# The AEGIS Experiment at CERN: Measuring the Free Fall of Antihydrogen

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erc

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$$\bar{g}$$

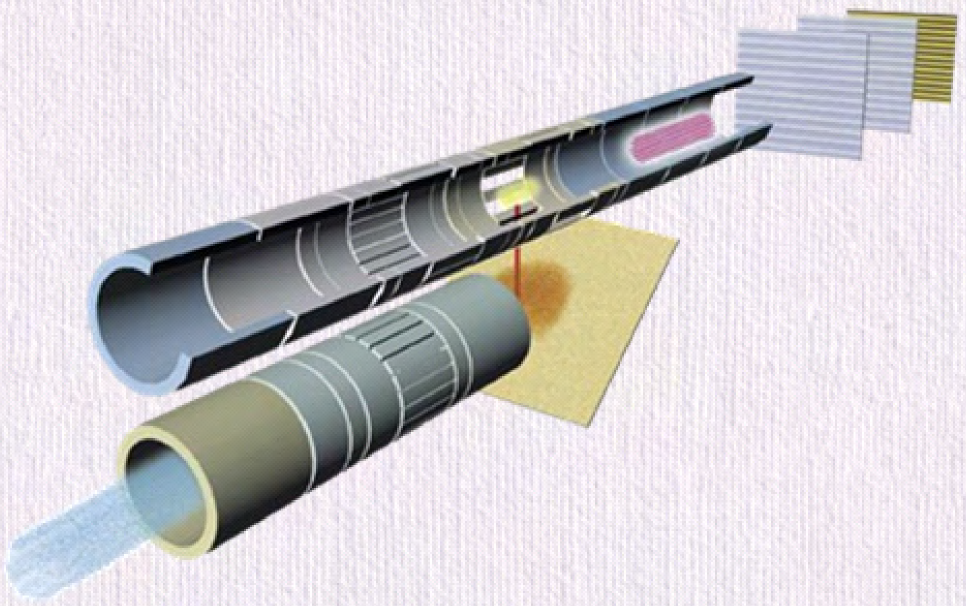
# AEGIS

**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 ($10^5\ \overline{\mathrm{H}}$)

- Requirements / challenges:
  - Production of a **bunched cold beam** of antihydrogen (100 mK)
  - Measurement of beam deflection by interferometry



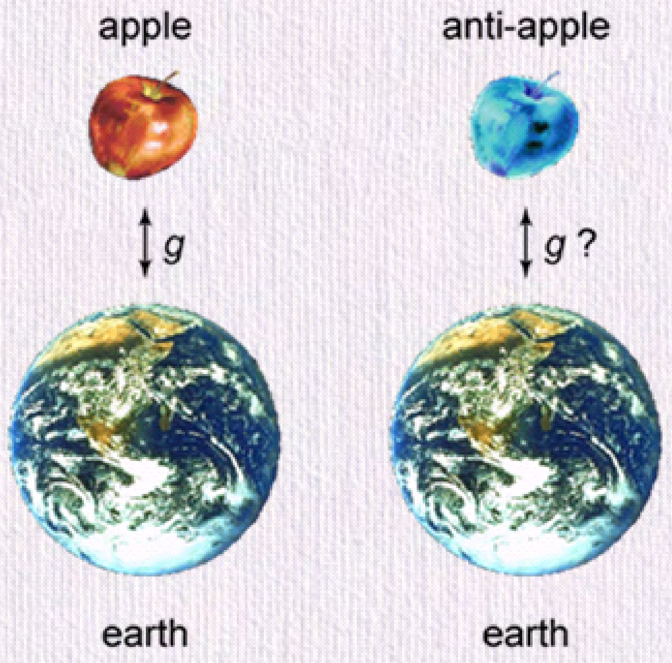
* Higher precision possible after future upgrade

# Outline

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

# Antimatter gravity tests

- The effect of gravity on ordinary matter has been studied extensively
- Antimatter gravity has to this day never been investigated
  - Charged elementary antiparticles are sensitive to electromagnetic stray fields
  - Neutral antimatter was previously not available




- Copious amounts of cold antihydrogen produced by ATHENA and ATRAP pave the way for direct antimatter gravity experiments

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

- Not CPT-symmetric situation!
- Weak equivalence principle:

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

$$\overline{m}_g \equiv m_g$$

# Quantum gravity

- Gravity is the only force not described by a quantum field theory
- Unification could be achieved with quantum gravity
  $\Rightarrow$ "Theory of Everything"
- Hypothetical exchange particles:

| | | |
|---|---|---|
| • Tensor graviton | (Spin 2, "Newtonian") | always attractive |
| • Vector graviton | (Spin 1) | repulsive between like charges |
| • Scalar graviton | (Spin 0) | always attractive |

- Quantum gravity potential (static limit):

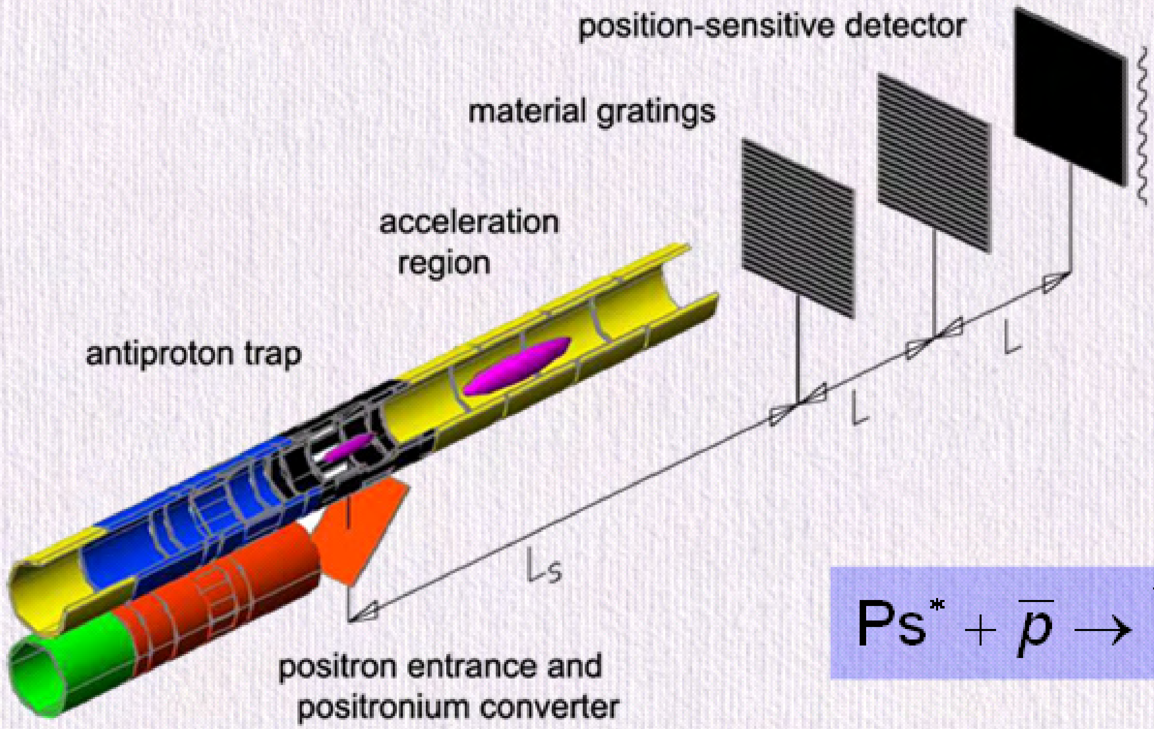
$$V = -\frac{Gm_1 m_2}{r}\left(1 \pm \alpha_v e^{r/\lambda_v} + \alpha_s e^{r/\lambda_s}\right)$$

where $\alpha_v, \lambda_v$ – vector c.c./range
$\alpha_s, \lambda_s$ – scalar c.c./range

- The non-Newtonian terms could (almost) cancel out
  if $\alpha_v \approx \alpha_s$ and $\lambda_v \approx \lambda_s$, but produce a striking effect on antimatter

# Antimatter gravity test

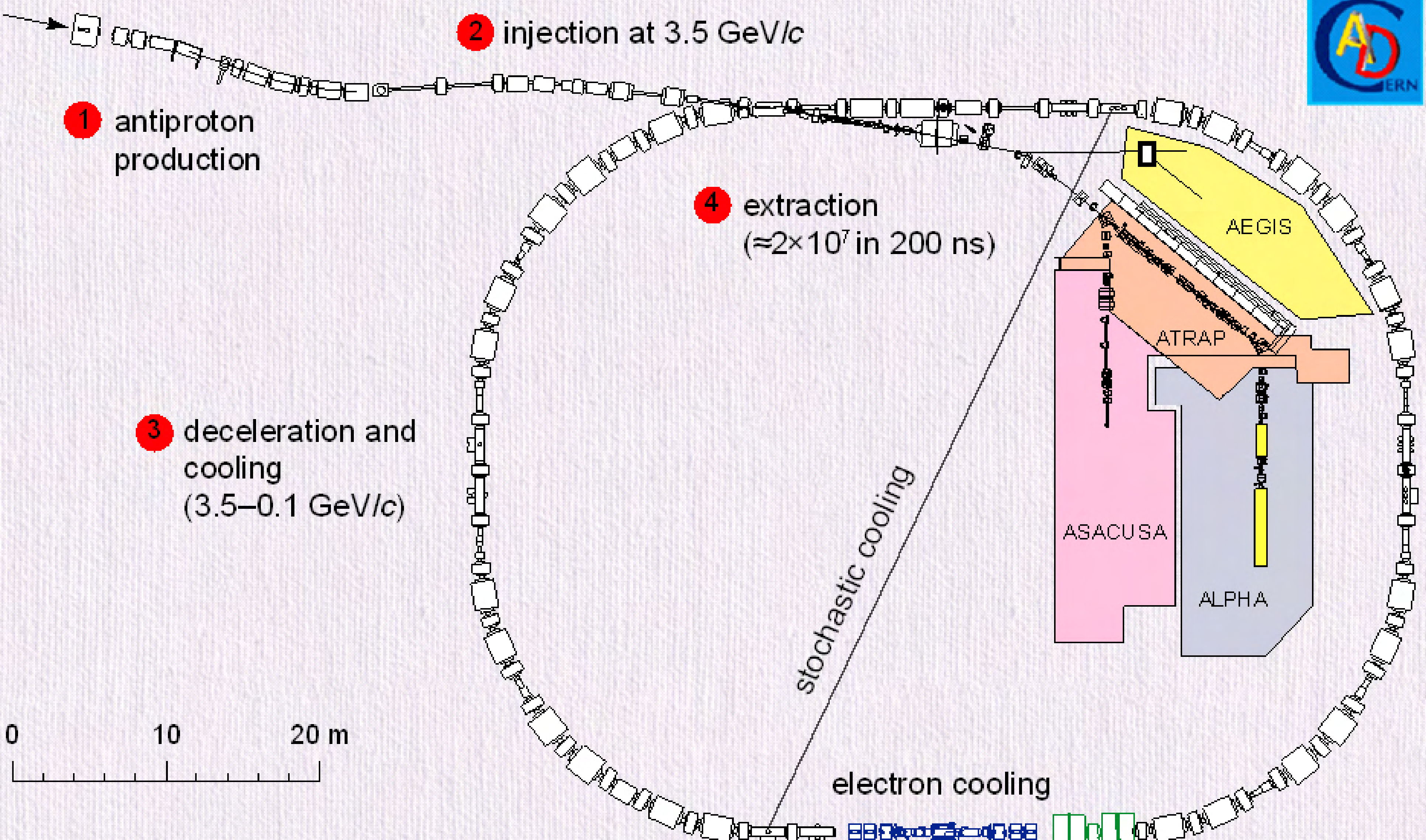
- AEGIS principle sketch:




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

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

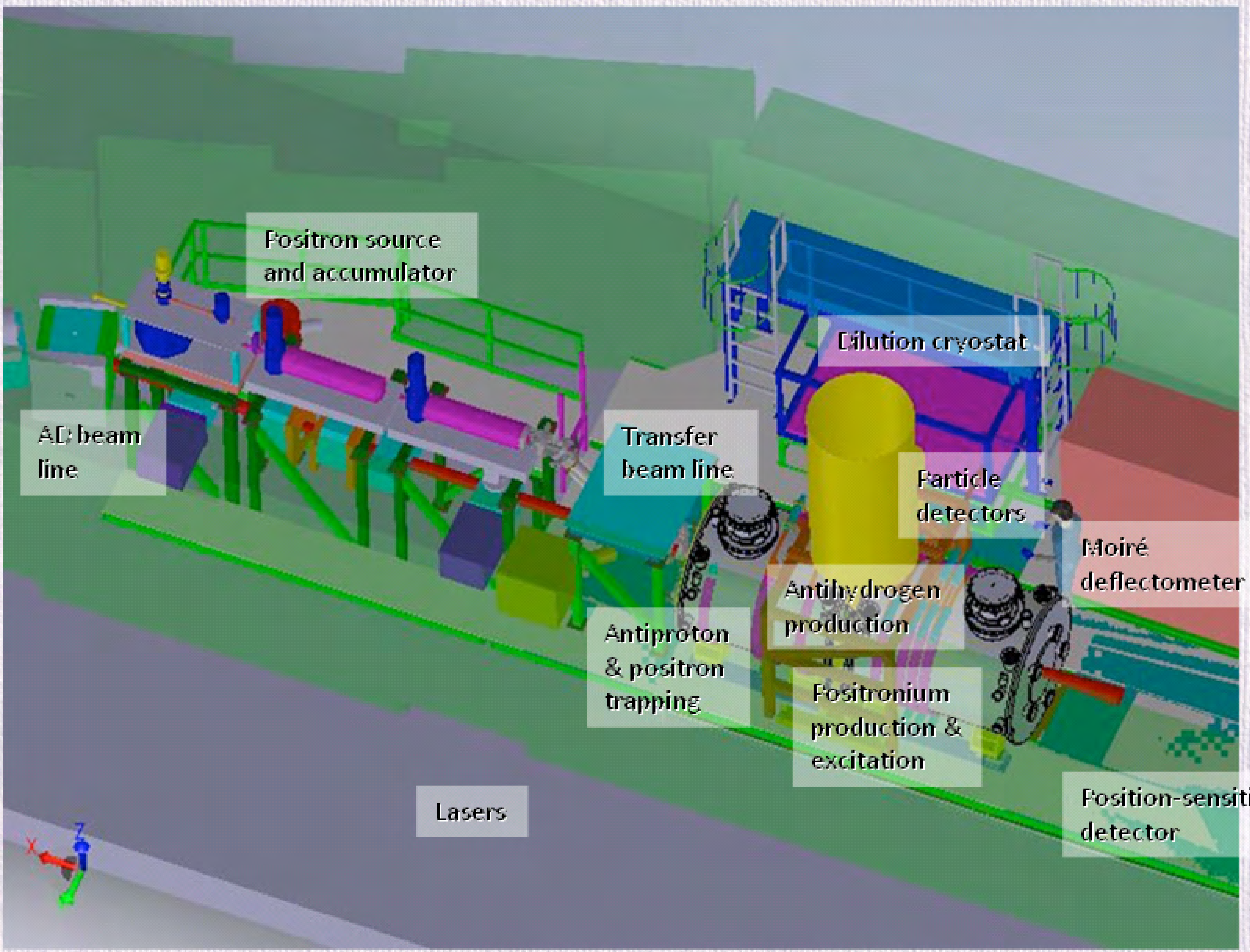
# AEGIS at the AD




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

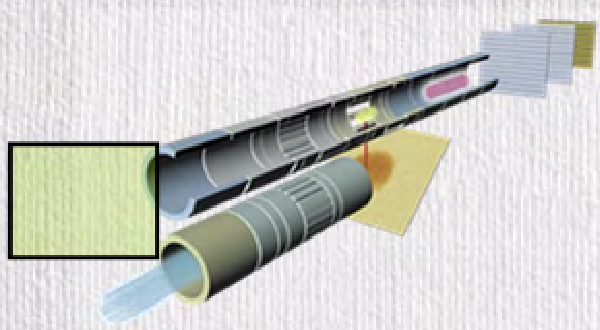
# AEGIS zone at the AD

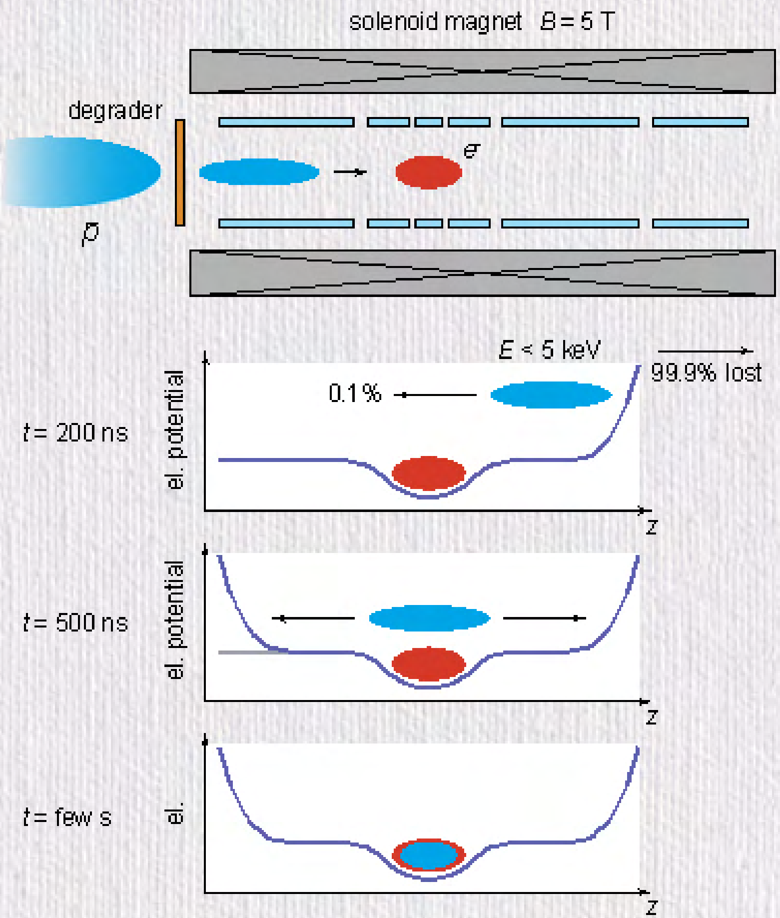
# AEGIS overview sketch



# 1) Antiproton capture and cooling

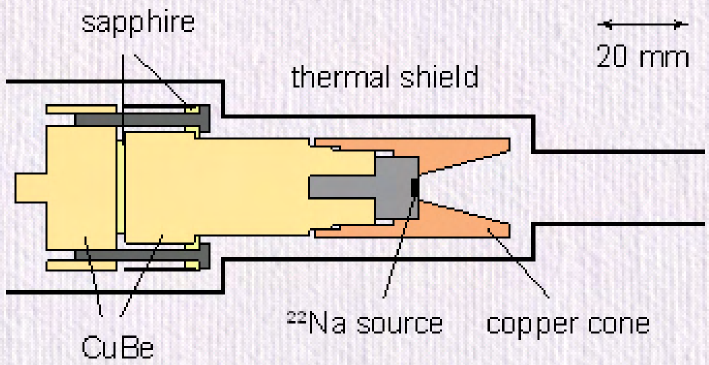
- Energy reduced by 50-µm Al degrader foil
- Trapping sequence:
  1. Trap is prepared with plasma of $10^8$ cold electrons
  2. Small fraction of antiprotons with $E < 5$ keV is reflected
  3. Axial potential on entrance side is raised to trap $\bar{p}$
  4. Antiprotons are sympathetically cooled by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






> $10^4$ antiprotons @ 100 mK

# 2) Positron production & accumulation

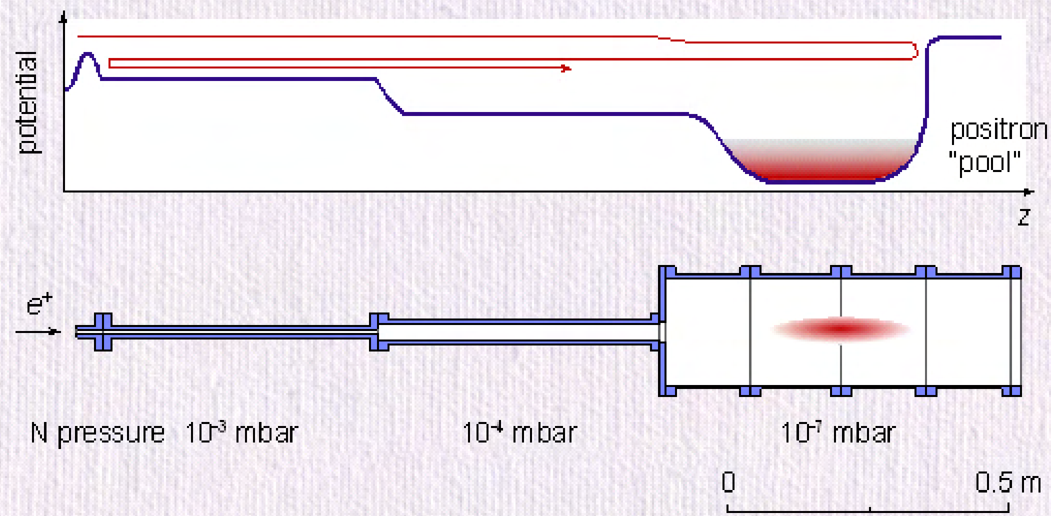


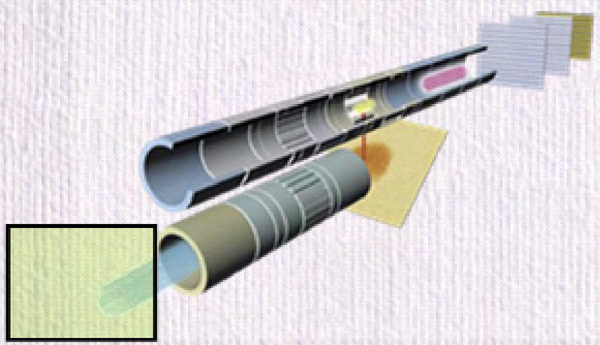

- Production from $\beta^+$ emitter:

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

- 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



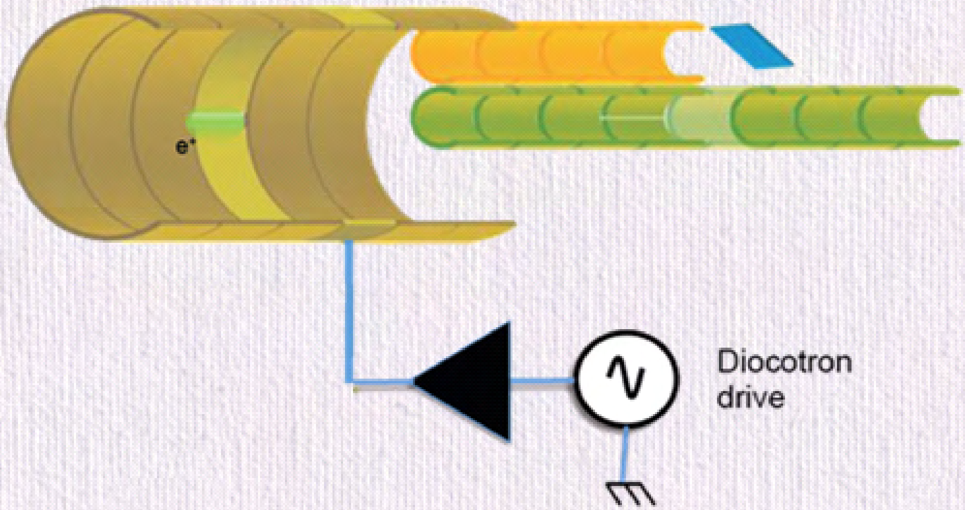



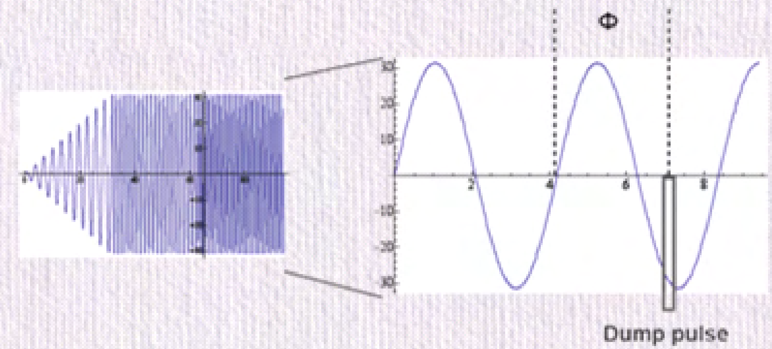
≈ $10^8$ positrons every 200 s

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

# 2) Positron production & accumulation

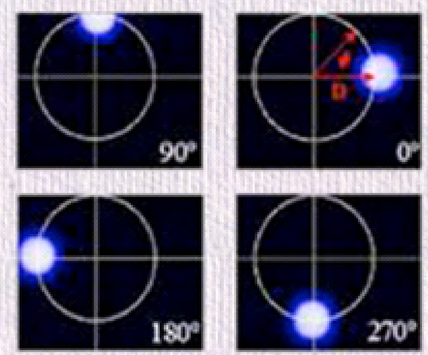
- Positron displacement by diocotron excitation:



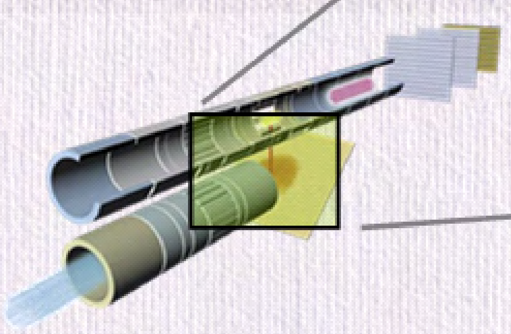

Diocotron amplitude and frequency initially increase, then stay constant at ≈ 2 V, ≈ 10 kHz

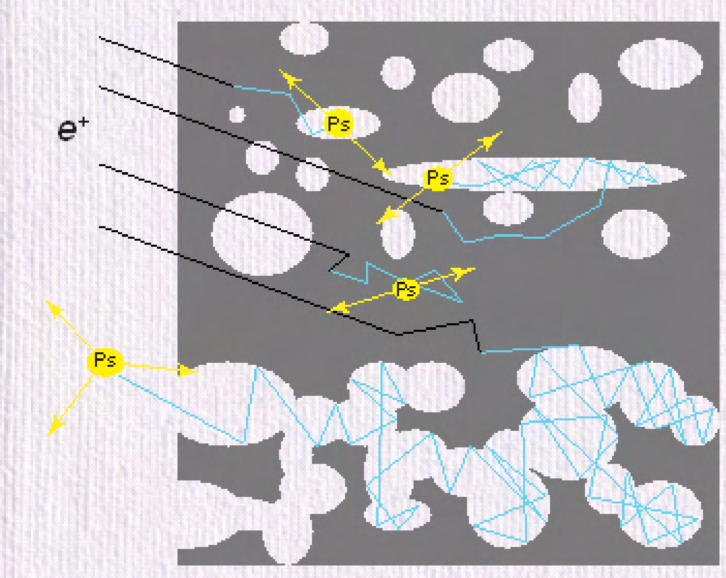
  - Plasma is brought into autoresonance with driving diocotron signal
  - Plasma moves along circular path around trap axis
  - Excitation amplitude and extraction pulse phase determine radial distance and angle



# 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
  - Reduced dielectric strength in defects ⇒ accumulation of positronium in voids
  - 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





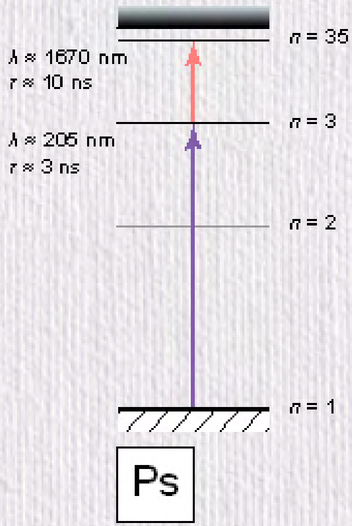

[D. W. Gidley *et al.*, Annu. Rev. Mater. Res. **36** (2006) 49]

High-efficiency positronium converter

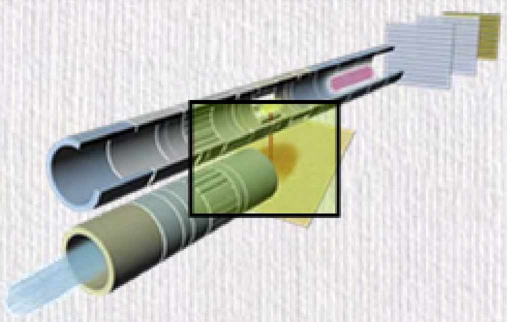
# 4) Positronium excitation

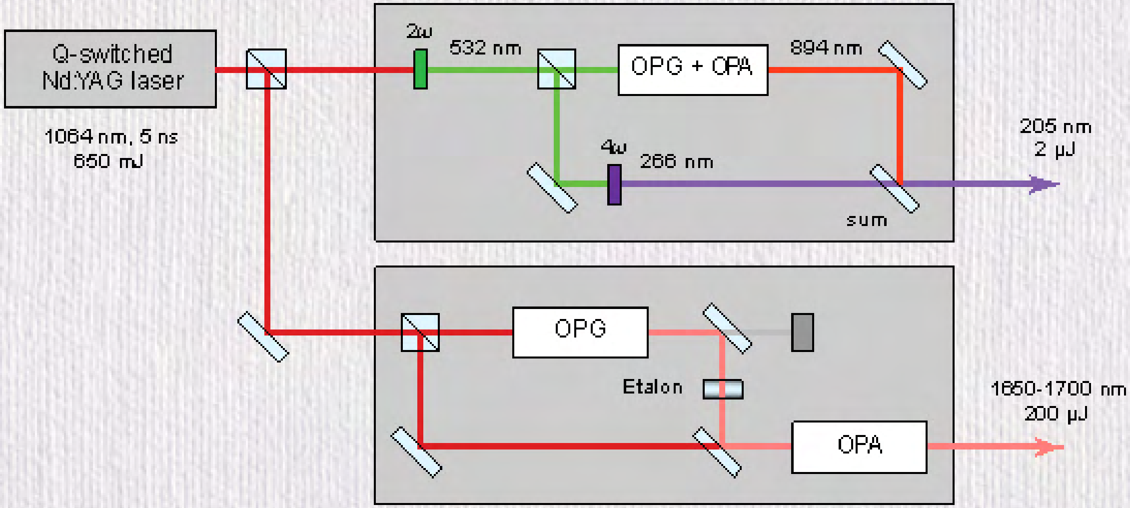
- Cross-section of Ps charge exchange reaction is enhanced for large $n$: $\sigma \approx a_0 n^4$
- Two-step excitation $n = 3 \rightarrow n = 35$

  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:



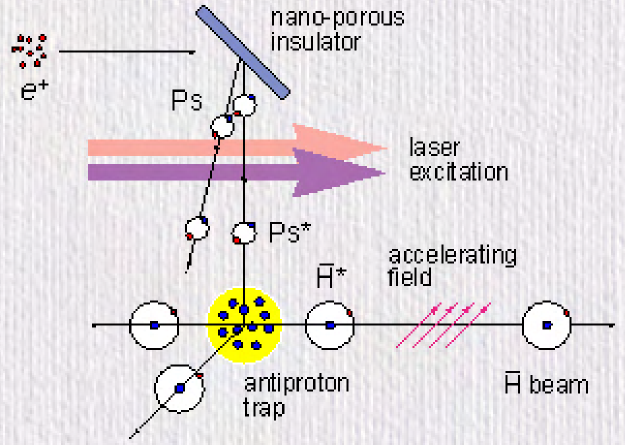


# 5) Antihydrogen recombination

- Charge exchange reaction:

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

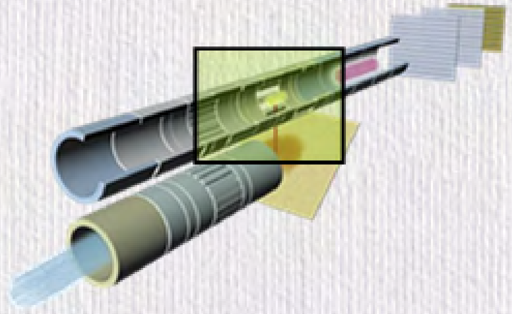
- Principle demonstrated by ATRAP
  $\mathrm{Cs}^* \rightarrow \mathrm{Ps}^* \rightarrow \bar{\mathrm{H}}^*$
  [C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]




- Advantages:
  - Large cross-section:

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

  - Narrow and well-defined $\bar{\mathrm{H}}$ *n*-state distribution



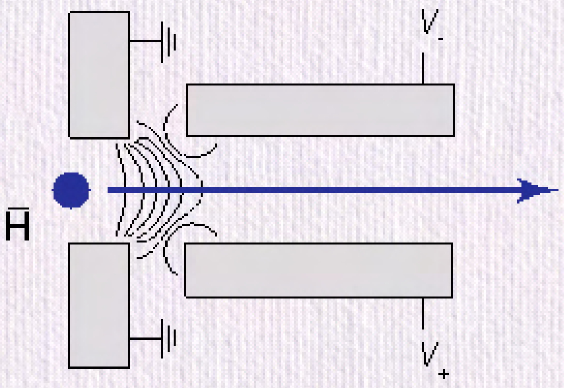
  - Antiproton temperature essentially determines antihydrogen temperature:

At $T(\bar{p})$ = 100 mK, $n_{\mathrm{Ps}} = 35$
$\Rightarrow$ $v(\bar{\mathrm{H}}) \approx$ 45 m/s
$T(\bar{\mathrm{H}}) \approx$ 120 mK

$\Rightarrow$ cold / ultracold $\bar{\mathrm{H}}$

# 6) Antihydrogen beam formation

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



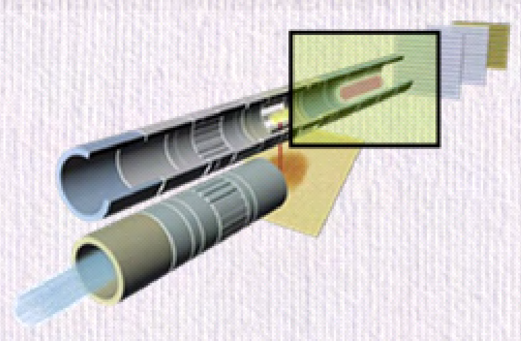

$$U = \frac{2}{3} e a_0 \boxed{n(n-1)} F$$

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

(max. induced dipole)

⇒ Rydberg atoms are very sensitive to inhomogeneous electric fields

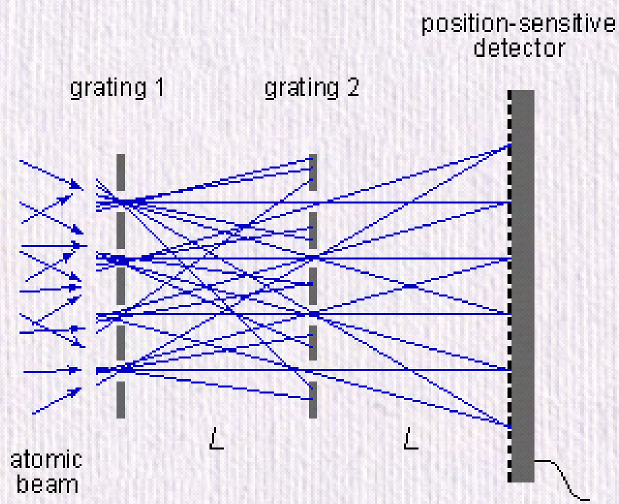
- Stark deceleration of hydrogen demonstrated (ETH group):
  [E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241]



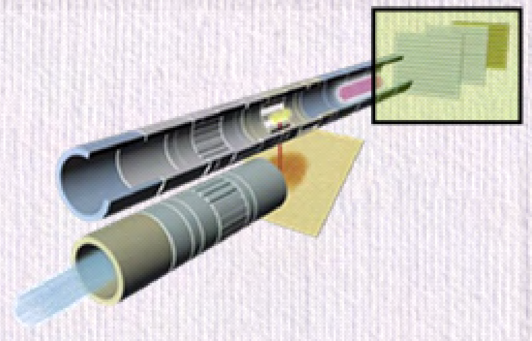
- $n = 22,23,24$
- Accelerations of up to $2{\times}10^8$ m/s² achieved
- Hydrogen beam at 700 m/s can be stopped in 5 μs over only 1.8 mm

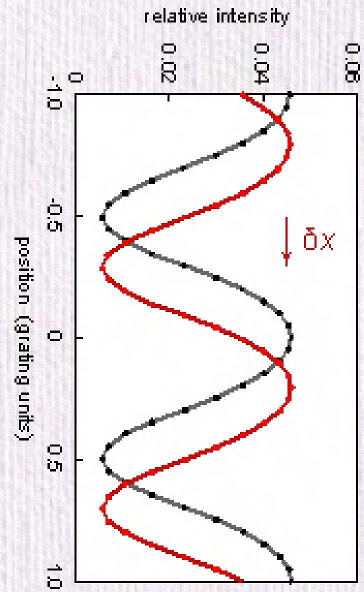
# 7) Gravity measurement

- Moiré deflectometer:




Position-sensitive detector enhances transmission by factor ≈ 3





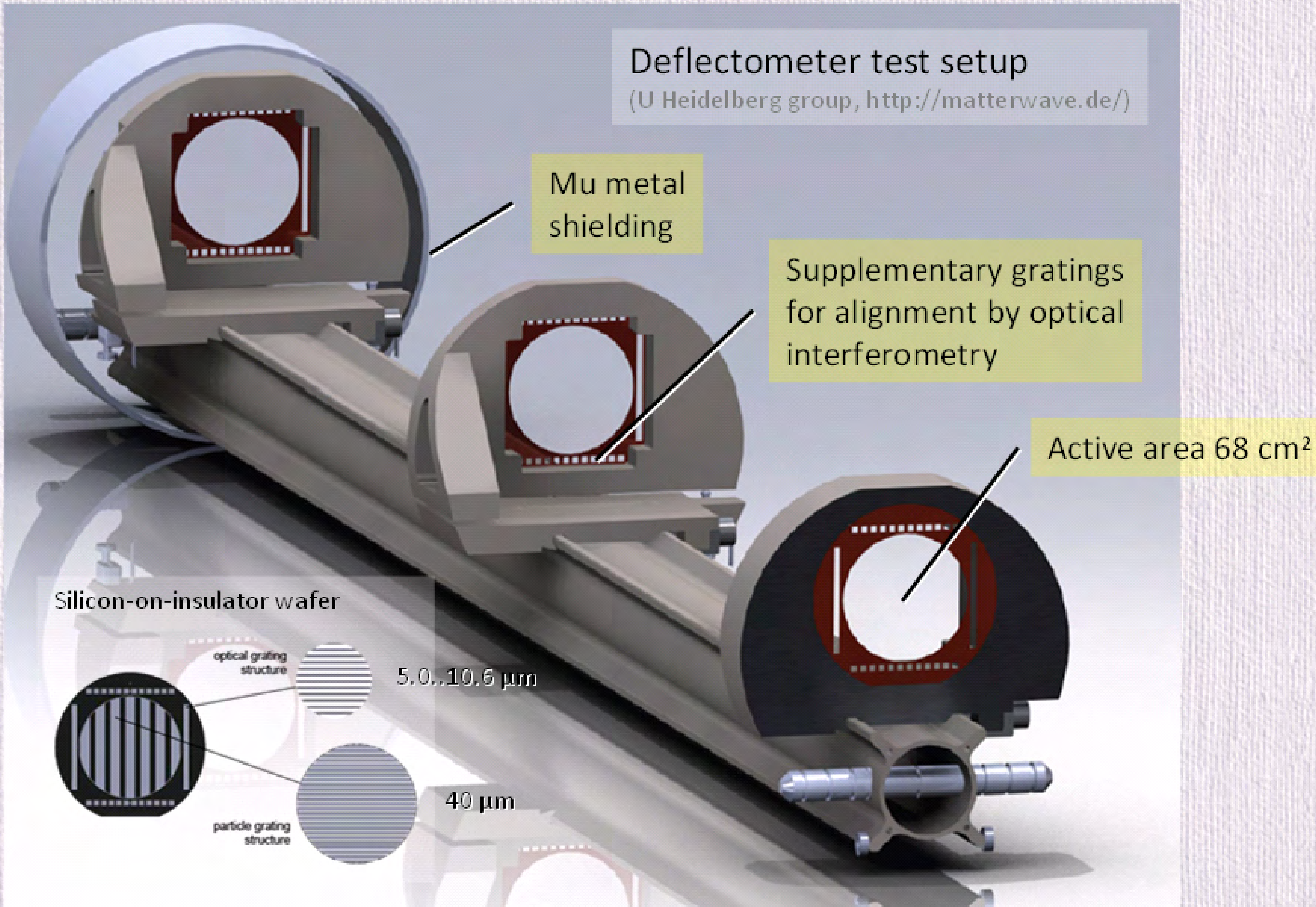

Interference pattern "falls" by

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

- Classical counterpart of Mach-Zehnder interferometer
- Two gratings create shadow pattern on third grating
- "Self-focusing" effect
- 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]

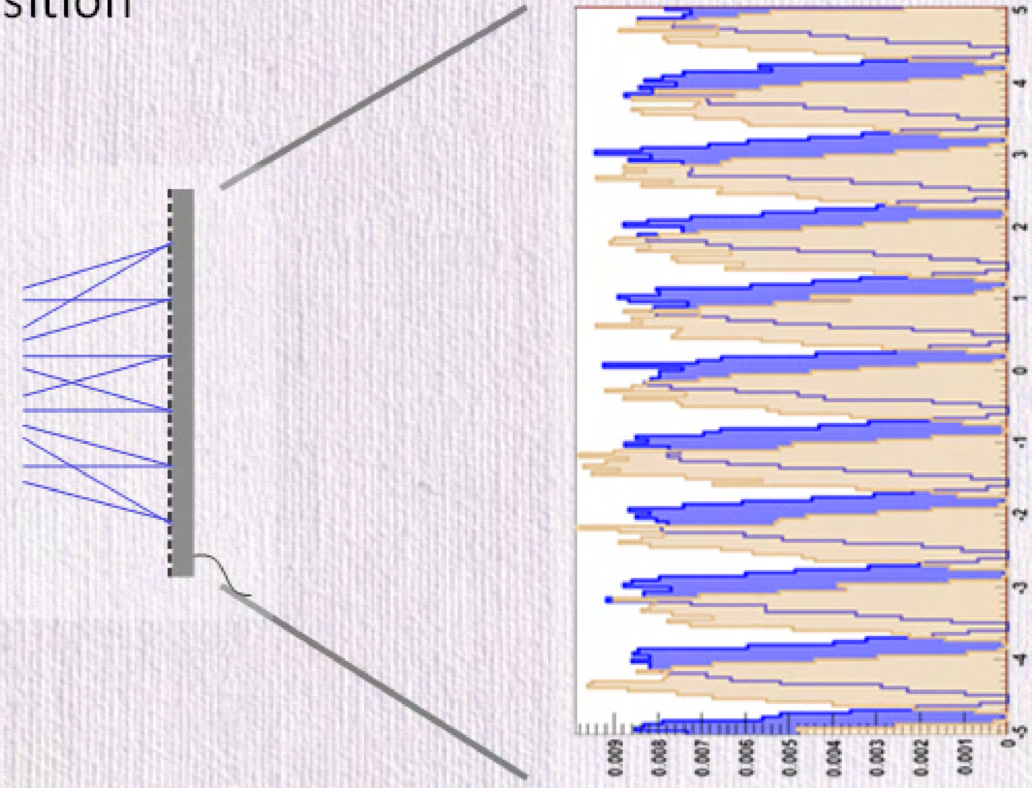
# 7) Gravity measurement



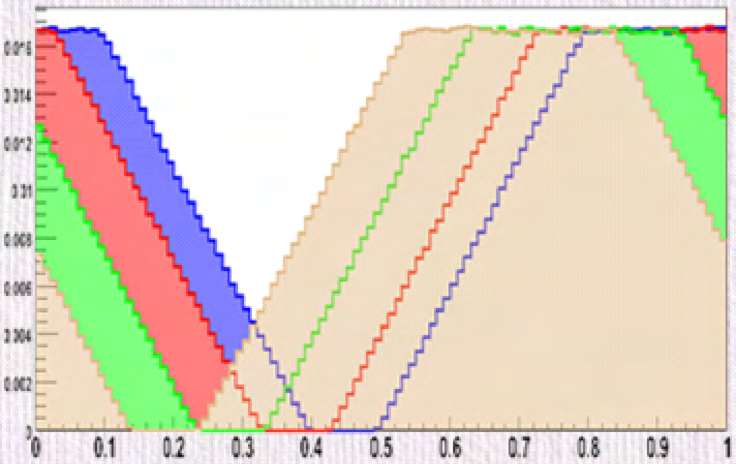
# 8) Data analysis

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

(Monte Carlo simulation)



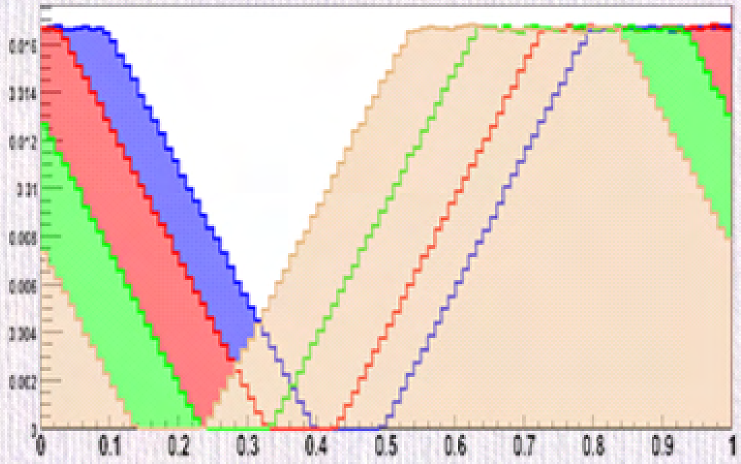
- Binning modulo grating period:

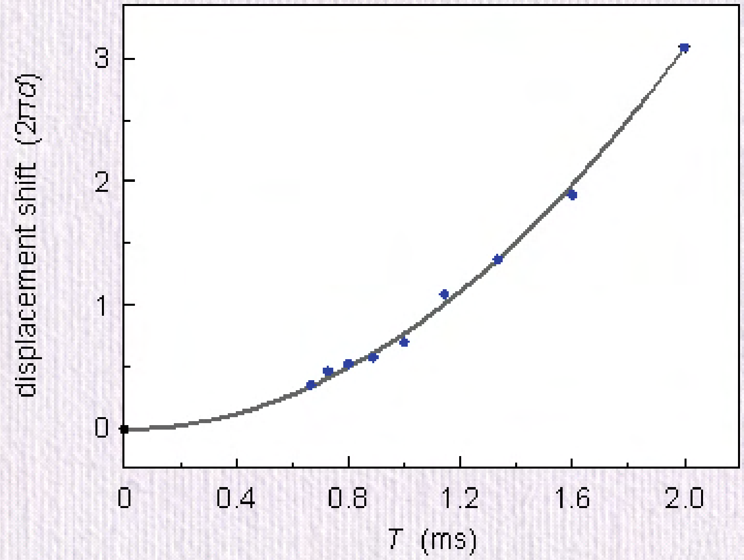



$v_{beam}$ = 600, 400, 300, 250 m/s

# 8) Data analysis

- Extraction of *g*:



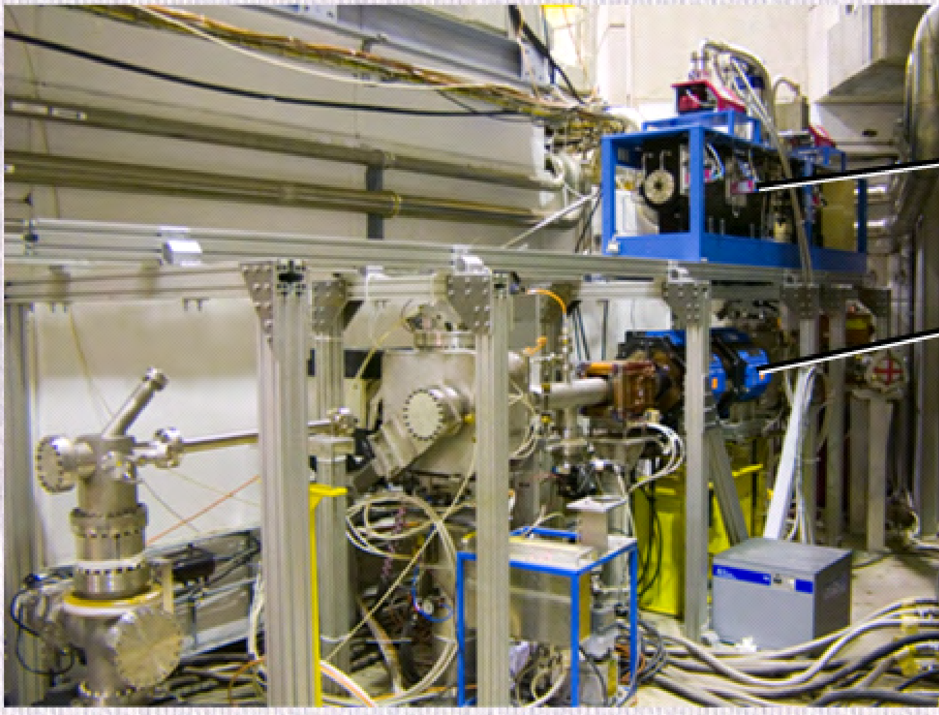




Measurement of $g$ to 1%:

- $\approx 10^5$ $\overline{\mathrm{H}}$ atoms at 100 mK
- 2 weeks of beam time
- 1 Hz event rate

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

# Status of AEGIS apparatus



- Completed components:

  Positron source, rare-gas moderator and trap

  AD beam line and diagnostics

  5-T magnet and trap (completed, to be installed October 2011)

  Laser system
  1-T magnet
  } (completed, to be installed January 2012)

- Main components under design / construction:
  - Positron accumulator: ordered, delivery March 2012
  - 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, parts ordered, 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, effects could be nil or measurable at the 1% level
- The AEGIS experiment intends to measure $\delta g/g$ of antihydrogen to (initially) 1%
- Construction of AEGIS apparatus ongoing
- Schedule:
  - Nov. 2011: First $\bar{p}$ capture; $e^+$ source commissioning
  - 2012: $\bar{p}$ capture, cooling and transfer; $e^+$ capture, accumulation and transfer; Ps formation and excitation; $\overline{\text{H}}$ formation and acceleration
  - 2014: First antimatter gravity experiment

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