AstroPix: monolithic active pixel sensors for space based applications and collider experiments

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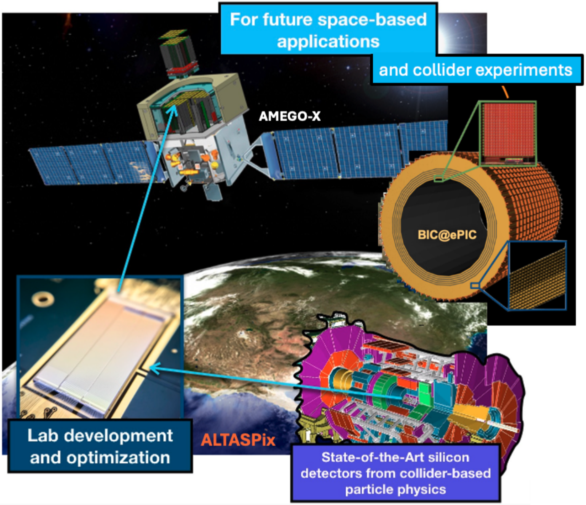
ELMA Workshop on "Energy loss measurements with MAPS"

Sep 10 – 11, 2025
Dipartimento di Studi Umanistici UNITS - Androna Baciocchi

The AstroPix Project

- Goal: develop and test **pixelated silicon sensor** for use in space-based gamma-ray instruments and calorimeters for future colliders
- **AstroPix sensors**: developed based on the experience from ATLASPix and MuPix - from 2019



[Developing the future of gamma-ray astrophysics with monolithic silicon pixels, Nucl. Instrum. Meth. A **1019**, 165795 (2021)]

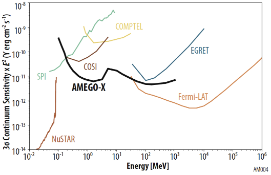
AMEGO-X: All-sky Medium Energy Gamma-ray Observatory eXplorer

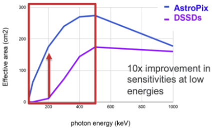
- Si-stacked Compton Telescope planned to explore multi-messenger astronomy
- 4 towers, 40 layers each, $0.5\times0.5\ \mathrm{m}^2$
- Energy range: 25 keV–1 GeV
- AstroPix replaced double-sided strip detectors as the new baseline:
  - Provides pixelated readout
  - Lower energy threshold
  - Room temperature readout
  - Affordable

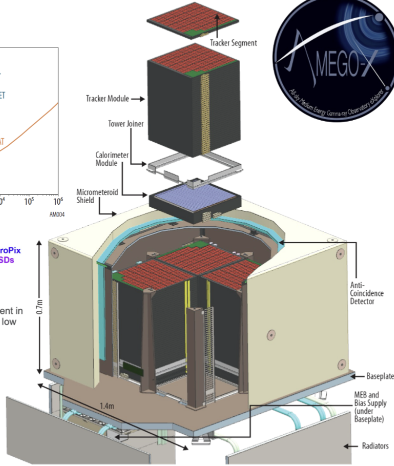
[AMEGO-X mission concept, J. Astron. Telesc. Instrum. Syst. **8**, no.4, 044003 (2022)]

Table 1: The Gamma-Ray Telescope baseline capabilities.

Parameter	
Energy Range	25 keV – 1 GeV
Energy Resolution	5% FWHM at 1 MeV, 17% (68% containment half width) at 100 MeV
Point Spread Function	4° FWHM at 1 MeV, 3° (68% containment) at 100 MeV
Localization Accuracy	transient: 1° (90% CL radius), persistent: 0.6° (90% CL radius)
Effective Area	1200 cm^2 at 100 keV, 500 cm^2 at 1 MeV, 400 cm^2 at 100 MeV
Field of View	2π sr (<10 MeV), 2.5 sr (>10 MeV)



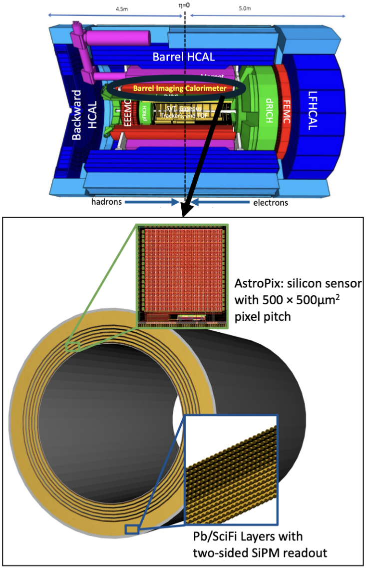




BIC: Barrel Imaging Calorimeter for EIC

Hybrid lead/scintillating fiber calorimeter with silicon tracking layers to precisely measure electromagnetic shower profile:

- main detector for electron-pion separation
- 4(+2) layers of Astropix sensors interleaved with the first 5 Pb/SciFi layers follow by a large section of Pb/SciFi
- Total radiation thickness ~ 17.1 X_o at $\eta = 0$
- Sampling fraction ~ 10%



Requirements:

- Electron ID up to 50 GeV and down to 1 GeV and below
- Energy resolution < $10\%/\sqrt{E} + (2-3)\%$
- High power for e/π separation down to 1 GeV/c
- Photon measurements up to 10 GeV
- γ/π^0 separation up to 10 GeV

[EIC Yellow Paper Nucl. Phys. A **1026**, 122447 (2022)]

Energy resolution - Primarily from Pb/ScFi layers (+ AstroPix energy information)
Position resolution - Primarily from Imaging Layers (+ 2-sided Pb/ScFi readout and φ-R segmentation)

AstroPix: High-voltage CMOS monolithic active pixel sensor (HV-CMOS MAPS)

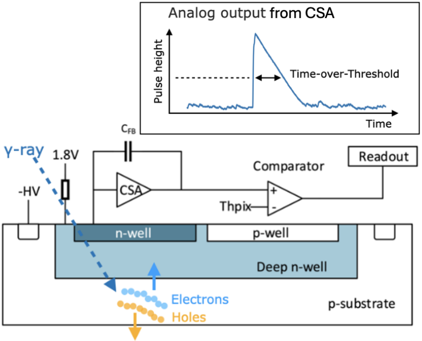
Design Goals

- Energy Resolution: aim for low energy gamma rays ⇒ thicker sensors
- Low Power: limited by solar panels & payload ⇒ fewer/larger pixels and slower readout
- Low Mass: to avoid photon conversions in dead material
- High Position Precision: pixelated tracking

Parameter	Goal
E_{Res}	< 10% (FWHM) at 122 keV
Power Usage	$< 1.5\,\mathrm{mW/cm^2}$
Passive Material	<5% on the active area of Si
Pixel Size	$500 \times 500\ \mu m^2$
Si Thickness	$500\ \mu m$
Time Tag	$\sim 1\ \mu s$

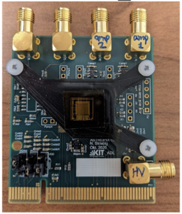
Sensor Features:

- Large sensitive volume: full depletion achieved by applying HV
- Low power consumption and low noise: charge collection and signal processing (Charge Sensitive Amplifier → Comparator for ToT) on each pixel



[Performance evaluation of the HV CMOS active pixel sensor AstroPix for gamma-ray space telescopes, Nucl. Instrum. Meth. A **1068**, 169762 (2024)]

AstroPix Development Timeline

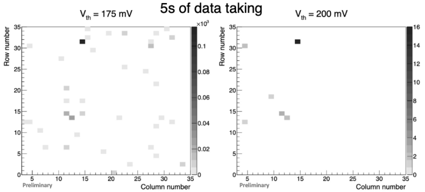
2019	2020	2021	2023
ATLASPix	**AstroPix_v1**	**AstroPix_v2**	**AstroPix_v3**
			
100 μm thick wafer	---------------------720 μm thick wafer ---------------------		
40 x 130 μm² pitch	175 x 175 μm² pitch	250 x 250 μm² pitch	500 x 500 μm² pitch
0.3 x 1.6 cm² chip	0.5 x 0.5 cm² chip	1 x 1 cm² chip	2 x 2 cm² chip
150 mW/cm²	14.7 mW/cm²	3.4 mW/cm²	4.12 mW/cm²
	1st prototype based on ATLASPix HV-CMOS MAPS.	SEE radiation tolerance tested	Voltage/Current DACs included on-chip Beam Tests in '23, '24 Flight prototype

AstroPix_v3 Performance: Bench Tests

Noise Scans:

Goal: quantify fraction of pixels with a response sensitive to dynamic range and intrinsic noise rate lower than threshold.

- v3 dynamic range: 25-200 keV ⇒ comparator threshold values up to 200 mV above baseline
- < 0.5% of pixels with > 2 Hz noise rate (masked): **low noise BIC/AMEGO-X requirements fulfilled**



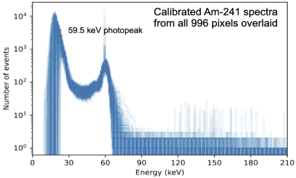
- Active pixels: 99.5%
- 6/1,120 pixels disabled

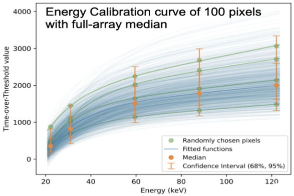
- Active pixels: 99.9%
- 1/1,120 pixels disabled

Radiation Source Test:

Energy resolution/calibration from 22 keV to 122 keV: Cd-109, Ba-133, Am-241, and Co-57

- v3 dynamic range: 25-200 keV (requirement for BIC/AMEGO-X: 25-700 keV)
- **44% of pixels meet the energy resolution requirement of 10% at 59.5 keV** with a median FWHM of 6.2 keV (10.4%)
- **92.4% of pixels achieve the low-energy floor requirement of 25 keV sensitivity**





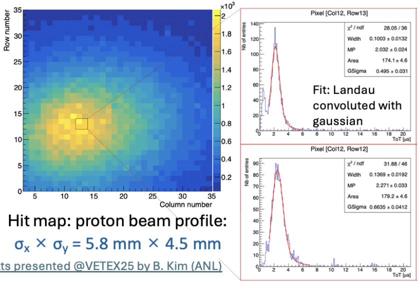
[AstroPix: A Pixelated HVCMOS Sensor for Space-Based Gamma-Ray Measurement, [arXiv:2501.11698]]

AstroPix_v3 Performance: Beam Test

Single Layer:

- Data collected with a 120 GeV proton beam
- The hit map reveals the proton beam profile with 500 um position resolution.
- ToT histograms with MIP response for each pixel
- **First 120 GeV proton response: ~ 35 keV for MIP sits well within dynamic range (25 - 200 keV) in AstroPix_v3.**

[Performance of the AstroPix Prototype Module for the BIC at the ePIC Detector and in Space-Based Payloads, VERTEX25]]



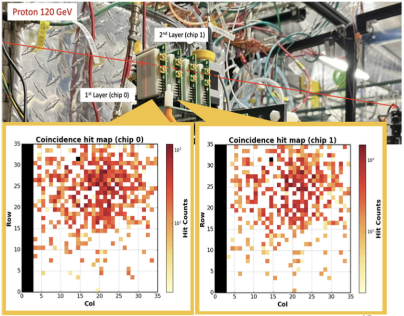
Hit map: proton beam profile:
$\sigma_x \times \sigma_y$ = 5.8 mm × 4.5 mm

Results presented @VETEX25 by B. Kim (ANL)

Double Layer:

- 120 GeV proton beam events from the first two layers, read in coincidence, showing the position of the hit pixel.
- **The proof-of-concept demonstration of the integration of two daisy-chained AstroPix_v3 layers in a beam-like environment**

[AstroPix: Low power high voltage CMOS active pixel sensors for space and collider experiments, PIXEL24]]



Results presented @PIXEL24 by Manoj Jadhav (ANL)

AstroPix_v3: Configurations Under Tests

Test Setup

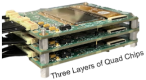
- 1x1

Single chip

- 2x2

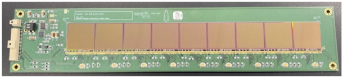
Quad-chips

- (2x2)x3



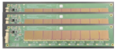
Multi-layer quad-chips

- 1x9



9-chip daisy-chained Prototype Module

- (1x9)x3



9-chip prototype module for the BIC imaging layer

Bench test

- Noise scan (w.r.t thresholds)
  - → Masking noisy pixels
- Injection test
  - → ToT response vs injection voltages
- Radiation source test
  - → Calibration curve each pixel
  - → w. Sr-90: Validation of configuration

Beam test

- 120 GeV Proton beam @FNAL (June.2024)
  - → MIP response
  - → Depletion depth

Test Results

	Single chip	Quad chip	Three layer of Quad-chips	9-chip Module	Three layer of 9-chip Module
Noise scan	✅	✅		✅	
Injection test	✅	✅		✅	On-going
Source test	✅	✅	✅	✅	
Beam test	✅ (2024)				

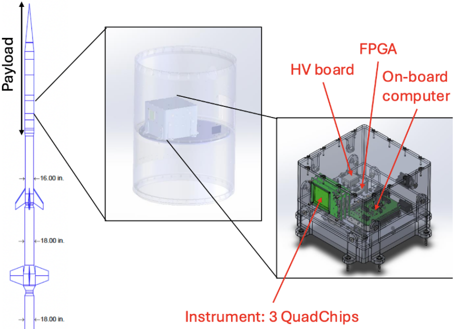
Slide from Bobae Kim (ANL) presented @VERTEX25

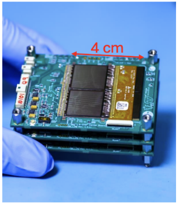
[Performance of the AstroPix Prototype Module for the BIC at the ePIC Detector and in Space-Based Payloads, VERTEX25]]

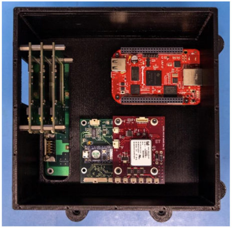
A-STEP: the AstroPix Sounding rocked Technology dEmonstrator Payload

- Multi-stage sounding rocket launch from Wallops Flight Facility (Virginia, USA) at the end of March 2026
- 3 layers of Astropix_v3 QuadChips with data collected by the FPGA and sent to ground via the on-board computer
- It will be the "A step" between a single chip and a space telescope
- Current Status:
  - Validate capability to read data from all 3 QuadChips
  - Test Calibration procedure
  - Assembly of flight detectors

[A-STEP, the AstroPix Sounding rocked Technology dEmonstrator Payload: Multi-detector performance, ASAPP25]]



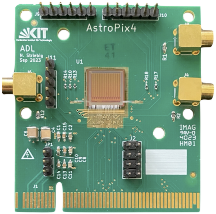




AstroPix_v4

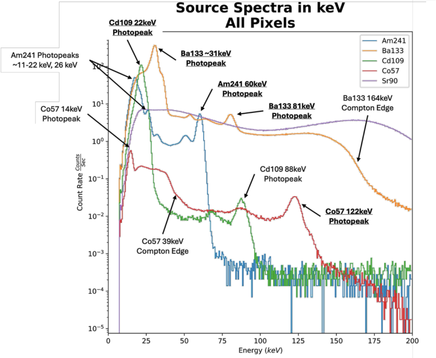
Potentially the final design but in small size 1×1 cm^2:

- Thickness 700 μm, $V_{BD} \sim 400$ V
- 16×16 pixel matrix
- Pixel pitch 500 μm with pixel size 300μm



Features:

- Individual pixel readout with individual hit buffer
- Time stamp w/ 3.125 ns time resolution
- Increase Time-Over-Threshold (ToT) bits
- TuneDACs - Pixel-by-pixel threshold tuning and pixel masking



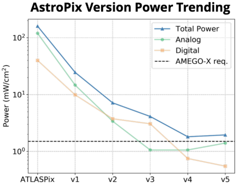
Performance and Characterization are ongoing

[Evaluation of gamma-ray response of the AstroPix4 HV-CMOS active pixel sensor, [arXiv:2501.21618]]

Astropix_v5, Astropix_v6 and COMPAIR2

AstroPix_v5:

- $2 \times 2\,\text{cm}^2$ size
- same size but half the power of AstroPix_v3
- Improved dynamic energy range: up to 700 keV

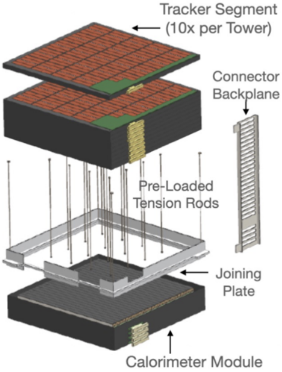


AstroPix - future:

- Full-volume depletion

ComPair-2

- Compton-Pair telescope prototype
- High-altitude balloon hosted flight
- Prototype of AMEGO-X tower
- 10 tracker segment layers of AstroPix_v5 (1300cm^2 active area per segment).
- Instrument integration and gamma-ray beam test end of 2026



[ComPair-2: a next-generation medium-energy gamma-ray telescope prototype, Proc. SPIE Int.Soc.Opt.Eng. **13093**, 130932L (2024)]]

Summary and Outlook