Testing the Weak Equivalence Principle with Antimatter

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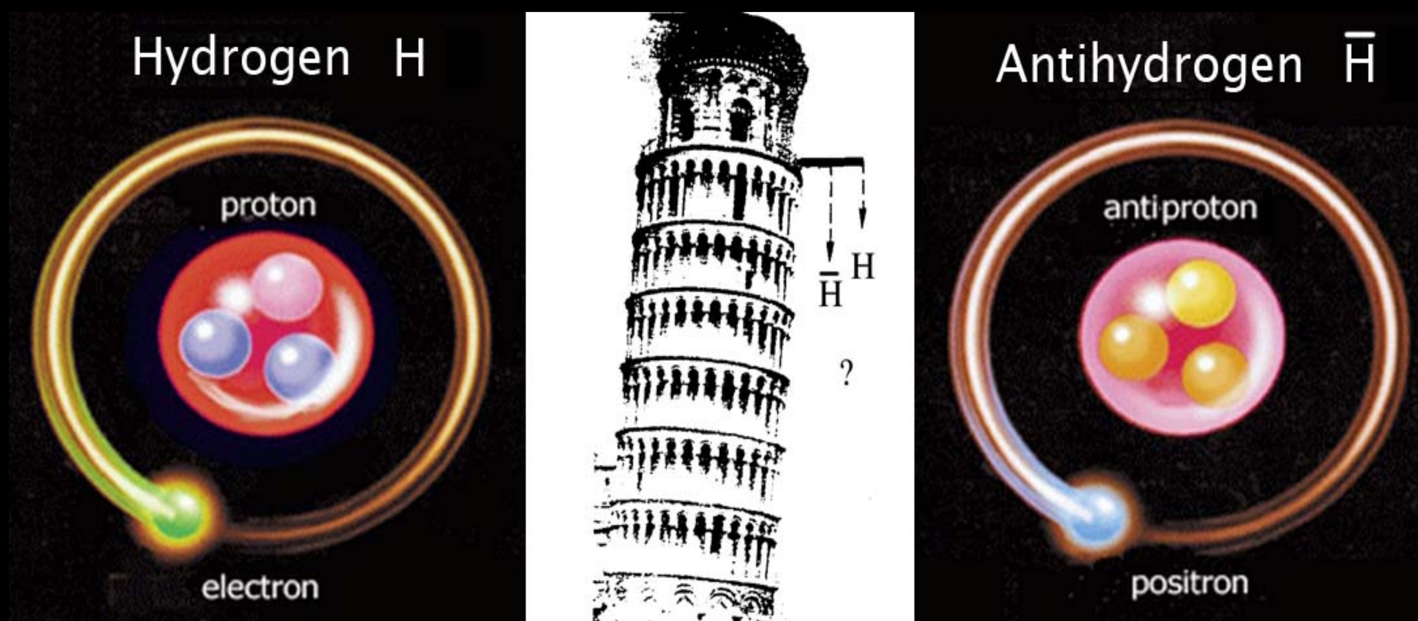


AEḡIS: Antimatter Experiment: Gravity, Interferometry, Spectroscopy

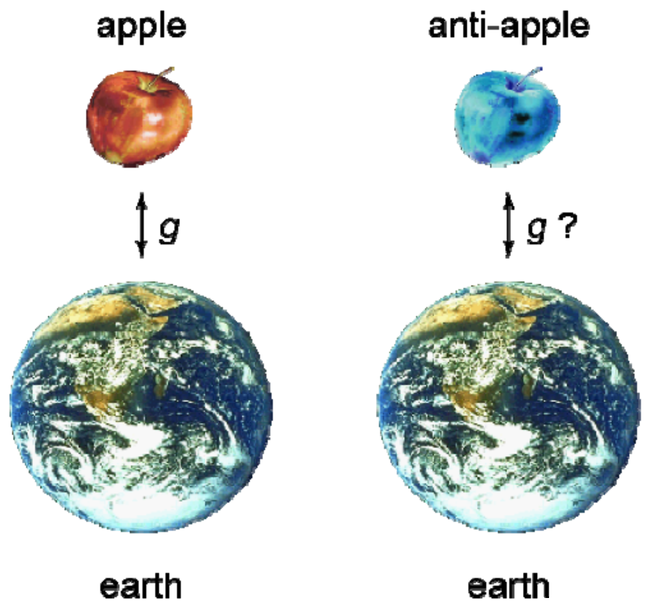
- Main goal: Measurement of g with a few percent* precision on antihydrogen

  * (initially)

- Proposed in 1997 by Tom Phillips

  [T. J. Phillips, Hyp. Int. **109** (1997) 357]

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



Outline

- Motivation / Prospects for anti-gravity
- AEGIS principle and setup
- Current status
- Conclusions and outlook

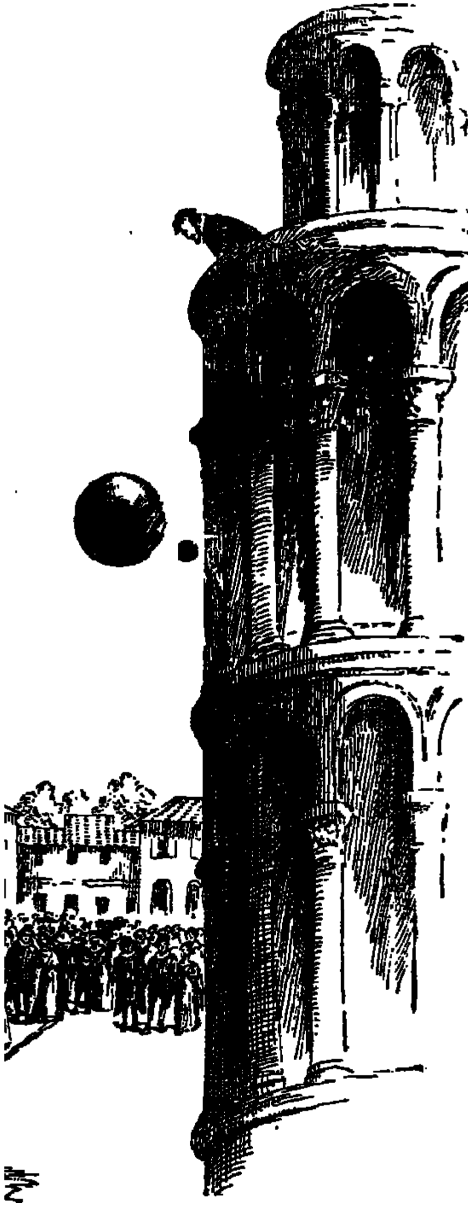
Motivation

- **Weak equivalence principle (WEP):**

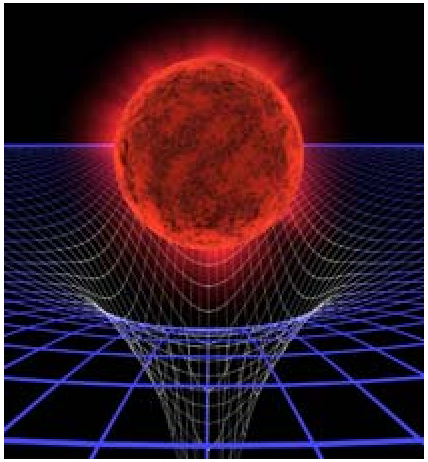
  "In a uniform gravitational field all objects fall with the same acceleration, regardless of their composition."

- WEP extremely well tested with matter, but never with antimatter
- electric charge of subatomic particles

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

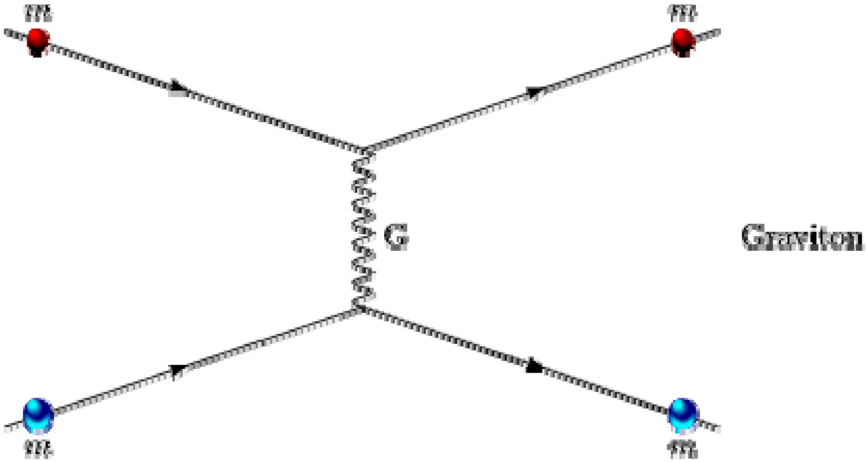


Motivation



[http://physics.usu.edu/htm/research/field-theory]

- Gravity is the only force **not** described by a quantum field theory
- QFT formulations of gravity open the way for
  - Non-Newtonian gravity
  - WEP violation
  - Fifth forces etc.



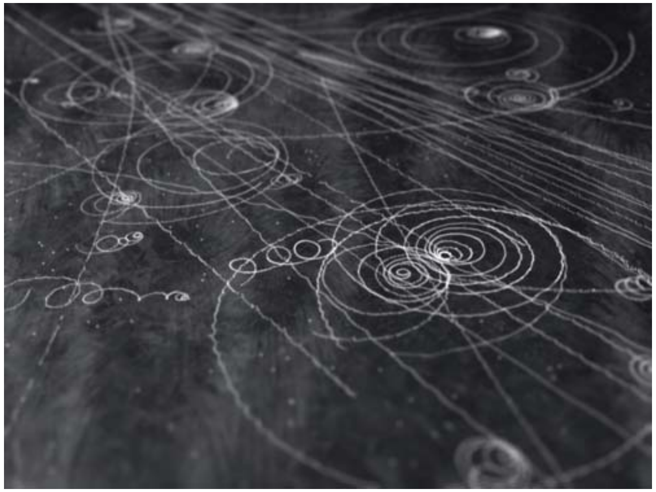
[http://uni-ka.the-jens.de/html/exphys2/exse1.htm#x4-100001.1.4]

- Since 2002 copious amount of neutral antiatoms have become available

[M. Amoretti *et al.*, Nature **419** (2002) 456;
G. Gabrielse *et al.*, Phys. Rev. Lett. **89** (2002) 213401]

Antimatter

- 1928 Paul Dirac predictes antimatter
- 1932 Carl Anderson discovers
  the positron in cosmic rays



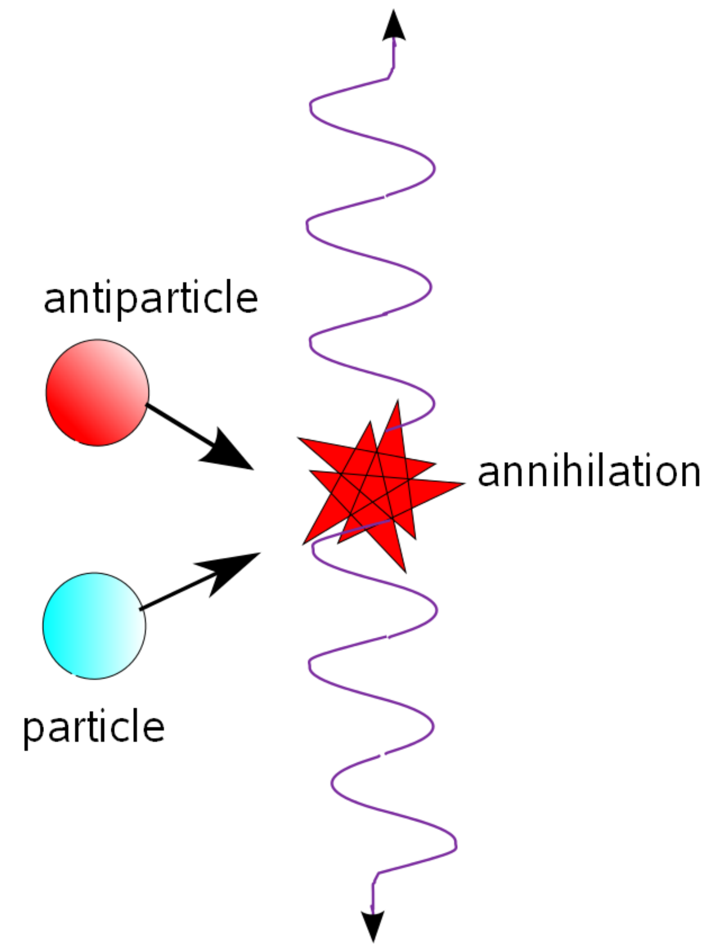
- 1955 Owen Chamberlain et al. publish
  “Observation of antiprotons ”
- 1956 discovery of antineutrons
- 2002 first production of cold antihydrogen atoms
- 2011 first storage of antiatoms for 1000 s

Antimatter

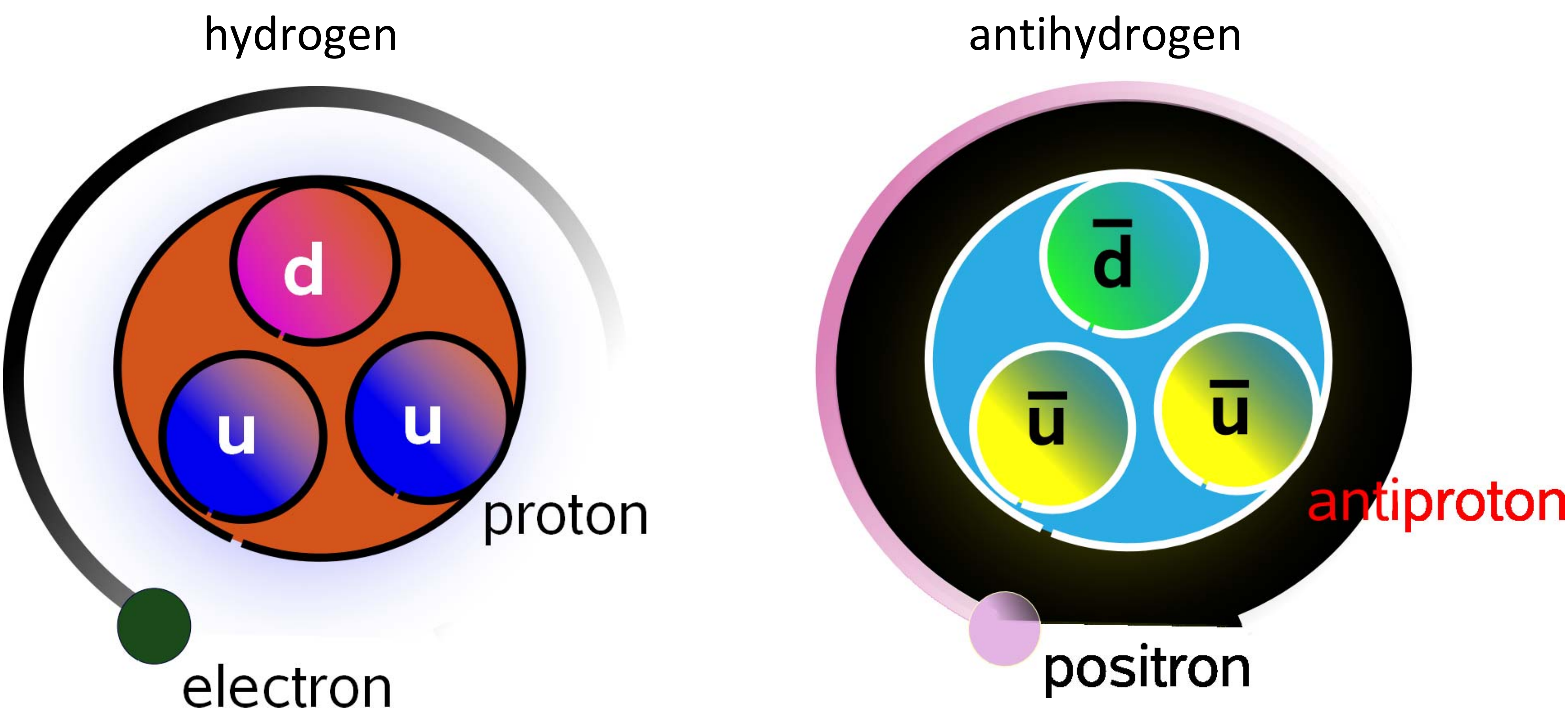
- When matter and antimatter collide particles anihilate

- **CPT theorem by W. Pauli:** *"Every canonical quantum field theory is invariant under simultaneous inversion of charge, parity, and time."*

- Antimatter perfect mirror image of matter



Antihydrogen



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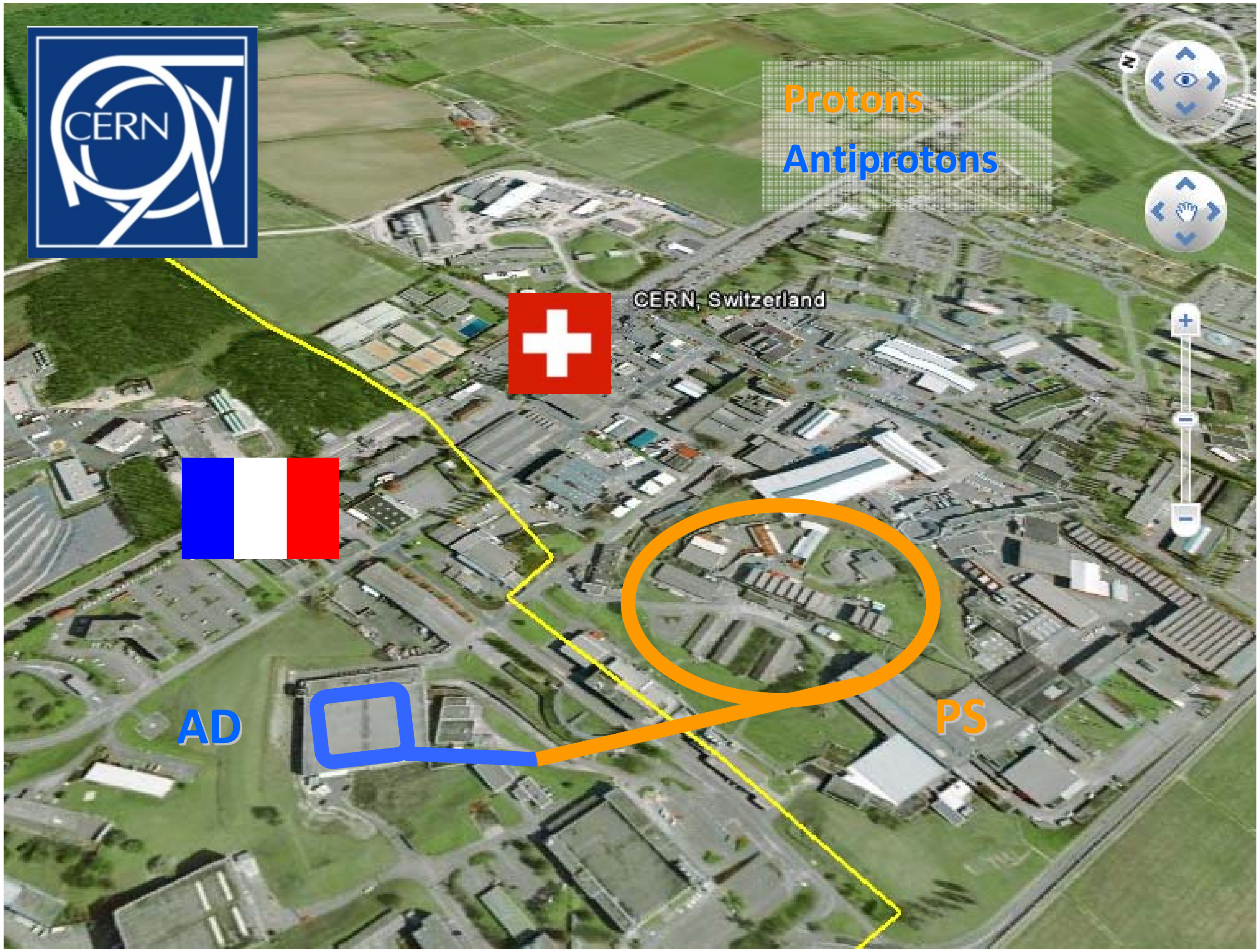
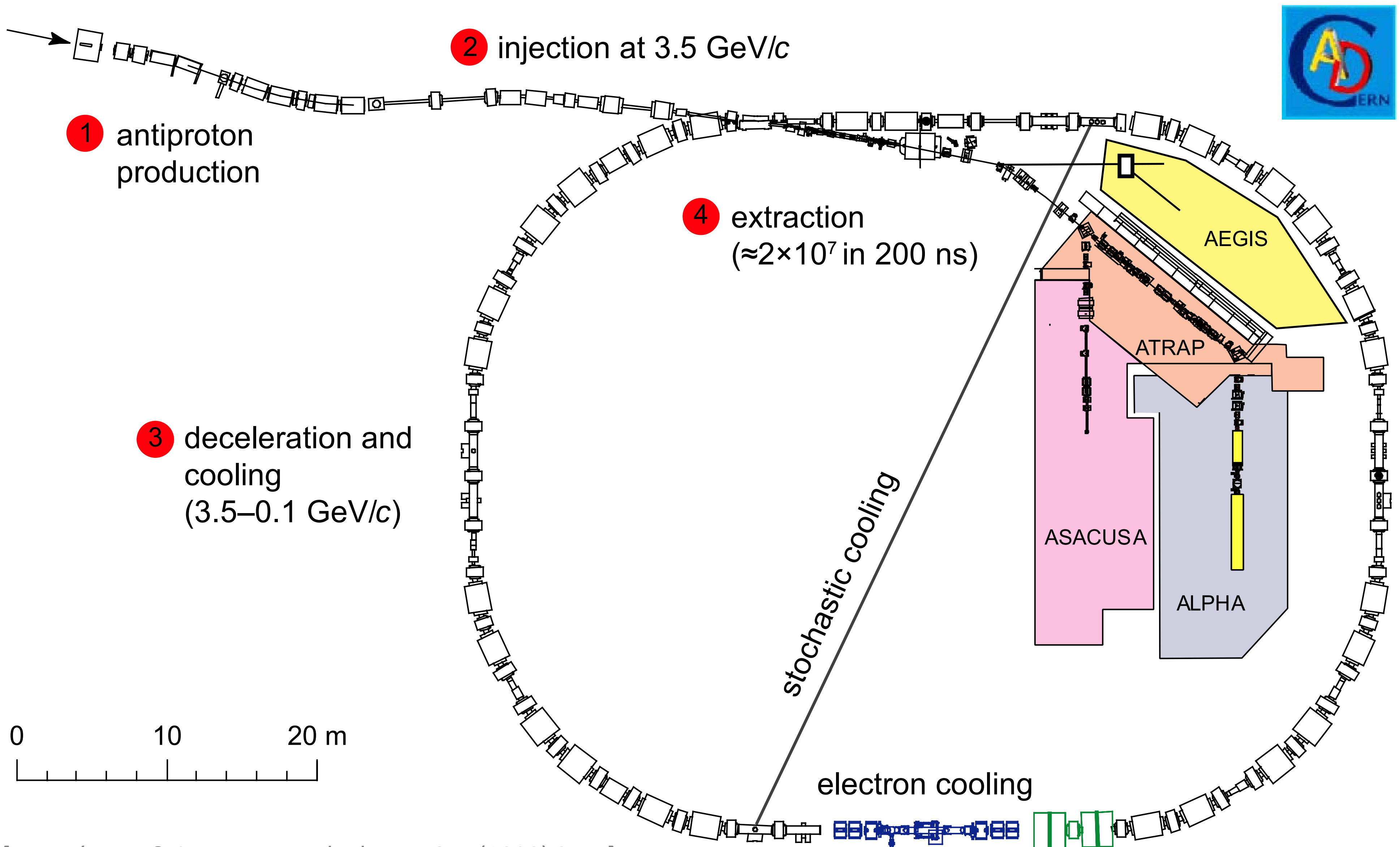
Antiproton Decelerator at CERN



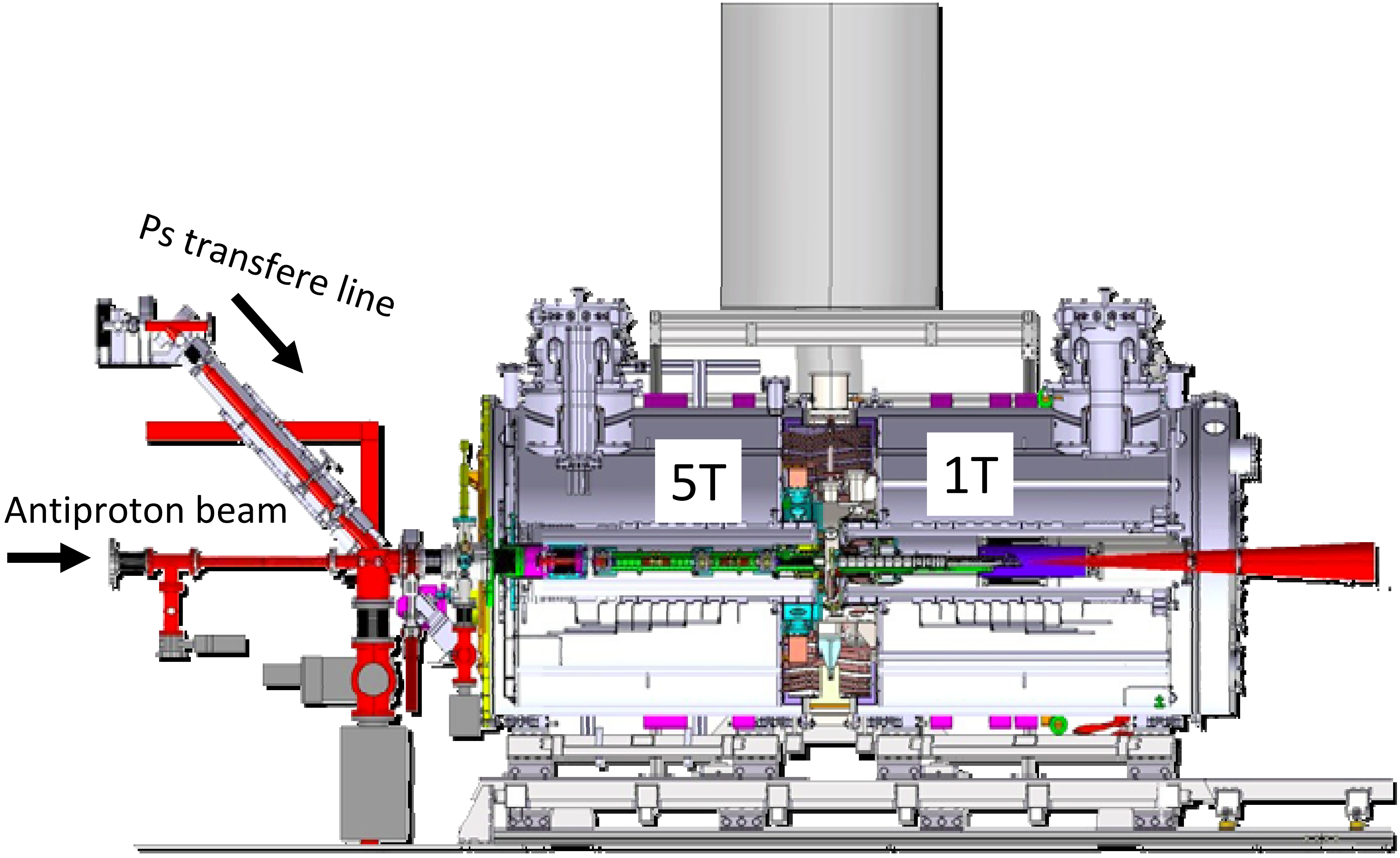
- $10^7\,\overline{p}$ produced every ≈ 90 s
- Deceleration from p = 3.5 GeV/c to 100 MeV/c
- Fast extraction (200-ns bunches)

AD experiments

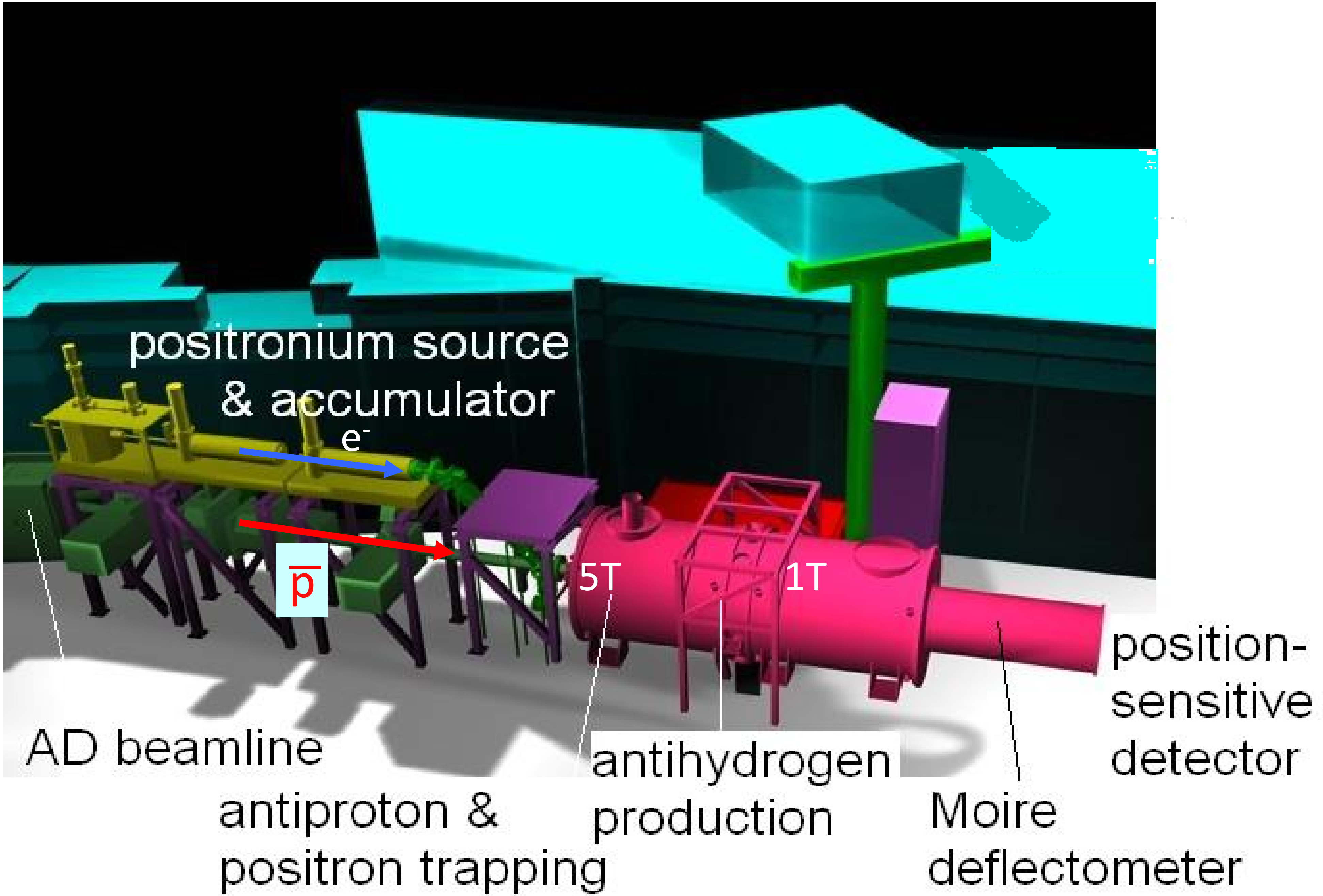


[J. Y. Hémery & S. Maury, Nucl. Phys. A **655** (1999) 345c]

Scematic overview of the apparatus



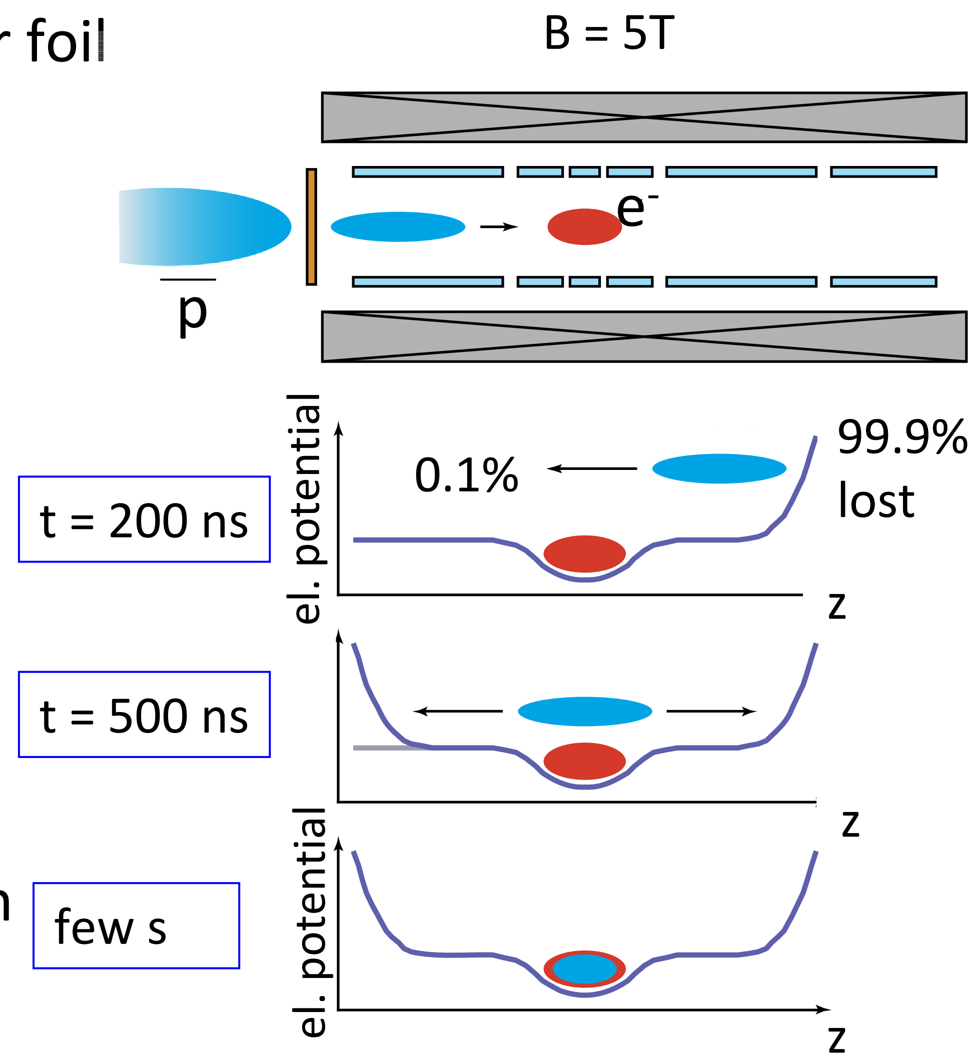
AEGIS overview sketch



Antiproton capture and cooling

- Energy reduced by 50-µm degrader foil

- Trapping sequence:
  1. Trap is prepared with plasma of 10^8 cold electrons
  2. Small fraction of antiprotons with $E < 9$ keV is reflected
  3. Axial potential on entrance side is raised to trap $\bar{p}$
  4. Antiprotons are sympathetically cooled by electrons



- Trap cooled to 100 mK by a dilution refrigerator
- sympathetic cooling

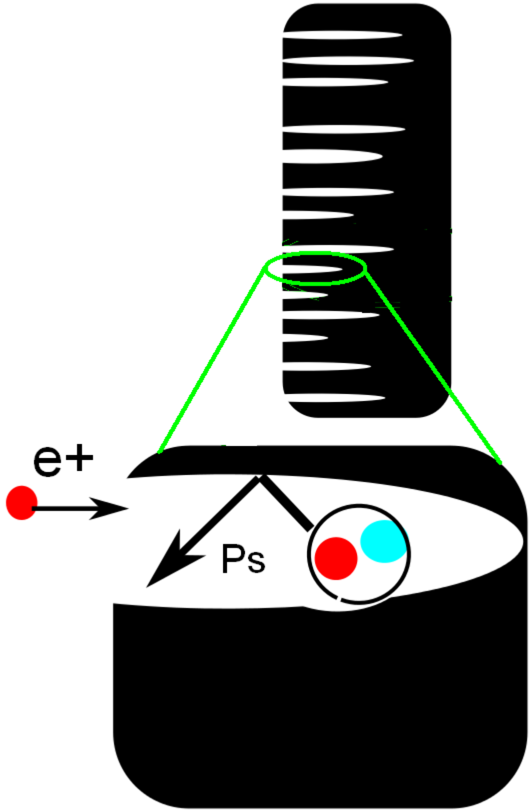
  with laser cooled negative ions

> 10^5 cold antiprotons

Positronium production

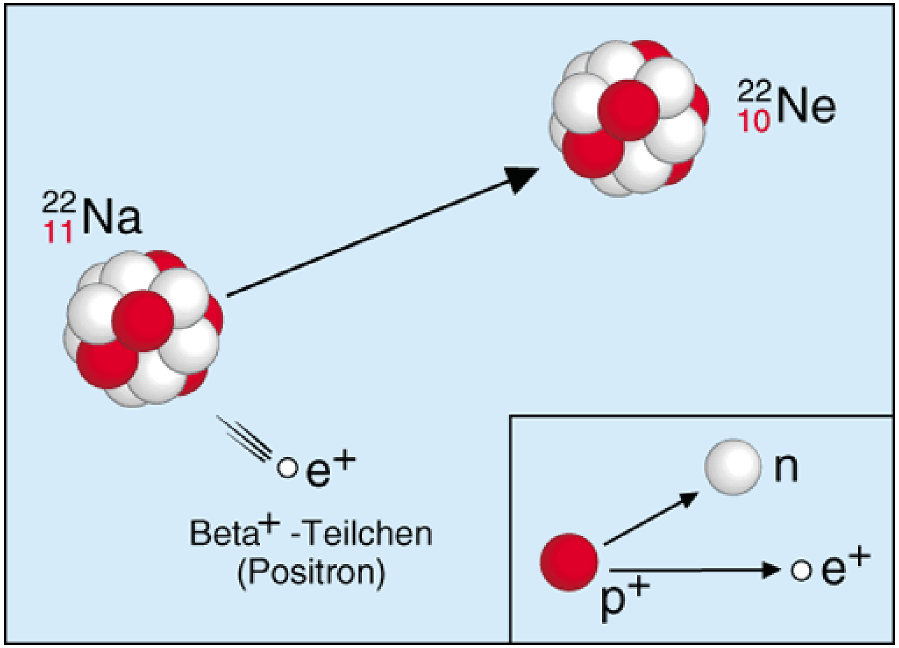
- Positrons from a ^{22}Na source

- Formation of positronium in nano-porous silica based materials



Ortho Ps
τ = 140 ns

Para PS
τ = 125 ps



- Measurements ongoing at Trento and Munich (NEPOMUC) to optimize Ps conversion targets
  - at 50 K, 9% of positrons converted to Ps

[S. Mariazzi, P. Bettotti, et al. Phys. Rev. B 81, 235418 (2010)]

Antihydrogen recombination

$$\sigma \approx a_0 n^4$$

- Charge exchange reaction:

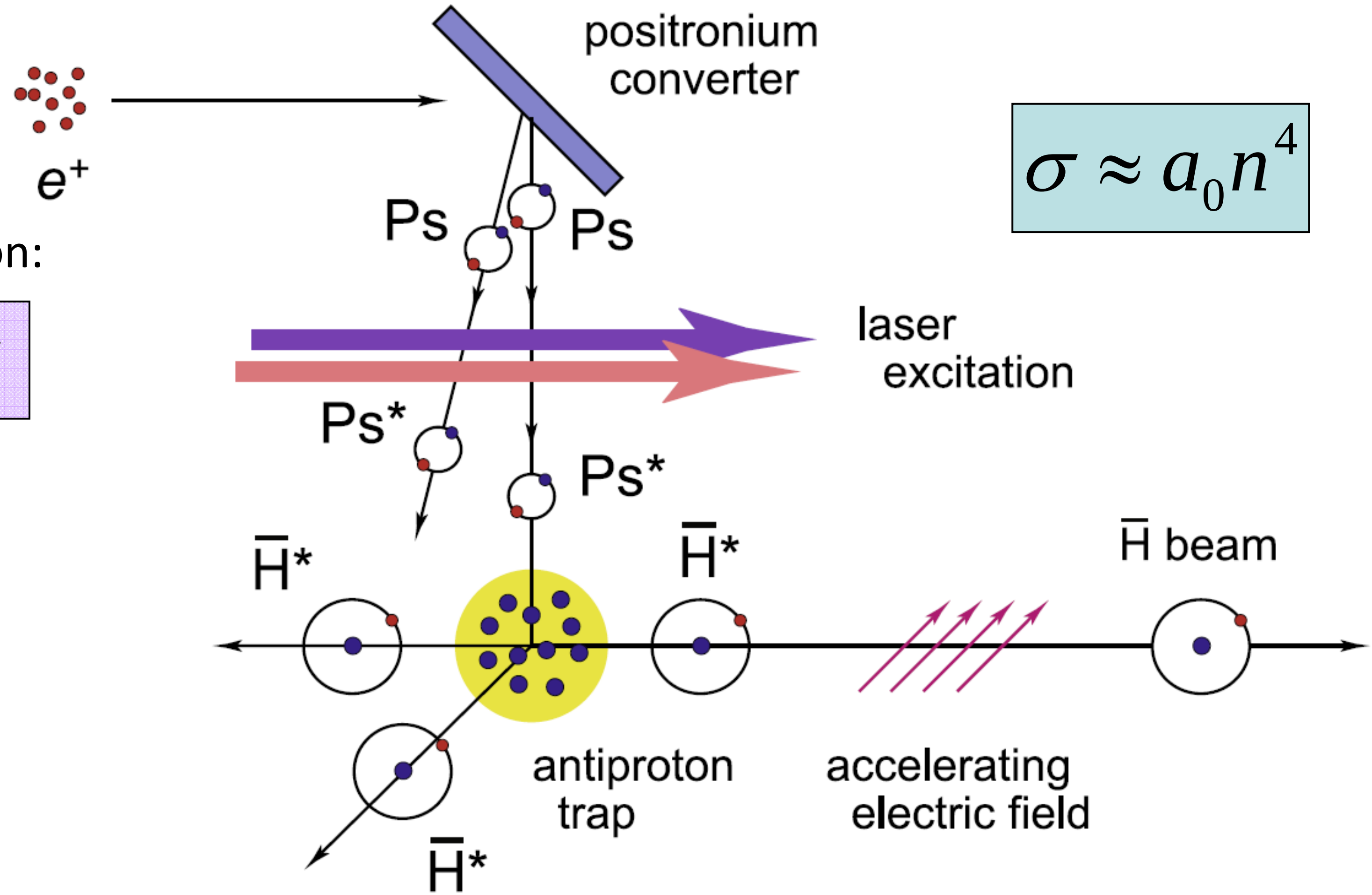
$$\mathrm{Ps}^* + \bar{p} \rightarrow \bar{\mathrm{H}}^* + e^-$$

- Principle demonstrated

  by ATRAP

  $\mathrm{Cs}^* \rightarrow \mathrm{Ps}^* \rightarrow \bar{\mathrm{H}}^*$

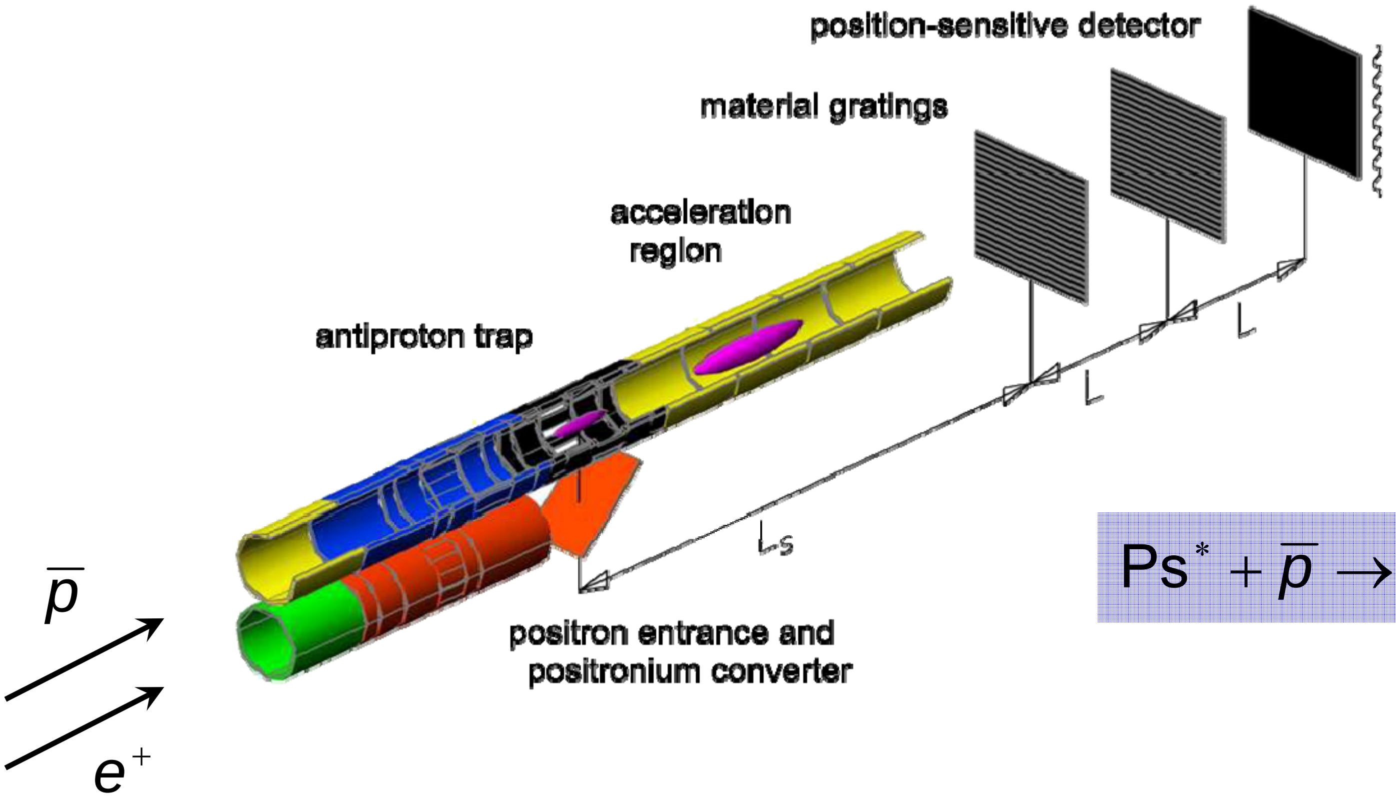
- Advantages:
  - Large cross-section:
  - Narrow and well-defined *n*-state distribution
  - Antiproton temperature determines antihydrogen temperature



[C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]

Experimental sequence

- Principle sketch (not to scale):



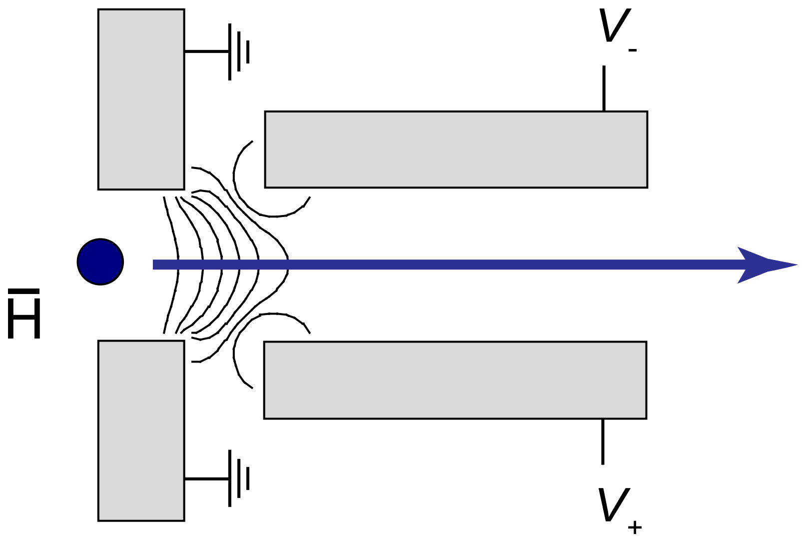
$$\mathrm{Ps}^* + \bar{p} \rightarrow \bar{\mathrm{H}}^* + e^-$$

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

Antihydrogen acceleration

- Rydberg antihydrogen accelerated into a beam by inhomogeneous electric field

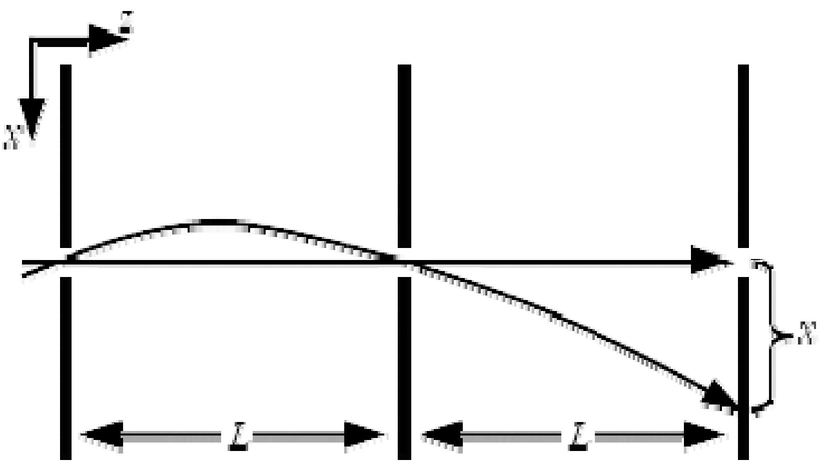
$$\vec{F} = -\frac{2}{3} e a_0 n(n-1) \nabla \vec{E}$$



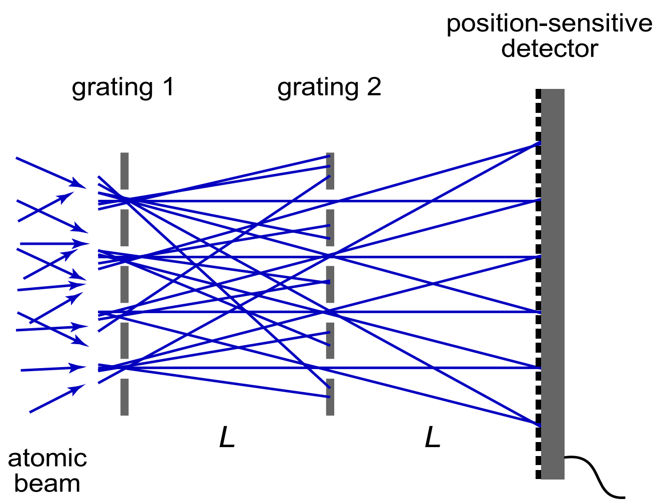
[E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241]

Gravity measurement

- Forces can be measured with a series of slits
  - Formation of an interference or shadow pattern with two slits
  - Measurement of the vertical deflection δx with a third (analysis) slit



- Many slits: interferometer/deflectometer



- Vertical deflection due to gravity:

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

- Vertical beam extent:

  $\Delta x \approx 5.8\ cm$

(antihydrogen beam at 100 mK, accelerated to 500 m s^{-1}, $L \approx 0.5$ m)

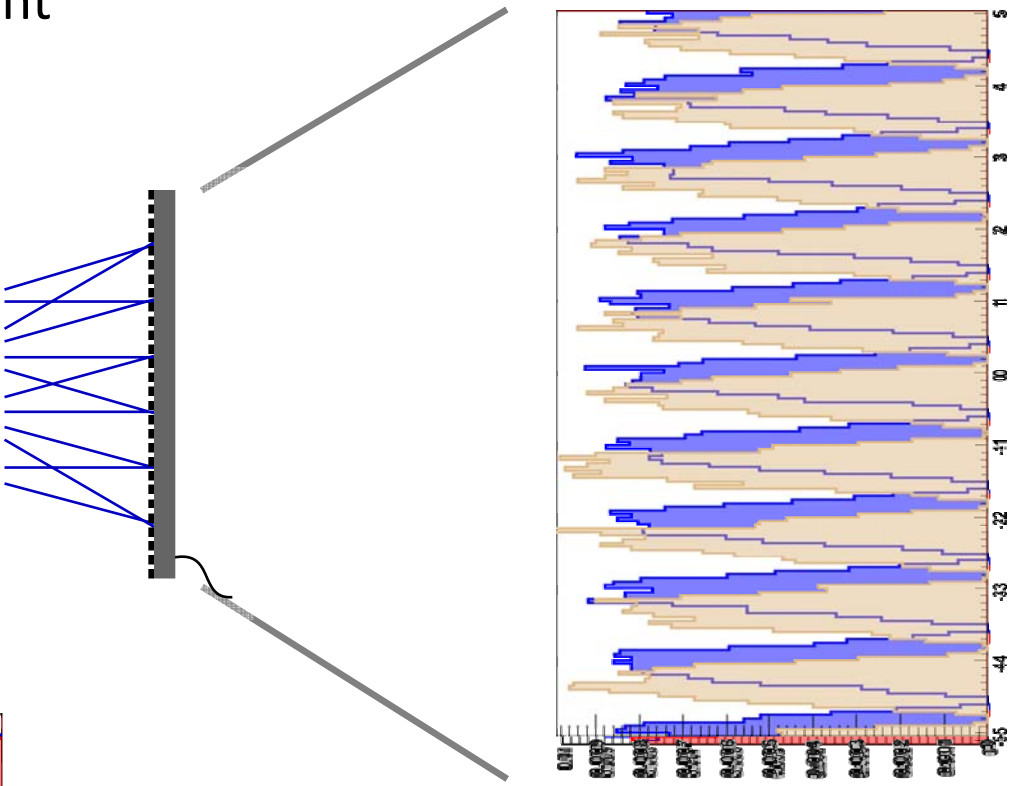
Data analysis

- Record vertical position for each event as a function of TOF/velocity:

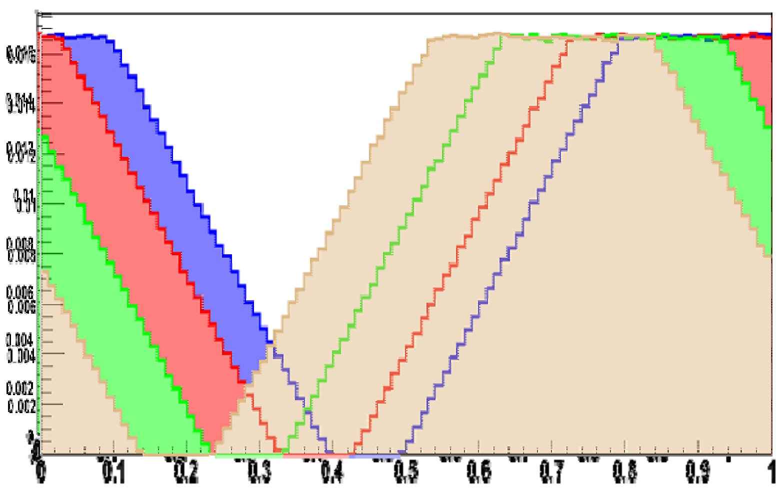
v_{beam} = 600, 400, 300, 250 m s^{-1}

$\delta x = -gT^2 \quad = -g\,(L/v)^2$

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



- Summing up the peaks:



Measurement of *g* to 1%:

- ≈ 10^5 $\bar{H}$ atoms at 100 mK
- about 2 weeks of beam time

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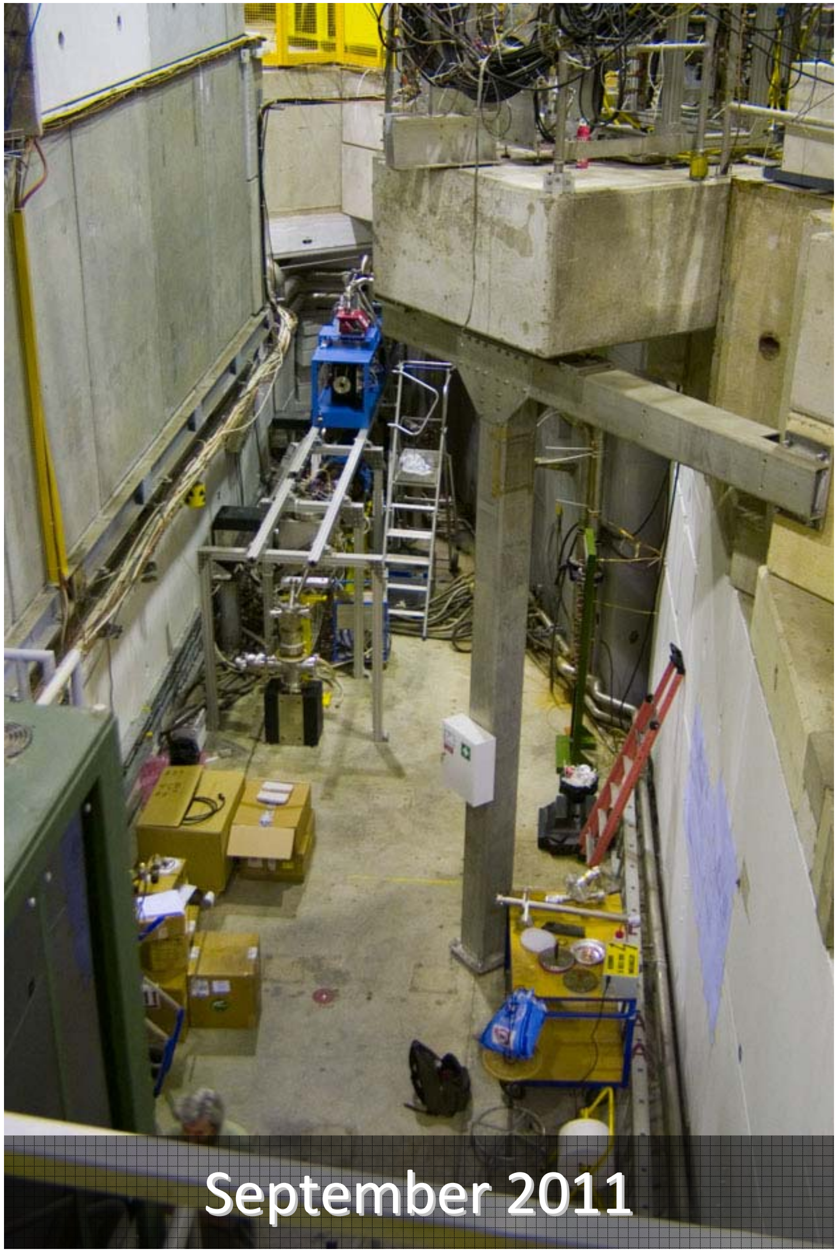
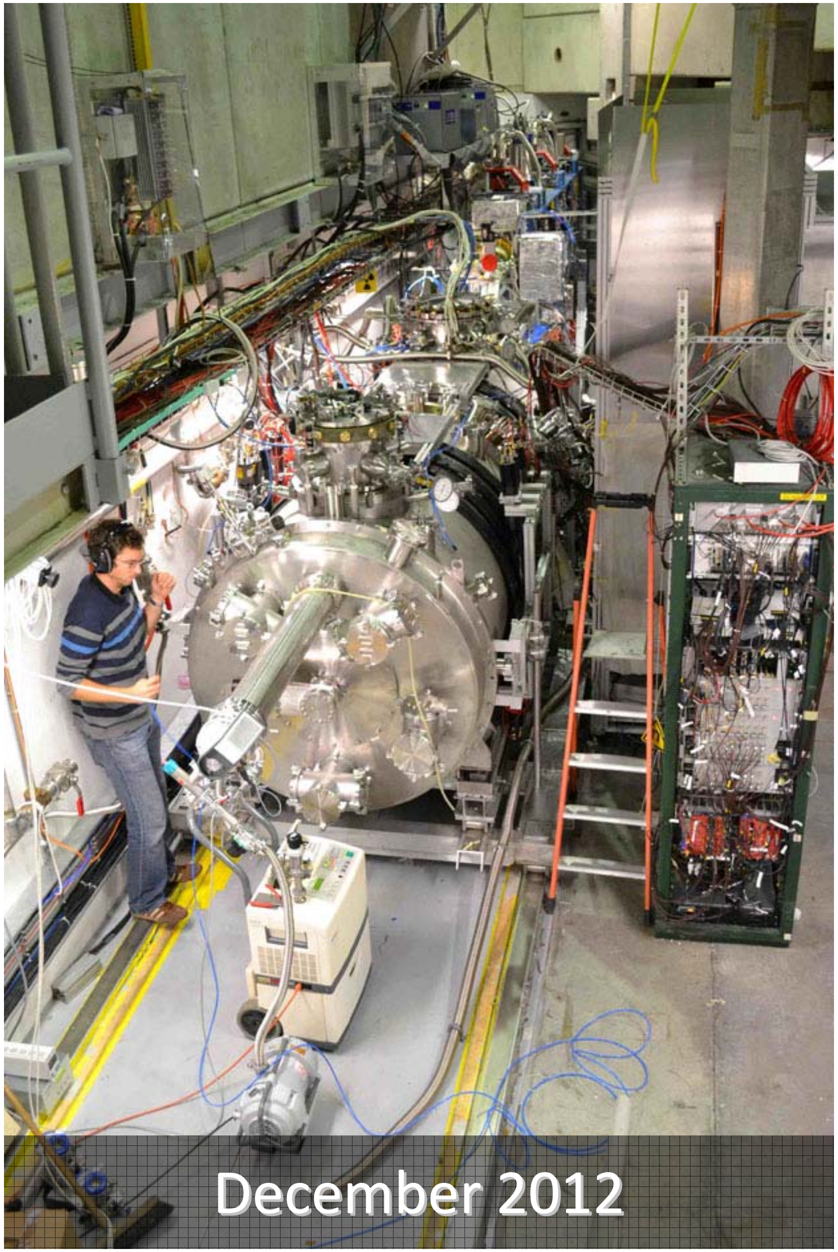
AEGIS construction 2010–2012



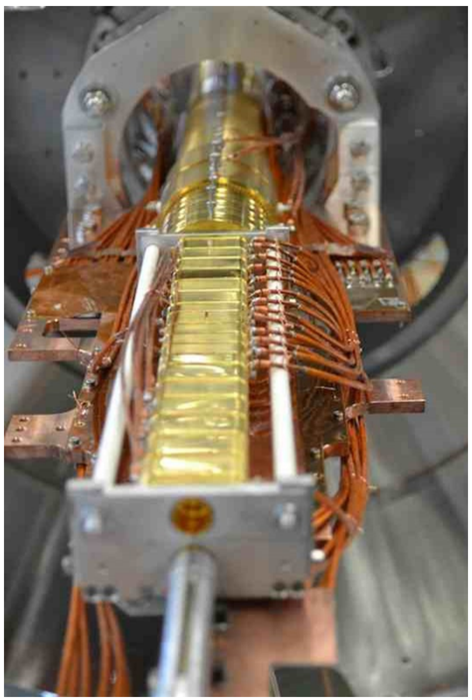
September 2011

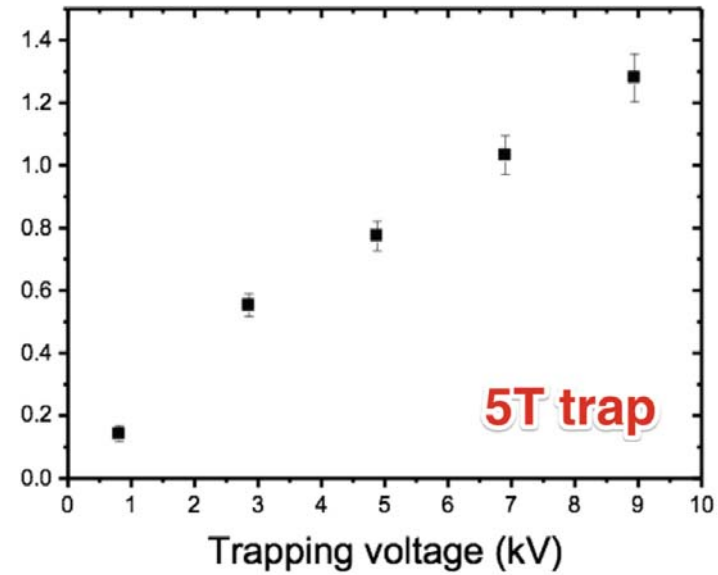


December 2012

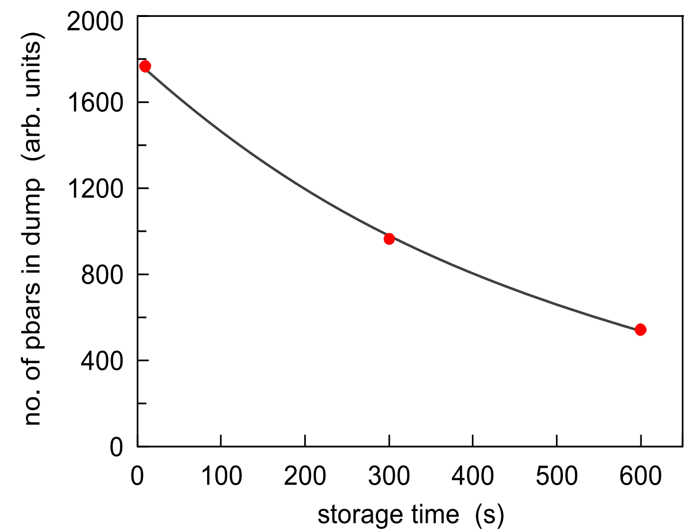
Magnets and traps

- 5 T magnet (capture) and 1 T magnet ($\bar{H}$ recombination) installed and commissioned
- All traps completed & commissioned





About 1.3 10^5 p caught at 9kV
per AD bunch ~3 10^7

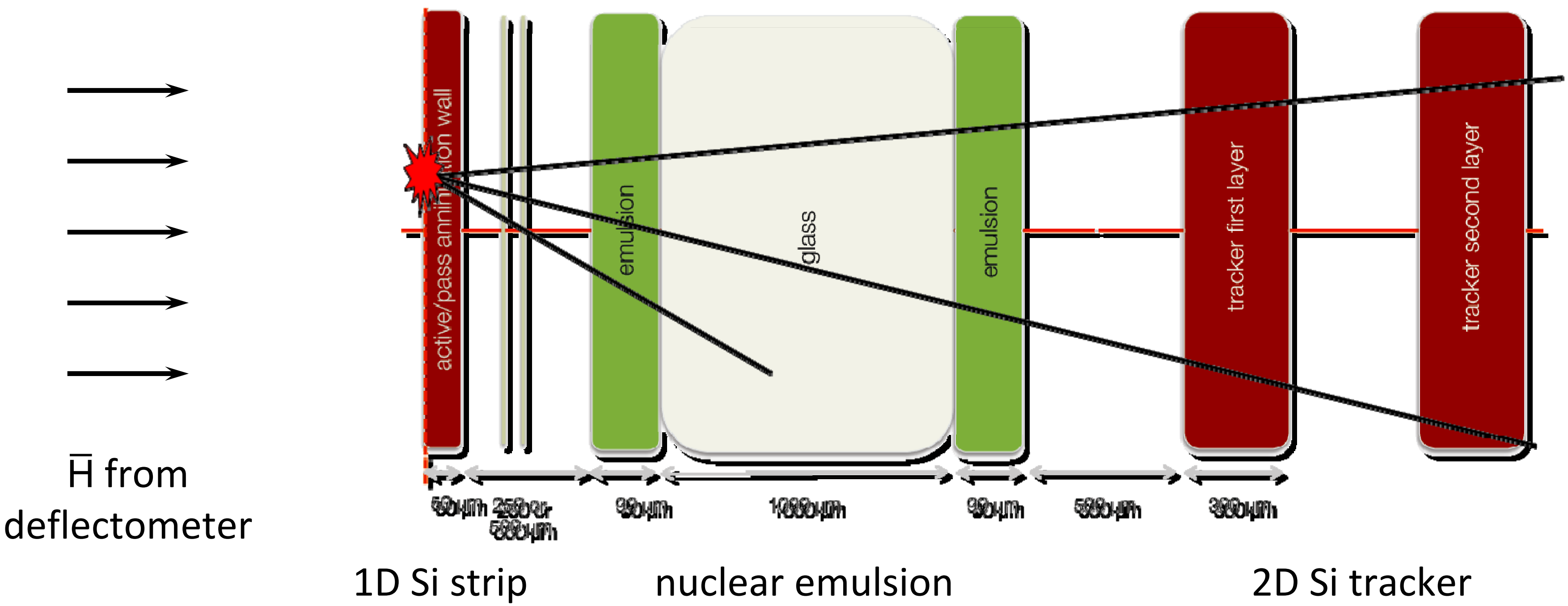


- Beam times May & Dec. 2012:
  - Successful $\bar{p}$ stacking (4 shots, 4×10^5 $\bar{p}$)
  - Storage of cooled $\bar{p}$ (τ = 570 s)

Moiré $\bar{H}$ detector

- Requirement: Detect $\bar{H}$ annihilations with resolution $\Delta t \approx 1\ \mu s$, $\Delta x \approx 10\ \mu m$
- Currently favored design:

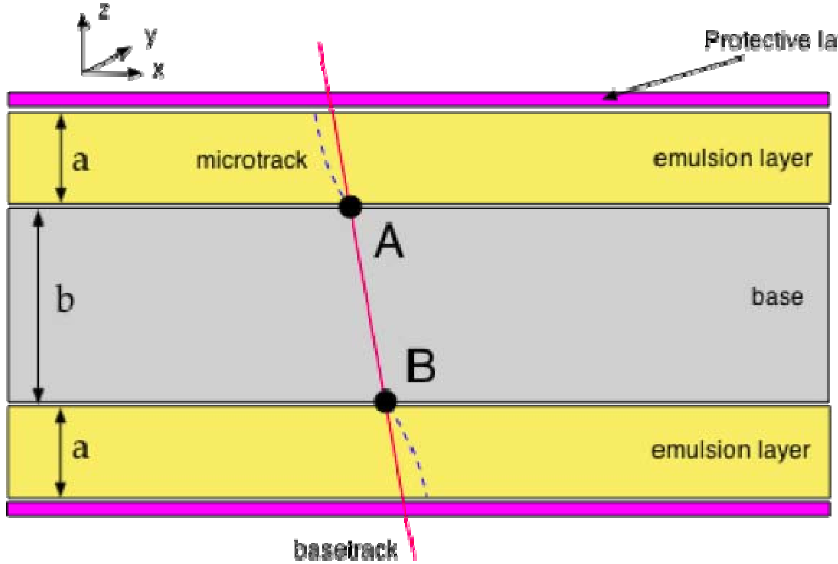
(distances and thicknesses not to scale)



  - Time of flight from 1D Si strip
  - High spatial resolution provided by emulsion
  - 2D Si tracker correlates emulsion tracks with timed events

Moiré $\overline{H}$ detector

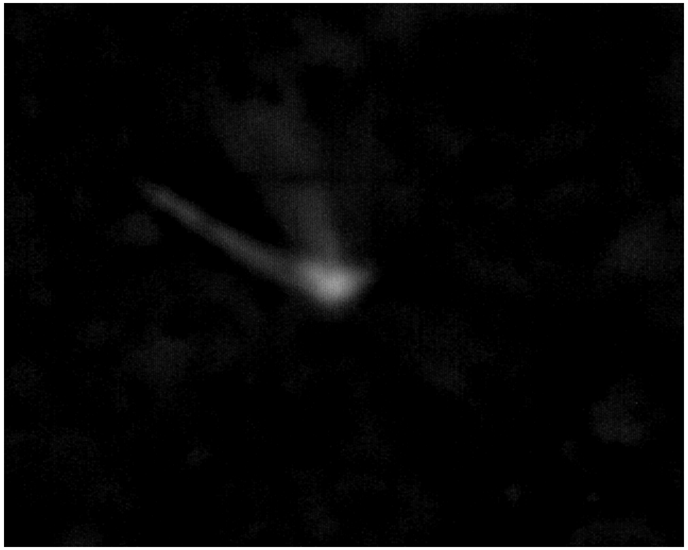
- Nuclear emulsions:
  - 90 µm thick gels on glass substrate (0.5…1 mm thick)

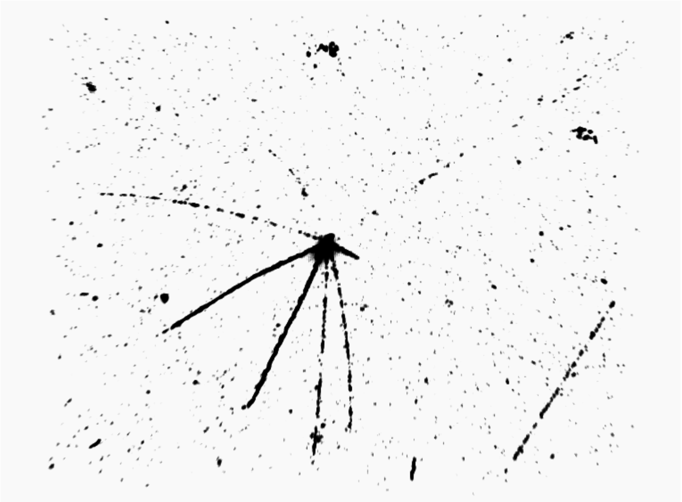


  - Based on technology developed for OPERA, modified for vacuum operation and tested at low temp
  - Off-line analysis by automatic 3D scanning

Intrinsic resolution 58 nm

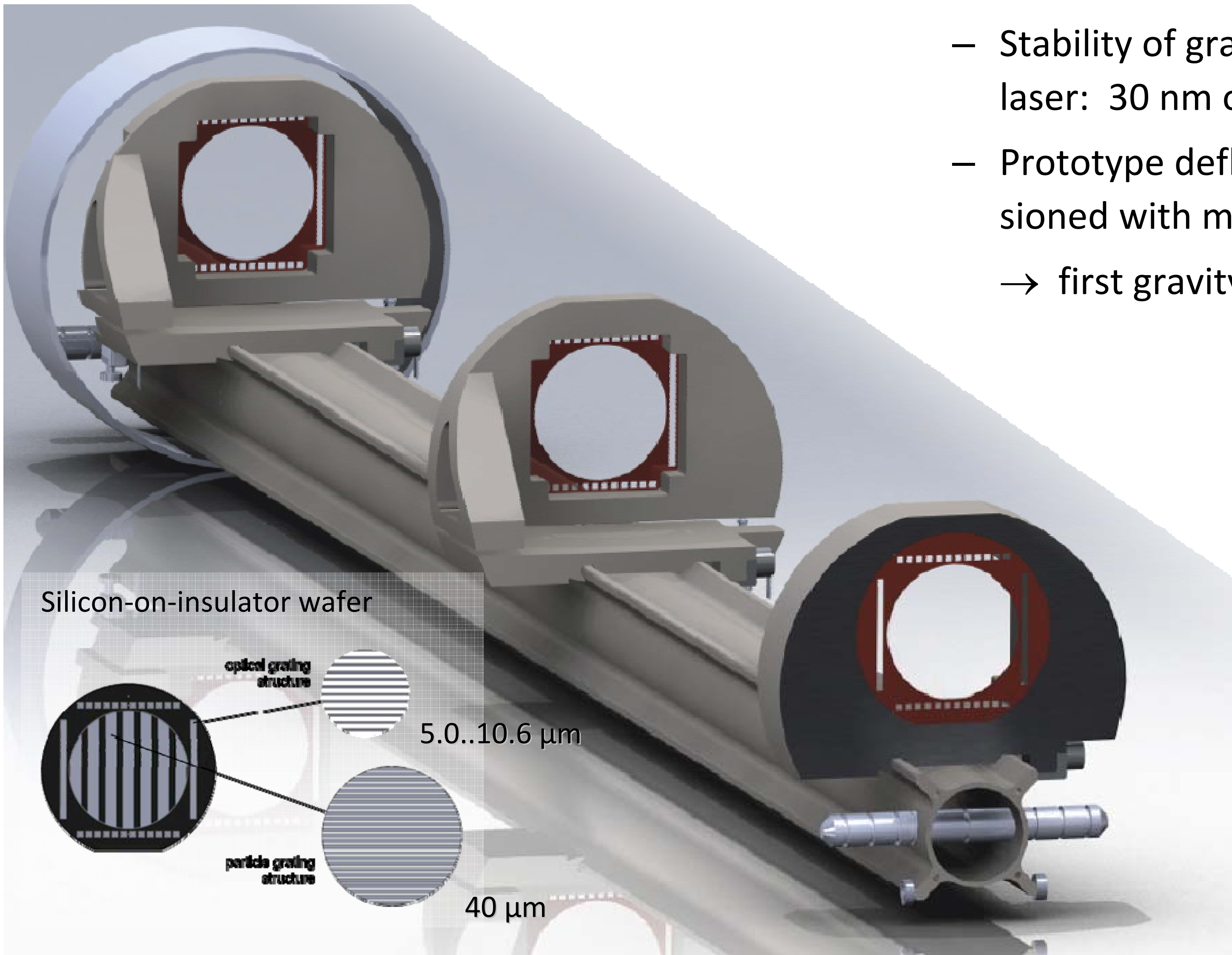
Vertex resolution ≈ 1.4…2.3 µm





Moiré deflectometer

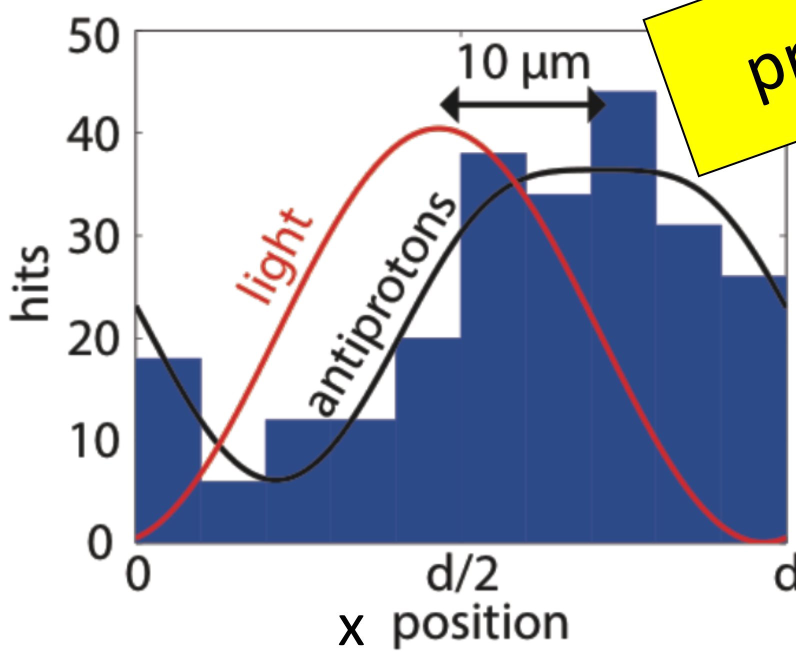
- Deflectometer test setup



– Stability of gratings measured with laser: 30 nm over 1 h
– Prototype deflectometer comis-sioned with metastable Ar atoms
→ first gravity measurement

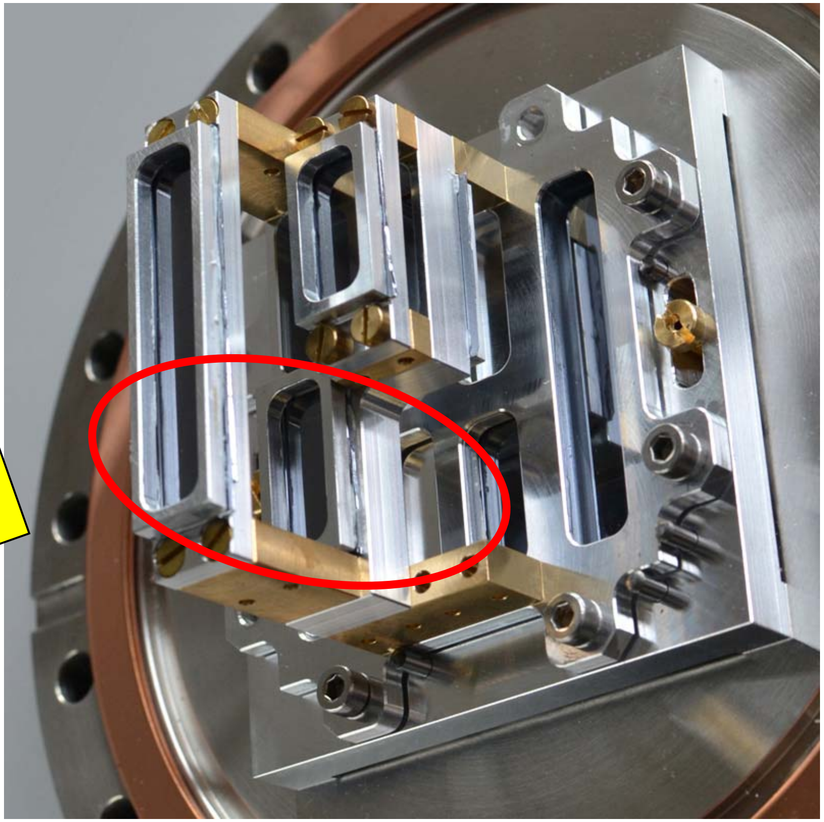
Moiré deflectometer

- December 2012:
  Deflectometry measurement with $\bar{p}$ in "mini moiré" setup
  - d = 40 µm, L = 25 mm
  - 100 keV $\bar{p}$, 7 h exposure
  - Reference measurement with laser light in Talbot-Lau regime



preliminary

[Aghion et al., submitted 2013]



Result:

-Phase shift: 10.0 µm ±0.9 µm(Stat.)
±6.3 µm (Sys.)

-Force: F = 540 ± 50 ± 340 aN,
corresponds to magnetic field ≈ 8 G

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Conclusions & outlook

- the weak equivalence principle has never been tested for antimatter
- depending on the chosen model, effect could be nil or dramatic
- the AEGIS experiment intends to measure g of antihydrogen to few percent precision
- construction and commissioning of AEGIS apparatus largely completed
- next milestones:
  - 2013 / first half 2014: Commissioning of all remaining components;
  - from second half 2014: First antimatter gravity experiment

AEGIS Collaboration

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