Performance evaluation of the AstroPix v3 and v4 HV-CMOS Sensors

Results from the DESY II test beam

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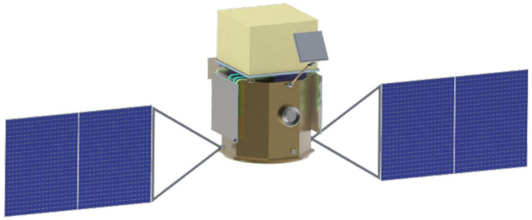
AMEGO-X

The All-sky Medium Energy Gamma-ray Observatory eXplorer

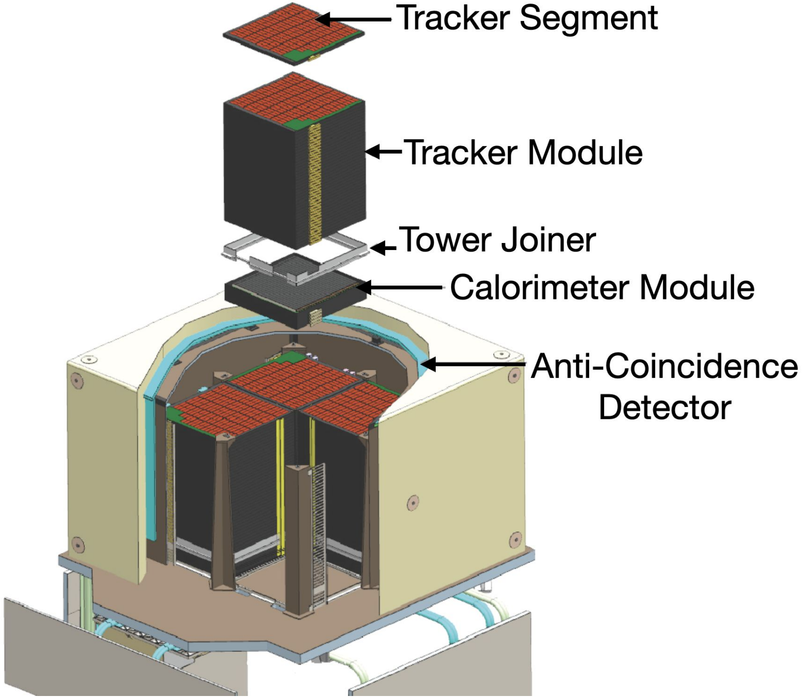


Gamma ray observations in the MeV band:

- supermassive black holes
- neutron stars and their mergers
- remnants of Galactic supernovae

Detector:

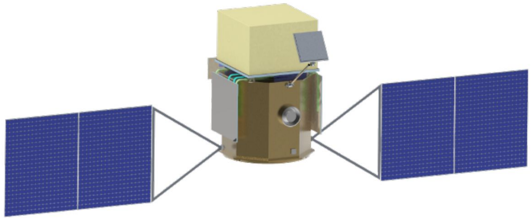
- Tracker: 40 silicon layers
  - to measure energy and position of gamma-ray and charged-particle interactions
- Calorimeter: 4 CsI layers
  - to measure position and energy of Compton-scattered photons and the EM showers from electrons and positrons
- Anti-coincidence detector: 5 scintillator panels around the main detector
  - to reduce the cosmic-ray background



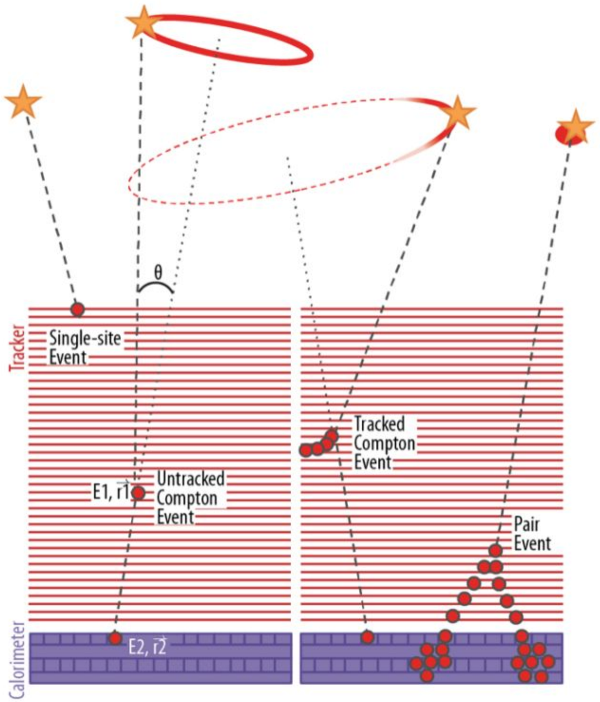
[10.1117/1.JATIS.8.4.044003]

Photon detection

Different energies = different interaction mechanisms



- **Photoelectric absorption** for photons with energy below 100 keV
  - In one tracker layer
  - No directional information in a single event, but aggregate information can be used to localize the source
- **Compton scattering** for photons with energy between 100 keV and 10 MeV:
  - Position + energy ➡ circle in the sky
  - (**Untracked Compton Event**)
  - Position + energy + Compton electron track ➡ arc (**Tracked Compton Event**)
- **Pair production** for photons with energy above 10 MeV:
  - Two tracks ➡ direction

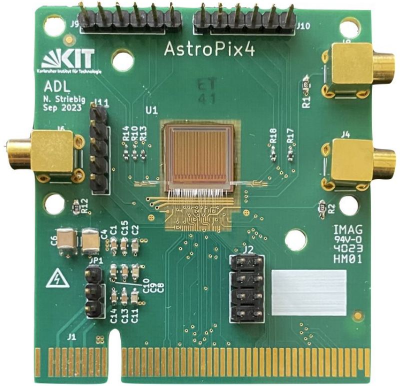


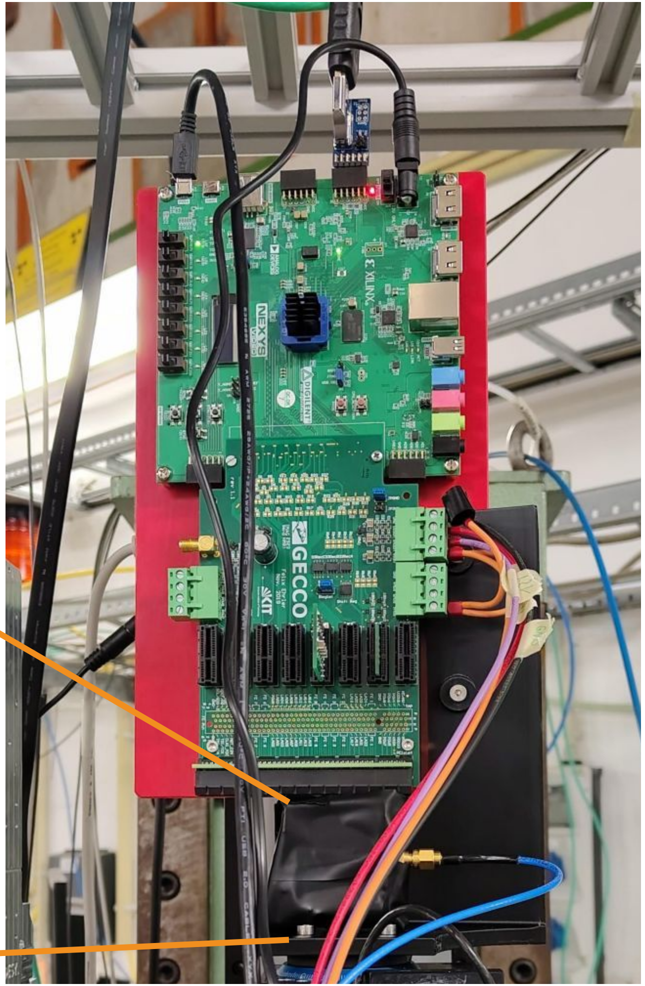
AstroPix chips

AstroPix

The chips and the readout system

- HV-MAPS sensor
- 500 μm pixel pitch, 300 μm implant size
- Chip thickness 500 μm
- Matrix:
    - v3: 35 × 35 pixels
    - v4: 13 × 16 pixels
- Front-end power consumption goal < 1.5 mW/cm^2
- Expected hit rate in a pixel: O(1) mHz
- The chip is mounted on a carrier PCB
- The data from the chip is read out using an FPGA board



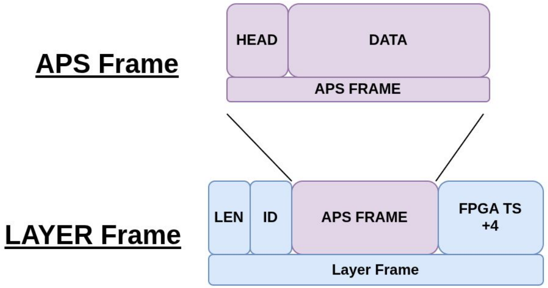


Data readout in v3

v3

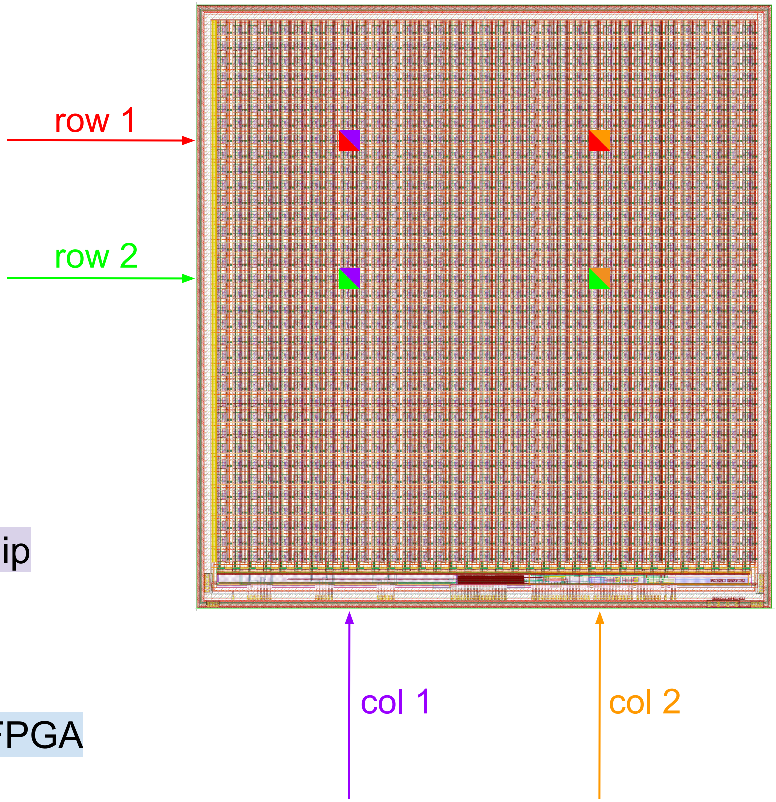
Rows and columns are read out separately

- Pixels in rows and columns are connected using logical OR
- Hits from rows and columns are read separately – “halfhits”
- Row halfhit + column halfhit = pixel hit
- Halfhit data is packaged into APS frames on the chip
- APS frames are extended to LAYER frames on the FPGA, which are stored in a buffer and read out periodically



created by the chip

created by the FPGA

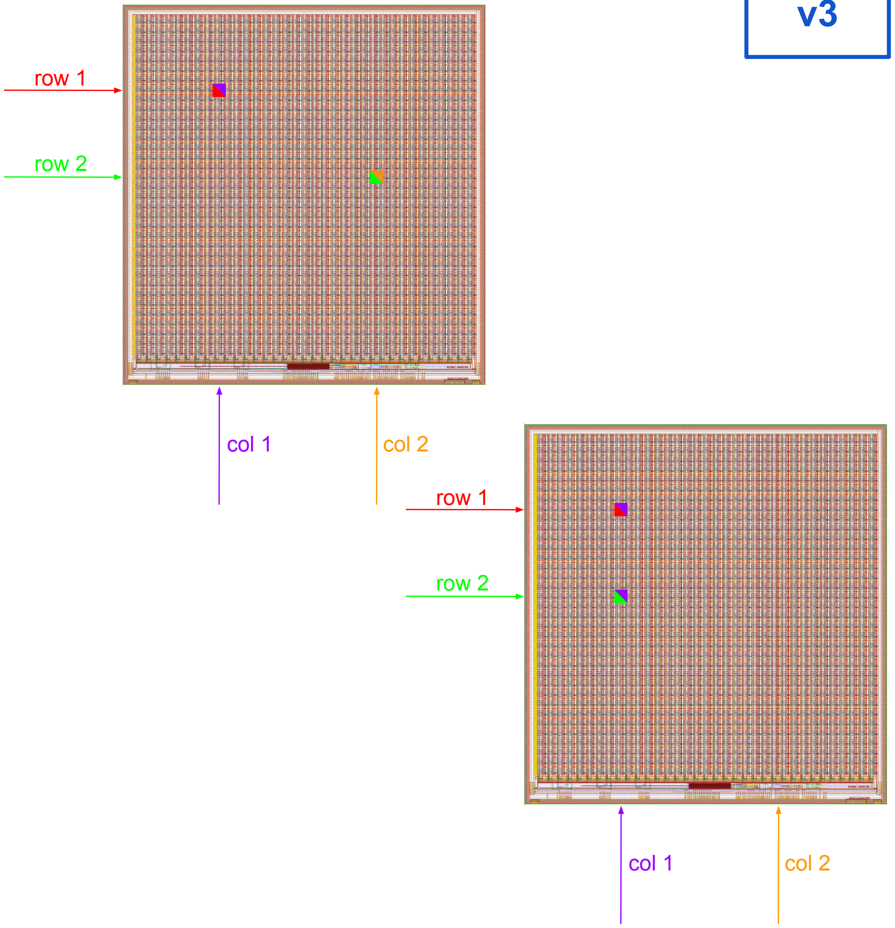


Halfhit matching

The most problematic part

v3

- Row halfhits are read from the chip before the column ones
- Row and column halfhits match if:
  - ToT difference is within the given tolerance (column ToT no more than 20% different from row ToT)
  - ToA are within the given tolerance (difference within 2 clock cycles = 1 μs)
- Three matching strategies:
  - ALL: all matches are converted to pixel hits
  - CLOSEST: only the match, where the row and column halfhit are closest to each other within the data stream, is converted to a pixel hit
  - CLOSEST_ROWFIRST: same as CLOSEST, but only those matches are considered, where the row comes first in the data stream

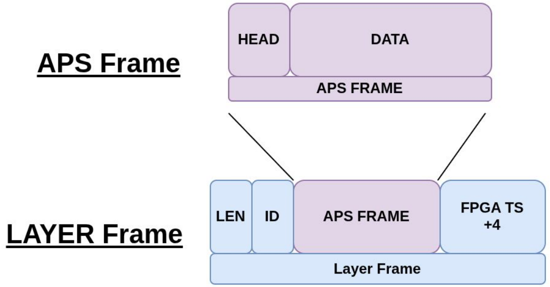


Data readout in v4

v4

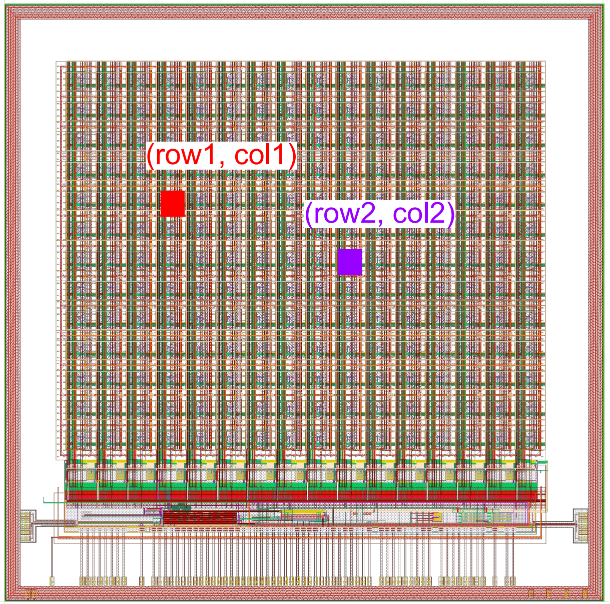
No separate row and column readout

- Per-pixel readout = no matching necessary
- Hit data is packaged into APS frames on the chip
- APS frames are extended to LAYER frames on the FPGA, which are stored in a buffer and read out periodically



created by the chip

created by the FPGA



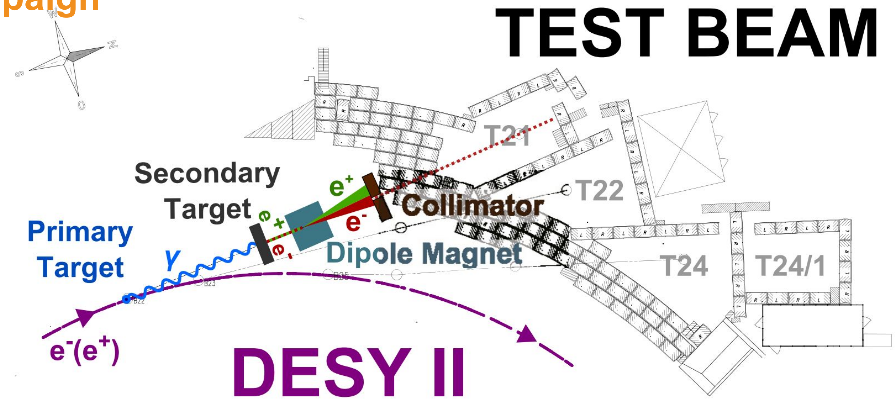
Test Beam integration

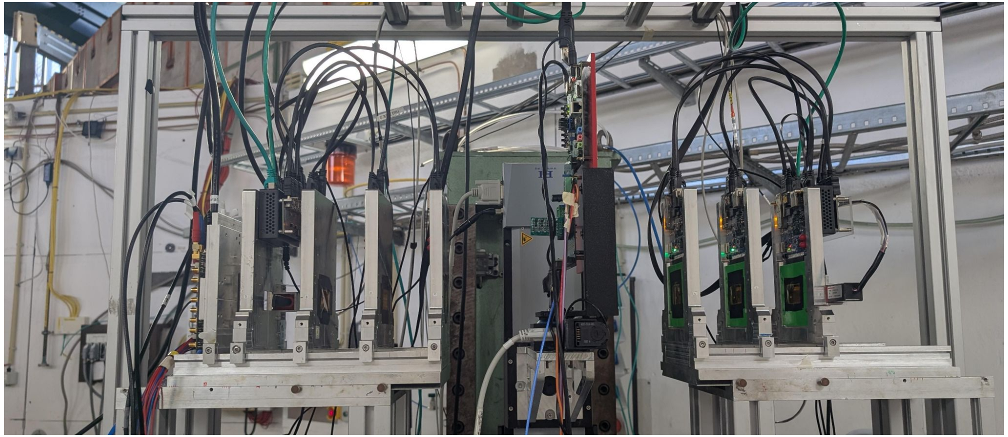
[10.1016/j.nima.2018.11.133]

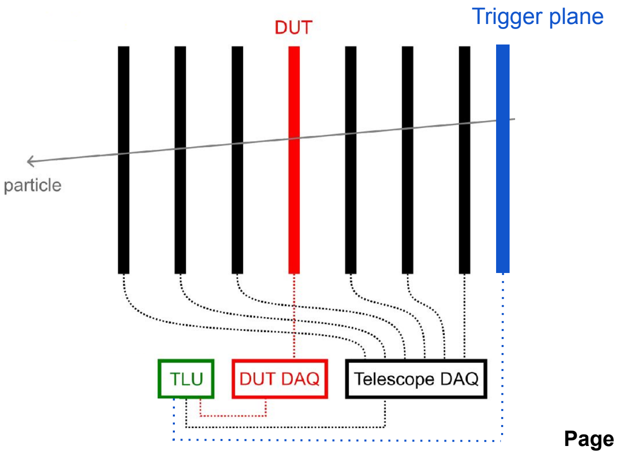
DESY II test beam facility

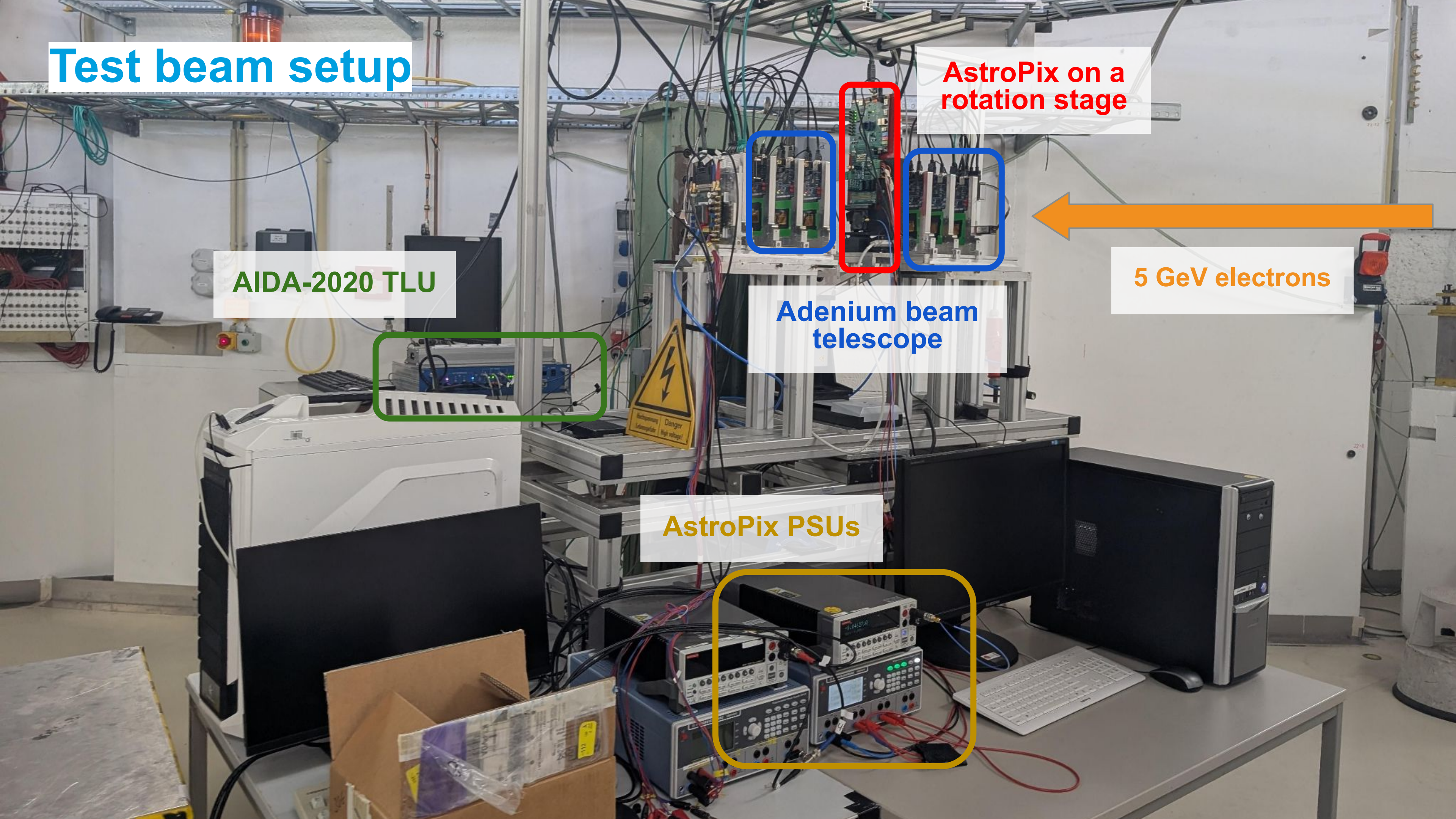
And the equipment used during the test beam campaign

- Beam of electrons with energies of 1–6 GeV
- Adenium Beam Telescope
  [10.1088/1748-0221/18/06/p06025]
- AIDA-2020 Trigger Logic Unit (TLU)
  [10.1088/1748-0221/14/09/p09019]
- Rotation stage
- AstroPix chip + readout system
- Power supplies for AstroPix









Test beam setup
AstroPix on a rotation stage
AIDA-2020 TLU
5 GeV electrons
Adenium beam telescope
AstroPix PSUs

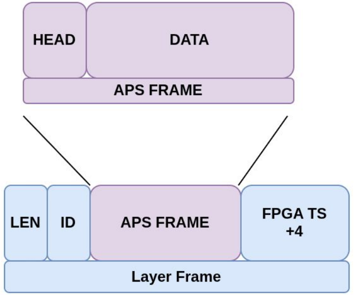
TLU and firmware

Clock synchronization

- TLU and FPGA clocks are synchronized
- Data transfer from the chip to the FPGA at 2 Mbps
- FPGA timestamp is sampled after an APS frame is read out of the chip

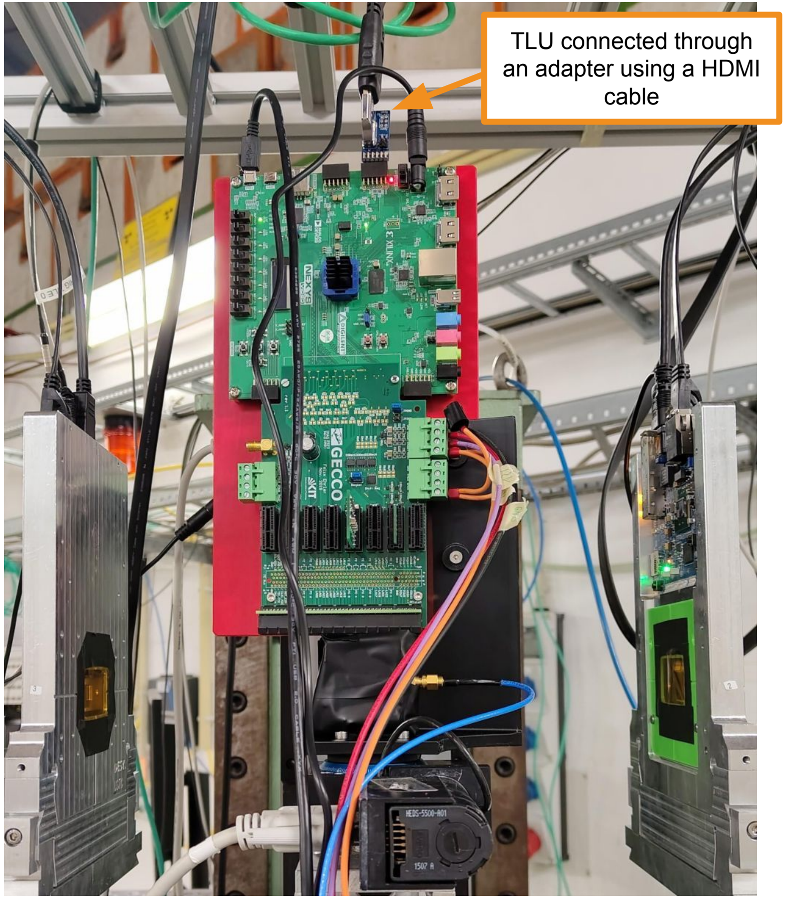
APS Frame

LAYER Frame



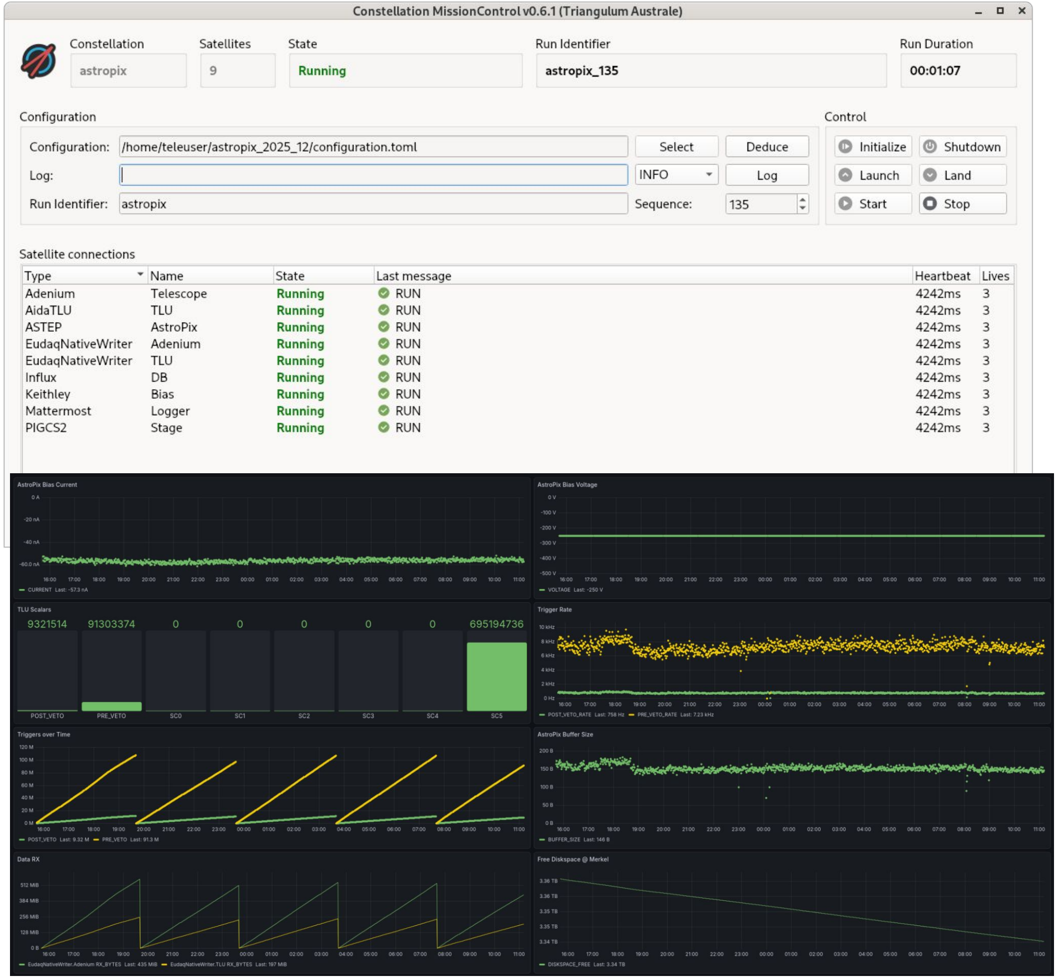
created by the chip

created by the FPGA



Constellation

- AstroPix was integrated into the Constellation framework
- It was used successfully together with the existing satellites for the other components of the setup during test beam
- Grafana display was used to monitor the status of data taking
- Autonomous data taking supervised using integration into mattermost



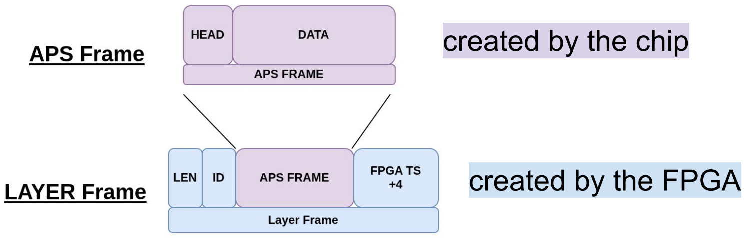
[10.1016/j.nima.2026.171279]

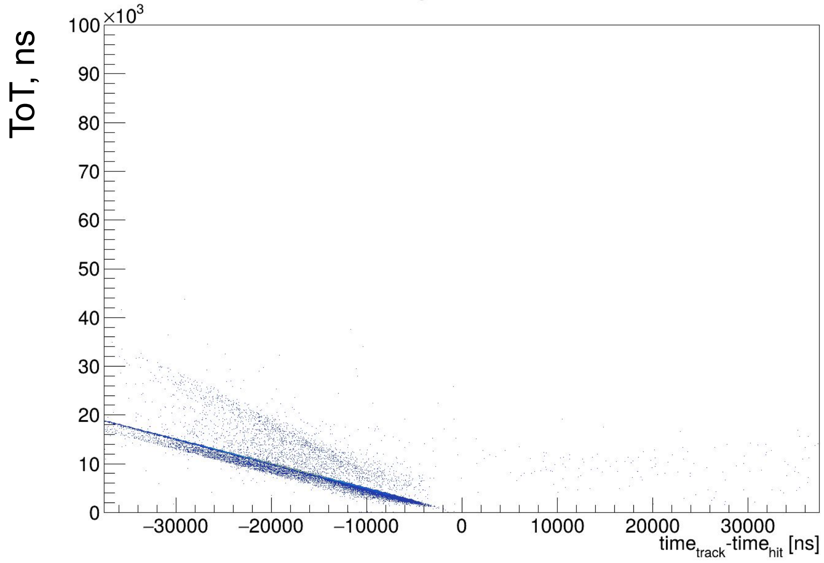
Data analysis

Timestamp adjustment

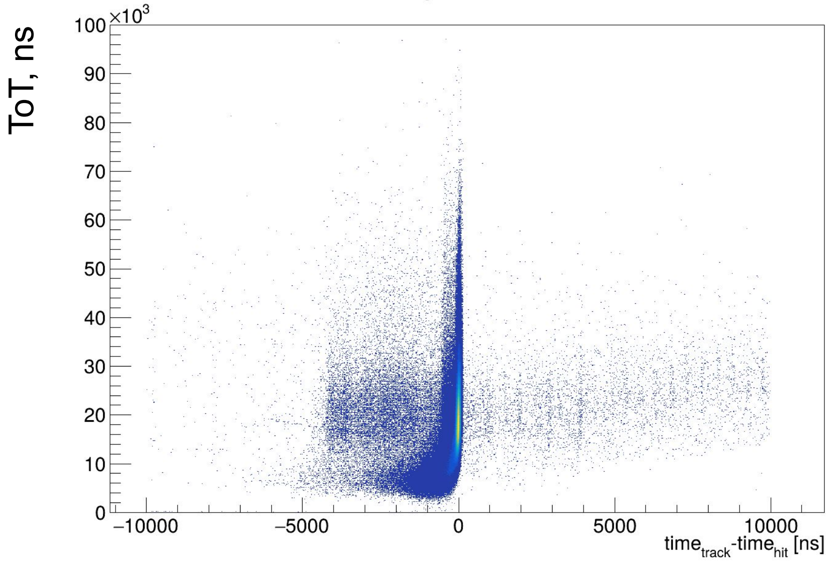
FPGA timestamp = ToA + ToT

v3 + v4





$time_{hit}$ = FPGA TS



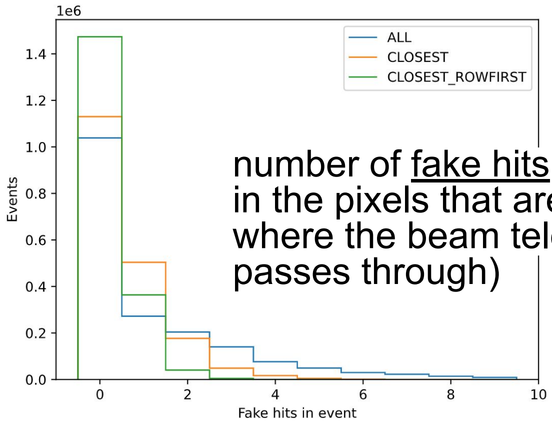
$time_{hit}$ = FPGA TS - ToT

In-pixel efficiency in v3

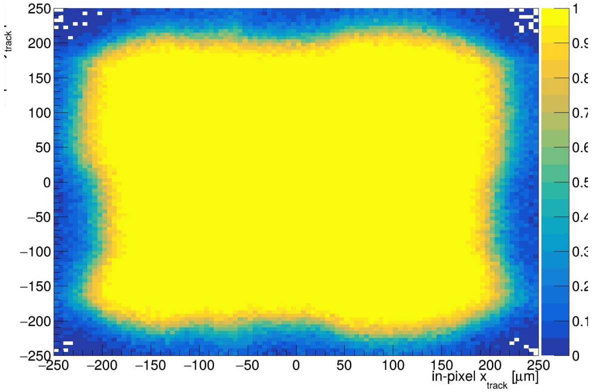
Dependence on halfhit matching strategy

v3

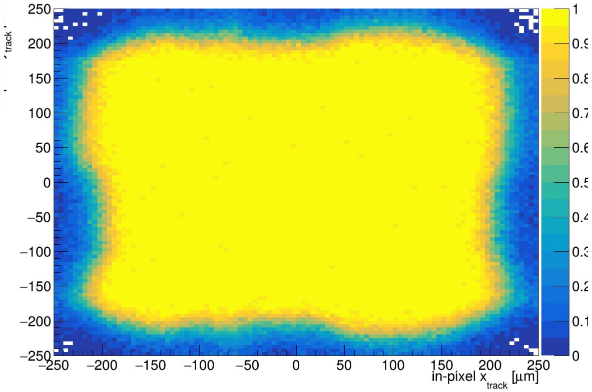
- Bias voltage –250 V
- 1.9M triggers
- 2.6M row halfhits + 2.7M column halfhits



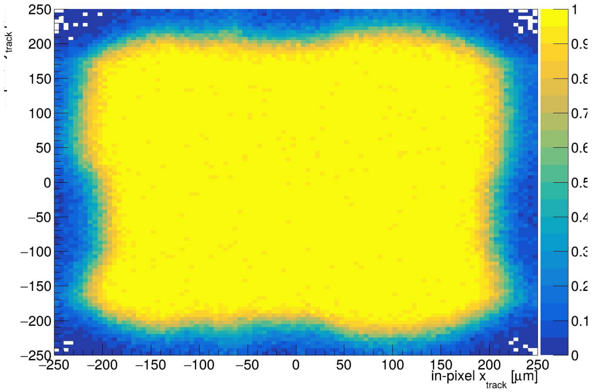
number of fake hits (AstroPix hits in the pixels that are far from where the beam telescope track passes through)



Strategy ALL:
Number of hits = 6M
Total efficiency = 73.99%



Strategy CLOSEST:
Number of hits = 3.8M
Total efficiency = 73.23%



Strategy CLOSEST_ROWFIRST:
Number of hits = 2.6M
Total efficiency = 72.83%

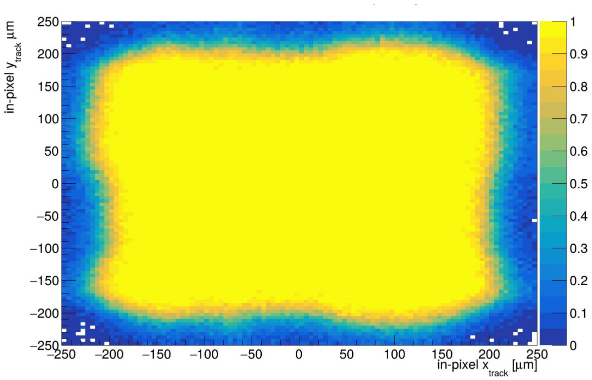
Threshold scan

v3

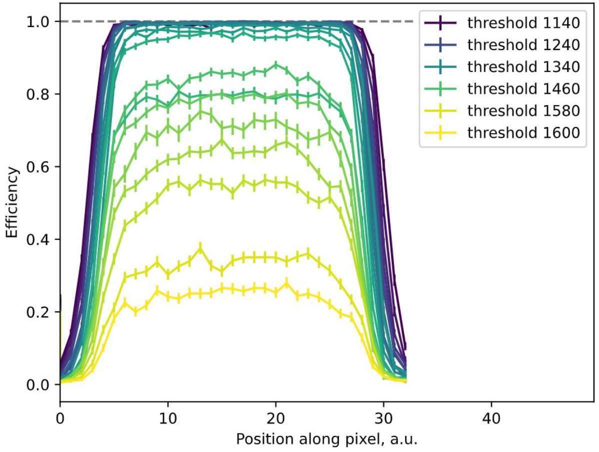
Halfhit matching strategy ALL

- The efficiency in the pixel center falls below 100% at ~1380 mV
- With increase of threshold the 100% efficient zone in the pixel center becomes narrower

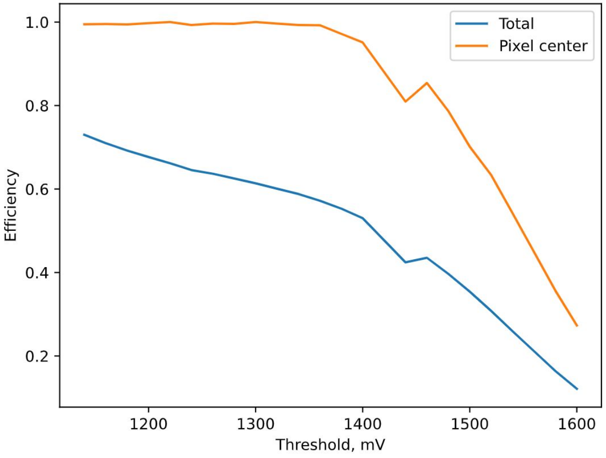
Averaged in-pixel efficiency at 1140 mV threshold



Averaged 3-bin slice in the middle of the in-pixel histogram



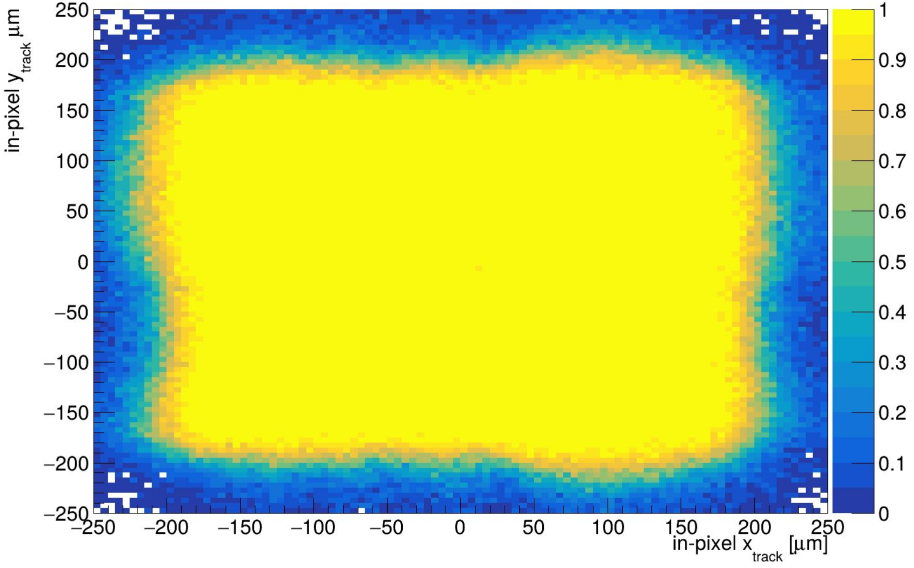
Efficiency depending on threshold

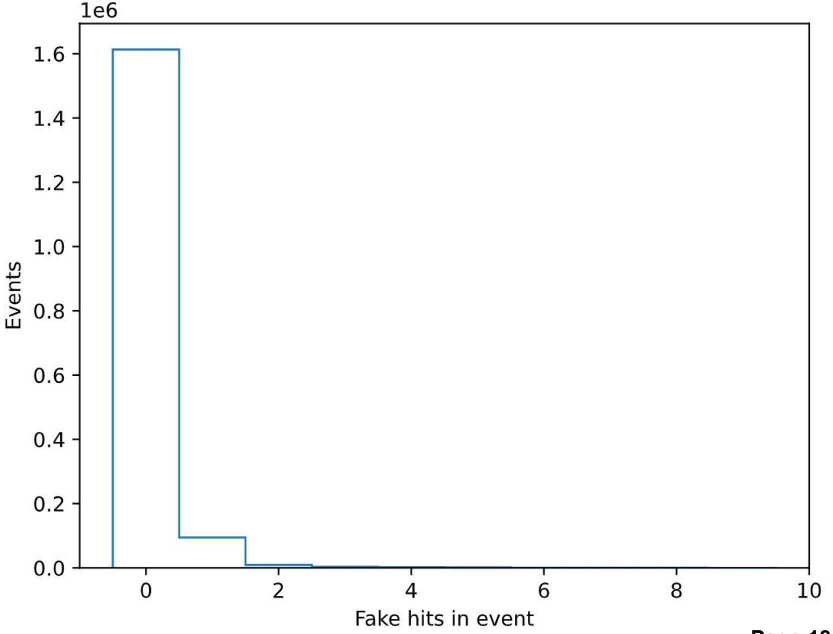


In-pixel efficiency in v4

v4

- Bias voltage –250 V
- 1.7M triggers
- 3.9M hits
- Total efficiency 71.82%



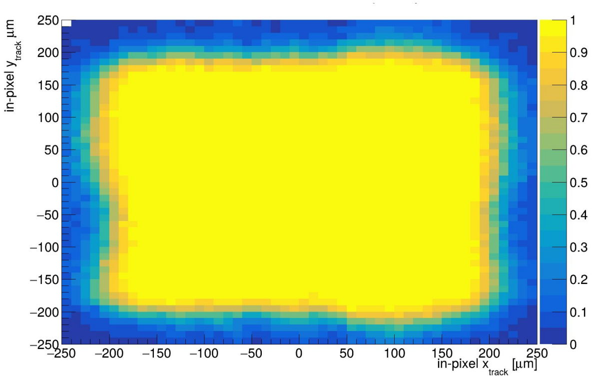


Threshold scan

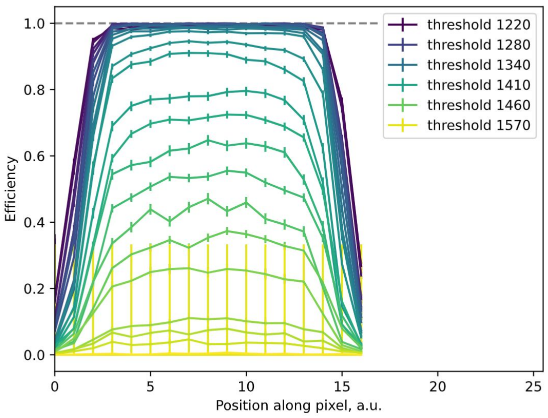
v4

- The efficiency in the pixel center falls below 100% at ~1380 mV
- With increase of threshold the 100% efficient zone in the pixel center becomes narrower

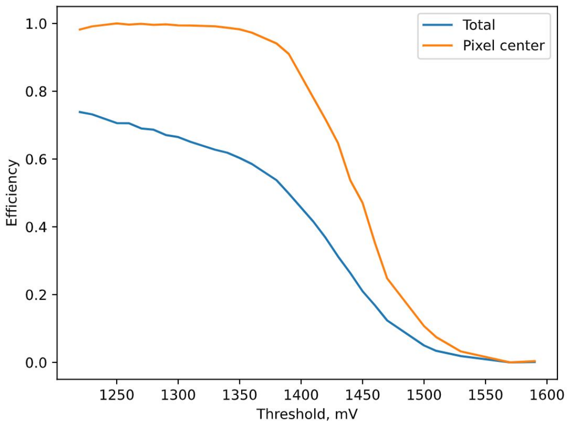
Averaged in-pixel efficiency at 1260 mV threshold



Averaged 3-bin slice in the middle of the in-pixel histogram

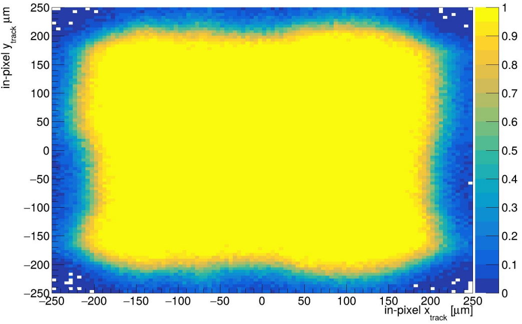


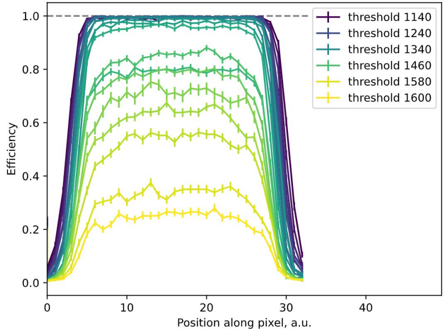
Efficiency depending on threshold

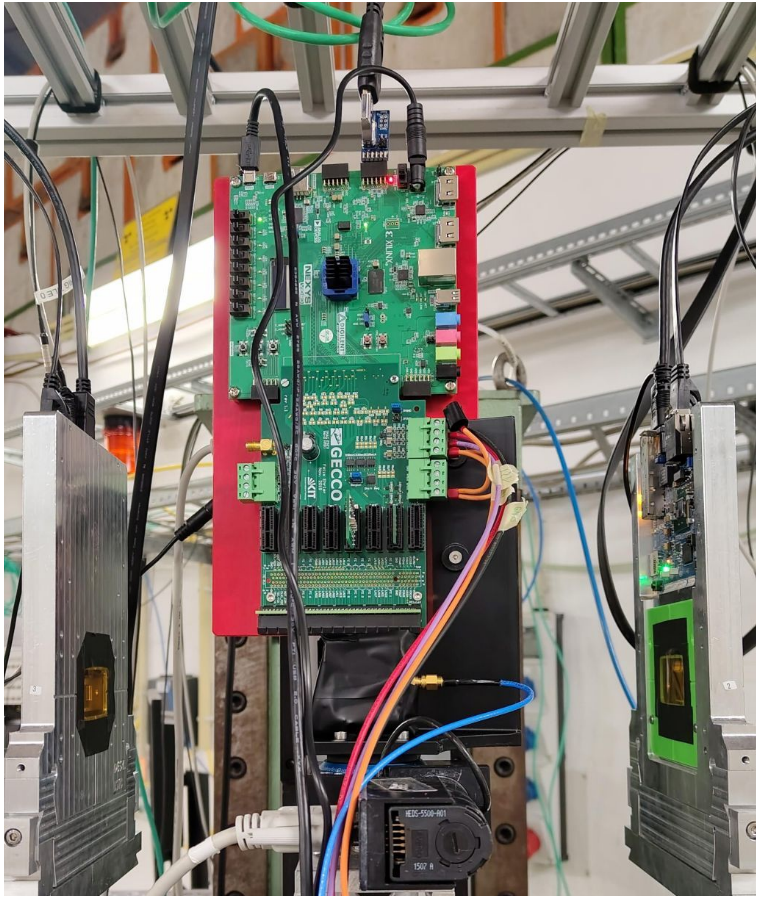


Summary and outlook

- AstroPix chip was designed for photon detection
- The chip was characterized at the DESY II test beam facility:
  - The test beam setup allows to perform precise measurements of the detector characteristics
  - The results complement other measurements and provide insights into the reasons for low measured efficiency [10.1016/j.nima.2026.171869, 10.48550/arXiv.2605.07681]
- Efficiency is not uniform within a pixel, but in the center is reaches 100% for both studied chip versions





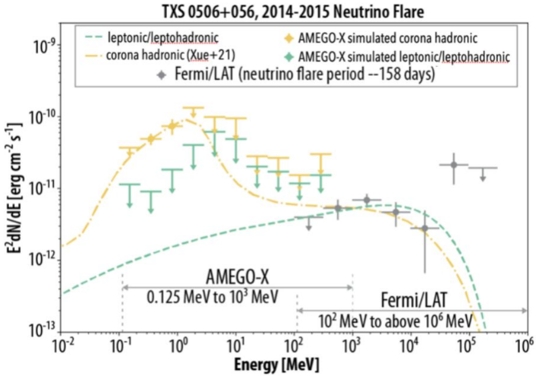


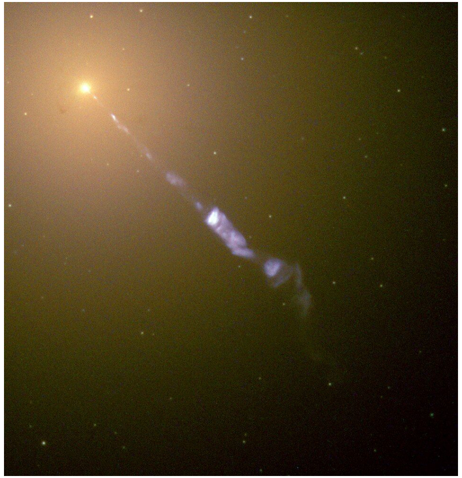
Backup

Why supermassive black holes?

- Active galactic nuclei (AGN) at the centers of galaxies provide extreme conditions that are accelerating particles
- Blazar – AGN with a relativistic jet of ionized matter aligned along our line of sight
- It was observed experimentally that at least some blazars accelerate protons, but it is not yet clear which AGN can accelerate protons
- The "smoking gun" signatures of proton acceleration in AGN are:
  - high-energy PeV neutrinos + medium-energy MeV gamma rays
  - polarized emission in the MeV band

AMEGO-X measurements could shed light on the nature of the gamma ray production in blazars [source]

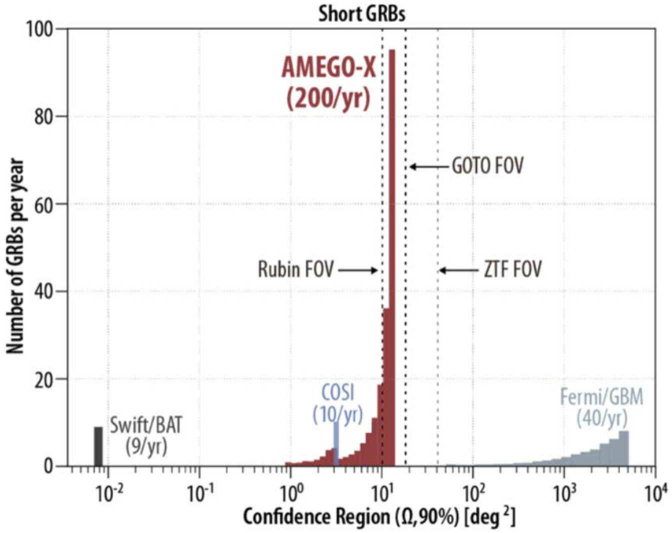




The elliptical galaxy M87 emitting a relativistic jet, as seen by the Hubble Space Telescope. The jet is not pointing close to the line of sight, so not a blazar [source]

Why neutron stars and their mergers?

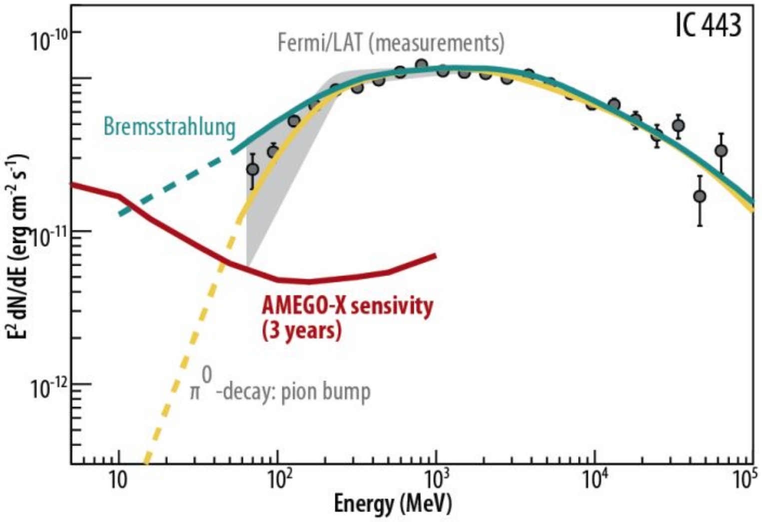
- After a merger of in-spiraling binary neutron stars, narrowly collimated relativistic jets are launched along their rotational axis. When they point towards Earth, a short gamma-ray burst can be observed
- Gamma rays can be used to probe the nature of the merger remnant:
  - Stable neutron star
  - Long-lived massive neutron star supported by its fast rigid-body like rotation
  - Short-lived massive NS supported by internal differential rotation
  - Prompt black hole formation
- SGRB can be used to localize the source of emission



Comparison of the detection rate vs localization accuracy for AMEGO-X and some other experiments [source]

Why remnants of the galactic supernovae?

- Remnants of massive stellar explosions provide environment for charged particle acceleration
- Two main questions regarding galactic cosmic rays remain:
  - In what environments are protons accelerated? -> AMEGO-X can help discover more of them
  - What is the origin of the positron excess? -> AMEGO-X can test if pulsars are the source



AMEGO_X measurement could help distinguish between the emission models in the supernovae remnants [source]

Timestamp correction

Different halfhit matching strategies and chip versions