AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

The AEgIS experiment: current status and outlook

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MARIE CURIE ACTIONS

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CERN

AEgIS collaboration

- ÖAW SMI – Stefan Meyer Institute
- CERN
- Czech Technical University
- ETH Zurich
- University of Genova
- University of Milano
- University of Padova
- University of Pavia
- Institute of Nuclear Research of the Russian Academy of Science
- Max-Planck Institute Heidelbert (Max-Planck-Institut für Kernphysik)
- Politecnico di Milano
- University College London
- University of Bergen
- University of Bern (Universität Bern, AEC Albert Einstein Center for Fundamental Physics)
- University of Brescia
- Heidelberg University
- CNRS – University of Lyon 1
- University of Oslo
- University of Paris Sud (Université Paris Sud)
- University of Trento
- INFN sections of: Genova, Milano, Padova, Pavia, Trento

Outline

- Antimatter and gravity
- AEgIS experiment
  - Research objectives
  - Antihydrogen production scheme
  - The AEgIS apparatus
  - Status and recent progress on different parts of the experiment
- Conclusions and outlook

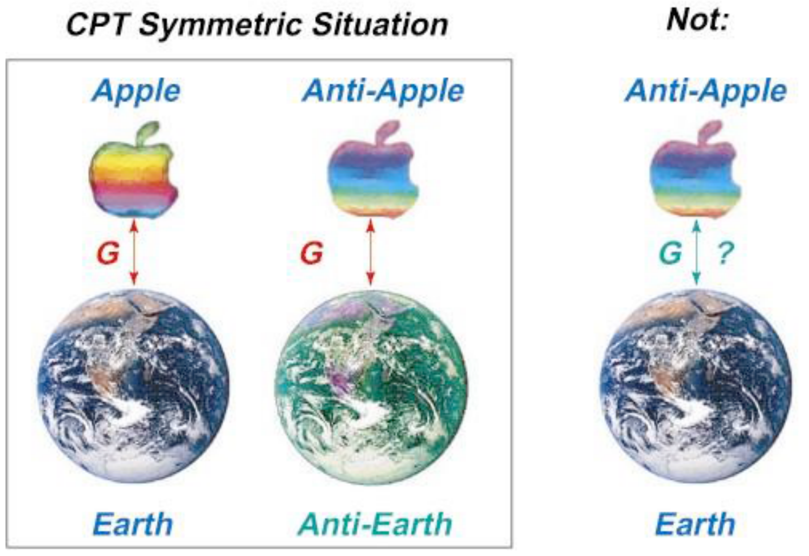
Antimatter and gravity

Currently no experimental WEP test available for antimatter.

- Normal matter $\Delta g/g$: 10^{-13} *[J.G. Williams et al. Phys. Rev. D 53, 6730, 1996].*

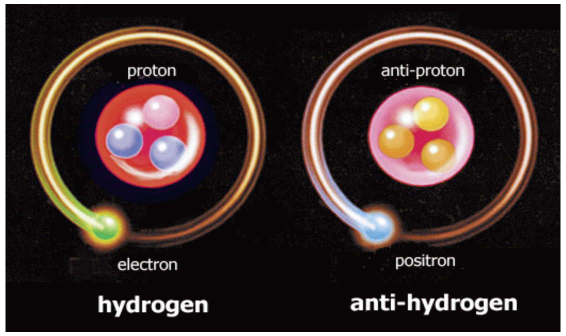
Three main hypothesis of gravitational interaction of matter with antimatter:

- Normal gravity - Einstein Equivalence Principle and Weak Equivalence Principle.
- Antigravity - CPT theorem, assuming its invariance also in curved space-time, and combining it with General Relativity *[M. Villata, EPL, 94(2) 2011].*
- Interaction with slightly different magnitude - Gravivector (spin 1)/graviscalar (spin 0) in quantum gravity theory *[T. Goldman et al. Phys. Rev. D, 36,1987].*

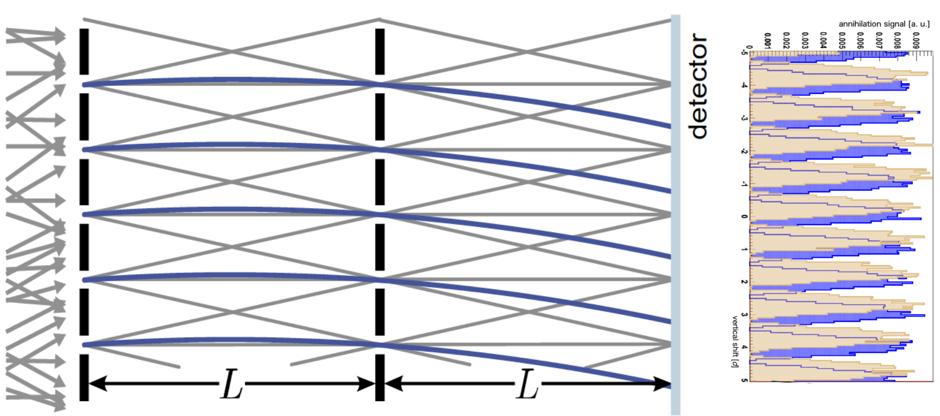


AEgIS experiment

- **AEgIS main goal: first direct measurement of the Earth's gravitational acceleration for antihydrogen, with 1% relative precision (Δg/g).**
  - Test of WEP on antimatter in Earth's gravitational field.
  - Direct measurement of g - free of any assumptions.
  - Antimatter gravity test with neutral particles (antihydrogen).



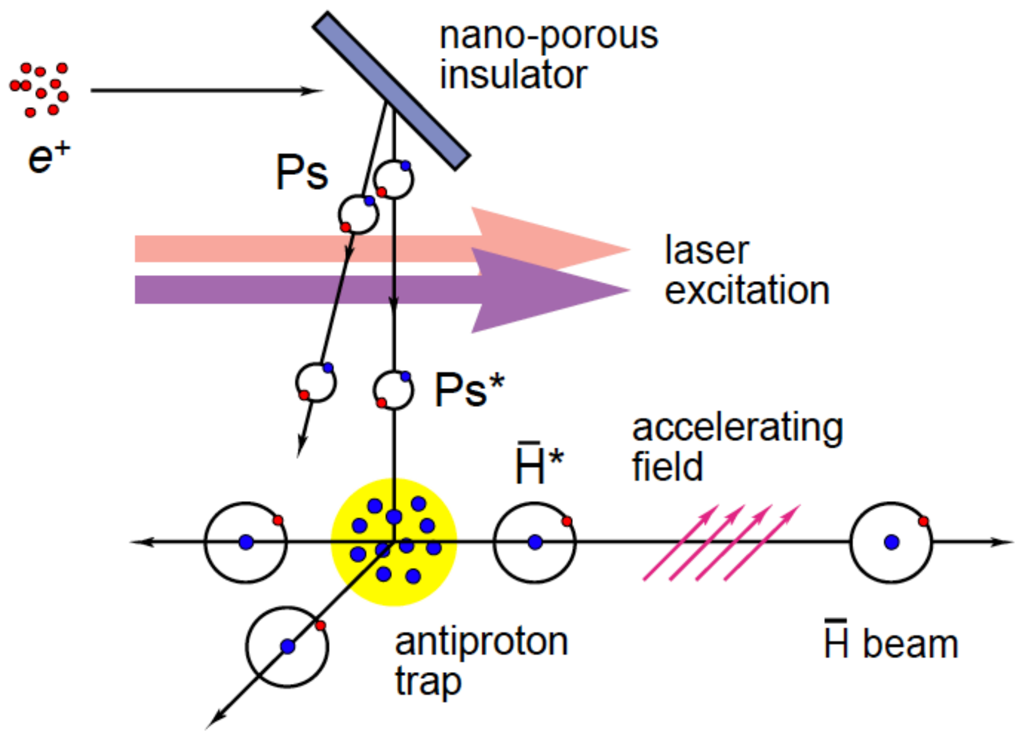
- **Method:**
  - Production of cold antihydrogen via charge exchange reaction *[C. H. Storry et al., Phys. Rev. Lett.* ***93*** *(2004) 263401]*.
  - Stark acceleration of antihydrogen -> beam.
  - Propagation of the beam through moiré deflectometer and detection of the free fall.



Antihydrogen production scheme

- Catching and cooling of 5.3 MeV antiprotons from the AD at CERN.
- o-Ps produced by implanting e^+ on SiO_2 target.
- Two step laser excitation of Ps into Rydberg levels:

  UV n=1 -> 3 IR n=3 -> Rydberg (10-20)
- Charge exchange reaction between cold antiprotons and Rydberg state positronium. *[AEgIS proposal, http://cdsweb.cern.ch/record/1037532]*
- Stark acceleration of the Rydberg atoms (to few 100 m/s) with electric field gradients.
- Production of cold, pulsed antihydrogen beam.

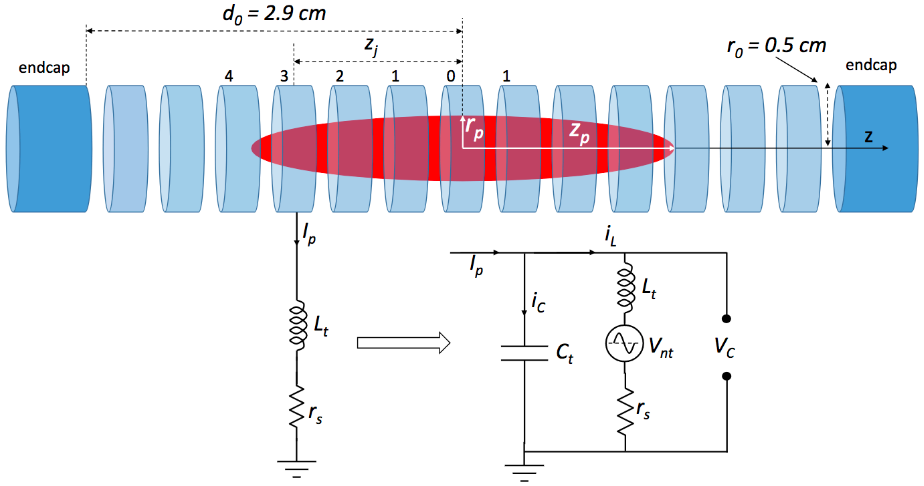


$$\mathrm{Ps}^* + \bar{\mathrm{p}} \rightarrow \bar{\mathrm{H}}^* + \mathrm{e}^-$$

Antiproton cooling

- $\bar{\mathrm{H}}$ **temperature is defined by the** $\bar{\mathrm{p}}$ **temperature -> cooling mechanisms needed**
  - Sympathetic radiation electron cooling (R&D for reaching ~7 K -> current trap temperature).
  - Evaporative/adiabatic plasma cooling (limited by $\bar{\mathrm{p}}$ number and axial confinement).
  - Resistive cooling (e^- cooled resistively with a tuned LC circuit in a harmonic trap).

    [S. Di Domizio et al., JINST Vol.10 (2015)]

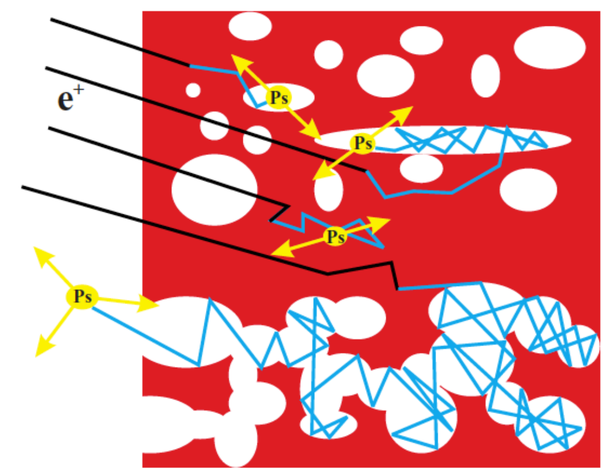


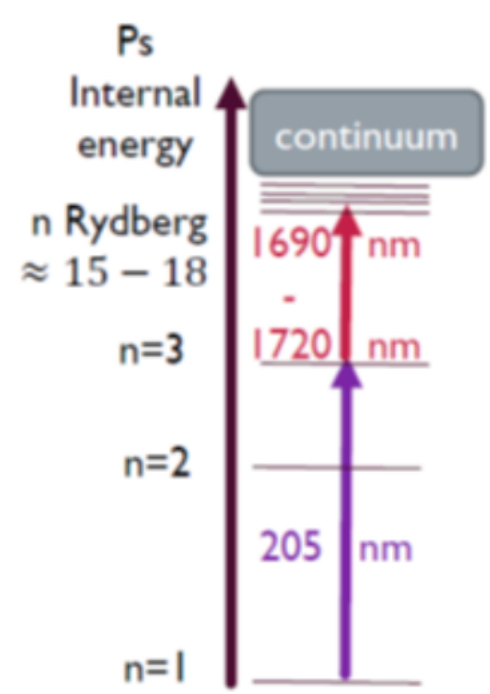
  - Sympathetic laser cooling with anions and molecules:
    - La^- spectroscopy *[E. Jordan et al., Phys. Rev. Lett.* ***115*** *113001 (2015)].*
    - C_2^- cooling [*P. Yzombard et al., Phys. Rev. Lett.* ***114*** *213001 (2015)].*

Positronium conversion and excitation

$$e^+ + e^- \rightarrow Ps \rightarrow Ps^*$$

- **Ps formation in nano-porous silica:**
  - Implantation of ~5 keV positrons -> scatter and slow to eV in few ns.
  - Positronium formation by capture of electrons.
  - ~37% Ps production efficiency expected *[S. Mariazzi et al., Phys. Rev. B 81 235418 (2010)]*.
  - Cold o-Ps (velocity < 10^5 m/s).
- **Ps excitation to Rydberg states:**
  - UV (205 nm) n=1 -> 3 *[S. Aghion et al., Phys. Rev. A 94 (2016) 012507]*.
  - IR (1650-1700 nm) n=3 -> Rydberg(16-30).





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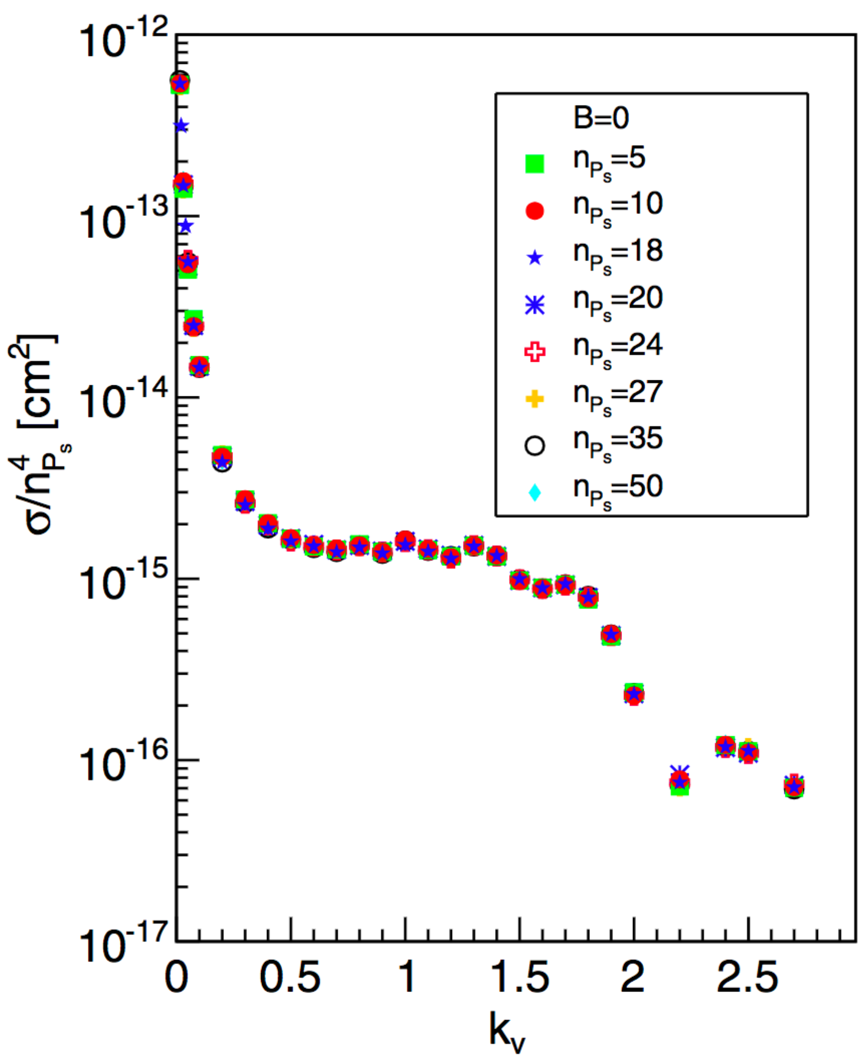
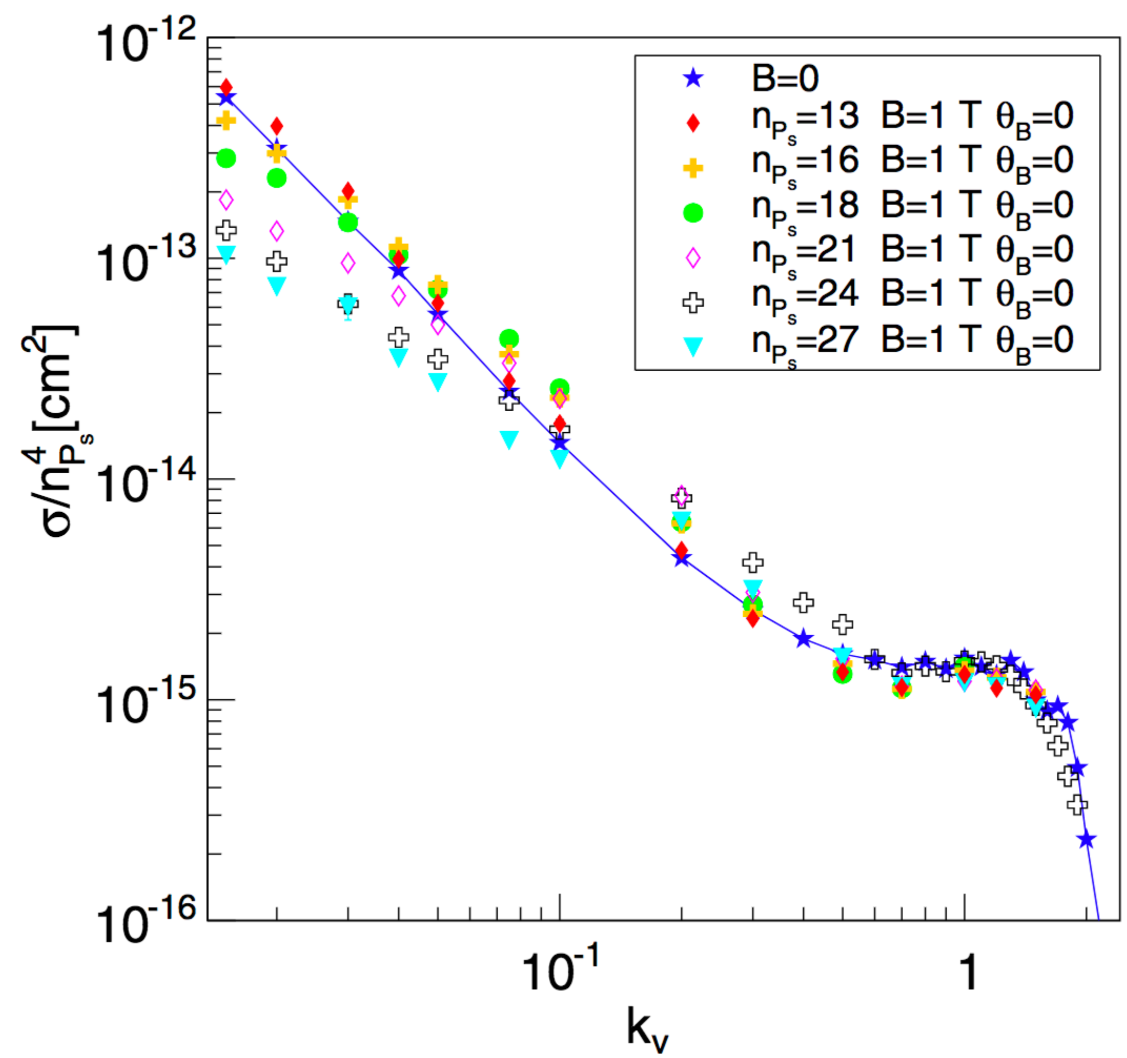
Antihydrogen production cross section $\sigma = a_0 {n_{Ps}}^4$

- Classical Trajectory Monte Carlo (CTMC) calculation of the cross section *[D. Krasnický et al., Phys. Rev. A 94, 022714 (2016)].*
- Only small variations to σ in 1 T magnetic fields.

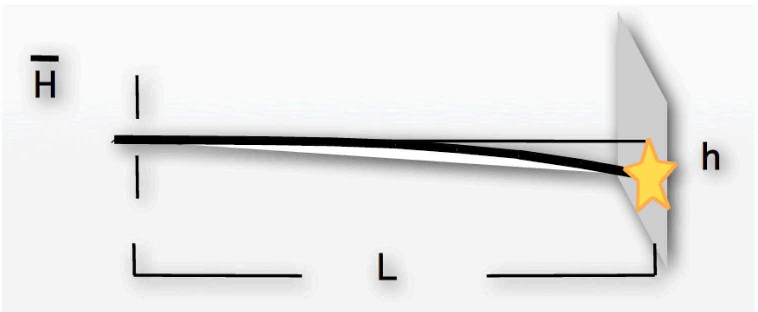




$$k_v = \frac{v^{cm}_{P_s}}{2 n_{P_s}}$$

AEgIS experiment: the gravity measurement

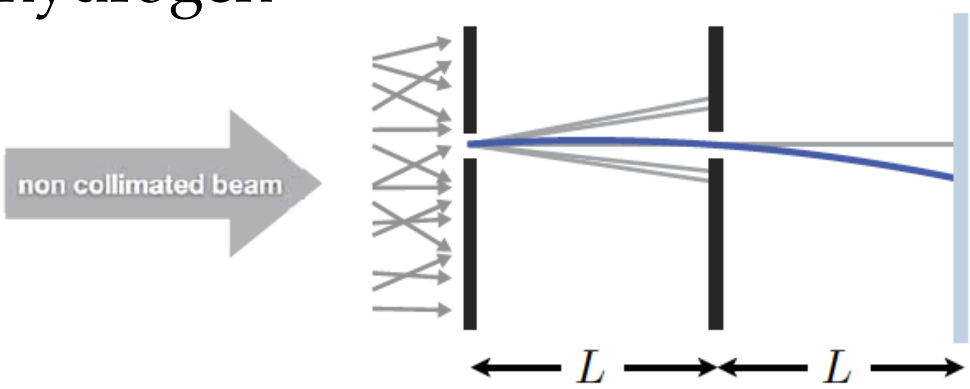
- **Antihydrogen pulsed beam**
    - velocity of few 100 m/s;
    - horizontal path of ~ 1 m;
    - time-of-flight ~ ms;



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

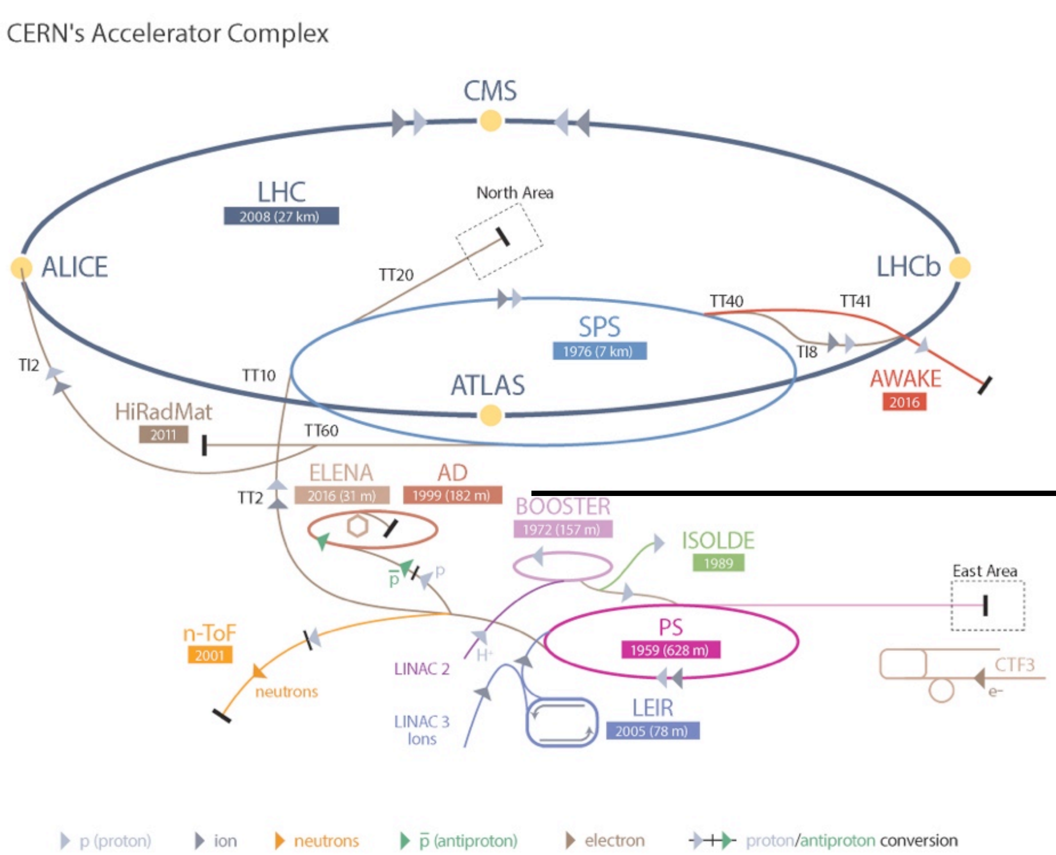
Vertical shift due to gravity ~20 μm (for v=500 m/s, L=1 m), time-of-flight ~ ms.

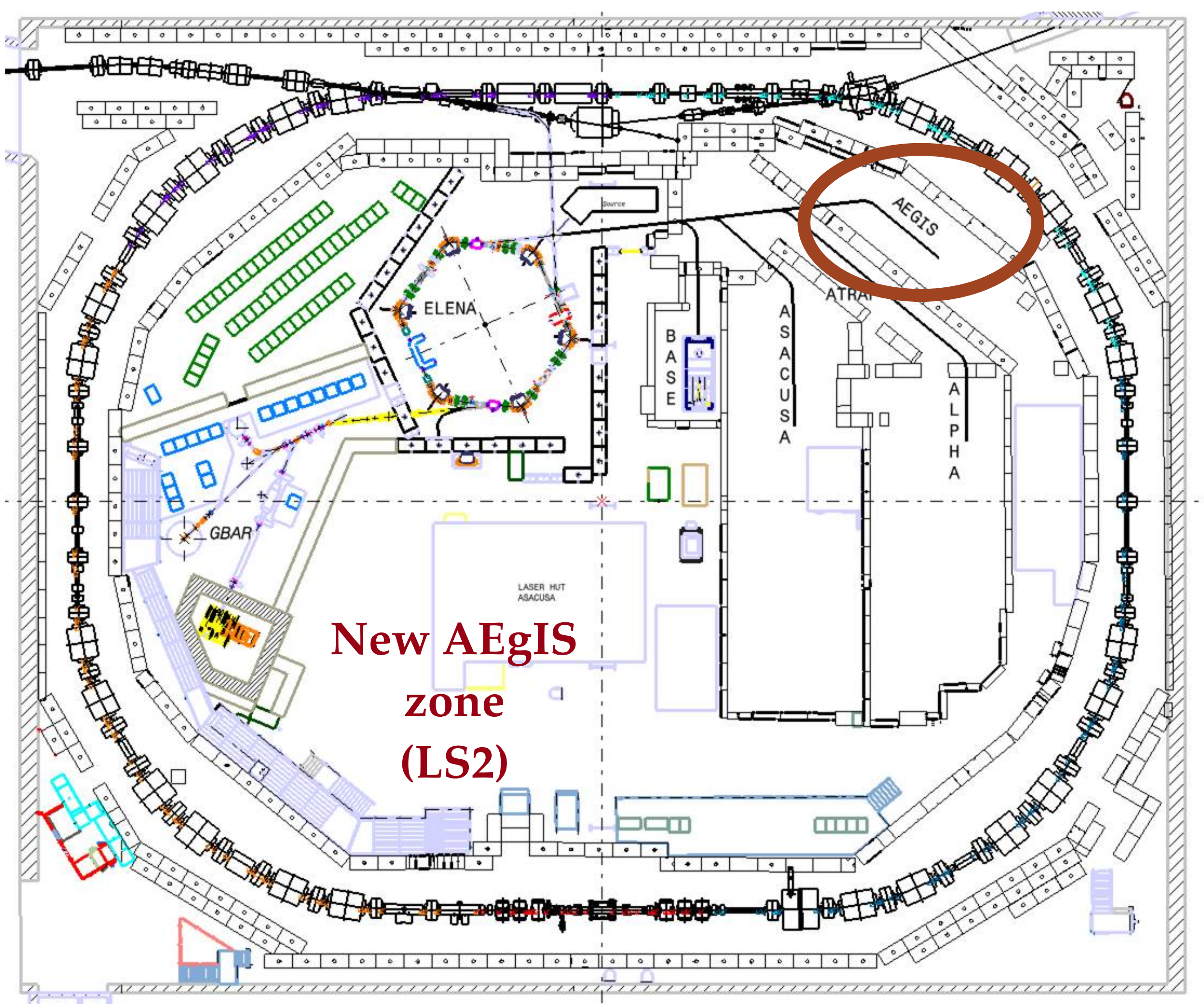
- Non-collimated beam.
- Maxwell distribution of the radial velocity of antihydrogen at 100 mK:
- $v_{thermal}$=300 m/s @ 5 K
- $v_{thermal}$=70m/s @ 0.3 K -> beam size of few cm!
- Introducing slits (40 μm pitch) to measure the shift of a pattern *[M. K. Oberthaler et al., Phys. Rev. A 54 (1996) 3165].*



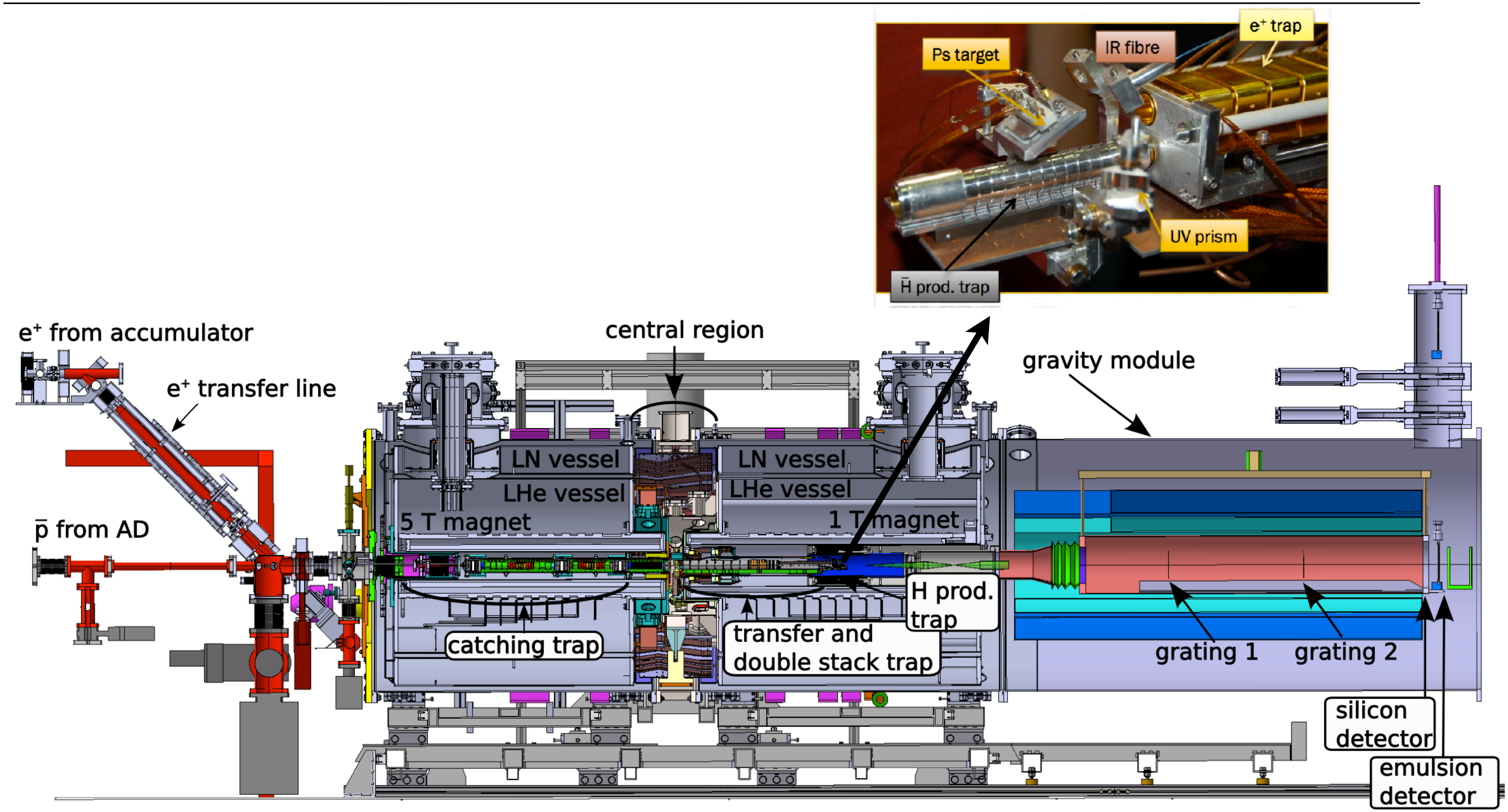
The Antiproton Decelerator at CERN

- **AEgIS current and new zone (after LS2):**

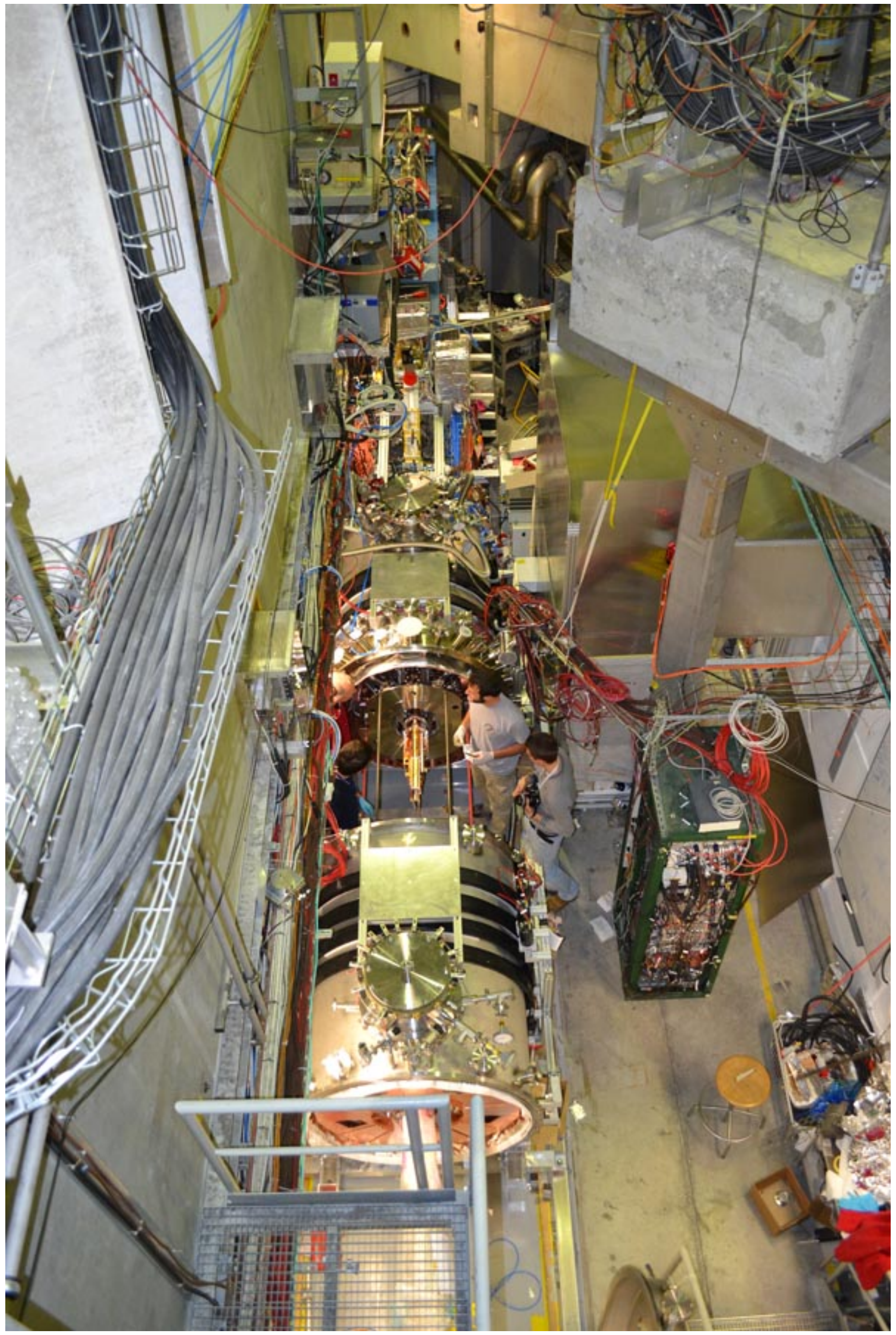




The AEgIS apparatus

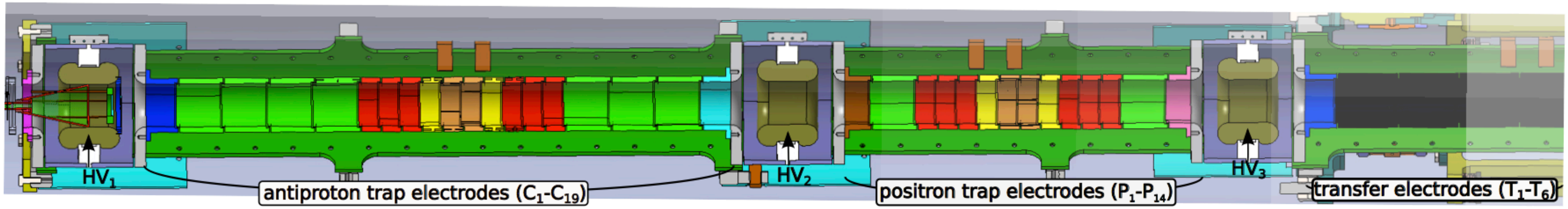


Status and recent progress of the AEgIS experimental apparatus



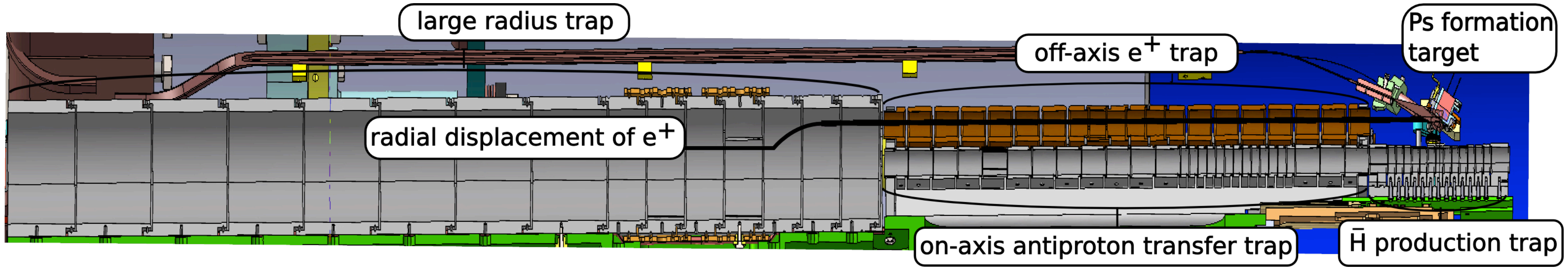
AEgIS trapping system

- **4.5 T catching traps:**



  - Antiproton catching, cooling & storage before transfer to 1 T region.
  - Multi Ring Trap: 1 m long, r = 15 mm, kept at ~10 K.
  - Variable trapping length: 46 cm or 76 cm (HV typically around 9 kV).

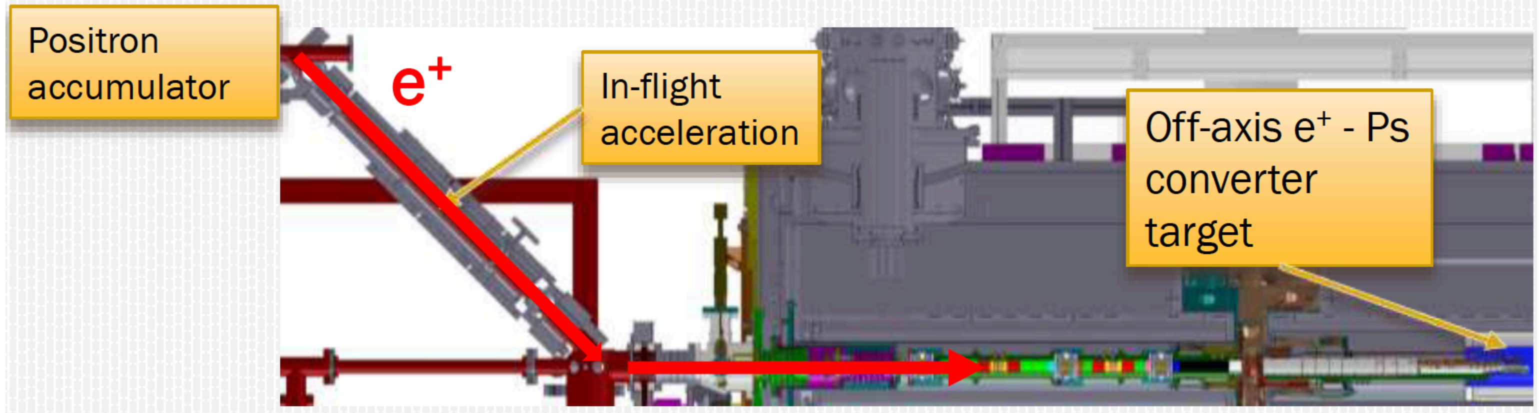
- **1 T antihydrogen production traps:**



  - Large radius trap: r = 22 mm.
  - Double stack traps: r = 5 mm.

Direct positron injection

- **Developed and commissioned a new positron injection method in AEgIS:**

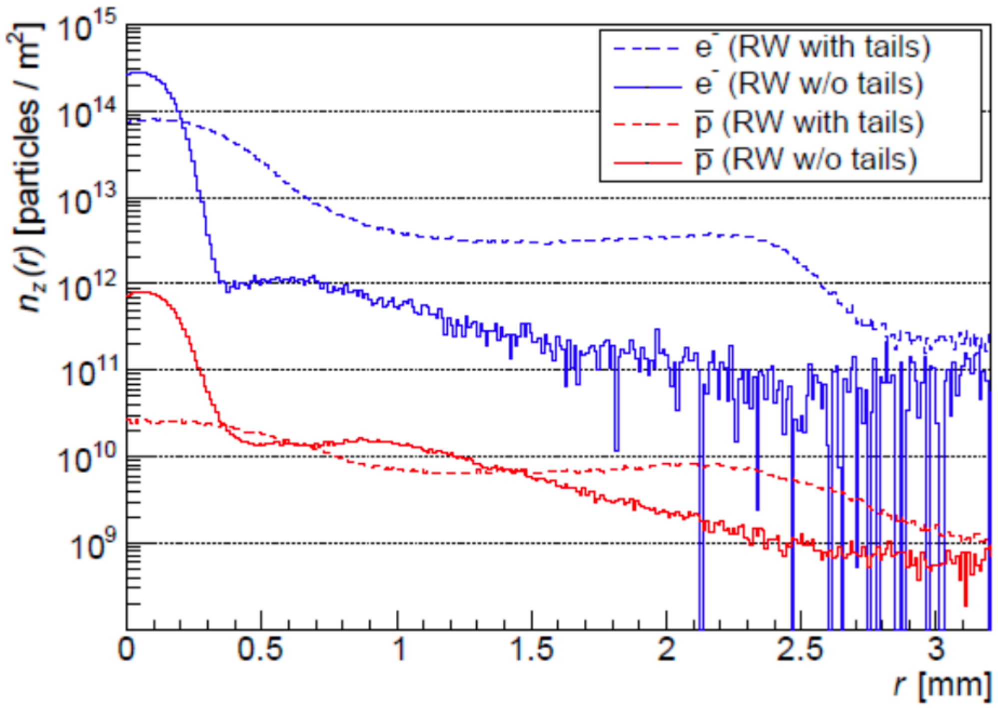


- Direct injection of accelerated (max 8 keV) e^+ from the accumulator into the target.
  - ~ 5m of total e^+ flight path in inhomogeneous magnetic fields.
  - Acceleration tube used to increase energy of positron cloud located ~3.5 m distant from the target, inside the positron transfer line vacuum chamber.
- Advantages:
  - No recapture in catching traps or other time consuming parallelized operations.
  - Potentially lossless transport and acceleration.
  - Immediate operation on trigger (once accumulator is full).

[Daniel Krasnický, LEAP 2018 - Paris]

Progress on antiproton plasma manipulation

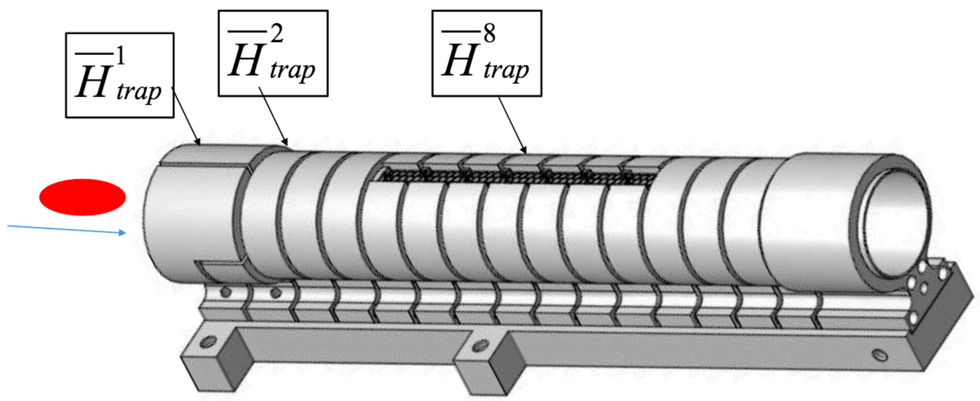
- **Cooling and compression in 4.5 T catching traps**
  - ~4.5x10^5 antiprotons trapped per AD shot (~3x10^7 antiprotons).
  - Electron cooling of the antiprotons with previously loaded electrons (~10^8 in the trap, coming from a source (barium oxide disc cathode)).
  - The antiproton cooling efficiency is ~50-60% (optimum for efficient radial compression of the mixed antiproton and electron plasma).
  - Compression by applying RF voltages to radial sectors of some trap electrodes (Rotating Wall).
  - A ten-fold antiproton radius compression has been achieved.
    - A typical antiproton radius of only 0.17 mm.

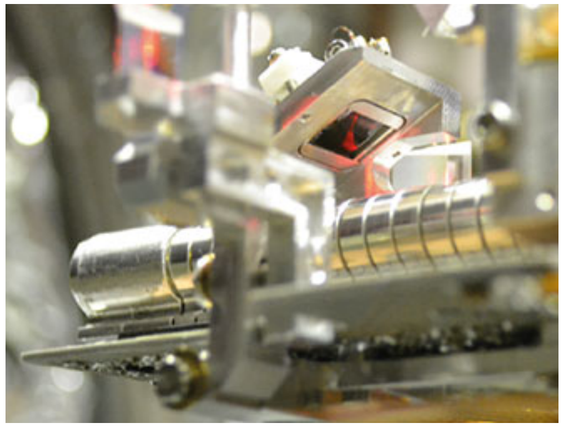


[Aghion, S., Amsler, C., Bonomi, G. et al. Eur. Phys. J. D (2018) 72: 76]

Progress on antiproton plasma manipulation

- **Manipulation of the confined plasmas in 1 T traps**
  - Strongest challenge: the semi-transparent region on top of the trap (~80% transparency) -> Radial asymmetry of the trap electric field (also limits the plasma trapping time).

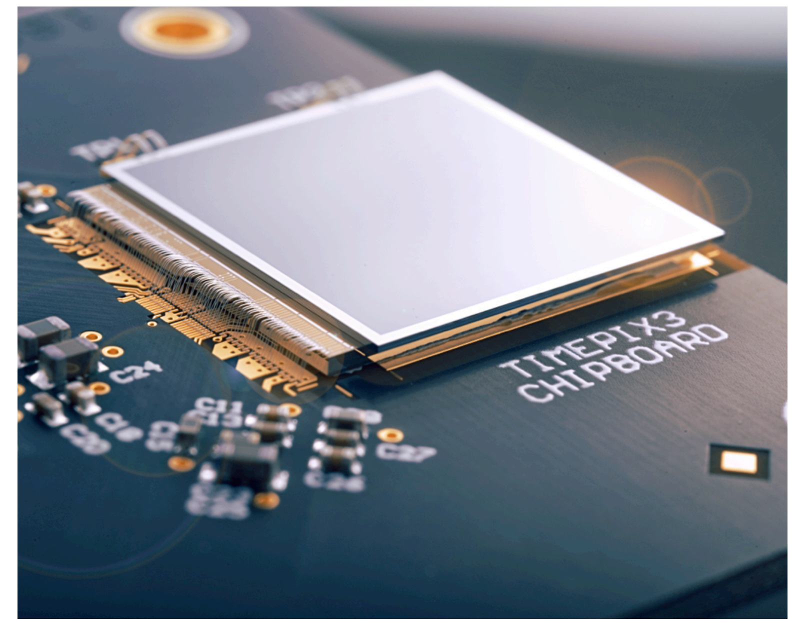




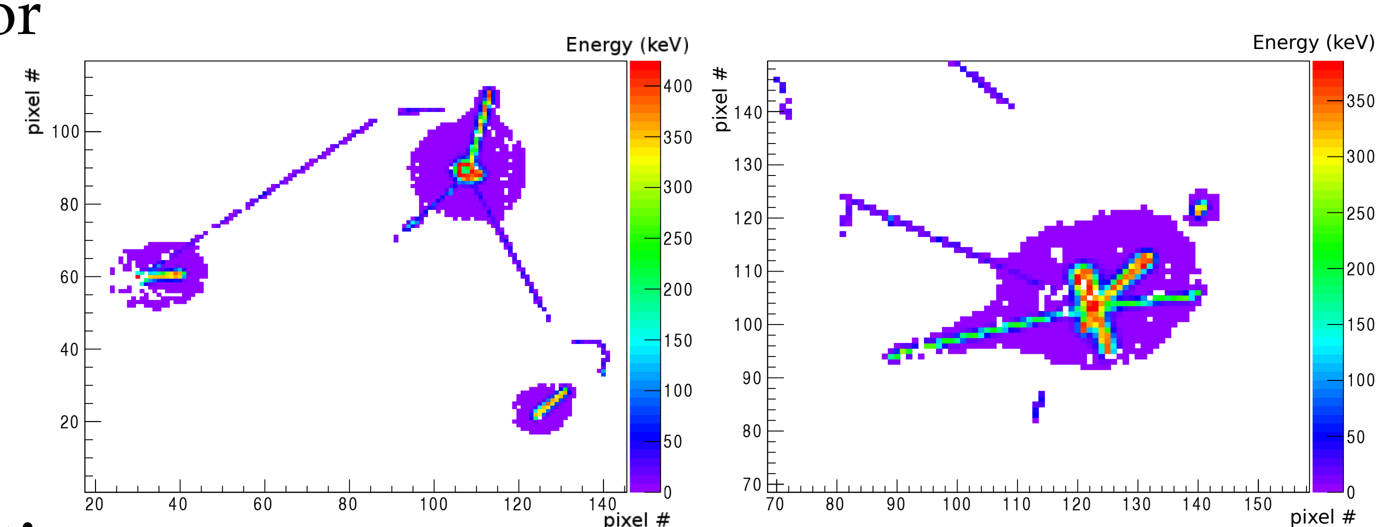
  - Ballistic transfer of antiprotons from 4.5T to 1T region (re-catching in-flight of an antiproton cloud).
  - ~ 2/3 of antiprotons are successfully transferred to the final trap
  - ~1/3 annihilates -> not compressed in the P-trap and do not fit into the 5 mm trap
  - 33% of total efficiency (cooling, compression and transfer) -> ~ 1.5 x 10^5 antiprotons/AD shot.

[Aghion, S., Amsler, C., Bonomi, G. et al. Eur. Phys. J. D (2018) 72: 76]

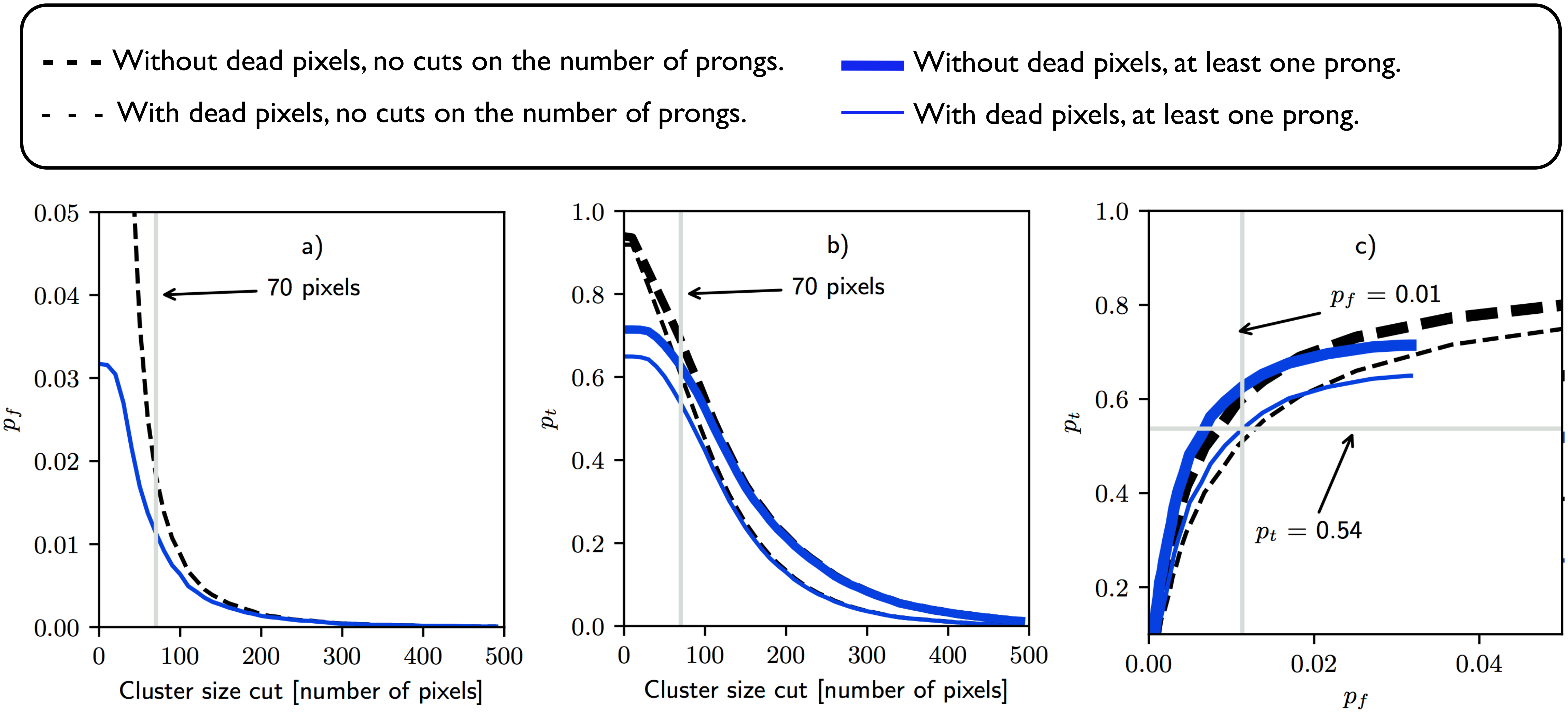
Progress on detector studies



- **Timepix3:**
  - Developed by the Medipix3 collaboration at CERN.
    - 55 µm pixel pitch.
    - 256 x 256 pixels.
  - Simultaneous measurement of ToT and ToA.
  - 40 MHz readout, 640 MHz fast clock for the ToA.
  - Time resolution of 1.6 ns.
  - Dynamic range: up to ~500 keV / pixel.
  - Bonded to 675 µm thick Si sensor.
- **Study of individual antiproton annihilations**



Antiproton tagging efficiency with Timepix3



a) Cluster size cut vs. tagging false rate

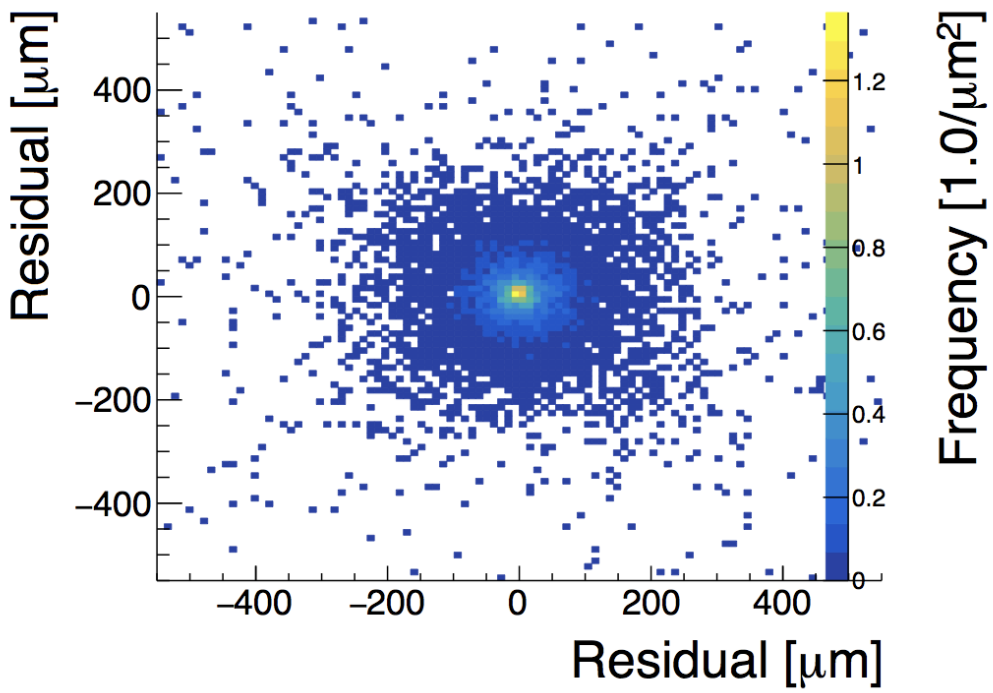
b) Cluster size cut vs. tagging efficiency

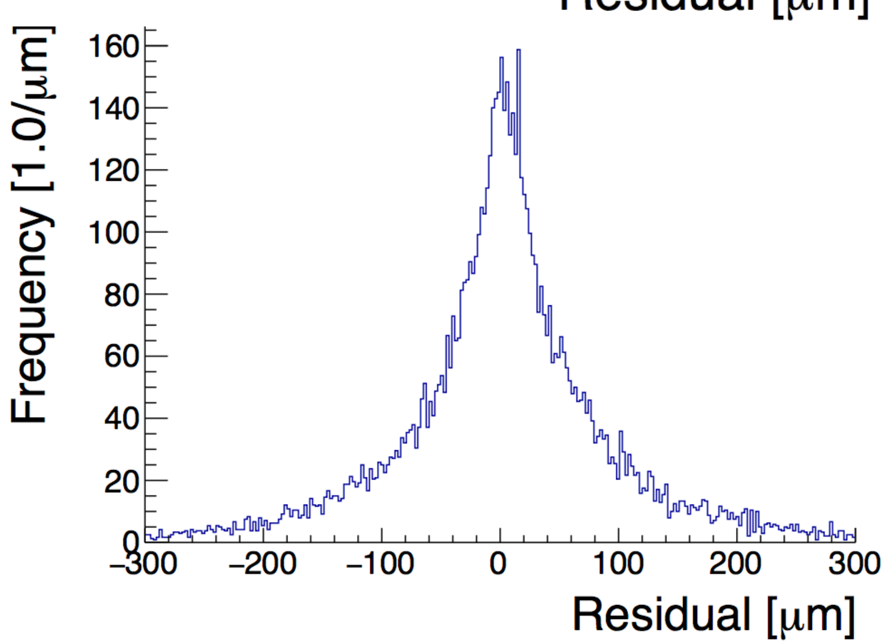
c) Tagging false rate vs. tagging efficiency

[S. Aghion et al 2018 JINST ***13*** *P06004]*

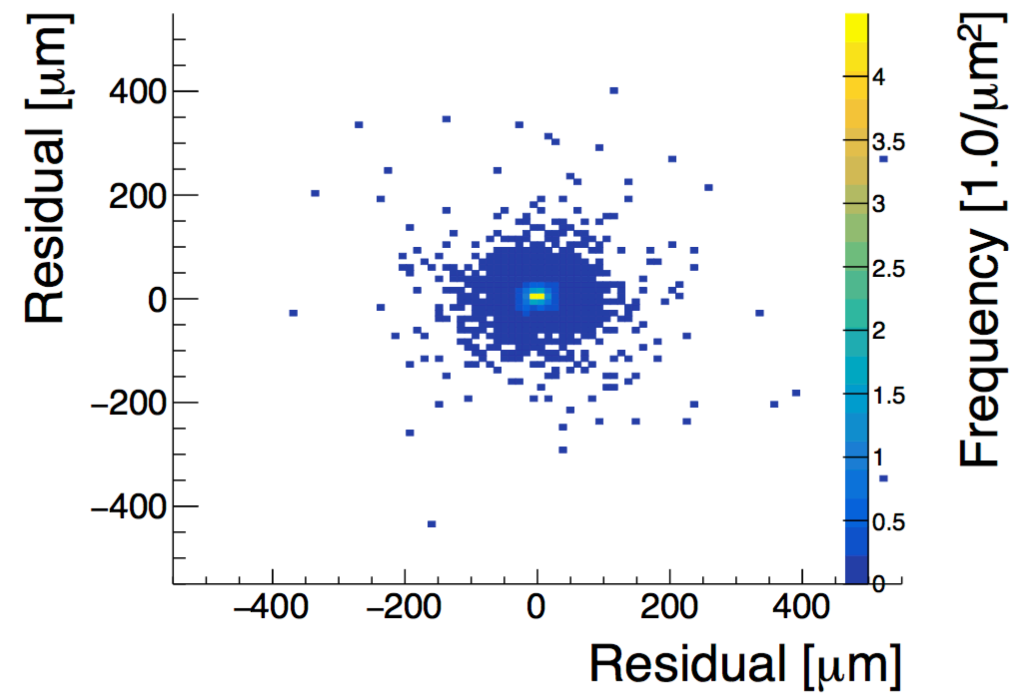
Vertical position resolution with Timepix3

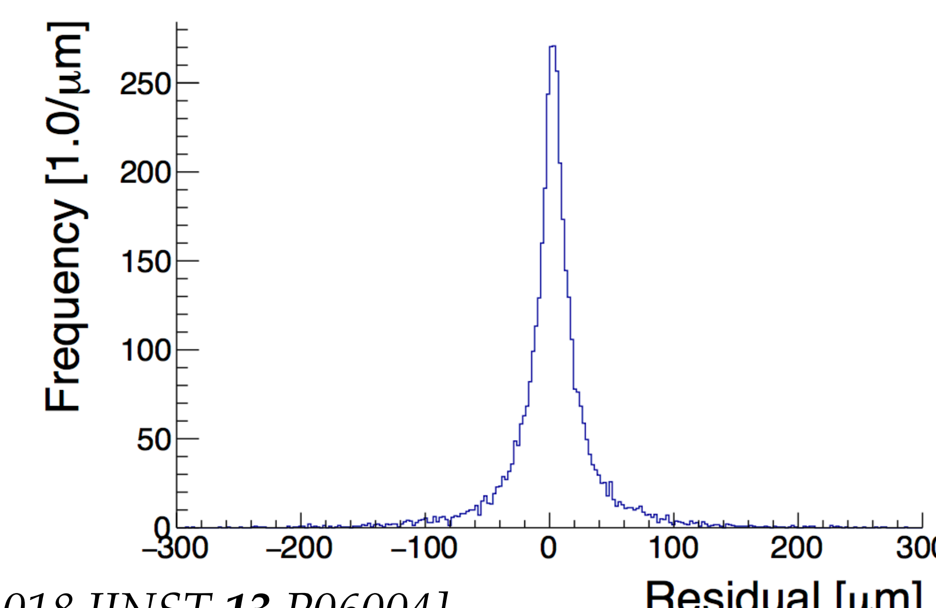
- Center of mass method, σ=96.6 μm





- Vertex fitting method, σ=22.1 μm





*[S. Aghion et al 2018 JINST **13** P06004]*

Conclusions and outlook

- The AEgIS experiment aims to measure the gravitational acceleration of antihydrogen to 1% accuracy:
  - Cold antihydrogen beam + moiré deflectometer.
- New, simpler and highly efficient positron injection scheme for significantly simplified particle manipulation in AEgIS.
- Antiprotons compressed in 4.5 T field down to 0.17 mm radii.
- 1.5 x 10^5 antiprotons / AD shot are routinely available for antihydrogen production.
- Vertical position resolution of 22.1 μm and antiproton tagging efficiency of ~ 55% achieved with Timepix3 detector.
- Antihydrogen production by charge exchange reaction is expected during 2018 beam time.