Antimatter annihilation detection with AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) using silicon detectors

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AEḡIS collaboration

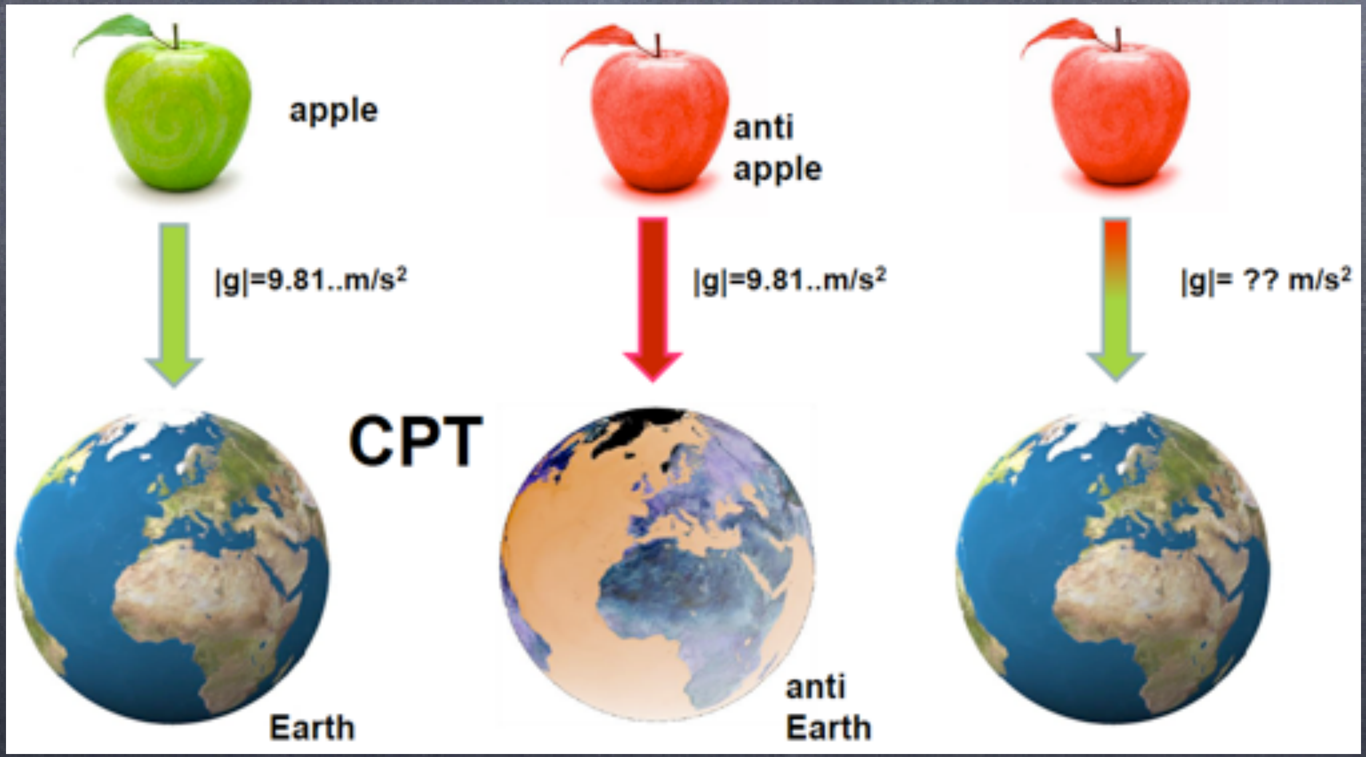
- Stefan Meyer Institute
- CERN
- Czech Technical University
- ETH Zurich
- University of Genova
- University of Milano
- University of Padova
- University of Pavia
- Institute of Nuclear Research of the Russian Academy of Science
- Max-Planck Institute Heidelberg
- Politecnico di Milano
- University College London
- University of Bergen
- University of Bern
- University of Brescia
- Heidelberg University
- University of Lyon 1
- University of Oslo
- University of Paris Sud
- University of Trento
- INFN sections of: Genova, Milano, Padova, Pavia, Trento

Outline

- The AEgIS experiment (physics motivation, principle, apparatus...)
- Development of Silicon position detector.
  - Beam tests: low energy antiproton annihilations in silicon detectors-measurements and results
    - MAPS detector
    - 3D silicon pixel detector
    - silicon microstrip detector
  - Tests with Timepix3 detector and current work
- Conclusions

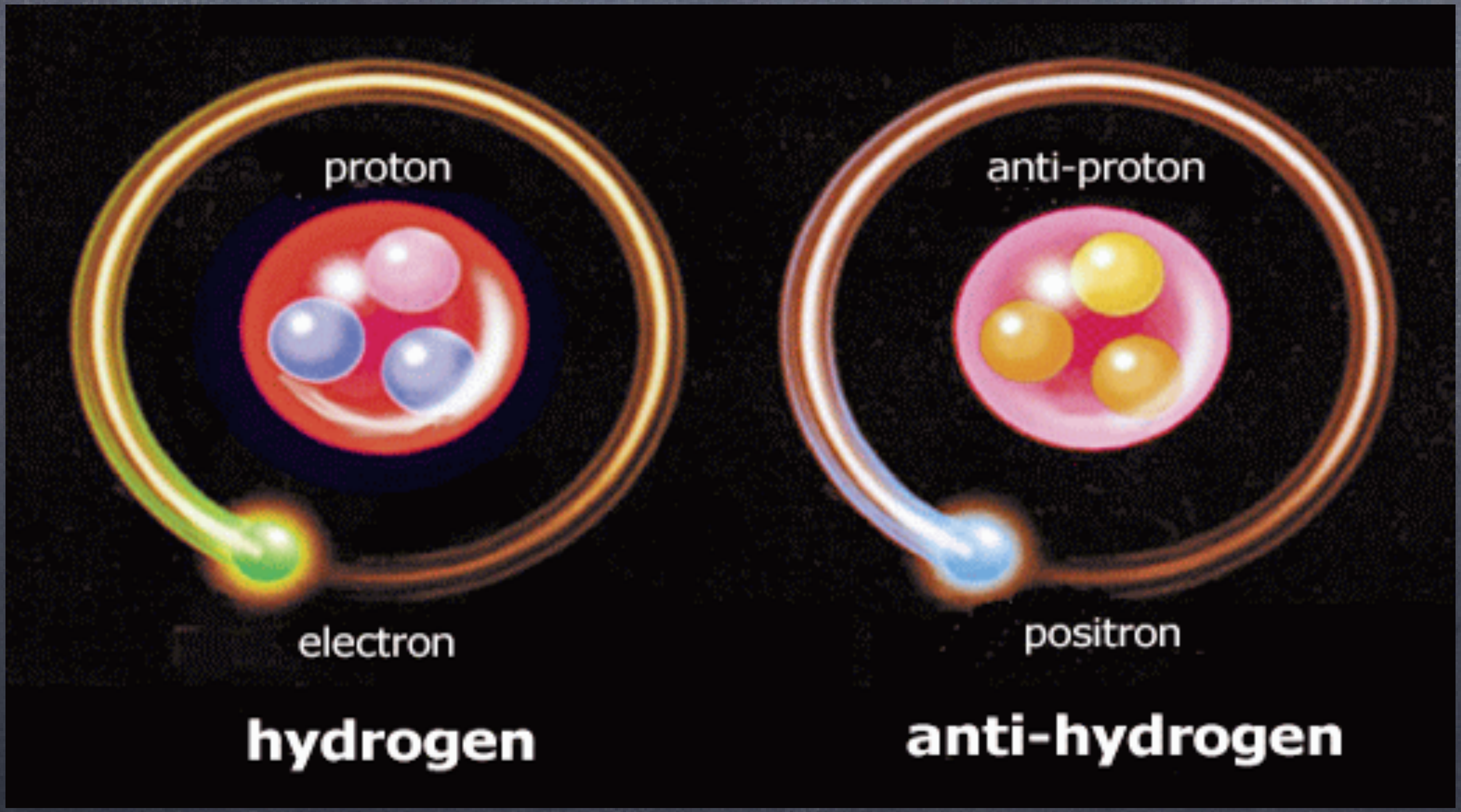
Physics motivation for measuring the free fall of antimatter

- Principle of equivalence between gravitational and inertial mass is a foundation of General Relativity.
- General relativity: classical theory that makes no distinction between matter and antimatter.
  - Einstein field: Tensor graviton (spin 2)
- Quantum theories of gravity predict the existence of additional gravitational forces.
  - Quantum theories of gravity: Gravivector (spin 1), Graviscalar (spin 0)
- Universality of Free-Fall tested to 1 part in 10^{12}, but only with matter based experiments.



AEgIS - Antimatter experiment: gravity, interferometry, spectroscopy

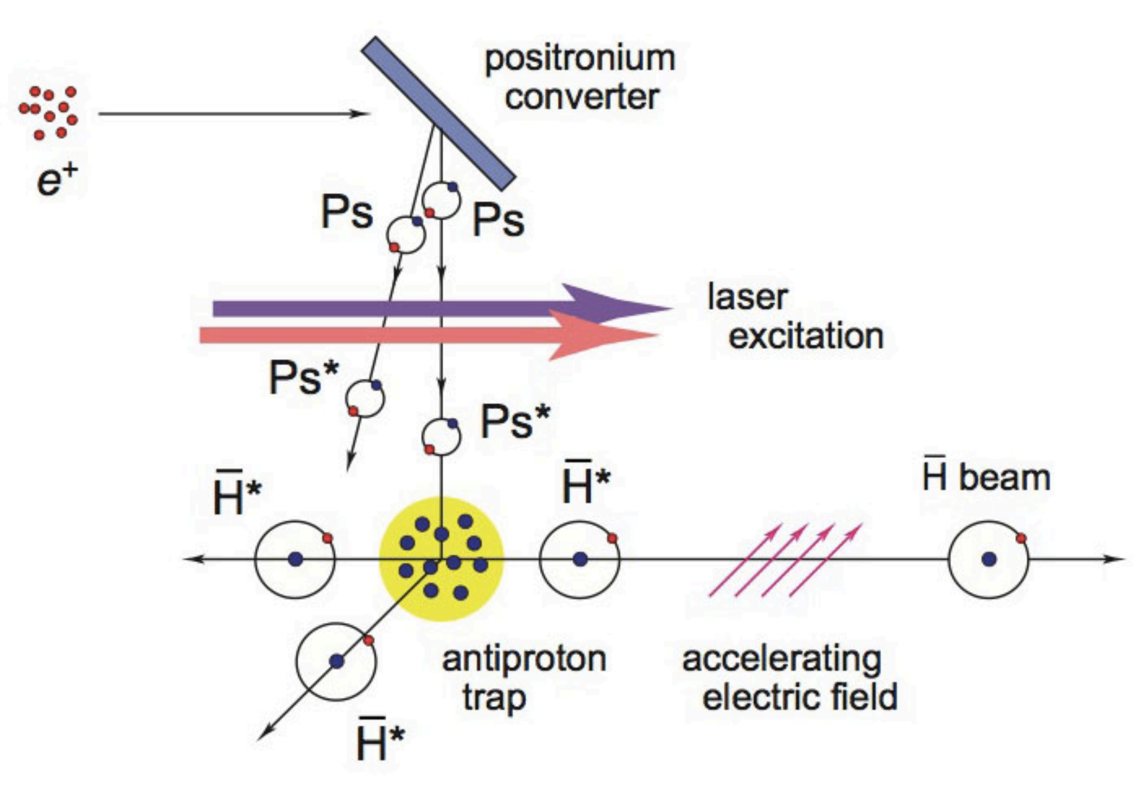
- AEgIS: Test the Universality of Free-Fall with antimatter by measuring the Earth's gravitational acceleration for antimatter.
- Simplest form of electrically neutral antimatter: antihydrogen.
- 1% relative precision ($\Delta g/g$) in the first phase (2016) will be attempted.



AEgIS principle of antihydrogen formation

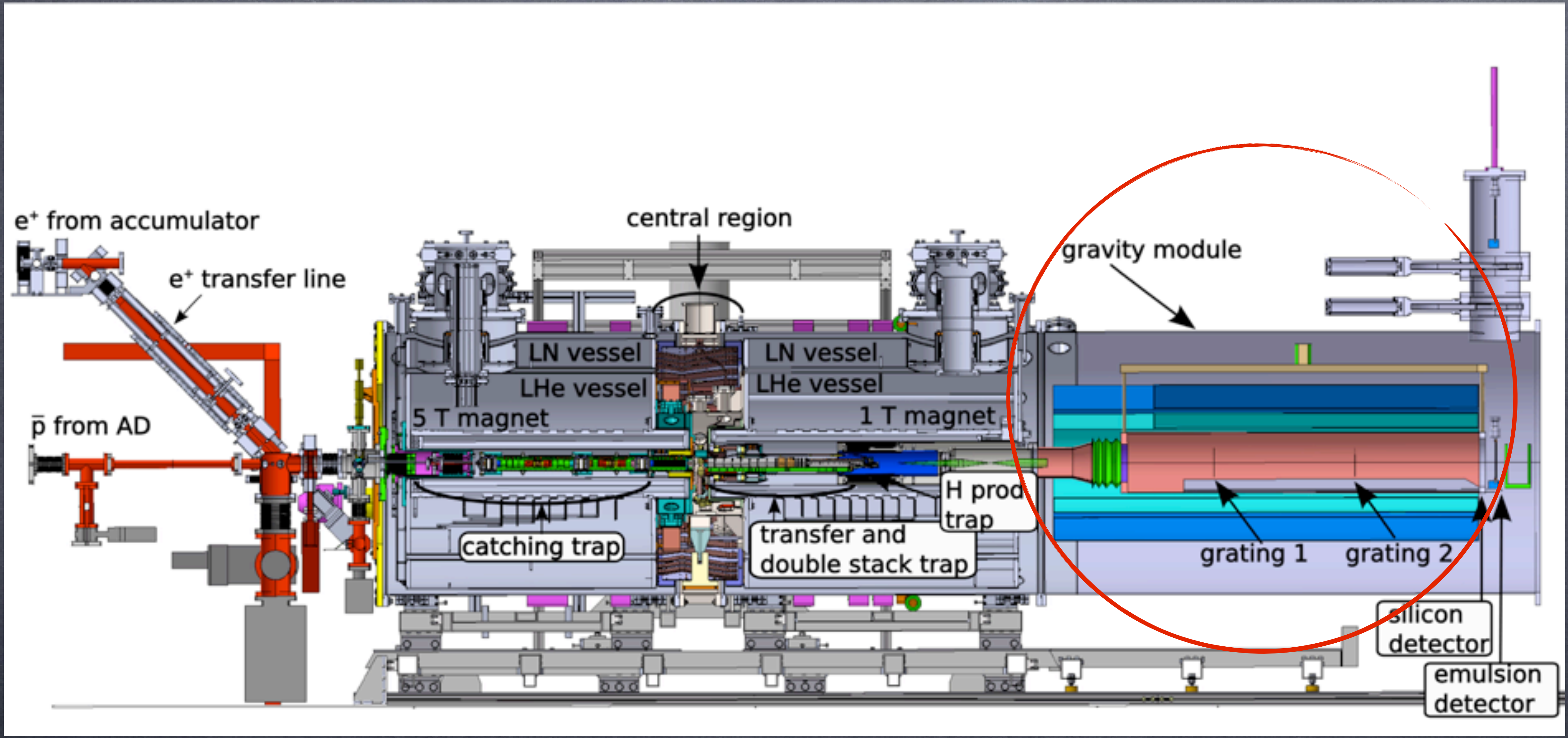
$$\bar{\mathrm{p}} + \mathrm{Ps}^* \rightarrow \bar{\mathrm{H}}^* + \mathrm{e}^-$$

- Slowing down, catching (< 10 keV) and cooling (preferably to 100 mK) of antiprotons with 5 MeV initial energy coming from the Antiproton Decelerator (AD);
- Accumulation of positrons from ^{22}Na source;
- Formation of positronium (Ps) and laser excitation to Rydberg state (n=20-30);
- Antihydrogen production by resonant charge exchange reaction.
- Formation of antihydrogen beam by Stark acceleration.
- Detection of free fall antihydrogen with position detector.



Schematic overview of the antihydrogen production in AEgIS.

AEgIS apparatus



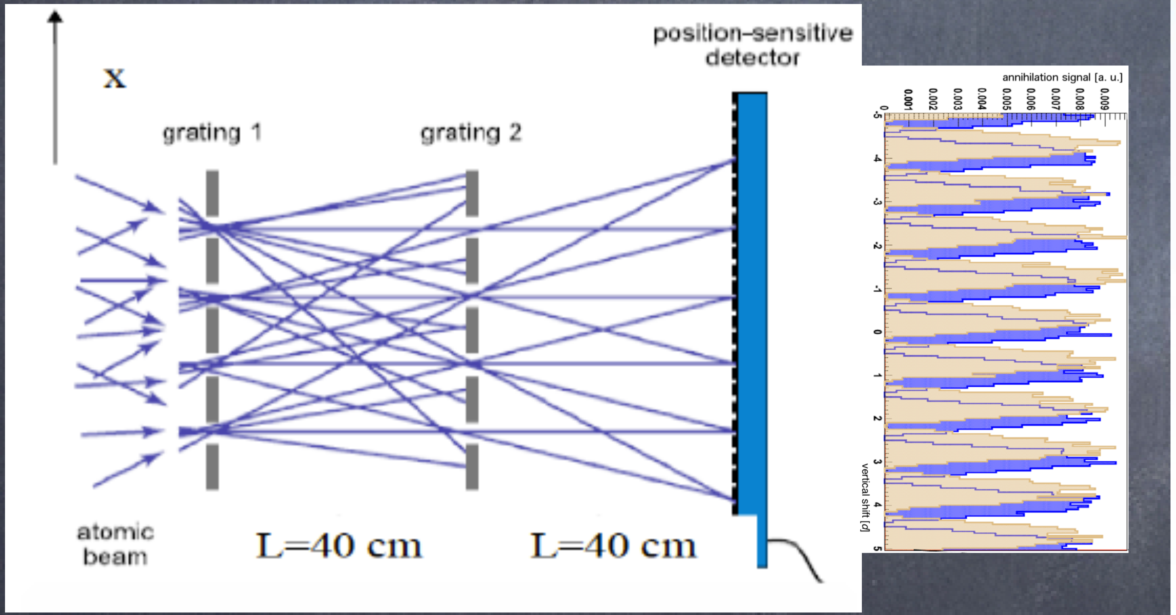
Schematic view of the AEgIS apparatus.

AEgIS gravity measurement

- Maxwell distribution of the radial velocity of antihydrogen at 100 mK.
- Fringe pattern with same period as the gratings, which is shifted due to Earth's gravity.
- Vertical shift (~20 µm for v=500 m/s, L=1 m):

$$\frac{\Delta_x}{d} = -\frac{g}{d}T^2 = -\frac{g}{d}\frac{L^2}{v_z^2} \qquad \Delta\Phi_g = \frac{2\pi\Delta_x}{d} = \frac{2\pi}{d}gT^2$$

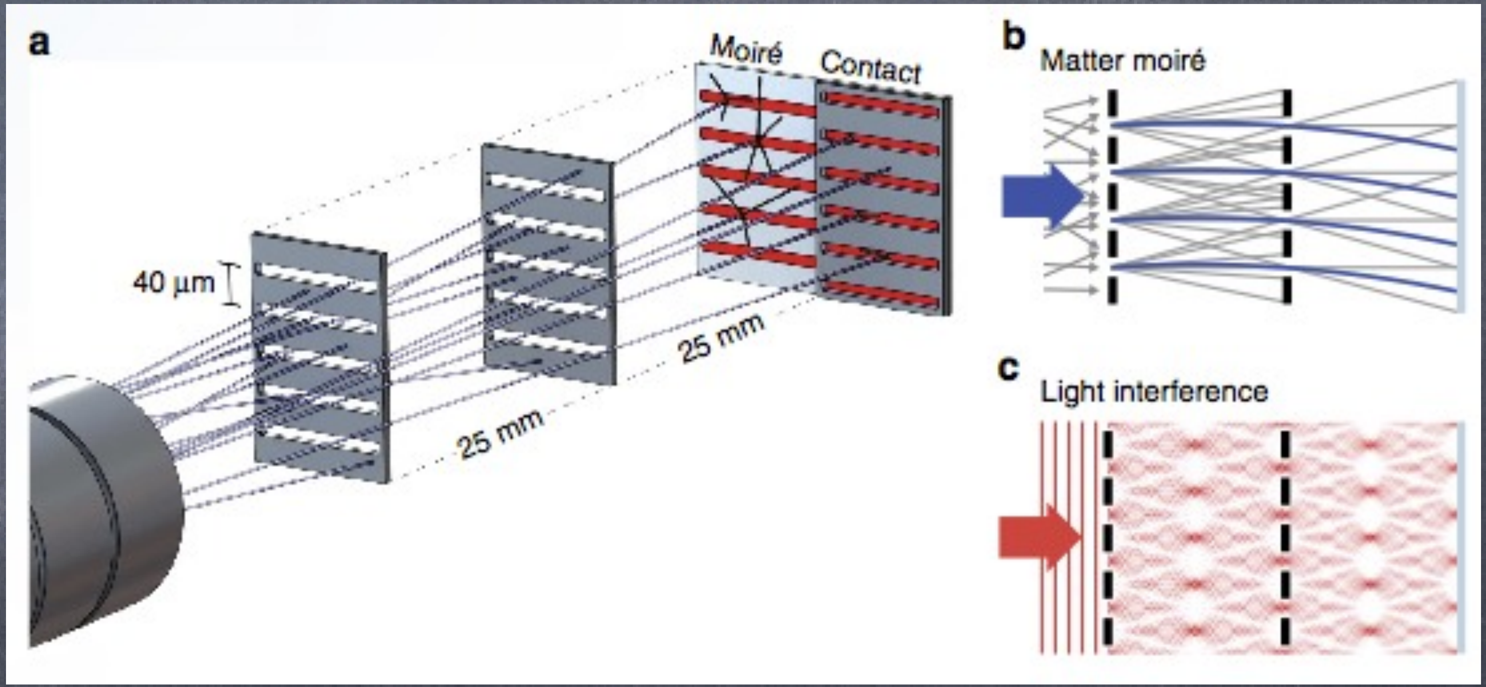
$$T = T_{det} - T_{off}$$



Scheme of the moiré deflectometer with a simulated signal from the detector for two different antihydrogen velocities (250 m/s and 600 m/s).

Proof of principle, mini-moiré

Aghion, S. et al. Nature Communications, 5, 4538 (2014)



- shift between light and antiproton pattern observed
- consistent with residual B, E fields
- sensitivity of µm reached

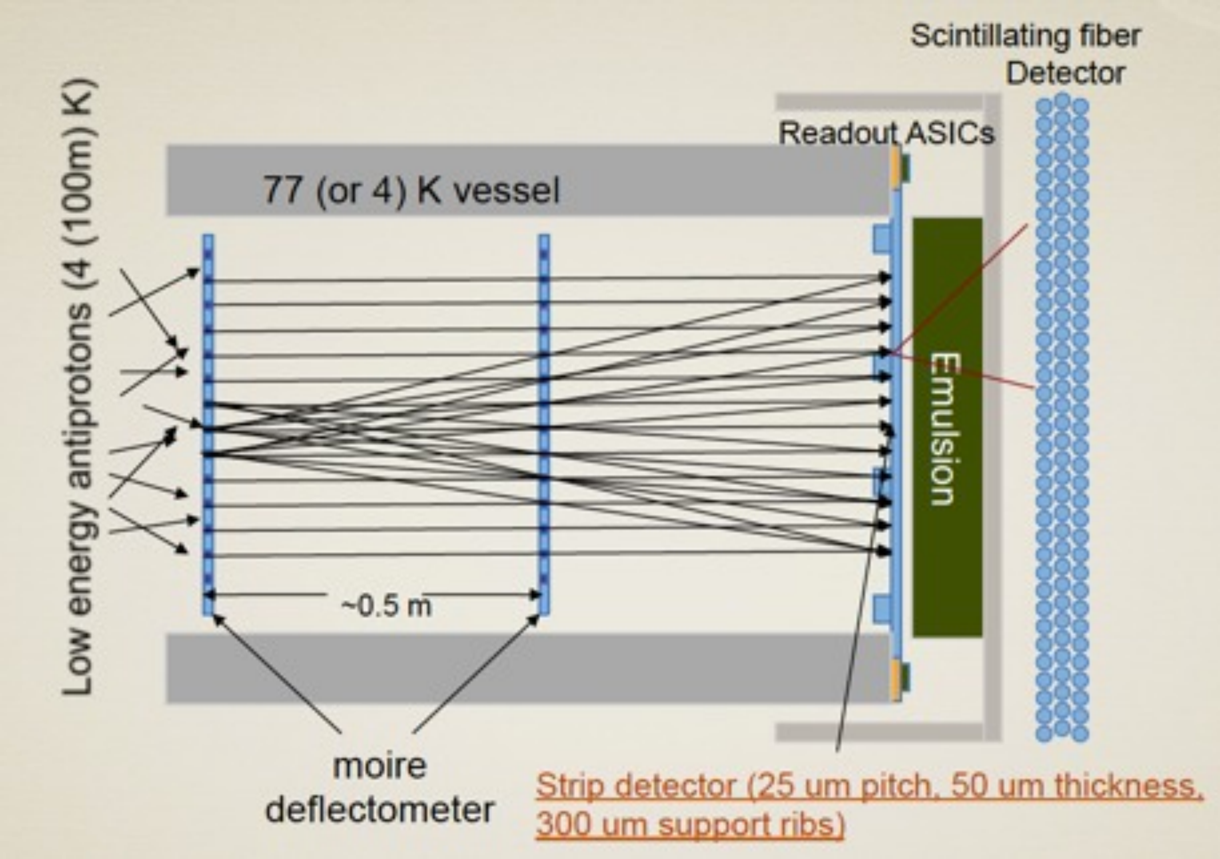
AEgIS position detector

Position detector

Silicon position detector, where the annihilation of antihydrogen takes place (~10 µm resolution) .

Emulsion detector, for more precise reconstruction of the annihilation point (~1 µm).

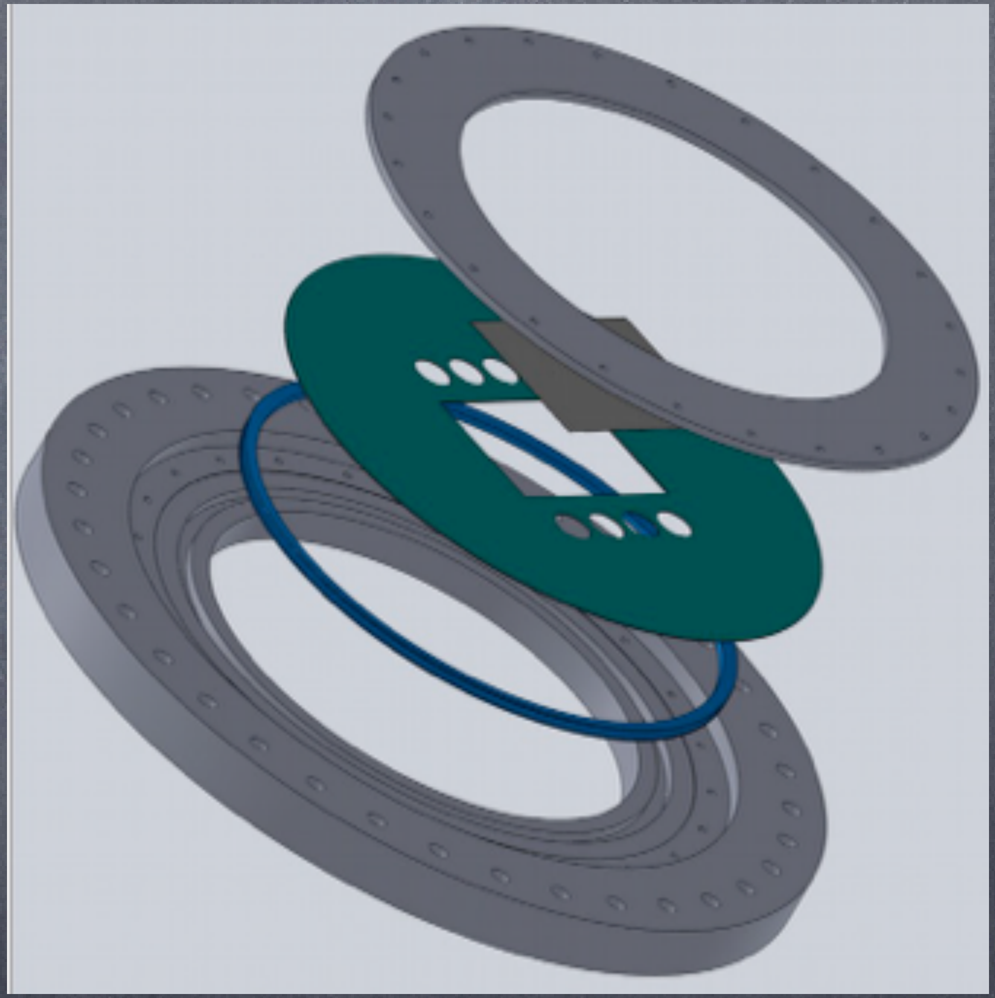
Fibre time-of-flight for timing information on the emulsion detector.



Scheme of the position detector in AEgIS.

Requirements for AEgIS silicon position detector

- Online measurement of the annihilation events:
    - spatial information of the antihydrogen annihilation position (~10 µm) and the arrival time for each antihydrogen atom.
- Separation membrane between the ultra-high vacuum (10^{-12} mbar), and the secondary vacuum (10^{-6} mbar).
- Wide area (10x7 cm^2).
- 50 µm maximum thickness on active areas to minimize scattering for the emulsion detector.
- Time resolution of the order of µs.
- Cryogenic operation (77 K or 4 K).



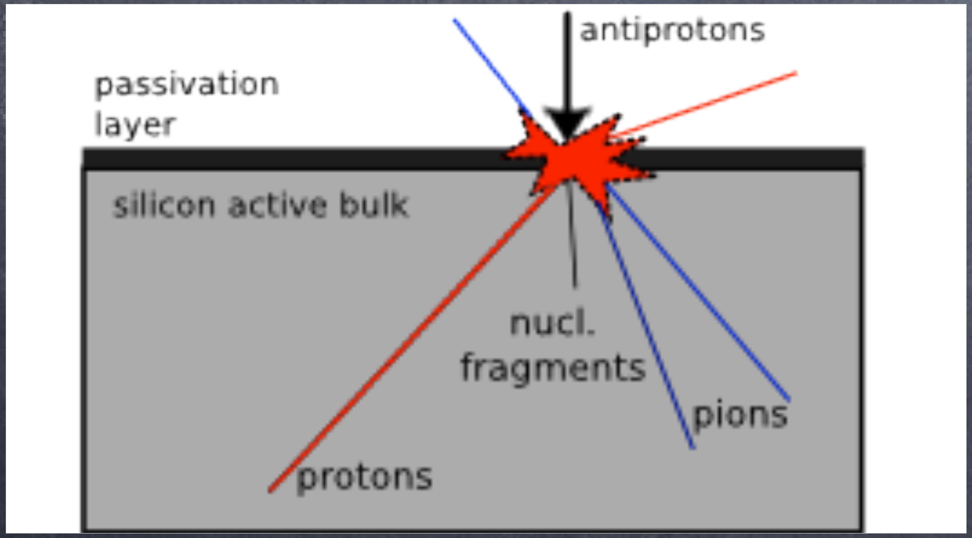
Mounting scheme of the silicon detector.

New approach of detection of low energy antiproton annihilations in silicon

$$\bar{\mathrm{p}} + \mathrm{Si} \rightarrow \mathrm{n}\pi + \mathrm{X} \qquad e^+ + e^- \rightarrow 2\gamma$$

X: nuclear recoils, p, t, n, α, ^{3}He, ^{4}He, ^{6}He, ^{8}He, Li...

- Antiproton-proton annihilation: 1880 MeV energy release, 5 pions on average are produced.
- Antiproton-nucleus annihilation: evaporation/fragmentation of residual nucleus.



Scheme of antiproton annihilation event in silicon sensor.

- The annihilation takes place in the first few microns of the silicon bulk.
- The total energy deposited form the charged annihilation prongs in the detector is measured.
- Study of the impact of detector's parameters on the specific application.

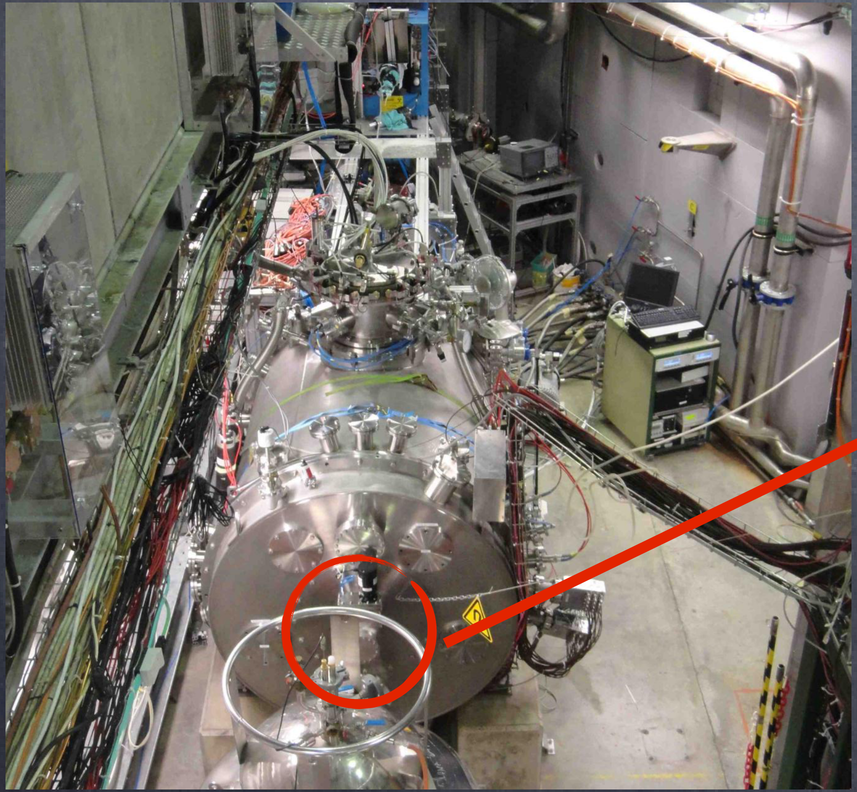
Beam test measurements and results

Test beam with antiproton annihilations in MAPS detector

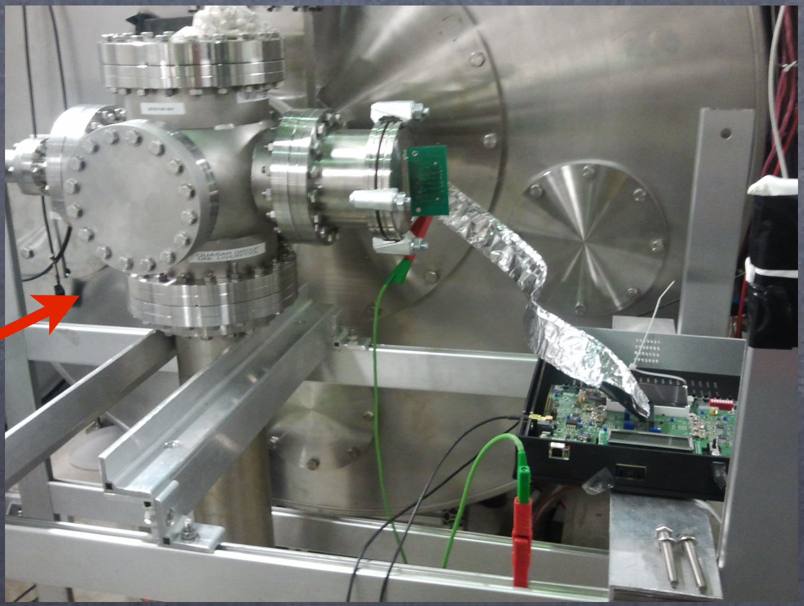
Goal: To study the signature of low energy antiproton annihilation in segmented silicon detector. Preliminary simulations suggested that annihilations could deposit significant amounts of energies inside the silicon bulk.

MIMOTERA: Monolithic active pixel sensor (MAPS).

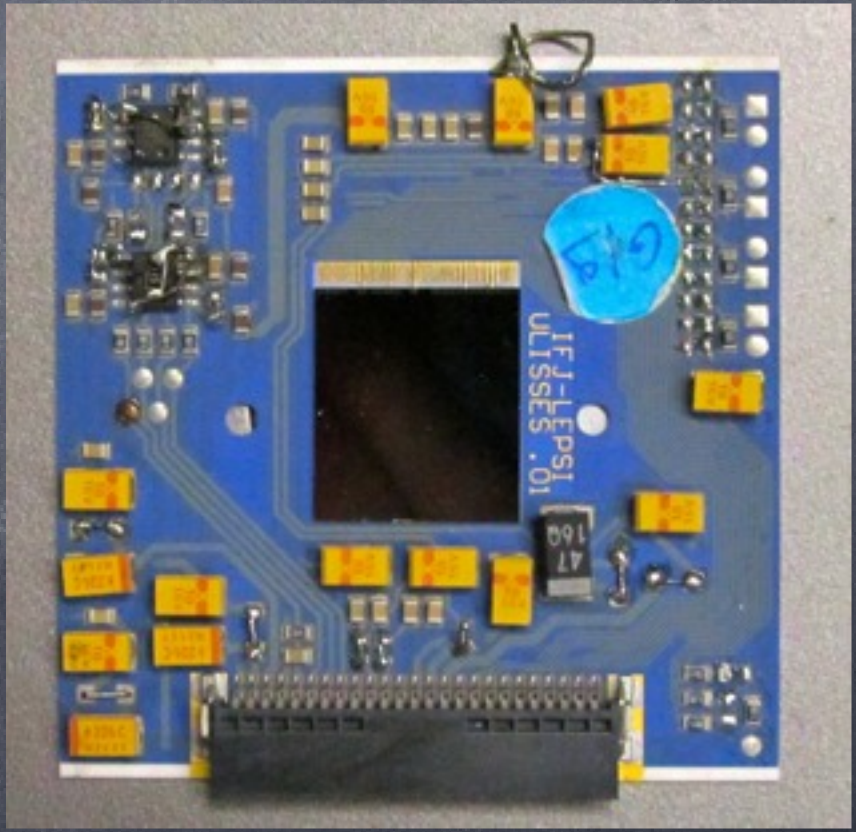
- 2 x 2 cm^2; 14μm thick, 153 x 153 μm^2 pixel size; 100 nm passivation layer.
- Remarkable dynamic range (30 keV - 30 MeV per pixel, over 3 orders of magnitude).



AEgIS apparatus in the experimental zone.

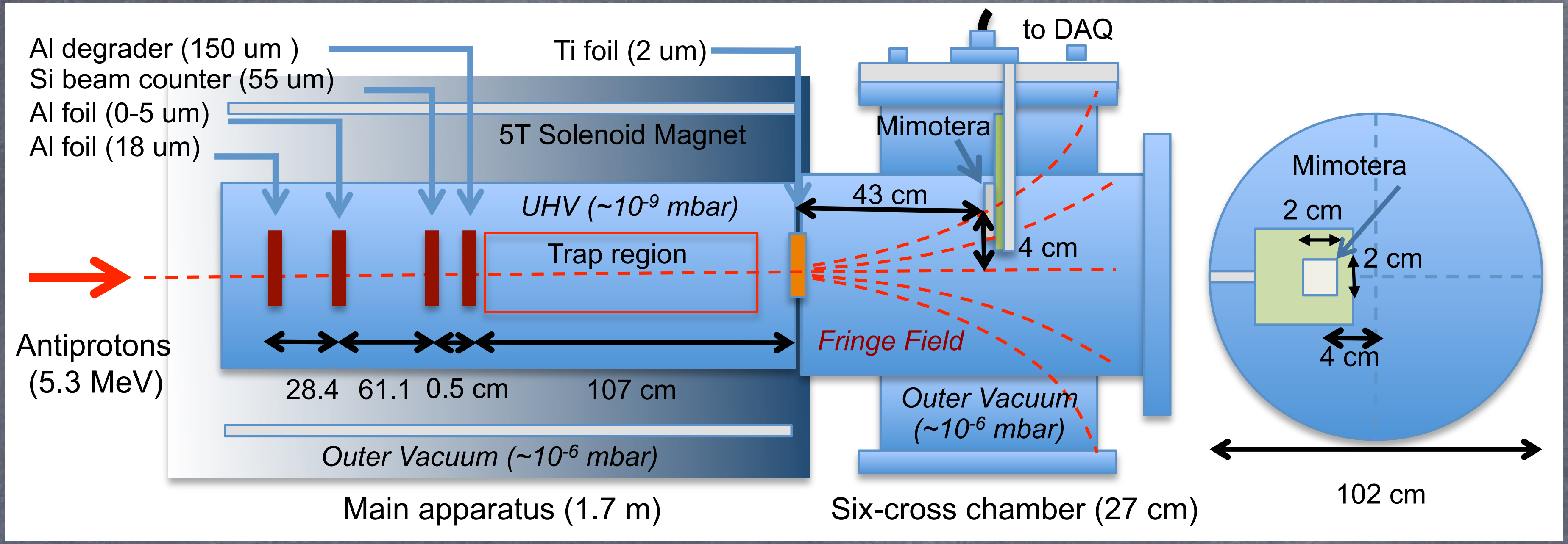


Six way cross where the detector was installed.

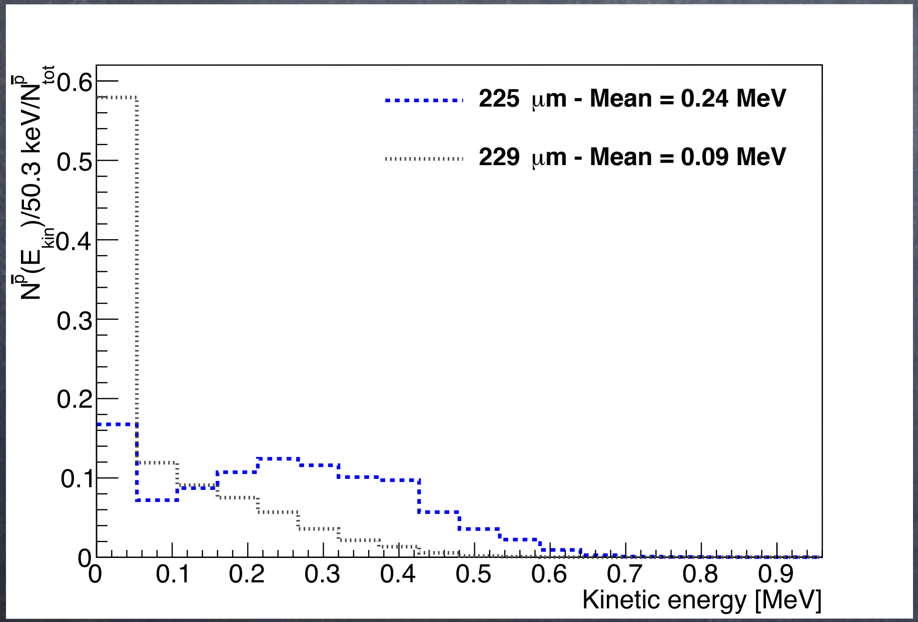


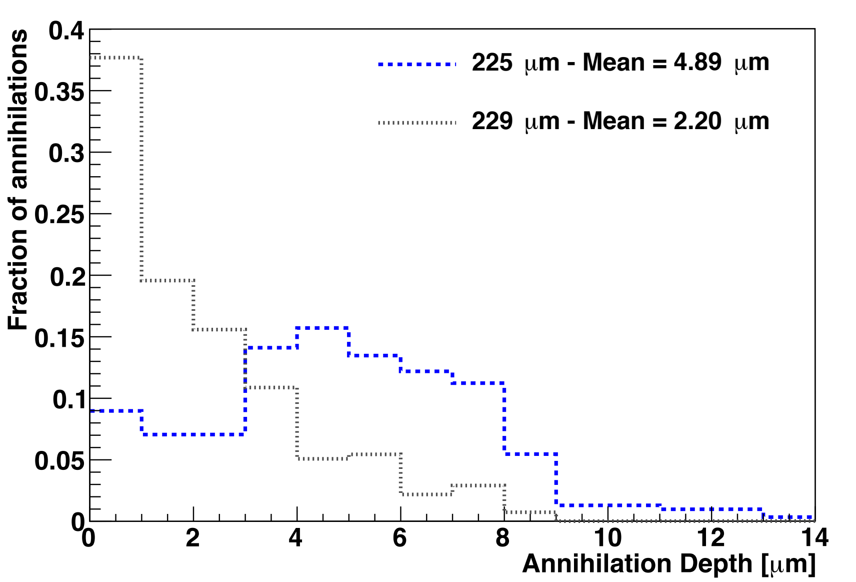
MIMOTERA mounted on the PCB.

Experimental setup



Top view (left) and axial view (right) of the test set-up.

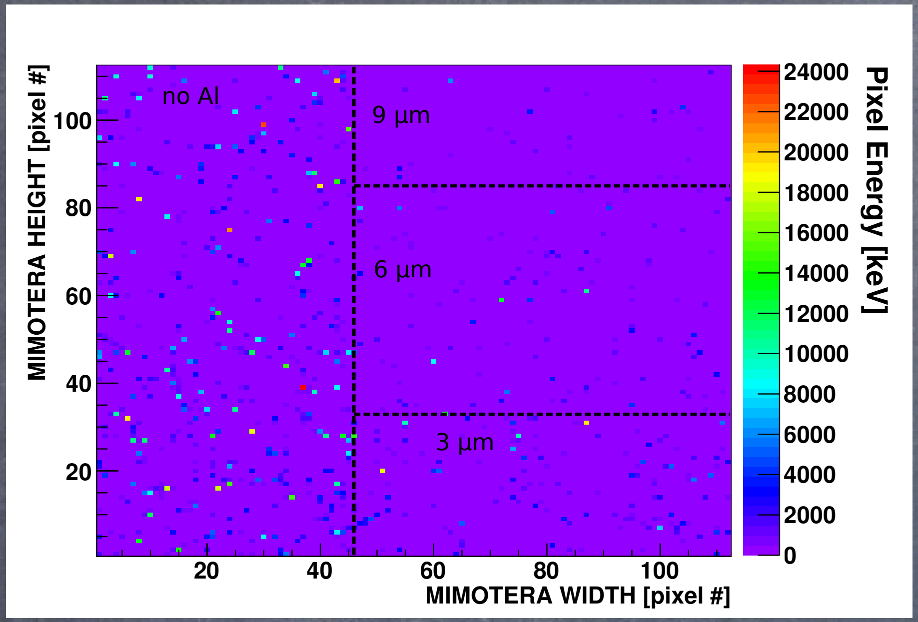




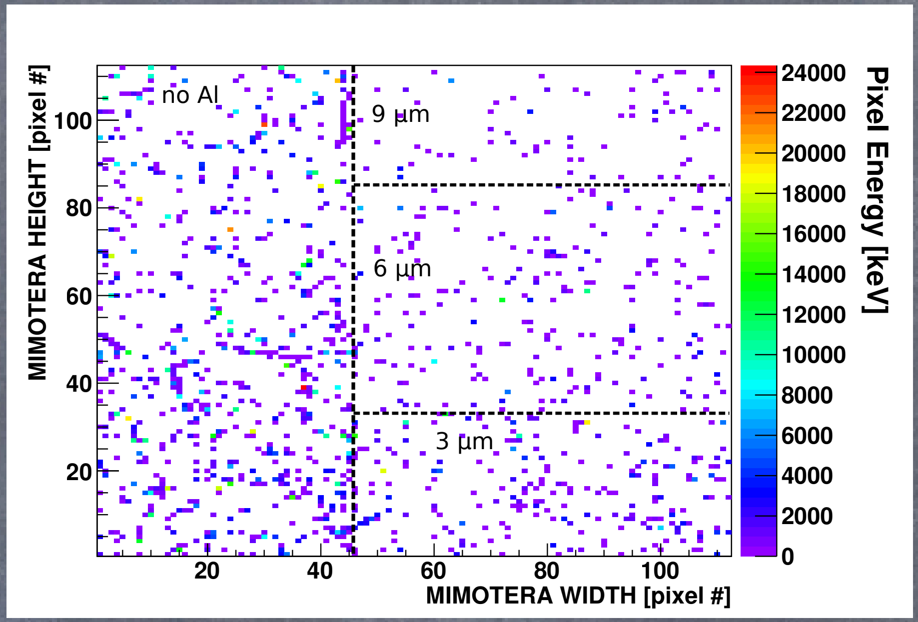
Kinetic energy distribution of the antiprotons before they reach the detector, simulated with GEANT4.

GEANT4 simulation showing the annihilation depth.

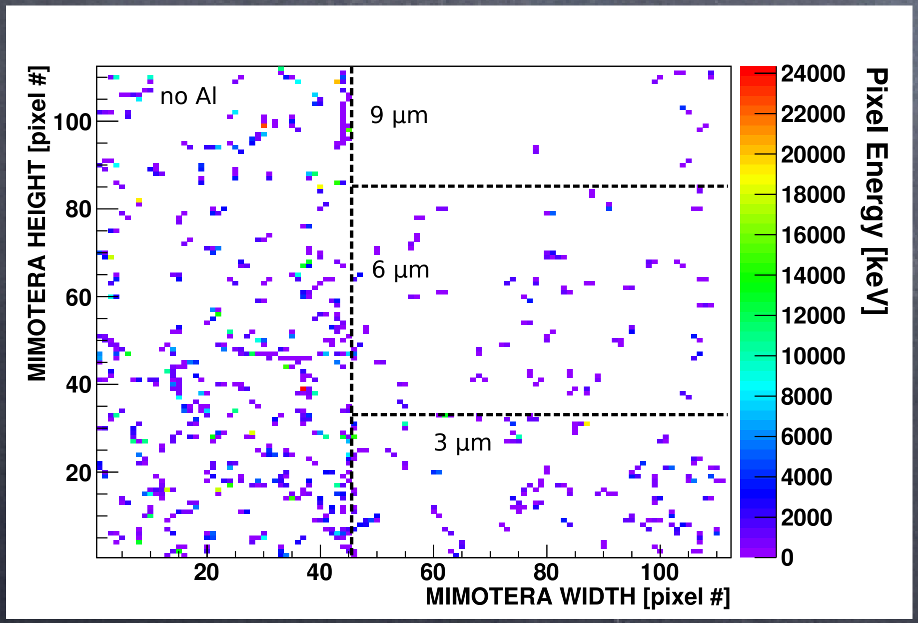
Sample frames from measurements with MAPS



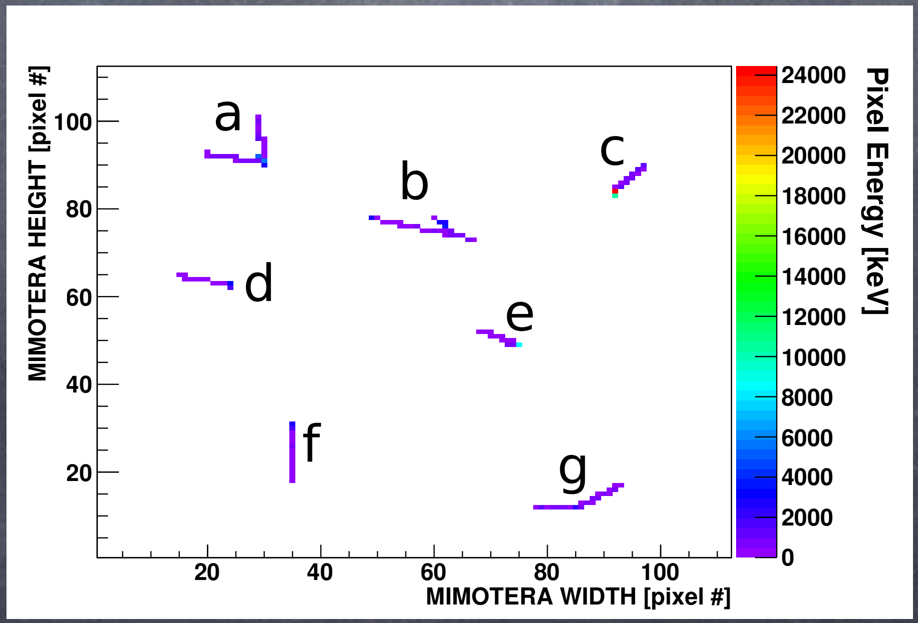
Sample of a raw triggered frame.



Sample frame with noise cut of 150 keV.

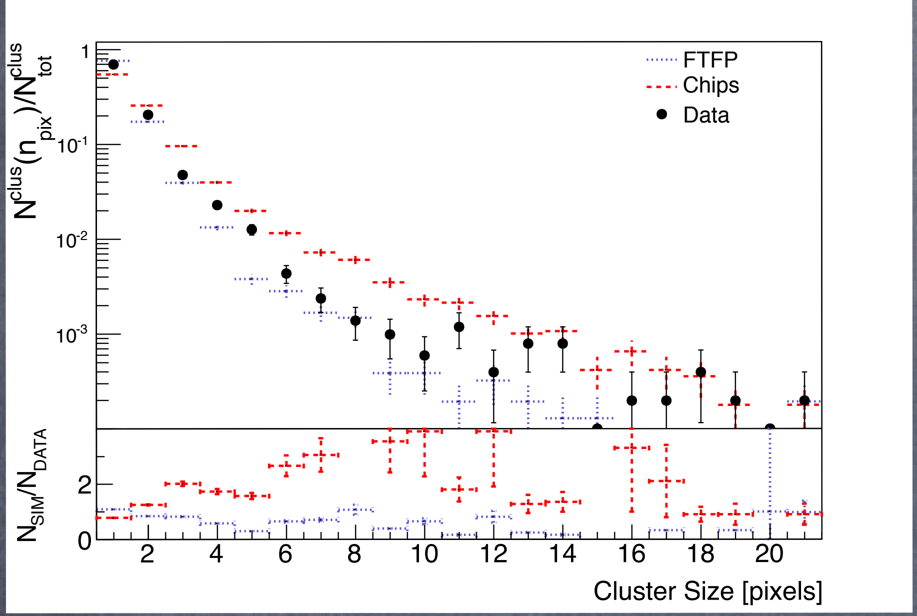


Sample frame with noise cut of 150 keV and 1 pixel clusters excluded.

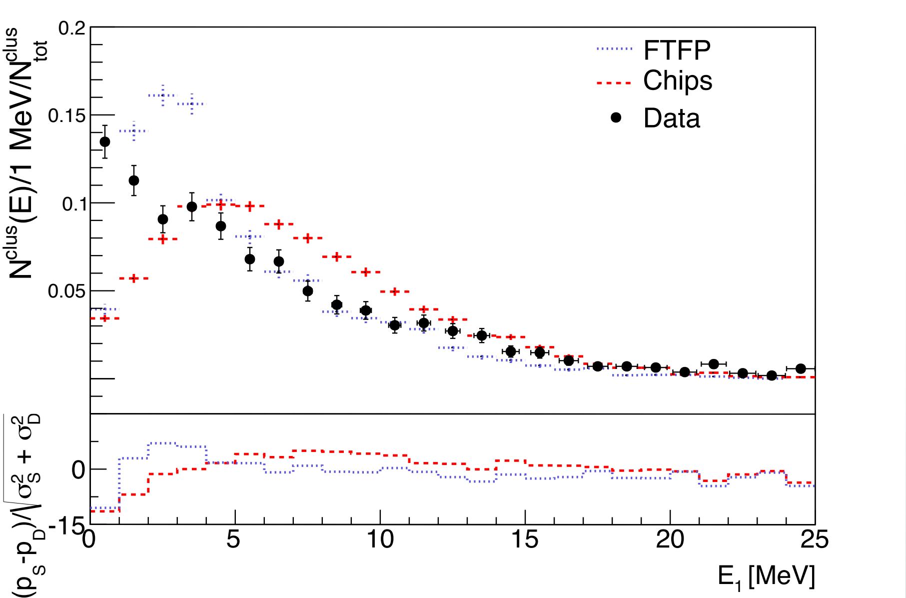


Sample of in-plane tracks observed with the MIMOTERA detector.

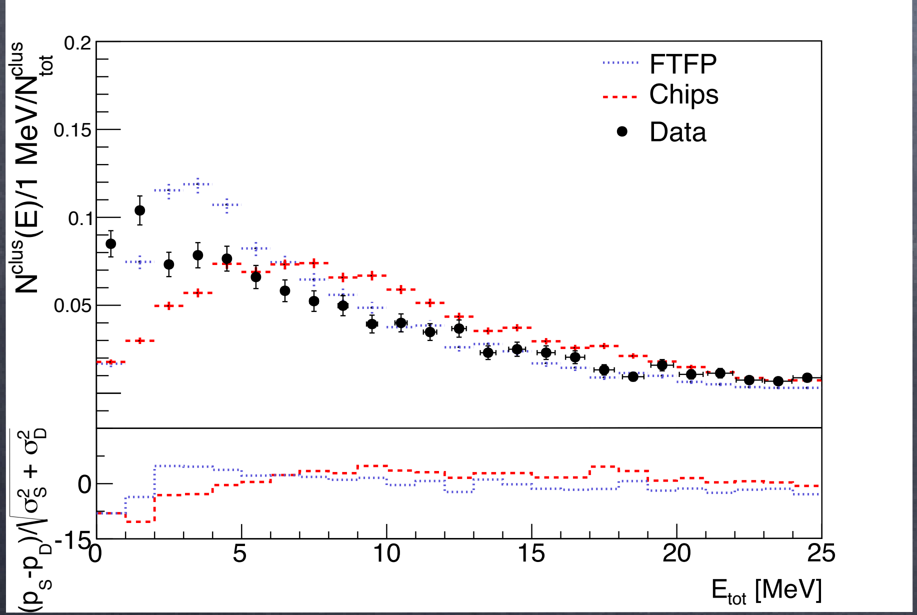
Results and comparison with simulation models: CHIPS and FTFP



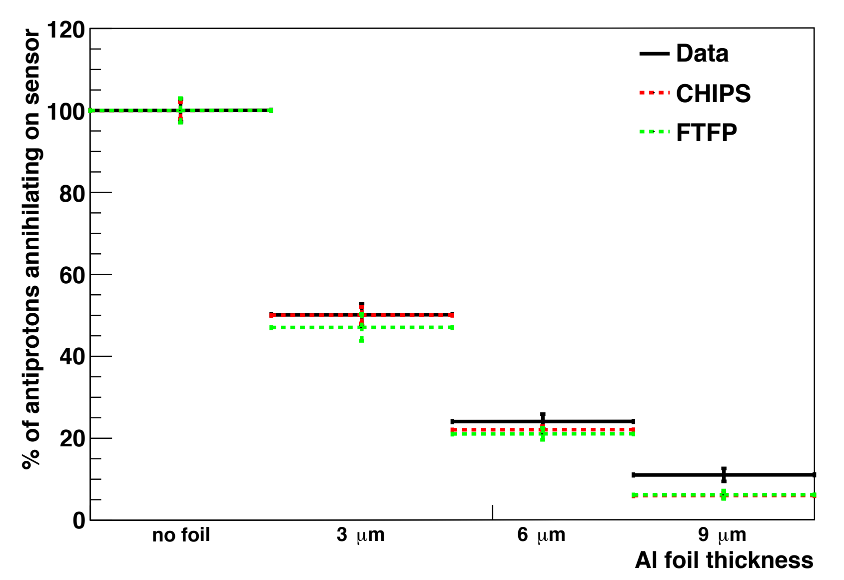
Cluster size distribution.



Distribution of the energy deposited only in the pixel collecting the highest charge.



Cluster energy distribution.



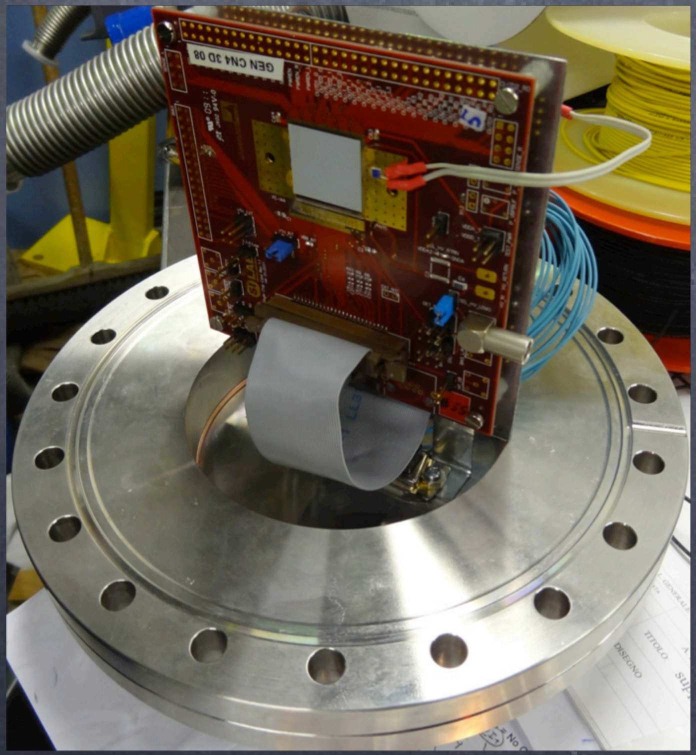
Fraction of annihilations on the sensor parts covered with different thicknesses of Al foil.

S. Aghion et al., JINST 9 P06020, 2014

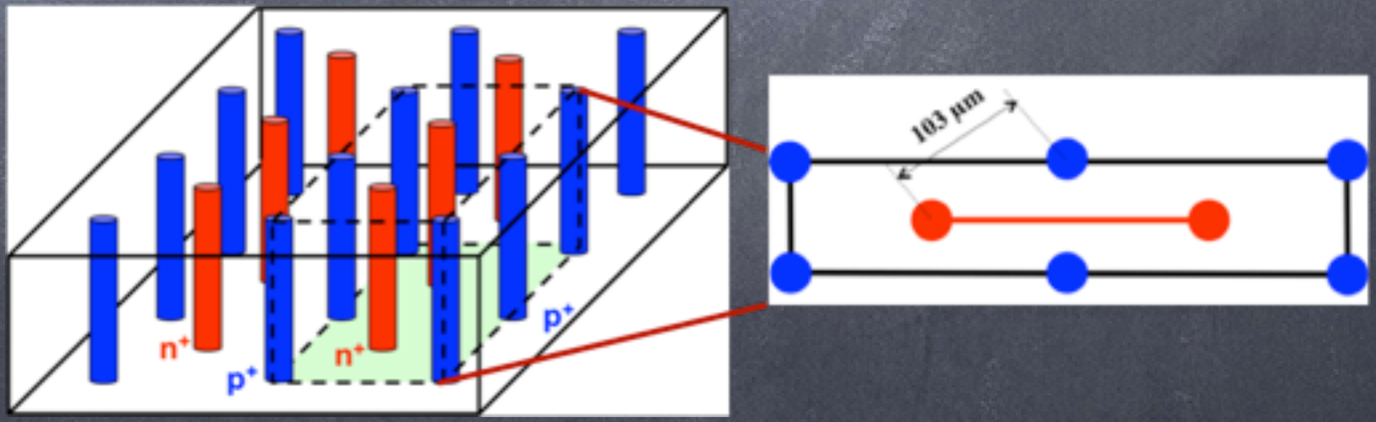
Test beam with antiproton annihilations in 3D silicon pixel detector

Goal: More information on the signature of the antiproton annihilation event, observation of tracks form the annihilation prongs. Estimation on the resolution of the annihilation point.

- 3D CNM 55 silicon detector with FE-I4 readout system designed for ATLAS IBL.
- 2 x 2 cm^2; 230 μm thick, 50 x 250 μm^2 pixel size.
- Passivation layer: 1.5 μm Al + 0.8 μm + doped polysilicon +1.150 μm thermal oxide.
- Saturation occurs at ~126 keV/pixel, 35% of all hit pixels were saturated.



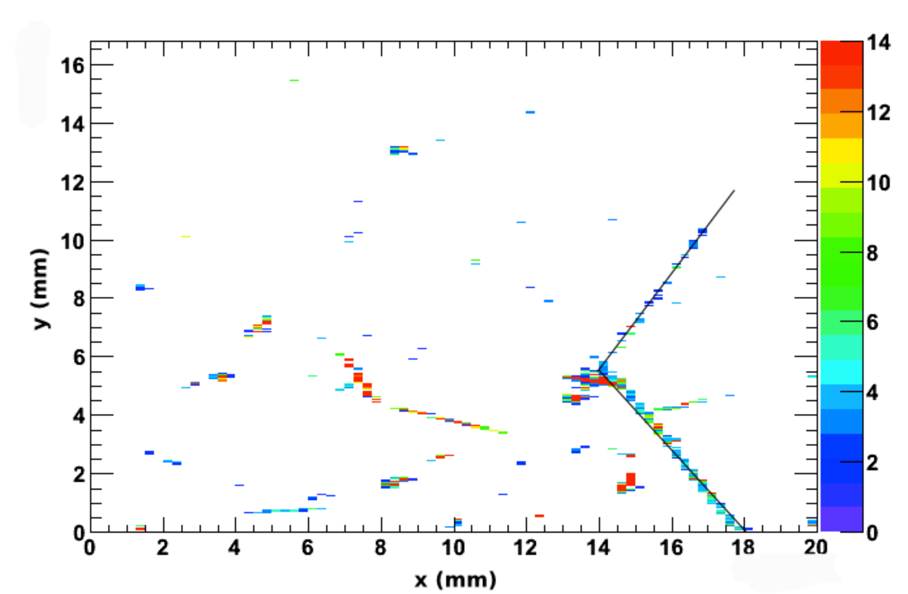
The CNM 55 sensor with the FE-I4 R/O chip mounted on a flange.



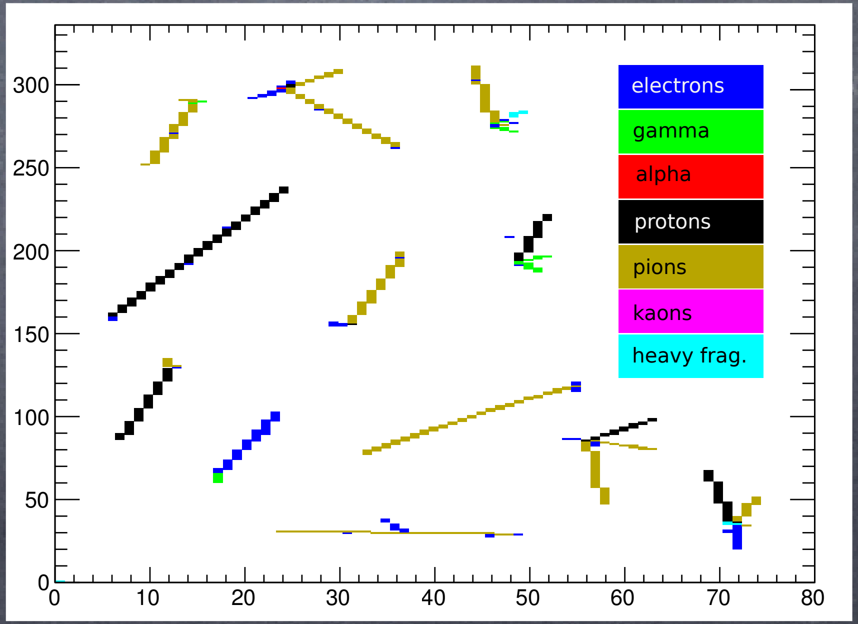
Schematic view of the 3D electrodes.

Results from measurements with 3D pixel detector

- Total energy deposition up to 10 MeV per antiproton annihilation.
- Cluster size ranging form 1 to 80 pixels, with mean value of 3.93±0.031 pixels.
- Identification of tracks from annihilation prongs up to 1.5 cm long.
- Position resolution of 56.5 μm for X and 24.3 μm for the Y coordinate of the annihilation point.
- A better resolution could be achieved by employing weighted fitting with a saturation-free readout.



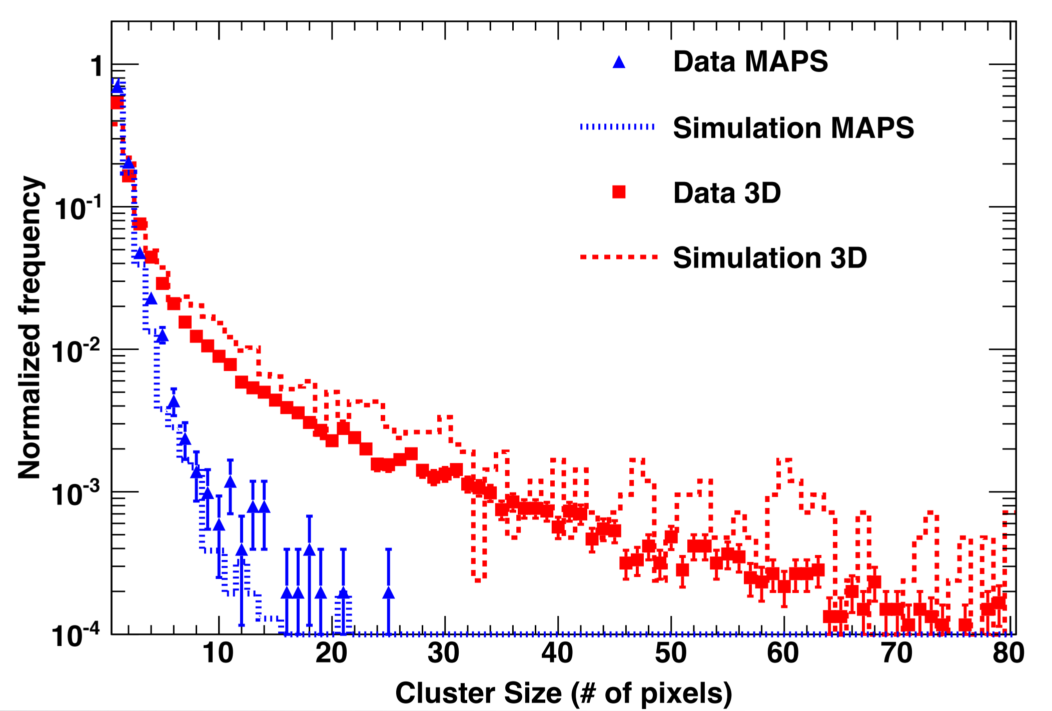
Sample hitmap of the 3D pixel sensor with two fitted proton tracks coming from an antiproton annihilation.



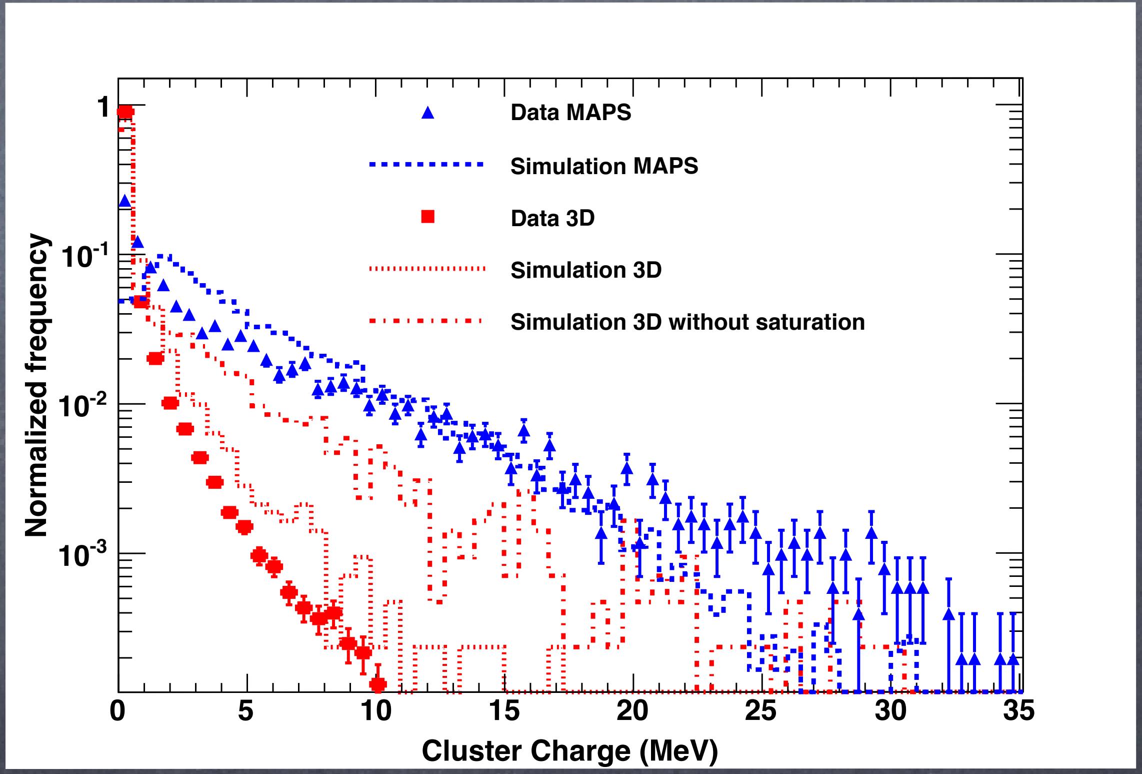
Samples of simulated annihilation events (GEANT4, FTFP) in a silicon pixel sensor.

Comparison between MAPS and 3D pixel detectors

- 3D : detection of tracks of lower ionizing products, suitable for fitting and reconstruction of annihilation point with precision of the order of ~10 μm.
- MAPS: high saturation limit, allowed measurement of the localized energy released in an annihilation event, with a mean value measured in the order of several MeV.



Cluster size distribution for the MAPS and 3D pixel sensors with the respective simulation results in GEANT4.



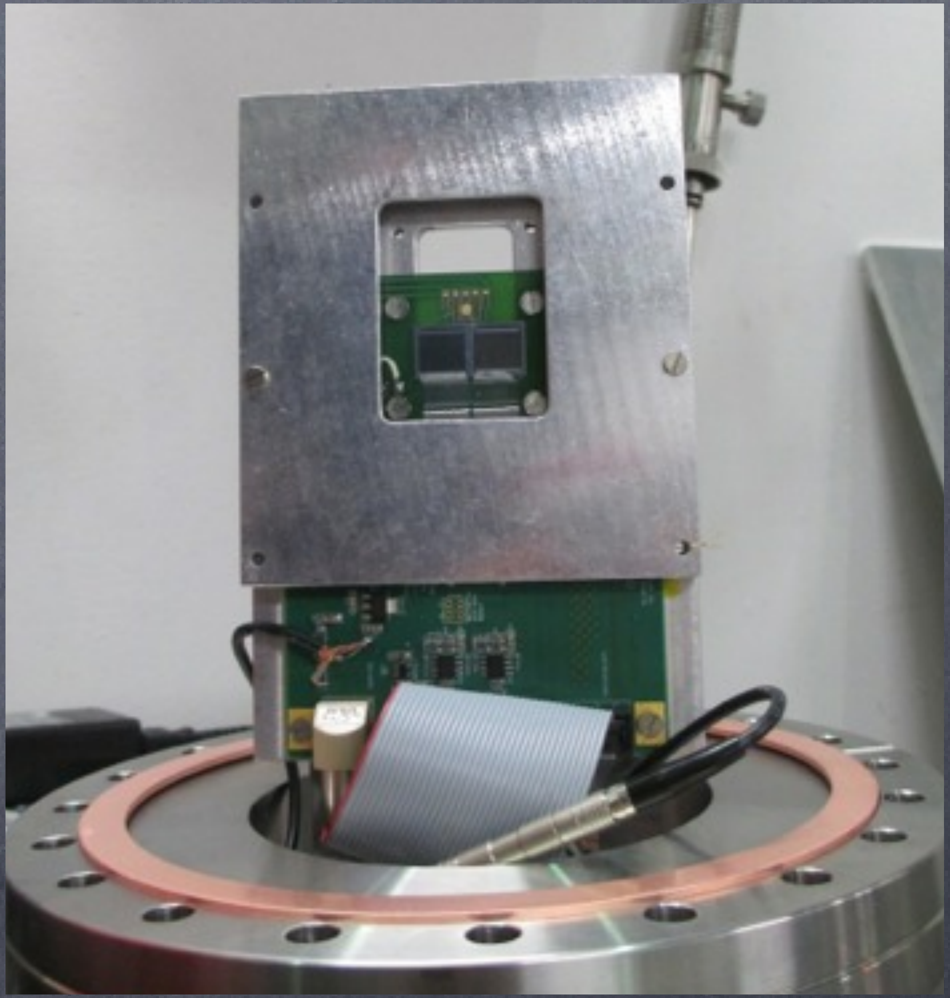
Cluster energy distribution for the MAPS and 3D pixel sensors with the respective simulation results in GEANT4.

A.Gligorova et al., Nuclear Science, IEEE Transactions on , vol.61, no.6, pp.3747, Dec. 2014

Beam test with silicon strip detector

Goal: To observe and to verify the response to annihilation events of a 1D detector, as the one to be installed in AEgIS. Also to evaluate the performance of the microstrip technology.

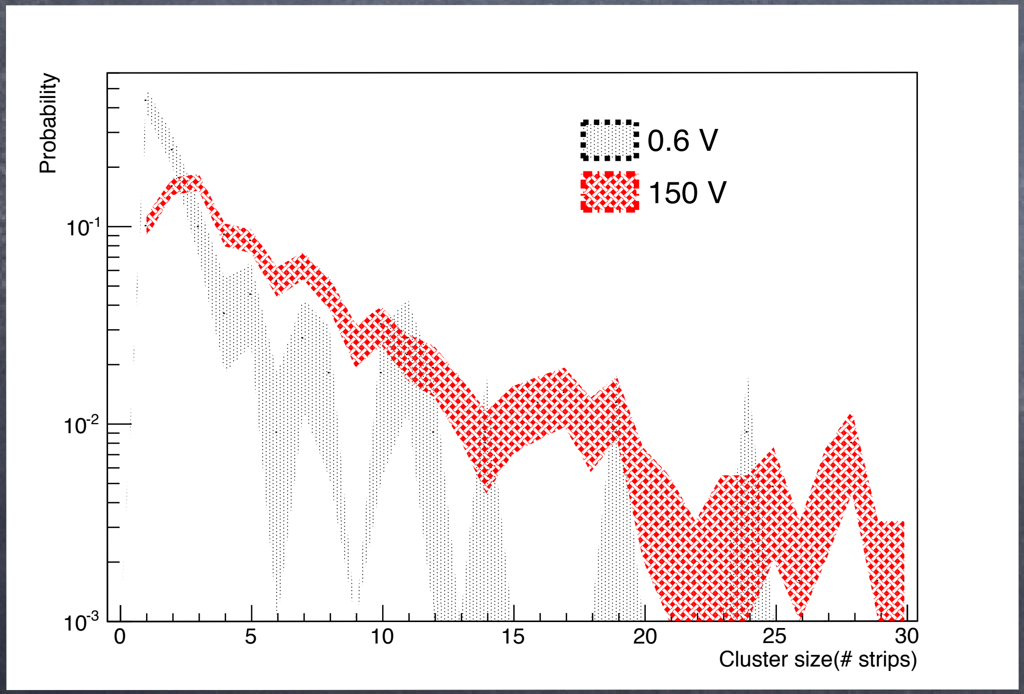
- Planar strip sensors on standard 300 μm thick, MCz n-type wafers.
- p^+ strip implants, with AC coupled aluminum readout strips.
- Two sensors (strip length: 1 cm.)
    - 50 μm strip pitch
    - 80 μm strip pitch
- Alibava R/O system with two Beetle chips, used in the LHCb VELO readout system.
- Dynamic range: from 20 keV (5 noise RMS) up to 800 keV.
- Full depletion voltage: 120 V. Breakdown voltage: 300 V. Maximum applied voltage: 150 V.



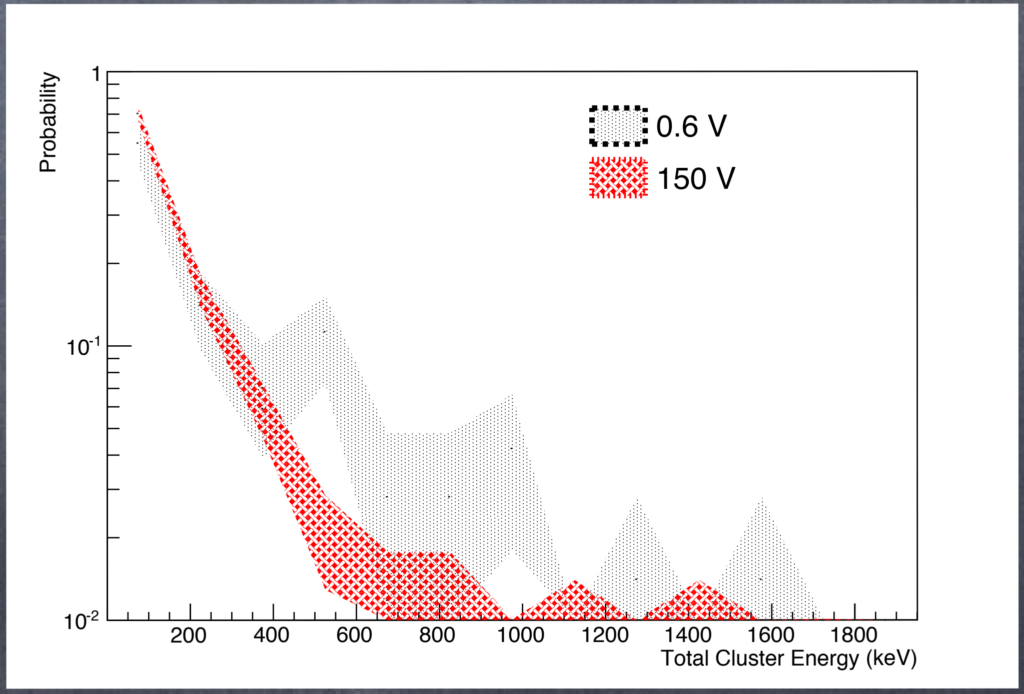
The two microstrip sensors bonded to the Beetle R/O chips, mounted on a flange.

Results from measurements with silicon strip detector

- The cluster size increases with voltage: sensors become sensitive to long-range particles (pions and high energy protons).
- The total cluster energy is higher at low depletion: the detector is only sensitive to highly ionizing fragments.
- A thin active volume produces small clusters: better spatial localization of the annihilation event through detection of highly ionizing fragments.



Cluster size distribution, normalized to unit total integral.



Deposited energy distribution of the clusters, normalized to unit total integral.

N. Pacifico et al., Nuclear Inst. and Methods in Physics Research, A, Volume 765, p. 161-166.

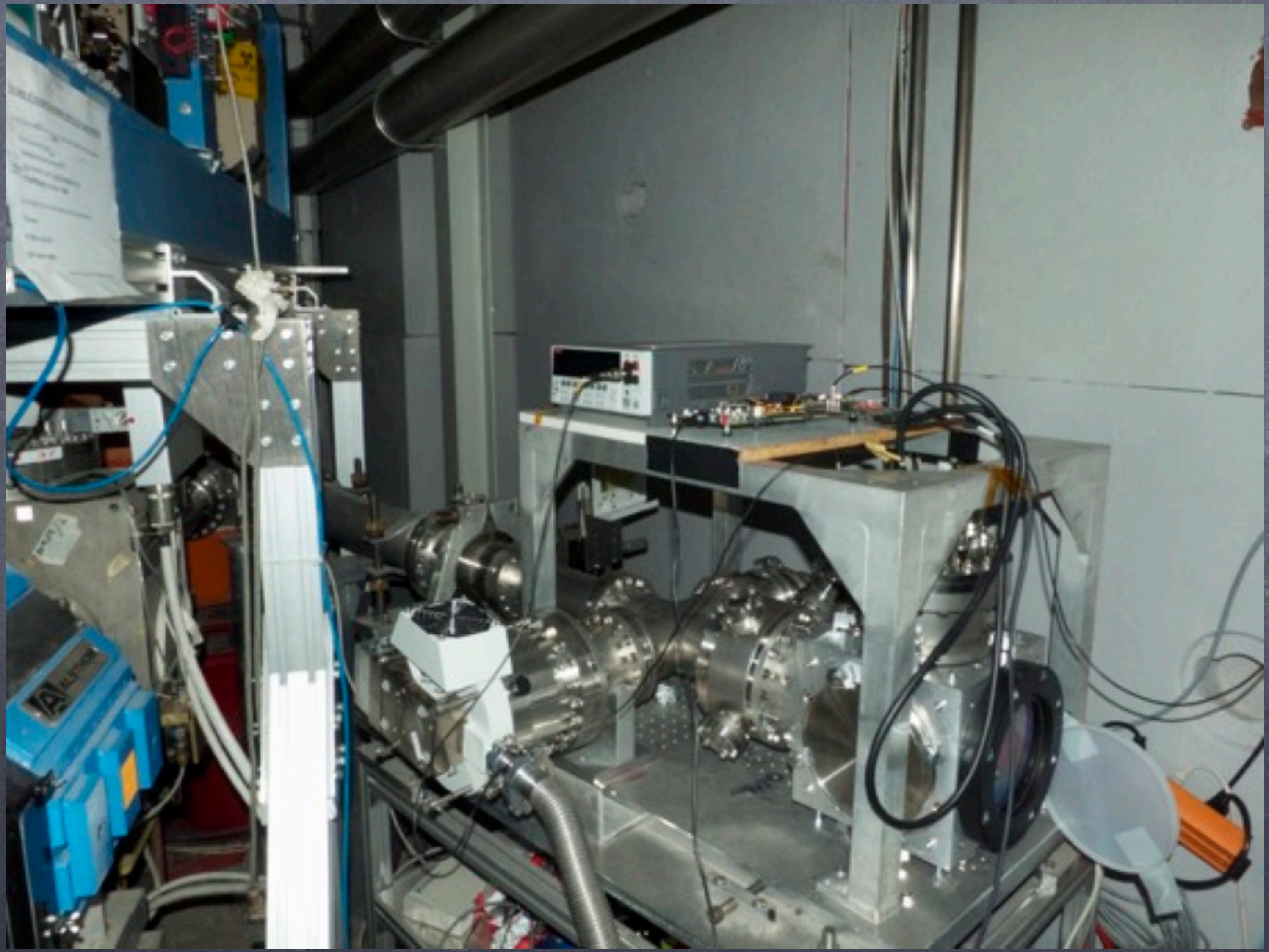
Design specification of the AEgIS detector

- Silicon sensor specifications:
    - 2560 strips of p-implant in a n-type substrate.
    - Strip length of 105 mm and a pitch of 25 µm, total active area of 105 x 64 mm^2.
    - Thinned active areas down to 50 µm by anisotropic etching, 300 µm thick support ribs.
- ASIC specifications:
    - The detector module will contain 10 ASICs, 256 channels each, in 2 daisy chained units (a PCB/hybrid) of 5 ASICs each.
    - Self triggering (the ASIC shall issue a trigger signal if any input channel goes above a tunable threshold).
    - No saturation until ±100 fC, the linear range shall be between -30 fC and 30 fC.
    - The heat dissipation will be less than 0.5 mW per channel.

Prototype of the silicon sensor with support ribs and 5x3 cm^2 thinned areas.

Tests with Timepix3 detector

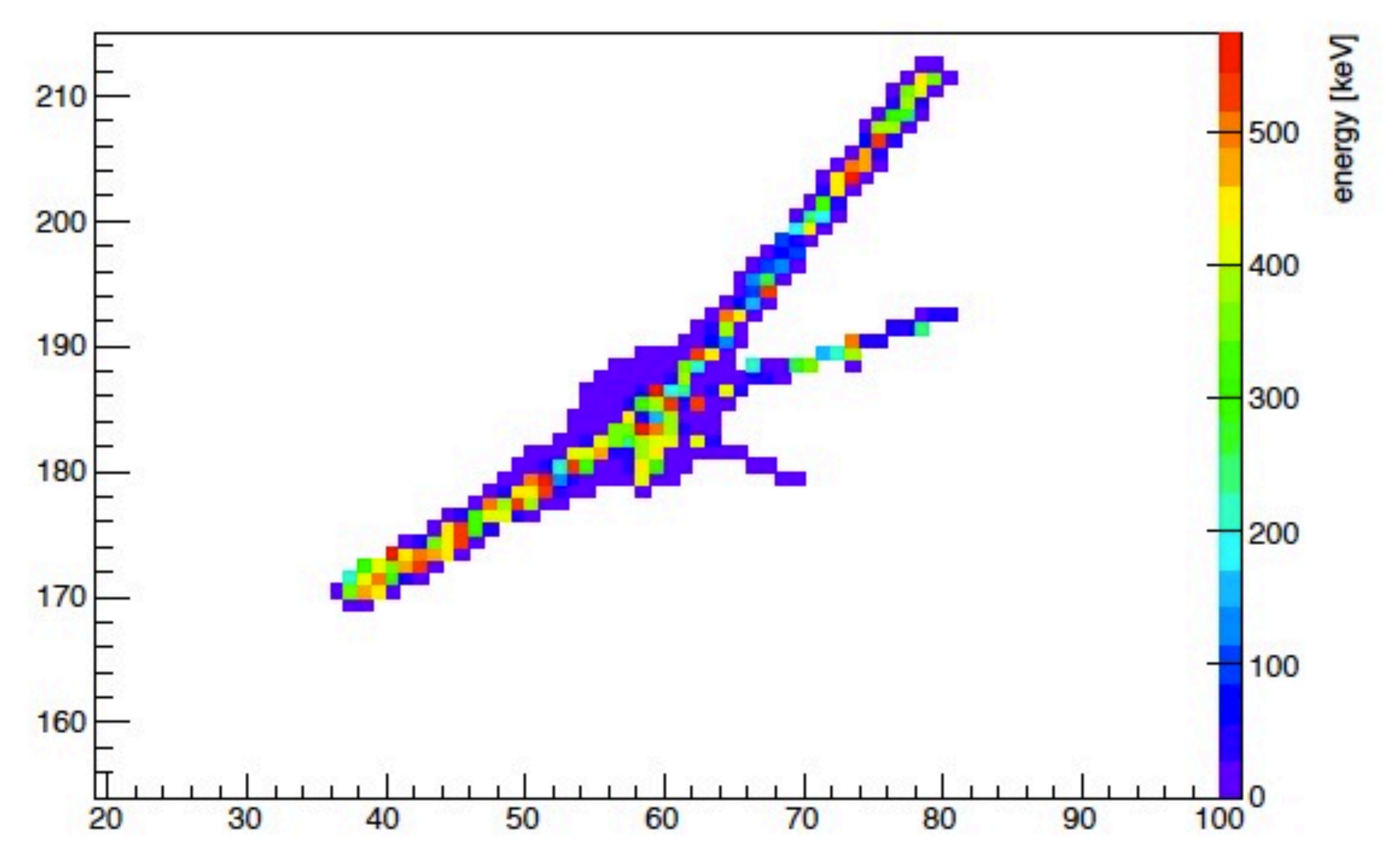
- A secondary AEgIS beam line dedicated to detector tests.
- Measurements with Timepix3 detector.
- Data analysis in progress.
- A systematic study of low energy antiproton annihilations in different materials (Li, Ag, Cu, Au).



Secondary AEgIS beam line.

Work in progress

- Timepix3 detector
  - 14.08 mm x 14.08 mm, 230 um thick, 256x256 pixels, pixel pitch of 55 µm.
  - Time resolution 1.5 ns.
  - Analysis of the Timepix3 data using weighted fitting algorithms/development of detector-response model.
  - Cold tests (77 K, 4 K)...



Cluster showing an antiproton annihilation in the Timepix3 detector.

Conclusions

- A new semiconductor detector application has been developed.
- First successful use of silicon sensors as low-energy antiproton annihilation detectors.
- First comparison of antiproton annihilations in silicon with GEANT4 simulation models.
- Improved design for the detector: thickness, strip pitch, dynamic range.
- The AEgIS gravity measurement, where the detector will be implemented, would lead to new physics results that might change our fundamental understanding about the Universe and its laws.

Thank you for your attention!

...and thanks to University of Insubria for the Mimotera, the ATLAS 3D community for the CNM55 and the Timepix collaboration for the Timepix3, for their help and support.