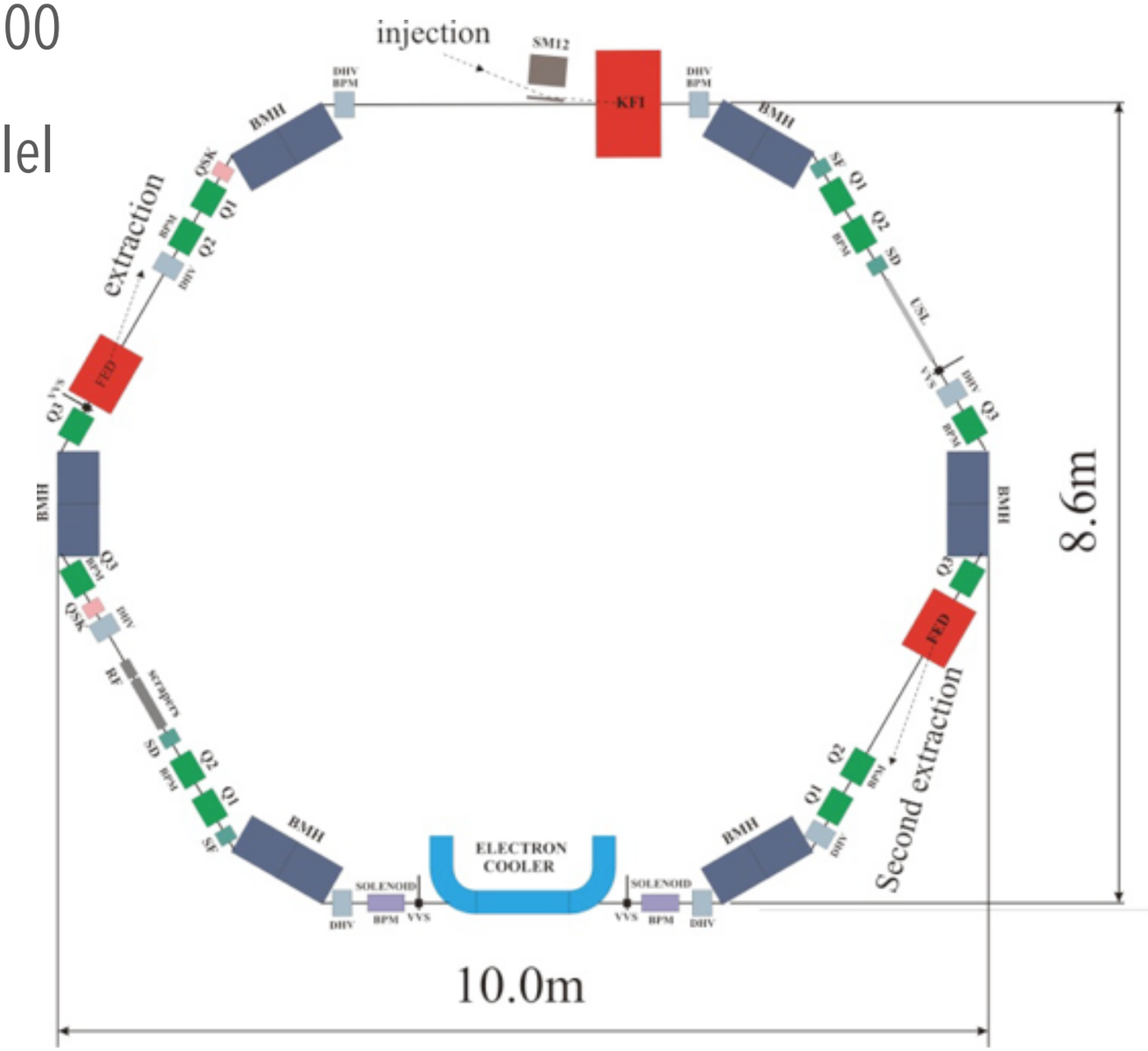
ELENA

From 2017: new low energy $\bar{p}$ decelerator ELENA.



ELENA

- Dramatically slows down the antiprotons from the AD
- Increases the trapping efficiency x 100
- Allows 4 experiments to run in parallel
- Allows new experiments to come in



OUTLOOK

Antihydrogen research at CERN covers a wide range

- Atomic physics
- Gravity
- Nuclear physics
- Plasma physics
- Cosmology
- Material science

- Requires modest resources but much patience & time
- Relies on many technologies from many fields of science
- Requires breakthroughs in numerous areas, most of which come from atomic and laser physics (cooling, manipulations, ...)

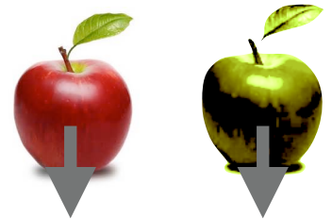
SUMMARY

- Antimatter lends itself to studying fundamental structures of nature
- The CERN Antimatter Factory, uniquely designed for the purpose, is currently hosting five experiments
- Many advances within antimatter research have been made the last years, many developments are underway
- The main challenges of the field are: acquiring sufficient amount of antimatter and having it cold enough to obtain precision in measurements
- The AEgIS experiment aims to carry out the first precise direct measurement of gravity on antimatter by the use of a cold antihydrogen beam and a Moiré deflectometer
- The 2017 AEgIS goal is antihydrogen production – we are entering data-taking mode: very exciting
- The Extra Low ENergy Antiproton ring is currently being commissioned: the field of antimatter research will get a big boost after the Long Shutdown 2 of the LHC (2019-2020) – *the future is bright!*

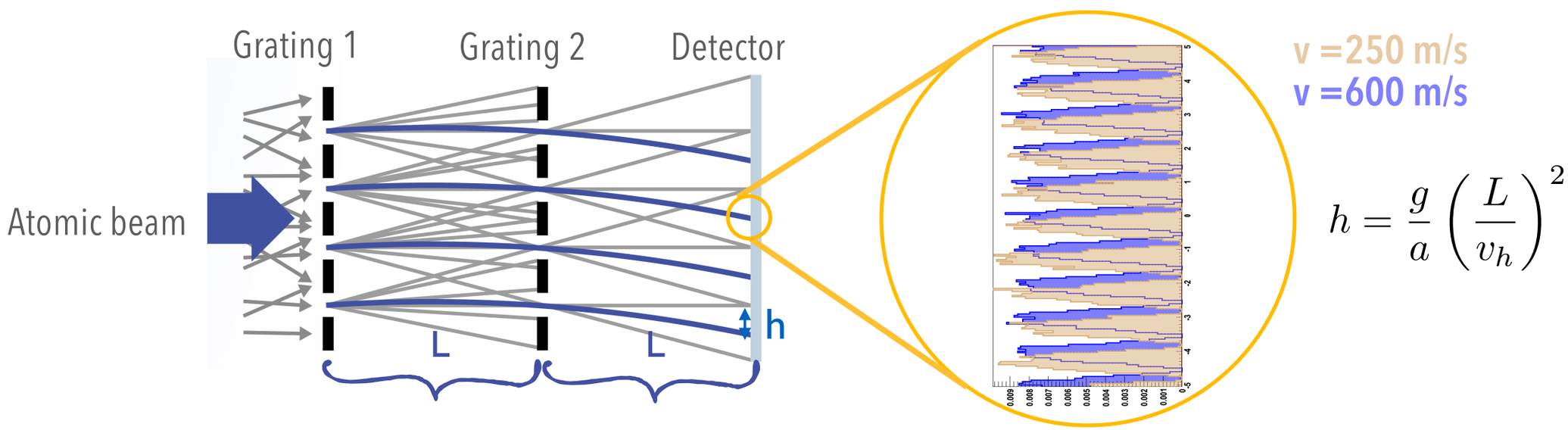
Thank you for your attention!

BACK-UP

A BEAM FOR DEFLECTION



- Rydberg atoms are very sensitive to inhomogeneous electric fields
  - Stark deceleration of hydrogen demonstrated
    E. Vliegen&F. Merkt, J. Phys. B 39 (2006) L241
- Beam deflection measured with a moiré deflectometer
  - Has been successfully used for a gravity measurement with ordinary matter, $\Delta(g)/g = 2\times10^{-4}$
- $\Delta(g)/g = 1\%$ expected with 10^5 $\bar{H}$ at 100mK



$$h = \frac{g}{a}\left(\frac{L}{v_h}\right)^2$$

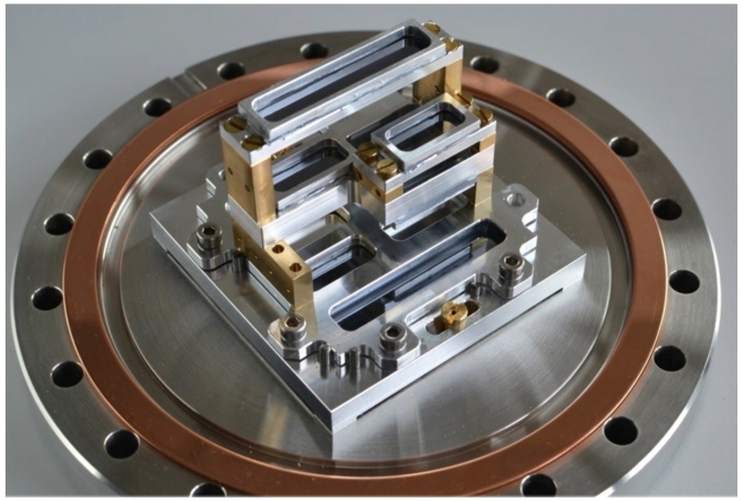
MOIRÉ DEFLECTOMETER

A proof-of-principle measurement

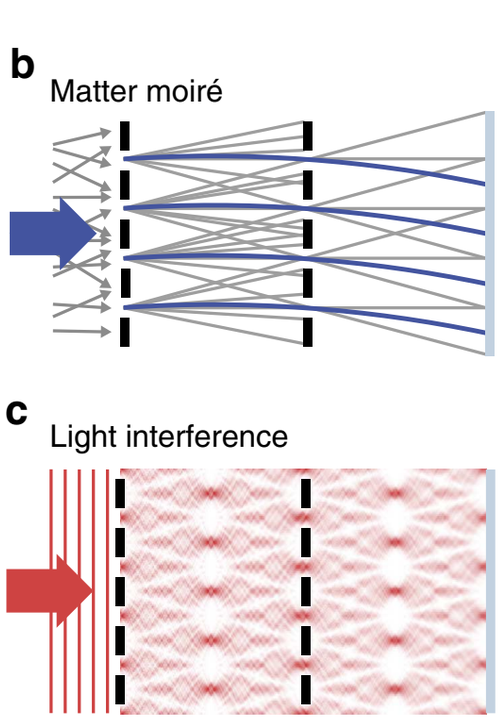
AEgIS, Nature Communications 5 (2014) 4538

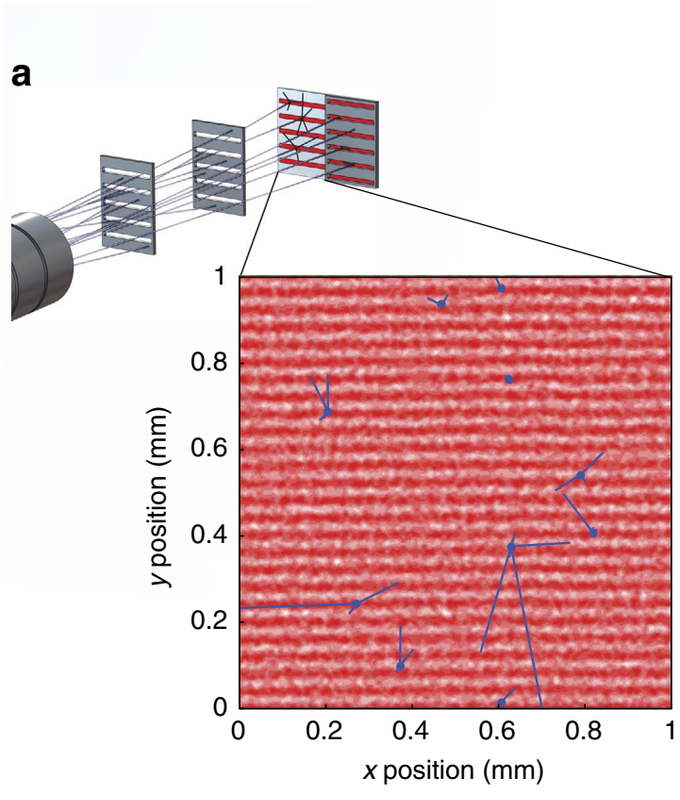
Mini-moiré deflectometer:
L=25mm, slit=12μm, pitch=40μm, 100μm thick gratings

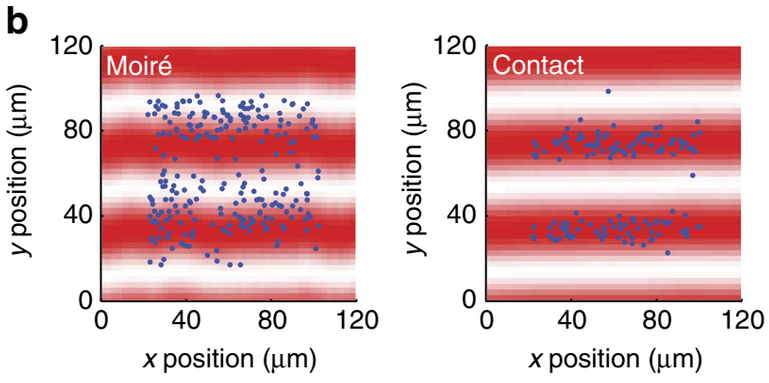
- Tested 2012 in the AEgIS antiproton beam line, $E_{\bar{p}}$~100keV
- Measured with emulsion detector (next slide)

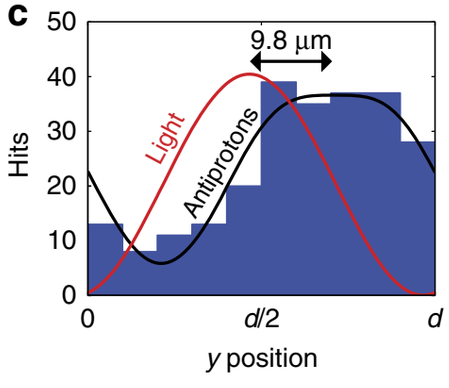


Mini-moiré deflectometer









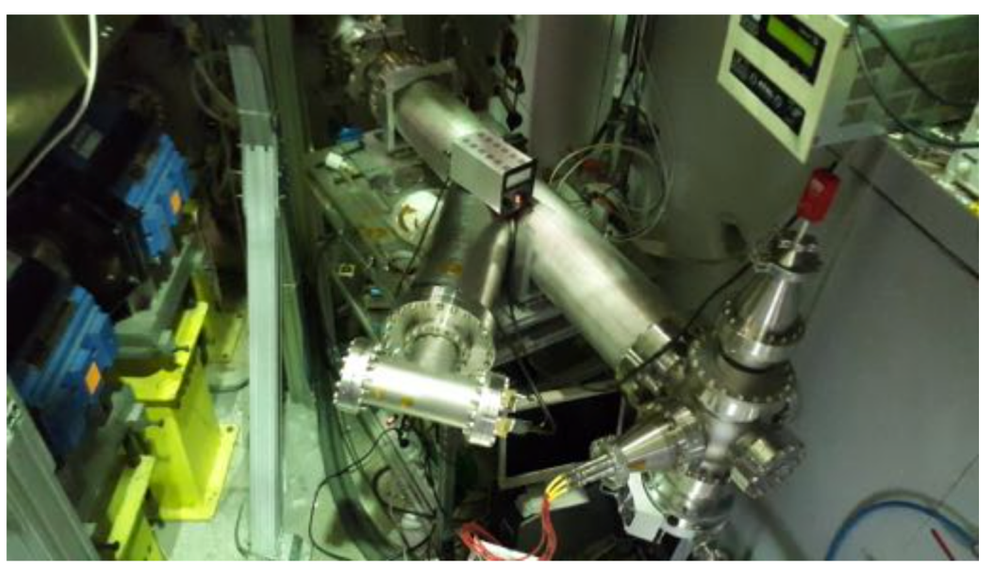
EM deflection of antiprotons: $\Delta y = 9.8 \pm 0.9\,(\text{stat.}) \pm 6.4\,(\text{syst.})\ \mu\text{m}$

DETECTOR TEST CHAMBER

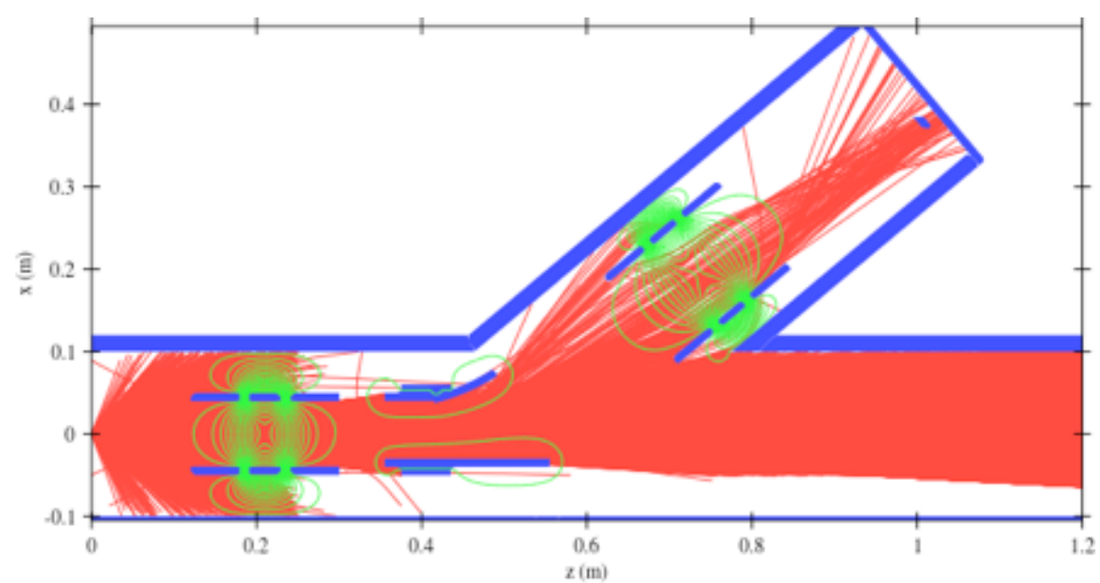
A new test-chamber installed on the secondary $\bar{p}$ extraction line in the AEgIS experimental area

- Moderating AD shot of 5.3 MeV to 0-16 keV with foils and electrostatic setup
- Use of clean, low energy antiprotons for detector and material studies
- Has been used for measuring silicon pixel detector
- Will be used for optimizing gravity detector design

Expanding the physics programme of AEgIS

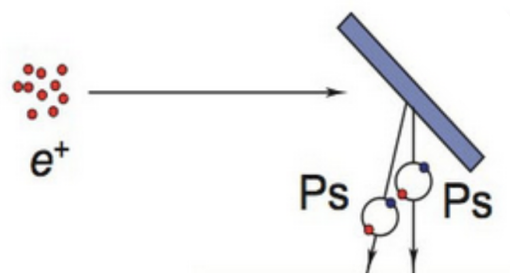


GRACE



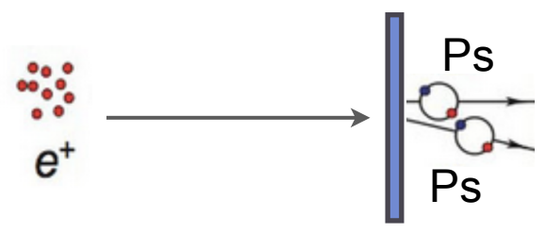
Ion Beam Simulator

ON-AXIS PS PRODUCTION



Change from

reflection mode production



to

on-axis transmission mode production

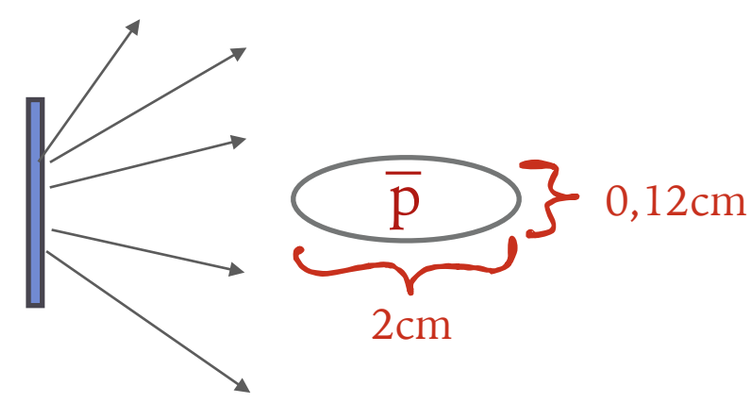
Likely to result in an improvement of $\overline{H}$ production

Depends on

Distance to antiproton cloud

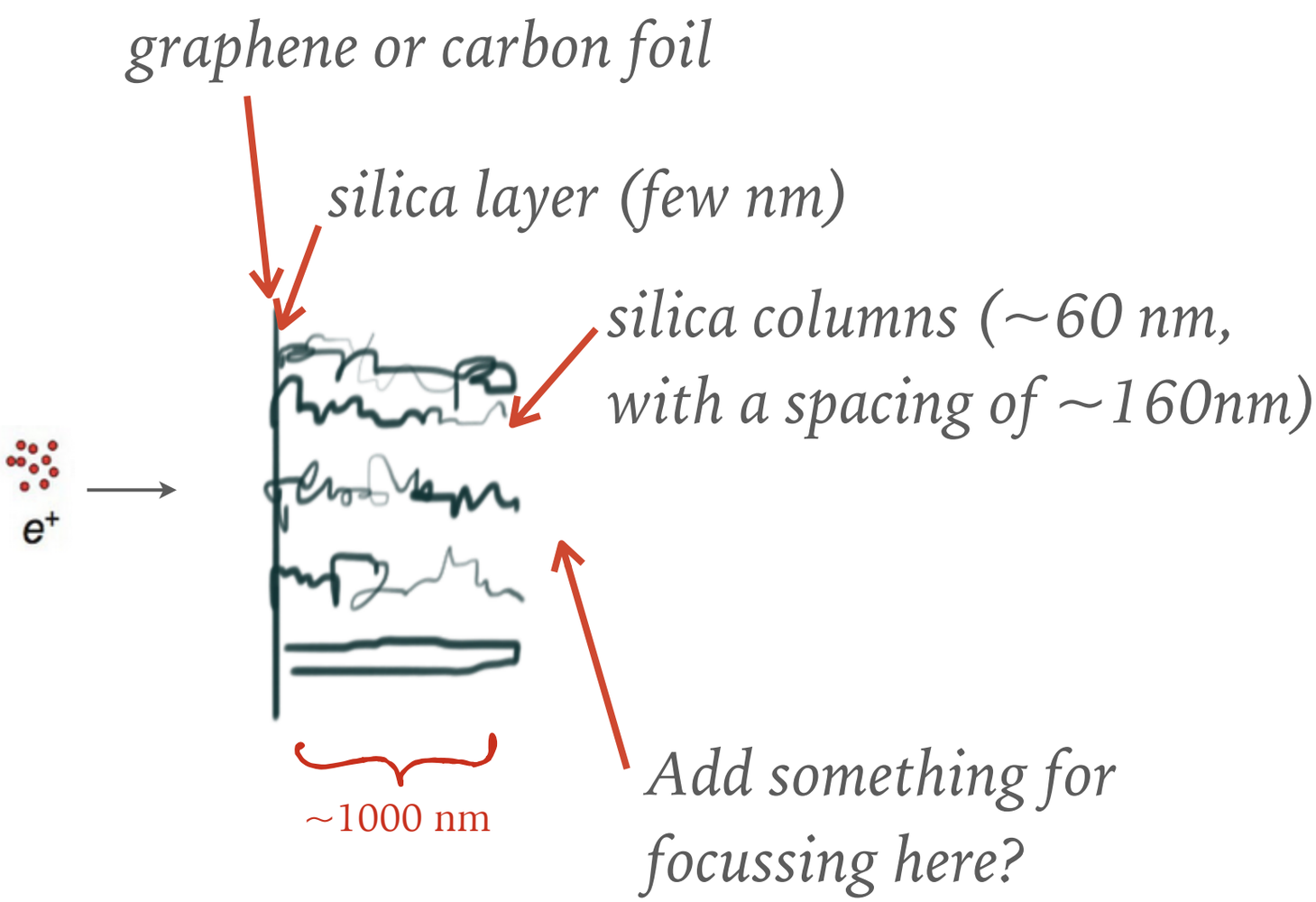
Emission pattern

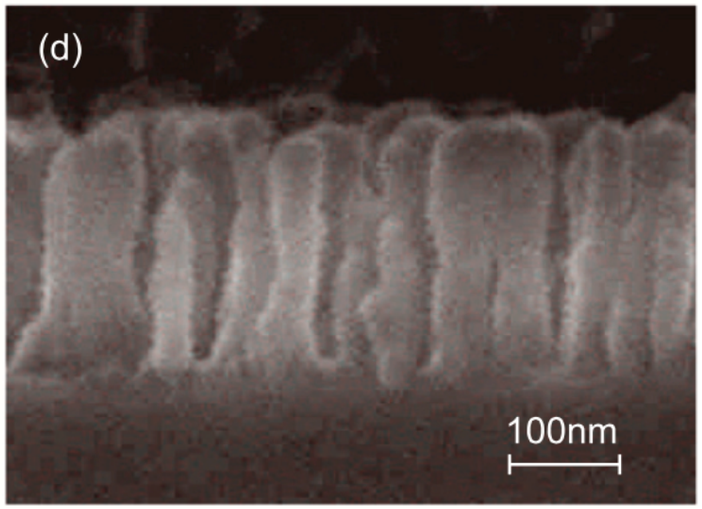
Thermalisation



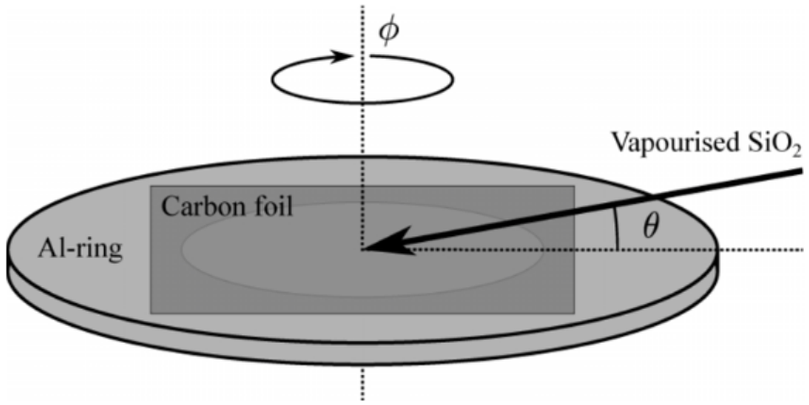
Possible bonus (if antiprotons cold enough): Remove the need for Stark acceleration of antihydrogen?

PS TARGET CONSTRUCTION





Eur. Phys. J. D (2014) 68: 124



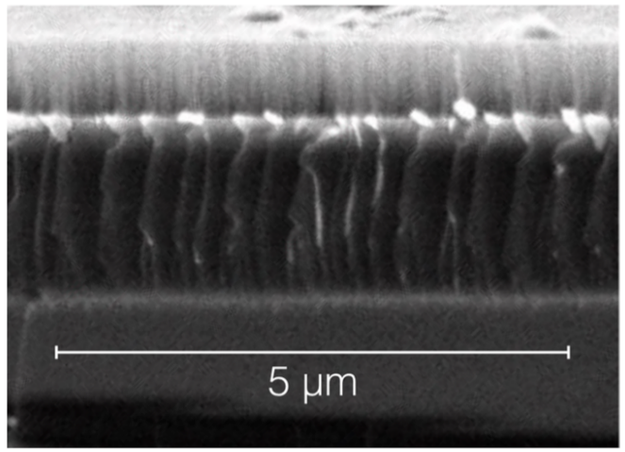
PS TRANSMISSION TARGET

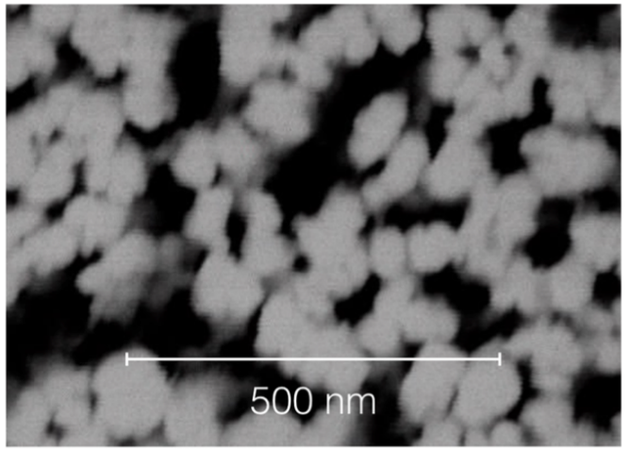
Characterization of a transmission positron/positronium converter for antihydrogen production

S. Aghion[a,b], C. Amsler[c,d], T. Ariga[c], G. Bonomi[e,f], R. S. Brusa[g,h], M. Caccia[b,i], R. Caravita[j,k], F. Castelli[b,m], G. Cerchiari[n], D. Comparat[o], G. Consolati[a,b], A. Demetrio[p], L. Di Noto[j,k], M. Doser[l], A. Fredita[c], C.

AEgIS, NIMB (2017) 407, 55-66

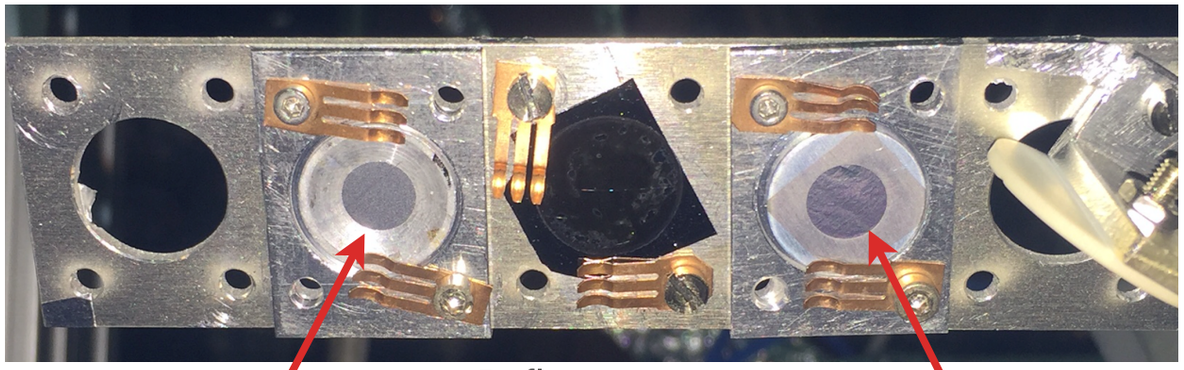
Targets developed in collaboration with Aarhus University





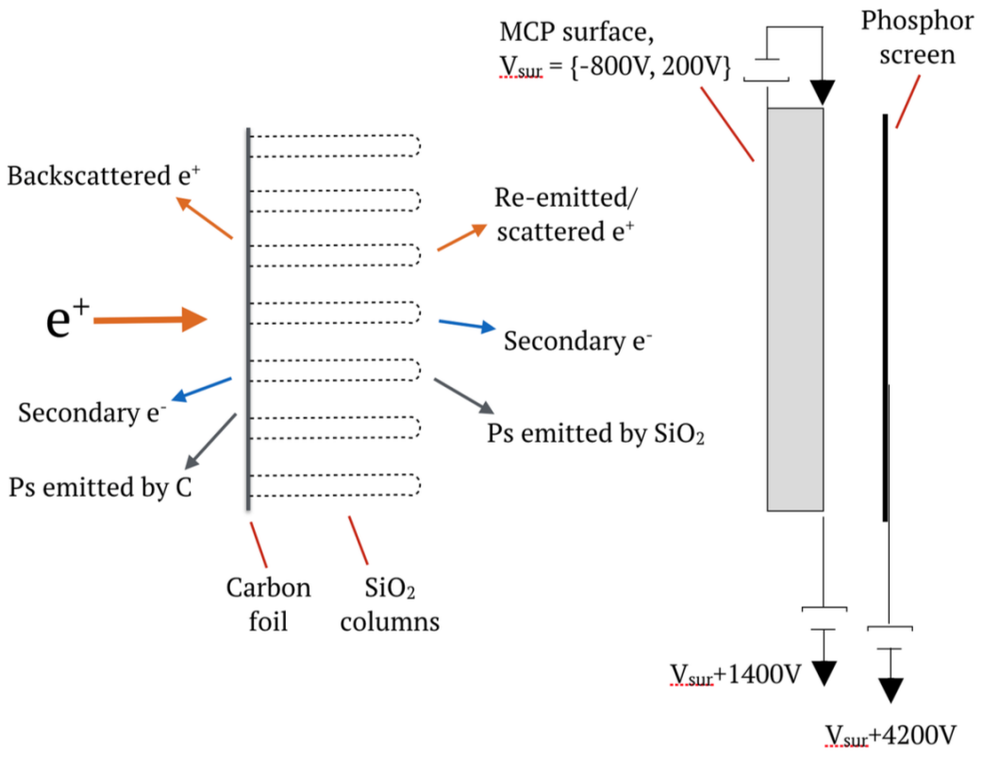
- 20 nm carbon foil, ~750nm silica layer
- Ultraporous meso-structured silica film (~0.4 g/cm3)

PS TRANSMISSION TARGET

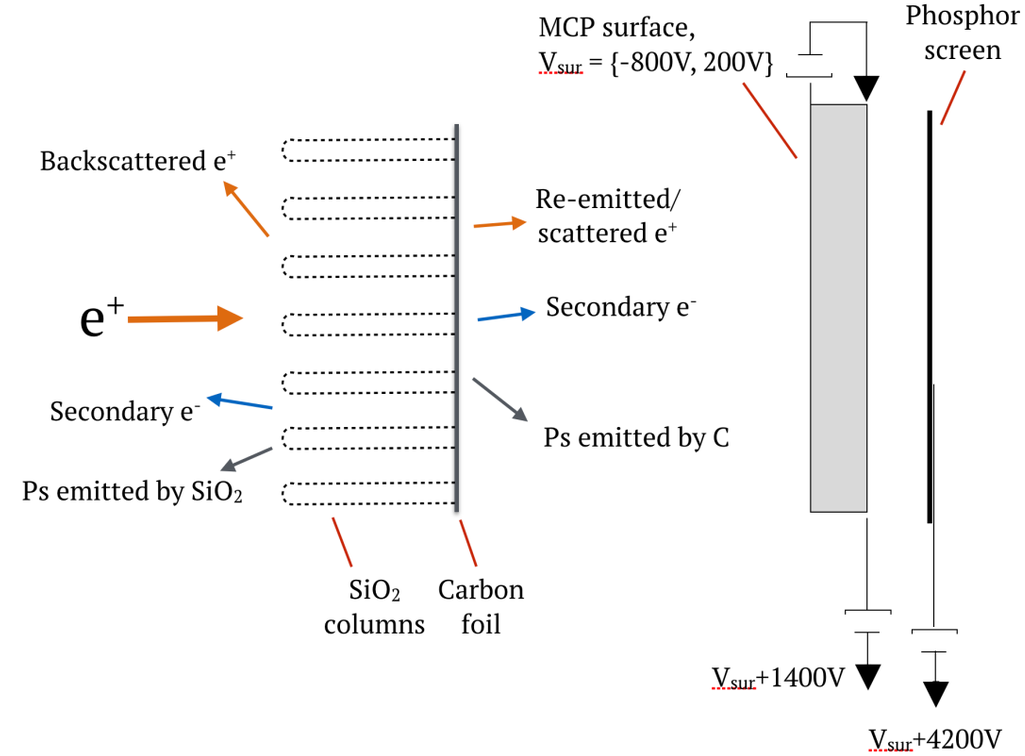


Reflection target

Transmission target in **transmission mode**

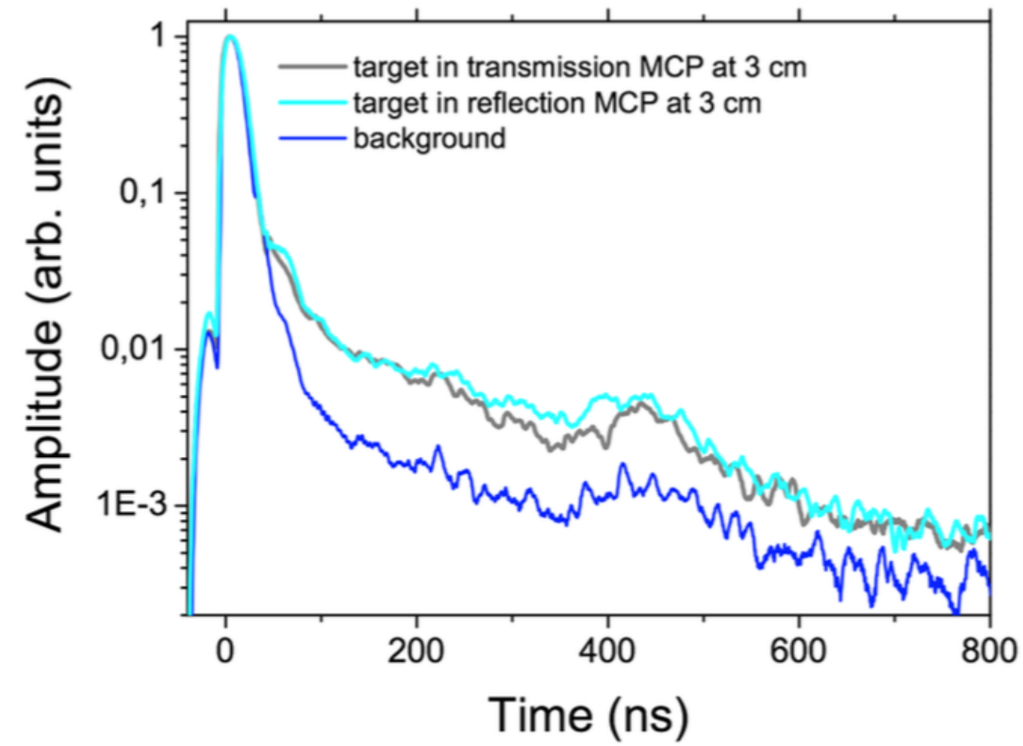


Transmission target in **reflection mode**



PS TRANSMISSION TARGET

1. **SSPALS measurement (PbWO4)**
2. Imaging of the forward-emitted particles (MCP–phosphor screen coupled to a CCD camera)
3. Time of Flight measurement of forward-emitted particles (MCP–phosphor screen coupled to a fast PMT)



$$f_d = \int_{35ns}^{350ns} V(t)dt \; / \int_{-3ns}^{350ns} V(t)dt$$

Only o-Ps can be present after this time

Around 10% Ps emitted in transmission (in agreement with previous work on similar target)

	Transmission mode	Reflection mode
Fraction of e^+ stopped in C	0.02	0.10
Fraction of e^+ stopped in SiO_2	0.65	0.57
f_d, distance 0.8 cm	0.03	0.07
f_d, distance 3 cm	0.07	0.08

PS TRANSMISSION TARGET

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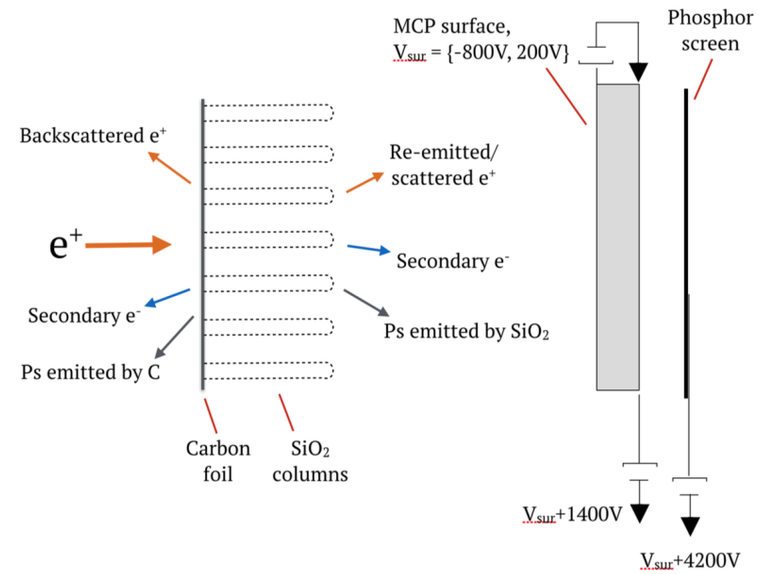

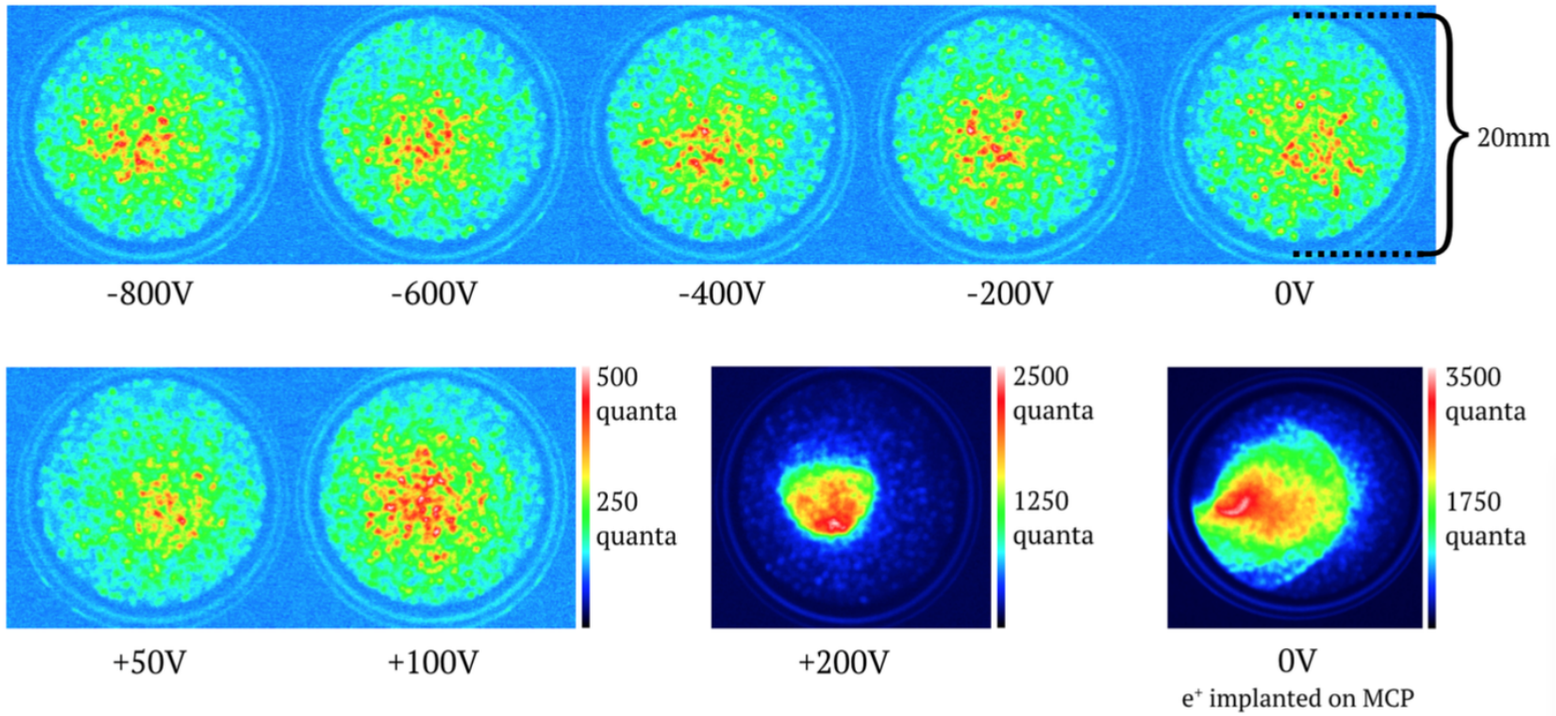

Based on intensity of image when implanting on the MCP; lower limit of ~10% of e^+ crossing the target

PS TRANSMISSION TARGET

1. SSPALS measurement (PbWO4)
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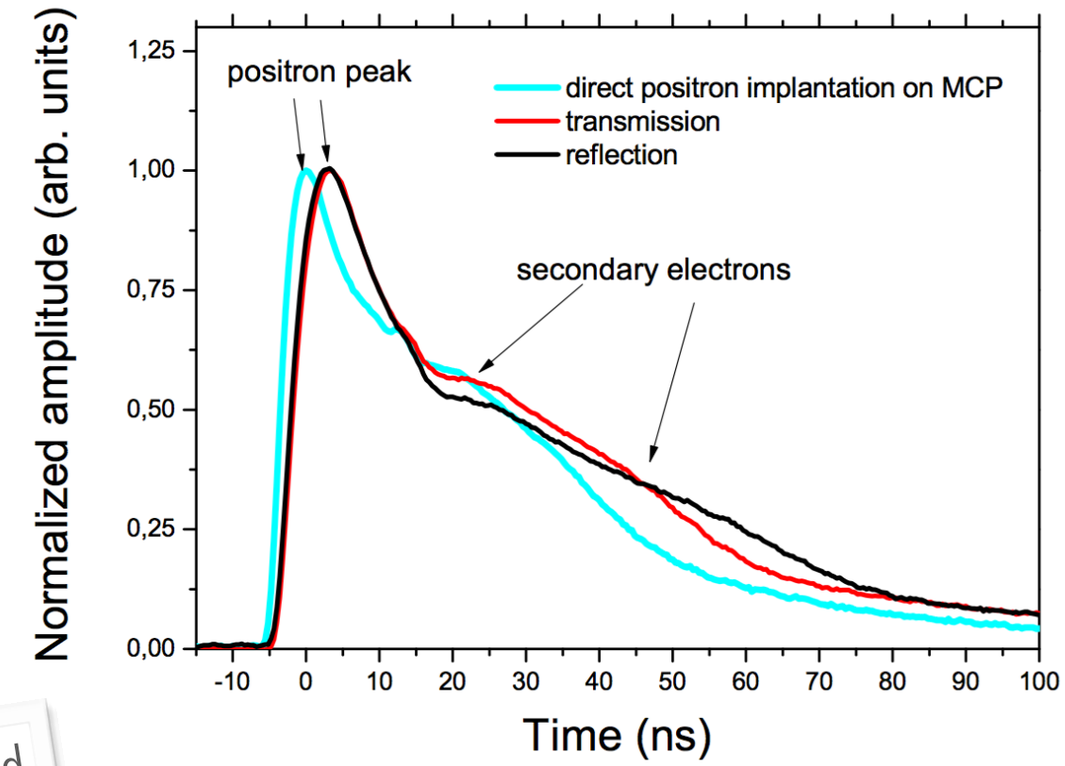
3. **Time of Flight measurement of forward-emitted particles (MCP–phosphor screen coupled to a fast PMT)**



fast e+ crossing the target with around 1 keV.

secondary electrons emitted with few eV

Must be deflected for the purpose of antihydrogen production: possible with a set of grids

Successful first tests, developments planned:

- **target design**
- **change of positron test chamber to facilitate measurements**