The AEGIS Experiment: Measuring the Free Fall of Antihydrogen

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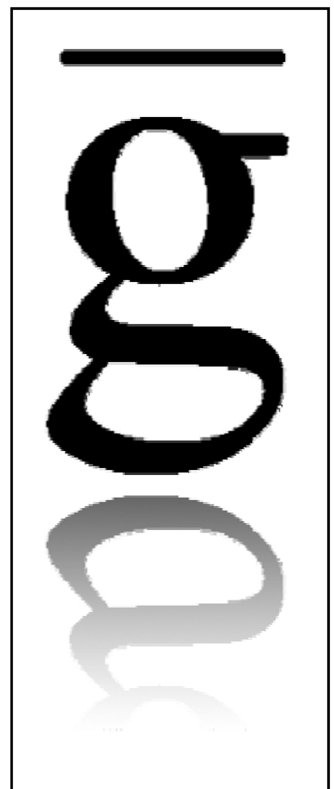


"If there is negative electricity, why not negative gold, as yellow and valuable as our own, [...] different only in so far that if brought down to us it would rise up into space with an acceleration of 981 [cm/s^2]."

Arthur Schuster, Nature **58** (1898) 367

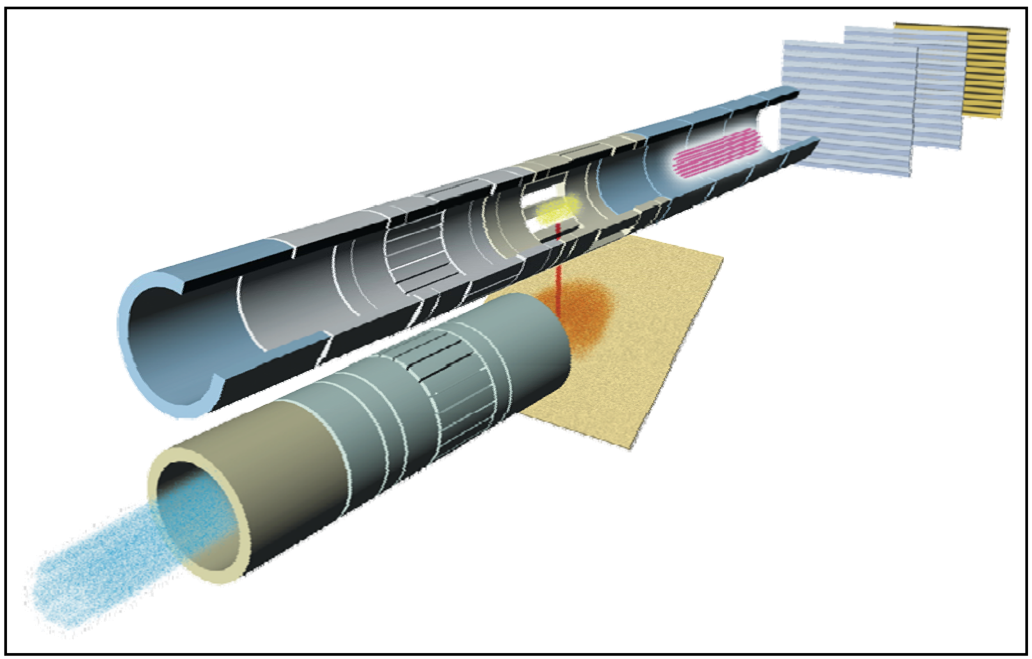
AEGIS

Antimatter Experiment: Gravity, Interferometry, Spectroscopy

- Main goal: First direct measurement of the effect of gravity on antimatter

  Measurement of *g* with 1% precision* on antihydrogen (10^5 $\bar{H}$)

- Requirements / challenges:
  - Production of a **bunched cold beam of antihydrogen** (100 mK)
  - Measurement of beam deflection by interferometry (10 µm drop over 1 m)



* Higher precision possible after future upgrade

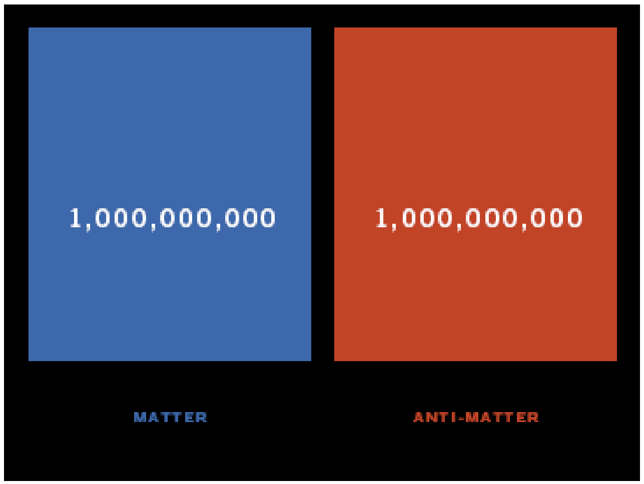
Outline

- Motivation
- AEGIS principle and main components
- Experimental sequence
- Status & outlook

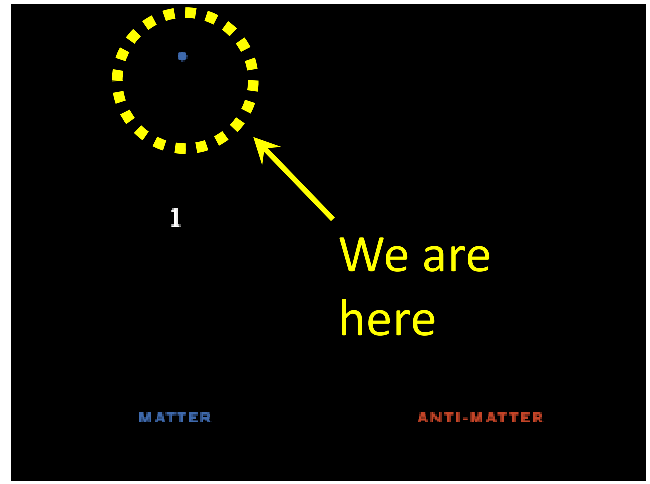
Where is the antimatter?

- Baryon asymmetry:

13.7 billion years ago:



Today:



$$\frac{n(B)-n(\overline{B})}{n(\gamma)} < 10^{-9}$$

$\Rightarrow$ Tiny deviation is responsible for the existence of all baryonic matter!

- Possible explanations:

1. Difference in matter/antimatter properties (CP or CPT violation)

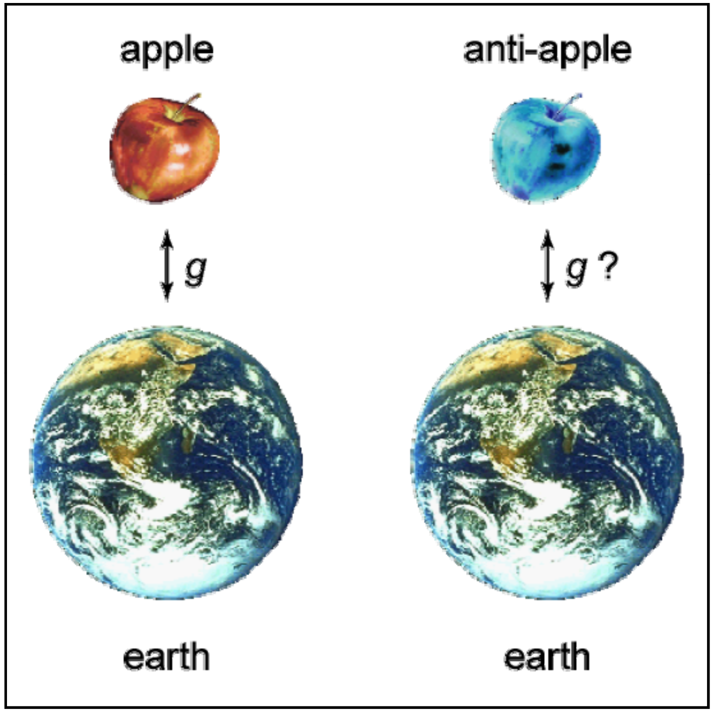
2. Anomalous gravitation, segregation in different parts of the universe

Antimatter gravity tests

- The effect of gravity on ordinary matter has been studied extensively
- Antimatter gravity has to this day never been investigated
  - Charged subatomic antiparticles are sensitive to electromagnetic stray fields
  - Neutral antimatter was previously not available
- Since 2002 copious amount of neutral antiatoms have been available

  [M. Amoretti *et al.*, Nature **419** (2002) 456;
  G. Gabrielse *et al.*, Phys. Rev. Lett. **89** (2002) 213401]
- Test of the Weak equivalence principle:

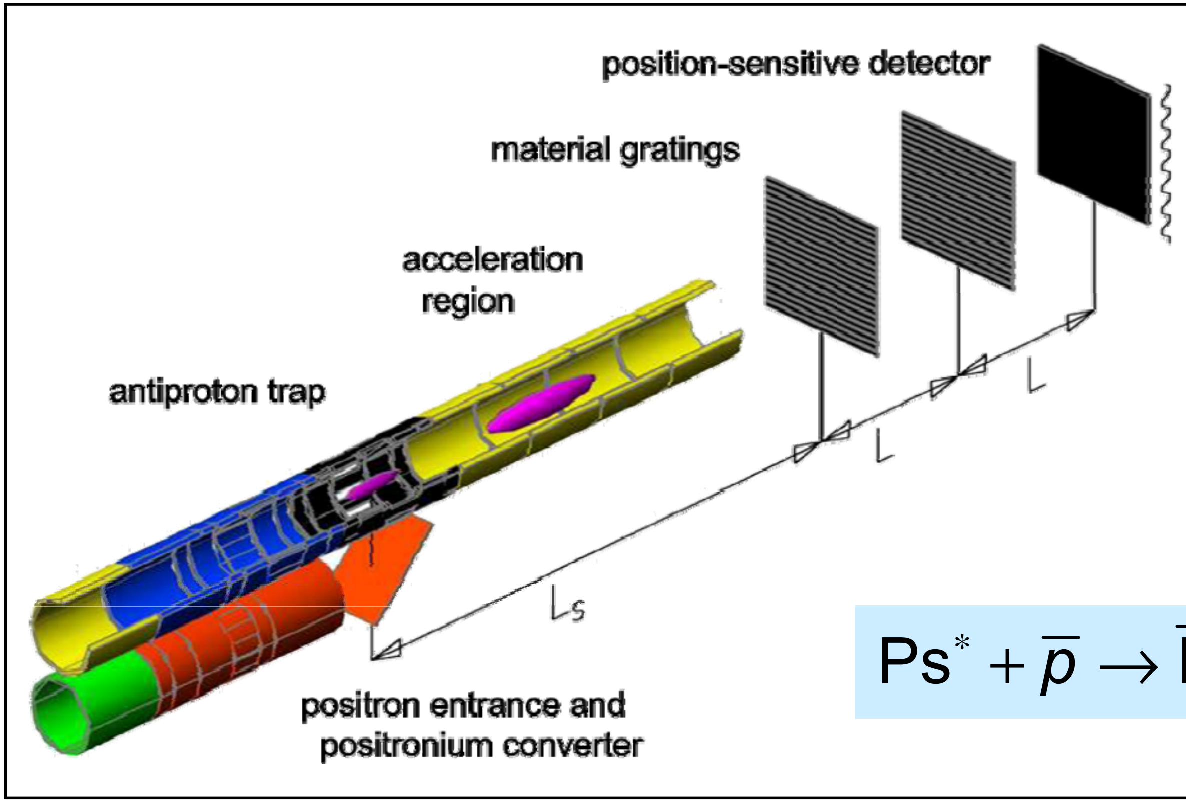
  "The trajectory of a falling test particle is independent of its composition."



$$\overline{m}_g \overset{?}{=} \overline{m}_i$$

AEGIS principle

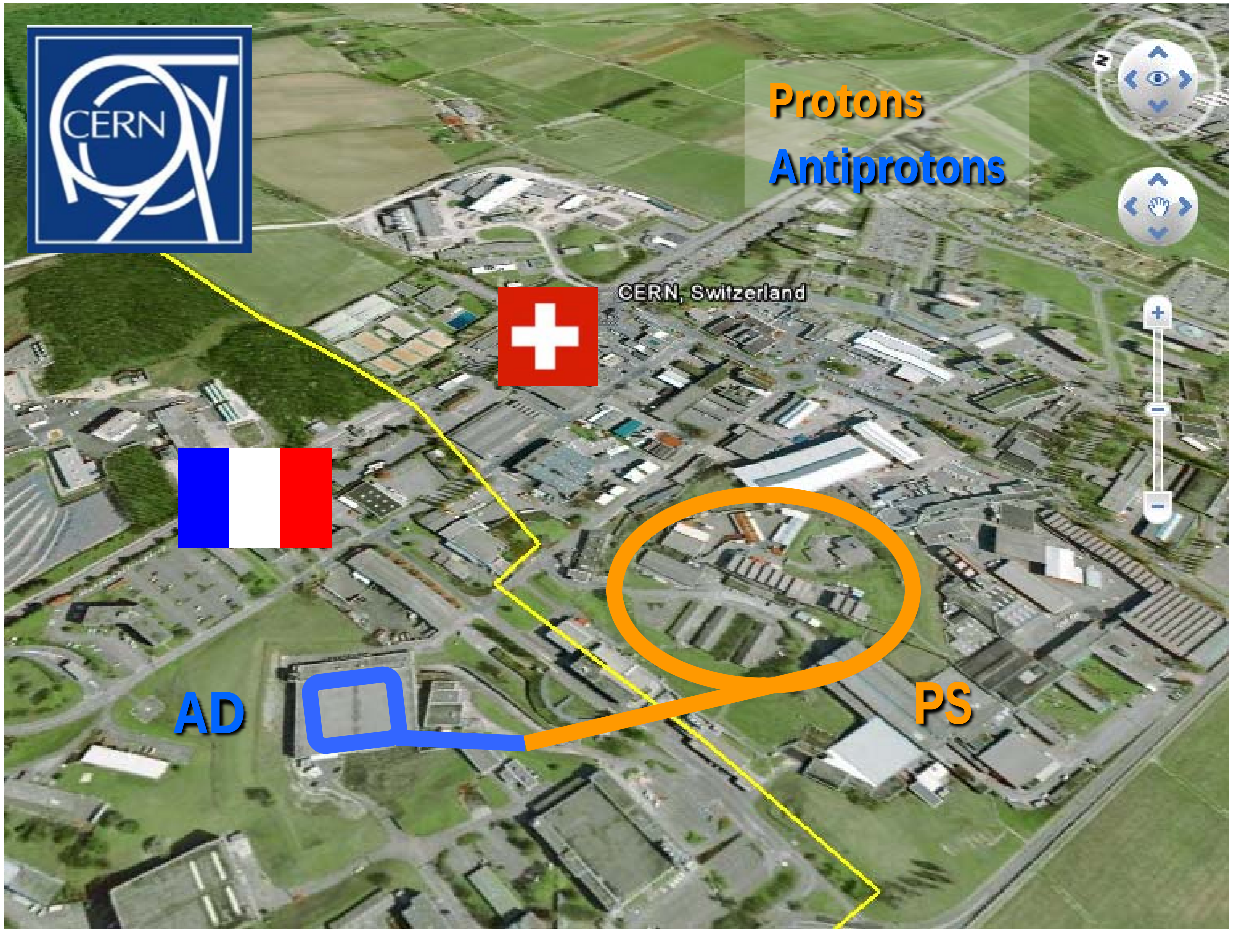
- AEGIS principle sketch:



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

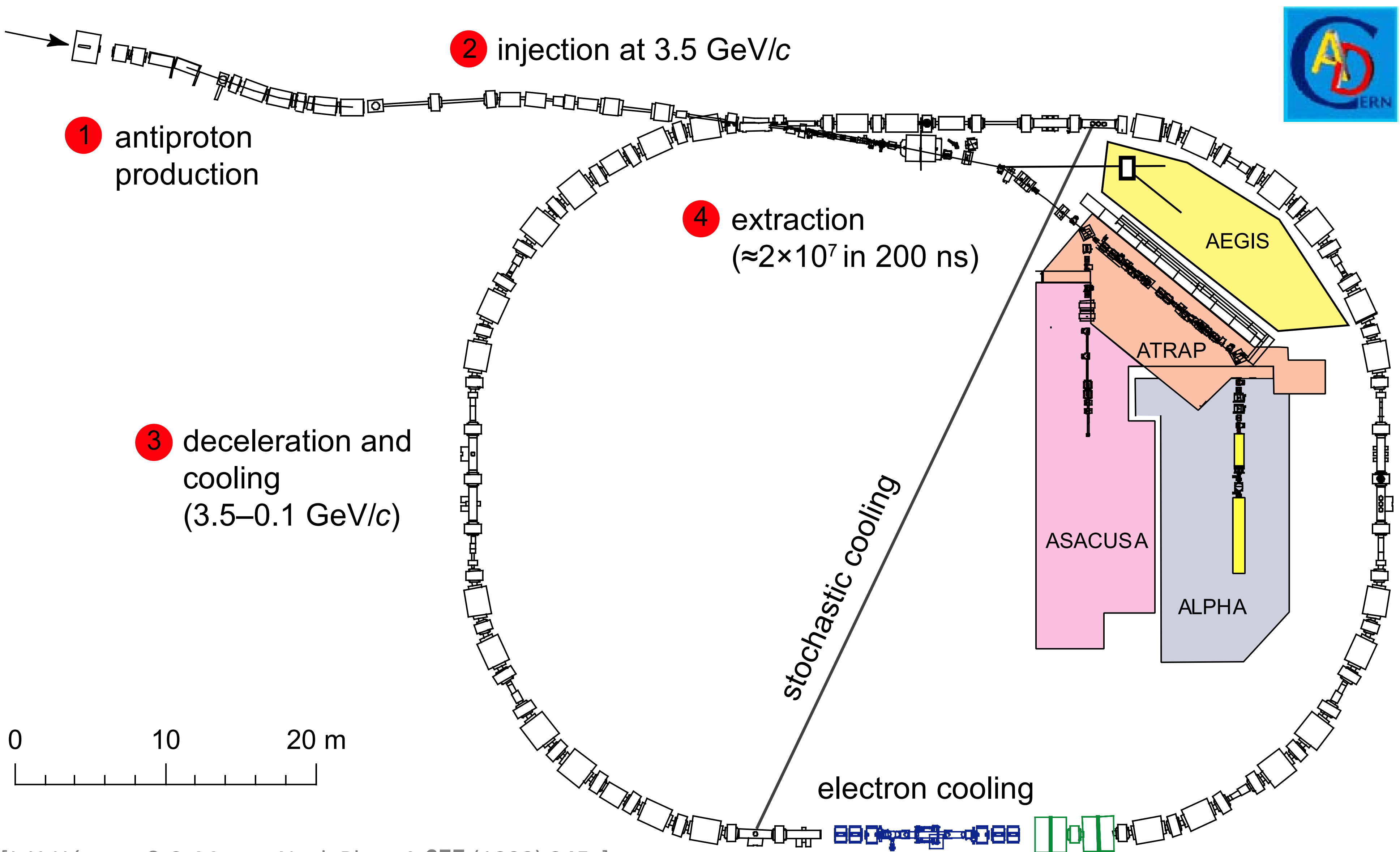
1) Antiproton capture & cooling
2) Positron production
3) Positronium conversion
4) Positronium excitation
5) Antihydrogen recombination
6) Antihydrogen beam formation
7) Gravity measurement
8) Data analysis

Antiproton Decelerator at CERN



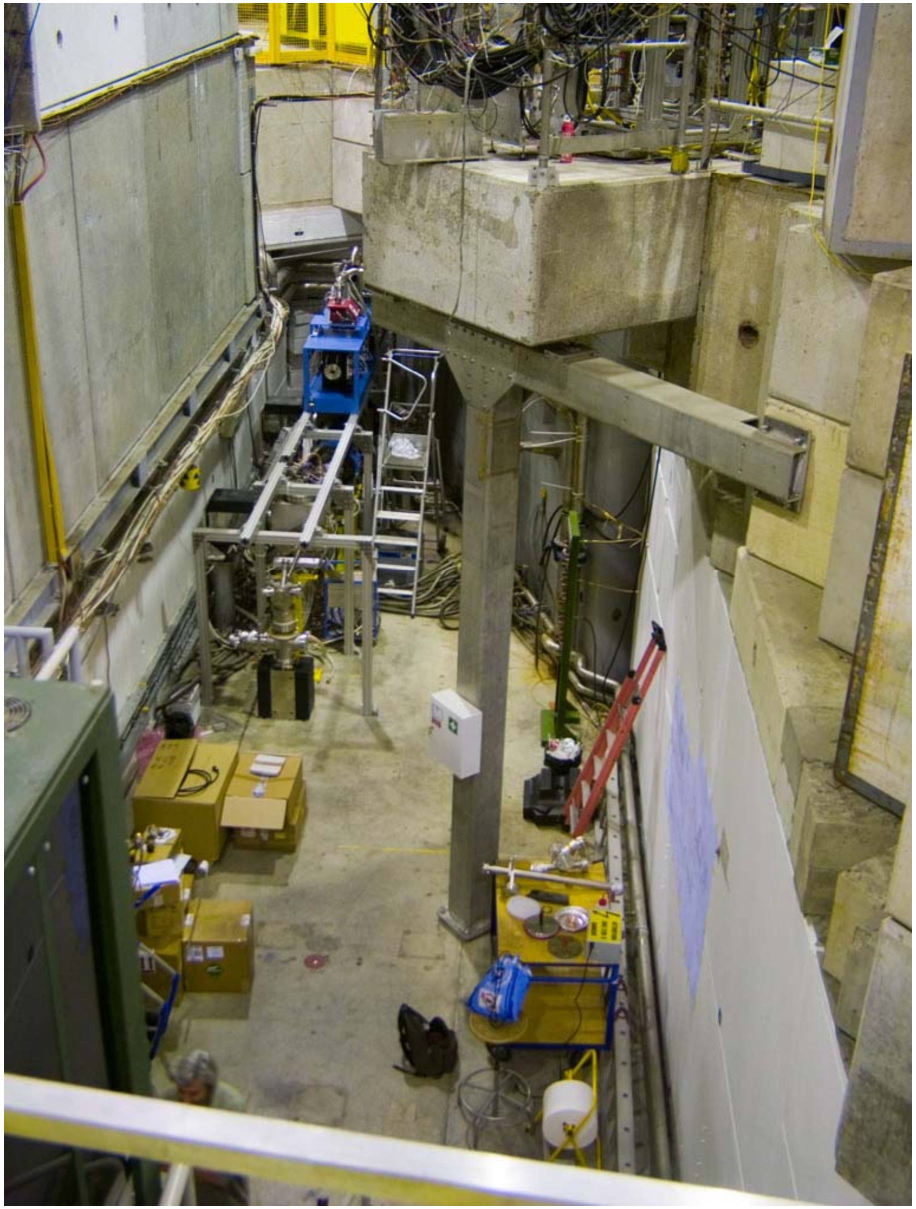
- 10^7 $\bar{p}$ produced every ≈ 90 s
- Deceleration
  p = 3.5 GeV/c $\rightarrow$ 100 MeV/c
- Fast extraction
  (200-ns bunches)

AEGIS at the AD



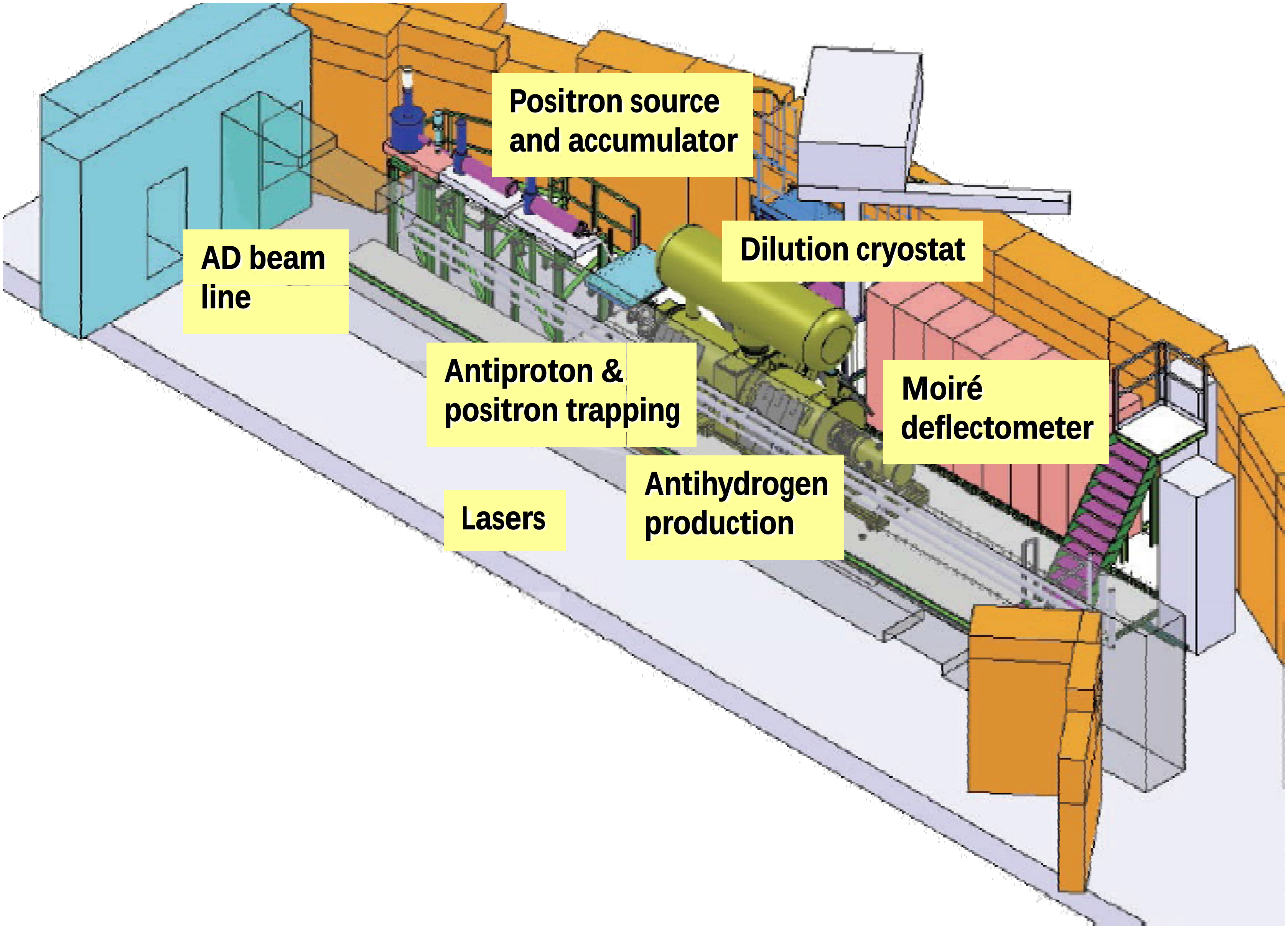
[J. Y. Hémery & S. Maury, Nucl. Phys. A **655** (1999) 345c]

AEGIS zone at the AD



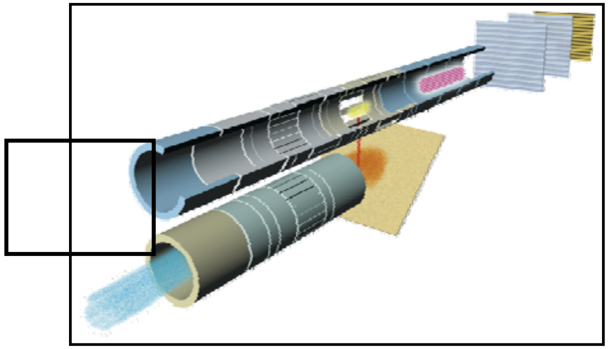
Status prior to installation of main components

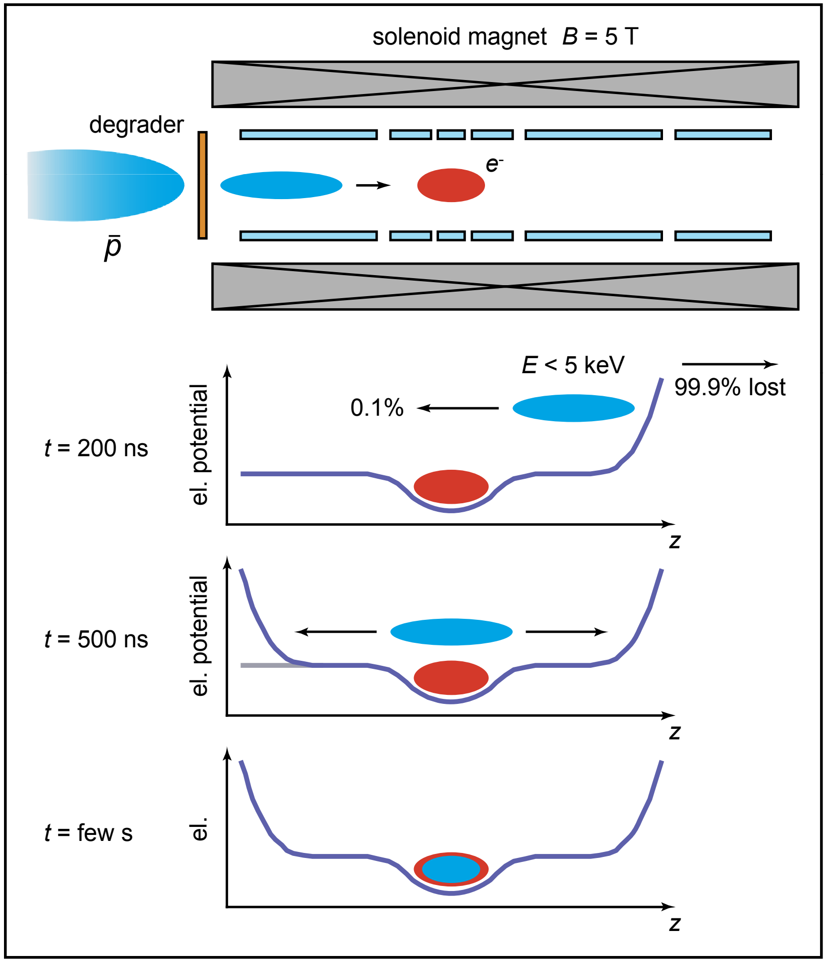
AEGIS overview sketch



1) Antiproton capture and cooling

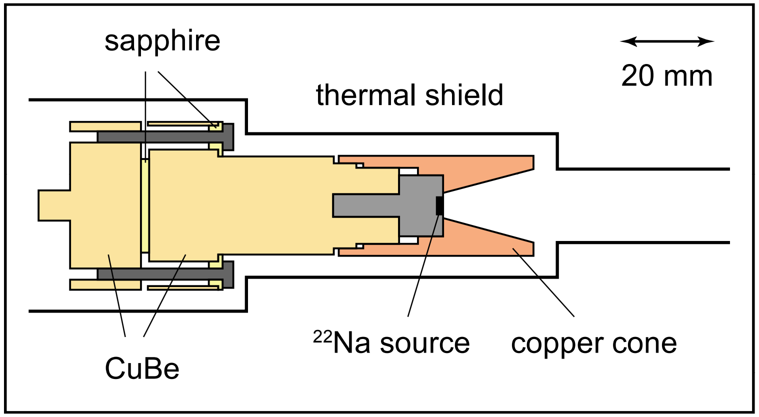
- Energy reduced by 50-µm Al degrader foil
- Trapping sequence:
  1. Trap is prepared with plasma of 10^8 cold electrons
  2. Small fraction of antiprotons with $E < 5$ keV is reflected
  3. Axial potential on entrance side is raised to trap $\bar{p}$
  4. Antiprotons are sympathetically cooled by electrons
- Transfer to 1-T trap, further cooling to 100 mK by a dilution refrigerator





> 10^4 antiprotons @ 100 mK

2) Positron production & accumulation



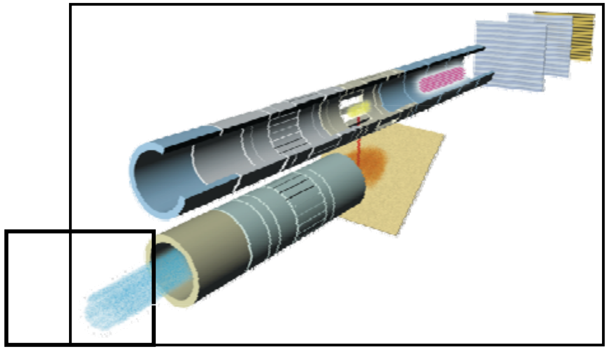
- Production from β^+ emitter:

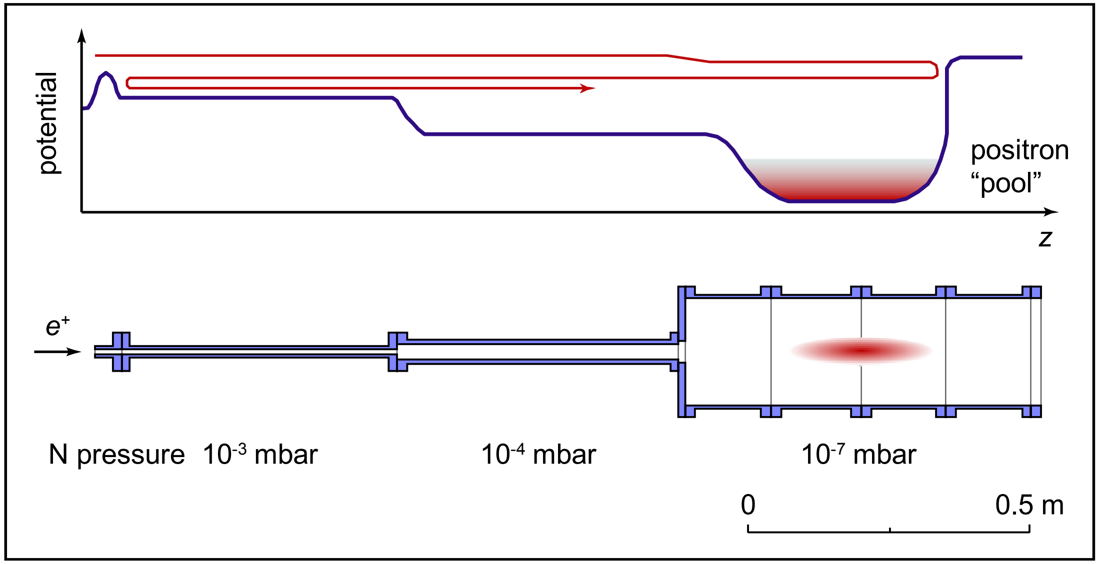
$$^{22}\text{Na} \rightarrow {}^{22}\text{Ne} + e^+ + \nu_e$$

≈ 1 GBq source

- Moderation to 50 eV in solid neon

- Trapping & cooling sequence:
  - Confinement in 0.14-T trap
  - Deceleration in N buffer gas
  - Accumulation in axial electric-field minimum



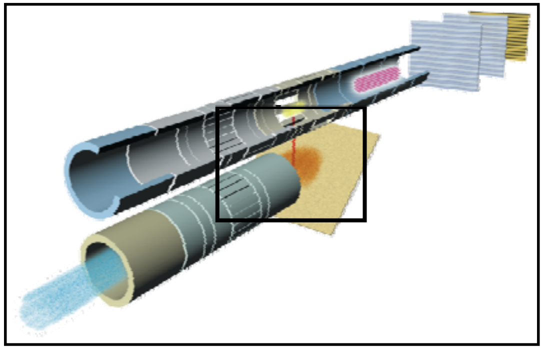


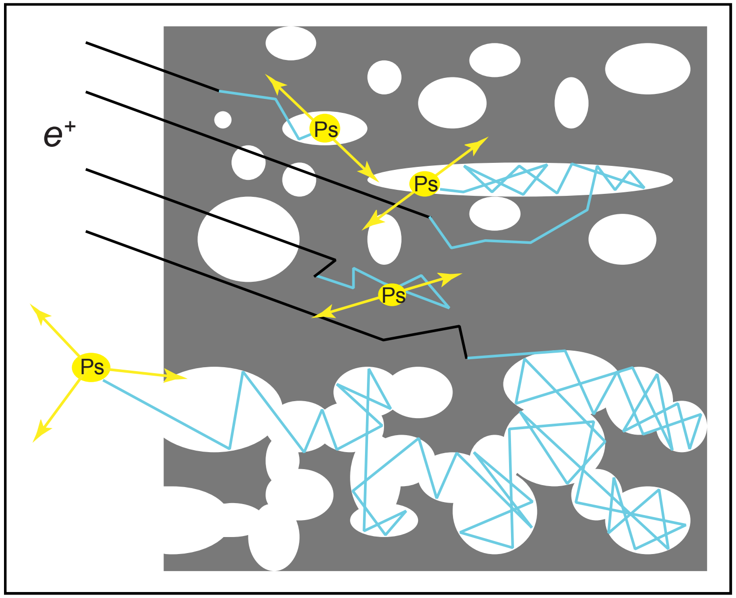
≈ 10^8 positrons every 200 s

[M. Amoretti *et al.*, Nucl. Instrum. Methods A **518** (2004) 679]

3) Positronium production

- Ps formation in nanoporous insulators:
  - Implanted positrons scatter off atoms and electrons, slow to eV in few ns
  - Positronium forms by capture of bound electrons or free electron from collisions
  - Positronium accumulates in voids due to reduced dielectric strength
  - If pores are fully interconnected, (almost) all ortho-Ps diffuses out of the film
- ortho-Ps yield and velocity distribution depend on
  - Converter material
  - Implantation depth (energy)
  - Target temperature
  - → up to 30% at 50 K





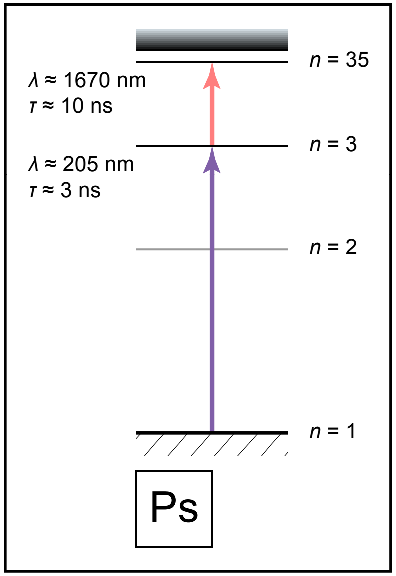
[D. W. Gidley *et al.*, Annu. Rev. Mater. Res. **36** (2006) 49]

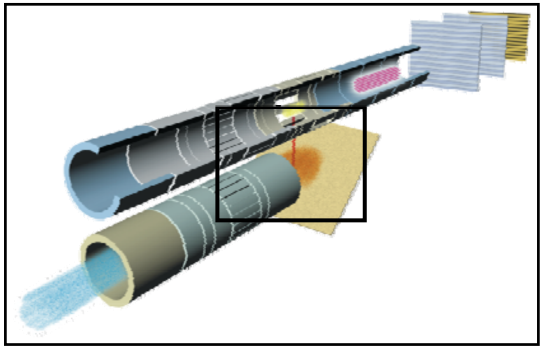
High-efficiency positronium converter

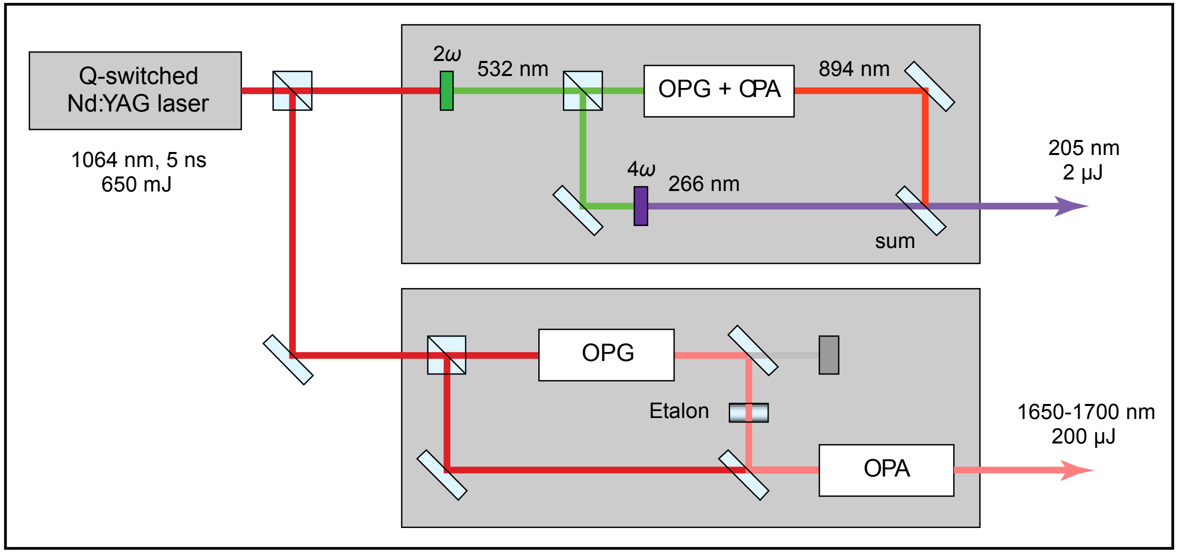
4) Positronium excitation

- Cross-section of Ps charge exchange reaction is enhanced for large *n*: $\sigma \approx a_0 n^4$
- Two-step excitation $n = 3 \rightarrow$ Rydberg

  Excitation efficiency ≈ 30%
- Requirements
  - Bandwidth matched to broadened Rydberg levels
  - Sufficient power to excite Ps cloud within few ns
  - Beam tailored to geometry of expanding cloud
- AEGIS laser system:







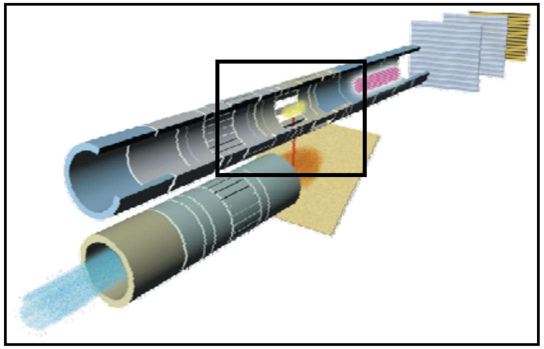
5) Antihydrogen recombination

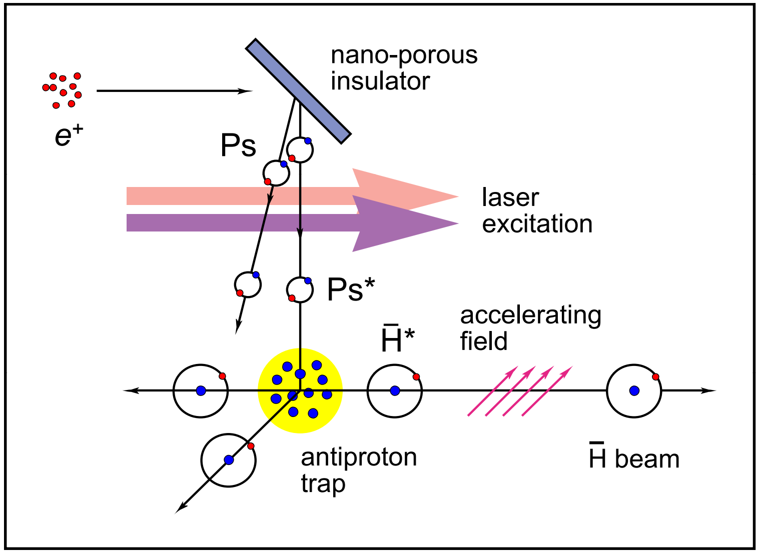
- Charge exchange reaction:

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

- Principle demonstrated by ATRAP
  Cs* → Ps* → $\bar{\mathrm{H}}$*
  [C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]

- Advantages:
  - Large cross-section: $\sigma \approx a_0 n^4$
  - Pulsed production
  - Narrow and well-defined $\bar{\mathrm{H}}$ *n*-state distribution





- Antiproton temperature essentially determines antihydrogen temperature:

At $T(\bar{p})$ = 100 mK, n_{Ps} = 35
⇒ $T(\bar{\mathrm{H}}) \approx$ 120 mK

⇒ cold / ultracold $\bar{\mathrm{H}}$

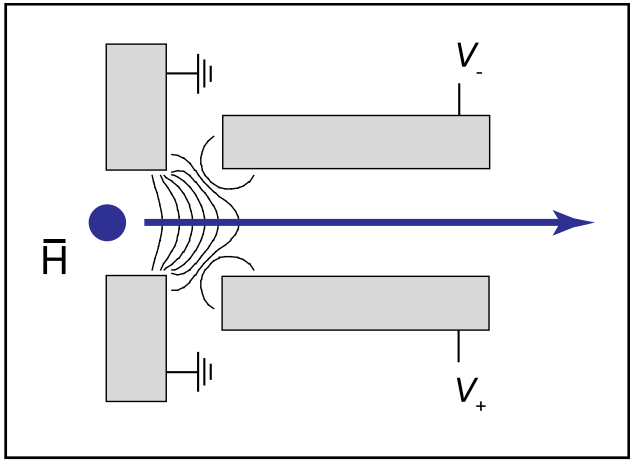
6) Antihydrogen beam formation

- Electric field gradients exert force on electric dipole moments of neutral atoms:

$$U = \frac{2}{3} e a_0 \boxed{n(n-1)} F$$

$$\boldsymbol{F} = -\frac{2}{3} e a_0 \boxed{n(n-1)} \nabla F$$

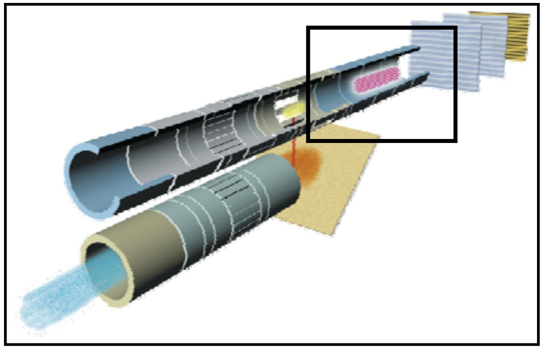
(max. induced dipole)



$\Rightarrow$ Rydberg atoms are very sensitive to inhomogeneous electric fields

- Stark deceleration of hydrogen demonstrated (ETH group):

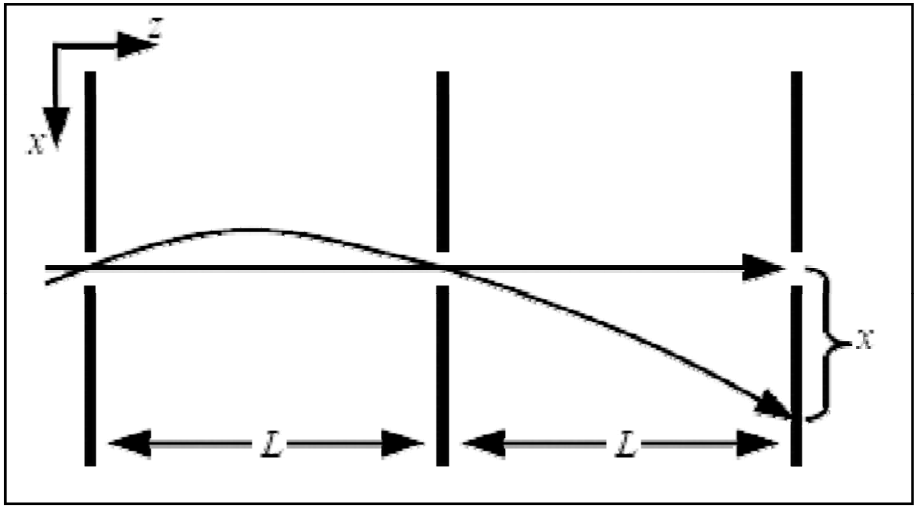
[E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241]



– n = 22,23,24
– Accelerations of up to 2×10^8 m/s^2 achieved
– Hydrogen beam at 700 m/s can be stopped in 5 µs over only 1.8 mm

7) Gravity measurement

- Measuring forces:



– Vertical deflection:

$\delta x \approx -10\ \mu m$

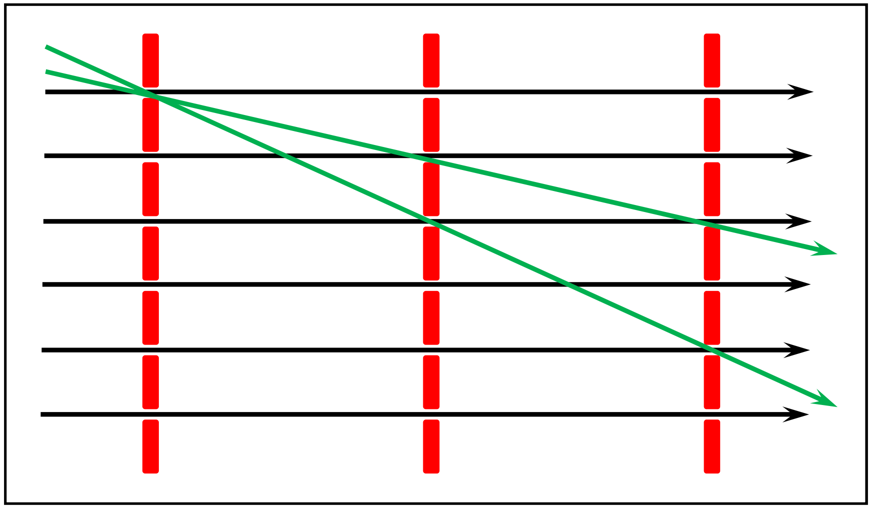
– Vertical beam extent:

$\Delta x \approx 5.8\ cm$

(Antihydrogen beam at 100 mK, accelerated to 500 ms^{-1})

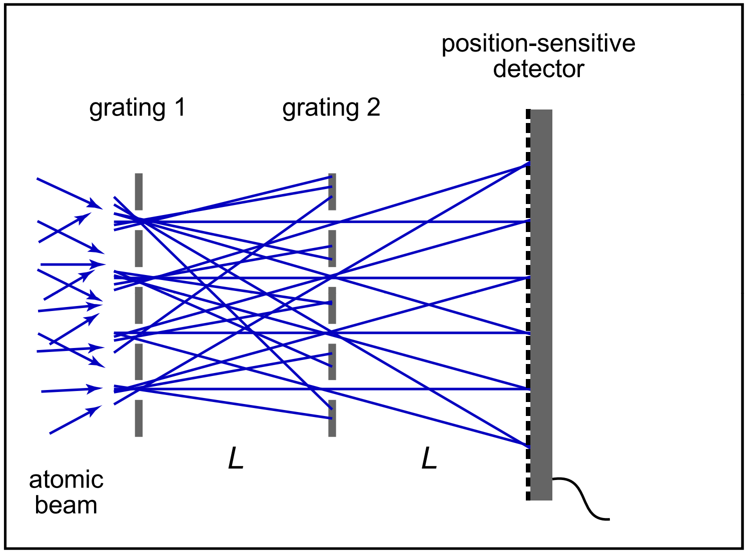
- Improve transmission by increasing number of slits:

$N \times N/2$

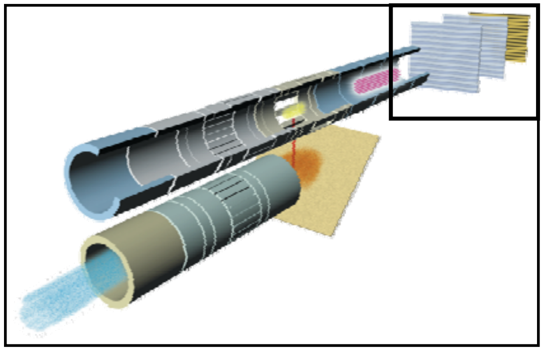


7) Gravity measurement

- Moiré deflectometer:

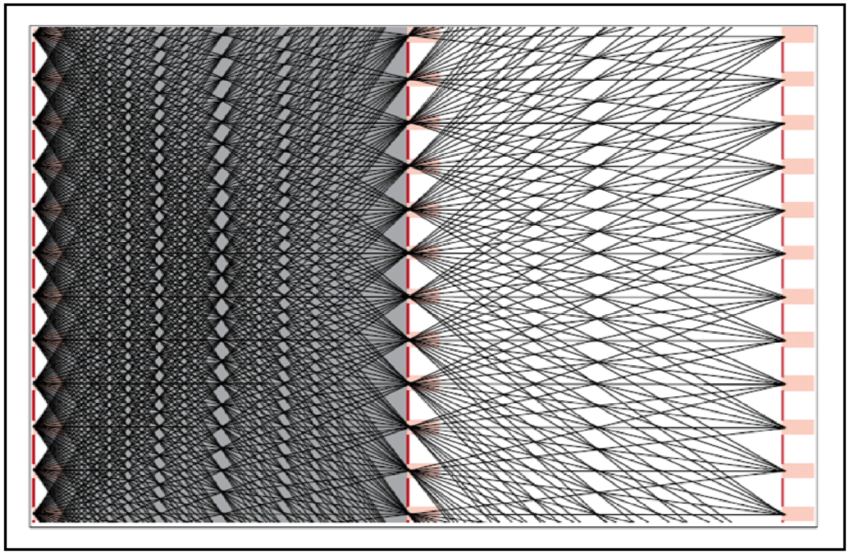


Position-sensitive detector enhances transmission by factor ≈ 3

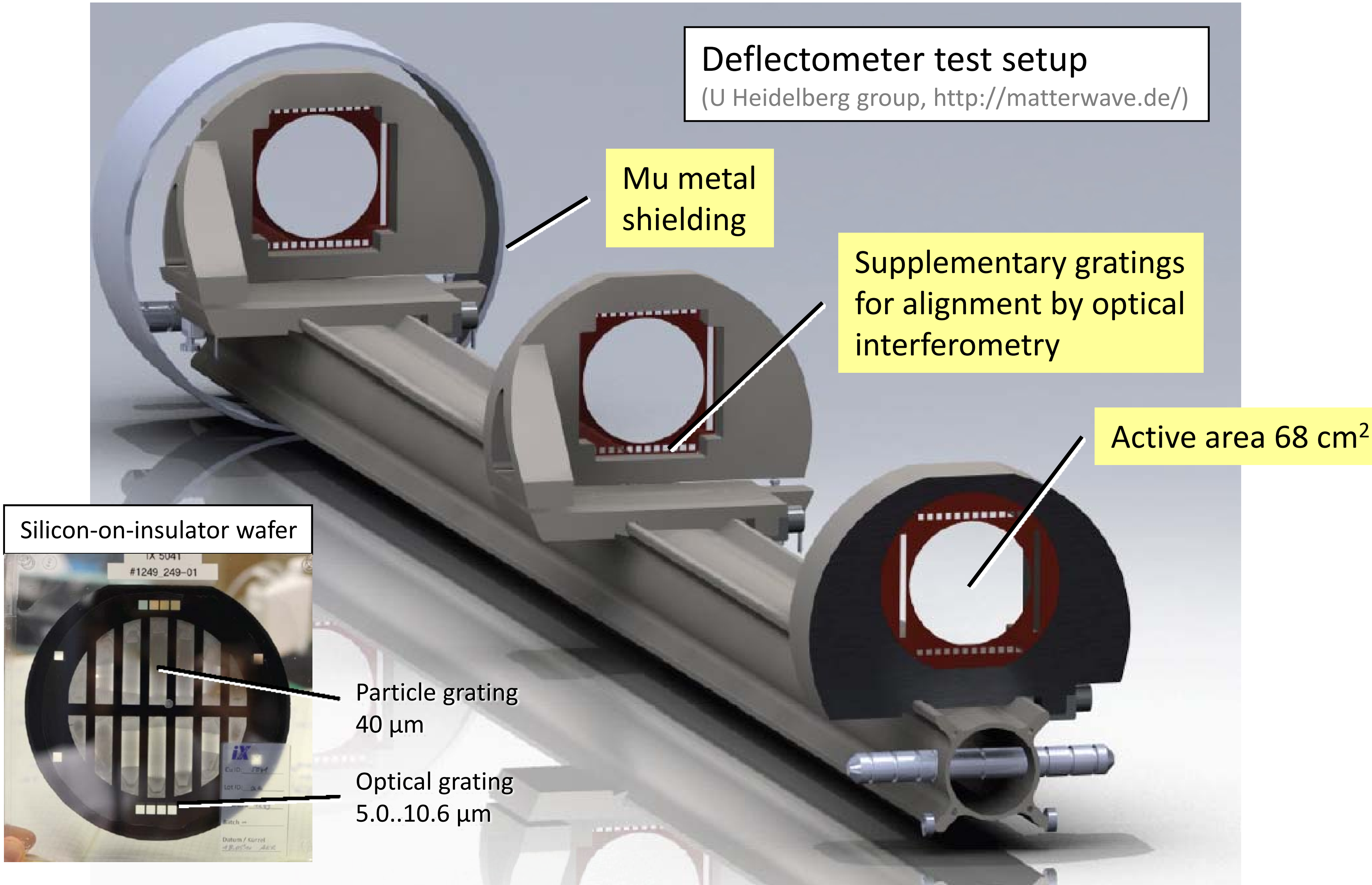


- Classical counterpart of Mach-Zehnder interferometer
- Two gratings create fringe pattern on third grating
- Successfully used for gravity measurement on Ar atoms, $\sigma(g)/g = 2\times10^{-4}$

[M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]



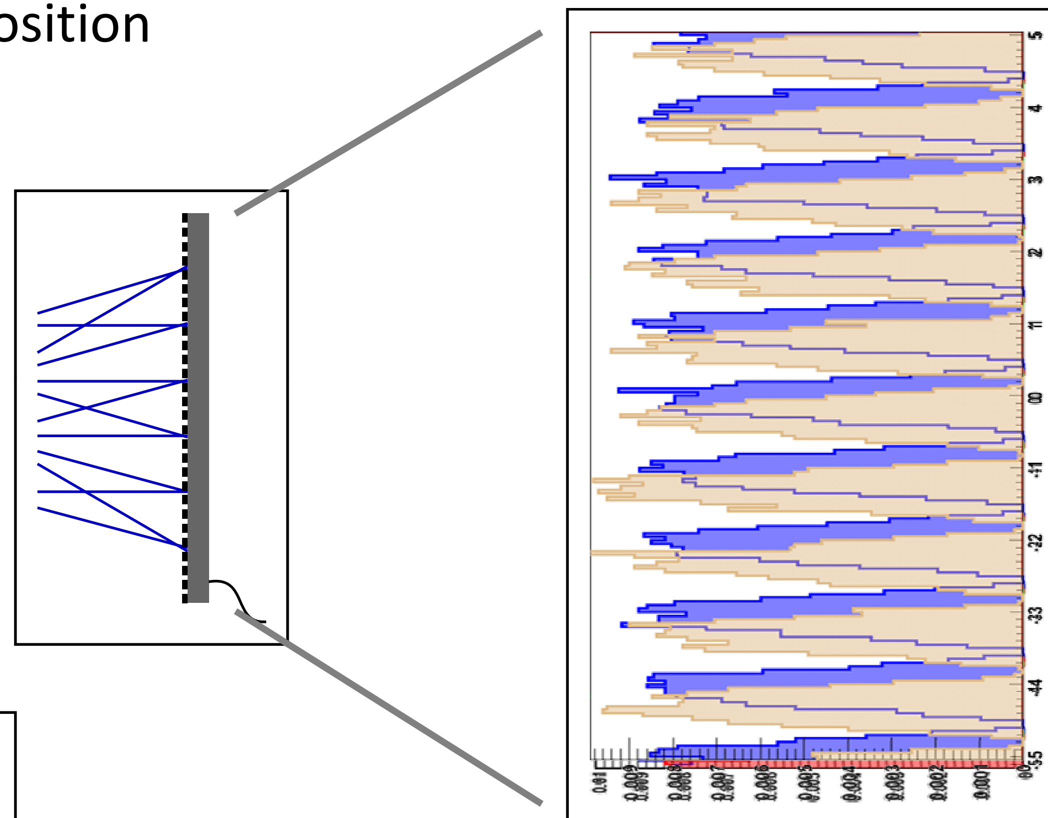
7) Gravity measurement



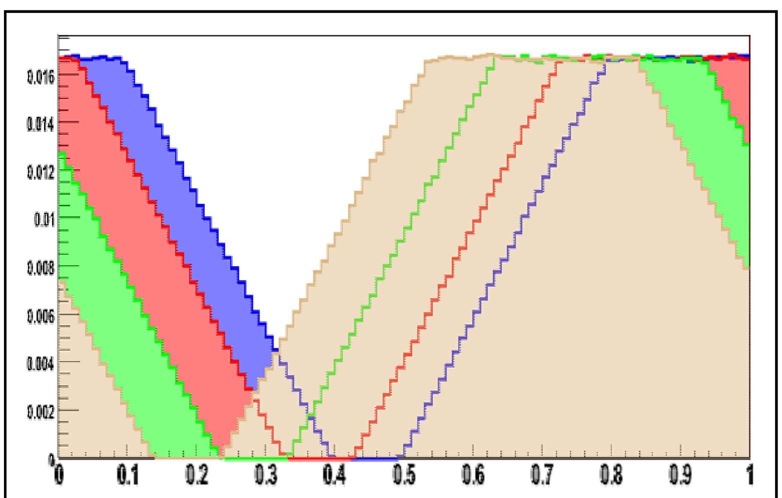
8) Data analysis

- Detection of vertical annihilation position as a function of TOF / velocity:

$$\delta x = -g\left(\frac{L}{v}\right)^2$$



- Binning modulo grating period:

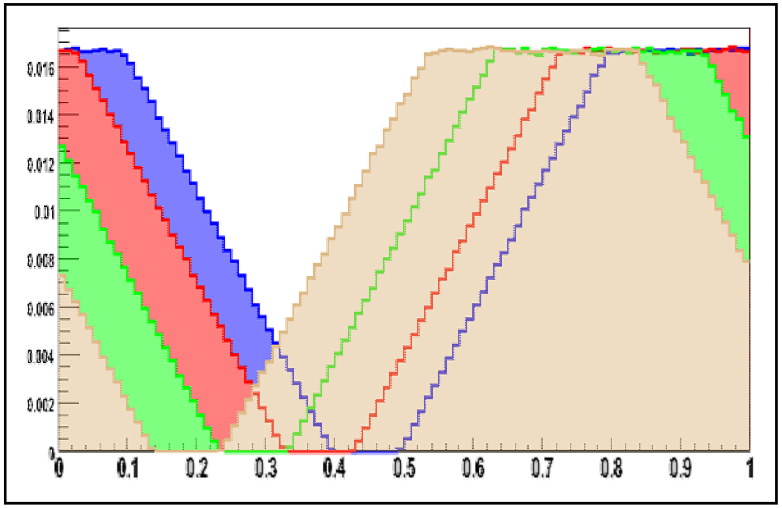


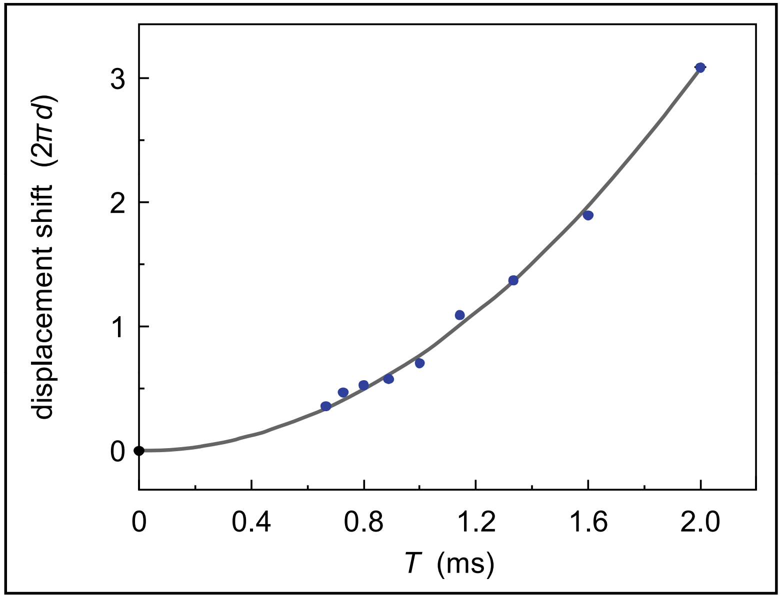
v_{beam} = 600, 400, 300, 250 m/s

(Monte Carlo simulation)

8) Data analysis

- Extraction of acceleration *g*:

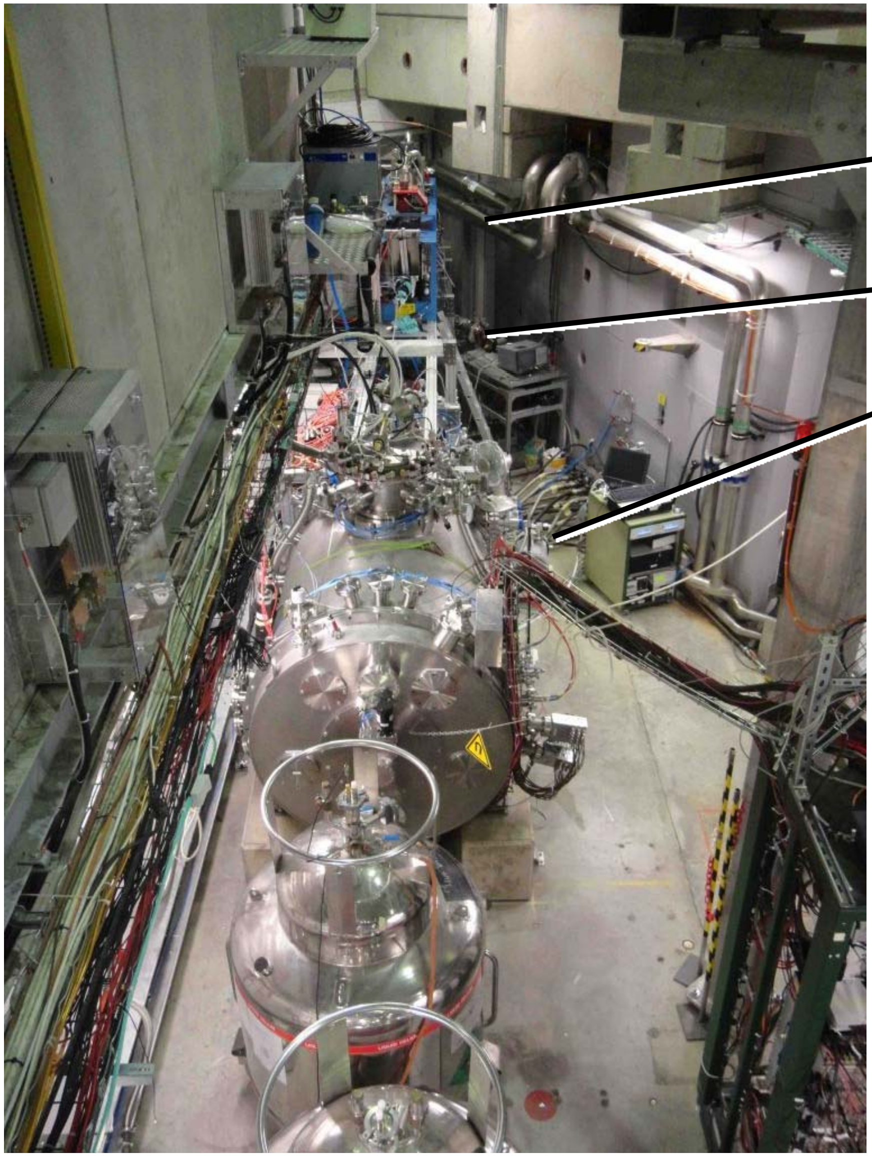




Measurement of *g* to 1%:
- ≈ 10^5 $\bar{\mathrm{H}}$ atoms at 100 mK
- 2 weeks of beam time
- 1 Hz event rate

$$\delta x = -gT^2$$

Status of AEGIS apparatus

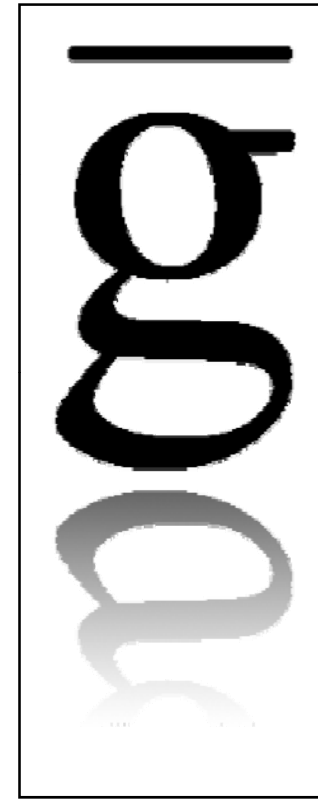


- Completed components:
  - Positron source, rare-gas moderator, trap and accumulator
  - AD beam line and diagnostics
  - 5-T magnet and trap
  - Laser system
  - 1-T magnet
- Components under design/construction:
  - Dilution cryostat: design completed, delivery 2012
  - Moiré deflectometer: prototype being tested in Heidelberg
  - Position-sensitive detector: tests with prototype by summer 2012
  - Antihydrogen detector: design completed, assembly by summer 2012
  - 1-T Penning traps: being designed

Conclusions & outlook

- The effect of gravity on antimatter has never been measured
- Depending on the chosen model, effect could be nil or dramatic
- The AEGIS experiment intends to measure *g* of antihydrogen to (initially) 1% precision
- Construction of AEGIS apparatus ongoing
- Schedule:
  - 2012: $\bar{p}$ capture, cooling and transfer; e^+ capture, accumulation and transfer; Ps formation and excitation; $\bar{\mathrm{H}}$ formation and acceleration
  - 2014: First antimatter gravity experiment

Done Done Done



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