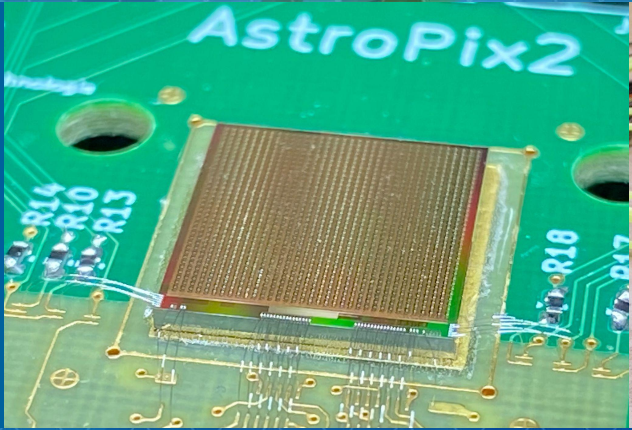
ePIC Barrel ECal Review, March 13-14, 2023

The Imaging Calorimeter for ePIC
Sensors and FEE



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Imaging Layers

Sensors: Monolithic HVCMOS
(Monolithics Active Pixel Sensor (MAPS)

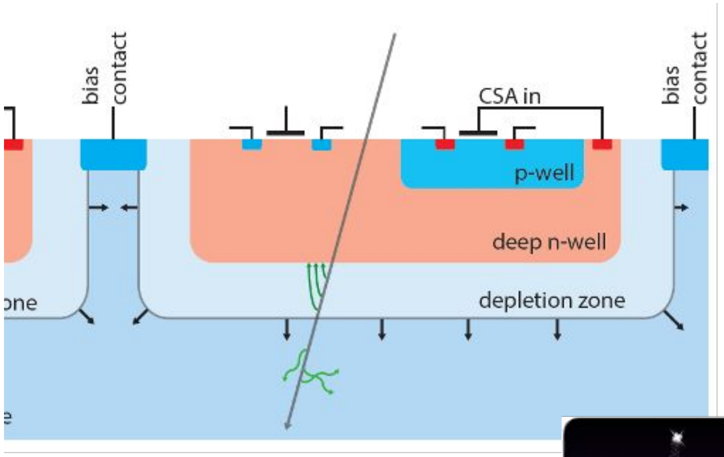
Monolithic: combines a traditional silicon pixel sensor wafer and the Front-End ASIC in a single wafer

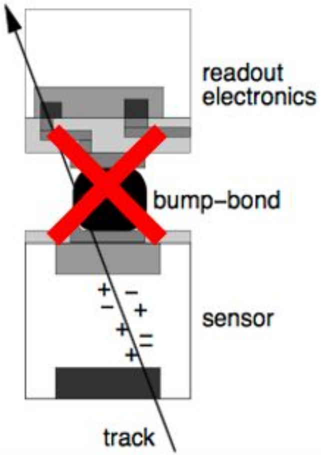
- Each pixel has it's own amplifier in a deep n-well
- High-resistivity substrates enable sensor depletion for collection via drift rather than diffusion
- Technology uses more typical CMOS wafer processing for cost effective production
- Single wafer enables shorter design cycle

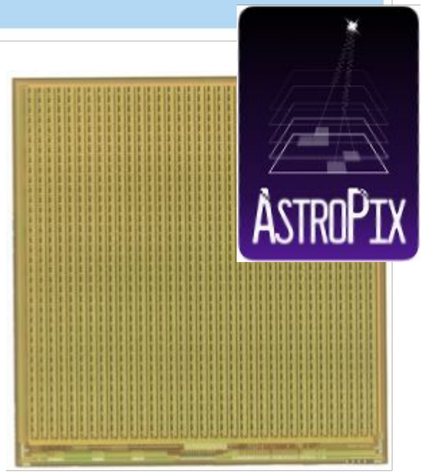
History: <u>HVCMOS</u> developed by Ivan Peric at Karlsruhe Institute of Technology (KIT). He has designed MuPix, ATLASPix, AstroPix, etc.

AstroPix: initially for space-based applications

- Upgrade to the next generation Fermi Telescope—AMEGO-X







AstroPix: Monolithic HVCMOS Sensor

AstroPix Design Goals:

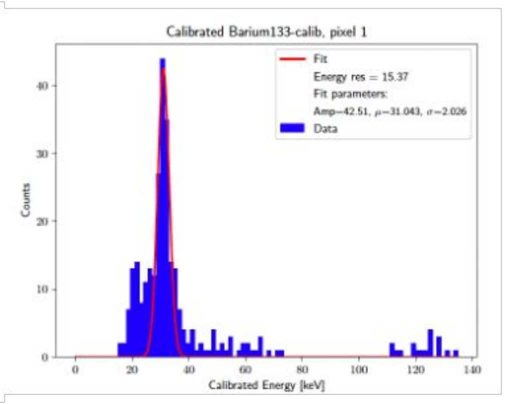
- Low power (limited by solar panels in space) à fewer/larger pixels, slower readout
- Energy Resolution: aim for low energy gamma rays thicker sensors
- 180 nm CMOS technology is rad hard

AstroPix Specs:

- 500 µm x 500 µm pixels; 700 µm thick
- Power consumption: ~1.5 mW/cm^2
- Energy resolution target (single sensor) 2% @ 600keV

AstroPix Features (v4):

- Time stamp w/ 3.125 ns time resolution
- Row & Column from individual pixel hitbuffer
- Time-Over-Threshold (ToT)
- Threshold tuning (5-bit)
- Mask noisy pixels
- Pass hits to next chip (daisy chain)
- Self-triggered (only read out active hits)



arXiv:2208.04990 **[astro-ph.IM]**

	Energy Resolution at 30.97 keV [%]	Wafer Thickness [µm]
Requirement	38%	500
ATLASPix	7.3 ± 1.2	100
AstroPix_v1	19.9 ± 7.4	700
AstroPix_v2	15.4 ± 2.9	700

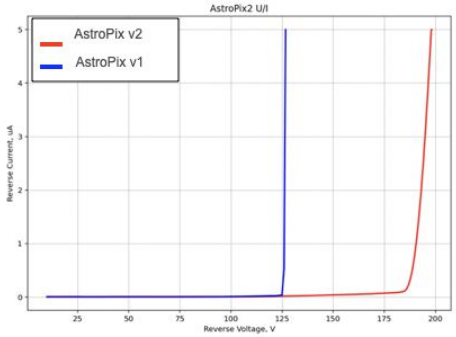
Imaging layers R&D

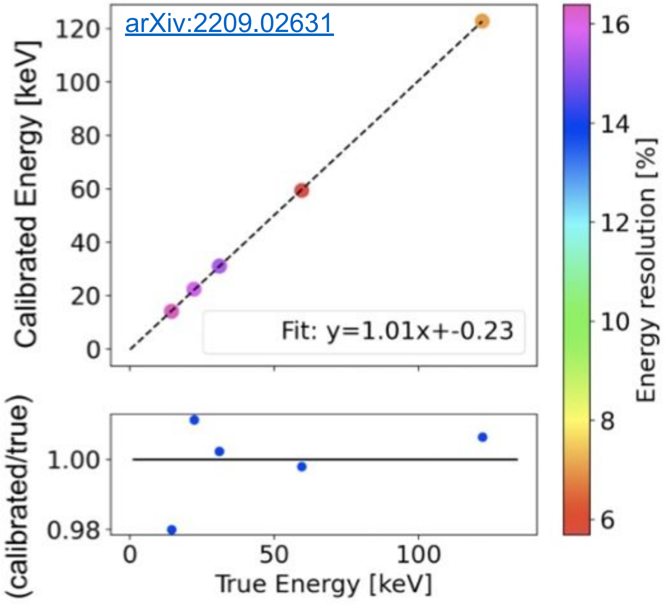
AstroPix sensor validation testing

- Bench tests with **AstroPix v2**
  - Energy resolution studies
  - Noise measurements
  - Digital data acquisition
  - Sensor characterisation (IV, edge-TCT, depletion depth)

- **Testbeam campaign at Fermilab FTBF**
  - Validate detector performance at 120 GeV proton beam
  - Intergration of AstroPix with ATLAS telescope
  - **AstroPix telescope tracker (4 layers of AstroPix)**
  - **Feasibility with Calorimeter environment** with pions/electron beam at FTBF with tungsten radiator, readout aspects (ANL LDRD grant)

- **Irradiation test**
  - 400 MeV proton (2.5E15 protons/hr) at the FNAL ITA Facility (ANL LDRD)
  - Latch up tests by NASA with heavy ions (from Argon to Xenon with an atomic tune of 16 MeV/a.m.u.) at LBNL (BASE)

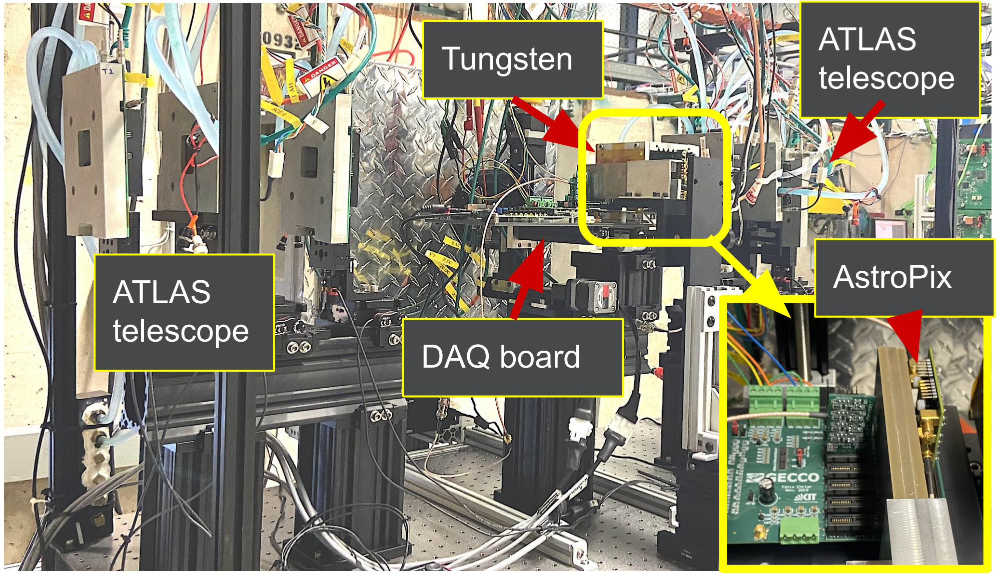


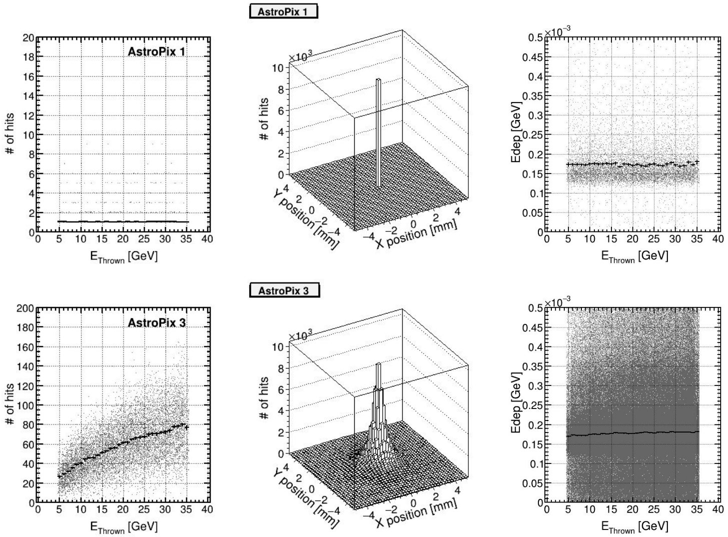


Imaging layers R&D

AstroPix detector test-beam measurements

- **Simulation study**
  - Sensor response to electromagnetic shower
- **FY24 Plan**
  - Response to electromagnetic/hadronic shower with multilayer AstroPix v3 prototype





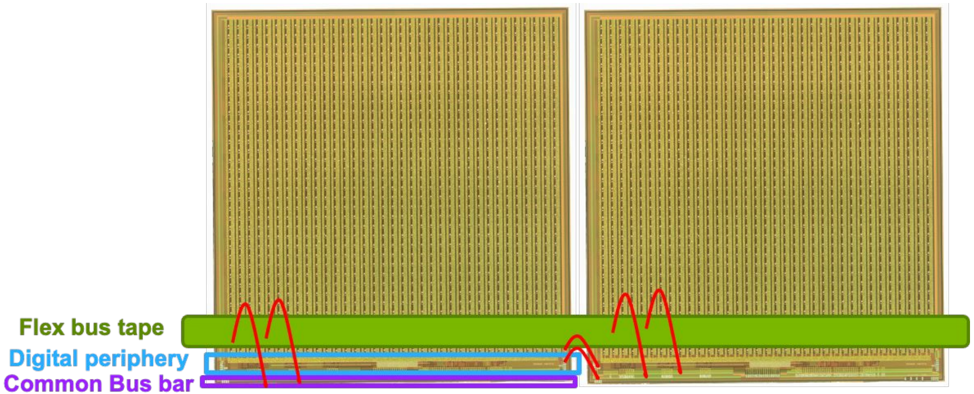
Simulations

Run Feb 14-28, 2023 in Fermilab

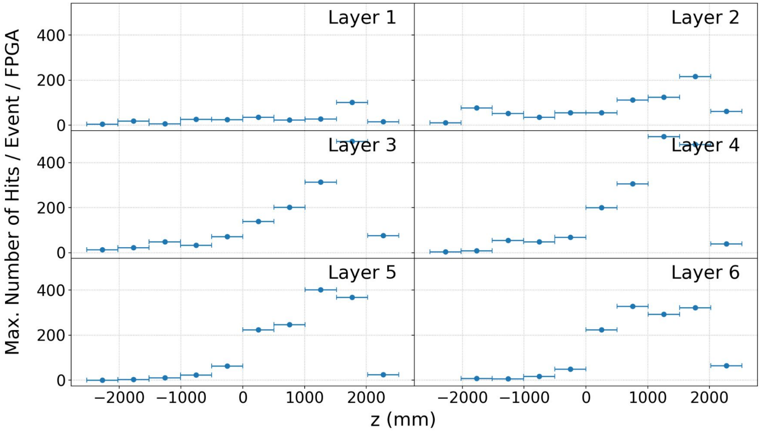
- Mostly focus on setting up the measurement
- Testing DAQ conditions with v2
- Studying optimal pixel thresholds
- Runs with proton, pion/electron beam with and without radiator

Readout

- SPI I/O daisy chained
- 8 bytes per hit (header, time stamp, row/column, ToT)
- Zero-suppression below threshold
  - programmable threshold
  - min threshold 4x above noise floor, 5 keV → **4σ = 4×5 keV**
- Signals passed from chip-to-chip
- Data sent to an FPGA at the end of stave
- FPGA aggregates data before sending off-detector
- 1st level aggregations for ~0.1 m^2
- 2nd level aggregator injects into the main data stream
- Total expected data rate < 5 Gbps



- Command/Power is distributed through a bus tape
- Wire bonded from bust tape
- Signals are digitized and routed out to the neighbor chip via wire bonds



Example max occupancy for NC DIS for 18×275 GeV beam energies and minimal Q^2 = 1000 GeV^2

AstroPix Timeline & Production

AstroPix versions
- v1 early prototype
- v2 current test bench & test beam studies
  - extensive test bench characterization
  - higher noise due to larger pixel size
  - LET radiation testing
  - first test beam run a few weeks ago
- v3 full size chip
  - minor fixes from v2
  - OR’d rows & columns
  - just received
- v4 new features for better performance (MPW)
  - ‘final version’, but smaller chip (1 cm x 1 cm)
  - plan to submit in May 2023
  - better noise/threshold performance
  - per pixel hitbuffer
- v5 full size chip
  - fix any bugs from v4
  - Final production version
  - chips available November 2024

Design Validation
- test bench characterization complete
- LET irradiations done
- test beam measurements on-going
- multi-chip DAQ development
- daisy chain readout validation
- NASA balloon test Fall 2023
- AMEGO-X system development
- Sounding rocket January 2025

Multi-layer calorimeter prototype (ANL)
- full scale prototype to be built and tested w/ v3
- DAQ development joint with NASA

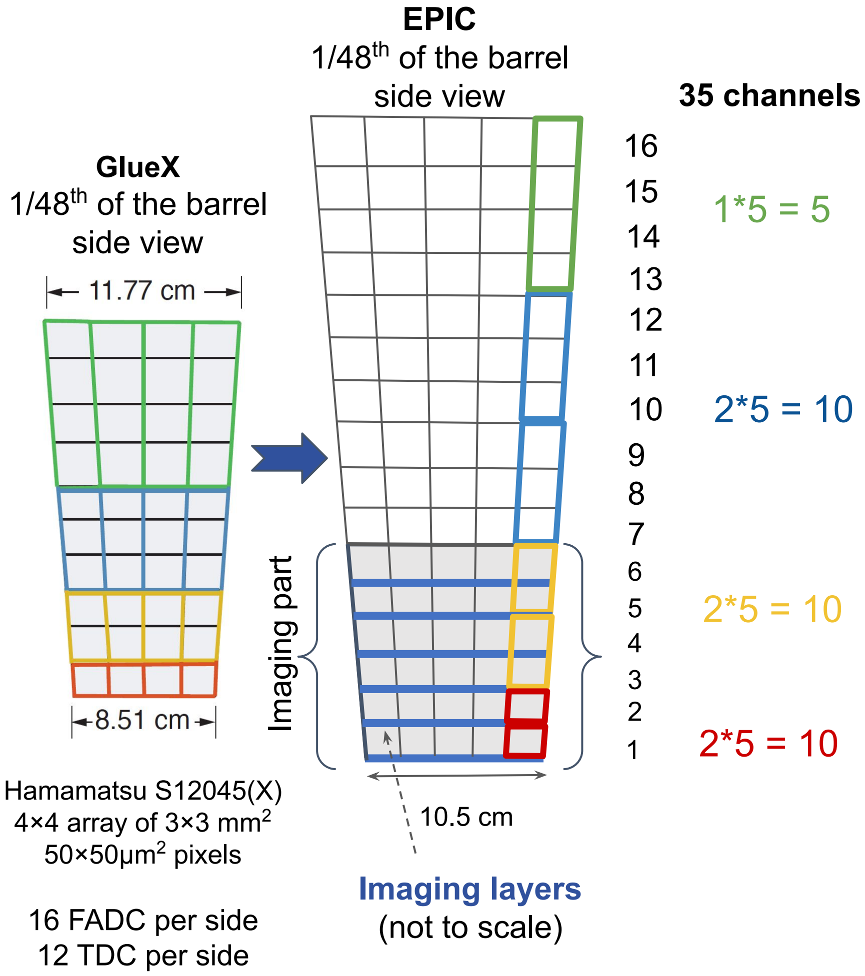
Production
- fabrication by TSI
  - AMS is a backup, but need a large order

Pb/ScFi

Readout Pb/ScFi

Similar readout scheme as GlueX

- **2-side SiPM readout**
- **Lightguides** attached to the stave sides
  - inner surface ~2×2 cm^2
  - output face 1.3×1.3 cm^2
- Possible SiPM candidate: S13360-6050PE (6×6 mm^2, 50×50μm^2 pixels) - 4 per lightguide
  - Consolidated option
- **Summing scheme**
  - Following the preamp stage, outputs summed by columns (see picture)
  - Optimization of the scheme based on simulations in progress
  - **35 channels per side** (3360 in total)
- To be implemented in the common readout strategy (e.g. HGCROC)



GlueX SiPM Performance - I

Normal plots

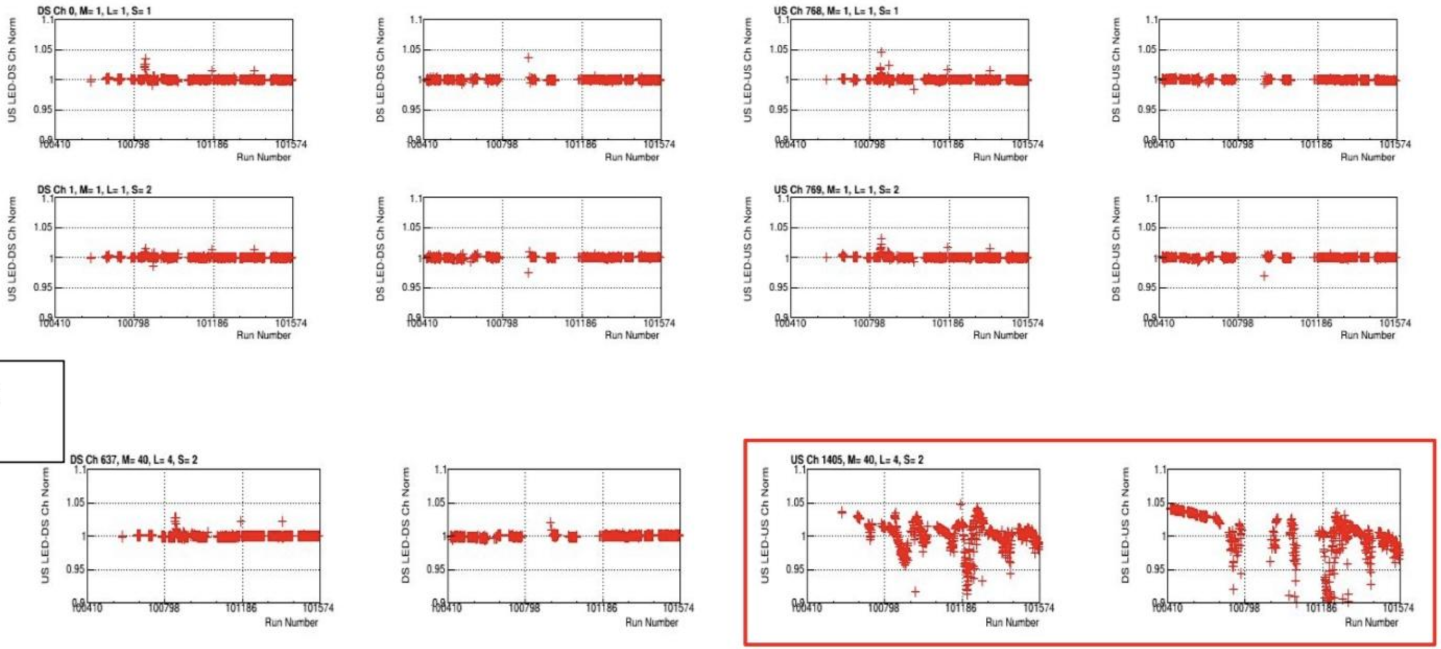
Y Axis
0.95
To
1.05

Run Number

Channel 1405
6% deviation

Y Axis
0.92
To
1.08

US LED | DS LED | US LED | DS LED



Downstream SiPMs

Upstream SiPMs

GlueX SiPM Performance - II

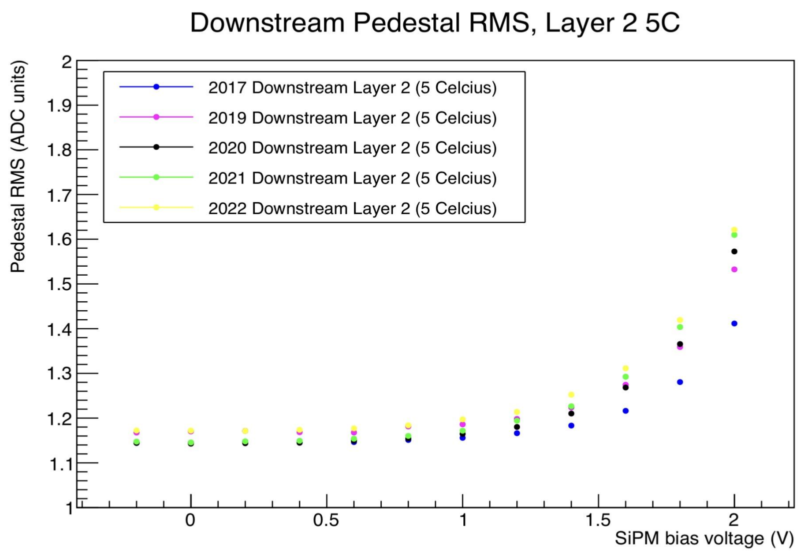
- GlueX - First full scale calorimeter using SiPMs

- BCAL operational since 2015 (cosmics), since 2016 (photons)

- 3840 BCAL SiPMs
  - 1 dead unit
  - 2 showing deviation from unity normalization (6%, 9%, respectively)
  - 3837 within 1% of normal

- 3840 LEDs
  - 20 deviating between 10-20% from normal
  - 96 deviating more than 10%
  - System has redundancy: no complete LED failure on any readout channel
  -

- SiPM radiation damage: 8% dark rate increase in 7 years of running, at 1.4 V overbias



Backup

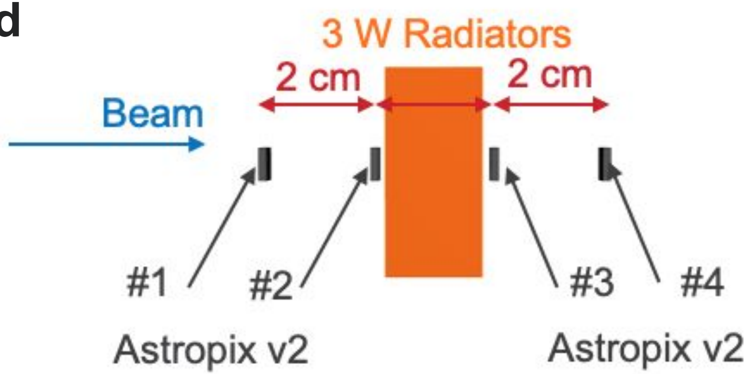
Sensors and FEE

a. Status of sensor selection (a single consolidated option, more options under consideration) and photosensor characteristics?
b. Status of sensor validation for the specific application and related potential issues?
c. Perspectives of sensor mass production and timelines for the production period?
d. Status of FEE selection (a single consolidated option, more options under consideration)?
e. Characteristics of the FEEs considered?
f. Status of the FEE development and related potential issues?
g. Perspectives of FEE mass production and timelines for the production period?

R&D program AstroPix in FTBF Test Beam @ Fermilab

- **Goal**
  – Assess feasibility of using AstroPix-like sensors in a calorimeter environment
- **Milestones** with AstroPix v2 sensor
  - Sensor characterization (noise study)
  - **Debug DAQ, testbeam conditions, and mechanical assembly of setup** using **proton beam**
  - **Simulation study** on **sensor response to electromagnetic shower** with interleaved Tungsten plates using **pion/electron beam**

Simulation geometry



AstroPix Sensor Layer Size

For **6 layers** of imaging layers that cover **$-1.5 < |eta| < 1.2$** the AstroPix sensors area is about **140 m^2**
24 staves: ~2.5×10^3 sensors per stave, ~3.7×10^6 pixels per stave, ~4.6×10^5 pixels per aggregator area

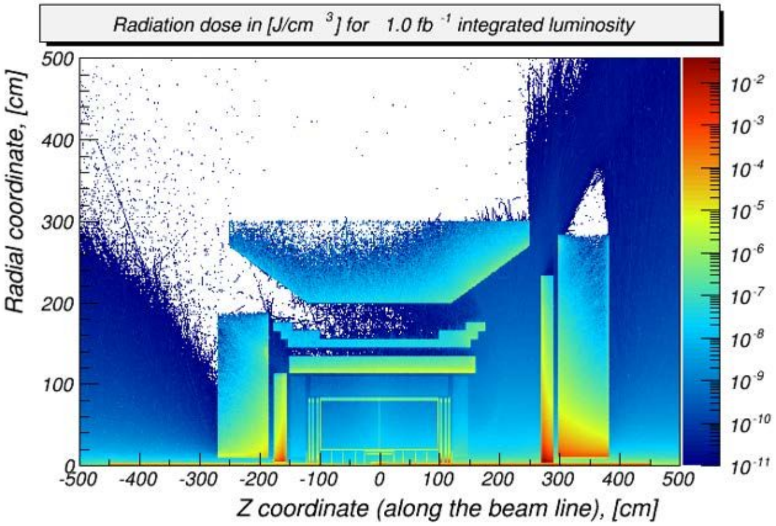
Large Si detector arrays in advanced stage (large scale prototypes)
- ATLAS Inner Tracker - silicon strips[1] (ITk pixel) 160 m^2 (50 million channels)
- CMS high granularity calorimeter [2] ~ 600 m^2 (6.5 million channels)

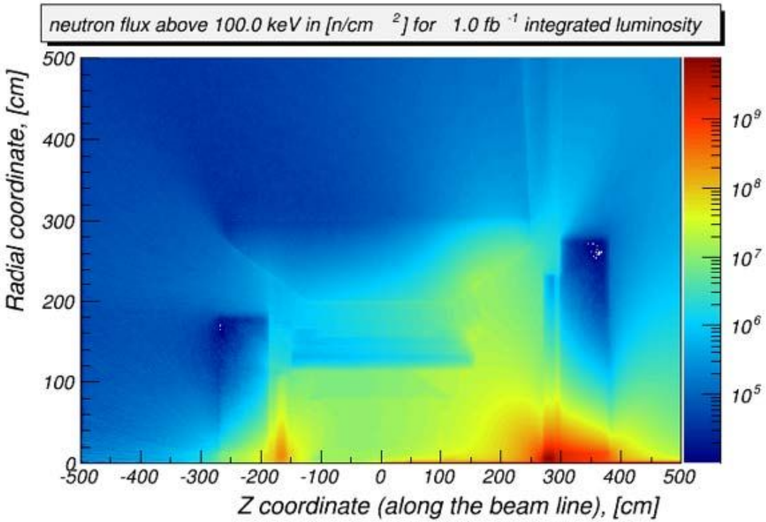
- AstroPix sensors (derived from ATLASpix) will be used in the **AMEGO-X NASA mission**, which is a 40 m^2 experiment sent into space.
- We plan to use chips off-the-shelf, **meaning with no design modifications**.

Advantages of AstroPix with respect to pixels used in e.g. ATLAS
- AstroPix has very low power consumption (used in space) - 100 times smaller power consumption per cm^2 than ITk pixel
- AstroPix is a monolithic sensor - less complicated structure
- No bump bonding - less risk of damaging sensors

[1] arXiv:2105.10367, ATLAS ITk Pixel Detector Overview
[2] arXiv:1802.05987, The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC2

Ionization radiation and neutron flux





- Maximum ionizing radiation dose from e+p collisions at the highest EIC luminosity ($10^{34}cm^{-2}s^{-1}$): ~1 Rad/year
- Neutron flux: 10^8 neutrons/cm^2 per year at the top luminosity (two order of magnitude lower than the near-beam-line detectors)

Imaging layers technology

Imaging layers based on AstroPix sensors

- 180nm HV-CMOS MAPS sensor
- Developed for AMEGOX NASA mission
- Based on ATLASpix3 arXiv:2109.13409 [astro-ph.IM]

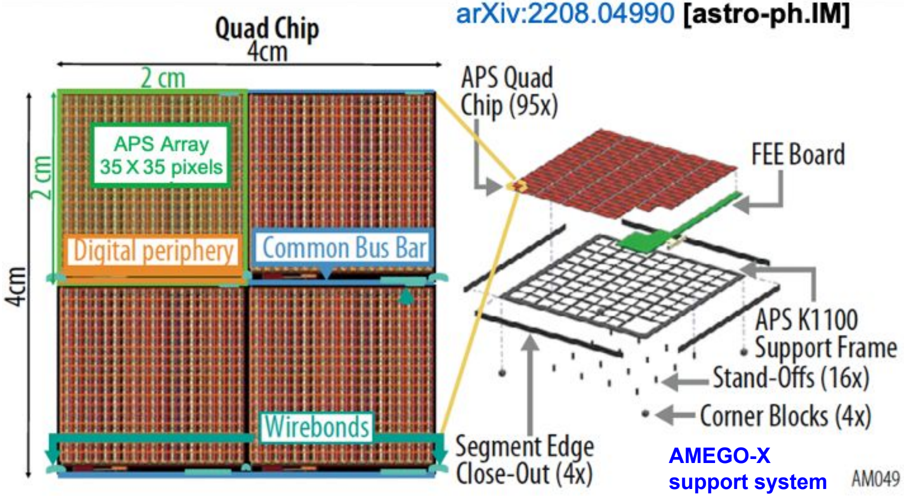
Key features:

- Very low power dissipation requirement < 1.5 mW/cm^2 (ATLASpix3: 150 mW/cm^2)
- The good energy resolution (<10% @ 60 keV) (20-700 keV dynamic range; 5 keV noise floor)
- 500 µm X 500 µm pixel size
- Sensor thickness of 700 µm
- Time resolution < 50 ns
- Passive material <5%
- Daisy chain readout (row and column)

Event driven readout scheme → self trigger

- On-pixel charge amplification using CTIA (Capacitive Trans-Impedance Amplifier)
- Provides threshold crossing hit timestamp
- Energy measurements using Time-over-Threshold
- Hit triggers start of ToT clock

arXiv:2208.04990 [astro-ph.IM]



AMEGO-X support system

Imaging layers R&D

AstroPix chip R&D:

v1 (4.5×4.5 mm^2, 175 µm pixel) - January 2021

v2 (1×1 cm^2, 250 µm pixel) - December 2021

- arXiv:2209.02631 [astro-ph.IM]

v3 (2×2 cm^2, 500 µm pixel, single and **quad chip**)

- Received **February 2023**

AstroPix v2/v3:

- Time Resolution < 50ns
- Timestamp clock 2MHz, ToT 200 MHz
- 5 byte data frame (10 byte per hit - row/column)
- Integrated temperature sensor

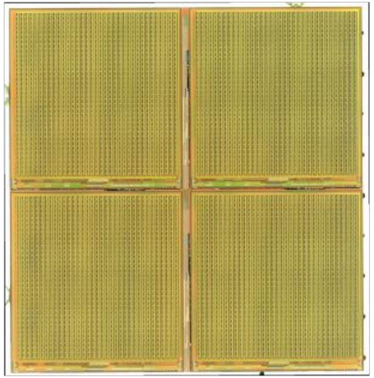
AstroPix v4

- Chip size 1×1 cm^2; pitch 500 µm pixel
- Individual pixel readout
- Will be submitted **May 2023**
- Not a final Version

Planned choice of the foundry TSI (v1-v4).

With a large production order, AMS is a backup.

v2 carrier board



v3 Chip

AstroPix v4:

High resistivity substrate 10kΩ-cm

Breakdown voltage 400V

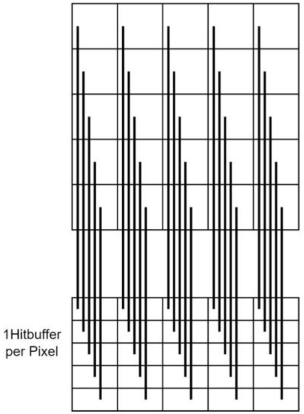
Hitbuffers (1225/APS)

ToT measurement using Flash TDC

- No fast clocks
- Timestamp 2.5 MHz
- Fine Timestamp 20 MHz
- Flash TDC

Tune DACs

Improved time resolution



AstroPix future developments

Current issues with AstroPix v2

- Larger pixel size → higher noise than targeted
- hit identification with Row/Column readout

Design development

- Noise is reduced by chip design modifications in AstroPix v3
  - reducing pixel size keeping same pitch
  - ENC of 225 e- with estimated 1 pF pixel capacitance
  - RMS Noise equals an 800 eV input signal
- Individual Hitbuffers in AstroPix v4
  - 35 x 35 pixel matrix → 1225 hitbuffers
  - Low power; Improved Time Resolution

AstroPix v3 already delivered and ready to test

AstroPix v4 is under review and will be submitted May 2023

Astropix v5 timeline for design & fabrication is complete November 2025

DAQ board development

- Nasa - developing DAQ board for hosted payload mission - **January 2025**
- ANL - DAQ for full size prototype
  - Felix board
  - Carrier board for single and quad chips for Felix board is under discussion
  - Timeline - Fall 2023

Potential Issue and mitigation

- Readout data structure recognised by Felix
  - Optical signal
  - May superfluous
- Considering an alternative FPGA for Felix
- **Joint effort between ANL and NASA**

TSI will be the primary fabrication foundry for the AstroPix (AMS is backup foundry) and chips can be distributed to different sites for the production