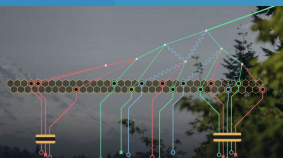


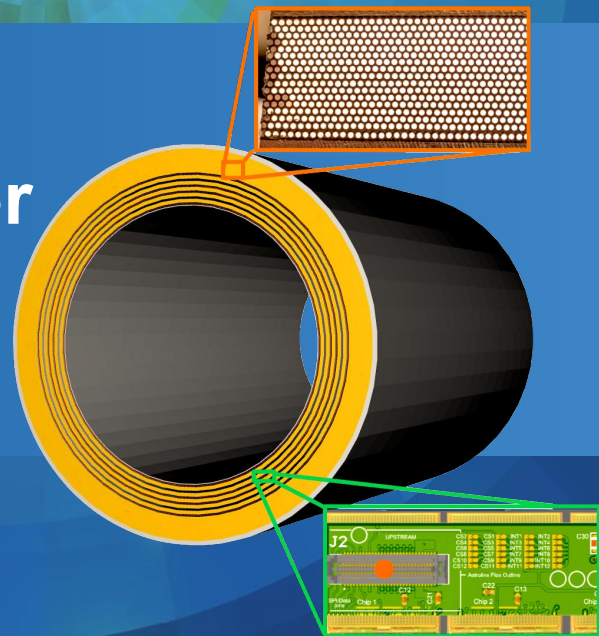
COORDINATING PANEL ON ADVANCED DETECTORS APS-EPF
CPAD 2026

Instrumentation and detector R&D workshop

20–23 October 2026 University of Washington · Seattle, WA



The ePIC Barrel Imaging Calorimeter for the EIC



Manoj Jadhav for the ePIC Collaboration
Argonne National Laboratory

mjadhav@anl.gov



CPAD 2026, Seattle
Oct 20, 2026



Detector Requirements for Barrel ECal

From the EIC Yellow Report: stringent requirements for Barrel ECal

<https://eic.jlab.org/Requirements/>

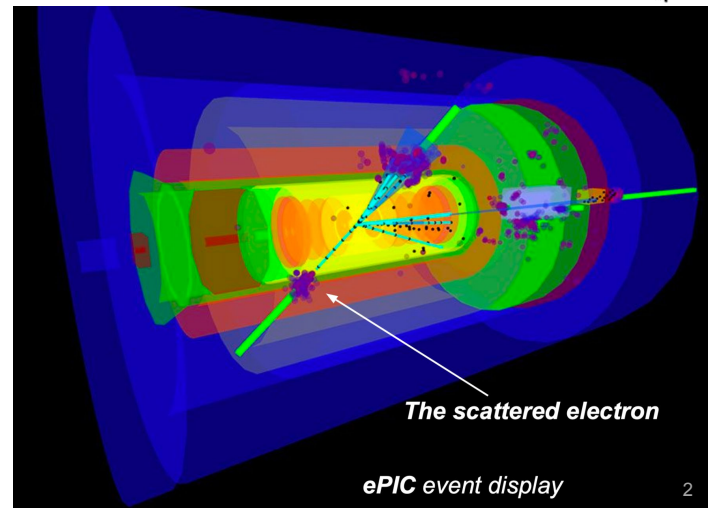
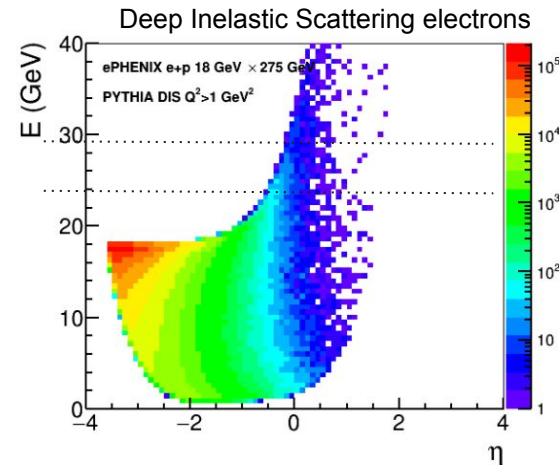
EIC is an electron scattering machine: The electromagnetic calorimeter is the main detector for **electron-pion separation**. The inclusive physics program requires up to 10^4 pion suppression at low momenta in the barrel

- **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**
 - Fine granularity for good shower reconstruction with separation down to 30 mrad

Assist with muon identification

Sufficient dynamic range to **detect MIP** signals in all layers

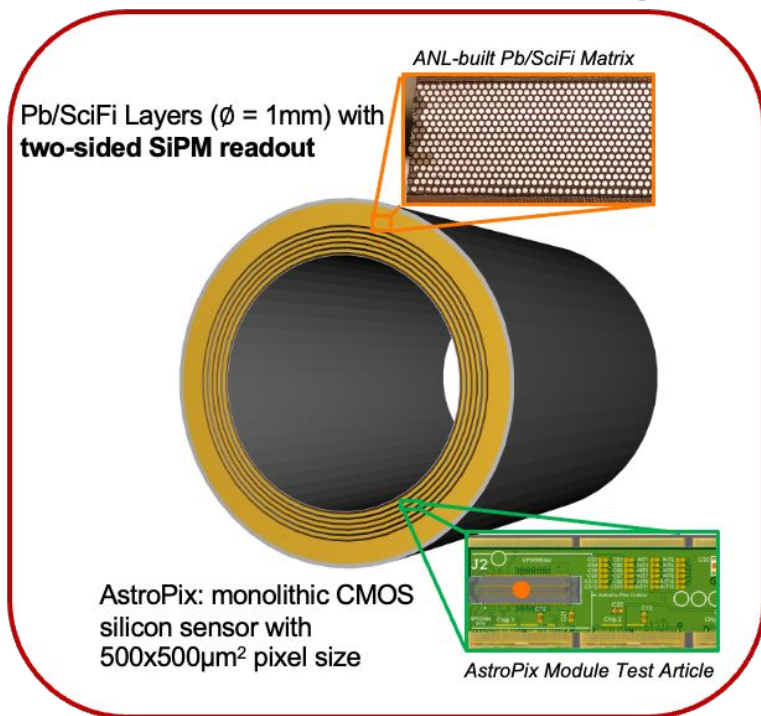
The system is space-constrained inside the solenoid



The concept of Barrel Imaging Calorimeter (BIC)

These stringent requirements for Barrel Electromagnetic Calorimeter can be achieved using Hybrid lead/scintillating fiber calorimeter with a silicon tracker

High-performance 3D imaging of electromagnetic shower



Multiple layers of monolithic AstroPix silicon sensors
(Inexpensive low-power silicon sensor developed for NASA space application) to capture a **3D image of the shower**

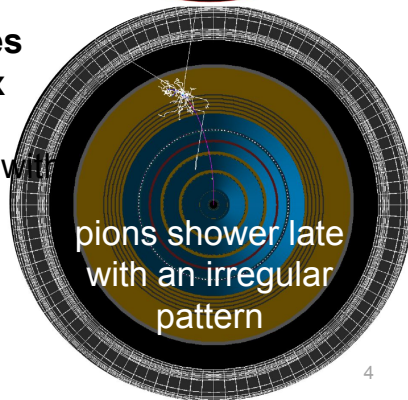
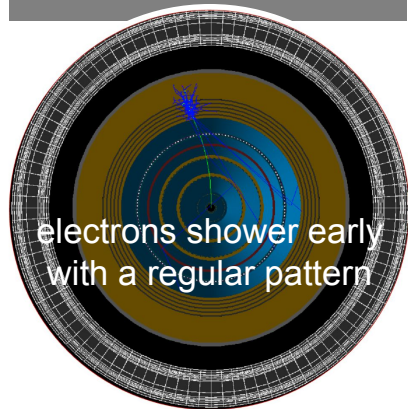
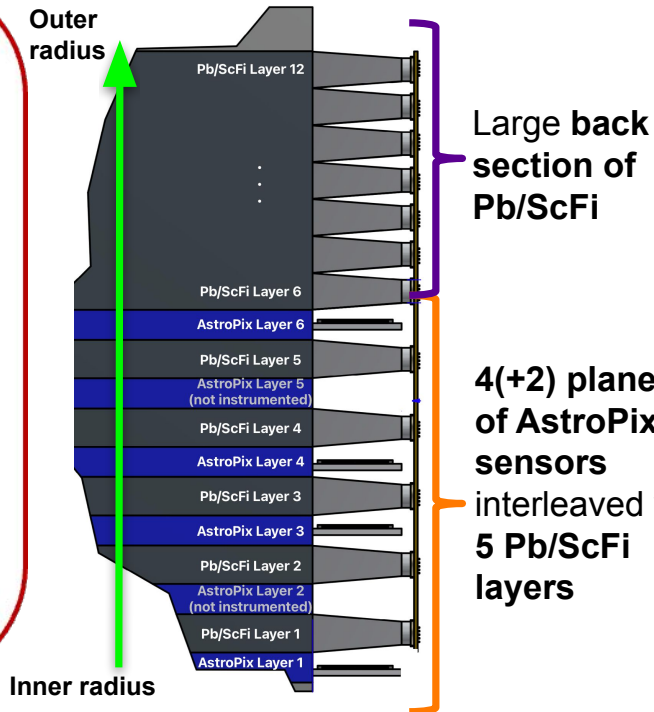
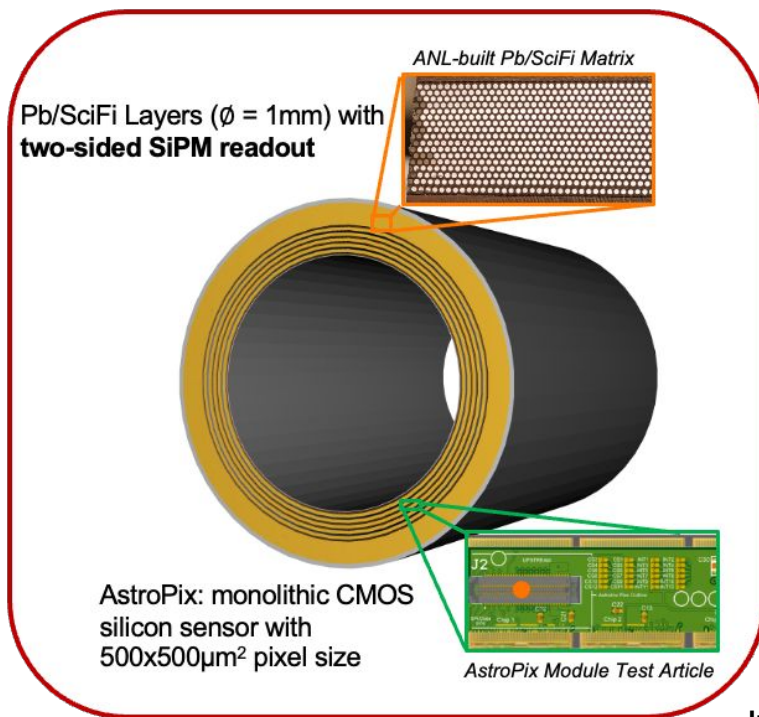
Start from mature layered Pb/SciFi technology with side-readout (same as the GlueX calorimeter) for state-of-the-art sampling calorimeter performance

The concept of Barrel Imaging Calorimeter (BIC)

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

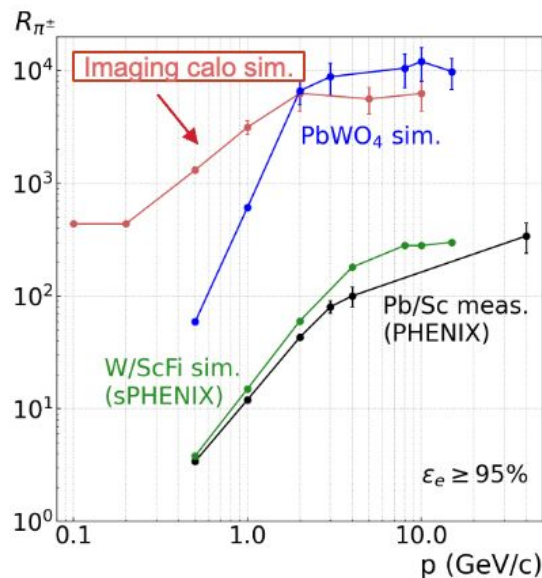
Energy resolution - Primarily from Pb/ScFi layers (+ AstroPix energy information)

Example: 3D Shower Imaging for electron selection

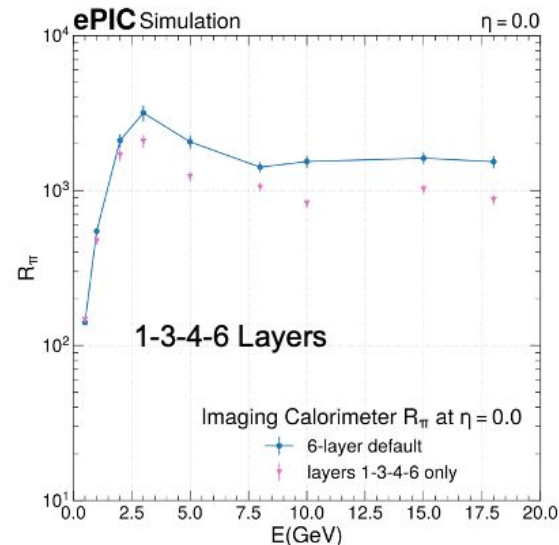
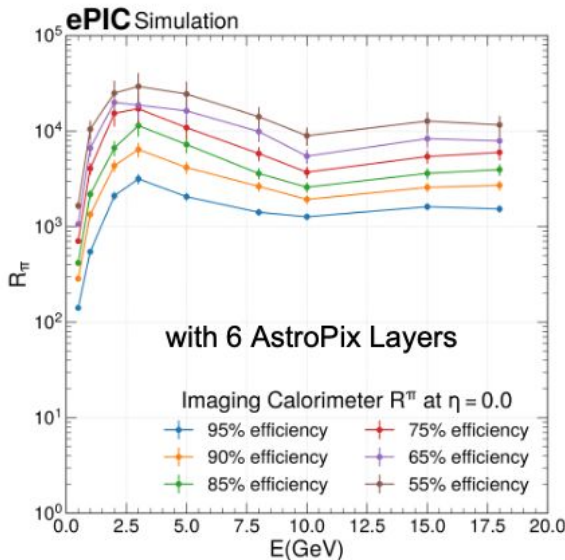


The concept of Barrel Imaging Calorimeter (BIC)

Standalone simulation



Realistic ePIC simulation



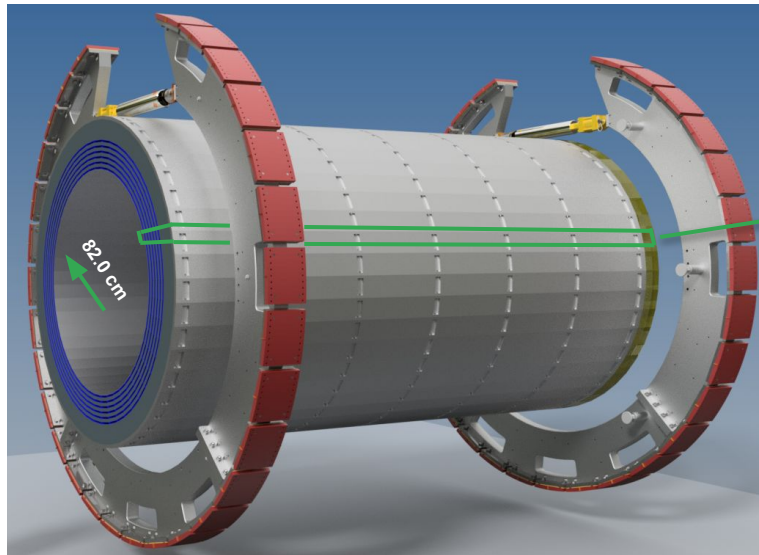
Goal: Separation of electrons from background in Deep Inelastic Scattering (DIS) processes

Method: **E/p cut (Pb/ScFi) + Neural Network** using **3D position and energy info** from imaging layers

Eventually will perform holistic reconstruction, incorporate SciFi/AstroPix information together in ML

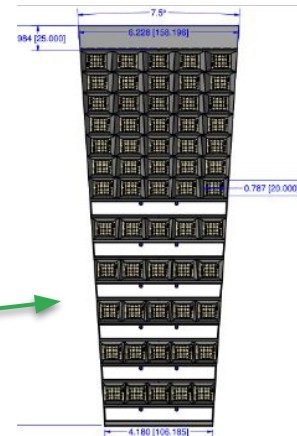
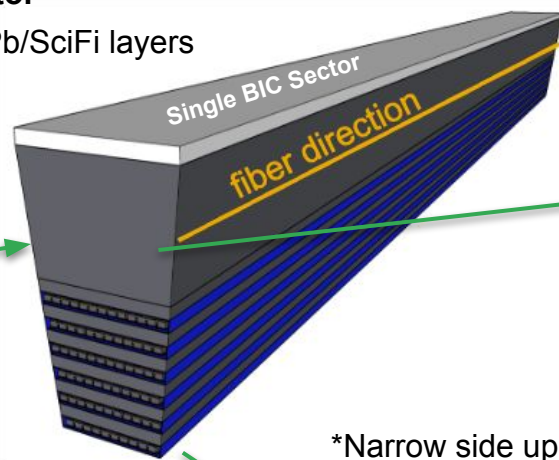
e- π separation exceeds **10^3** in pion suppression at **95% efficiency** above 1 GeV in realistic conditions!

The BIC Design



Sector

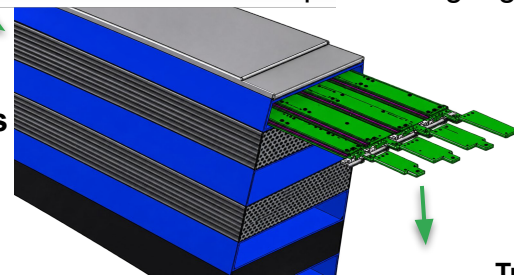
12 Pb/SciFi layers



Pb/SciFi layer ($1.4X_0$)
5 per layer x 12 layers
1 light guide per cell

**4(+2) layers of
AstroPix interleaved
with 5 Pb/SciFi layers**

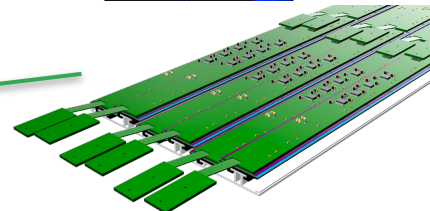
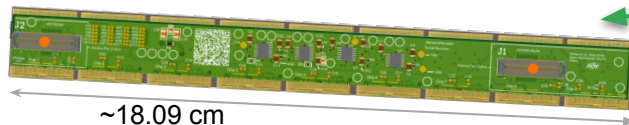
*Narrow side up



AstroPix Module - Nine AstroPix sensors
daisy-chained together on Flex PCB.

A stave consists of 12 modules.

A tray contains of 6-7 staves.



Tray - Structure
holding the AstroPix
staves for a single
layer (217.5 cm
long).

Length: ~435 cm

Inner Radius: ~81.5 cm

Structure: 48 sectors

η Range: $-1.71 < \eta < 1.31$

Depth: $17.1X_0$ at $\eta = 0$

Sampling fraction: ~10%

Pb/ScFi Layers

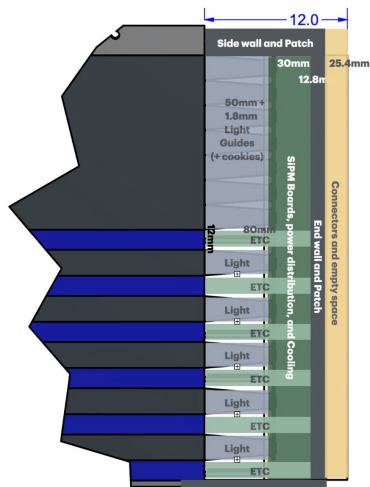
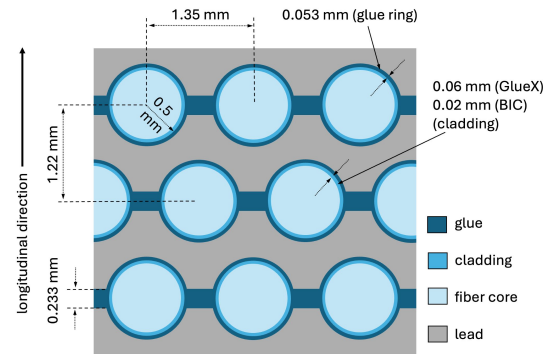
Matured design - Pb/ScFi layers follow the GlueX BCAL

Energy resolution at GlueX:

- $5.2\% / \sqrt{E} \oplus 3.6\%$ from GlueX extracted for low energy $\gamma < \sim 2.5$ GeV ⁽¹⁾
- Constant term for energy up to 10 GeV constrained at FNAL and Hall D: $\sim 1.5\%$

Position resolution in z:

- $1.1\text{cm}/\sqrt{E}$ 2-side SiPM readout, Δt measurement ⁽²⁾



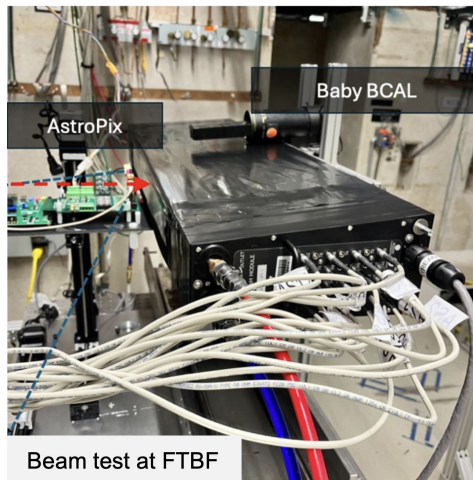
Pb/ScFi:

- light guides
- cookies
- SiPMs
- SiPM amp/sum boards (UofR)
- CALOROC
- LMS system (KNU)

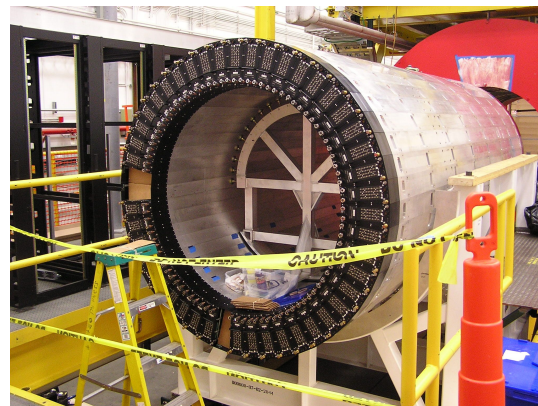
Tracker:

- ETC: End of Tray Card for AstroPix readout

Cooling



Beam test at FTBF



- 1) Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018
- 2) Nucl. Instrum. Meth. A, vol. 596, pp. 327–337, 2008

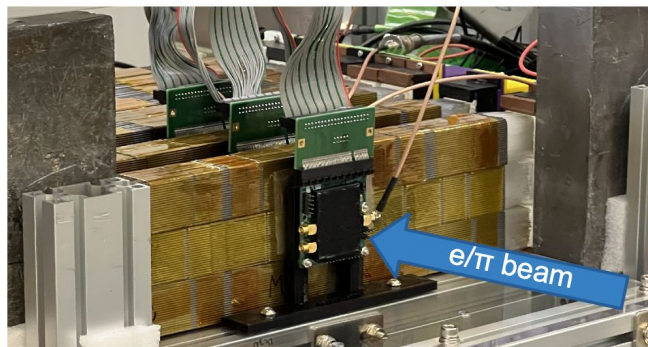
Imaging Layers

HV-CMOS Monolithic Active Pixel Sensor (MAPS)

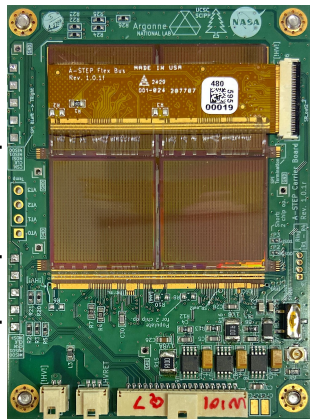
J. Bok, AstroPix-SciFi/Pb Beam Test in KEK

AstroPix (based on ATLASPix3 arXiv:2109.13409)

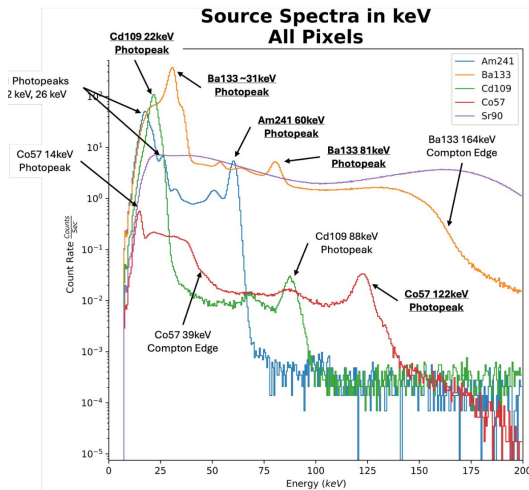
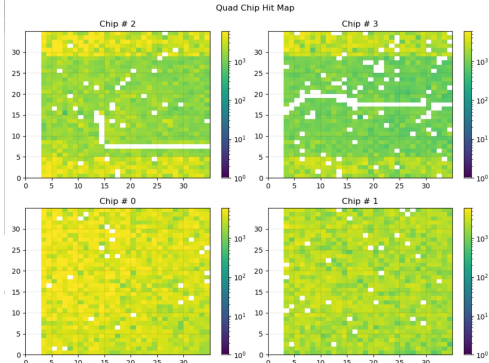
- 180nm HV-CMOS MAPS sensor designed at KIT (also designed ATLASPix, MuPix, etc.)
- Developed for **AMEGO-X GSFC/NASA mission** (Upgrade to the Fermi's LAT)
- Low power consumption < 2 mW/cm²
- Energy resolution target of 10% @ 60keV
- 500 μm $\times$ 500 μm pixel pitch, 525 μm thickness



Astropix quadchip board



AstroPix v4

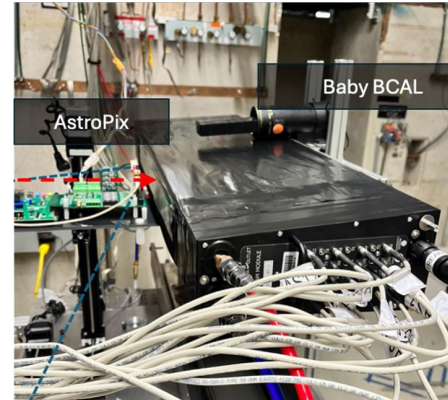


AstroPix v4

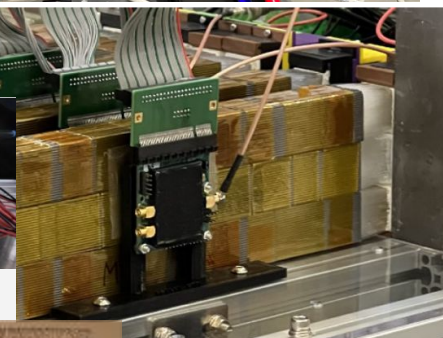
Technology Advancement - Pb/SciFi

Testbeam campaigns and test articles

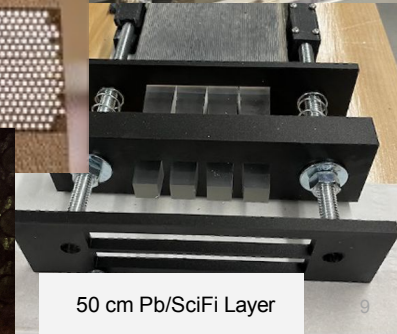
- FTBF 2024: Beam test with the Baby BCAL (GlueX BCAL prototype)
 - 60 cm transverse size, $15.5 X_0$ depth
 - 40 light guides and 40 SiPMs per side
- KEK 2024/ CERN 2025: First Pb/SciFi test article by BIC S. Korea team
 - 32 cm transverse size, $17.4 X_0$ depth
- Built and tested Pb/SciFi test articles
 - Pb/SciFi calorimeter layers at Argonne for production development & tolerance optimization
 - 50 cm transverse size, $1.4 X_0$ depth
 - 4 light guides and 4 SiPMs per side
 - Tested at JLab Hall D testbeam summer 2026
 - SciFi + AstroPix synchronization tested
 - HGCROC readout commissioned (first time for BIC)
 - BIC S. Korean team replicated the test article
 - CERN beam test in Aug. 2026



Pb/SciFi test article built by BIC S. Korea team



Argonne-built lead-scintillating fiber matrix

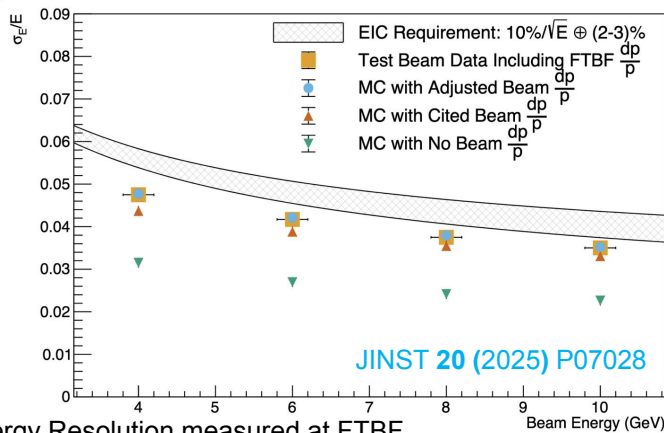


50 cm Pb/SciFi Layer

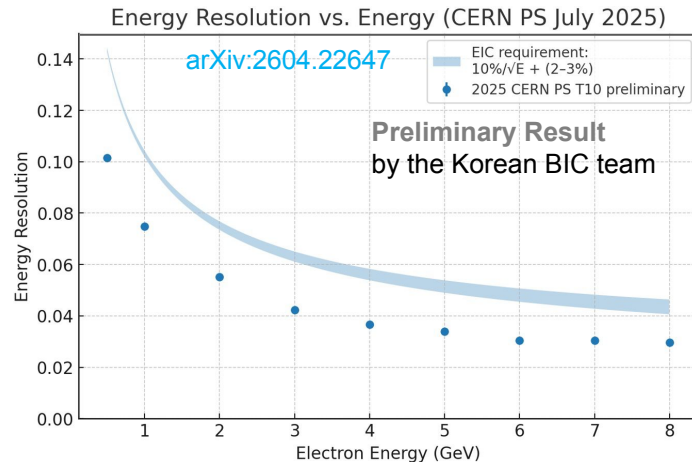
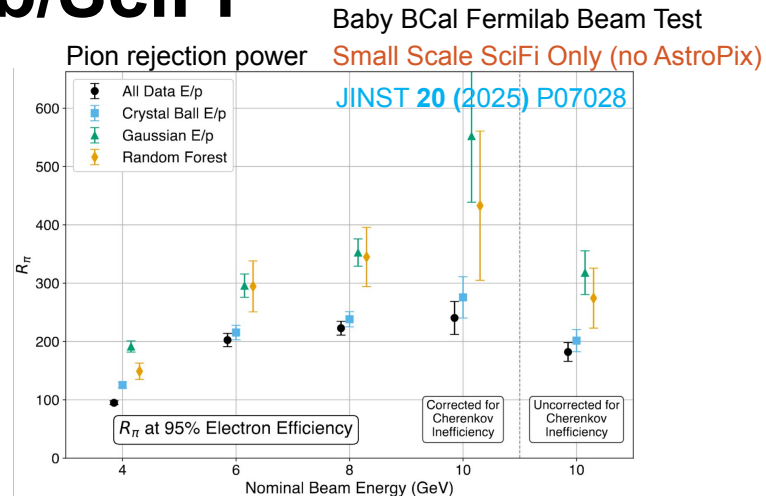
Technology Advancement - Pb/SciFi

Detector performance test results

- Electron energy resolution meets the EIC Barrel Ecal requirements
 - FTBF 2024 - 15.5 X_0 Baby BCAL
 - CERN 2025 - 17.4 X_0 Pb/SciFi test article
 - Requirement achieved with the first test articles
- BIC: e- π separation exceeds 10^3 in pion suppression at 95% efficiency above 1 GeV
- Response to pions and electrons benchmarked in Beam Test for the SciFi/Pb technology only (AstroPix not included)



Electromagnetic Energy Resolution measured at FTBF

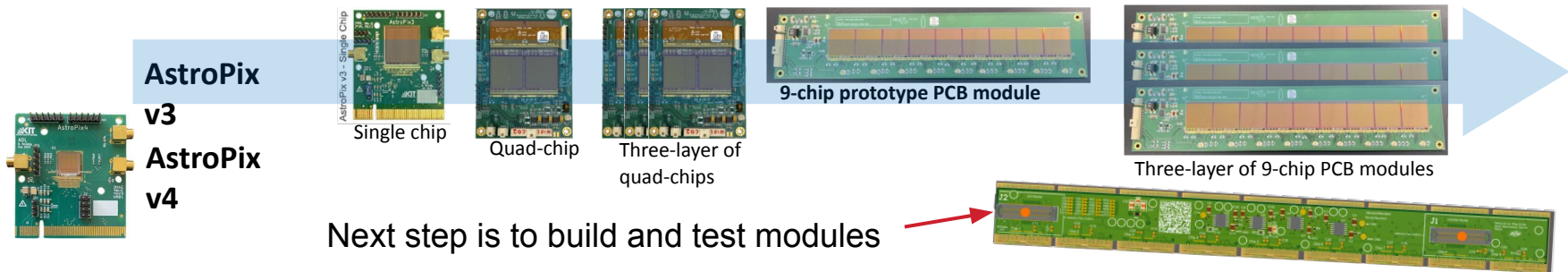
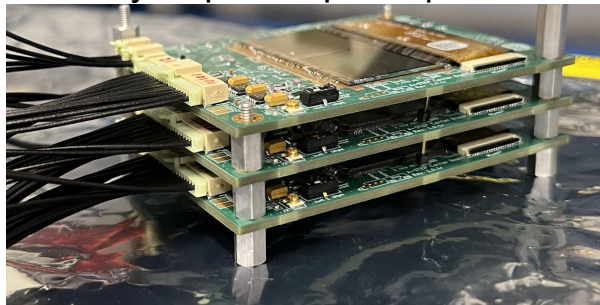


Technology Advancement - AstroPix

Testbeam campaigns and test articles

- In-lab bench as well as testbeam testing at FTBF, KEK, DESY, and CERN (Astropix version 3 and 4)
 - BIC collaboration as well as NASA-AstroPix Collaboration efforts
 - Characterization, energy calibration, efficiency, depletion depth, optimization, etc
 - Multiple layer coincidence
 - MIP response and irradiation studies ongoing
- Synchronization of H2GCROC/CALOROC and A-STEP/ETC readout systems
- Expect to receive at end of this month
 - Latest AstroPix version 5
 - AstroLinux (Readout PCB) for BIC modules

Multi-layer quadchip setup at ANL



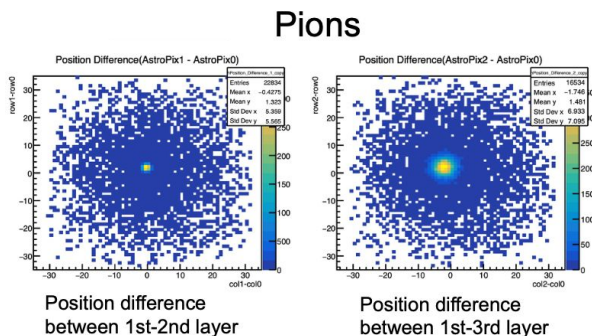
Next step is to build and test modules

Technology Advancement - AstroPix

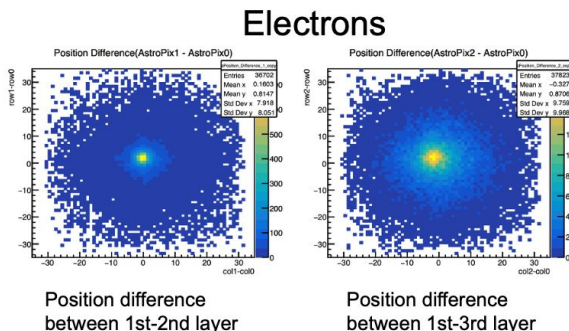
Detector performance test results

- AstroPix v3/v4 single/multi-chip bench and beam tests
- Efficiency and shower imaging demonstrated for v3 [2605.07681](#), [2602.06084](#)
- Absolute energy calibration developed and tested [2602.06084](#), [report](#)
- Multi-chip v3 operation demonstrated on bench and 2026 test beam campaigns [2511.05639](#)

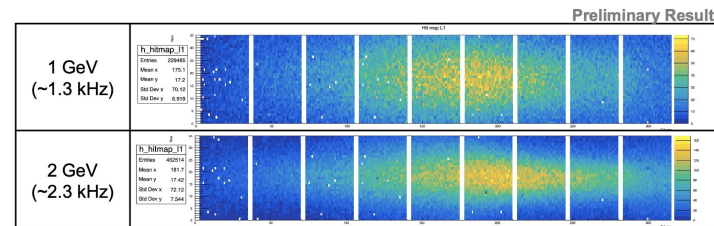
AstroPix single- and multi-chip performance and calibration have been demonstrated in beam and on bench.



[Arxiv: 2605.07681](#)

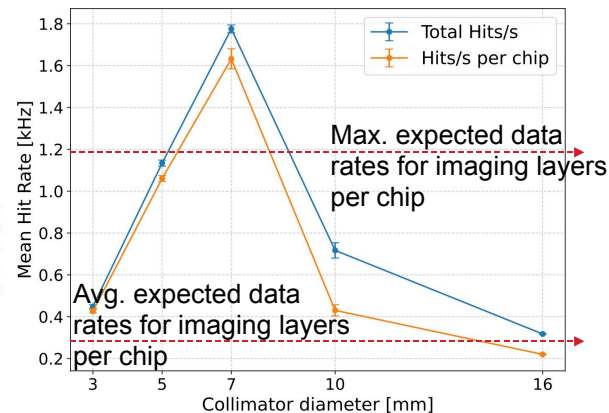


Current AstroPix chips provide the platform to develop and validate calibration, efficiency, and multi-chip test procedures for future versions.



The first beam test of the 9-chip PCB board, a first module test article showed stable operation up to 2.7 kHz beam rate

AstroPix v3 hit rates

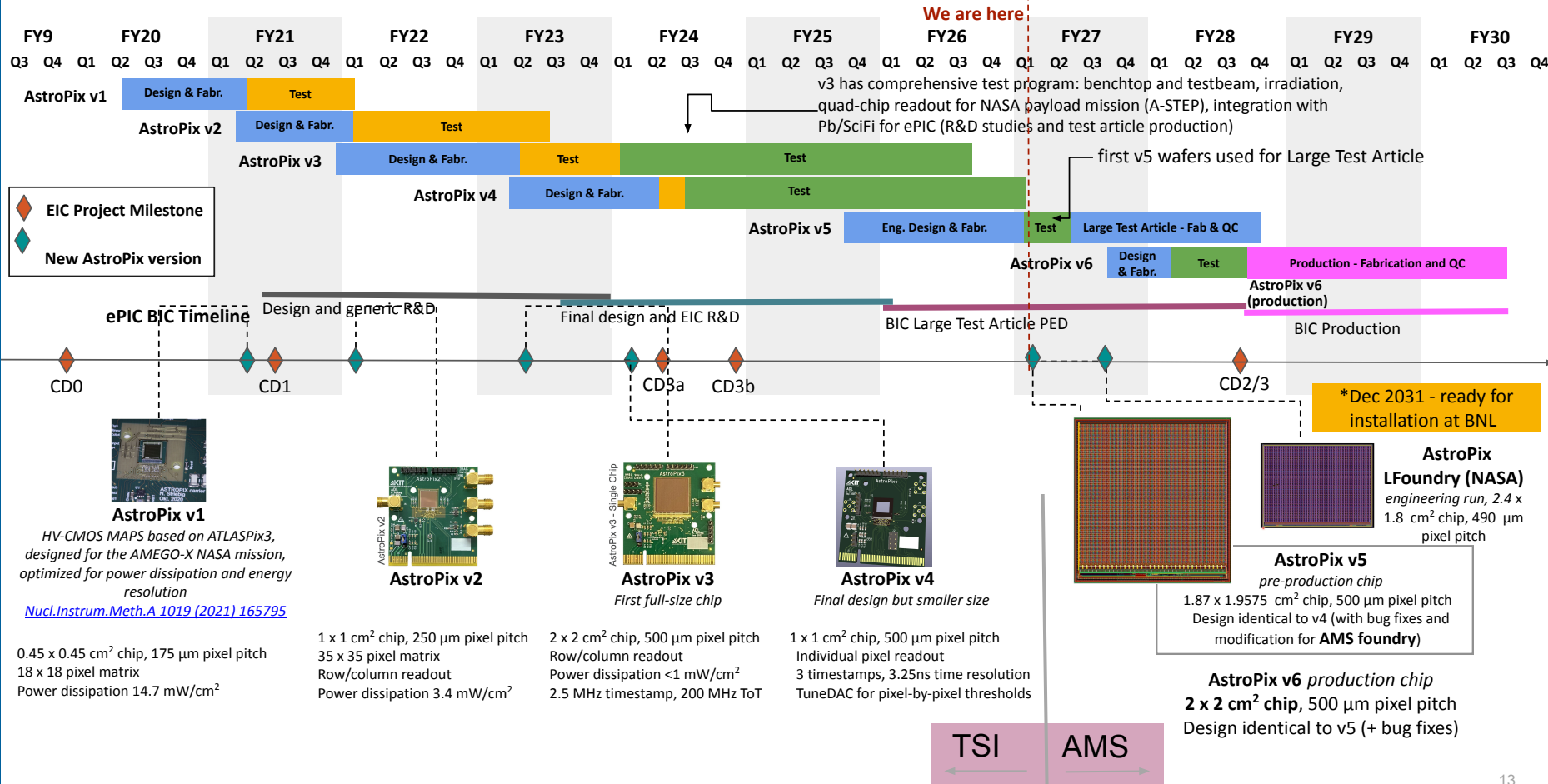


AstroPix v4-v5 response is much faster compared to AstroPix v3

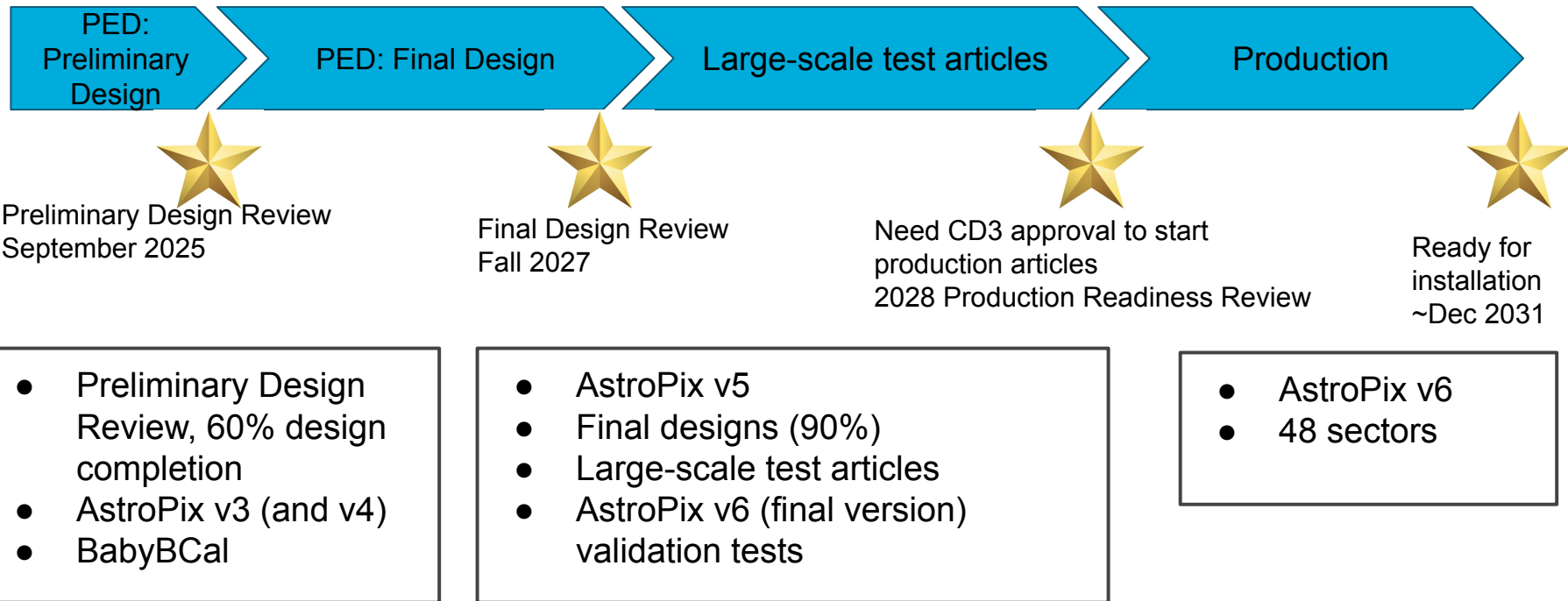
AstroPix Timeline

Not shown:
Early CD4 (Oct 2032)
CD4 (Oct 2034)

Test Readiness Review (TRR)
Critical Design Review (CDR)
Program Implementation Review (PIR)



BIC Project Phases



USA

Argonne National Laboratory



NASA Goddard Space Flight Center



Oklahoma State University



Oakridge National Laboratory



University of California Santa Cruz



University of Connecticut



Purdue University



University of Colorado Boulder



Canada

University of Manitoba



University of Regina



Mount Allison University



Korea

Kyungpook National University



Yonsei University



University of Seoul



Pusan National University



Korea University



Sungkyunkwan University



Hanyang University



Gangneung-Wonju National University



Germany

Karlsruhe Institute of Technology



University of Giessen



BIC Collaborating Institutions

Summary

- Barrel Imaging Calorimeter for ePIC at EIC
 - Consist of two sub detectors - Hybrid lead/scintillating fiber calorimeter and AstroPix silicon tracker
- Excellent energy and spatial resolution
 - Exceptional electron–pion discrimination at low energies by integrating energy measurements with shower imaging
 - High-performance sampling calorimeter with Si sensors provide precision 3D shower profiling
- Current Focus
 - Final design optimizations driven by simulations, engineering design and testing
 - Work towards Final Design Review
 - AstroPix v5 chip testing and test article building
 - Large scale sector (Pb/SciFi+AstroPix) building and testing

5th BIC Workshop at ANL, Jun 2026



Test Beam at CERN, 2025



Test Beam at Jefferson Lab, 2026

Thanks!

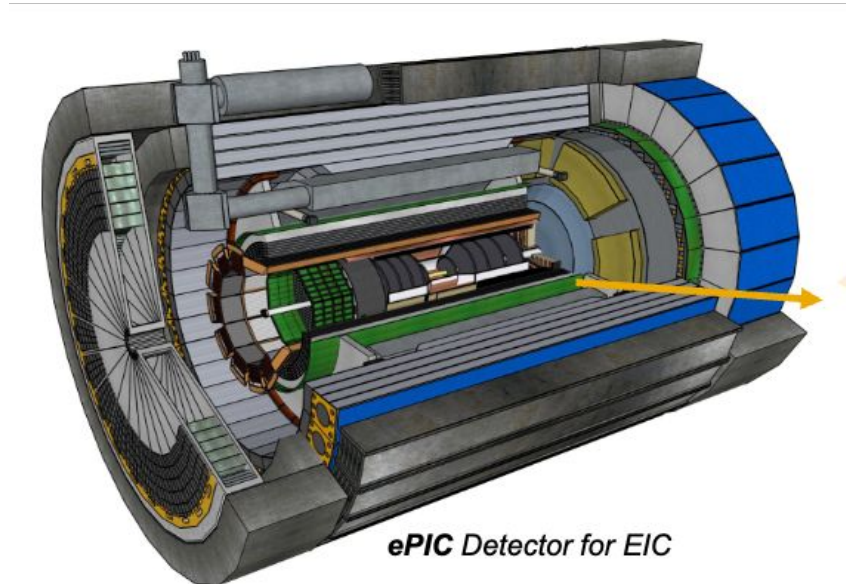
Backup

Detector Requirements for Barrel ECal

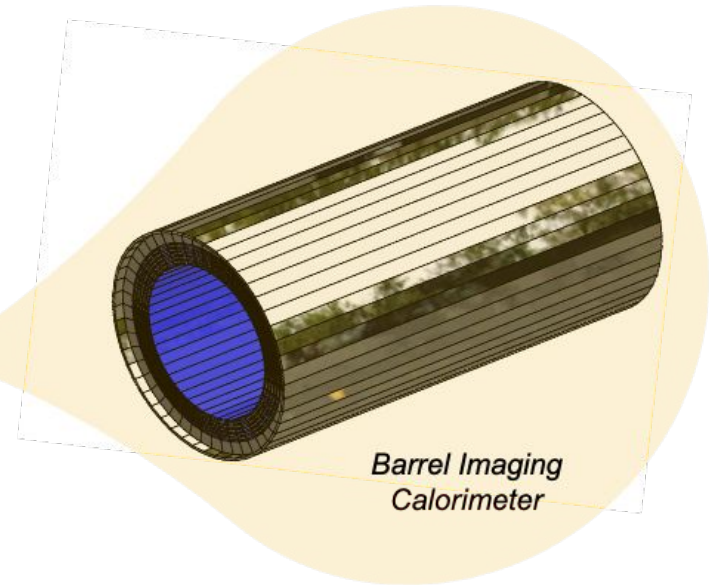
These stringent requirements for Barrel Electromagnetic Calorimeter can be achieved using Hybrid lead/scintillating fiber calorimeter with a silicon tracker

Precisely measure 3D image of electromagnetic shower

- Barrel Imaging Calorimeter (BIC)



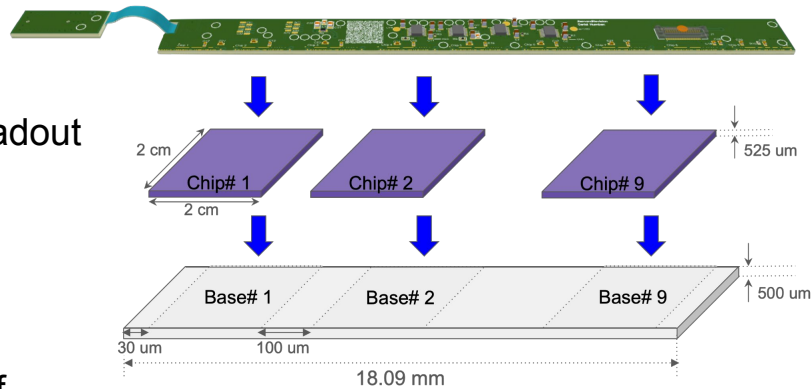
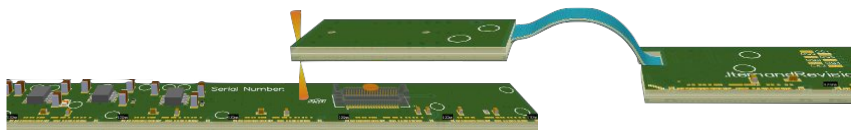
ePIC Detector for EIC



*Barrel Imaging
Calorimeter*

The BIC Imaging Layers

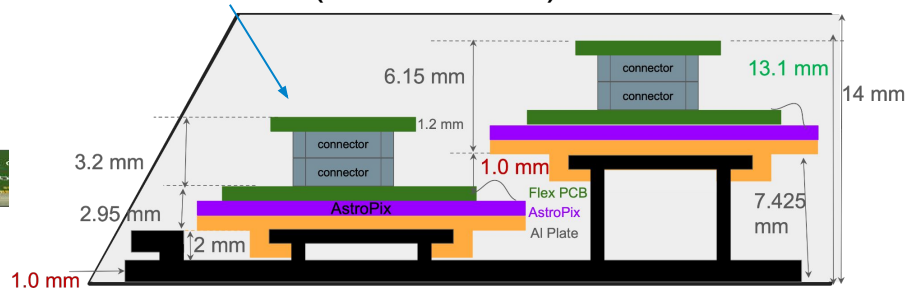
- **Module** is a elementary unit for imaging layers
 - **9 AstroPix HV-CMOS chips** with rigid-flex readout
- It consist of three components
 - Aluminum base rail plate
 - AstroPix chips
 - Hybrid rigid-flex PCB
- 12 modules forms a Stave and readout at the end of Sector using End of Tray Card (FPGA) (~217cm)
- Tray consists of (6, 7, 7, 8) Staves (56 Staves/Sector)
- There are total 48 sectors with length of ~435 cm
- The BIC is made up of 31104 Modules using ~280k chips
- The silicon active area is ~ 100 m²



Module (9 chips)

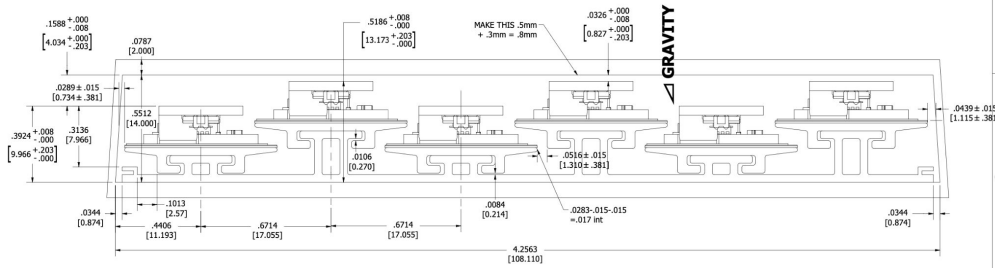
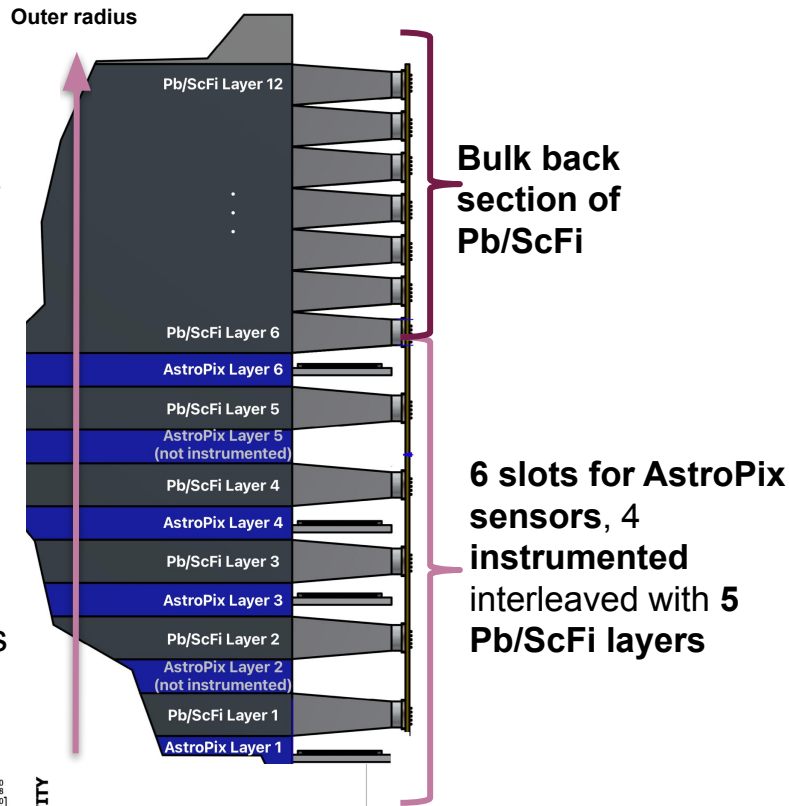


Stave (12 modules)



The BIC Imaging Layers

- **Module** is a elementary unit for imaging layers
 - **9 AstroPix HV-CMOS chips** with rigid-flex readout
- It consist of three components
 - Aluminum base rail plate
 - AstroPix chips
 - Hybrid rigid-flex PCB
- 12 modules forms a Stave and readout at the end of Sector using End of Tray Card (FPGA) (~217cm)
- Tray consists of (6, 7, 7, 8) Staves (56 Staves/Sector)
- There are total 48 sectors with length of ~435 cm
- The BIC is made up of 31104 Modules using ~280k chips
- The silicon active area is ~ 100 m²
 - All this made up of **AstroPix**

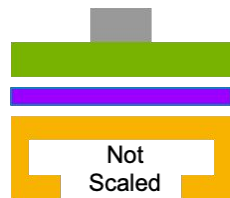


Modules Assembly

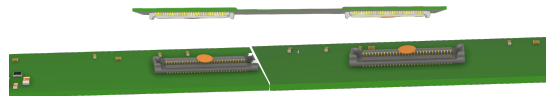
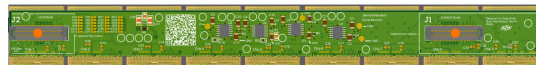
Assembly and Loading procedure

- Chip to module base & AstroLinX alignment tooling design completed & under fabrication, ready December 2026
- 3D printed assemblies under trial using dummy silicon chips with wire bonding
- Performed several trials for encapsulations (TBC)
- Build full-scale modules with v5 spring 2027

Module Stackup:



1.7 mm - Connector
 1.2 mm - AstroLinX
 0.1 mm - Glue
 0.525 mm - AstroPix
 0.1 mm - Glue
 1 mm - Module Baseplate

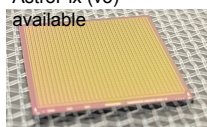


Adjacent Modules connected using flex bus bar

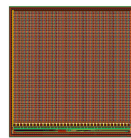
AstroLinX (v3) - Reviewed (ready for Fabrication)



AstroPix (v3) - available



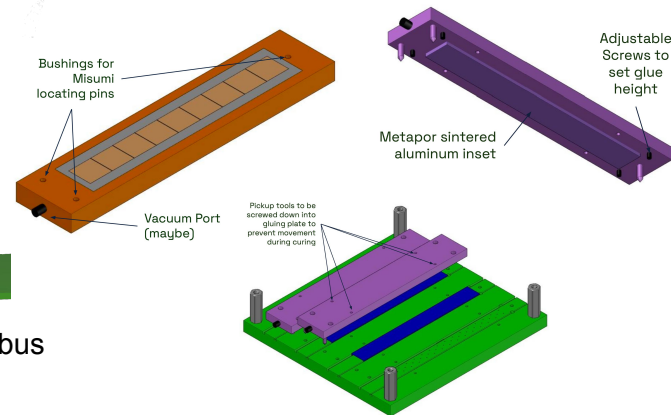
AstroPix v5 (preproduction)



First test article - module base with stave like railing

AstroLinX

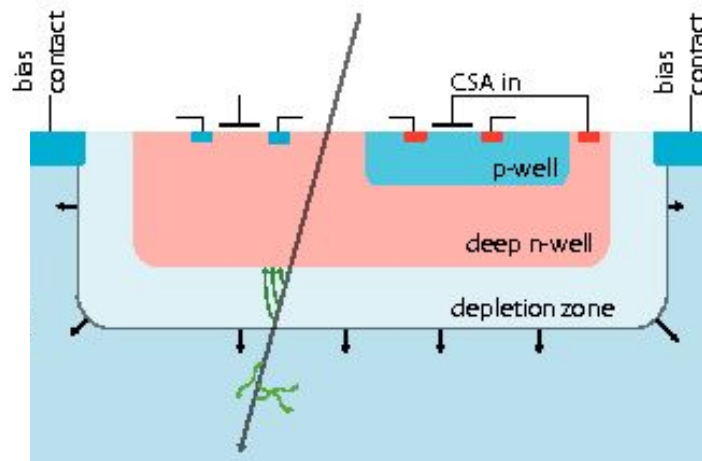
- Initial electrical design validated through 9-chip PCB
- AstroLinX PCB first test article under fabrication (expected November 2026)
- Final design of AstroLinX with AstroPix v5 ongoing
 - expect fabrication submission in Jan 2027



AstroPix

HV-CMOS Monolithic Active Pixel Sensor (MAPS):

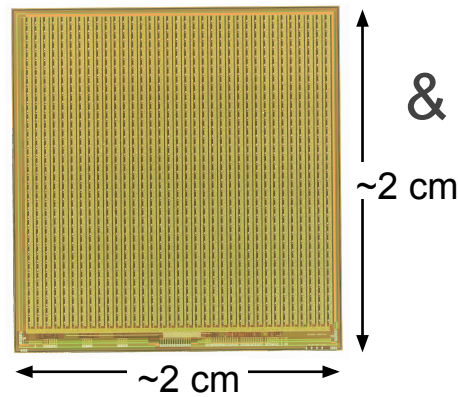
- Combination of silicon pixel & Front-End ASIC
- On-pixel charge amplification and digitization
- Technology uses more typical CMOS wafer processing for cost effective mass production
- Fabrication on single wafer enables shorter design cycle
- No need to bump-bond to each pixel - improves yield



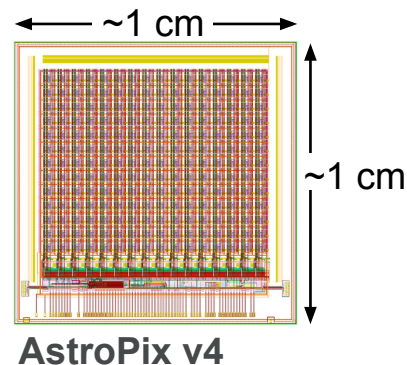
AstroPix (based on ATLASPix3 [arXiv:2109.13409](https://arxiv.org/abs/2109.13409))

- 180nm HV-CMOS MAPS sensor designed at KIT (also designed ATLASPix, MuPix, etc.)
- Developed for AMEGO-X GSFC/NASA mission (Upgrade to the Fermi's LAT)
- Power consumption $< 1.5 \text{ mW/cm}^2$
- Energy resolution target of 2% @ 662keV

AstroPix v3



&

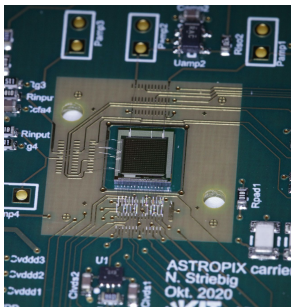


Overview of AstroPix

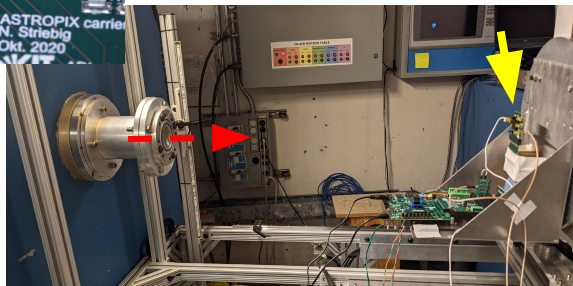
Monolithic Silicon CMOS sensor for gamma-ray astrophysics

2020 AstroPix_v1

First prototype:
testing and
characterization

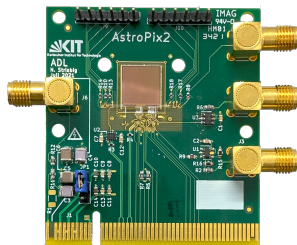


Design based
on HV MAPS
~20 years of
development
at KIT



2021 AstroPix_v2

Second prototype



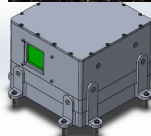
Radiation testing April,
June 2022

2023 AstroPix_v3

Flight prototype and final design



3-layer
Quad-chip
Payload
Launch:
Fall 2025

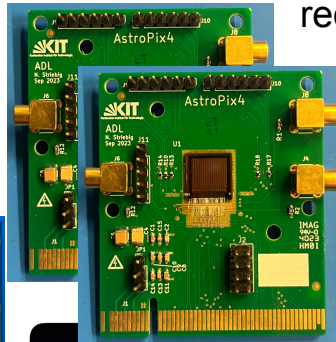


Beam Test
FNAL
2023, 2024*



2024 AstroPix_v4

Pixel readout, power
reduced



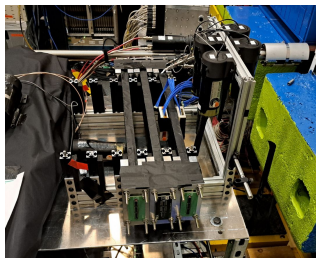
All produced by
TSI
Semiconductors

AstroPix selected for BIC

TestBeams



From detector components to integrated system tests



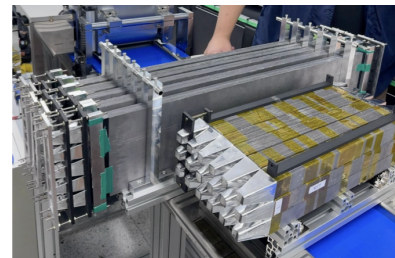
May 2026: Commissioning Hall D + KEK

Bulk + SFILs + 4/9-chip AstroPix
production SiPMs + HGCROC



Aug 2026: Hall D e⁻ beam

Bulk + 5 SFILs (ANL built) + 9-chip AstroPix
production SiPMs + HGCROC



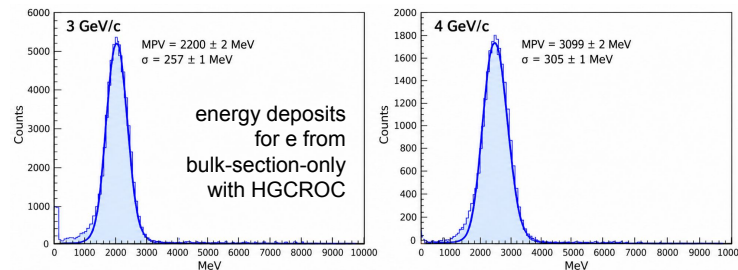
Aug 2026: CERN e⁻/pion beams

production-style fiber Bulk + 5 SFILs (Korea built)
production SiPMs/LGs + HGCROC

2026 system-test accomplishments

- HGCROC readout commissioned (first time for BIC)
- Multi-element BIC configurations operated in beam
- SciFi + AstroPix synchronization tested
- e⁻ and hadron data collected for energy/position reconstruction

Analysis in progress: synchronization, energy and position resolution



BIC system testing has progressed from component validation to beam operation of increasingly integrated test articles.

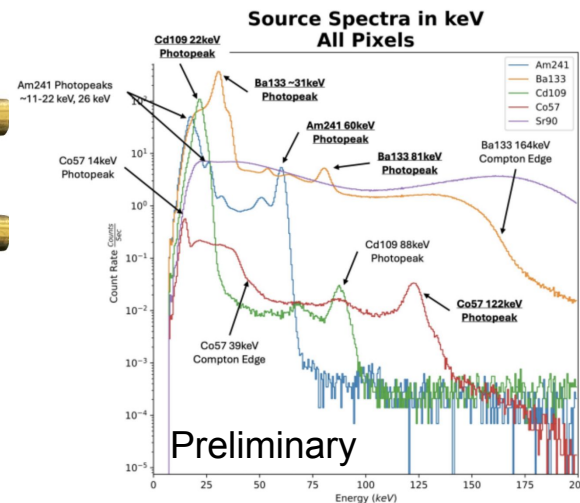
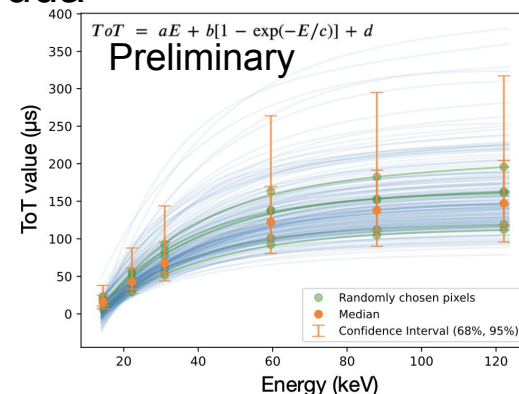
Next: baseline-electronics / CALOROC engineering-test-article validation. Tests of long and thick SciFi w/ AstroPix v5.

AstroPix v4

*Yusuke Suda Energy calibration curves

AstroPix v4 : Final design engineering version

- Chip size $1 \times 1 \text{ cm}^2$; Thickness $700 \text{ }\mu\text{m}$, $V_{\text{BD}} \sim 400\text{V}$
- Pixel pitch $500 \text{ }\mu\text{m}$ with pixel size $300 \text{ }\mu\text{m}$, 16×16 pixel matrix
- Individual pixel readout with individual hit buffer
 - No identification issue due to ghost hits
- 3 Timestamps - 2.5MHz (TS), 20 MHz (Fine TS), and 16 bit Flash TDC
 - Fast ToT and Timestamp with 3.125 ns time resolution
- TuneDACs - Pixel-by-pixel threshold tuning and pixel masking
- Daisy Chain readout - pass hits to next chip through QSPI
- Self-triggered (reads out active hits)



*Grant Sommer

AstroPix v5 design specifications

Pixel Matrix:

- 36 cols x 34 rows
 - 32 Columns with Standard NMOS Comparator
 - 2 Columns with dynamic Feedback
 - 1 Column with NMOS Comparator and Resistor Load
 - 1 Column with NMOS Comparator and PMOS Load
- 500u Pixel Pitch and 300u Pixel Size
- 3 Tunebits per Pixel
- Pixel Dynamic Range 20 keV - 700 keV
- Noise Floor 5 keV (2% @ 662 keV)
- Bias Voltage up to 400-500 V to maximize depletion
- Fully NMOS Comparator
- In Pixel amplifier with Dynamic Feedback option for improved Dynamic Range

Power Consumption:

- Pixel 4.6 uW
 - Pixel matrix 5.3 mW
 - Digital 2.2 mW
 - 700 uW DigitalTop
- Total:** ~2 mW/cm² for 2x2 cm chip

AstroPix5 : ready for submission

